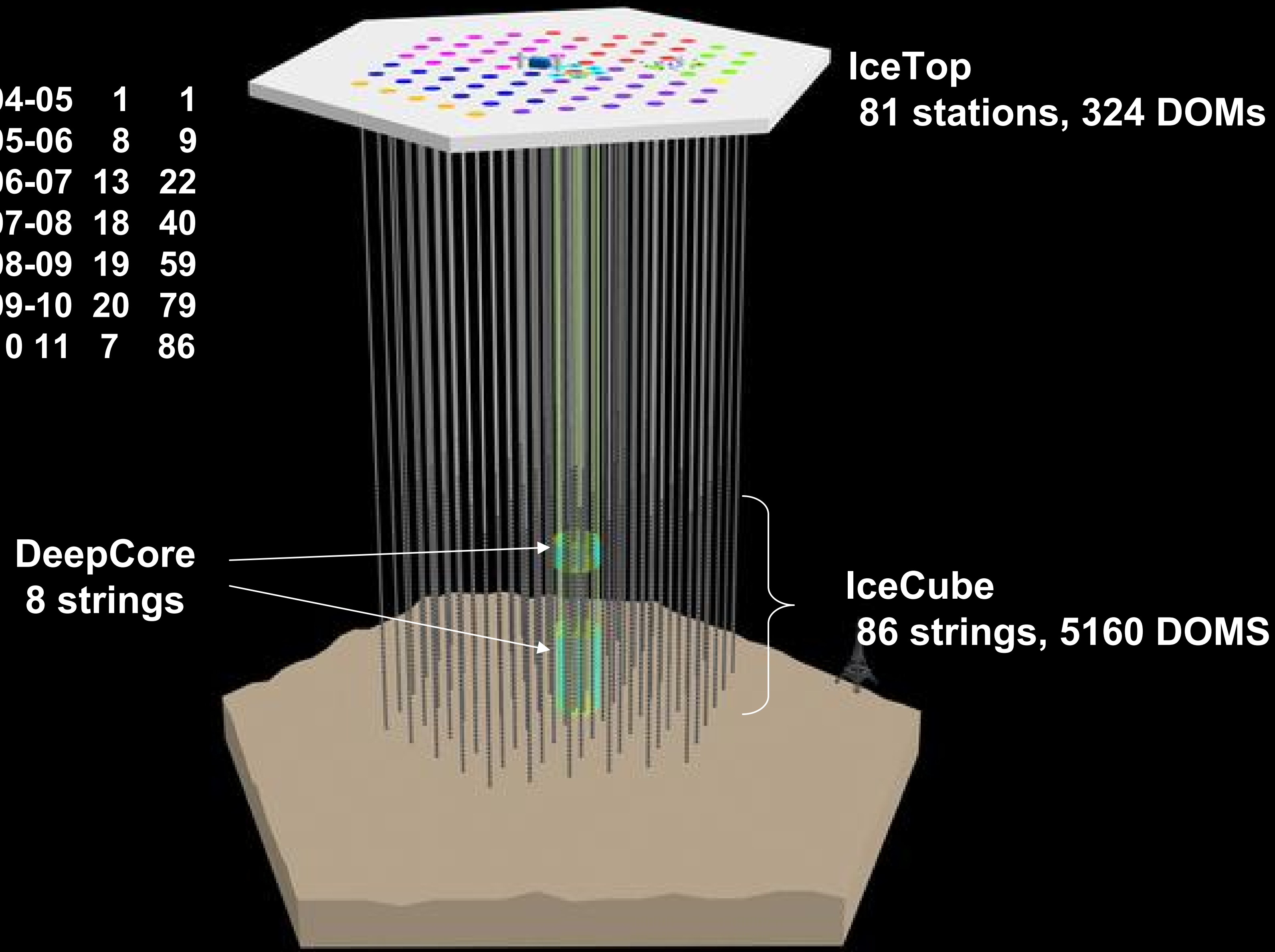
IceCube construction complete!

Last string deployed December 18, 2010

86 strings (inc. 8 Deep Core) + 81 IceTop stations

Turn-on scheduled for April 2011

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



IceCube

Status and developments

IceCube Collaboration: 217 scientists, 36 institutions, 10 countries
Construction supported by the U.S. National Science Foundation
plus Sweden, Germany, Belgium

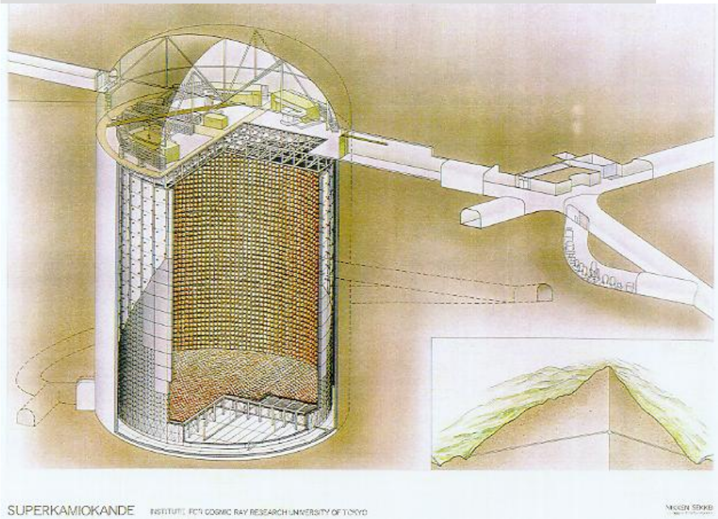
Outline

- Motivation and history (since 1960)
- Effective area and event reconstruction
- Atmospheric neutrinos
- New limits on astrophysical neutrinos
- Implications for models of sources
- Search for specific sources
  - SNR, micro-quasars, AGN, GRB
- Status and future

Detecting neutrinos in $H_2 0$

Proposed by Greisen, Reines, Markov in 1960

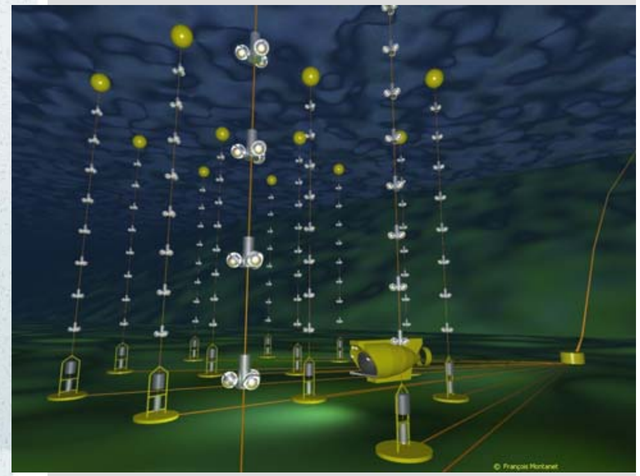
Heritage:
- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA



Super-K

SNO

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

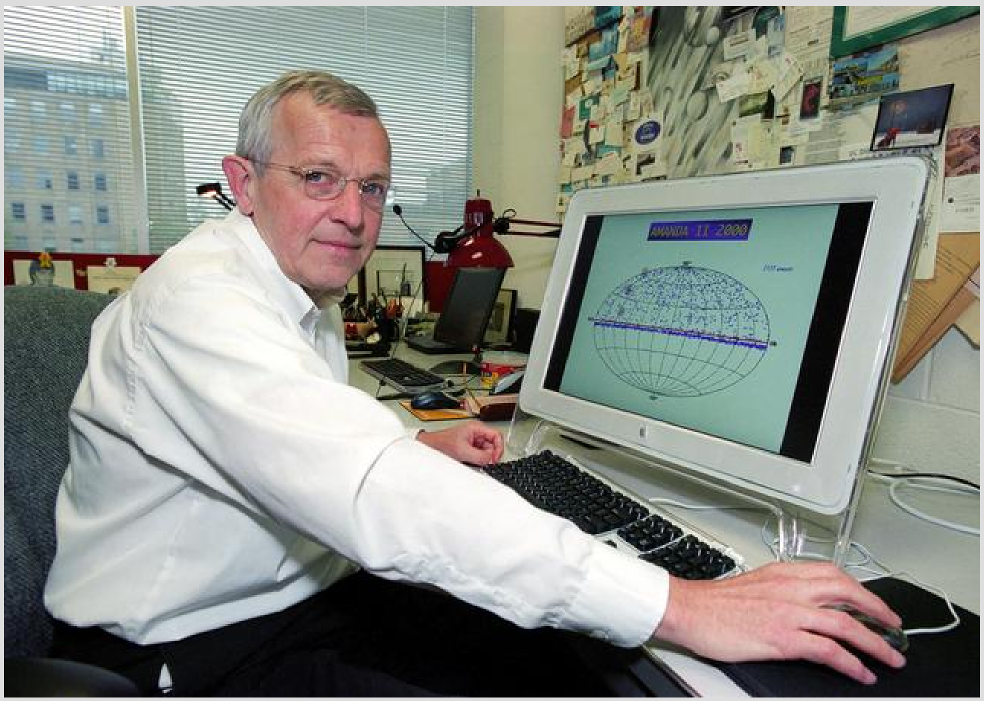


ANTARES

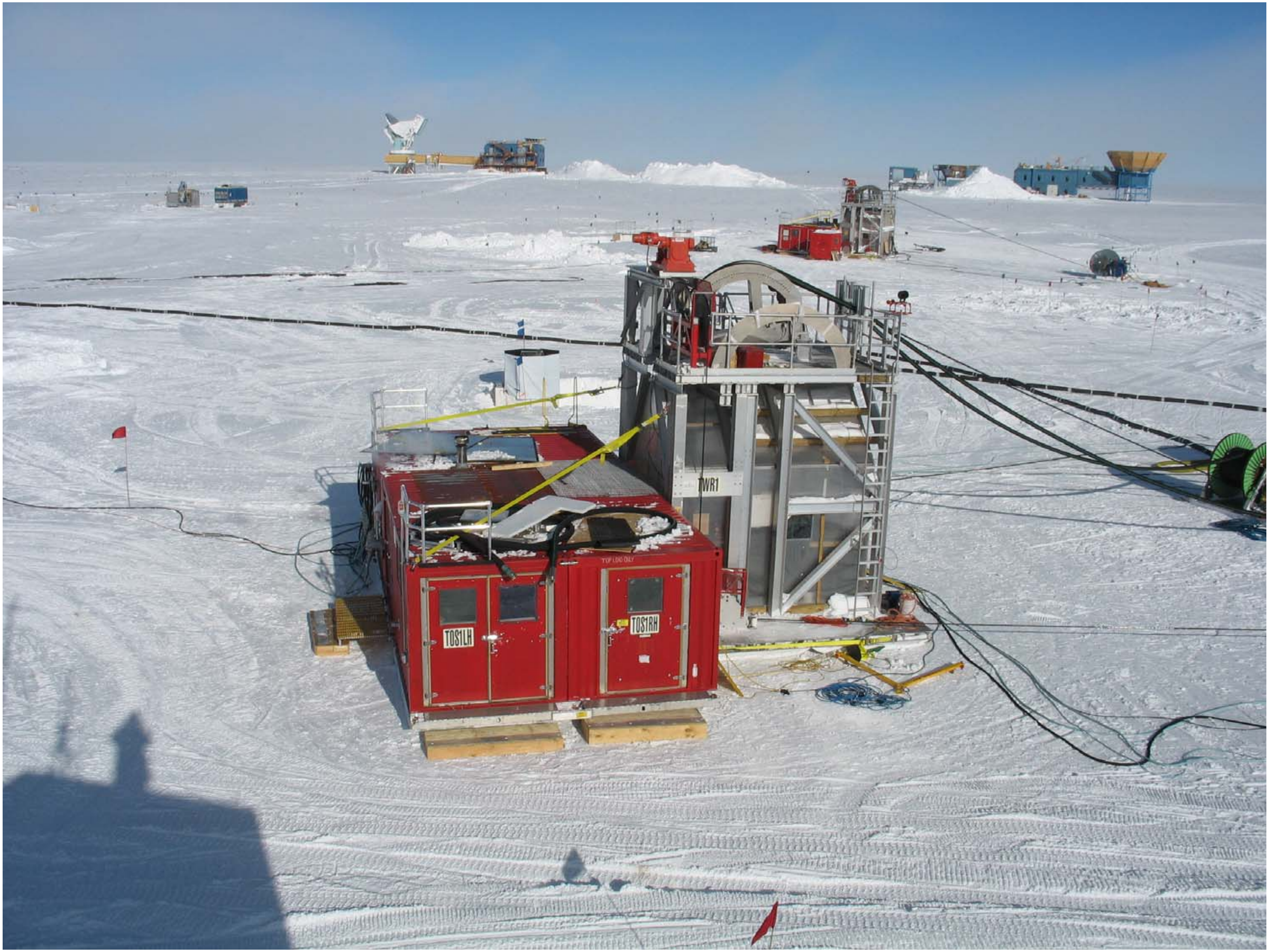
All use Cherenkov light from charged products of ν interactions

Detecting neutrinos in ice

The idea
(see Halzen, Learned, Stanev,
A.I.P. Conf. Proc. #198, pp. 39-51, 1989)



The reality: AMANDA drilling &
deployment outside at -40º!


