School and Workshop on Dark Matter and Neutrino Detection
Dark Matter — Direct Detection
Lecture 2

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Northwestern
Outline

- Lecture 1:
  - The dark matter problem
  - WIMP and WIMP-like DM detection
- Lecture 2:
  - WIMP detection technologies
  - Current and future limits
- Lecture 3:
  - More 1-10 GeV DM detection technologies
  - To the Neutrino Floor, and beyond!
- Lecture 4:
  - The SuperCDMS Experiment
  - meV - 1GeV direct detection
- Lecture 5:
  - Indirect sterile neutrino detection
Last Time: Separating Signal from Background…

- **By Detector Response**
  - Obtain particle identification from the physics of the detector response to different types of particle interactions.

- **By Astrophysical Modulation**
  - Annual Modulation in the WIMP recoil spectrum. Earth’s velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)
  - Can be Event-by-Event or Statistical
Last time: Particle ID Through Detector Response

Phonons
- 10 meV/ph
- 100% energy

Ionization
- 10 eV/e
- 20% energy

Scintillation
- ~1 keV/γ
- few % energy

CLEAN
DAMA
DEAP
NAIAD
ZEPLIN I
XMASS
Xe, Ar, Ne
NaI(Tl)

CRESST
ROSEBUD
CaWO₄, BGO
ZnWO₄, Al₂O₃ ...

CDMS
EDELWEISS
Ge, Si

ANAIIS
CoGeNT
COSME
COUPP
DM-TPC
DRIFT
IGEX
Ge, CS₂, C₃F₈

ArDM
DarkSide
LUX
WARP
XENON
ZEPLIN II, III
Xe, Ar, Ne
Annual Modulation

Earth’s motion about the Sun produces small changes in velocity relative to the dark halo

→ Modulates expected rate of dark matter interactions detected on Earth

If you see a signal, check for an annual modulation

OR

If you have irreducible backgrounds, use the modulation to pick out a signal

A dark-matter-induced modulation will have extrema in June and December (whether it’s max or min depends on target and threshold)
Annual Modulation

Target: Ge
\( \sigma_{SI} = 1 \times 10^{-4} \text{ pb} \)
\( M_\chi = 10 \text{ GeV/cm}^2 \)

\( \frac{dR}{dE} [\text{kg keV d}]^{-1} \)

\( E [\text{ keV}] \)


220 km/s  30 km/s

\( \sigma_{SI} \)
The modulation shape is target dependent!
Diurnal Modulation (a.k.a. Directional Detection)

The mean recoil direction rotates over one sidereal day.

The distribution of the angle $\alpha$ between the solar motion and recoil directions: peaks at $\alpha=180^\circ$.

Low pressure TPC’s preserve dE/dx profile such that “head to tail” measurement can be made.
Summary of Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

2: Low Energy Threshold

3: Low Backgrounds

4: Discrimination between Signal and Backgrounds
WIMP Direct Detection Technologies, Experiments, and Current Results
DAMA/LIBRA: a Model-Independent Signal

DAMA/NaI and successor DAMA/LIBRA operate large arrays of NaI detectors. Their combined data yield a 12.9σ modulation consistent with dark matter. It has never been verified by another experiment, yet no one has a really good alternative explanation.
Non-dark matter explanations for the modulation

- Alternative sources of modulation have been proposed
  - DAMA has addressed some of these

<table>
<thead>
<tr>
<th>Source</th>
<th>Main comment</th>
<th>Cautious upper limit (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADON</td>
<td>Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.</td>
<td>( &lt;2.5 \times 10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded</td>
<td>( &lt;10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>NOISE</td>
<td>Effective full noise rejection near threshold</td>
<td>( &lt;10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>ENERGY SCALE</td>
<td>Routine + intrinsic calibrations</td>
<td>( \leq 1.2 \times 10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>EFFICIENCIES</td>
<td>Regularly measured by dedicated calibrations</td>
<td>( &lt;10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>No modulation above 6 keV; no modulation in the (2-6) keV multiple-hits events; this limit includes all possible sources of background</td>
<td>( &lt;10^{-4} \text{ cpd/kg/keV} )</td>
</tr>
<tr>
<td>SIDE REACTIONS</td>
<td>Muon flux variation measured at LNGS</td>
<td>( &lt;3 \times 10^{-5} \text{ cpd/kg/keV} )</td>
</tr>
</tbody>
</table>

