Dark Matter and the XENON100 Experiment

Marc Schumann  
*Physik Institut, Universität Zürich*

DPNC University of Geneva, April 14\textsuperscript{th}, 2010

www.physik.uzh.ch/groups/groupbaudis/xenon/
95% of the Universe is DARK
2 colliding galaxy clusters
separation of Dark and Light (baryonic) matter
→ Dark Matter and not modified gravity
Galactic Rotation Curves

Expect: Kepler Rotation (as in the solar system)

\[ v^2 = \frac{G M(r)}{r} \]
Galactic Rotation Curves

Measurement: **Flat Rotation Profile**

„ball of ideal gas at uniform temperature“

*V. Rubin, K. Ford (1970)*
Cosmic Microwave Background

generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

→ Cold
   Invisible
   Cold (\(v < 10^{-8} \, c\))

Dark
   Collisionless
   Stable
   from „new physics“

\(\Omega = \rho / \rho_{\text{crit}} = 1.02(2)\)

\(\Lambda\)-CDM model fits data remarkably well

\(H = 71(4) \, \text{km/s/Mpc}\)

\(t_0 = 13.7(2) \, \text{Gyr}\)

\(\Omega = 0.73(4)\)

\(\Omega_{\Lambda} = 0.044(4)\)

\(\Omega_m = 0.27(4)\)
SUSY and the WIMP

SUSY was introduced to solve Standard Model problems (i.e. hierarchy problem, Higgs mass)

New fundamental space-time symmetry between fermions and bosons

R-parity avoids B/L number violation:

$$R = (-1)^{(3B+L+2S)}$$

→ lightest supersymmetric particle (LSP) is stable → cold DM candidate:

WIMP = weakly interacting massive particle

Neutralino:

$$\tilde{\chi}^0_1 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0$$
SUSY WIMP production

In early Universe:
WIMPs in thermal equilibrium
creation ↔ annihilation

expanding Universe: „freeze out“
WIMPs fall out of equilibrium, cannot annihilate anymore

→ non relativistic when decoupling from thermal plasma
→ constant DM relic density
→ relic density depends on $\sigma_A$

WIMP relic density:

\[ \Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle \sigma_A v \rangle} \approx \frac{0.1 \text{pb}}{\langle \sigma_A v/c \rangle} \]

$O(1)$ when $\sigma_A \sim 10^{-9}$ GeV → weak scale
Outline

Motivation: Dark Matter ✓

Direct Dark Matter Detection

Xenon as a Detector Medium

XENON100

The Future
Dark Matter Search

- Direct Detection
- Indirect Detection
- Production @Collider
Direct WIMP Detection

- Tracking: Drift, DM-TPC
- COUPP PICASSO
- Phonons
- CDMS EDELWEISS
- Charge
- CRESST ROSEBUD
- Light
- XENON LUX, ZEPLIN WARP, ArDM
- GERDA MAJORANA ConGeNT
- DEAP/CLEAN DAMA, KIMS XMASS
Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
→ nuclear recoil

Recoil Energy:
\[ E_r = \frac{|q|^2}{2m_N} = \frac{\mu^2v^2}{m_N}(1 - \cos \theta) \sim \mathcal{O}(10 \text{ keV}) \]

Event Rate:
\[ R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \]

→ need information on halo and interaction to get rate

M. Schumann (U Zürich) – Dark Matter & XENON100
WIMP Interactions
Detector Requirements

Result: Tiny Rates
\[ R < 0.01 \text{ evt/kg/day} \]
\[ E_r < 100 \text{ keV} \]

What do we look for?
- nuclear recoils, single scatters
- recoil spectrum falls with \( E \)
- dependence on \( A \), spin?
- annual flux modulation?
- other possibilities? iDM, ...?

How to build a WIMP detector?
- large total mass, high \( A \)
- low energy threshold
- ultra low background
- good background discrimination
Background Sources:

- Environment: U, Th chains, K

- Gamma and Beta Decays (electron recoil)
  - Careful material selection, discrimination, shielding (Pb, Cu, Xe, Ar, water)

- Neutrons from ($\alpha$,n) in rocks
  - Neutron moderators (paraffin, poly)

- Neutrons from cosmic ray muons
go deep underground

Experimental Sensitivity:

- Without background: $\propto (mt)^{-1}$
- With background: $\propto (mt)^{-1/2}$

Neutrons are most dangerous background since they interact like WIMPS! (nuclear recoil)
CDMS: Cryogenic Detectors

Located underground in Soudan Lab, Minnesota (USA)

**Principle:** measure charge and heat (phonons)

A deposited energy $E$ produces temperature rise $\Delta T$

Crystals: Ge, Si cooled to few mK

→ low heat capacity

→ measurable $\mu$K temperature!

