DM-Ice: A Search for Dark Matter in the Antarctic Ice

Reina Maruyama
University of Wisconsin - Madison

Astrophysics from the South Pole Workshop
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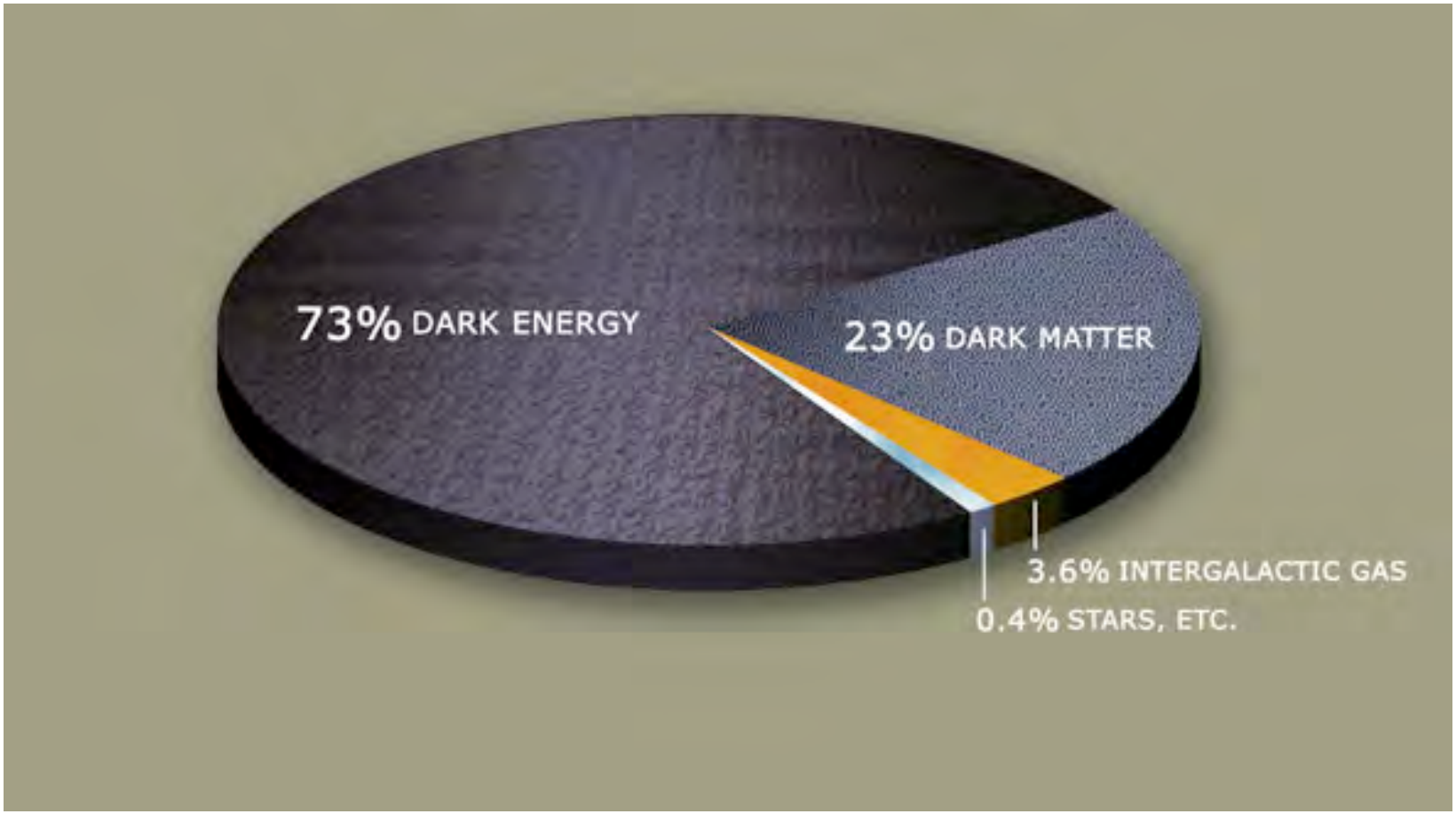
Our Universe

Matter Content of the Universe



Firs

1933

cluster

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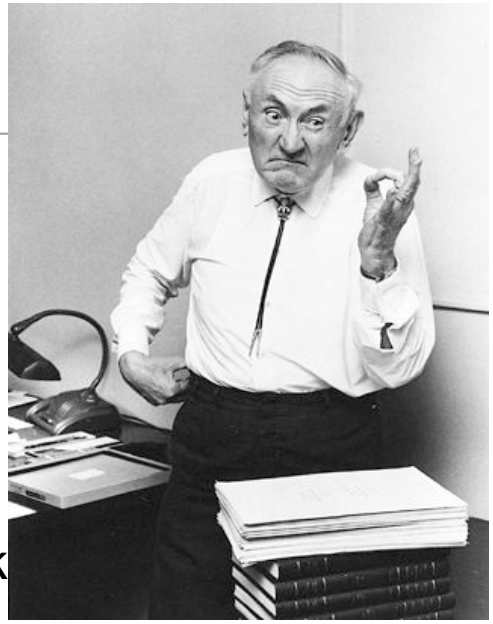


Fritz Zwicky

"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."
F. Zwicky, Helvetica Physica Acta 6: 110–127 (1933).

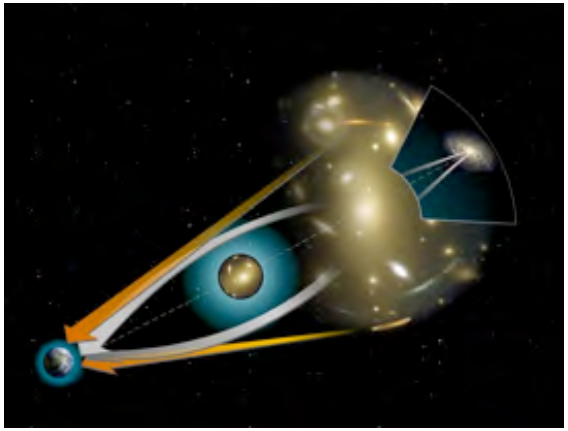
Zwicky inferred average mass of galaxies within the Coma cluster and proposed that most of the matter was dark.

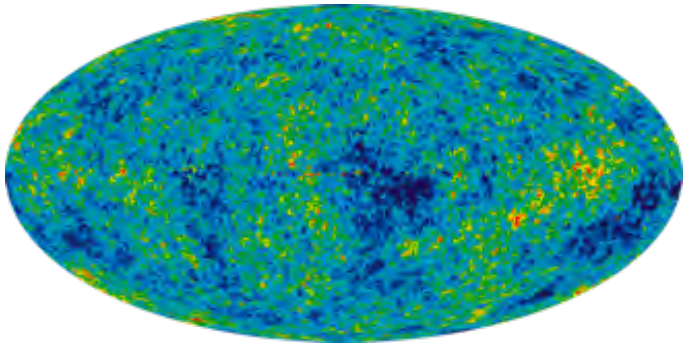
Con

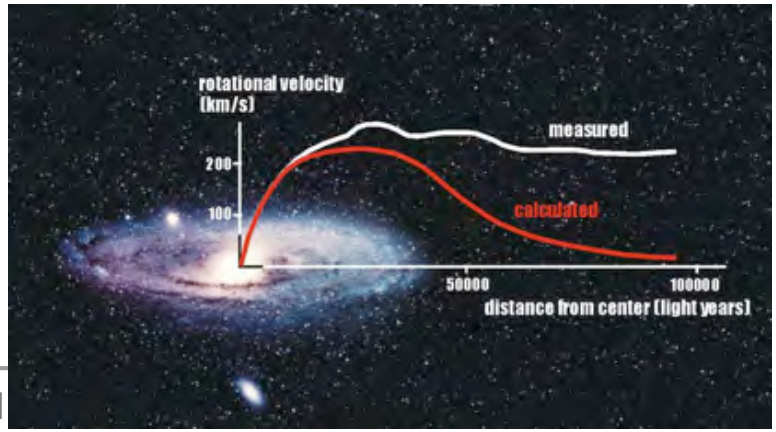
Luminosity $\propto M^4$ & $M = v^2R/G$

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.