Modulation Amplitude in Signal is \( \sim 1 \times 10^{-2} \text{ cpd/kg/keV} \)

Slide taken from DAMA/LIBRA

Further discussed in:
- EPJC 56:333 (2008),
- EPJC 72:2064 (2012),
- EPJC 74:3196 (2014)
## Checking DAMA with NaI Detectors

<table>
<thead>
<tr>
<th>Northern Hemisphere</th>
<th>Gran Sasso DAMA/LIBRA 250 kg running</th>
<th>Boulby DM-Ice North 37 kg R&amp;D 250 kg planned</th>
<th>Canfranc ANAIS 37 kg R&amp;D 250 kg planned</th>
<th>Y2L KIMS 45 kg R&amp;D 200 kg planned</th>
<th>Gran Sasso SABRE R&amp;D</th>
<th>Kamioka PICO-LON KamLAND-PICO R&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Hemisphere</td>
<td>South Pole DM-Ice 17 kg running 250 kg planned</td>
<td></td>
<td></td>
<td>Stawell SABRE Lab completion 2017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ultra-pure crystal development underway by DM-Ice, KIMS, ANAIS, SABRE, and PICO-LON collaborations

**South Pole** offers:
- Ultra-clean and ultra-stable environment
- Seasonal variation unambiguously different from dark matter modulation
- IceCube offers muon monitoring and veto as well as experience
- NSF-run South Pole Station for logistical support

Note: Annual Modulation is also being looked for with other detector technologies!
The COSINE-100 Experiment @ Yangyang

- Model-independent test of DAMA’s result
- 106 kg of same target material (NaI(Tl))
- Located 700 m underground at Yangyang Underground Lab in Korea
- Physics run began Sept. 2016
The SABRE Experiment @ LNGS & Stawell

Ultrapure NaI:Tl Target Detector

Intrinsic radioactivity limits WIMP sensitivity. SABRE has made the most radiopure NaI:Tl to date.

- ‘Astrograde’ powder (Sigma Aldrich).
- Carefully-developed powder preparation and growth protocols (Princeton + RMD).

Lower radioimpurity than DAMA. Production growth underway. High QE + low background PMTs: 1 keV threshold design.

<table>
<thead>
<tr>
<th>Element</th>
<th>DAMA powder [ppb]</th>
<th>DAMA crystals [ppb]</th>
<th>Astro-Grade [ppb]</th>
<th>SABRE crystal [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>100</td>
<td>∼13</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Rb</td>
<td>n.a.</td>
<td>&lt;0.35</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>U</td>
<td>∼0.02</td>
<td>0.5-7.5×10⁻³</td>
<td>&lt;10⁻³</td>
<td>&lt;10⁻³</td>
</tr>
<tr>
<td>Th</td>
<td>∼0.02</td>
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<td>&lt;10⁻³</td>
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</tr>
</tbody>
</table>
The ANAIS Experiment @ Canfranc

ANAIS-112:
- Commissioning in March-April 2017
- Calibration and general assessment from April to July 2017
- Dark matter run is underway since 3rd, August 2017: first year of data taking is about to be successfully completed
DM-ICE 17

Location: South Pole, Antarctica
Depth: 2457 m (2200 m.w.e)
Deployment: Dec. 2010
Uptime: > 99%
Exposure: 60.8 kg-yr
Target: NaI(TI)
Mass: 2 x 8.5 kg

Still going...
This question will be answered in a year or two!
The Model-Dependent Playing Field
Current Limits

![Graph showing current limits for dark matter mass and cross-section]

- NMSSM: J. Can - 1311.0676
- Asymmetric DM: T. Lin + 1111.0293
- XENON1T
- PandaX-II, 54 ton-d
- CMSSM T. Cohen and J.G. Wacker + 1305.2914

Dark Matter Mass [GeV/c²] vs. Dark Matter–nucleon σ_{SI} [cm²]
How Far Can We Push?

