Direct Detection of Dark Matter – an Overview

Dan McKinsey, LUX Co-Spokesperson
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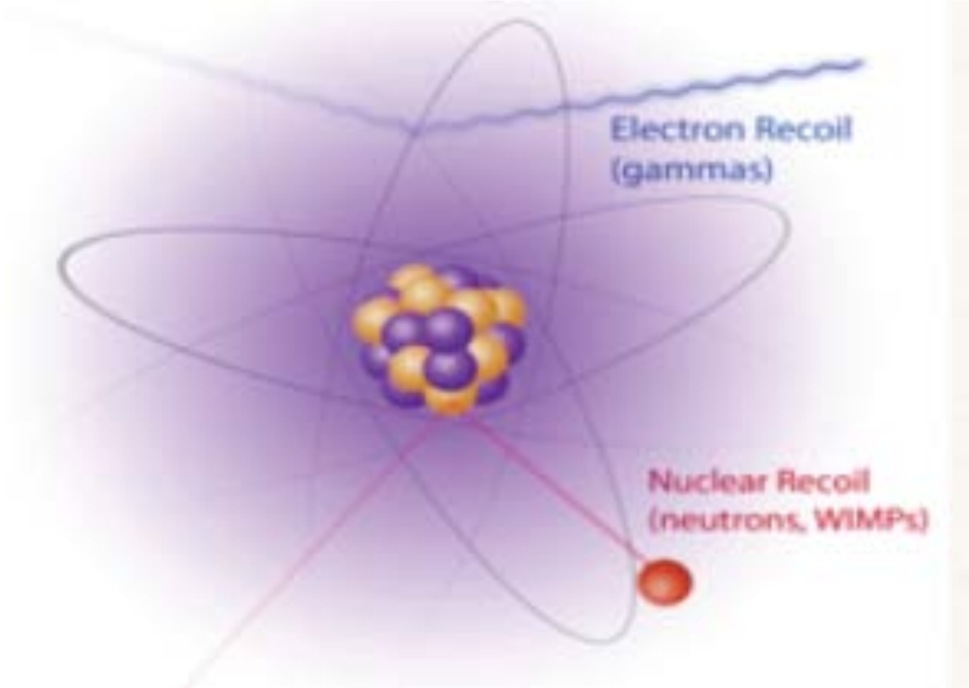
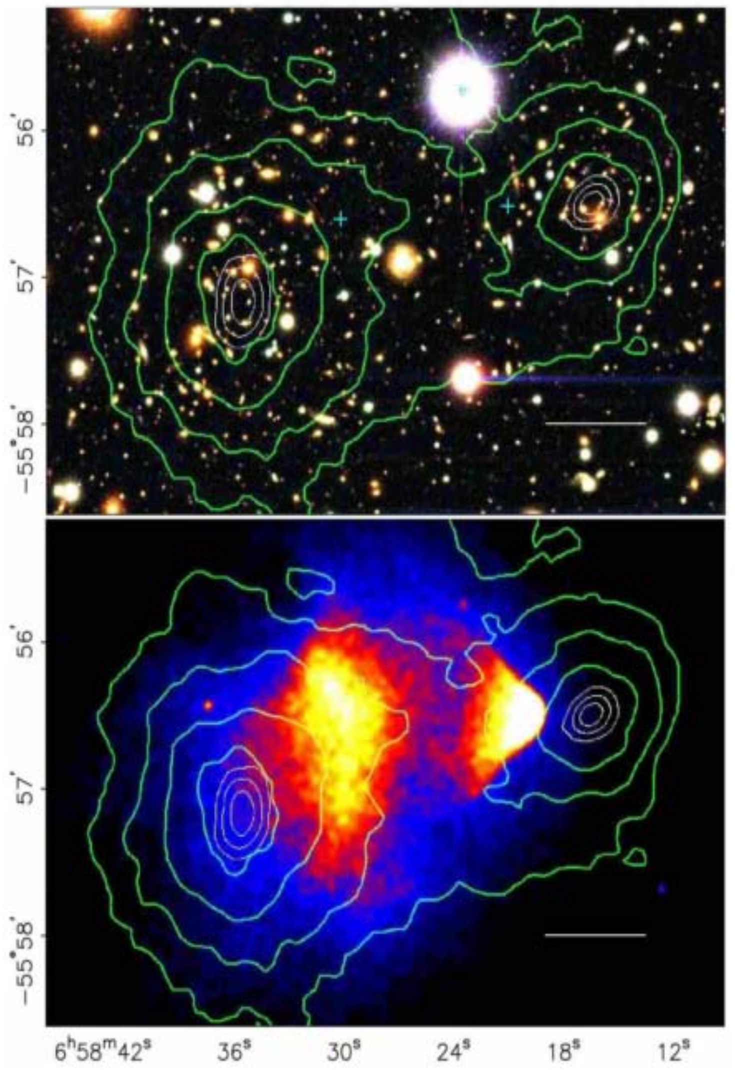
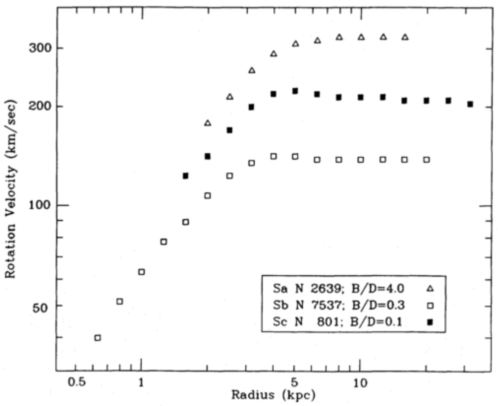
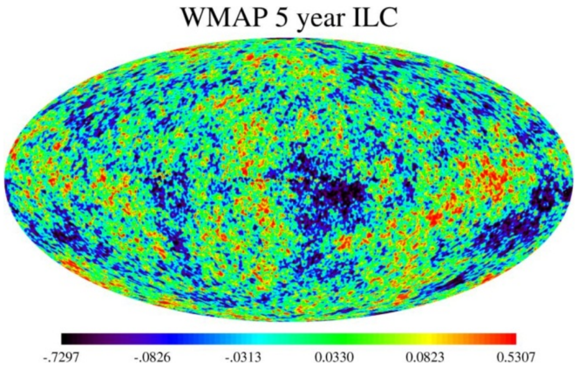


Brookhaven Forum
Brookhaven National Laboratory
May 3, 2013

The Dark Matter Problem







Searching for WIMPs

Accelerators: Look for dark matter candidates at the LHC.

Squark and gluino decays result in leptons, jets, and missing energy.

BUT: 1) can't show that dark matter candidate is stable
2) hard to determine couplings/interactions of dark matter candidate
3) can't prove that candidate particle actually makes up the dark matter

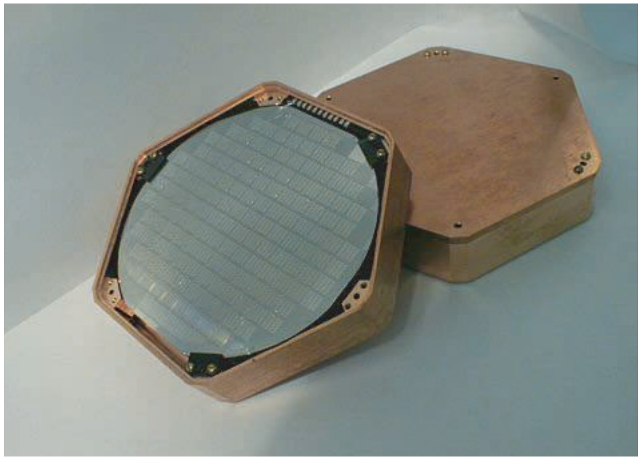
Indirect Searches: Look for $\chi\chi$ annihilation in form of high energy cosmics, neutrinos

Direct Searches: Look for anomalous nuclear recoils in a low-background detector

$R = N \rho < \sigma v >$
From $<v> = 220$ km/s, get order of 10 keV
Key technical challenges:

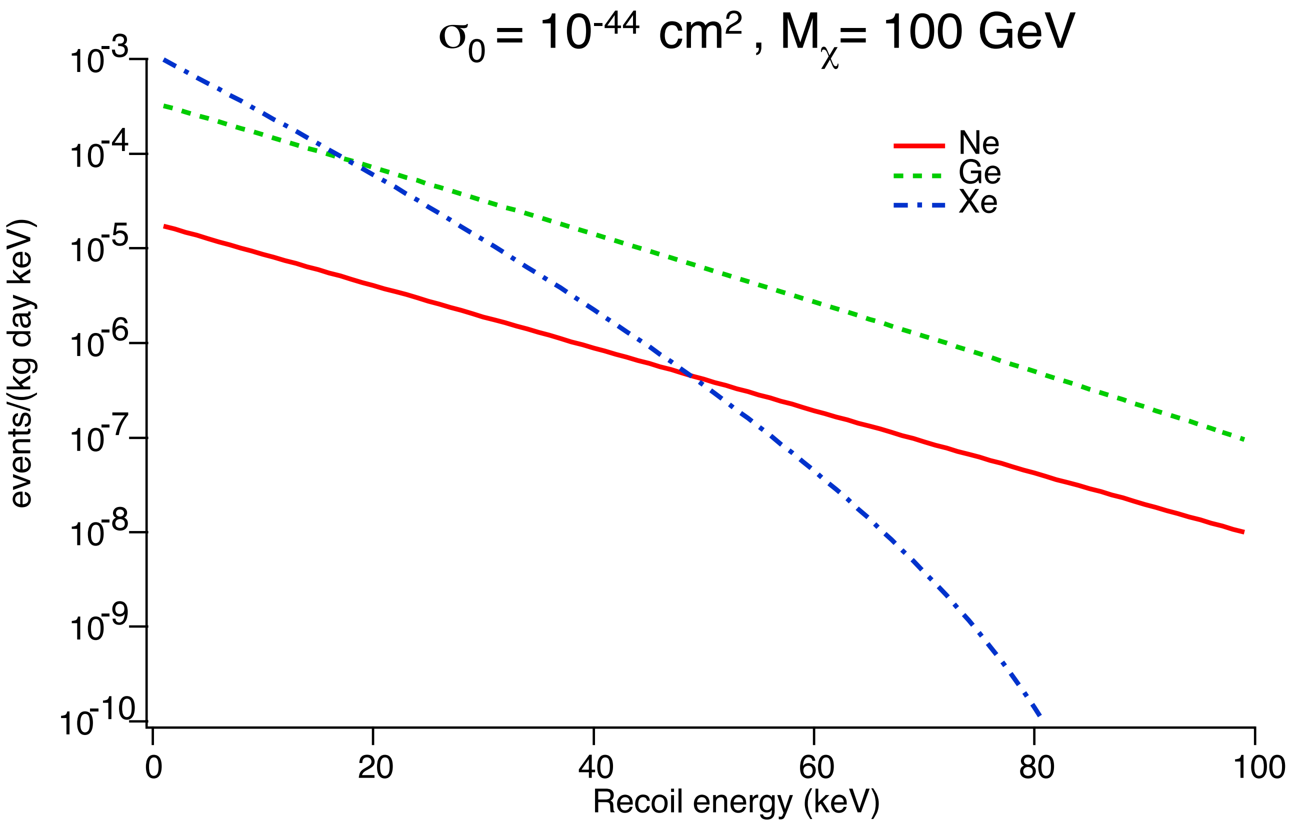
- Low radioactivity
- Low energy threshold
- Gamma ray rejection
- Scalability

Detect heat, light, or ionization
(or some combination)



Germanium detector
(as in CDMS, Edelweiss)

WIMP recoil spectra


$\sigma_0 = 10^{-44}\ \mathrm{cm}^2$, $M_\chi = 100$ GeV

Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

$$dR/dQ = (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0\, m_\chi\, m_r^2)\ F^2(Q)\ T(Q)$$

WIMP energy density, 0.3 GeV/cm³

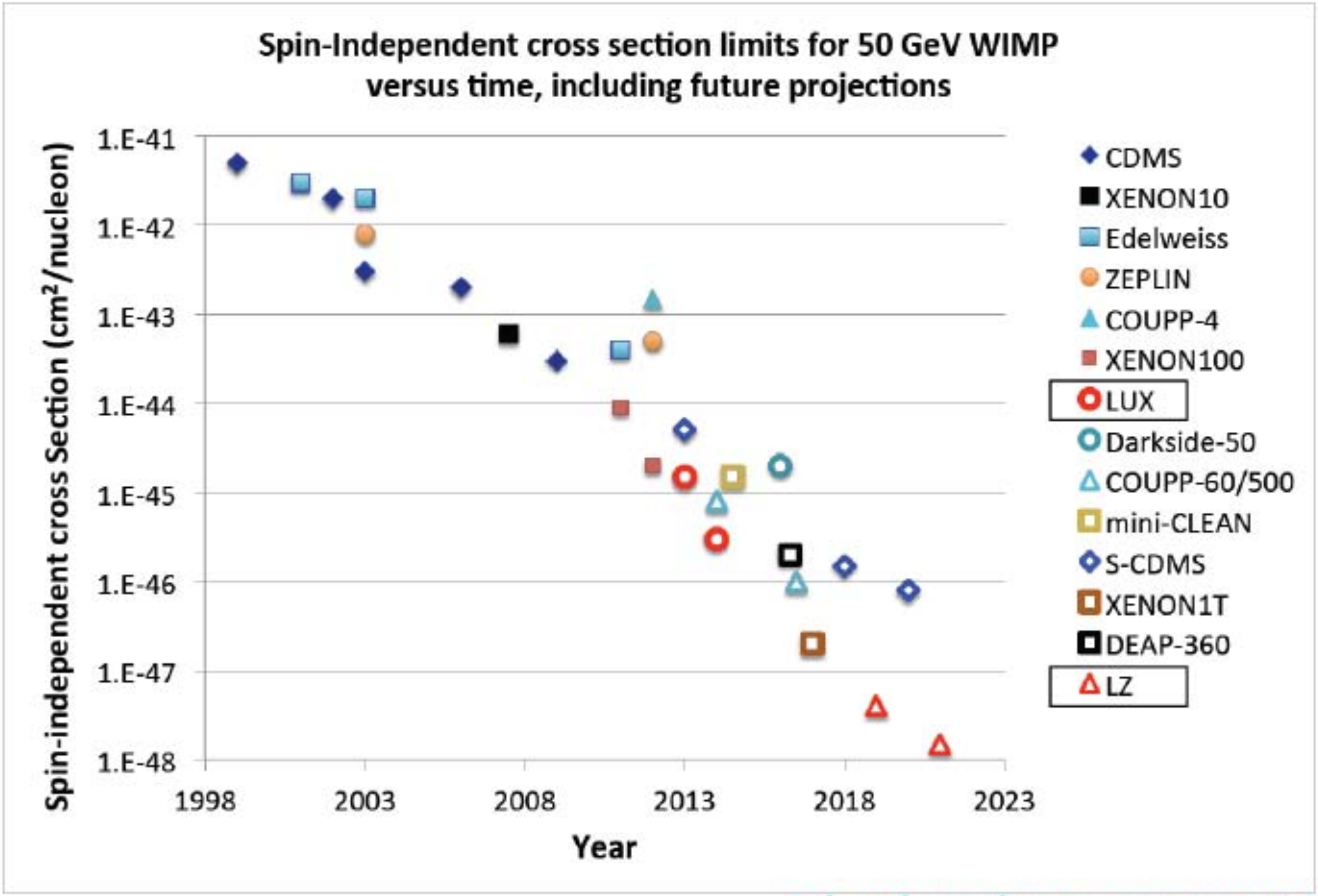
Form factor

Many International Efforts

Picture from L. Baudis, 2012

For lack of time, I will not cover…

- DAMIC (CCD-based light WIMP detector)
- Most crystal detectors
  - ANAIS, DM-Ice, KIMS, CINDMS, ELEGANT
- Superheated liquid detectors
  - COUPP, Picasso, SIMPLE
- Directional detectors
  - DMTPC, DRIFT, D^3, MIMAC, NEWAGE
- Most noble liquid detectors
  - XMASS, Panda-X, DEAP-3600, MiniCLEAN, ArDM
- Some cryogenic detectors
  - Edelweiss, EURECA, Rosebud, TEXONO, CDEX



Selected experiments – courtesy M. Witherell

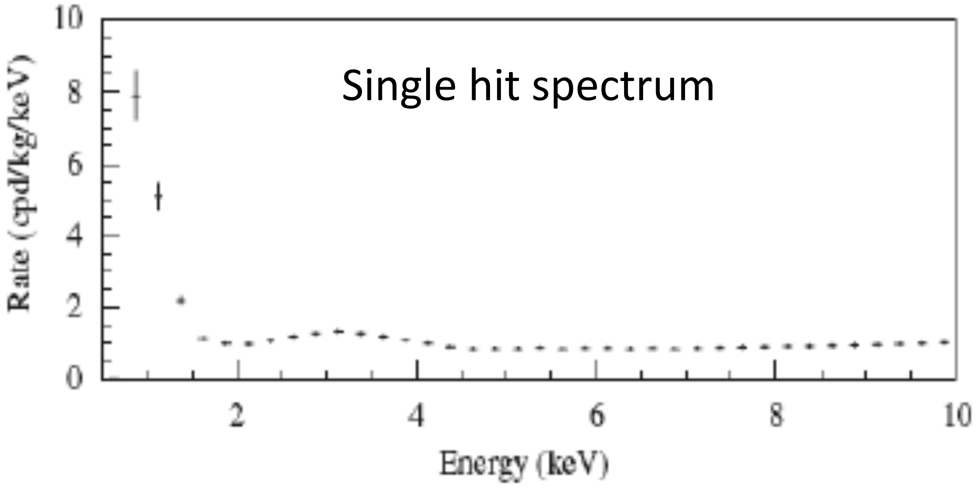
Anomalies at low mass

- DAMA: NaI target, scintillation channel only, annual modulation seen since 1998.
- CRESST: $CaWO_4$ target, scintillation + heat channels, anomalous events seen in 2011.
- CoGeNT: Ge target, charge channel only, event excess seen since 2010.
- CDMS: Ge and Si targets, charge+ heat channels, Si excess seen early 2013.

