New Light on the Dark Side of the Universe

Doing Physics with a Noble Element

Elena Aprile
Columbia University
National Science Foundation
MPS Directorate, April 21, 2008
What is the Universe made of?

Dark Energy: 74%

Dark Matter: 22%

Atoms: 4%

>95% UNKNOWN
Visible Matter

Galaxy: NGC253
Dark Matter

If we could see it...
Dark Matter in Galaxy Clusters

Gravity of the stars not enough to hold clusters together. Clusters must be held together by gravity of unseen DM.
Dark Matter in Galaxy Clusters

=> All cluster mass measurements give $\Omega_m > 0.15$, so majority of mass must be some new non-baryonic form (remembering $\Omega_b \sim 0.05$)
Dark Matter in Galaxies

Inferred from Flat Rotation Curves

First Measurement: Vera Rubin


ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS

Vera C. Rubin and W. Kent Ford, Jr.
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory
Dark Matter in Galaxies: Measurements

Observations of interstellar gas (21 cm HI-Emission Line) at large radii

$\Rightarrow$ the rotation curves are constant as far as one can measure!

$\Rightarrow \sim 10 \times$ more Matter, as one can directly see $\Rightarrow M_{\text{dark}} \geq 10 M_{\text{stars}}$

![Graph of dark matter distribution in NGC 3198](image)

- Bulge, disk & halo
- V ~ const
- Bulge & disk V ~ r^{-1/2}

Not a good fit!

Large Scale Structure

Measurement: 2dF Survey

Simulation results depend primarily on whether the dark matter is hot (relativistic) or cold (non-relativistic) when structures were formed.

Most of the Universe's matter must be Cold Dark Matter.

Simulation: [http://krone.physik.unizh.ch/~moore/](http://krone.physik.unizh.ch/~moore/)

Dark matter dominates & provides first structures in the Universe.
Early Distribution: CMB Radiation

- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years

Dark Energy Accelerated Expansion

NASA/WMAP Science Team
Conclusion from All Evidence

\[ \Omega_{\text{total}} = 1 \]
\[ \Omega_\Lambda \approx 0.74 \]
\[ \Omega_M \approx 0.27 \]
\[ \Omega_B \approx 0.04 \]
\[ \Omega_\nu \approx 0.005 \]

\[ \Omega_M - \Omega_B = \Omega_{\text{CDM}} \approx 0.23 \]

Challenge will be to discover the physics that generates Dark Energy and Dark Matter!
Origin of Dark Matter: the Particle Physics Connection

Different models and theories of elementary CDM particles

Supersymmetry inspired:

Mass: $1\div1000$ GeV

Weak interaction with ordinary matter:

$\sigma = 10^{-5} \div 10^{-12}$ pb

$= 10^{-41} \div 10^{-48}$ cm$^2$

NB: Mirror matter is not considered here
Supersymmetry

New fundamental space-time symmetry: Fermions $\Rightarrow$ Bosons

$\Rightarrow$ SM particles get superpartners

(differ in Spin by 1/2, otherwise same quantum numbers)

$\Rightarrow$ Natural and coherent extension beyond SM, solving known issues

$\Rightarrow$ Natural Grand Unification hierarchy and Higgs mass stability

$\Rightarrow$ Supersymmetric particles have not been observed (yet) so they
must be heavier- SUSY must be broken by some mechanism

Discrete symmetry (to prevent rapid proton decay): R-Parity

$R$ (SM Particles) = +1; $R$ (SUSY Particles) = -1

$\Rightarrow$ The lightest SUSY-Particle (LSP) is stable, and a 'natural' WIMP candidate

$$\chi_1^0 = \alpha_1 \tilde{B} + \alpha_2 \tilde{W} + \alpha_3 \tilde{H}_u^0 + \alpha_4 \tilde{H}_d^0$$
Weakly Interacting Massive Particles

WIMPS:

$10^6$ per second through your thumb without being noticed!

