

Direct Detection of Dark Matter

- Signal or No Signal?
- The Best Way Forward

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(Supported by US DOE HEP)

see information at

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

<http://luxdarkmatter.org>

- Have we discovered WIMPs?
- Have we got what it takes to (re)discover them?
 - Acc: \$/TeV
 - I.D.: Weak Annihilation Signal from Dwarf Galaxies
 - D.D.: ~ 1 / kg / Century to < 1 / tonne / Century
- Complementarity
/ This Talk Focuses on Direct Detection

Dark Matter Underground Searches - Silver Jubilee in 2012

- First publication on an underground experimental search for cold dark matter (Ahlen et al. 1987. PLB 195, 603-608).

<http://www.pnnl.gov/physics/darkmattersymp.stm>



Volume 195, number 4

PHYSICS LETTERS B

17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

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Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy. Using a realistic model for the galactic halo, large regions of the mass-cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is $< 0.4 \text{ GeV/cm}^3$ for masses between 17.5 GeV and 2.5 TeV, at the 68% confidence level.

- 1986 operating a 0.8 kg Ge ionization detector at Homestake Mine, SD (adjacent to Ray Davis's operating Solar Neutrino Experiment)

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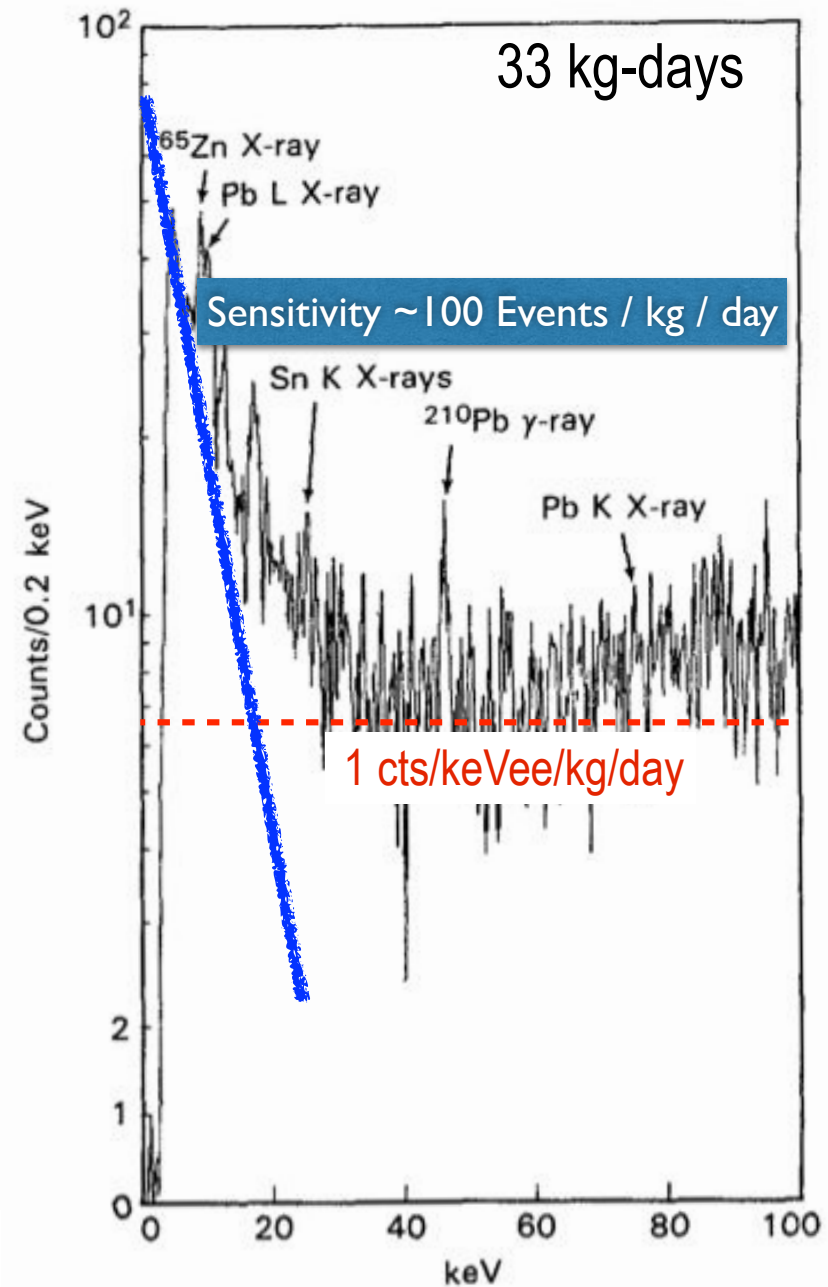
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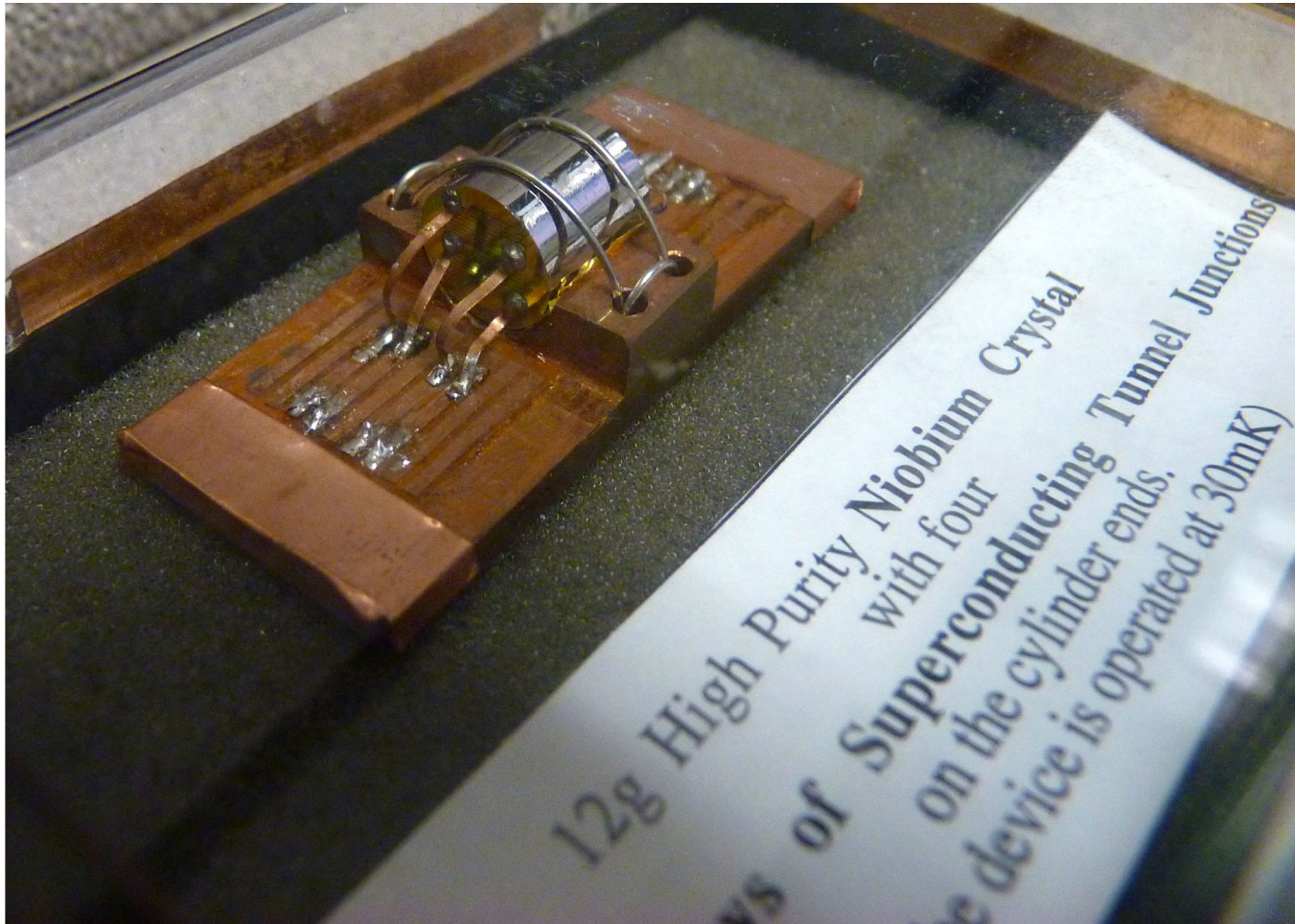
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An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy. Using a realistic model for the galactic halo, large regions of the mass-cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^2 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is $< 0.4 \text{ GeV/cm}^3$ for masses between 17.5 GeV and 2.5 TeV, at the 68% confidence level.



Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

- 1 cm long - 12 g - 250 eV Threshold - “One Careful Owner”

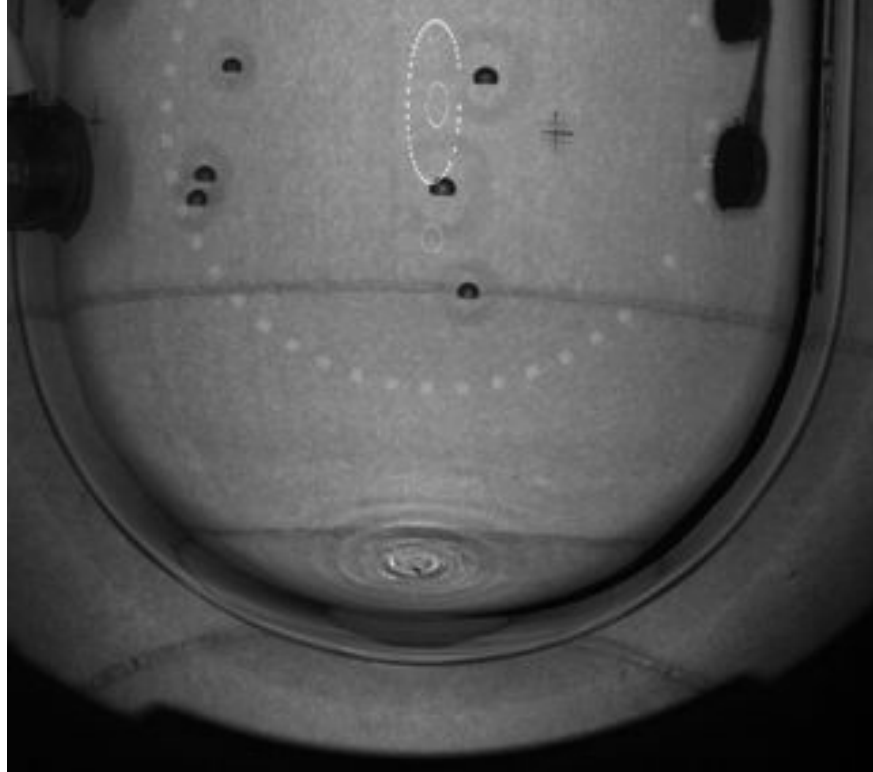


Idealized Dark Matter Direct Detection Experiment

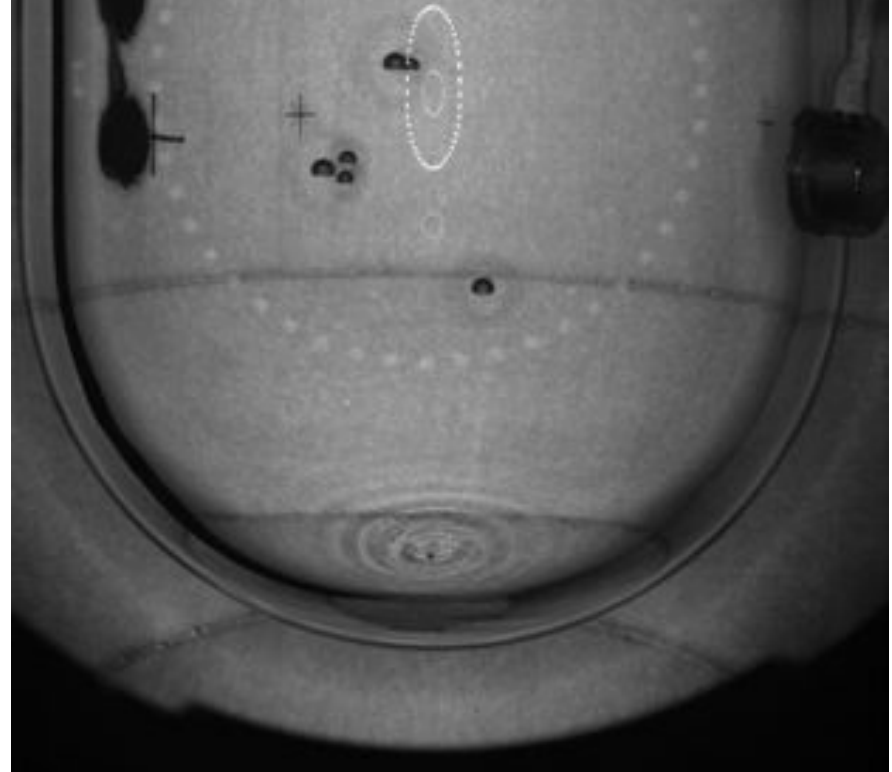
- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
 - ◆ We almost have this in PICO (COUPP) bubble chambers

COUPP-60

- Filled with 37 kg of CF_3I on April 26, 2013
- First bubble May 1, 2013 (radon decay)
- Installation completed May 31, 2013



