What is the universe made of?

Reconciling what we measure on Earth with what we see in the cosmos
Outline

- Dark Matter Evidence and Models
- Direct Detection Overview
- Liquid Noble Detection
  - LUX Experiment
  - LZ Experiment
- What UW Madison does
Standard evidence

M33 Rotation Curve

2dF Survey data

Bullet cluster
red: hot gas
blue: dark matter

2dF Galaxy Redshift Survey

v(km/s) vs. R(kpc)

Observed

Expected from luminous disk
What We Know

- Isotropy, homogeneity, flat universe, dark energy, cold dark matter, big bang, inflation

- Local Dark Matter density: 0.3 GeV/cm$^3$
Particles with masses of ~100 GeV and interactions at the weak scale would give current dark matter density of .3 GeV/cm$^3$.

WIMPs fit naturally with SuSy: lightest neutralino, the LSP
Searching for WIMPs

Direct (Scattering)

Indirect (Annihilation)

Collider (Production)

X

SM
Direct Detection Needs

- Ability to see low energy WIMP induced recoils
- Radiogenically pure
- Low threshold (< 10s keV)
- Ability to distinguish nuclear recoils
  - Difference between electronic recoils & nuclear recoils
  - Difference between alphas and nuclear recoils
- Position reconstruction and fiducialization
- Shielding from radiogenic and cosmogenic backgrounds
Searching for WIMPs

Nuclear Recoil Only
(CF$_3$I, C$_4$F$_{10}$, C$_2$ClF$_5$)
COGENT, DAMIC
DMTPC
DRIFT
~20% energy deposited
IONIZATION

Phonons
~100% energy deposited

CDMS
EDELWEISS

(Xe, Si)

ZEPLIN II, III
ZEPLIN I
ZEPLIN
XENON 10, 100, 1T
LUX, LZ
PANDA-X
DarkSide

XMASS
DEAP-3600
DAMA/LIBRA
DM-Ice, KIMS, SABRE

(CaWO$_4$)

CRESST II
CRESST I

(D)Ar

Scintillation
few% energy deposited

ZEPLIN I
XENON 10, 100, 1T
LUX, LZ
PANDA-X
DarkSide

XMASS
DEAP-3600
DAMA/LIBRA
DM-Ice, KIMS, SABRE

(CaWO$_4$)

CRESST II
CRESST I

(D)Ar

Phonons
~100% energy deposited

CDMS
EDELWEISS

(Xe, Si)

ZEPLIN II, III
ZEPLIN I
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CRESST II
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(D)Ar

Phonons
~100% energy deposited

CDMS
EDELWEISS

(Xe, Si)
Direct Detection Techniques
Direct Detection Signals?

Similarly, the peak date associated to $T = 365$ days for this group of events is $t_{\text{max}} = 102 \pm 47$ days. We note this is compatible with the $t_{\text{max}} = 136 \pm 7$ days found for DAMA/LIBRA in the 2-4 keVee region of its spectrum [14, 33]. Best-fitted $T$ and $t_{\text{max}}$ for the other three groups of events appear at random values. Fits to these other three groups with $T = 365$ days imposed do not favor the presence of a modulation (Fig. 5). We ascertain that significant power centered around $T = 365$ days appears only for the low-energy bulk group via a periodogram analysis (Fig. 6, [34–36]), taking binning precautions similar to those described in [38].

This straightforward treatment, which incorporates an improved discrimination against surface backgrounds compared to our previous analyses, confirms our earlier indication of an annual modulation in CoGeNT data [23], exclusively for the subset of events liable to contain a low-mass WIMP dark matter signal. Its significance is modest in the present unoptimized form of analysis: using the likelihood ratio method described in [23] the hypothesis of an annual modulation being present in the low-energy bulk group is preferred to the null hypothesis (no modulation) at the $\sim 2.2\sigma$ level [39, 40]. However, this frequentist approach does not take into consideration information from DAMA/LIBRA and other searches as a prior, specifically the potential relevance of the modulation amplitude favored by CoGeNT, a subject developed next. In this respect, we call attention to incipient applications of Bayesian methodology in this area [42–44].

The remainder of this paper focuses on the possibility of using our observations to obtain a common phenomenological interpretation of recent intriguing results in direct searches for dark matter.

**DISCUSSION**

A best-fit value of $S = 12.4 (\pm 5)$% is observed for the low-energy bulk group when the L-shell EC contribution is subtracted directly (top panel in Fig. 5). If a free $T_1/2$ is allowed (second panel in the figure), this becomes $S = 21.7 (\pm 15)$%. If the irreducible low-energy excess in the CoGeNT spectrum is considered to be the response to a $m_\chi \sim 8 \text{ GeV} / c^2$ WIMP, it would account for 35% of the bulk events in the 0.5-2.0 keVee region, the rest arising from a flat component originating mainly in Compton scattering of gamma backgrounds (see discussion around Fig. 23 in [7]). This fraction is approximate, as it can change some with choice of background model, and of rise-time cuts leading to slight variations in the irreducible “pure” bulk spectrum. This putative WIMP signal would then be oscillating with an annually-modulated fractional amplitude in the range between $\pm 35\%$ and $\pm 62\%$. This is larger by a factor $\sim 4-7$ than the $\pm 9\%$ expected for a WIMP of this mass in this germanium energy region, when the zeroth-order approximation of an isotropic Maxwellian halo is adopted [21].

