New Results from the XENON100
Dark Matter Search Experiment

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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
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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 - with little against...
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!
High Priority on just about all Roadmaps and Influential Advisory Documents
A Growing Field
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei → nuclear recoil

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

Event Rate: $R \propto N \frac{\rho_X}{m_X} \langle \sigma v \rangle$

- Detector
- Local DM Density $\rho_X \sim 0.3 \text{ GeV/cm}^2$
- Physics

WIMP Expectations
- CMSSM: Trota et al.
- CMSSM+LHC: Buchmueller et al.

Detectable Signal
- $E_X \sim O(10 \text{ keV})$
- $v \sim 230 \text{ km/s}$
- 1 event/kg/yr
- 1 event/ton/yr
WIMP Detection Techniques

Heat and ionisation bolometers:
- CDMS
- EDELWEISS

Bubbles and Droplets:
- CUOPP
- PICASSO

Phonons

Light and heat Bolometers:
- CRESST
- ROSEBUD

Charge

Light

dE/dx

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

Ionisation detectors:
- DRIFT, DMTPC, GENIUS, NEWAGE, HDMS, IGEX

Scintillators:
- DAMA
- LIBRA
- XMASS
- CLEAN
- DEAP
- ANAIS
- KIMS
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**Liquid Xenon Time Projection Chambers**

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

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

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

x-y localization

Δt : z localization
WIMP Signals in a Dual-Phase Xenon Detector
Particle Discrimination

Light (S1) and charge (S2) depend on recoil $dE/dx$
Event Position Reconstruction

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 601

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, see Astroparticle Physics 35, 2011
(spin-independent) **WIMP Limit 2011**

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**XENON100** sets the most sensitive limit over a large WIMP mass range.

Challenges the CoGeNT, DAMA, CRESST-II signals as being due to light mass WIMPs.

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**Limit derived with Profile Likelihood method**

*PRL 107, 131302 (2011)*

already cited 362x

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*PRL 81, 052003 (2011)*

**OUTDATED!!**
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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 $^{228}$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)
- Event selection, remove bad events:
  - noise
  - S1/S2 not matching
  - Select single interaction events
- Physics analysis input: astrophysics, nuclear physics, DM data sidebands, NR and ER calibration ⇒ response, background estimate
- Profile likelihood
- Results
- Root trees

Acceptances!
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
XENON100 neutron calibration

- Nuclear Recoil band calibration performed with a 220 n/s AmBe neutron source.
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): $^{19}\text{F} + n \rightarrow ^{19}\text{F} + n + \gamma$ (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

$^{137}\text{Cs}$
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 $^{137}$Cs (662 keV) at different positions, from the 40 keV neutron inelastic scattering line, and the 164 keV line from n-activated $^{131m}$Xe (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 $LY_{122\text{keV}} = (2.28 \pm 0.04) \text{ PE/keV}$.

LCE correction map using the 40 keV line

Light yield for different gamma lines
Improved S2 Trigger Efficiency

- 100% efficiency above S2= 150 photoelectrons
- ability to trigger on very low energy events (~10 electrons!)
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)

Before applying LXe veto cut
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
Improved Statistics of ER & NR Calibration Data

Gamma and neutron calibration data

Lower Run10 S2 threshold visible
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
Volume Fiducialization: power of a TPC

- 3D event imaging allows to select only central volume with lowest background exploiting LXe self-shielding
- Gammas from detector components and external sources stopped at edges
- Remaining background in fiducialized volume dominated by internal sources like $^{85}$Kr and $^{222}$Rn in LXe

Background from published data (PRL 107)
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

\[
E_{nr} = \frac{S1}{L_{\text{eff}} \cdot L_y}
\]

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
- $0.17 \pm 0.12 - 0.7$ 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 ± 0.2) events expected
2 events observed
→ 26.4% probability that background fluctuated to 2 events
→ 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 keVr

"standard" $L_{\text{eff}}$

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

[Graph showing the new XENON100 limit on WIMP-nucleon cross section as a function of WIMP mass, with data points from various experiments such as DAMA/Na, CoGeNT, CDMS (2011), DAMA/I, SIMPLE (2012), CRESST-II (2012), EDELWEISS (2011), CDMS (2010), XENON100 (2011), COUPP (2012), and ZEPLIN-III (2012). The graph includes observed limits (90% CL) and expected limits (±1σ and ±2σ) for this run.]
What XENON100 sees...
A light mass WIMP...