TWR1
TOS1LH
TOS1RH

Drilling, deployment team
2010-2011

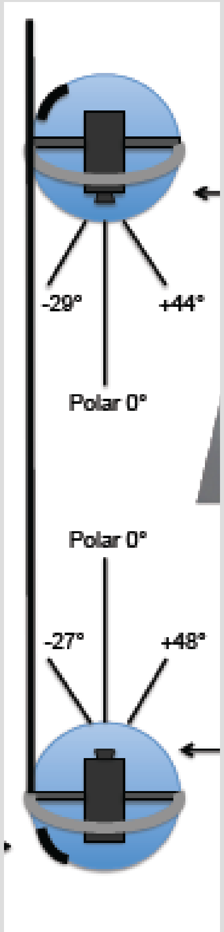
IceCube Digital Optical Module and deployment

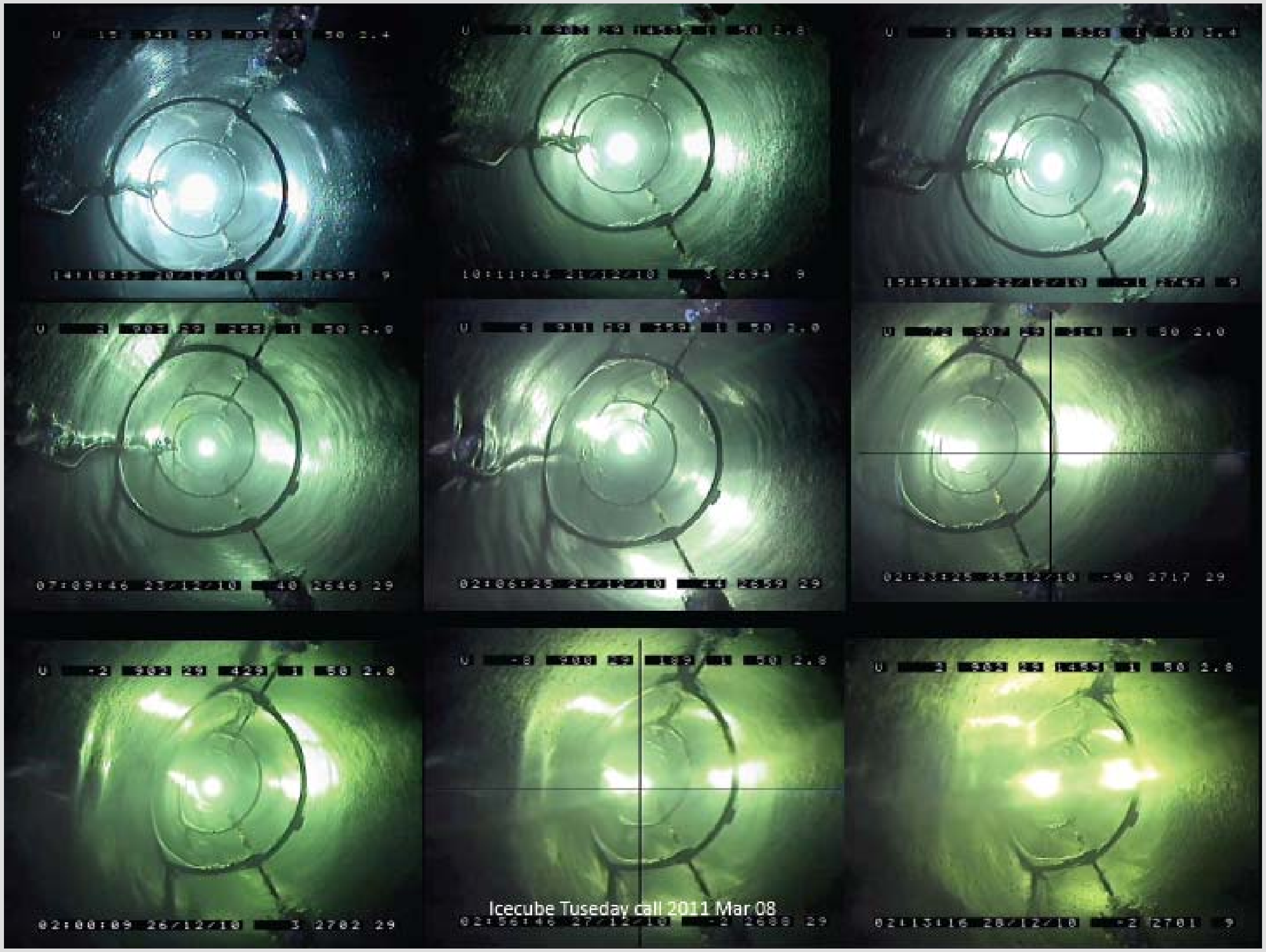
LED Flasher board

HV board

Main board for digitizing & time stamping

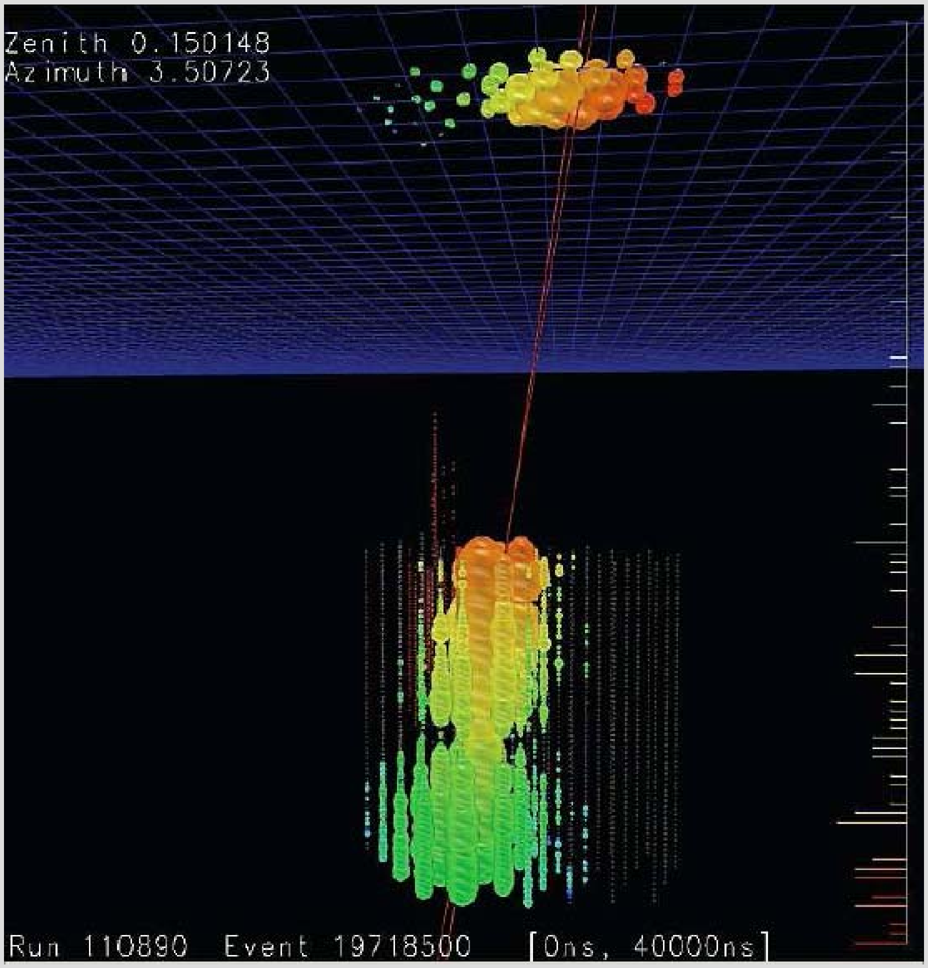
Swedish camera at 2450 m
March 2011

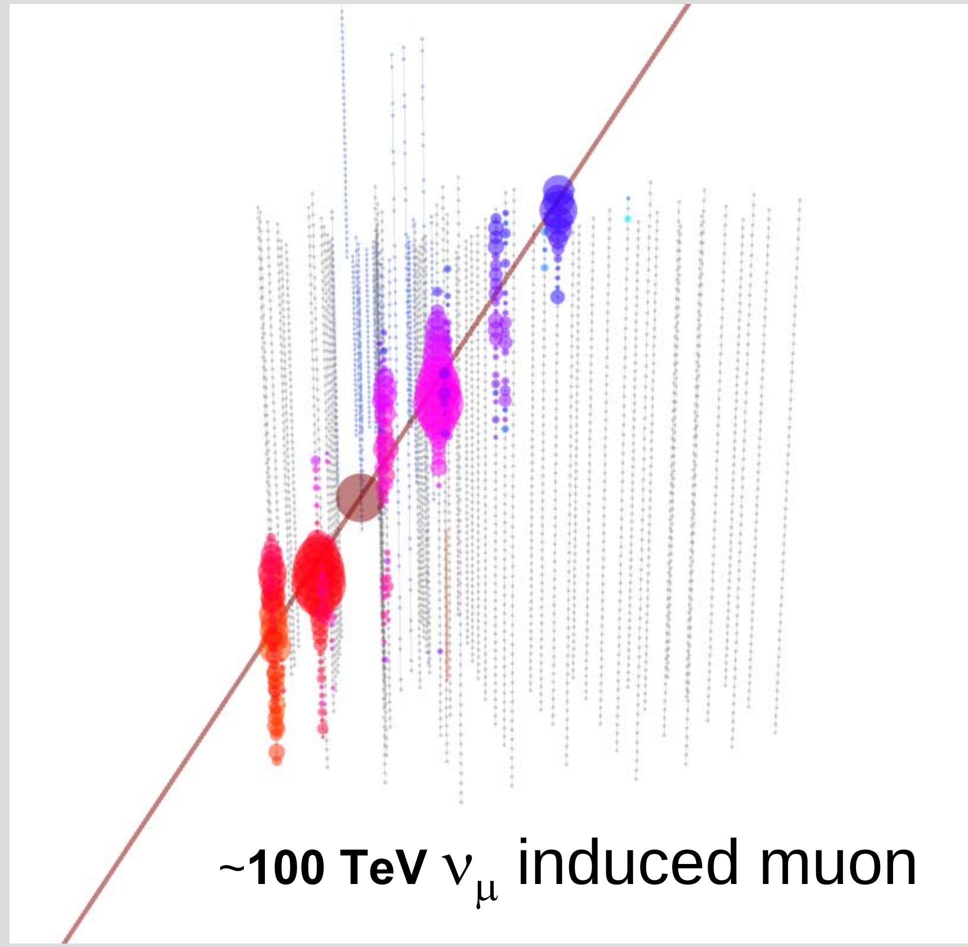




High-energy events in IceCube-40

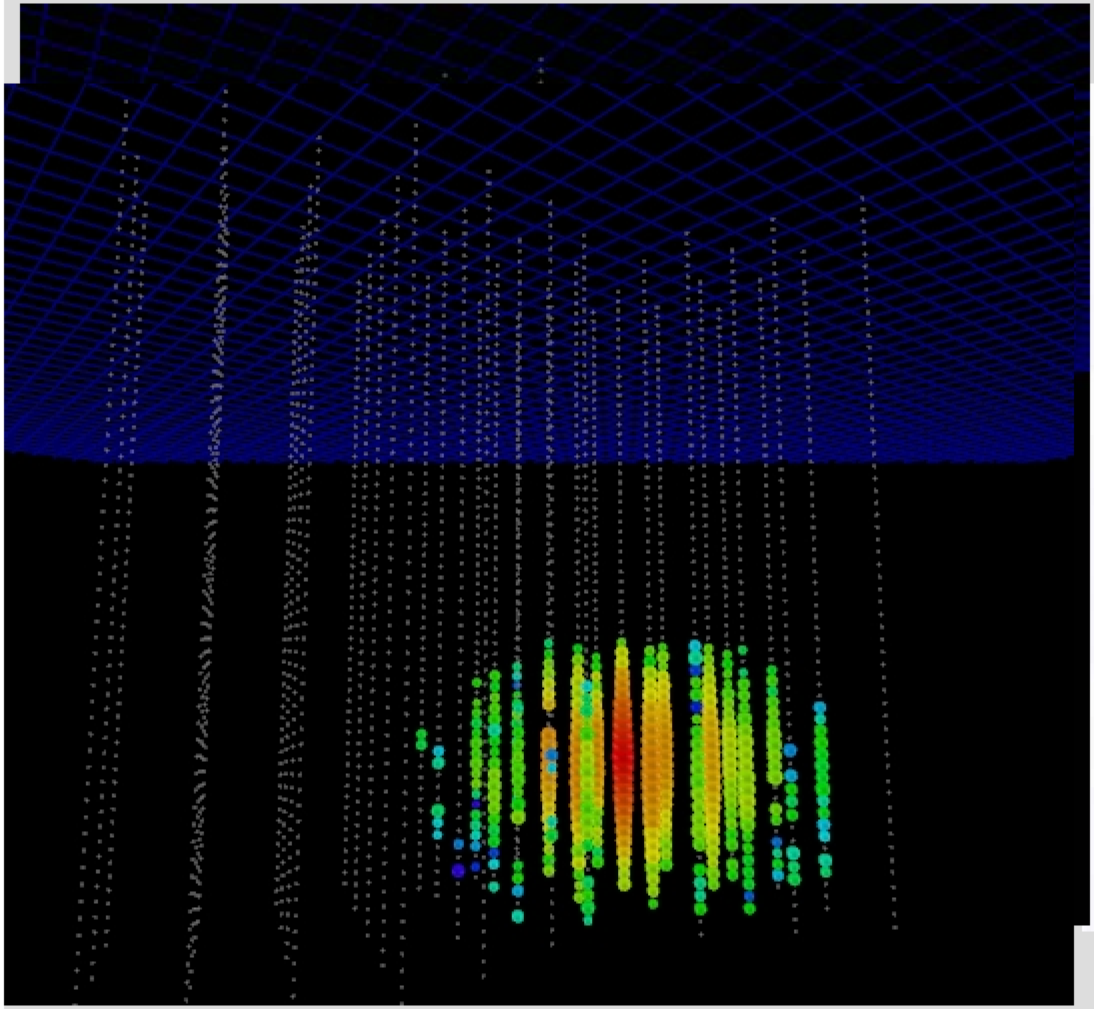
~ EeV air shower

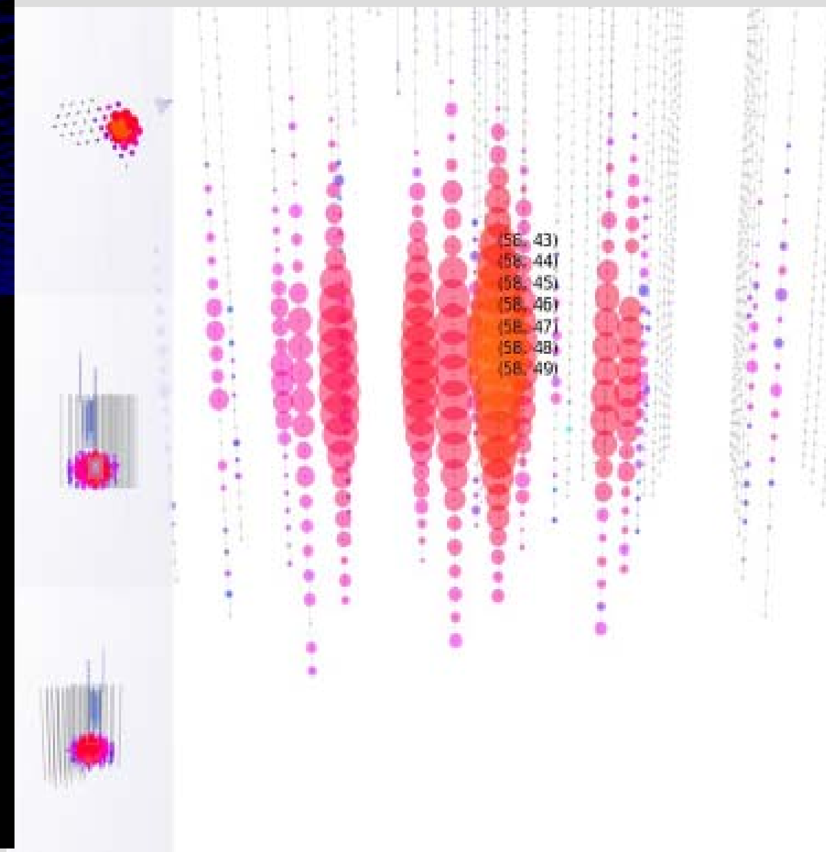




~**100 TeV** ν_μ induced muon

More events

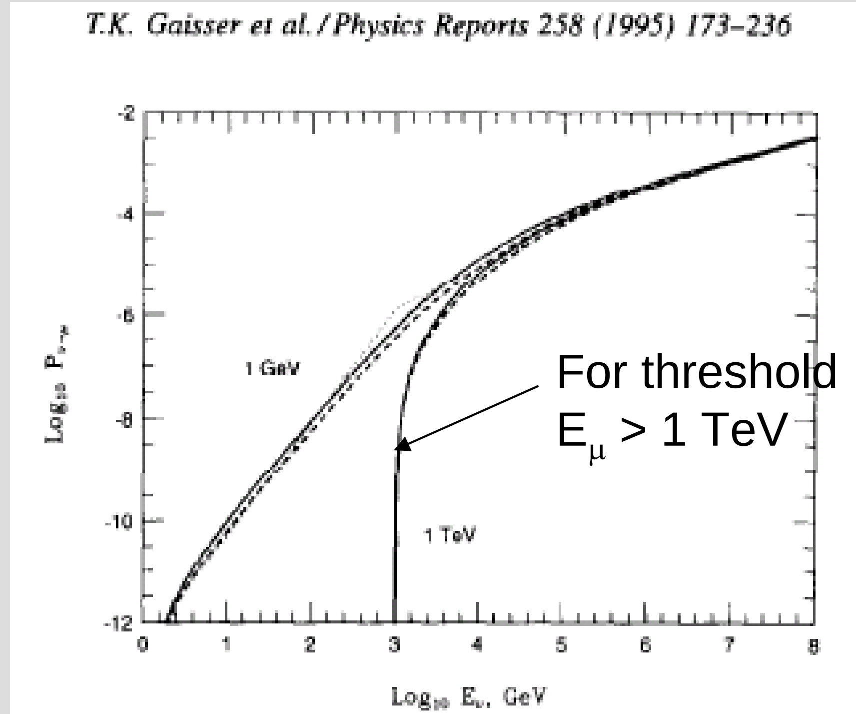




A cascade event, candidate for a high energy ν_e ~50 TeV

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

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

