DM-Ice
A Direct Dark Matter Search at the South Pole

Karsten Heeger
University of Wisconsin - Madison
Shanghai Jiao Tong University, May 22, 2011
Neutrinos and photons are the most abundant particles in the Universe.
There are 0.3 GeV/cm$^3$ of galactic Dark Matter.

We pass through this matter at 220 km/s.

How do we know?
How can we detect it?
Matter in the Universe

Heavy Elements: 0.03%

Ghostly Neutrinos: ~0.3%

\[ \sum m_\nu \leq 0.006 < \Omega_\nu < 0.015 \]

Stars: 0.5%

Free Hydrogen and Helium: 4%

Dark Matter: 25%

Dark Energy: 70%
Content of the Universe

Matter Content of the Universe - Now and 13.7 billion years ago

Today:
- Dark Energy: 72%
- Dark Matter: 23%
- Atoms: 4.6%

13.7 billion years ago:
- Atoms: 12% 380,000 years old
- Dark Matter: 63%
- Neutrinos: 10%
- Photons: 15%
Zwicky used virial theorem to infer the existence of unseen matter, what is now called dark matter.

1933

First Hints of Dark Matter

Zwicky inferred average mass of galaxies within the Coma cluster and proposed that most of the matter was dark.

Fritz Zwicky

“[If this overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter.”

Discovery of Dark Matter

Rotation Curve of Galaxies

95% of the matter in galaxies is unknown dark matter

1975
Vera Rubin found that rotation curves are flat

95% of the matter in galaxies is unknown dark matter
Galactic Halo
Galactic Halo
Evidence of Dark Matter

Merger of Galactic Clusters

custers collide at millions of miles per hour. normal, baryonic matter in each interacts with the similar matter in the other and slowed down, emits X-rays

dark matter did not interact significantly and passed through without disruption. difference caused the dark matter to move ahead, leaving X-ray luminous, baryonic matter lagging behind
Evidence for Dark Matter

- There is more stuff out there that exerts gravity than we can see!
  - Galactic rotation curves
  - Galaxy clusters and gravitational Lensing
  - Velocity dispersions of galaxies
  - Cosmic microwave background
  - Baryon Acoustic Oscillation clustering
  - Type Ia supernovae distance measurements
  - Lyman alpha forest
  - Structure formation

All consistent with 23% dark matter content.
Dark Matter in the Galaxy

- Isothermal, spherical dark matter halo around the galaxy, with Maxwell-Boltzmann velocity distribution

\[ f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v \]

- \( v_0 \sim 230 \text{ km/s}, v_{\text{esc}} \sim 550 \text{ km/s}, \rho_\chi = 0.3 \text{ GeV/cm}^2 \)

- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

\[ R \propto N \sigma_{\chi N} \rho_\chi \int_{v_\text{min}}^{v_{\text{esc}}} f(v)dv \]

- What can we look for?
  - individual interactions,
  - annual modulation, or
  - diurnal modulations.
Favored Dark Matter Candidate

WIMPs

- Weakly interacting massive particles (best motivated dark matter candidates)
- Lightest supersymmetric particles, are their own antipartners.

- Annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density.
- Mass fraction of WIMPs can be predicted to be 23% if
  - the dark matter is weakly interacting
  - WIMP mass: GeV - 10 TeV
Techniques for Detecting Dark Matter

- **Indirect detection** (IceCube, etc.)
  - observe products of WIMP annihilation/decay in terrestrial or space based detectors

- **Direct detection** (CDMS, XENON, DEEP, LUX, DAMA, etc.)
  - observe WIMPs through with matter in terrestrial detectors

- **Colliders**
  - produce WIMPs directly at the LHC
Dark Matter Bounds from Terrestrial Experiments

Spin-Independent

Spin-Dependent

One, maybe two signals.