$10^{15}$ through a human body each day: only $<10$ will interact

If their interaction is so weak, how can we detect them?
WIMPs Production by Accelerators

Geant4., fig. from H. Baer
scattering off nuclei in terrestrial detectors...deep underground to shield them from cosmic radiation.
Program towards the solution of the Dark Matter Puzzles

1. Proof of Dark Matter Particles in our Milky Way
   (Direct and Indirect Detection Experiments)

2. Proof of Dark Matter Particles in a controlled experimental environment
   (Accelerators)

3. Proof that both particles are one and the same particle!
Direct Detection

10–100 WIMPs/liter, $v \approx 10^{-3}c$

WIMPs scatter elastically with nuclei:

**Rate** $\sim N \frac{\rho_X}{m_X} \langle \sigma_{X-N} \rangle$

$N$ = Number of target nuclei in detector
$\rho_X$ = Local WIMP Density
$\langle \sigma_{X-N} \rangle$ = Scattering Cross Section

Rate $\ll 1$ Event/kg/Day
WIMPs Density in our Galaxy

Measured Rotation Curve of the Milky Way: flat up to \( \approx 50 \text{ kpc} \)

Acceptable range: \( \rho_0 = 0.3 - 0.6 \text{ GeV/cm}^3 \)

\( \sim 10^5 \) larger than in the universe at large

\( M_{\text{virial}} = 1-2 \times 10^{12} M_{\text{sun}} \)

(Klypin, Zhao & Somerville 2002)
WIMP–Nucleon Cross Section

Nature 448, July 19, 2007
CMSSM (Roszkowski, Ruiz, Trotta)

1 event/kg/yr
XENON100

10 events/ton/yr
XENON1T
Experimental Challenges

Ultra Low Background (< $10^{-4}$ evts/kg/keV/day)
- deep underground labs
- low radioactivity materials
- active/passive shielding

Very large target mass (1000 kg)

Very low energy threshold (KeV)

Excellent long-term stability

Event-Discrimination ($\text{WIMPs}=\text{NR}$, Background=ER)

WIMP Scattering

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} \nu_0 m_\chi \mu^2} \exp\left(-\frac{Q m_N}{2 \mu^2 \nu_0^2}\right) F^2(Q)$$

$$M_\chi = 100 \text{ GeV}, \sigma_{\chi-p} = 10^{-45} \text{ cm}^2$$

Rate [evts/keV/kg/day] vs Recoil Energy [keV]
Direct Detection Methods & Experiments

Scintillation:
- ZEPLIN,
- XENON

Ionization:
- EDELWEISS
- Ge/Si

Phonon:
- CRESST
- CaWO$_4$

ER:
- ZEPLIN, XENON
- XMASS, WARP, ArDM
- LXe & LAr
World Wide WIMP Searches

- Kamioka
  - KIMS
- Yangyang
- Homestake
  - DUSEL-ISE
- Soudan
  - CDMS
- Frejus/Modane
  - EDELWEISS
- SNOLAB
  - DEAP/CLEAN
  - PICASSO
- Boulby
  - ZEPLIN
  - DRIFT
- Gran Sasso
  - CRESST
  - DAMA/LIBRA
  - WARP
  - XENON
- Yangyang
  - KIMS
- Kamioka
  - XMASS
- Homestake
  - DUSEL-ISE
- Soudan
  - CDMS
- Frejus/Modane
  - EDELWEISS
- SNOLAB
  - DEAP/CLEAN
  - PICASSO
- Boulby
  - ZEPLIN
  - DRIFT
- Gran Sasso
  - CRESST
  - DAMA/LIBRA
  - WARP
  - XENON
The Cryogenic Experiments

Detectors with excellent background discrimination (> 99.99 % for Er >10 keV). Simultaneous measurement of Heat @ 50 mK with Ge/NTD thermometers and Ionization @ fewV/cm with Al electrodes. Mass in the range of a few kg. Next generation (>2009) expts aim at 25 -1000 kg

