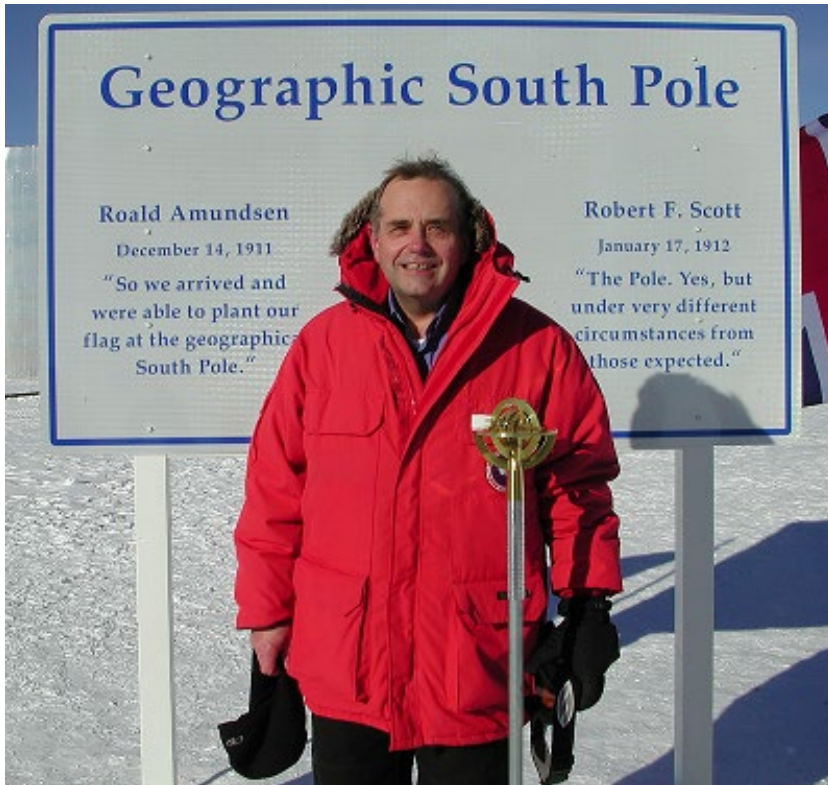


Solar Physics with IceTop



(How I Learned to
Stop Worrying and
Love the South Pole)

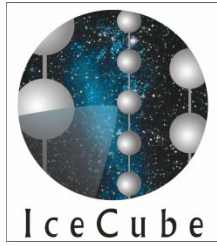
Paul Evenson

University of Delaware,
Department of Physics and
Astronomy

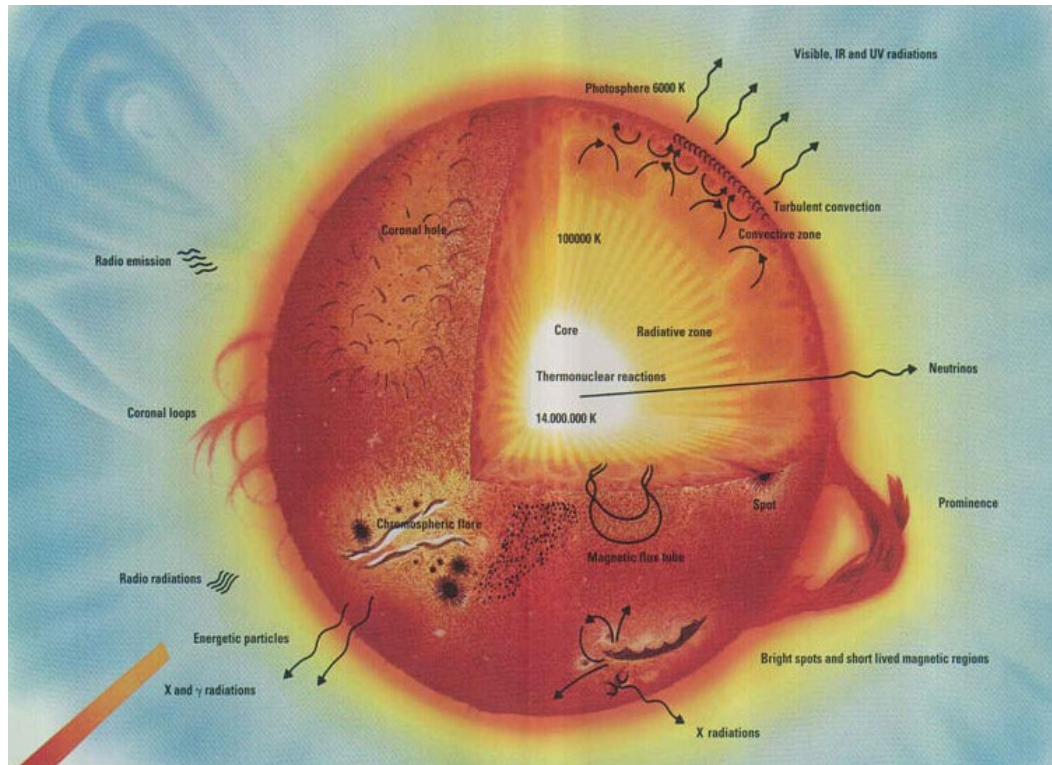
ThaisCube

Chiang Mai

August 10, 2023

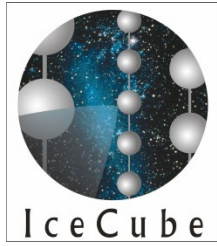


The Sun is a Giant Heat Engine

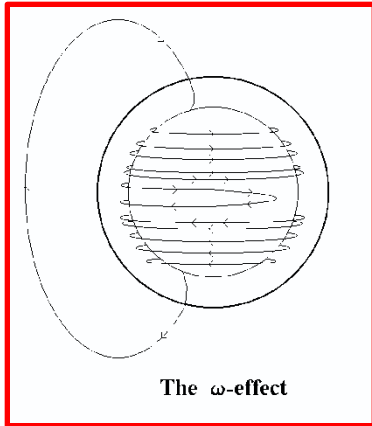


It takes approximately one million years for the energy to be conducted (by radiation) to the outer part of the sun.

Near the surface, convective motion sets in. Approximately 100,000 years of sunlight is stored in the convection zone

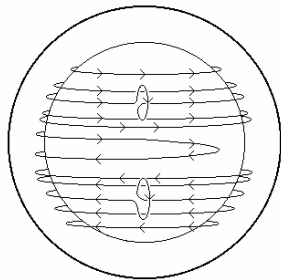


The Heat Engine Powers a Magnetic Dynamo

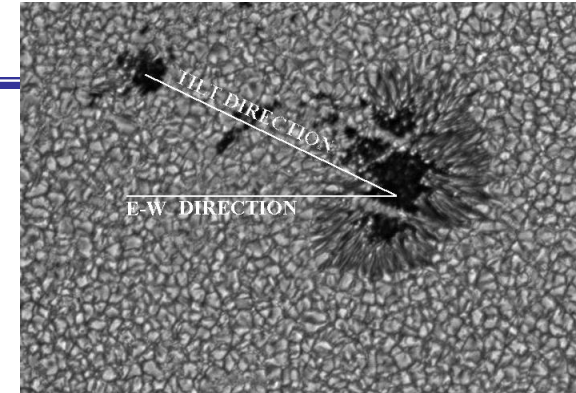


Magnetic fields within the Sun are stretched out and wound around the Sun by differential rotation

This is called the *omega-effect* after the Greek letter used to represent rotation.

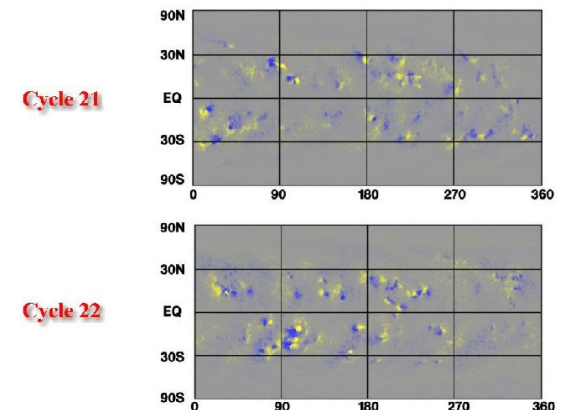


The Sun's differential rotation with latitude can take a north-south oriented magnetic field line and wrap it once around the Sun in about 8 months.

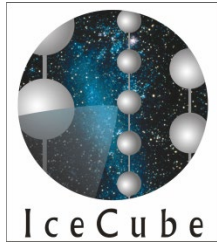


Hale's Polarity Law:

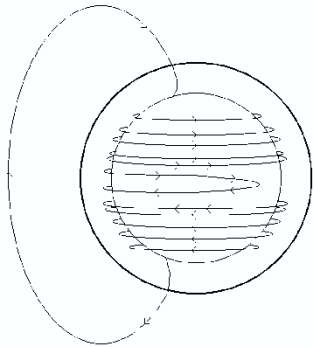
The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.