Current picture and detection of Dark Matter

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

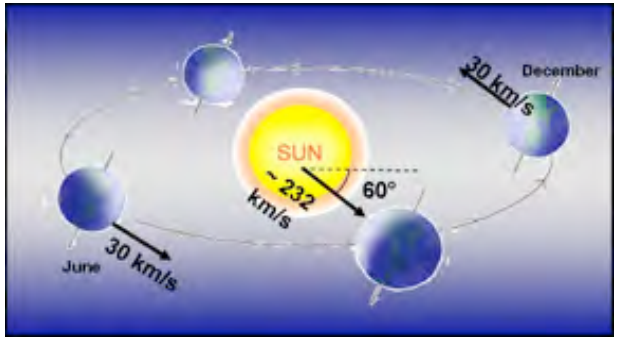
$$f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$

  - v_0 ~ 230 km/s, v_{esc} ~ 550 km/s, ρ_χ = 0.3 GeV / cm^2

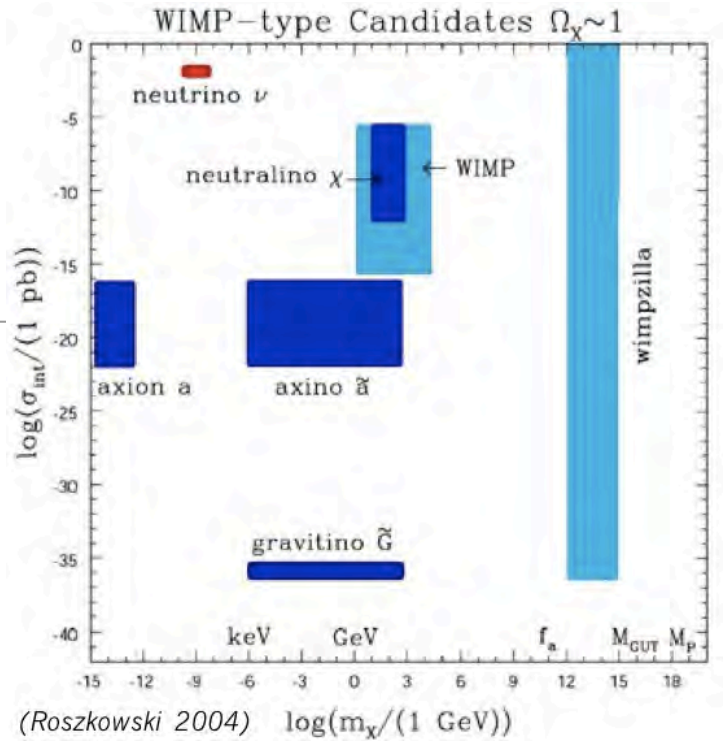
WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

$$R \propto N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi \int_{v_{min}}^{v_{esc}} \frac{f(v)dv}{v}$$

- We can look for individual interactions, annual modulation, or diurnal modulations.



Favored Dark Matter Candidate

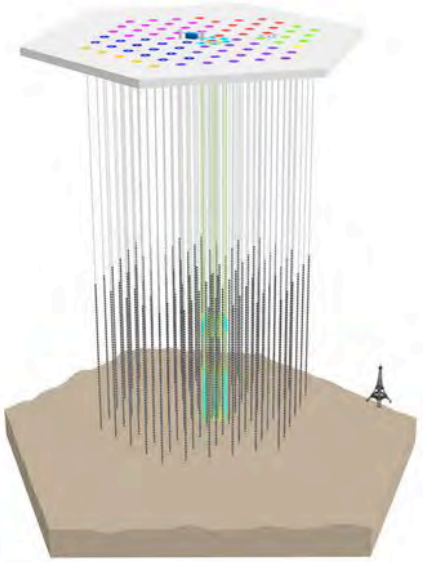


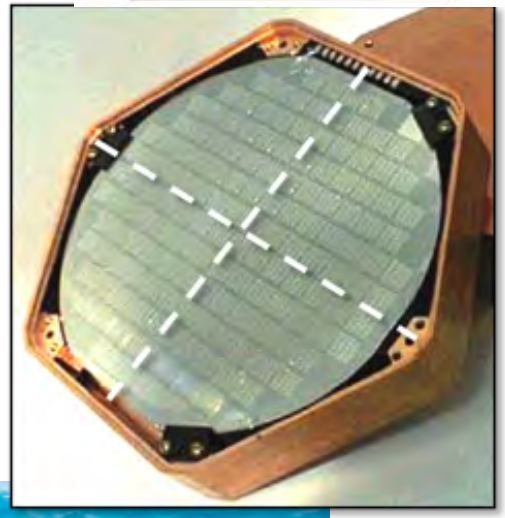
WIMPs

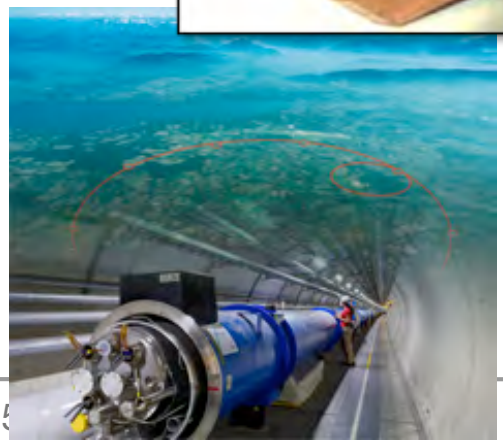
- Weakly interacting massive particles (best motivated dark matter candidates)
- Lightest supersymmetric particles are their own antipartners.
- Annihilation rate in the early universe determines density today.
- Annihilation rate comes purely from particle physics and automatically gives the right answer 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 WIMPs

- 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

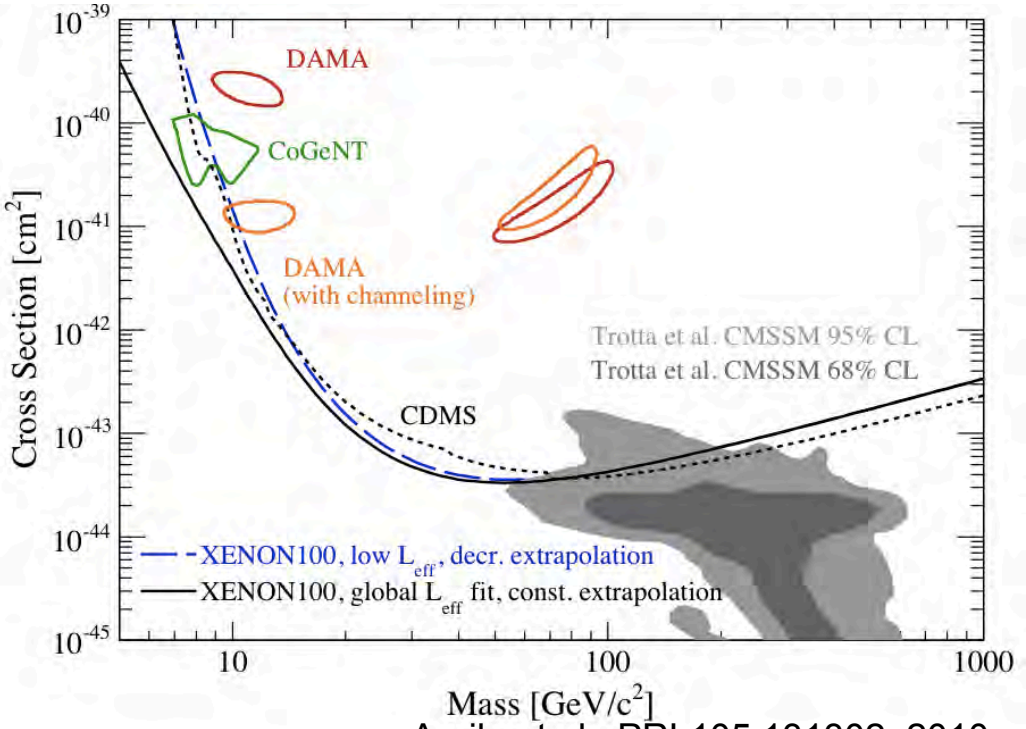






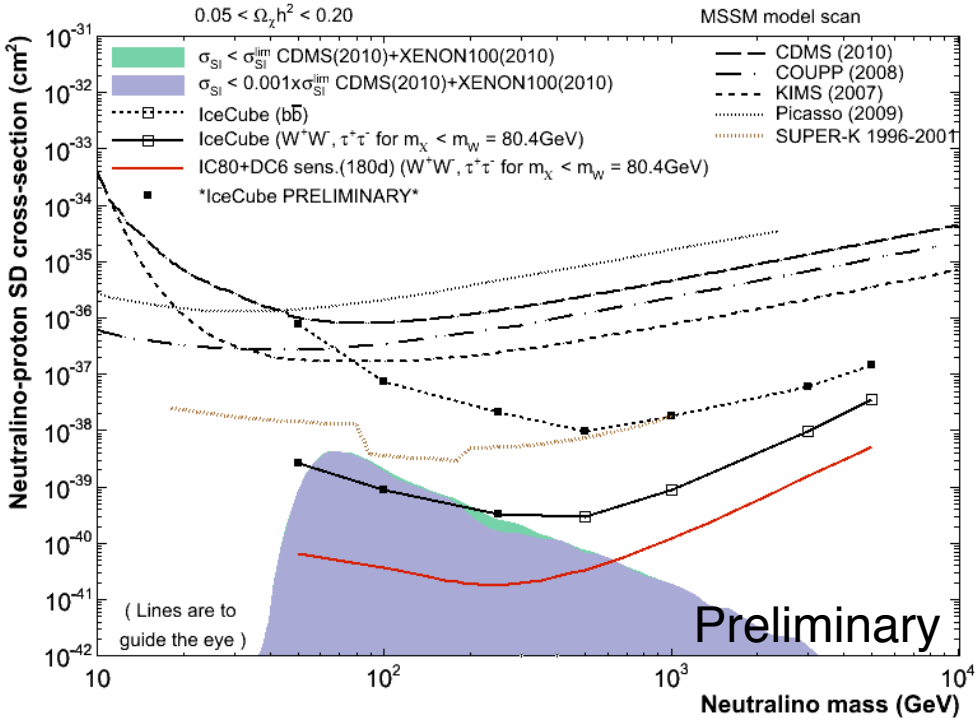
Current Status of Bounds on Dark Matter from Terrestrial experiments