**CDMS II (Soudan Mine):** 19 Ge (4.75 kg) and 11 Si (1.1 kg)

**EDELWEISS II (Frejus Tunnel):**
21 Ge (NTD) and 2 NbSi for up to 40 kg

**CRESST II (Gran Sasso):** 16 CaWO₄ crystals (5 kg) and 10 kg in future with multiple targets
The Noble Liquid Experiments

Detectors with fine position sensitivity in one homogeneous large volume filled with either liquid Xe or liquid Ar. Scalable to multi-ton mass at modest cost compared to cryogenic detectors. Background discrimination (> 99.95 % for Er ~ 5 keV demonstrated by the XENON experiment). Simultaneous measurement of Scintillation @ 178 (128) nm with PMTs and Ionization @ 1 kV/cm with 2-phase TPCs. Mass in the range of a 10 kg. Next generation (2009- 2012) expts aim at 100 - 1000 kg in fiducial volume.

XENON10 (Gran Sasso Lab): 22 kg LXe 2-phase TPC

ZEPLiN II & III (Boulby Mine): up to 30 kg LXe 2-phase TPC

WARP (Gran Sasso): up to 140 kg LAr 2-phase TPC
### Why (Liquid) Noble Gases for DM Searches?

#### Liquified Noble Gases: Basic Properties

- Dense and homogeneous
- Do not attach electrons, heavier noble gases give high electron mobility
- Easy to purify (especially lighter noble gases)
- Inert, not flammable, very good dielectrics
- Bright scintillators

<table>
<thead>
<tr>
<th></th>
<th>Liquid density (g/cc)</th>
<th>Boiling point at 1 bar (K)</th>
<th>Electron mobility (cm²/Vs)</th>
<th>Scintillation wavelength (nm)</th>
<th>Scintillation yield (photons/MeV)</th>
<th>Long-lived radioactive isotopes</th>
<th>Triplet molecule lifetime (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHe</td>
<td>0.145</td>
<td>4.2</td>
<td>low</td>
<td>80</td>
<td>19,000</td>
<td>none</td>
<td>13,000,000</td>
</tr>
<tr>
<td>LNe</td>
<td>1.2</td>
<td>27.1</td>
<td>low</td>
<td>78</td>
<td>30,000</td>
<td>none</td>
<td>15</td>
</tr>
<tr>
<td>LAr</td>
<td>1.4</td>
<td>87.3</td>
<td>400</td>
<td>125</td>
<td>40,000</td>
<td>39Ar, 42Ar</td>
<td>1.6</td>
</tr>
<tr>
<td>LKr</td>
<td>2.4</td>
<td>120</td>
<td>1200</td>
<td>150</td>
<td>25,000</td>
<td>81Kr, 85Kr</td>
<td>0.09</td>
</tr>
<tr>
<td>LXe</td>
<td>3.0</td>
<td>165</td>
<td>2200</td>
<td>175</td>
<td>42,000</td>
<td>136Xe</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Basic microscopic processes in medium

- Electronic stopping of ionizing particles (mip, e, α, fast ions, FF, ...) leading to scintillation and electron-ion pair production has been experimentally and theoretically studied for LAr & LXe for several decades.

- Columnar recombination decreases the secondary electron yield at the favor of scintillation photons. It is affected by an external drift field $E_{\text{drift}}$.

- For slow moving ions, nuclear stopping becomes important. This energy does not lead to scintillation or ionization → “nuclear quenching factor” $q_{n\text{c}}$.