- ~3000 kg-days of exposure between 9 and 25 keV threshold
- >1500 neutron source events
- Ultimate goal of 3 year run (50000 kg-days exposure)

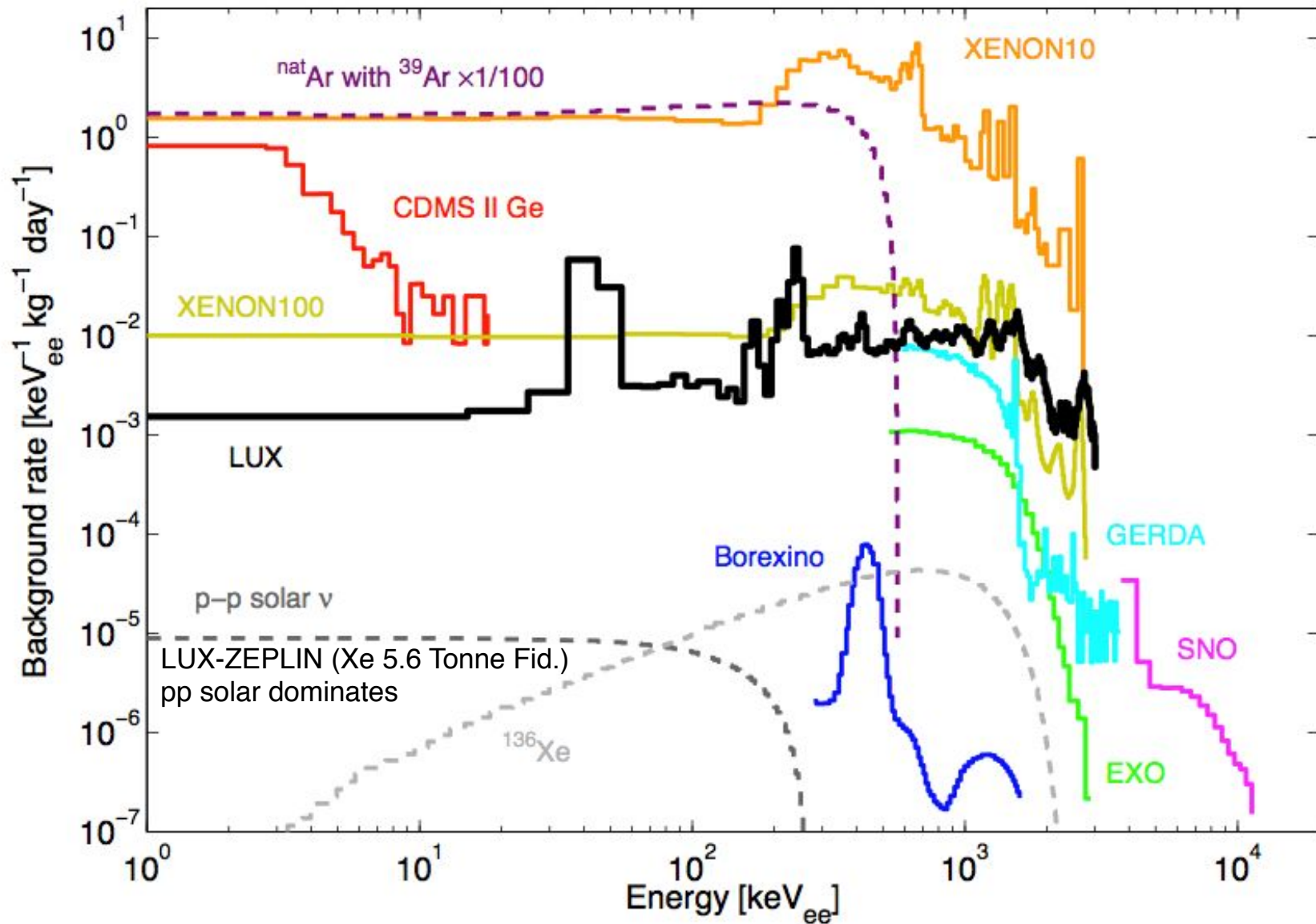


Idealized Dark Matter Direct Detection Experiment

- A Simple Binary Indicator that only registers nuclear/Dark Matter recoil events and nothing else - “Platonic ideal”
 - ◆ We almost have this in PICO (COUPP) bubble chambers
- However,
 - ◆ We will naturally be skeptical of the occasional events - do they fit the pattern
 - CF3I nuclear recoil events were time clustered
 - ◆ The absence of a dark matter beam off test means that it is particularly difficult to address the possibility of misidentification of backgrounds/systematic
- So we require more information about each event
and for the detector response to be as homogeneous as possible
 - ◆ We also want to do physics with recoil energy spectrum / target dependence
 - ◆ Maybe we can return to the platonic ideal ... reduce competing backgrounds

Reduction in Backgrounds

- Electron Recoil Events



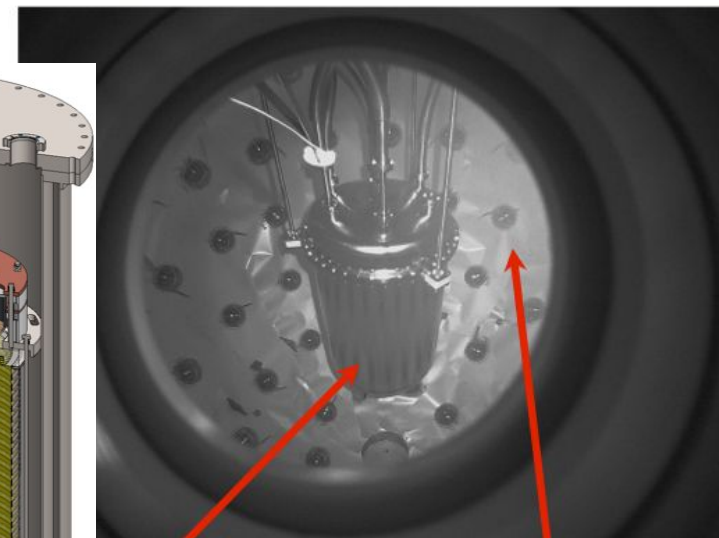
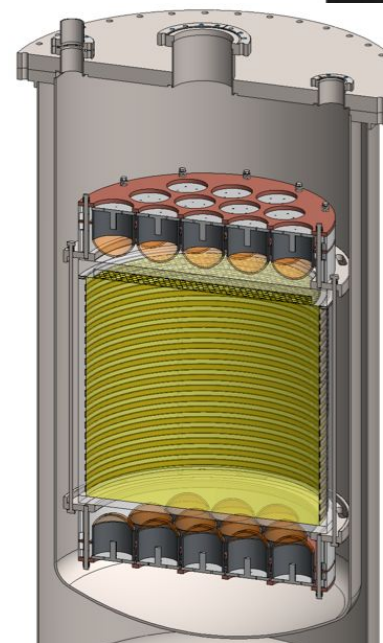
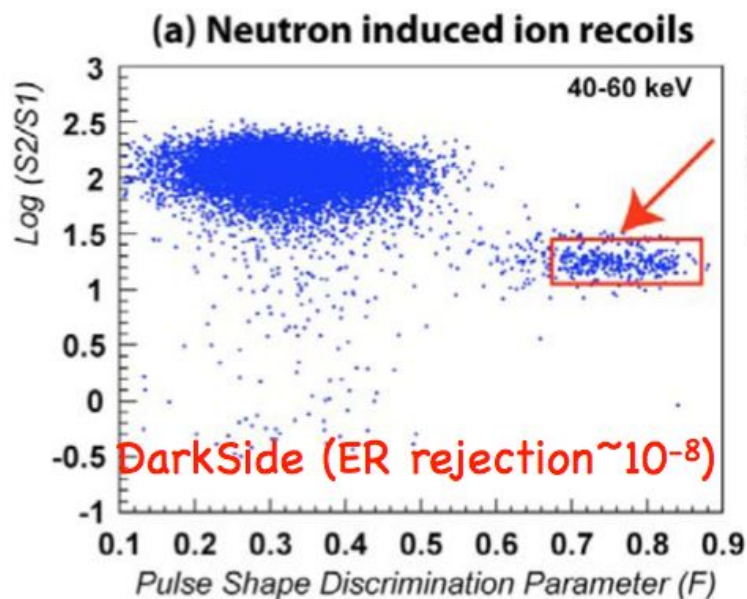
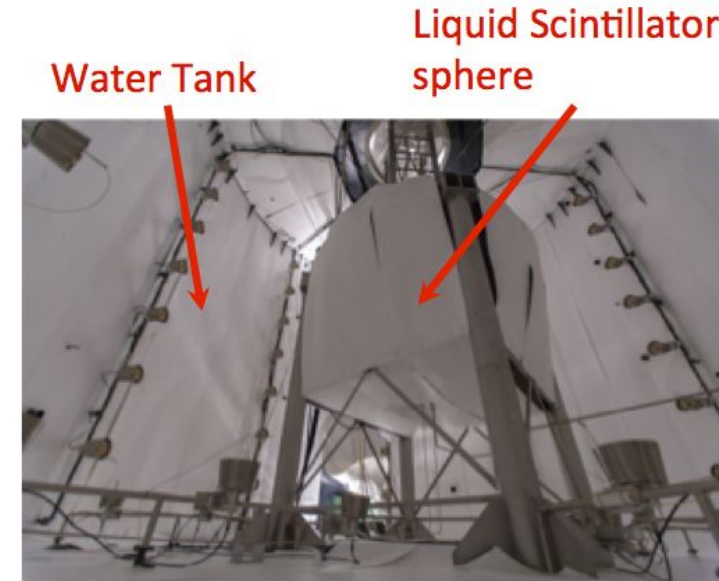
Thanks to David Malling, Brown, for preparing slide

Recent Key Sensitivity Improvements

- Some targets have been scaling in size significantly
 - ◆ Provides raw sensitivity for lower cross sections - Club Sub Zepto $<10^{-45}$ cm² (<1 events/kg/century)
 - In 2 years sensitivity to 50 GeV WIMPs has improved by a factor 10. Recent LUX detector sensitivity ~ 10 / kg / Century
- Low Mass WIMPs - energy thresholds very important for sensitivity
 - ◆ Improving energy sensitivity/thresholds
 - Greater rate of sensitivity improvement for low mass WIMPs, all the way down to 3 GeV WIMPs
 - ◆ Improvements => Potential Signals - seen in multiple detectors, motivated detector energy threshold reduction
 - ◆ We have re-spawned quite an industry - smaller mass detectors able to make interesting contributions
- Very Low Energy Calibrations (Electron Recoil + Nuclear Recoil) are being hotly pursued in a range of materials
 - ◆ Some calibrations are up-ending previous shibboleths
 - ◆ Others are showing convergence in the understanding of response of specific targets
- Importance of Background Calibrations/Discrimination with very High Statistics
 - ◆ Allows Convincing Use of Likelihood Models for Signal + Background
 - ◆ Accuracy of Monte Carlos has become remarkable good
 - ◆ But requires the right detector geometry/calibrations to be credible
- Improving understanding of the detector response/physics of target material
 - ◆ In 90's/00's we saw a lot of effort in phonon, quasiparticle, electron-hole
 - ◆ In 00's/10's have seen tremendous progress in photon/ionization, and superheated liquids

