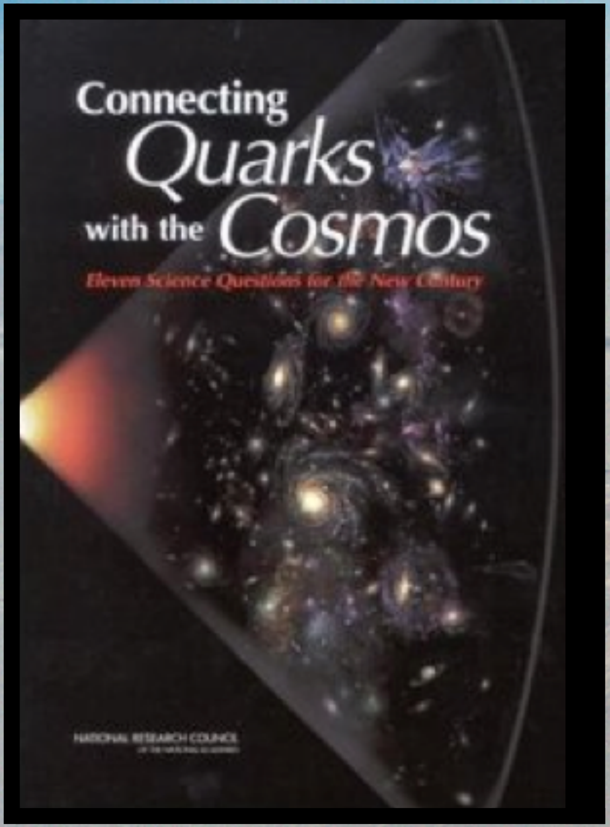
The IceCube Physics Program and First Results


Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL


5 January 2007 | $10

Science

CATCHING Cosmic Clues

AAAS

Joanna Kiryluk
Lawrence Berkeley National Laboratory
8 April 2011

Seminarium Fizyki Wielkich Energii
Wydzial Fizyki, Uniwersytet Warszawski

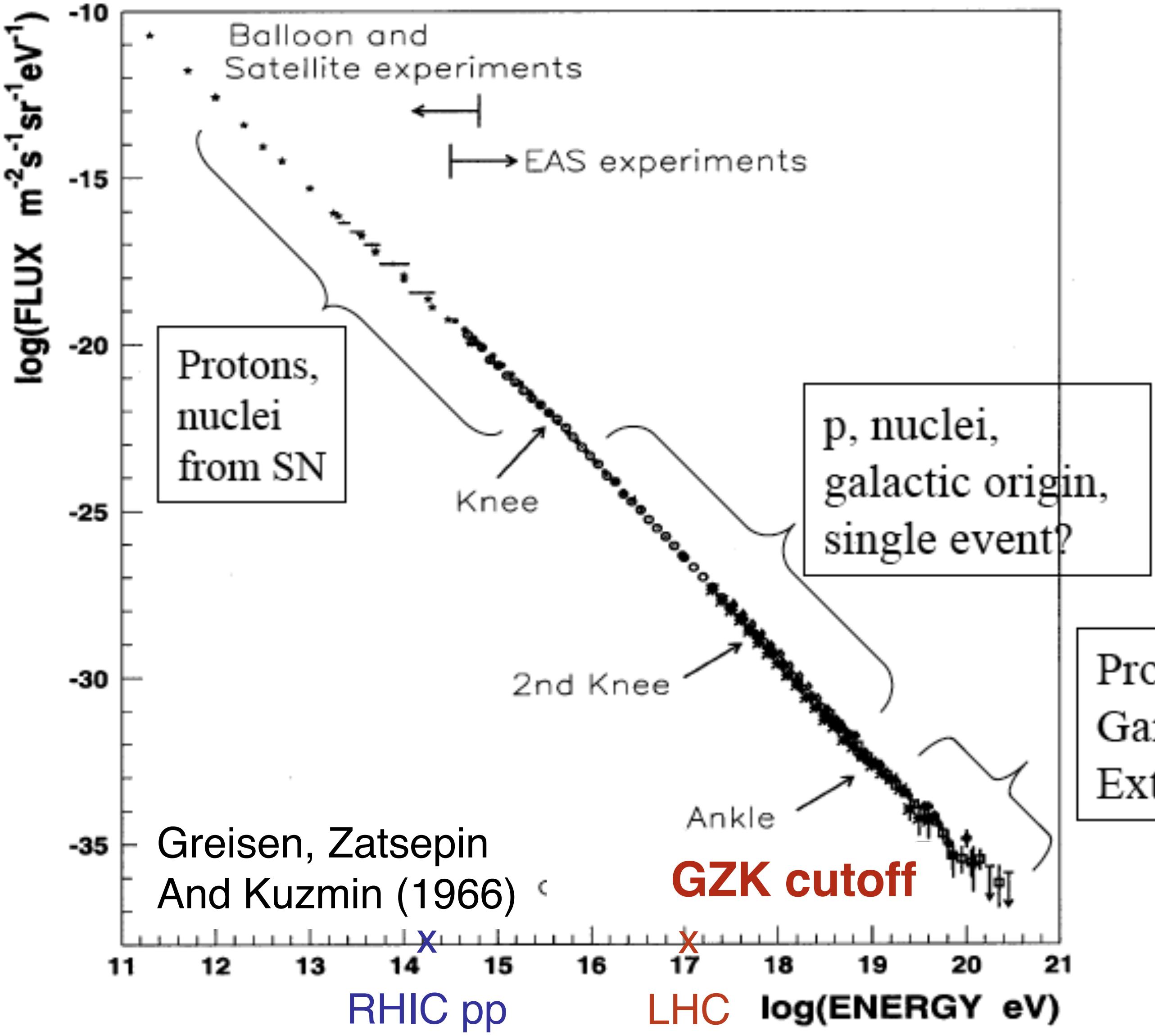
IceCube

Outline:

- Motivation: why a km^3 scale detector?
- Neutrino detection concept
- The IceCube detector
- Latest results
- Prospects and Summary

Neutrino Sources and Cosmic Rays

What is the origin of Cosmic Rays with E up to 10^{20} eV ?



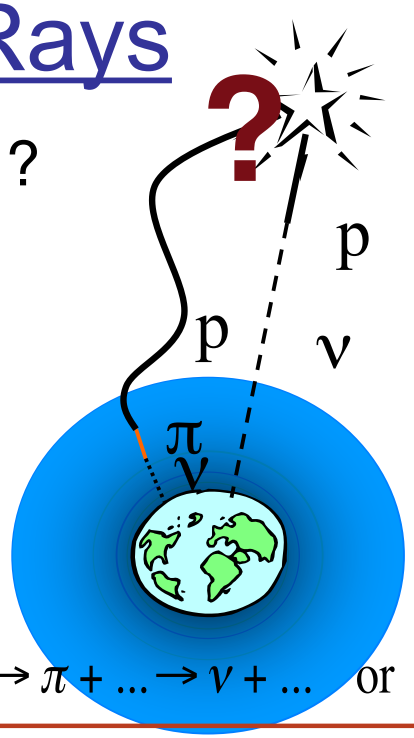
Greisen, Zatsepin
And Kuzmin (1966)

GZK cutoff

RHIC pp

LHC

Protons? Nuclei?
Gammas? Exotics?
Extra-galactic origin



$p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots$ or

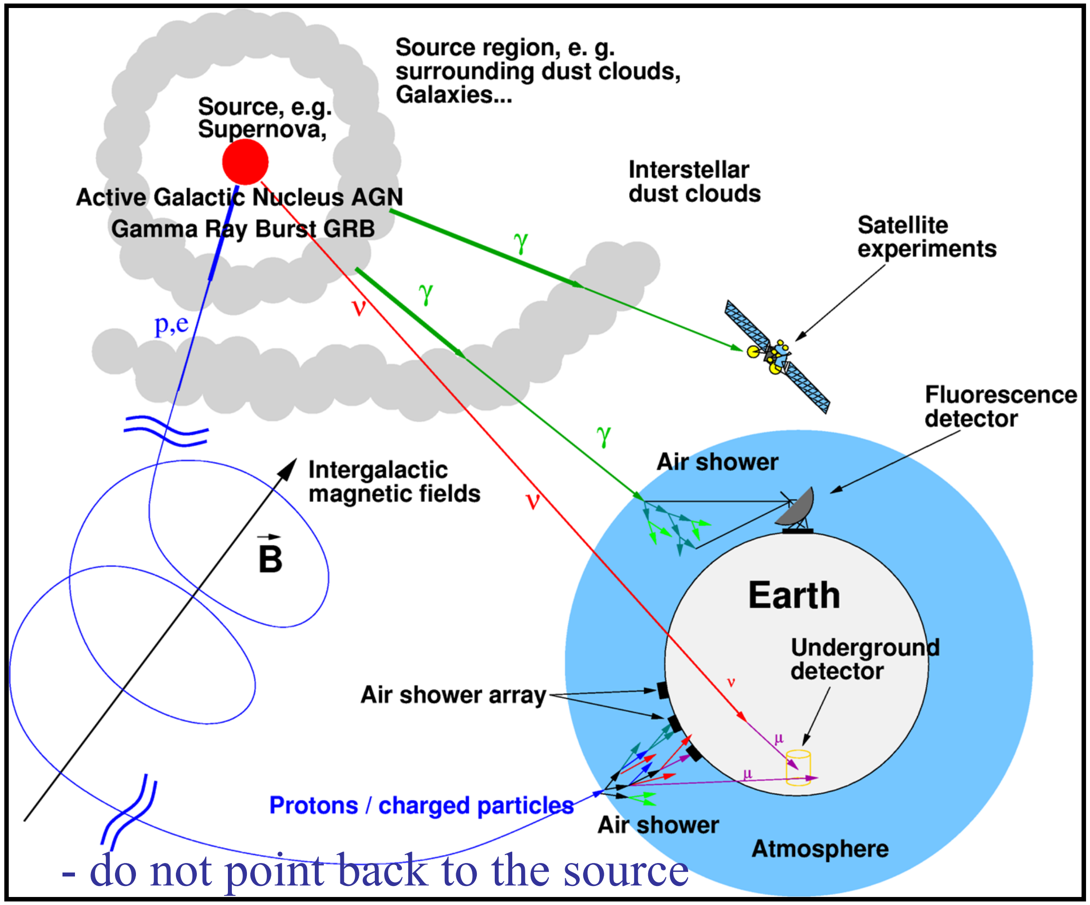
$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$

$E_p > 6 \times 10^{19} eV$ GZK cutoff

Neutrino Astronomy

Neutrinos as probes of the high-energy Universe

- Protons with $E_p < 10$ EeV directions scrambled by magnetic fields
- γ-rays: straight-line propagation but reprocessed in the sources; TeV γ–ray astronomy: many newly discovered (galactic and extragalactic sources)



- do not point back to the source

- Neutrinos: straight-line propagation, unabsorbed, not GZK suppressed, but difficult to detect

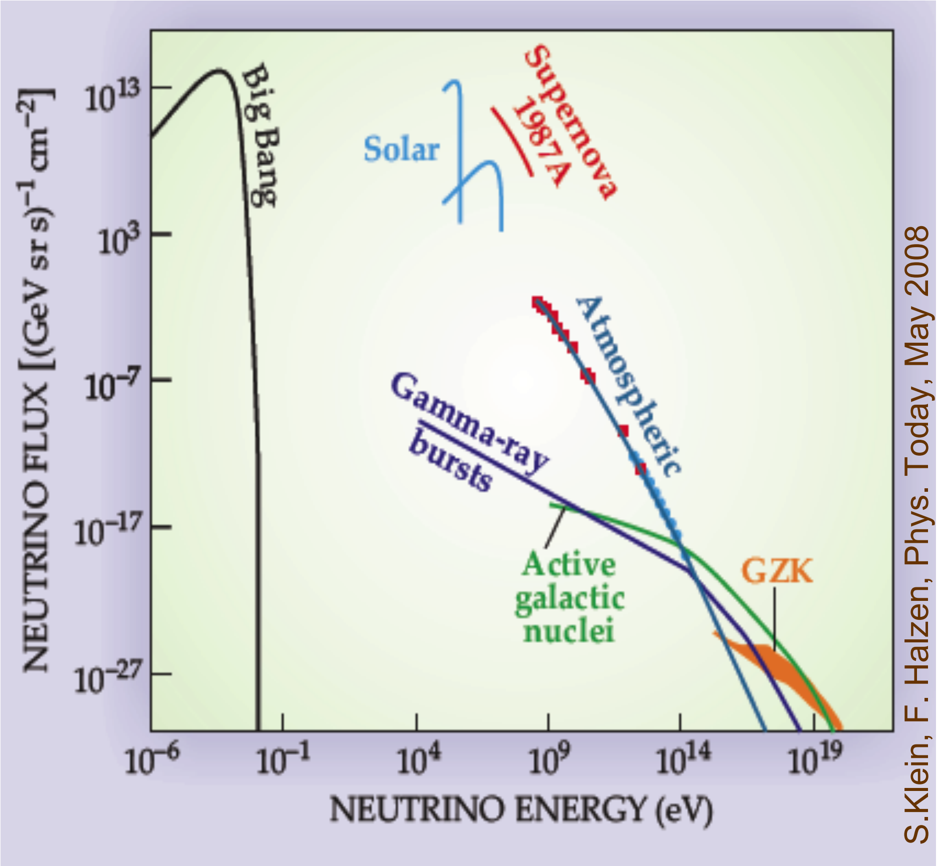
Extraterrestrial high-energy neutrinos: discovery potential!

The only confirmed extraterrestrial low energy neutrino sources detected so far are the Sun and the supernova SN1987A

Need for a 1 km^3 Neutrino Detector

Rate ~ Neutrino flux x Neutrino Cross Section x Absorption in Earth
x Size of detector x (Range of muon for ν_μ)

- Neutrino flux:



S.Klein, F. Halzen, Phys. Today, May 2008

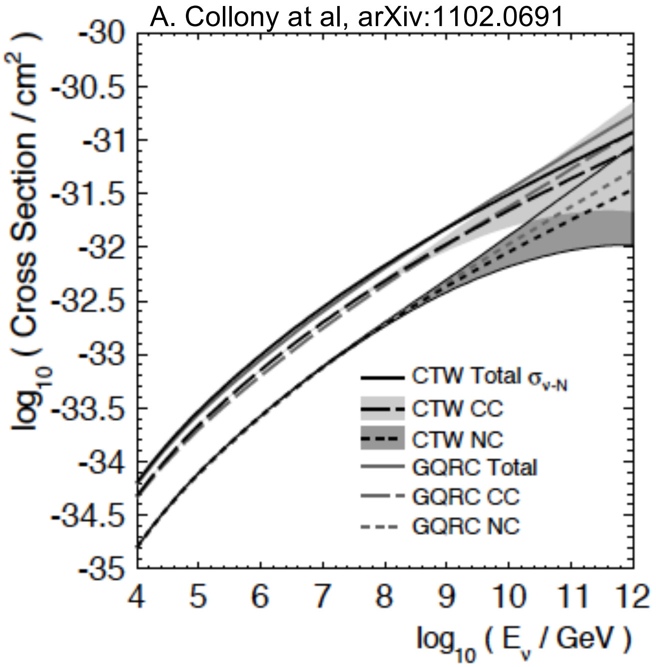
Need for a 1 km^3 Neutrino Detector

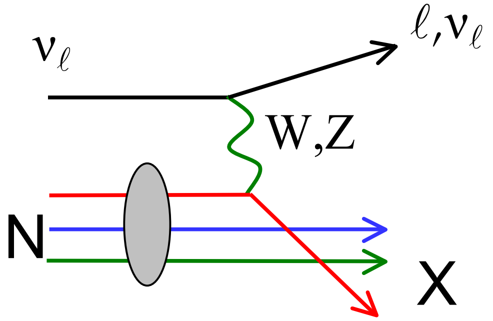
Rate ~ Neutrino flux x Neutrino Cross Section x Absorption in Earth

x Size of detector x (Range of muon for ν_μ)

- νN cross section

A. Collony at al, arXiv:1102.0691





$\nu_l + N \rightarrow l + X$ (CC)

$\nu_l + N \rightarrow \nu_l + X$ (NC)

$$\sigma_{CC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[q + (1-y)^2 \bar{q}\right]$$

$$\sigma_{NC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy\, dx \left(\frac{M_Z^2}{Q^2 + M_Z^2}\right)^2 \left[q^0 + (1-y)^2 \bar{q}^0\right]$$

G_F=1.17x10^{-5}GeV^{-2} ,M_W=80.398 GeV, M_Z=91.187 GeV, M_N=0.938 GeV

q,q^0 - combinations of quark distributions

y - fraction of the incoming neutrino energy transferred to the nucleon

Q^2 - 4-momentum transfer

Need for a 1 km^3 Neutrino Detector

Rate ~ Neutrino flux x Neutrino Cross Section x Absorption in Earth x Size of detector x (Range of muon for ν_μ)

- absorption in Earth

Muon Neutrinos

-starts at 10-100 TeV

-biggest effect near vertical

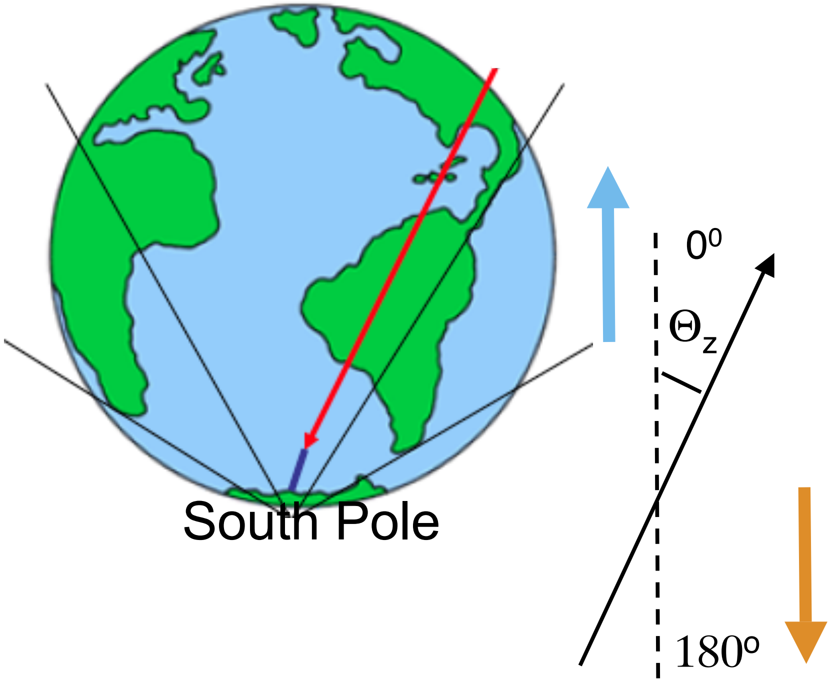
-higher energy ν's absorbed at larger angles

Tau Neutrinos

- not absorbed by the Earth, but detected with lower energy

- high energy ν_τ will cascade down to O(100 TeV) where Earth is transparent.

ν interacts in the Earth and puts μ into the detector

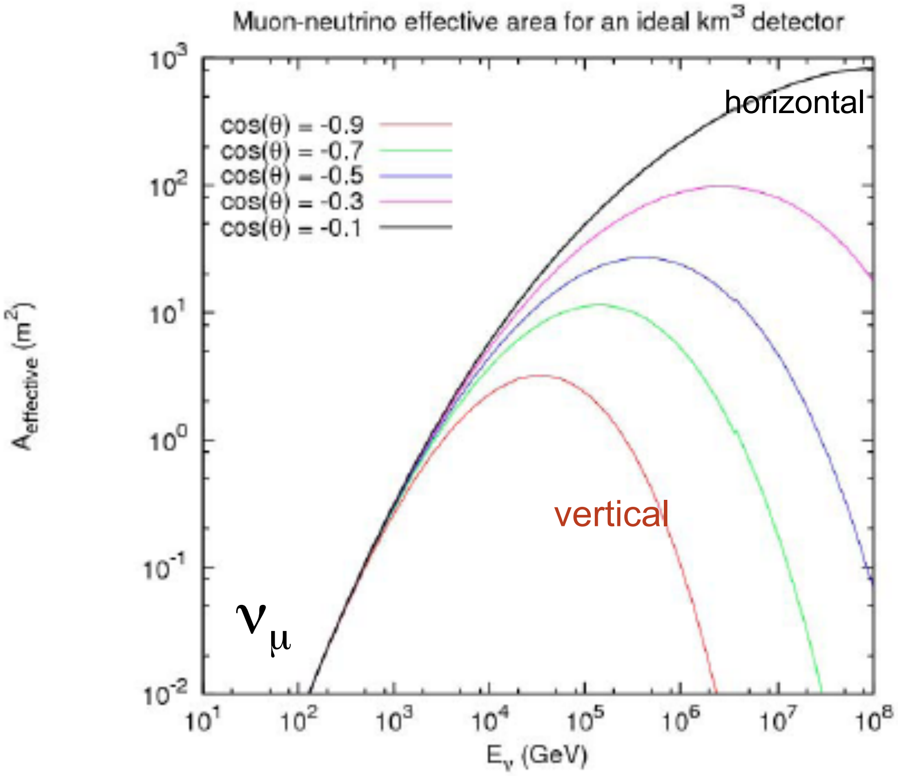


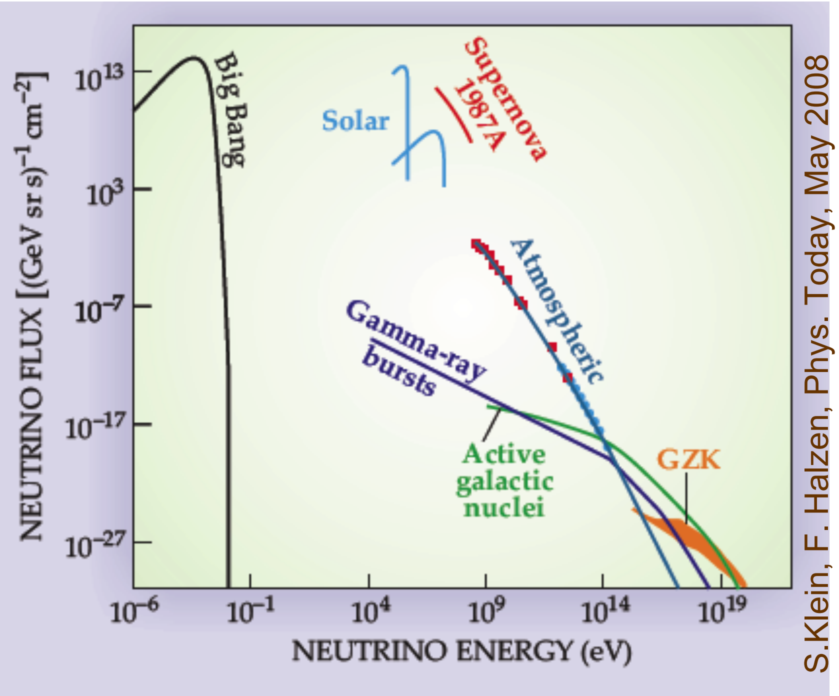
Need for a 1 km^3 Neutrino Detector

Rate ~ Neutrino flux x Neutrino Cross Section x Absorption in Earth

x Size of detector x (Range of muon for ν_μ)

= Neutrino flux x Neutrino Effective Area





S.Klein, F. Halzen, Phys. Today, May 2008

Expected GZK neutrino rates in 1 km^3 detector: ~ 1 per year

Science with IceCube

Main Goal: *Detect neutrinos of all flavors at energies from $\sim 10^{10}$ eV to 10^{20} eV, and low energy ν's from supernovae*

Astronomy:

✓ Search for astrophysical neutrino *point sources* and/or *diffuse flux* from all sources

Cosmic Rays:

✓Spectrum
✓Composition

Standard Model Physics:

✓High pT muons from Cosmic Rays (Charm production)
✓ Neutrino cross section at high energies

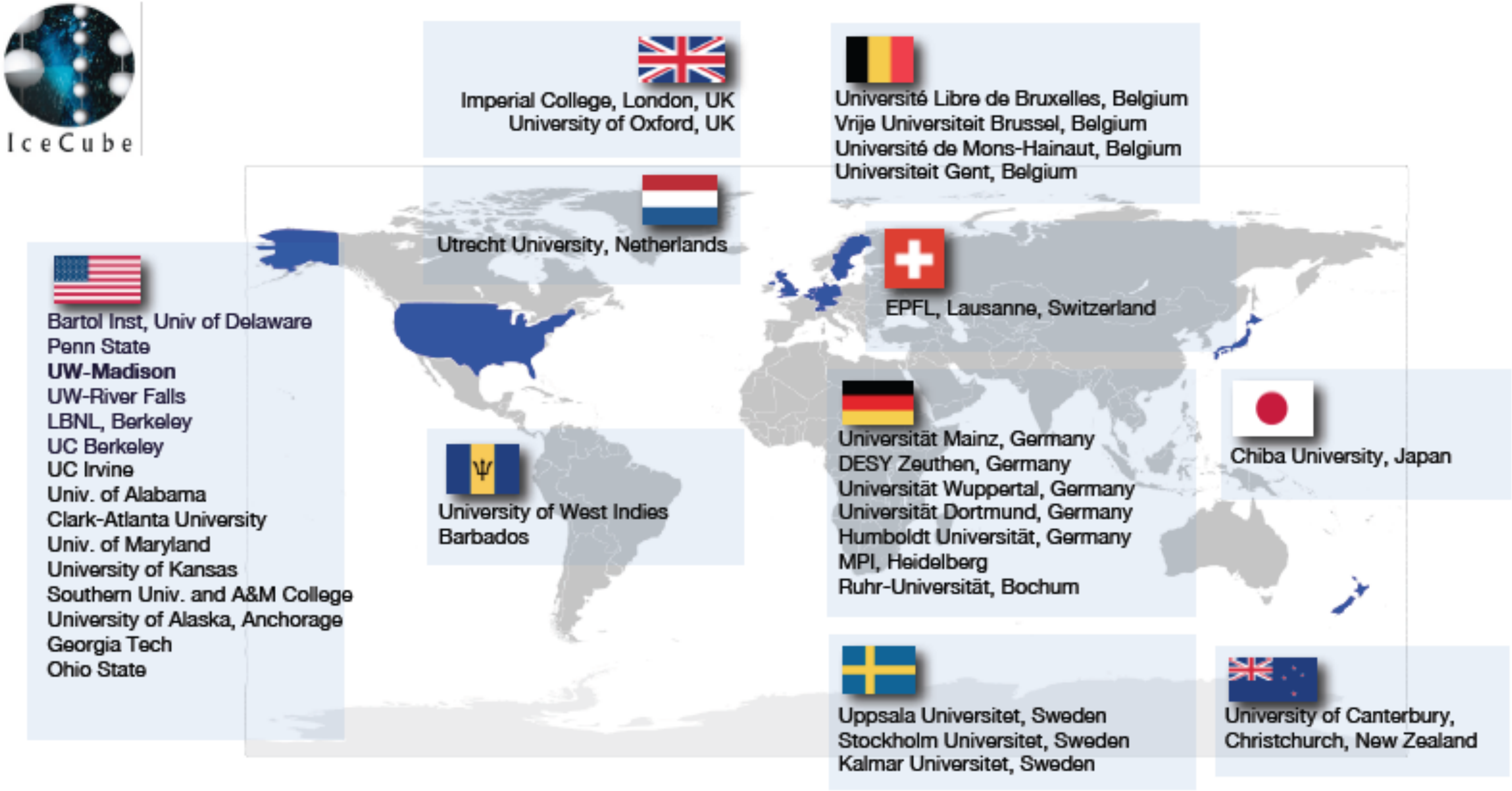
} Low x physics, parton distributions

Physics Beyond Standard Model:

✓ Neutrino oscillations
✓ Search for Dark Matter, Magnetic Monopoles,
✓ non-standard model neutrino interactions

THE ICECUBE COLLABORATION

http://icecube.wisc.edu



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University of Oxford, UK

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium

Utrecht University, Netherlands

EPFL, Lausanne, Switzerland

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Penn State
UW-Madison
UW-River Falls
LBNL, Berkeley
UC Berkeley
UC Irvine
Univ. of Alabama
Clark-Atlanta University
Univ. of Maryland
University of Kansas
Southern Univ. and A&M College
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MPI, Heidelberg
Ruhr-Universität, Bochum

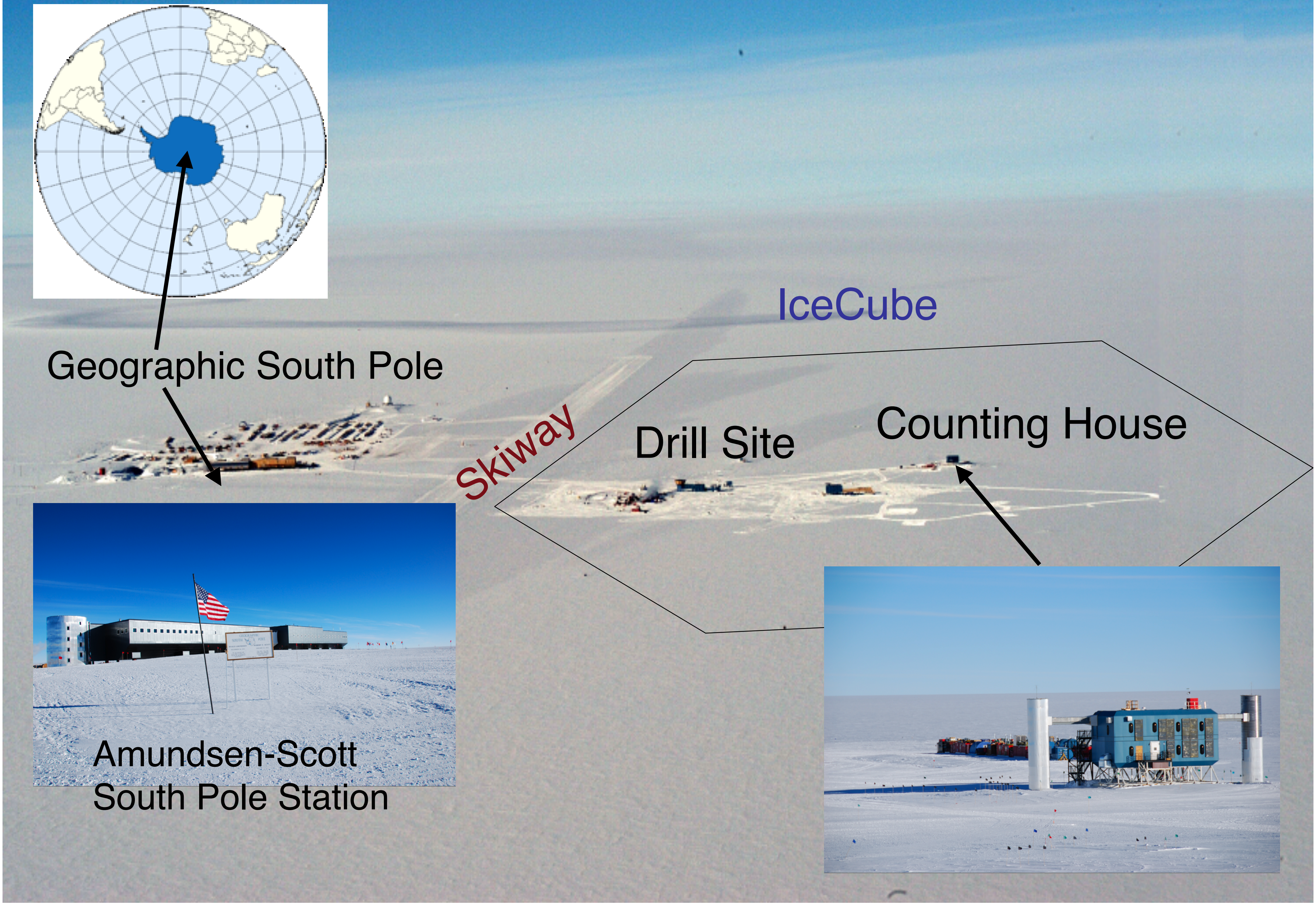
Chiba University, Japan

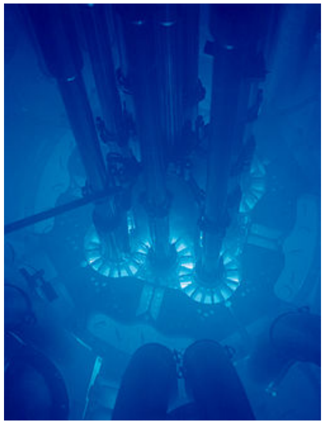
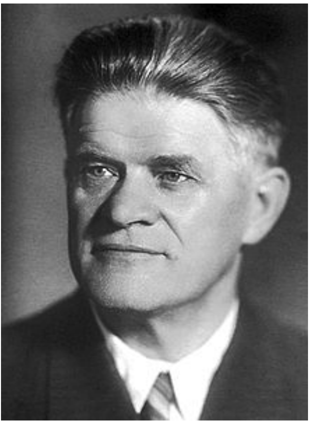
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden

University of Canterbury,
Christchurch, New Zealand

IceCube Collaboration
10 countries
36 institutions
~260 collaborators

IceCube at the South Pole



Cherenkov Radiation

- 1934: Cherenkov radiation was observed as a faint blue glow by Pavel Cherenkov when he was asked to look at the effects of radioactivity in liquids.
- 1958: Nobel prize shared with Ilya Frank and Igor Tamm

Cherenkov radiation is emitted when a charged particle passes through a dielectric medium with velocity

$\beta \geq \beta_{thr} = 1/n$ n: refractive index

may emit light along a conical wave front.

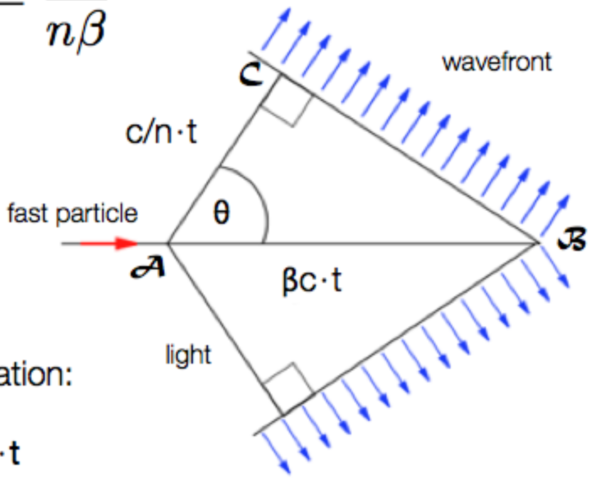
The charged particles polarize the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the process.

medium	n	θ_{max} (deg.)
air*	1.000283	1.36
isobutane*	1.00127	2.89
water	1.33	41.2
quartz	1.46	46.7

Polarization effect ...
Cherenkov photons emitted if v > c/n ...

Cherenkov angle:

$$\cos\theta_c = \frac{1}{n\beta}$$



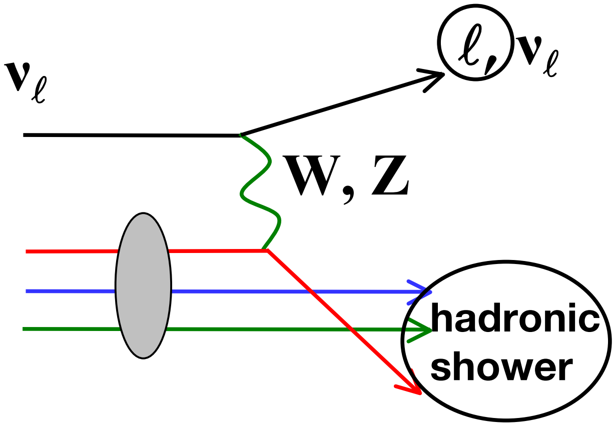
Simple
Geometric derivation:

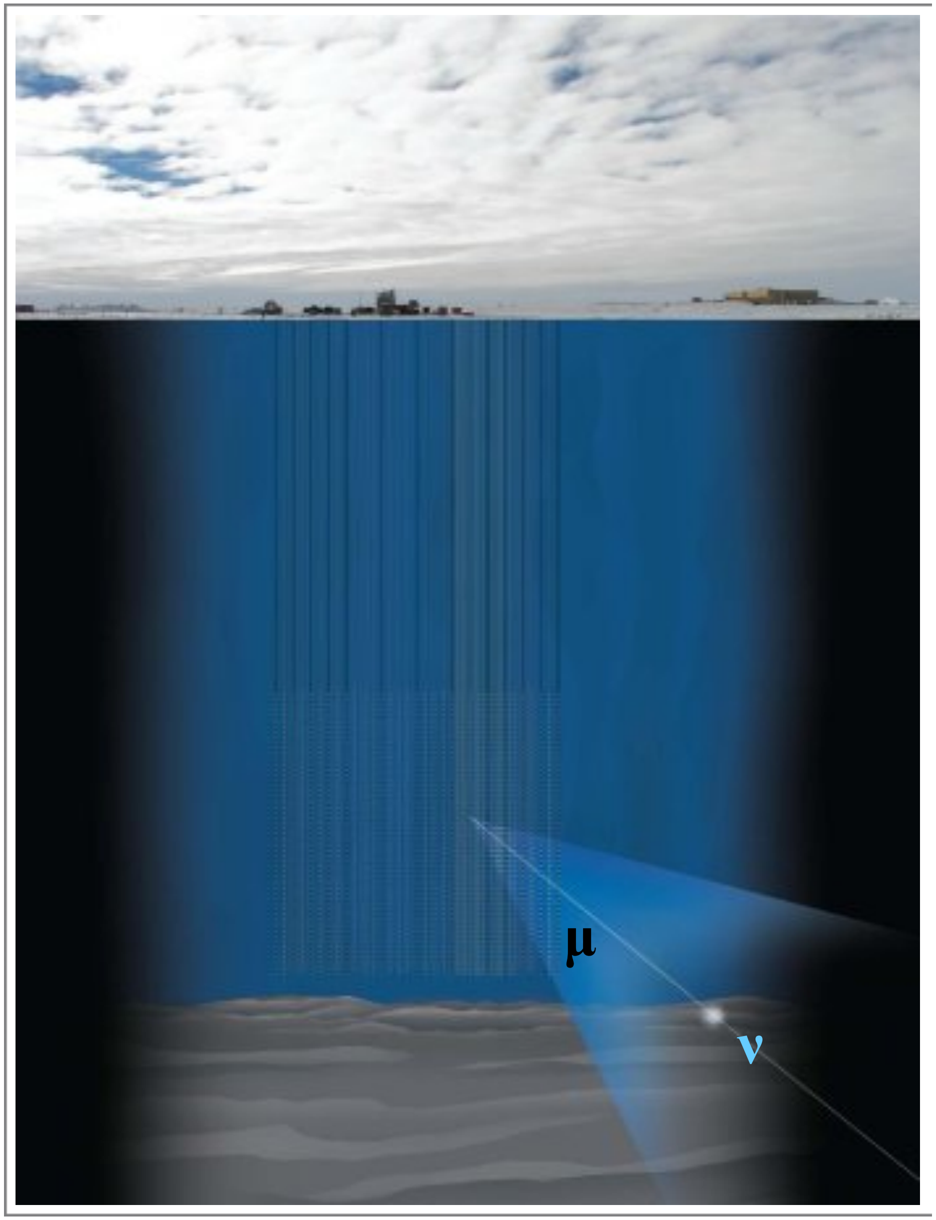
$AB = \beta c \cdot t$
$BC = c/n \cdot t$

$\cos\theta = AC/AB = c/n \cdot t/(\beta c \cdot t)$
$= 1/n\beta$

Neutrino detection principle

Neutrinos of all flavors interact in or near the detector through charged current (CC) Or neutral current (NC) weak interaction:





Neutrino interaction identification method: Observe the secondaries

- O(km) muon tracks from ν_μ CC

  1 TeV ~ 2.5 km, 1PeV ~ 15 km
- O(10 m) e-m and/or hadronic cascades from ν_e CC, low energy ν_τ CC, and ν_x NC

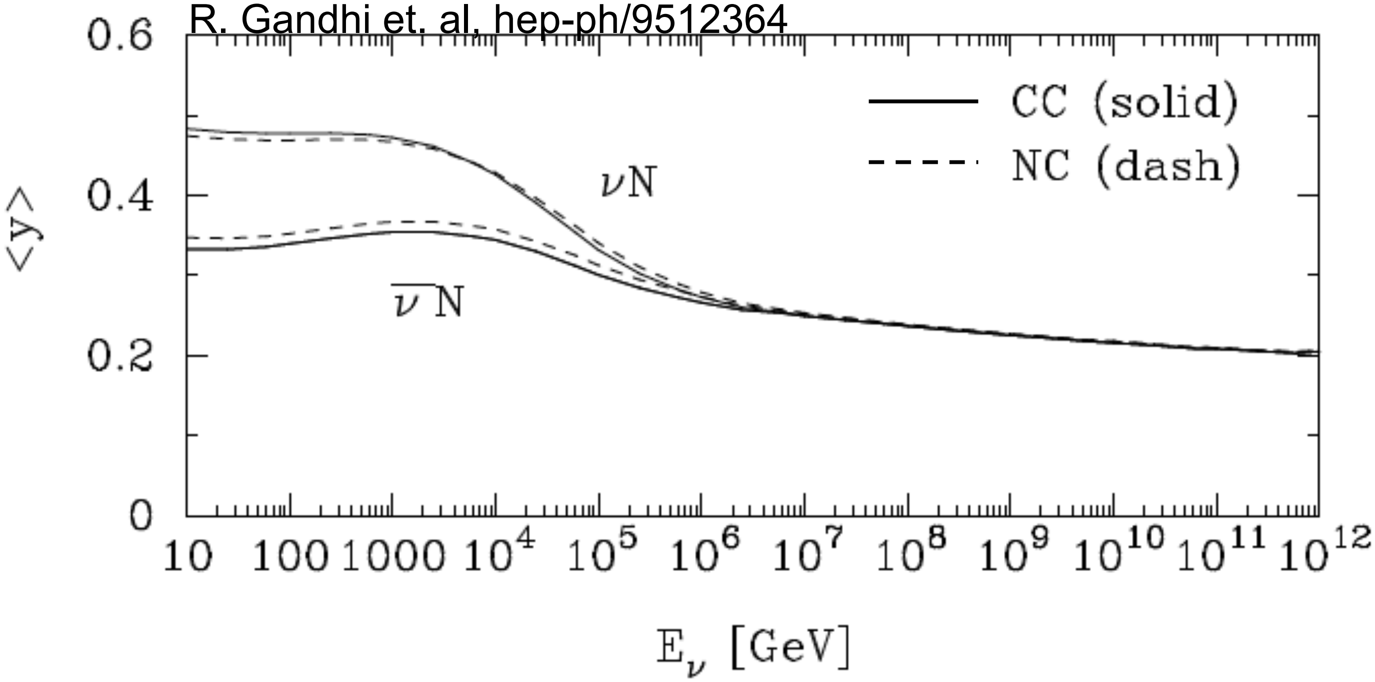
via Cherenkov radiation detected by

a 3D array of optical sensors

At ultra high energies, 20% of incident neutrino energy goes into hadronic cascades X:

$$\nu_l + N \rightarrow l + X$$
$$\nu_l + N \rightarrow \nu_l + X$$

R. Gandhi et. al, hep-ph/9512364

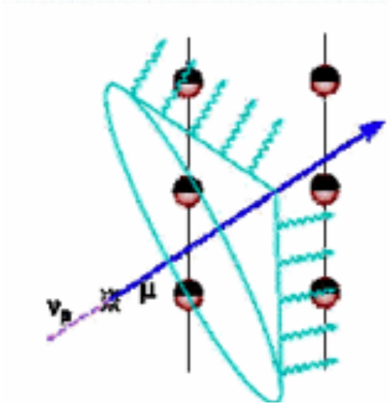


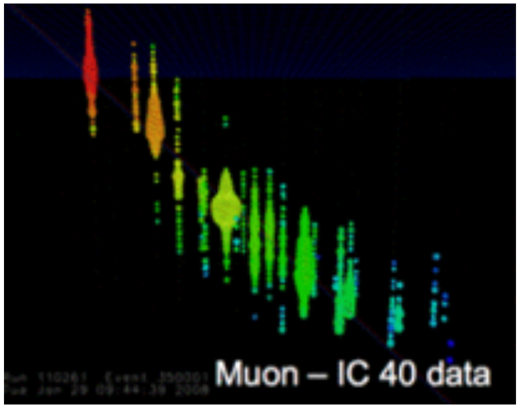
Energy dependence of the inelasticity parameter y for charged-current (CC) and neutral-current (NC) interactions as a function of the incident neutrino energy.

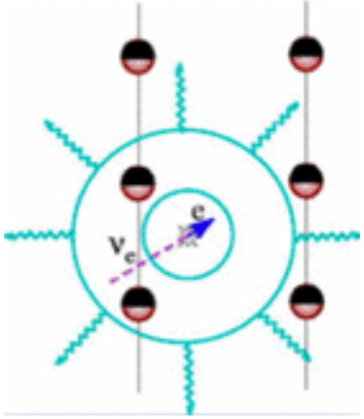
Neutrino Signatures

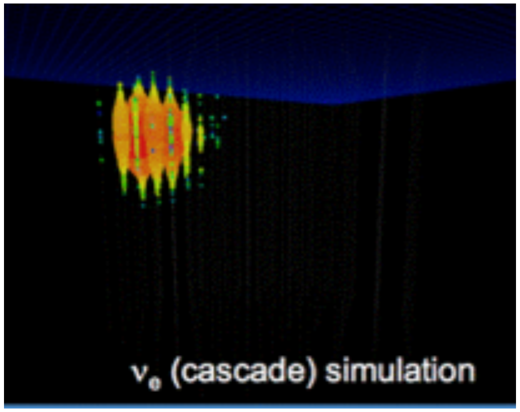
Tracks:

- $\nu_\mu + N \rightarrow \mu + X$
- through-going muons
- pointing resolution ~1°
- used for *point source and diffuse flux searches*




Muon – IC 40 data



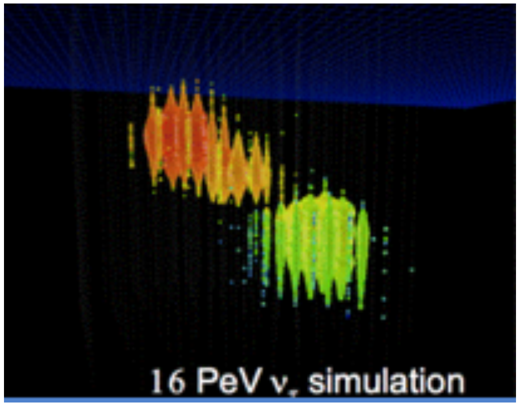

ν_e (cascade) simulation

Cascades:

- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
  $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- energy resolution 10% in log(E)
- used for *diffuse flux searches*

Composites

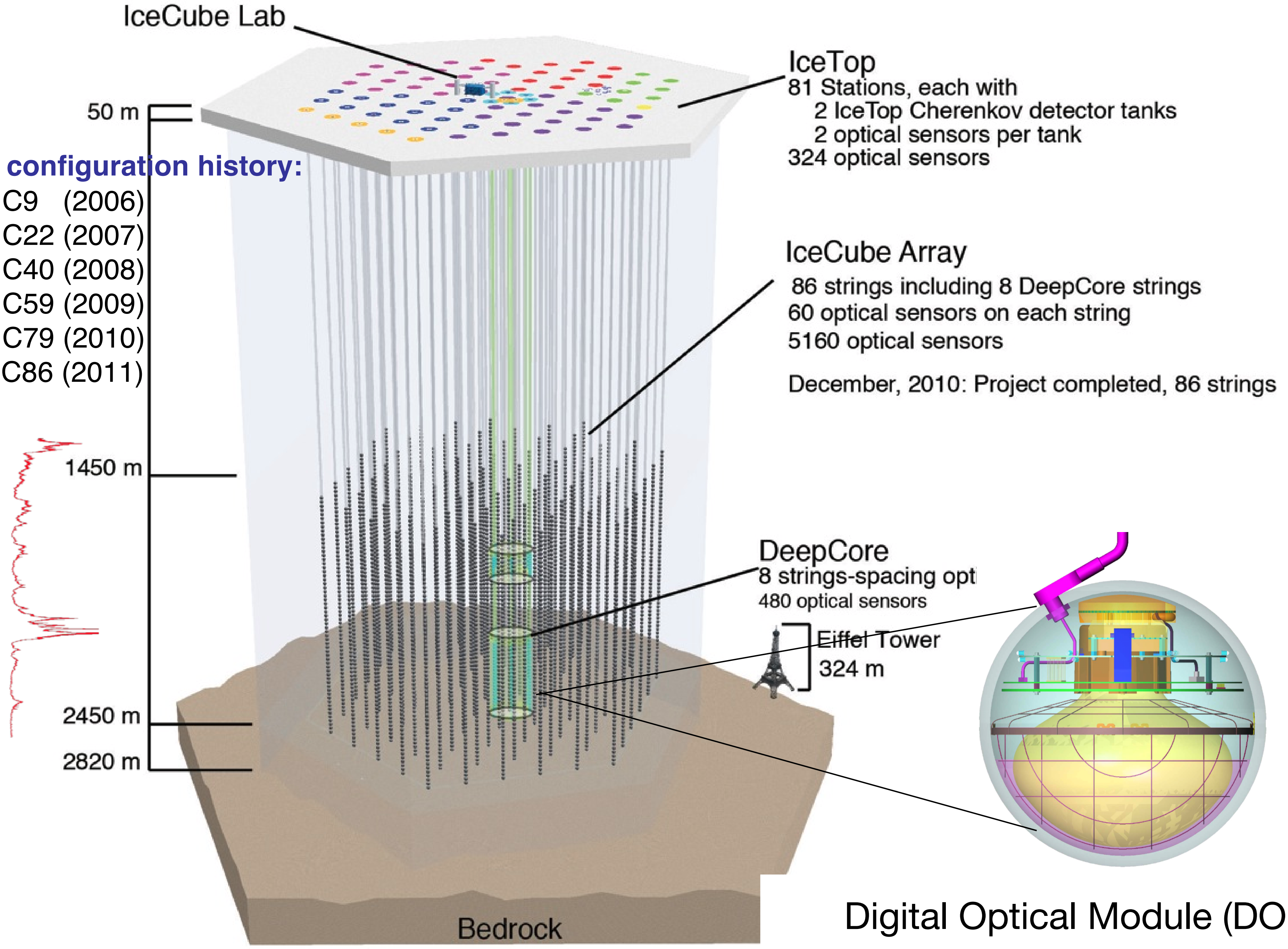
- starting tracks
- tau double bangs
- good directional and energy resolution


16 PeV ν_τ simulation

IceCube Detector

Detector configuration history:

IC9 (2006)
IC22 (2007)
IC40 (2008)
IC59 (2009)
IC79 (2010)
IC86 (2011)