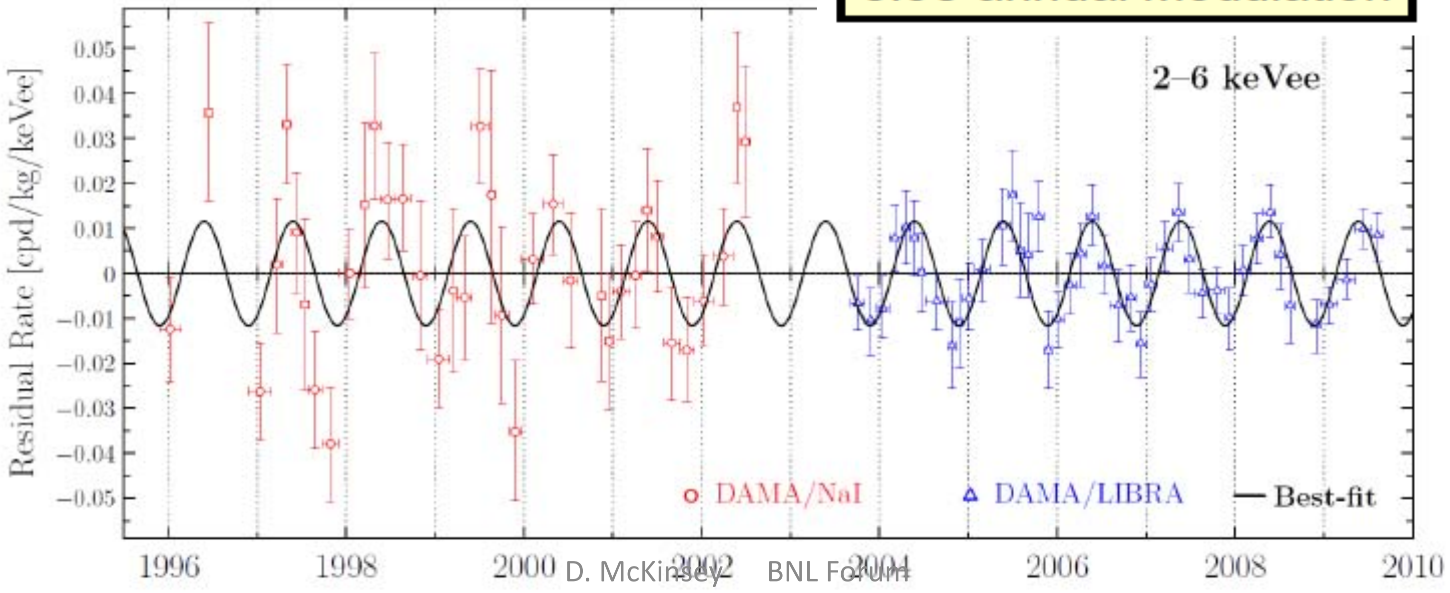
DAMA

Array of NaI detectors, with PMT readout
DAMA/NaI: 100 kg of NaI(Tl)
DAMA/LIBRA: 250 kg of NaI(Tl)
Annual modulation of 2-6 keV single hits
No modulation at higher energies
No modulation of multiple hit events

New runs: DAMA has been operating with high-QE phototubes since Dec 2010.


Single hit spectrum

8.9σ annual modulation



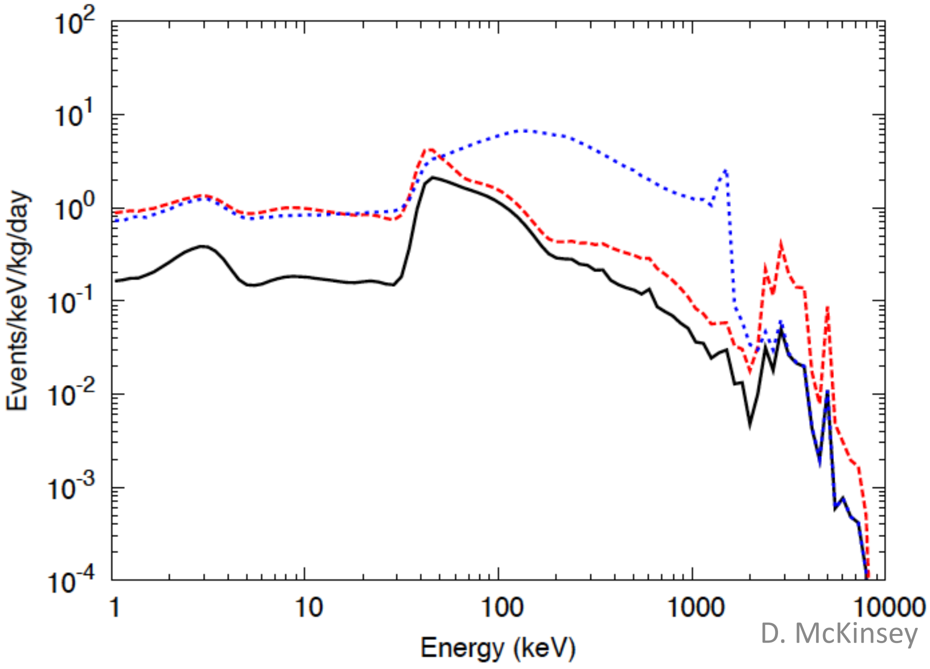
DAMA background studies

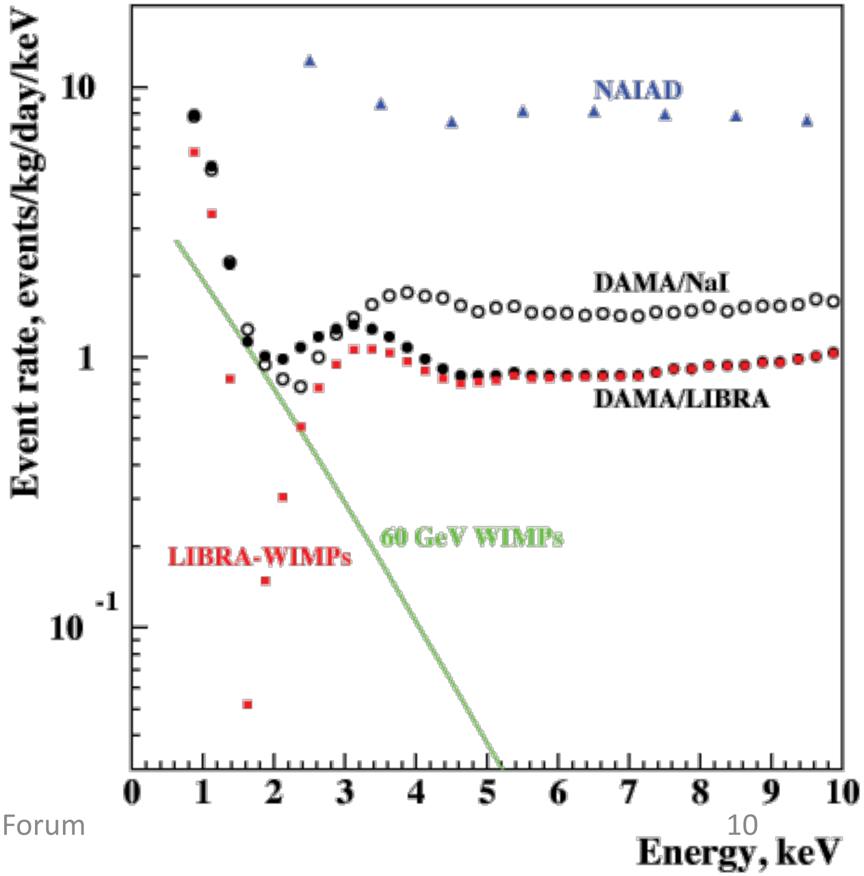
Annual modulation is an unexplained mystery.

Subtracting WIMP spectrum from measured spectrum predicts a minimum in background spectrum from 1.5 – 2 keV. This is difficult to obtain from background simulations.

Little room for continuous, non-modulated part of WIMP signal when backgrounds are included. See Kudryavtsev et al, *Astroparticle Phys.*, **33** (2010) 91-96

Simulated background spectra



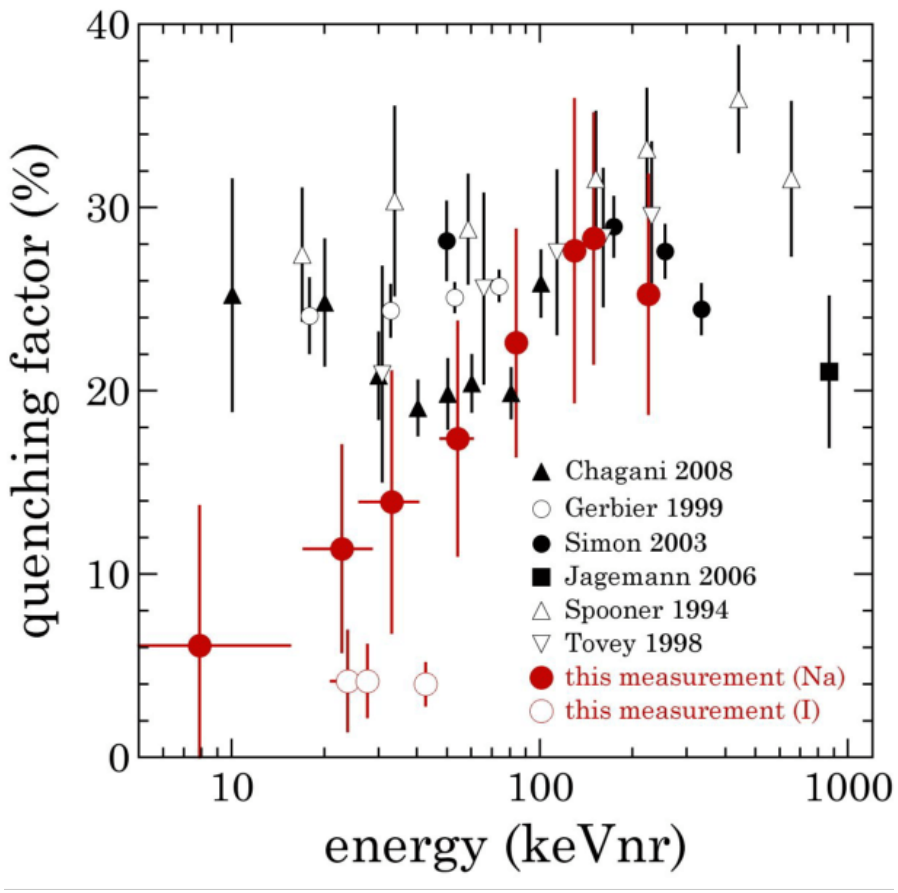


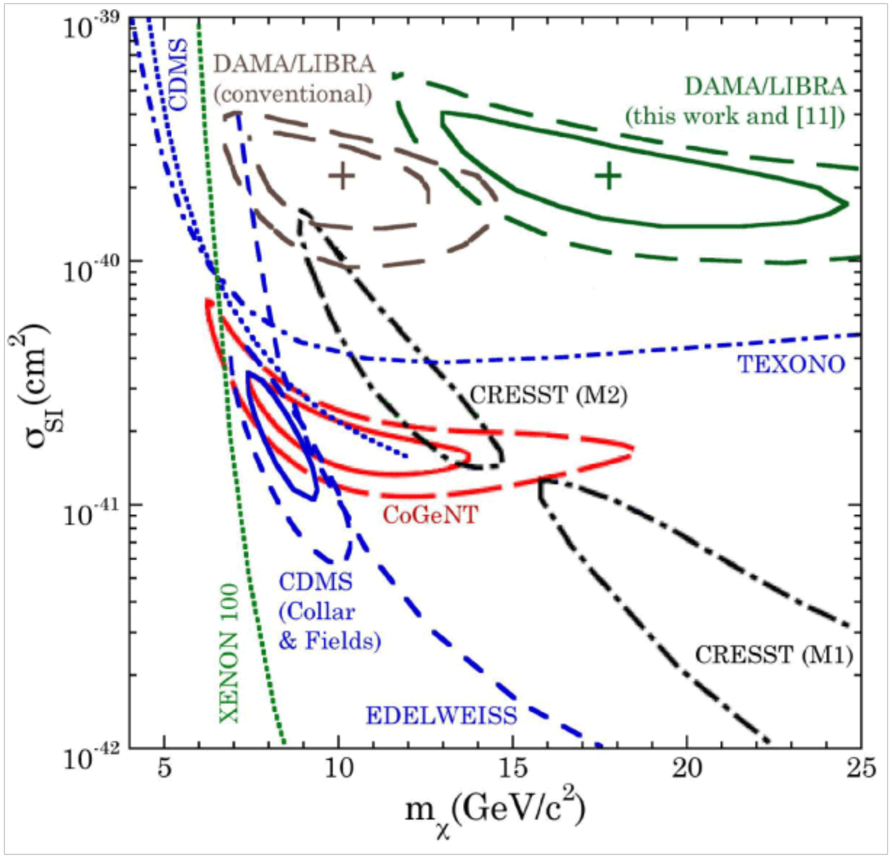
NaI quenching factor

How much scintillation light is produced by nuclear recoils, relative to electron recoils

New measurement: J. Collar, arXiv:1302.0796, arXiv:1303.2686

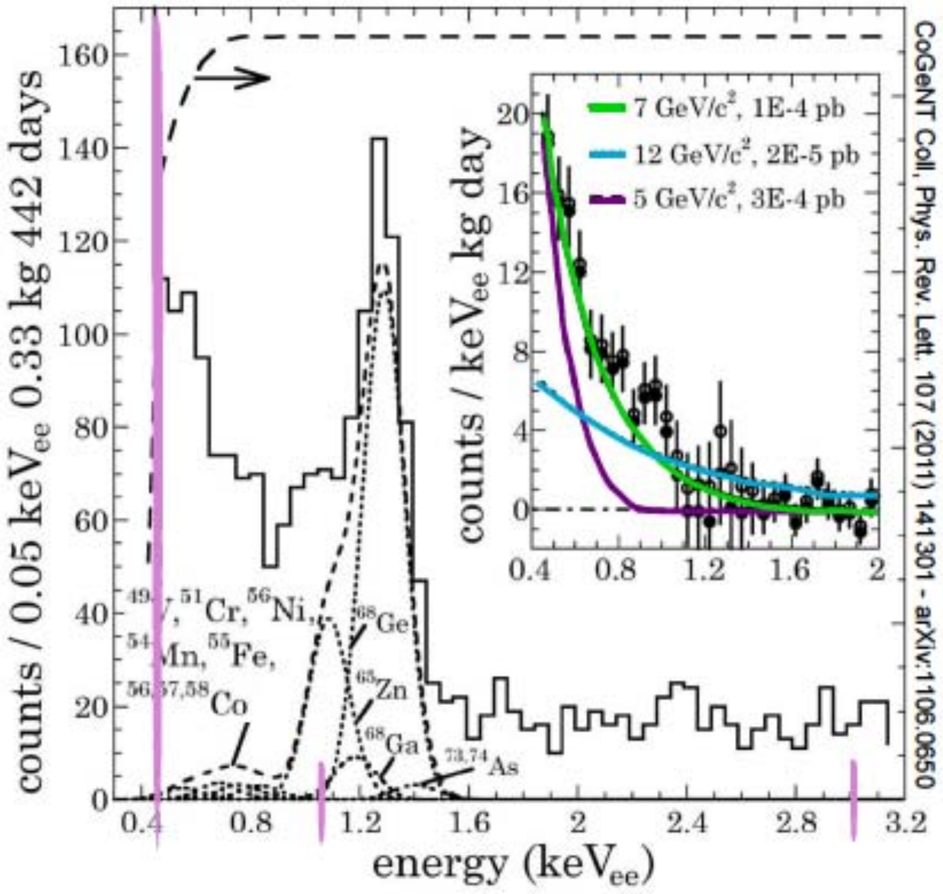
Hard to see how DAMA could be consistent with CoGeNT and CDMS anomalies