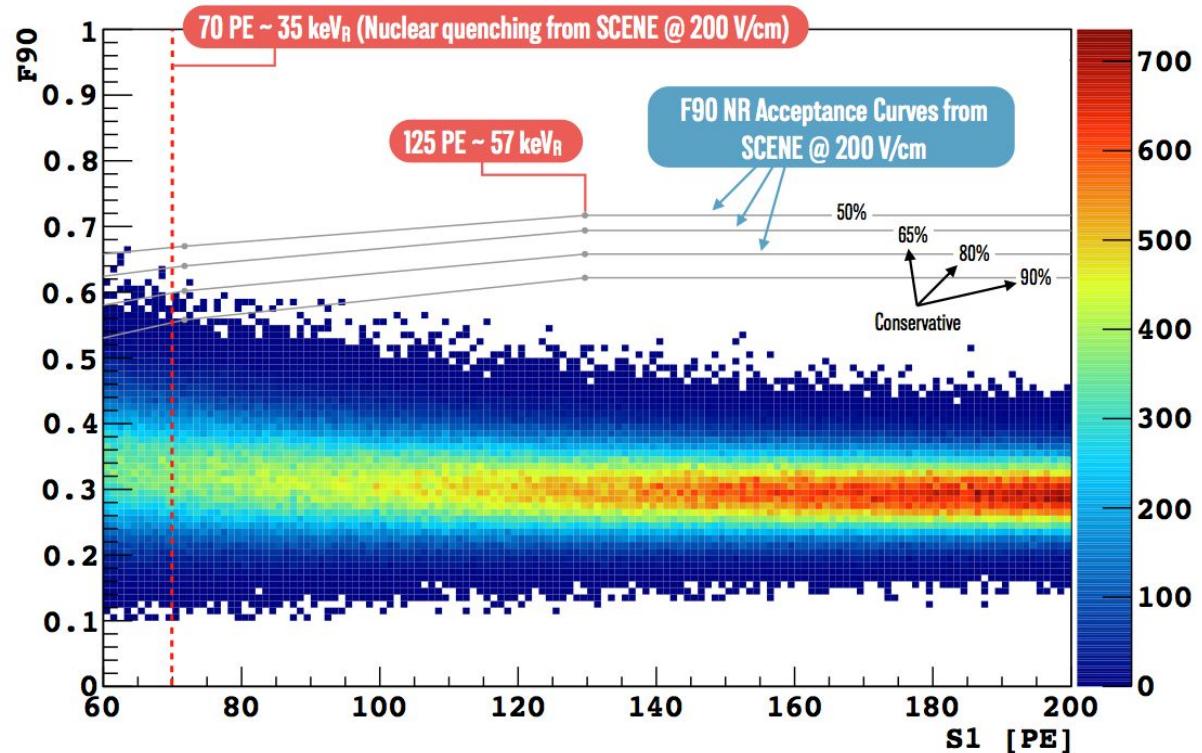
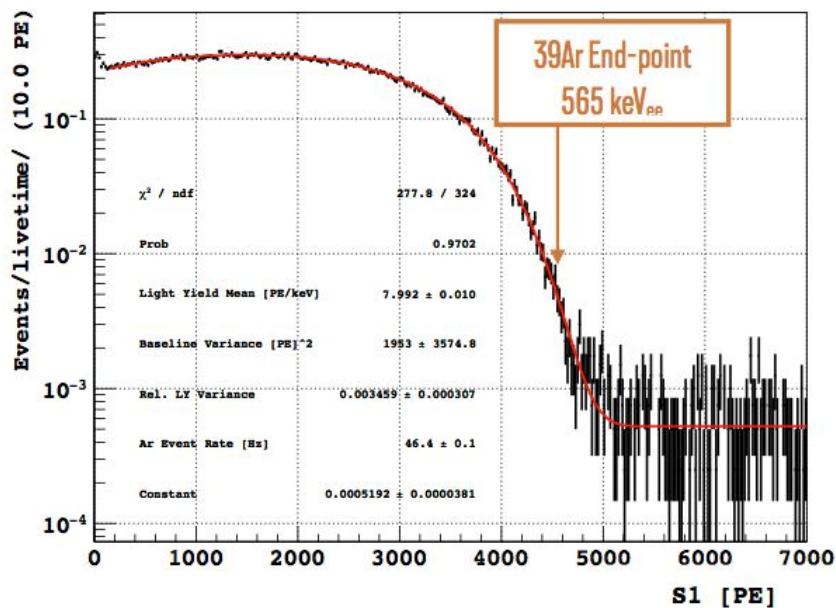
Darkside-50 First Results

- The DarkSide-50 has been operating @LNGS since Oct. 2013 with all three detectors filled
 - ◆ Ensure able to reject neutrons
- Commissioned using regular argon in order to measure PSD performance
 - ◆ Collect in a few days, the background from ^{39}Ar expected in few years of run with underground argon
- Results from 6 days operation



Darkside DS-50 Calibration

- Pulse shape discrimination based on the shape of primary light
 - ◆ Nuclear recoil pulses are faster => F90 is larger ~ 0.7 . Electron recoils F90 ~ 0.3
- ^{39}Ar intrinsic background used as ER calibration
 - ◆ 44 kg fiducial single scatters x 6.3 days = # of ^{39}Ar events equivalent to 2.6 year exposure with 1/200 th reduced ^{39}Ar



LUX in Water Tank - First Run 2013

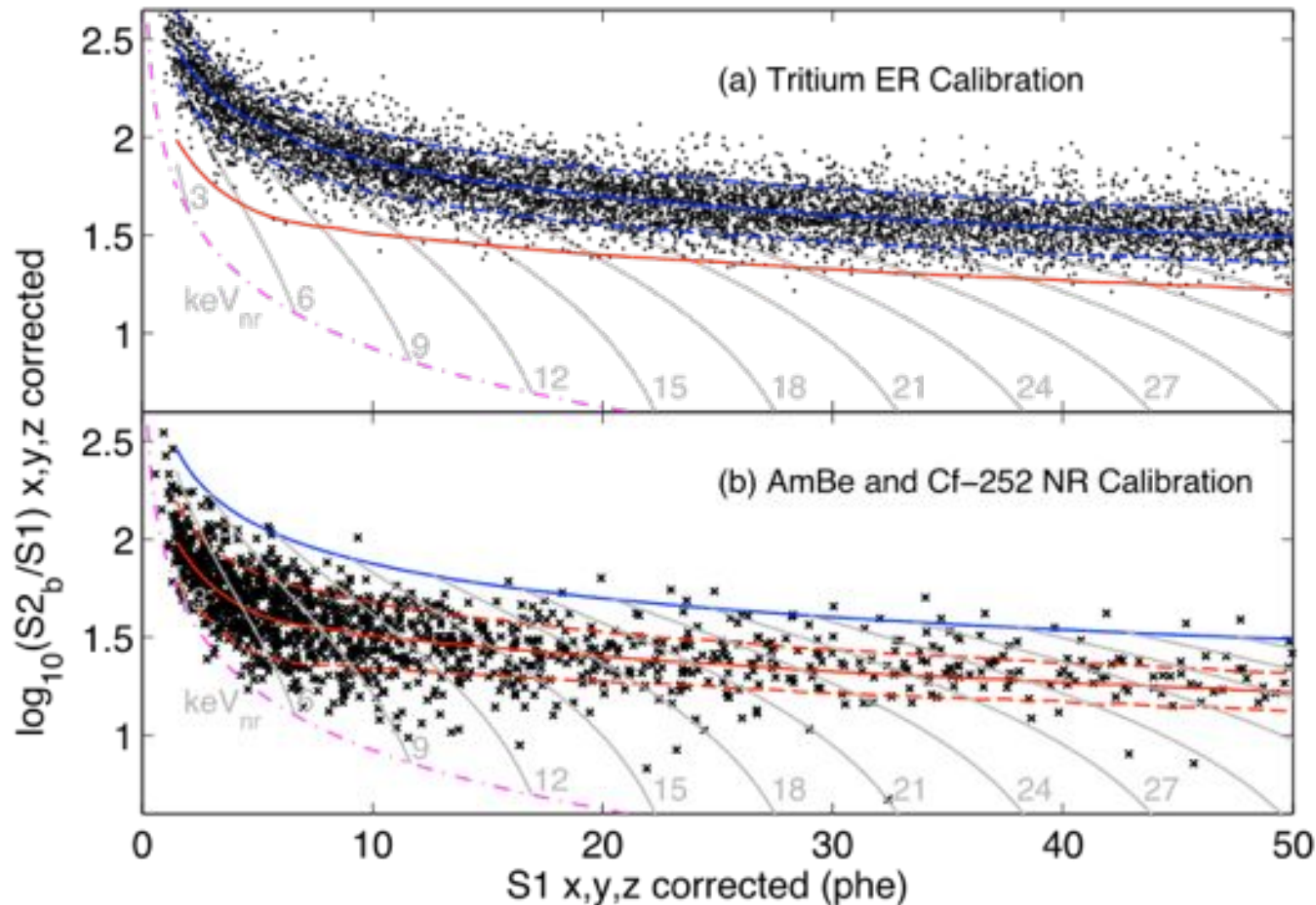


Alex Lindote, LIP-Coimbra, will be giving a talk on LUX results at this conference

www.sanfordlab.org

LUX - Electron Recoil and Nuclear Recoil Bands

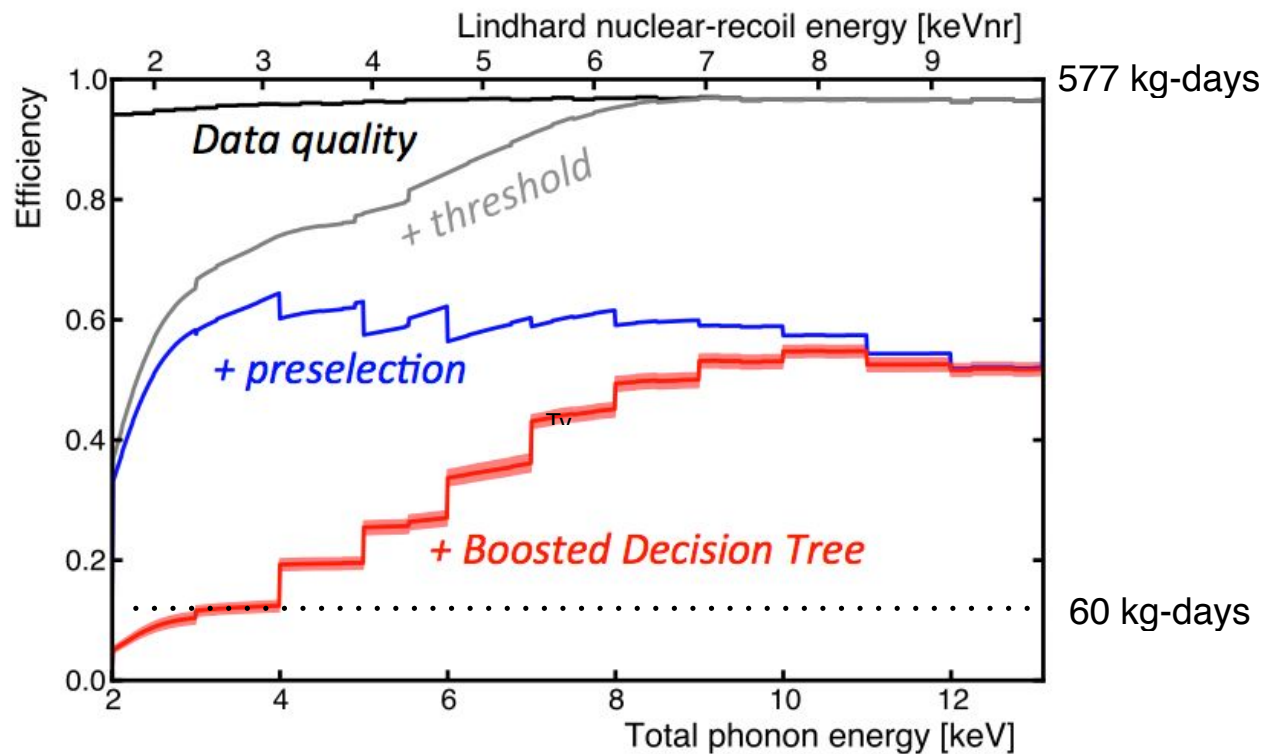
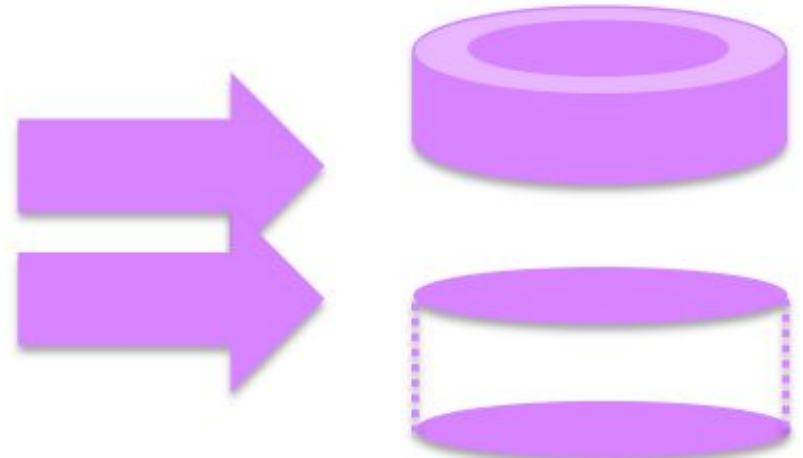
Tritium provides very high statistics electron recoil calibration (200 events/phe)
Neutron calibration is consistent with NEST + simulations



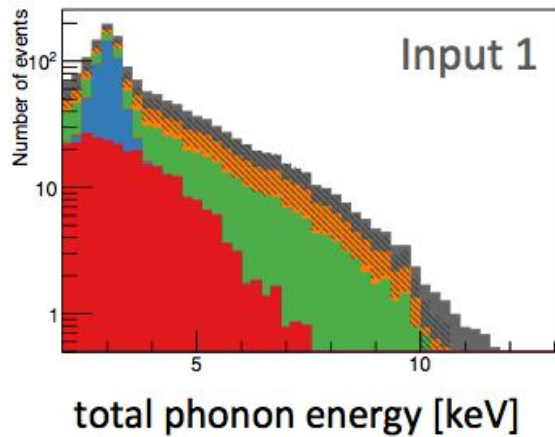
Gray contours indicate constant energies using a S1-S2 combined energy scale

Slides from Lauren Hsu, Fermilab @ UCLA DM 2014

sidewall & surface events =
betas and x-rays from ^{210}Pb , ^{210}Bi ,
recoils from ^{206}Pb , outer radial
comptons and ejected electrons from
compton scattering

