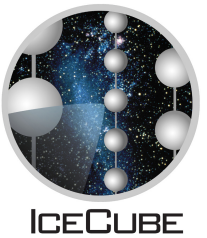


The IceCube Neutrino Observatory

Status and Recent Results

Markus Ahlers,

on behalf of the IceCube Collaboration

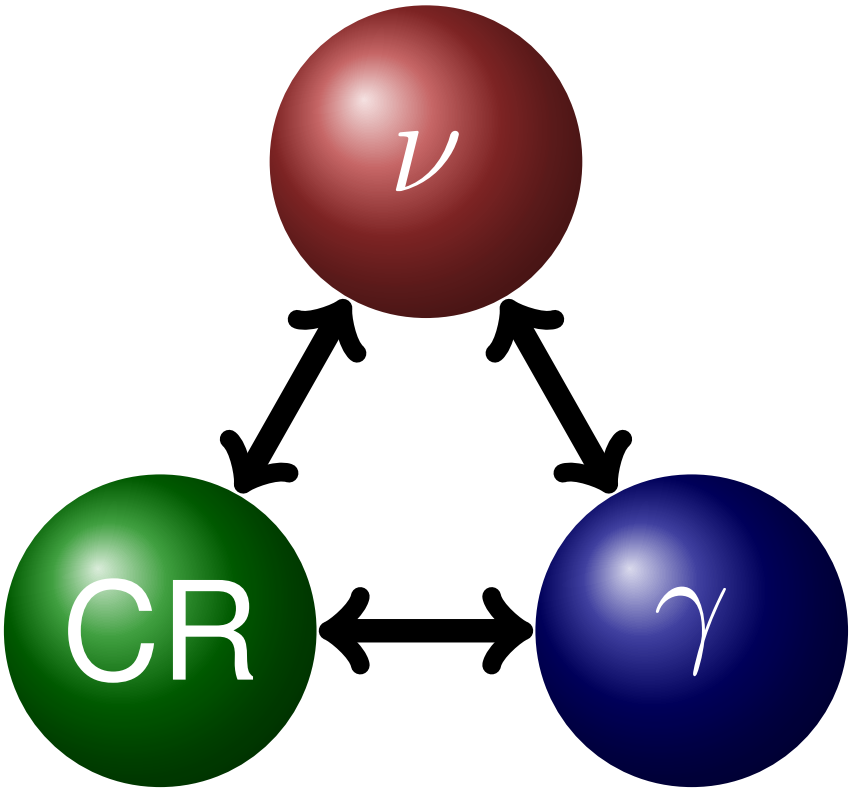
WIPAC & Department of Physics, UW-Madison

Very High Energy Phenomena in the Universe

La Thulie, March 12, 2013

Multi-messenger paradigm

- Neutrino astronomy:
  - ✔ **natural extension**: "optical" + "multi-wavelength" + "multi-messenger"
  - ✔ closely **related** to cosmic rays (CRs) and γ-rays
  - ✔ **smoking-gun** of CR sources
  - ✔ **weak interaction** during propagation
- Challenges:
  - ✘ **low** statistics
  - ✘ **large** backgrounds



Multi-messenger paradigm

- pion production in CR interactions with ambient radiation & matter

$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

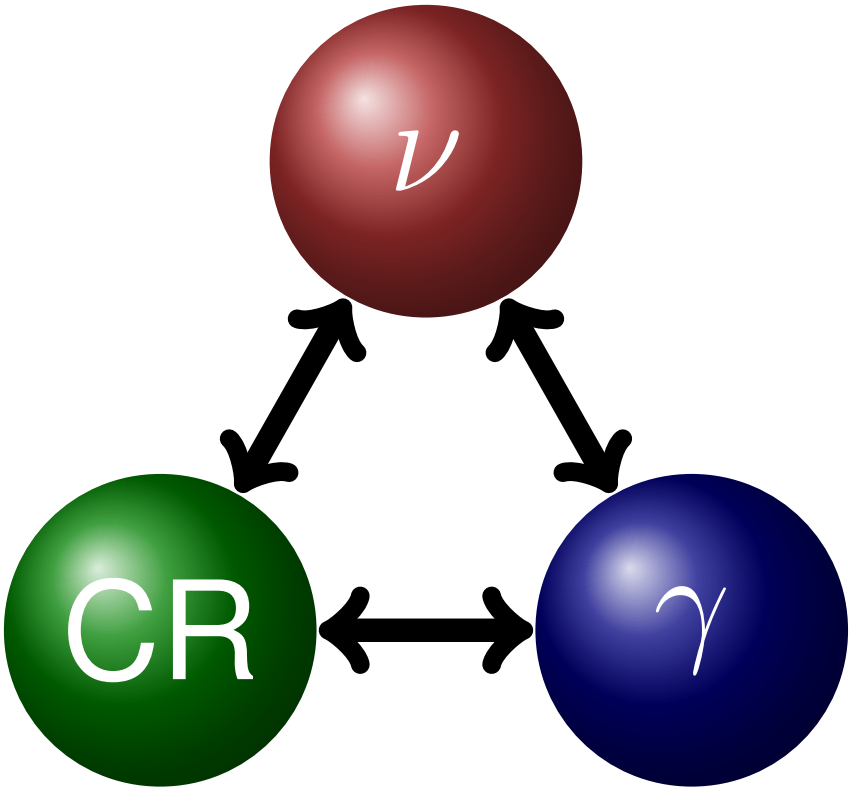
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction via optical depth:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



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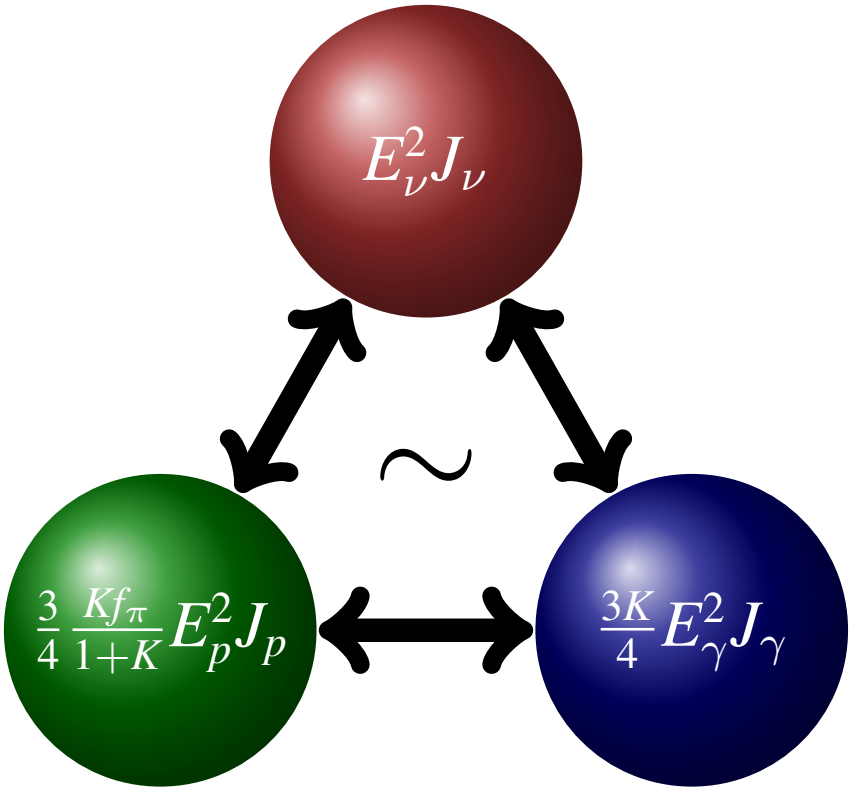

($E_\nu^2 J_\nu \sim$ energy density ω)

Multi-messenger paradigm

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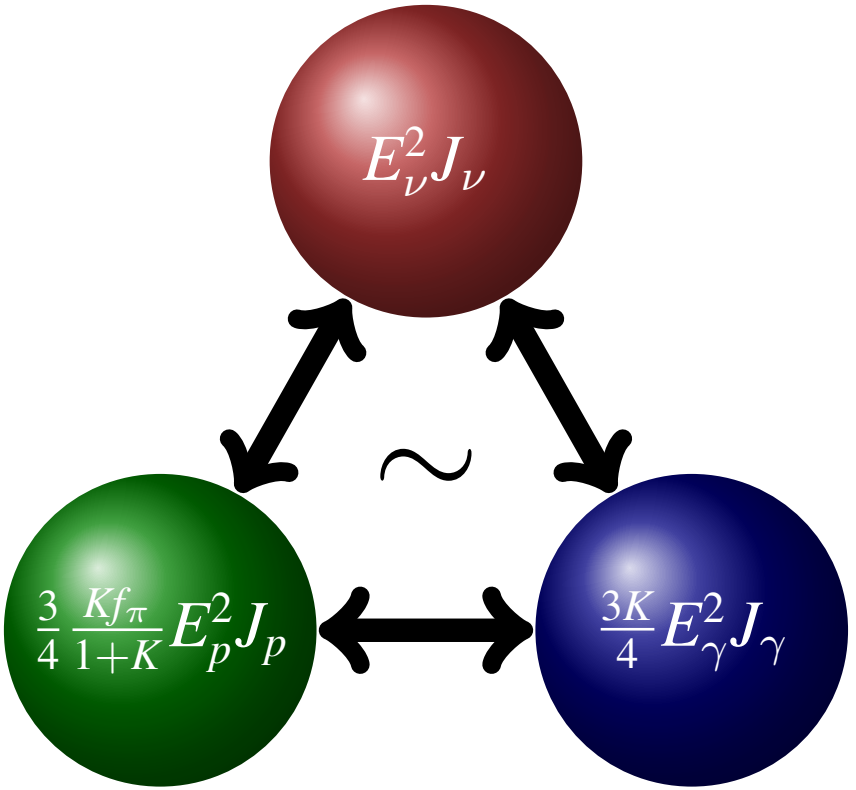

$$\omega_{\gamma-\mathrm{bgr}} \simeq 6 \times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\mathrm{UHECR}} \simeq 1 \times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\nu_{\mathrm{all}}} \lesssim 2 \times 10^{-8}\ \mathrm{eV/cm^3}$$

High-energy neutrino detection

- High energy neutrino collisions with nuclei are **rare**.

➜ Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media.

back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

- **flux of neutrinos** : $\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5 \mathrm{yr}}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-33} \mathrm{cm}^2$
- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

➜ **rate of events** :

