Astrophysical neutrino results

--overview and comments

(Neutrino telescope session tomorrow includes
IceCube, Antares, Baikal-GVD, KM3NeT)

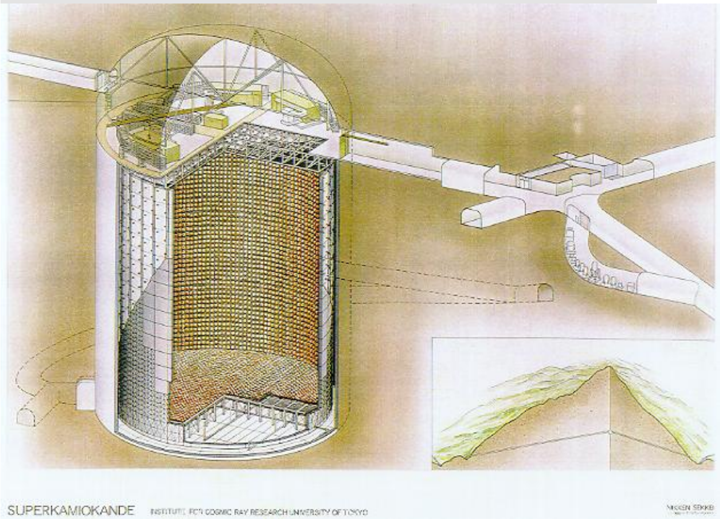
Outline

- Motivation and history (since 1960)
- Effective area and event reconstruction
- Atmospheric neutrinos
- New limits on astrophysical neutrinos
- Implications for models of sources
- Search for cosmogenic neutrinos
- Status and future

Detecting neutrinos in H_20

Proposed by Greisen, Reines, Markov in 1960

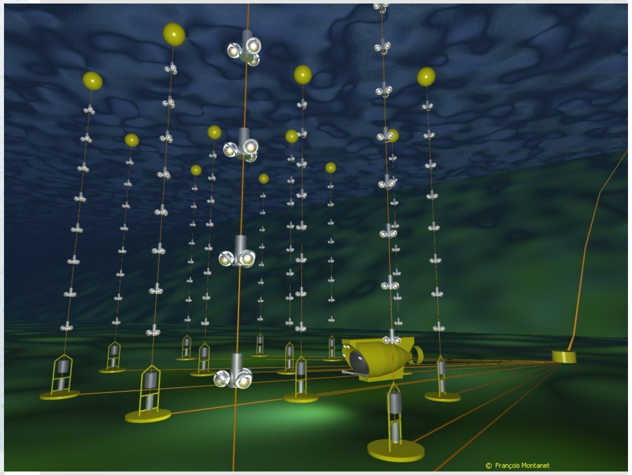
Heritage:
- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA



Super-K

SNO

IceCube in 2008-09 with 40 strings & 40 IceTop stations

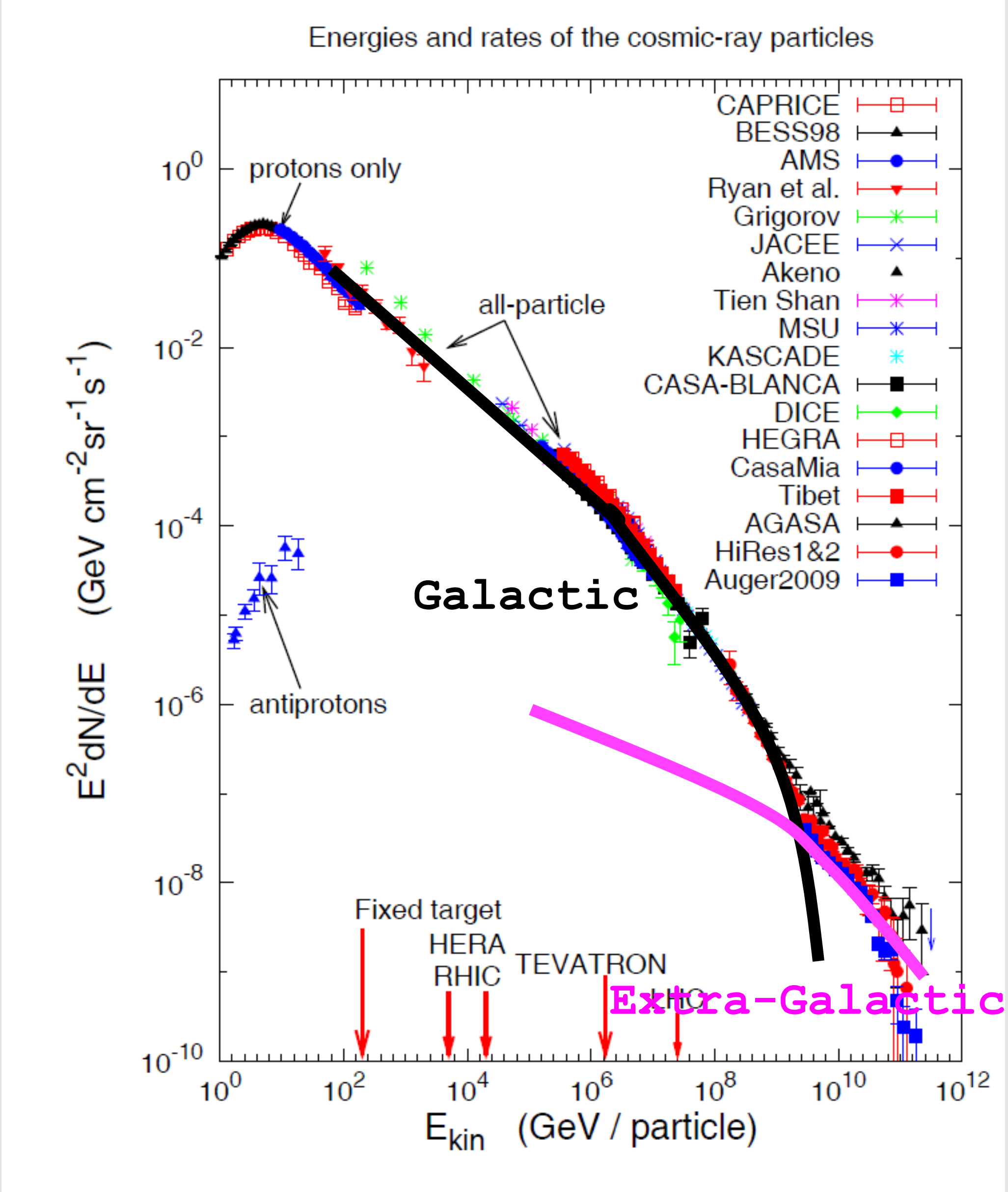


ANTARES

All use Cherenkov light from charged products of ν interactions

Cosmic-ray connection

- Galactic SNR can accelerate particles into nearby molecular clouds
- Extra-galactic jets (in AGN or GRB) may share power between c.r. & ν
- Expect a few TeV ν/yr in a gigaton detector in hadronic scenarios
- Sets km^3 scale for HE neutrino astronomy



High-energy Neutrino telescopes

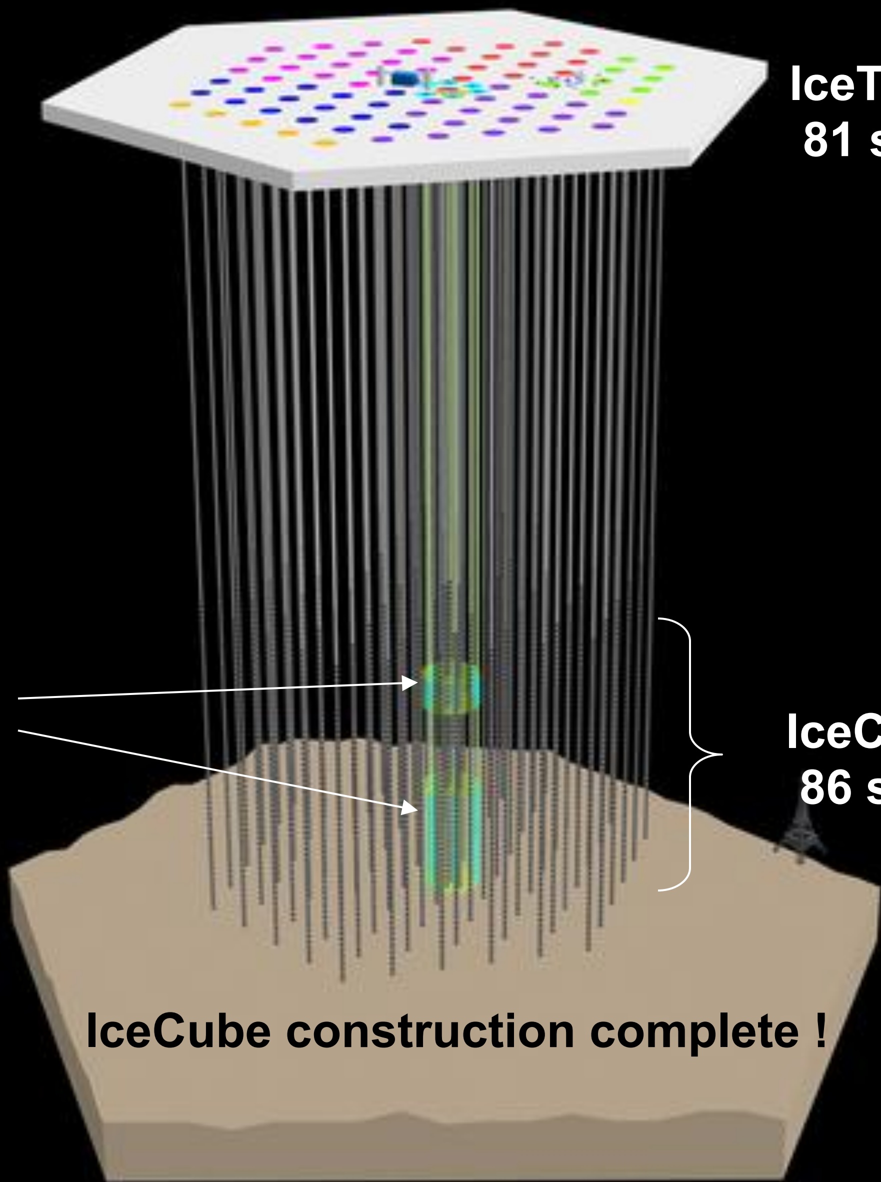
Detector	Number of OMs	Enclosed volume (Megatons)	Depth (m.w.e.)	Status
Baikal (NT200+)	230	10	1100-1310	Operating
AMANDA	677	15	1350-1850	2000 - 2009
ANTARES	900	10	2050-2400	Operating
IceCube	5160 + 324	900	1350-2250	Operating
KM3NeT	∼10,000	km^3	2300-3300 (NEMO)	Design study
		km^3	3000-4000 (NESTOR)	
		km^3	1400-2400 (ANTARES site)	
GVD (future Baikal)	∼2500	km^3	800-1300	Design study

Large volume--coarse instrumentation--high energy (> TeV)

as compared to Super-K with 40% photo-cathode over 0.05 Mton

= 4 x 10^5 cm^2 / kT compared to 50 for Antares & 2 for IceCube

2004-05	1	1
2005-06	8	9
2006-07	13	22
2007-08	18	40
2008-09	19	59
2009-10	20	79
2010 11	7	86



