Dark Matter Searches with XENON

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Seminar, EPFL Lausanne, March 23, 2015

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95% of the Universe is dark!
2 colliding galaxy clusters
separation of dark and light (baryonic) matter
Galactic Rotation Curves

Expect: Kepler Rotation (as in solar system)

\[ v^2 = \frac{G M(r)}{r} \]
Dark Matter (isothermal sphere, $\rho \sim r^{-2}$)
Cosmic Microwave Background

power spectrum of $\Delta T$
"typical variation at typical distance"

$\Omega = \rho / \rho_{\text{crit}} = 1.00(1) \quad \Omega_\Lambda = 0.692(10)$

$H = 67.80(77) \text{ km/s/Mpc} \quad \Omega_b = 0.048(1)$

$t_0 = 13.798(37) \text{ Gyr} \quad \Omega_{\text{cdm}} = 0.258(7)$

→ Cold
   invisible

Dark
   cold ($v << c$)

Matter:
   collisionless
   stable
   from "new physics"

generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

$\Lambda$CDM model fits data remarkably well

WMAP

Planck 2013
WIMPs
= weakly interacting massive particles

stolen from G. Bertone
The WIMP Miracle

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:

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

O(1) when $\sigma_A \sim 10^{-36} \text{ cm}^2$ → weak scale

$E/k_B T$
Dark Matter: (indirect) Evidence

Particle Dark Matter Candidates:
- **WIMP** → „WIMP miracle“
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...

![Dark Matter Pie Chart](chart.png)

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%

![MAP Image](map.png)

![Graph Image](graph.png)
Dark Matter Search

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

Elastic Scattering of WIMPs off target nuclei

→ nuclear recoil

Recoil Energy:

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

Event Rate:

\[ R \propto N \frac{\rho_x}{m_x} \langle \sigma_{\chi-N} \rangle \]

- \( N \) number of target nuclei
- \( \rho_x \) local WIMP number density
- \( m_x \) WIMP mass
- \( \langle \sigma \rangle \) velocity-averaged scattering cross-section

\( \rho_x \sim 0.3 \text{ GeV}/c^2 \) 

Detector

Local DM Density

Physics

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**Direct WIMP Search**

**Summary:** Tiny Rates  
\[ R < 0.01 \text{ evt/kg/day} \]  
\[ E_R < 50 \text{ keV} \]

**Recoil Energy:**  
\[ E_r \sim \mathcal{O}(10 \text{ keV}) \]

**Event Rate:**  
\[ R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle \]

- Detector
- Local DM Density  
\[ \rho_\chi \sim 0.3 \text{ GeV/c}^2 \]
- Physics

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**XENON: Dark Matter Searches**

**Detector:** Argon, Xenon

**Form factor:**  
\[ m_\chi = 100 \text{ GeV/c}^2 \]  
\[ \sigma = 4 \times 10^{-43} \text{ cm}^2 \]

**WIMP Expectations:**  
- Spin-independent interactions

**CMSSM:** Trotta et al.

**CMSSM+LHC:** Buchmueller et al.

**Summary:** 
- 1 event/kg/yr
- 1 event/ton/yr

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Direct WIMP Search

**Summary:** Tiny Rates
- $R < 0.01$ evt/kg/day
- $E_R < 50$ keV

How to build a WIMP detector?
- large total mass, high $A$
- low energy threshold
- ultra low background
- good background discrimination

We are dealing with
- extremely low rates (1 – 1000 Hz)
- extremely low thresholds (2 keV)
- extremely low radioactive backgrounds
Cosmic rays (p, n, μ) enter any shielding or induce secondary particles.
Laboratori Nazionali del Gran Sasso
Background Sources

Electronic Recoils
Nuclear Recoils

Background Sources

muon-induced neutrons
muons

neutrons from $(\alpha, n)$ and sf

natural gamma backgrounds
Low-background in CH

Vue des Alpes Laboratory (600 mwe)

