DIRECT DARK MATTER DETECTION

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HEP Seminar
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1. Very Brief Intro to Dark Matter and Direct Detection

2. The LXeTPC & XENON100

3. Latest Results

4. The Next Generation (Tonne scale) Detectors
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Early evidence for Dark Matter

1930’s - Fritz Zwicky
1970’s - Vera Ruben
Measured rotational velocity of galaxies and observed flat curves rather than expected Keplerian fall-off with distance from galactic centre

GALAXIES ARE ROTATING TOO FAST!

Lots more evidence since then...
We have a ‘Missing Mass’ Problem!

85% of the mass of the Universe is **DARK**!
Dark Matter Detection

Favoured candidates are Weakly Interacting Massive Particles (WIMPs)

- Indirect - observe annihilation products
- Accelerator - produce WIMPs
- **Direct** - interact with galactic WIMPs (*our* Dark Matter!) in ultra-low background terrestrial detectors

Direct detection is internationally recognised as one of THE highest priorities in science!
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei $\rightarrow$ nuclear recoil

Recoil Energy: $E_r \sim O(10 \text{ keV})$

Event Rate: $R \propto N \frac{\rho_x}{m_x} (\sigma_{\chi N})$

Detector $\rightarrow$ WIMP-Nucleon Cross Section [cm$^2$]

Local DM Density $\rho_x \sim 0.3 \text{ GeV/cm}^3$

Physics $\rightarrow$ WIMP Mass [GeV]

WIMP Expectations
- 1 event/kg/yr
- 1 event/ton/yr

CMSSM: Trotta et al.
CMSSM+LHC: Buchmueller et al.
WIMP Detection Techniques

Heat and ionisation bolometers:
- CDMS
- EDELWEISS

Bubbles and Droplets:
- CUOPP
- PICASSO

Phonons

Light and heat Bolometers:
- CRESST
- ROSEBUD

Charge

Scintillation and ionisation charge detectors:
- XENON
- DarkSide
- ZEPLIN
- LUX

Light

Scintillators:
- DAMA
- LIBRA
- XMASS
- CLEAN
- DEAP
- DEAP
- KIMS

Ionisation detectors:
- DRIFT, DMTPC, GENIUS, NEWAGE,
- HDMS, IGEX
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Liquid Xenon Time Projection Chambers

- **S1: LXe is an excellent scintillator**
  - Density: 3 g/cm³
  - Light yield: >60 ph/keV (0 field)
  - Scintillation light: 178 nm (VUV)
  - **Nuclear recoil threshold ~5-8 keV**

- **S2: Even better ionisation detector**
  - S1+S2 allows mm vertex reconstruction
  - Sensitive to single ionisation electrons
  - **Nuclear recoil threshold ~1 keV**

- **And a great WIMP target too**
  - Scalar WIMP-nucleon scattering rate dR/dE~A²
  - Odd-neutron isotopes (¹²⁹Xe, ¹³¹Xe) enable spin-dependent sensitivity
  - Excellent ionisation threshold: ‘light WIMP’ searches using S2 only
  - No intrinsic backgrounds (⁸⁵Kr can be removed, low rate from ¹³⁶Xe 2νββ)
  - Easily scaled with no loss of performance (actually improves!)
top hit pattern: x-y localization

Δt : z localization
Particle Discrimination

Light (S1) and charge (S2) depend on recoil dE/dx

Electronic Recoils (gamma, beta)

Nuclear Recoils (neutron, WIMPs)
Example of a low energy (9 keVnr)

4 photoelectrons detected from about 100 S1 photons

645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

Event Z-position from measured drift time $t(S2) - t(S1)$ and known e-velocity. $dZ < 0.3$ mm

event X-Y position from measured S2-hit-pattern, $dR < 3$ mm
The XENON Roadmap

**XENON10**
- 2005-2007
- PRL100
- PRL101
- PRL 107
- PRD 80
- NIM A 801

**XENON100**
- 2007-2013
- First results: PRL105, PRL107, PRD84

**XENON1T**
- 2012-2017
- Approved at LNGS, Hall B construction starts in fall 2012

- Gradually increasing the WIMP target mass while decreasing the background level
The XENON Collaboration