IceTop
81 stations, 324 DOMs

DeepCore
8 strings

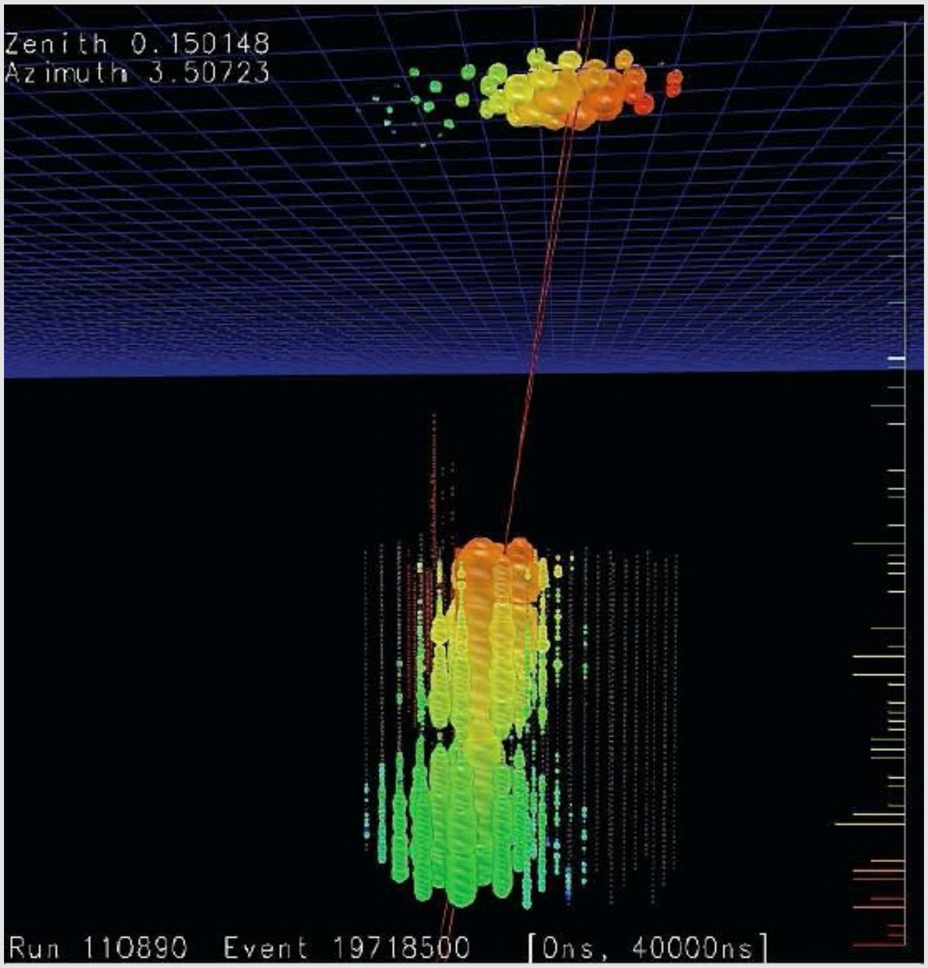
IceCube
86 strings, 5160 DOMS

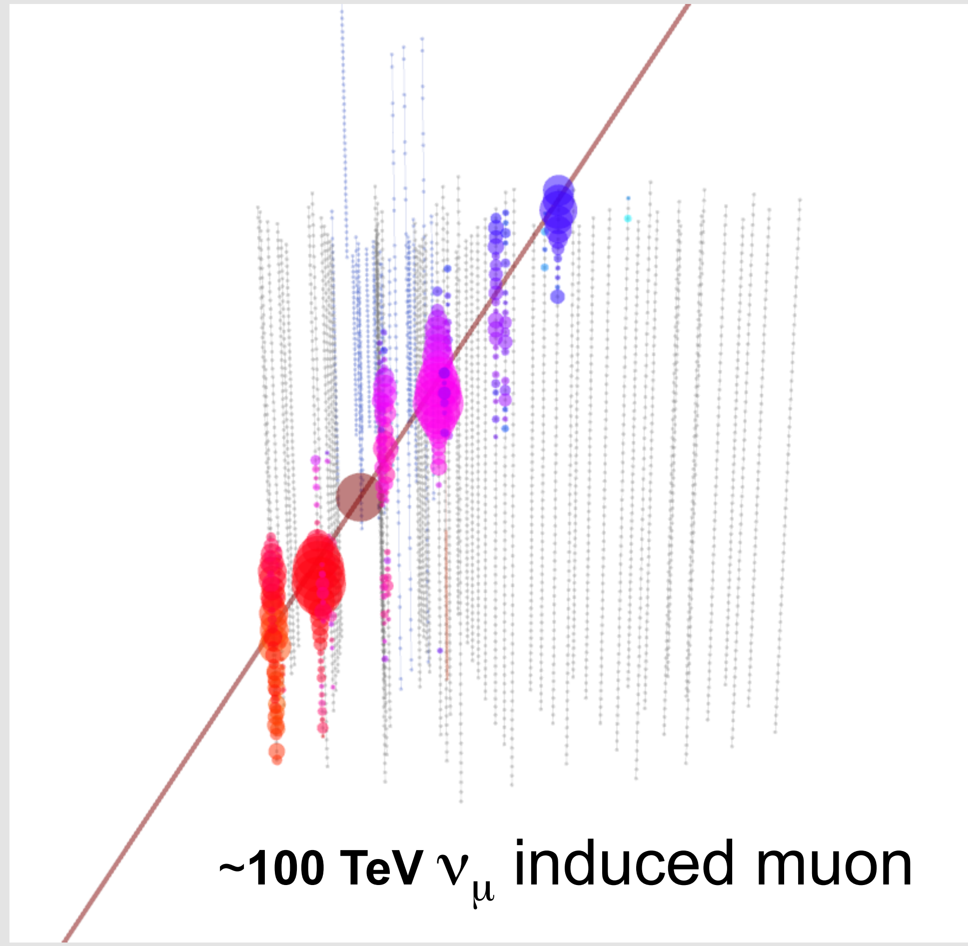
IceCube construction complete !