![Graph showing the relationship between Dark Matter Mass [GeV/c^2] and Dark Matter–nucleon σ_{SI} [cm^2] and Dark Matter–nucleon σ_{SI} [pb].]

- **Dark Matter Mass [GeV/c^2]** axis ranges from 0.1 to 10^4.
- **Dark Matter–nucleon σ_{SI} [cm^2]** axis ranges from 10^{-38} to 10^{-48}.
- **Dark Matter–nucleon σ_{SI} [pb]** axis ranges from 10^{-12} to 10^{-2}.

Key experimental collaborations and their sensitivities include:
- CRESST
- DAMIC
- COEX-10
- PICASSO
- CDEX
- DarkSide-50
- DEAP-3600
- XENON1T
- NEWS-G
- PandaX-II, 54 ton·d
- CDMSlite R2
- CRESST
- PICO-60

Each line represents the sensitivity of a particular experiment or collaboration, indicating the range of Dark Matter–nucleon σ_{SI} values they can detect at different Dark Matter Mass values.
To Neutrinos, and Beyond!

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

Dark Matter Mass [GeV/c²]
Noble Liquid Detectors

**Phonons**
- 10 meV/ph
- 100% energy

**Scintillation**
- ~ 1 keV/γ
- few % energy

**Ionization**
- ~ 10 eV/e
- 20% energy

- CLEAN
- DEAP
- ZEPLIN I
- XMASS
- Xe, Ar, Ne

- ArDM
- DarkSide
- LUX / LZ
- WArP
- XENON1T
- ZEPLIN II, III
- Xe, Ar, Ne
Noble Liquid Time Projection Chambers

• Obtain vertex position from S2 hit pattern and drift time
• Ratio of S2/S1 provides nuclear/electron recoil discrimination
Noble Liquid Time Projection Chambers

- Obtain vertex position from S2 hit pattern and drift time
- Ratio of S2/S1 provides nuclear/electron recoil discrimination
Signal Production in Noble Liquids

- Electron Recoils and Nuclear Recoils are Separated in Log(S2/S1) vs S1 plane
- Look for WIMPs below the mean of the nuclear recoil distribution (the red line in the plot)
Noble Liquid Time Projection Chambers

ArDM  XENON1T  LUX  DarkSide-50

NOT TO SCALE!
XENON1T: Current World-leading Limit > 6 GeV
XENON1T: Current World-leading Limit > 6 GeV

LARGEST 2-PHASE LXe TPC

2-tonne Active Volume
(3.2 t total)

121+127 low-background Hamamatsu 3” PMTs

1m-long Drift Region

Drift Field ~100 V/cm
Upgrades required for XENONnT
- Larger cryostat inner vessel
- New TPC
- Additional ~200 PMTs, PMTs with lower radioactivity currently under development
- Additional DAQ electronics
- LXe

Target mass of ~6 tons, sensitivity to spin-independent WIMP-nucleon elastic scattering cross sections of $1.6 \times 10^{-48} \text{ cm}^2$
Darwin Large Xe Experiment Concept

- High-voltage feedthrough
- Connection to cryogenics; purification, data acquisition
- Top photosensor array
- Double wall cryostat
- PTFE reflector
- 50 tonnes LXe
- Anode
- TPC with central dark matter target
- Bottom photosensor array
- Cathode

Exposure: 200 t y

\[
\begin{align*}
\sigma_s [\text{cm}^2] & \quad 10^{-45} & \quad 10^{-47} & \quad 10^{-49} \\
154 & \quad 224 & \quad 60 \\
\end{align*}
\]

\[
\begin{align*}
\sigma_s [\text{cm}^2] & \quad 10^{-45} & \quad 10^{-47} & \quad 10^{-49} \\
10 & \quad 100 & \quad 1000 \\
\end{align*}
\]
LUX-ZEPLIN (LZ)

- LZ: Funded G2 Experiment
- 50 x LUX fiducial volume
- 10 Ton Xenon, 7 Ton Active, 5.6 Ton fiducial
- Begin taking data in 2019
The DarkSide Program: Liquid Argon TPC