- Scintillation quenching (e.g. by biexcitonic collisions) also occurs in the high ionization density “core” → “electronic quenching factor” $q_{\text{el}}$.
The Merits of LXe for Dark Matter

✦ **Large nucleus (A~131)**: good for SI plus SD sensitivity (~50% odd isotopes)

✦ **Scalability**: relatively cheap ($1500/kg) and “easy” cryogenics at 160 K

✦ **Background reduction**: via self-shielding (Z=54, ρ=3 g/cc)

✦ **Intrinsically background free**: Kr in Xe can be purified to ppt level

✦ **Low threshold**: high scintillation yield (~80% of NaI but much faster)

✦ **Gamma rejection**: electron and nuclear recoil discrimination
Two Phase Time Projection Chamber
The XENON10 TPC

- Pulse Tube refrigerator: stable operation at 170 K
- TPC active volume: 20 cm (Φ) x 15 cm (H) - 15 kg
- PTFE Teflon: ~95% UV reflectivity at 175 nm
- 89 PMTs (R8520): 20% QE, low radioactivity
Self-Shielding in XENON10 TPC

15 < drift time < 65 μs, r < 80 mm (5.4 kg fiducial mass)
Overall Background in Fiducial Volume ~0.6 event/(kg day keVee)
XENON10 at the Gran Sasso Underground laboratory

3100 mwe flat overburden
(surface muon flux reduced by $10^6$)
XENON10 SI WIMP–Nucleon Cross Section Upper Limits


(90 % CL)

8.8 \times 10^{-44} \text{ cm}^2 \text{ at } 100 \text{ GeV}

4.5 \times 10^{-44} \text{ cm}^2 \text{ at } 30 \text{ GeV}

supersymmetry models
Natural Xe has non-zero nuclear spin isotopes: $^{129}$Xe (spin-1/2) @ 26.4% and $^{131}$Xe (spin-3/2)@ 21.2%. Both contain unpaired neutron thus XENON10 is mostly sensitive to WIMP-neutron spin-dependent couplings, yielding the best sensitivity to-date.

FIG. 1: Combined exclusion Limits for $^{129}$Xe and $^{131}$Xe for pure neutron (left) and pure proton (right) couplings (solid curves). The dashed curves show the combined Xe limits using the alternate form factor. Also shown are the results from the CDMS experiment [18] (diamonds), ZEPLIN-II [19] (circles), KIMS [20] (triangles), NAIAD [21] (squares), PICASSO [22] (stars) and SuperK [30] (crosses). The theoretical regions (constrained minimal supersymmetric model) are taken from [29].
Feb 08: CDMS Reports a new WIMP-Nucleon Cross Section Limit
XENON100: the current step in the XENON program (2007-09)

A new and improved TPC design guided by the XENON10 experience and for the same underground location and passive shielding

- 170 kg LXe (vs. 20 kg in XE10); 50 kg fiducial mass (vs. 5 kg in XE10). x10 fiducial mass
- 242 R8520 PMTs with lower background and higher QE (vs. 89 in XE10)
- lower background stainless steel cryostat and inner chamber
- a factor of 100 lower background
XENON100 Sensitivity Reach by 2008
The XENON100 Collaboration

Elena Aprile
Columbia University

Laura Baudis
University of Zurich

Uwe Oberlack
Rice University

Jose Matias Lopes
University of Coimbra

Francesco Arneodo
LNGS

6 faculty - 2 research scientist - 7 postdocs - 10 Ph.D. students = 25

+UCLA recently joined (now ~30)
Welding the top cover
All materials were screened at LNGS with high purity Ge-spectrometers.

<table>
<thead>
<tr>
<th>Material</th>
<th>Th-232 (mBq/kg)</th>
<th>U-238 (mBq/kg)</th>
<th>K-40 (mBq/kg)</th>
<th>Co-60 (mBq/kg)</th>
<th>amount of material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless Steel</td>
<td>2.4</td>
<td>1.9</td>
<td>10.5</td>
<td>8.5</td>
<td>65.4 kg</td>
</tr>
<tr>
<td>Teflon</td>
<td>0.44</td>
<td>0.87</td>
<td>6.2</td>
<td>_</td>
<td>8.49 kg</td>
</tr>
<tr>
<td>PMT</td>
<td>0.21 mBq/PMT</td>
<td>0.25 mBq/PMT</td>
<td>9.30 mBq/PMT</td>
<td>0.59 mBq/PMT</td>
<td>242 pieces</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.69</td>
<td>3.54</td>
<td>5.88</td>
<td>0.90</td>
<td>1542 kg</td>
</tr>
</tbody>
</table>