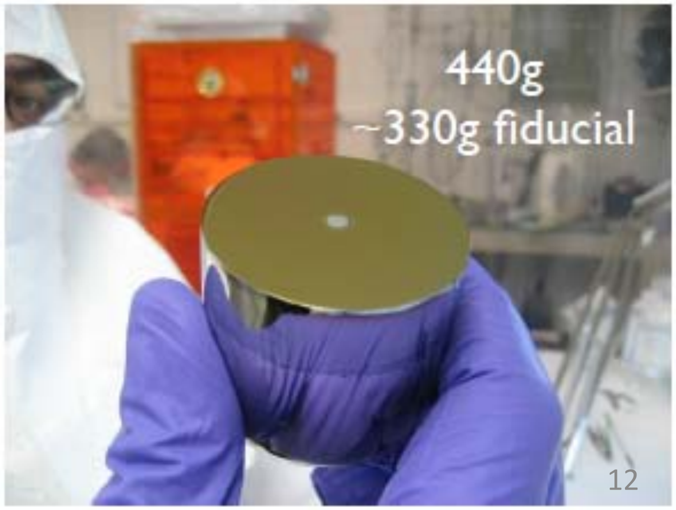


CoGeNT

Technology: P-type, point contact Germanium detectors

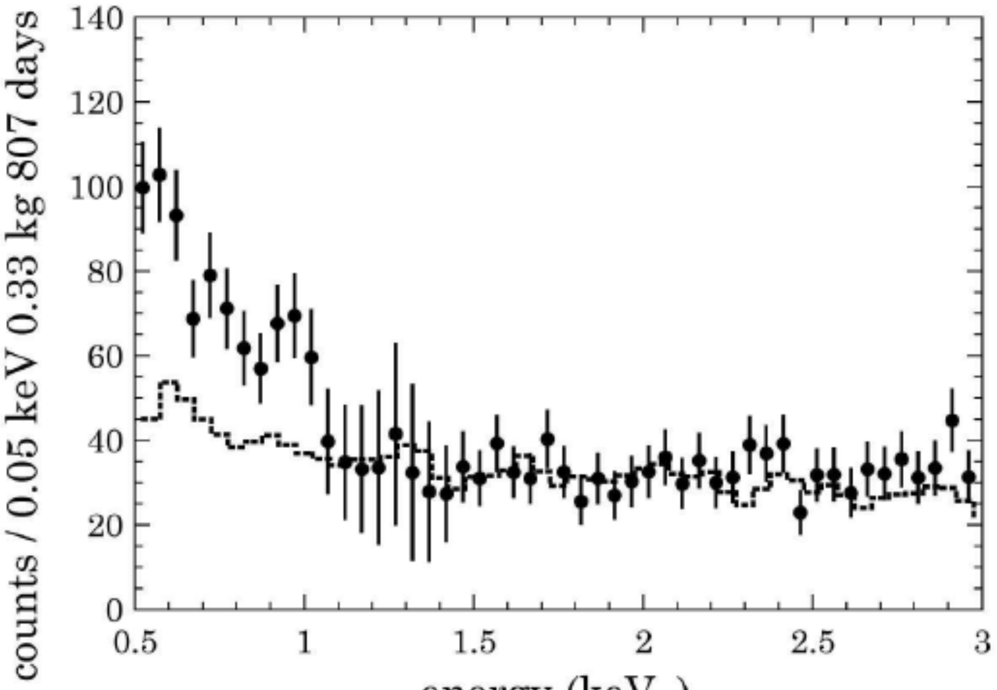


CoGeNT Coll, Phys. Rev. Lett. 107 (2011) 141301 - arXiv:1106.0650

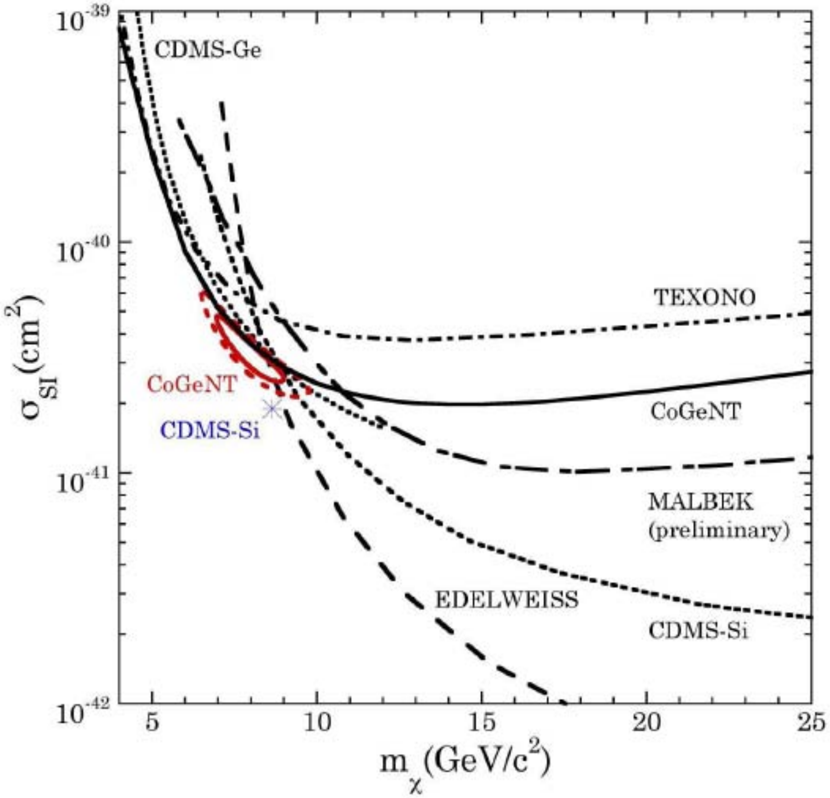


CoGeNT results

CoGeNT spectrum after subtracting off efficiency corrections, surface events, and cosmogenics



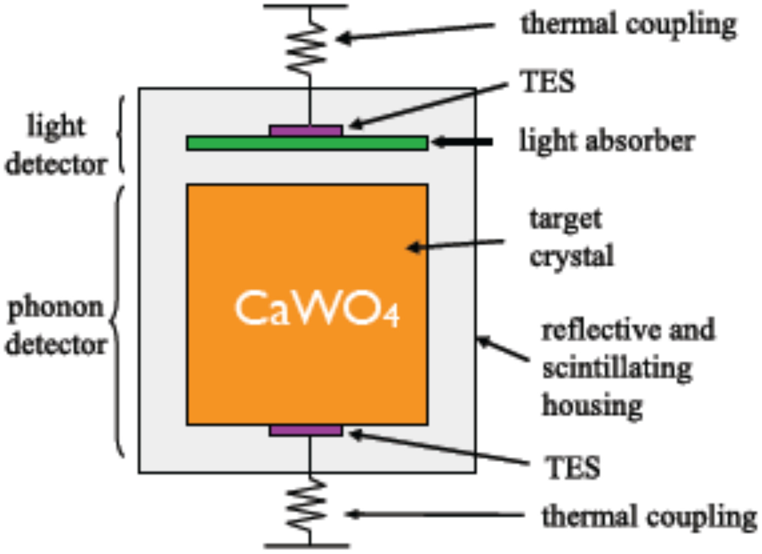
CoGeNT limits and 90% WIMP ROI

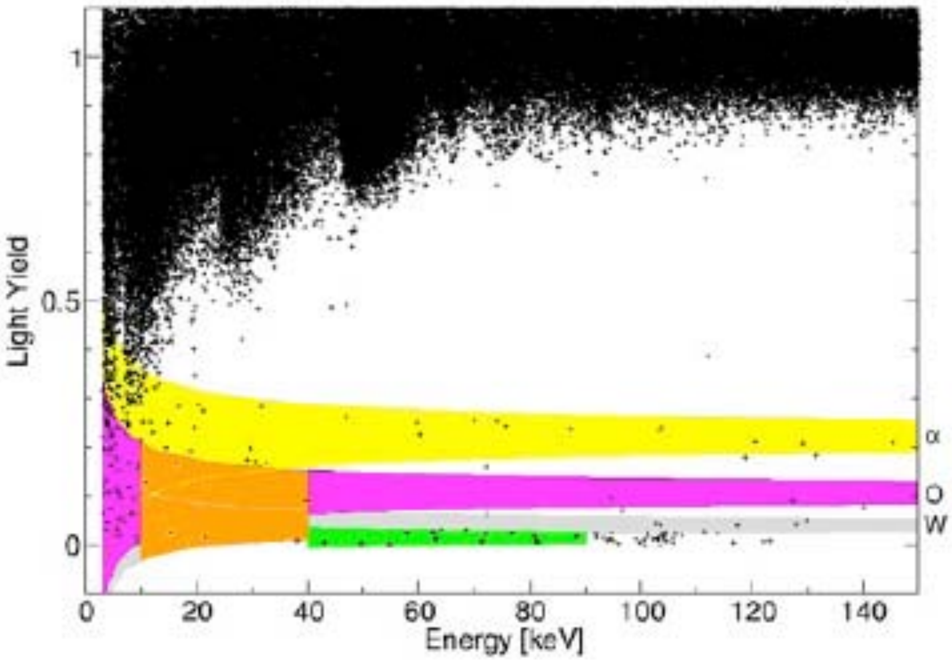


CRESST

Cryogenic detector, using both scintillation and phonon channels
Discrimination based on ratio of signal channels

67 events in acceptance region, half of which are attributed to backgrounds



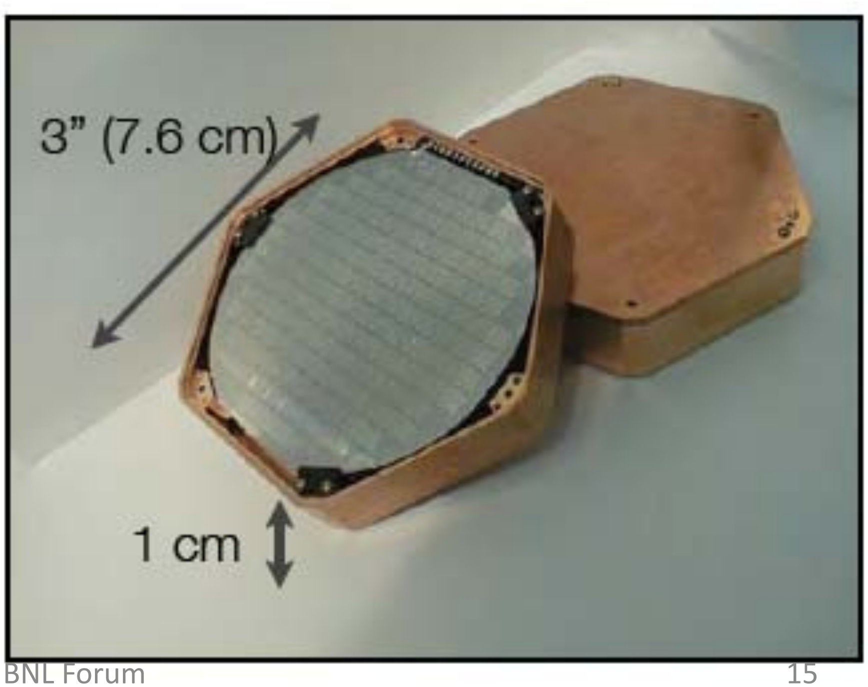


CDMS-II

Germanium or silicon "hockey pucks" operated at ~ 100 mK, heavily instrumented with charge and phonon readout.

Ionization per unit energy deposition is higher for electron recoils than for nuclear recoils, provides discrimination.

Particles in "surface dead layer" result In reduced ionization yield. These surface events are reduced through pulse rise time cut.



New CDMS-II Si results

Agnese et al, arXiv:1304.4279

Blind analysis of eight Si detectors, with 140.2 kg day exposure, from July 2007 – Sept 2008

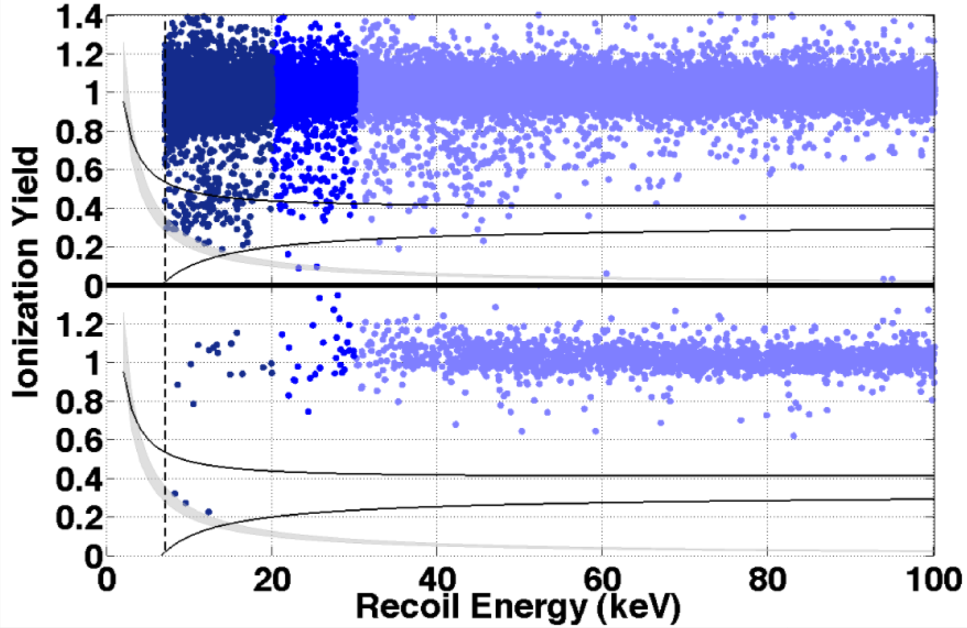
For low-mass WIMPs, more recoil energy is transferred to Si than to Ge.

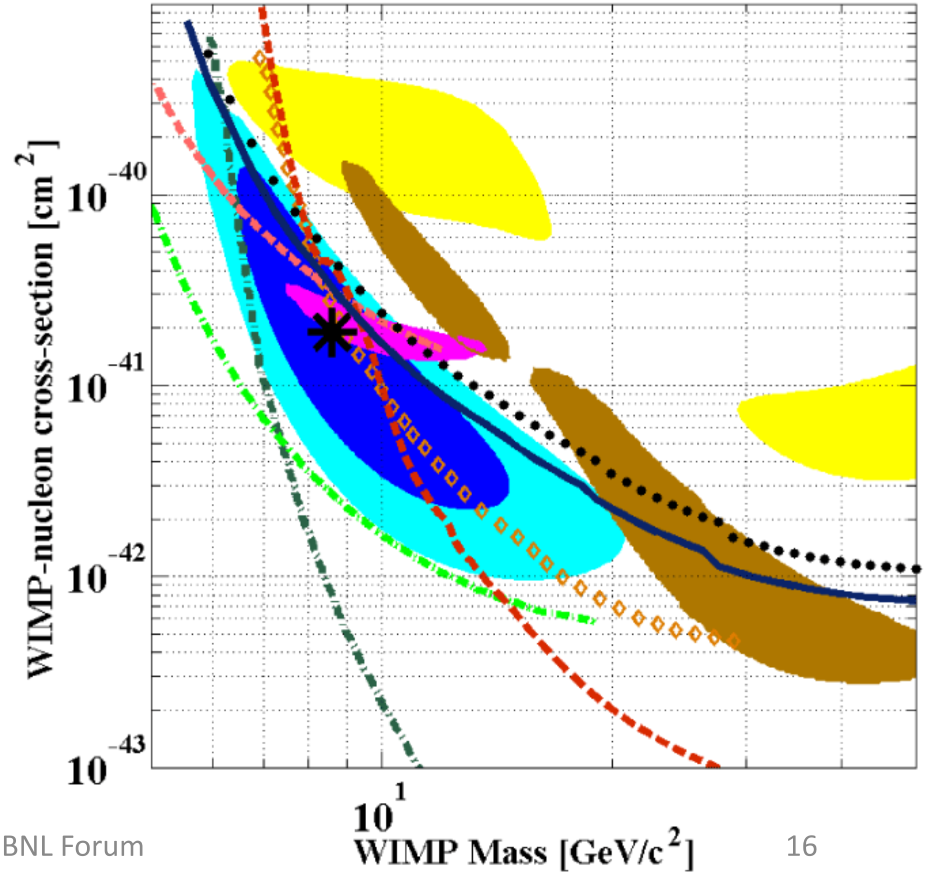
Three events seen, with a 5.4% probability of a statistical fluctuation producing 3+ events.

Best fit under WIMP hypothesis gives 8.6 GeV mass, 1.9e-41 cm^2 WIMP-nucleon cross-section

“We do not believe this result rises to the level of a discovery, but it does call for further investigation”

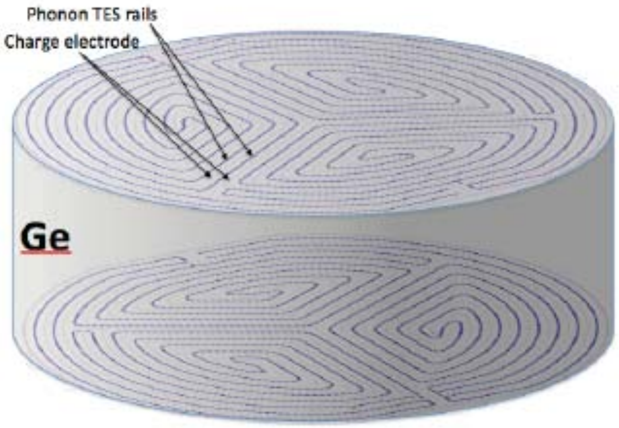
Top = all events. Bottom = after pulse timing cut

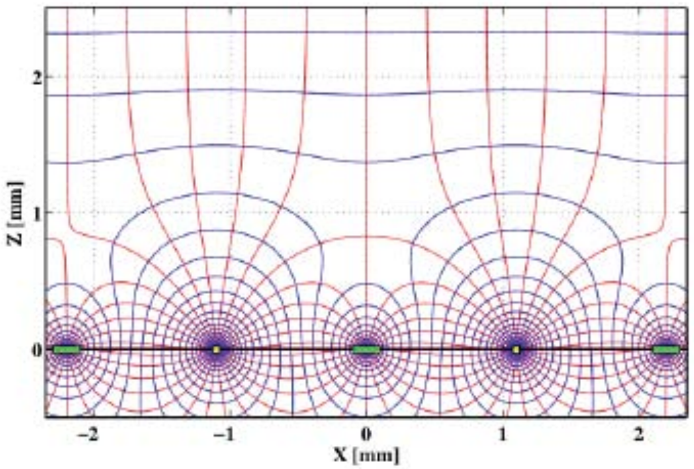




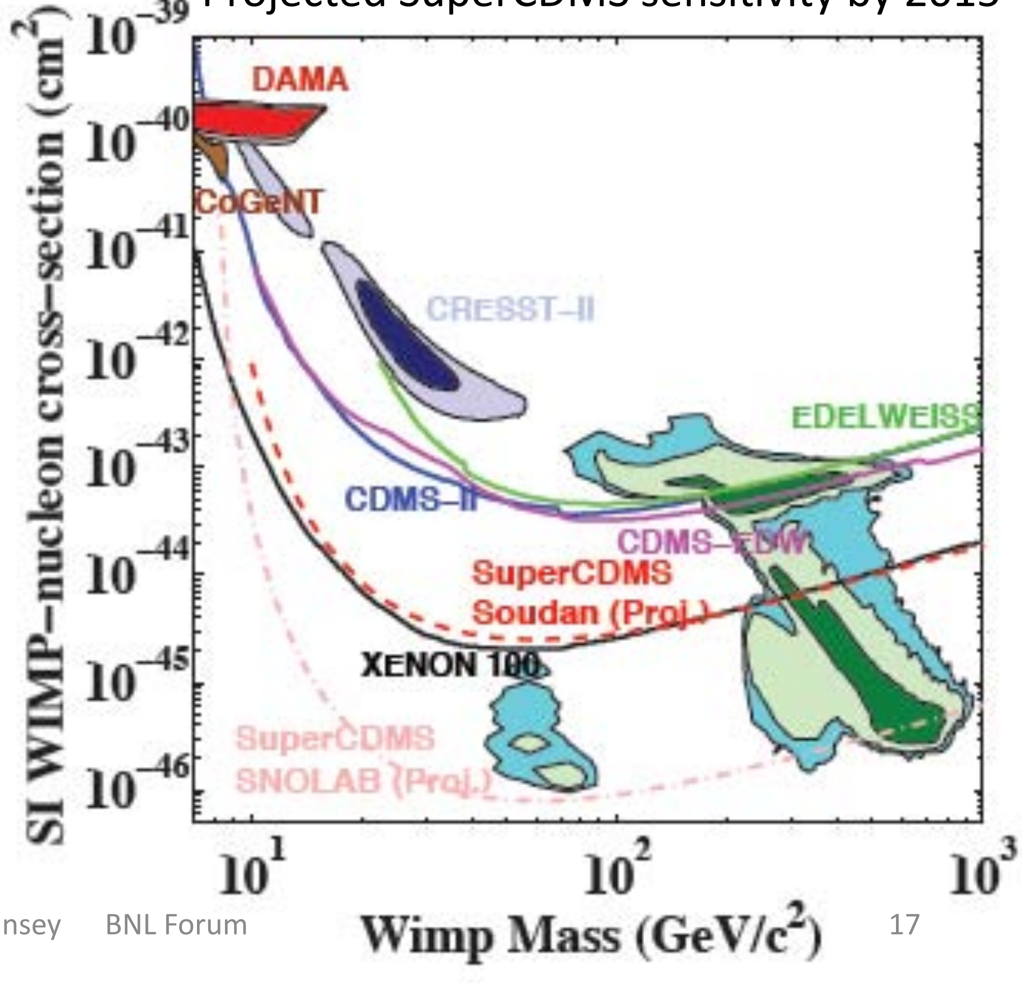
SuperCDMS

New iZip detectors have interleaved z-sensitive ionization and phonon sensors on both faces
Charge near the surface of the detector is collected on only one side
Charge in the bulk is collected on both faces
15 iZIPs are in the Soudan infrastructure built for CDMS-II