One claim for discovery: DAMA

Preliminary
DAMA Annual Modulation

DAMA

- DAMA/LIBRA (2003 - present)
- 1.17 ton-yr (13 annual cycles)
- 8.9σ C.L.
- modulation amplitude of the single-hit events in the (2 - 6) keV:
  - (0.0116 +/- 0.0013) cpd/kg/keV
- phase: (146 +/- 7) days (June 2)
- period: (0.999 +/- 0.002) yr

★ Claim for 9σ observation of annual modulation
★ DAMA attributes the modulation to dark matter.
DAMA/NaI, DAMA/LIBRA

DAMA

- Gran Sasso National Laboratory, Italy under ~3800 m.w.e of rock.
- DAMA/NaI consisted of ~100 kg of NaI
- DAMA/LIBRA ~250kg
  - 25 crystals (10 x 10 x 25 cm$^3$, 9.7 kg)

- Look for scintillation in NaI with two PMTs, 5 - 7 p.e./keV
- background: ~1-2 events/kg/d/keV
- $E_{\text{threshold}}$: 2 keV$_e$ (25 keV$_r$)
Annual Modulation in CoGeNT?

uses point-contact Ge detector

...awaiting preprint

Rafael F. Lang: How To Detect Dark Matter Particles

from Lang, Pheno2011
Hints of Dark Matter?

Some tantalizing signals...

- Claim for observation from DAMA.
- Recent results from CoGeNT show some unexplained events at low energies and annual modulation?
- Excess events in CDMS (but no observation in their low-energy analysis), null results from XENON 100.
- Experimentalists’ reaction: Background? Detector?
- Theorists’ reaction: Light WIMPs? Asymmetric WIMPs? ????
- DAMA result requires careful investigation!

arxiv:1002.1028

Hooper, Collar, Hall, McKinsey

arXiv:1007.1005v1
Are recent results compatible?

Isospin-violating inelastic dark matter helps alleviate this tension and allows marginal compatibility.

\( f = \) effective coherent couplings to neutron and proton.

arXive: 1105.3734v
What is going on?

- Possible factors that can contribute to an annual modulation
  - Ambient temperature variation
  - Muon flux depend on temperature in the upper atmosphere
  - Spallation neutrons from muons interaction in rock
  - Radon diffusion from rocks may be varying with time
  - Threshold effects
  - Detector and lab maintenance timing
  - Many of these factors tend have periodicity of 1 year

- Modify astrophysics?
  - $f(v)\sim v_{esc}\sim v_0$ co-rotating?

- More exotic particle?
  - Spin-dependent, inelastic scattering, momentum-dependent scattering.

- Proposed solution: look for annual modulation with NaI(Tl) in the Southern Hemisphere.
Requirements for Testing DAMA

- **Environment/location with different systematics**
  - Site with different systematics and backgrounds that might mimic the annual modulation signal from dark matter

- **Background rates of < 1 event/kg/keV/day**
  - Use clean detectors and surrounding materials. Limited by intrinsic NaI(Tl) background.
  - Deep underground site (e.g. depth of ~2400 m in the Antarctic ice)

- **> 250kg of NaI(Tl) detectors**
  - same or larger size than DAMA to collect sufficient statistics

- **Long-term stability in operation (> 2 years)**
  - would like to see at least 2 annual modulations if signal is seen
Testing DAMA

Sensitivity

5-σ detection of DAMA signal with a 250-kg / 2-year running time (2 - 4 keV) and comparable backgrounds to DAMA

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<tr>
<th>Years</th>
<th>2 NAIAD (kg)</th>
<th>NAIAD size</th>
<th>DAMA size</th>
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<td>8.62</td>
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<th>1/10 DAMA background</th>
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<td>16.27</td>
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Going to the South Pole
Verifying DAMA at the South Pole

- Phase of the dark matter modulation is the same.
- Opposite seasonal modulation, e.g. muon rate (max in December).
- > 2500 m.w.e. of overburden with clean, radiopure ice.
  - Many sources of backgrounds either non-existent or different from other underground sites.
  - Clean ice → Very little uranium/thorium. No radon.
  - Ice is a great neutron moderator.
  - Ice as an insulator → No temperature modulation.