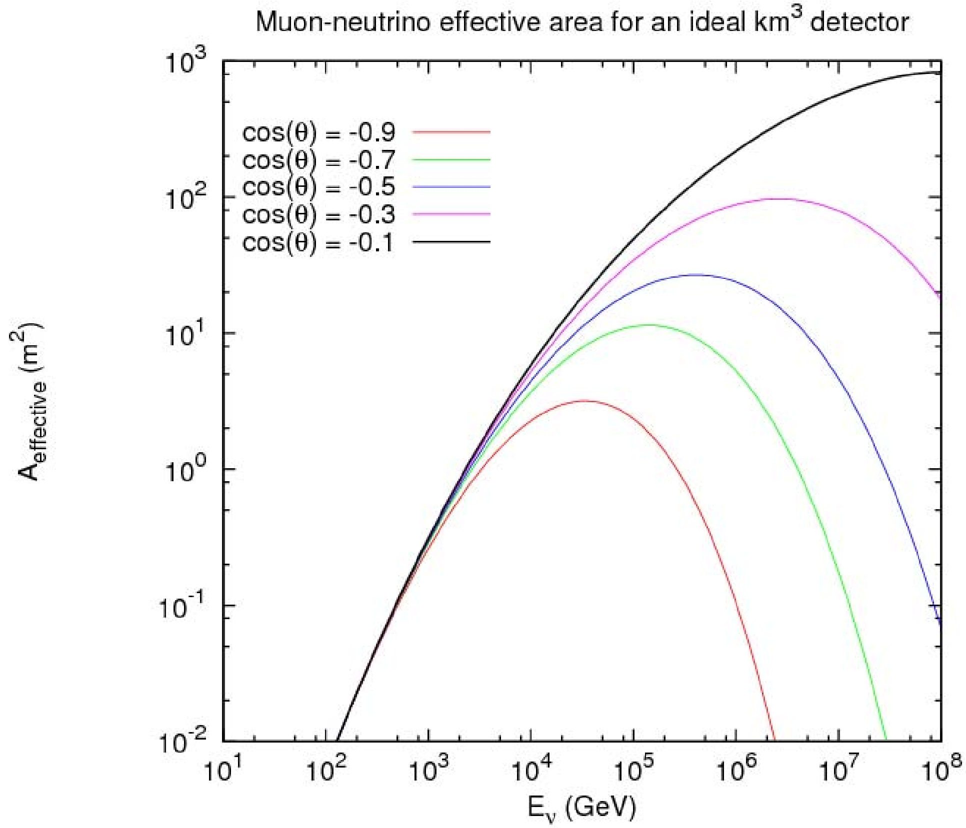
Neutrino effective area

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

- Rate:

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

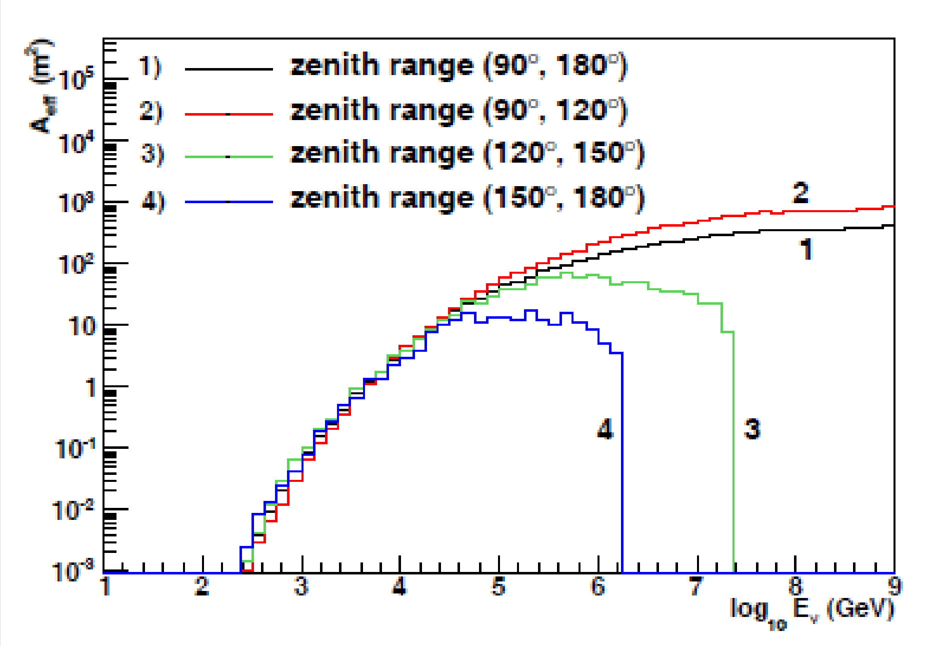
- Earth absorption
  - Starts 10-100 TeV
  - Biggest effect near vertical
  - Higher energy ν's absorbed at larger angles

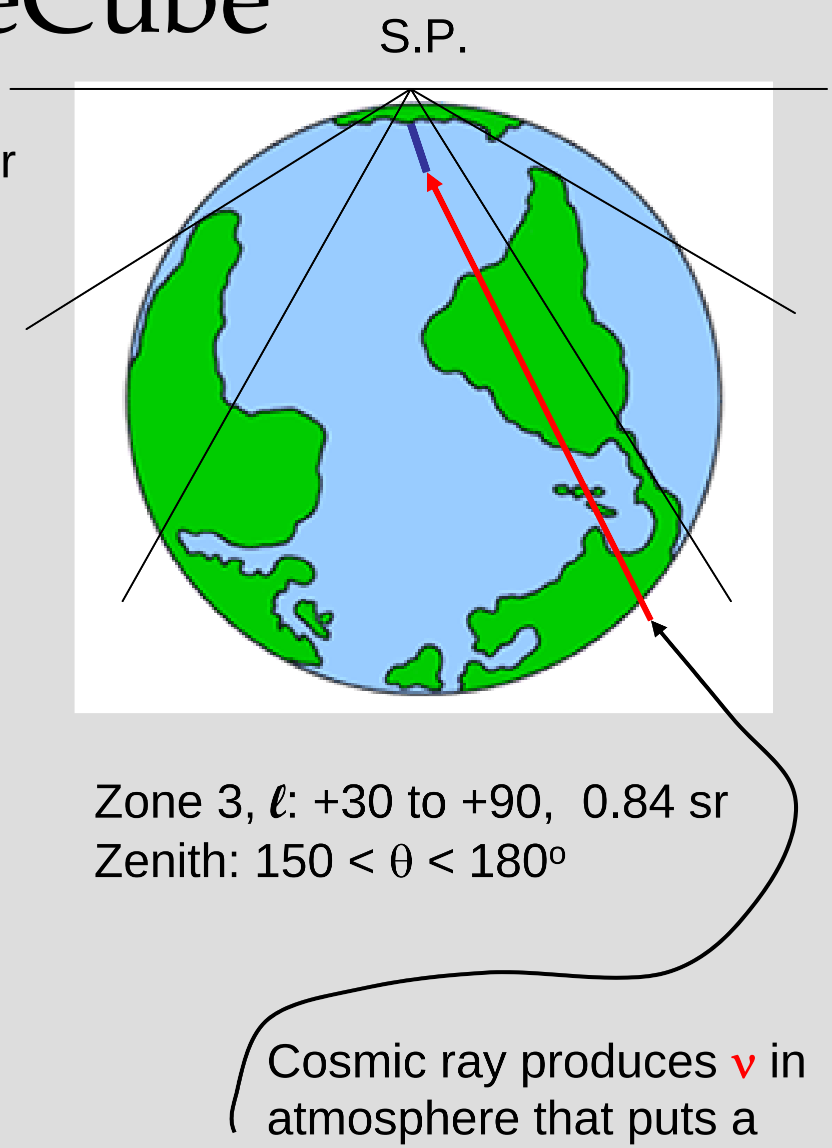


Atmospheric ν in IceCube

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

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



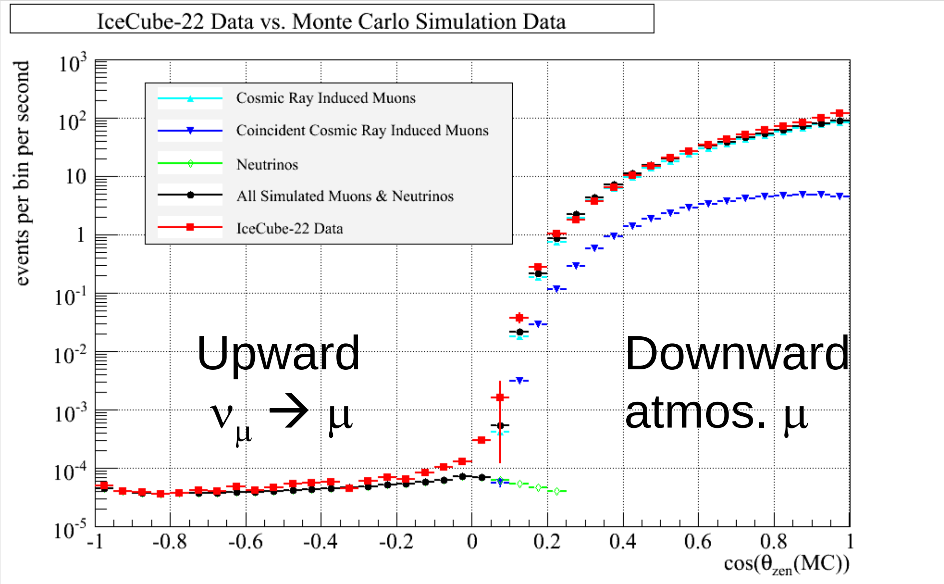


Zone 3, ℓ: +30 to +90, 0.84 sr
Zenith: 150 < θ < 180º

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 $=3.3\times10^{10}$ 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