$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

High-energy neutrino detection

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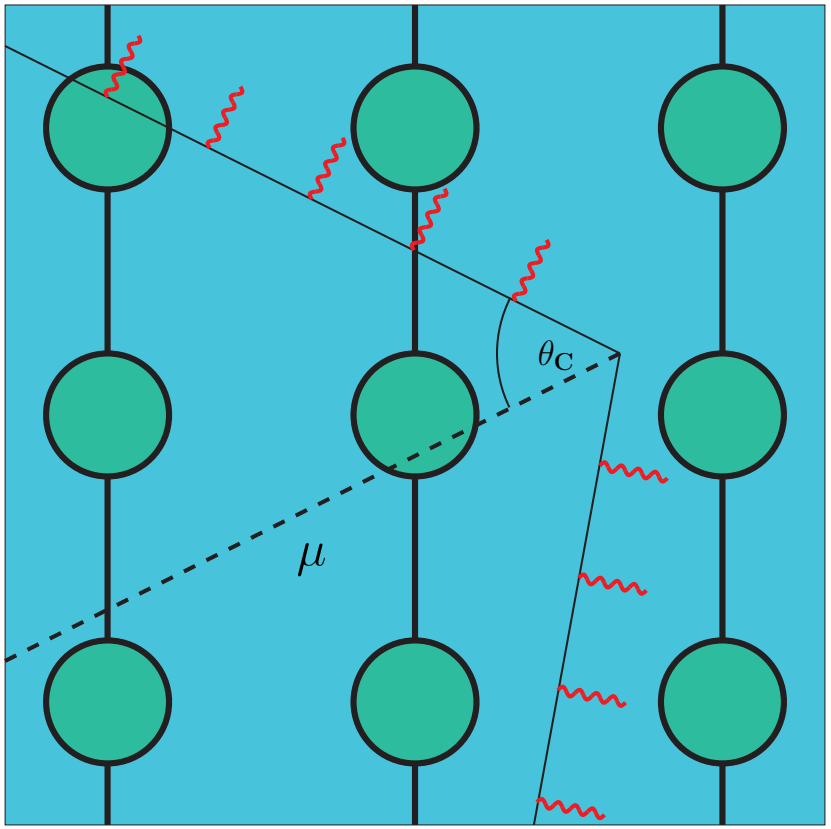
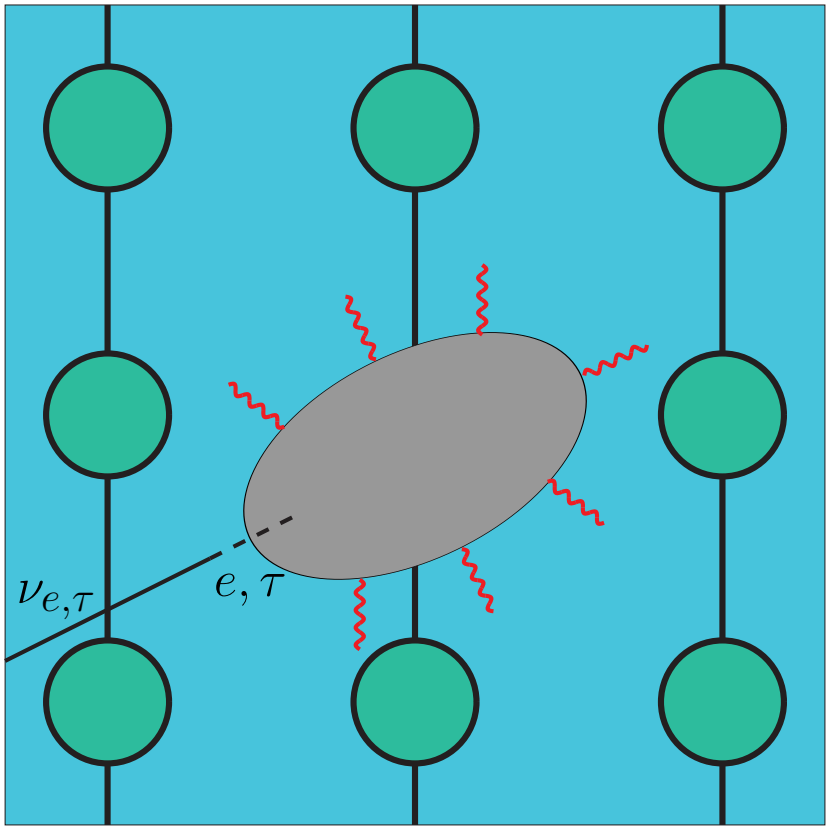
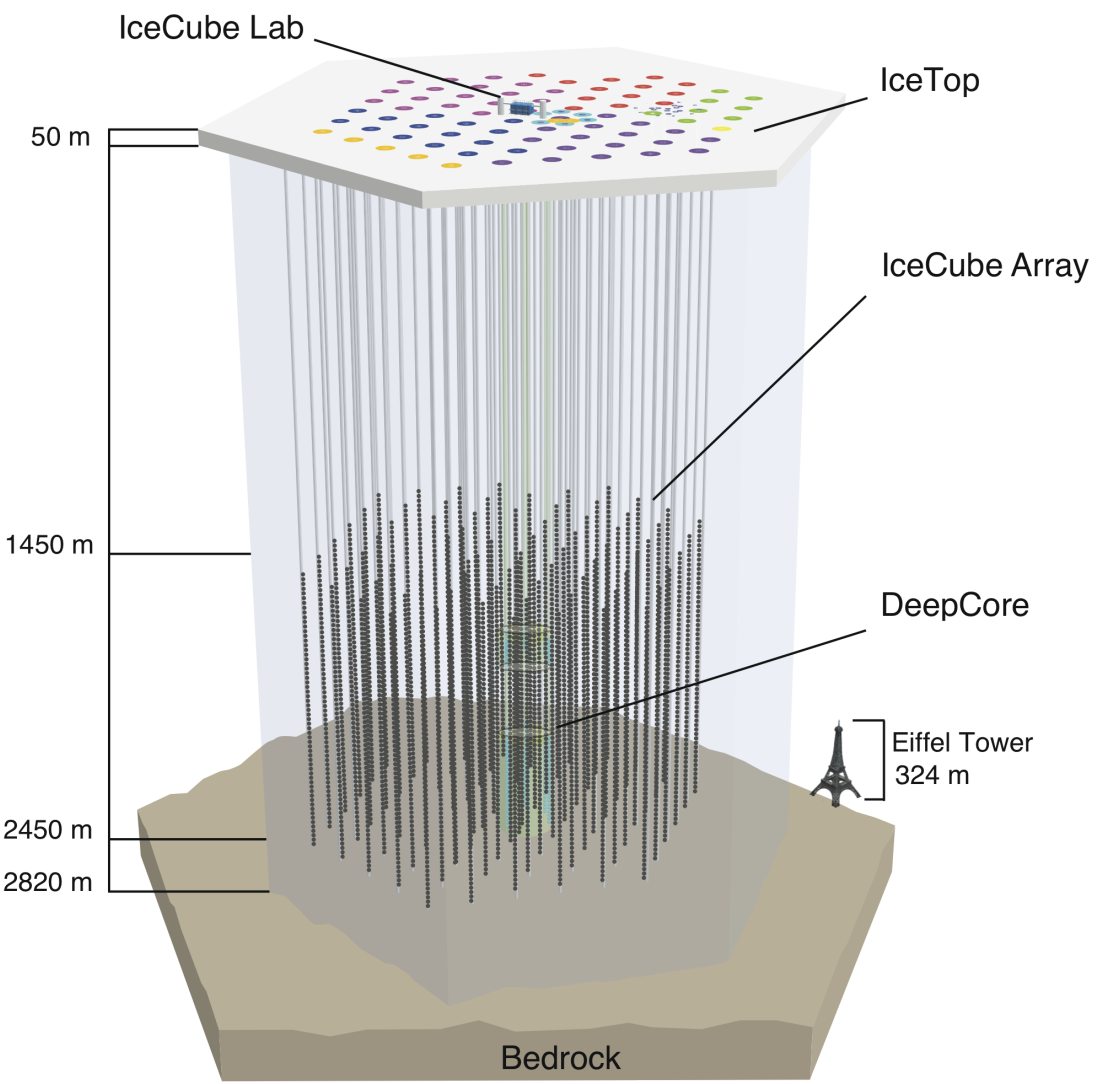
➜ Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media.



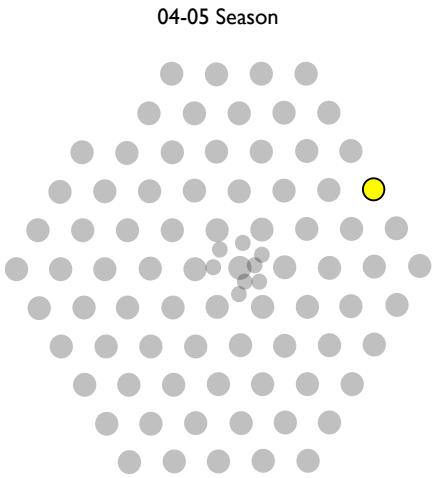


The IceCube Observatory

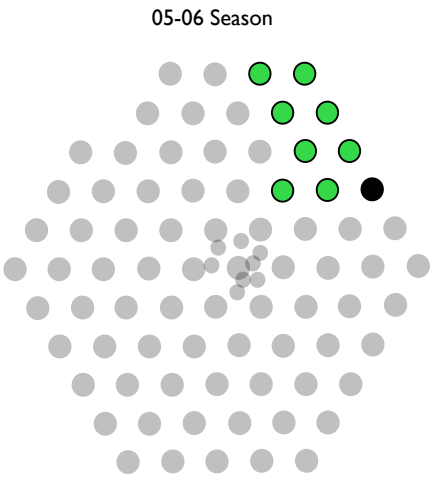


- price tag: 279 million USD
- **78 IceCube strings**
  125 m apart on triangular grid
- 60 digital optical modules (DOMs) per string
- 2 days to drill a hole; 18,000 l fuel consumption
- 1/2 day string deployment; 7 days to freeze-in
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- surface 2,300 meters above sea level (680 g/cm^2)

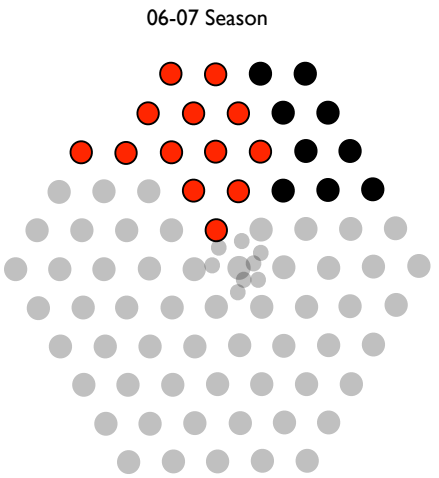
The IceCube Observatory



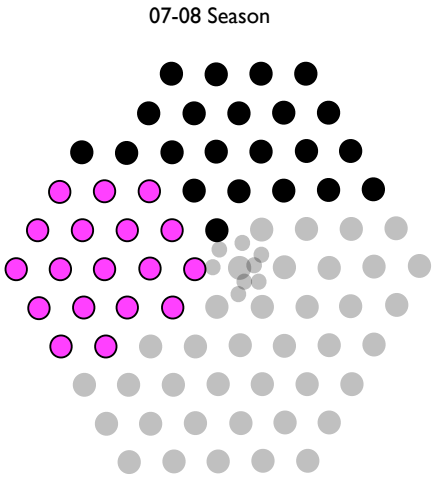
IC-1(IT-4)



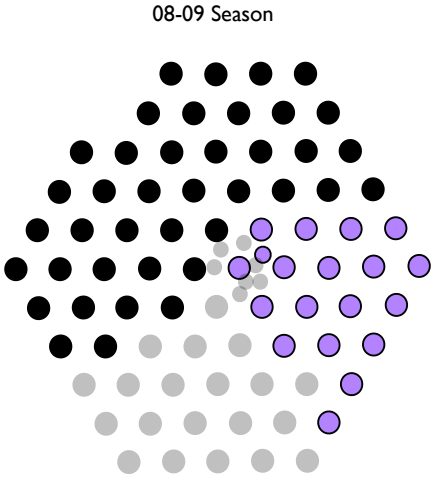
IC-9 (IT-16)



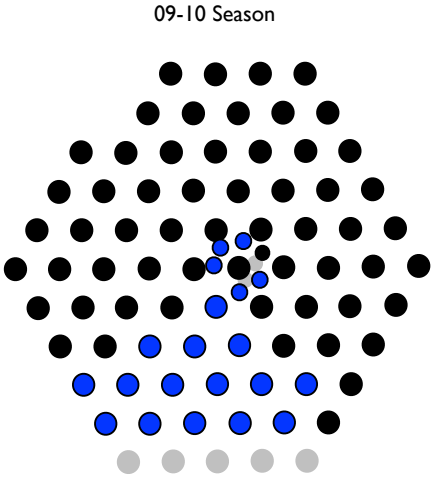
IC-22 (IT-26)



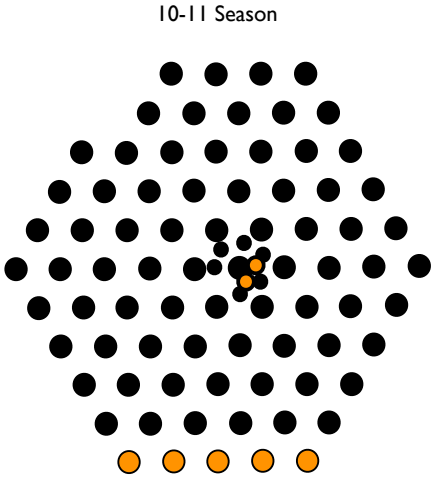
IC-40 (IT-40)



IC-59 (IT-59)