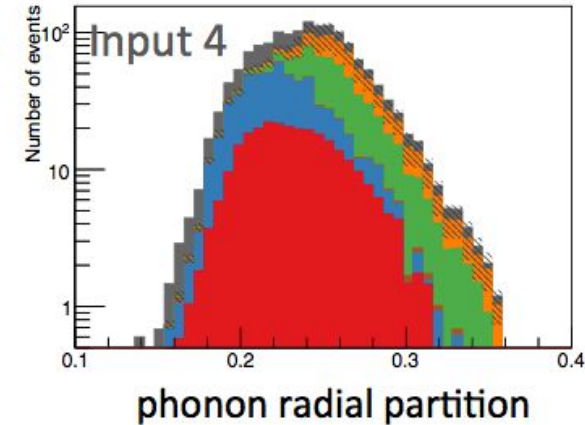
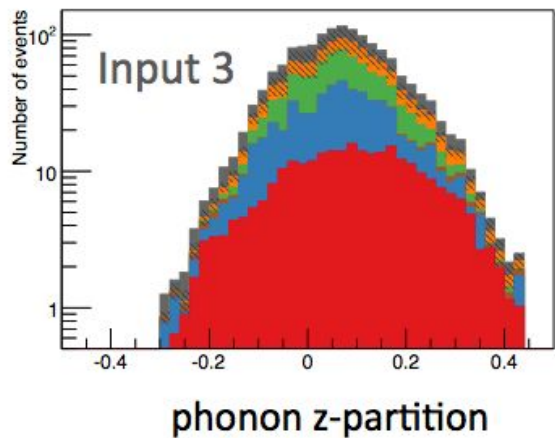
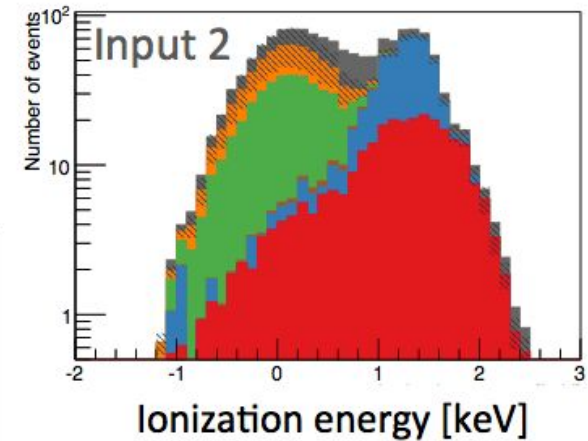
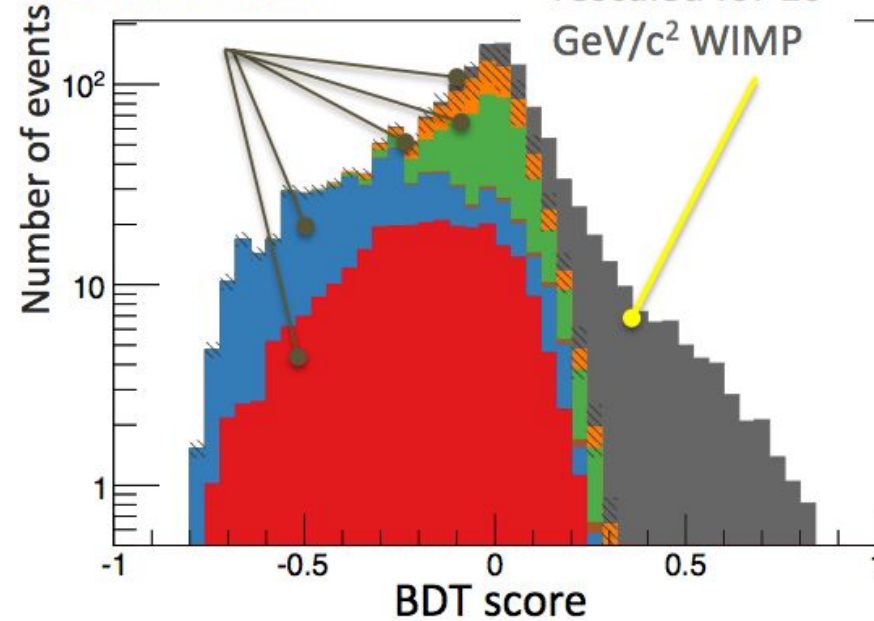


Multiple Background / BDT

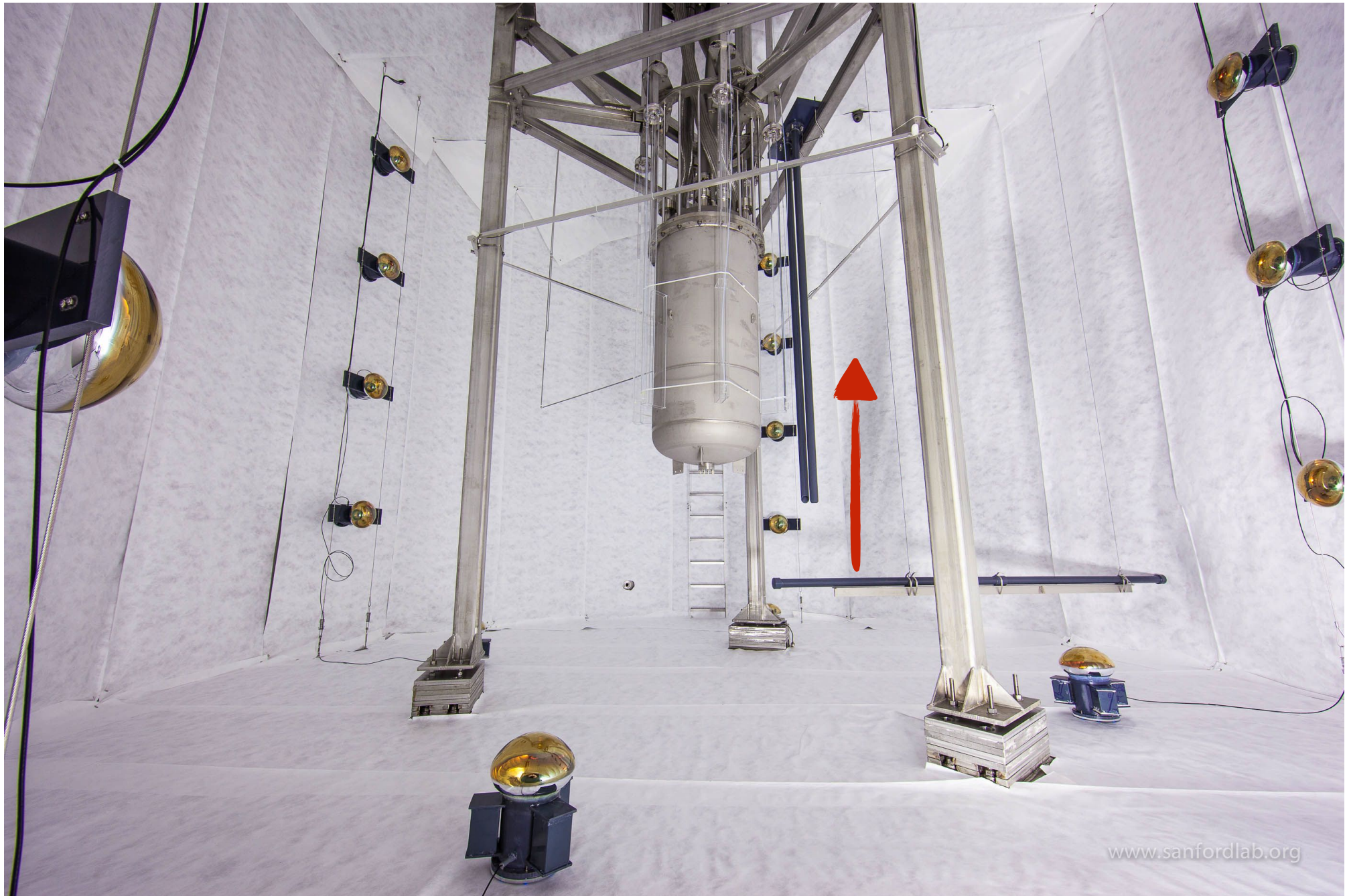


Modeled w/simulated data based on sidebands and calibration

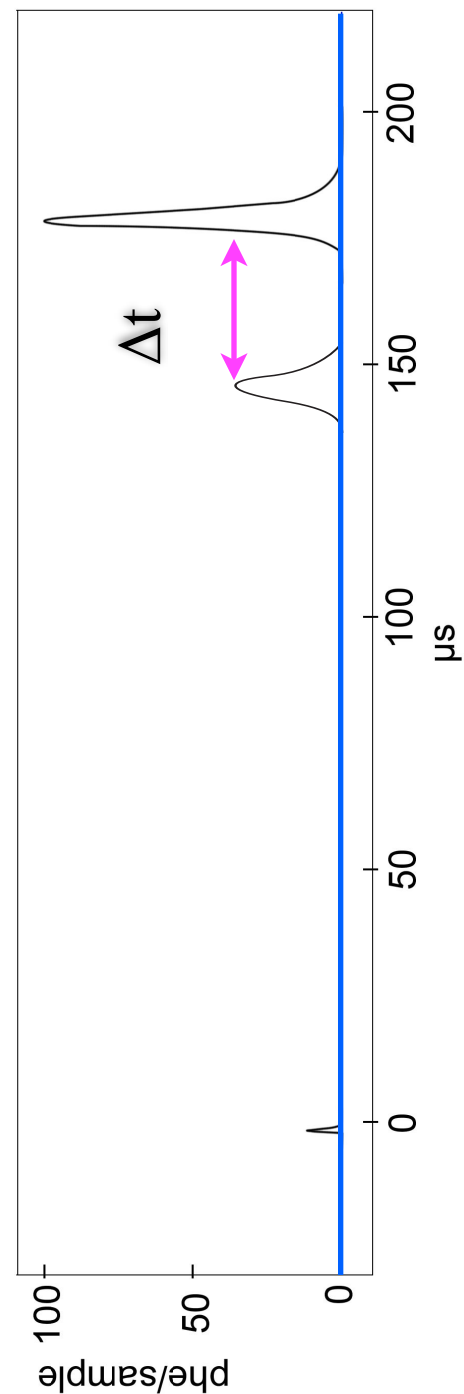
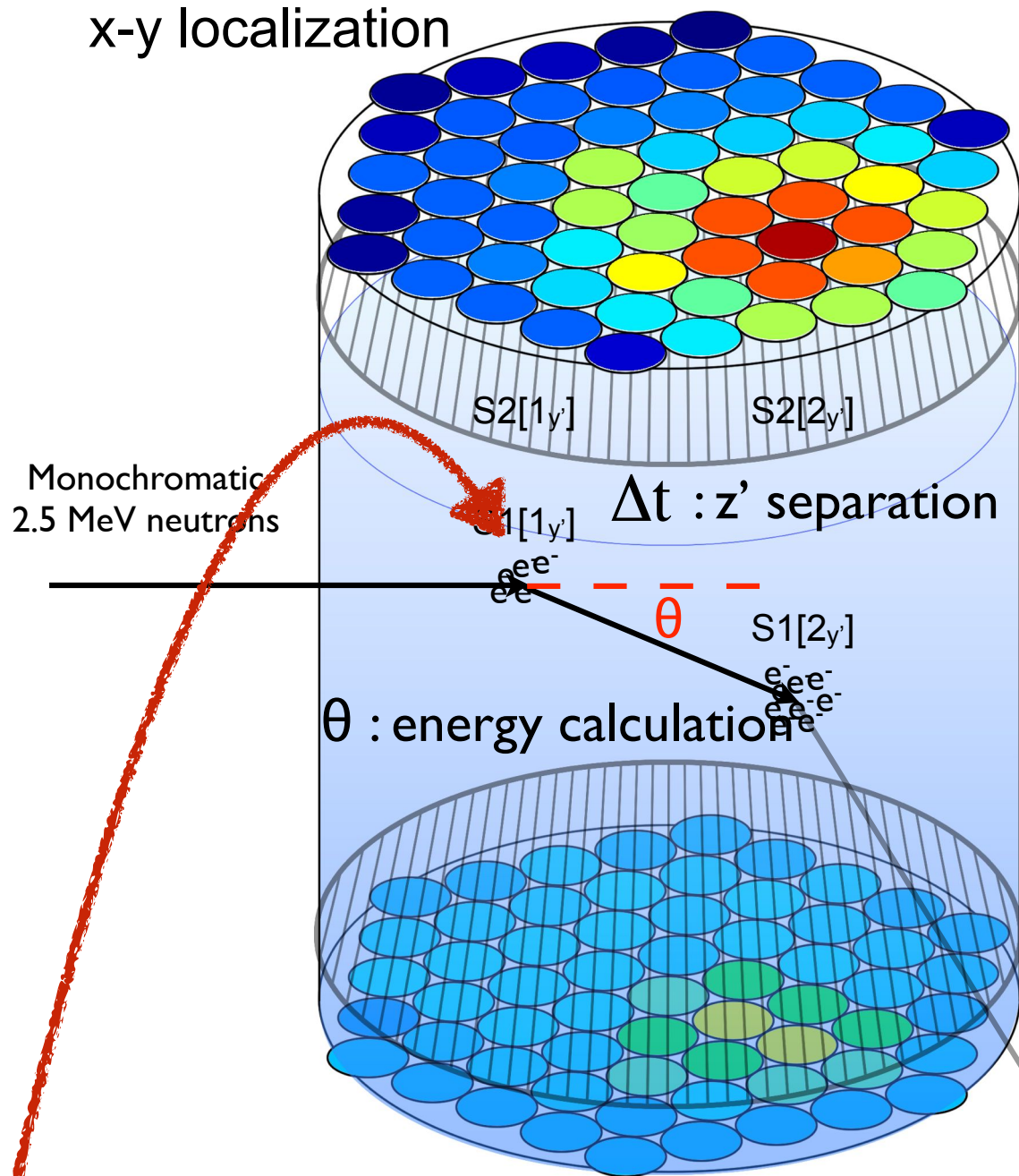
Modeled w/ NR from ^{252}Cf rescaled for 10 GeV/c^2 WIMP