Columbia, Zürich, Coimbra, Mainz, LNGS, WIS, Münster, MPIK, Subatech, UCLA, Bologna, Torino, Nikhef, Purdue

XENON meeting at LNGS, April 2012
The XENON100 detector overview

- 100 x less background than XENON10
- 10 x more fiducial mass than XENON10
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- LXe scintillator active veto system
- Improved passive shield system
- Dedicated Kr distillation column
- TPC with 30 cm drift x 30 cm diameter
- 161 kg ultra pure LXe - 62 kg as target
- 1" square PMTs with ~1 mBq (U/Th)
XENON100 Location and Shield

- LNGS provides the shield against cosmic rays: 1.4 km of mountain
- Passive shield:
  - 5 cm (2 tons) of Cu, 20 cm (1.6 tons) of PE, 20 cm (33 tons) of Pb, plus 20 cm water shield
- Detector housing is continuously purged with boil-off N₂, to maintain a radon level < 0.5 Bq/m³
- All materials screened with HPGe detectors at LNGS
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New XENON100 Dark Matter Search: Run10

- Data taking period: February 2011 - March 2012
- 224.56 live days of dark matter data
- 48 live days of $^{60}$Co and $^{238}$Th calibration data; 2 AmBe runs (beginning/end of science run)
From raw waveforms to results

- Majority trigger, efficiency > 99% for S2 > 150 pe
- Data acquisition: sample PMT traces @ 100 MS/s in windows around signals > 0.35 pe
- Raw data processing, baseline and noise measurement; S1, S2 signal recognition; signal integration; position reconstruction; signal correction (gain, spatial)

Physics analysis input:
- astrophysics, nuclear physics, DM data sidebands, NR and ER calibration => response, background estimate

Event selection, remove bad events:
- noise
- S1/S2 not matching
Select single interaction events

Profile likelihood
XENON100 gamma calibrations

- $^{137}$Cs data to monitor the charge & light yields
- $^{60}$Co and $^{232}$Th data used to map the electron recoil band and predict EM background (irradiate at three points around TPC)
- $^{232}$Th data also used to understand spectrum up to high energies

![Graph showing electron lifetime data](image1)

![Graph showing Th-232 data](image2)
XENON100 neutron calibration

- Nuclear Recoil band calibration performed with a 220 n/s AmBe neutron source

Absolute matching (rate(pos, E)) demanded!
Gammas from neutron calibrations

- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}\text{Xe} + n \rightarrow ^{129,131}\text{Xe} + n + \gamma$ (40 keV, 80 keV)
- Inelastic n-scattering on F (in PTFE): $^{18}\text{F} + n \rightarrow ^{18}\text{F} + n + \gamma$ (110 keV, 197 keV)
- Also Xe activation lines: $^{129m}\text{Xe}$ (236 keV) and $^{131m}\text{Xe}$ (164 keV)

All gammas from the neutron irradiation of XENON100 are used to check/correct signal dependency with position and also to infer the LY at 122 keV
XENON100 energy resolution

- Energy dependent energy resolution
- In S1, in S2 and in the “combined energy scale”
- Because of the anti-correlation of the S1 and S2 signals, the resolution is much improved when using both
S1 Signal Corrections

- S1 light collection depends on the event position in the TPC: a 3D map of the light collection efficiency (LCE) is inferred from irradiation with $^{137}\text{Cs}$ (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated $^{131}\text{mXe}$ (all agree within 3%)

- Light yield at 122 keV is interpolated using NEST model and measurements at lower/higher energies with conservative 5% uncertainty. For Run10 the $\text{LY}_{122\text{keV}} = (2.28 \pm 0.04) \text{ PE/keV}$

![LCE correction map using the 40 keV line](image1.png) ![Light yield for different gamma lines](image2.png)
Intrinsic backgrounds

LXeTPCs easily identify surface backgrounds, alphas and delayed coincidences with 3D vertex and energy reconstruction
Measured Background Level in Run10

- Reached background level before S2/S1-discrimination: $5.3 \times 10^{-3}$ events/(kg day keV)
- Same level as in 1st XENON100 results (E. Aprile et al., Phys. Rev. Lett. 105, 131302, 2010)
- See also PRD 83, 082001 (2011)

Background tracked as a function of $(r, z)$ through TPC
Measured Background in good agreement with MC prediction.

