Dark Matter search with liquid xenon: from XENON100 to next generation experiments

Presented by
Samuel DUVAL
Direct detection of Dark Matter
  • the XENON100 experiment
  • XENON100 results

Toward large scale detectors
  • XENON1T
  • DARWIN

Photodetection in liquid xenon
  • a large-area GPM
Rotational curves of stars in galaxies

In Newton dynamics

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]

NGC 1309: NASA, ESA, The Hubble Heritage Team, (STScI/AURA) and A.Riess (STScI)

Something is missing...

Rotational curves of stars in galaxies

... a halo of Dark Matter surrounding visible one

In Newton dynamics

\[ v(r) = \sqrt{\frac{GM(r)}{r}} \]
One can see it by gravitational effects...

Gravitational lensing

W.N. Colley and E. Turner (Princeton University), J.A. Tyson (Bell Labs, Lucent Technologies) and NASA
One can see it by gravitational effects...

Gravitational lensing

Dark matter reconstructed map by Canada-France-Hawaii Telescope Lensing Survey

Previous DM map

W.N. Colley and E. Turner (Princeton University), J.A. Tyson (Bell Labs, Lucent Technologies) and NASA

L. Van Waerbeke, C. Heymans, CFHTLensing Collaboration, AAS meeting (2012)
One can see it by gravitational effects...

The gravitational potential does not follow the plasma distribution (main baryonic mass component) but rather traces the galaxies distribution...

What do we know about Dark Matter?

From observations

73%-dark energy ($\Omega_{\Lambda}$: Dark Energy density)  
27% Matter ($\Omega_m$: Matter density)  
- 22.5% non-baryonic matter  
- 4.5% baryonic matter; only 0.5% is visible!

Characteristics of the DM candidate

Low interaction rate with electromagnetic radiation and baryonic matter  
Must be stable (relic density)  
Should be non-relativistic (structures)

Weakly Interactive Massive Particle

Supersymmetry provides an excellent DM candidate: the lightest neutralino.

K. Nakamura et al. (PDG), JP G 37, 075021 (2010), updated in 2012
Direct Dark Matter Detection

WIMP – nucleus elastic scattering

Energy deposition by nuclear recoil (~1-100 keV_{nr})

Event rate as low as 1 evt/kg/year

Exclusion limits

J.D. Lewin, RF. Smith, Astroparticle Physics 6 (1996) 87-112
E. Aprile et al. (XENON100), Phys. Rev. Lett. 107, 131302 (2011)
Direct Dark Matter Search Modalities

- CRESST-I, CUORICINO
- CRESST-II
- DAMA/LIBRA, KIMS, XMASS, DEAP/CLEAN, ZEPLIN-I
- ZEPLIN-II/III, XENON, LUX, WARP, ArDM, PANDA-X
- EDELWEISS CDMS
- CoGeNT, DM-TPC, DRIFT, MIMAC, NEWAGE

Instruments:
- Cuoricino module
- CDMS module
- ZEPLIN-III
- XMASS
- DRIFT
Direct DM Detection around the world

Techniques:
- Cryogenic (Ge, Si etc.)
- Solid Scintillator (NaI, CsI)
- Noble Liquids (LXe, LAr)
XENON100 : Underground experiment

Laboratori Nationali del Gran Sasso, Italy
1400 m Rock (3600 water equivalent, reducing muon flux ~$10^6$)
A double phase liquid xenon TPC

Nuclear/Electronic recoil discrimination and fiducialization
XENON 100 detector

Meshes

TPC

161 kg of LXe
- 99 kg active veto
- 62 kg TPC
- 48 kg fiducial volume

Top Array: 98 PMTs

PTFE panels

Veto PMTs

Bottom Array: 80 PMTs

R8520-06-Al 1”

(X,Y) reconstruction

Maximum coverage
Removing the background

- **Electromagnetic background:**
  - Self-shielding
  - Nitrogen purging (\(^{222}\text{Rn}\))
  - OFH copper
  - Low activity materials (TPC)
  - Pb layer + Pb with low \(^{210}\text{Pb}\) contamination

- **Neutron background:**
  - Water and Polyethylene

- **Multiple scattered events:**
  - Veto PMTs
  - Z position and PMT pattern

- **Krypton removal:**
  - \((^{85}\text{Kr}/^{\text{nat}}\text{Kr} \sim 10^{-11})\)
  - \(\beta\) emitter
  - \(E_{\text{max}} = 687\ \text{keV}; \tau=10.76\ \text{y}\)
Electromagnetic background