IceCube Digital Optical Module and deployment

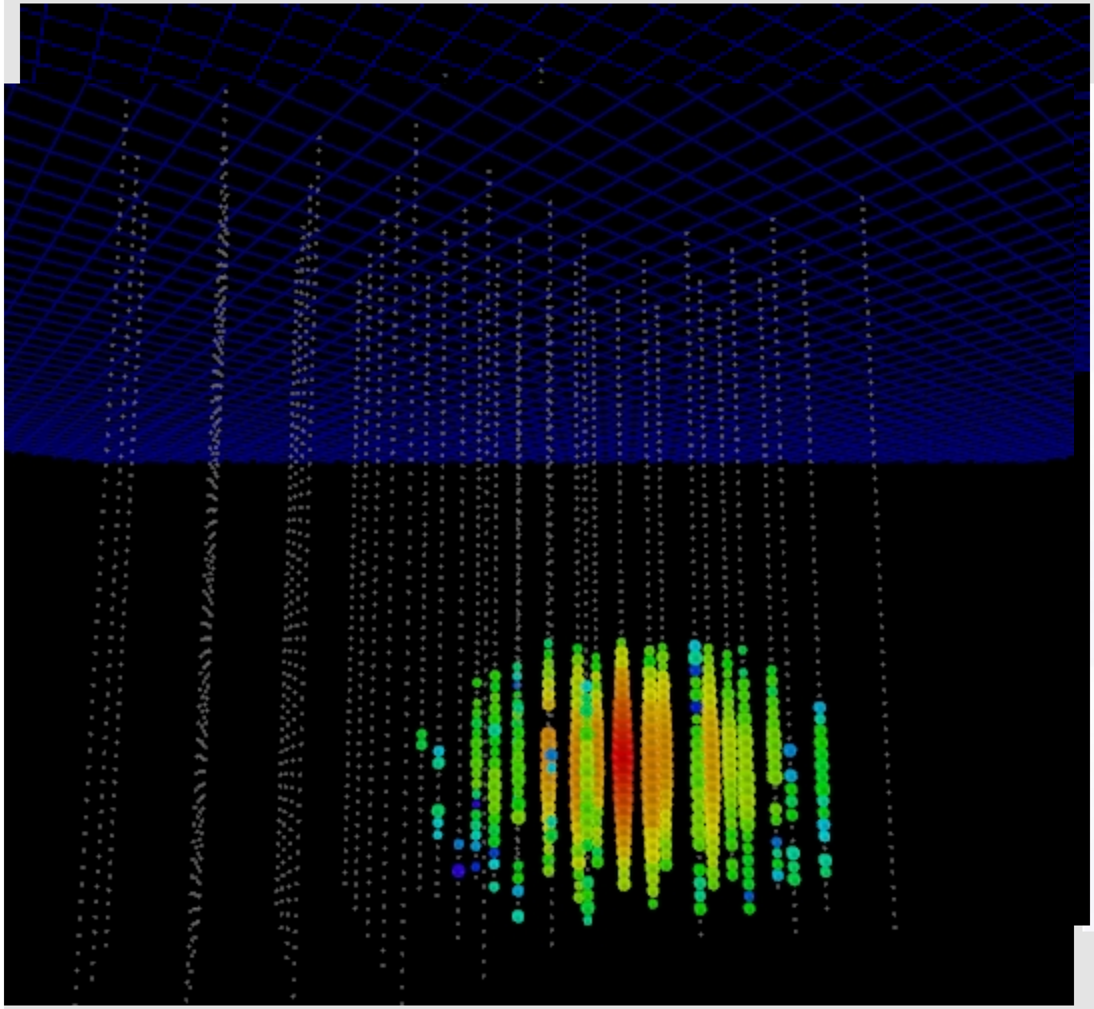
High-energy events in IceCube-40

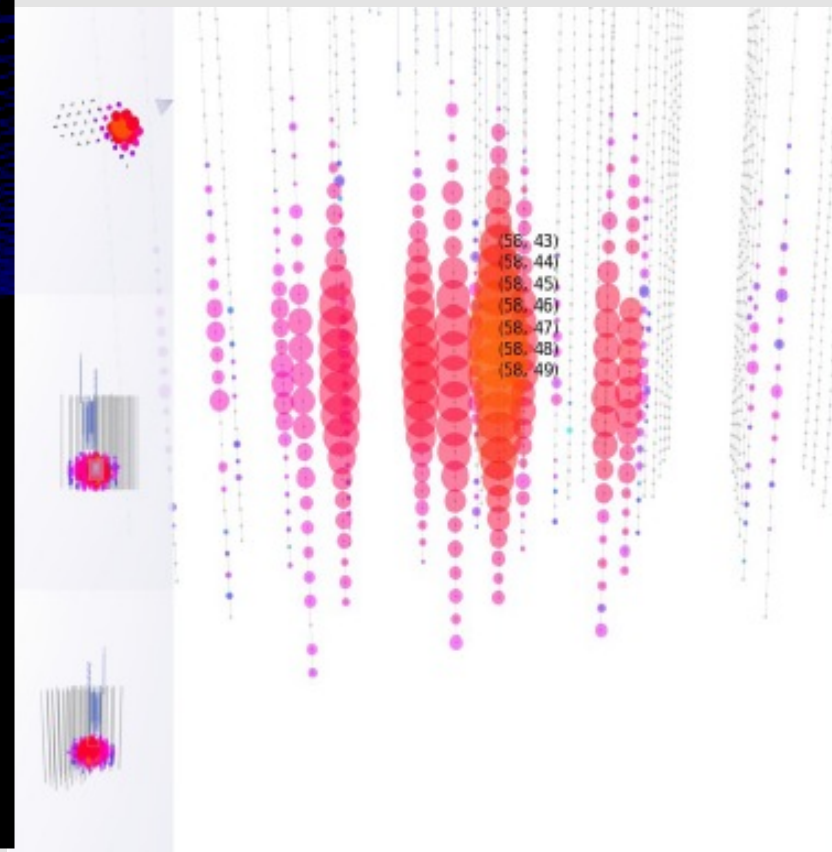
~ EeV air shower





More events

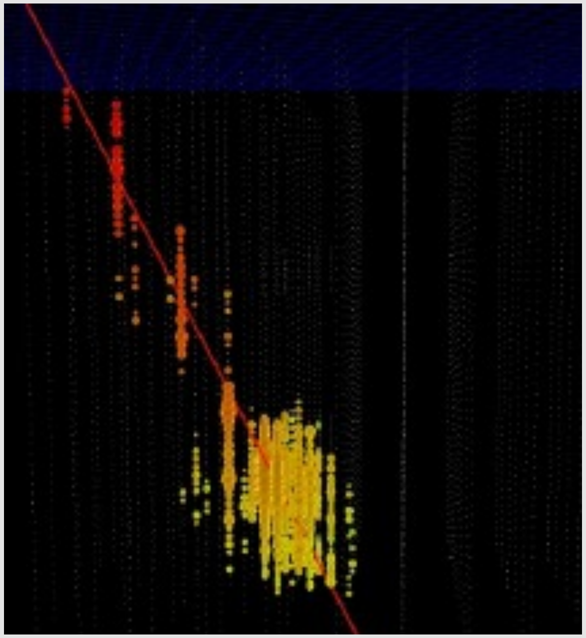


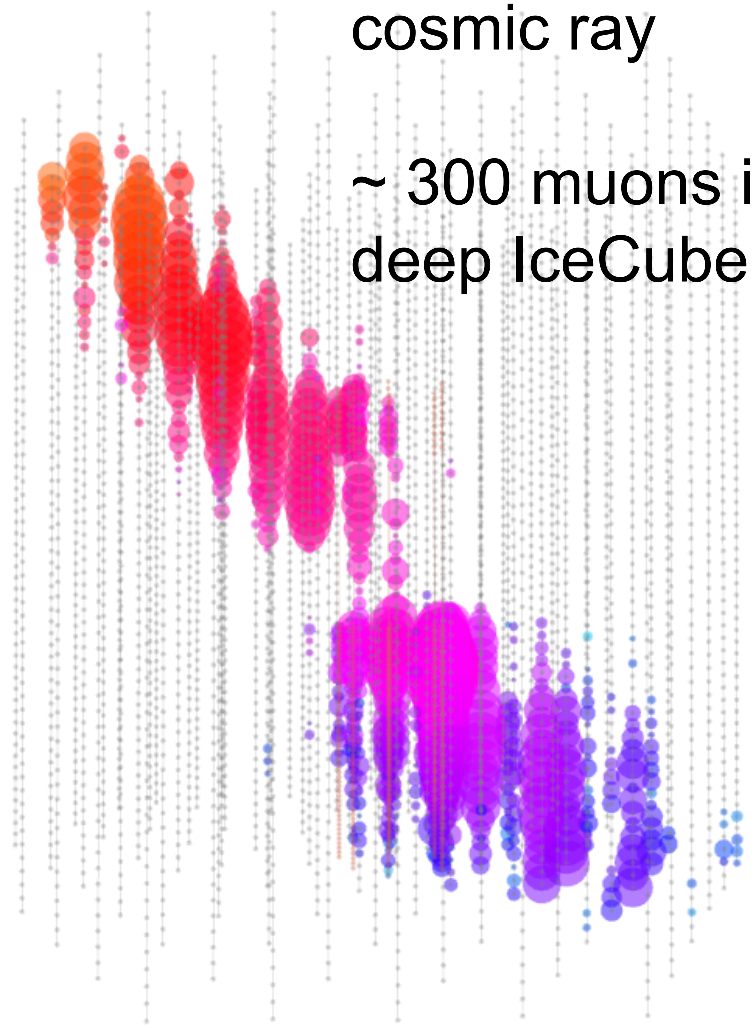


A cascade event, candidate for a high energy ν_e ~50 TeV

IC-79 events illuminate deep core

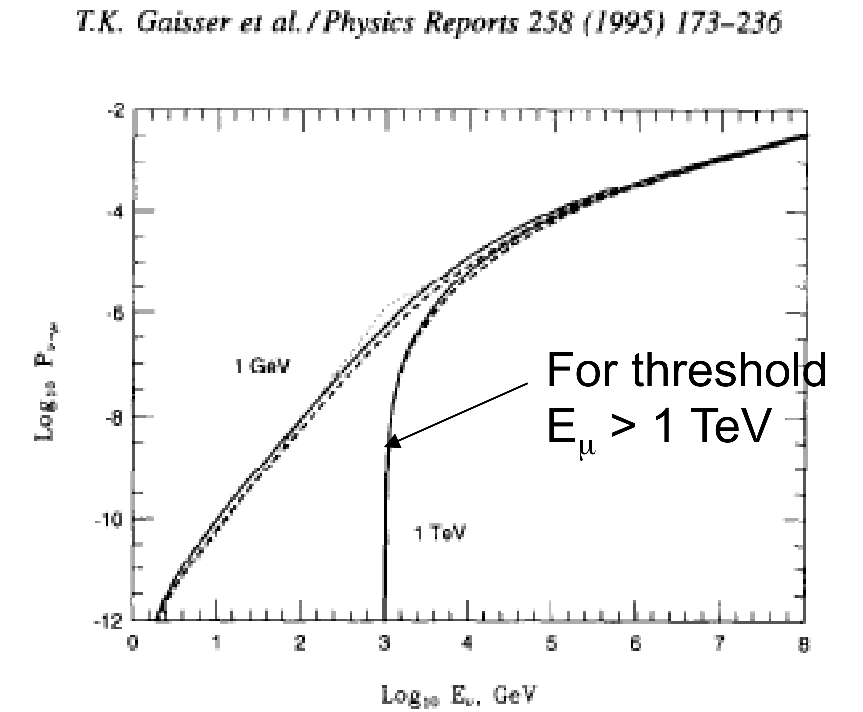
IceCube Deep Core talk by Ty DeYoung in afternoon session





Detecting neutrinos

- Rate = Neutrino flux
  x Absorption in Earth
  x Neutrino cross section
  x Size of detector
  x Range of muon (for ν_μ)
- Range favors ν_μ
  - ~4 to 15 km.w.e. for E_ν ~ 10 to 1000 TeV



Probability to detect ν_μ-induced μ

$$P_\nu(E_\nu, E_{\mu,min}) = N_A \int_{E_{\mu,min}}^{E_\nu} dE_\mu \frac{d\sigma_\nu(E_\nu)}{dE_\mu} R(E_\mu, E_{\mu,min})$$

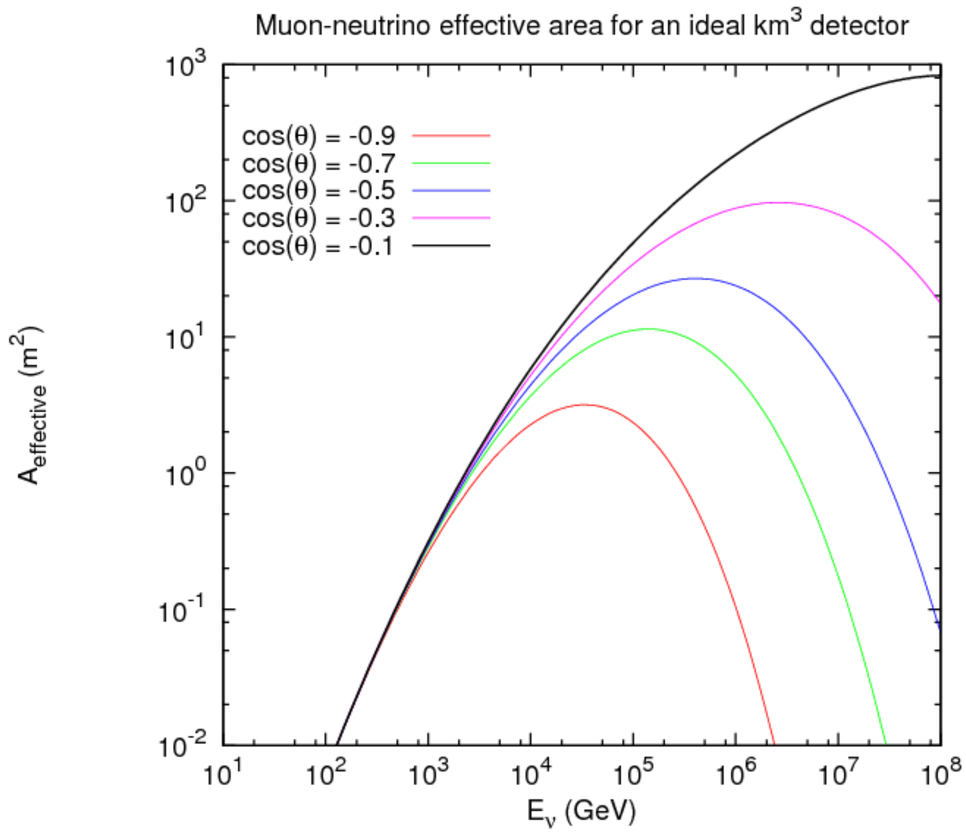
Neutrino effective area

$$A_{eff}(\theta, E_\nu) = \epsilon(\theta) A(\theta) P_\nu(E_\nu, E_{\mu,min}) e^{-\sigma_\nu(E_\nu) N_A X(\theta)}$$

- Rate:

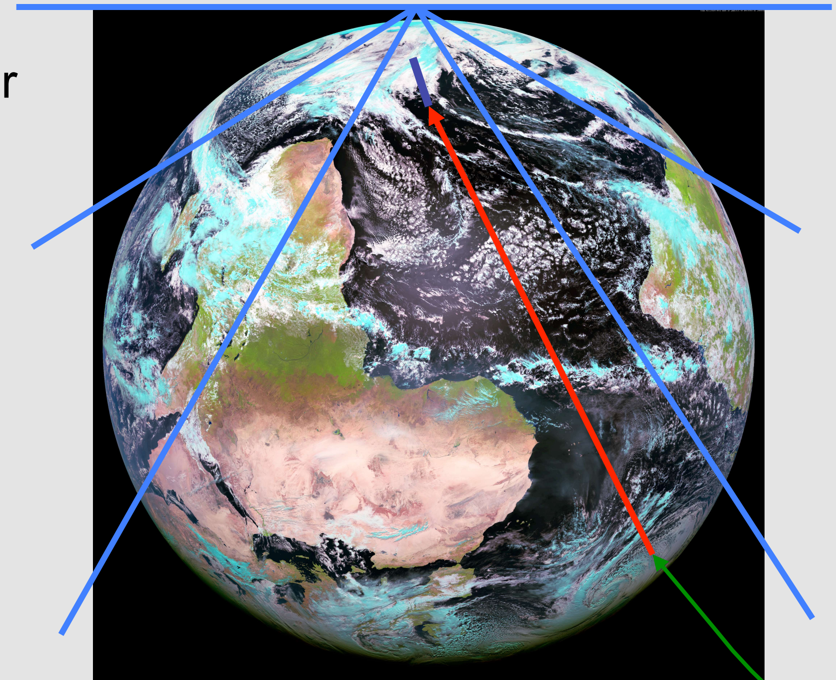
$= \int \phi_\nu(E_\nu) A_{eff}(E_\nu) dE_\nu$

- Earth absorption
  - Starts 10-100 TeV
  - Biggest effect near vertical
  - Higher energy ν' s absorbed at larger angles



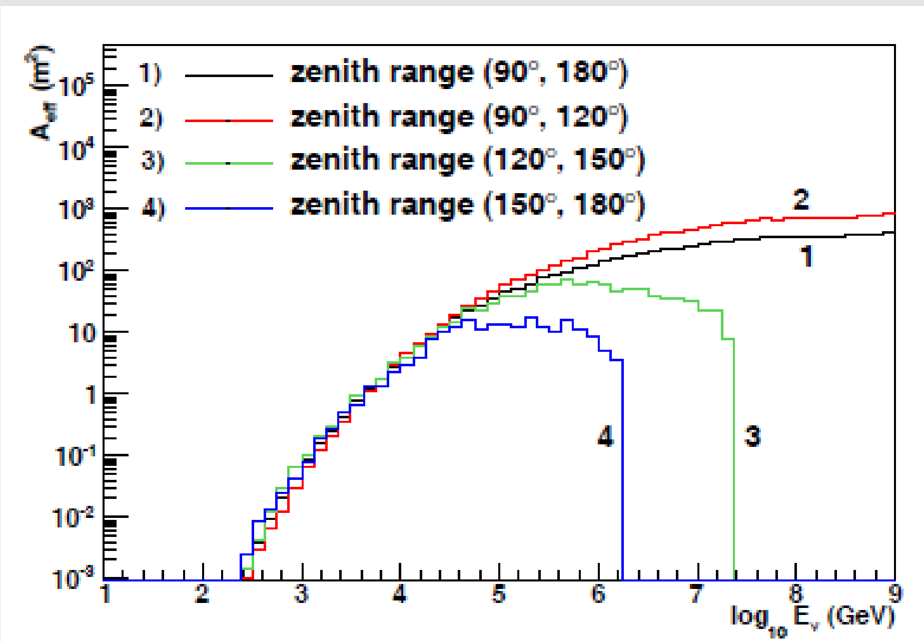
Atmospheric ν in IceCube

S.P.