IceCube Lab

IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

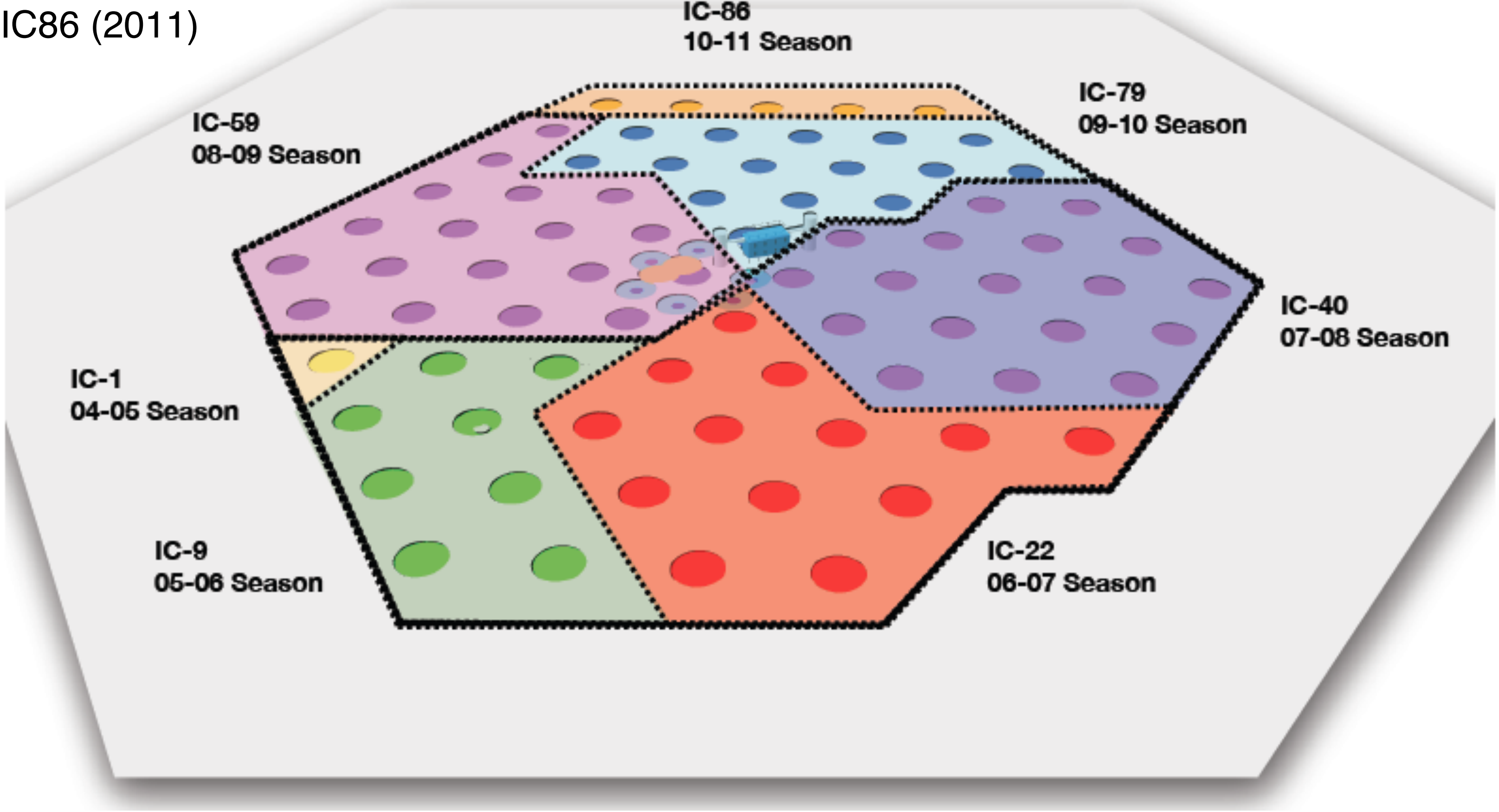
December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing opt
480 optical sensors

Digital Optical Module (DOM)

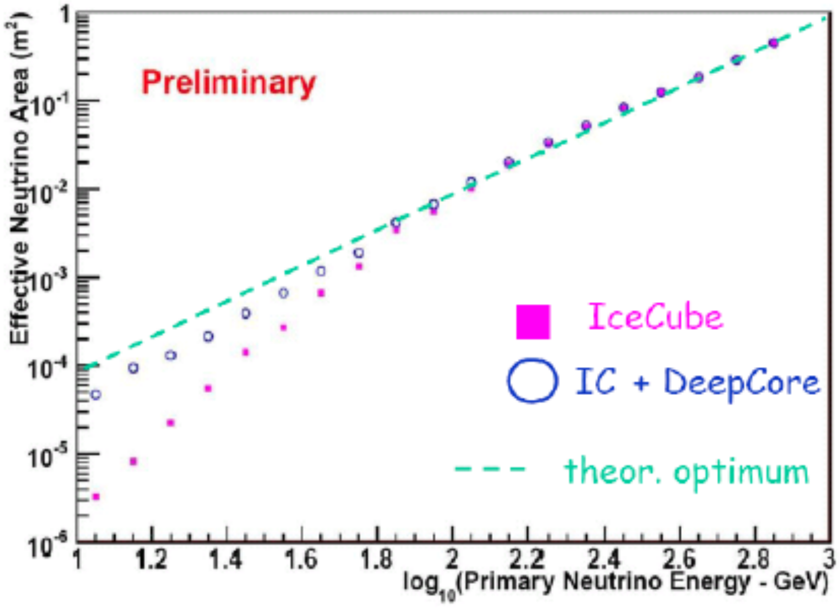
Detector configuration history:

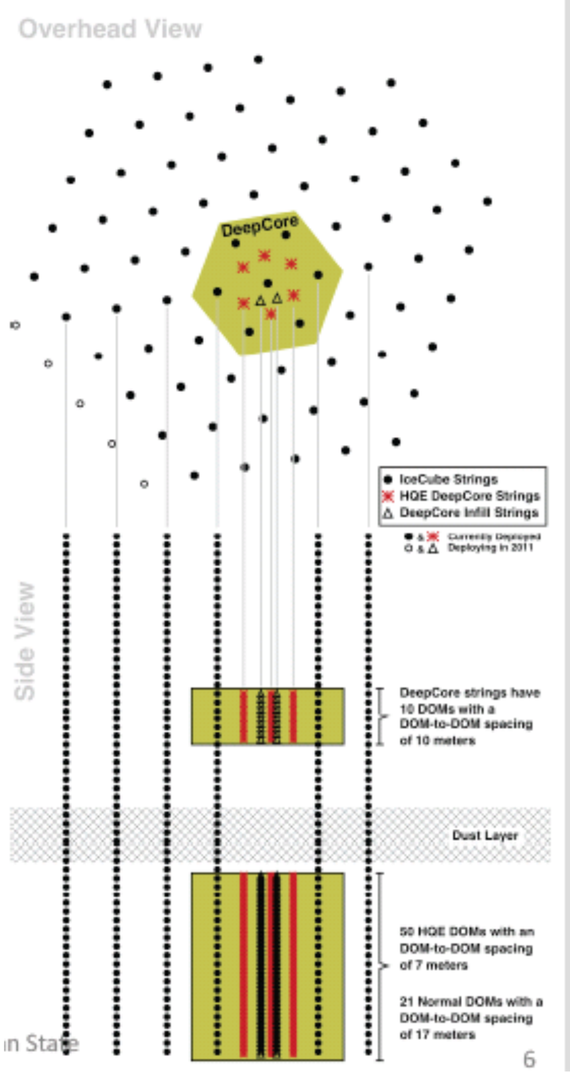
IC9   (2006)
IC22 (2007)
IC40 (2008)
IC59 (2009)
IC79 (2010)
IC86 (2011)



Deep Core subarray

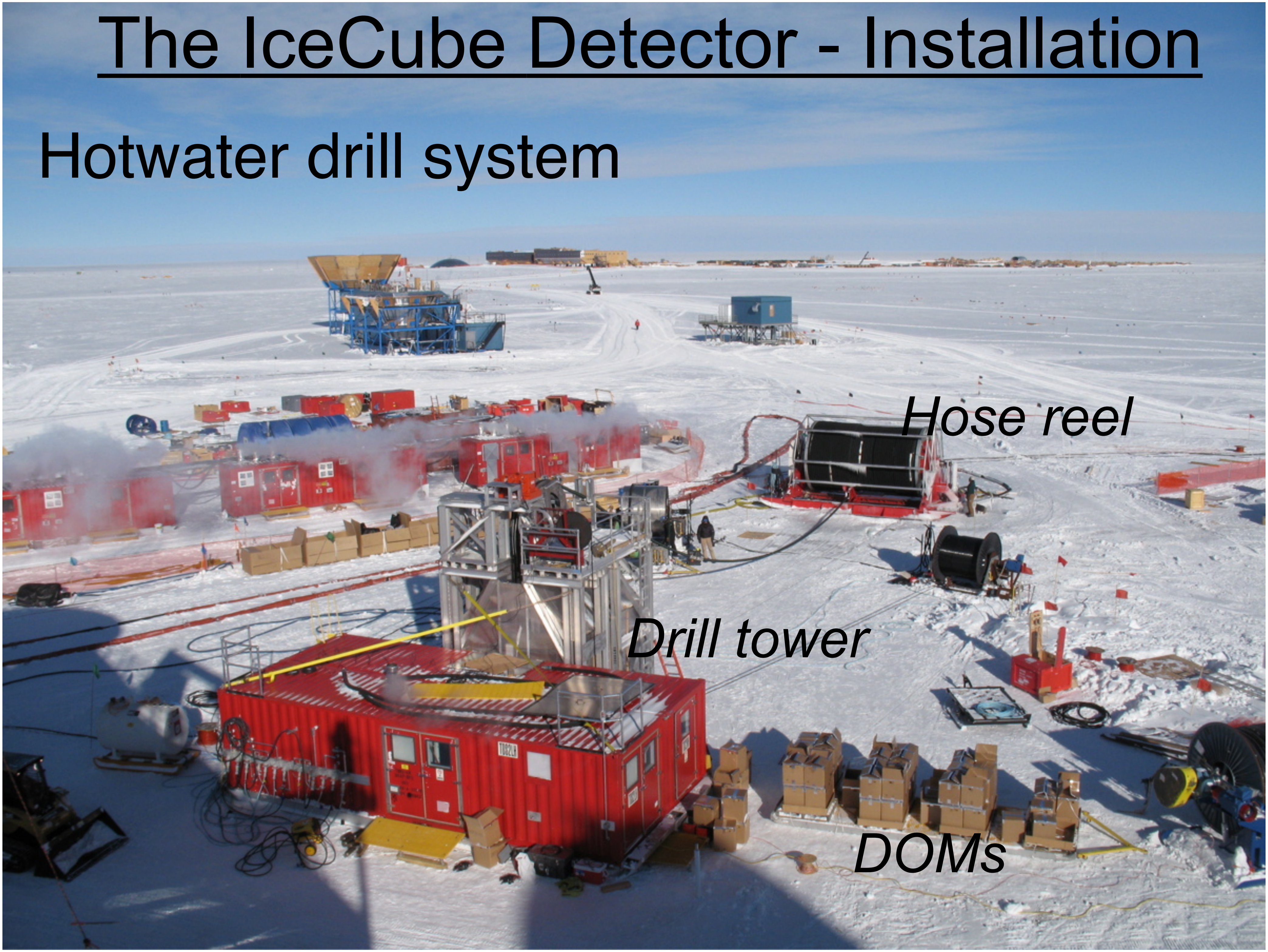
- 78 standard strings + 8 more densely instrumented cables
- In the deep center of IceCube
- E_μ threshold 10 GeV
- Main IceCube used as veto



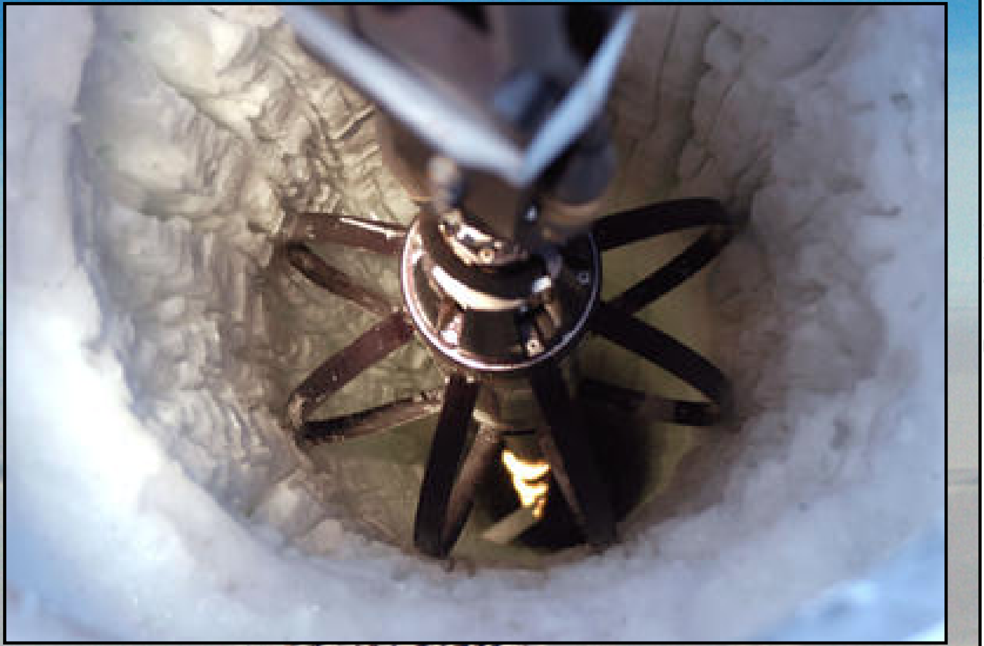


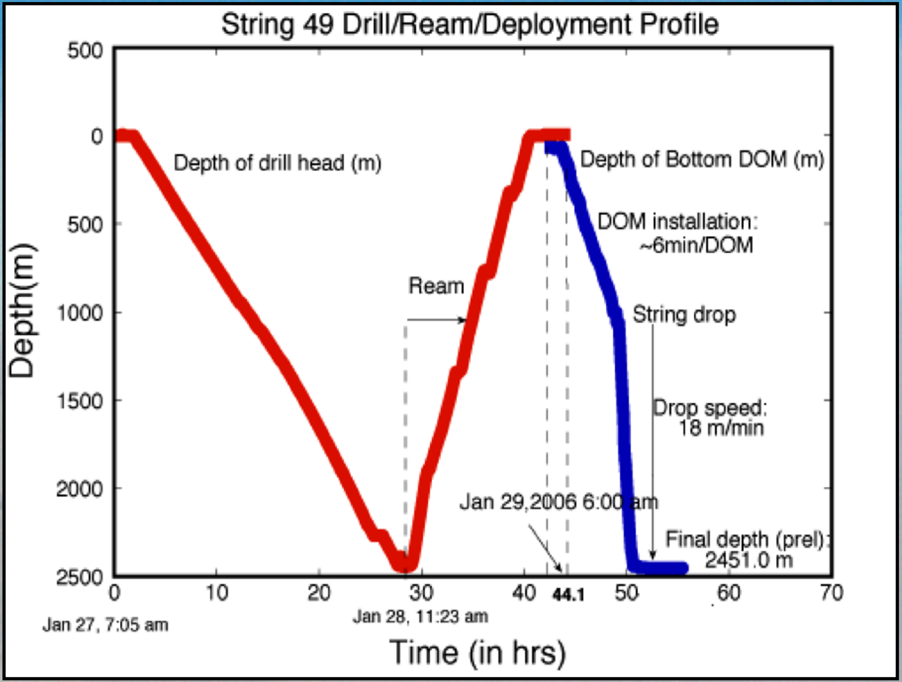
The IceCube Detector - Installation

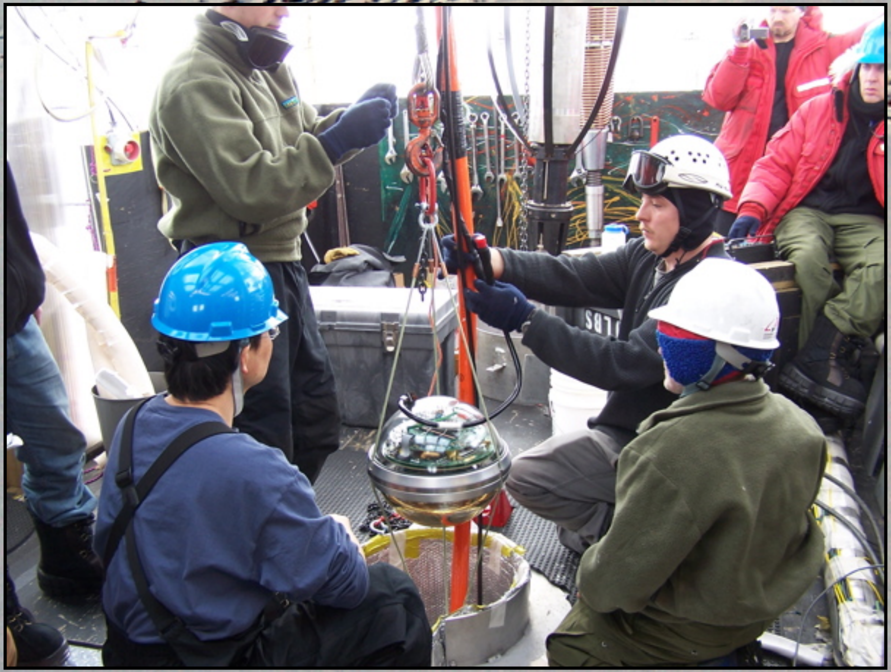
Hotwater drill system



The IceCube Detector - Installation

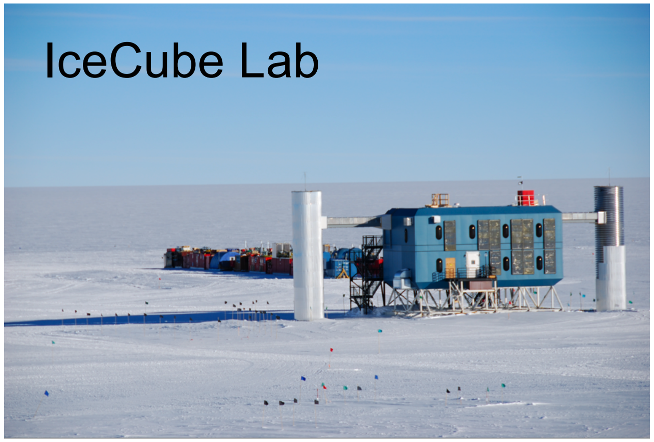






Experienced field team deals very well with issues and harsh conditions.

Connecting the Detector - Cable Pull Team



Connecting the under-ice sensors to servers inside the IceCube Lab (labor intensive process)

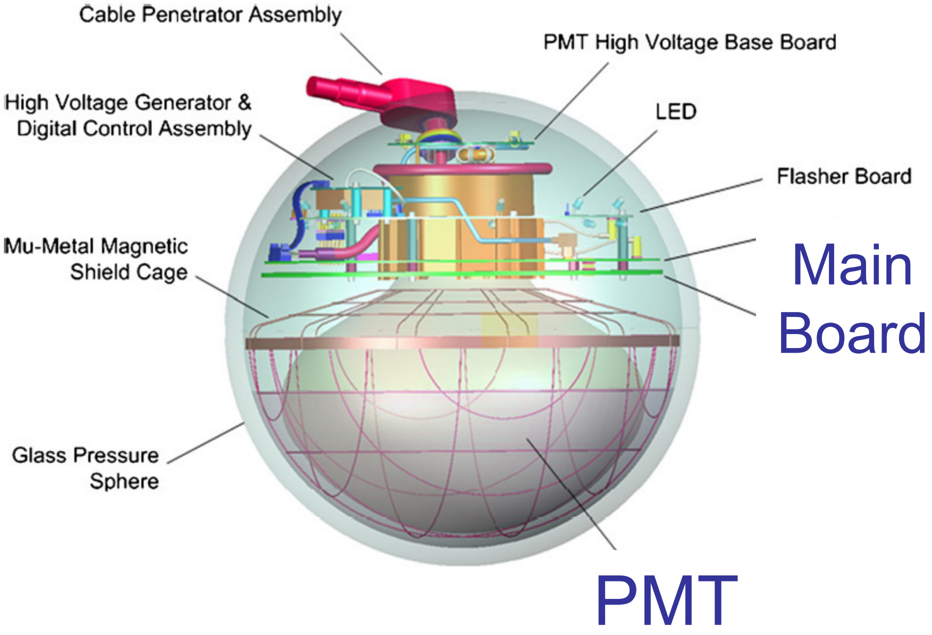
Hundreds of pounds of cables must be pulled up into the second floor of the IceCube Lab

Digital Optical Module (DOM)

DOM - a complete data acquisition system:

- internal digitization and time stamping the photonic signals from the PMT
- can perform PMT gain and time calibration
- transmitting digital data to the surface

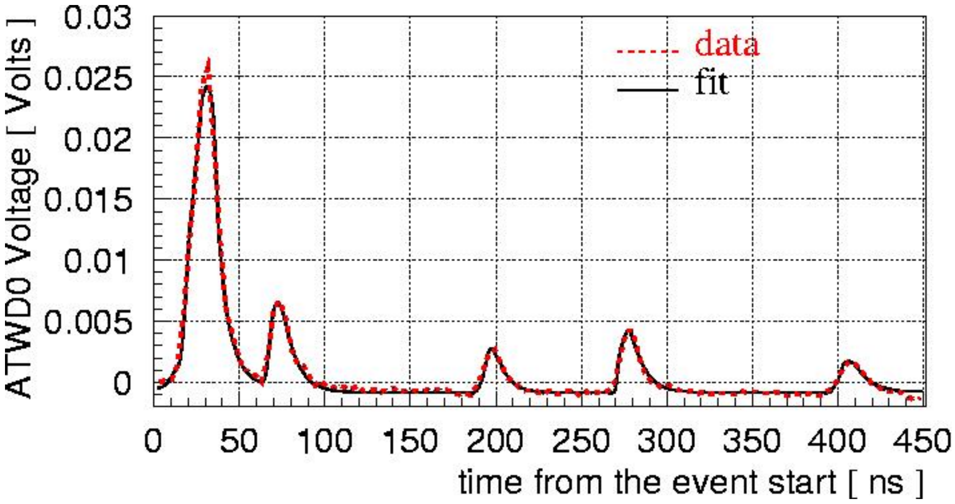
- power consumption: 3W
- deadtime < 1%
- Dark noise rate < 400 Hz
- Local Coincidence rate ~ 15 Hz



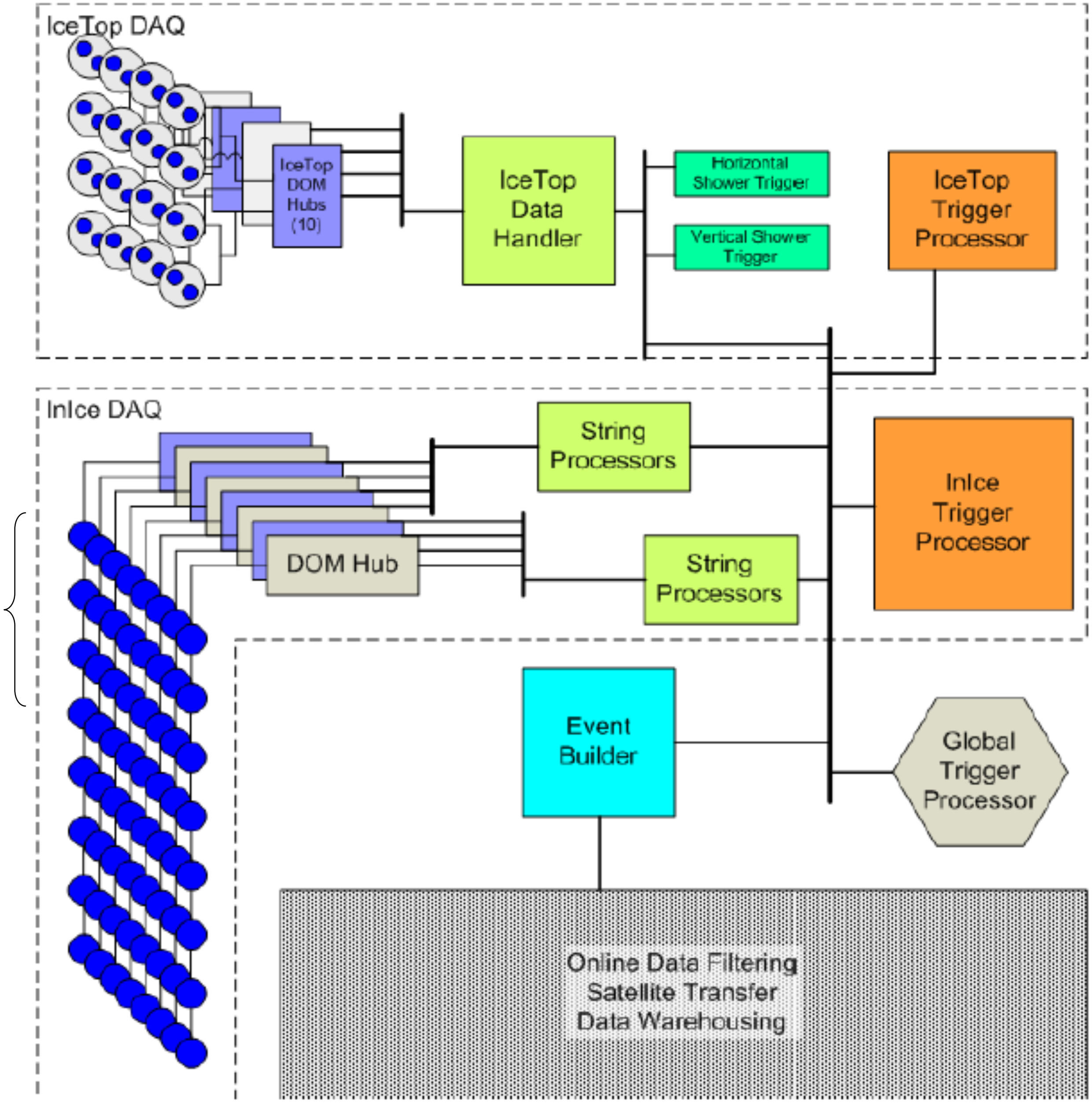
PMT: Hamamatsu 10”

Main Board:
PMT output collected with waveform digitizers:
- ATWD: 3 channels, sampling 300 MSPS, capture 400 ns with a nominal gain ratios 0.25:2:16.
- FADC: sampling 40 MSPS, capture 6.4 μs

Combined they provide wide dynamic range: from single p.e. to thousands p.e.