Measured ER background in agreement with MC
- No fine tuning of rate!
- Activity taken from screening measurements

Rate below 100keV: $6.1 \times 10^{-3} \text{ evts.kg}^{-1}.\text{keV}^{-1}.\text{d}^{-1}$
Toward ultra-pure LXe

Charge yield

- Electrons are captured by **electronegative impurities** during the drift (30 cm)
- Xenon is **continuously purified** in gaseous phase
- Electron lifetime is measured with $^{137}$Cs $\gamma$ source during calibrations

![Graph showing electron lifetime over time](image)

*E. Aprile et al. (XENON100), arXiv:1107.2155*
Position corrections of S1 & S2 signals

**Primary scintillation (S1):**
- Light collection efficiency measured with $^{137}$Cs, AmBe, $^{131m}$Xe

**Proportional scintillation (S2):**
- Charge attenuation by drift time ($\tau_e$)
- XY corrections

**Spatial resolution:** $\sigma_{(x,y)} \sim 3$ mm and $\sigma_z \sim 0.3$ mm

S1 correction map factor = $f(r,z)$

40 keV line

Top of the TPC

S2 = $f(x,y)$
Gamma Calibrations

**S1, S2 anti-correlation**

**Different calibration sources**

- $662 \text{ keV}_{\text{ee}} (^{137}\text{Cs})$, $1.17/1.33 \text{ MeV}_{\text{ee}} (^{60}\text{Co})$
- $40 \text{ keV}_{\text{ee}} (^{129}\text{Xe} (n,n'\gamma)129\text{Xe})$ by $^{241}\text{AmBe}$
- $80 \text{ keV}_{\text{ee}} (^{131}\text{Xe} (n,n'\gamma)131\text{Xe})$ by $^{241}\text{AmBe}$
- $164 \text{ keV}_{\text{ee}} (^{131m}\text{Xe})$ by $^{241}\text{AmBe}$
- $236 \text{ keV}_{\text{ee}} (^{129m}\text{Xe})$ by $^{241}\text{AmBe}$

**LY(122 keV_{ee}) = 2.20\pm0.09 \text{ pe/keVee @ 0.53kV/cm}**
Background discrimination

Identification of recoil species by S2/S1 ratio

- from $^{60}$Co $\gamma$-ray source and $^{241}$AmBe neutron source
- selecting single scattered events

Results from 100.9 days run

**Electron Recoils**

*Statistical Leakage:*
1.14 ±0.48 Events

*Anomalous Leakage:*
0.56 (+0.21/-0.27) Events

**Nuclear Recoils**
0.11 (+0.08/-0.04) Events

**Predicted Background:** 1.8 ± 0.6 Event

3 WIMP candidates in search region consistent with background prediction

---

E. Aprile et al. (XENON100), Phys. Rev. Lett. 107, 131302 (2011)
WIMP exclusion curves in $\sigma_{SI}$ vs $m_\chi$ space

Lowest limit in the world: $7.0 \times 10^{-45} \text{ cm}^2 \text{ @ 50 GeV/c}^2$

E. Aprile et al. (XENON100), Phys. Rev. Lett. 107, 131302 (2011)
XENON is progressing fast
and is still taking data!

**Improvements**
- Less Kr (50% background reduction)
- Improved S2-based trigger with lower trigger threshold
- Better LXe purity, much more calibration data

- New analysis released soon
XENON is moving in Hall B
XENON1T experiment
is already under construction!

Goal: 1T fiducial volume with $10^{-47}$ cm$^2$ sensitivity!

2013: installation
2014: commissioning
2015: data taking
XENON collaboration: 15 institutes

- Purdue
- Columbia
- UCLA
- Rice
- Coimbra
- Subatech
- Subatech
- Bologna
- LNGS
- SJTU (XENON100)
- WIS
- Zurich
- NIKHEF
- Mainz
- Münster
- MPIK
- NIKHEF
RESTOX : A Liquid Xenon station
(REcovering and STOrage system of Xenon1T)

**Motivations:**
- Very compact station
- 3T storage capacity from 20° to -108°C
- Able to keep high purity all the time

**Time schedule:**
- Construction will start in summer 2012
- Installation for end of 2013

RESTOX will be easily scalable to larger sizes
RESTOX: A Liquid Xenon station
(REcovering and STOrage system of Xenon1T)

Pressure difference and ReStox cooling power (1 kW net) will offer a fast and safe recovering process.