Gamma-BG from Poly shield is “simulated” after the addition of 5 cm of copper inside top/back/side walls and 5 mm of copper on bottom of Poly cavity.
The XENON100 Expected Gamma/Neutron Background

**Single scatters rate in XENON100**

in the energy region of 1. – 30. keV

with energy threshold 20 keV in the Active Veto

<table>
<thead>
<tr>
<th>Material</th>
<th>Rate [mdru]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>1.95 ± 0.22</td>
</tr>
<tr>
<td>Teflon</td>
<td>0.32 ± 0.04</td>
</tr>
<tr>
<td>PMT</td>
<td>4.73 ± 0.60</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.52 ± 0.29</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9.52 ± 0.67</strong></td>
</tr>
</tbody>
</table>

less than one gamma bkg event / two months

**Neutron rates in XENON100**

in the energy region of 4.5 – 26.9 keV

<table>
<thead>
<tr>
<th>Material</th>
<th>Neutron Rate [mdru]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>2.93e-4</td>
</tr>
<tr>
<td>PMTs</td>
<td>3.18e-4</td>
</tr>
<tr>
<td>Teflon</td>
<td>16.26e-4</td>
</tr>
<tr>
<td>Copper</td>
<td>0.11e-4</td>
</tr>
<tr>
<td>Poly</td>
<td>4.87e-4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.74e-3</strong></td>
</tr>
</tbody>
</table>

The total neutron bg from detector materials and shielding in XENON100 is **0.9 single neutron recoils/year**
The XENON100 TPC Assembly

170 kg LXe (70 kg target)
The XENON100 Photomultipliers

- 1 “ square metal channel Hamamatsu R8520-06-AI
- Low radioactivity (<1 mBq U/Th per PMT)
- 98 on top - 80 on bottom - 64 in active LXe shield
- QE~23% for top array; QE~33% for bottom array
“First Light” from XENON100 Underground

57Co source S1 spectrum

| Co57 Source | \( \chi^2 / \text{ndf} \) | 213.9 / 127 |
|            | \( \text{Constant} \)     | 517.2 ± 3.4  |
|            | \( \text{Mean} \)         | 124.9 ± 0.2  |
|            | \( \text{Sigma} \)        | 30.64 ± 0.17 |

4 p.e. / keV Light Collection
Status of XENON100: Installed Underground at LNGS

- Shield modification/improvement: Jan 08
- Detector underground: Feb 08
- Xe Purification/Kr-distillation: May-June 08
- Gamma/Neutron Calibration: May-July 08
- 1st DM Search: Aug-Sep 08

XENON10 (2006-2007)

XENON100 (Feb.2008)
Kr Purification System for XENON100
XENON1T: the next step in the XENON program (2009-12)

- Studies of a TPC design with full coverage of a new ultra low radioactivity 3" photodetector (QUPID) started.

- A 1m³ TPC with 3000 kg of LXe: 1000 kg as target and 2000 kg as active LXe shield for gamma and neutron background rejection. Additional neutron shielding by liquid scintillator or water.

- Experiment proposal being prepared for Fall 08 for construction start in 2009.

- Modest construction cost: ~$20M shared by NSF + DOE + Foreign.