Neutron Conduit Installed in the LUX Water Tank - Fall 2012



top hit pattern:
x-y localization

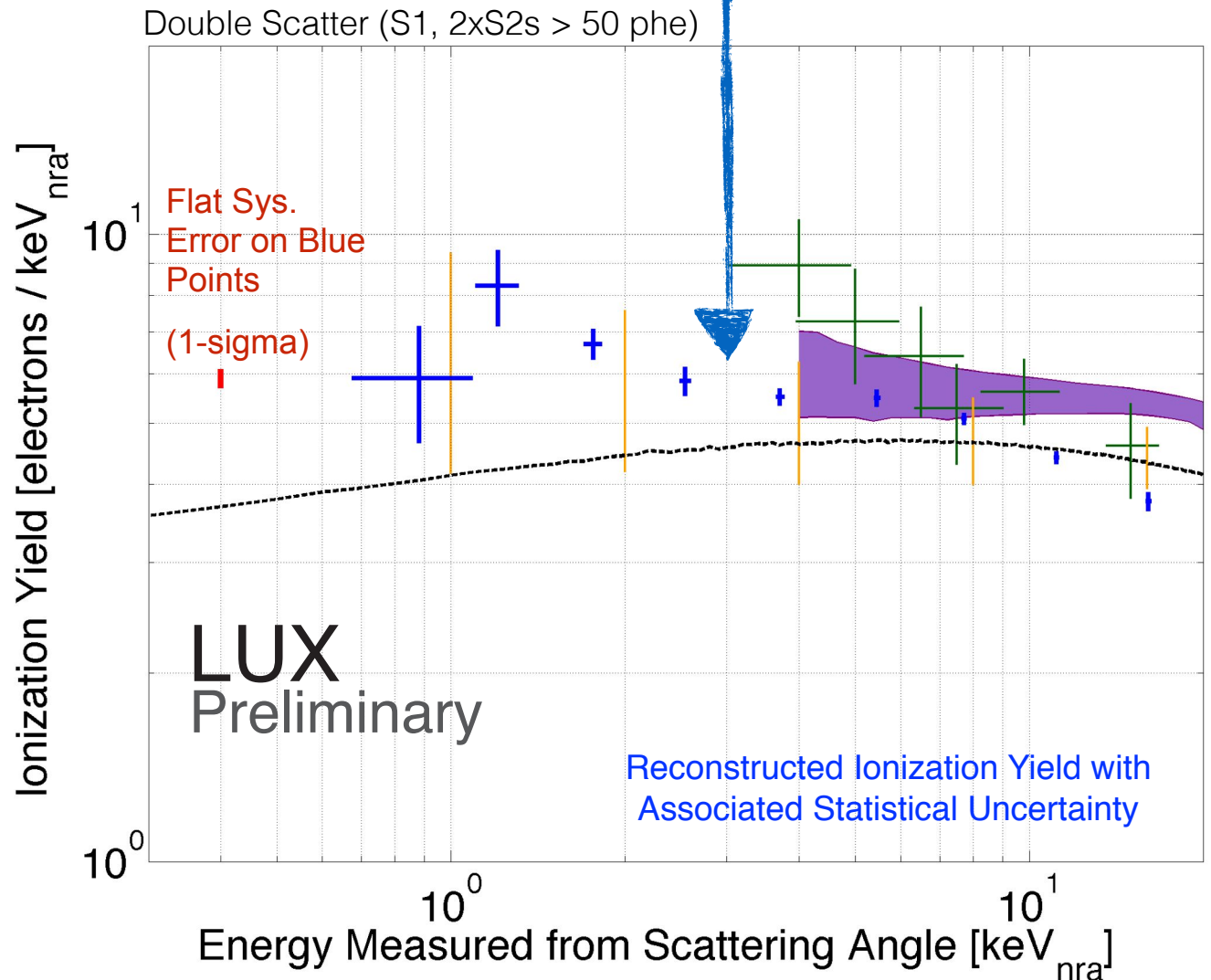


$$E_r = E_n \frac{4m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos \theta}{2}$$

Ionization Yield Absolutely Measured below 1 keV_{nra} in LUX

- Systematic error of 7% from threshold correction for (lowest energy) 0.7-1.0 keV_{nra} bin
- Red systematic error bar shows common scaling factor uncertainty. Dominated by uncertainty in electron extraction efficiency.
- Current analysis cut-off at 0.7 keV_{nra}; measurement will be extended lower in energy by including smaller scattering angles in future analysis

LUX 2014 PRL Conservative Threshold Cut-Off



Blue Crosses - LUX Measured Qy; 181 V/cm (absolute energy scale)

Green Crosses - Manzur 2010; 1 kV/cm (absolute energy scale)

Purple Band - Z3 Horn Combined FSR/SSR; 3.6 kV/cm (energy scale from best fit MC)

Orange Lines - Sorensen IDM 2010; 0.73 kV/cm (energy scale from best fit MC)

Black Dashed Line - Szydagis et al. (NEST) Predicted Ionization Yield at 181 V/cm

The Practical Matter of a Low Energy Rare Event Search

- Dark Matter signals will be expected to appear first in the lowest energy bins of an experiment that is still in search mode
- Unfortunately, that is also where the first indications that systematics are starting to dominate

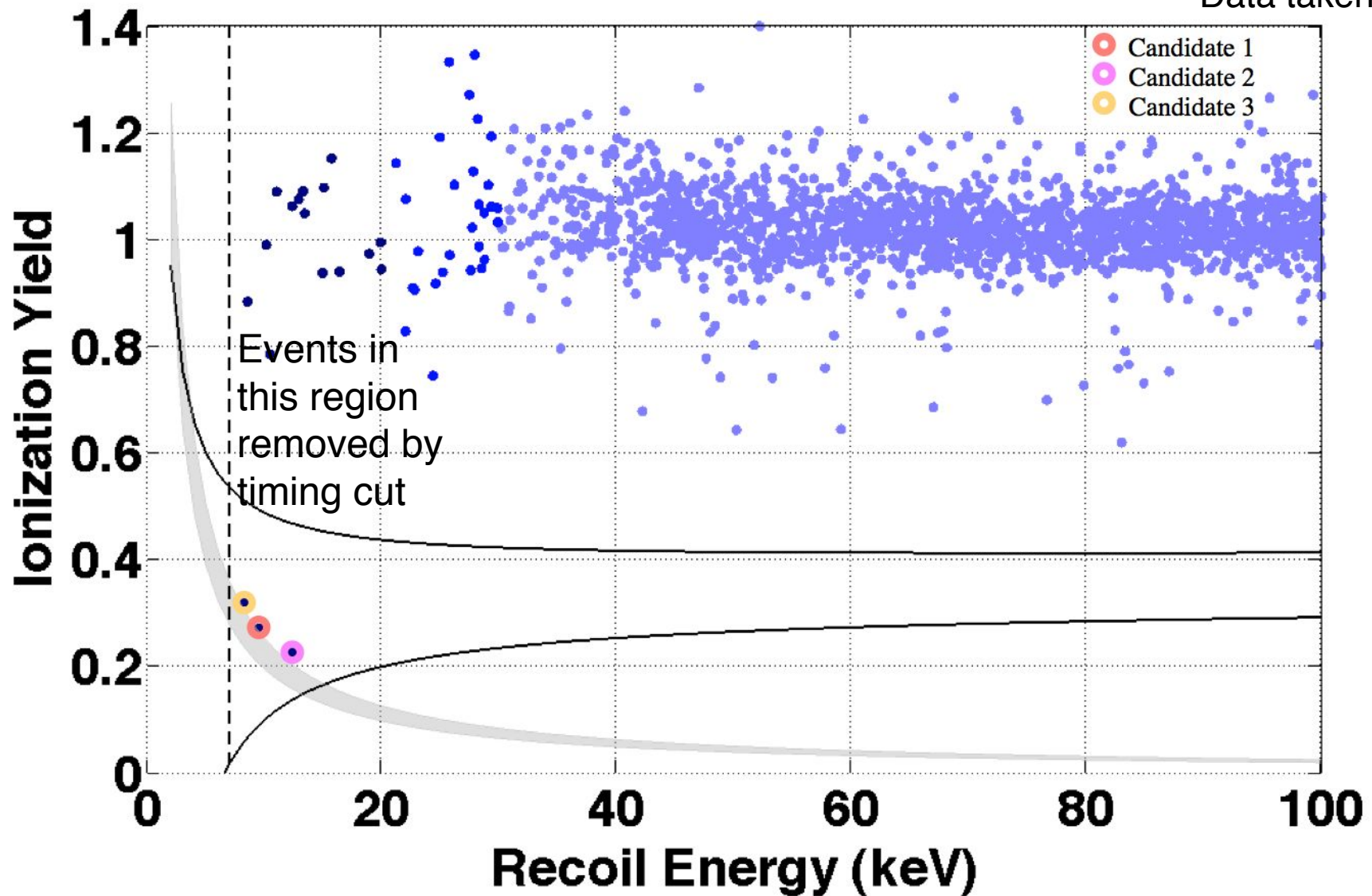
Thresholdinos

- You should be ready to be skeptical of the results from your uppermost and lowermost bins of your histogram - Attributable, in spirit to Rutherford (I believe)
- It is difficult to control systematics that may cause events to be in edge bins/tails
 - ◆ This is particularly important when a result is dependent on subtle effects
- And we will need to push the detectors by another 10^4 before we reach the irreducible coherent scattering atm. neutrino backgrounds

CDMS II Si 2013 (140.23 kg-days in 8 Si detectors)

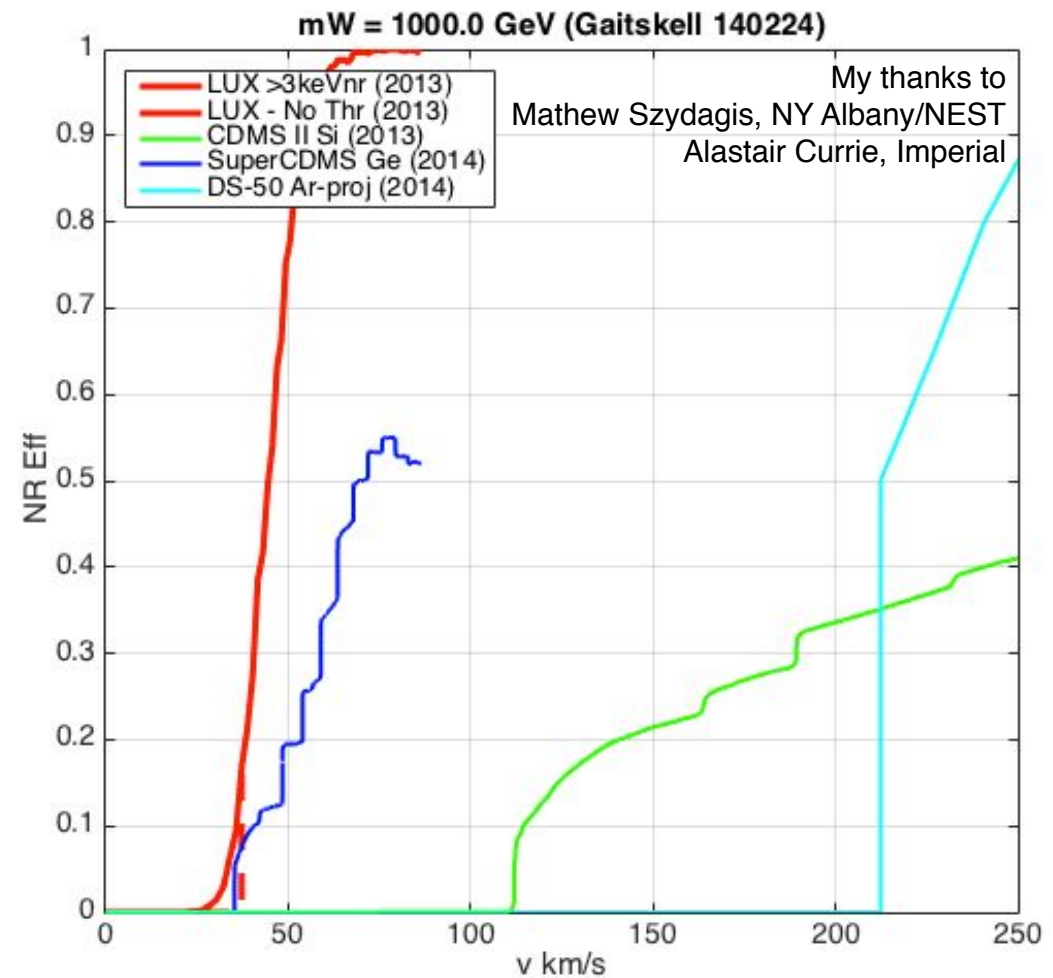
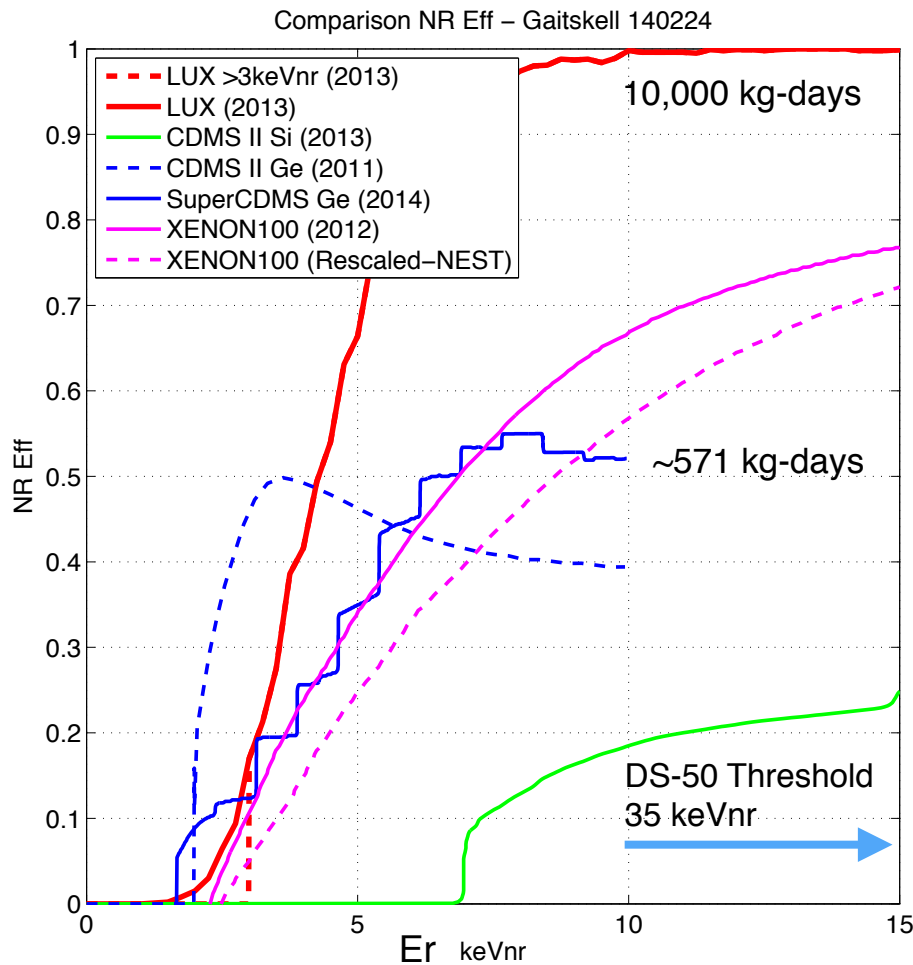
Unblinding Results - after timing cut