Spin-Independent



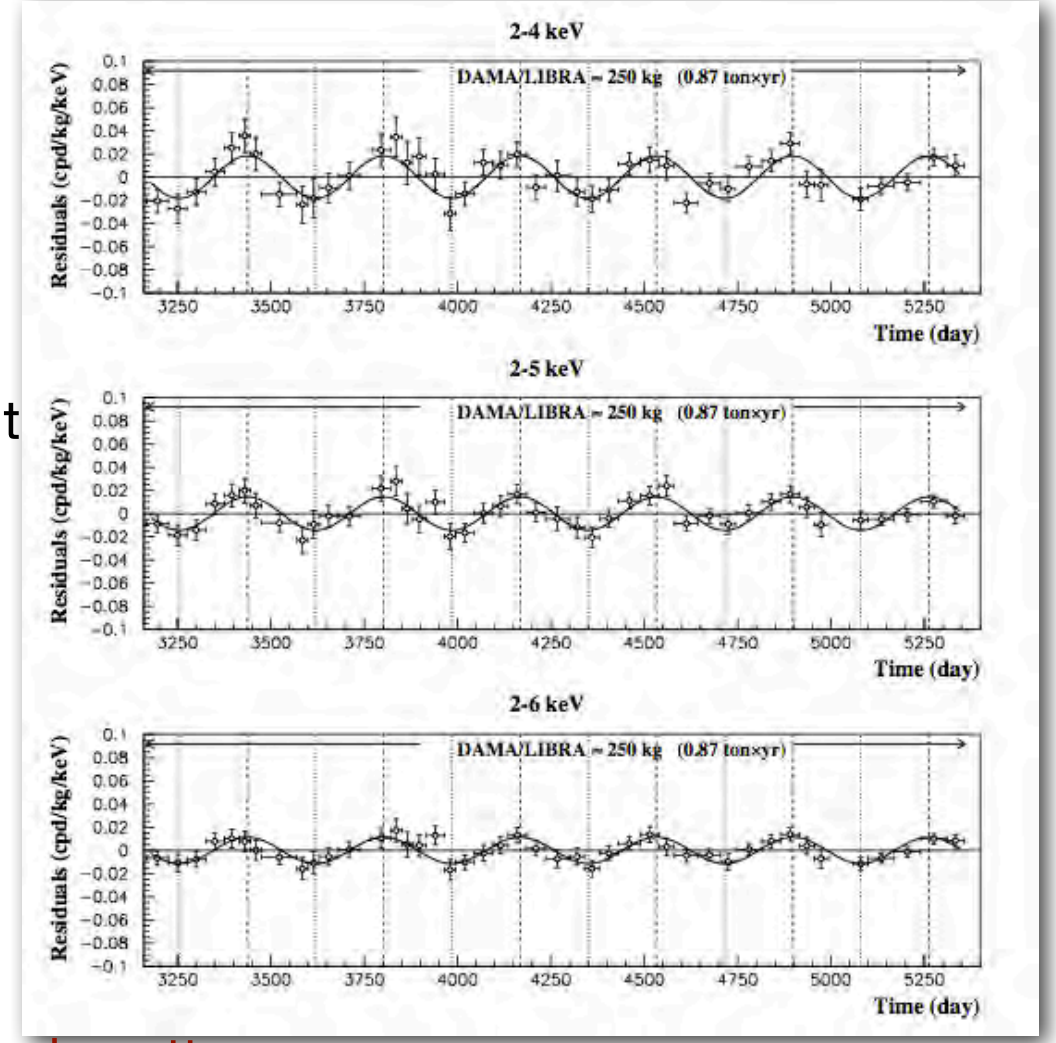
Aprile et al., PRL105:131302, 2010

Spin-Dependent



Modulation Observed by DAMA

- DAMA/NaI (1996 - 2003)
- 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



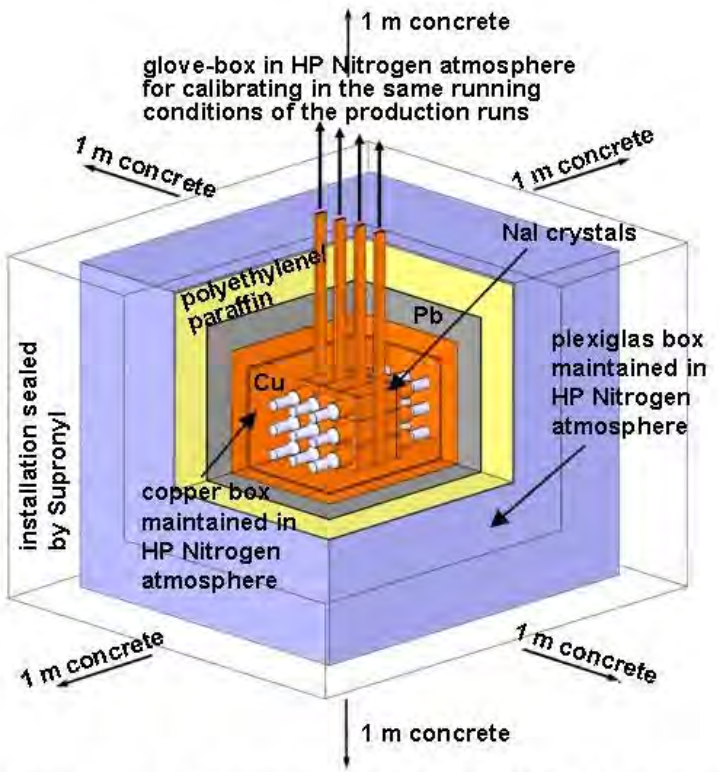
★ DAMA attributes the modulation to dark matter.

arxiv:1002.1028

DAMA/NaI, DAMA/LIBRA

- Gran Sasso, Italy under ~3800 m.w.e of rock.
- DAMA/NaI consisted of ~100 kg of NaI
- DAMA/LIBRA ~250kg
  - 25 xtals (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
- $E_{threshold}$: 2 keV_e (25 keV_r)

Claim for 9σ observation of dark matter

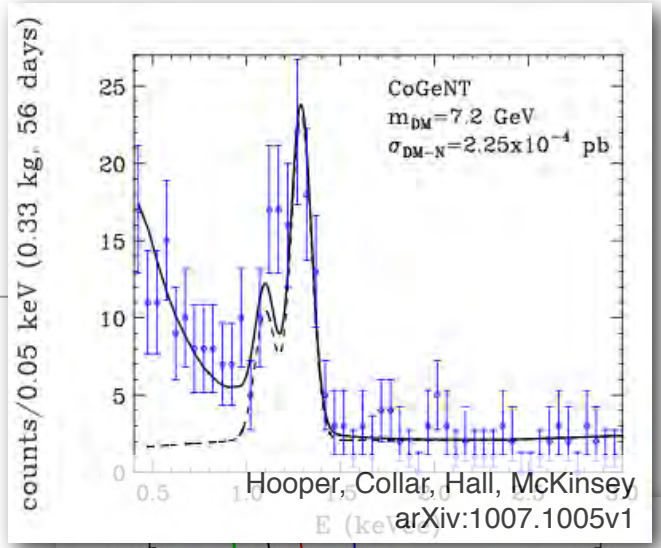


Simplified schema of ~ 100 kg NaI(Tl) set-up

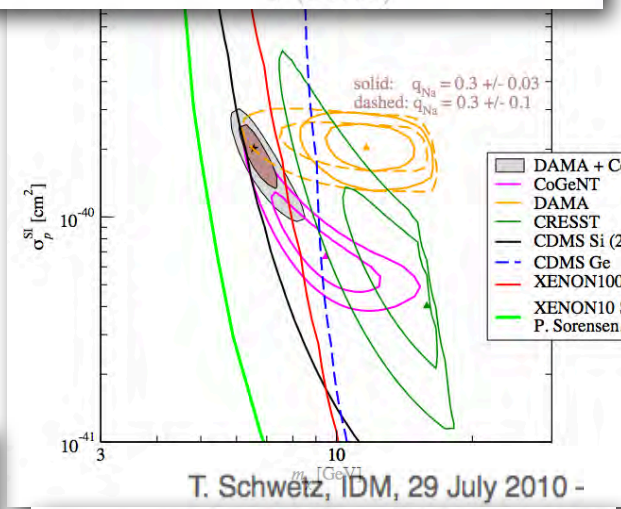
Direct detection of dark matter

Some tantalizing signals...