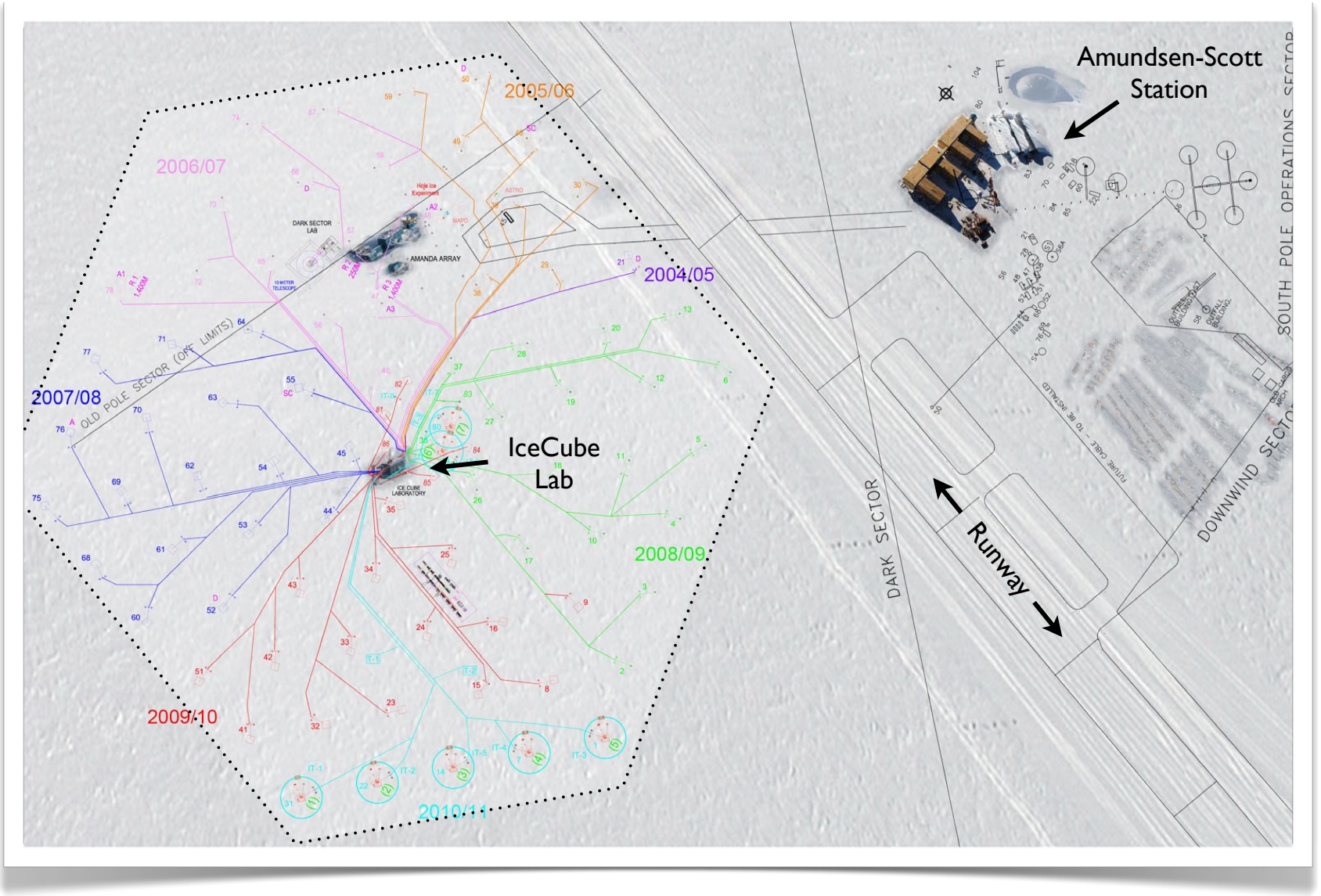
IC-79 (IT-73)



IC-86 (IT-81)