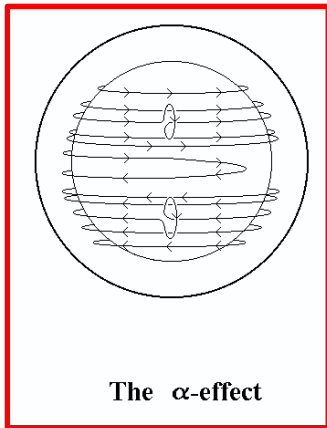
- <http://solarscience.msfc.nasa.gov/dynamo.shtml>



The Heat Engine Powers a Magnetic Dynamo



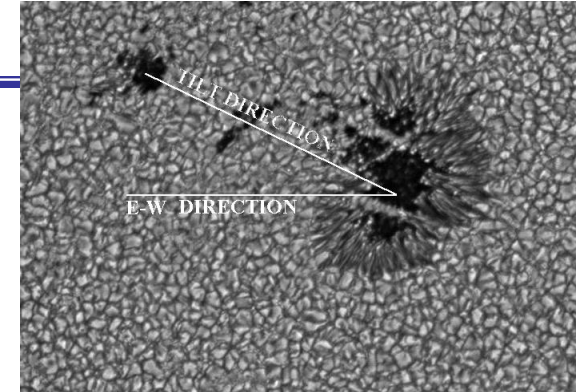
The ω -effect



The α -effect

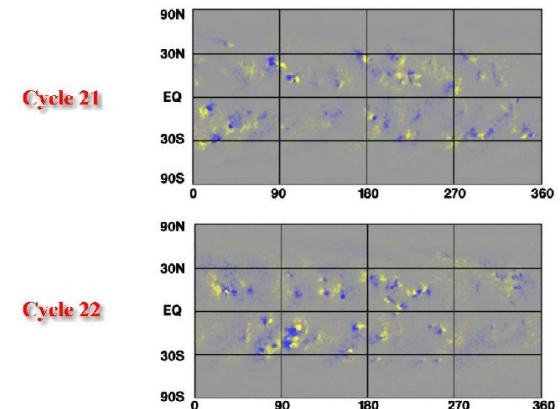
Twisting of the magnetic field lines is called the *alpha-effect* after the Greek letter that looks like a twisted loop.

Early models of the Sun's dynamo assumed that the twisting is produced by the effects of the Sun's rotation on very large convective flows that carry heat to the Sun's surface.

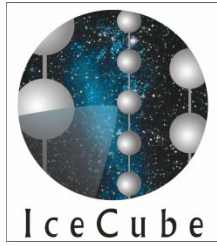


Hale's Polarity Law:

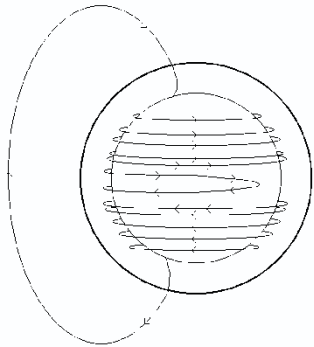
The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.



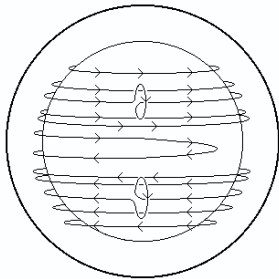
- <http://solarscience.msfc.nasa.gov/dynamo.shtml>



The Heat Engine Powers a Magnetic Dynamo



The ω -effect

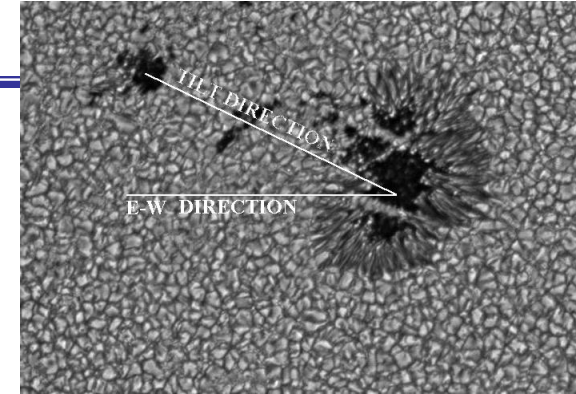


The α -effect

More recent dynamo models assume that the twisting is due to the effect of the Sun's rotation on the rising "tubes" of magnetic field from deep within the Sun.

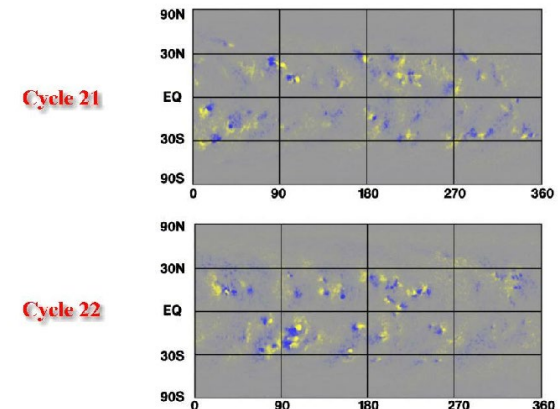
The twist produced by the alpha effect makes sunspot groups that obey "Joy's law" – the relation of the angle between sunspots in a group to location on the sun.

It also makes the magnetic field reverse from one sunspot cycle to the next (Hale's Law).

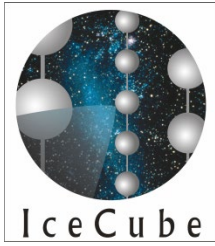


Hale's Polarity Law:

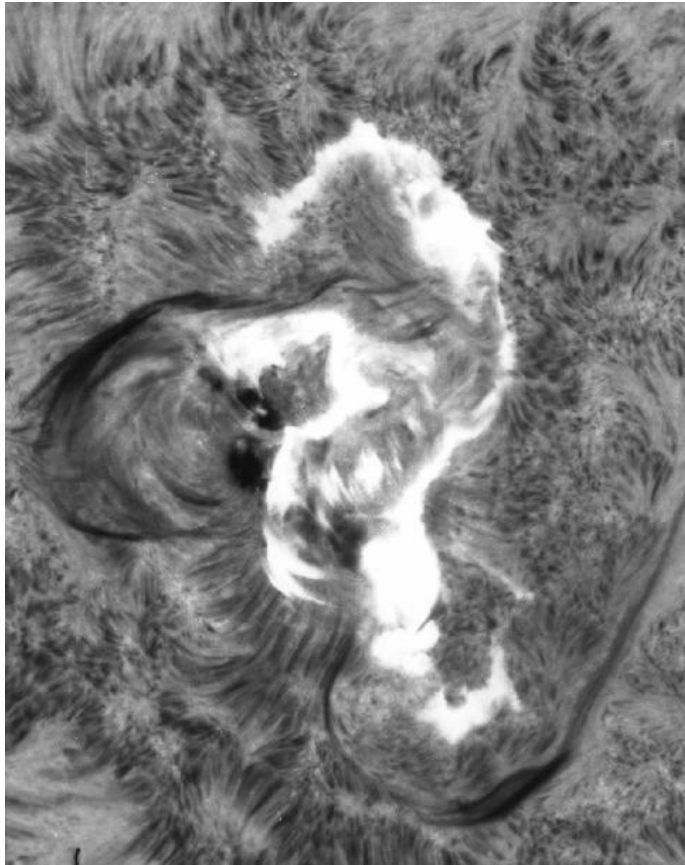
The polarity of the leading spots in one hemisphere is opposite that of the leading spots in the other hemisphere and the polarities reverse from one cycle to the next.



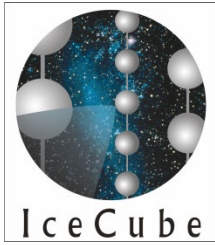
- <http://solarscience.msfc.nasa.gov/dynamo.shtml>



Magnetic Energy Powers Flares

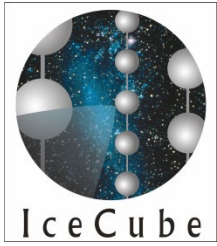


- Somewhere in this picture, particles are being accelerated to GeV energy.
- Can you tell where?
- I certainly cannot!
- Possibly different mechanisms are even operating at the same time.



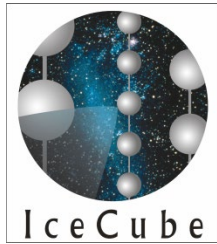
What Does This Have to do with Antarctica?