Illustration only!

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

$m_\chi = 50 \text{ GeV/c}^2 \quad \sigma = 3.0 \times 10^{-45} \text{ cm}^2$
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

- In ZEPLIN-III, single electrons detected within 36 µs timeline and with dedicated runs

- 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
  - **Low mass WIMP searches**
  - **Neutrino physics**
XENON100: New Spin-Independent Results

Upper Limit (90% C.L.) is $2 \times 10^{-45} \text{ cm}^2$ for 55 GeV/c$^2$ WIMP
Single electron emission in two-phase xenon with application to the detection of coherent neutrino-nucleus scattering

ZEPLIN-III Collaboration


Expected Sensitivity to Galactic/Solar Axions and Bosonic Super-WIMPs based on the Axio-electric Effect in Liquid Xenon Dark Matter Detectors


Abstract

We present systematic case studies to investigate the sensitivity of axion searches by liquid xenon detectors, using the axio-electric effect (analogue of the photoelectric effect) on axion atoms. Liquid xenon is widely considered to be one of the best target media for detection of WIMP (Weakly Interacting Massive Particles) which may form the dark matter using axion models. Since those detectors also provide an extremely low background environment for electronic noise, they weakly interacting particles (less than 100 keV/ν) such as the hypothetical axion, could be detected as well — in this case using the axio-electric effect. Future ton-scale liquid xenon detectors will be limited in sensitivity only by inelastic neutrino background (production mass axion neutrinos and the double beta decay of 136Xe) in the mass range between 1 and 300 GeV. Assuming our two-year of exposure, galactic axions (as non-relativistic dark matter) could be detected if the axio-electric coupling, γ, is greater than $10^{-12}$ at 1 keV/ν or $10^{-13}$ at 300 keV/ν. Below a few-year exposure, the sensitivity is independent of the mass, a solar axion搜寻 would be sensitive to a coupling $γ < 10^{-12}$. This limit will set a stringent upper bound on axion mass for the DPHV and B-non models for the mass ranges $m_a < 0.1$ keV/ν and $< 30$ keV/ν, respectively. Vector-boson dark matter could also be detected for a coupling constant $γ_a > 10^{-12}$ for the mass 1 keV/ν or $> 30$ keV/ν.
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The Next Step: XENON1T

- High transparency electrodes
- Active LXe veto
- 1 kV/cm drift field with external field shaping rings
- No charge insensitive regions below photocathode
- No top array screening mesh
- Three interlocking PTFE panels
- Titanium cryostat and vacuum jacket
- 2 arrays of 121 high QE 3” photodetectors

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

Davis Cavern (5th May 2011)
4850 ft depth

Dec 2011

Water Shield and lab ready for LUX!

Sept 5th 2012

World leader in 2013

World leader in 2013
Status: Underground commissioning
The ZEPLIN Programme at Boulby

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

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

**ZEPLIN III**
Double phase, 31 PMTs,
high E field, 10/6.4 kg
Run 2009-11
Limit: $3.9 \times 10^{-8}$ 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
- Scaling the proven, world-leading technology that UK pioneered
- SI WIMP-nucleon cross-section sensitivity to $\sim 10^{-48} \text{ cm}^2$
**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
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.

• Demonstrated stability over periods of years; most construction and operational techniques perfected.

• XENON100 achieved sensitivity an order of magnitude better than any competing experiment.

• Exploiting the ionisation channel lowers threshold from existing 6-7 keV down to 1 keV.
  LXeTPCs perform ‘broadband’ Dark Matter searches - not just the SUSY neutralino.

• 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!
Exciting times ahead....

Thank you all for listening!