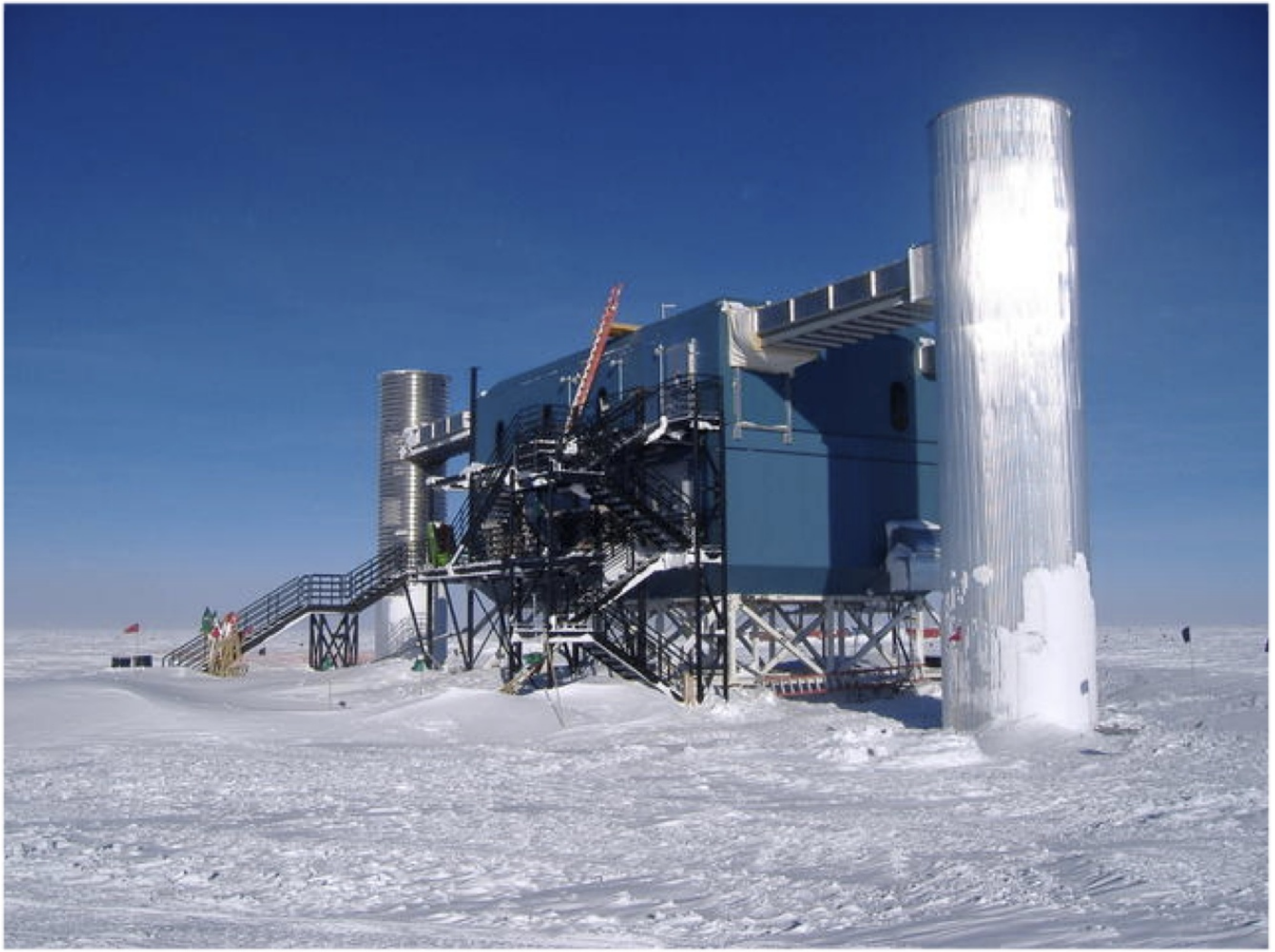
The IceCube Observatory

The IceCube Observatory



Area overview

The IceCube Observatory



IceCube Lab

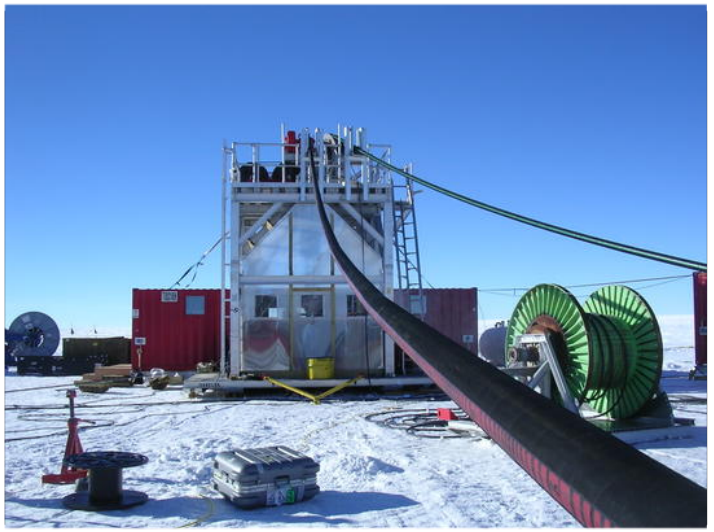
The IceCube Observatory

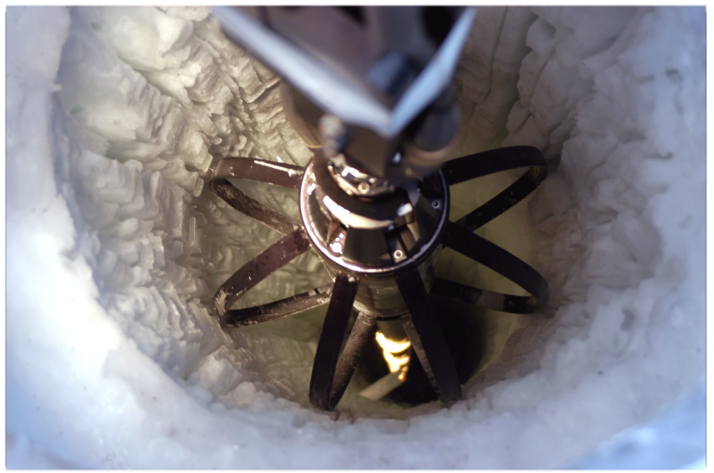
Drilling with new IceTop tanks

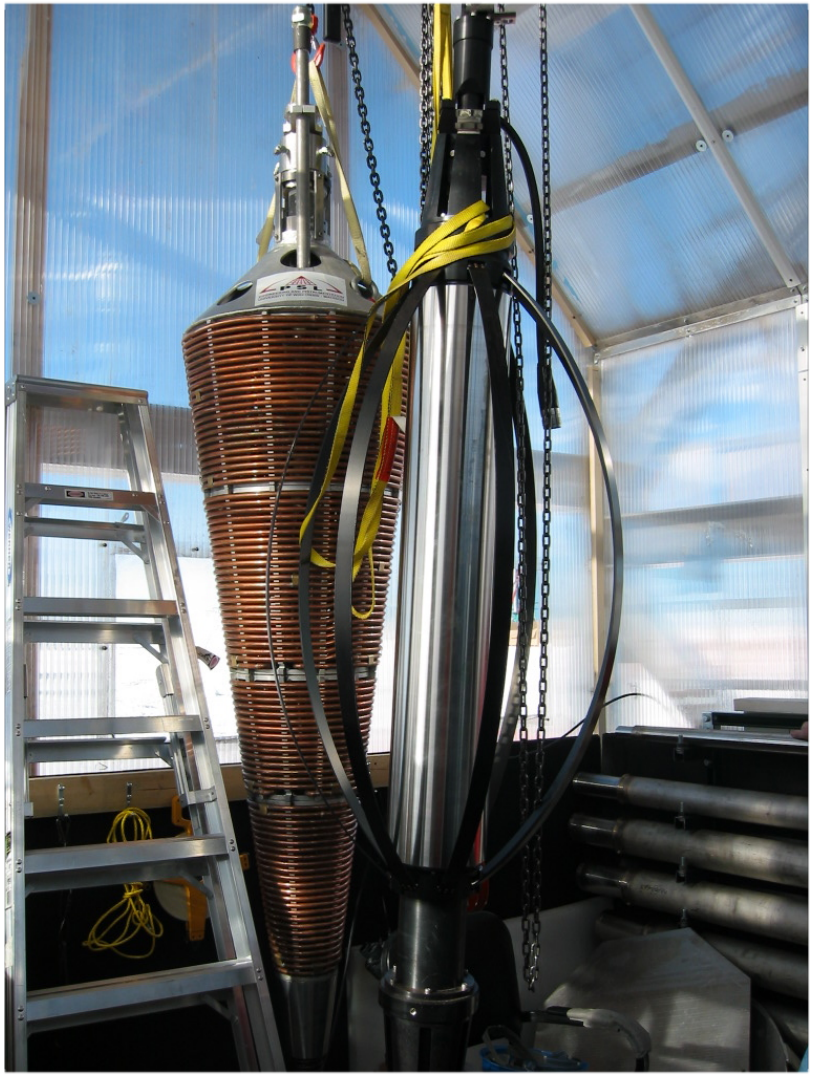
The IceCube Observatory

Inside an IceTop Tank

The IceCube Observatory

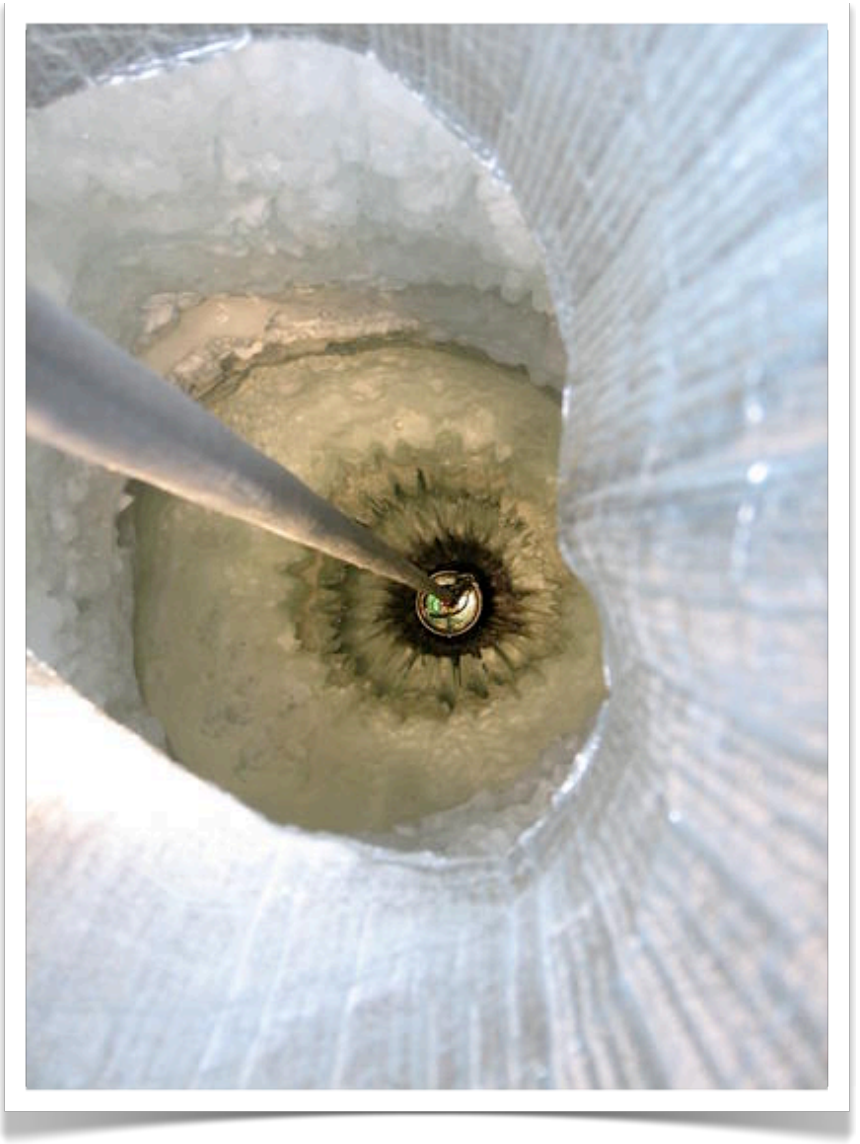






Firn & Ice Drilling

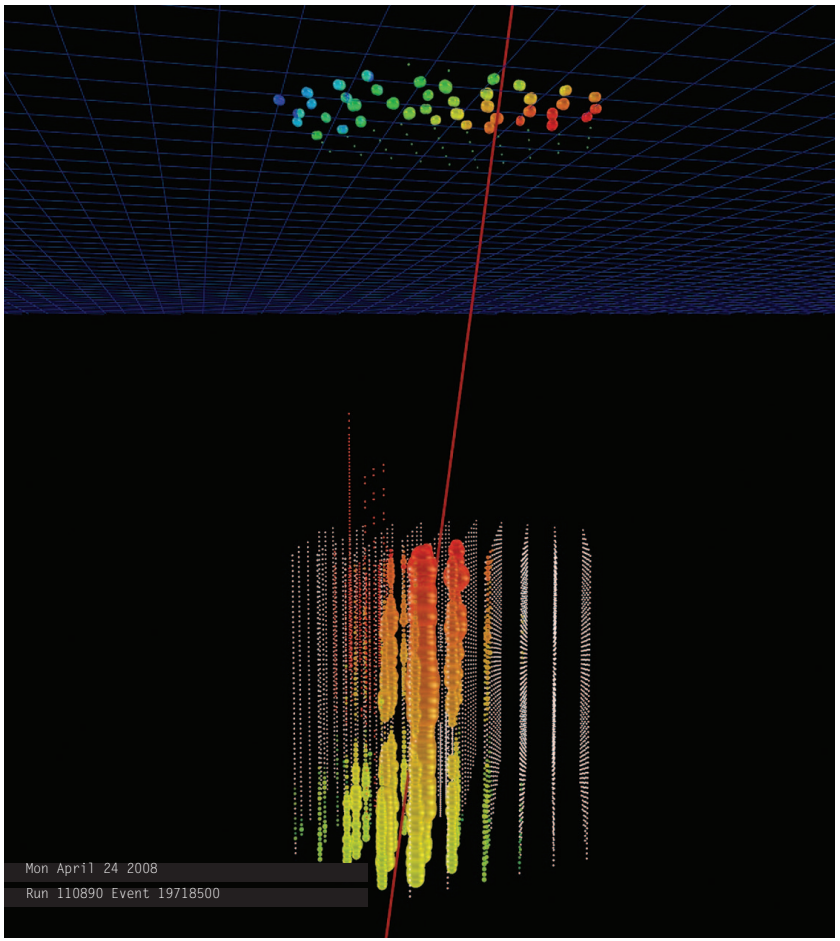
The IceCube Observatory



String & Optical Module

IceCube at work

The **individual and combined results** of IceCube, DeepCore and IceTop and the unique geographical location allows for a wide scientific program:



- atmospheric neutrino fluxes and oscillations
- diffuse high-energy neutrino fluxes
- point source fluxes
- cosmic ray flux in the knee region
- CR anisotropies in the Southern hemisphere
- CR composition measurements
- indirect dark matter detection
- galactic supernova
- exotic signals
- ...

Atmospheric neutrino flux and diffuse limit

- high-energy atmospheric ν_μ/ν_e-spectrum as seen by **IC-40** & **IC-79/DC**

  [IceCube'11,'12]

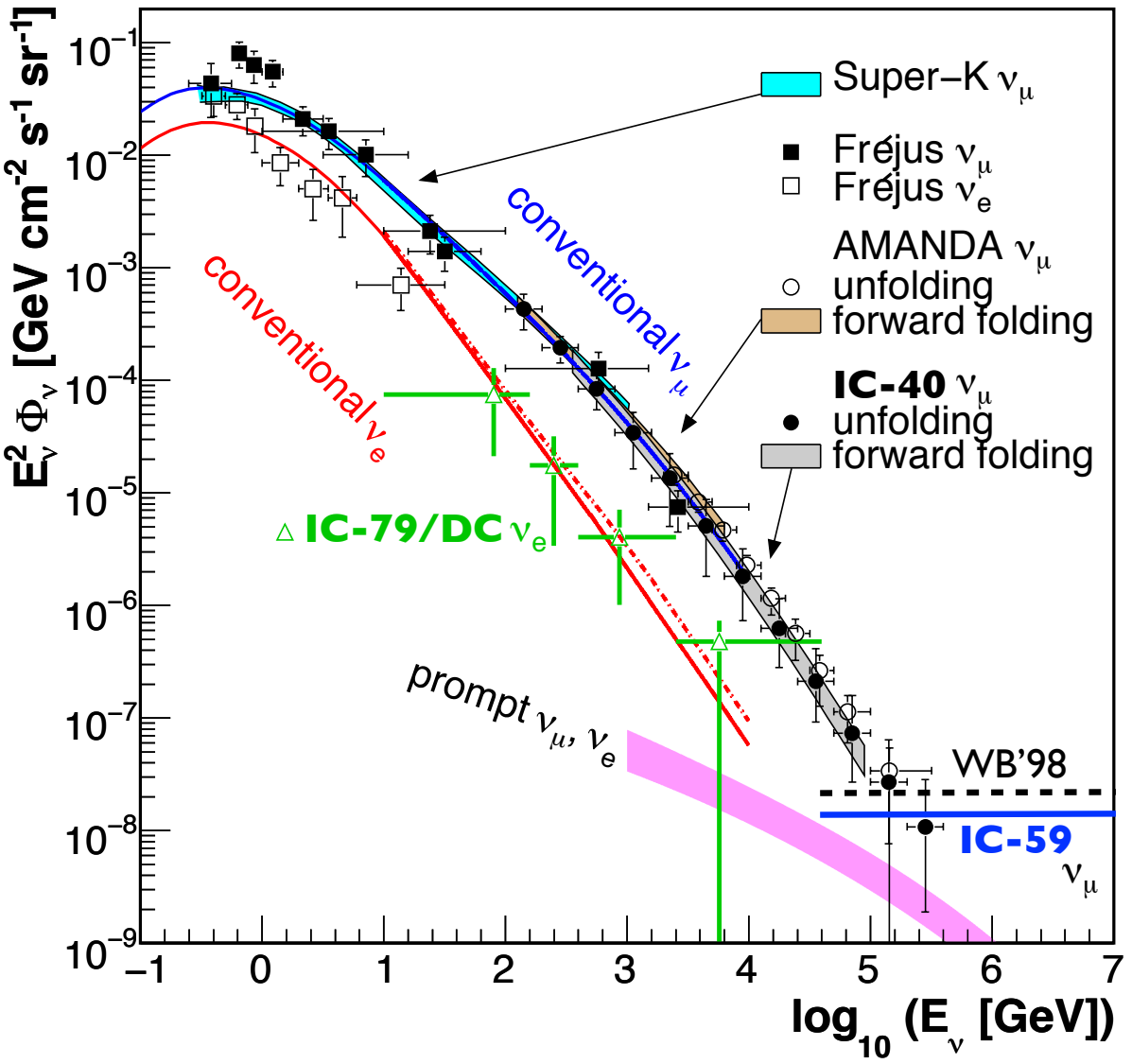
- diffuse ν_μ limit from **IC-59** (90% C.L.) (**preliminary**)

- predicted prompt atmospheric ν-fluxes (charmed meson decay)

