Towards direct detection of non-baryonic dark matter

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When I heard the learn'd astronomer,
When the proofs, the figures, were ranged in columns before me,
When I was shown the charts and diagrams, to add, divide, and measure them,
When I sitting heard the astronomer where he lectured with much applause in the lecture-room,
How soon unaccountable I became tired, and sick,
Till rising and gliding out I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.

Walt Whitman, 1865

Poets say science takes away from the beauty of the stars - mere globs of gas atoms. I too can see the stars on a desert night, and feel them. But do I see less or more? ... It does not do harm to the mystery to know a little about it.

Richard Feynman, circa 1960
Most of the mass in the universe is dark

Focus of this seminar

![Pie chart showing the composition of the universe with Dark Matter at 24%, Dark Energy at 71.4%, Atoms at 4.6%, and a note that the remainder is made up of other components.]

From velocity dispersion measurements of the Coma Cluster, c. 1933, F. Zwicky concluded that stars account for <1% of the mass.!

He suggested we should "throw some light on the problem of the density of internebular matter in clusters."

He suggested using gravitational lensing.

NASA/JPL-Caltech/GSFC/SDSS
Radioastronomy weighed in first, on a galactic scale: rotation curves

from classical dynamics, one expects: \[ v_{\text{rot}}(r) = \sqrt{\frac{GM(r)}{r}} \]

it seems \( M(r) \sim r \)

implying \( \rho(r) \sim \frac{1}{r^2} \)

arrows indicate a span of \( \sim 20 \) kpc
Gravitational lensing (weak + strong) of galaxies suggests a dark halo

our approximate position in the Milky Way


distribution of dark matter

distribution of visible matter

stars deVauc.
DM NFW
Total (with rms)

R^{-2} slope
This outcome is expected for ~collisionless stars, and especially for collisionless dark matter.
Cosmic web of dark matter: predicted, recently observed!

weak-lensing mass reconstruction of a filament stretching between two clusters, separated by ~15 Mpc/h

large-scale DM structure filaments in the Bolshoi simulation

Very brief history of the universe

Planck Collaboration, arxiv:1303.5062
So what is the dark matter?

The "WIMP miracle" explanation

\[ \Omega \chi h^2 = m_\chi n_\chi / \rho_c \simeq (3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1} / \langle \sigma_A v \rangle) \]

weak scale
How can we directly detect dark matter?

\[ \frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r} \]
Expected energy spectrum for spin-independent elastic scattering

\[ m_\chi = 100 \text{ GeV}, \quad \sigma_n = 3 \times 10^{-45} \text{ cm}^2 \]

\(~ O(1) \text{ event in 30 kg xenon in 225 days}\)

(rare event search!)

(spin-dependent coupling also generally expected, but less sensitive than SI)
Back in the day...

Quoting from page 3:

eters. The detector is located in the Homestake mine at a depth equivalent to 4000 m of water to eliminate the cosmic ray induced background. The detector cryostat is constructed from high-purity copper and is surrounded by 11 tons of lead, sheet cadmium and neutron moderator, to eliminate the radioactive background and neutrons from the rock. The inner shield was made from high-purity copper, when the 14 d of data used in this work were taken. These data were selected because they correspond to a period of decreased level of mining operations in the vicinity of the detector. This resulted in fewer microphonic

(1) go underground
(2) build a castle
(3) avoid miners
The basic tricks haven’t changed

LUX is installed 1.5 km below the surface

- the muon rate is reduced from ~50 Hz to <1/day
- 8 meter Ø water shield renders ambient radioactivity irrelevant

remaining challenge: radioactivity from the detector itself
Understanding and mitigating internal backgrounds is critical

...if mildly esoteric

arxiv:1112.1376 Radio-assay of Titanium samples for the LUX Experiment
arxiv:1205.2272 An Ultra-Low Background PMT for Liquid Xenon Detectors

bottom line:

**all internal materials sub-dominant** to long-lived isotopes in PMTs

10 mBq U / 2 mBq Th / 65 mBq K per PMT

! reference: a banana, ~x4 in mass, has ~15 Bq $^{40}$K (x60 activity)

xenon is radiopure, but other noble gases are not:

$^{85}$Kr ($\tau_{1/2} \sim 11.7$ y), present at $\sim 10^{-12}$ in $^{nat}$Kr.

$^{nat}$Kr present at $\sim O(10)$ ppb + in commercial Xe

$\Rightarrow$ dedicated chromatographic separation system reduces this to ~5 ppt

! reference: XENON100 results from 2011 (700 ppt) and 2012 (20 ppt)

$^{222}$Rn ($\tau_{1/2} \sim 3.8$ d): quickly decays to $^{210}$Pb ($\tau_{1/2} \sim 22.3$ y).

scary enough to have DAMA working in $N_2$ atmosphere


LUX during construction

Peter Sorensen
Available signal, and example experiments

CDMS, Phys Rev D 82 122004 (2010)

CoGeNT ANOMALY!