**similar:** CRESST, EDELWEISS, Rosebud

**good discrimination**

→ „background-free experiment“

→ BUT: reject surface events via PSA
The latest CDMS Result

Science 327, 1619 (2010)

- 2 events remain after all cuts after un-blinding
- Background expectation: $0.9 \pm 0.2$ events
- Probability for 2 or more events: 23%
Why Xenon?

- efficient, fast scintillator (178nm)
- high mass number $A \sim 131$:
  SI: high WIMP rate @ low threshold
- high atomic number $Z=54$, high density (~3kg/l):
  self shielding, compact detector
- SD: 50% odd isotopes
  allows further characterization after detection by testing only SI or SD
- no long lived Xe isotopes, Kr-85 can be removed to ppt
- "easy" cryogenics @ -100°C
- scalability to larger detectors
- in 2-phase TPC:
  good background discrimination
Xenon: Light and Charge

- energy deposited in LXe produces *electron-ion pairs* and *excited atom states*; both processes can lead to scintillation
- anti-correlation between charge and light → improvement of energy resolution possible
- E-field dependence (field quenching)
- response also depends on particle energy

![Diagrams showing energy deposition and scintillation processes in xenon.](image)

(from: Aprile et al., PRL 97, 081302 (2006)
from: Aprile et al., PRB 76, 014115 (2007))

\[
\text{Excitation + Ionization} \\
\text{atom motion} \\
\begin{align*}
&\xrightarrow{\text{excitation + ionization}} \\
&\text{Xe}^* \\
&+\text{Xe} \\
&\text{Xe}^+ + e^- \\
&\text{Xe}^+ + \text{e}^- \\
&2\text{Xe} + h\nu \\
&\text{scintillation light} \\
&\text{ionization electrons}
\end{align*}
\]
Why Xenon?

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Dual Phase TPC

- ionization/scintillation ratio \( \frac{S_2}{S_1} \) allows electron recoil rejection to >99.5%
- 3d position reconstruction in TPC
Localization / Discrimination

Localization / Discrimination

Discrimination:

99.5% bg rejection (99.9% at low $E$), 50% acceptance (Xe10 performance) definition of WIMP search region

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Outline

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XENON100

The Future
The XENON program

XENON: A phased WIMP search program

2010-2015: XENON1T

2007-2010: XENON100

2005-2007: XENON10

XENON R&D
XENON100 Collaboration

www.physik.uzh.ch/groups/groupbaudis/xenon

Columbia  Rice  UCLA  U Zürich  Coimbra  LNGS

~45 people

+ new groups:  Münster  Bologna  NIKHEF  Subatech (F)  Shanghai  MPIK Heidelberg

M. Schummann (U Zürich) – Dark Matter & XENON100
Goal:
• increase target $\times 10$
• reduce gamma background $100 \times$
→ material selection & screening
→ detector design

Quick Facts:
• 165 kg LXe TPC (mass: $10 \times \text{Xe10}$)
• $\sim 50$ kg in fiducial volume
• active LXe veto ($\geq 4$ cm)
• 242 PMTs
• improved Xe10 shield
  (Pb, Poly, Cu, $\text{H}_2\text{O}$, $\text{N}_2$ purge)
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**Quick Facts:**
- 165 kg LXe TPC (mass: 10 × Xe10)
- ~50 kg in fiducial volume
- active LXe veto (≥4 cm)
- 242 PMTs
- improved Xe10 shield
  (Pb, Poly, Cu, H₂O, N₂ purge)
underground since end of February 08
first filled with Xe in mid May 08
detector fully operational, taking science data

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Photosensors

242 Hamamatsu R8520 PMTs
1"x1", optimized for response @ Xe scintillation wavelength
low radioactivity (>10 mBq/PMT)
80 with high QE ~35%

- 98 in top array: arranged for good fiducial cut efficiency
- 80 in bottom array: optimized for S1 collection → low threshold
- 64 in active veto: gain factor 3-4 compared to passive shield
TPC is transparent...

we can see events from all parts of the TPC...

