Evidence for Dark Matter

- Many gravitational evidence for dark matter

All consistent with ~25% dark matter (give or take).

But... what is it?
What is Dark Matter?

Observational evidence indicates:

- Non-baryonic
- Cold(ish) and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived

Leading Candidates:

Axions
- mass $\sim 10^{-3} - 10^{-6}$ eV
- Arises in the Peccei-Quinn solution to the strong-CP problem

WIMPs: Weakly Interacting Massive Particles
- mass of $1$ GeV – $10$ TeV
- weak scale cross sections results in observed abundance

$$\sigma \approx 10^{-39} - 10^{-46} \text{ cm}^2$$
$$\langle \sigma_A \nu \rangle \approx 10^{-26} \text{ cm}^3/\text{s}$$
$$m_\chi \approx 100 \text{ GeV}$$

(Roszkowski 2004)
Detecting WIMPs

**“Indirect Detection”**
Collect dark matter in Stars and Galaxies, then let them annihilate among themselves.
Detect the decay particles

**“Direct Detection”**
Let dark matter recoil off of nuclei
Look for nuclear recoil

Production
Colliders
Look for the missing energy

Scattering
WIMP
nuclear recoil

Annihilation

Reina Maruyama

Monday, September 23, 13
Dark Matter Distribution

Large scale dark matter distribution
Millenium Simulation
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Planck all-sky image of the distribution of
dark matter via distortions on CMB by
gravitational lensing (April 2013)

Artist's impression of the Milky Way galaxy. The blue halo of
material surrounding the galaxy indicates the expected distribution
of dark matter. (ESO/Calçada)
Direct Detection Search Strategies

1. Count individual nuclear recoils
2. Look for annual modulation
3. Diurnal directional modulation

(Modified from: NASA/CXC/M.Weiss)
Direct Detection Experiments

here: recent results + future

Laura Baudis
DM Overview
Neutrino 2012
“Tension” in Direct Detection Experiments

- Exclusion from CDMS, SIMPLE & XENON100
- Hints in CoGeNT and CRESST-II
- Claim for 9.3σ signal from DAMA

Assumptions for this plot:
- Dark matter is made of WIMPs
- Scattering is spin-independent
- Elastic scattering off of nuclei
- WIMPs are distributed in an isothermal halo with:
  - \( v_0 = 220 \text{ km/s} \)
  - \( v_{\text{esc}} = 544 \text{ km/s} \)
  - \( \rho_X = 0.3 \text{ GeV/cm}^3 \)
Hints and Claims for Direct Detection of DM

Low Mass WIMPs?

Snowmass 2013

Reina Maruyama

WIDG, Sept. 2013

Monday, September 23, 13
Modulation Observed by DAMA

9.3 $\sigma$ modulation observed

- Modulation consistent with dark matter:
  - **Phase:** $144 \pm 7$ days (peak on May 24)
  - **Period:** $0.998 \pm 0.002$ yr
  - **Background:** $\sim 1$ cnts/keV/kg/day
  - **Amplitude:** $0.0112 \pm 0.0012$ cnts/keV/kg/day
- Two generations:
- 1.33 ton-yr over 14 annual cycles

but is it dark matter?

arxiv:1308.5109
## Annual Modulation Dark Matter Searches with NaI Detectors

<table>
<thead>
<tr>
<th>Northern Hemisphere</th>
<th>Gran Sasso DAMA/Libra 250kg running</th>
<th>Gran Sasso Princeton-NaI R&amp;D</th>
<th>Canfranc ANAIS 250 kg starting in 2014?</th>
<th>PICO-LON KIMS etc...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Hemisphere</td>
<td>South Pole DM-Ice 17 kg running R&amp;D for 250 kg</td>
<td>ANDES Lab (proposed) expected start 2018 2017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Several Groups conducting ultra-pure crystal with several vendors to go to the full scale **DM-Ice:**

- NaI dark matter search in an entirely different environment
- 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
Testing DAMA’s Dark Matter Claim

Definitive (5σ) detection or exclusion with

- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- same or lower threshold (< 2 keVee)
- background < (DAMA x 5)

500 kg-year NaI detector sensitivity
(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