Triggering and Filtering



- Local coincidence communication between DOMs In ice

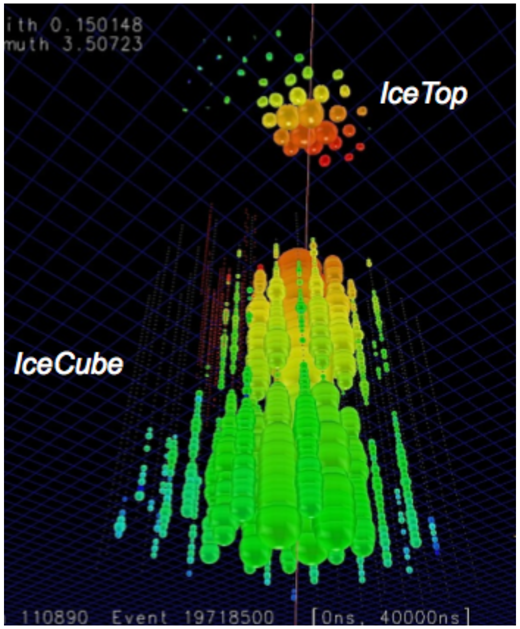
- Triggering on surface

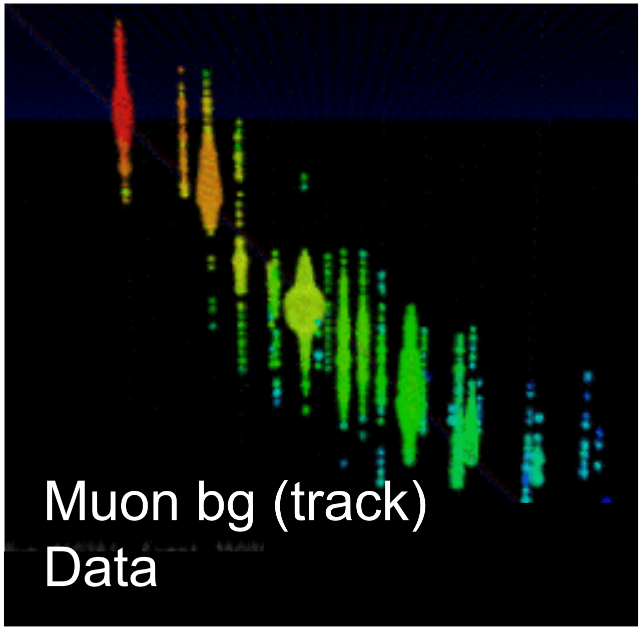
- Physics <u>filtering</u> (simple reconstruction algorithms) on data sent to the North via sattelite

Trigger Rates:

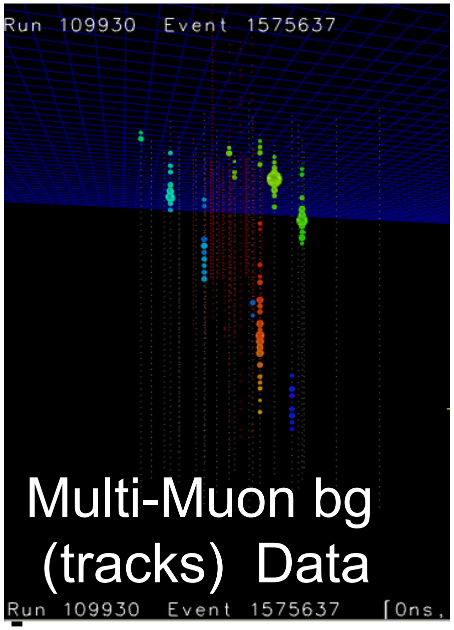
- IC22: CR rate is ~550 Hz
- IC40: ~1000 Hz
- IC86: ~2000 Hz (complete detector)

High trigger rates due to Atmospheric μ Background





Muon bg (track)
Data

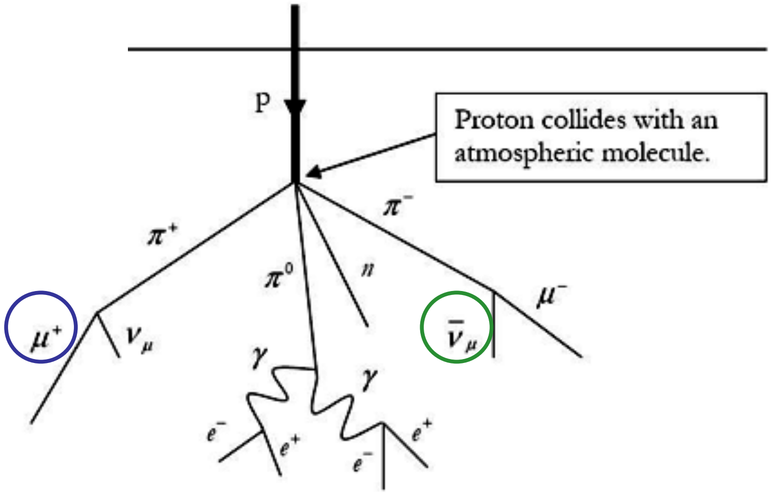


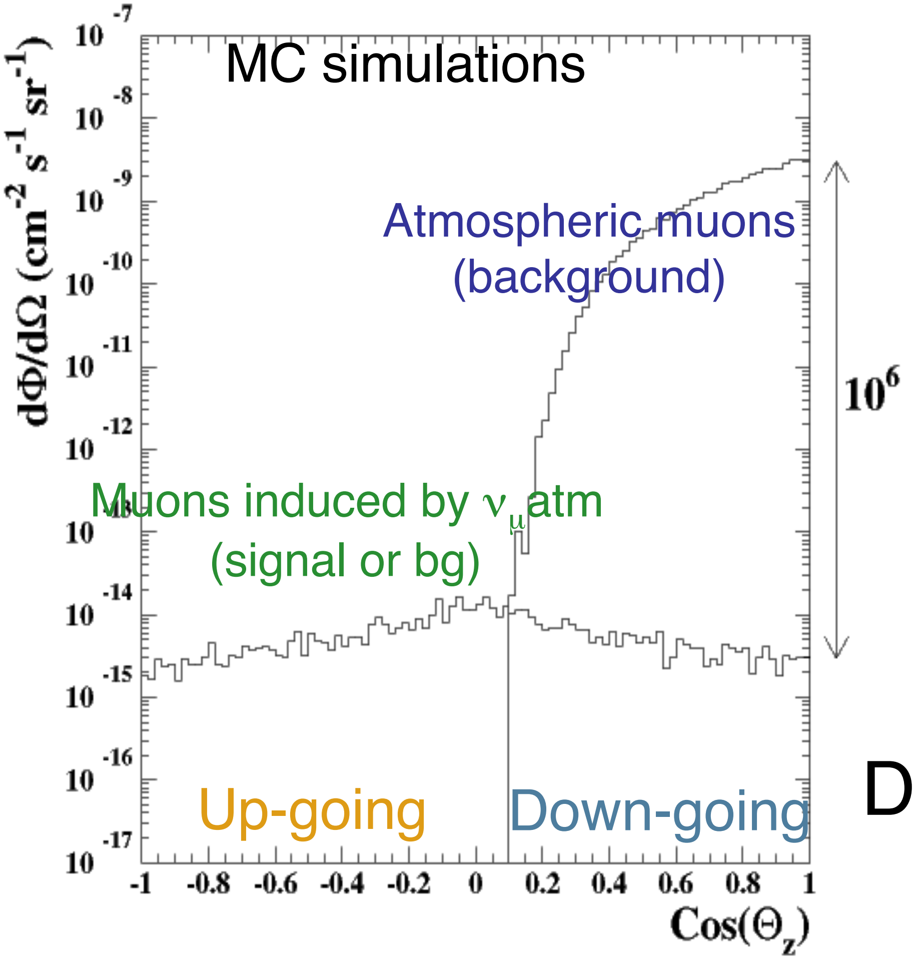
Multi-Muon bg
(tracks) Data

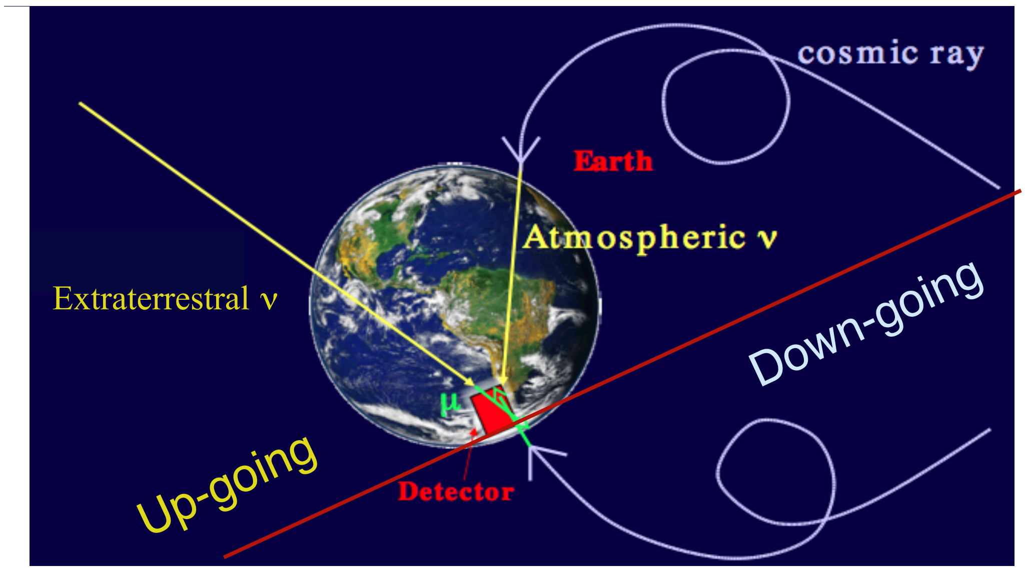
Main challenge: background rejection

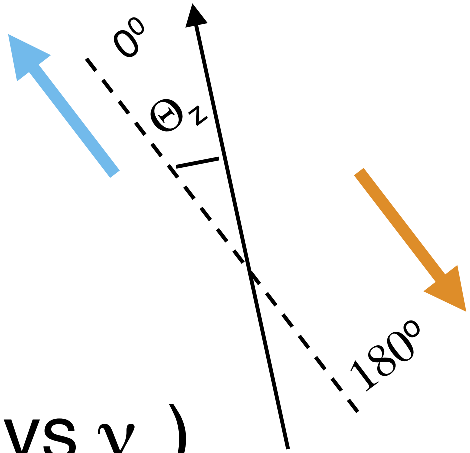
The approach is filtering based on hit topology and online reconstruction (including measured ice properties)

Atmospheric Muons Background (low energies)





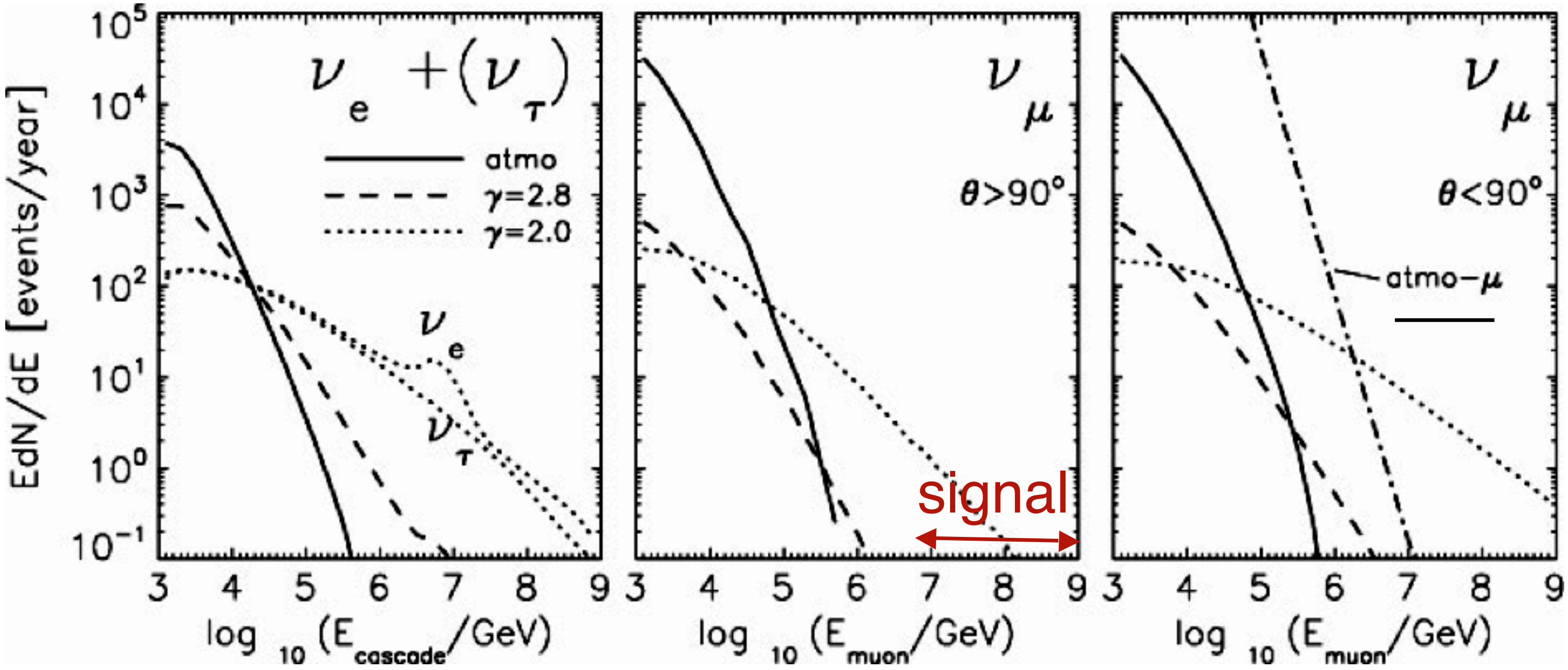




Distinguish μ (CR vs ν_μ)
by their direction

Signal vs Background Neutrinos (high energy)

- atmospheric neutrinos (mostly ν_μ): $dN/dE \sim E^{-3.7}$ bg ν
- neutrinos from charm decay in the atmosphere: $dN/dE \sim E^{-2.8}$ bg ν
- astrophysical neutrinos: $dN/dE \sim E^{-2.0}$ (model) signal ν



M.Kowalski [astro-ph/0505506]

Distinguish Signal vs bg ν by their energy

High energy ($E > 10^8$ GeV):

- Small μ and ν bg produced in CR interactions with the atmosphere
- Distinguish ν flavor by their topology (Earth opaque to $\nu_{\mu,e}$, ν_τ regeneration)

Particle (μ) Tracking

$$\nu_\mu + N \rightarrow \boxed{\mu} + X$$

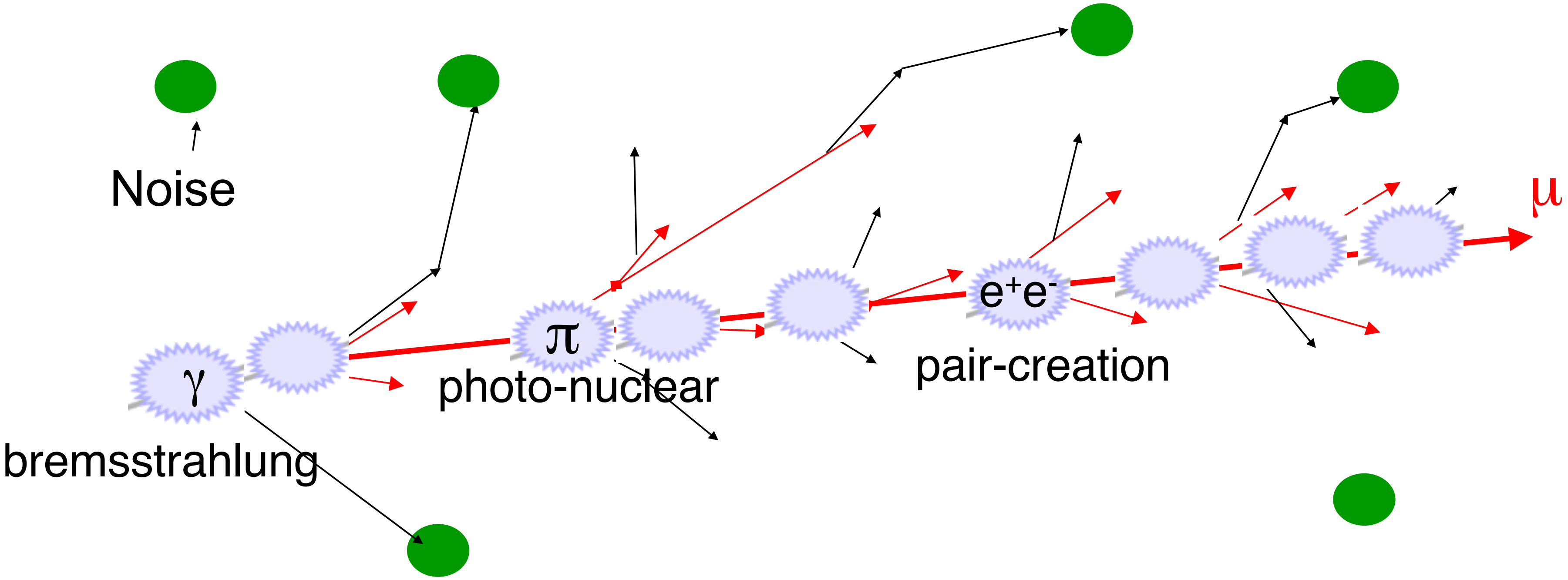
μ tracks lose energy by emitting γ, e^+e^- pairs and hadronic interactions (via virtual γ)

- Charged particles emit Cherenkov radiation angle $\theta = \mathrm{Cos}^{-1}(1/n) = 41^0$
- The photons scatter (L ~ 25 m)
- Some ($<10^{-6}$) photons are observed in photodetectors
- We measure points 0-30 meters from the μ track
- Angular resolution $< 1^0$

Ice Properties:

scattering λ_{sca}~20m@400 nm

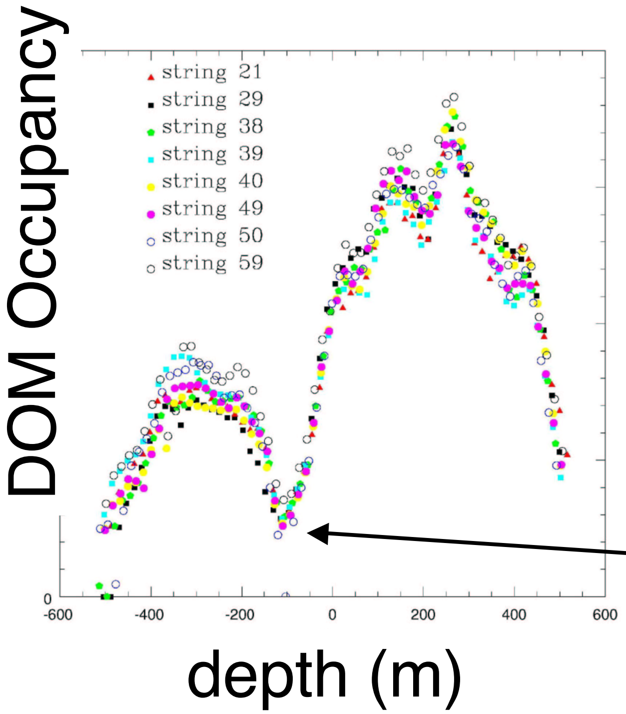
absorption λ_{abs}~110m@400nm



Ice Properties: scattering and absorption

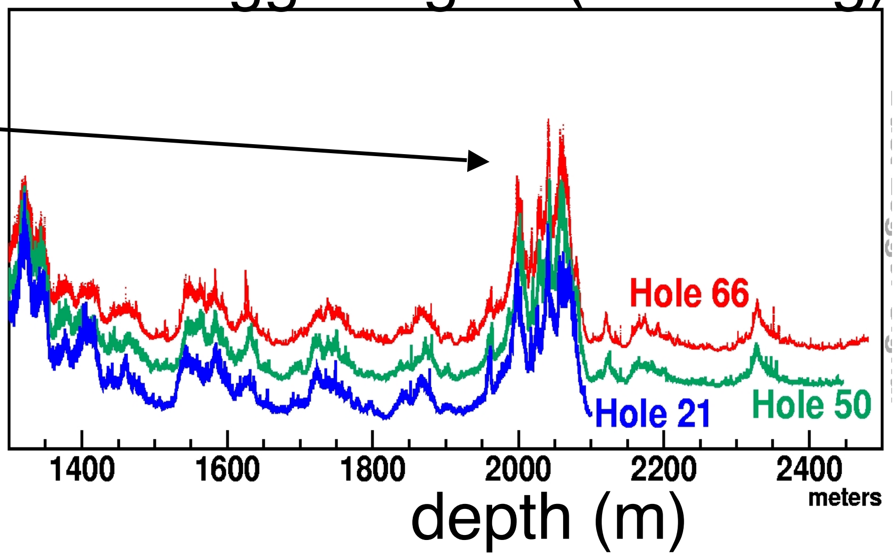
Average optical ice parameters: λ_{abs}~110m@400nm
λ_{sca}~20m@400 nm

Ice dust layers/bubbles/ash make them depth dependent



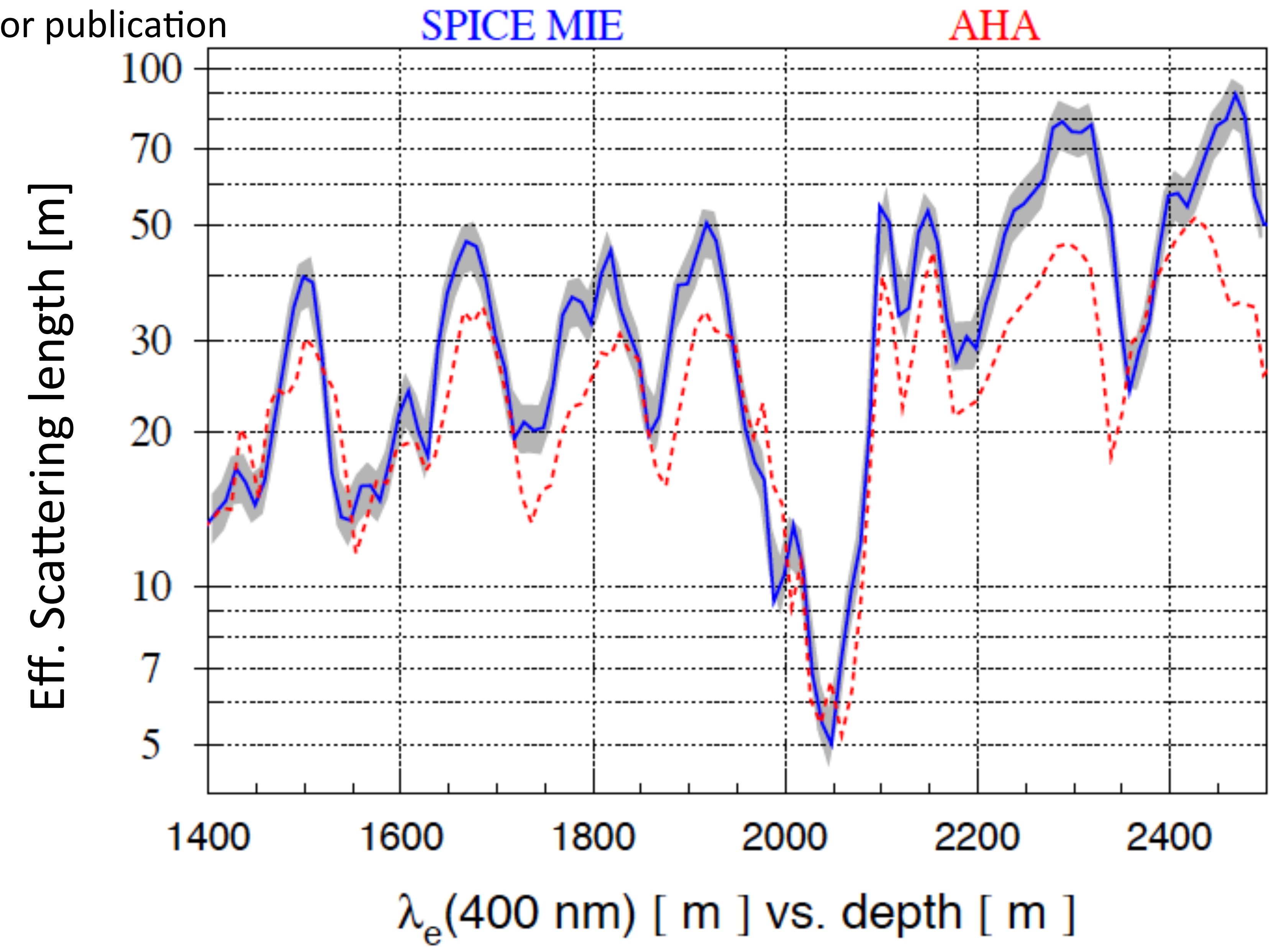
- Affect DOM occupancy (probability a DOM is hit in events that have >7 hits on a string)
- Key to modelling IceCube
- Measurements: in-situ light sources, atmospheric muons and Dust Loggers (one per string on 3 strings)

Dust Logger signal (scattering)