\[ \Delta t = 159.3 \text{ us} \]
3D-Vertex Reconstruction

$\Delta t \rightarrow z$

Positions of real S2s
uniform Cs137 illumination
Least Squares Analysis

S2 xy-Position Reconstruction:
- Least Squares Minimization
- Neural Network
- Support Vector Machine

Resolution $O(\text{mm})$
(measured and from MC)

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Calibration

Gain calibration:
blue LED (+optical fibers)

\(\gamma\)-sources (ER band):
Co-57, Co-60, Cs-137, Th-228, Xe*, Kr-83m

Neutrons (NR band):
AmBe
Calibration at low Energy

expect signal <40 keV (calibration from outside not possible)

⇒ n-activated Xe131, Xe129m
  was used for Xe10, τ~O(10d)

⇒ Kr83m

R&D in Zürich:

Manalaysay et al., arXiv:0908.0616
Calibration at low Energy

expect signal <40 keV (calibration from outside not possible)

⇒ n-activated Xe131, Xe129m was used for Xe10, \( \tau \sim O(10\text{d}) \)

⇒ Kr83m

\[
\begin{align*}
\text{Kr83m} & \quad 75\% \\
1/2^- & \quad 32.1 \text{ keV, } T_{1/2}=1.83\text{h} \\
7/2^+ & \quad 9.4 \text{ keV, } T_{1/2}=154\text{ns} \\
9/2^+ & \quad \text{Kr83}
\end{align*}
\]

R&D in Zürich:

Manalaysay et al., arXiv:0908.0616
Calibration of the NR Band

Elastic Recoils

- $^{129}\text{Xe}$, 40 keV
- $^{131}\text{Xe}$, 80 keV
- $^{131m}\text{Xe}$, 164 keV
- $^{129}\text{Xe}$, 236 keV
- $^{19}\text{F}$, 110 keV
- $^{19}\text{F}$, 197 keV

$S_2 = 8\, e$
ER/NR Discrimination via S2/S1 ratio

- Discrimination efficiency similar to XENON10 (>99%)
Material Screening

GATOR: 2.2kg high purity Ge detector operated by UZH in low bg environment @ LNGS

<table>
<thead>
<tr>
<th>TPC Material</th>
<th>Unit</th>
<th>Quantity used</th>
<th>$^{238}\text{U}$ [mBq/unit]</th>
<th>$^{232}\text{Th}$ [mBq/unit]</th>
<th>$^{40}\text{K}$ [mBq/unit]</th>
<th>$^{60}\text{Co}$ [mBq/unit]</th>
<th>$^{210}\text{Pb}$ [Bq/unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8520 PMTs</td>
<td>PMT</td>
<td>242</td>
<td>0.15±0.02</td>
<td>0.17±0.04</td>
<td>9.15±1.18</td>
<td>1.00±0.08</td>
<td></td>
</tr>
<tr>
<td>PMT bases</td>
<td>base</td>
<td>242</td>
<td>0.16±0.02</td>
<td>0.07±0.02</td>
<td>&lt; 0.16</td>
<td>&lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>kg</td>
<td>70</td>
<td>&lt; 1.7</td>
<td>&lt; 1.9</td>
<td>&lt; 9.0</td>
<td>5.5±0.6</td>
<td></td>
</tr>
<tr>
<td>PTFE</td>
<td>kg</td>
<td>10</td>
<td>&lt; 0.31</td>
<td>&lt; 0.16</td>
<td>&lt; 2.2</td>
<td>&lt; 0.11</td>
<td></td>
</tr>
<tr>
<td>QUPID</td>
<td>QUPID</td>
<td>-</td>
<td>&lt; 0.49</td>
<td>&lt; 0.40</td>
<td>&lt; 2.4</td>
<td>&lt; 0.21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shield Material</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>kg</td>
<td>1600</td>
<td>&lt; 0.07</td>
<td>&lt; 0.03</td>
<td>&lt;0.06</td>
<td>&lt;0.0045</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>kg</td>
<td>1600</td>
<td>&lt; 3.54</td>
<td>&lt; 2.69</td>
<td>&lt; 5.9</td>
<td>&lt; 0.9</td>
<td></td>
</tr>
<tr>
<td>Inner Pb (5 cm)</td>
<td>kg</td>
<td>6300</td>
<td>&lt; 6.8</td>
<td>&lt; 3.9</td>
<td>&lt; 28</td>
<td>&lt; 0.19</td>
<td>17±5</td>
</tr>
<tr>
<td>Outer Pb (15 cm)</td>
<td>kg</td>
<td>27200</td>
<td>&lt; 5.7</td>
<td>&lt; 1.6</td>
<td>14±6</td>
<td>&lt; 1.1</td>
<td>516±90</td>
</tr>
</tbody>
</table>

use results for Monte Carlo Simulations
Monte Carlo Simulations

GEANT4 simulations of full experiment (detector+shield+surrounding)