The IceCube Project: A New View of the Universe from the South Pole





Ice Cube Collaboration



THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta-Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

ITALY
University of Padova

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

SOUTH KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

TAIWAN
Academia Sinica

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Columbia University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University

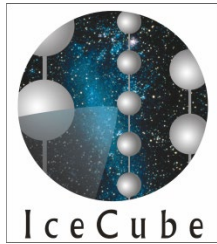
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas

University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin-Madison
University of Wisconsin-River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS) Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)	Federal Ministry of Education and Research (BMBF) German Research Foundation (DFG) Deutsches Elektronen-Synchrotron (DESY)	Japan Society for the Promotion of Science (JSPS) 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)
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icecube.wisc.edu

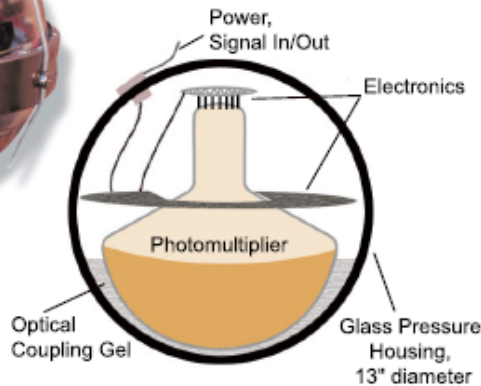
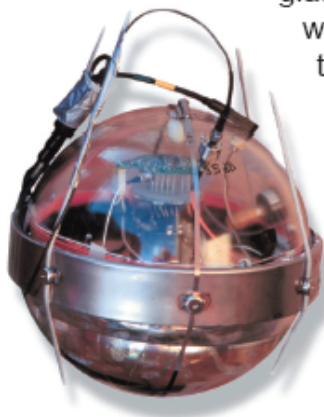


Ice Cube Operation

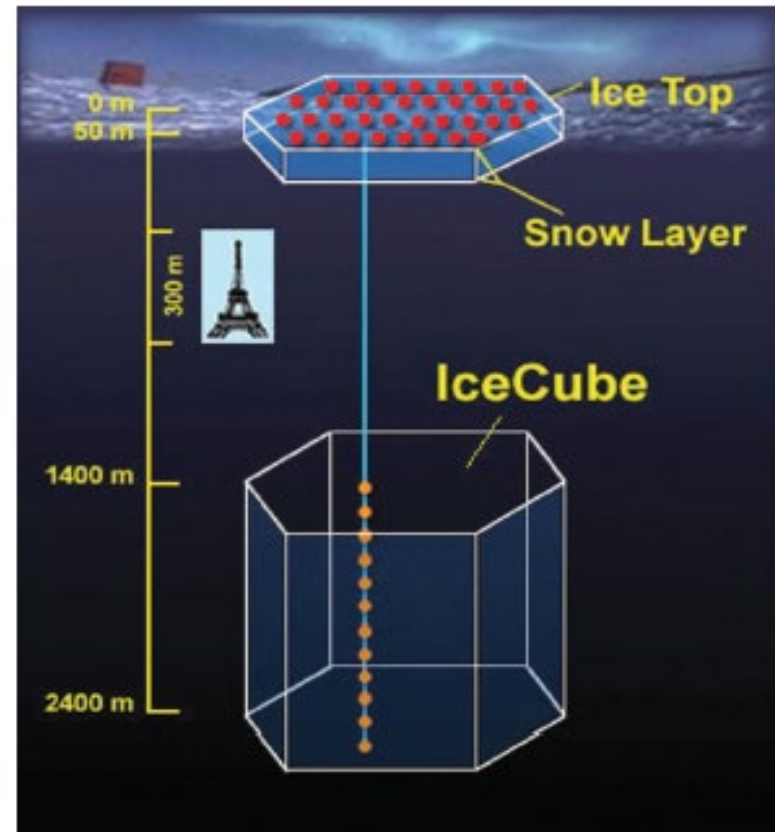


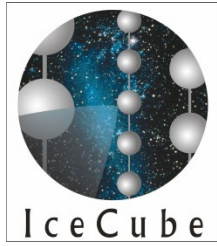
How does IceCube “see” a neutrino?

Like its predecessor, AMANDA, the basic component of IceCube is the sensor that transforms light into electrical signals. A sensor is a photomultiplier tube housed in a glass pressure vessel; IceCube will boast nearly 5000. The technology used in IceCube will be more advanced than that of AMANDA. IceCube will have “smart”



sensors, meaning that each sensor will contain a computer chip connected through the internet to computers in scientists’ offices! It is not too fanciful to think of the device as a cubic-kilometer, continuously sensing computer.



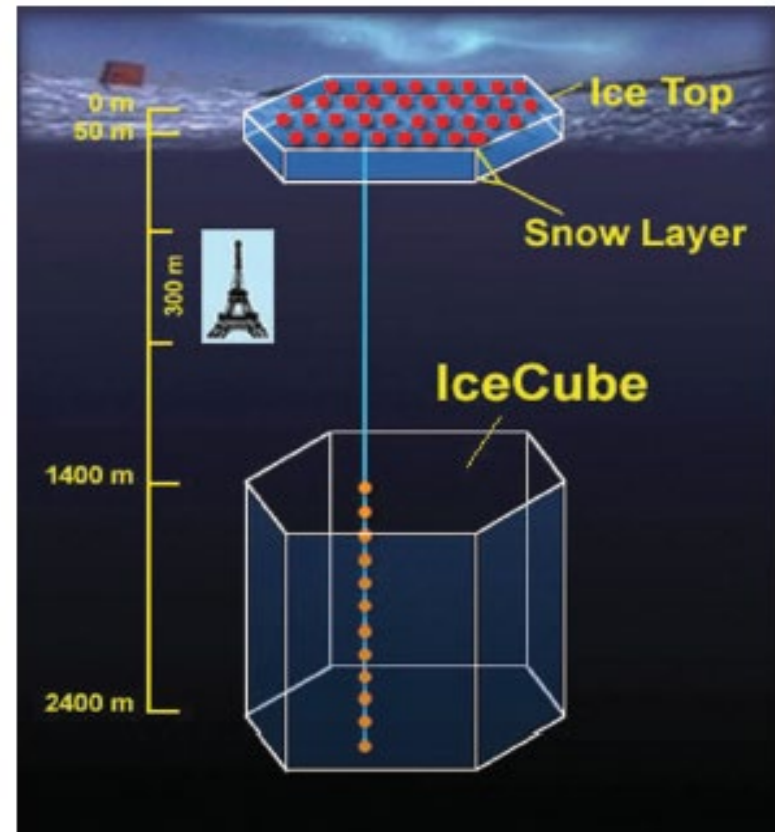


The Surface Air Shower Array (IceTop)