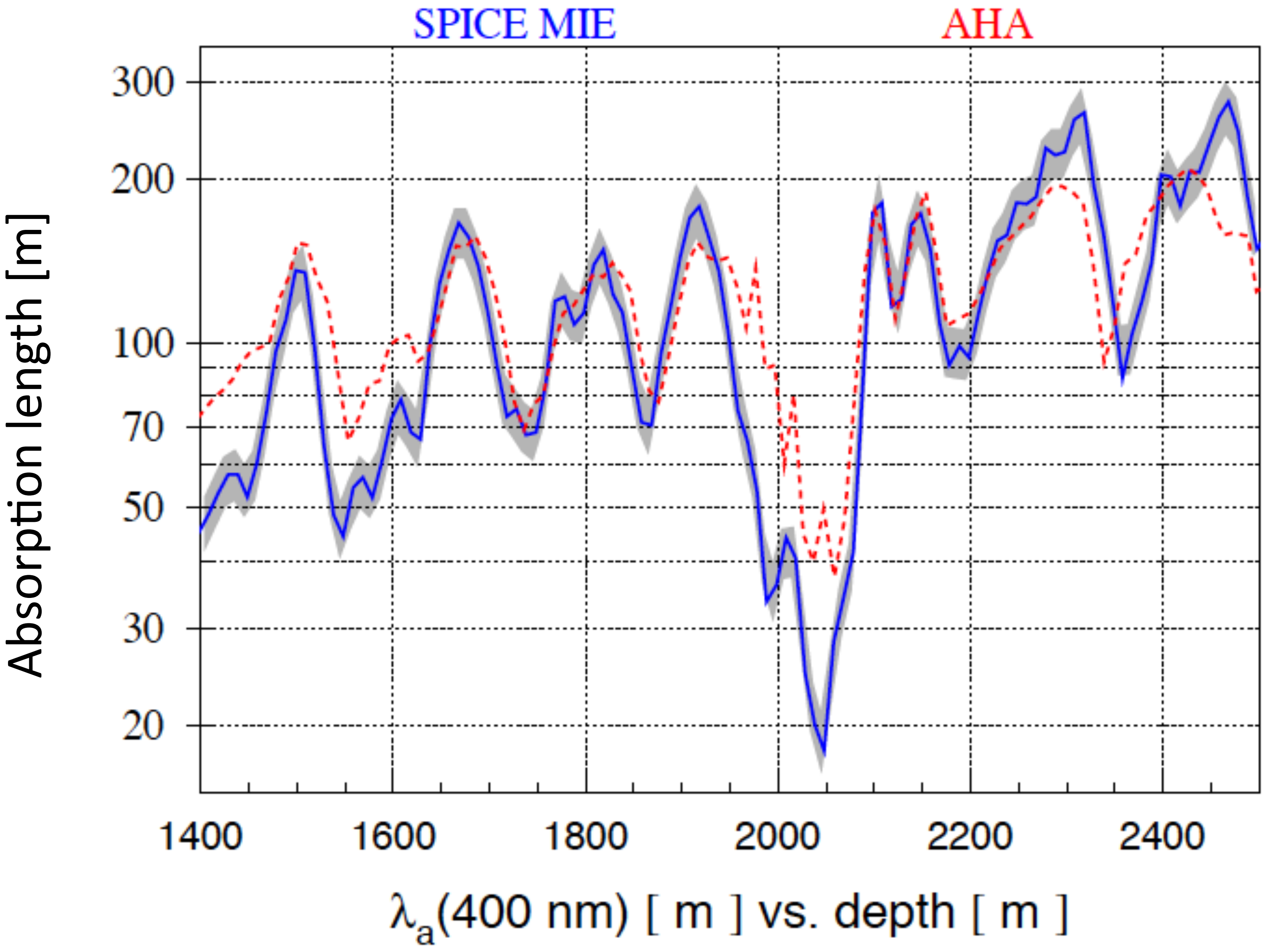


Effective Scattering length vs Depth

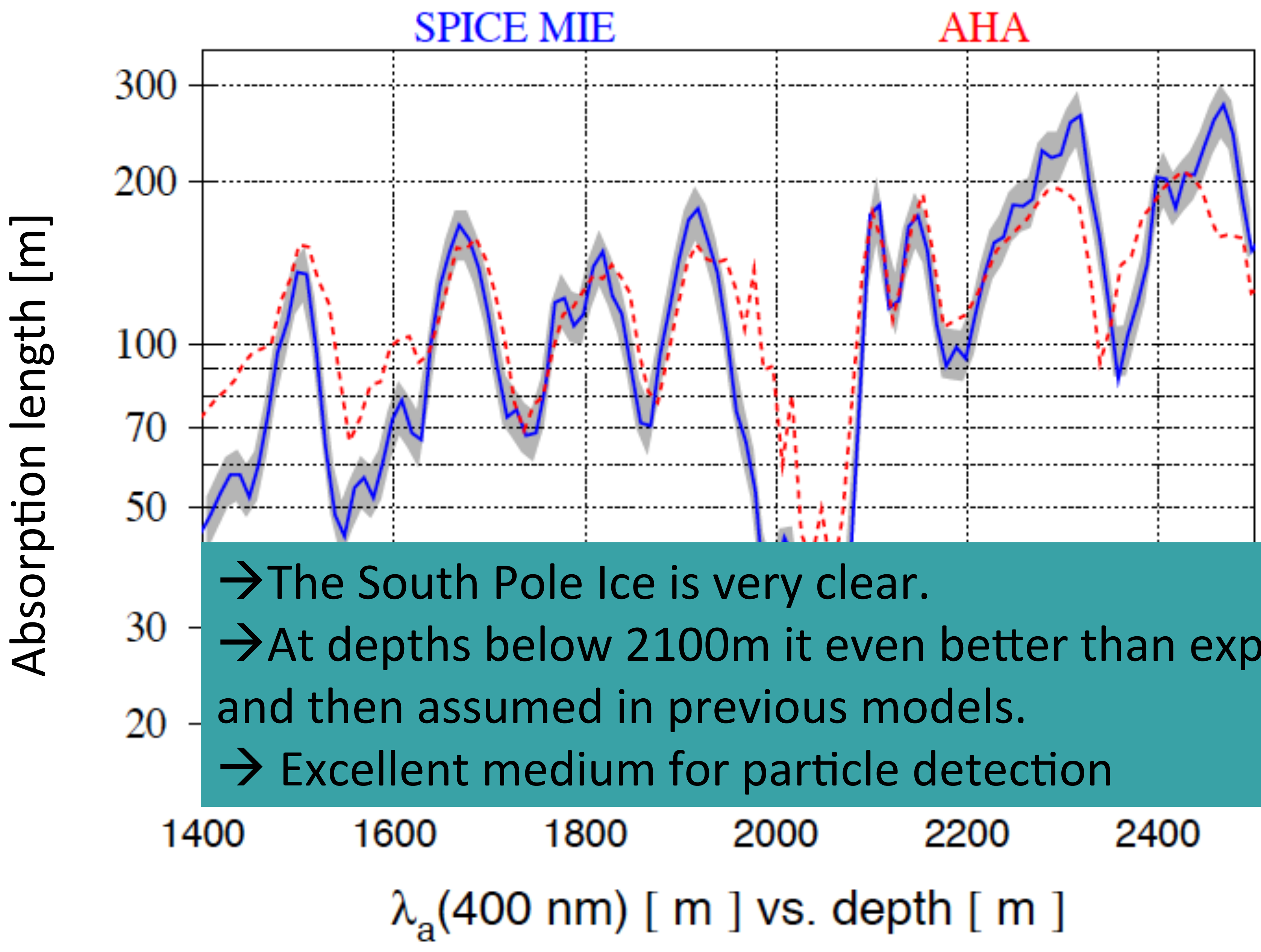
in internal review
for publication



Absorption length vs Depth



Absorption length vs Depth

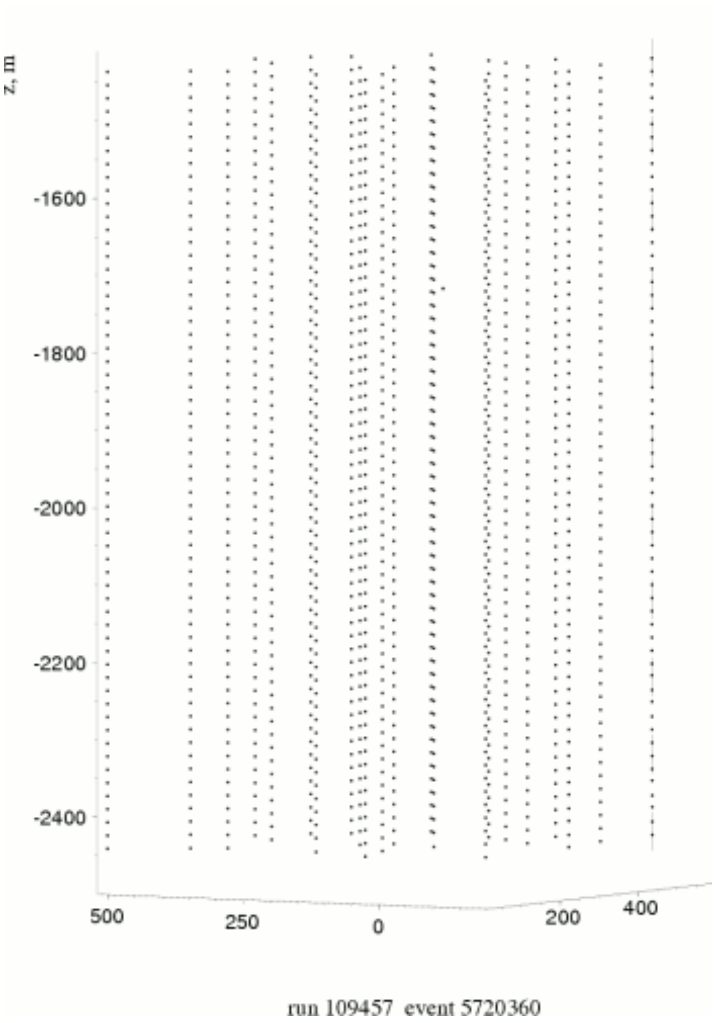


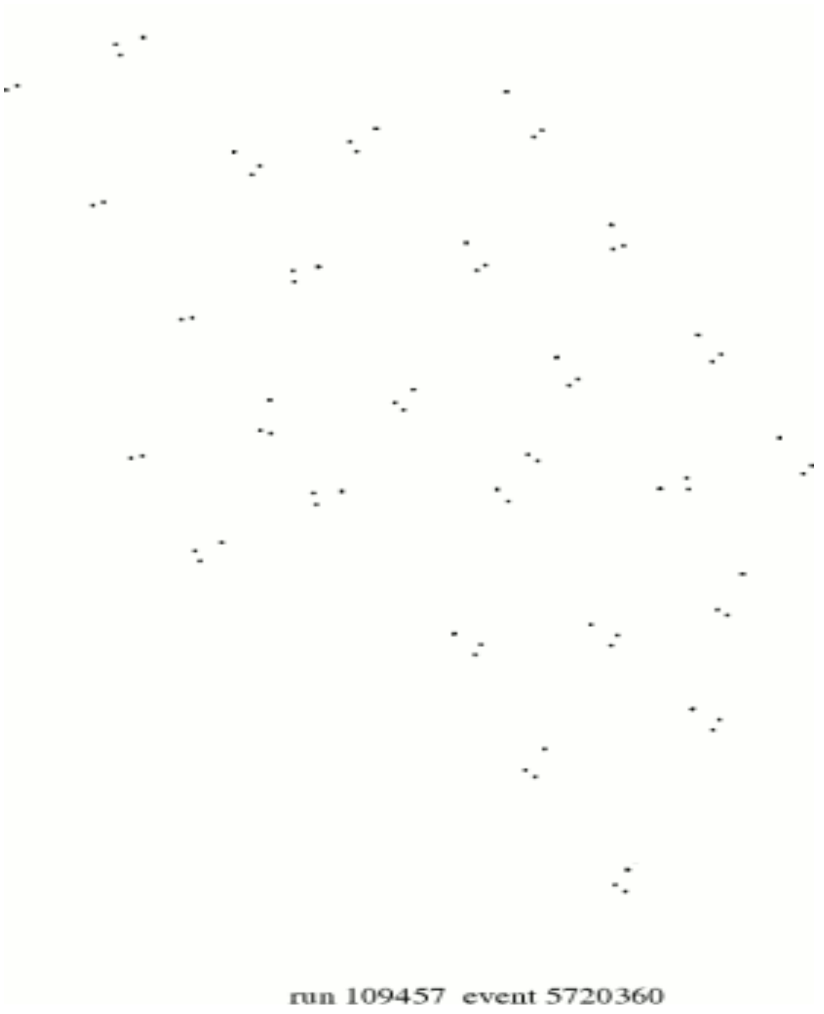
→The South Pole Ice is very clear.

→At depths below 2100m it even better than expected and then assumed in previous models.

→ Excellent medium for particle detection

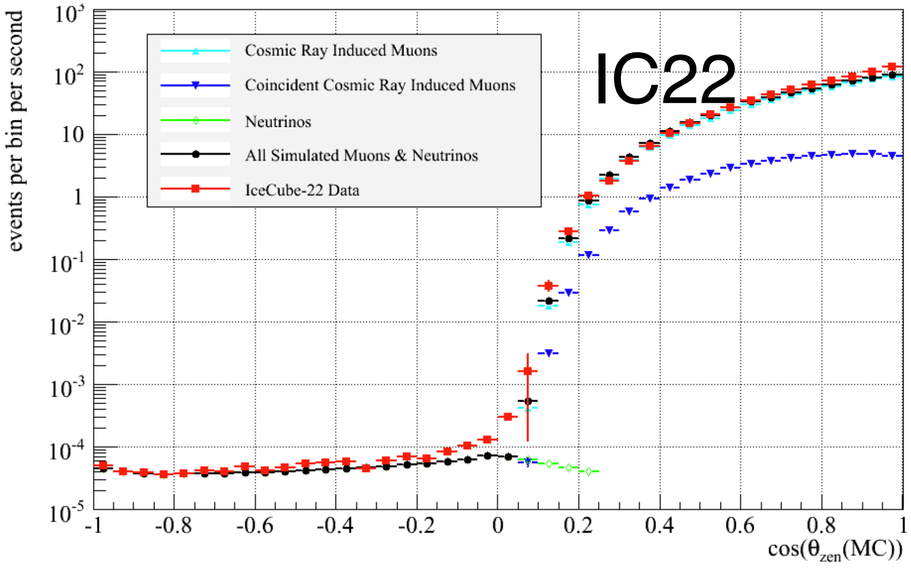
IC22 up-going muon event
Signature of ν_μ event



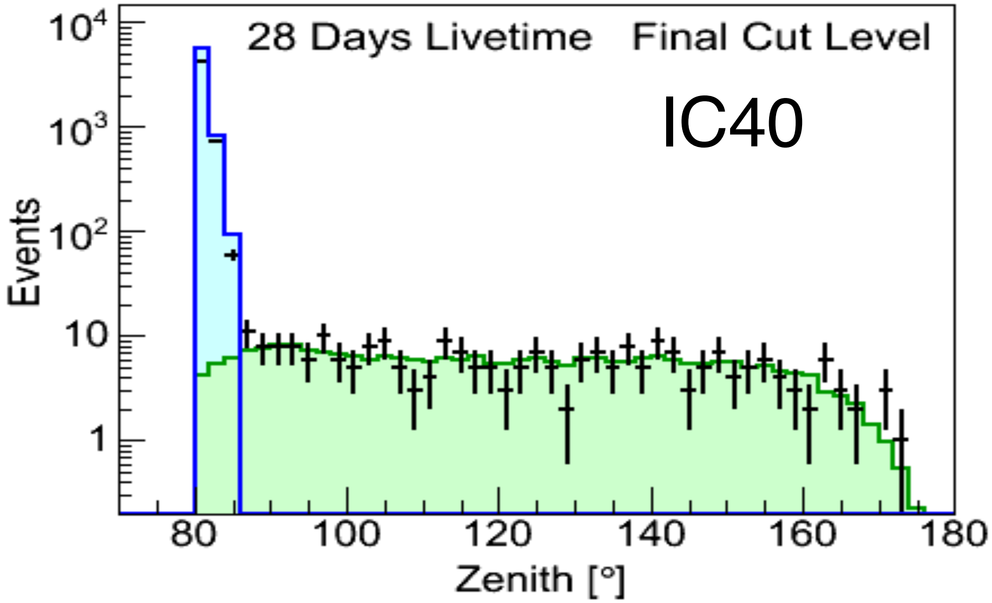


IC59 ~160 atmospheric neutrinos /day

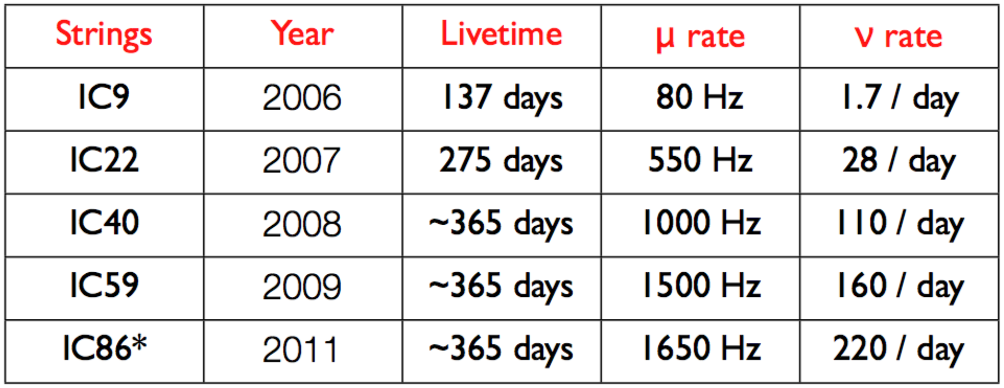
Atmospheric neutrinos



- Good agreement between MC simulations and the data (trigger level)
- Clear cutoff of cosmic-ray muons near horizon



- High-purity atmospheric neutrino sample achieved after quality cuts



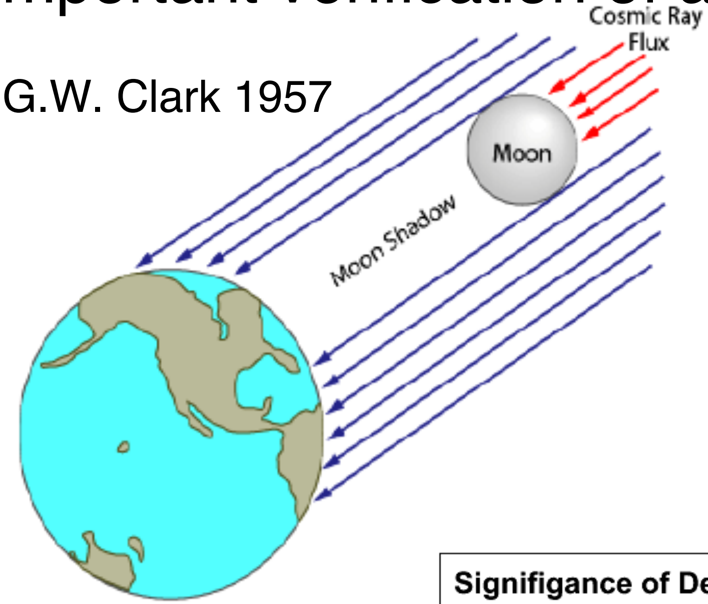
Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1500 Hz	160 / day
IC86*	2011	~365 days	1650 Hz	220 / day

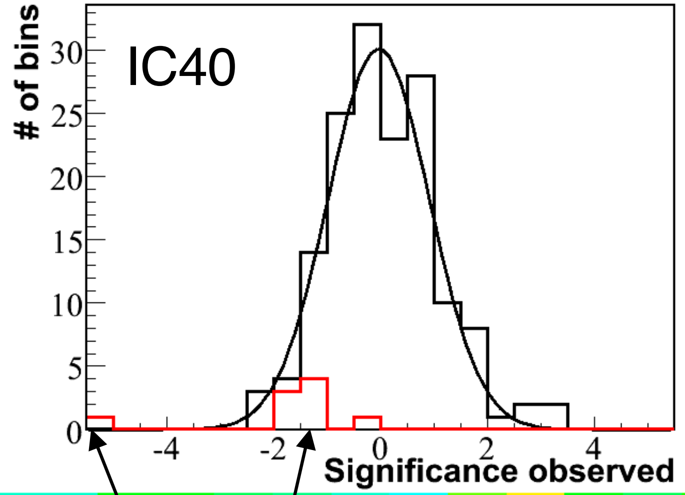
*estimated

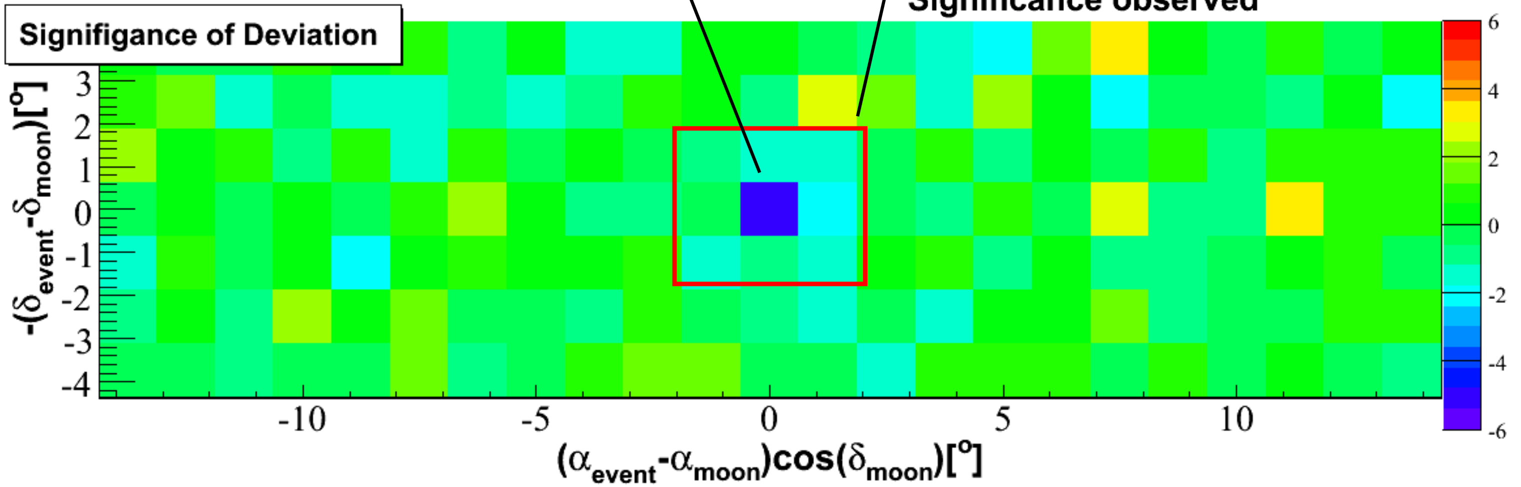
Moon shadow observed in muons

Important verification of angular resolution and absolute pointing

G.W. Clark 1957





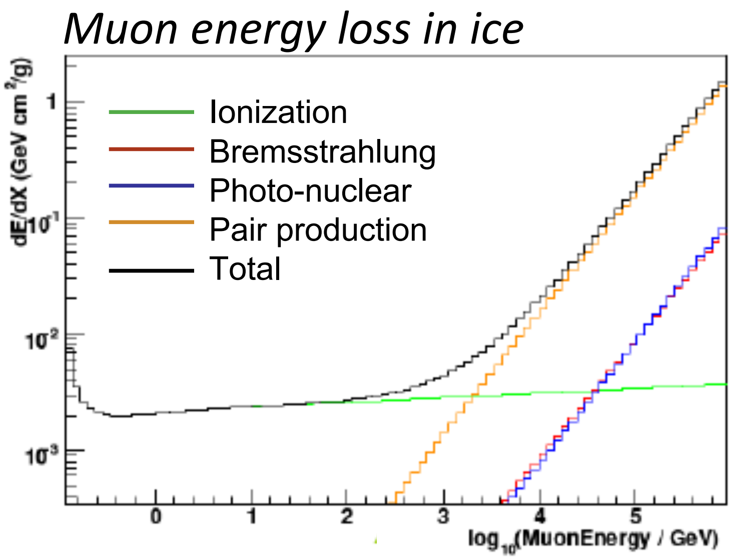


- Moon shadow seen with ~5σ (deficit of ~900 events out of 28k)
- Systematic pointing error less than 1.25 degrees