At low energies: Lowest background ever achieved in a Dark Matter Experiment!

Xenon keVee-Scale not precisely known below 9 keVee
Analysis sequence for the 225 live days of data

(Different colors represent the events removed with the successive cuts)

1. Start from all non-blind data in 48kg FV
2. Apply basic quality cuts and single scatter

(3) Set low energy threshold, restrict to low energies and apply FV cut
(4) Add consistency cuts for the remaining events
Optimization of the fiducial volume and signal region

- The fiducial volume and signal region are simultaneously adjusted to maximize sensitivity.

- Given the lower beta background in this run, we choose a smaller FV (34 kg) to profit from LXe self-shielding.

- The signal region is chosen below the 99.75% constant rejection line for ER.

- The signal region for the Maximum-Gap based analysis is set between 3 and 20 PE.
Cuts acceptance and $L_{\text{eff}}$ parameterization

$S_1$ [PE]

- $S_2$ threshold cut ($S_2 > 150$ PE)
- Combined acceptance
- NR acceptance for a 99.75% ER rejection (Maximum Gap analysis only)

$E_{\text{nr}} = \frac{S_1}{L_{\text{eff}} \cdot L_y}$

Mean (solid) and 1-2-sigma uncertainties (blue bands) of $L_{\text{eff}}$ direct measurements.
The background expectation is computed from the calibration data. The number of events in the signal region from ER calibration data is counted. That number is scaled to the number of events in the non-blinded region. An additional contribution from neutrons from the materials is added to the final number and scaled to the total exposure. Background expectation: $1.0 \pm 0.2$ events ($0.79 \pm 0.16$ from gammas, $0.17 + 0.12 - 0.07$ from neutrons).
And the result.....
Unblinding: Distribution of events in the TPC

Exposure: 225 days x 34 kg fiducial mass

**Fiducial mass region:**
- 34 kg of liquid xenon
- 406 events in total

**Signal region:**
- 2 events are observed
- $0.79 \pm 0.16$ gamma leakage events expected
- $0.17 +0.12-0.7$ neutron events expected
- visual inspection: valid waveforms
- at 7.1 keVr and 7.8 keVr both events between 3 and 4 PE
- rather low wrt the NR calibration data
- no low S2/S2-events below threshold

(1.0 \pm 0.2) events expected
2 events observed
\rightarrow 26.4\% probability that background fluctuated to 2 events
\rightarrow PL analysis cannot reject the background only hypothesis

No significant excess due to a signal seen in XENON100 data.
XENON100: New Spin-Independent Results

Upper Limit (90% C.L.) is $2 \times 10^{-45}$ cm$^2$ for 55 GeV/c$^2$ WIMP.
No Impact of $L_{\text{eff}}$ below 3 keVnr

$L_{\text{eff}}=0$ below 3 keVnr
The new XENON100 Limit

- DAMA/Na
- CoGeNT
- CDMS (2011)
- DAMA/I
- SIMPLE (2012)
- XENON100 (2011)
- CRESST-II (2012)
- EDELWEISS (2011)
- CDMS (2010)
- XENON100 (2011)

Expected limit of this run:
- ± 1σ expected
- ± 2σ expected

WIMP-Nucleon Cross Section [cm²]

WIMP Mass [GeV/c²]
What XENON100 sees...
A light mass WIMP...

$\log_{10}(S_2 / S_1) - \text{ER mean}$

$E_{\text{nr}} \text{[keV]}$

$m_X = 8 \text{ GeV/c}^2 \quad \sigma = 1.0 \times 10^{-40} \text{cm}^2$

Illustration only!
A CRESST-like signal...

$m_X = 25 \text{ GeV}/c^2 \quad \sigma = 1.6 \times 10^{-40} \text{ cm}^2$
What XENON100 sees...
What XENON100 excludes...

$m_\chi = 50$ GeV/c$^2$  $\sigma = 3.0 \times 10^{-45}$ cm$^2$
What could the Events be?