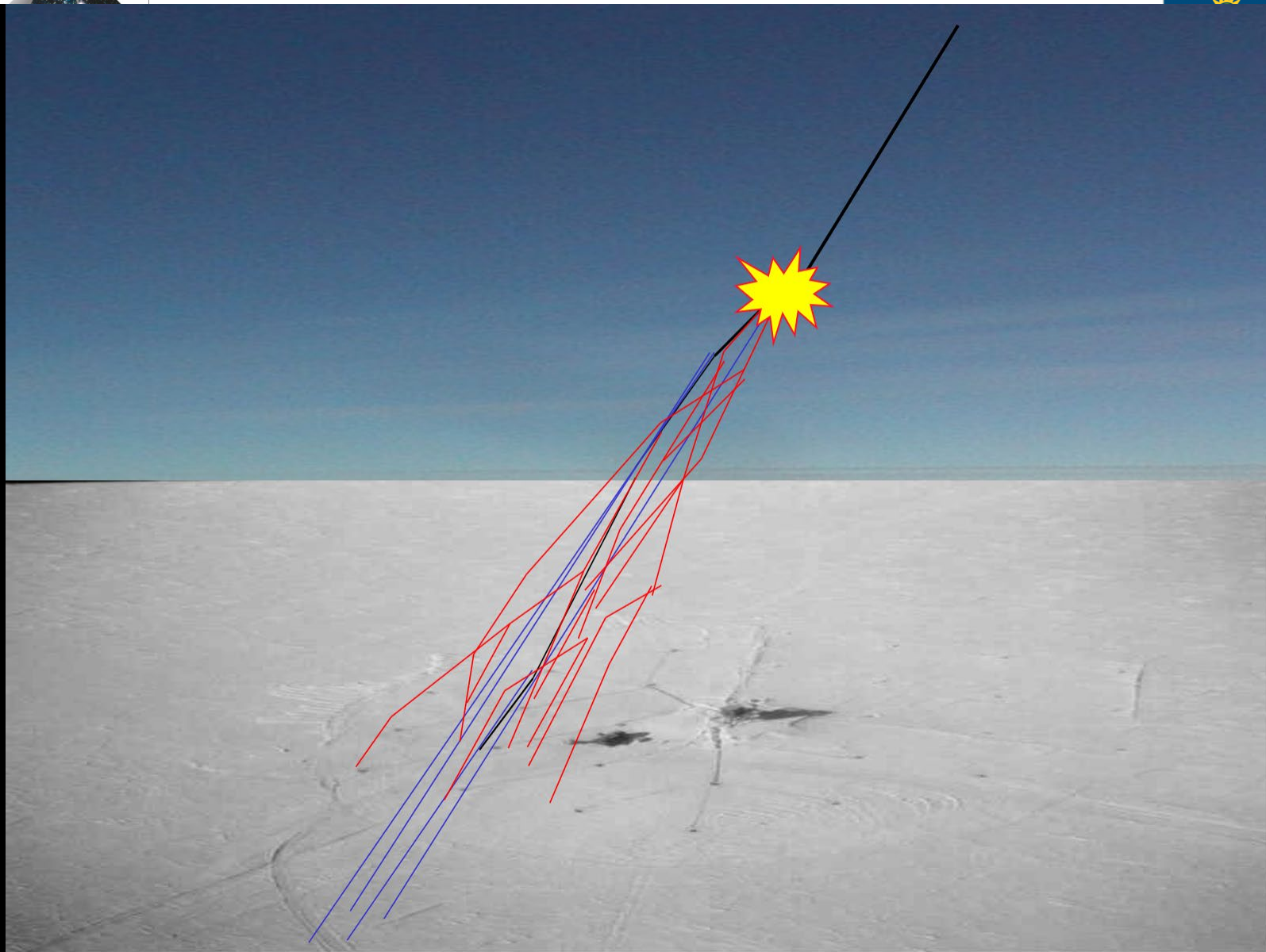


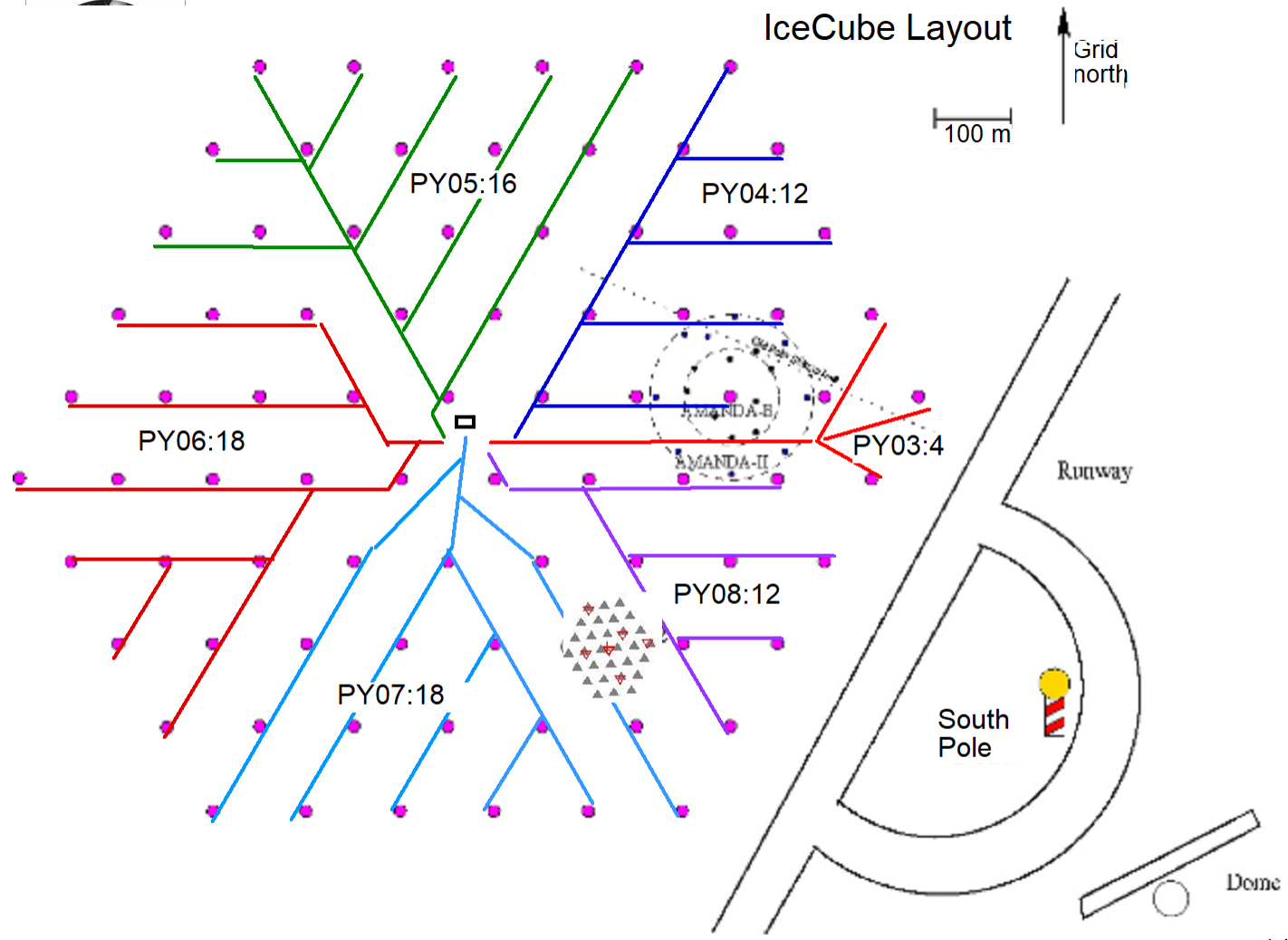
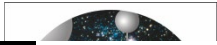
Developing and deploying the surface air shower detector is where I spent most of my time, so I focus on the unexpected results from that part of the detector.

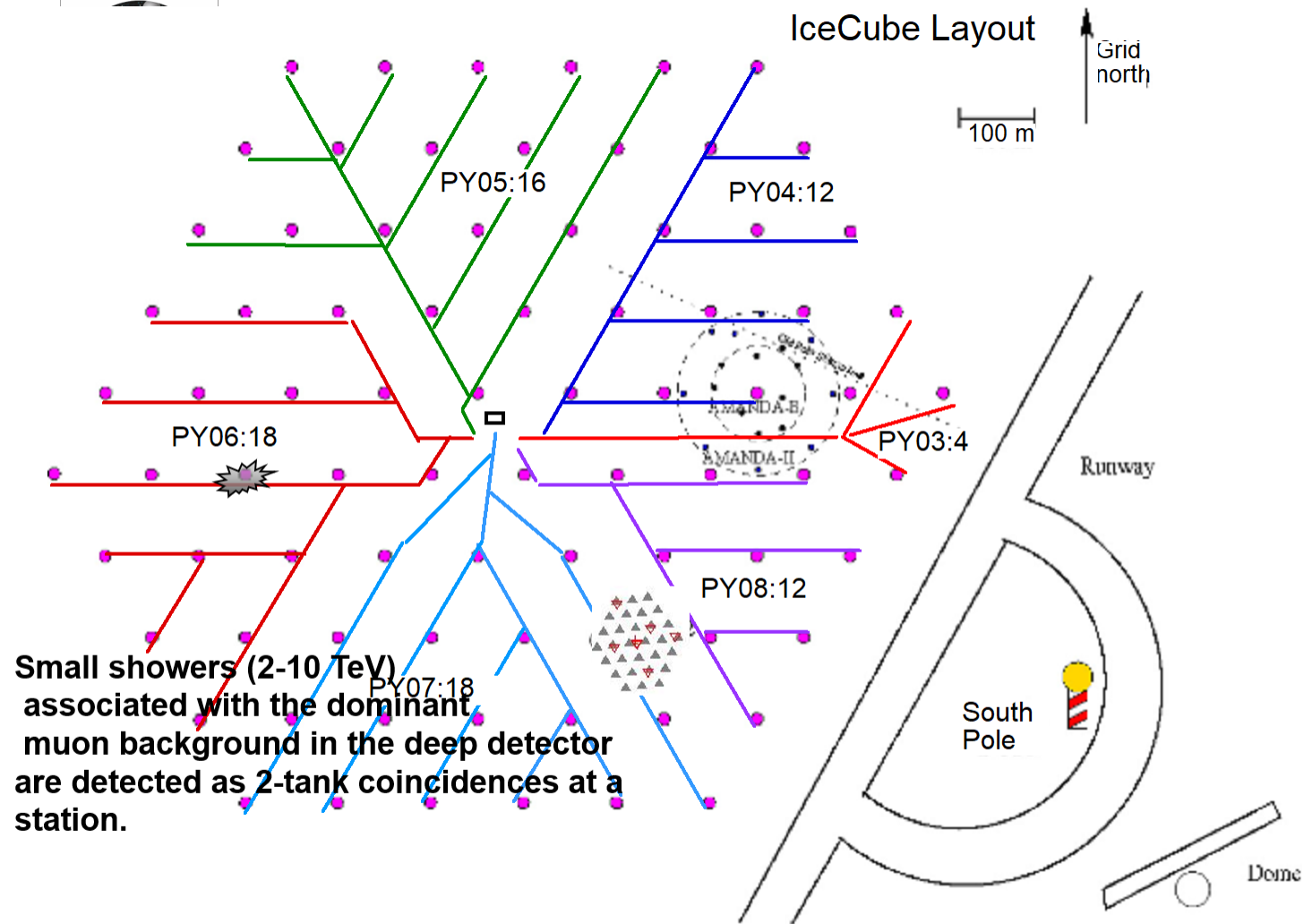
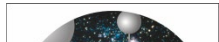
It is also an important part of the collaboration with Mahidol and Chiang Mai.