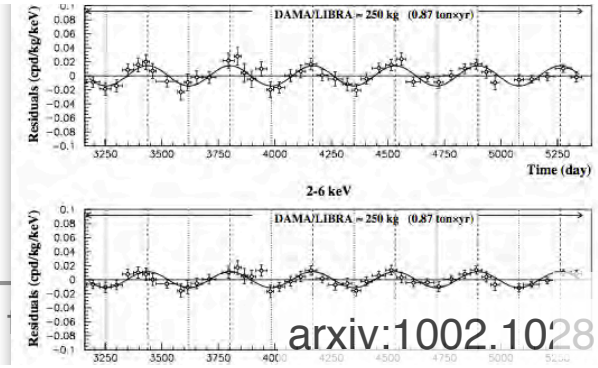
- Claim for observation from DAMA.
- Recent results from CoGeNT show some unexplained events at low energies.
- Excess events in CDMS (but no observation in their low-energy analysis), null results from XENON 100.
- Experimentalists' reaction: Background?
- Theorists' reaction: Light WIMPs? Asymmetric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



Hooper, Collar, Hall, McKinsey
arXiv:1007.1005v1



T. Schwetz, IDM, 29 July 2010 -



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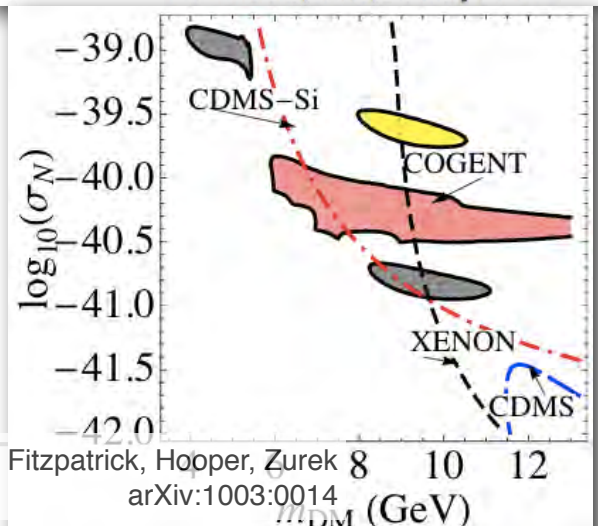

Fitzpatrick, Hooper, Zurek
arXiv:1003:0014

What is going on?

- Experimental issues?
  - These experiments are extremely challenging. We need to understand our detectors and uncertainties on quenching factors, energy scale, threshold effects, backgrounds, etc. etc....
  - Repeat the experiment with well understood detectors with well understood or different backgrounds.
- Modify astrophysics?
  - f(v)? v_{esc}? v_0? co-rotating?
- More exotic particle?
  - spin-dependent, inelastic scattering, momentum-dependent scattering...
- Proposed solution: look for annual modulation with NaI in the Southern Hemisphere.

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South Pole

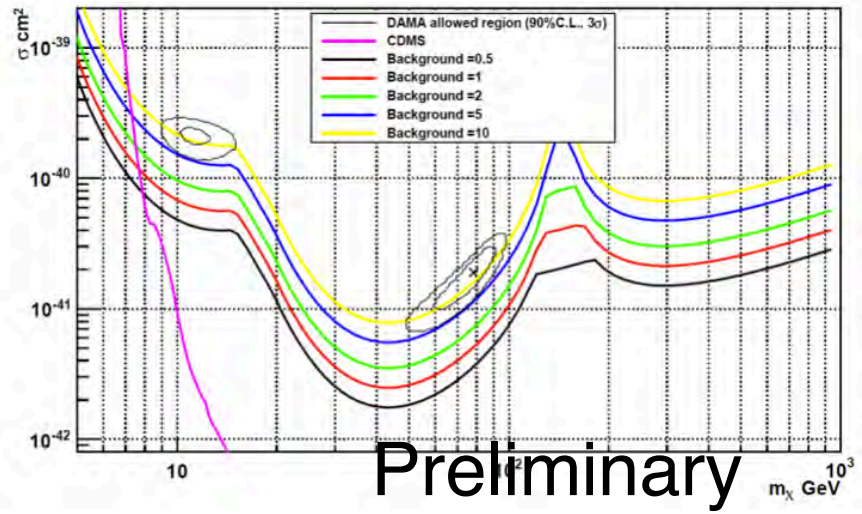
Why South Pole?

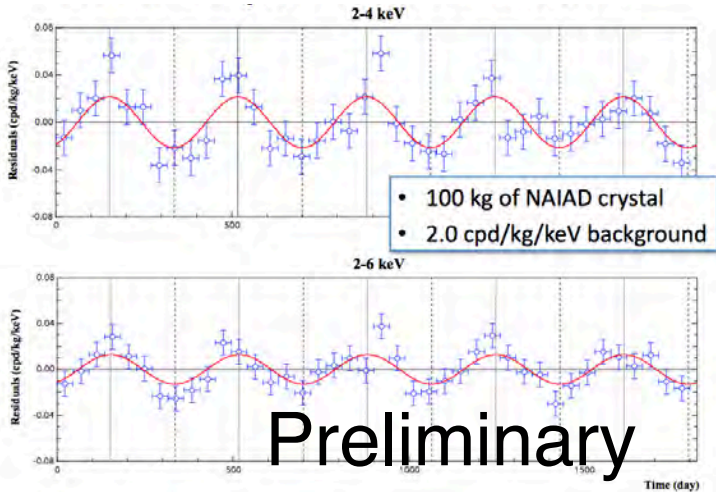
- The phase of the dark matter modulation is the same.
- Opposite seasonal modulation, e.g. muon rate (max in December).
- > 2500 m.w.e. of overburden with clean ice.
  - Many sources of backgrounds either non-existent or different from other underground sites.
  - Clean ice → no lead/copper shielding necessary. No radons.
  - Ice → 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 veto by IceCube/DeepCore
  - Infrastructure for construction, signal readout, and remote operation

Requirements for Testing DAMA

- Background rates of < 1 event/kg/keV/day
  - Use clean detectors and surrounding materials.
  - Depth of ~2400 m in the Antarctic ice
  - Co-location with IceCube can be useful for muon veto
- > 250kg of NaI(Tl) detectors
  - 2 - 4 holes, 70 cm diameter
- Long-term stability in operation
- Schedule:
  - Proposal submission fall 2011 (or spring 2012)
  - Drilling and deployment season: 2013/14 or 2014/15

5-σ detection of DAMA signal with a 250-kg NaI detector with 2-year running time (2 - 4 keV)





DM-Ice (Concept 2)
Large Pressure Vessel
Segmented Crystals

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

50 mm Copper Radial Shield
60 mm Copper End Shield

2205 SS External Pressure Vessel Shell
650 mm (25.6 inch) Outer Diameter
1700 mm (67 inch) Length

250 kg NaI (38@6.5 kg crystals)
850 kg Cu (2@153 end plates, 12@58 rings)
450 kg 2205 SS (2@76 hemisphere, 285 cylinder)
1550 kg total

* one of several designs under consideration.

Electronics Space at each end
Electronics and Feedthrus not modeled

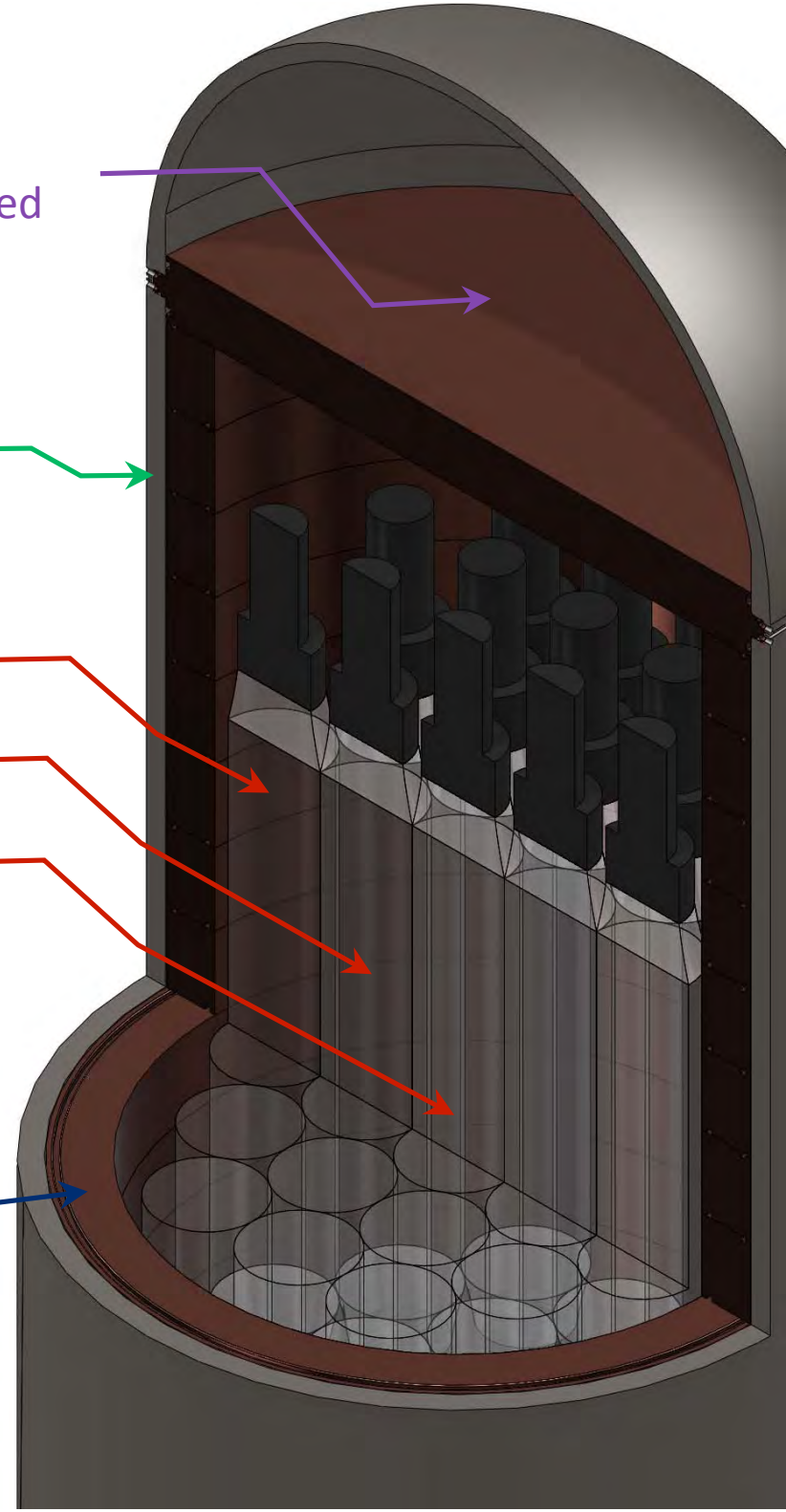
Pressure Vessel Cylinder & Hemisphere
Needs to be high strength to survive
7200 psi freeze pressure
Could be copper if 3500 psi maximum pressure