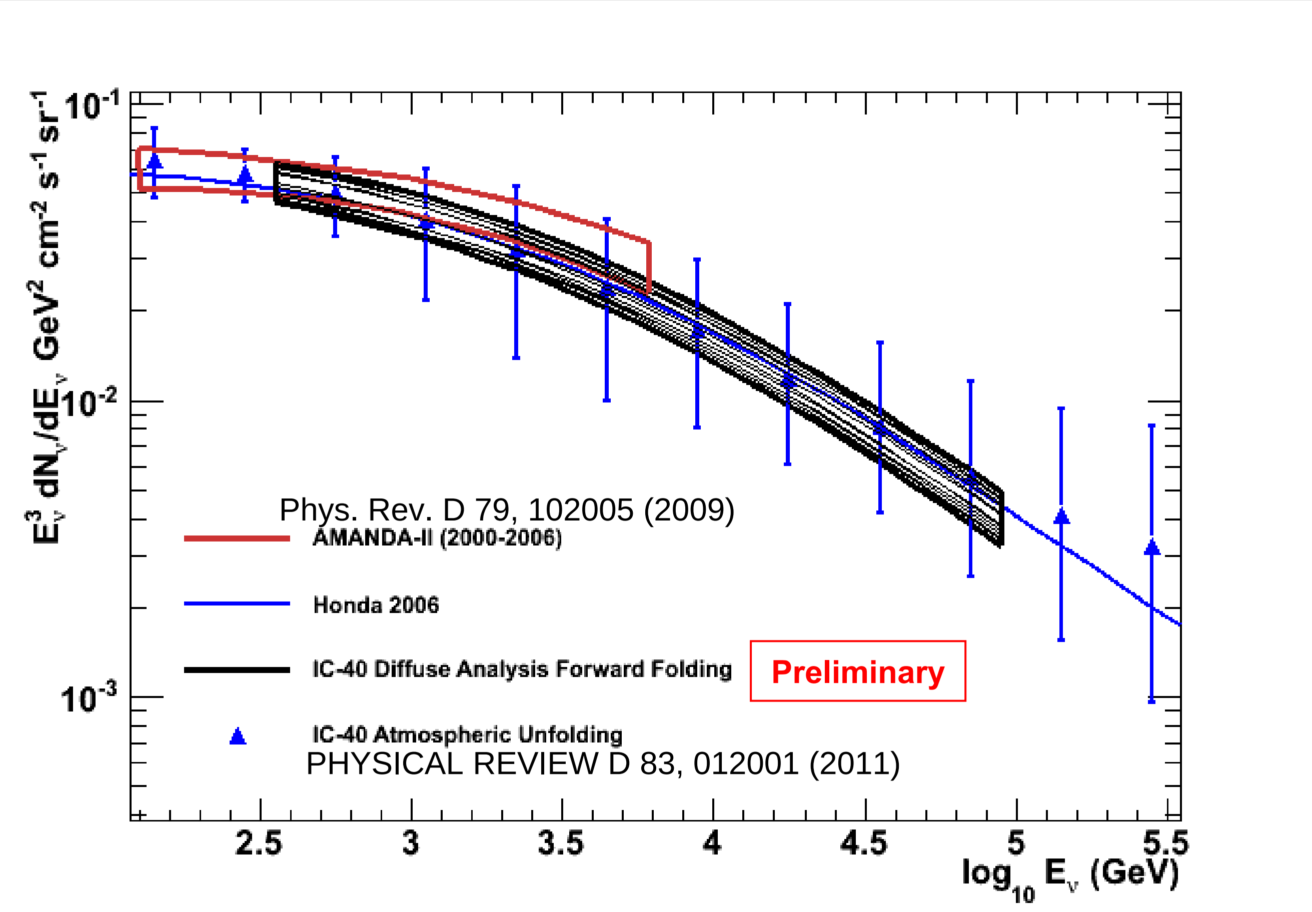
All-sky plot of muons in IceCube-22 from 2007 (P. Berghaus, IceCube, ISVHECRI-2008 arxiv.org/abs/0902.0021)

Atmospheric ν_μ with IceCube-40

Two analyses:

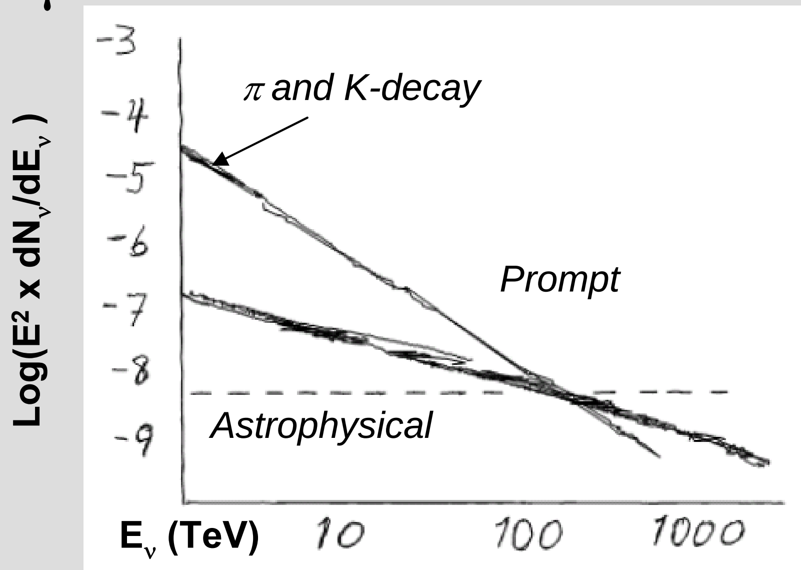
1. Unfolding
2. Forward folding as a by-product of a search for diffuse astrophysical ν

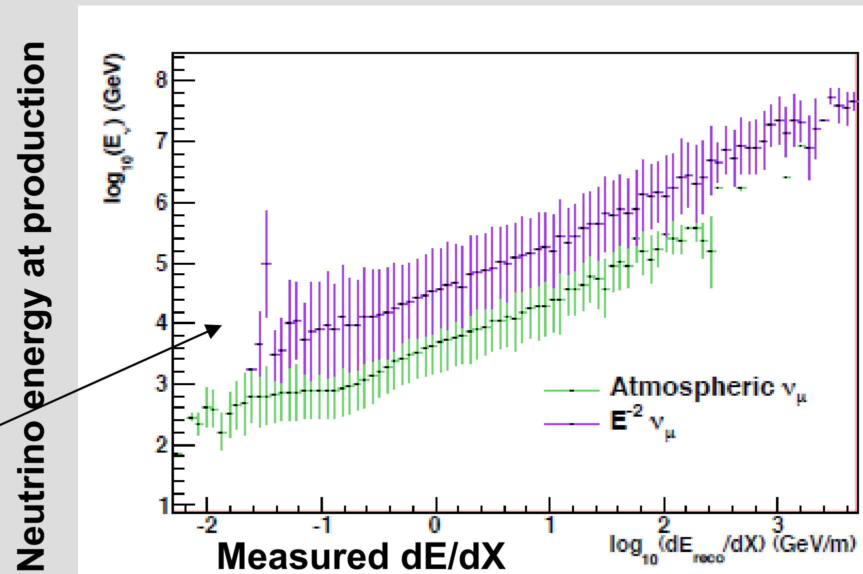
Look in detail at 2



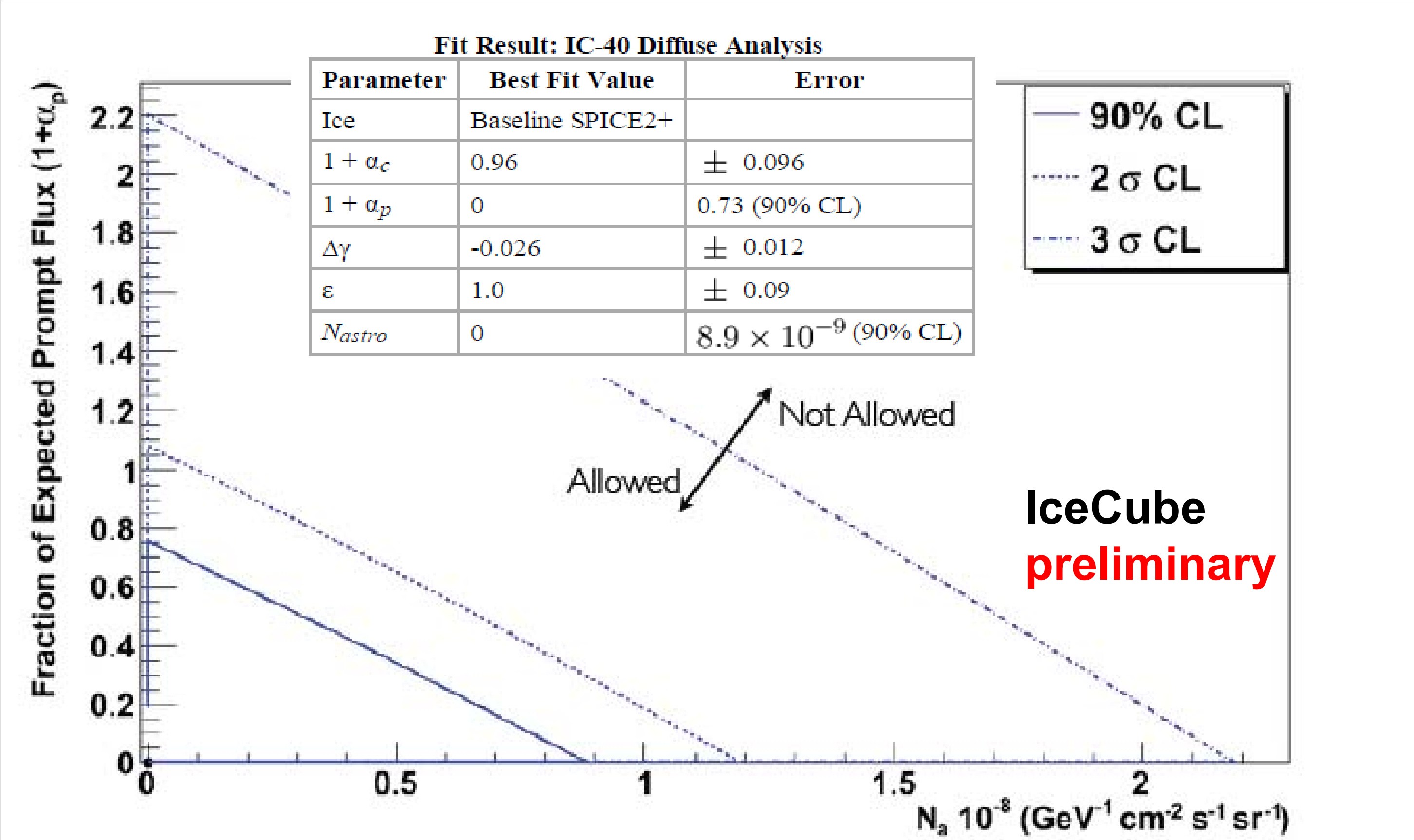
Measurement of ν_μ-induced μ

- 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

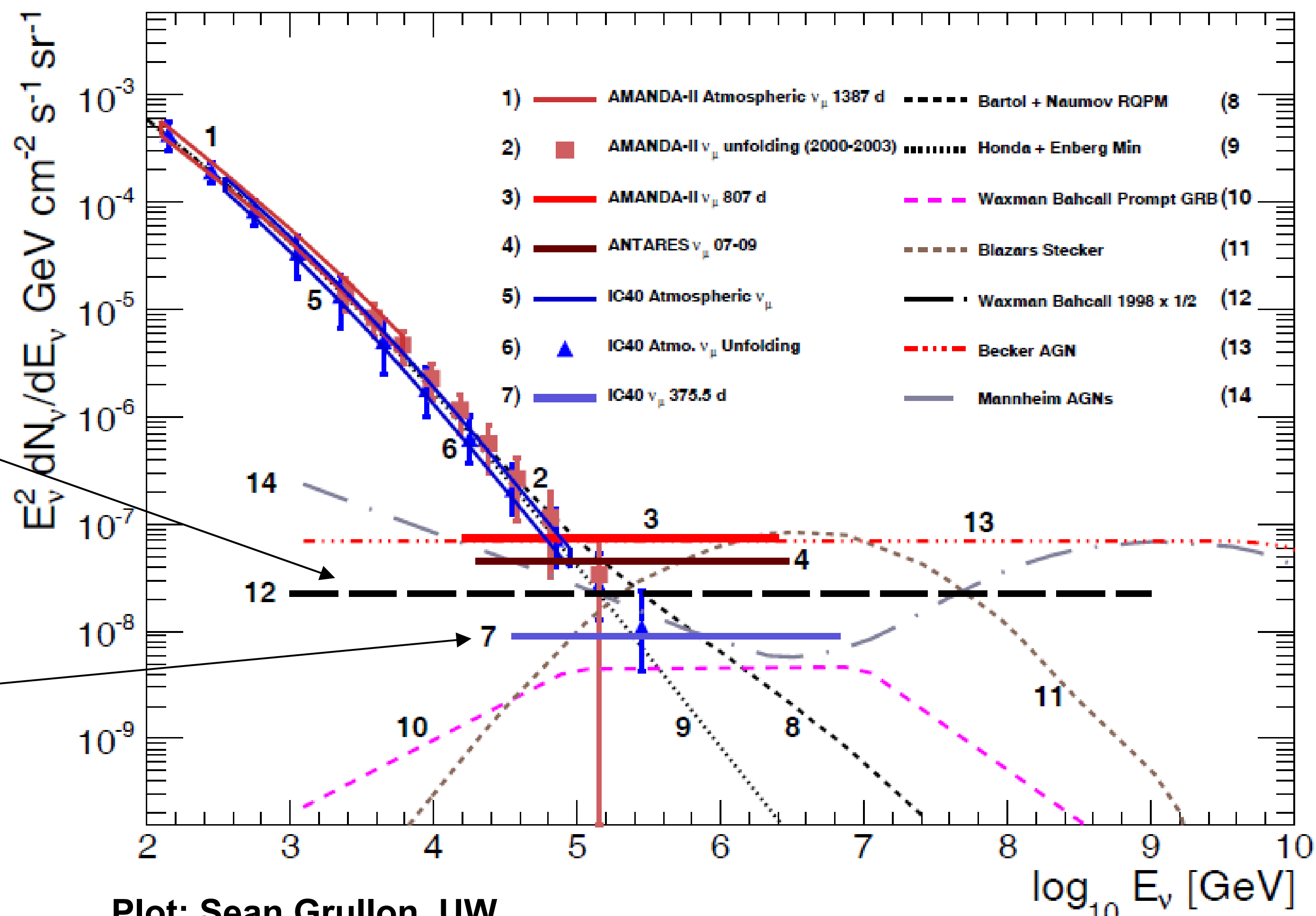
Parameter	Best Fit Value	Error
Ice	Baseline SPICE2+	
$1+\alpha_c$	0.96	$\pm$ 0.096
$1+\alpha_p$	0	0.73 (90% CL)
$\Delta\gamma$	-0.026	$\pm$ 0.012
ε	1.0	$\pm$ 0.09
N_{astro}	0	8.9×10^{-9} (90% CL)