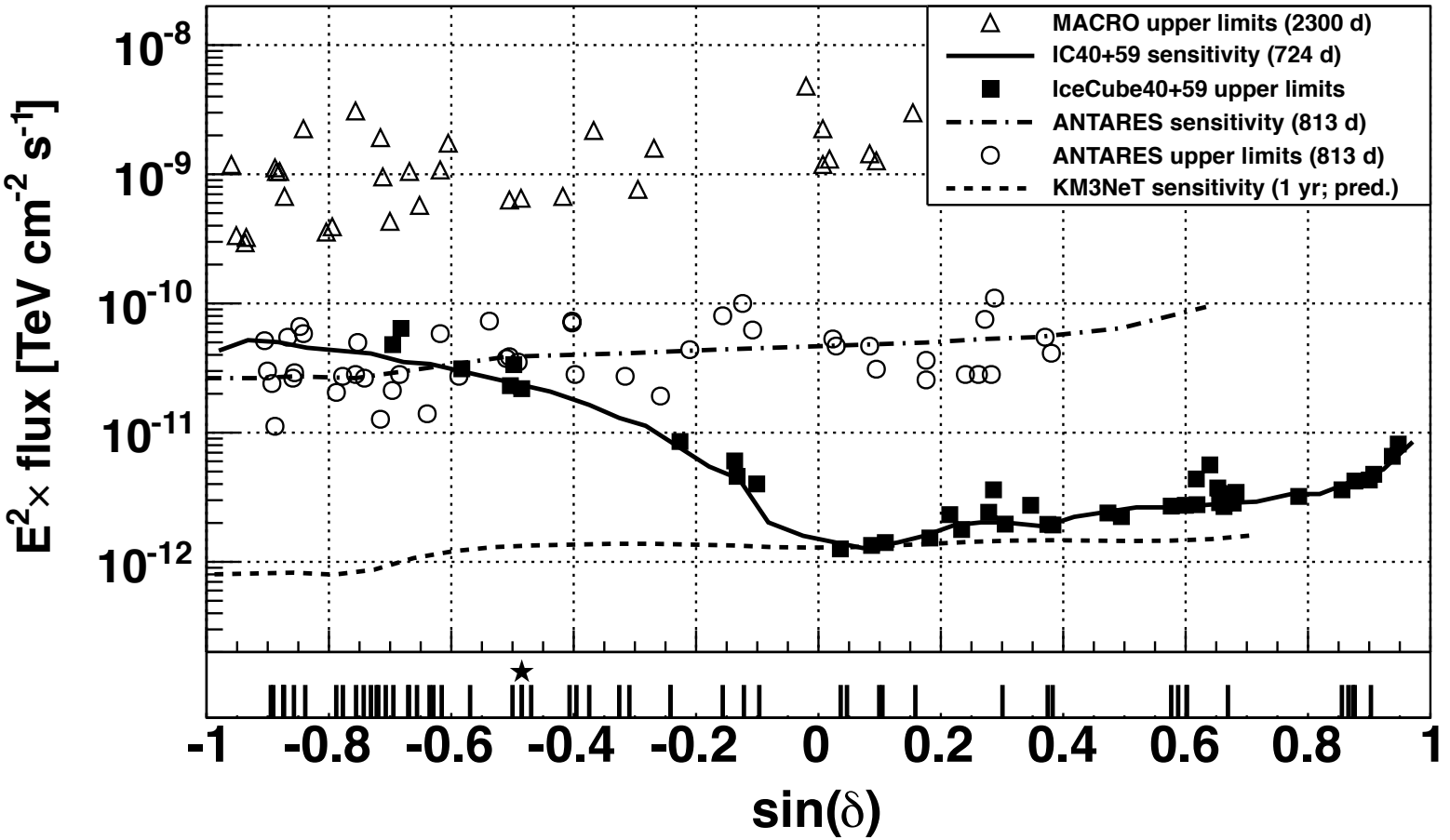
  [Enberg *et al.*'08]

- **theoretical limit** on diffuse astrophysical ν_μ's

  [Waxman&Bahcall '98]

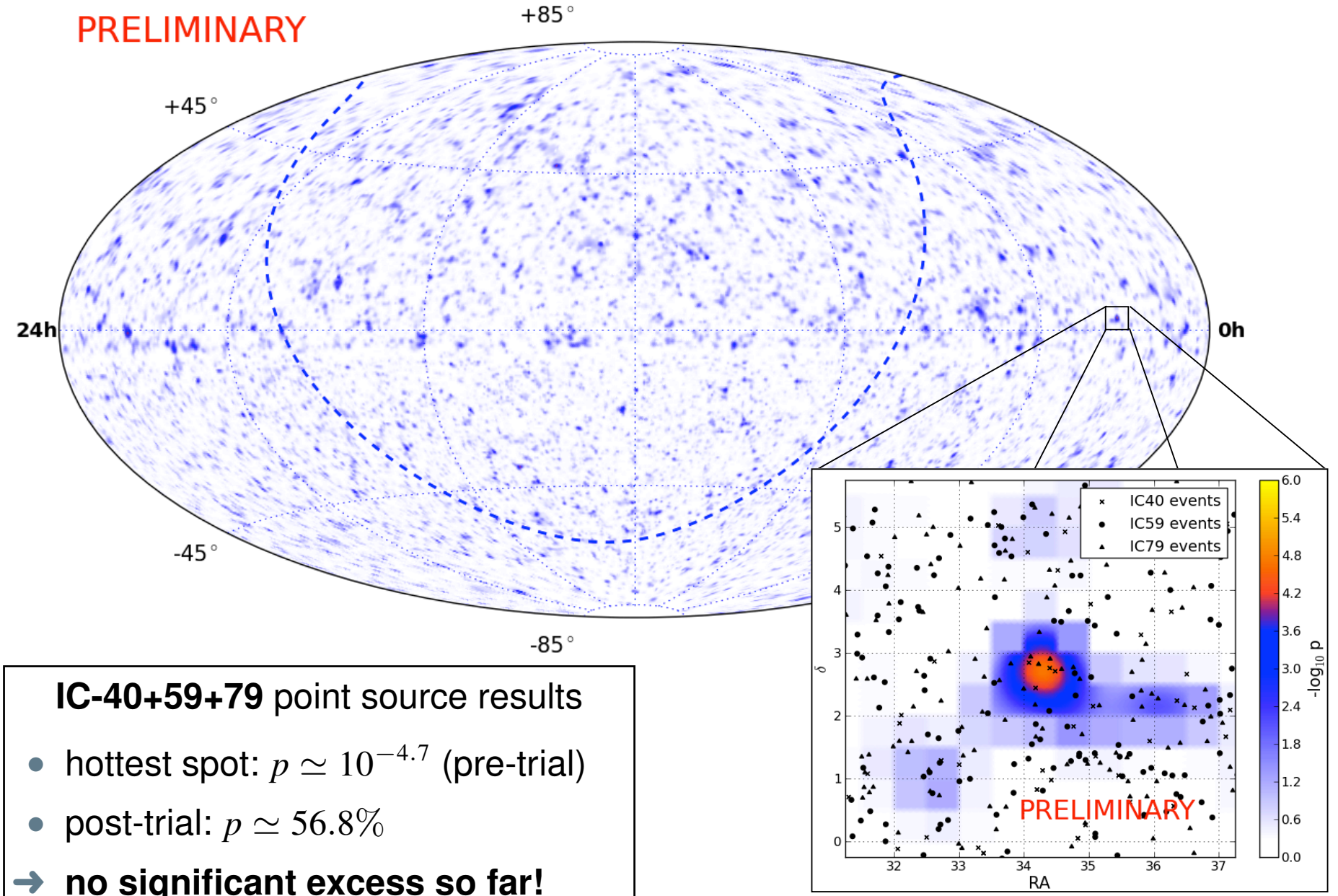


Steady point-source search



Upper limits (symbols) and sensitivities (lines) (90% CL) for point-like sources with an E^{-2}-spectrum as function of declination.

Steady point-source search



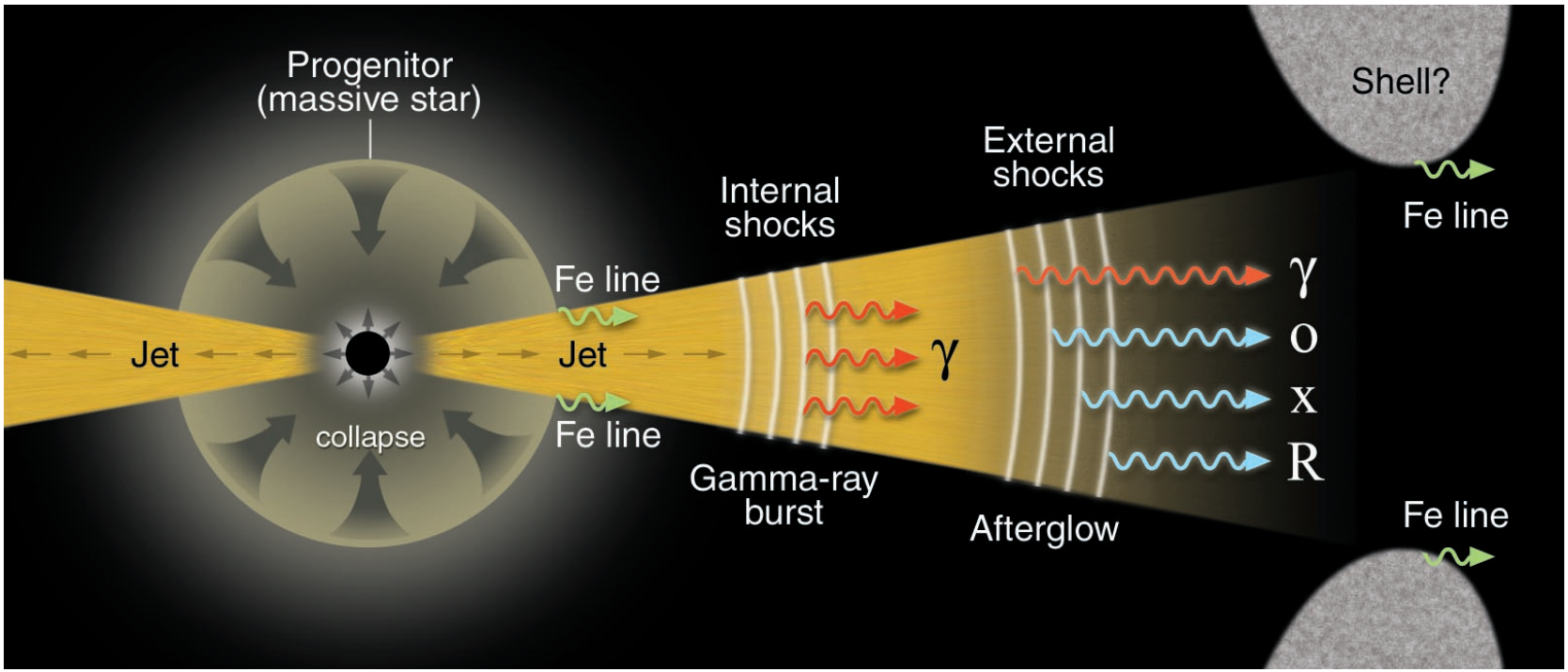
IC-40+59+79 point source results

- hottest spot: $p \simeq 10^{-4.7}$ (pre-trial)
- post-trial: $p \simeq 56.8\%$

➜ **no significant excess so far!**

GRB neutrino emission

- Neutrino production at various stages of gamma-ray burst (GRB), from precursor to afterglow [Waxman&Bahcall'97,'00;Razzaque,Meszaros&Waxman'03]
- Neutrino emission of GRBs is one of the best-tested models: [IceCube, Nature'12]
  - ✔ **cosmological sources** ("one per day and 4π")
  - ✔ **wealth of data** from Swift and Fermi
  - ✔ good information on **timing and location** (➜ background reduction)



[Meszaros'01]

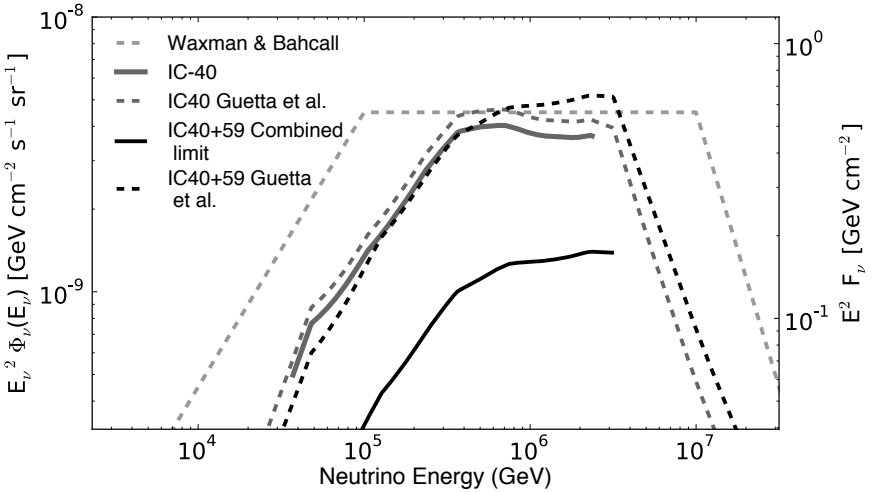
GRB neutrino emission

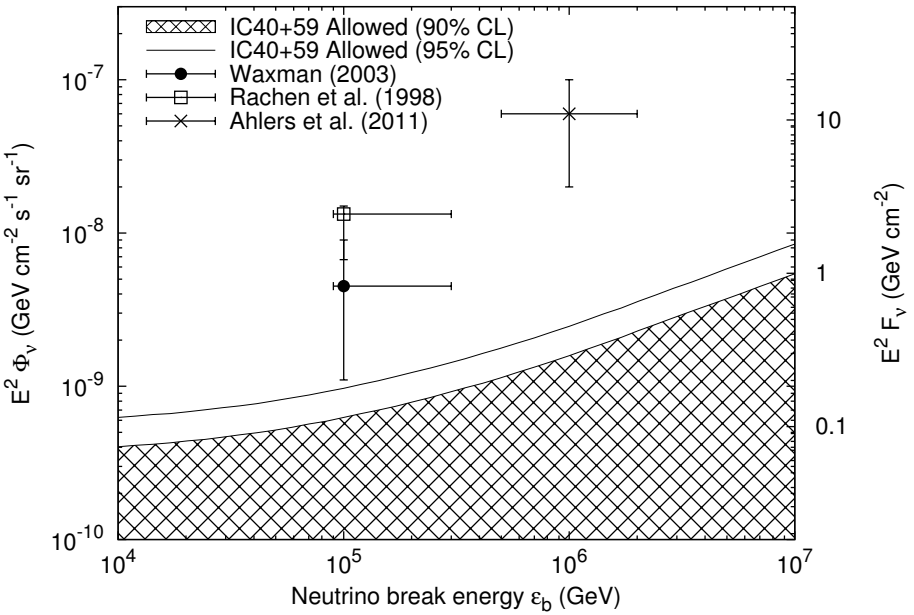
- Limits on neutrino emission coincident with 215 (85) northern (southern) sky GRBs between April 2008 and May 2010 (**IC-40+59**). [IceCube'11;'12]

- Stacked point-source flux below "benchmark" prediction by a factor 3-4. [Guetta *et al.*'04]

- IceCube limit below **benchmark diffuse models** normalized to UHE CR data. [Waxman&Bahcall'03; Rachen *et al.*'98]

➜ **IceCube's results challenge GRBs as the sources of UHE CRs!**





GRB neutrino emission

"Search for Neutrino Flares from AGN with the IceCube Detector."