Tests on a small model (130 kg capacity) are foreseen in 2013 at Subatech.
DARWIN: DARk matter WImp search with Noble liquids

13 laboratories involved

8 t (5 t) of LXe in total (fiducial)
20 t (10 t) of LAr in total (fiducial)

Laboratoire Souterrain de Modane
Laboratori Nationali del Gran Sasso
DARWIN project

Design study of a next-generation noble liquid dark matter facility in Europe

- WP1 Management (UZH)
- WP2 Detector infrastructure (Münster)
- WP3 Light read-out (INFN)
- WP4 Alternative charge read-out methods (ETHZ)
- WP5 Electronics and DAQ (Subatech)
- WP6 Underground and shielding infrastructure (IFJ PAN)
- WP7 Material screening and background modeling (MPIK)
- WP8 Science impact (Nikhef)

Improving the charge-readout sensitivity by maximizing the photodetection coverage and keeping localization power
Large-Area Gaseous PhotoMultipliers

Using Micro-Pattern Gaseous Devices: THGEMs and/or micromeshes

Collaboration between Subatech/WIS-Israel/Coimbra-Portugal

@ WIS: multiple THGEM concept (in two-phase LXe)
@ Nantes: THGEM/PIM/MICROMEGAS (in single phase LXe)
Gaseous Photomultiplier principle

Collection (THGEM)

Amplification (PIM)

Induction (MICROMEGAS)

THGEM: Efficient photoelectron collection + low gain
PIM/MICROMEGAS: ion blocking (prevents CsI damage) & gain

S. Duval et al., 2009 JINST 4 P12008 & S. Duval et al., 2011 JINST 6 P04007
GPM detector

THGEM/PIM/MICROMEGAS
Internal structure

- 500 lpi grid
- 670 lpi grid
- Kapton spacer (125 microns)
- MICROMEGAS (50 microns)
- Anode (ROGERS)
- Base (stainless steel)

Viewport (MgF$_2$)

LXe GPM prototype (LXe side)

Gas

Vacuum side

SHV
Experiments in single-phase liquid-xenon

\[ P_{\text{GPM}} = 1100 \text{ mbar}, \ T = 171 \text{ K}, \ P_{\text{Xe}} = 1200 \text{ mbar}, \ \text{flow rate} < 2 \text{ l/min}, \ \Delta T_{\text{in/out}} \sim 2\text{K} \]
LXe Scintillation pulses recording

First pulse of a GPM in LXe!

Vacuum PMT pulse

GPM pulse

Ne/CF₄ (90:10)
T = 173K
P = 1100 mbar

GPM viewport

Coincidence assembly

PMT Hamamatsu (R7600-06MOD-ASSY)

Source $^{238}$Pu

S. Duval et al., 2011 JINST 6 P04007
Gain measurements with $^{55}\text{Fe}$

THGEM/PIM/MICROMEGAS in Ne/CF$_4$ (90:10)

$P = 1100$ mbar
X-rays (5.9 keV)

Total gain above $10^6$!

$T = 171$ K; $E_{\text{coll}} = 0.25$ kV/cm; $E_{\text{extr1}} = 1$ kV/cm; $E_{\text{extr2}} = 0.8$ kV/cm

- $\Delta V_{\text{THGEM}} = 900$ V; $\Delta V_{\text{PIM}} = 490$ V
- $\Delta V_{\text{THGEM}} = 800$ V; $\Delta V_{\text{PIM}} = 500$ V
- $\Delta V_{\text{THGEM}} = 700$ V; $\Delta V_{\text{PIM}} = 520$ V

$T = 293$ K; $E_{\text{coll}} = 1$ kV/cm; $E_{\text{extr1}} = 0.5$ kV/cm; $E_{\text{extr2}} = 0.4$ kV/cm

- $\Delta V_{\text{THGEM}} = 800$ V; $\Delta V_{\text{PIM}} = 400$ V
- $\Delta V_{\text{THGEM}} = 600$ V; $\Delta V_{\text{PIM}} = 400$ V
- $\Delta V_{\text{THGEM}} = 600$ V; $\Delta V_{\text{PIM}} = 500$ V

Fast signal direct readout

$^{55}$Fe Hybrid GPM pulse

Really like a PMT!

Conclusion & Prospects

• Proof of concept (2010)

• High gains at LXe T \( \sim 10^6 \) (2011)

• Efficient ion blocking expected also in Ne-mixtures

• CsI photocathode studies in progress*

• Large-size prototype is designed and ready for being assembled

Toward 20 inches diameter window

Other interesting applications:

• **$3\gamma$ medical imaging** with single phase TPC at SUBATECH (collaboration with KEK-Japan)
• **Rare event noble-liquid detectors** (collaboration with WIS-Israel and BINP-Russia)