<table>
<thead>
<tr>
<th></th>
<th>NAIAD size</th>
<th>DAMA size</th>
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<tbody>
<tr>
<td></td>
<td>Years</td>
<td>17.0 kg</td>
</tr>
<tr>
<td>x8 DAMA background</td>
<td>1</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.18</td>
</tr>
<tr>
<td>x4 DAMA background</td>
<td>1</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.41</td>
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<tr>
<td></td>
<td>7</td>
<td>1.67</td>
</tr>
<tr>
<td>Double DAMA background</td>
<td>1</td>
<td>0.85</td>
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<tr>
<td></td>
<td>3</td>
<td>1.47</td>
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<td>DAMA background</td>
<td>1</td>
<td>1.20</td>
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<td></td>
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<td>2.08</td>
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<td>1/10 DAMA background</td>
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<td>3.80</td>
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<td></td>
<td>3</td>
<td>6.58</td>
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<td>5</td>
<td>8.50</td>
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<td></td>
<td>7</td>
<td>10.06</td>
</tr>
</tbody>
</table>

arXiv:1106.1156
The IceCube Neutrino Observatory

- Completed in 2011, South Pole
- Partial detector in operation since 2005
- Search for **astrophysical neutrinos**, dark matter, nu oscillations, cosmic ray, atmospheric neutrinos, glaciology...
The IceCube Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)

German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat

The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
IceCube Detector Completion
December, 2010

Monday, September 23, 13
DM-Ice-17, DM-Ice

Currently in Operation: DM-Ice17

- 17 kg of NaI(Tl), operation since 2011
- Funding: NSF-Polar Programs & NSF-CAREER for R&D
- First results expected in Spring

Proposed Full-Scale: DM-Ice

- 250 kg of ultra-pure NaI(Tl)
- Proposed deployment: Dec. 2015
Prototype: DM-Ice-17

Co-Deployed with IceCube at the South Pole in December 2010
• A 17 kg NaI detector
• Operation since Feb. 2011
• Data run from June 2011
• Data sent over satellite

Goals:
• Feasibility of deploying a remotely-operable dark matter detector in the Antarctic Ice
• Assess the environmental stability
• Establish the radiopurity of the antarctic ice / hole ice
• Explore the capability of IceCube to veto muons
• Look for modulations
DM-Ice-17 Construction & Deployment

Design begin Feb. 2010

Revive NAIAD xtals
July 2010

Detector assembly
Sep - Oct. 2010

Shipment to Antarctica
Dec. 1, 2010

Deployment
Dec. 11, 2010

Detector in the hole
DM-Ice-17 Detector

- DM-Ice-17 Detector
- 2 IceCube mainboards + HV control boards
- PMTs: 5” ETL 9390UKB
- NAIAD NaI Crystal (5”x5”, 8.5 kg)
- quartz light guides
- PTFE light reflectors
- Stainless Steel Pressure Vessel

36 cm (14”)
1.0 m
7 m
DM-Ice17 DAQ Overview

- Remotely programable sample rate, HV & threshold
- Each PMT set to trigger ~0.2 spe
- Waveform recorded only when coincidence between both PMTs w/in 800 ns on a single crystal
- Waveform from each PMT digitized separately in the ice by IceCube mainboards and sent to hub
- Time stamp synchronized to IceCube GPS and calibrated for transit time
- Data sent over satellite to Madison, WI
Antarctic Ice: Overburden at -2500 m (2200 m.w.e.)

- ~85 muons/m²/day at bottom of IceCube
- IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude.

Muon flux vs. depth in the ice, total and those untriggered by IceCube/DeepCore.
Antarctic Ice: Radiopurity

- Measurements from ice cores at Vostok.
- Absorption and scattering lengths measured by AMANDA/IceCube
- ~2500 m at South Pole is ~100,000 years old
- Most of the impurities come from volcanic ash, < 0.1 ppm
- Radioactive contaminants in ice:
  - U ~ 0.1 - 1 ppt
  - Th ~ 0.1 - 1 ppt
  - K ~ 0.1 - 1 ppb

Antarctic Ice: Stability & Temperature

- Temperature measured by each IceCube DOM & additional sensors on the cables
- At -2500 m, the ice is -20 °C
- Temperature is stable throughout the year
IceCube as a Muon Detector