Data taken 2007/8



Comparing Thresholds in Direct Detection Experiments

- Threshold Efficiencies as function of E_{recoil} and v_{min} . m_T is the mass of the target nucleus.



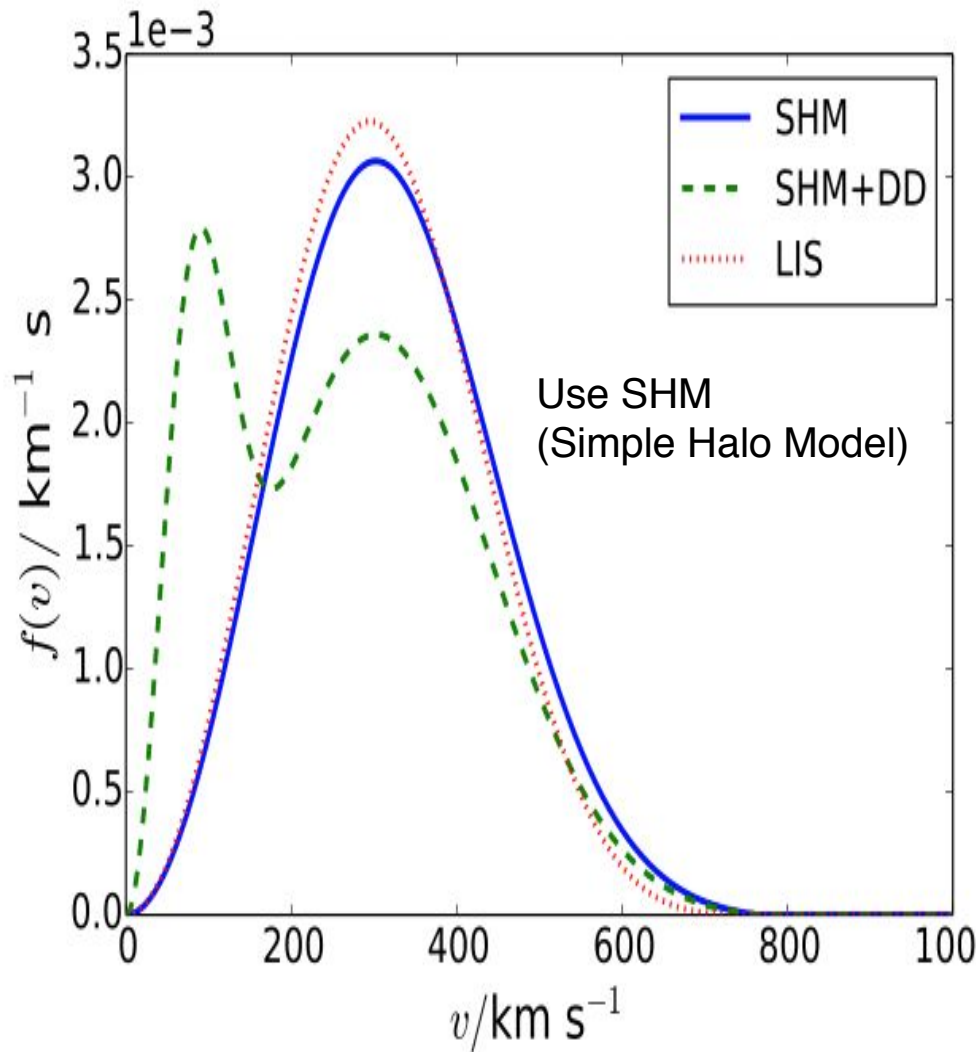
$$E_r = 4(m_W + m_T) / (m_W + m_T)^2 \cdot 1/2 m_W (v_{\text{min}})^2$$

v_{min} WIMP in Lab Frame
to achieve E_{recoil}

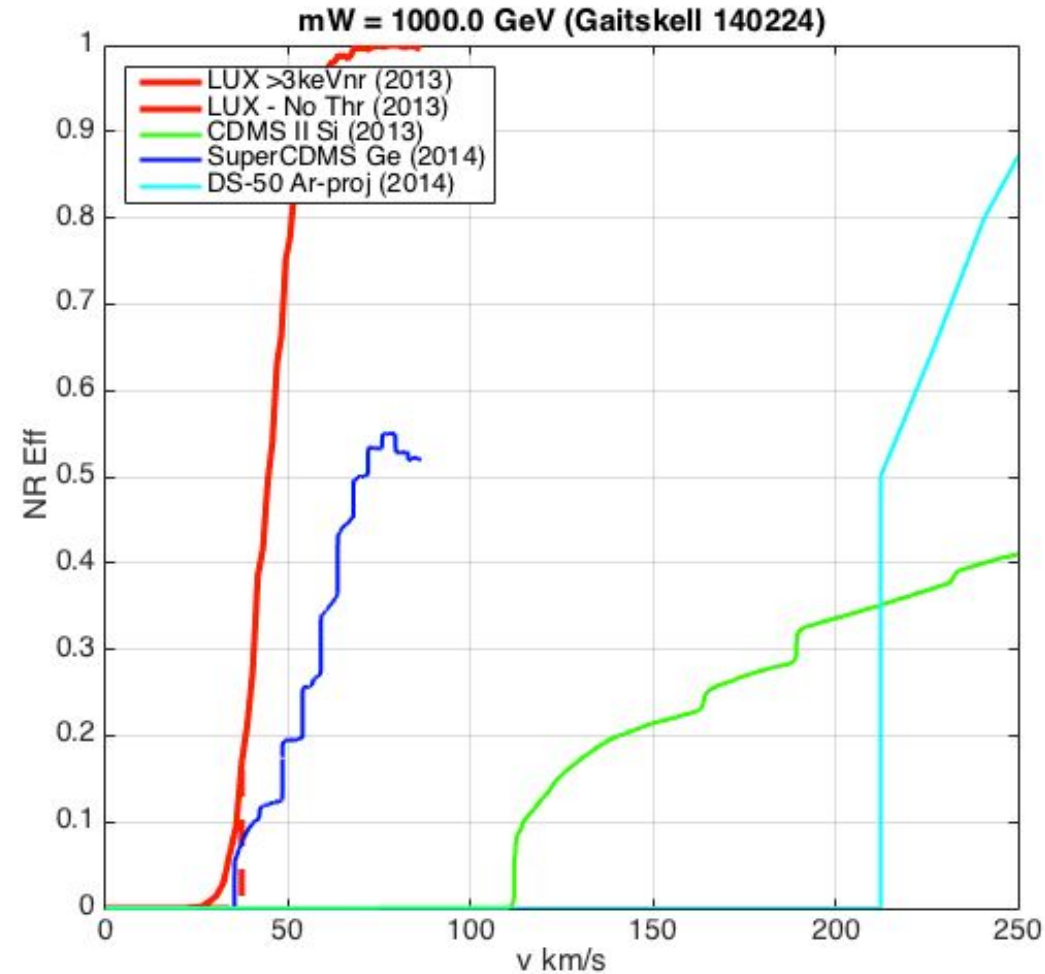
Restate the E_r value as the minimum WIMP velocity in Lab frame able to generate that recoil energy

Sensitivity Compared using WIMP Velocity in Lab

- WIMP Mass 1000 GeV



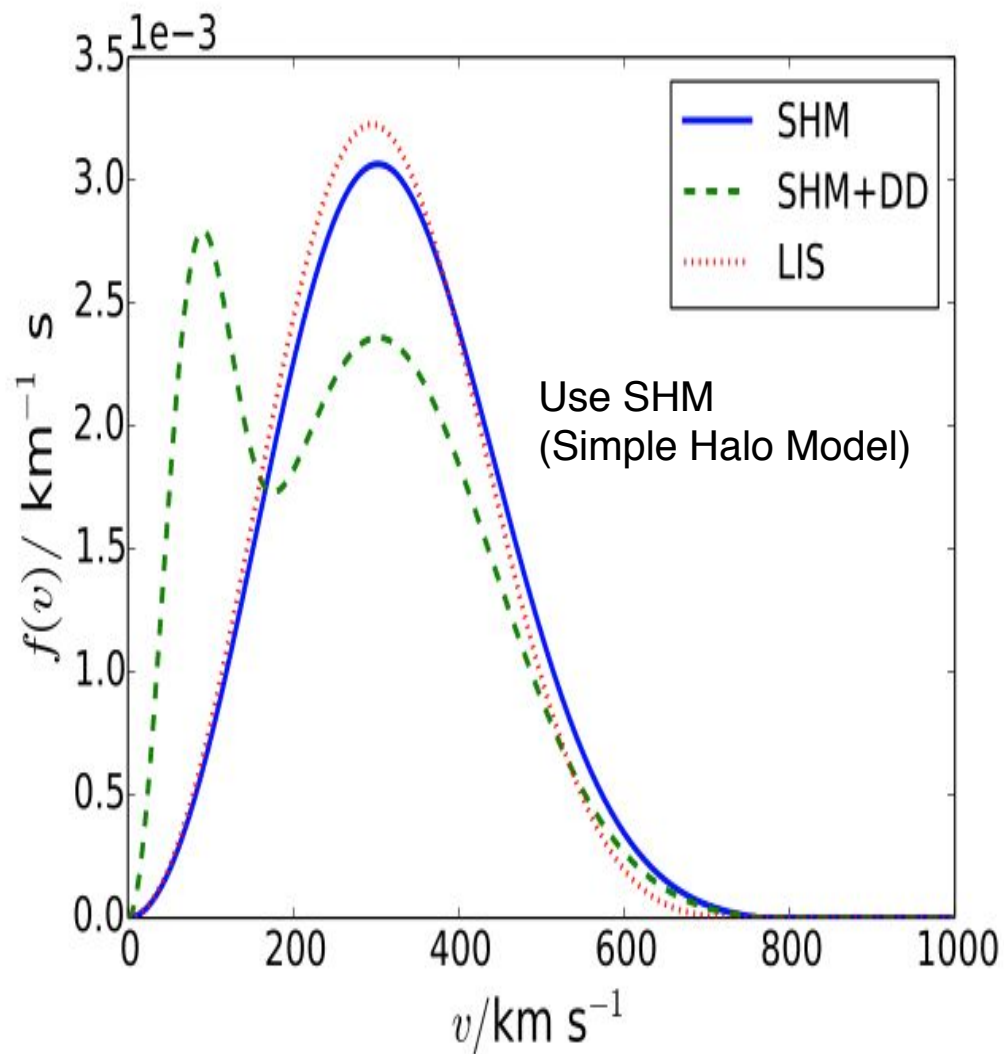
Velocity distribution from
 “WIMP physics with ensembles of direct-detection
 experiments” AHG Peter et al. arXiv:1310.7039