Thirteen Crystal Outer Zone

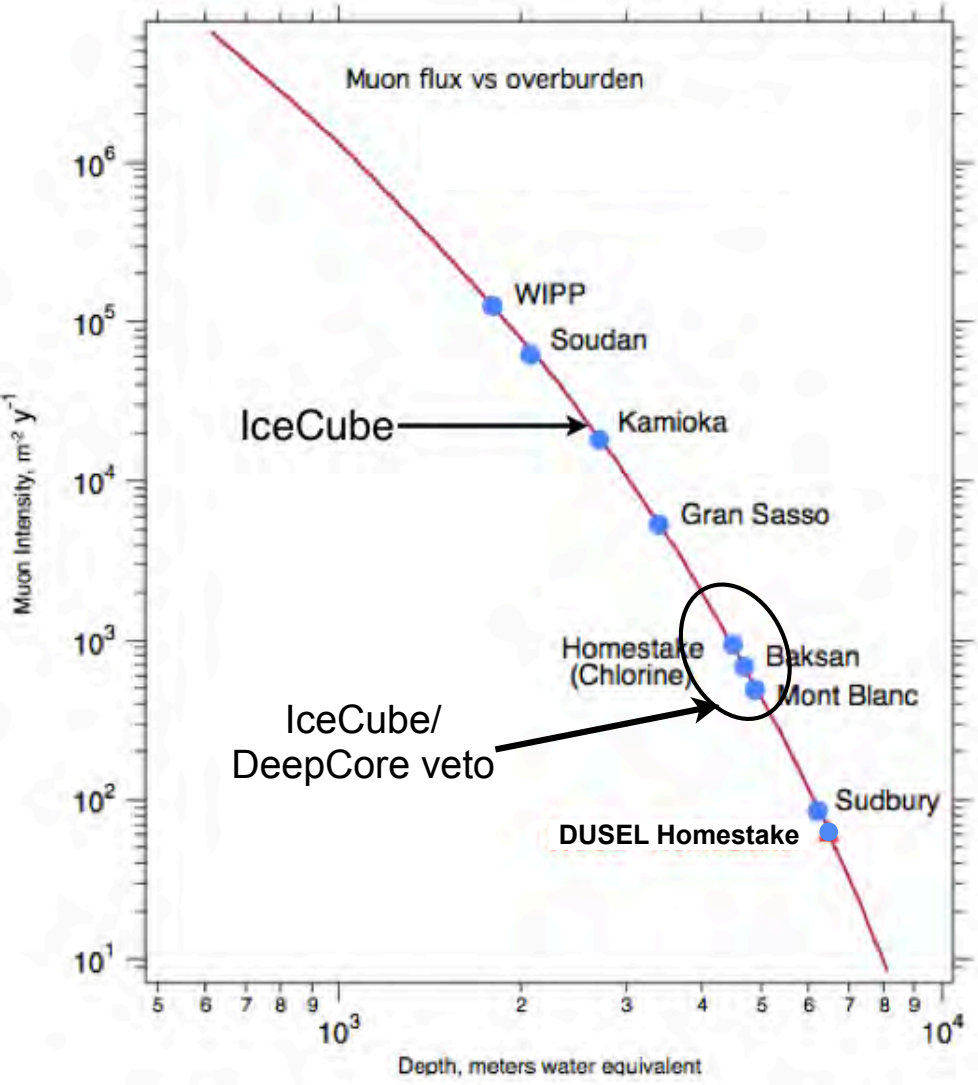
Six Crystal Middle Zone

One Crystal Inner Zone

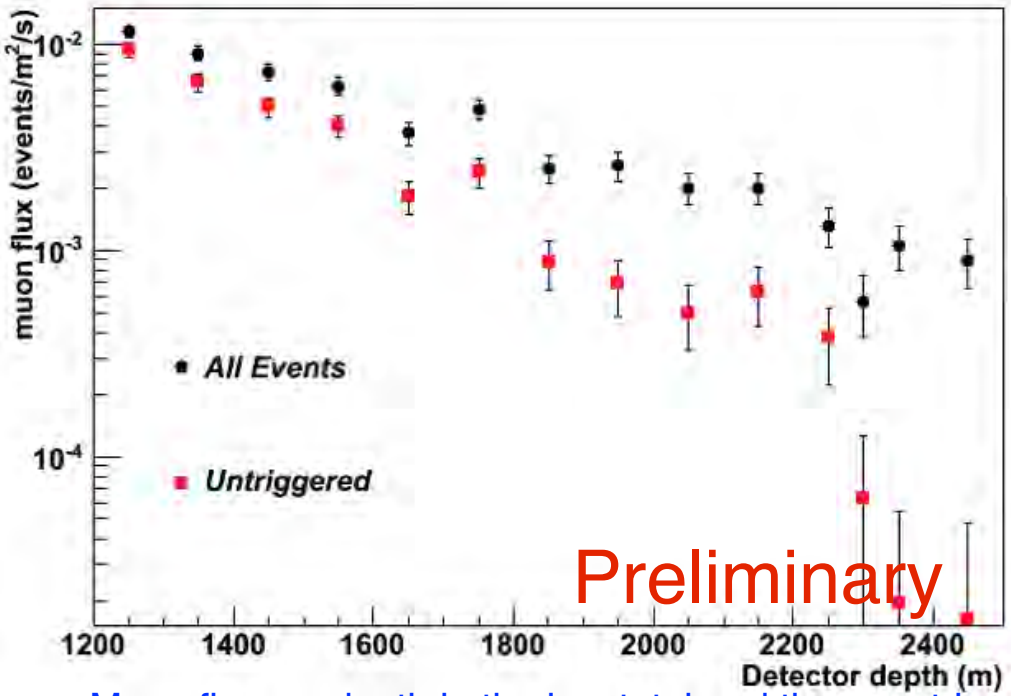
Stacked 75 mm thick shielding rings
Can be sealed together with O-rings to form leak tight cylinder
Can carry structural pressure load is freeze pressure is limited



Antarctic Ice: Overburden at -2500 m (2200 m.w.e.)



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

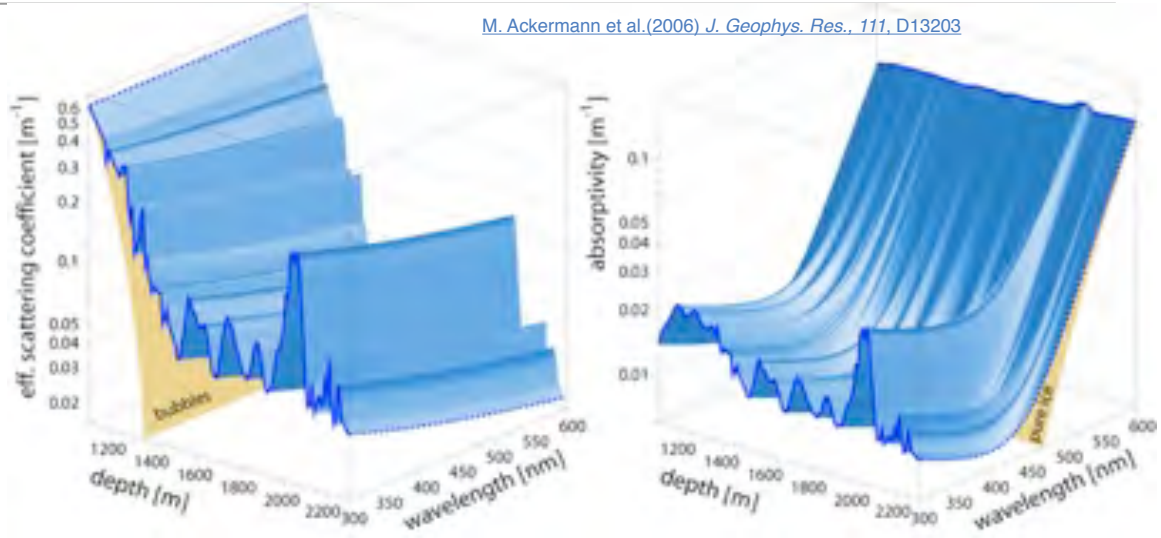


Muon flux vs. depth in the ice, total and those untriggered by IceCube/DeepCore. (Darren Grant)