CDMS, Phys Rev D 82 122004 (2010)

LUX, XENON

DAMA ANOMALY!


Modulation would be a nice extra discriminant

minor prerequisite: direct detection of dark matter

annual modulation

http://www.hep.shef.ac.uk/research/dm/intro.php

but see e.g. Nygren, arXiv:1102.0815

2-6 keV


but see e.g. Nygren, arXiv:1102.0815
Limits and projections on dark matter cross section with nucleons

Experimental sensitivity assuming spin-independent interactions

![Graph showing dark matter cross section with nucleons](image)

- CDMS II
- Edelweiss II
- Zeplin III
- XENON100 (2012): 225d x 34kg
- LUX: 300d x 100kg
- LZ: 1000d x 5000kg
- Theory from Cheung et al., arXiv:1211.4873
Spin-dependent sensitivities

![Graph showing spin-dependent sensitivities](image)
LUX: the view from 10,000’

(aactually, this would be the view from -4850’)

- 370 kg (300 kg active) LXe
- 122 PMTs (2” round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)

Thermosyphon
Titanium Vessels
PMT Holder Copper Plates
Dodecagonal field cage + PTFE reflector panels

2” Hamamatsu R8778 Photomultiplier Tubes (PMTs)
**What is LUX, and how does it work?**

**what:** a monolithic, “wall-less,” radiopure, ~350 kg xenon target viewed by 122 Photomultiplier Tubes
- 3D vertex reconstruction => no edge effects!
- target is self-shielding

**how:** detect scintillation photons and ionized electrons
- $n_\gamma$ and $n_e$ are the fundamental measured quantities you want to know
- $\alpha_1 \sim O(0.10)$ and $\alpha_2 \sim O(10)$ are the probabilities for detection of each quanta
- $\alpha_1$ is often quoted as “photoelectrons per keV,” which can be confusing (even to “experts”).
- examples:
  - LUX $\alpha_1 \sim 0.15$
  - XENON100 $\alpha_1 \sim 0.06$

$$S_1 = \alpha_1 n_\gamma, \quad S_2 = \alpha_2 n_e$$
The beauty of self-shielding

Simulation of 5-25 keV depositions due to gamma activity from the PMTs. Background neutrons also range out or multiply scatter (easy to tag).

\( \chi = 100 \text{ GeV}, \sigma_n = 3 \times 10^{-45} \text{ cm}^2 \)

1e-4 => 0.2e-4 due to nuclear recoil quenching factor ~ x0.2

this is before the factor ~x200 discrimination from \( \frac{S2}{S1} \sim \frac{n_e}{n_\gamma} \)
2010-2011: we built LUX in the surface lab at SURF, SD ...

sealed it up, and sent it underground
... Meanwhile, we waited for the underground laboratory to be ready.
and busied ourselves studying what we could, on the surface

- in the liquid noble gas detector business, we obsess over purity:
- electronegative impurities capture electrons
- manifests itself as a free electron lifetime

- XENON10, $\tau = 2000 \, \mu s$, max $t_{\text{drift}} = 80 \, \mu s$ (up to 4% e- loss)
- XENON100, $\tau = 514 \, \mu s$, max $t_{\text{drift}} = 160 \, \mu s$ (up to 26% e- loss)

200 $\mu s$ lifetime achieved in 2012 during surface operation, despite broken plumbing connection
Summer of 2012: underground in the Davis Cavern at SURF!

Assembling all the ancillary support systems

perspective:
Ray Davis swimming in his water shield, 1971

Unfortunately, swimming in a "confined space" is strictly forbidden

LUX water shield
Now (finally!)

LUX is nearly ready for dark matter search

!!
Looking ahead to LUX results

let's first review the recent XENON100 results

and compare a simulation of a XENON100-like detector

NB: apparent difference in band width is a binning artifact -- the lower dashed line is $-3\sigma$ in both plots
• LUX is bigger, self-shielding benefit increases exponentially with linear dimension
  • lower background rate => **increased discovery potential**
• LUX will have a factor ~2.5 lower photon detection threshold, period.
  • \( n_\gamma \) does not depend on energy calibration \( (L_{eff}, Q_y) \)
  • probably leads to 1-2 keV in energy

most of the 2 keV signal is lost down here

both derived quantities assume the same “$L_{\text{eff}}$” curve! ($L_{\text{eff}}$ is the energy calibration for scintillation)
Why you care