Zone 1, l: -30 to -90 ; 3.14 sr
Zenith: 90 < θ < 120°
(40% of Zone 1 is over the Antarctic continent)

Zone 2, l: -30 to +30; 2.30 sr
Zenith 120 < θ < 150°

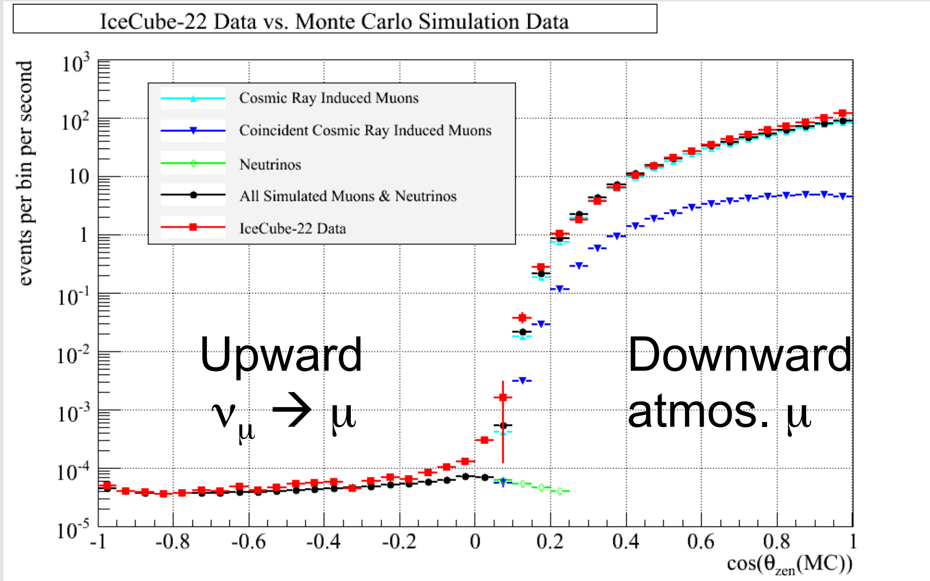


Zone 3, l: +30 to +90, 0.84 sr
Zenith: 150 < θ < 180°

Cosmic ray produces **ν** in atmosphere that puts a **muon** into the detector

Cuts and event reconstruction

- 40-string IceCube:
  - 375 days livetime in 08/09 @ 1 kHz =3.3×10^{10} triggers, 99.9999% muons
  - 8×10^8 filtered & sent over satellite from S.P.
  - Quality cuts applied to get ~14,000 upward ν_μ induced muons



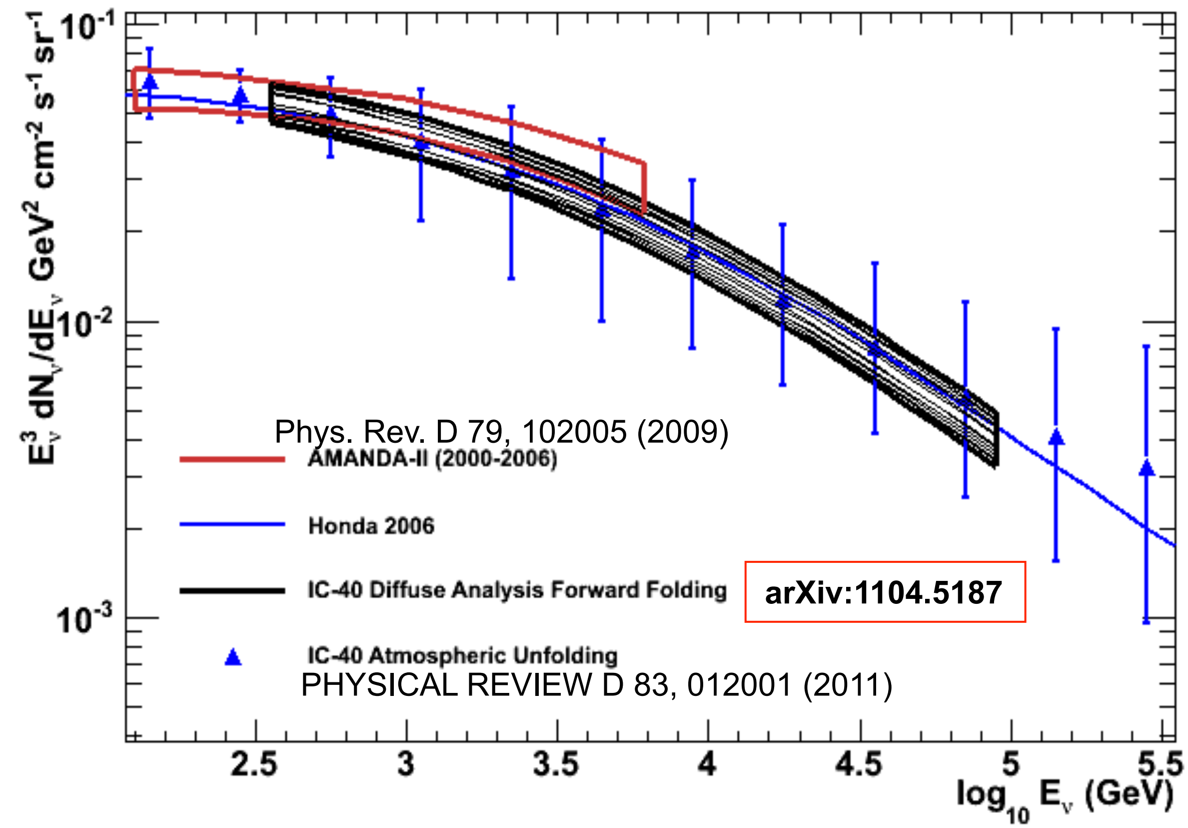
All-sky plot of muons in IceCube-22 from 2007 (P. Berghaus, IceCube, ISVHECRI-2008 arxiv.org/abs/0902.0021)

Atmospheric ν_μ with IceCube-40

Two analyses:

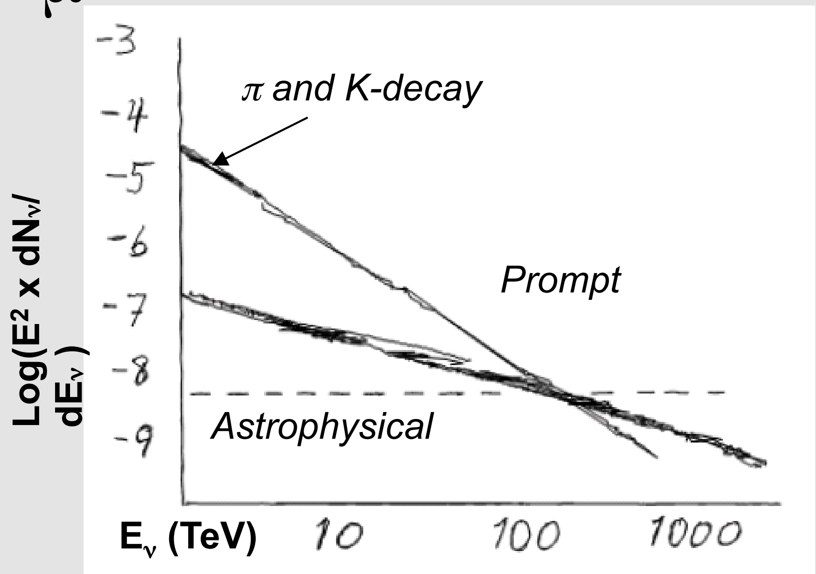
1. Unfolding
2. Forward folding as a by-product of a search for diffuse astrophysical ν

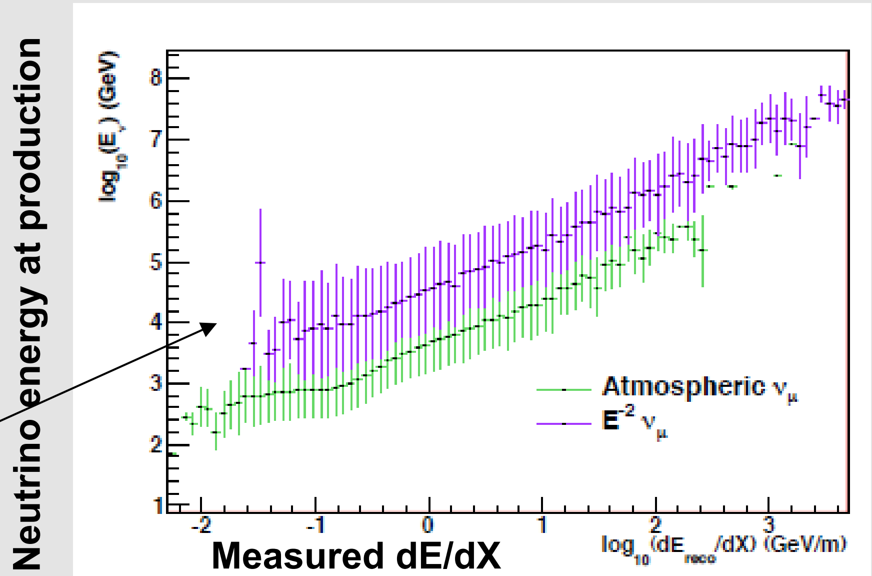
Look in detail at 2



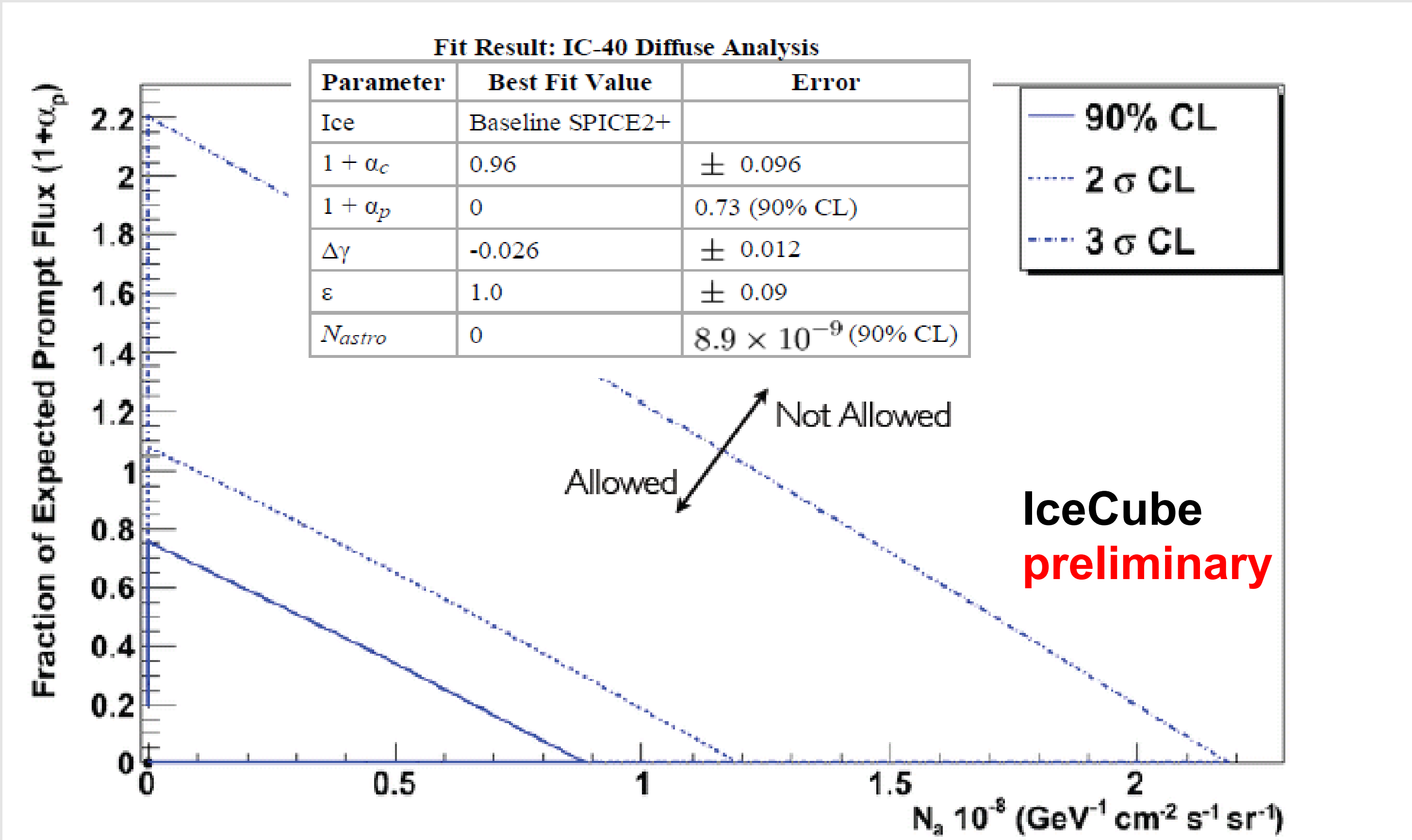
Measurement of ν_μ-induced μ

- Fit 3 components:
  - Atmospheric ν from $K^\pm$ and $\pi^\pm$
    - Use Honda 2007 to 10 TeV
    - + power-law extrapolation
    - ~ $\cos^{-1}(\theta)$
  - Prompt ν
    - Harder spectrum to > 10^7 GeV ($\sim E^{-2.7}$), isotropic
  - Astrophysical ν
    - Isotropic, with E^{-2} spectrum assumed
  - Note different response for astro. ν *vs* atmos. ν