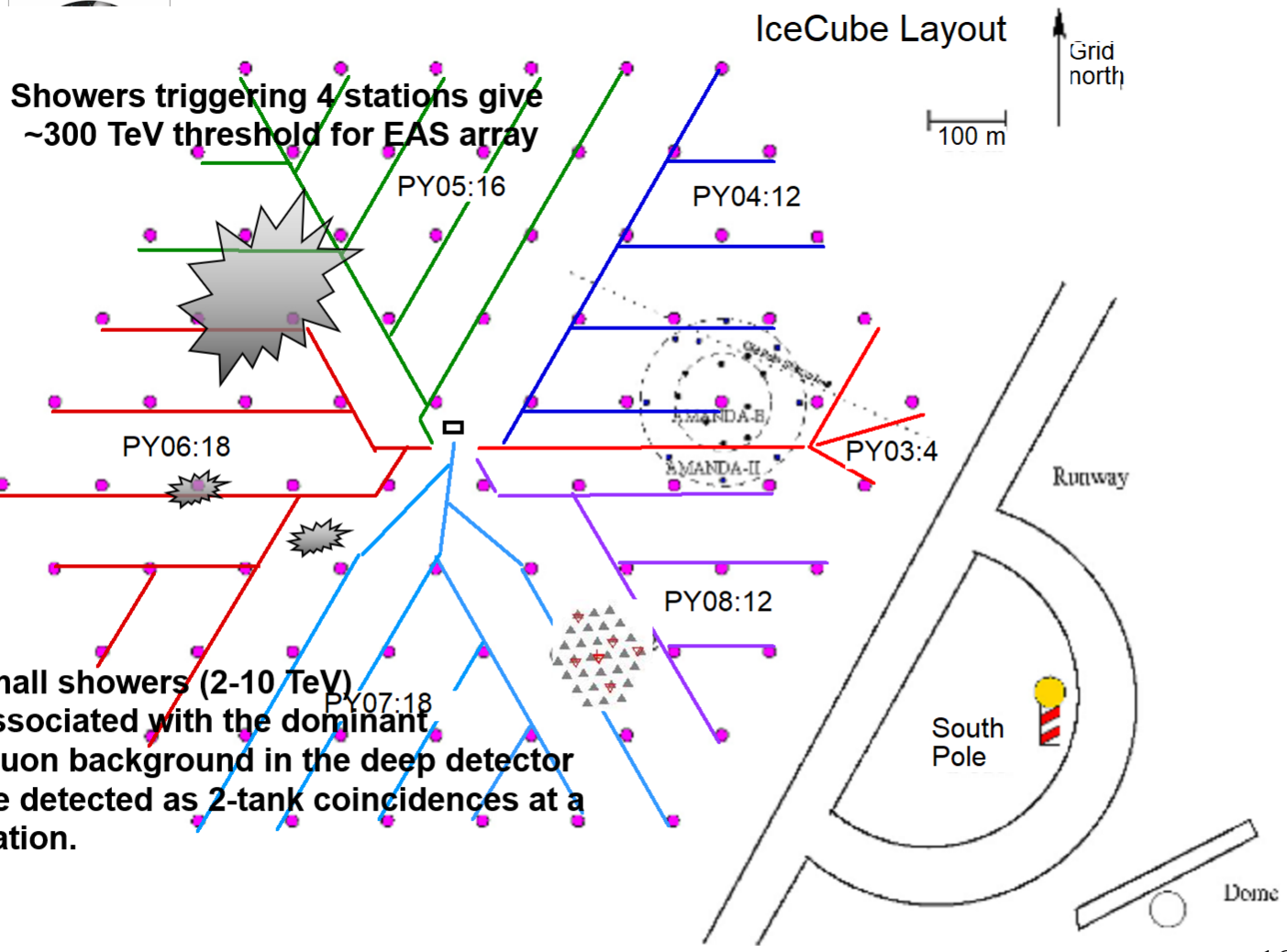








15



Showers triggering 4 stations give
~300 TeV threshold for EAS array

Small showers (2-10 TeV)
associated with the dominant
muon background in the deep detector
are detected as 2-tank coincidences at a
station.

Showers triggering 4 stations give
~300 TeV threshold for EAS array

PY05:16

IceCube Layout

Grid
north

100 m

PY04:12

Large showers with $E \sim 100\text{-}1000\text{ PeV}$
will clarify transition from galactic to
extra-galactic cosmic rays.

PY06:18

PY03:4

Runway

PY08:12

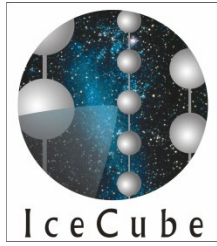
Small showers (2-10 TeV)
associated with the dominant
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station.

PY07:18

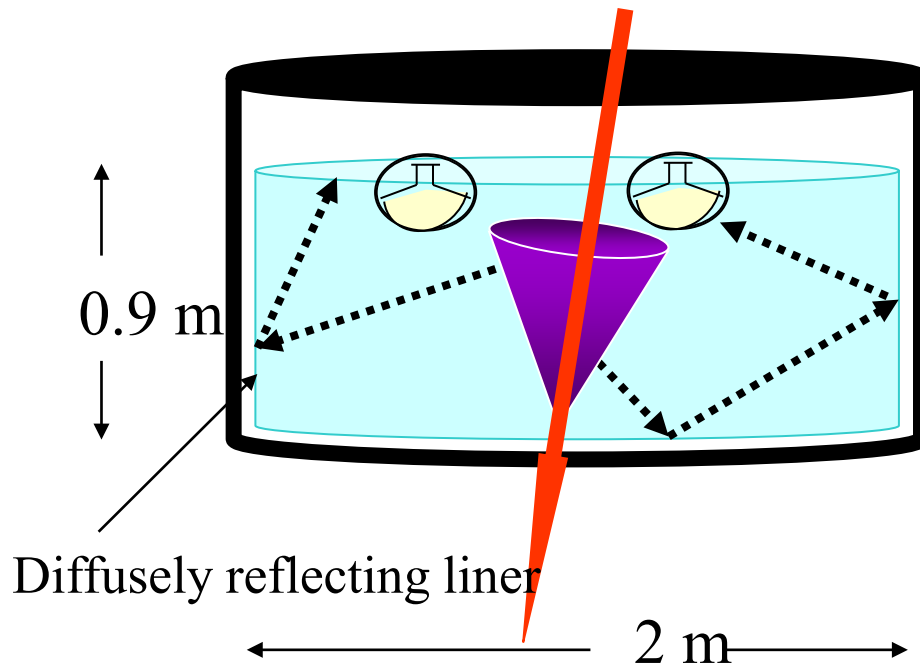
South
Pole

Dome

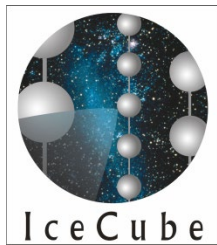
17



IceTop Detectors

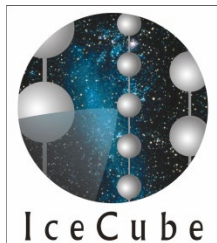


- Blocks of clear ice produced in tanks at the Pole
- Cherenkov radiation measured by standard IceCube photon detectors
- Two tanks separated by 10 meters form a station