Angel Cruz, Zeuthen, Germany

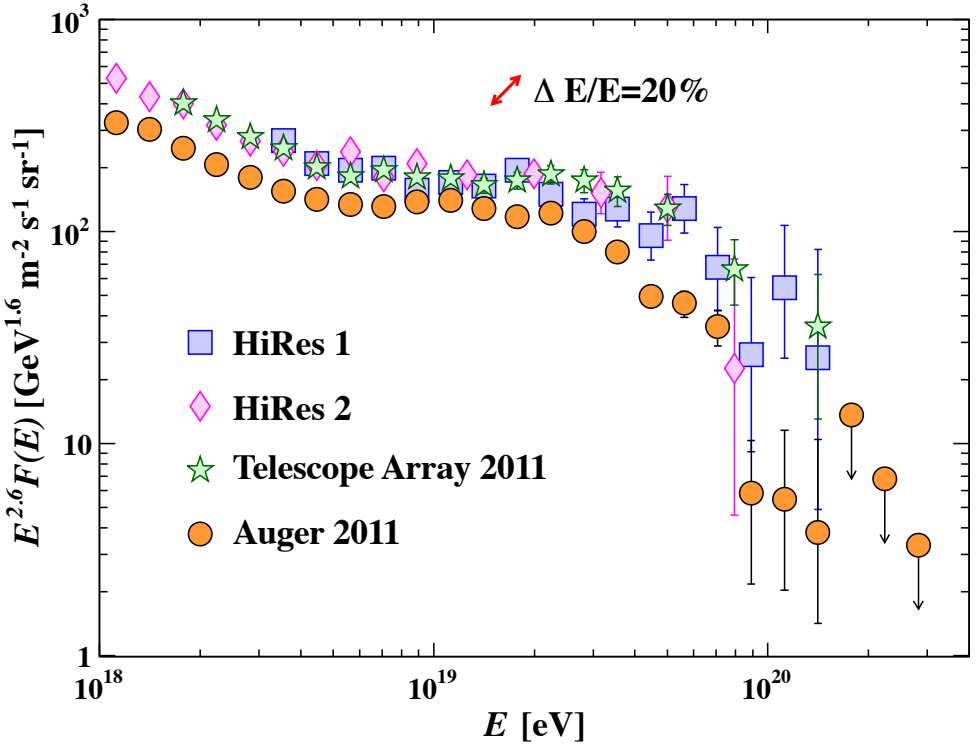
Cosmogenic neutrinos

- "Guaranteed" neutrino production from UHE CR propagation in cosmic radiation background. [Greisen&Zatsepin'66;Kuzmin'66;Berezinsky&Zatsepin'70]

➜ resonant proton interaction $p\gamma \to \Delta \to n\pi^+$ with CMB: $E_{\rm CR} < E_{\rm GZK} \simeq 40{\rm EeV}$

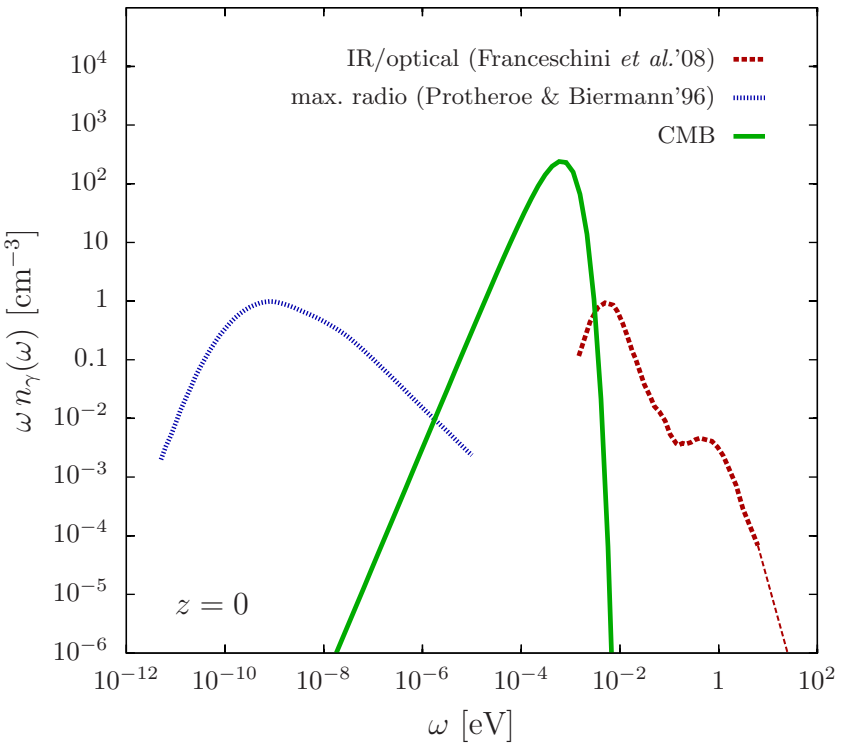
➜ peak neutrino contribution at $E_\nu \simeq 1{\rm EeV}$

UHE CR spectrum



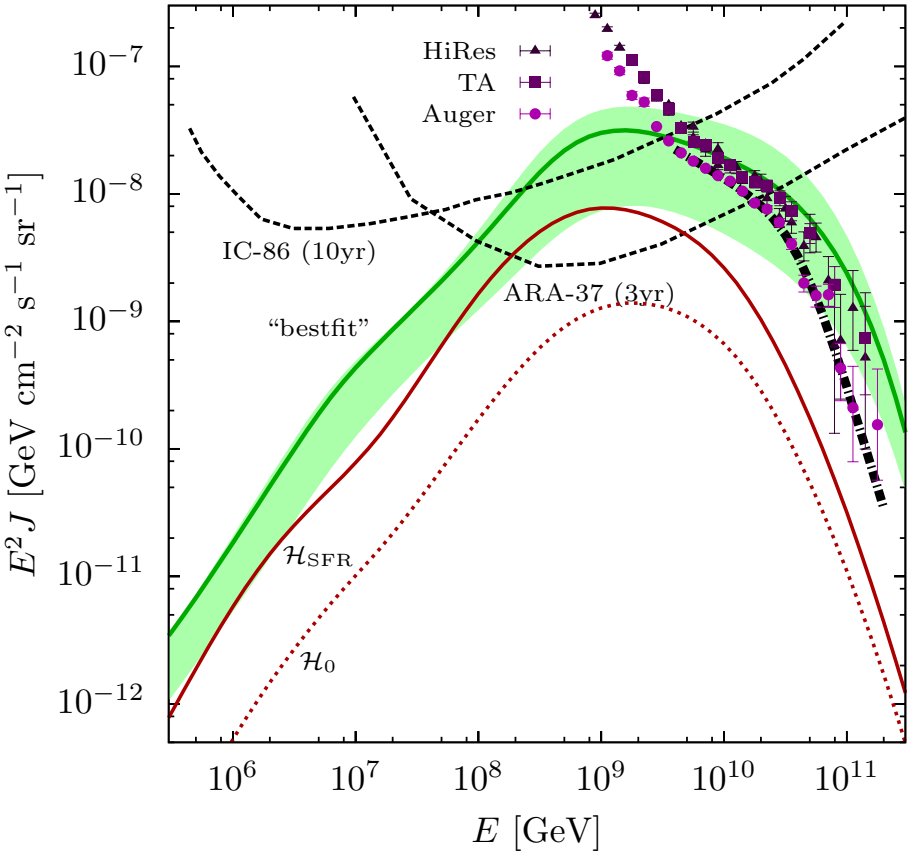
[Particle Data Group'12]

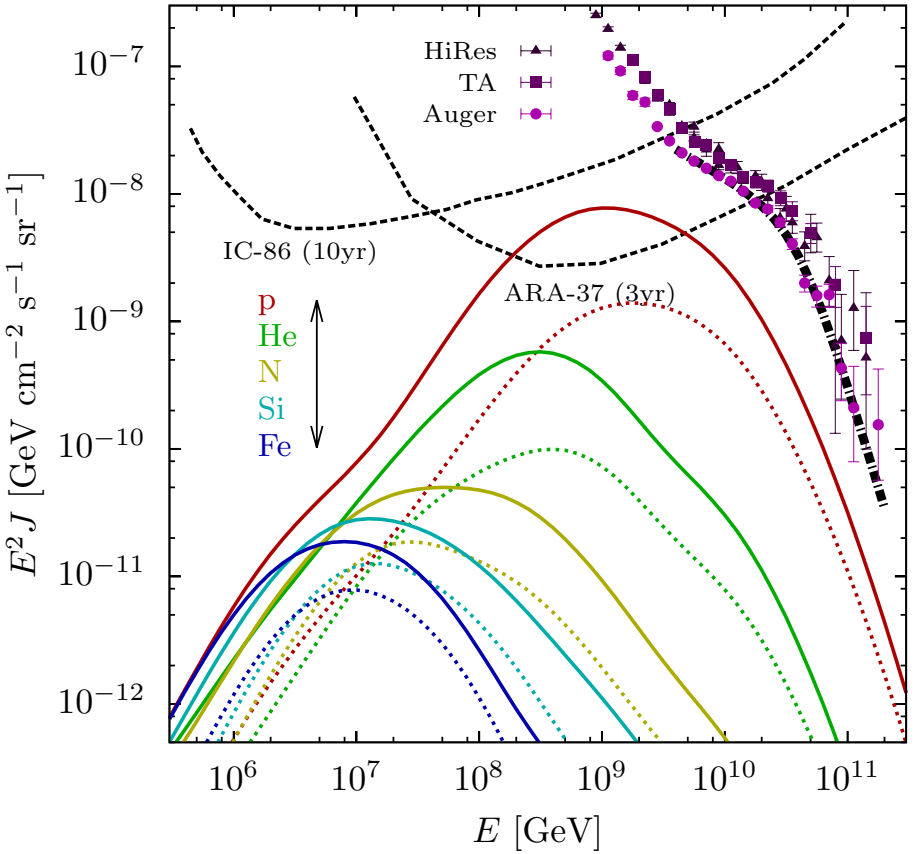
radiation background



Cosmogenic neutrinos

. . . "guaranteed", but **model-dependent**, in particular UHE CR **composition**.