**Gamma Background:**

in DM search region, after cuts
50 kg: $< 9.8 \times 10^{-3}$ events/kg/keV/day
30 kg: $< 3.2 \times 10^{-3}$ events/kg/keV/day

*before S1/S2 discrimination cut!*

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• Xe has no long lived radioactive isotope
• BUT: Xe contains Kr-85

in air: \( \text{Kr/Xe} \approx 10 \)
in Xe gas (commercial): \( \text{Kr/Xe} \approx \text{ppm-ppb} \)
necessary (Xe100): \( \text{Kr/Xe} \approx 100 \text{ ppt} \)  
(<1 evt in 0.5 yr)

\( \Rightarrow \) dedicated Kr-85 removal to ppt level
XENON100 Background

- 30 kg fiducial mass
- active LXe veto not used

Measured Background in good agreement with Monte Carlo prediction.
This is the lowest Background ever achieved in a Dark Matter Experiment!
A first glimpse at XENON100 data...

- Background data taken in stable conditions October-November 2009
- 11.2 life days
- Data analyzed non-blinded
- Cuts developed and optimized on calibration data, mostly AmBe and Co60

Let's have a look...
Basic Event Selection

- select events with acceptable signal/noise ratio (very sensitive detector: SPE & single electron S2 sensitivity)
- select single S1 peak (remove accidentals)
- select single scatters (single S2 peak)
- remove gas events
- apply active veto cut
Energy Cut

- select events with an S1 energy of < 28 keVnr
- this is the upper border of the XENON10 WIMP search region
- most remaining events are located at the edges
40kg Fiducial Mass

- make use of excellent self-shielding capability of liquid xenon
- cylindrical fiducial volume with 40 kg mass
- shape of volume will be further optimized
A Look at the Bands

- "Background free" in 11.2 days after S2/S1 discrimination
- Both plots show similar exposure

NR acceptance ~ 50%
cut efficiency ~ 85%
(conservative)
A first Limit from XENON100

XENON100 is working extremely well and is back at the sensitivity frontier.
This is just a first glimpse! We have much more (blinded) data waiting to be analyzed.

Results to be published soon

Xe100: based on the non-blind analysis of 11.2 days background
Ongoing Data Taking

XENON100 is taking science data since mid Jan 2010
XENON100: Sensitivity

- **50 kg Target: 40 days**
  \[ \sigma = 6 \times 10^{-45} \text{ cm}^2 \text{ ( @ 100 GeV)} \]

- **30 kg Target: 200 days**
  \[ \sigma = 2 \times 10^{-45} \text{ cm}^2 \text{ ( @ 100 GeV)} \]

Spin-independent WIMP-nucleon interaction
The next step: XENON1T

- 2.2t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background
  (10 cm self shielding, QUPID)
- MC studies, design studies already started 2009
- bigger collaboration
- currently: working on the details; secure funding
- Timeline: 2010 – 2015 ???

A possible design:

- Ti Cryostat
- Radiation- free Photon Detector
  (3” QUPID, Total 242)
The QUPID

- invented and developed by UCLA group (Arisaka/Wang)
- very low radioactive photosensor to replace PMTs
  APD, quartz, only a few pins, no voltage divider
- QUPIDs are „invisible“ in GATOR screening facility
- first units were build by HAMAMATSU,
ongoing tests and R&D at UCLA (later also UZH)

QUPID
Quartz
Photon
Intensifying
Detector

arXiv:0808.3968
It is actually working...

Work done at UCLA (Arisaka/Wang):

QUPID Test in Liquid Xenon
XENON1T: Location?