- Within 2012 XENON1T will explore the full region in CMSSM space (or accumulate WIMP statistics for DM physics).
The XENON Phased Program (2006–2012) and Beyond

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fiducial Mass (kg)</strong></td>
<td>5</td>
<td>50</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Gamma background</strong></td>
<td>1</td>
<td>$10^{-2}$</td>
<td>goal: $&lt;10^{-4}$</td>
</tr>
<tr>
<td>(dru: events/kg/keV/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neutron background</strong></td>
<td>$&lt;1$ per year</td>
<td>$&lt;1$ per year</td>
<td>goal: &lt; 1/two years</td>
</tr>
<tr>
<td><strong>Exposure</strong></td>
<td>2 months</td>
<td>2 months</td>
<td>2 year</td>
</tr>
<tr>
<td><strong>Photodetectors</strong></td>
<td>R8520</td>
<td>lower bkg, higher QE R8520</td>
<td>QUPID (or + R8520)</td>
</tr>
<tr>
<td><strong>WIMP Sensitivity at 100 GeV</strong></td>
<td>$0.9 \times 10^{-43}$ cm$^2$</td>
<td>$2 \times 10^{-45}$ cm$^2$ (projected)</td>
<td>$3 \times 10^{-47}$ cm$^2$ (projected)</td>
</tr>
</tbody>
</table>

SuperXENON: the next step is a 20 T Experiment for DUSEL
Sensitivity reach of current/next generation experiments

http://dmtools.brown.edu/
Gaitskell, Mandic, Filippini

Cross-section [cm$^2$] (normalised to nucleon)

WIMP Mass [GeV/c$^2$]

XENON10 (2007)
CDMS (2008)

XENON100
Projected (2009)

SuperCDMS 25kg
Projected (2012)

LUX 300kg
Projected (2010)

XENON1T Projected (2012)
But..I do not like getting drunk to see WIMPs..I rather prefer to discover them with the help of a Noble Element
The new high QE PMTs for XENON100

- LED Calibration System
- Measured SPE response for all tubes
XENON100 Data Acquisition

242 FADC channels: CAEN V1724
32 modules 100 MHz
continuous buffer (zero deadtime)
analog sum output for S2 trigger
Zero Length Encoding via FPGA
--> enables rate > 60 Hz (XENON10 < 5 Hz)

S1 and S2 trigger capability
high energy veto
automatic baseline adjustment
deadtime measurement
Direct Detection with XENON and Complementarity with LHC

- **LHC**: 2 TeV Grenze für Gluinos, Squarks, Sleptonen
  \( m_X \sim \frac{1}{6} m_c = 300 \text{ GeV} \)
  in den meisten SUSY Modellen

- **LHC**: schwierig, die Natur des WIMPs zu bestimmen
  => dazu ILC
  (Battaglia, Peskin hep-ph/0509135)

**Direkte Detektion**: begrenzt im WQ, empfindlich auf höhere WIMP-Massen

=> Komplementarität zwischen LHC/ILC und XENON
Warum Flüssiges Xenon?

Hohe Massenzahl ($A \sim 131$): günstig für SI-WW ($\sigma \sim A^2$)
Hohe Atomzahl ($Z=54$) und Dichte (3 g/cm$^3$)
  $\Rightarrow$ selbstabschirmende, kompakte Geometrie

In großen Mengen verfügbar

'Einbache' Cryogenik bei -100 °C

Keine langlebigen radioaktiven Xe-Isotope (Ausnahme: $^{136}$Xe, $\beta\beta$-emitter)

Hohe Licht- ($\sim$NaI(Tl)) und Ladungsausbeute

SI und SD WIMP Empfindlichkeit: $^{129}$Xe (1/2), $^{130}$Xe, $^{131}$Xe (3/2), $^{132}$Xe, $^{134}$Xe, $^{136}$Xe
WIMP Rückstosssspektrum

$M_{\text{WIMP}} = 100 \text{GeV}$

$\sigma_{\text{WIMP-n}} = 4 \times 10^{-7} \text{ pb}$

Xe Rate erhöht (hohes A), doch niedrige Schwelle wichtig (Formfaktorunterdrückung)

Streuung ist kohärent bei niedrigen Energietransfer $Q$ und $\sim A^2$.

Wenn $Q$ wächst, spielt die Ausdehnung des Kerns eine Rolle: durch Formfaktor $F^2(Q)$ ausgedrückt

$F(Q) = \left[ \frac{3j_1(qR)}{qR_1} \right]^2 e^{-(qs)^2}$