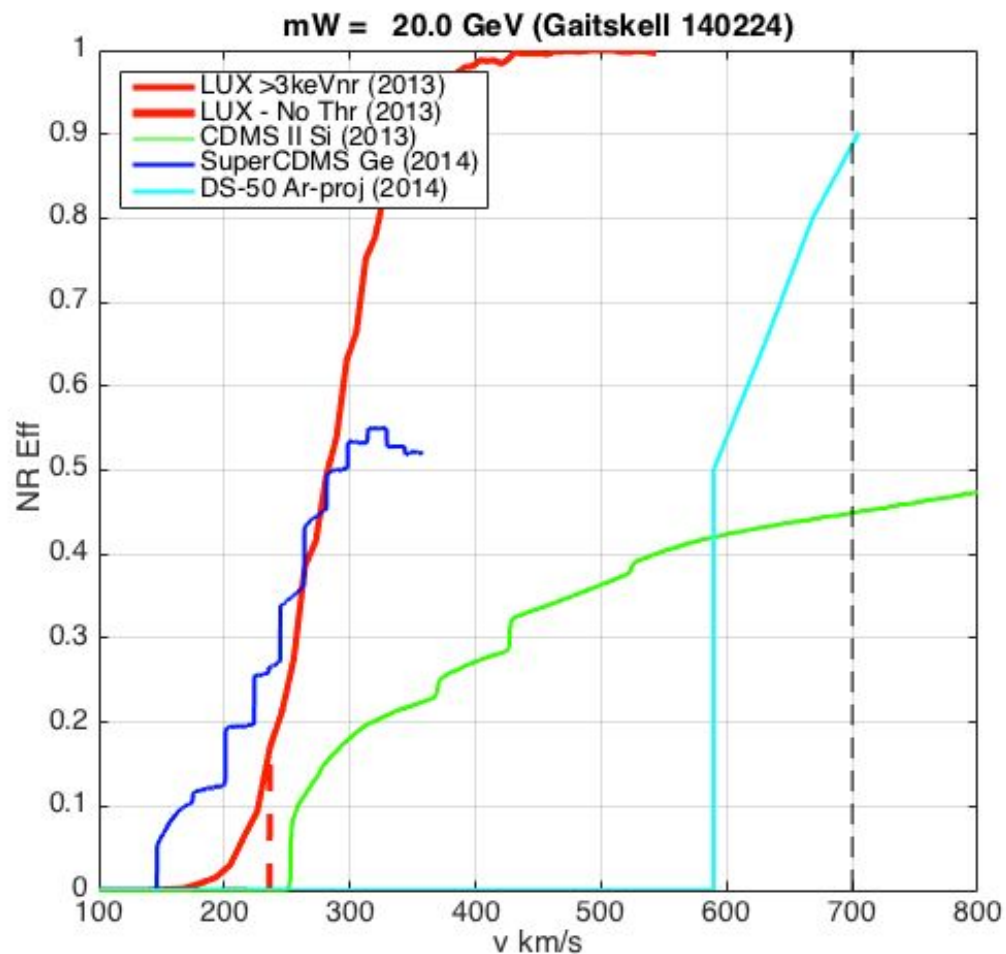
LUX >3 keVnr - can see why the limit
 of the sensitivity is $\sim 6 \text{ GeV}$ WIMP
 because v_{min} is at tip of SHM

Sensitivity Compared using WIMP Velocity in Lab

- WIMP Mass 20 GeV



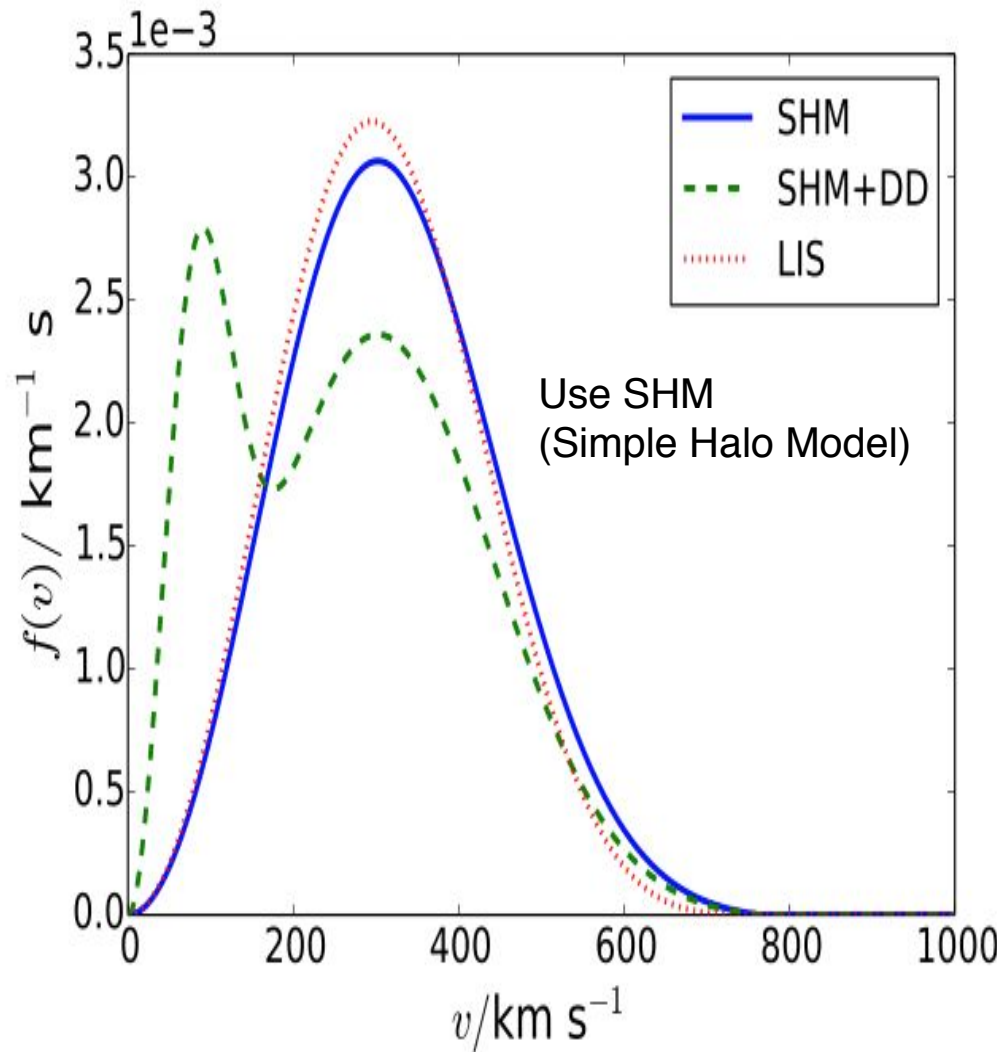
Velocity distribution from
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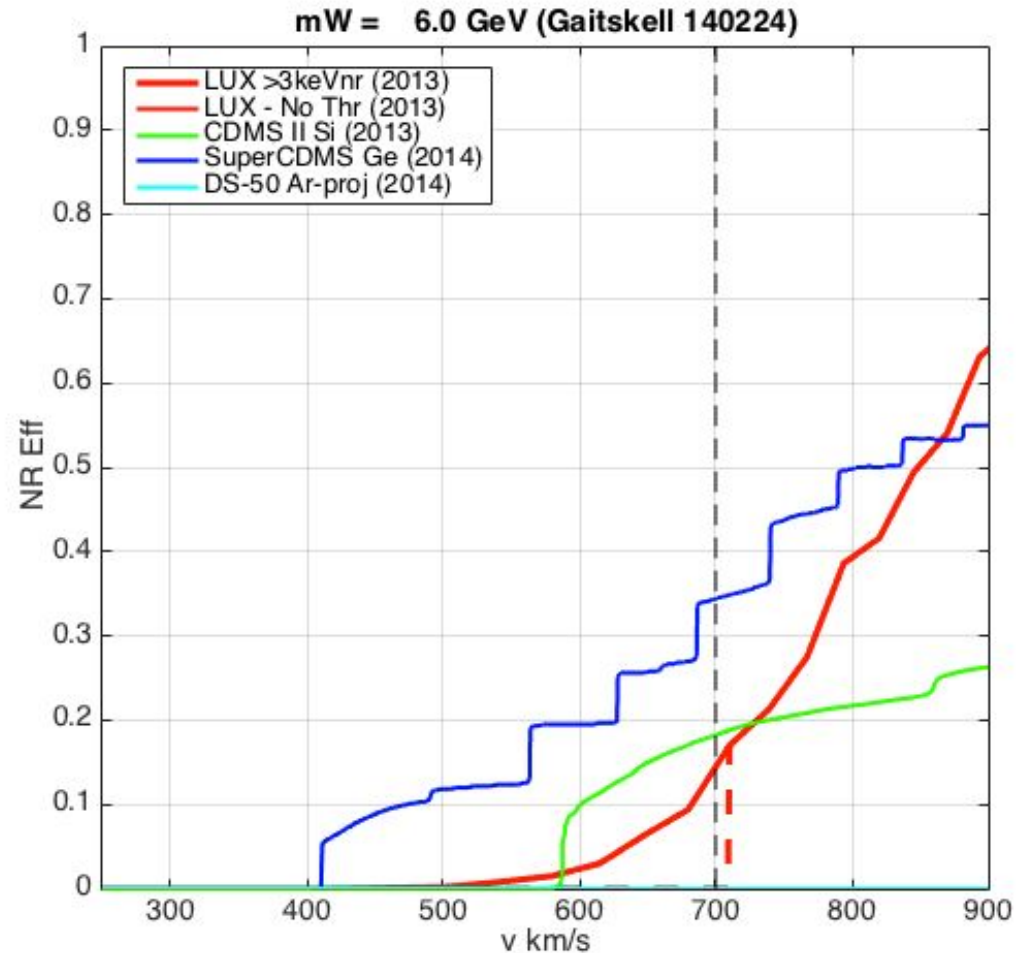
Lower WIMP mass means target
 mass causes relative shifts
 Ar (Er>35 keVnr) reaching sensitivity

Sensitivity Compared using WIMP Velocity in Lab

• WIMP Mass 6 GeV



Velocity distribution from
 “WIMP physics with ensembles of direct-detection
 experiments” AHG Peter et al. arXiv:1310.7039



LUX >3 keVnr - can see why the limit
 of the sensitivity is ~6 GeV WIMP for
 2013 result because v_{\min} is at tip of
 SHM

Further Threshold Improvements

- CoGENT

- ◆Continue to reduce noise in Ge ionization detectors

- SuperCDMS “HV” would re-task its detectors to operate in high drift field mode

- ◆Measure the e-h pairs using Luke phonons they generate in $\sim 100V$ drift field

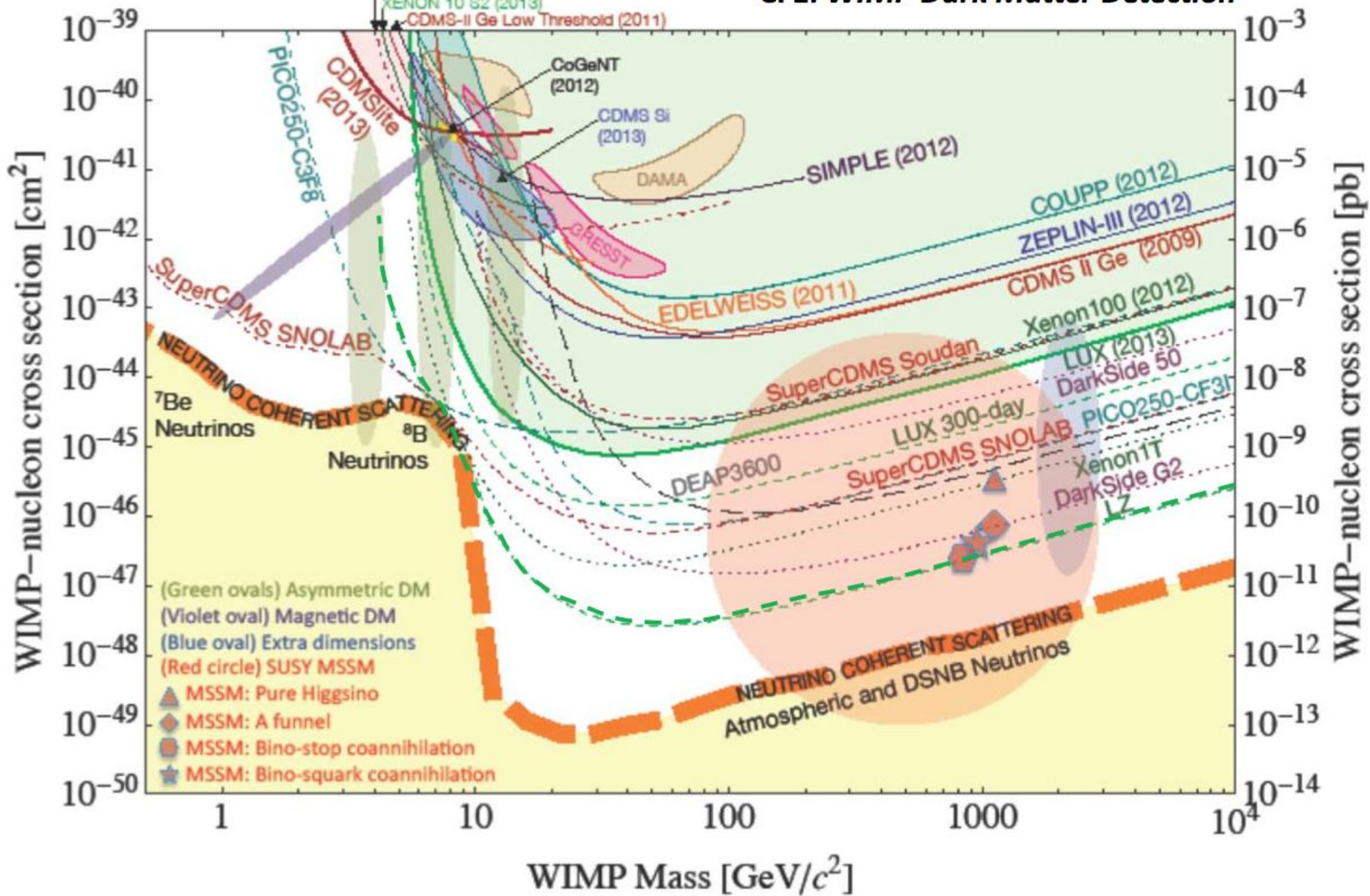
- Xe TPC's

- ◆Improving Xe NR Calibrations at lowest energies ~ 1 keVnr
- ◆S2-only operation

