Matter and Energy Content of our Universe

- Dark Matter: 25%
- Dark Energy: 70%
- Free Hydrogen and Helium: 4%
- Stars: 0.5%
- Ghostly Neutrinos: 0.3%
- Heavy Elements: 0.03%
Particle Dark Matter Candidates

- Masses and cross sections span many orders of magnitude
- From $10^{-6}$ eV to $10^{15}$ GeV
- From non-interacting to strongly interacting
- We know that the dark matter particle must be some state not contained in the Standard Model
Weakly Interacting Massive Particles

- One good idea: WIMPs; in thermal equilibrium in the early Universe

\[ \chi + \bar{\chi} \leftrightarrow X + \bar{X} \]

- Decouple from the rest of the particles when \( M >> T \) ("cold")

- Their relic density can account for the dark matter if the annihilation cross section is weak (\( \sim \) pb)

\[ \Omega_\chi h^2 \approx 3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1} \frac{1}{\langle \sigma_A v \rangle} \]

- Such particles are predicted to exist in most Beyond-Standard-Model theories (neutralino, lightest Kaluza-Klein particle, etc)
The WIMP Hypothesis is Testable

Deep underground

In space

At the LHC

We should learn a lot from direct detectors, from indirect detectors and from accelerators!
Direct Detection of WIMPs: Principle

- Elastic collisions with nuclei in ultra-low background detectors
- Energy of recoiling nucleus: *few tens of keV*

\[ E_R = \frac{q^2}{2m_N} = \frac{\mu^2v^2}{m_N} (1 - \cos\theta) \]

- \( q \) = momentum transfer
- \( \mu \) = reduced mass (\( m_N \) = nucleus mass; \( m_X \) = WIMP mass)
- \( v \) = mean WIMP-velocity relative to the target
- \( \theta \) = scattering angle in the center of mass system
Expected Rates in a Terrestrial Detector

- For now strongly simplified:

\[ R \sim N \frac{\rho_X}{m_X} \sigma_{XN} \langle v \rangle \]

- **Astrophysics**
  - \( N \): number of target nuclei in a detector
  - \( \rho_X \): local density of the dark matter in the Milky Way
  - \( \langle v \rangle \): mean WIMP velocity relative to the target

- **Particle physics**
  - \( m_X \): WIMP-mass
  - \( \sigma_{XN} \): cross section for WIMP-nucleus elastic scattering
Local Density of WIMPs in the Milky Way

\[ \rho_{\text{halo}} = 0.1 - 0.7 \text{GeV cm}^{-3} \]

\[ \rho_{\text{disk}} = 2 - 7 \text{GeV cm}^{-3} \]

0.3 GeV cm\(^{-3}\) \(\Rightarrow\) \(~ 3000\) WIMPs m\(^{-3}\)
(M\(_W\) = 100 GeV)

WIMP flux on Earth: \(~ 10^5\) cm\(^{-2}\) s\(^{-1}\) (100 GeV WIMP)

Even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

(J. Diemand et all, Nature 454, 2008, 735-738)
Example for recent predictions from supersymmetry:
- cross sections down to a few $\times 10^{-47}$ cm$^2$
Expected Interaction Rates

- Differential recoil rate: integrate over WIMP velocity distribution

\[
\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2m_\chi \mu^2} F^2(E_R) \int_{v>\sqrt{m_N E_R/2\mu^2}}^{v_{max}} f(\vec{v}, t) \frac{d^3v}{v} 
\]

Different WIMP masses

Different target nuclei

(Standard halo model with \( \rho = 0.3 \text{ GeV/cm}^3 \))
The Challenge

- **To observe a signal which is:**
  - very small (few keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

- **Why is it challenging?**
  - Detection of low-energy particles - done!
    - e.g. micro-calorimetry with phonon readout
  - Rare event searches with ultra-low backgrounds - done!
    - e.g SuperK, Borexino, SNO, etc

- **But: can we do both?**
Direct Dark Matter Detection Techniques

---

**Phonons**
- \( \text{Al}_2\text{O}_3 \): CRESST-I

**Charge**
- C, F, I, Br: PICASSO, COUPP
- Ge: Texono, CoGeNT
- CS\(_2\), CF\(_4\), \(^3\)He: DRIFT
- DMTPC, MIMAC
- Ar+C\(_2\)H\(_6\): Newage

**Light**
- NaI: DAMA/LIBRA
- NaI: ANAIS
- CsI: KIMS
- LXe: XMASS
- LAr, LNe: DEAP/CLEAN

---

here: focus on recent results

Laura Baudis, University of Zurich, Dark Matter, PANIC 2011
Phonons: Cryogenic Experiments at $T \sim \text{mK}$

- Detect a temperature increase after a particle interacts in an absorber

- T-sensors: superconductor thermistors or superconducting transition sensors
**Phonons:** Cryogenic Experiments at $T \sim \text{mK}$

- **Advantages:** high sensitivity to nuclear recoils (measure the full energy in the phonon channel); good energy resolution, low energy threshold (keV to sub-keV)

- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination

![Graph](image.png)
Phonons: The CDMS Experiment

- Final WIMP search runs - 191 kg-d: **2 events passing all cuts**

  - Event 1: Tower 1, ZIP 5 (T1Z5)  
    Sat. Oct. 27, 2007
  - Event 2: Tower 3, ZIP 4 (T3Z4)  

- Expected background: $0.8 \pm 0.1 \text{ (stat)} \pm 0.2 \text{ (syst)}$ events
- Probability to observe two or more events is 23%
**Phonons: CRESST and EDELWEISS**

**EDELWEISS at Modane**
- Ge detectors at 18 mK
- 5 events (427 kg-day)
- 3 expected from backgrounds
- operates new, 800 g detectors with improved background rejection

**CRESST at LNGS**
- CaWO₃ detectors at 10 mK
- 57 events (730 kg-day)
- focus on reducing backgrounds

<table>
<thead>
<tr>
<th></th>
<th>α events</th>
<th>9.3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>neutron events</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>e/γ events</td>
<td>9.0 (fixed)</td>
</tr>
<tr>
<td>signal events</td>
<td>22.6</td>
<td></td>
</tr>
</tbody>
</table>

\[ m_\chi \sim 13 \text{ GeV}/c^2 \]

\[ \sigma \sim 3 \cdot 10^{-5} \text{ pb} \]
Future Cryogenic Dark Matter Projects

- **US/Canada: SuperCDMS** (15 kg to 1.5 tons Ge experiment)
  - Larger Ge detectors (650g) with improved readout
  - To be located at SnoLAB

- **Europe: EURECA** (100 kg to 1.0 ton cryogenic experiment)
  - Multi-target approach
  - To be located at the ULISSE Lab (Modane extension) in France
Light: Noble Liquids TPCs

- Large, scalable, homogeneous and self-shielding detectors
- Prompt (S1) light signal after interaction in the active volume
- Charge is drifted, extracted into the gas phase and detected as proportional light (S2)

- charge/light depends on dE/dx
- good 3D position resolution

=> particle identification

Ar (A = 40); $\lambda = 128$ nm
Xe (A = 131); $\lambda = 178$ nm
The XENON Experiment

XENON100

In conventional shield at LNGS
2008 - 2011; taking science data

XENON1T

In water Cerenkov shield at LNGS
2011- 2015; construction to start soon

1 m

10 m

Total of 2.4 ton LXe (1 ton fiducial)
Drift length ~1m
100x background reduction with respect to XENON100
Enclosed by a 5m water shield (passive and active muon veto)
Timeline 2011 - 2015
The XENON100 Detector

- 161 kg of ultra-pure liquid xenon (LXe), 62 kg in the active target volume
- 30 cm drift gap TPC with two PMT arrays (242 PMTs) to detect the prompt and proportional scintillation signals
Example of a 9 keV Nuclear Recoil Event

- 4 photoelectrons detected from about 100 S1 photons
- 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

70\mu s \sim 12 cm

Amplitude / V

Time / \mu sec
Example of a 9 keV Nuclear Recoil Event

Top PMT array

Bottom PMT array
XENON100: New Results

- Exposure: ~ 1471 kg-days (48 kg fiducial mass); January - June 2010

Signal region: 3 events observed

Expected backgrounds:
1.8 ± 0.6 gamma leakage events
0.1 ± 0.08 ± 0.04 neutron events
(28% Poisson probability to see 3 events when ~ 2 are expected)

Blue bands:
1- and 2-σ expectation, based on zero signal

Limit (dark blue):
1.5 - 2 σ worse, given 2 events at high S1

Limit at $M_W = 50$ GeV: $7 \times 10^{-45}$ cm$^2$ (90% C.L.)
XENON: status and sensitivity

- New dark matter run started in March 2011 (~ 90 days of data)
- Concentration of $^{85}$Kr: lower by a factor of 5
- Improved LXe purity and lower trigger threshold
- In parallel: construction of XENON1T @ LNGS
**Light: Liquid Xenon Detectors**

- **LUX in the US**
  - 350 kg LXe TPC, 100 kg fiducial
  - In commissioning above ground at Homestake
  - To be placed underground in spring 2012

- **XMASS in Japan**
  - 800 kg single phase detector (642 PMTs), 100 kg fiducial, 10x10 m water shield
  - Commissioning run in 2011
Light: Liquid Argon Detectors

- **WARP at LNGS**
  - 140 kg LAr TPC
  - 8.4 t LAr veto shield
  - technical runs in 2008 and 2010
  - new technical run since June 2011

- **ArDM at Canfranc**
  - 850 kg LAr TPC
  - commissioned at CERN
  - approved by LSC in Oct 2010
  - to be installed underground by the end of 2011
Light: Liquid Argon Detectors

- Single-phase detectors: use pulse shape information + fiducialization

- MiniCLEAN at SnoLAB
  - 500 kg LAr (150 kg fiducial)
  - single-phase open volume
  - under construction at SNOLAB
  - to run 2012 - 2014