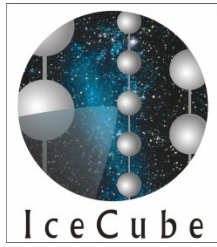
Getting to Antarctica: Christchurch, NZ



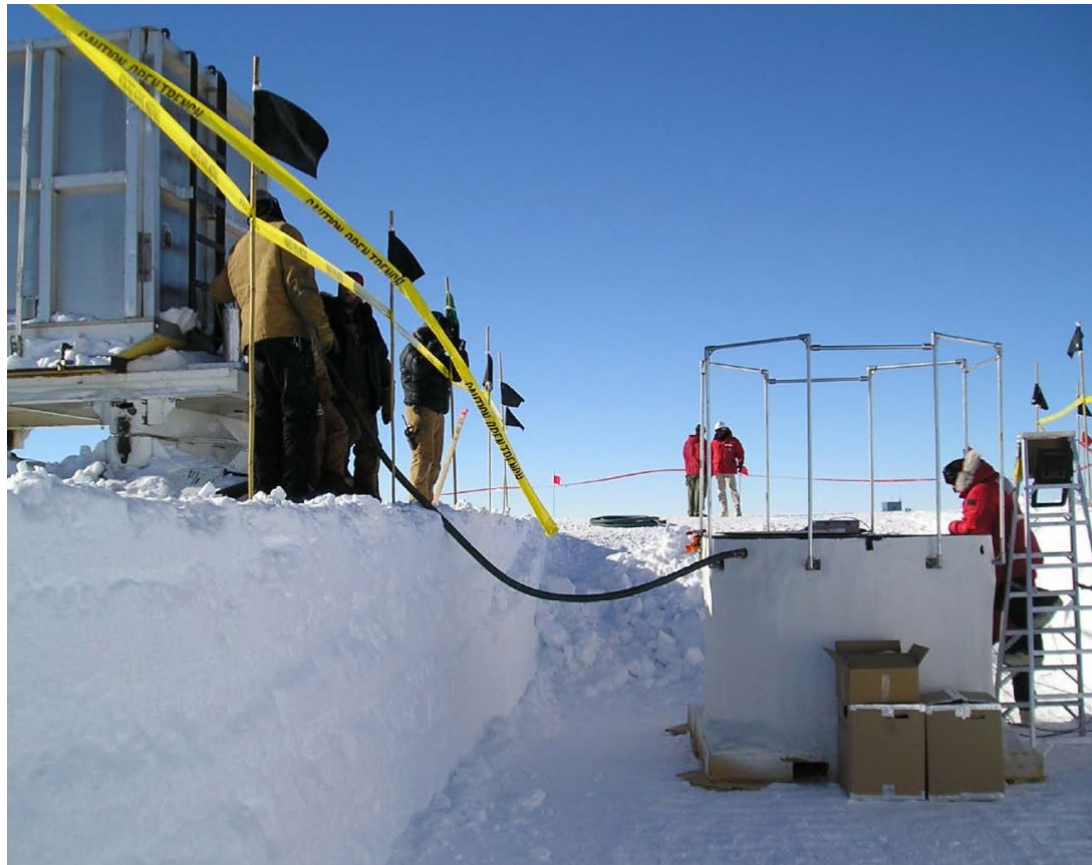


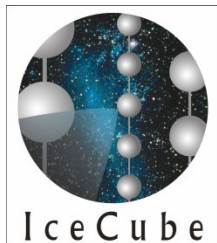
Installing the Detector “Tanks”



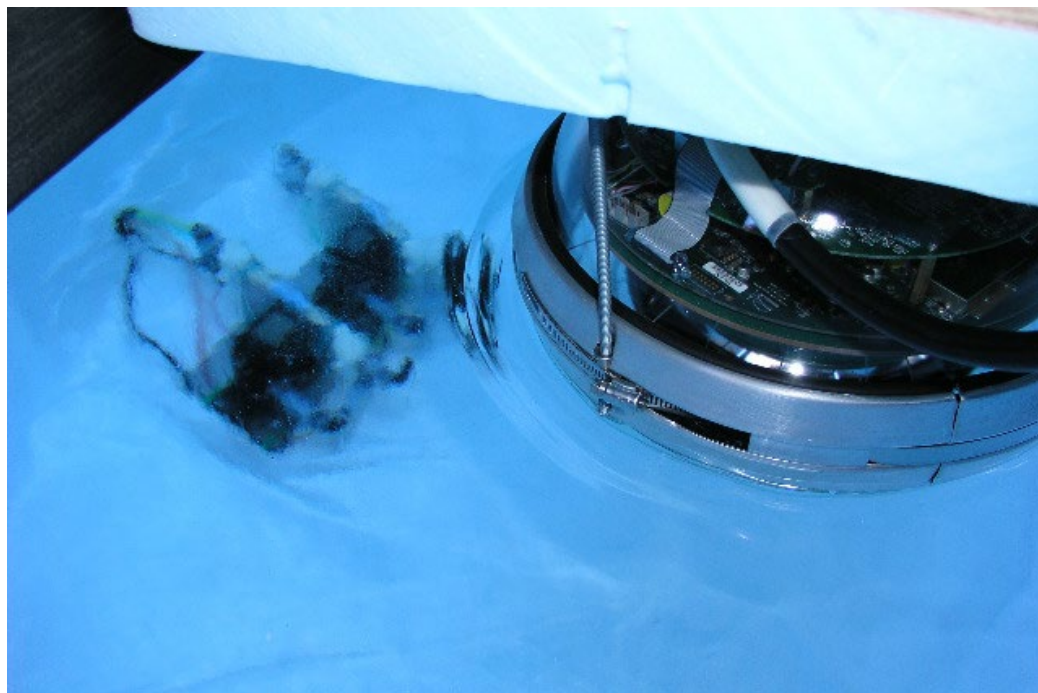


Fill Tanks with Water then Just Let Them Freeze



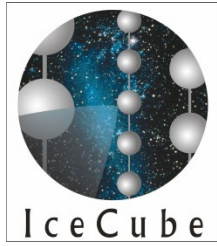


Removing Dissolved Air Produces Perfectly Clear Ice



Dual degassing
units are seen
under 75 cm of ice
DOMs are frozen
into the ice



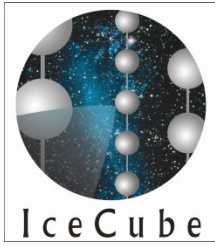


Finishing the Detector



- After filling the void at the top with perlite the lid is screwed down on the tank.
- In about 100,000 years these will fall off the coast of Antarctica, to the great surprise of some fish or another.



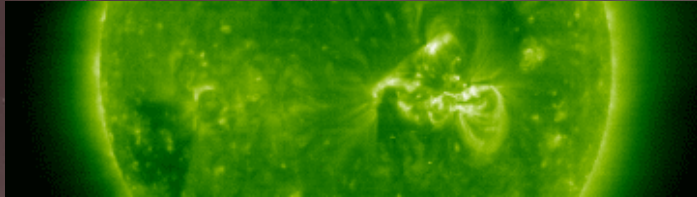


Solar Particles in IceTop

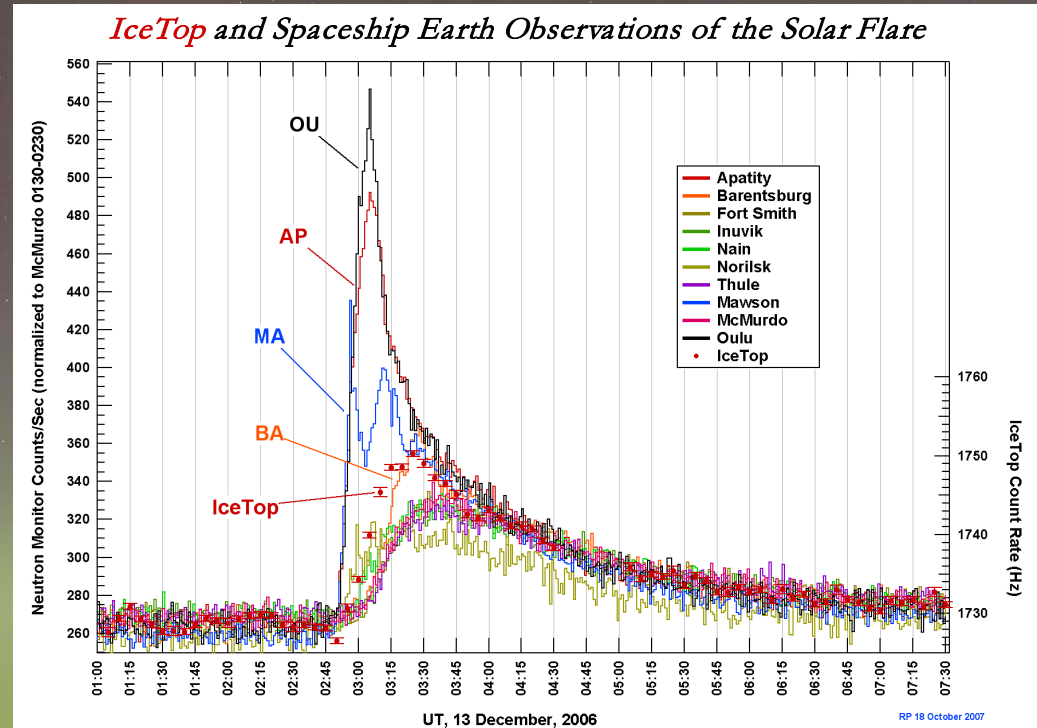


- It never occurred to us originally that IceTop could be used as a complement to the neutron monitor network.
- This realization has developed over time, and has been a significant part of my research for several years.
- As part of a huge collaboration, one has to find a niche in keeping with personal interest and expertise.