The muon rate at the South Pole well measured by IceCube

IceCube muon rate variation (solid) & $T_{\text{eff}}$ (dotted)

Muon rate modulation with a single IceCube DOM

IceCube Collaboration, arXiv:1108.0171
Muon Rate at Gran Sasso vs. South Pole

- **LVD:**
  Selvi, Proc. 31st ICRC. (2009)

- **Opposite Muon modulation at the South Pole:**
  Tilav, Proc. 31st ICRC. (2009)
Detector Uptime

- Commissioning and optimization from Feb - June 2011
- Data run since June 2011
- 99.8% uptime for most weeks with well defined down time for occasional power cycling + pedestal and dark noise runs

DM-Ice-17 Livetime

7 days/point
Detector Monitoring

• Monitored quantities:
  • Temperature of the boards
    • ~10°C above surrounding ice
    • Fast (2-3 weeks) decrease during freeze-in
    • slower decrease over a few months after freeze-in
  • Pressure follows similar trend as temperature (ADC resolution limited)
• Values recorded every 2 sec. before April 2012. Every 60 sec. since April 2012.
Detector Monitoring

• High voltage of each PMT
  • commissioning until day 167
• Single PMT total trigger rate
  • General decay over time
  • single trigger rate variation seems mostly in the noise (not observed in coincidence data after cuts)
Capturing Waveforms with IceCube Mainboards

**ATWD:**
- 213 MS/sec x 128 samples = 600 ns window
- 3 gains:
  - channel-0: high gain
  - channels-1 & 2: useful for > 1500 keV where ch-0 is saturated

**FADC:** slower sampling rate, wide time window
- 40 MS/sec x 256 samples = 6.4 μsec time window (3 μs shown)

Example waveform from all channels

- ATWD ch0 (x16)
- ATWD ch1 (x2)
- ATWD ch2 (x0.25)
- FADC
Waveform Examples

- **High energy events** (>100 keV)
  - Typical scintillation pulses with decay time ~350 ns

- **Low energy events** (<100 keV)
  - Single photo-electrons visible

- **“Thin” pulses**
  - Fast pulses with large amplitudes
  - Cut via waveform

- **“EMI” events**
  - Interference with detector monitoring.
  - Well characterized by timing and shape.
  - (No interference with IceCube or ARA seen)
DM-Ice17 Spectrum

DM-Ice17 Prototype1 Spectrum

Main backgrounds:
- U-chain
- Th-chain
- $^{40}$K
- $^{60}$Co

18 months of data from both PMTs on a single crystal

Internal contamination lines used for calibration
Low Energy Background Spectrum

Energy Spectrum < 150 keV

- 7 - 10 cpd/keV\textsubscript{ee}/kg between 8 - 30 keV\textsubscript{ee}.
- Low energy region calibrated with internal lines from Pb-210, I-125, & I-129
- Cosmogenic activation of $^{125}$I observed with $T_{1/2} = 59.4$ days
- K-40 line at 3.2 keV also visible.

Reina Maruyama

WIDG, Sept. 2013
Good agreement with simulation above 20 keV
- Surface event simulation at 12 keV in progress

We understand our detector to 4 keV
- NAIAD published to 4 keV; we are pushing lower

We model our 3 keV peak to within a factor of 2 of simulation
- Understanding efficiencies <3 keV in progress

Looking ahead:
- Backgrounds in ROI 5x higher than simulated for full scale DM-Ice
- Multi-crystal veto will suppress 3 keV events

18 months of data from both PMTs on a single crystal

3 keV from $^{40}\text{K}$

$7.2 \pm 0.4 \text{ cpd/kg/keV}$

$^{125}\text{I}$ cosmogenic

$^{210}\text{Pb}$ surface event; simulation in progress

Energy (keV)

$7.2 \pm 0.4 \text{ cpd/kg/keV}$

Energy (keV)
Event Selection: “Thin” pulses

- Characteristics:
  - high pulse-height relative to charge
  - asymmetric between two PMTs
- 90% of events between 5-10 keV are “thin”
- Current cut effective above 7 keV