XENON1T @ LNGS (Hall B)
- 4 m water shield

XENON1T @ LSM
- solid shield (55cm poly, 20cm Pb, 15cm poly, 2cm ancient Pb, >99% muon veto)
Projected Sensitivities

![Graph showing projected sensitivities for different experiments like XENON10, XENON100, XENON1T, CDMS, SuperCDMS, and LUX 300kg.](image)

- XENON10
- XENON100
- XENON1T
- CDMS
- CMSSM
- SuperCDMS
- LUX 300kg

Source: [http://dmtools.brown.edu/Gaitskell,Mandic,Filippini](http://dmtools.brown.edu/Gaitskell,Mandic,Filippini)
the future of liquid noble gas Dark Matter detectors (Xe/Ar) in Europe

DARWIN = design study towards the realisation of future astroparticle infrastructure in Europe as identified in the ASPERA Roadmap

the DARWIN consortium was founded in 2009; approved by ASPERA

DARWIN brings together several European and American groups working in the existing XENON, WARP and ArDM collaborations. It unites expertise on liquid noble gas detectors, low-background techniques, cryogenic infrastructure, shielding and astroparticle physics phenomenology.

http://darwin.physik.uzh.ch
Summary

- Dark Matter: One of the big unsolved puzzles
- **XENON100**
  - 65 kg dual-phase TPC
  - underground @ LNGS
  - extremely low background
  - first results from 11.2d data
- in science data mode now: stay tuned...

www.physik.uzh.ch/groups/groupbaudis/xenon/
Backup
Determination of \( L_{\text{eff}} \)

- WIMPs interact with Xe nucleus → nuclear recoil (\( nr \)) scintillation
- absolute measurement of \( nr \) scintillation yield is difficult → measure relative to Co57 (122keV)
- relative scintillation efficiency \( L_{\text{eff}} \):
  \[
  L_{\text{eff}} = \frac{E_{\text{ee}}}{E_{nr}}
  \]

measurement principle:

most recent measurements:
- Aprile et al., PRC 79, 045807 (2009)
Scaling I

Arisaka et al., arXiv:0808.2968

90% CF limits for one year of data taking
Arisaka et al., arXiv:0808.2968

Expected energy spectrum of WIMP interactions, solar neutrinos, double beta decays, and gamma ray backgrounds (from QUPIDs) as a function of self shielding cuts.

Expected number of bg events in WIMP signal region (3-15 keVee) as function of active shielding cut for 10 ton-years of data taking.
Cryogenics & Recirculation

200 W PTR cryocooler
- gas gets liquefied outside the shield

double wall SS cryostat
- (low radioactivity steel, GERDA type)

continuous Xe purification
- (high T Getter)
Detector Stability

PID controller: T stable <0.1°C

PTR cooling provides excellent stability

Slow Control System records:
- Temperatures
- Pressures
- Flow rates
- Xe Level
- TPC HV
- PMT HV
- DAQ rate
- Vacuum
- Rn level
- status of all important systems
- ...

preliminary
Ongoing LXe Purification

- Light yield is related to H$_2$O content in LXe
- Continuous improvement to lower levels (baking, GXe circulation, H$_2$O measurements)
- Charge yield related to O$_2$ content → continuous purification
TPC: Electric Fields

- cathode: -30kV → drift field 1kV/cm
- anode: extraction field ~5kV
- field inside TPC was optimized in simulations for field homogeneity → 40 double field shaping rings
- anode stack optimized for
  - optical transparancy
  - S2 energy resolution (+4%)
- hexagonal mesh structures, pitch cathode 5mm, anode 2.5mm
Data Acquisition

Requirements:
- digitize full waveform (320µs) of 242 PMTs
- no deadtime
- higher rate capability for calibration

CAEN V1724 Flash ADC: 14bit, 100MHz
- circular buffer → no deadtime
- on board FPGA: Zero Length Encoding

⇒ calibration rates ~20 Hz possible
Low Trigger Threshold (S2)

**XENON10**
- S2 trigger efficiency 100% above 100 PE
- threshold of 300 PE used in WIMP analysis
Averaged Light Yield

- Light collection is position dependent
- measured with Cs137, 40 keV, and 164 keV from AmBe data
- vertex reconstruction allows to obtain volume average
- maximal light yield reached corresponds to
  4.5 PE/keV (zero field) @ 122 keV
  → 80% of XENON10 (as expected from design)
Active Veto

TPC is surrounded by 100 kg LXe layer (>4 cm)
- passive shield
- +64 PMTs: active veto

Cs137
- backscatter band
- 662 keV full absorption

Cs137, veto cut

Monte Carlo

preliminary
Reminder: XENON10 Results

- successful operation at LNGS 2006/07
- 15 kg dual phase detector, 5.4 kg in fiducial volume
- Results:
  - Spin Independent:
    - *PRL 100, 021303 (2008)*
  - Spin Dependent:
    - *PRL 101, 091301 (2008)*

New best limits for pure neutron couplings ($a_p = 0$)