- 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 **preliminary**



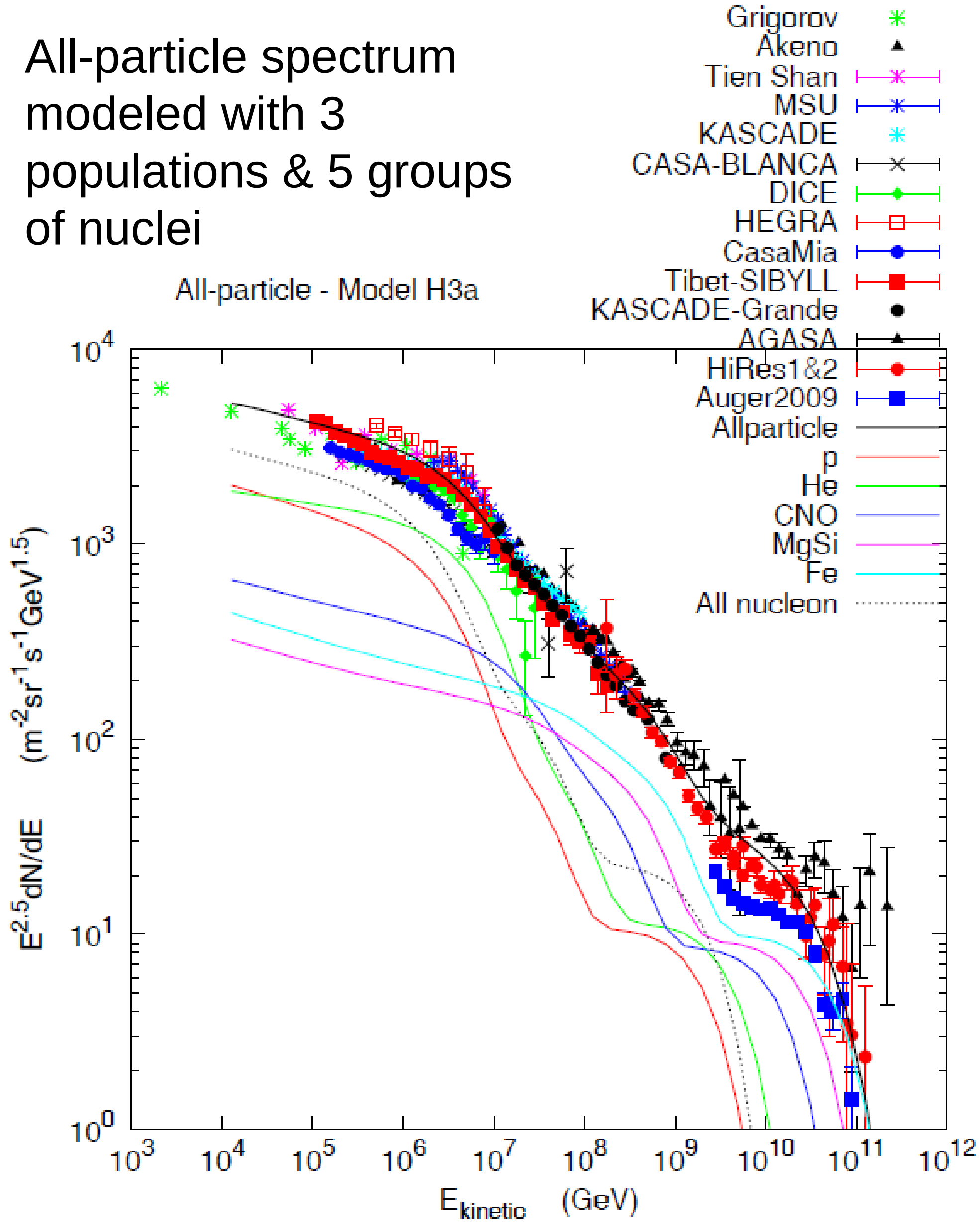
Plot: Sean Grullon, UW

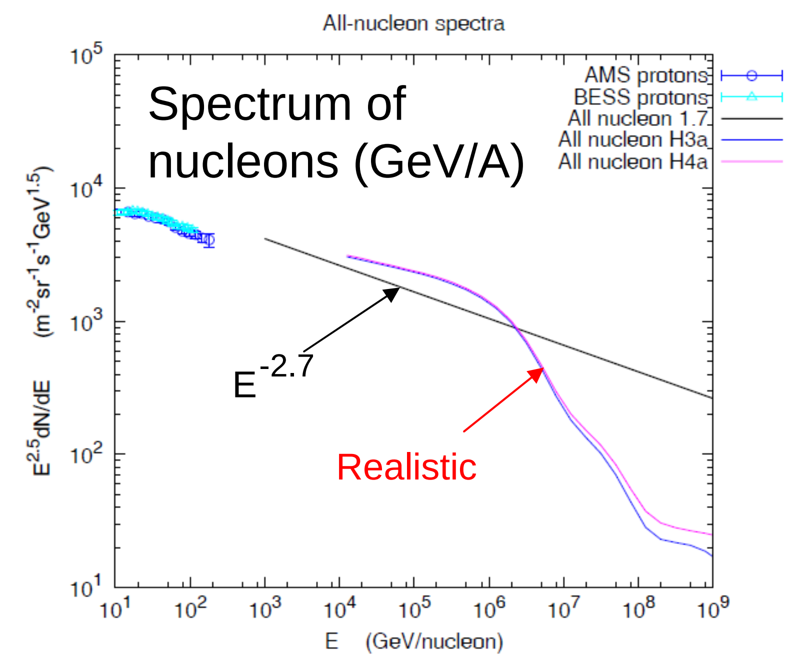
Comments on atmospheric ν results

- 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_ν > 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_ν > 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

Primary spectrum & composition affect atmospheric neutrinos

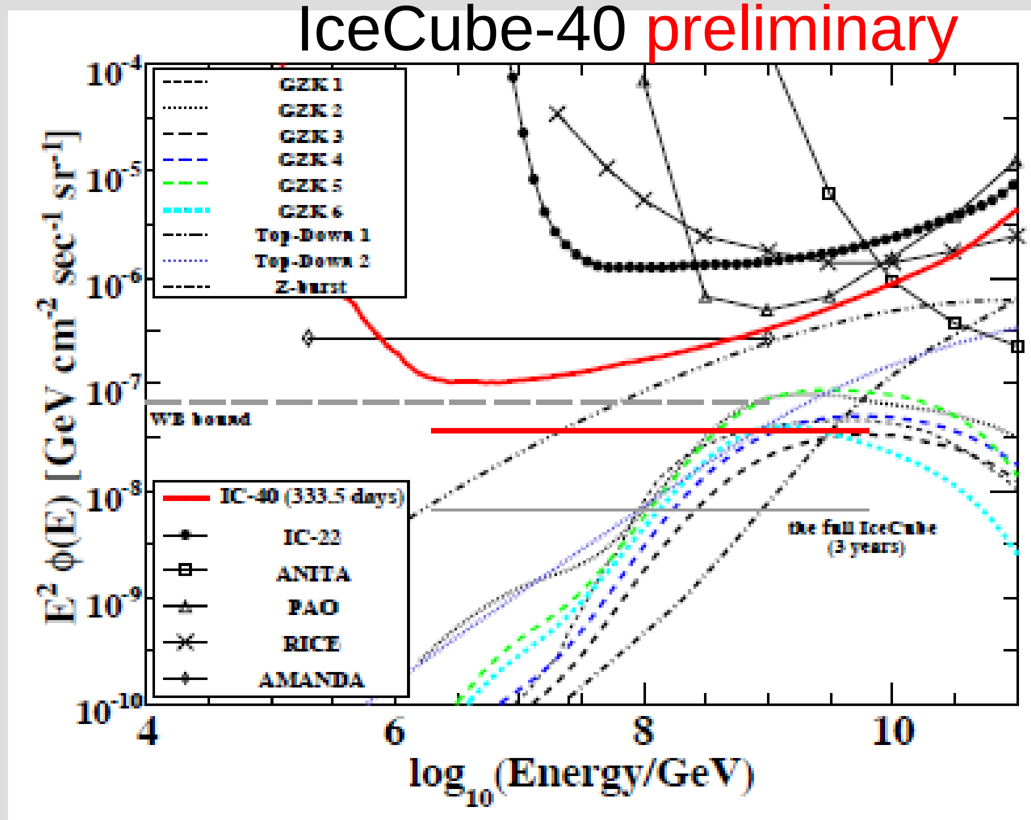
All-particle spectrum modeled with 3 populations & 5 groups of nuclei





Limits on cosmogenic neutrinos

- 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



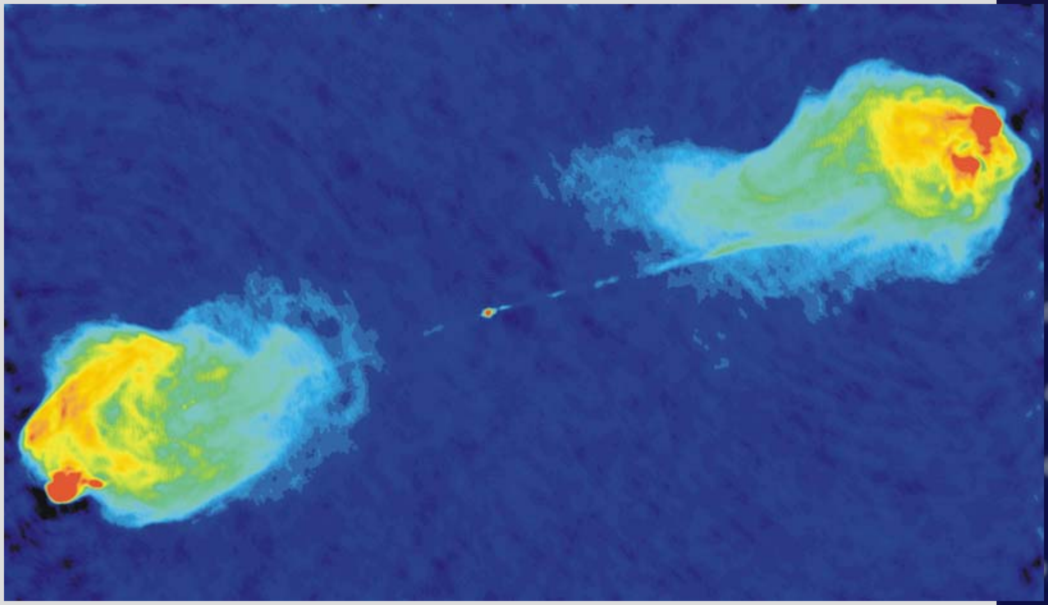
All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Accretion and astrophysical jets

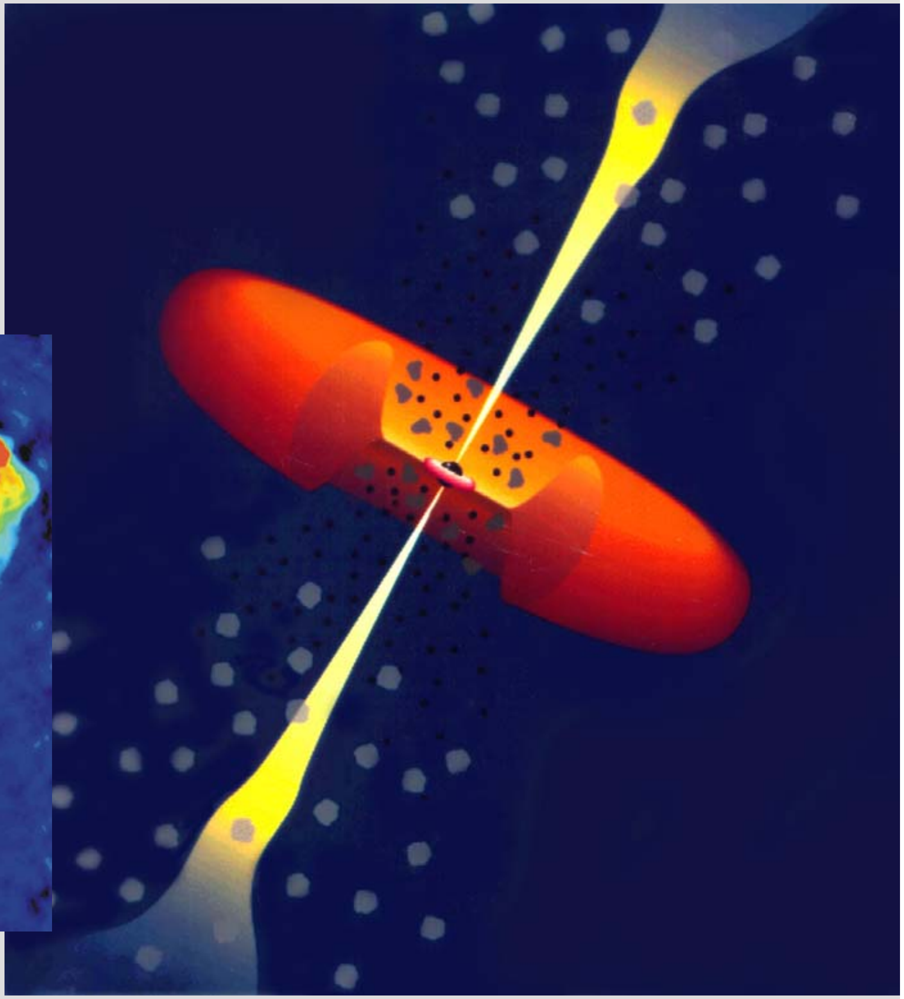
A common phenomenon on both stellar & galactic scales:

Matter falls onto black hole or neutron star driving collimated, relativistic jets perpendicular to the disk

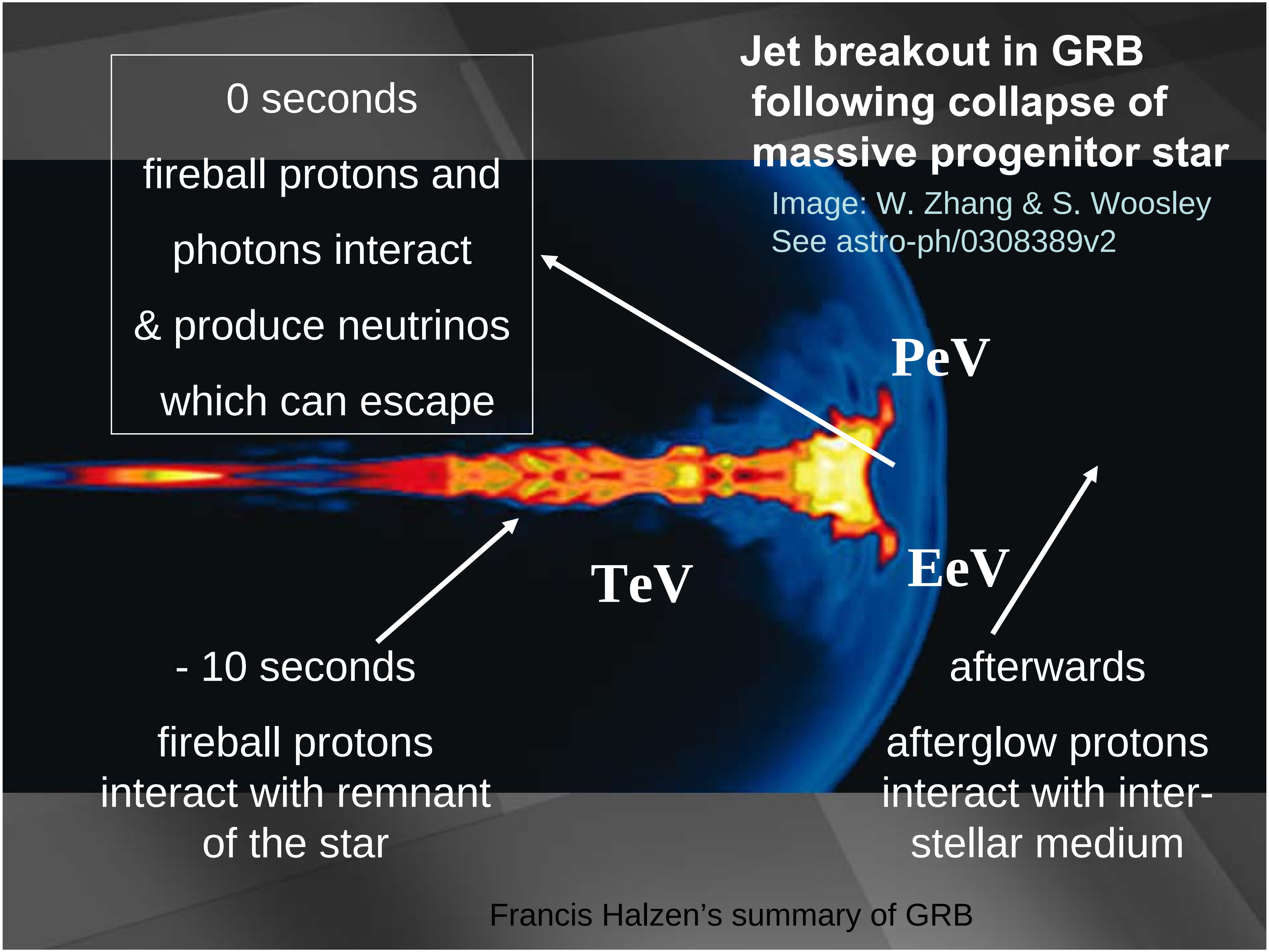
Acceleration can occur both at remote termination shocks and at internal shocks near the central engine



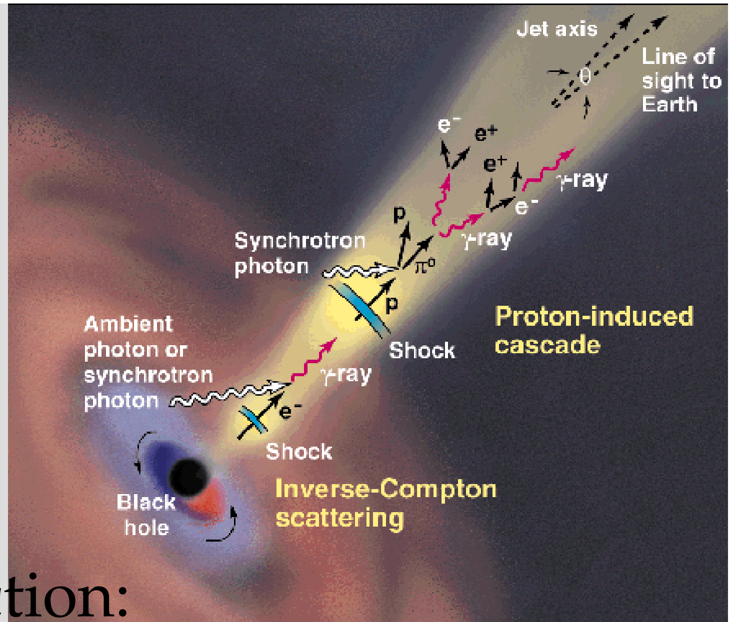
VLA image of Cygnus A
An active galaxy



M. Urry, astro-ph/0312545


Jet breakout in GRB following collapse of massive progenitor star
Image: W. Zhang & S. Woosley
See astro-ph/0308389v2
0 seconds
fireball protons and photons interact & produce neutrinos which can escape
PeV
TeV
EeV
- 10 seconds
fireball protons interact with remnant of the star
afterwards
afterglow protons interact with inter-stellar medium
Francis Halzen's summary of GRB

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
  - Approximate equality of energy content:

    Energy content in neutrinos $\approx$ energy in UHECR

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

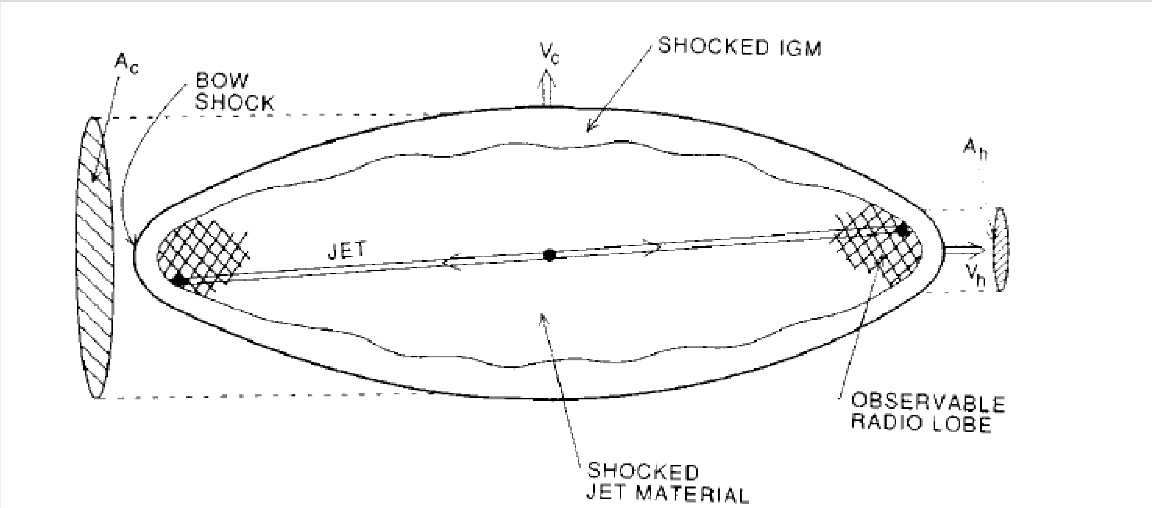
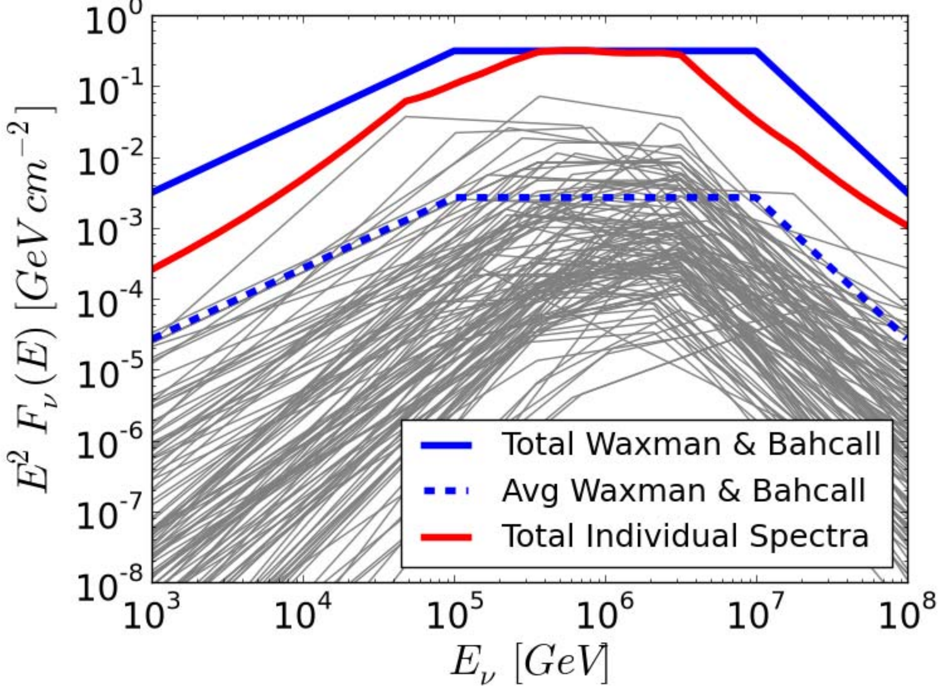


Diagram from A.Ferrari, Ann Revs A&A 36 (1998) 539

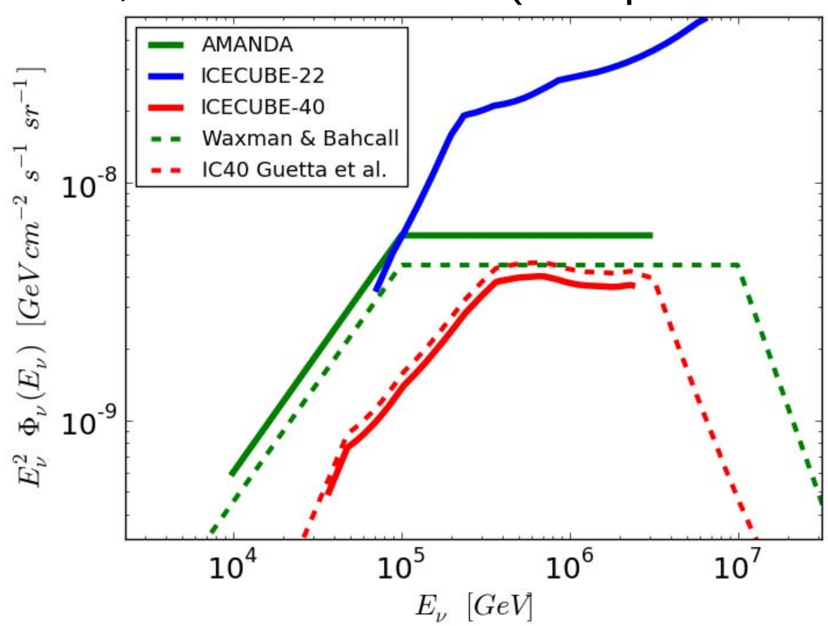
Searches for ν from GRB

Look for correlation with 117 GRBs with declination > 0 during IC40 run
Compare to expectation for each burst from model of Guetta et al.,
Astropart. Phys. 20 (2004) 429

2.8 events expected, none detected.