**Energy spectrum:**
before & after thin pulse cut

**Charge:** PMT-1 vs. PMT2

**Pulse height vs. charge**

**Combined Energy (keV)**

0 20 40 60 80 100 120 140 160 180 200

10^4
10^3
10^2
10

**Before cut**

**After cut**

WIDG, Sept. 2013

Reina Maruyama
Cosmogenic $^{125}\text{I}$ (in the NaI crystal)

Cosmogenic lines verify our energy calibration; this is particularly useful for the prototype since we do not have an in-ice source.
Pushing down the threshold: work in progress

- Since our crystals are separated by 500 m, not possible to look for $^{40}$K coincidence between 1460 keV and 3 keV
- Cut noise further by requiring there be multiple photo-electrons in both PMT. (“5 peak” cut shown here)
- 3 keV peak is visible above noise, we still don’t understand efficiency etc. still in progress...

Reina Maruyama  WIDG, Sept. 2013  Monday, September 23, 13
Energy Calibration

- power law < 100 keV
- linear >100 keV

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>K-40</td>
</tr>
<tr>
<td>12.5</td>
<td>Pb-210</td>
</tr>
<tr>
<td>46.5</td>
<td>Pb-210</td>
</tr>
<tr>
<td>67.3</td>
<td>I-125</td>
</tr>
<tr>
<td>252</td>
<td>Pb-212, Pb-214</td>
</tr>
<tr>
<td>301</td>
<td>Pb-212</td>
</tr>
<tr>
<td>352</td>
<td>Pb-214</td>
</tr>
<tr>
<td>599</td>
<td>Tl-208, Bi-214</td>
</tr>
<tr>
<td>1166</td>
<td>Bi-214, Co-60</td>
</tr>
<tr>
<td>1333</td>
<td>Co-60</td>
</tr>
<tr>
<td>1460</td>
<td>K-40</td>
</tr>
</tbody>
</table>

0 - 80 keV

0 - 2000 keV
Detector Stability

- Spectra are nearly identical over the course of one year
- Longer half-life cosmogenic lines also visible ($^{54}$Mn, $^{125}$I x-rays)

\[ \text{cpd/keV/kg} \]

\[ \text{keV keV} \]

\[ < 60 \text{ keV} \]

\[ 300 - 1100 \text{ keV} \]

\[ \text{December 2011} \]

\[ \text{December 2012} \]

\[ \text{December 2011} \]

\[ \text{December 2012} \]

\[ \text{Monday, September 23, 13} \]
Gain Stability

- Detector calibration is stable to 1% over 18 months.
- 1% decrease over 18 months in light collection (peak position) observed at 600 and 1460 keV
- No observable change in calibration at 45 keV

![Graphs showing stability over time](image)
Number of Photoelectrons / keV

Obtain 1p.e.-ped separation from dark noise runs (ie no coincidence requirement)

Normalize the energy to keV using the energy calibration

xtal-1 = 6.1 pe/keV
xtal-2 = 4.7 pe/keV
Backgrounds

Going from DM-Ice17 to DM-Ice

• Background goal: < 1 cpd/keV_{ee}/kg in 2 - 10 keV_{ee} (factor of 10 reduction)
• Contamination levels in DM-Ice17 estimated from in-ice data and radio-assay, verified by simulation
  • Dominant background in DM-Ice17: $^{40}$K & $^{210}$Pb in the crystals
  • Surrounded ice is extremely clean, drill ice is clean enough
  • Ultra-clean crystals are under development (see F. Calaprice’s talk)
  • Cleaner PMT, Pressure Vessel, & Quartz are available
  • Direct muon interaction contribute O(10^{-5}) below other backgrounds
  • Muon monitor & tag with IceCube

<table>
<thead>
<tr>
<th>Crystal contamination in DM-Ice17 &amp; DAMA</th>
<th>DM-Ice17</th>
<th>DAMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>nat K</td>
<td>500 ppb</td>
<td>&lt; 20 ppb</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>50 ppt</td>
<td>0.5 - 7.5 ppt</td>
</tr>
<tr>
<td>$^{238}$U (upper part of chain)</td>
<td>7.5 ppt</td>
<td>0.7 - 10 ppt</td>
</tr>
<tr>
<td>$^{238}$U (below Pb-210)</td>
<td>2 mBq/kg</td>
<td>5 - 30 μBq/kg</td>
</tr>
</tbody>
</table>