Projected SuperCDMS sensitivity by 2015



Liquified Noble Gases: Basic Properties

Dense and homogeneous

Do not attach electrons, heavier noble gases give high electron mobility

Easy to purify (especially lighter noble gases)

Inert, not flammable, very good dielectrics

Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Direct WIMP Detection with Liquid Xenon

Goal: observe recoils between a WIMP and a target nucleus

Equation for WIMP interaction cross section

$$\frac{dN}{dE_R} \propto \left(\frac{e^{-E_R/(E_0 r)}}{E_0 r} \right) \cdot \left(F^2(E_R) \cdot I \right)$$

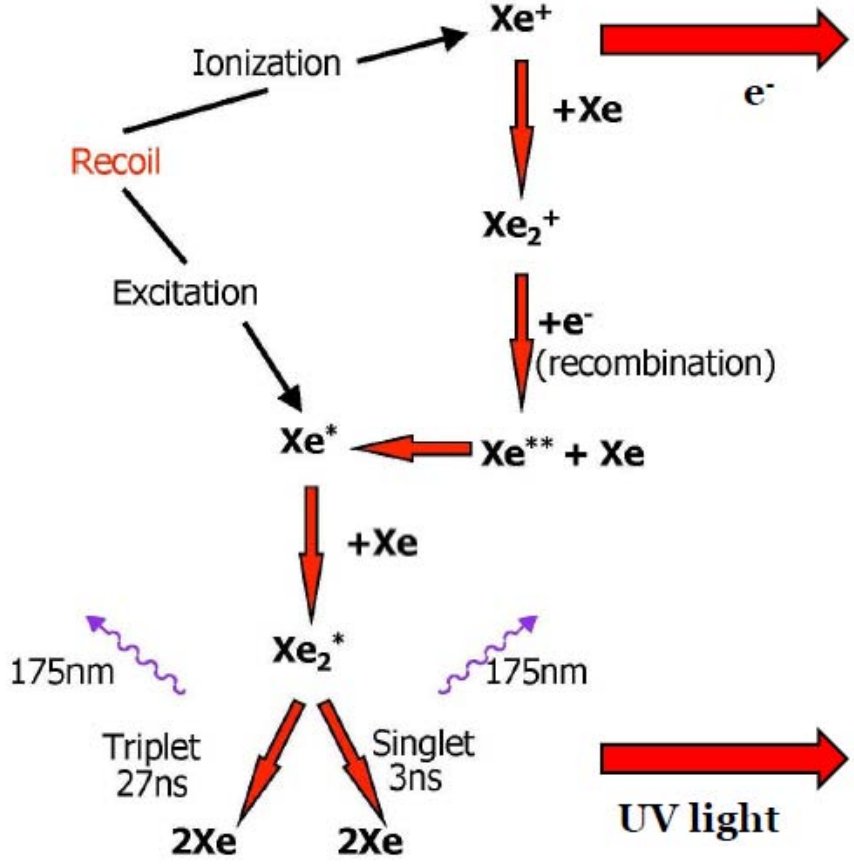
$I \propto A^2$ (for S.I. interactions)

Recoil energy deposited in three channels:

Scintillation (photons)

Ionization (charge)

Heat (phonons)



Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

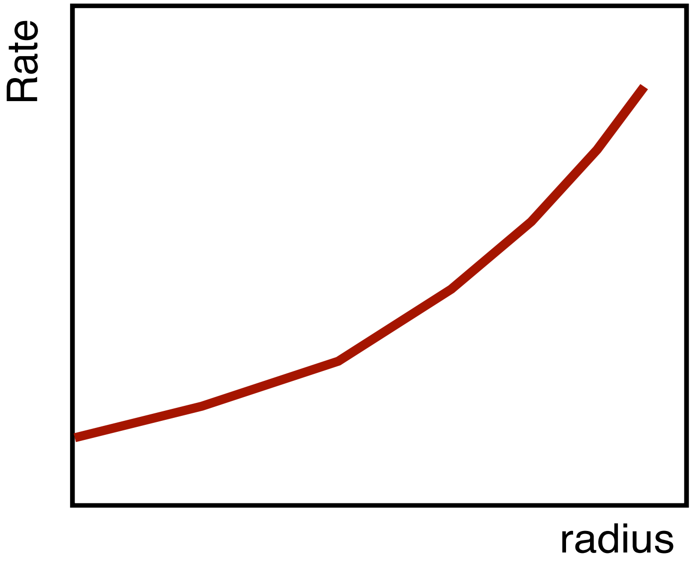
Require < 1 event in signal band during WIMP search

LXe: Self-shielding, Ionization/Scintillation ratio best

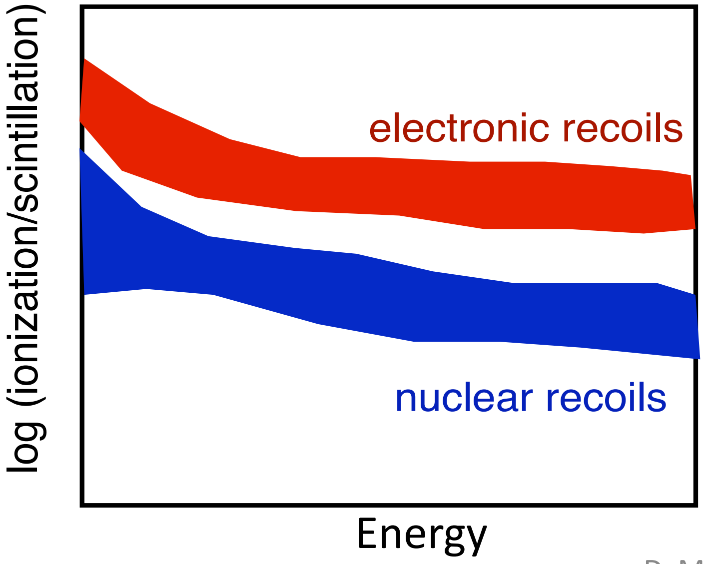
LAr: Pulse shape, Ionization/Scintillation ratio best

LNe: Pulse shape, Self-shielding best

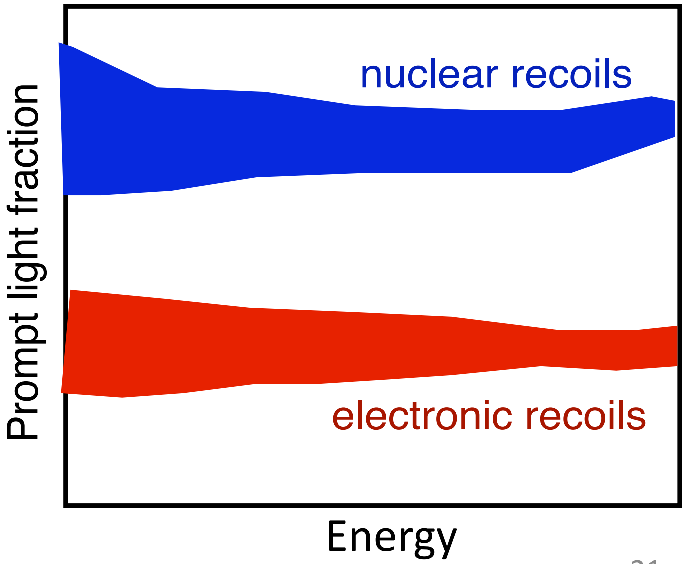
Self-shielding



Ionization/Scintillation Ratio



Pulse Shape Discrimination

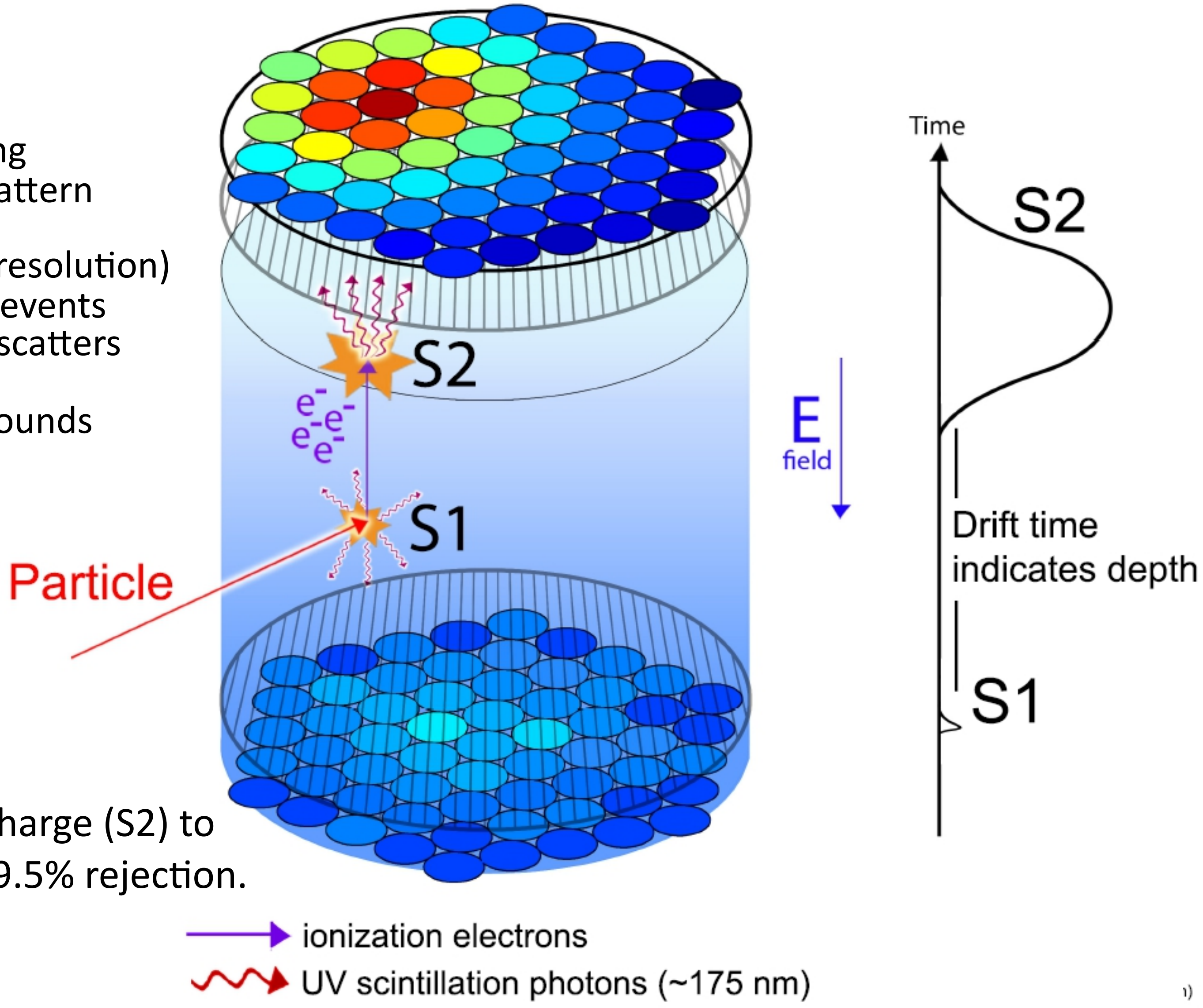


Two-phase Xenon WIMP Detectors

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds
reduced by self-shielding



Reject gammas, betas by charge (S2) to light (S1) ratio. Expect > 99.5% rejection.

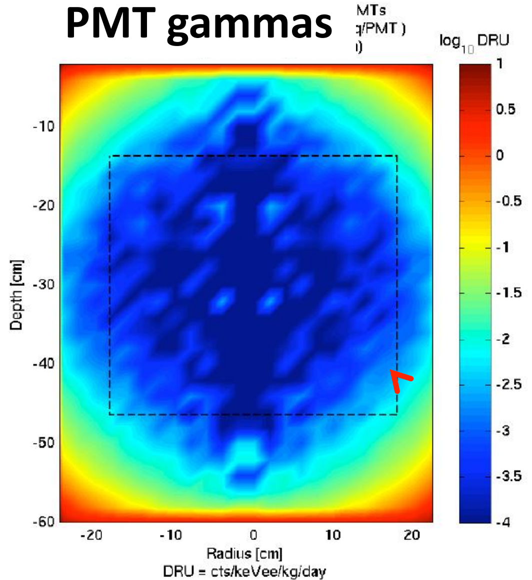
Xe Self-Shielding

Liquid xenon density = 3 g/cm^3.

To cause a background event,
gamma rays and neutrons must penetrate
Into the fiducial volume, scatter once, and
then escape without scattering again.

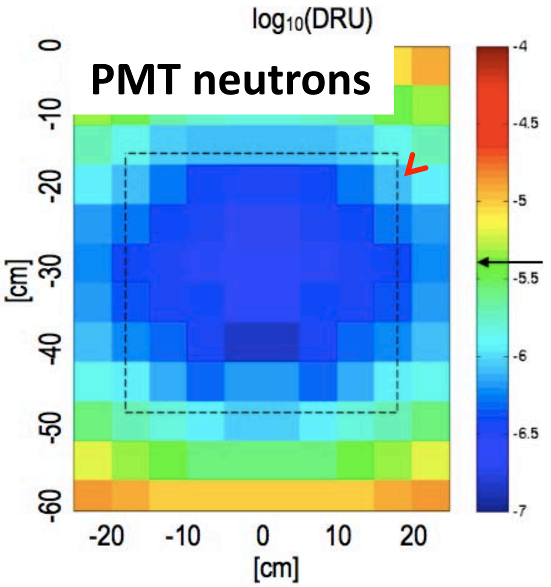
Gamma ray, neutron backgrounds
drop exponentially with detector size.