Results of likelihood fit



Fit Result: IC-40 Diffuse Analysis

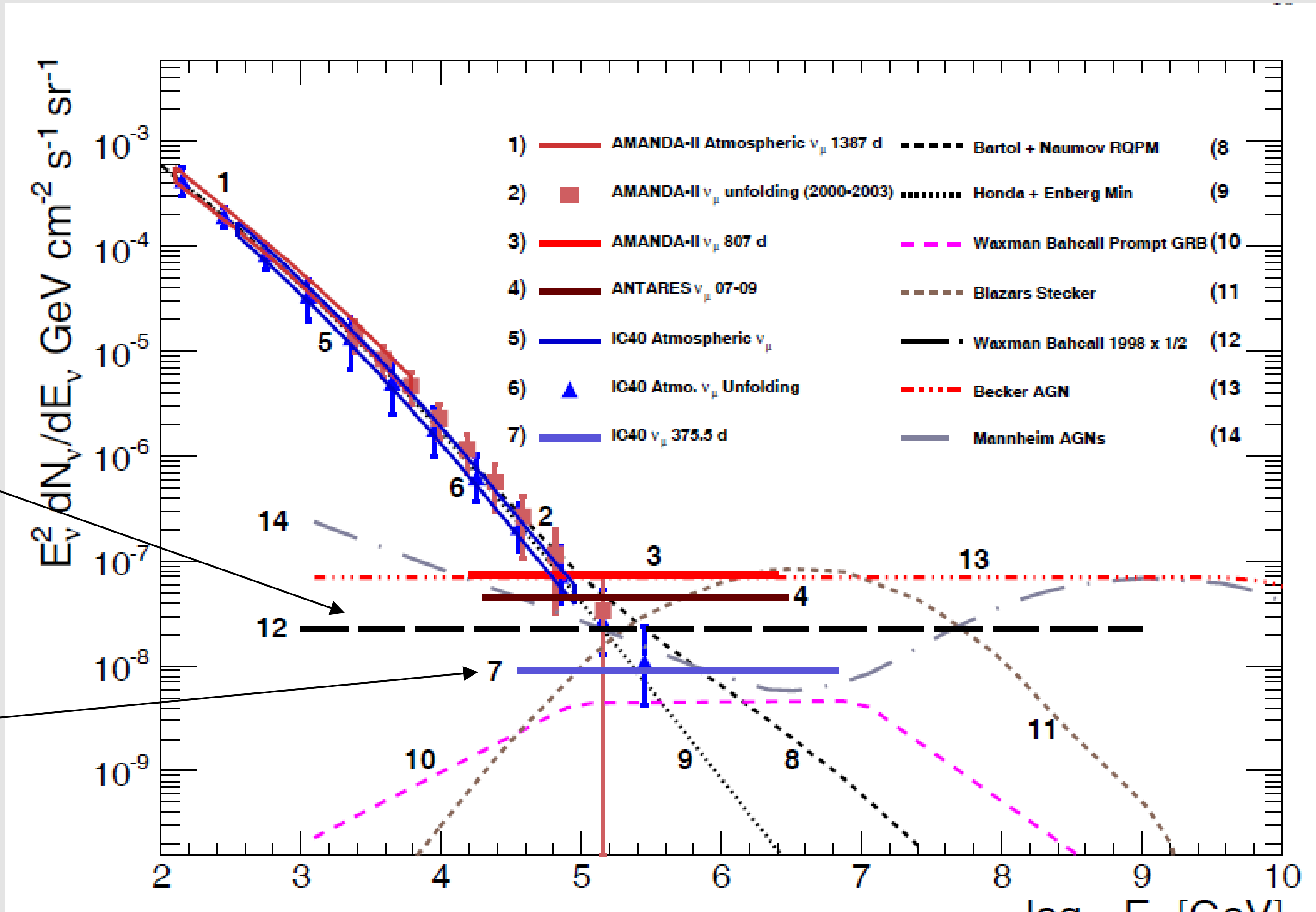
Parameter	Best Fit Value	Error
Ice	Baseline SPICE2+	
$1+\alpha_c$	0.96	$\pm$ 0.096
$1+\alpha_p$	0	0.73 (90% CL)
$\Delta\gamma$	-0.026	$\pm$ 0.012
ε	1.0	$\pm$ 0.09
N_{astro}	0	8.9×10^{-9} (90% CL)

- Consistent with only K, π atmospheric ν to 100 TeV
- Charm component not yet seen; “intrinsic” charm in doubt?
- No astrophysical neutrinos seen yet

IceCube ν_μ: measurements & limits

Waxman -Bahcall Limit

IceCube 40
arXiv:1104.5187



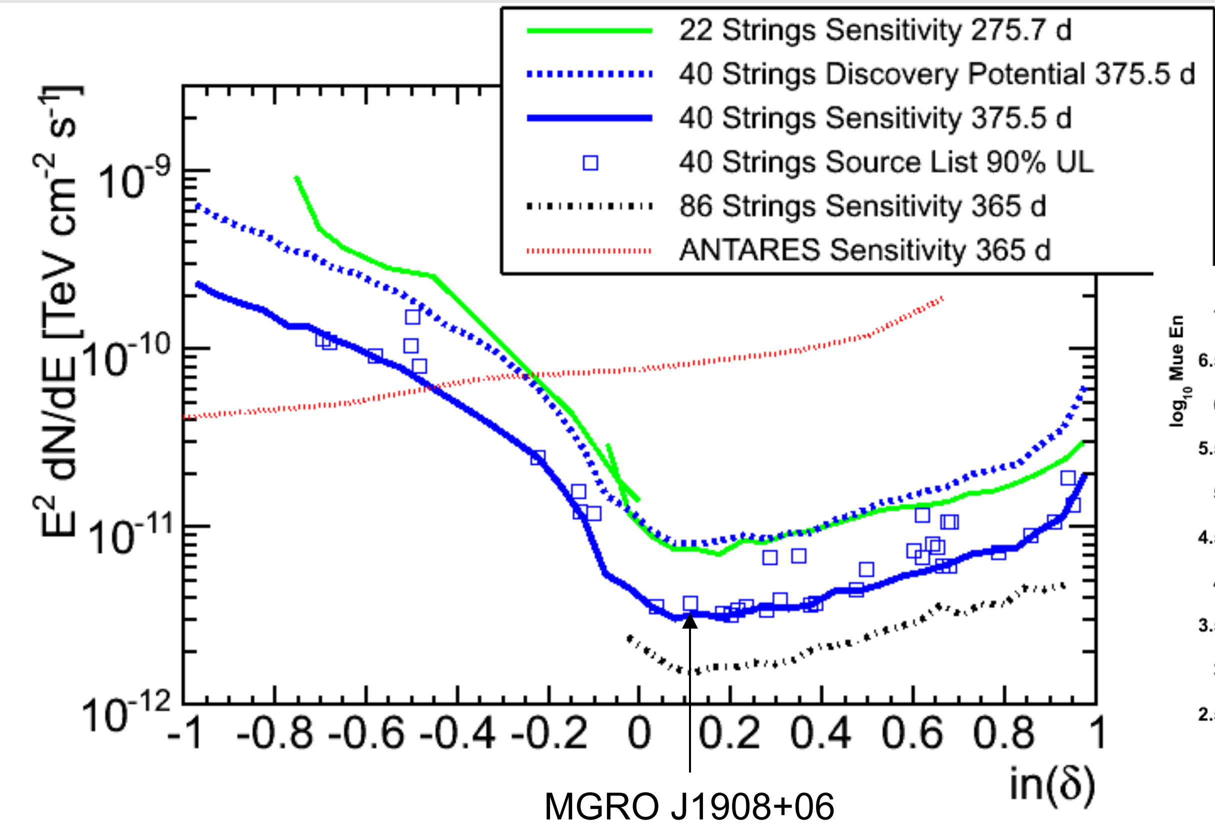
Plot: Sean Grullon, UW

Comments on diffuse ν results

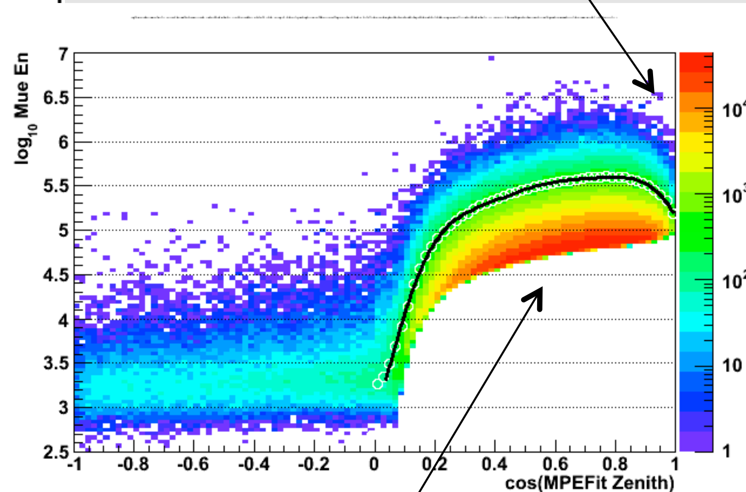
- Input to analysis
  - Specific spectrum assumed for atmospheric ν from decay of π and K (Honda et al., PR D75:043006,2007)
    - Extrapolate with power law for $E_\nu > 10$ TeV up to 10 PeV
  - For prompt ν use Enberg et al.. PR D 78, 043005, 2008
  - Overall normalization fitted for each component with a single fitted slope for both components
- Limitations of this analysis
  - Limits depend on simple power-law extension of conventional atmospheric ν_μ to $E_\nu >$ PeV
  - Neutrino spectrum must steepen to some extent above 100 TeV to reflect the knee in the primary spectrum
  - Bounds on prompt and astrophysical ν will be relaxed to some extent with a more realistic assumption for shape of atmospheric ν
  - Recent calculation extends calculation of ν_μ to > PeV
    - Illana, Lipari, Masip, Meloni, Astropart. Phys. 34 (2011) 663