Alpha region in DM-Ice17 vs. Simulation

preliminary
Nal Powder R&D

- From simulation, internal backgrounds dominate, particularly 3 keV $^{40}$K
  - $^{238}$U : 1 - 10 ppt
  - $^{232}$Th : 1 - 10 ppt
  - $^{\text{nat}}$K : < 20 ppb
- NAIAD crystals : 5 - 10x DAMA bkg (PLB 616 (2005) 17–24)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Form</th>
<th>Measurement</th>
<th>$^{238}$U (ppt)</th>
<th>$^{232}$Th (ppt)</th>
<th>$^{\text{nat}}$K (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint Gobain</td>
<td>Powder</td>
<td>DAMA (HPGe)</td>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Saint Gobain</td>
<td>Crystal</td>
<td>DAMA/LIBRA</td>
<td>0.7 - 10</td>
<td>0.5 - 7.5</td>
<td>&lt; 20</td>
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<tr>
<td>Saint Gobain</td>
<td>Crystal</td>
<td>ANAIS-0</td>
<td>6.1</td>
<td>3.2</td>
<td>410</td>
</tr>
<tr>
<td>Bicron/Saint Gobain</td>
<td>Crystal</td>
<td>NaIAD/DM-Ice</td>
<td>20*</td>
<td>20*</td>
<td>650*</td>
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<tr>
<td>Sigma-Aldrich</td>
<td>Powder (standard grade)</td>
<td>DM-Ice (HPGe)</td>
<td>40</td>
<td>89</td>
<td>440</td>
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<tr>
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<td>Powder (astro grade)</td>
<td>DM-Ice (HPGe)</td>
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<td>&lt; 95</td>
<td>&lt; 126</td>
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<td>Sigma-Aldrich</td>
<td>Powder (astro grade)</td>
<td>A-S (ICPMS)</td>
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<td>-</td>
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<tr>
<td>Alpha-Spectra</td>
<td>Powder</td>
<td>DM-Ice (HPGe)</td>
<td>&lt; 100</td>
<td>&lt; 200</td>
<td>&lt; 120</td>
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<tr>
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<td>Powder</td>
<td>ANAIS-25 (HPGe)</td>
<td>&lt; 55</td>
<td>&lt; 130</td>
<td>&lt; 90</td>
</tr>
</tbody>
</table>

*preliminary

- Also working with SICCAS (Shanghi)

Technical challenge == a method to measure K < 100 ppb level
- ICPMS $\rightarrow$ < 10 ppb?
Background Model for DM-Ice17

Additional reduction from crystal-crystal coincidence expected
Conclusions

• Success installation of DM-Ice17 along with IceCube and running stably
• Background level nominally as expected and in agreement with simulations
• Making good progress on cleaner NaI
• R&D and design for the full-scale experiment underway

500 kg·year NaI detector sensitivity (2 - 4 keV) with 1, 2, and 5 dru bgd.
DM-Ice Collaboration

Yale University
Reina Maruyama, Karsten Heeger, (and you)

University of Wisconsin – Madison
Francis Halzen, Albrecht Karle, Matthew Kauer, Carlos Pobes, Walter Pettus, Zachary Pierpoint, Antonia Hubbard, Bethany Reilly

University of Sheffield
Neil Spooner, Vitaly Kudryavtsev, Dan Walker, Matt Robinson, L. Thompson, Sam Telfer, Calum McDonald

University of Alberta
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University of Illinois at Urbana-Champaign
Liang Yang

Fermilab
Lauren Hsu

Shanghai Jiao Tang University
Xiangdong Ji, Changbo Fu

Penn State
Doug Cowen, Ken Clark

NIST-Gaithersburg
Pieter Mumm

University of Stockholm
Chad Finley, Per Olof Hulth, Klas Hultqvist, Christian Walach

DigiPen
Charles Duba, Eric Mohrmann

Boulby Underground Science Facility
Sean Paling

SNOLAB
Bruce Cleveland