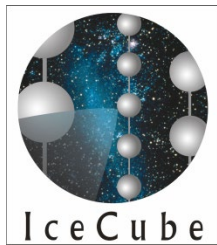
The First Extraterrestrial Event Detected by IceCube



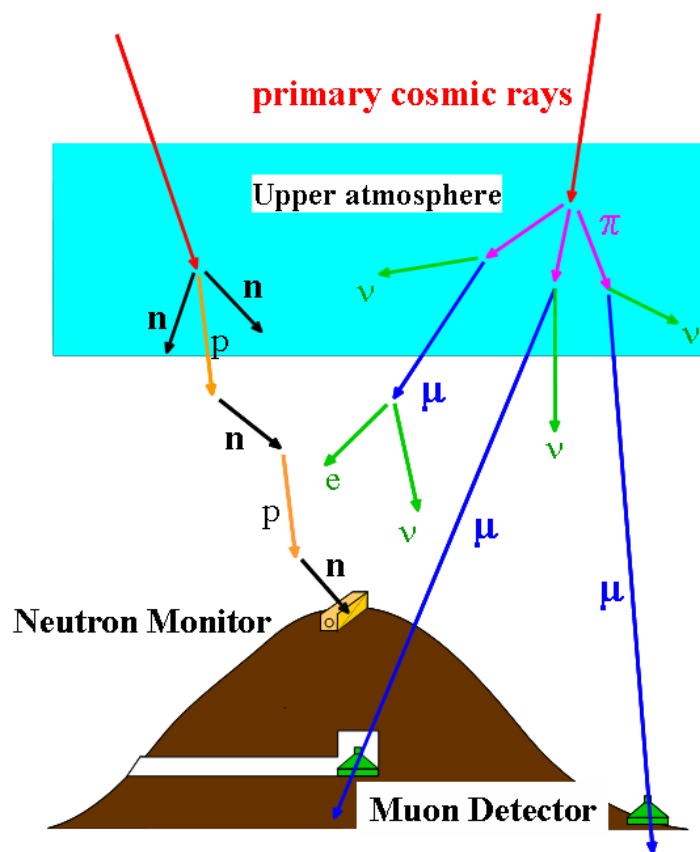
Dec 13, 2006 X3-Class Solar Flare (SOHO)



Dec 14, 2006 photograph of auroras near Madison, WI



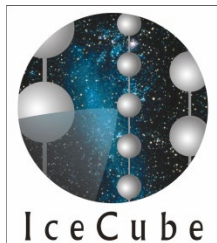
“Showers” from Low Energy (1 - 10 GeV) Primary Particles



Particles with energy as low as 1 GeV produce secondaries that survive to the surface

Rarely does a single detector see more than one secondary from a primary
Large detectors can have high enough counting rates to make statistically significant measurements of the primary flux

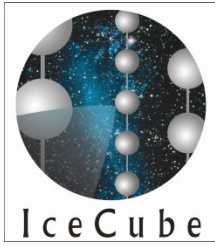
Conventional detectors count muons or neutrons



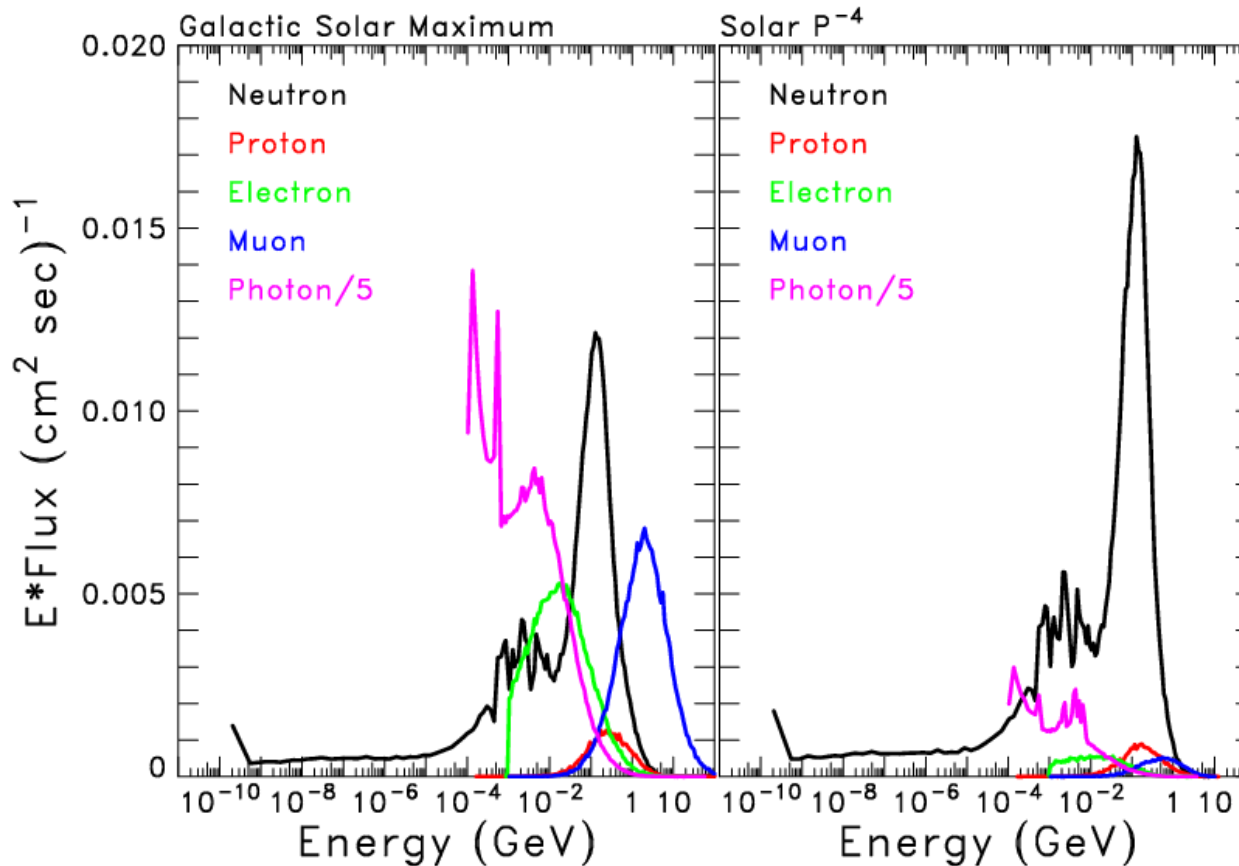
Why IceTop Works as a GeV Particle Spectrometer



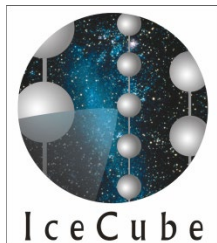
- Neutron monitors are comparatively insensitive to the particle spectrum
- IceTop detectors are thick (90 g/cm^2) so the Cherenkov light output is a function of both the species and energy of incoming particles
- Individual waveform recording, and extensive onboard processing, allow the return of pulse height spectra with ten second time resolution even at the kilohertz counting rate inherent to the detector



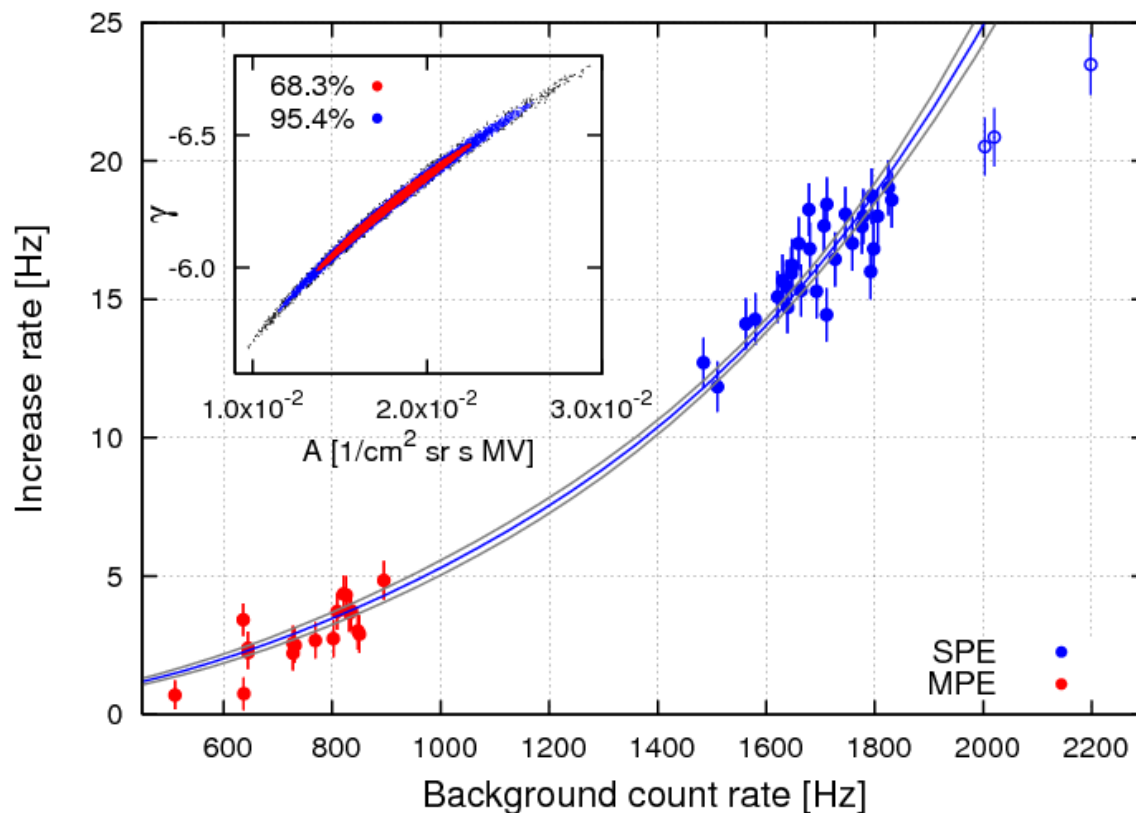
Secondary Particle Spectra



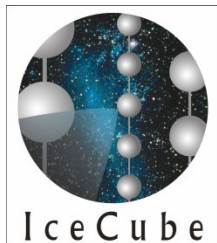
- At the South Pole, spectra of secondary particles “remember” a lot of information about the primary spectrum.