Particle (μ) Tracking

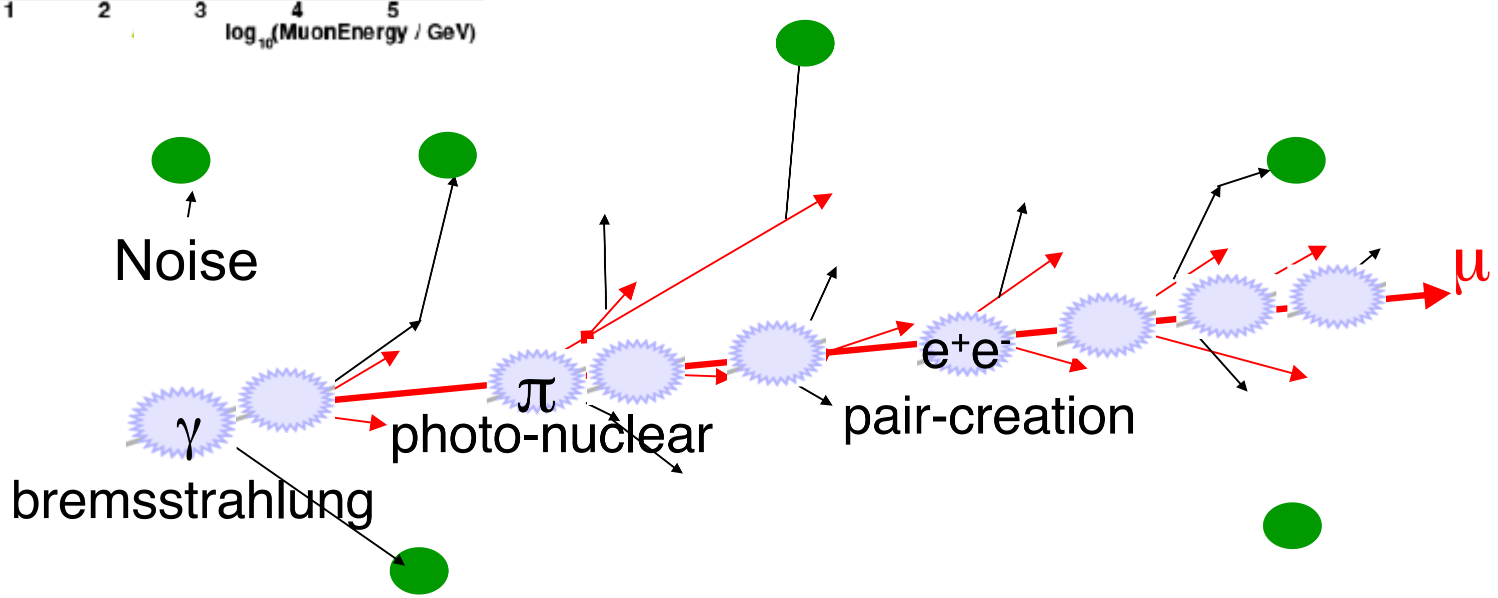
$$\nu_\mu + N \rightarrow \mu + X$$

μ tracks lose energy by emitting γ, e^+e^- pairs and hadronic interactions


Muon energy loss in ice

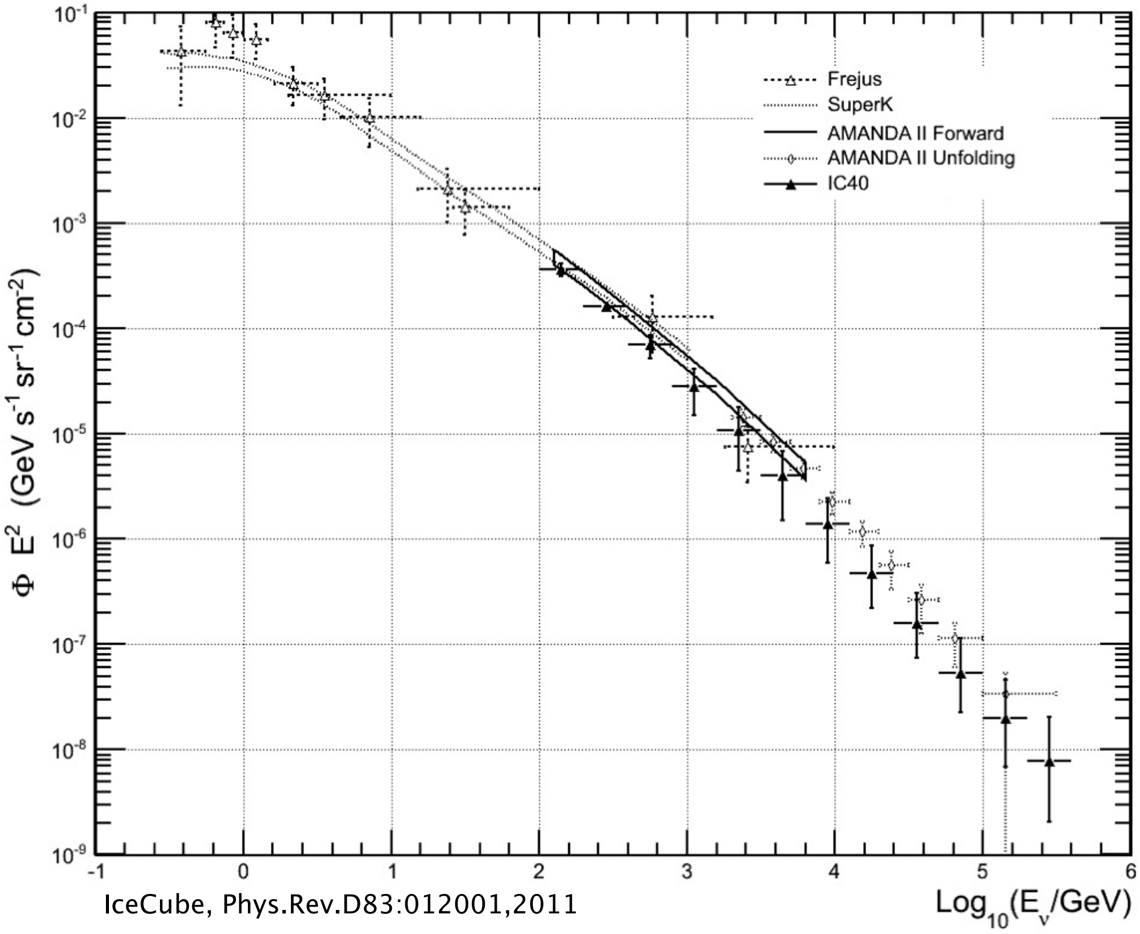
- E_μ<500 GeV (ionization dominant ~2 MeV/cm)
- E_μ>500 GeV (stochastic energy loss dominant)

- Muon energy measurement from dE/dx



Atmospheric Muon Neutrinos (IC40)

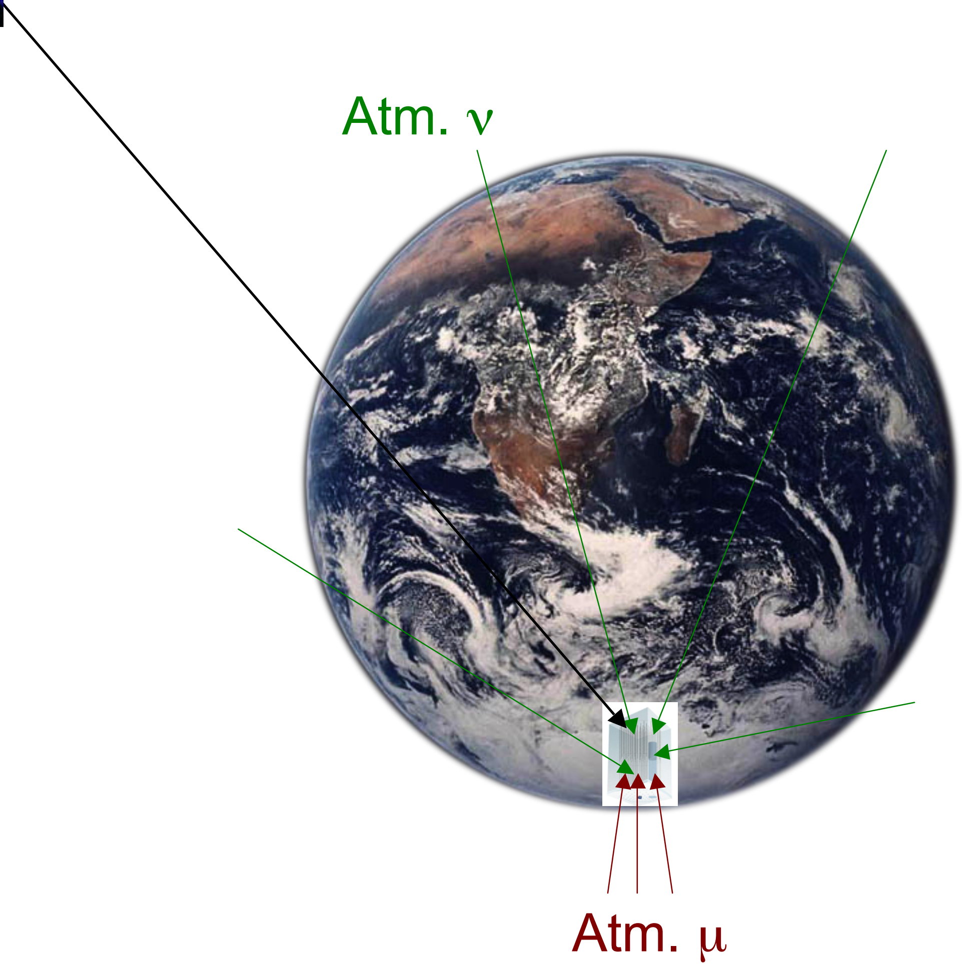
- Measurement of muons from atmospheric neutrinos
- Consistent with previous measurement in the overlap region.
- As detector size increases, this measurement can be extended up to > 1 PeV



IceCube, Phys.Rev.D83:012001,2011

Point Source Neutrino Search

Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos



Search for point sources

Point-like signals of few events need to be singled out among the large number of background e.g. atmospheric neutrino events

The unbinned likelihood ratio method:

- At any celestial direction, the data can modeled by 2 hypotheses: (i) data consists of bg events and (2) data consists of bg events and signal astrophysical neutrino events
- Test-statistics = $\log\left[\frac{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})}{\mathcal{L}(\vec{x}_s, 0)}\right]$

The likelihood function: $\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_N \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i\right)$

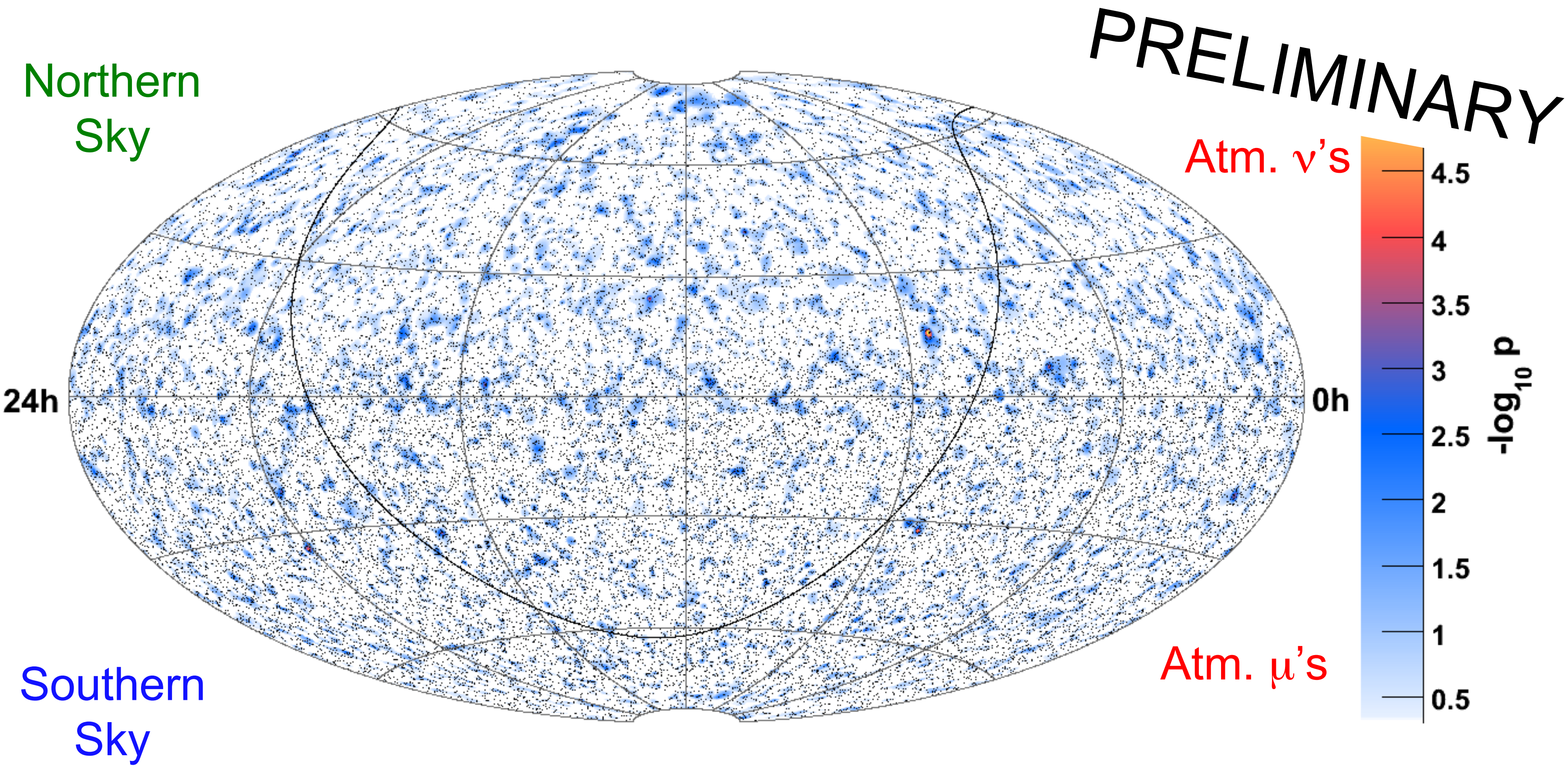
S_i ($\mathcal{B}_i$) = source (background) probability density function

-log($\mathcal{L}$) minimized to determine $\hat{n}_s, \hat{\gamma}$

It provides as estimate of the significance (pre-trial p-value) of deviation from bg at a given position in the sky.

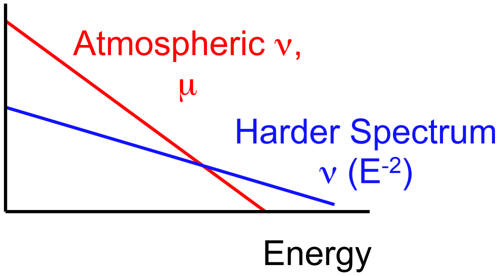
- Post-trial significance (p-value) is the fraction of scrambled data sets (right ascension of the events are randomized) containing at least one spot with log likelihood ratio higher than the one observed in the data.

IC40 All Sky Point Source Search



All sky neutrino search

- Unbinned likelihood analysis using energy and angular resolution of each event
- 37,290 neutrino candidates (23,151 atm. μ from southern hemisphere)
- Hottest Spot in IC40 not significant (96% scrambled maps had higher significance)

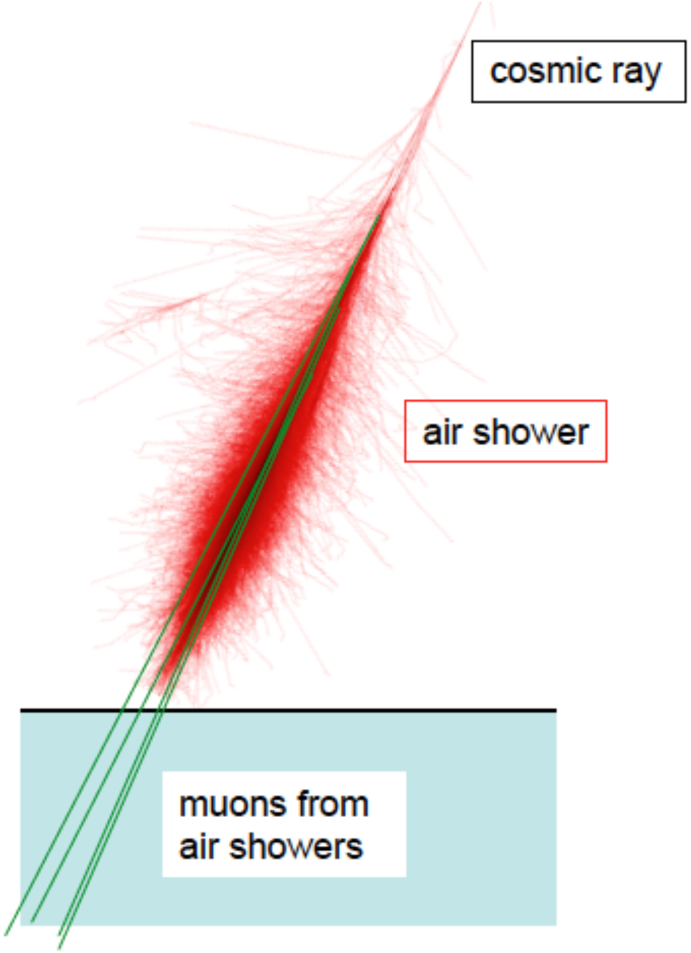


arXiv:1012.1633 (to appear in Ap.J.)

Cosmic Rays in IceCube

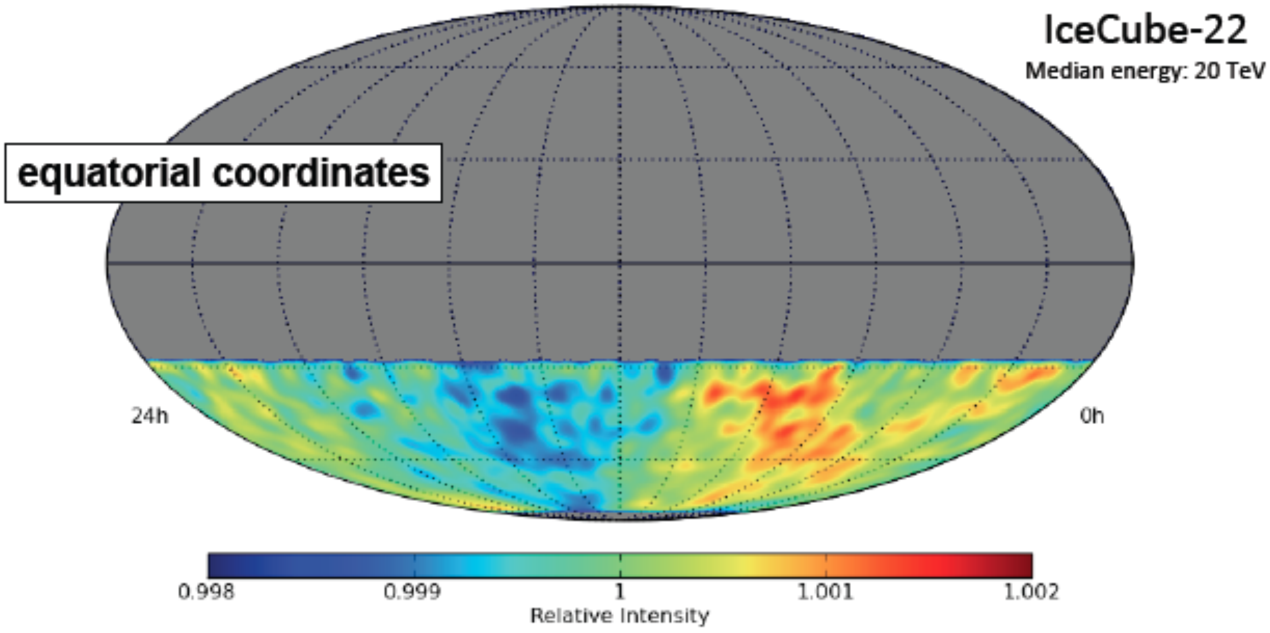
- IceCube tries to identify cosmic ray sources by their neutrino signal, but it also allows for a study of the *cosmic ray flux* itself, as the detector is sensitive to *downward going muons* produced in cosmic ray air showers in the southern hemisphere.

- By detecting downgoing muons, IceCube can study the *arrival direction distribution of cosmic rays* in the energy range ~10 TeV to several 100 TeV and produce a cosmic ray sky map of the southern sky.



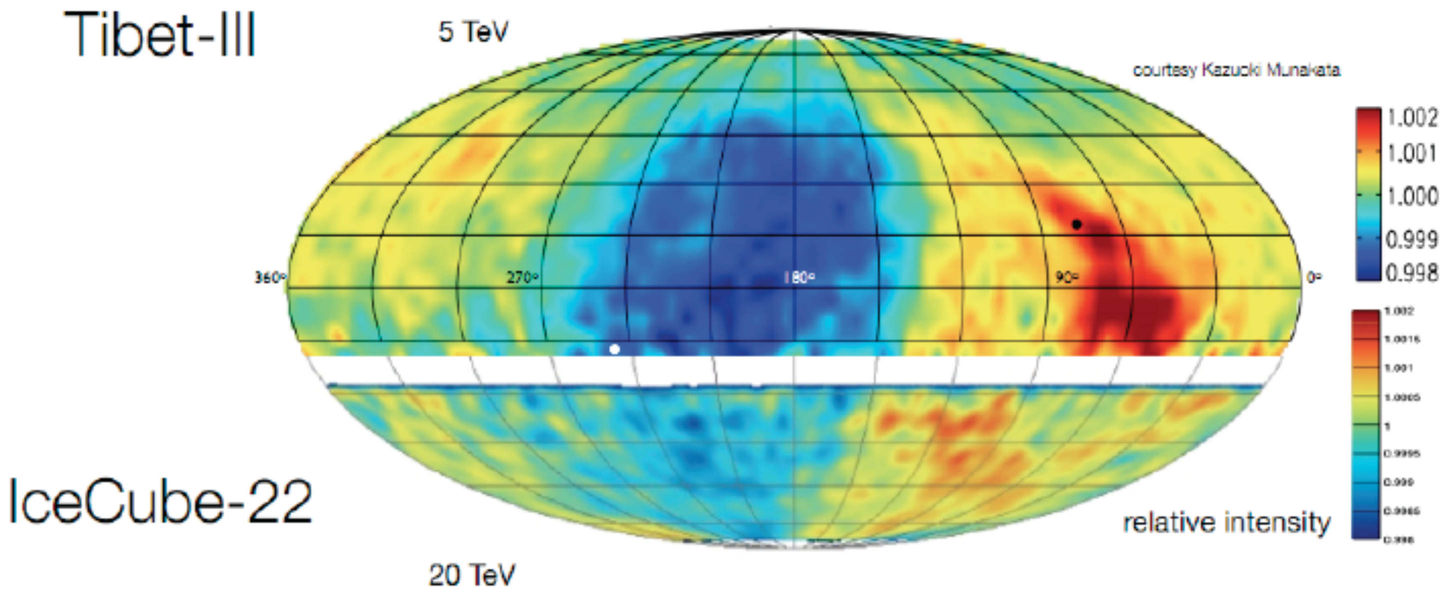
IceCube Large Scale Anisotropy

- Nevertheless, there have been several observations of *large-scale, part-per-mille anisotropies* in cosmic ray arrival directions between 0.1 and 100 TeV.
- *Relative intensity* of the cosmic ray event rate in equatorial coordinates: for each declination belt of width 3°, the plot shows the number of events relative to the average number of events in the belt.



IceCube Collaboration, Astrophys. J. 718 (2010) L194

Large Scale Anisotropy



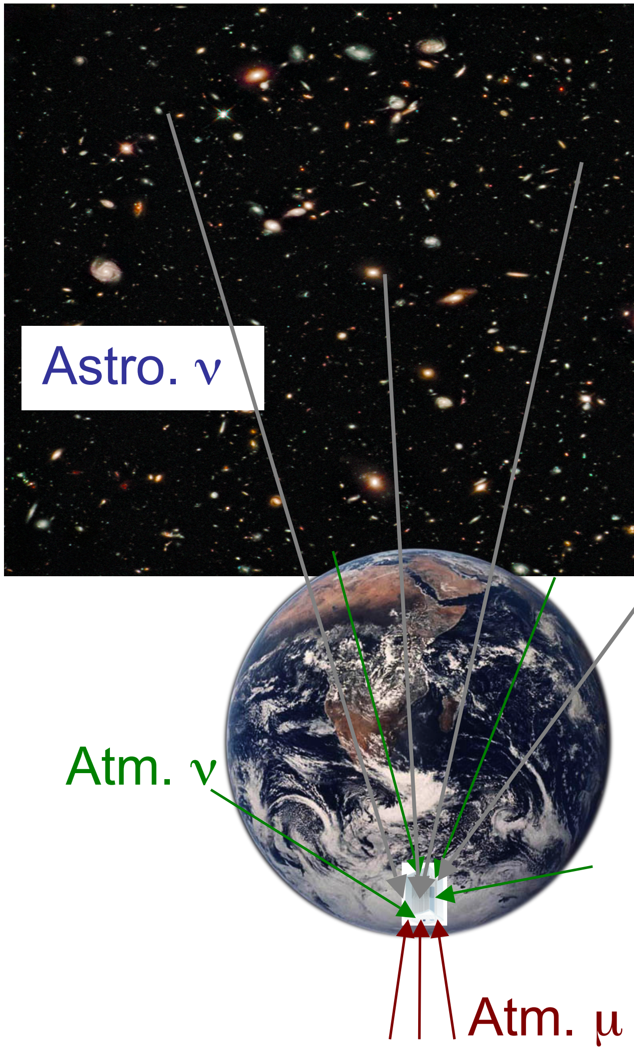
- Large scale anisotropy in IceCube-22 relative intensity map is at the 10^{-3} level (dipole+quadrupole); it is consistent with northern hemisphere observations.

- The origin of these anisotropies is currently not known. In the near future, IceCube can study whether the anisotropy persists at higher energy (>100 TeV).

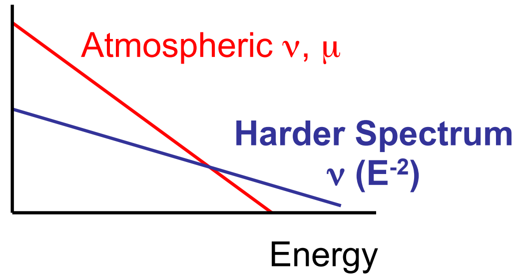
- The hot spots might indicate *unknown structure in the Galactic magnetic fields* or the heliosphere.

Search for Diffuse Neutrino Fluxes

Diffuse flux = effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs)
Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.