Background prediction:
~250 evts/day [100-2700 keV]
Dual Phase TPC

Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

TPC = time projection chamber

pos HV
$E \sim 10 \text{kV/cm}$

dual phase TPC

neg HV
$E \sim 1 \text{kV/cm}$

xenon gas

liquid xenon

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Image from C. Levy (U Münster)
Dual Phase TPC

3dim vertex reconstruction

Figures from XENON100

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XENON100

Quick Facts
- 62 kg LXe target
- active LXe veto
- 242 PMTs
- running @ LNGS (IT)

PRL 109, 181301 (2012)

34 kg x 225 d raw exposure
2 events observed, (1.0±0.2) expected
→ no indication for dark matter seen
full analysis employs profile likelihood

The **current** WIMP Landscape

![Graph showing the current WIMP landscape with various experiments and their results.]

- DAMA/Na
- CDMS-Si (2013)
- XENON10 (2013)
- DAMA/I
- CRESST-II (2014)
- SuperCDMS (2014)
- EDELWEISS (2011/12)
- PandaX-I (2014)
- DarkSide-50 (2014)
- CDMS (2010/11)
- XENON100 (2012)
- LUX (2013)

WIMP-Nucleon Cross Section [cm$^2$] vs. WIMP Mass [GeV/c$^2$]

**x100 → 100x lower background**
Water Cerenkov Shield

*JINST 9, P11006 (2014)*

- 9.6m diameter, 10m height
- external $\gamma$, neutrons irrelevant
- muon induced NRs irrelevant

→ dominating background of XENON1T will be intrinsic
XENON1T

dual-phase LXe TPC
- total mass ~3.2 t
- active mass ~2.0 t
- fiducial mass: ~1.0 t

TPC made from OFHC and PTFE

248 photomultipliers
- Hamamatsu R11410-21
- low background
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments
  *JINST 8, P04026 (2013)*

Low-background stainless steel cryostats
XENONnT in Hall B @ LNGS

- stronger support
- larger outer cryostat
- powerful cooling
- flexible purification
- scaleable DAQ
- LXe storage for 7.6 tons
- efficient Kr distillation
The XENON Future

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Coherent neutrino-nucleus scattering

- SM neutral current process: 
  \( \nu \) of any flavor interact coherently with all nucleons in a nucleus → rather large cross section

\[
\frac{d\sigma}{d(cos \theta)} = \frac{G^2_F}{8\pi} \left[ Z (4 \sin^2 \theta_W - 1) + N \right]^2 E^2_\nu (1 + \cos \theta)
\]

- cross section increases with \( A^2 \), but measurable recoil decreases with \( A \) → detector threshold is crucial
- cross section increases with \( E_\nu \): only high-\( E_\nu \) \( \nu \) lead to a detectable signal
- process has not yet been observed

CNNS creates single scatter nuclear recoils → indistinguishable from WIMPs → the ultimate limit for direct searches

JCAP 01, 044 (2014)
DARWIN The ultimate WIMP Detector

- aim at sensitivity of a few $10^{-49}$ cm$^2$, limited by irreducible ν-backgrounds

- design study
  - R&D ongoing
  - first publication on science and technology almost out

Baseline scenario
~20 t LXe TPC
~14 t fiducial mass

Timescale: start after XENONnT
(→ science run by ~2023?)

www.darwin-observatory.org
What (else) can we do with these instruments other than WIMPs?
Interactions in LXe Detectors

scattering off atomic electrons, excitations etc.
→ electronic recoil
• rare processes detectable if ER background is low

coherent scattering off xenon nucleus
→ nuclear recoil
• Dark Matter
• CNNS

Many new physics channels are accessible with multi-ton scale LXe detectors due to their extremely low ER background.
Axions and ALPs couple to xenon via **axio-electric-effect**

\[
\sigma_{Ae}(E_A) = \frac{3E_A^2}{16\pi\alpha m_e^2} \left( 1 - \frac{\beta_A}{3} \right) \frac{g_Ae^2}{\beta_A} \sigma_{pc}(E_A)
\]