- based on a consistent treatment of low-energy fluctuations
- light DM signal first appears at $-3\sigma$ from calibration centroid
- I don’t really think these two events are DM

consistent with the two XENON100 events
what is the mechanism behind the XENON100 background events?

in principle, random coincidence rate can be calculated, based on measured S1-only rate

(bottom line: need a comprehensive understanding of background pathologies)}

gamma X (red triangles) should preferentially populate higher-energy region
Other “backgrounds”: coherent neutrino nucleus scattering

- calculable, never-observed interaction
- $^8$B neutrino end point $\sim 15$ MeV
- predicted energy spectrum in xenon (below, red)

$\nu Xe \rightarrow Xe \nu$ 

$\sigma = 5 \times 10^{-45} \text{ cm}^2$

• detection in LUX is dependent on actual energy threshold: 1 keV is speculative

XENON10 simulated response (4 keV threshold)

LUX simulated response (1 keV threshold)

recent literature:
Anderson et al, Phys Rev D 84 013008 (2011)
Scientific progress looks like what?

2010: $\sigma \sim 4 \times 10^{-44} \text{ cm}^2$

2011: $\sigma \sim 7 \times 10^{-45} \text{ cm}^2$

2012: $\sigma \sim 2 \times 10^{-45} \text{ cm}^2$

(it looks mostly like pursuit of WIMPs)
standard WIMP hypothesis is “well-motivated” but not the only possibility

what odds do I really give the WIMP miracle?
• (right) re-analysis of XENON10 data, across full range of interest to inelastic hypothesis.
• found energy-localized background (!?)
• seems to be present in XENON100 data, too

• postulate that DM upscatters to a heavier state (~100 keV splitting)
• leads to peaked spectrum rather than exponential
• postulated to reconcile DAMA and CDMS

2009: searching for inelastic dark matter in XENON10
2010/2011: searching for O(10) GeV dark matter in XENON10

\[ \frac{\sigma}{\mu} = 0.19 \]

[Diagram showing nuclear recoil energy vs. S2 width with a shaded region indicating an "electron train" event occurring at 160 \( \mu s \).]

2010: sidetracked by atomic physics of xenon nuclear recoil energy scale

![Plot of electrons / keV vs. nuclear recoil energy (keV)]

- no data, need model
- case B
- case A
- stars: PRC 81 025808 (2010)

![Plot of photons / keV * 0.015 vs. nuclear recoil energy (keV)]

- ~ 15 photons !!
- stars: PRC 81 025808 (2010)
- diamond: PRC 79 045807 (2009)
- squares: PRC 84 045805 (2011)

![Plot of photon or electron fraction vs. nuclear recoil energy (keV)]

- electron fraction
- photon fraction

**Problem**

- what you really want to know is how many electrons and photons result from a nuclear recoil
- DM experiments have sensitivity below the lowest energy calibration data points
- dedicated (neutron scattering) calibration data shows systematic disagreement

**Step in the right direction**

- model (solid and dashed curves) predicts general trend but not absolute value
2012: thinking about MeV dark matter

• sub-GeV DM-nucleus scattering generally does not result in measurable signal (simple kinematics)
• so, look for DM-electron scattering!

obtained 15 kg day sensitivity (bkg not optional)

predicted 365 kg day sensitivity (only neutrino bkg)
Essig, Mardon and Volansky, Phys Rev D 85 076007 (2012)
2013+: Sorting out the nuclear recoil energy scale in xenon

- previous measurements use 2.5 MeV DD neutrons, need to tag low angle scatters (and detectors subtend several degrees)

- use $^7\text{Li}(p,n)^7\text{Be}$ reaction
- ...along with $^{56}\text{Fe}$ transmission resonances
- obtain a beam of mono-energetic neutrons at 24 keV and 73 keV
- measure endpoint nuclear recoil energy

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Diagram:

- Projected results (NOT data)

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Graph:

- Cts/phot/s vs. photoelectrons $N_{phe}$
- $0.73$ keV
- $2.2$ keV
- $\gamma$ bkg

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Graph:

- $Q_y$ vs. $E_{nr}$ [keV]
- Projected results (NOT data)

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in 2013, LUX will (probably) first and foremost address garden variety WIMPs

LUX is about to generate an awesome, unprecedented, low-background data set
exciting to think about new possible DM signals/searches

2014+: construction of LZ

- LZ: 7000 kg liquid xenon target
- 350 kg LUX shown inset for comparison
- LZ expected sensitivity: $\sigma \sim 10^{-48} \text{ cm}^2$
- The “ultimate” xenon detector, limited by neutrino backgrounds
Thanks!
Extra slides follow
Collaboration Meeting, UCSB March 2012

Collaboration was formed in 2007 and fully funded by DOE and NSF in 2008.
2013+: non-WIMP searches: e.g. axions (solar and/or galactic)?