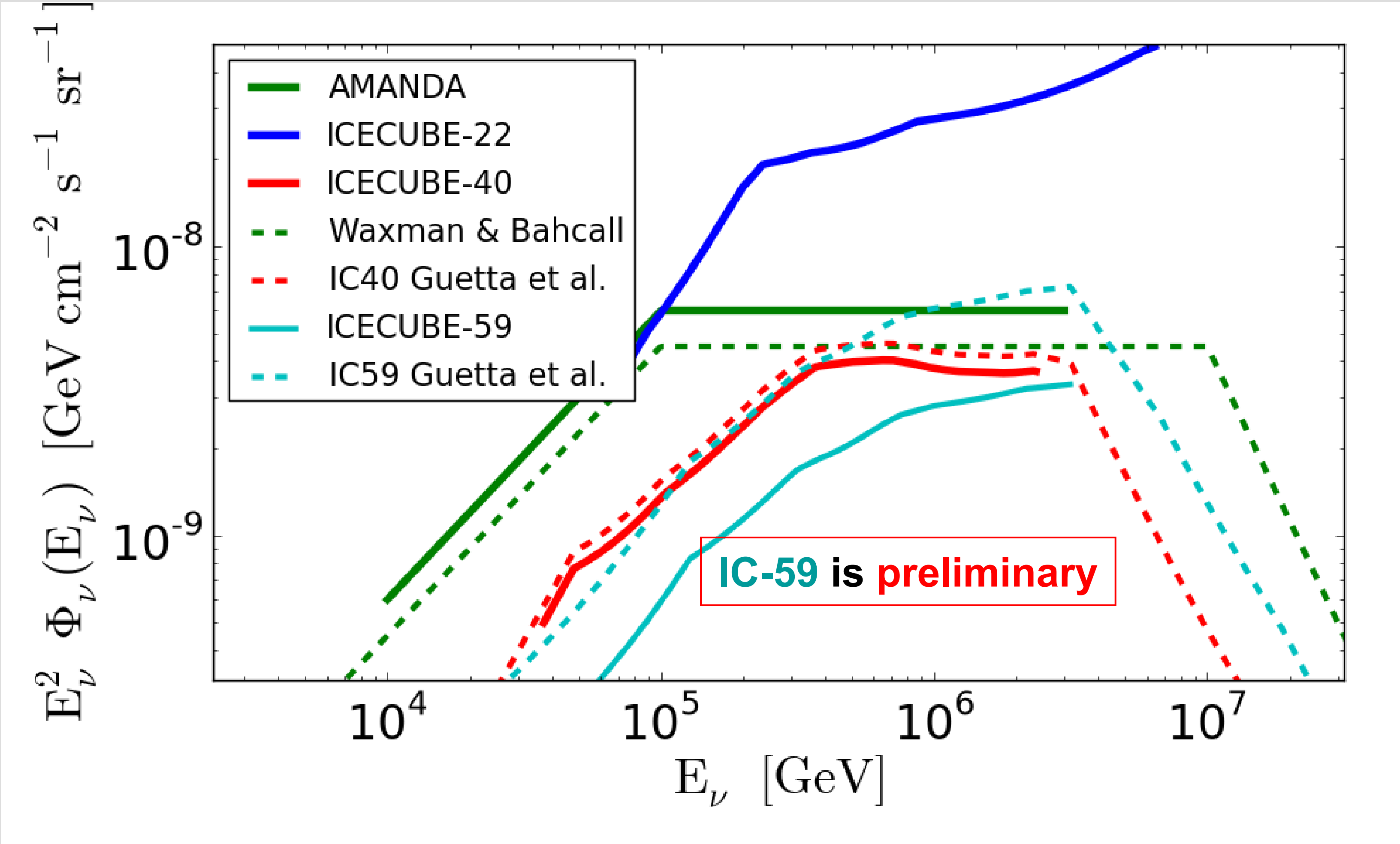


IceCube, arXiv:1101.1448 (accepted in PRL)

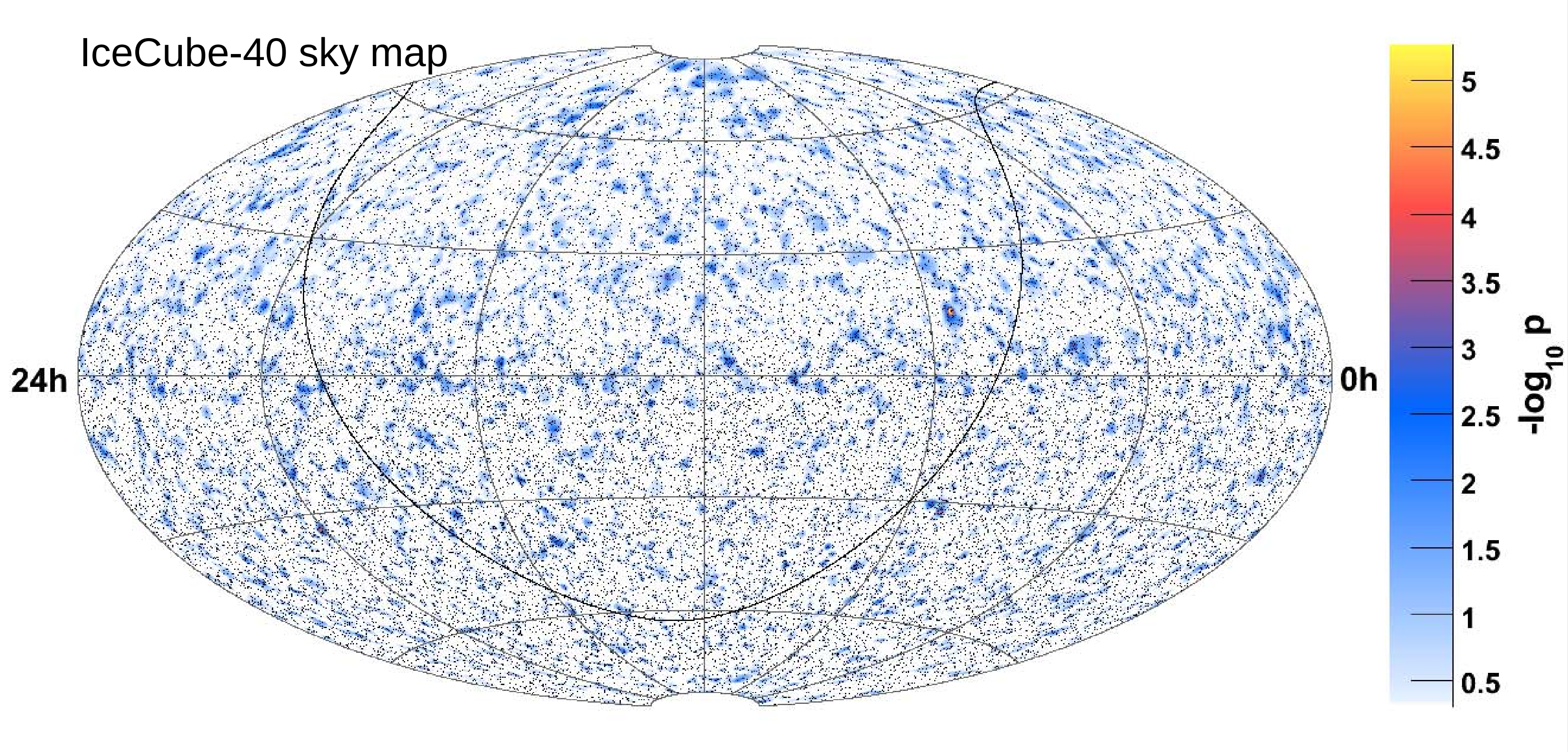


Model-independent search for ν within ±2.7 hrs of GRB is also negative.

59 strings 2009-10 (preliminary)
109 GRBs searched, 7 expected, 0 found



All-sky point source (IC40)



Unbinned likelihood analysis using energy and angular resolution of each event
arXiv:1012.1633 (to appear in Ap.J.)

Search for specific sources selected on the basis of photon activity

- Galactic sources in Northern sky
  - Expect cutoff ~ 100 TeV; use upward ν only
  - E.g. SNRs Cas A & IC433; Geminga, Cygnus…
- Galactic center (declination = -29^{o})
- Extra-galactic sources
  - 21 in Northern sky; 9 in Southern sky inc. Cen A
- 2.3 σ hot spot from IC-22

Neutrino Point Source Flux Limits

IceCube 40

Further Analyses:

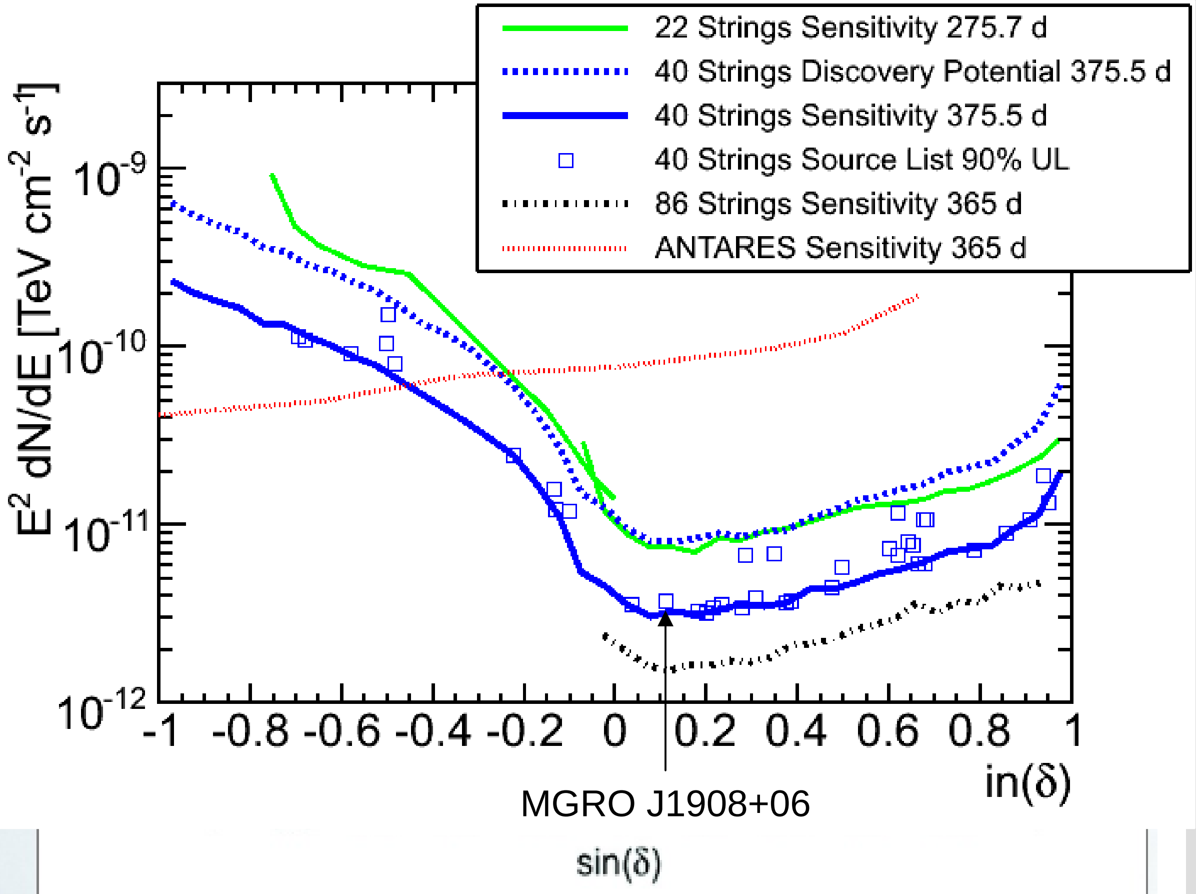
Flare Searches

Multi-Wavelength

Target-of-Opportunity

Optical Follow-Up

Source Stacking



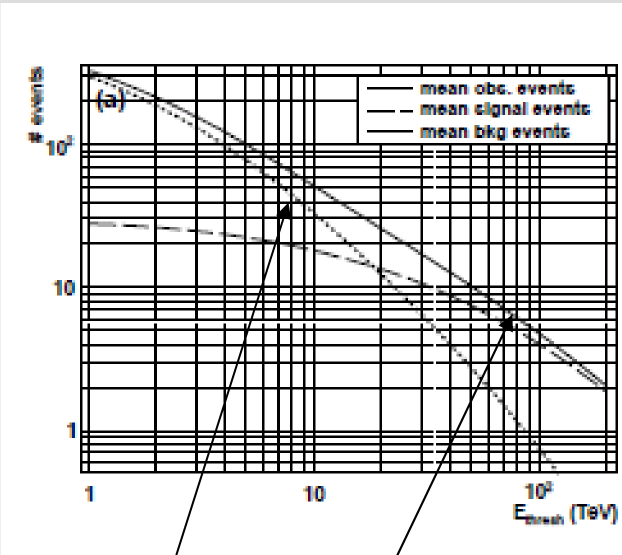
Note: IceCube energy threshold is set very high for Southern sources to reduce background of atmospheric muons. Antares is complementary.