- Existing infrastructure
  - NSF-run Amundsen-Scott South Pole Station
    - Ice drilling down to 2500 m developed by IceCube
    - Muon rates well understood by IceCube/DeepCore
    - Infrastructure for construction, signal readout, and remote operation
Antarctic Ice Overburden

2500 m depth (2200 m.w.e.)

~85 muons/m²/day at bottom of IceCube

IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude

Is is a good neutron moderator

Muon flux vs. depth in the ice, total and those untriggered by IceCube/DeepCore. (Darren Grant)
Antarctic Ice

• 60 - 70% of all of Earth’s fresh water is frozen here.
• Radio-purity available data:
  – Measurements from ice cores at Vostok.
  – Absorption and scattering lengths with lasers and LEDs from AMANDA/IceCube
• Glacial ice is moving ~10m/year along the 40° west meridian
• Depth (and contaminant concentration) versus age estimated by correlating Vostok/IceCube measurements
Antarctic Ice

Purity

-2500 m at South Pole is ~100,000 years old

Most of the impurities come from volcanic ash, < 0.1 ppm

Ice is nearly as clean as the cleanest materials used for ultra-low background experiments.
  - U ~ ppt
  - Th ~ ppt
  - K ~ ppb


Antarctic Drill Water

Purity Analysis

• Drill water may introduce impurities in the water
• Water samples from 3 holes taken during 2009 - 2010 season for leCube
• Additional analysis from 2010/11 holes
• Samples taken from return from the inlet into “Tank-1” as water is pumped out from the hole
• Samples counted at SNOLAB look very promising
  – < ppb of U/Th
  – < 200 ppb K-40
• Currently carrying out a more sensitive counting
Antarctic Ice

Temperature

- Each IceCube DOM can measure temperature in the ice
- At -2500 m, the ice is -20 °C
- Temperature is stable throughout the year
- at -20°C, NaI pulses are slower than at +25°C but light output is slightly better.
NaI(Tl) Detector Characteristics

Main properties of NaI(Tl)
- high light yield (38000ph/MeV)
- short decay time (230 ns)
- match well of emission wavelength (415nm) with PMT
- stable temperature coefficient
- forging easily
- hygroscopic
**Backgrounds**

likely to be limited by intrinsic background in NaI crystal.

Simulated background spectrum from intrinsic contamination in DAMA crystals near signal region

- DAMA uses NaI(Tl) crystals grown with proprietary process to achieve low U/Th/K content.
  - easy to take out U/Th. K is difficult.
Muon Rate Seasonal Modulation

Gran Sasso

- LVD:
  Selvi, Proc. 31st ICRC.

South Pole

- Opposite Muon modulation at the South Pole:
  Tilav, Proc. 31st ICRC. (2009)
Muon Rate Seasonal Modulation

South Pole

Fig. 1. The temporal behavior of the South Pole stratosphere from May 2007 to April 2009 is compared to IceTop DOM counting rate and high energy muon rate in the deep ice. (a) The temperature profiles of the stratosphere at pressure layers from 20 hPa to 100 hPa where the first cosmic ray interactions happen. (b) The IceTop DOM counting rate (black - observed, blue - after barometric correction) and the surface pressure (orange). (c) The IceCube muon trigger rate and the calculated effective temperature (red).
Starting a Dark Matter Experiment at the Pole

Window of Opportunity

• IceCube construction finished in Dec. 2010
• new holes will need to be drilled after this year.

Challenges

• Extreme environment
• Detector will be inaccessible once deployed.
• But.. NaI detectors have been launched into space (e.g. EGRET, Fermi LAT)
DM-Ice: A Dark Matter Experiment at the Pole

Dark matter

DM-Ice prototype

Detectors

- Two 8.5 kg NaI detectors from NAIAD

Goals

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

Installed Dec. 2010
DM-Ice Feasibility Study in 2010/2011 Season

2 Prototype Detectors

String 79 (DeepCore)