→ axion ionizes a Xe atom

**Axion**
arises naturally in the Peccei-Quinn solution of the strong CP-problem
→ well-motivated dark matter candidate

**Axion-like particle (ALP)**
generalization of the axion concept, but without addressing strong CP problem
(ALPs = Nambu-Goldstone bosons from breaking of some global symmetry)
Solar Axions and Dark Matter ALPs

Solar axions

Galactic ALPs

\( g_{\text{AX}} \)

\( g_{\text{AE}} \)

\( g_{\text{EDELWEISS}} \)

\( g_{\text{XENON100}} \)

\( g_{\text{KSVZ}} \)

\( g_{\text{DFSZ}} \)

\( g_{\text{EDELWEISS}} \)

\( g_{\text{XENON100}} \)

\( m_A \) [keV/c²]

\( S1 \) [PE]

\( 10^{-9} \)

\( 10^{-10} \)

\( 10^{-11} \)

\( 10^{-12} \)

\( 10^{-13} \)

\( 10^{-5} \)

\( 10^{-4} \)

\( 10^{-3} \)

\( 10^{-2} \)

\( 10^{-1} \)

\( 1 \)

\( 2 \)

\( 3 \)

\( 4 \)

\( 5 \)

\( 6 \)

\( 7 \)

\( 8 \)

\( 9 \)

\( 10 \)

\( 20 \)

\( 30 \)

PRD 90, 062009 (2014)
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Low-energy solar Neutrinos: pp, $^7$Be

→ vast majority of solar neutrinos; help to understand how the Sun works
→ very low energetic, hard to detect
→ mainly pp-neutrinos
pp-Neutrinos in DARWIN

a new physics channel!

Differential Recoil Spectrum in Xe

- Neutrinos interact with Xe electrons → electronic recoil signature
- Continuous recoil spectrum → largest rate at low E
  \(~0.26 ~\text{v evts/t/d in low-E region} ~\text{(2-30 keV)}\)

Neutrino interactions

- 14t target mass, 2-30 keV window → 1331 neutrinos per year (89% pp) → achieve 1.3% statistical precision on pp-flux (→ $P_{\text{ee}}$) in 5 years
pp-Neutrinos in DARWIN

BUT a background for the WIMP search...!

Realistic, detailed Background Study

- pp-neutrinos dominate low E spectrum
- main ER spectrum from $2\nu\beta\beta$ of $^{136}\text{Xe}$
- $^{85}\text{Kr}$ (0.1 ppt $^{nat}\text{Kr}$) and $^{222}\text{Rn}$ (0.1 $\mu$Bq) small, detector materials irrelevant

Low-energy solar Neutrinos: pp, $^7\text{Be}$

- $2\nu\beta\beta$ rejection

JCAP 01, 044 (2014)
0ν Double-beta Decay

$2\nu\beta\beta$  $0\nu\beta\beta$

- $\sigma/E \sim 1\%$ at $Q_{\beta\beta}$, combined $E$-scale
- Signal in plot assumes $T_{1/2} = 1.6 \times 10^{25}$ y
- Sensitivity: $T_{1/2} = 5.6 \times 10^{26}$ y (95\% CL, 6t x 5y)

No $^{136}$Xe enrichment!

EXO-200 limit

Background (6t): 4.6 evts/t/y in $\pm 3\sigma$
0ν Double-beta Decay

The graph illustrates the search for dark matter using XENON detectors. The horizontal axis represents the lightest neutrino mass, while the vertical axis shows the sensitivity of the experiment. The shaded regions represent the current limits and future expectations for detection. The inverted hierarchy and normal hierarchy are indicated, with DARWIN's capabilities marked as well.
Supernova Neutrinos

Chakraborty et al., PRD 89, 013011 (2014)

- $\nu$ from supernovae could be detected via CNNS as well
- signal from accretion phase of a $\sim 18$ M$_{\text{Sun}}$ supernova @ 10 kpc is visible in a 10t-LXe detector (=DARWIN)
- signal: NRs plus precise time information
- challenge: threshold
Exciting times ahead of us

adapted from arXiv:1310.8327

- axions/ALPs
- solar neutrinos
- 0νββ
- SN neutrinos
- CNNS
- +more rare processes