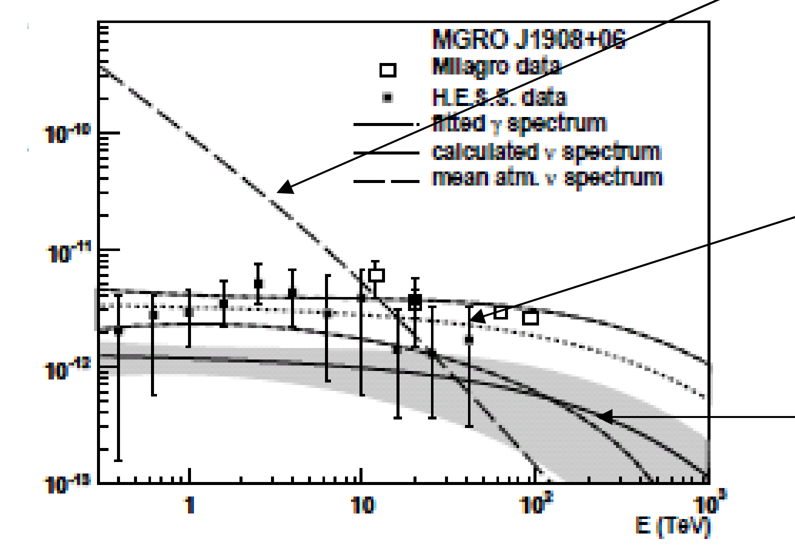
Galactic sources associated with SNR

Number of events

Flux

Atmospheric ν_μ





γ-rays

$\nu_\mu + \bar{\nu}_\mu$

Background

Signal

Halzen, Kappes, O'Murchadha
PR D78 (2008) 063004

Few events per year

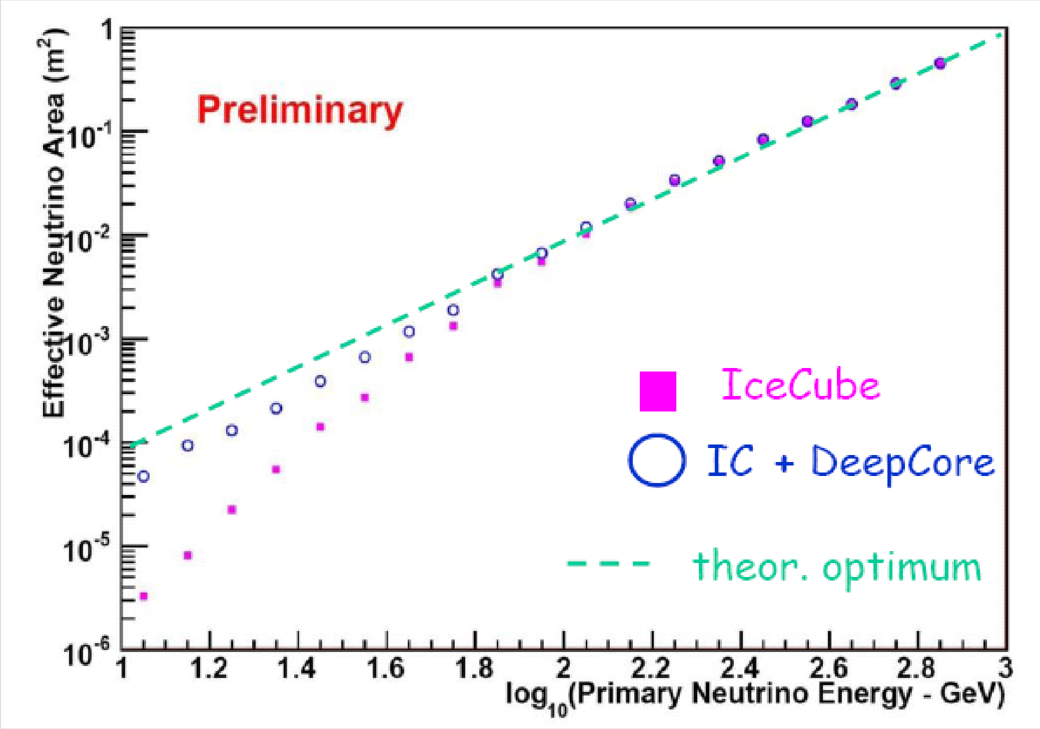
Several years to establish ν signal

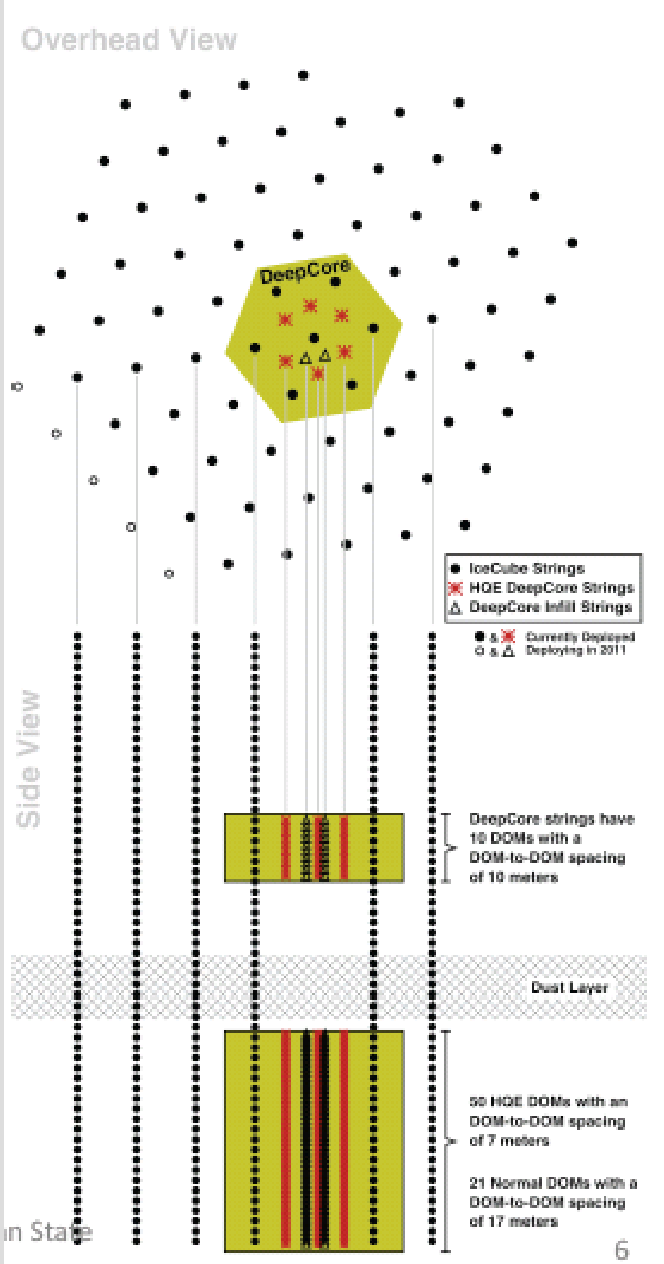
DeepCore subarray

78 standard strings plus

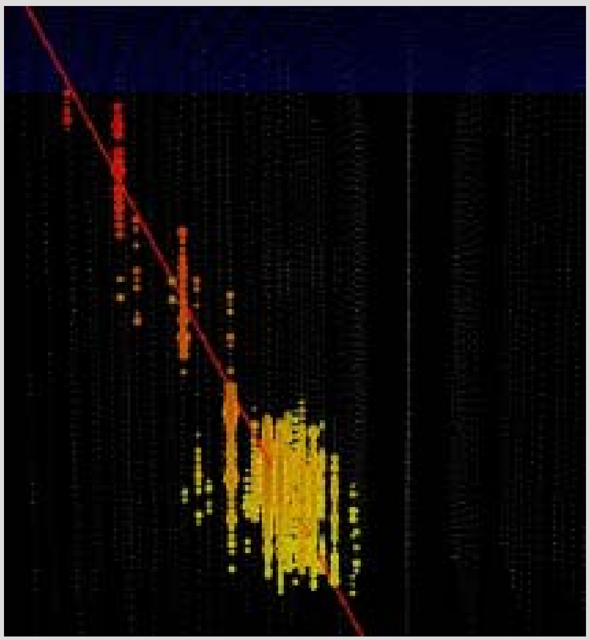
8 more densely instrumented cables in the deep center of IceCube

- >15 megaton fiducial volume
- E_{μ} threshold ~ 10 GeV
- Main IceCube used as veto



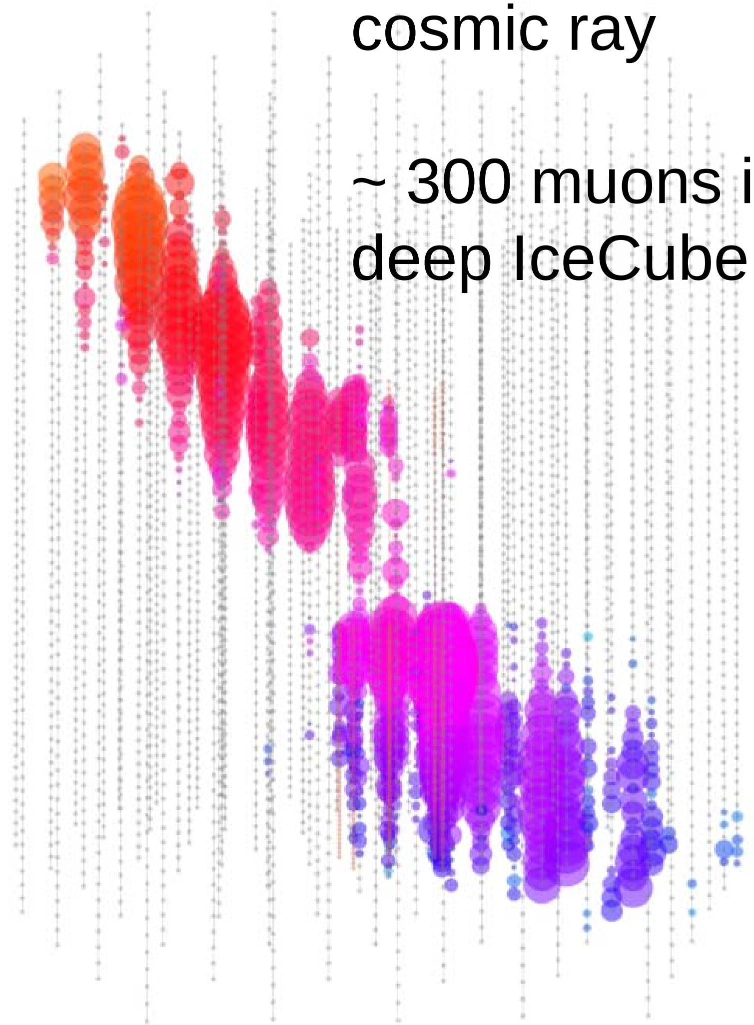


IC-79 events illuminate deep core



~100 PeV primary cosmic ray

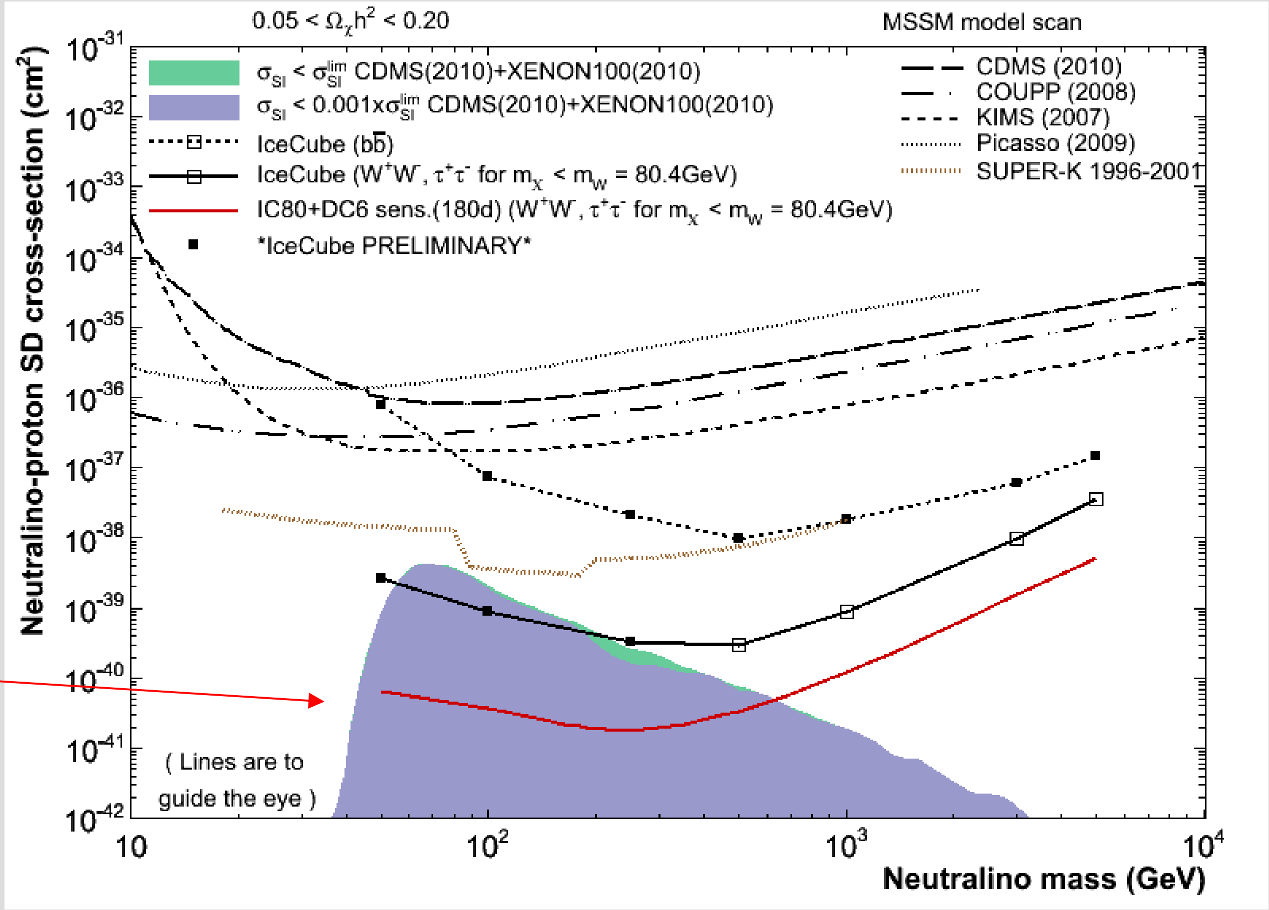
~ 300 muons in deep IceCube



Indirect dark matter search: WIMP annihilation in the Sun

Limits depend on WIMP mass & decay mode
PRL 102 (2009) 201302

Sensitivity with full IceCube including Deep Core

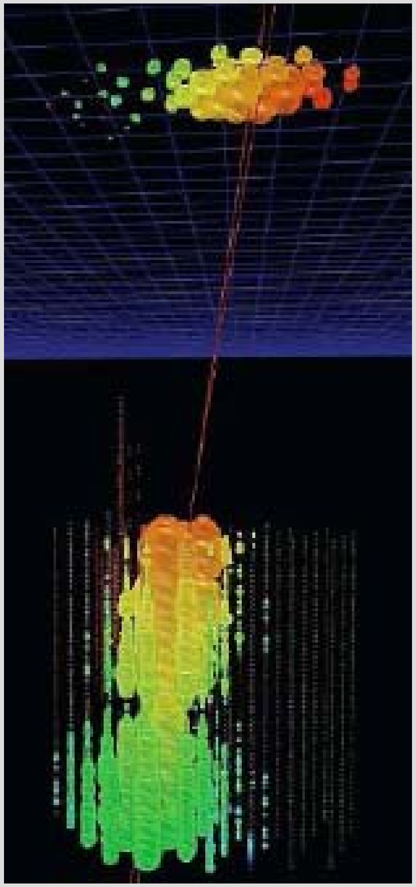


Related science with IceCube

- 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

- 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
- Dark Matter Ice – two pilot scintillators deployed at 2500 m in IceCube holes, December, 2010


Photo by Freija Descamps,
March 6, 2011