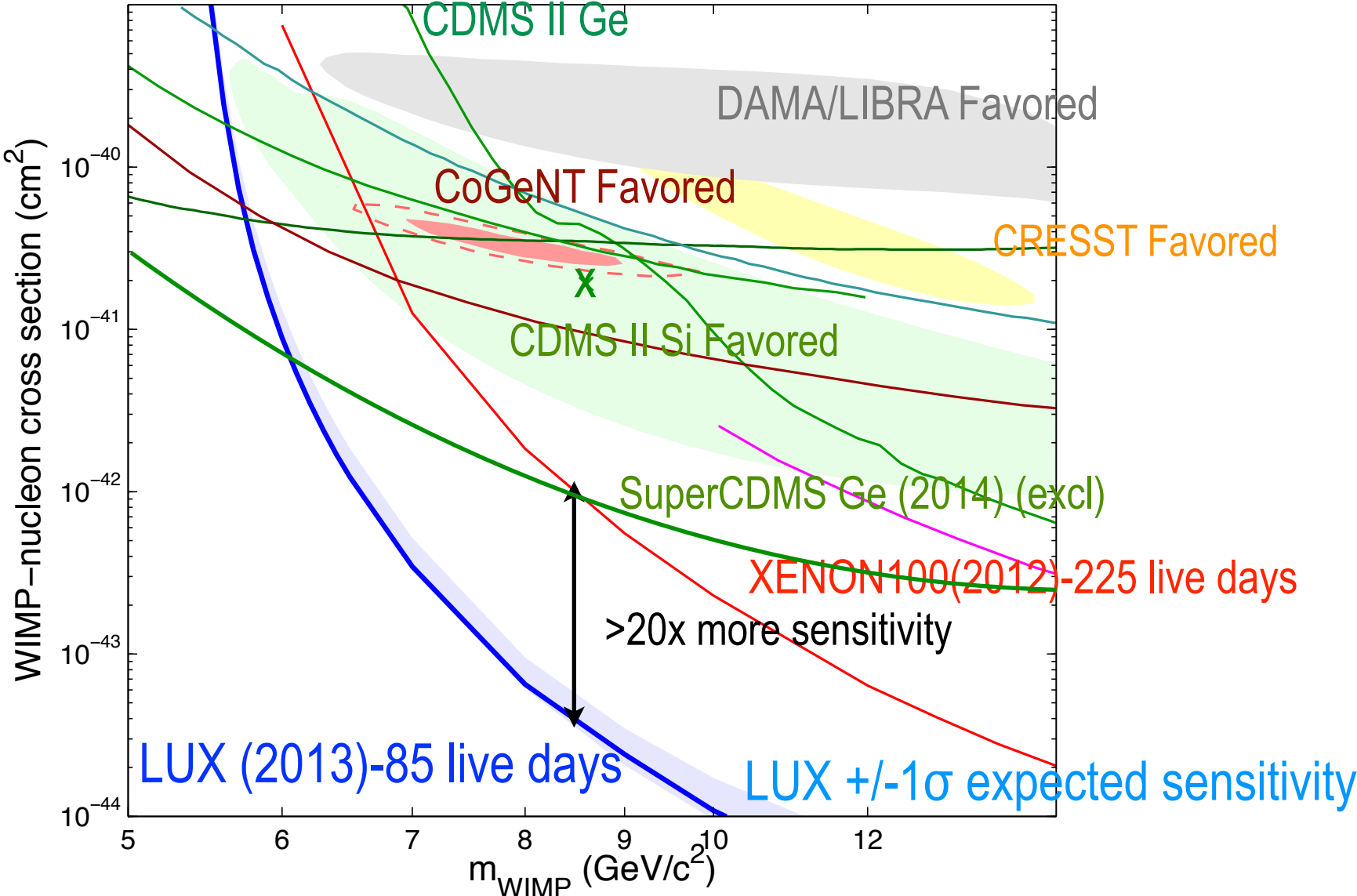
- Ar TPC

- ◆Threshold limited by ER discrimination, will continue to study
- ◆Current project increase in energy threshold from 35->47 keVnr, DS-50 -> DS-G2

CF1: WIMP Dark Matter Detection



Low Mass WIMPs - Fully Excluded by LUX



Blinding

- Blinding needed when there are concerns that analysis cuts will be “optimized” subjectively
 - ◆ This can cut both ways - leading to loss of events, or unwarranted confidence for a discovery
- It is necessary where calibrations don't fully cover the response and so some average characteristics have to be assumed for background response
- If we are able to calibrate all parts of the detector response at a level of statistics that is beyond the signal
 - ◆ e.g. Intrinsic sources mixed with liquid targets are allowing this - every part of the detector is oversampled
- Blinding can be avoided - we should not simply state it is better
 - ◆ If we apply simple cuts, results insensitive to boundaries
 - ◆ Use of Profile likelihood to input all aspects of background model - if well motivated and can be applied simply. Again results should be insensitive to uncertainties in model.
- We have to be concerned that blinding can induce overconfidence in ability to discover new signals, since a conservative estimation of response will reward experiments with WIMP candidates.
 - ◆ This could be described as a WIN (better discrimination) -WIN (WIMP events, if not) which is undesirable in blinding - what is the control for this?

The Practical Matter of a Rare Event Search

- In 28th year of searching - now at a sensitivity that 10^5 better than the first round - we need detectors with a

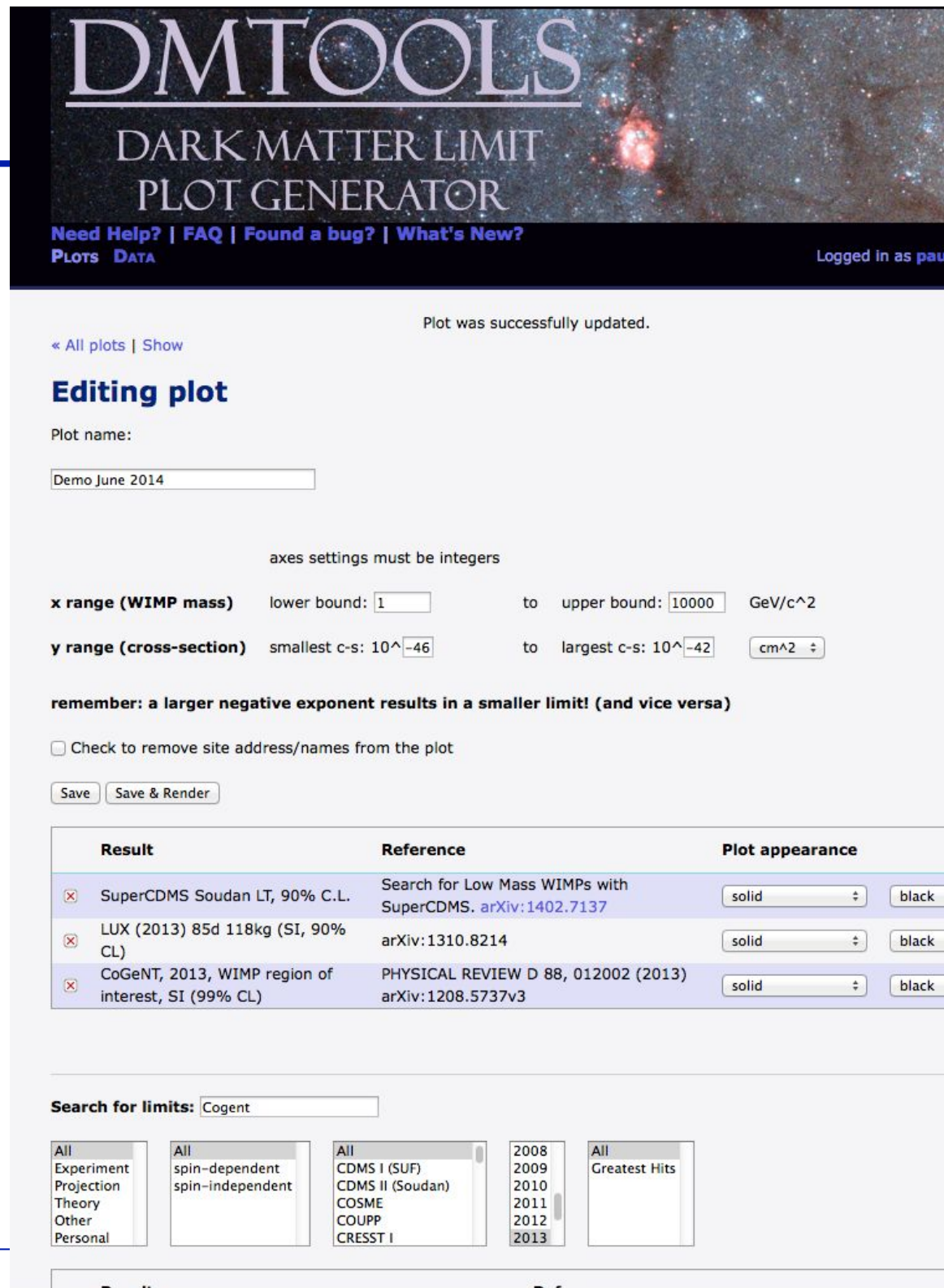
Low Sisyphean Index †

- They must want to work correctly / do so without misleading us / low complexity - mustn't roll back down the hill when we stop paying attention for a moment
- And we will need to push them (pun indented) by another 10^4 before we reach the irreducible coherent neutrino backgrounds

† Experimentalist's Perspective of the Technology itself, not the definition that the task can never be completed

- <http://dmtools.brown.edu>
- ◆ New DMTools has finished beta testing
 - Replaces old plotter - offline
- ◆ Allows more dynamic selection of data
- ◆ Store plots for recall/edit later

- ◆ All datasets can be uploaded/downloaded



DMTOOLS
DARK MATTER LIMIT
PLOT GENERATOR

Need Help? | FAQ | Found a bug? | What's New?
PLOTS DATA Logged In as pau

Plot was successfully updated.

◀ All plots | Show

Editing plot

Plot name:

axes settings must be integers

x range (WIMP mass) lower bound: to upper bound: GeV/c²

y range (cross-section) smallest c-s: 10⁻⁴⁶ to largest c-s: 10⁻⁴²

remember: a larger negative exponent results in a smaller limit! (and vice versa)

Check to remove site address/names from the plot

Result	Reference	Plot appearance	
<input checked="" type="checkbox"/> SuperCDMS Soudan LT, 90% C.L.	Search for Low Mass WIMPs with SuperCDMS. arXiv:1402.7137	<input type="text" value="solid"/>	<input type="text" value="black"/>
<input checked="" type="checkbox"/> LUX (2013) 85d 118kg (SI, 90% CL)	arXiv:1310.8214	<input type="text" value="solid"/>	<input type="text" value="black"/>
<input checked="" type="checkbox"/> CoGeNT, 2013, WIMP region of interest, SI (99% CL)	PHYSICAL REVIEW D 88, 012002 (2013) arXiv:1208.5737v3	<input type="text" value="solid"/>	<input type="text" value="black"/>

Search for limits:

All
Experiment
Projection
Theory
Other
Personal

All
spin-dependent
spin-independent

All
CDMS I (SUF)
CDMS II (Soudan)
COSME
COUPP
CRESST I

2008
2009
2010
2011
2012
2013

All
Greatest Hits

Conclusions

- US Selection Process of G2 “Generation 2” Dark Matter Experiments
 - ◆ P5 has reported (+ve for G2 and G3), with US agency decisions to follow at end of June 2014
 - ◆ Strong encouragement to US agencies to increase (double) the proposed project funds
 - This would allow a more competitive program to be backed with multiple targets
- Low Mass WIMP signal(s) - sensitivity has improved by two orders of magnitude since 2012
 - ◆ Critically there has also been an improvement in our understanding of potential systematics in detector response
 - ◆ This Focus - Has brought the best out of people. Yes, we are combative, but that is the spice that makes the best sauce, and it has caused us to hone our arguments, and improve our detailed understanding of the detectors/backgrounds
 - ◆ Calibration strategies that can provide abundant statistics, and have low systematic uncertainties are critically important
- We have improved the sensitivity to 50 GeV WIMPs by over an order of magnitude in the last two years
 - ◆ Let us look forward to doing something similar by 2016
- The Spectre of Discovery is always upon us, and is a great responsibility
 - ◆ Clearly, multiple detectors / multiple techniques will be required to build a robust case of discovery