String 7
DM-Ice Feasibility Study

- Stainless Steel Pressure Vessel: 1.0 m
- NAIAD NaI Crystal: (8.5 kg)
- Quartz light guides: (2)
- 2 IceCube mainboards + HV control boards
- 5" ETL PMTs from NAIAD: (2)
- PTFE light reflectors: (2)
- Extension cable: 35 m
- DOM 60: 7 m
- DOM 59: 1.0 m
- 36 cm (14")
NaI(Tl) Crystals from NAIAD, Boulby

- 2 crystals (17 kg) from the NAIAD experiment (2000 - 2003)
- Intrinsic background 5 – 10 times the reported DAMA background
- Boulby Underground Laboratory (1100 m deep)
- Revived and tested two NaI crystals (Bicron) with two 5-inch ETL PMTs each.
DM-Ice Pressure Vessel

• Stainless, Teflon, etc. selected from vendors known to produce clean material.
  – measurements currently underway at LBNL & SNOLAB.

• Pressure vessel tested to 6200 psi
  – static pressure of water ~ 3500 psi
  – 6000+ psi during ice refreeze in the hole
IceCube DOM Mainboards in DM-Ice

- Each ATWD contains 3 gain paths: x16, x2, x0.25 (giving effectively 14-bits)
- Coincidence trigger capabilities
- Controls a separate HV board
- Programmable from surface
- Established reliable technology
Hot Water Drilling into the Ice

Firn Drill

Deep Drill
DM-Ice Electronics in ICL

ICL "beer can" with string cables
string cable penetrations into ICL

patch panels
domhubs
event building
DM-Ice Data from the South Pole

- Preliminary look at the data from one of the PMTs in the ice using IceCube pulse viewing tools

example pulses

uncalibrated spectrum
DM-Ice Status & Outlook

- **DM-Ice prototype (17 kg) deployed in December 2010**
  - Functioning well
  - Currently taking data
  - Data transmitted over satellite
  - Pptimizing analysis, background studies with radio-assay & monte carlo simulation

- **Designing 250-kg scale DM-Ice detector**
  - Developing drilling and deployment plan for 2013/14
  - Starting R&D on low background crystals
  - Investigating low background PMTs
  - Designing pressure vessels, etc.
DM-Ice Conceptual Design

DM-Ice Concept
- Large Pressure Vessel
- Segmented Crystals

38 NaI Crystals (each vessel contains 19)
  - 95.6 mm Diameter
  - 250 mm Long
  - 6.5 kg each
  - 2 PMTs each
Instrument with few “DOMs” externally for veto

50 - 60 mm Copper Radial Shield

SS External Pressure Vessel Shell
  - 65 cm (25.6 inch) Outer Diameter
  - 1.7 m (67 inch) Length

250 kg NaI (38@6.5 kg crystals)
1500 kg total including pressure vessel
**DM-Ice Conceptual Design**

Electronics Space at each end
Electronics and Feedthrus not modeled

Pressure Vessel Cylinder & Hemisphere
Needs to be high strength to survive
7200 psi freeze pressure
Could be copper if 3500 psi maximum pressure

Thirteen Crystal Outer Zone
Six Crystal Middle Zone
One Crystal Inner Zone

Stacked 75 mm thick shielding rings
Can be sealed together with O-rings to form leak tight cylinder
Can carry structural pressure load is freeze pressure is limited
DM-Ice: A Dark Matter Experiment at the Pole

Summary & Conclusions

• We have opportunity for a unique annual modulation experiment in Southern Hemisphere.

• Backgrounds very different from any other underground location.

• Two prototype NaI(Tl) detector installed in the South Pole ice in 2010

• Full-scale experiment currently under design
Core Members of DM-Ice

UW-Madison
Francis Halzen*, Karsten Heeger, Albrecht Karle*, Reina Maruyama*, Walter Pettus, Antonia Hubbard*, Bethany Reilly

University of Sheffield
Neil Spooner, Vitaly Kudryavtsev, Dan Walker, Sean Paling, Matt Robinson

University of Alberta
Darren Grant*

Penn State
Doug Cowen*

Fermilab
Lauren Hsu

University of Stockholm
Seon-Hee Seo*

* IceCube collaboration members

... and we are working closely with IceCube
Thank you!