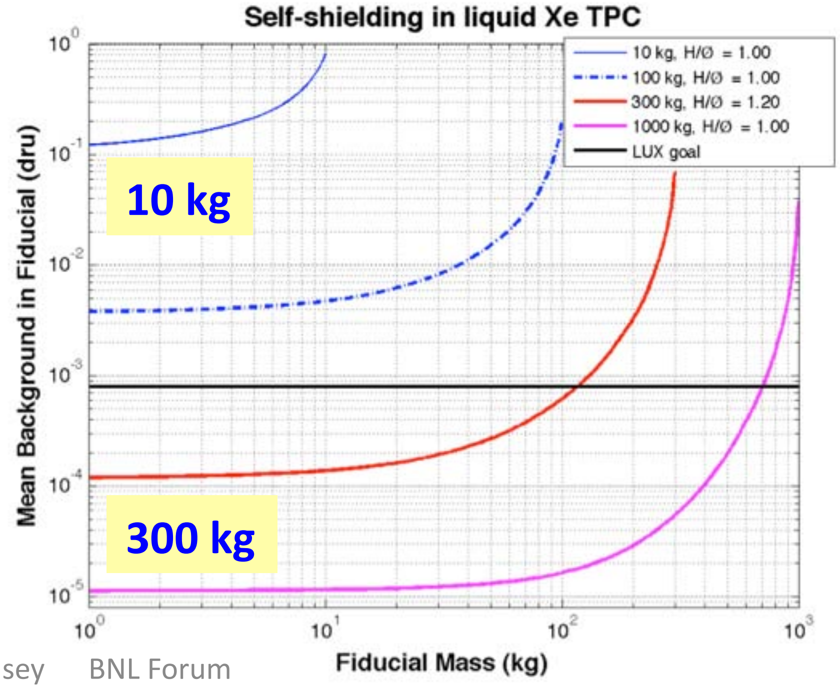
PMT gammas



Fiducial volume

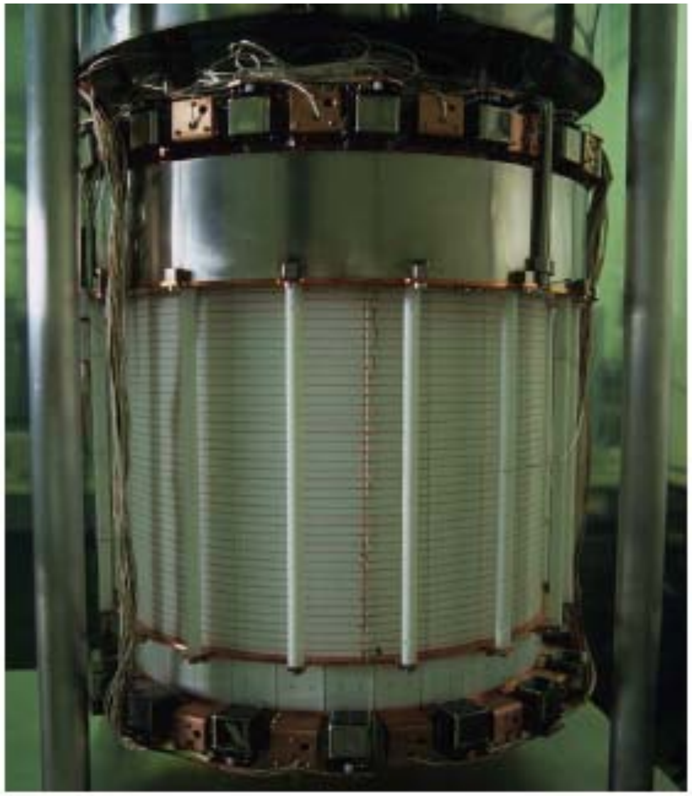
PMT neutrons



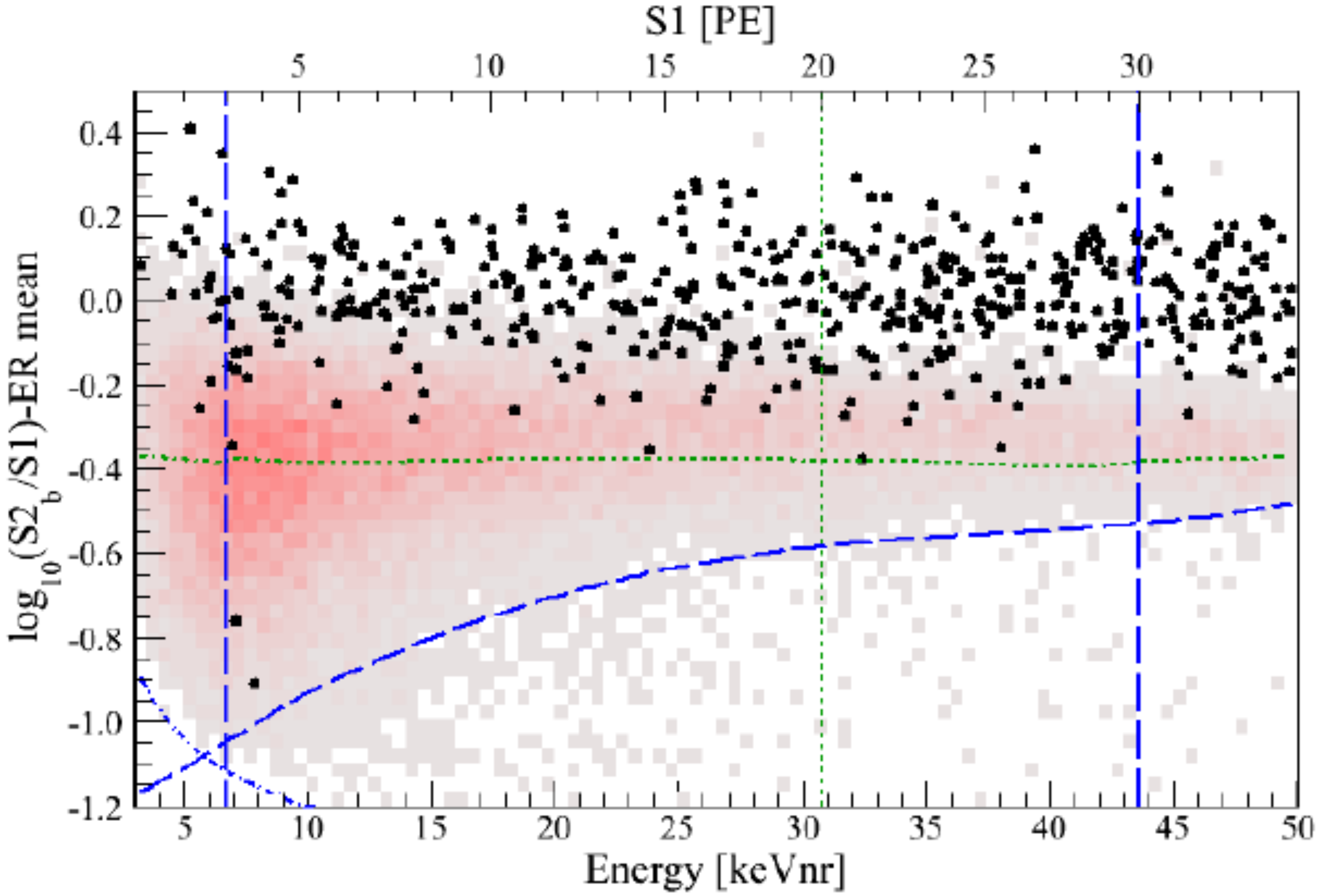


XENON100

- Two-phase Xe detector with 62 kg active target, 34 kg fiducial mass
- 242 1-inch square PMTs: 1 mBq (U/Th) and ~30% QE
- Multilayer passive shield (Cu, Poly, Pb+Water)
- Background rate of 5.3e-3 events/keV/kg/day after veto cut, before discrimination
- 19 ppt of Kr contamination

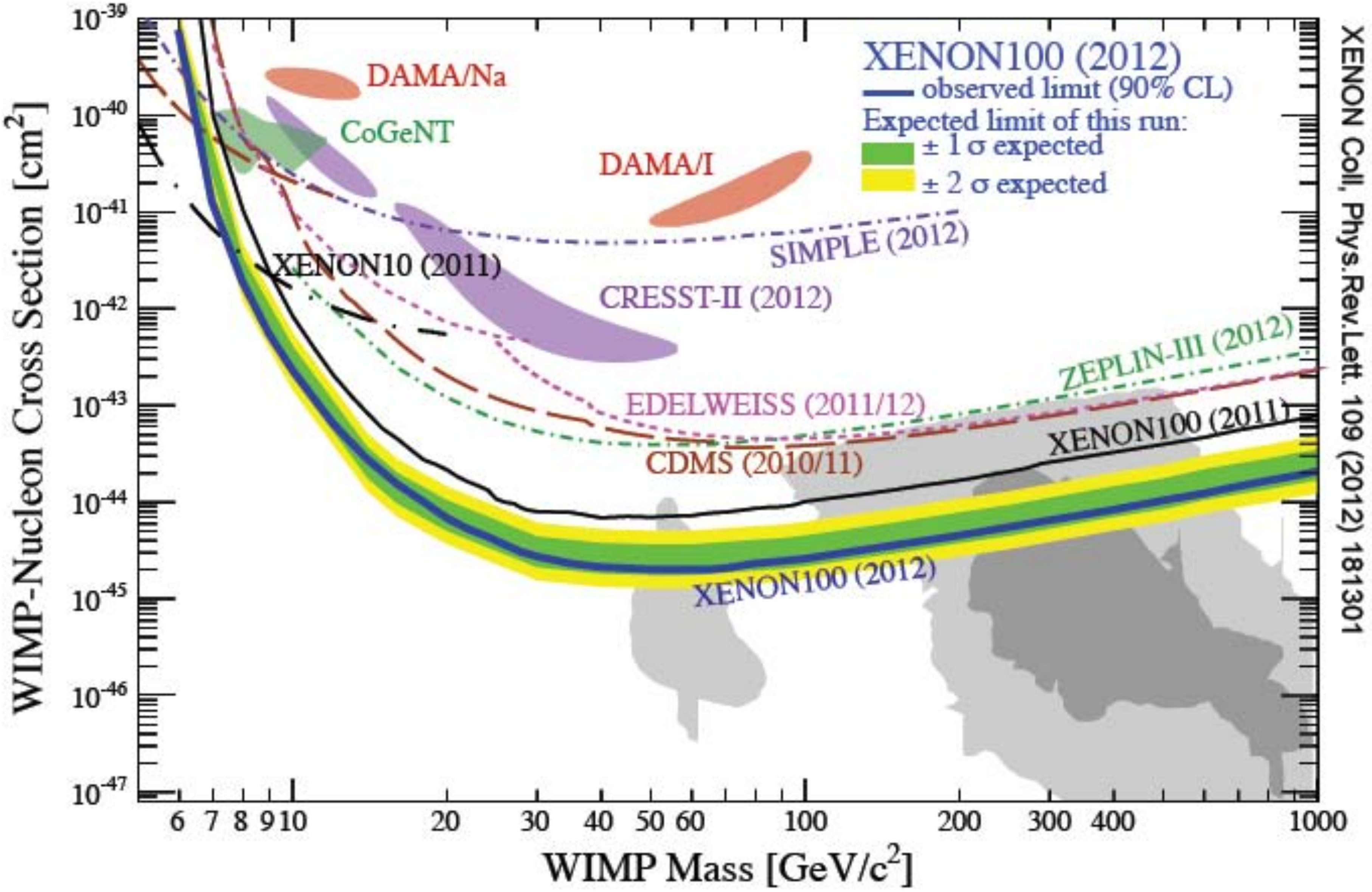


XENON100 results, 225 days of data



2 events, just above threshold, with 1.0 expected

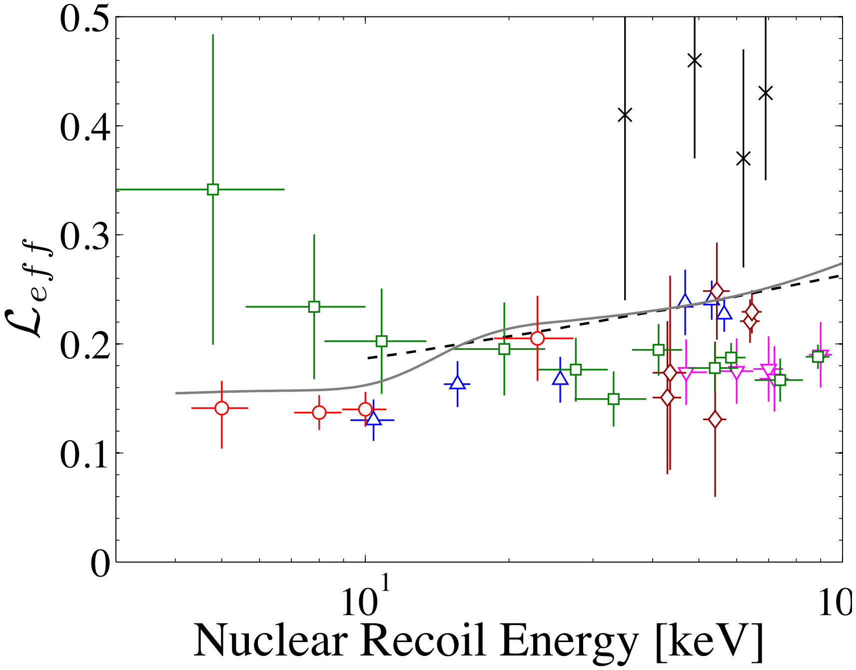
XENON100 Limit (2012)



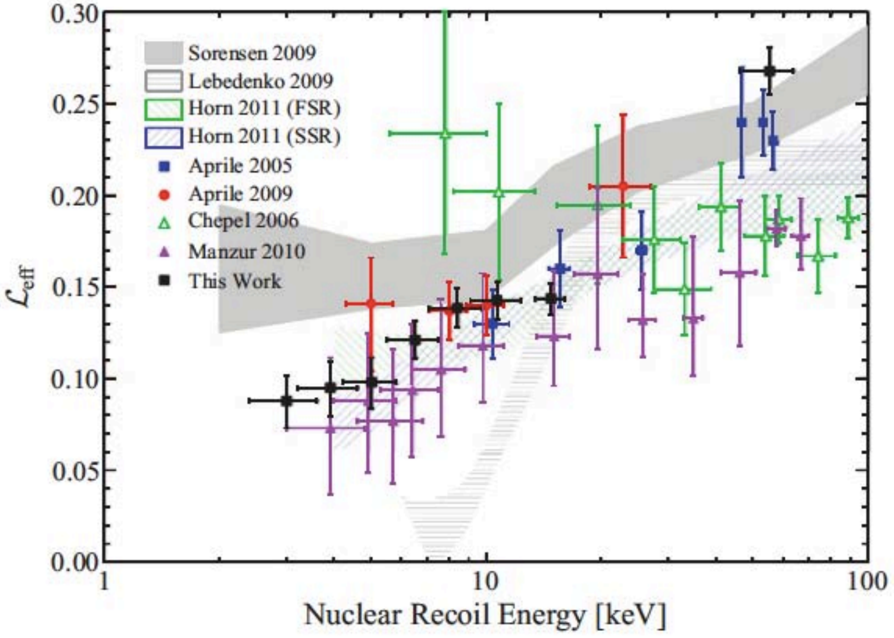
XENON Coll, Phys.Rev.Lett. 109 (2012) 181301