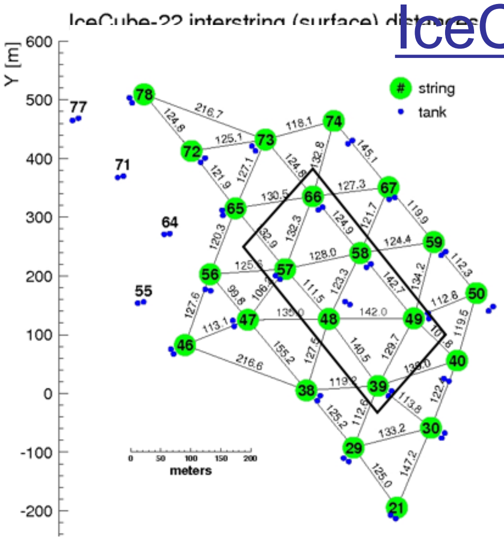


- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos

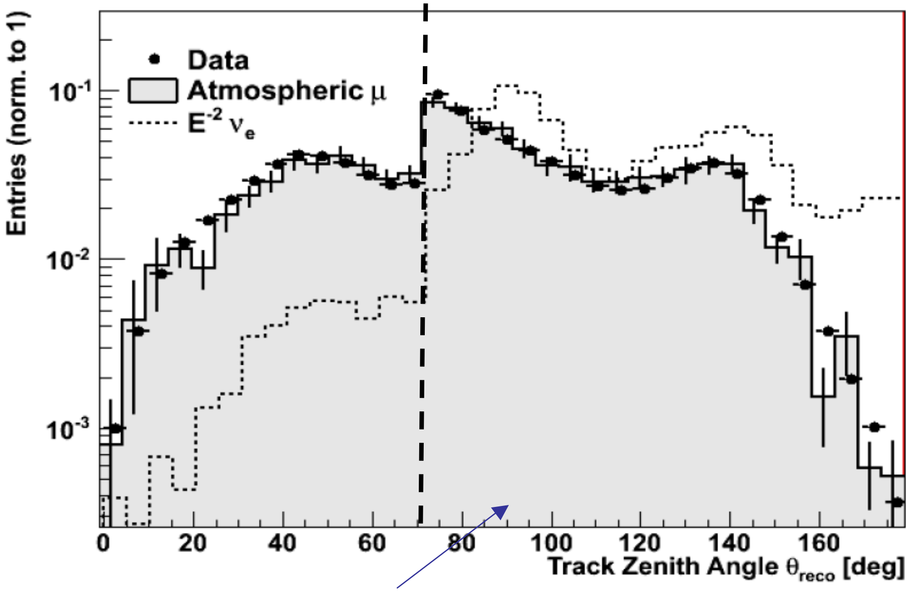


- Advantage over point source search: can detect weaker fluxes
- Disadvantage: high background
- Sensitive to all three flavors of neutrinos

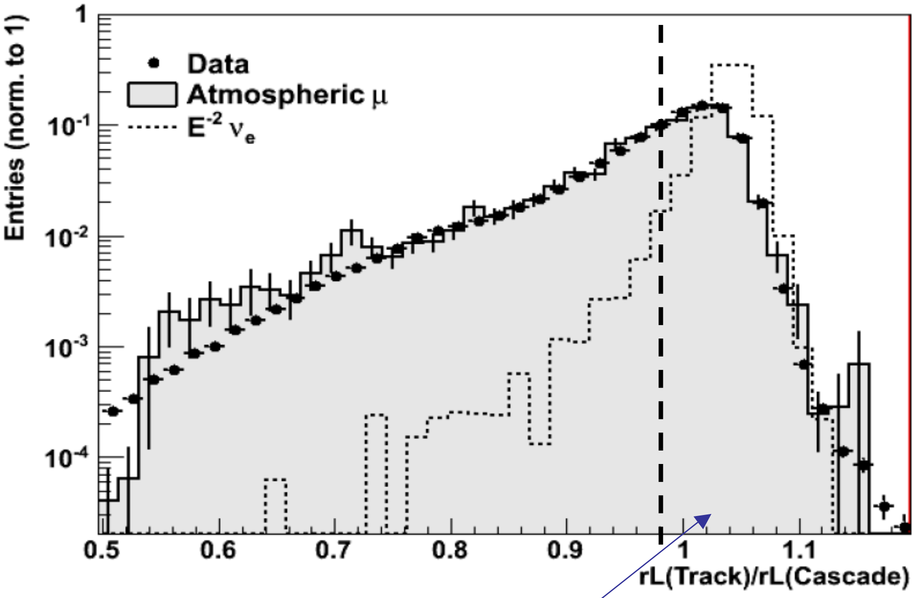
IceCube 22-string first extra-terrestrial cascade analysis
Data and Monte Carlo comparison (1)



- Cascade and track llh-reconstruction algorithms, to reject well reconstructed downgoing muon tracks and keep cascade-like events



Misreconstructed downgoing muons



Distinguish between track and cascade

J.Kiryluk, arXiv:0909.0989 (ICRC2009 proceedings)
IceCube, arXiv: 1101.1692 (Submitted to Phys.Rev.D)

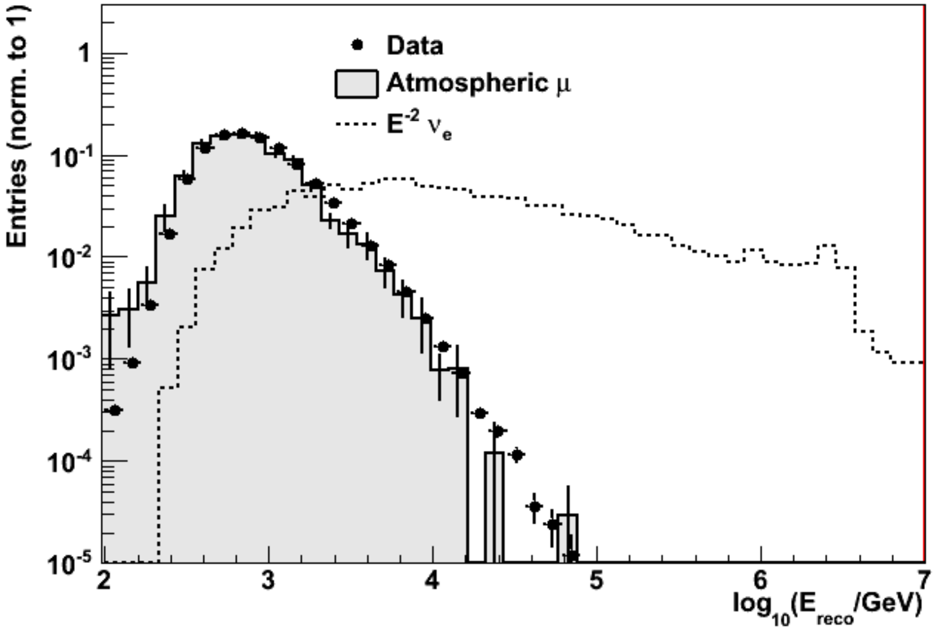
IceCube 22-string first extra-terrestrial cascade analysis Data and Monte Carlo comparison (2)

Energy reconstruction:

- takes into account variation of ice properties with depth

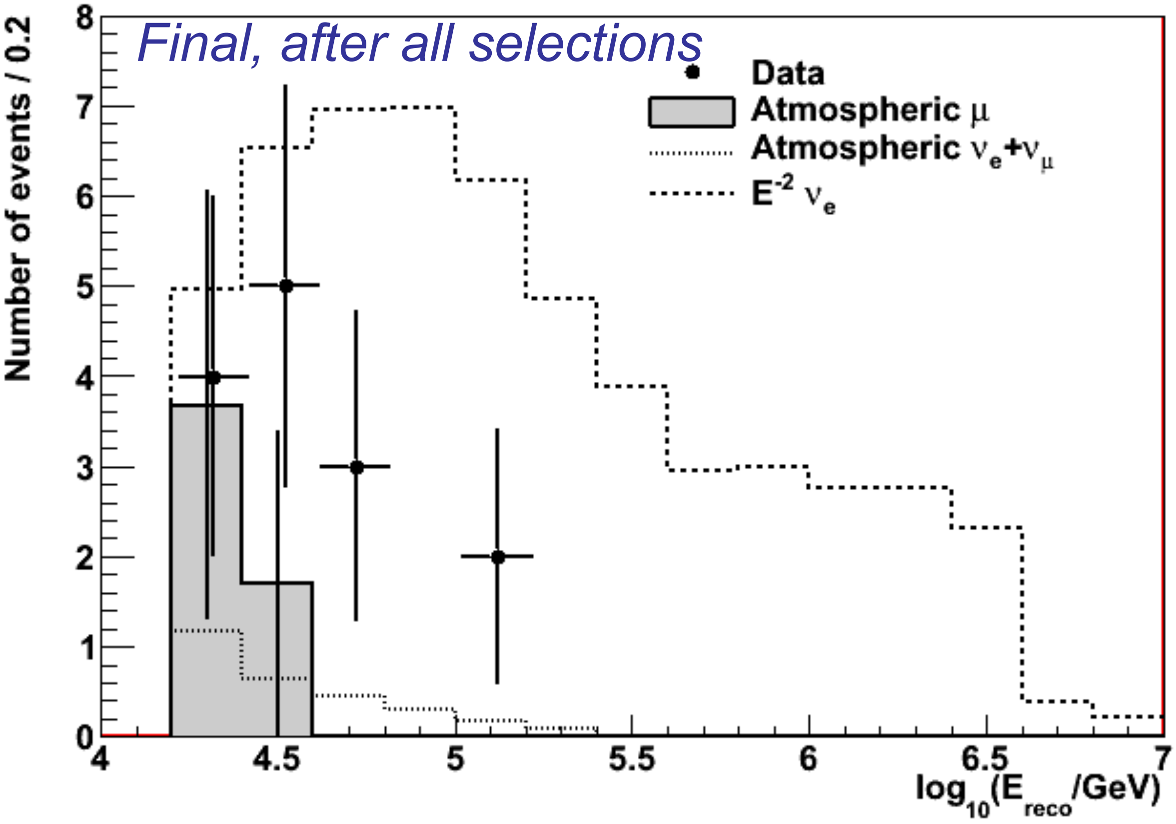
$$E_{\mathrm{reco}}/\mathrm{GeV} = \frac{\sum n_{pe}}{\sum \mu_0 \left(\vec{r}_v, \vec{r}_{DOM}\right)}.$$

n_{pe} = nr of p.e. observed in a DOM
μ_0 = nr of p.e. expected at a DOM position r_{DOM} from 1GeV cascade with vertex position r_v(Photonics)



J.Kiryluk, arXiv:0909.0989 (ICRC2009 proceedings)
IceCube, arXiv: 1101.1692 (Submitted to Phys.Rev.D)

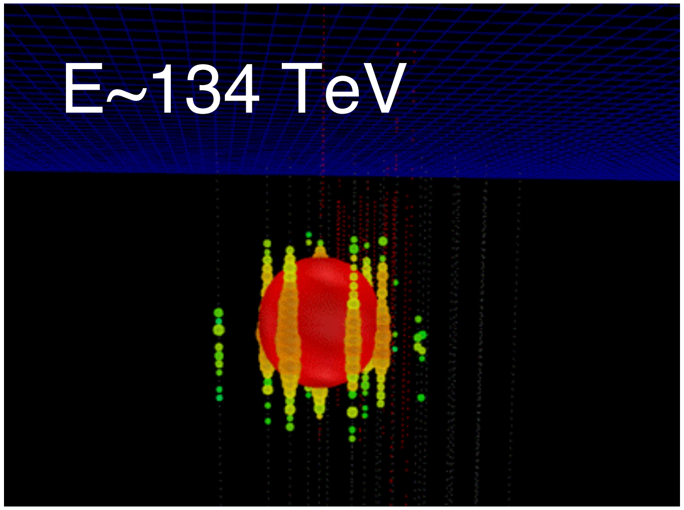
IC22 First Extraterrestrial (E^{-2}) Cascade Analysis Results

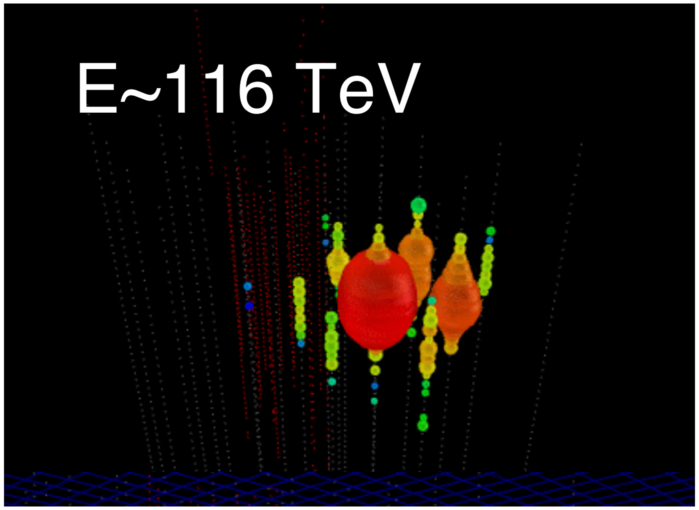


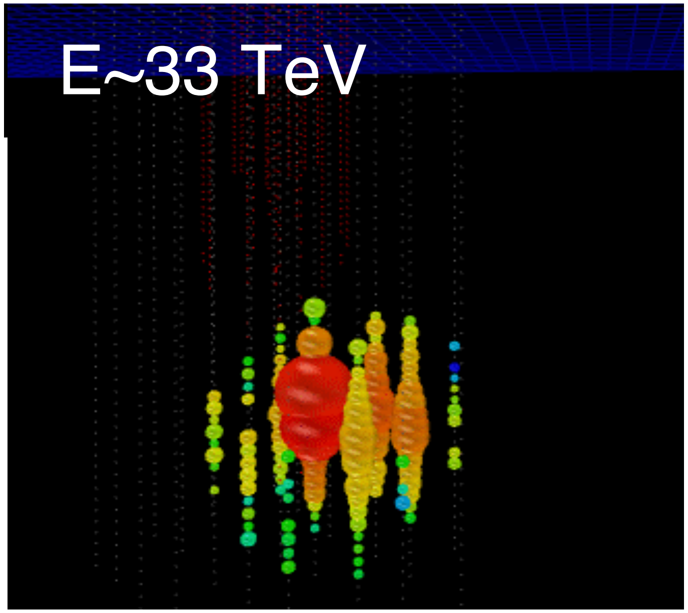
- $N_{obs}=14$, $N_{bg}= 8.3 \pm 3.6$, $\delta eff_{sig}= 22\%$
  No excess of events observed
- Event upper limit: **$\mu_{90\%}= 16.5$**
  stat. and syst. uncertainties included;
- Number of signal events (all flavor) for
  $\Phi_{model}=1\times10^{-6}\,(E/\text{GeV})^2\,(\text{GeV*s*sr*cm}^2)$
  N_{sig} =45.5
- Flux limit
  $\Phi_{90\%}= 3.6\times10^{-7}\,(E/\text{GeV})^2\,(\text{GeV*s*sr*cm}^2)$
- Energy range **24 TeV < E_ν < 6.6 PeV**
  (central 90% ν signal events)

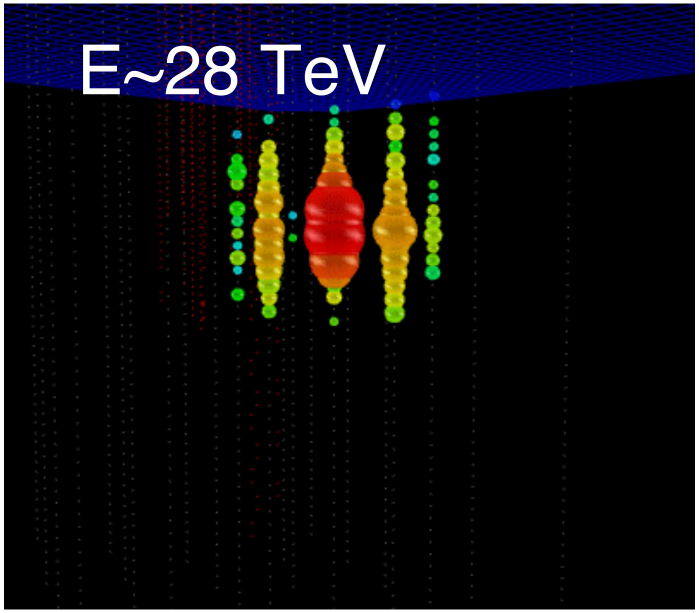
J.Kiryluk, arXiv:0909.0989 (ICRC2009 proceedings)
IceCube, arXiv: 1101.1692 (Submitted to Phys.Rev.D)

IC22 cascade-candidate events
Signature of ν_e event



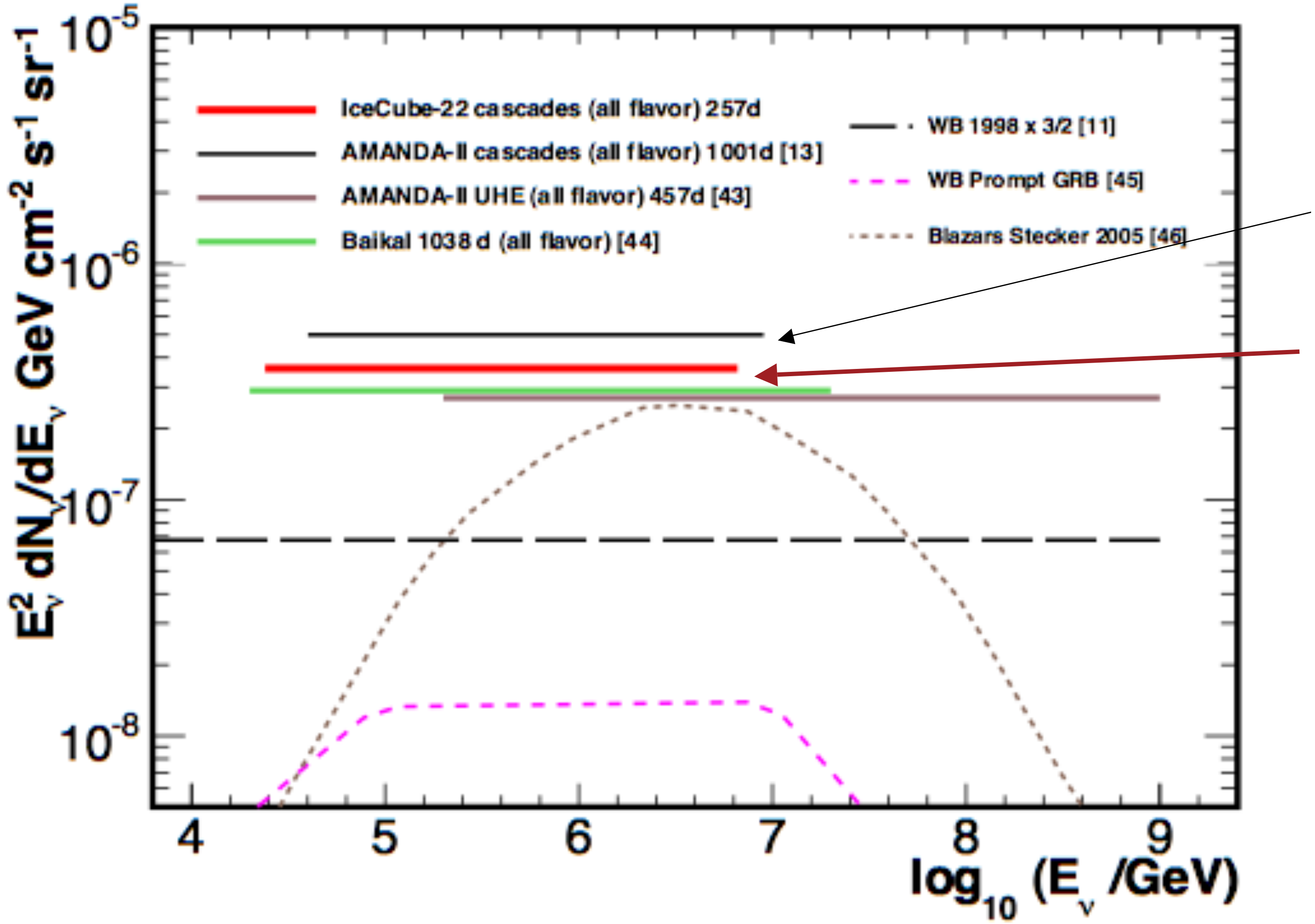






IC22 First Extraterrestrial (E^{-2}) Cascade Analysis Results

Experimental upper limits on the diffuse flux of neutrinos from sources with $\Phi \sim E^{-2}$ energy spectrum



2000-2004 Amanda cascade analysis Phys.Rev.D (2010)

IC22 cascade analysis

J.Kiryluk, arXiv:0909.0989 (ICRC2009 proceedings)
IceCube, arXiv: 1101.1692 (Submitted to Phys.Rev.D)

IC22 Extraterrestrial (E^{-2}) Cascade Analysis Results

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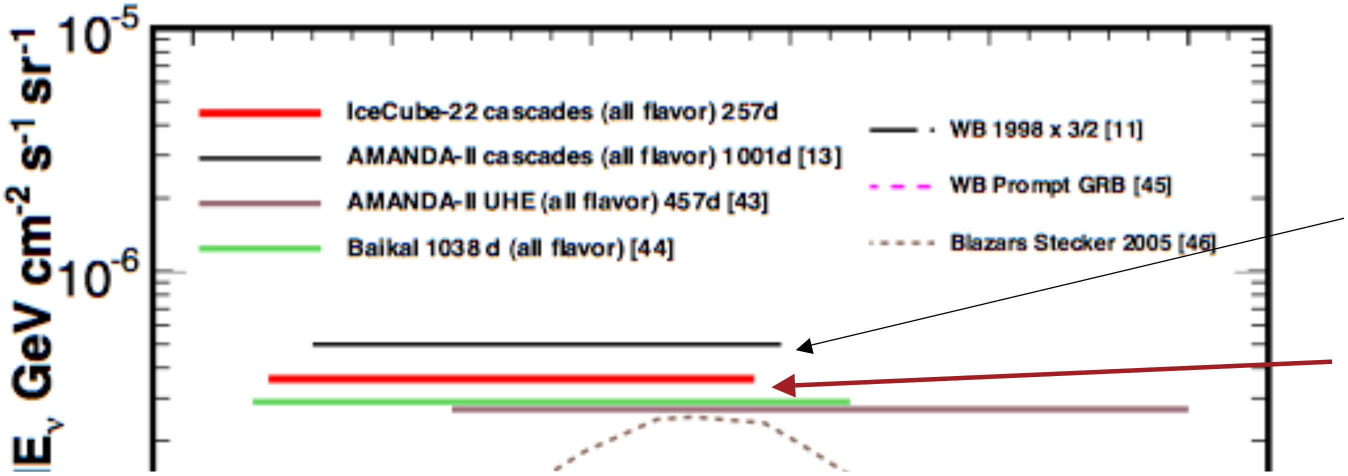
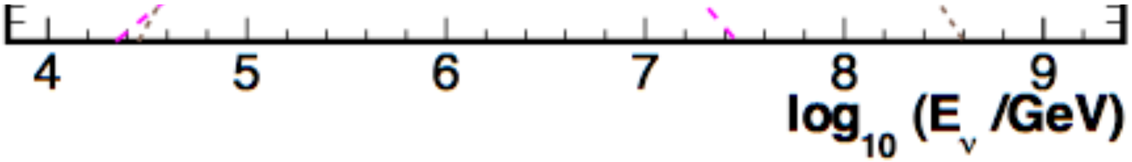


2000-2004 Amanda cascade analysis Phys.Rev.D (2010)

IC22 cascade analysis

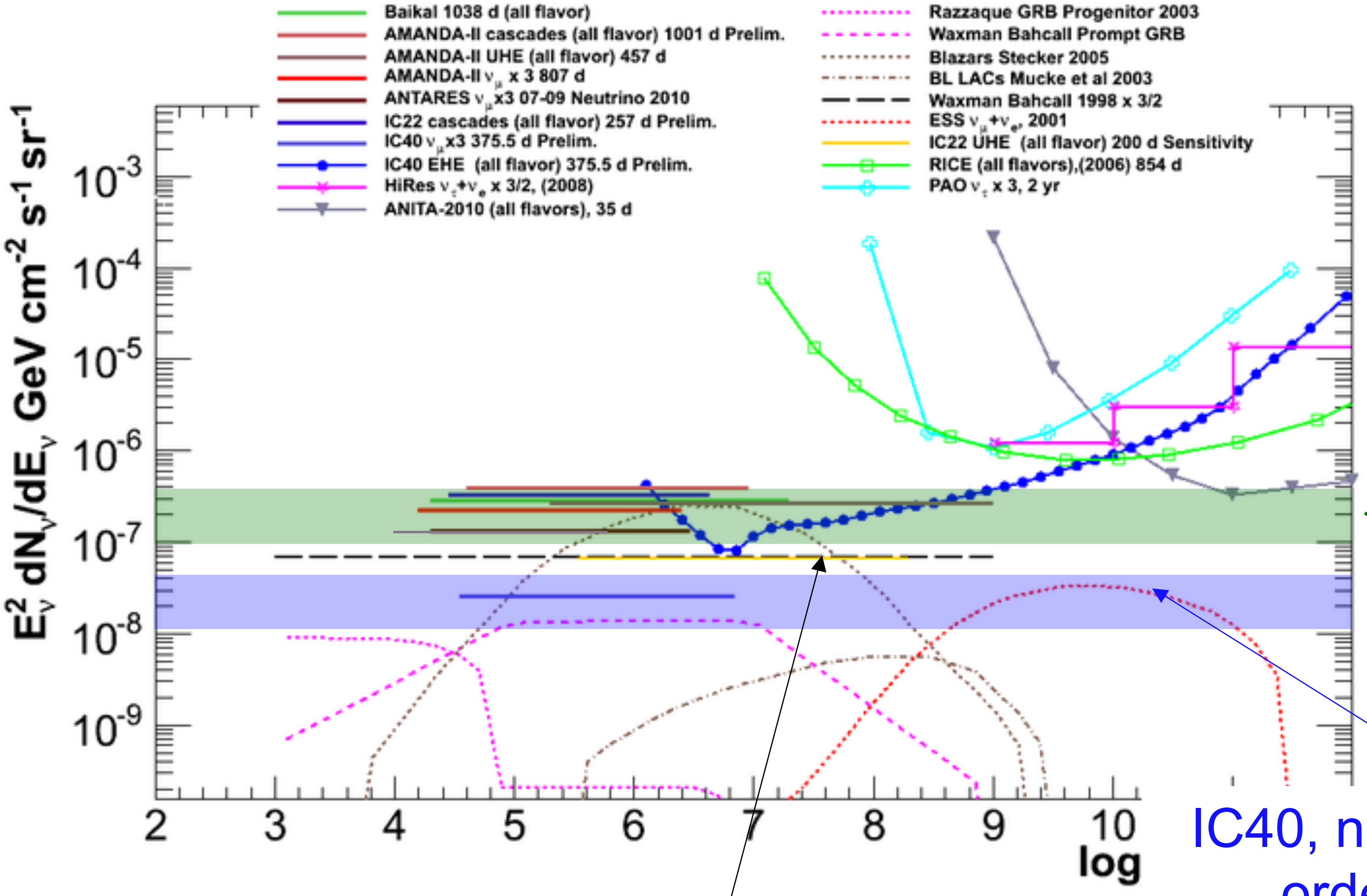
Improvements expected with a bigger detector



J.Kiryluk, arXiv:0909.0989 (ICRC2009 proceedings)
IceCube, arXiv: 1101.1692 (Submitted to Phys.Rev.D)

IceCube Diffuse Limits -Search status

PRELIMINARY



IC22/Multi-Year AMANDA

IC40, nearly an order of magnitude better (muon channel only!)