- DEAP-3600 at SnoLAB
  - 3600 kg LAr (1000 kg fiducial)
  - single-phase detector
  - under construction at SNOLAB
  - to run 2014 - 2019
DARWIN: DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector
- Location: Gran Sasso (Italy) or ULISSE (Modane Lab extension, France)
- Physics goal: prove WIMP-nucleon cross sections beyond $10^{-47}$ cm$^2$

2009 - 2012: R&D and Design Study
2013: Submission of LoI, engineering studies
2014 - 2015: Construction and commissioning
2016 - 2020: Operation, physics data
Charge: DAMA/LIBRA

- 250 kg of ultra-pure NaI crystals at LNGS; 0.82 tons-year
- Observes a time variation in the event rate with $T = 1$ year, $\phi = \text{June } 2\pm7$ days
- Amplitude of the modulation: $\sim 0.018 \text{ counts day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$

Charge: DAMA/LIBRA

- Origin of the time variation in the observed rate:
  - motion of the Earth-Sun system through the WIMP halo?
  - environmental effects?
  - unclear!

see also David Nygren, arXiv:1102.0815

Muon rate variation at LNGS: Amplitude: ~ 0.015; T = 1 year, \( \phi = \text{July 15±15 days} \)

* M.Selvi et al., Proc. 31st ICRC, ŁÓDŹ 2009
Charge: CoGeNT

- Point-contact, 330 g Ge detector at Soudan
- Energy threshold: ~ 0.5 keV ionization (~ 2 keV NR energy)
- 2011: claim of an annual modulation at 2.8-σ level (0.5 - 3 keVee), ~ 450 days

arXiv: 1002.4703; C. E. Aalseth et al., PRL106

arXiv: 1106.0650; C. E. Aalseth et al.

0.5 - 0.9 keV
0.5 - 3.0 keV
3.0 - 4.5 keV

surface events

1 keVee ~ 4 keV nuclear recoil energy
New results from CDMS and XENON10

- CDMS: 241 kg-days with 8 Ge detectors
- XENON10: 14 kg-days using LXe

CDMS

CDMS Collaboration, PRL 106, 131302 (2011)

CDMS: 241 kg-days with 8 Ge detectors
CDMS Soudan (10 keV thresh)
CDMS SUF (1 keV thresh)

90% CL upper limits on elastic scattering cross section

DAMA/LIBRA

CoGeNT

These results

m_\chi [GeV]

10^{-39}

10^{-40}

10^{-41}

10^{-42}

4

6

8

10

12

WIMP mass (GeV/c^2)

WIMP-nucleon \sigma_{SI} (cm^2)

10^{-39}

10^{-40}

10^{-41}

10^{-42}

XENON10

XENON10 Collaboration, arXiv:1104.3088, accepted in PRL

analysis down to 2 keV nuclear recoil energy

analysis down to 1.4 keV nuclear recoil energy

Laura Baudis, University of Zurich, Dark Matter, PANIC 2011
Directional Detectors

- Correlate direction of nuclear recoil with galactic motion
- Would provide robust signature
- 10 - 100 events needed, depending on directional capabilities

- DMTPC (CF₄ gas TPC, at MIT)
  → first results from 10 lTPC
  → 1 m³ planned for WIPP

- DRIFT (negative ion, CS₂ TPC, at Boulby)
  → results from 1.5 kg-days
  → 24 m³ planned (4 kg target)
Summary and Prospects

Direct detection
- discover relic particle
- constrain \((m, \rho \times \sigma)\)
- with input from LHC/ILC
- determine \(\rho_{\text{local}}\)

Indirect detection
- discover relic particle
- constrain \((m, \sigma \int \rho^2)\)
- with input from LHC/ILC
- determine \(\rho_{\text{GC/halo}}\)

LHC/ILC
- discover new particles
- determine physics model and \(m_{\text{WIMP}}\)
- predict direct/indirect cross sections
Beyond Current Detectors: DARWIN

- To reconstruct WIMP properties such a mass and scattering cross section we will (likely) need larger detectors for high-stats recoil spectra

XENON100 Backgrounds: Data and Predictions

- Data versus Monte Carlo simulations (no MC tuning, input from screening values for U/Th/K/Co/Cs etc of all detector components); no active liquid xenon veto cut
- Background is 100 times lower than in XENON10 and meets design specifications
XENON100 Backgrounds: Data and Predictions

- Data versus Monte Carlo simulations (no MC tuning, input from screening values for U/Th/K/Co/Cs etc of all detector components); no active liquid xenon veto cut

- Background is 100 times lower than in XENON10 (and any other dark matter experiment) and meets design specifications
XENON100: New Results

- Exposure: ~ 1471 kg-days; data taken during January - June 2010

**Fiducial mass region:**
48 kg of liquid xenon
900 events in total

**Signal region:**
3 events are observed
1.8 ± 0.6 gamma leakage events expected
0.1 ± 0.08 ± 0.04 neutron events expected
Cuts acceptance and light yield parameterization

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

mean (solid) and 1-, 2-sigma uncertainties (blue bands) of \( L_{eff} \) direct measurements
The Local Dark Matter Distribution

- The dark matter distribution around the solar position seems very smooth, substructures are far away from the Sun.
- The velocity distribution of dark matter at the solar circles is smooth, close to Maxwellian.