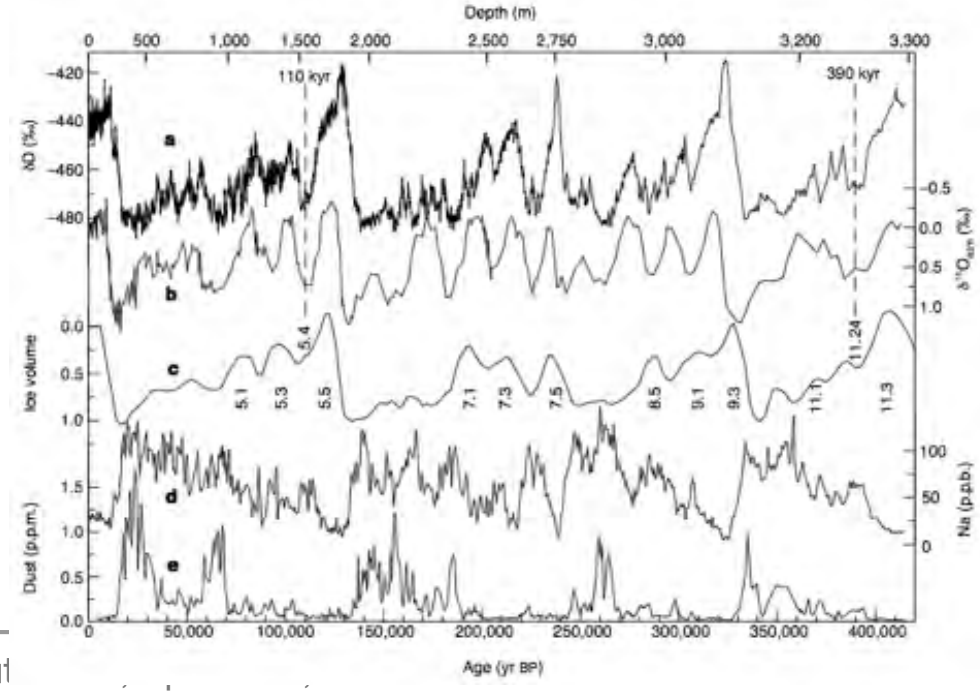
Radiopurity of Antarctic Ice

- -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

M. Ackermann et al.(2006) *J. Geophys. Res., 111*, D13203



Petit et al, (1999) Nature 399 p. 429



Water Purity Analysis

- Drill water may introduce impurities in the water
- Water samples from 3 holes taken during 2009 - 2010 season for IeCube
- Additional analysis from 2010/11 holes
- Samples taken from return from the inlet in to “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


Jonas Kalin, Jan. 2010

DM-Ice prototype deployment in 2010

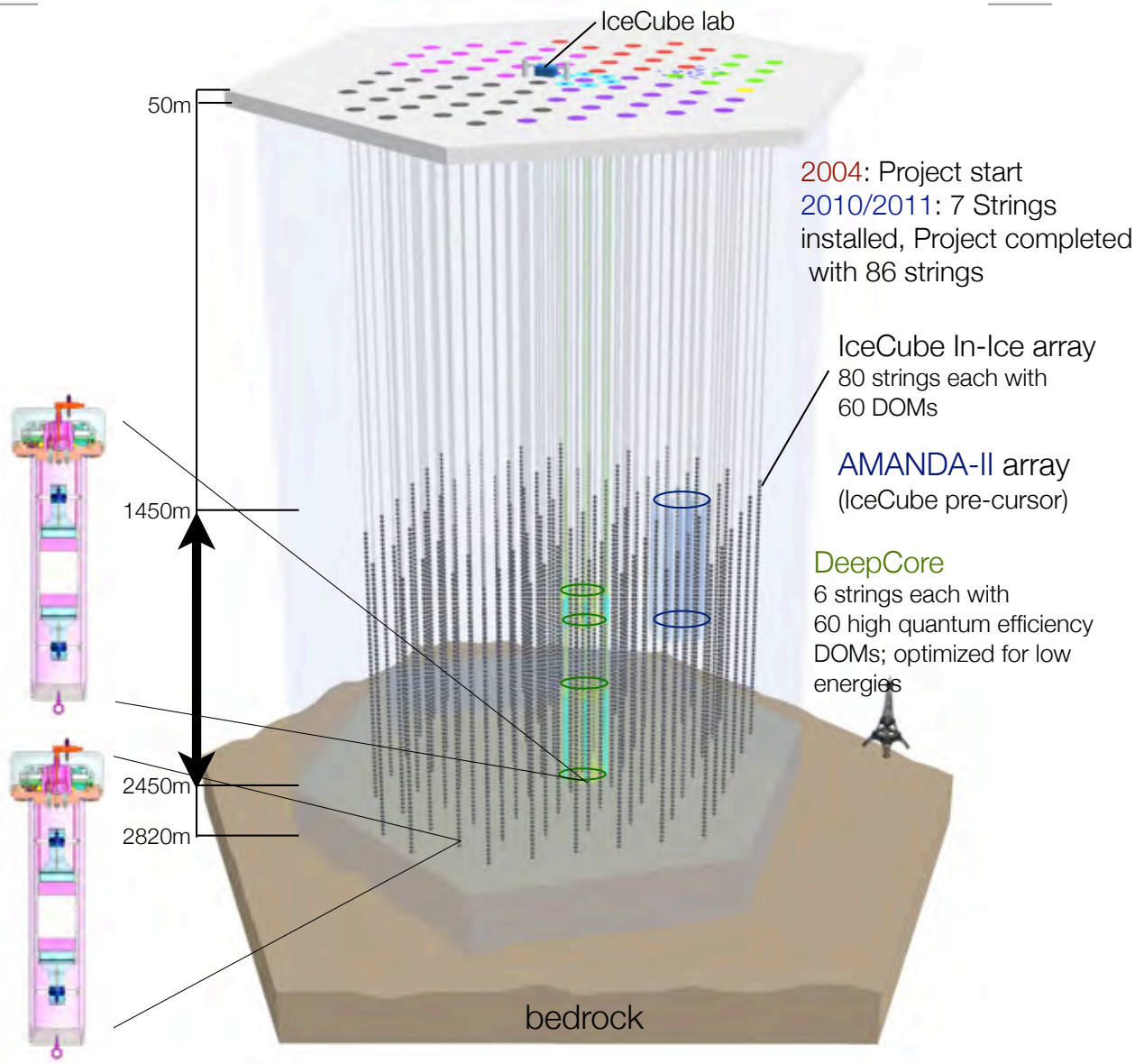
Detectors:

- 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

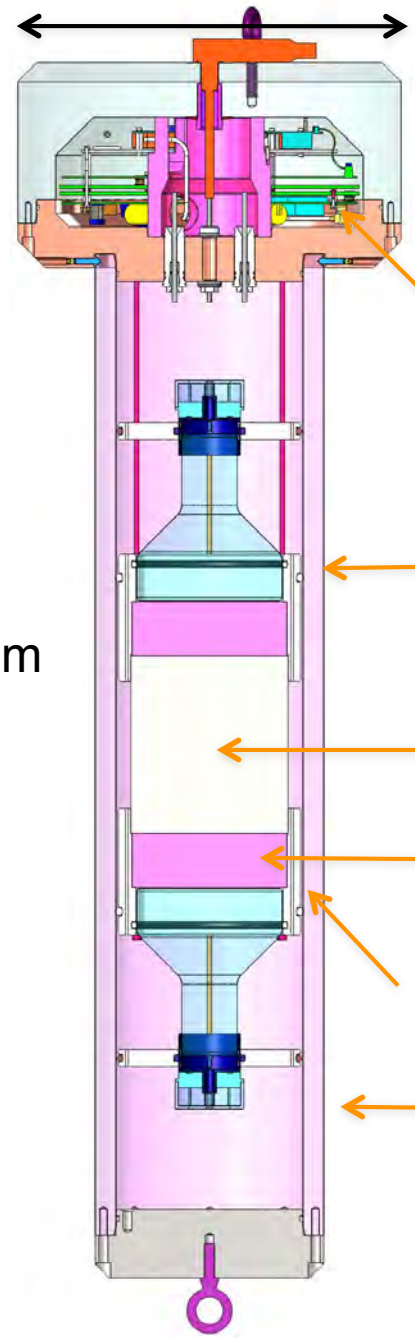
Installation in Dec. 2010

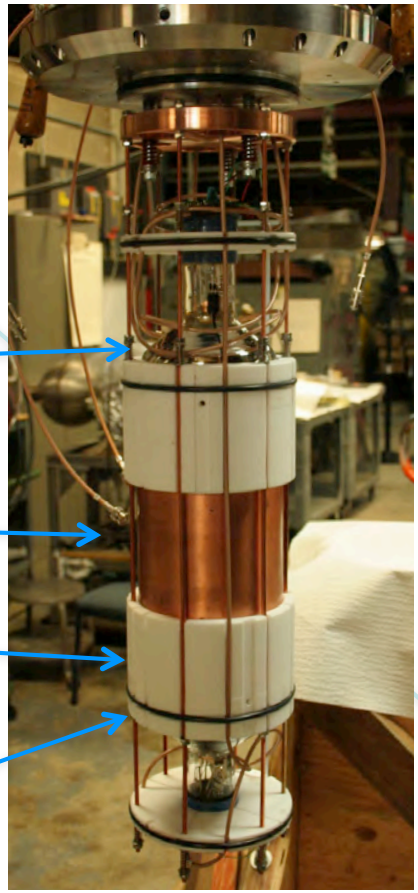


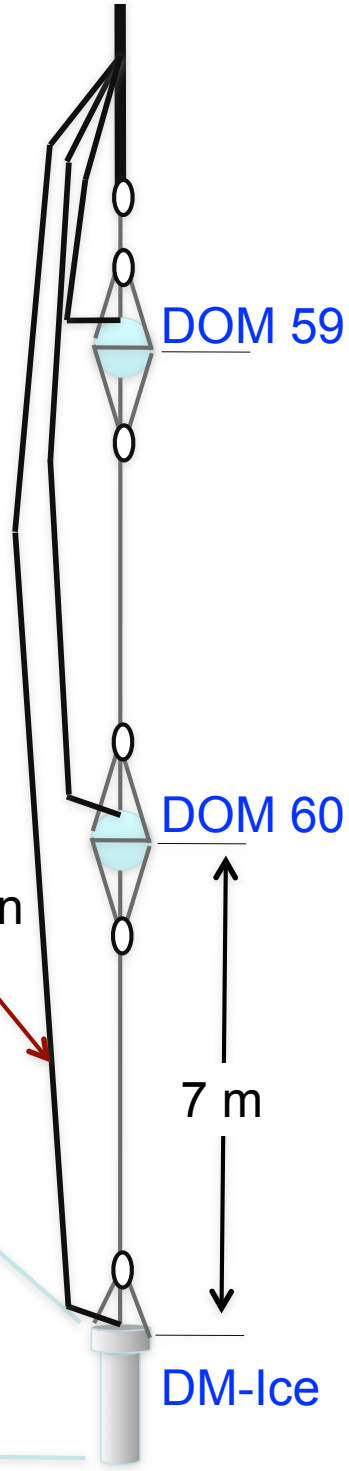
Prototype schedule and design criterion

- Schedule
  - Start design in Feb. 2010. Funding through UW-Madison.
  - Small funding via NSF Rapid in August 2010.
  - Ship to the South Pole by November 5, 2010 to meet IceCube construction schedule.
  - Deployment along with the last 7 IceCube strings: December 5 - 20, 2010.
- Design
  - Find the cleanest possible crystals, PMTs & surrounding materials.
  - Enclose detector in a pressure vessel to withstand 6000 psi from 2500 m of water above + water refreeze process.
  - Record waveforms from NaI pulses, transmit data North.
  - No interference with IceCube operation, minimal impact on construction schedule.

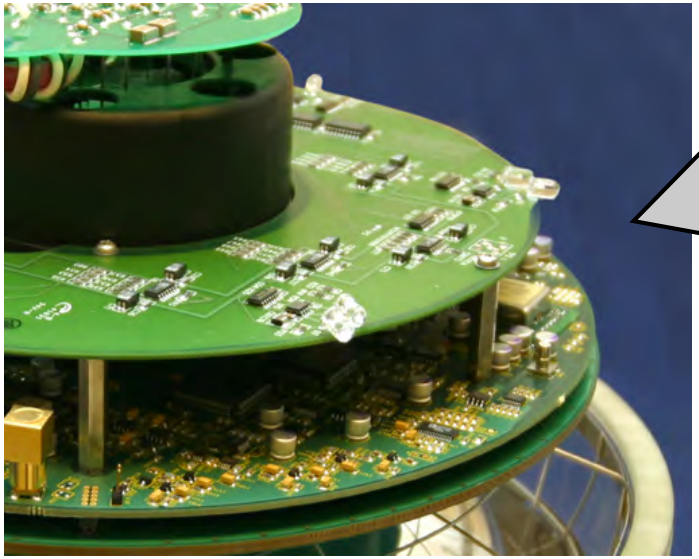
DM-Ice Feasibility Study Detector

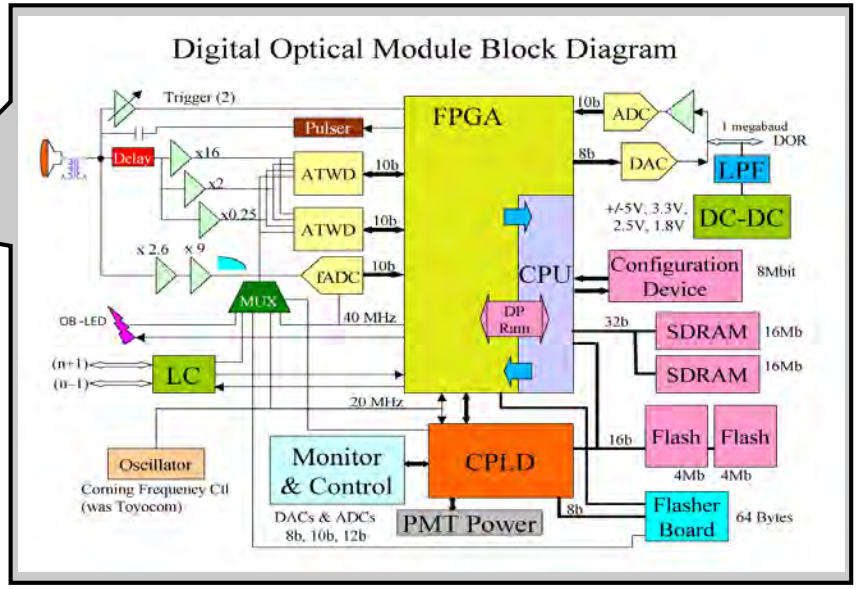


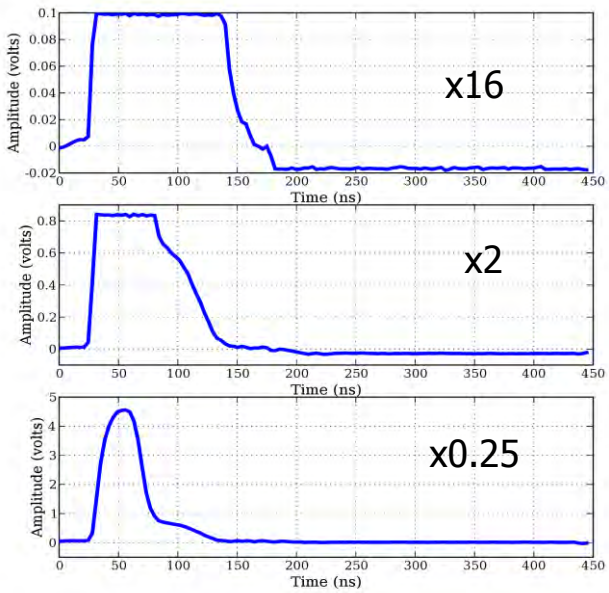




IceCube DOM mainboards





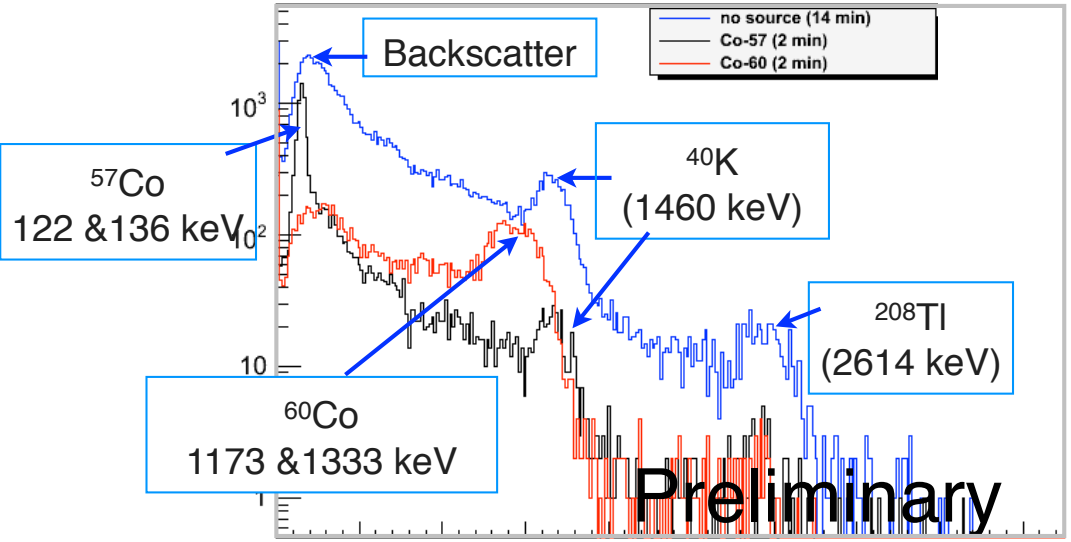


- 40 MHz 10-bit flash ADC for slow high energy events
- 2 parallel Analog Transient Waveform Digitizer (ATWD) chips, 10-bit resolution and programmable sampling speeds from 250 MHz to 1 GHz
- Each ATWD contains 3 gain paths: x16, x2, x0.25 (giving effectively 14-bits)
- Coincidence trigger capabilities
- Controls a separate HV board
- Programmable from surface