After some controversy, Leff is now believed to decrease at low energy

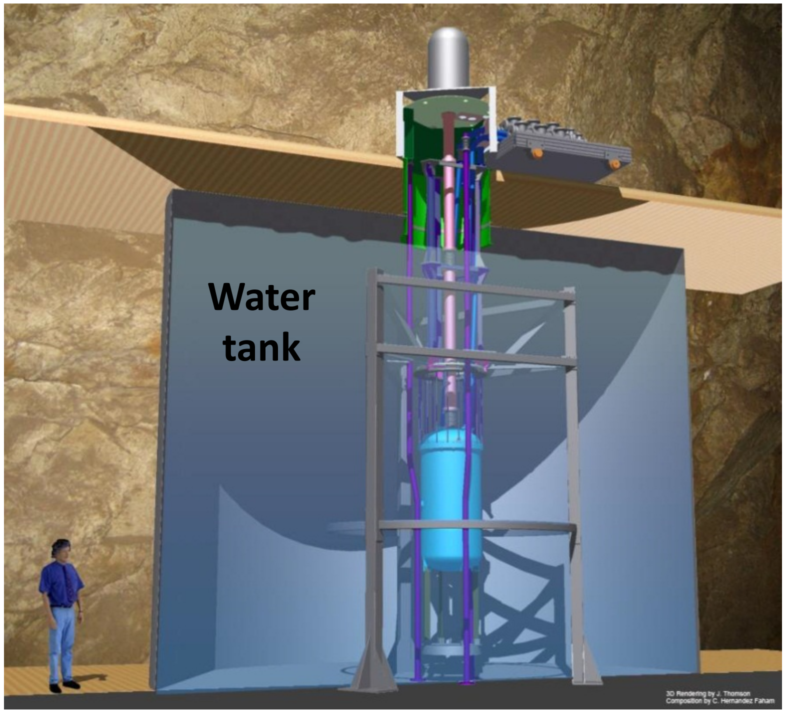
Aprile et al, 2009



Plante et al, 2011



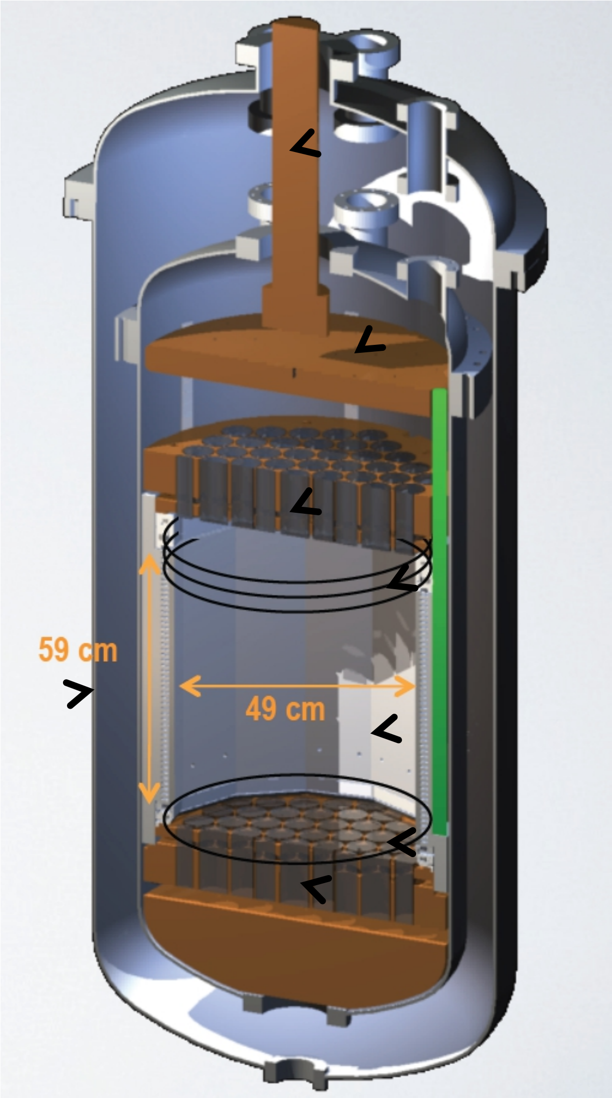
The LUX Detector



3D Rendering by J. Thomson
Composition by C. Hernandez Faham

**Low-radioactivity
Titanium Cryostat**

350 kg xenon
100 kg fiducial



Thermosyphon

Copper shield

Top PMT array

Anode grid

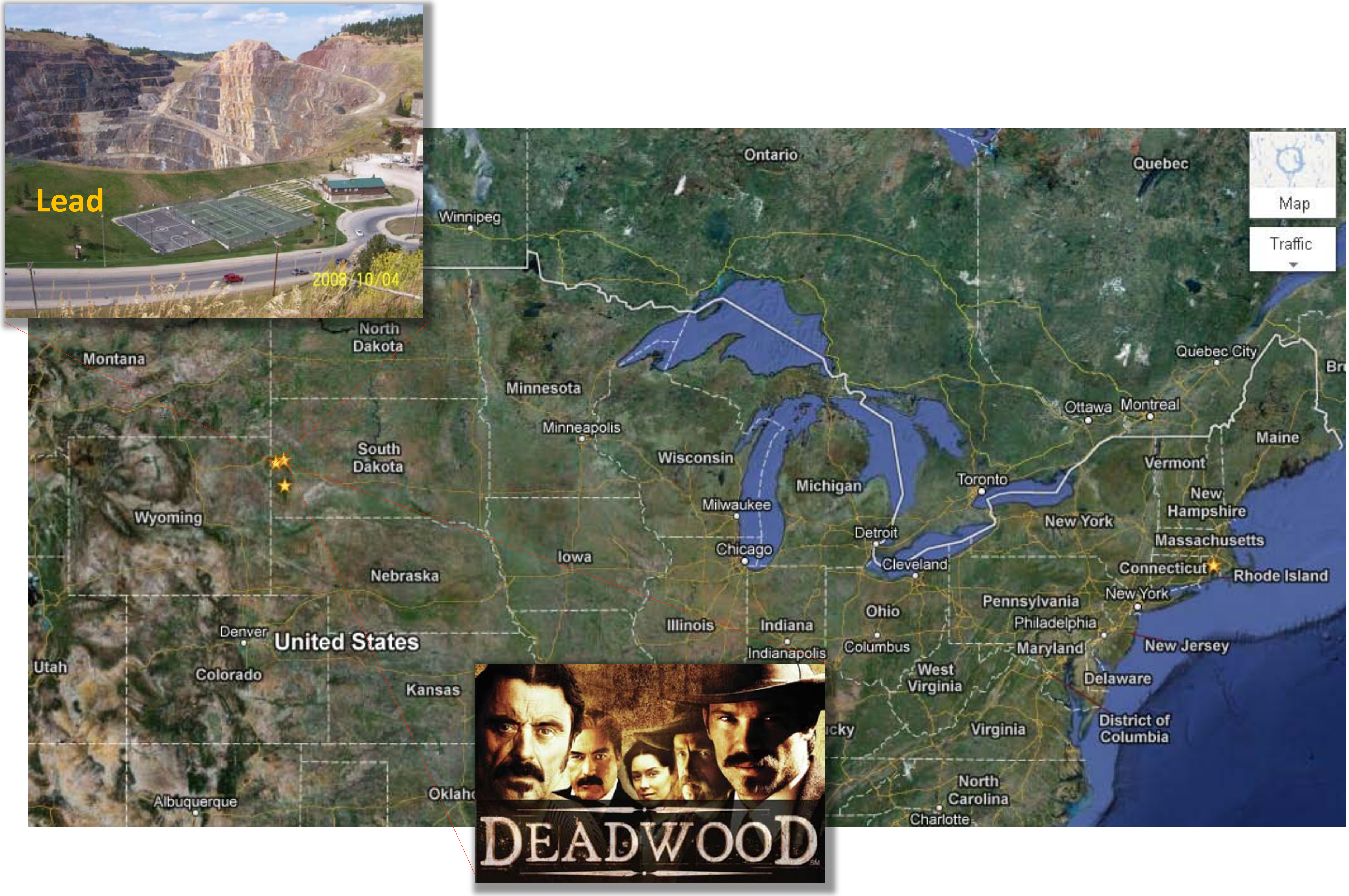
**PTFE reflector
panels and
field cage**

Cathode grid

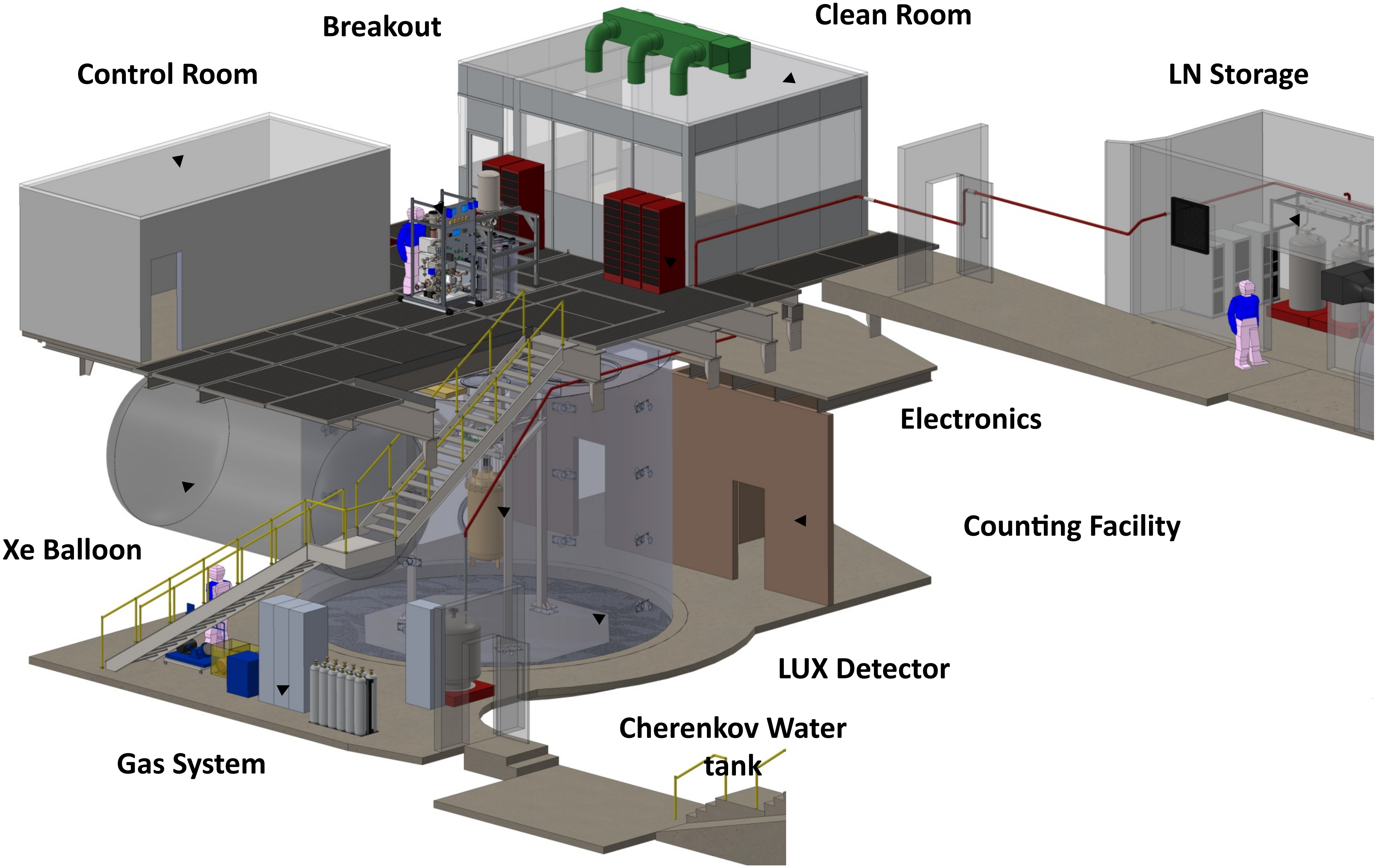
Bottom PMT array

Construction

The Sanford Underground Research Facility



SURF – Davis Laboratory



Breakout

Clean Room

Control Room

LN Storage

Electronics

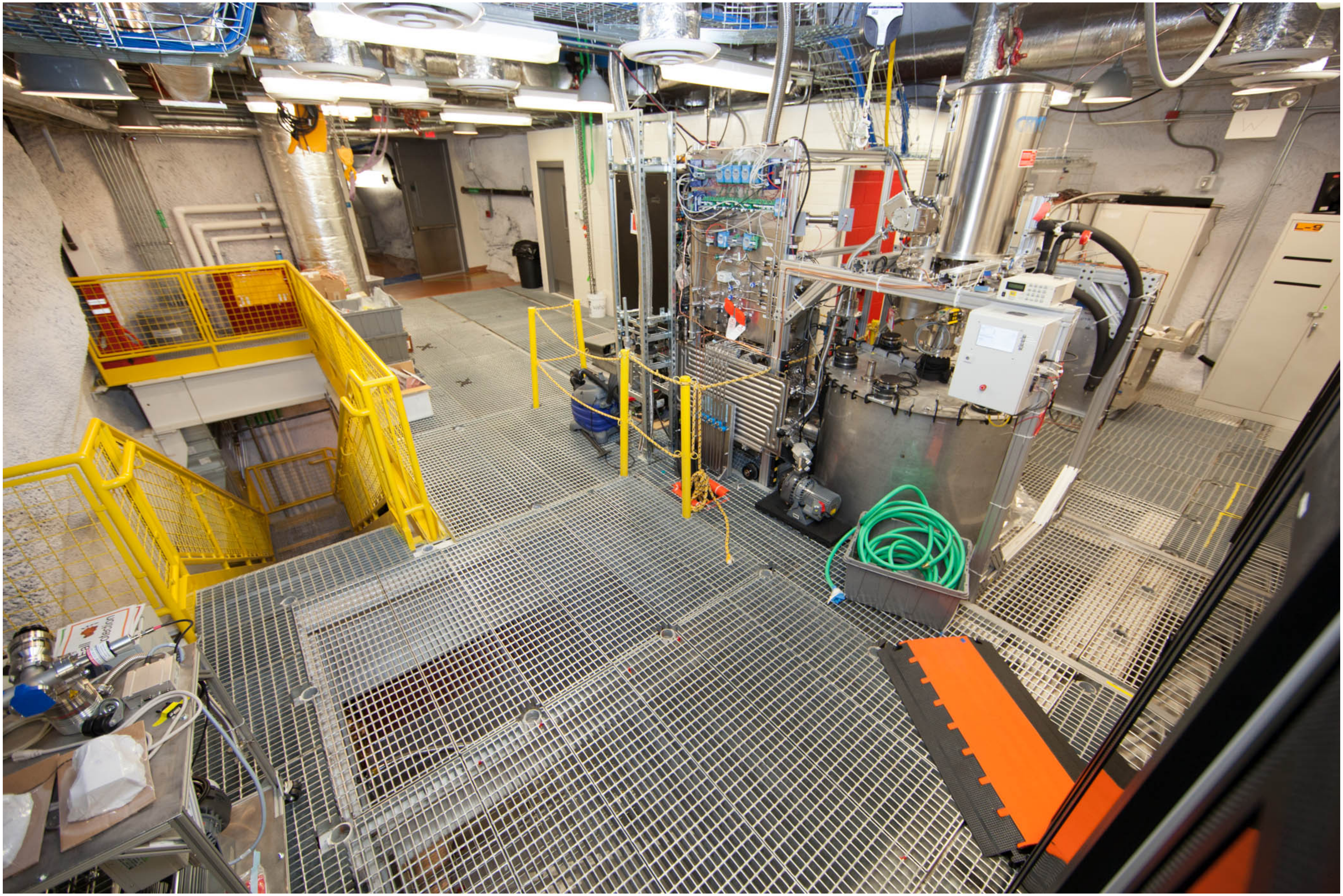
Counting Facility

Xe Balloon

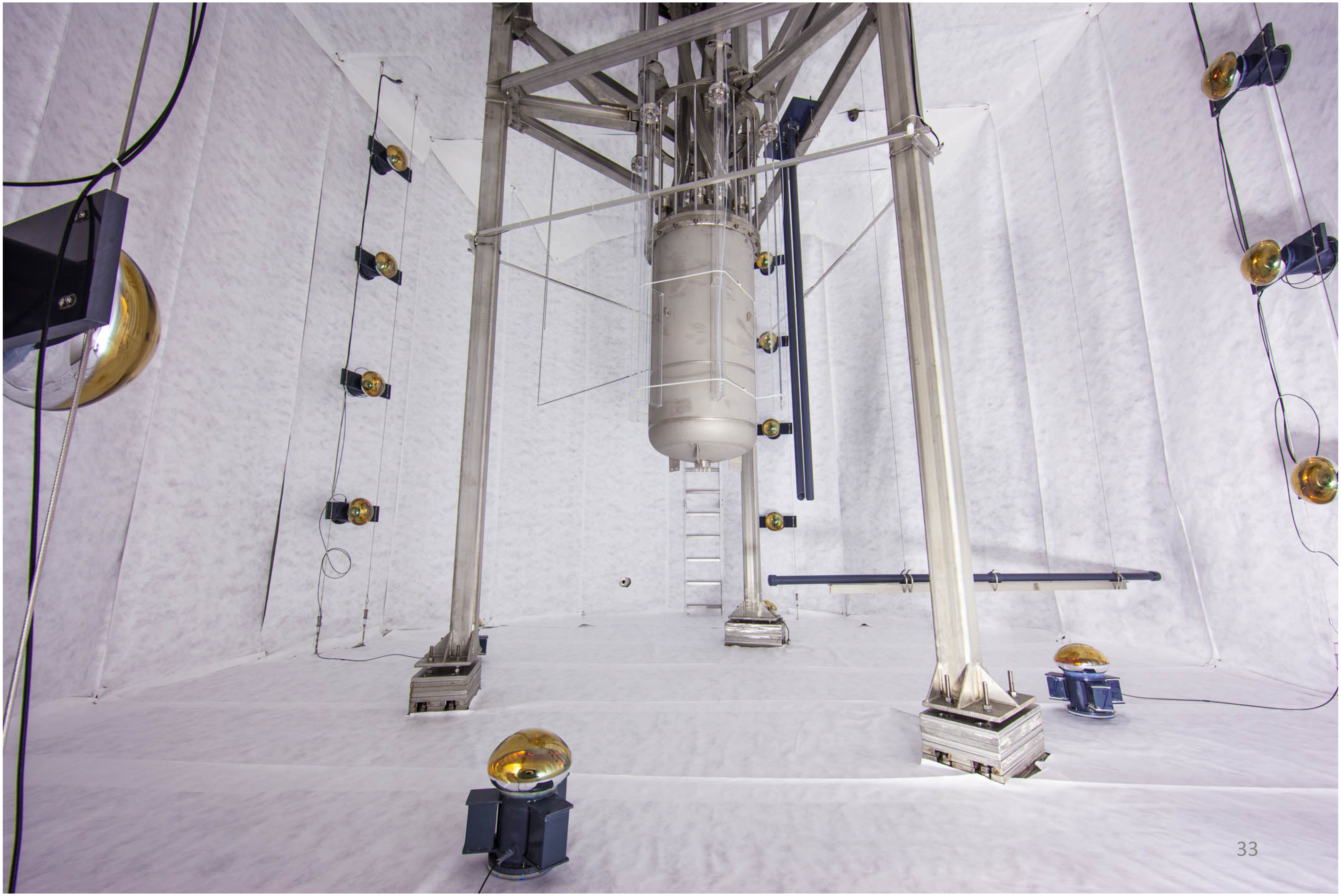
LUX Detector

Cherenkov Water tank

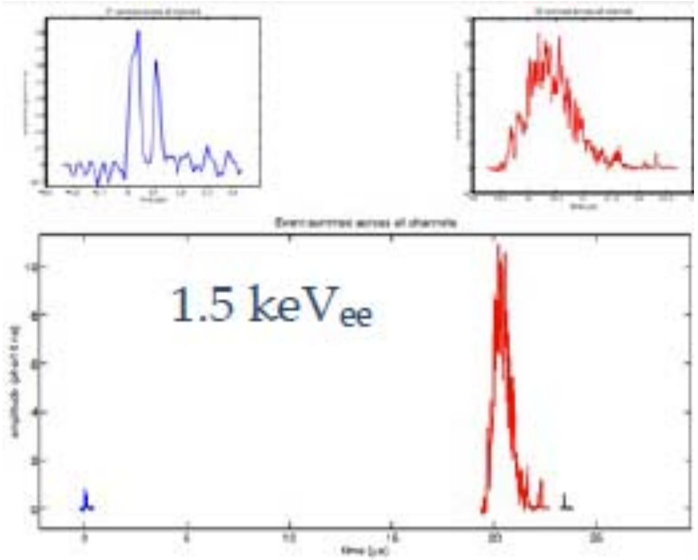
Gas System



LUX is cold, filled with liquid xenon, and operational, a mile underground in South Dakota



LUX Timeline



✓ Detector cooldown and gas phase testing
Completed early February 2013

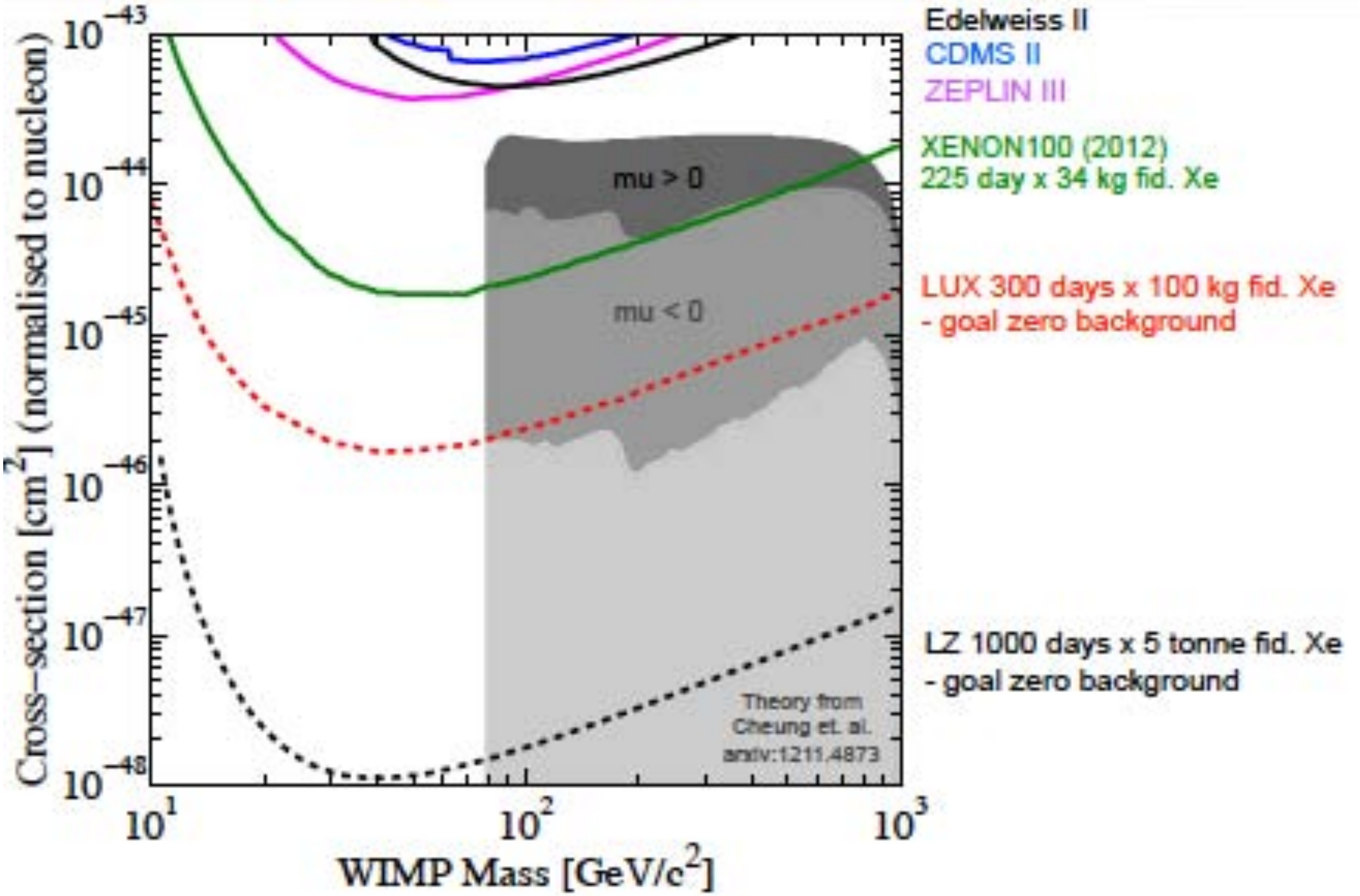
✓ Xenon condensation
Completed mid February 2013