Global Argon Dark Matter Collaboration

- GADMC incorporates members from all existing argon experiments
- DarkSide-20k is a 50 tonne dual-phase argon TPC, 30 tonne fiducial
- >20 m² SiPM detectors
- goal of 0.1 “instrumental” background events in 100 tonne-years

DarkSide-50
Dual Phase Liquid Argon TPC

PSD parameter: $F_{90} = \text{fraction of light in first 90 ns}$
Dual Phase Liquid Argon TPC

S2 allows for **3D position reconstruction** and additional discrimination power.
Single-phase Noble Liquid Detectors

XMASS

DEAP3600
Noble Liquids Will Cover the High Mass Region!

```
0.1  1   10   100  1000  10^4
0.1  1   10   100  1000  10^4

Dark Matter Mass [GeV/c^2]

Dark Matter–nucleon σ_{SI} [cm^2]

Dark Matter–nucleon σ_{SI} [pb]

Neutrino Background
```

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581
And are also looking for light DM as well!

- Limit is for 95 live-days of data (with 13,775 kg·day exposure).
- Result from the complete LUX exposure is forthcoming.
Cryogenic Crystal Detectors: Low Mass DM

Phonons
10 meV/ph
100% energy

CRESST I
ROSEBUD
CaWO₄, BGO
ZnWO₄, Al₂O₃ ...

CDMS
EDELWEISS
Ge, Si

Scintillation
~ 1 keV/γ
few % energy

Ionization
~ 10 eV/e
20% energy

CRESST I
CUORE
TeO₂, Al₂O₃, LiF
Cryogenic Crystal Detectors

The Phonon Channel

Absorber

Weak Thermal Link

Refrigerator
10–40 mK

Thermometer

The height of the pulse is proportional to the energy deposited

Time

Temperature

The height of the pulse
is proportional to the energy deposited
Microcalorimeters 102: Transition-Edge Sensors

- Refrigerator temperature has to be close to absolute zero
- Thermometer is a Superconducting Transition-Edge Sensor (TES)
- Readout is done with Superconducting Quantum Interference Devices (SQUIDs)
SuperCDMS SNOLAB

CDMS II
- 4.6 kg Ge (19 x 240 g)
- 1.2 kg Si (11 x 106 g)
- 3” Diameter
- 1 cm Thick
- 2 charge + 4 phonon

SuperCDMS Soudan
- 9.0 kg Ge (15 x 600 g)
- 3” Diameter
- 2.5 cm Thick
- 2 charge + 2 charge
- 4 phonon + 4 phonon

SuperCDMS SNOLAB
Funded G2 Experiment
Data Taking in 2020
- 25 kg Ge (18 x 1.4 kg)
- 3.6 kg Si (6 x 0.6 kg)
- 4” Diameter
- 3.3 cm Thick
- 2 charge + 2 charge
- 6 phonon + 6 phonon
Graded shield reduces environmental $\gamma$ by $10^6$. Sufficiently clean materials used so that internal contamination of detectors ($^3$H, $^{32}$Si) dominates.

Outer 10 cm: new lead
9 cm < 19 Bq/kg $^{210}$Pb
1 cm < 0.08 Bq/kg $^{210}$Pb
- ~870g detectors (φ=70 h=40 mm)  
- 2 GeNTDs heat sensor per detector  
- Electrodes: concentric Al rings (2 mm spacing) covering all faces  
- XeF$_2$ surface treatment → low leakage current (<1 fA) between adjacent electrodes  
  

- R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs  
- *Optimized* NTD heat sensor on a 32g crystal, no electrodes (i.e. 1 keV = 1 keV$_{NR}$)  
- Kept at 17 mK in IPNL low-vibration dilution fridge [ArXiv:1803.03463]  
- Stable $\sigma = 18$ eV baseline resolution  
- One day blinded for WIMP search in [0-2] keV region
CRESST

- CRESST: phonon + light
- Scintillating CaWO$_4$ crystals as target
- Separate cryogenic light detector to detect scintillation light signal
- New small 24g detectors optimized for light DM
- 4.5 eV sigma Baseline Resolution
CRESST New Results

Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM
The Low Mass Region Is an Exciting Place To Look for DM!
End of Lecture 2