Limits from point src searches

IceCube 40, Ap.J. 732 (2011) 18



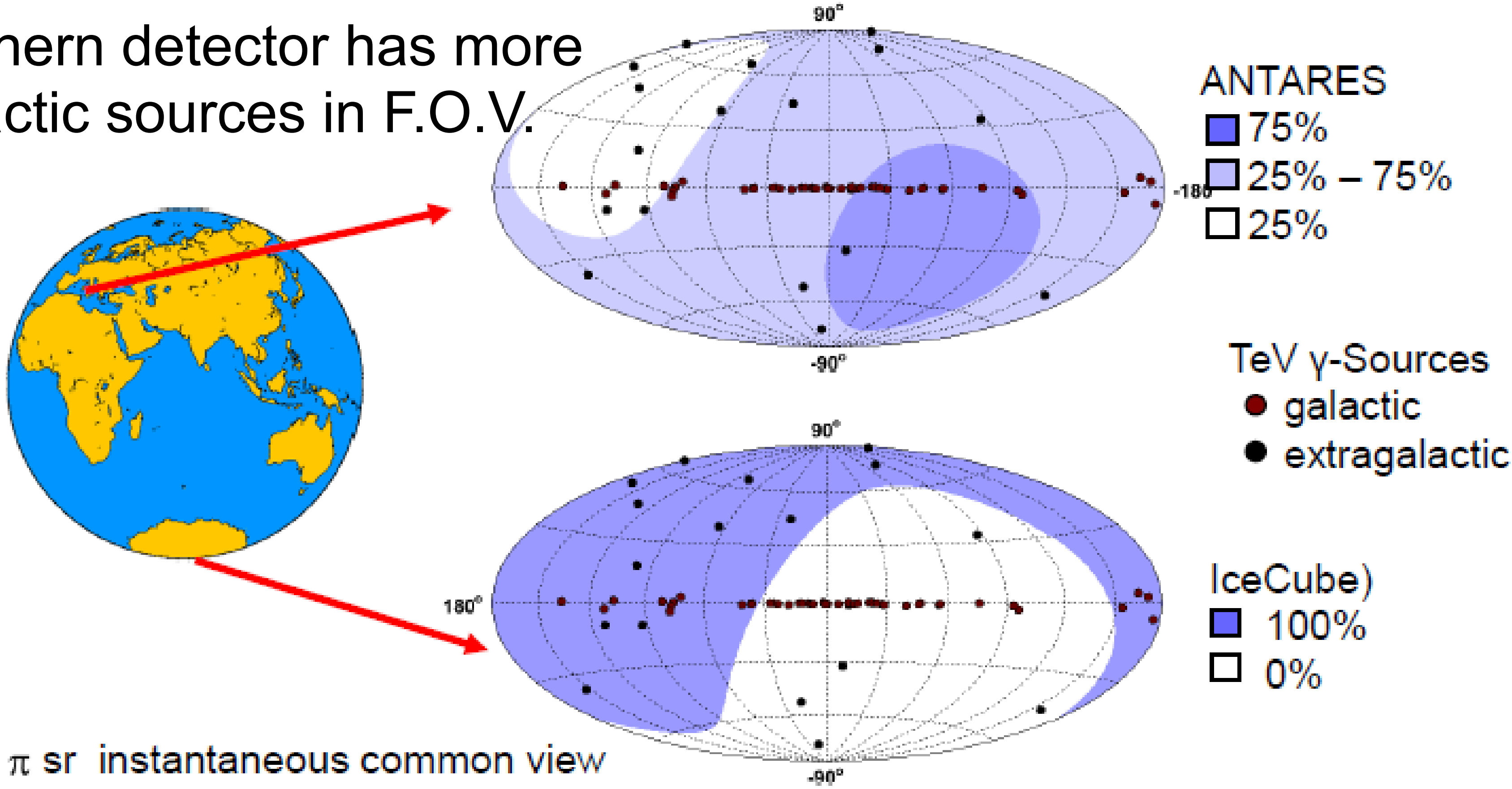
For IceCube-59
add IceTop veto



Note: IceCube energy threshold is set very high for Southern sources to reduce background of atmospheric muons. Antares is complementary.

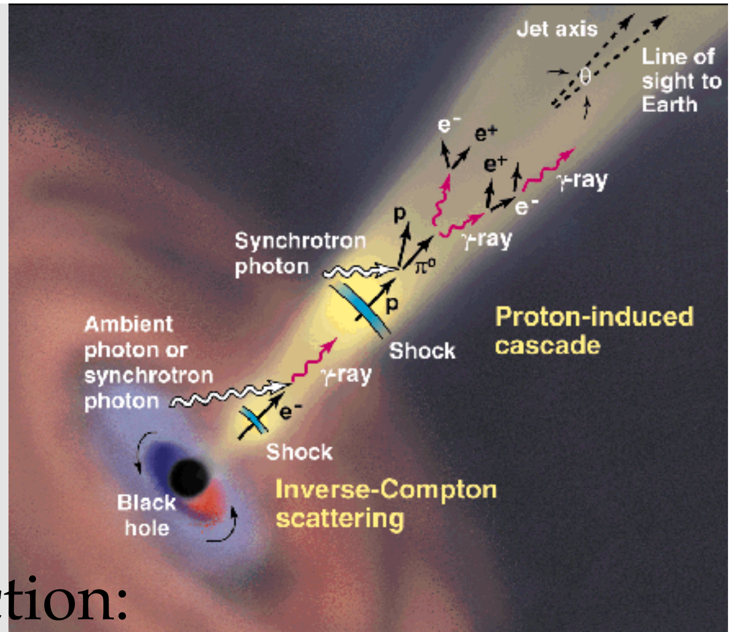
Sky coverage in Galactic coordinates **(Gisela Anton, ν-2010)**

Northern detector has more
Galactic sources in F.O.V.



0.5 π sr instantaneous common view
1.5 π sr common view per day

Generic model I



http://www.ucd.ie/math-phy/rieger/science.gif

- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\,\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR
- This picture disfavored as limits go below W-B

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Generic model II

- UHECR are accelerated in external shocks analogous to SNR
  - See E.G. Berezhko, 0809.0734 & 0905.4785
  - mixed composition (accelerate whatever is there)
  - Low density of target material
  - → lower level of neutrino production

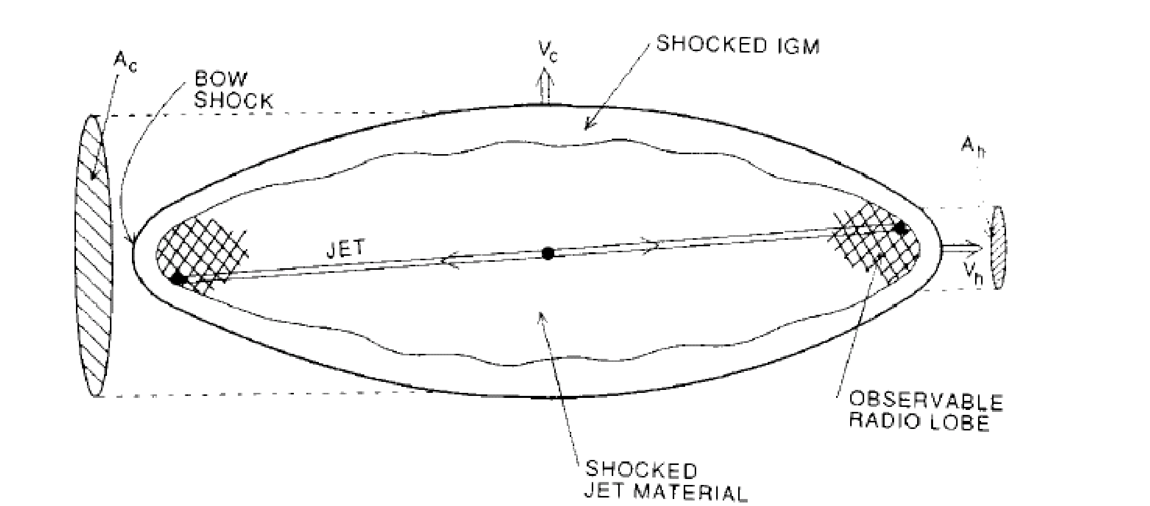
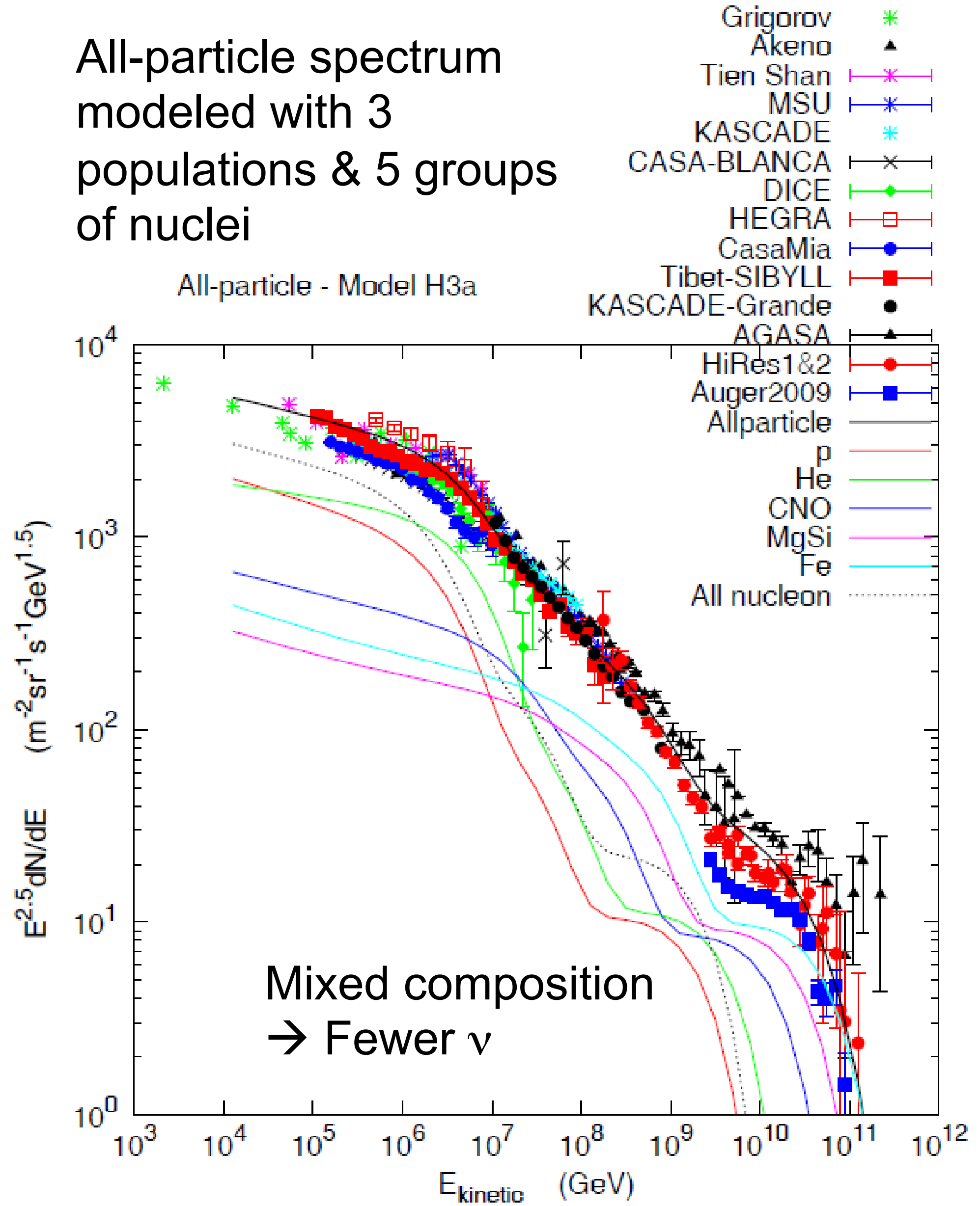


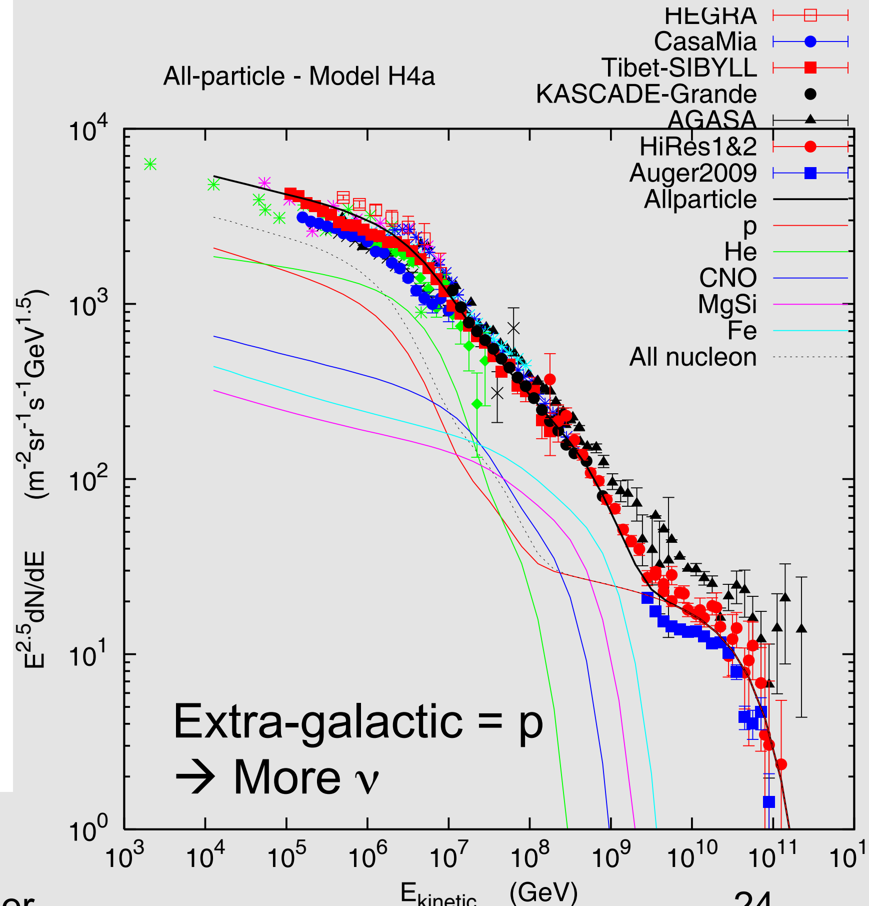
Diagram from A.Ferrari, Ann Revs A&A 36 (1998) 539