Indirect Dark Matter searches

$\Omega_m \sim 24\%$, $\Omega_b \sim 4\%$

$\Omega_{DM} \sim 20\%$ non-baryonic and non-relativistic

(cold) DM currently favored candidate: WIMP

Look at objects where the DM particle can be gravitationaly trapped and annihilate:

Sun, Earth and galactic halo (point sources)

- MSSM CDM candidate: neutralino, χ
- UED CDM candidate: lightest Kaluza-Klein (LKK)

⟶ CDM annihilation and decay to neutrinos:

$$\tilde{\chi}\tilde{\chi} \to \left\{ \begin{array}{c} q\bar{q} \\ l\bar{l} \\ W^{\pm},Z,H \end{array} \right\} \to \cdots \to \nu_{\mu}$$

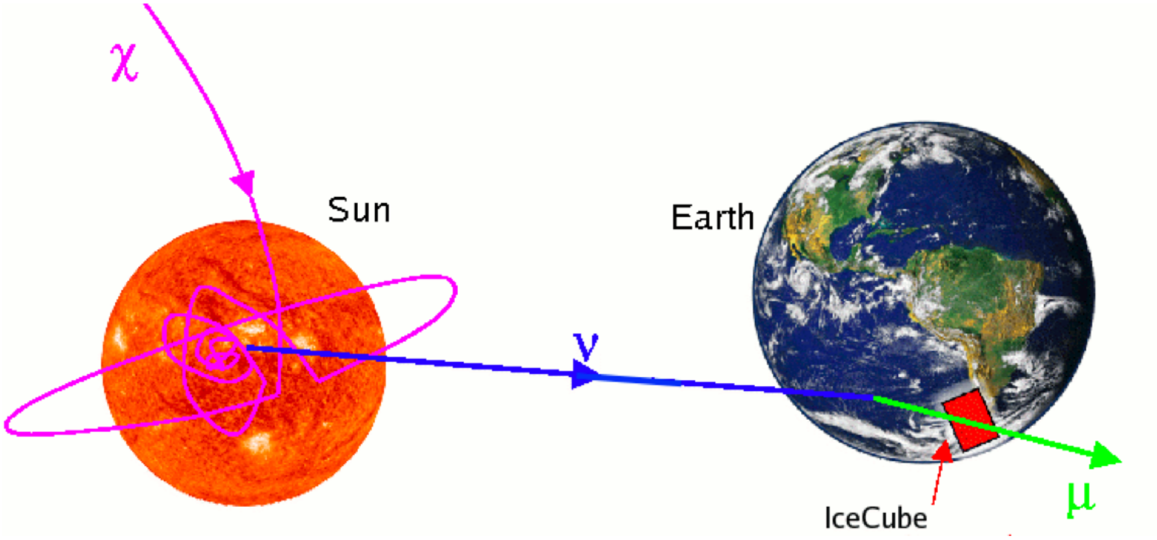
$$KK \to \nu\nu$$

Signature: neutrino excess from Sun,Earth or galactic halo direction
ν energy range: ~ 10 GeV to a few TeV

Example: WIMPs in Sun

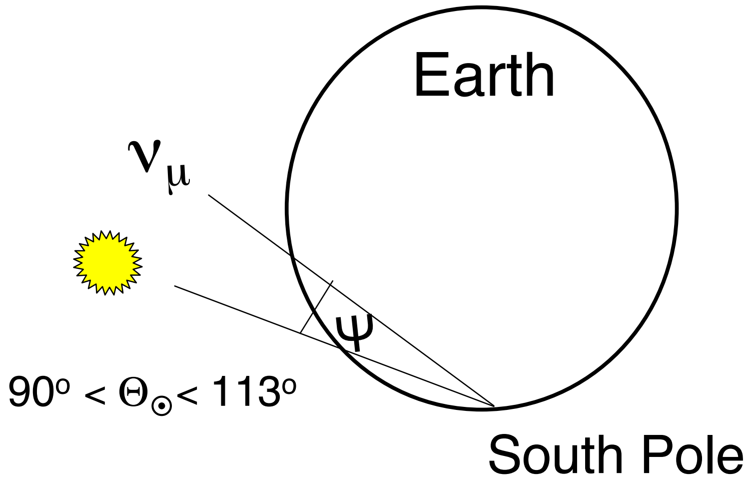
$$\frac{dN}{dt} \sim C_c - C_A N^2 = C_c - 2\Gamma_A$$

in equilibrium (dN/dt = 0)
capture rate ~ annihilation rate

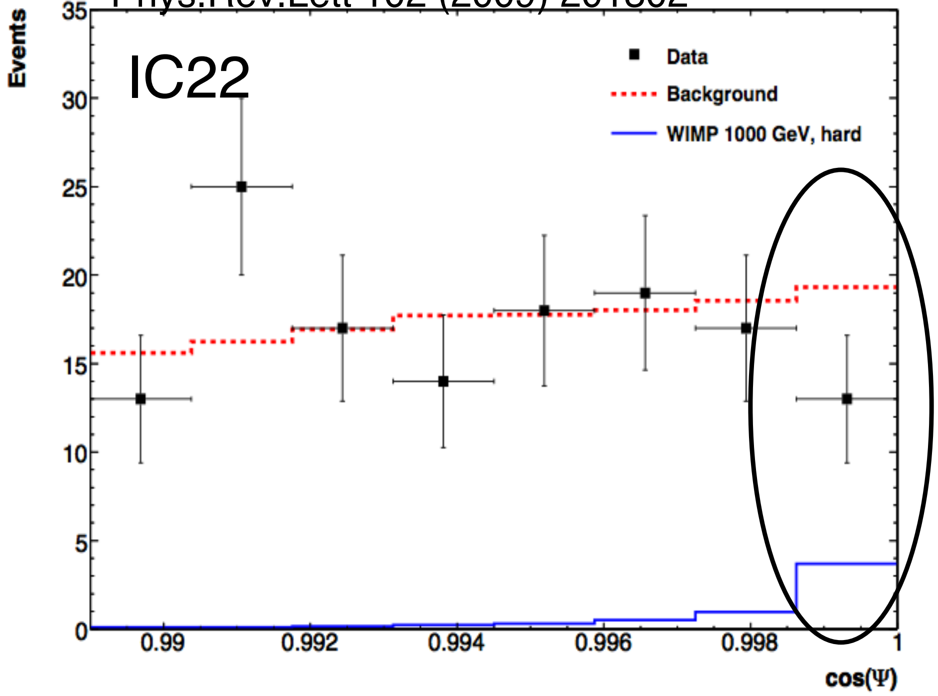


Indirect Dark Matter searches: Solar WIMPs

Data collected when the Sun is below the horizon at the South Pole



Phys.Rev.Lett 102 (2009) 201302



No excess of events from the Sun, observation consistent with the expected bg

⇒ upper limit on the number of signal events at 90% CL : μ_s

⇒ 90% CL limit on the neutrino to muon conversion rate: $\Gamma_{\nu\to\mu} = \dfrac{\mu_s}{V_{eff} \times T}$

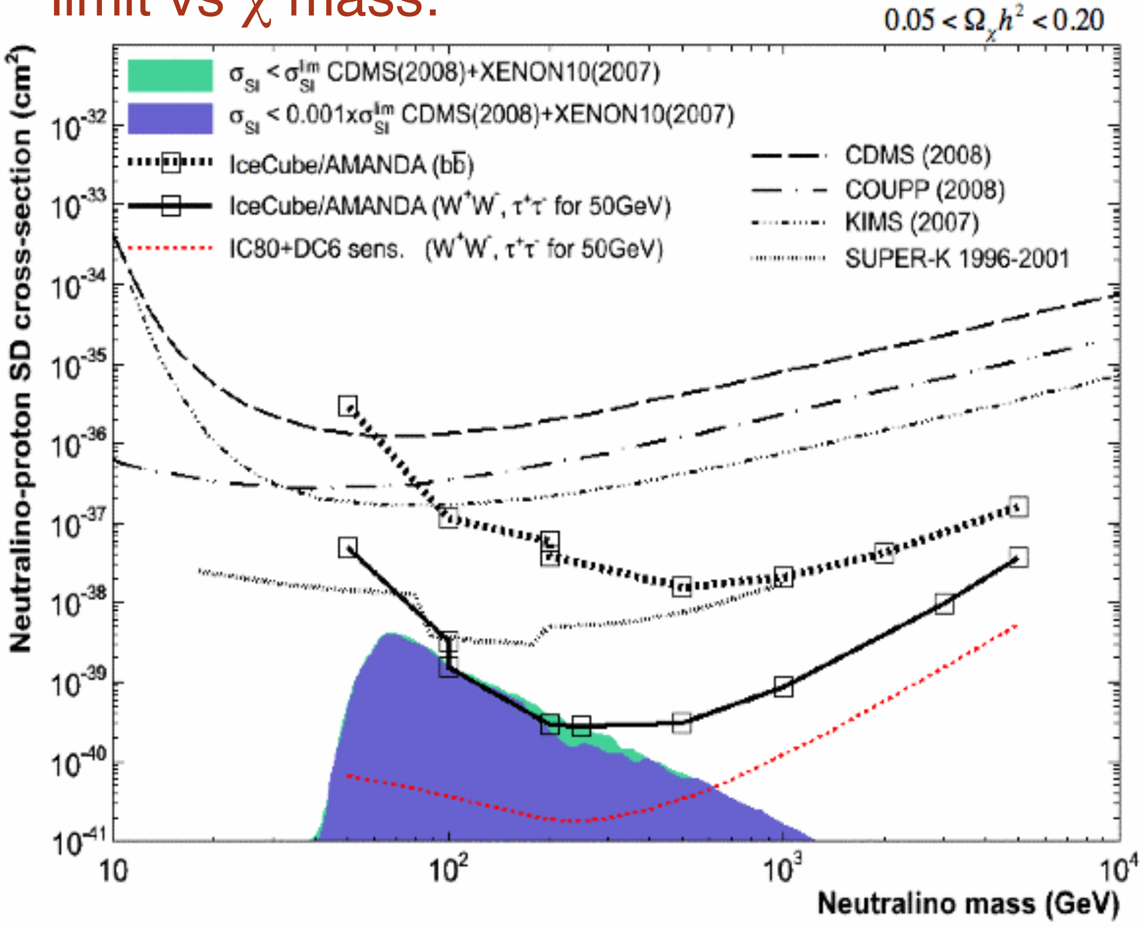
⇒ 90% CL limit on the neutralino annihilation rate in the Sun: $\Gamma_A = \kappa^{-1}(\chi) \times \Gamma_{\nu\to\mu}$

Indirect Dark Matter searches: Solar WIMPs

Limits on the spin-dependent (SD) and spin-independent (SI) χ-p cross sections assumming equilibrium between capture and annihilation:

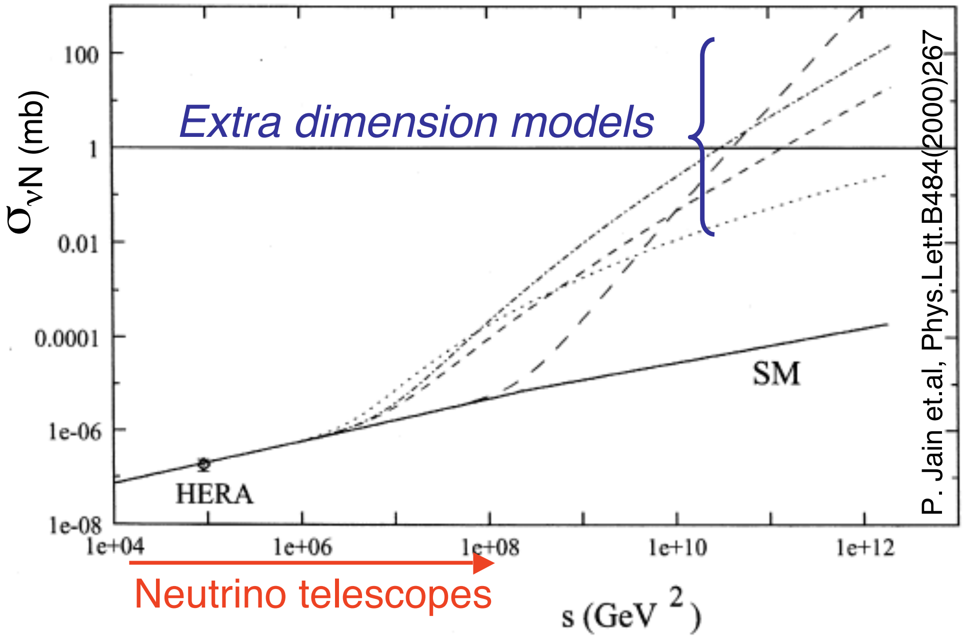
- $\sigma^{SI} = \lambda_{SI}(m_\chi)\Gamma_A$ and $\sigma^{SD} = 0$ ⇒ *constrained well by direct searches*
- $\sigma^{SI} = 0$ and $\sigma^{SD} = \lambda_{SD}(m_\chi)\Gamma_A$ ⇒ capture in the Sun dominated by σ^{SD} competitive limits by indirect searches

90% CL χ-p σ^{SD} limit vs χ mass:

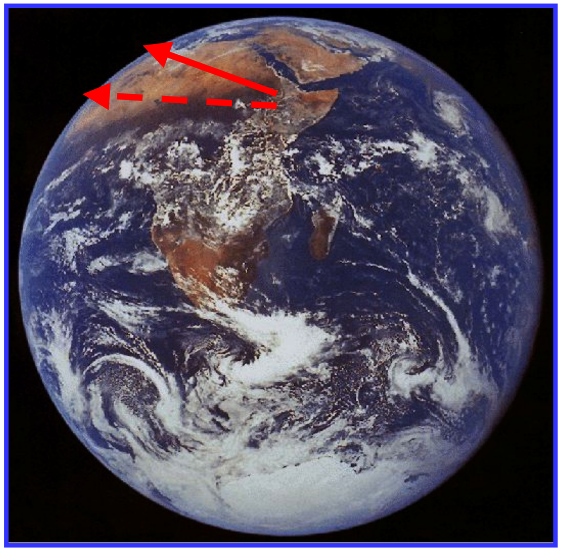


Future: Measuring $\sigma_{\nu N}$ at high energies by neutrino absorption in Earth

- information on small-x parton distribution functions
- constraints on physics beyond Standard Model $\sigma_{\nu N} / \sigma_{SM}$



P. Jain et.al, Phys.Lett.B484(2000)267



Absorber thickness depends on zenith angle

- interaction length for a particle traversing matter: $l=(\sigma n)^{-1}$
- for $l=2R_{Earth}$, $\sigma=(2R_{Earth}\ n)^{-1} \sim 2x\ 10^{-7}$ mb ($E_\nu \sim 100$ TeV)

  predicted!
- maximum energy ~ 10 - 100(?) PeV
- measure cross section by studing ν flux as a function of zenith angle and energy

…. but need to find non-zero flux first!

A 100 km^3 detector

Radio emission from neutrino-induced electromagnetic cascades

:-(Optical (IceCube) technology does not scale

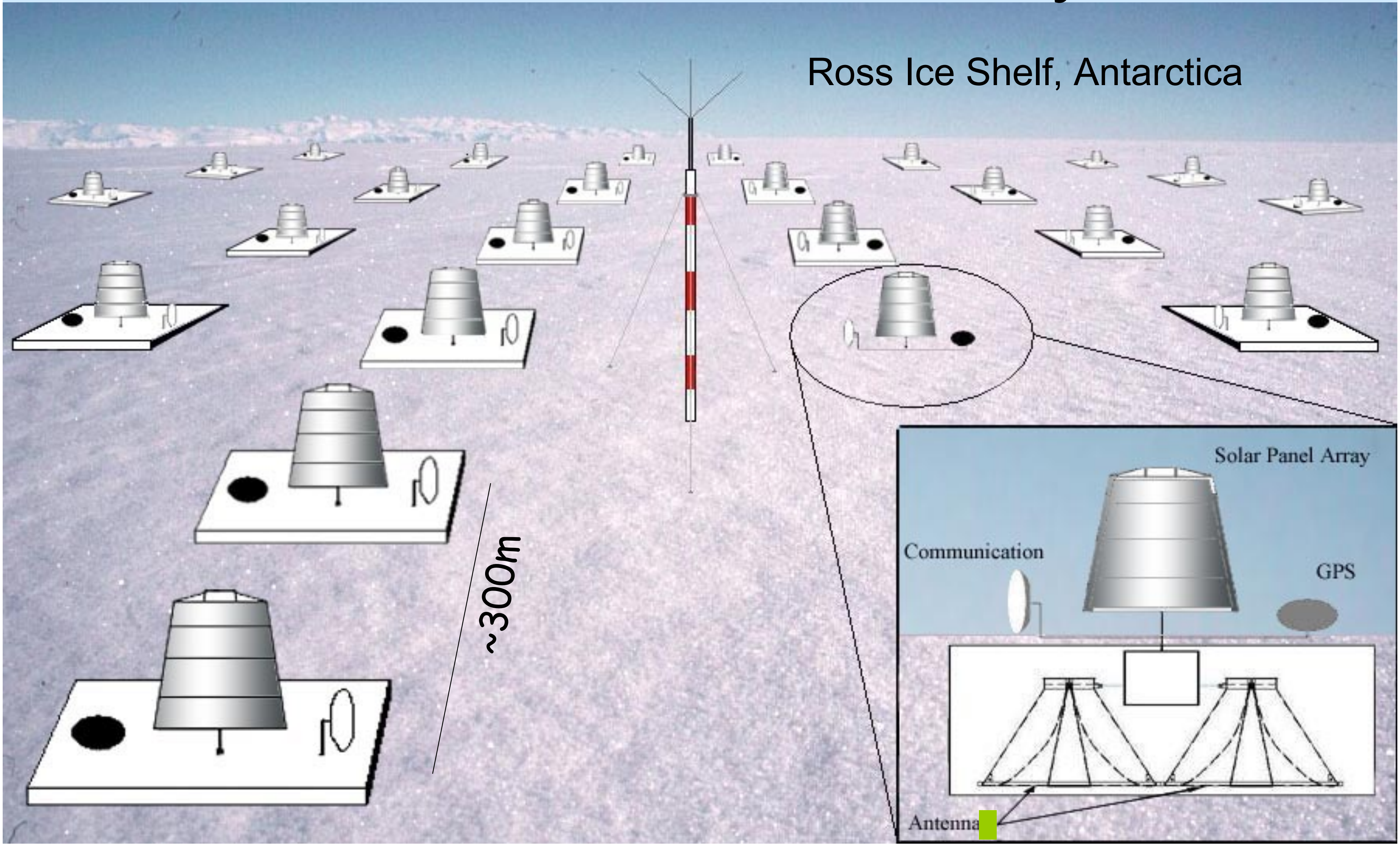
Absorption length ~ 100-200 m

:-) Detect radio waves emitted by the shower as a whole

- Electromagnetic cascades: electron-positron pairs and (mostly) gammas → electrically neutral, no radio emission.
- But, Compton scattering of photons on atomic electrons creates negative charge excess of ~ 20%
- Negative charge radiates coherently at MHz ~ GHz (radio energy ~ E_ν^2)
- Askarian effect demonstrated at SLAC: consistent with calculations
- Radio waves can travel long distances in ice
  Absorption length ~ 500 m – 1 km
  thus can put stations on a 1 km grid!

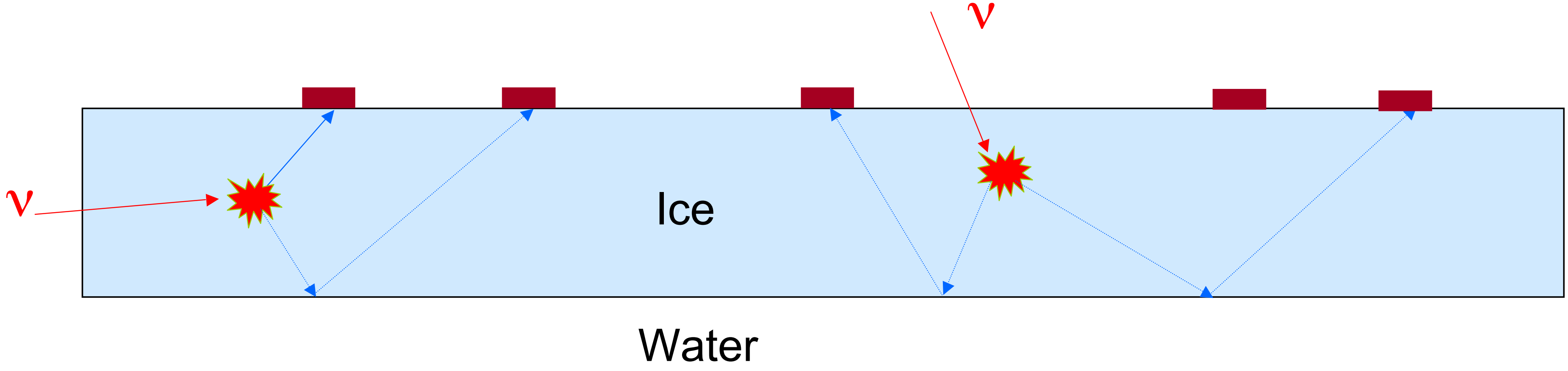
ARIANNA concept

100 x 100 station array

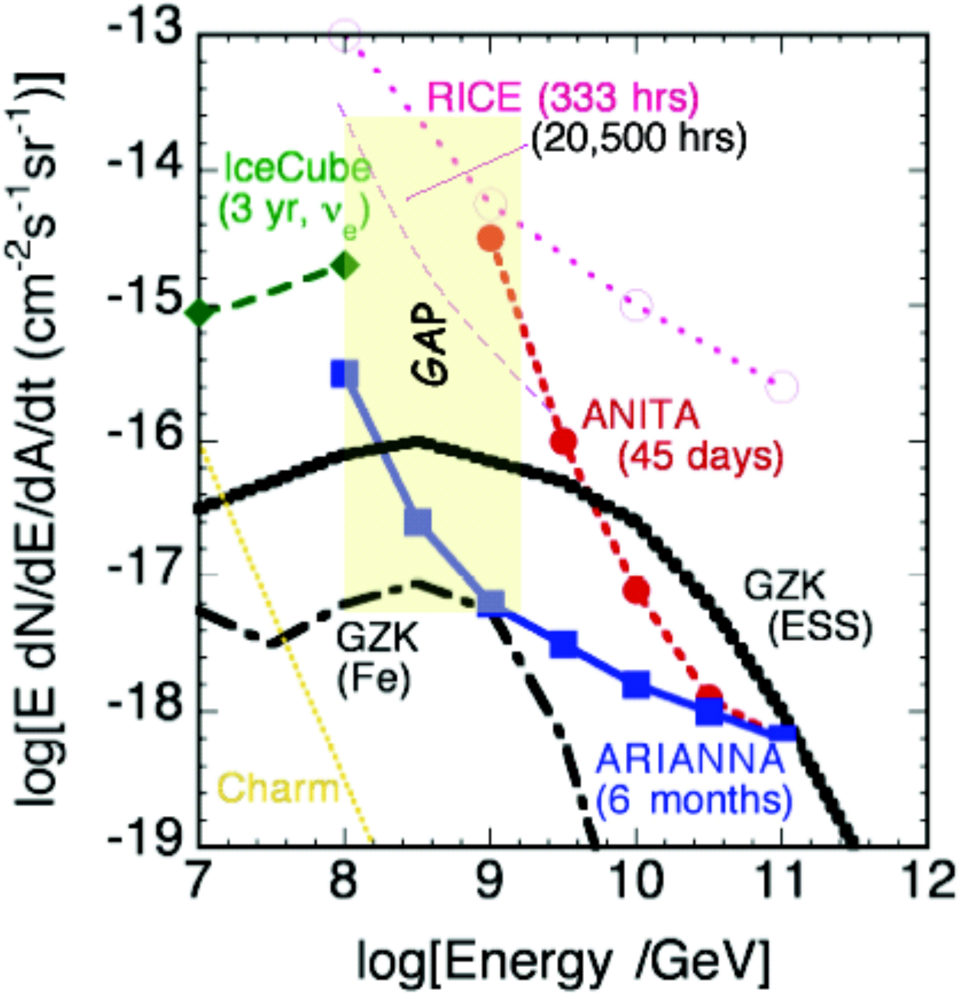


ARIANNA: Radio in the Ross Ice Sheet

- The Ross ice shelf is a 650 m of ice atop water
  Site is ~ 100 km south of from McMurdo station
- The ice-water interface reflects radio waves
  Surface detectors can be sensitive to downward going Cherenkov photons
  - -Large increase in solid angle
  - - No need for ice drilling



Sensitivity and limits



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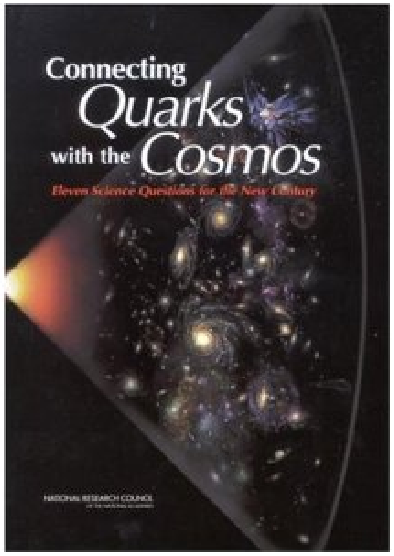
Summary



- IceCube construction is complete (2011) and ready for 15+ years of data taking

- Initial IceCube results
  - Atmospheric neutrinos: 160/day atmospheric muon neutrinos with IC59
  - Ongoing searches for extraterrestrial neutrinos: point sources (ν_μ) , diffuse flux (all-flavor ν), GRB searches

    No sources of extraterrestrial neutrinos found as of today.
    The sensitivity increases with the detector size and the data taking.

- Deep Core construction is complete, low energy extension
  - will allow studies of neutrino oscillations $E_\nu > 10$ GeV

- To study the highest energy cosmic-rays, a ~ 100 km^3 detector is needed
  - at very high energies (above 10^{17} eV), neutrino interactions produce a detectable pulse of radio waves (proposed experiment ARIANNA)

“The study of the very large (Cosmology) and very small (elementary particles) is coming together” (David N. Schramm)

Thank you!