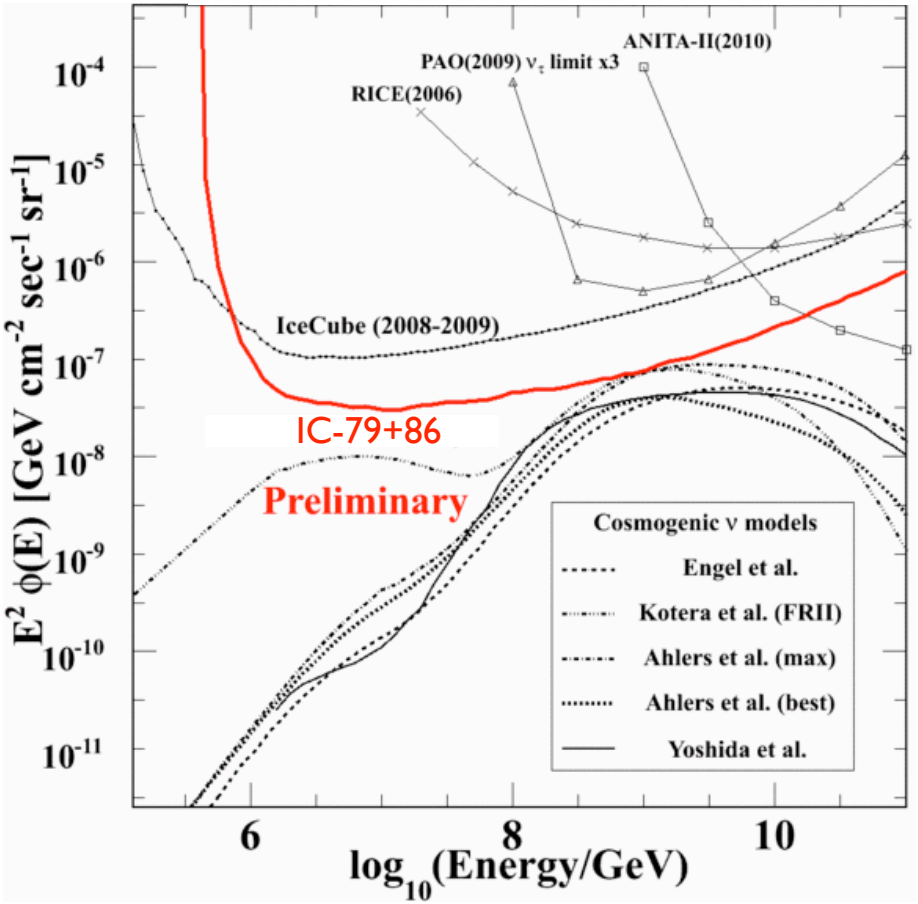


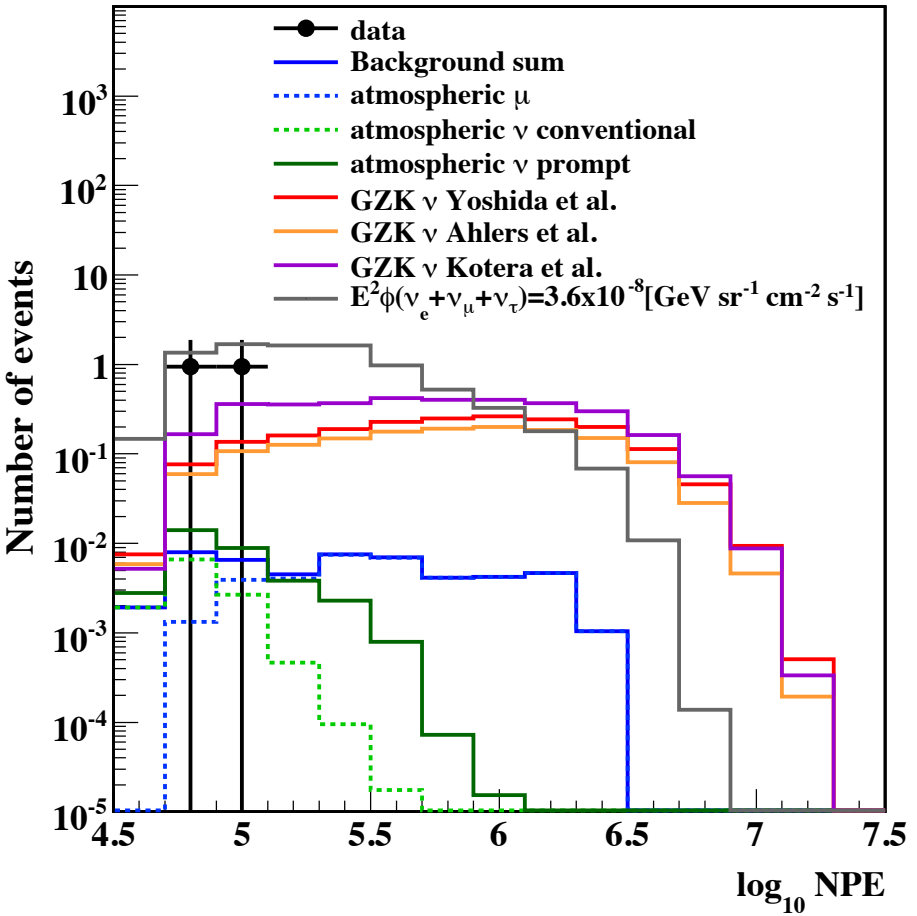
[MA&Halzen'12]

Extremely-high energy analysis

- Study for cosmogenic neutrino fluxes in **IC-79+86**
- optimized cuts on zenith angle and “brightness” (NPE: number of photo-electons)

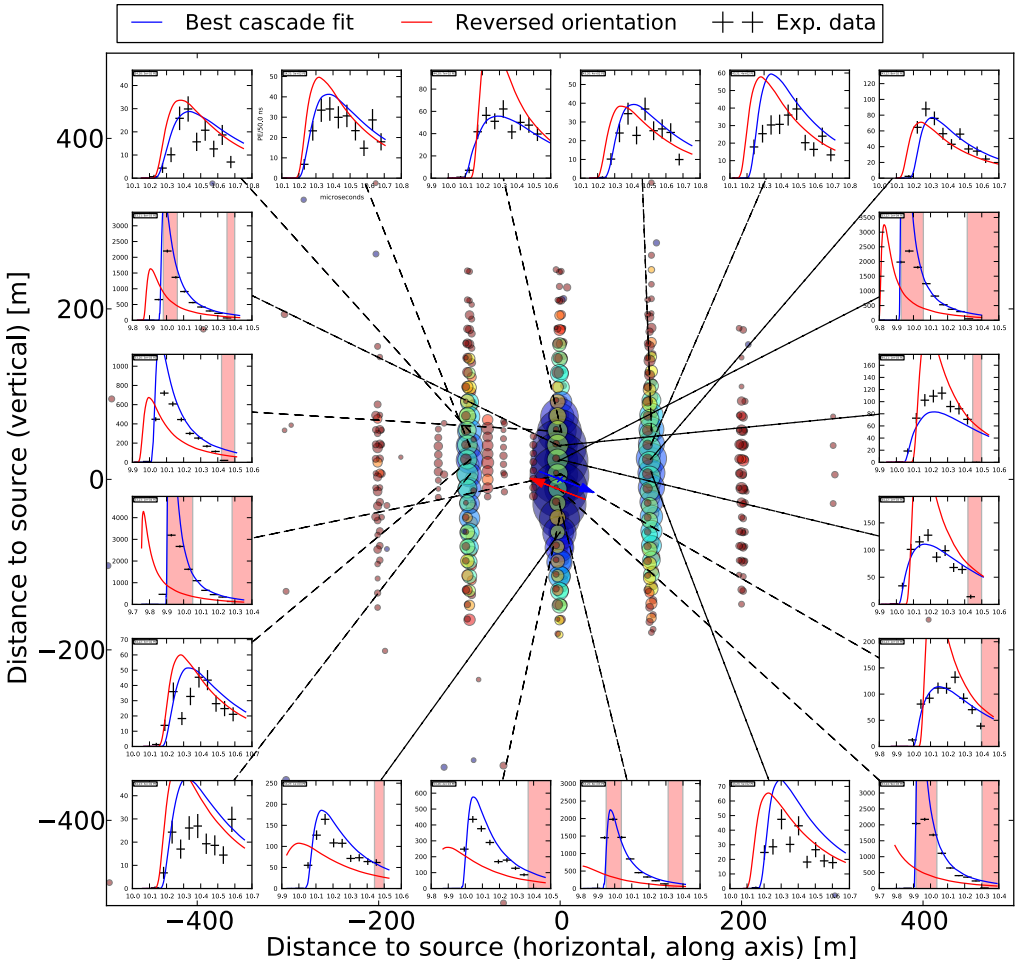
➜ two “background” events above NPE threshold

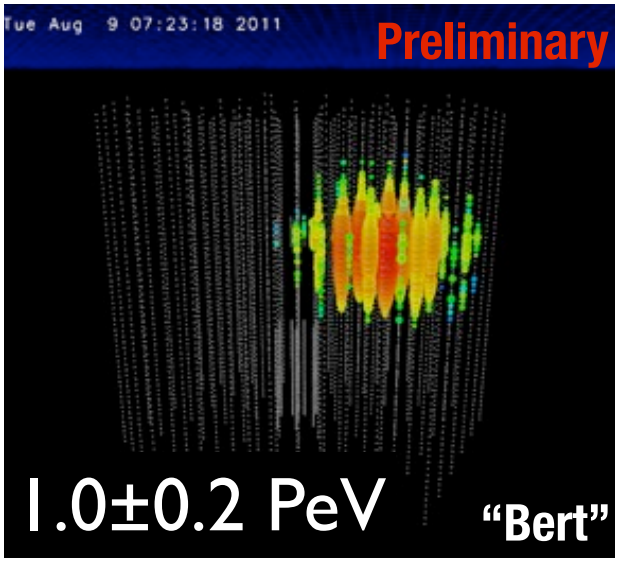


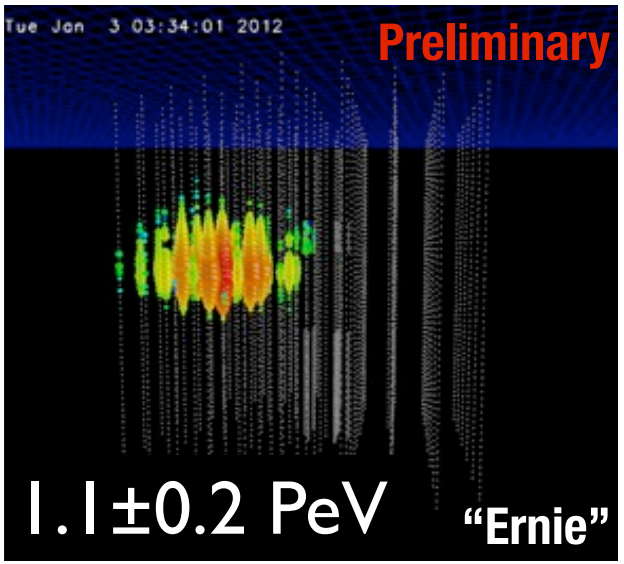


Extremely-high energy analysis

Follow-up studies of background events:
energy, **orientation**,. . .
➜ Are there more contained events?







Extremely-high energy analysis

"A search for extremely high energy cosmogenic neutrinos with the IceCube detector."