- (above) calculated event rate for axio-electric conversion in xenon
- (top right) first sub-keV energy calibration of liquid argon detector... we plan to apply this technique to liquid xenon detectors
- (right) predicted sensitivity (LUX roughly represented by G1.5 curve)
- other DM models could give electromagnetic line signal, e.g. Luminous DM

Arisaka et al, arxiv:1209.3810

DM allowed region based on Pospelov, Ritz and Voloshin, Phys Rev. D 78 115012 (2008)

Arisaka et al, arxiv:1301.4290

Sangiorgio et al, arxiv:1301.4290
There are other dark matter relic production mechanisms (and particle candidates)

- e.g. “freeze-in”

- Another possibility: relic density determined by baryon asymmetry ("asymmetric dark matter")

- A completely different possibility: relic density of pseudo-Nambu-Goldstone bosons, e.g. the axion
Electronic signal from nuclear recoils is quenched: Lindhard theory

**Electromagnetic interactions**

\[ E_{er} = \epsilon (n_\gamma + n_e) \]

**Neutral particle interactions**

\[ E_{nr} = \frac{\epsilon (n_\gamma + n_e)}{f_n} \]

**Electromagnetic interactions**

- \( \epsilon = 13.8 \text{ eV} \), the average energy to create a single quanta (e or \( \gamma \))
- \( f_n \) = energy dependent Lindhard prediction for signal quenching

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**Neutral particle interactions**

Lindhard prediction for \( f_n \)

(parametrized by the electronic stopping power \( k \))

well-known that combined energy gives the best resolution

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**Graph**


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**Graph**


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**Graph**

- *Aprile et al. 2009*

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**Graph**

- *Manzur et al. 2010*
In liquid xenon, $E_{nr}$ partitions into photons and electrons

this has caused a lot of confusion concerning measured versus expected liquid xenon scintillation response

($L_{eff}$, the “effective” Lindhard factor)

Two-step model:

1. Lindhard model gives quenching, $f_n$
2. Thomas-Imel model gives partioning

$$F_e = \frac{\ln(1 + \xi)}{\xi(1 + N_{ex}/N_i)}$$

$$Q_y = \frac{F_e f_n}{\epsilon} = \frac{S_2}{\alpha_2 E_{nr}}$$

$$L_{eff} = \frac{(1 - F_e) f_n \alpha_1 S_e}{\epsilon \frac{L_y S_n}{L_{eff}}}$$

$\xi$ and $N_{ex}/N_i$ as free parameters

curves are fits with $\xi$ and $N_{ex}/N_i$

remainder:

1. origin of ionization: Xe+
2. origin of scintillation: Xe* and Xe+
Model compared with neutron scattering data

\[ E_{nr} \text{[keV]} \]
\[ Q_y \]
\[ L_{eff} \text{[keV]} \]
\[ E_{nr} \text{[keV]} \]

- Case A:
  - \( k = 0.110 \)
  - \( 4\xi/N_i = 0.037 \)
  - \( N_{ex}/N_i = 1.00 \)

- Case B:
  - \( k = 0.166 \)
  - \( 4\xi/N_i = 0.032 \)
  - \( N_{ex}/N_i = 1.09 \)

\[ \sim 15 \text{ photons !!} \]

\[ \text{electrons / keV} \]

\[ \text{photons / keV} \times 0.015 \]

\[ \text{suspect threshold bias} \]

\[ \text{cf. JCAP 09 (2010) 033} \]

stars: PRC 81 025808 (2010)
CoGeNT repartee


J. Collar at TAUP 2011

Preliminary (work in progress)
Detecting neutrinos from a supernova in our galaxy?

2011 HST image of SN1987a (~51 kpc away in LMC)

SN1987a antineutrinos detected by Kamiokande (11), IMB (8) and Baksan (5)

~10 coherent neutrino scatters above 5 keV in xenon, for SN at 10 kpc

- sitting around waiting for SN sounds silly; but,
- next generation DM experiments will have large target masses and long exposure times, and
- coherent interaction is flavor blind (x6), and
- signal is a burst, easily identifiable, and
- we have lots to learn about both SN and neutrinos
Maybe gravity is just “different” on galactic+ scales?

**MOND, TeVeS, f(R) models**

basic premise of MOND: postulate that for very small accelerations,

\[ a_N \rightarrow a_N \mu(a/a_0), \text{ where the function } \mu \sim 1 \text{ for } a \gg a_0, \text{ and } \mu \sim a/a_0 \text{ for } a \ll a_0 \]

MOND explains rotation curves, and to a degree, merging clusters.

**But it still requires dark matter**

TeVeS appears to be largely ruled out by weak lensing + galaxy velocity observations