➡ Detector commissioning underway
Subsystem verification, calibration, and Xe purification

Short (roughly 60 day) WIMP run
Result expected by end of the year

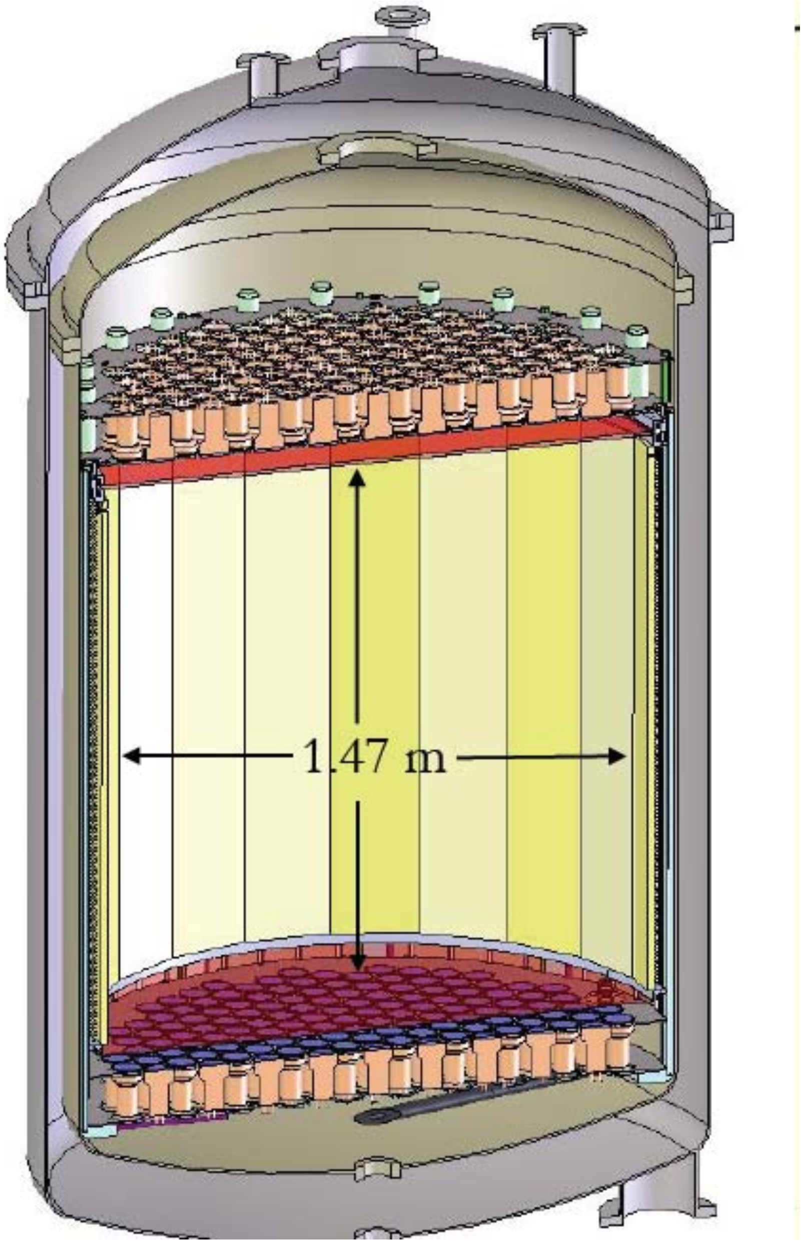
Full year-long WIMP search to begin in 2014
Result in 2015

LUX Projected Sensitivity



LZ Dark Matter Detector

- LZ = LUX + ZEPLIN
- Currently in development phase
  - NSF, DOE, and SDSTA funding
- Two-component veto system
  - 75-cm thick Gd-doped LAB scintillator shield
  - Instrumented LXe “skin”
  - Effective for both neutrons and gammas
- 20-fold scale-up from LUX mass
- Ultralow background Ti cryostat
- Low background R11410 PMT readout
- Thermosyphon cryogenics
- Fits in existing Davis cavern water shield
- DOE project organization, with LBL lead lab
- Projected sensitivity ~ 2 x 10^{-48} cm^2



Two-phase Xe beyond XENON1T and LZ

Option 1: Keep scaling bigger

- Optimize cost per kg, since readout cost scales with surface area.
- Neutron and gamma ray backgrounds will drop further with self-shielding.
- Favorable for ^{136}Xe neutrinoless double beta decay, where main background is 2.5 MeV gamma rays?
- But main dark matter background is neutrinos, which cannot be shielded.

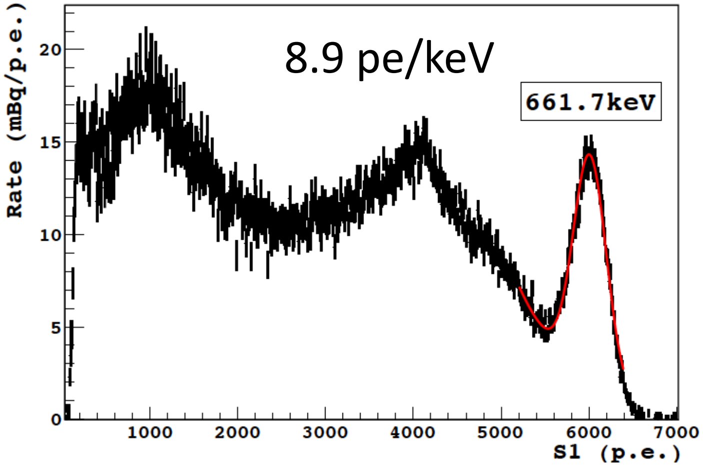
Option 2: Many modules (7-10 tonnes each)

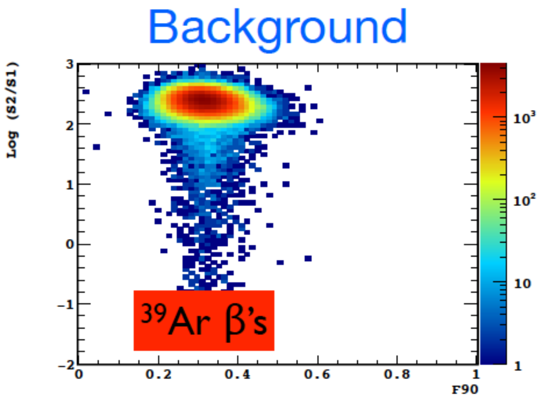
- Dark matter background dominated by neutrinos, so why keep scaling up?
- Solar neutrino and 2nuBB backgrounds minimized with higher drift fields, so if cathode voltage is limitation then smaller detectors may have smaller neutrino backgrounds.
- Cost savings from not having to keep redesigning – just build more modules.
- Different modules could have different isotope compositions (high Xe isotope masses 134 and 136 for 0nuBB and spin-independent dark matter, while low 129 and 131 masses used for spin-dependent dark matter, solar neutrinos).

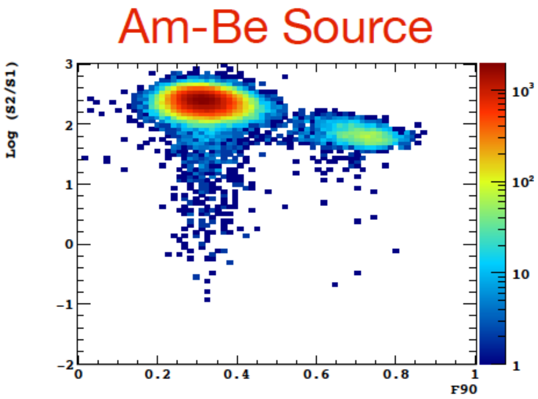
DarkSide-50

- A two-phase Argon detector.
- Funded by NSF, DOE, INFN.
- Uses both pulse shape and S2/S1 discrimination to reduce electron recoil backgrounds.
- Underground Ar, with ^{39}Ar reduced by factor > 100. Collected 125 of 150 kg needed, production at 0.5 kg/day.
- Located in Gran Sasso
- Projected sensitivity 2 x 10^{-45} cm^2.

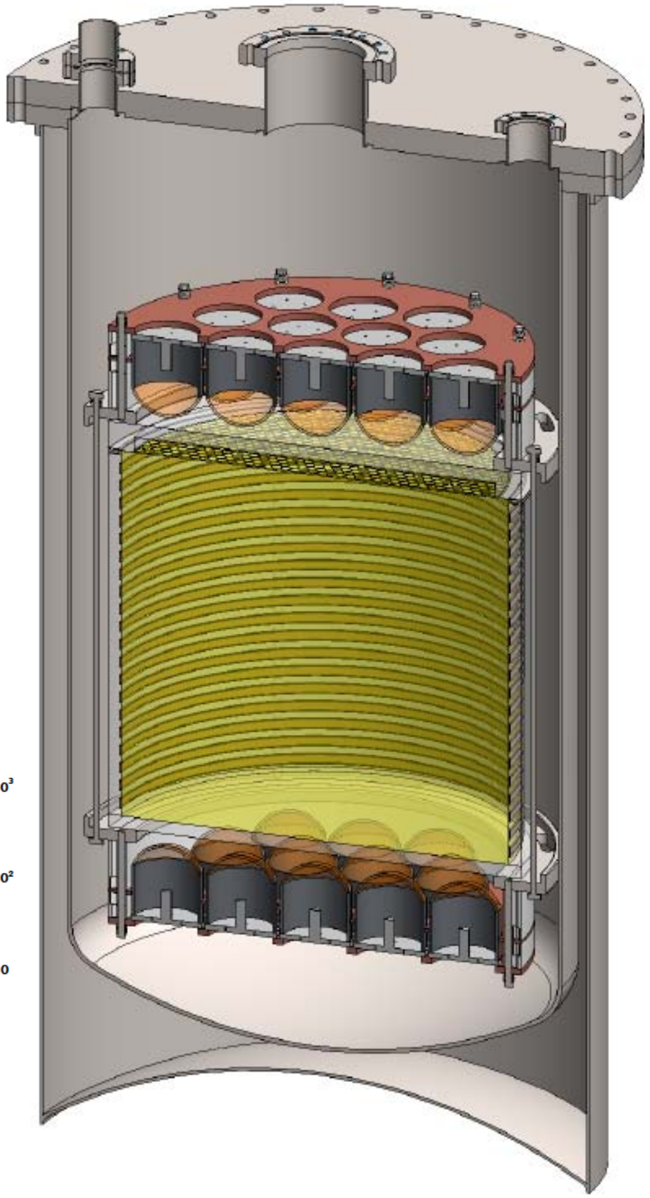
DS-10 data



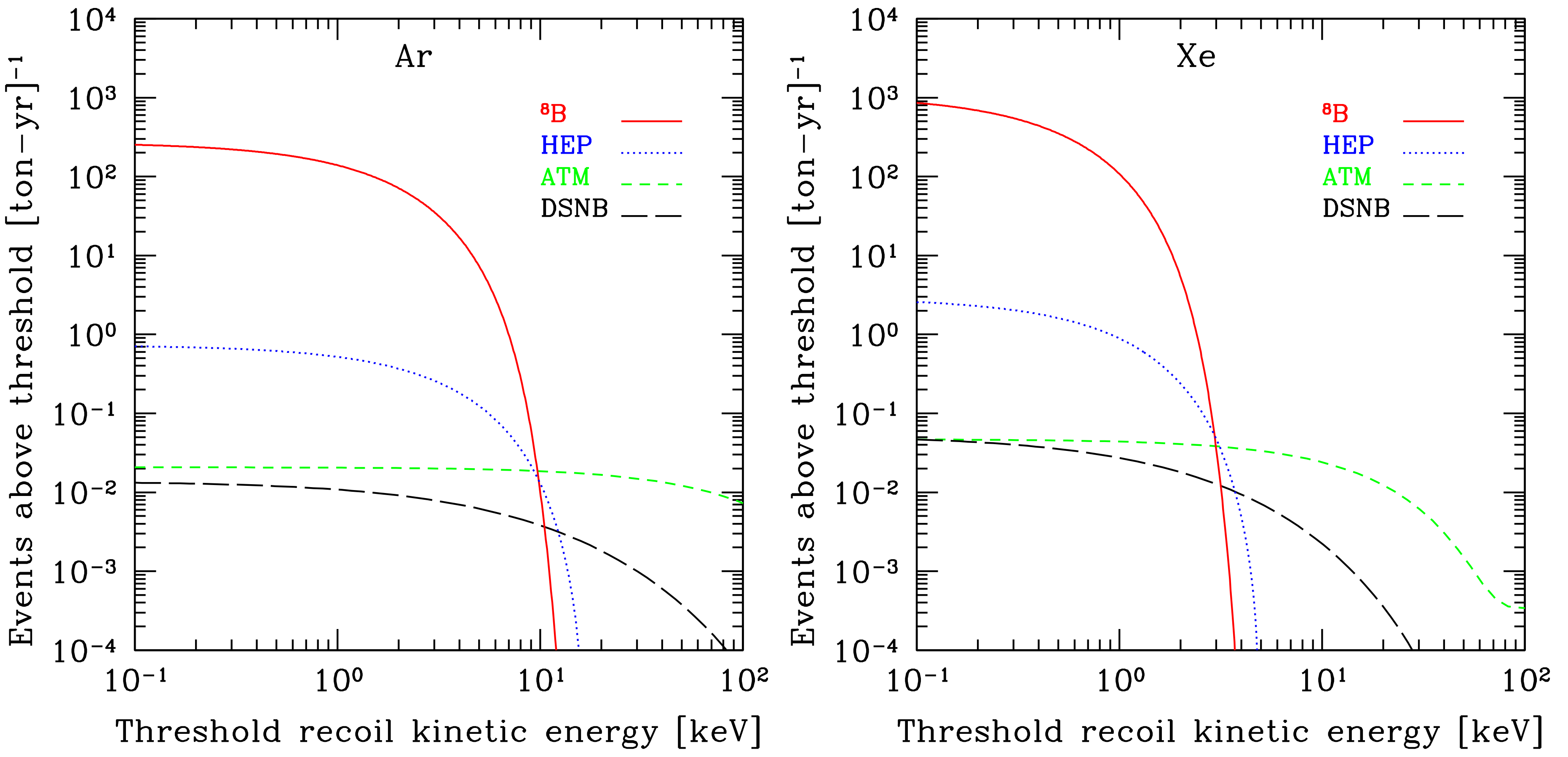




DS-50 model



Ultimate limits from neutrino-nucleus coherent scattering (L. Strigari, New J. Phys. 11 (2009) 105011)