Reminder:
Background is modeled using ER calibration data from Co60 and Th232
This data shows an increased probability for anomalous leakage below ~8 PE

Background prediction depends on the information which is put into the model
Sensitivity to single electrons

Relaxing the S2 threshold condition (S2>150 PE) leads to a band of events at very low S2/S1 (below signal range)

→ can the 2 events be in the tail of this band???
→ further studies are required
→ aim: quantify and put into background model for the next run
(Further) Exploiting the Ionisation Channel

- Resolution of primary scintillation is dominated by photon generation and photoelectron collection statistics

- Single electron detection demonstrated in LXe TPCs

- Origin:
  - Photon-induced (post S1): photoionisation and emission from cathode
  - Spontaneous emission: background related

- Application:
  - ★Electron lifetime measurement (extremely useful for ton and greater scale detectors)
  - ★Lower thresholds (~1 keV) and superior resolution
  - ★Neutrino physics
  - ★Low mass WIMP searches
XENON100: New Spin-Independent Results

Upper Limit (90% C.L.) is $2 \times 10^{-49}$ cm$^2$ for 55 GeV/c$^2$ WIMP
(Further) Exploiting the Ionisation Channel

To go from this...

to this...

...we need this!
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The Next Step: XENON1T

Scaleability has been demonstrated repeatedly - gets easier (no performance loss) as we get bigger!
I Tonne Fiducial Mass
2 Year Exposure (~2017)
Homestake mine
South Dakota

Davis Cavern (5th May 2011)
4850 ft depth

World leader in 2013

Sept 5th 2012
Water Shield and lab ready for LUX!

Dec 2011
Now submerged in water tank - cool-down imminent!
The ZEPLIN Programme at Boulby

**ZEPLIN I**
Single phase, 3 PMTs, 5/3.1 kg
Run 2001-04
Limit: \(1.1 \times 10^{-6} \text{ pb}\)

**ZEPLIN II**
Double phase, 7 PMTs, moderate E field, 31/7.2 kg
Run 2005-06
Limit: \(6.6 \times 10^{-7} \text{ pb}\)

**ZEPLIN III**
Double phase, 31 PMTs, high E field, 10/6.4 kg
Run 2009-11
Limit: \(3.9 \times 10^{-8} \text{ pb}\)

Single-phase

The first 2-phase LXe Dark Matter detector!

Europe’s most sensitive SI
World’s best WIMP-neutron SD
LUX-ZEPLIN (LZ)

- Merger of the UK-led ZEPLIN and LUX progressive programmes
- SI WIMP-nucleon cross-section sensitivity to $\sim 10^{-48} \text{ cm}^2$
- UK leading roles in 3/10 of WPs for LZ
  - Backgrounds/screening/analytics (UCL)
  - Inner detector/TPC (IC)
  - Ti vessels (RAL)

ZEPLIN-III

LUX

LZ

6 kg LXe

100 kg

5,000 kg
Elastic scattering Si cross-section

Results
ZEPLIN-III 2011 (magenta)
XENON100 2011 (green)
XENON100 2012 (grey)
EDELWEISS II 2011 (dark blue)
CDMS-II 2010 (blue)

Projections
LUX (red dash)
100 kg fiducial x 300 live days

LUX-ZEPLIN (black dash)
5-tonne fiducial x 1,000 live days

LZ will be >10x more sensitive than XENON1T (>1000x more than XENON100) and will sweep virtually all of the favoured electroweak parameter space!
Summary

• LXeTPCs, pioneered by the ZEPLIN and XENON collaborations have rapidly accelerated the race for WIMPs, excluding 3 orders of magnitude in WIMP-nucleon cross-section over the past decade.

• Scaling detectors lowers background, but does not harm threshold, discrimination, or event vertex reconstruction.

• XENON100 achieved sensitivity an order of magnitude better than any competing experiment - but no WIMPs!

• Exploiting the ionisation channel lowers threshold from existing 6-7 keV down to 1 keV. LXeTPCs perform broadband Dark Matter searches.

• Next up is LUX, to become the world leader in 2013.

• The tonne scale ‘G2’ Experiments, XENON1T (1.1T) and LUX-ZEPLIN (5T), will build on the LXeTPC track-record to deliver sensitivity for a robust and statistically significant first discovery!

• DarkSide uses the same technology with LAr - multiple targets needed for confirmation!
Exciting times ahead....

Thank you all for listening!