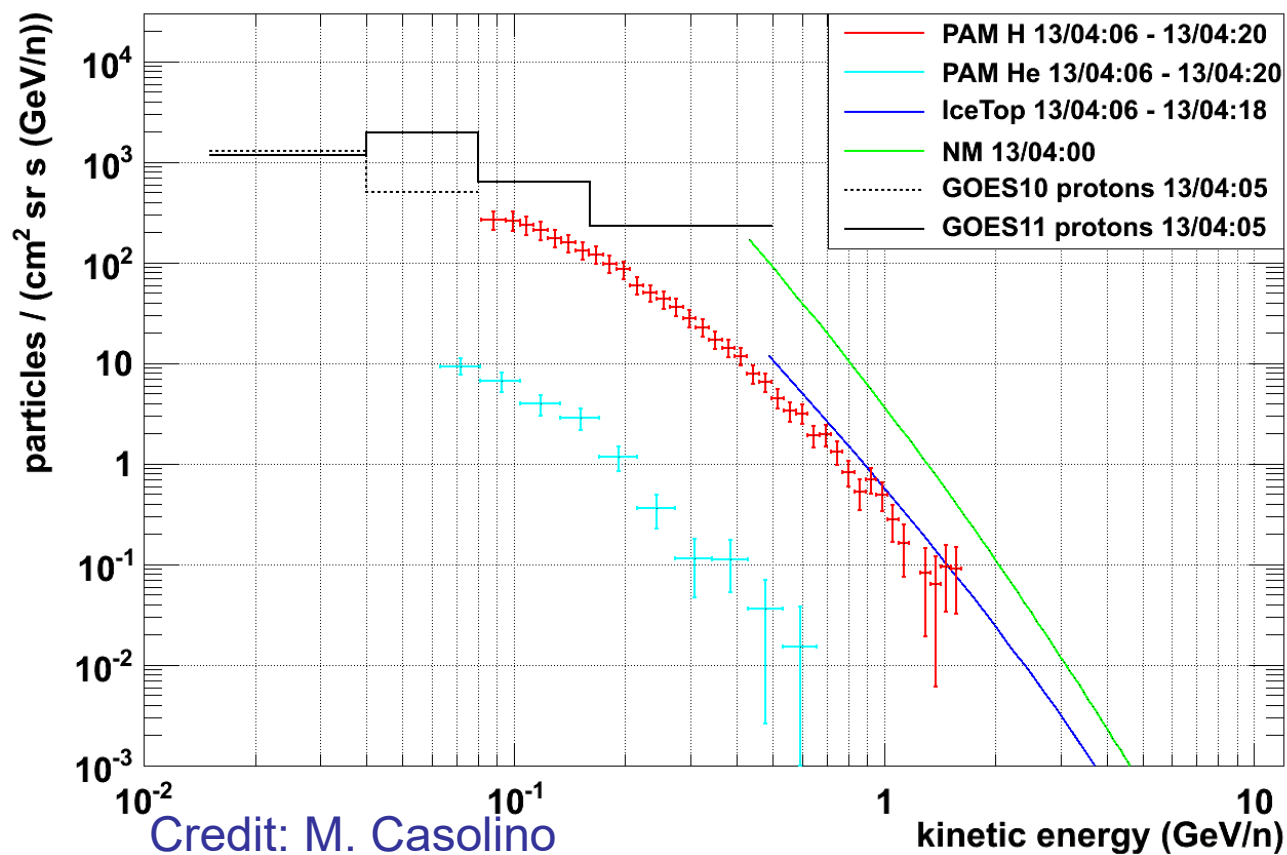
Solar Particle Spectrum Published in Ap J Letters

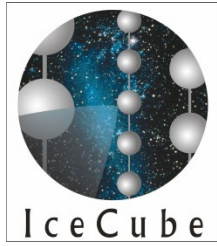


Excess count rate (averaged over approximately one hour near the peak of the event) as a function of pre-event counting rate. Each point represents one discriminator in one DOM. By using the response function for each DOM we fit a power law (in momentum) to the data **assuming that the composition is the same as galactic cosmic rays**. The lines show this fit and the one sigma (systematic) errors

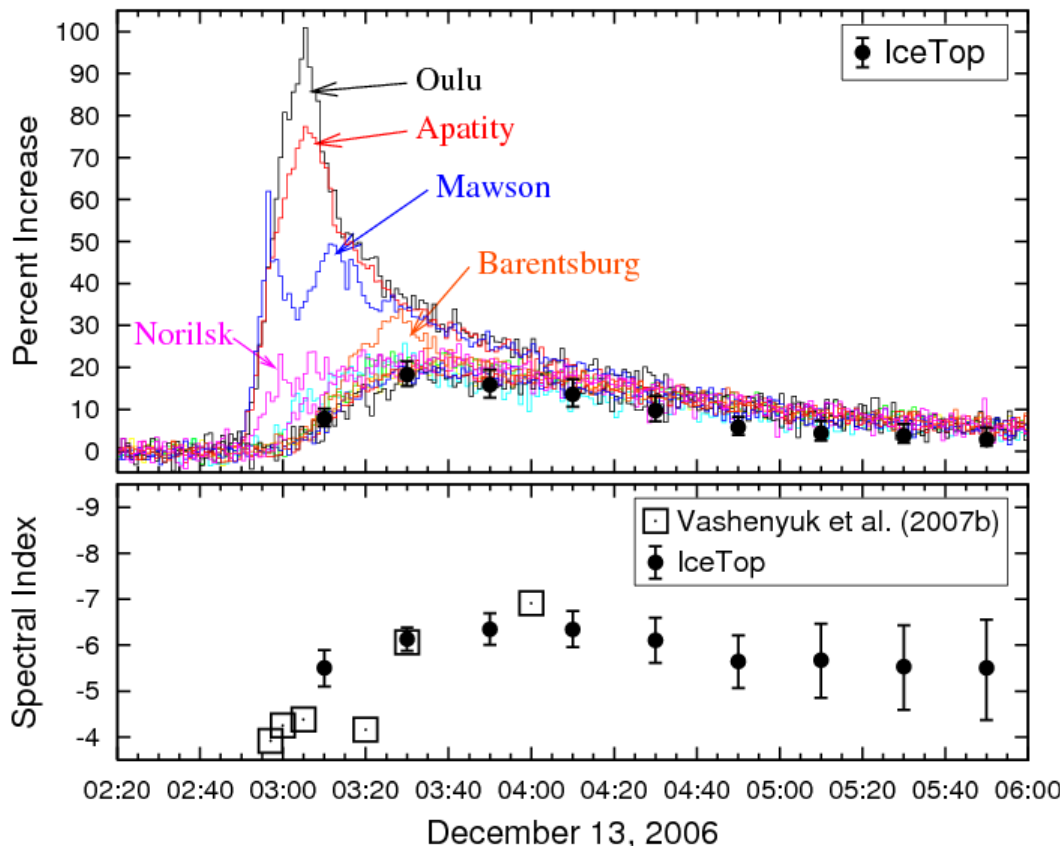


IceTop and PAMELA





Neutron Monitors and IceTop

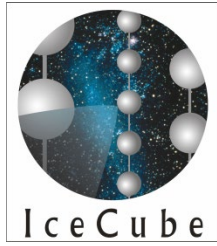


Good agreement (with understanding of viewing direction)

Continuous determination of precise spectrum

All information on anisotropy comes from the monitor network

Here we see the failure of the “separability” assumption in neutron monitor network analysis



Conclusions



- IceTop is a powerful new tool in the study of energetic solar particles
- I did not understand this when I agreed to work on it as “a favor to a friend”
- Moral: Keep your eyes open – in physics an opportunity is always there, one just has to recognize it!
- Now we just hope that the sun has not gone to sleep