Light WIMP Detector Kinematic Figure of Merit

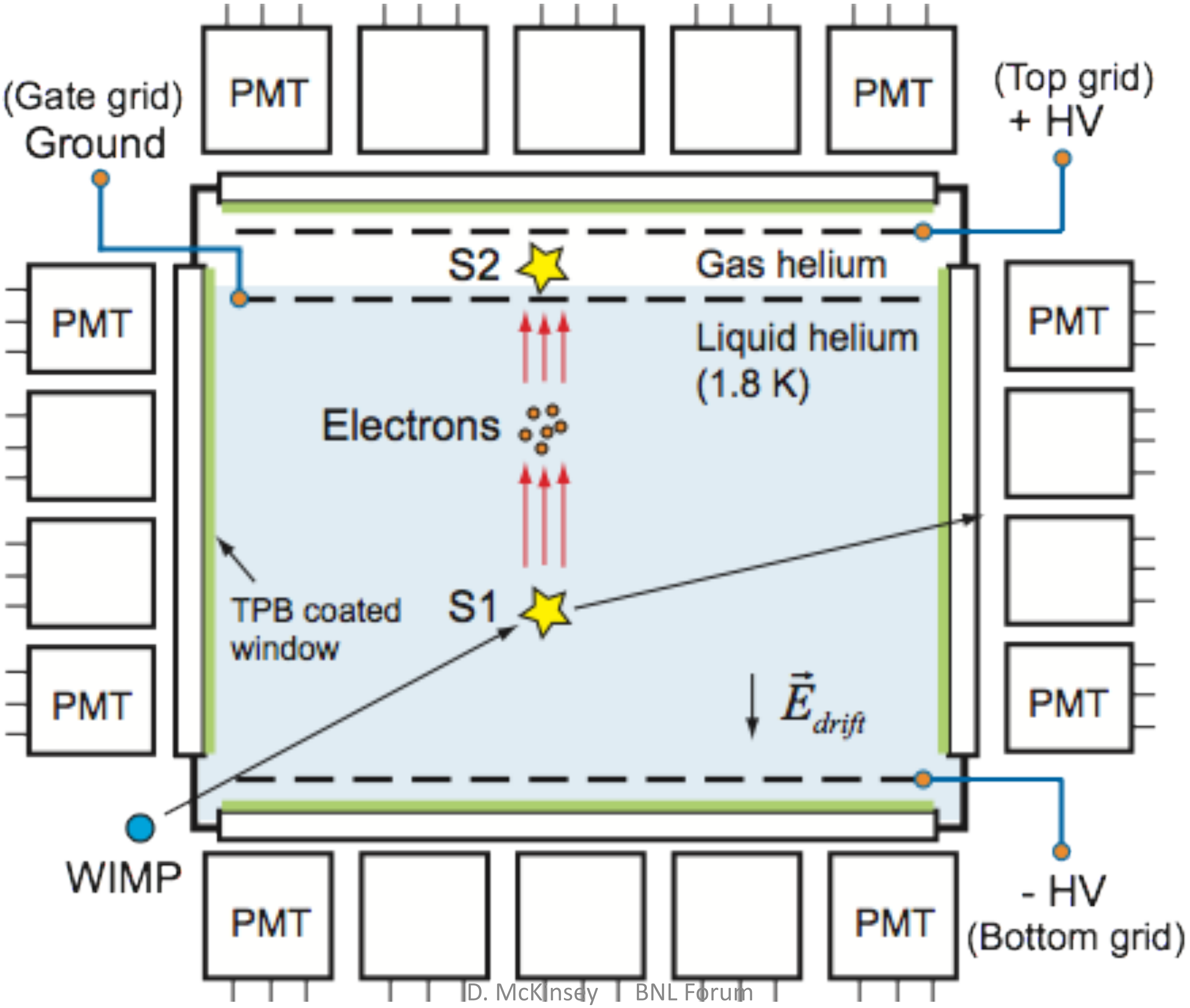
It is more difficult for heavy targets to be sensitive to light WIMPs, since for typical energy thresholds they are only sensitive to a small part of the WIMP velocity distribution. The lower limit of the WIMP-target reduced mass at which a detector can be sensitive is given by

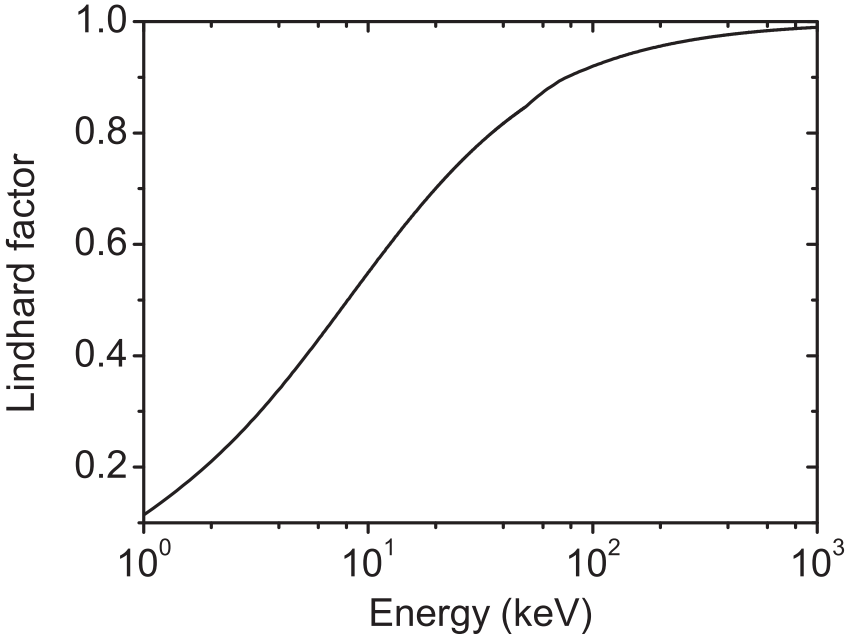
$r_{limit} = 1/v_{esc} * \mathrm{sqrt}\{E_t M_T/2\}$

where v_{esc} is the Galactic escape velocity of 544 km/s, E_t is the energy threshold, and M_T is the mass of the target nucleus. In the limit of small dark matter mass, the reduced mass is the mass of the dark matter particle.

So for reaching sensitivity to small dark matter masses, the kinematic figure of merit is the product of the energy threshold and the target mass, which should be minimized.

Light WIMP Detector Concept

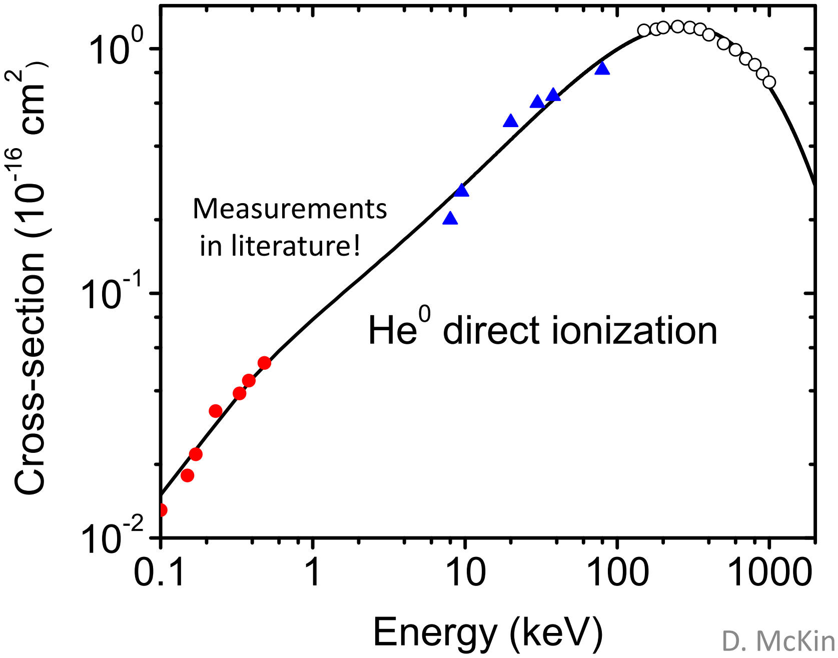


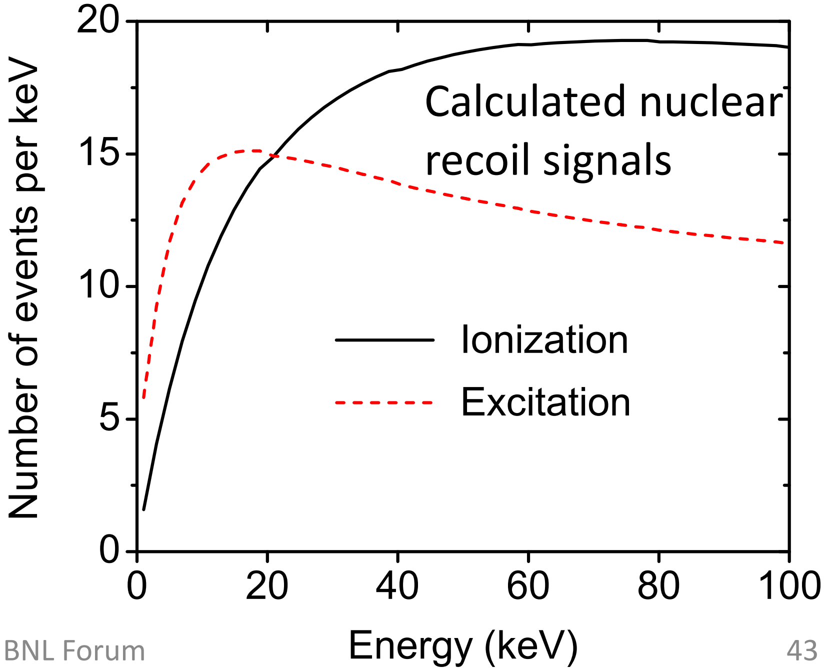


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534)

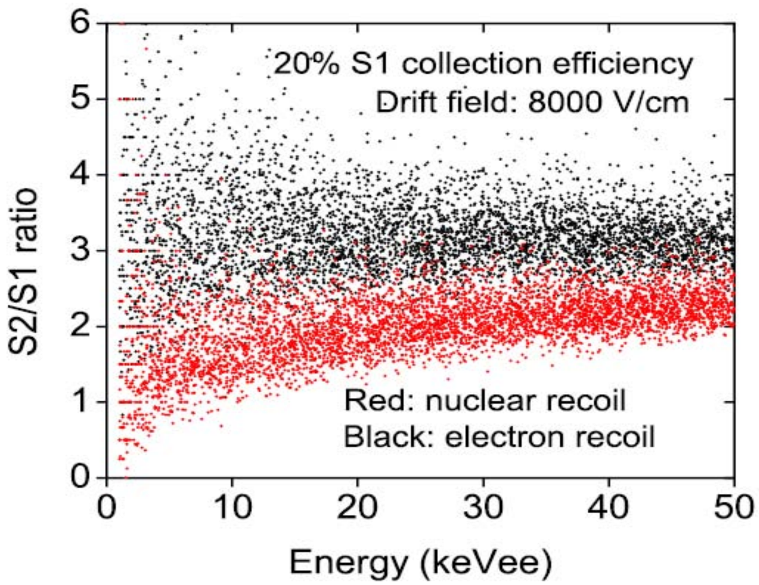
Lower electron scintillation yield (19 photons/keVee)

But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

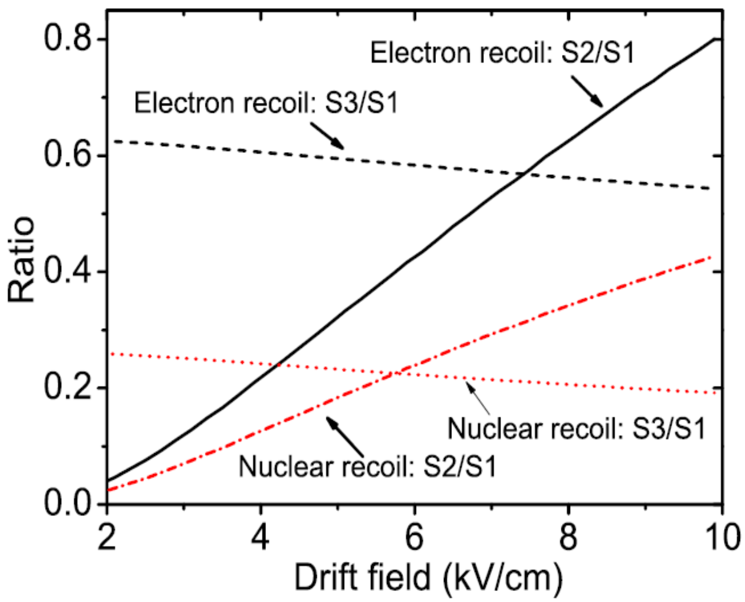


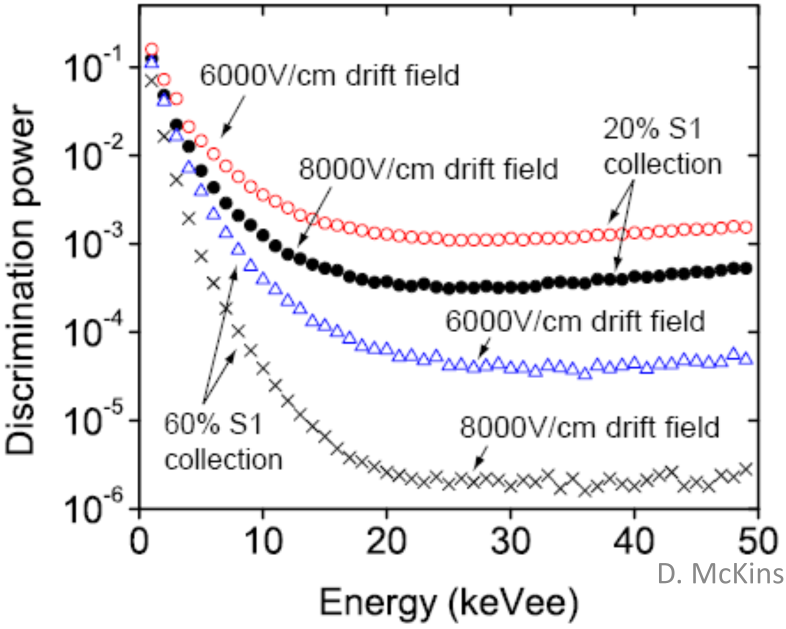


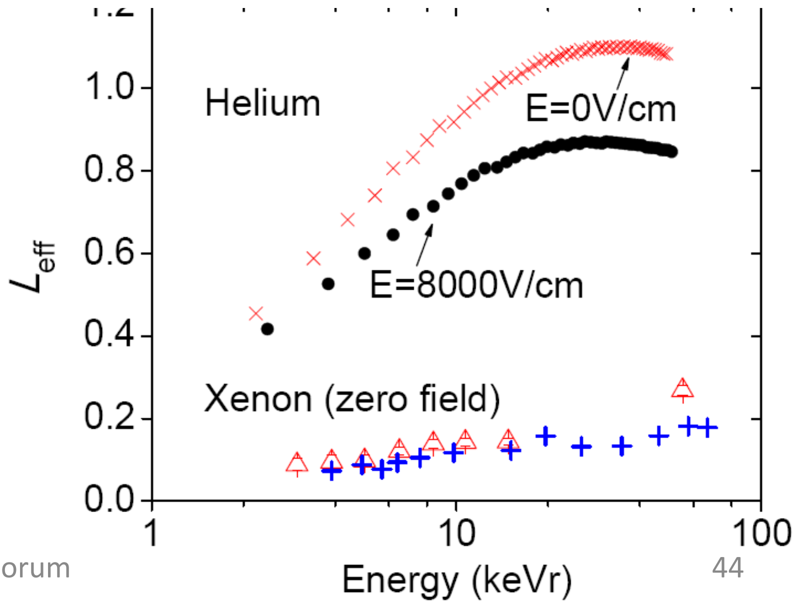
Predicted nuclear recoil discrimination and signal strengths in liquid helium



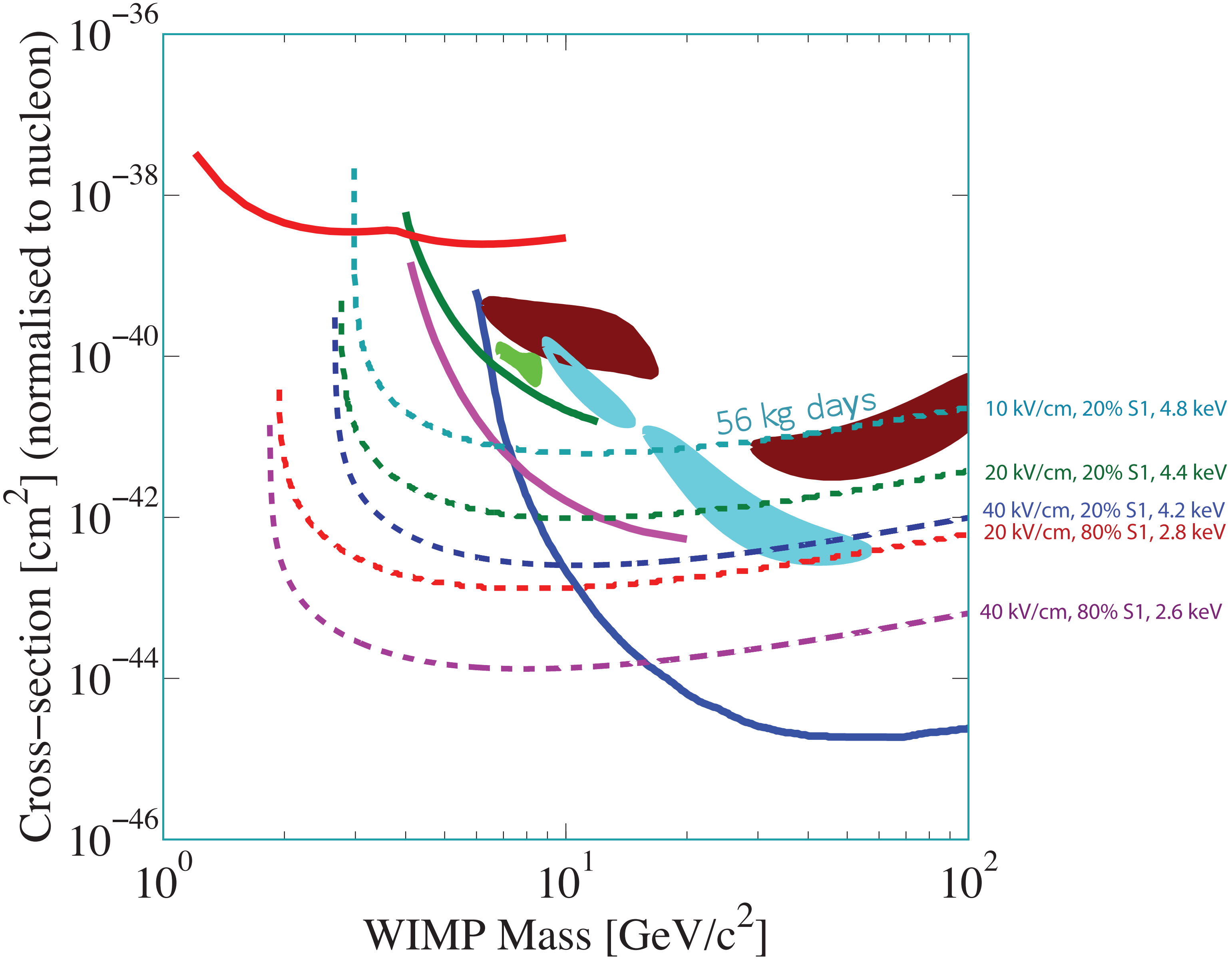
Event energy: 10 keV







Projected Sensitivity for Liquid Helium (with only charge and S1 readout)



It’s an exciting time for direct dark matter searches!

Stay tuned for more results from

- DAMA
- CoGeNT/C4
- CRESST
- CDMS
- XENON
- LUX
- DarkSide
- And the many other experiments I didn’t have time to cover