Primary spectrum & composition: expectations for > 100 TeV ν

All-particle spectrum modeled with 3 populations & 5 groups of nuclei



Mixed composition
→ Fewer ν



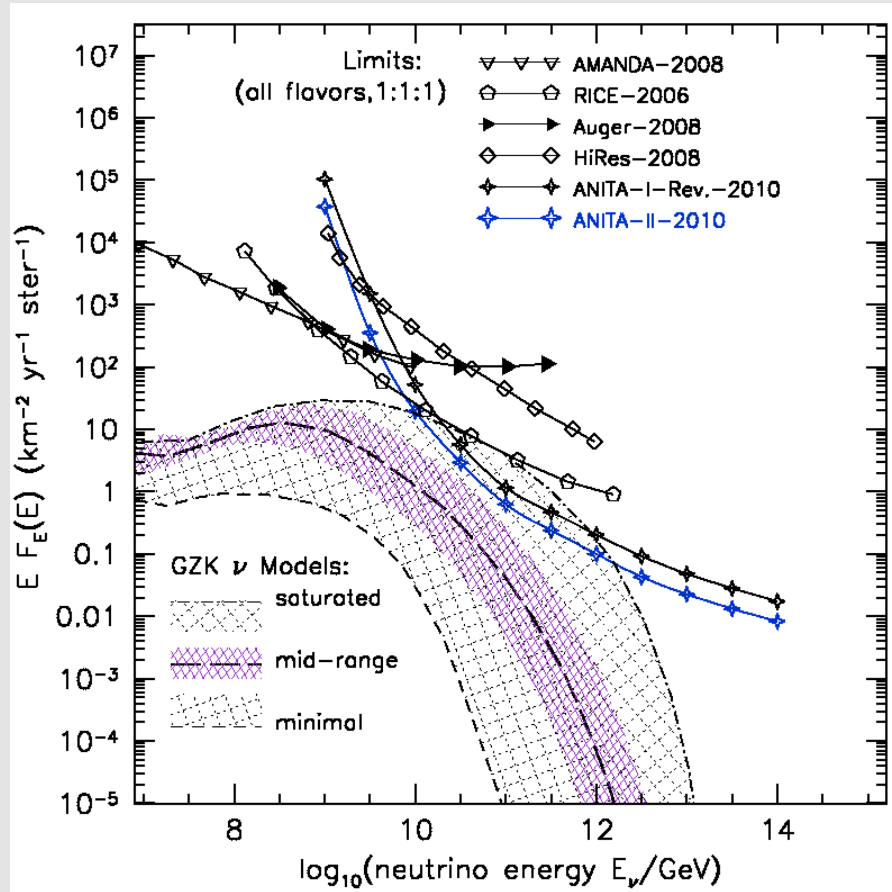
Extra-galactic = p
→ More ν

Cosmogenic (GZK) neutrinos

- Cosmogenic ν from

$$p + \gamma_{2.7^\circ} \rightarrow \pi^0 \rightarrow \gamma$$
$$\phantom{p + \gamma_{2.7^\circ}} \searrow \pi^+ \rightarrow \nu$$

- Intensity depends on
  - Spectrum at sources
  - Evolution of sources
  - Composition of UHECR (Heavy nuclei give less ν)
- Third flight of ANITA
  - Optimized for UHECR as well as GZK ν, 2011/12 ?



ANITA arXiv:1011.5004

Radio Detection of neutrinos

ANITA-II over Antarctica

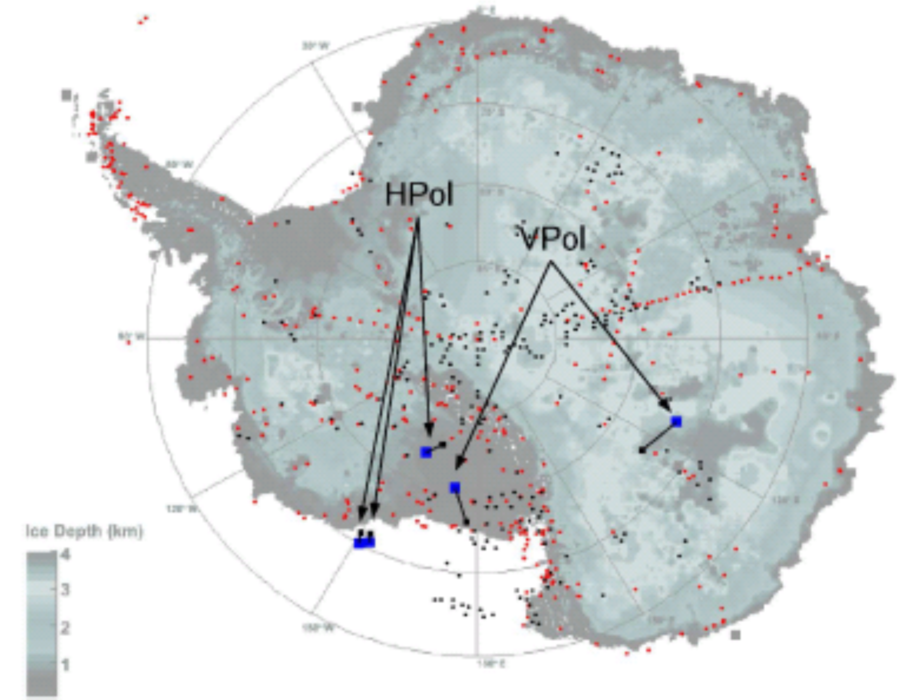
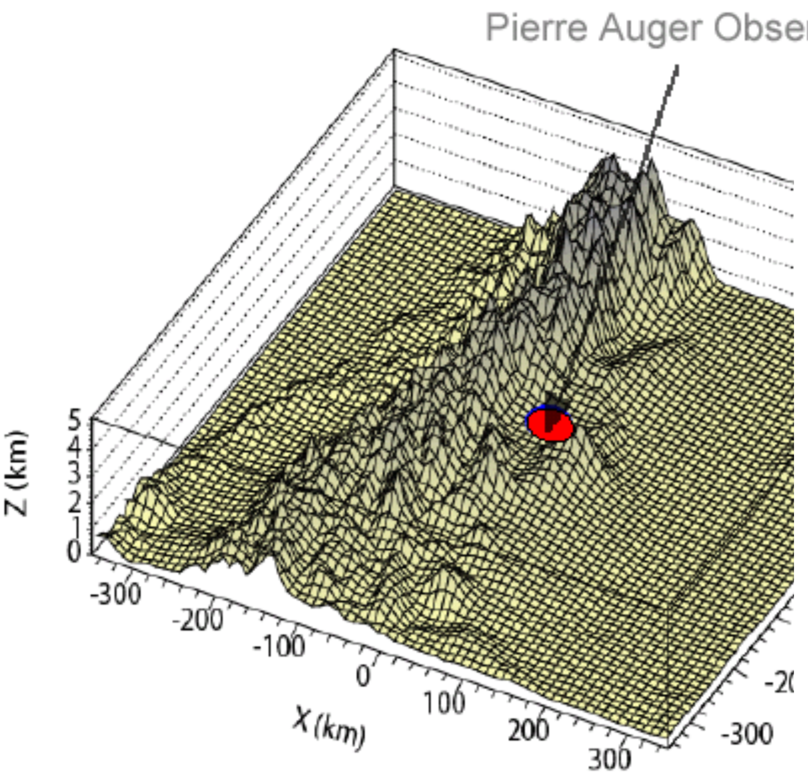


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

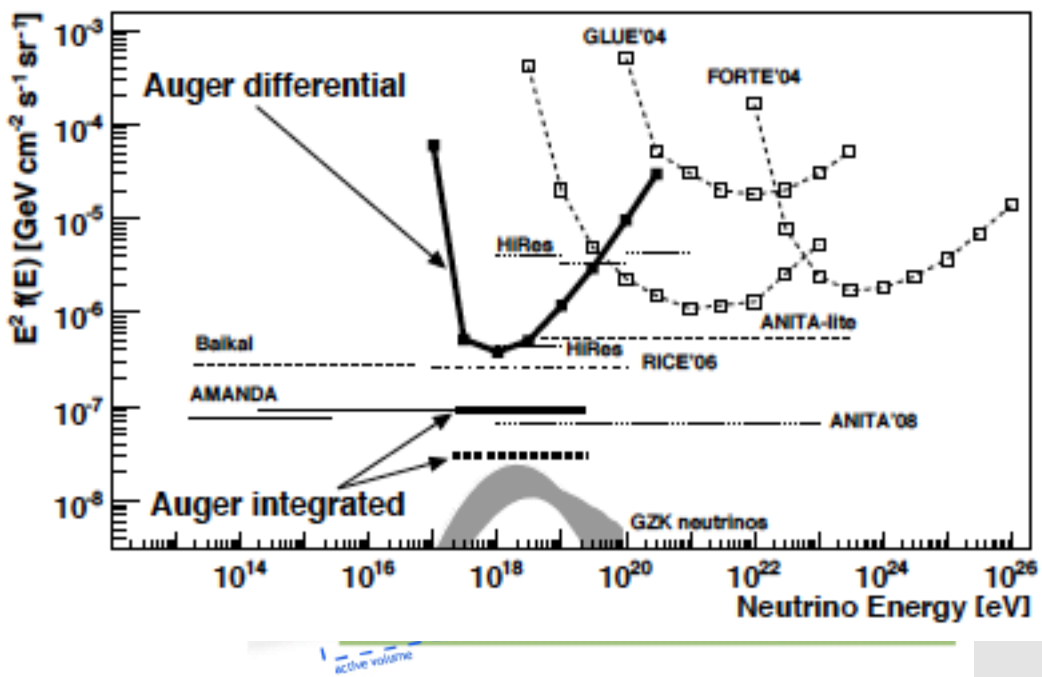
http://arxiv.org/abs/1003.2961

Vpol:1 neutrino candidate;
HPol:3 > 10^{19} eV cosmics

EeV ν_τ detection with Auger et al.



PRD 79 (2009) 102001



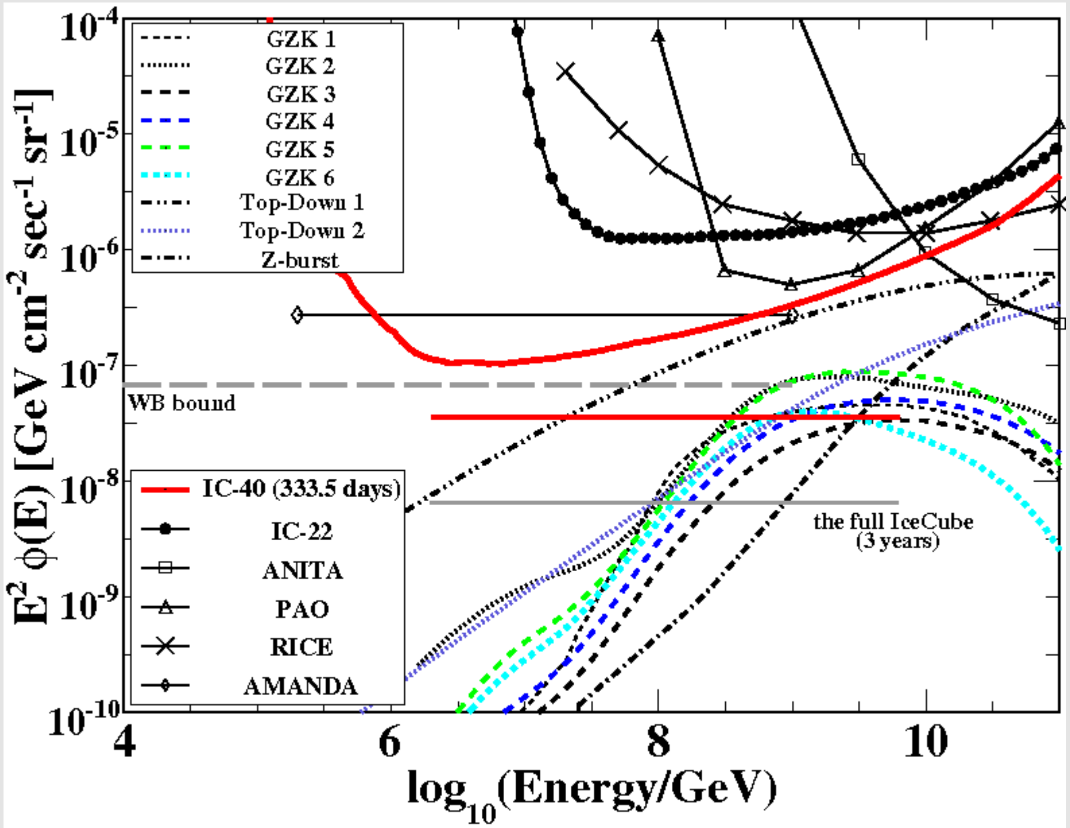
$\Gamma c\tau$ ~ 100 km for E_τ ~ 2×10^{18} eV followed by τ-decay shower