**Fig. 5.** Best-fit modulations for the four groups of events, after accounting for decaying background components (see text). Dotted lines and data points are for unconstrained modulations, solid lines for an imposed annual period. Vertical arrows point at the position of the DAMA/LIBRA modulation maxima [14]. A modulation compatible with a galactic dark halo is found exclusively for bulk events, and only in the spectral region where a WIMP-like exponential excess of events is present.

A growing consensus is that a Maxwellian description of the motion of dark matter particles in the local halo, the so-called standard halo model (SHM), is incomplete, as it excludes several expected halo components.
Liquid Xenon TPCs

- Ionized and excited states
- Primary Scintillation (S1) with some recombination and de-excitation in the liquid
- Ions drift in TPC electric field
- Amplification region in gas creates proportional light (S2)
- S2/S1 provides particle ID
- Events are hundreds of microseconds (set by electron drift velocity)
- Strong position reconstruction
Xenon, electron recoil

Branching (→) sketched for electron recoils

Xe

Heat

Xe

Excitation

Xe*

Ion

Xe+

Ionized molecule

Xe$_2^+$

Recombination

e$^-$

VUV photons 175nm

S1

S2

cartoons from Akerib and Shutt
Xenon: Nuclear Recoil

Branching (→) sketched for nuclear recoils
LUX results
Energy Calibration: Doke Plot

- Electron recoils with energy dependent varying recombination
- Total quanta remain, $W=13.7$ eV

$$\langle S1 \rangle \ [\text{phd}] = [0.1167 \pm 0.003] n_\gamma$$
$$\langle S2 \rangle \ [\text{phd}] = [12.05 \pm 0.83 \ n_e]$$
Electronic Recoils

- Inject gas source of tritiated methane
- Tritium populates the background model
- Utilizes energy scale from the Doke plot
Nuclear Recoils

- Mono energetic D-D Neutron beam (2.45 MeV)
- Double scatters kinematically give energy of first scatter for charge yield
- Single scatters studied for light yield
Events
Spin Independent Result

![Graph showing WIMP-nucleon cross section vs. WIMP mass.](image)
Direct Detection
Coming of Age

• Mature computing framework and simulations
  • Including evaluation of simulation tools
• Benchmarking fundamentals
  • Reflectivity, scattering and absorption lengths
• Developing designs and procedures
  • Cleanliness, materials handling
• Detector reliability and automation
• Likelihood analyses
• Full operator treatment of interactions
LUX to LZ
LZ @ SURF

Davis Cavern 1480 m
(4200 m water equivalent)
Sanford Underground Research Facility
Homestake Gold mine
Lead, SD (near Deadwood)
LZ design

7 tonne active mass liquid Xe TPC, 10 tonnes total

Instrumentation conduits

Existing water tank

Gadolinium-loaded liquid scintillator

Outer detector PMTs

Liquid Xe heat exchanger

Cathode high voltage feedthrough

Neutron beampipe

Nelson - Collaboration CD3 IPR at LBNL - January 10-12, 2017
TPC design

SECTION VIEW OF LXE TPC

- Top PMT array
- Side Skin PMTs
- TPC field cage

GAS PHASE AND ELECTROLUMINESCENCE REGION

- Anode
- Gate
- LXe surface
- Weir trough
- Skin PMT

HV CONNECTION TO CATHODE

- Cathode grid
- Reverse-field region
- Side skin PMT mounting plate
- Bottom PMT array
LZ Backgrounds

External Materials

Uniform in LXe

Nelson - Collaboration CD3 IPR at LBNL - January 10-12, 2017
Cold and Pure LXe

- Ex-situ removal of Kr via charcoal chromatography
- Constant removal of reactive impurities with a hot gas getter, flows at 500 slpm
- Gas circulation allows for injection of radioactive calibration sources
  - Kr83m, Xe131 workhorses
  - CH3T quarterly; must be removed with getter
LZ Projected Limit
LZ Signal Region

40 GeV WIMP

8B

ER
LZ @ UW Madison
Simulations

LZ, ROI: 0-20 phd S1c (single)

LZ, ROI: 0-20 phd S1c (with vetoes)
LXe Handling

Rn removal column

1 SLPM

Cable conduits

Primary 500 SLPM circulation circuit
SLAC System Test Platform
System Test TPC

- Test Grid High Voltage with single photon and single electron sensitivity
- Prototype many subsystems: circulation, slow controls, sensors
Coming Soon…

In 2017:

- DEAP-3600
- XENON 1T
LZ = LUX + ZEPLIN

38 Institutions, 217 People

Black Hills State University
Brookhaven National Laboratory (BNL)
Brown University
Fermi National Accelerator Laboratory (FNAL)
Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Northwestern University
Pennsylvania State University
SLAC National Accelerator Laboratory
South Dakota School of Mines and Technology
South Dakota Science and Technology Authority (SDSTA)
STFC Rutherford Appleton Laboratory (RAL)
Texas A&M University
University at Albany (SUNY)
University of Alabama
University of California (UC), Berkeley
University of California (UC), Davis
University of California (UC), Santa Barbara
University of Maryland
University of Massachusetts
University of Michigan
University of Rochester
University of South Dakota
University of Wisconsin-Madison
Washington University in St. Louis
Yale University
Conclusion

• LUX has presented world-leading limits with the most sophisticated dark matter analysis to date.

• Direct Dark Matter Detection is entering a new era of discovery capability, along with a more mature detector design and collaboration organization

• LZ will be the most sensitive to conventional ~100 GeV WIMPs, as well as being a versatile detector for other exotic searches

• The broad dark matter field, with collider, indirect, and direct detections will have interesting results over the next 7= 2pi years

• UWMadison is a great place to be working on LZ!