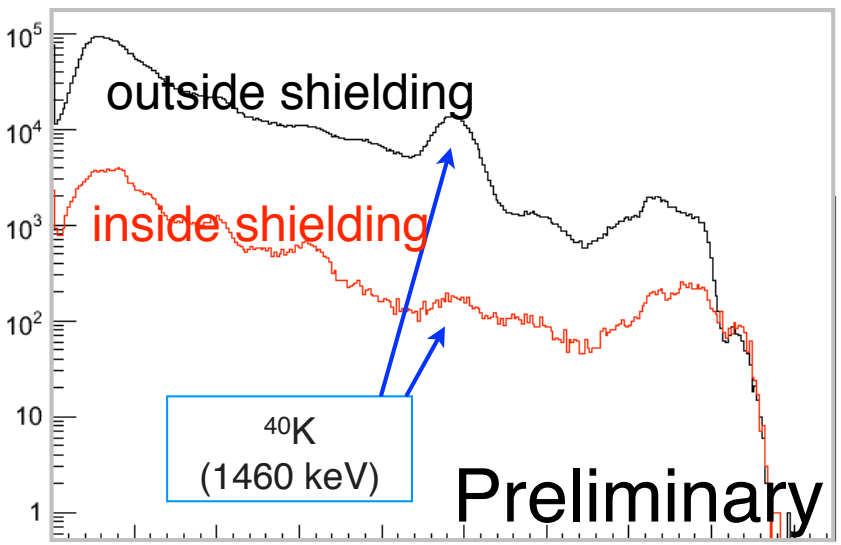
2 NAIAD Crystals from Boulby

- 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.

First look at the detectors at Boulby



^{57}Co & ^{60}Co calibration outside shielding

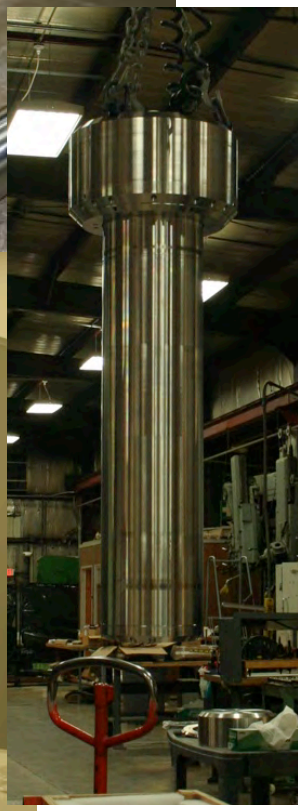


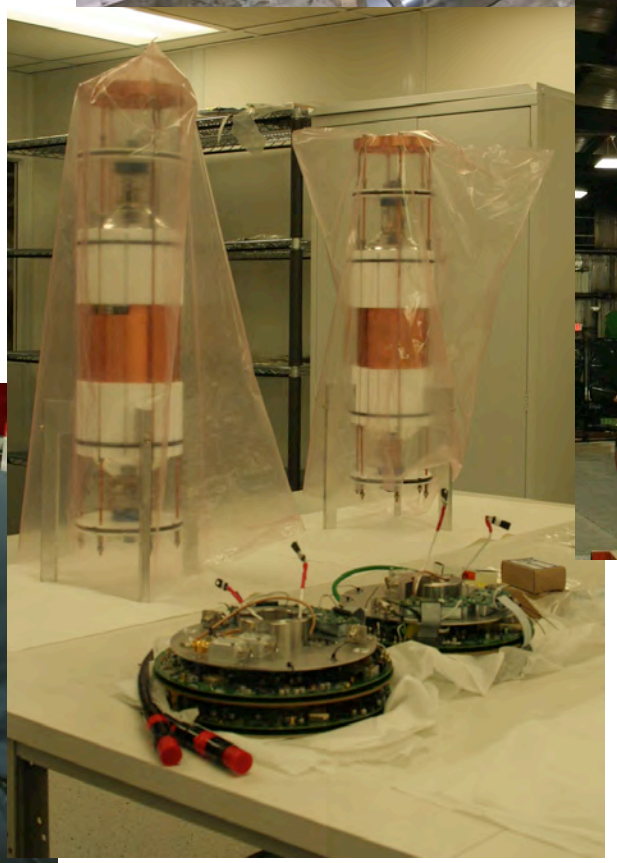
Background measurement inside and outside the shielding

- Detectors seem to be working as well as they did while NAIAD was in operation, background rates reasonable.

Pressure vessel, support structures, etc

- 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

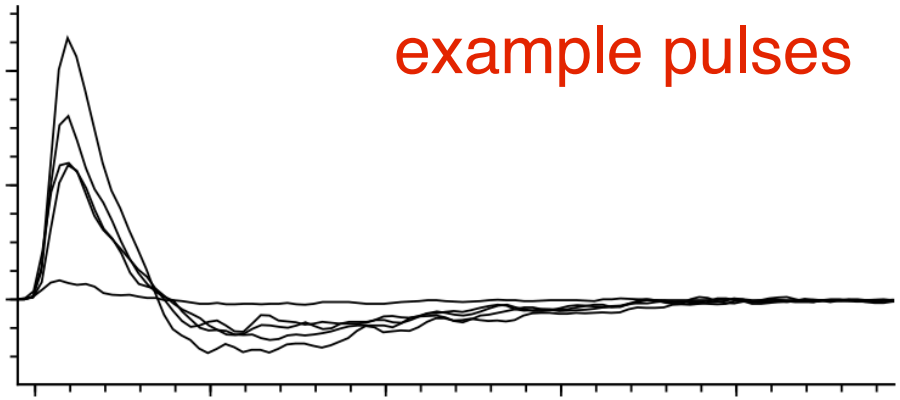




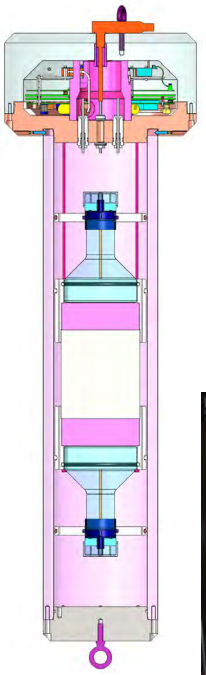

Arbuckle

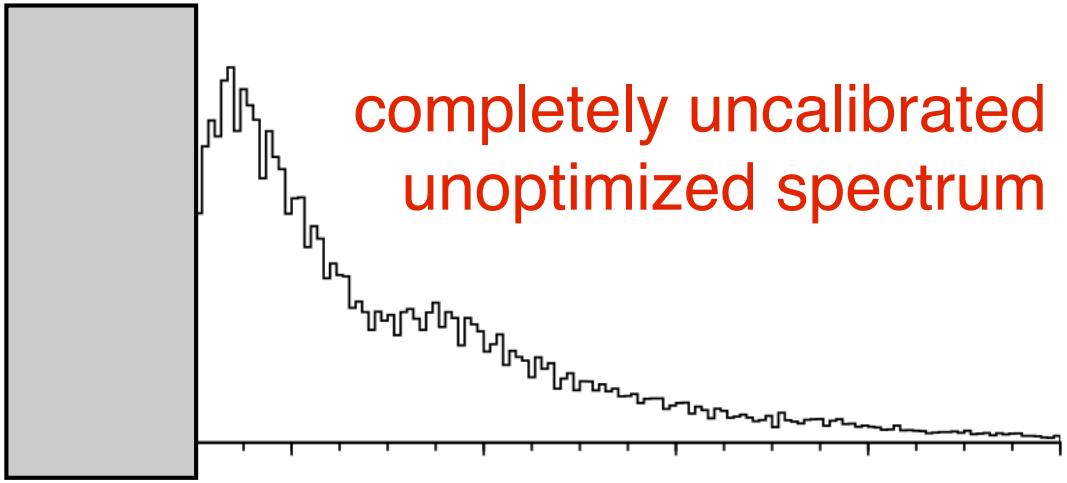
Data from the South Pole

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



example pulses

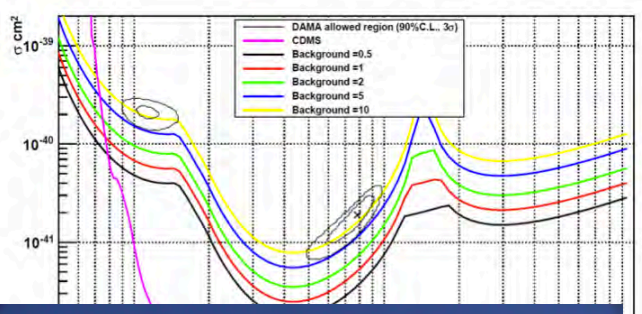




completely uncalibrated
unoptimized spectrum

Current Status & Future Outlook

- DM-Ice prototype (17 kg) deployed in December 2010
  - Currently taking data, tweaking operating parameters
  - data transmitted over satellite
  - optimizing analysis, background studies with radio-assay & monte carlo simulation
- >250-kg scale detector under consideration
  - Proposal in Fall 2011/Spring 2012
  - Drilling and deployment season: 2013/14 or 2014/15
  - Low background crystals are crucial
  - Low background PMTs, pressure vessels, etc.



Current DM-Ice Collaboration

- 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*
- + few possible future collaborators.

*members of IceCube Collaboration

Thank you!!