T. Weiler, D. Fargion

IceCube limits on cosmogenic ν

- GZK search looks for
  - Very bright events
  - Near the horizon
  - with compact initial burst of light
- Range of sensitivity
  - PeV – EeV
  - Complementary to diffuse ν_μ search that starts by measuring atmospheric ν_μ
  - Model 6 (Fermi max): expect 0.4 events

IceCube-40 arXiv:1103.4250



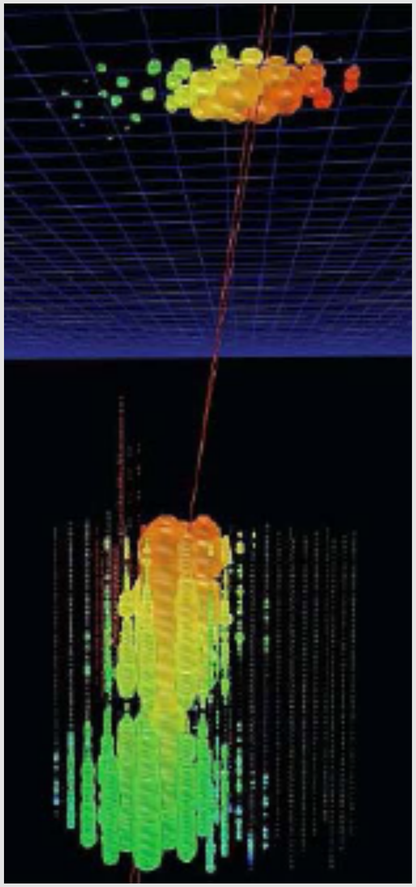
All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Related science with IceCube

- Cosmic-ray physics
  - Composition/spectrum with IceCube/IceTop
  - Cosmic-ray anisotropy with 5 x 10^{10} μ/yr (arXiv:1005.2960 Ap. J. Letters in press)
- Monitoring stream
  - Galactic SN ν will manifest as sharp increase in background counting rate of 5000 DOMs
  - Detect solar particle events as increase in IceTop DOM rates (2008 *ApJ* **689** L65)
- Neutrino alerts to optical follow-up (ROTSE, et al.)

Cosmic-ray physics with IceCube

- IceCube sees cosmic ray events from all directions
  - 30,000 atmospheric ν/year
  - 100 billion atmospheric μ/year
  - 1 billion air showers/yr in IceTop
  - ~10% in coincidence with deep IceCube
- Spectrum/composition:
  - TeV to EeV



Status

- Atmos. ν spectrum extended to 100 TeV
  - Models with intrinsic charm (e.g. RQPM) disfavored
  - New analysis underway with bigger detector
    - Will use more realistic shape for atmospheric ν
    - Will look at angular dependence to discriminate prompt ν
- Limit on an isotropic contribution of high-energy neutrinos is below W-B "bound"
  - Models with energy parity between UHECR and neutrinos are disfavored (**e.g. Ahlers et al., PR D79, 083009, 2009**)
  - Generic Model I with extra-galactic p is disfavored
- No point sources yet with 0.5 km^3yr data

Future projects at South Pole

- Acceptance and sensitivity of IceCube will increase rapidly as new analyses use full detector
- Larger acceptance needed to measure cosmogenic (GZK) neutrinos in EeV range
- ARA (Askaryan Radio Array) for higher energy
  - First test deployment next to IceCube in January, 2011
  - Aims for greater sensitivity than ANITA
- Beyond Deep Core for lower energy (~GeV)
  - Proposed expansion of present Deep Core
  - Talk by Ty DeYoung, May 25 afternoon session
- Dark Matter Ice – two pilot scintillators deployed at 2500 m in IceCube holes in December, 2010
  - Seasonal variation of background opposite to DAMA,
  - Seasonal vatriation of DM signal universal

DM-Ice

DM-Ice Concept
Large Pressure Vessel
Segmented Crystals

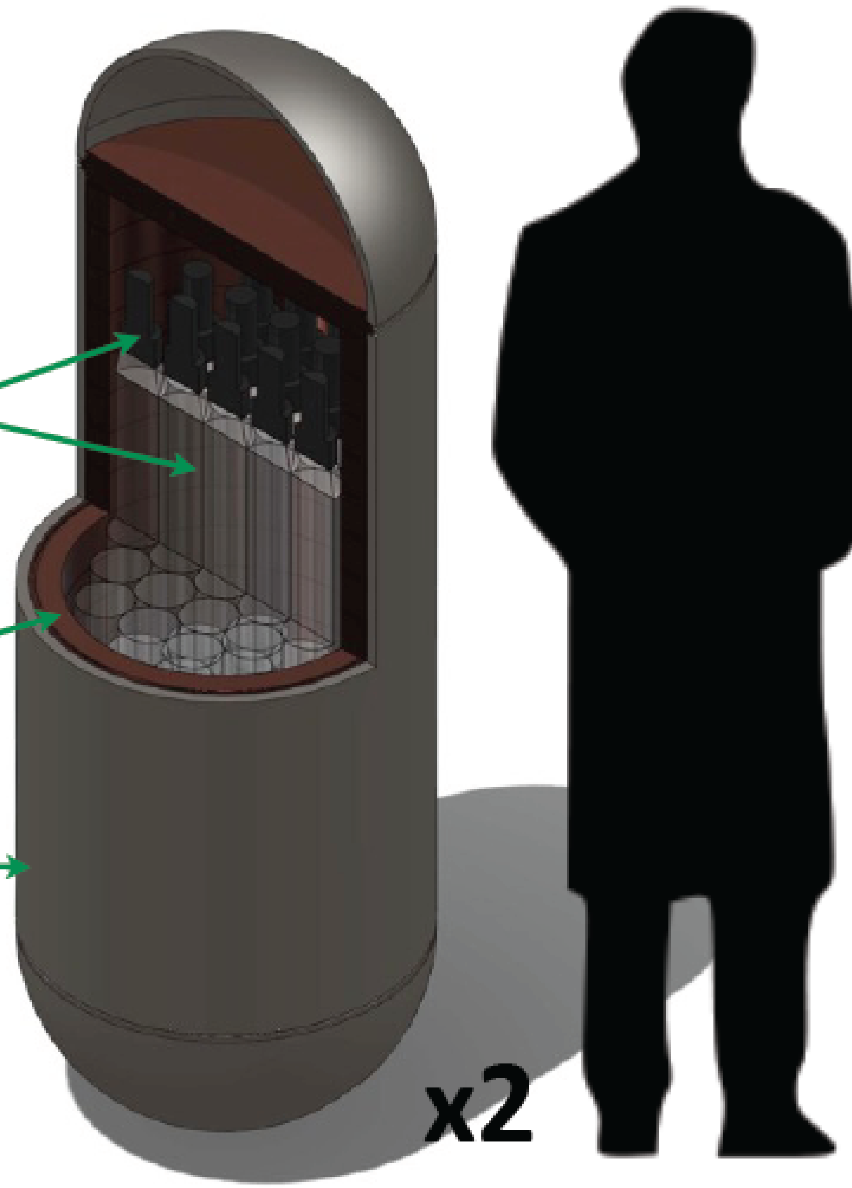
38 NaI Crystals (each vessel contains 19)
- 95.6 mm Diameter
- 250 mm Long
- 6.5 kg each
- 2 PMTs each

Instrument with few "DOMs" externally for veto

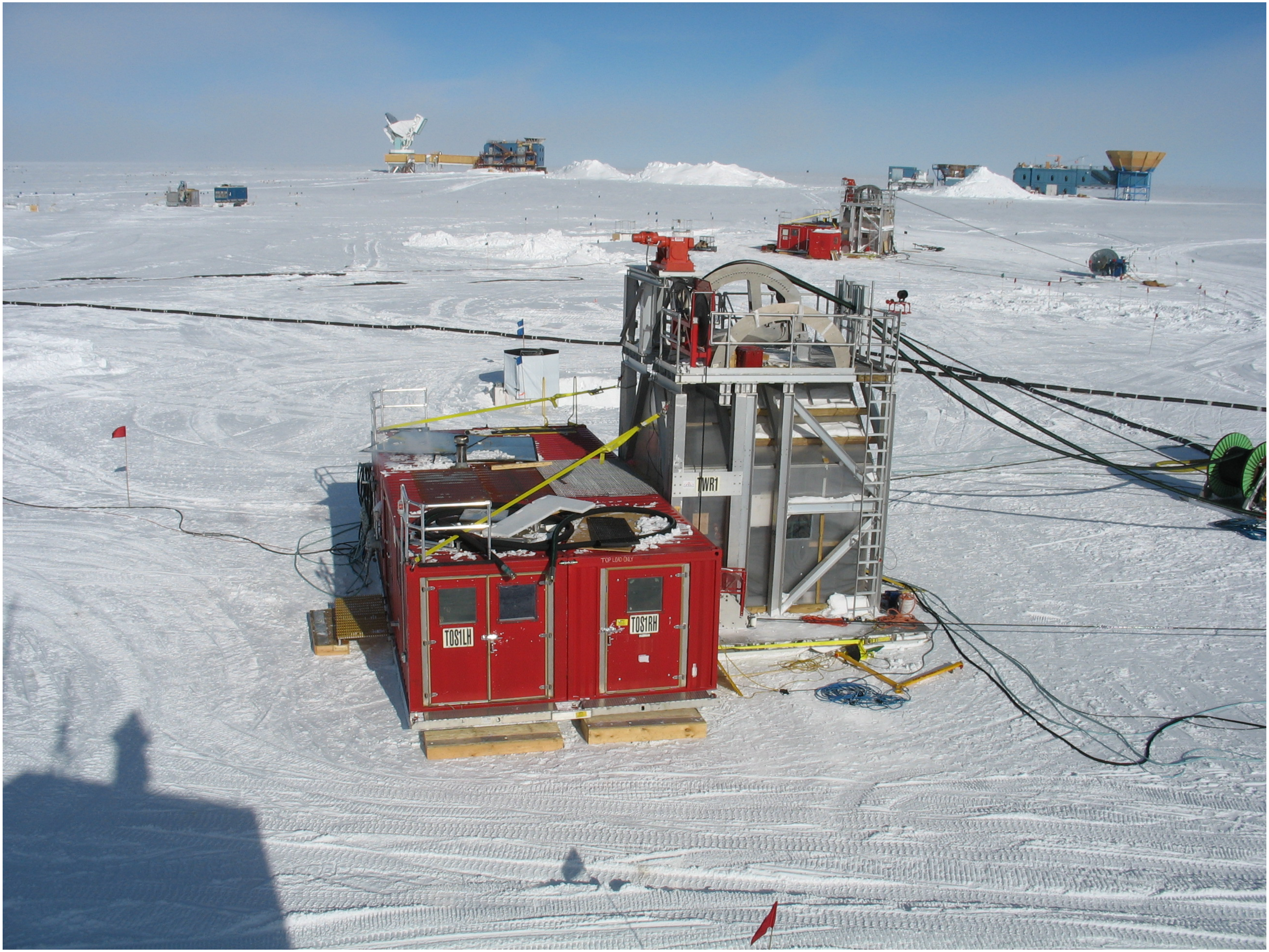
50 - 60 mm Copper Radial Shield

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




IceCube drill in action
December, 2010


TWR1
TOP LOAD ONLY
TOS1LH
TOS1RH

IceCube drill in storage
January, 2011