Keiichi Mase, Chiba, Japan

Cosmic ray anisotropies

- CR anisotropy studies by atmospheric muons with **IC-79**

$$\frac{\Delta N}{\langle N \rangle} = \frac{N(\alpha,\delta) - \langle N(\alpha,\delta) \rangle}{\langle N(\alpha,\delta) \rangle}$$

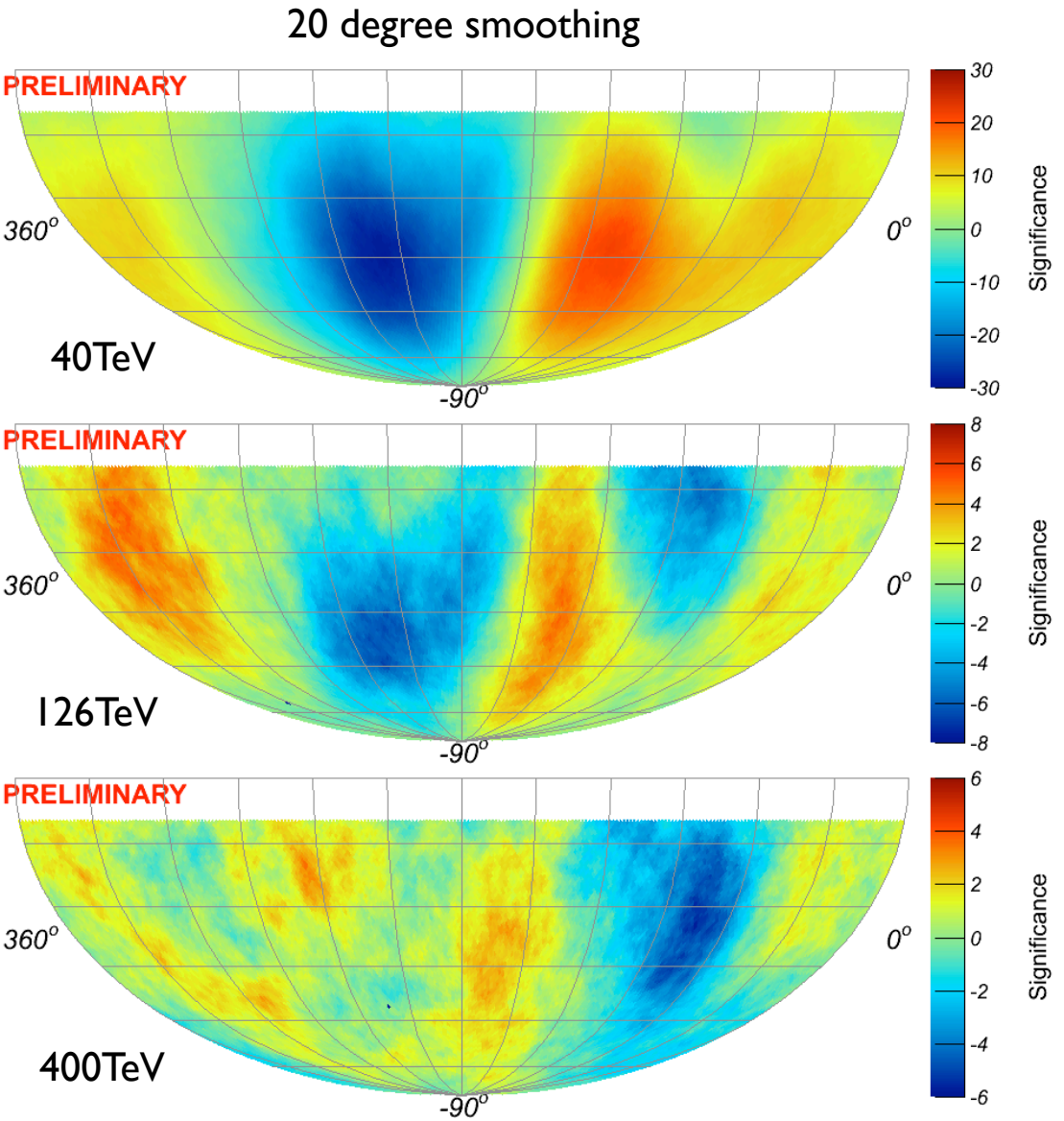
- **significant** CR anisotropy of 1‰ at various (median) CR energies and angular scales

➜ South Pole unique:

✔ study of the Southern hemisphere

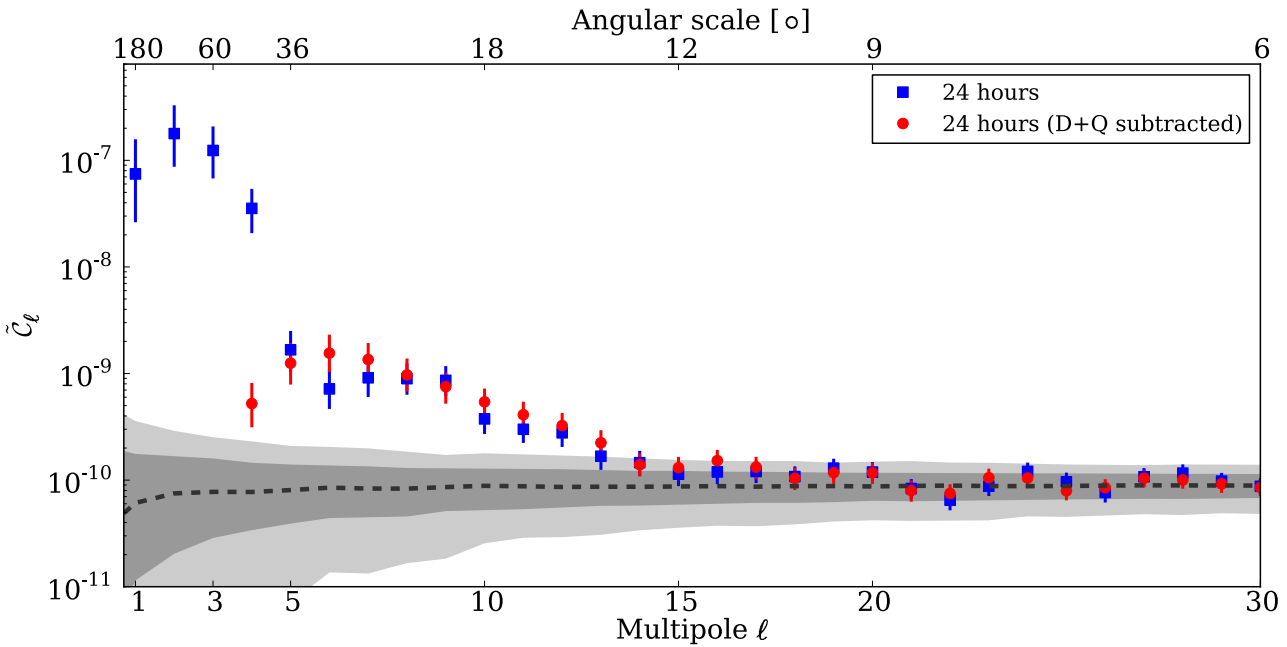
✔ stable atmospheric conditions over >24h

- pattern persists in the few 100 TeV to few PeV energy region (in IceCube & IceTop)



Cosmic ray anisotropies

- Compton-Getting effect? Amplitude **too low** and **wrong** phase. [Compton&Getting'35]
- pattern appears to be a **continuation** of anisotropies observed in the Northern hemisphere [Milagro'08 (∼TeV);Tibet'06,'11 (∼TeV);ARGO-YBJ'09 (∼TeV)]
- anisotropy pattern at few 10 TeV already present in AMANDA ('00-'06)
  ➜ stable on scales of ∼ **13 years**
- indications for small scale anisotropy in data (**IC-59**)



[IceCube'11]

Cosmic ray flux and composition

- IceTop's average atmospheric depth:

$$X_{\mathrm{IceTop}} \simeq 680\ \mathrm{g/cm^2}$$

- *e.g.*, **proton** shower maxima at PeV-EeV:

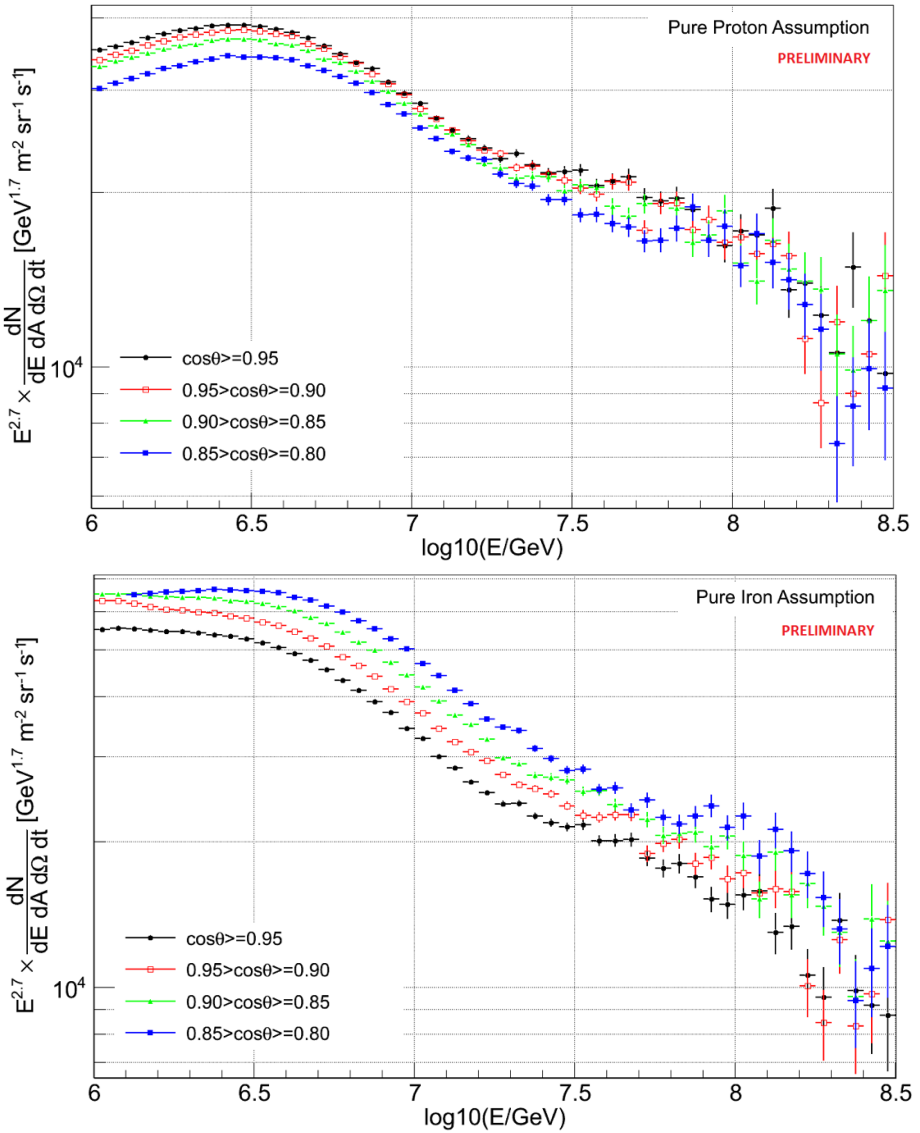
$$550\ \mathrm{g/cm^2} \lesssim \langle X_{\mathrm{max}} \rangle \lesssim 720\ \mathrm{g/cm^2}$$

✔ **good resolution** for $\langle X_{\mathrm{max}} \rangle \simeq X_{\mathrm{IceTop}}$

- energy estimation via lateral distribution function:

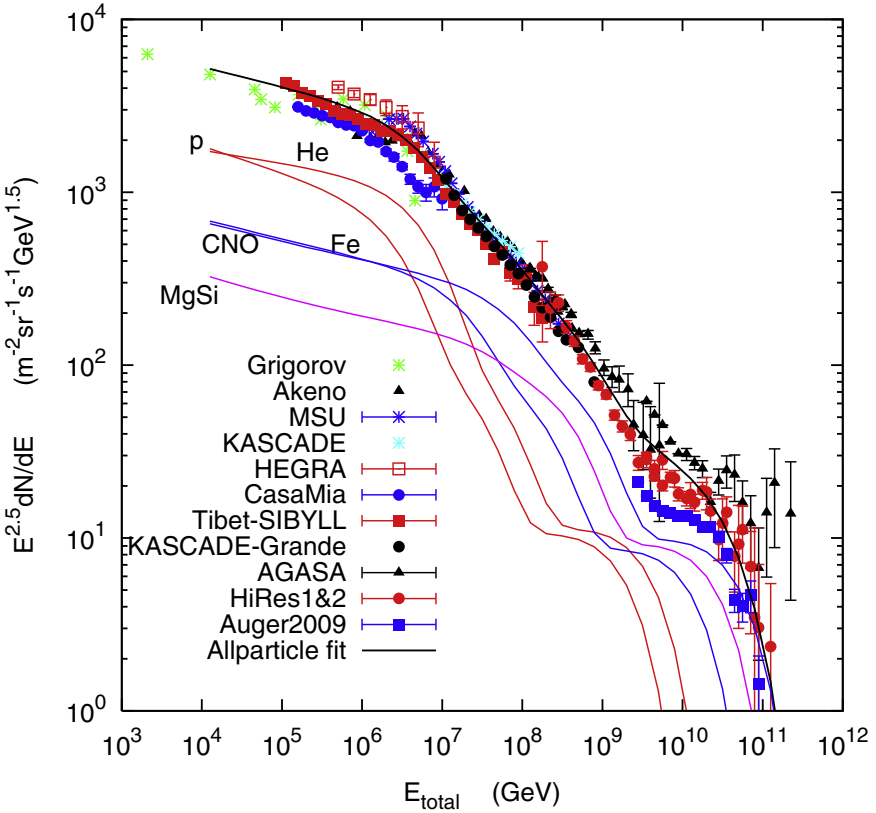
$$\log_{10} E \simeq p_0 + p_1 \log_{10} S_{125} + p_2 (\log_{10} S_{125})^2$$

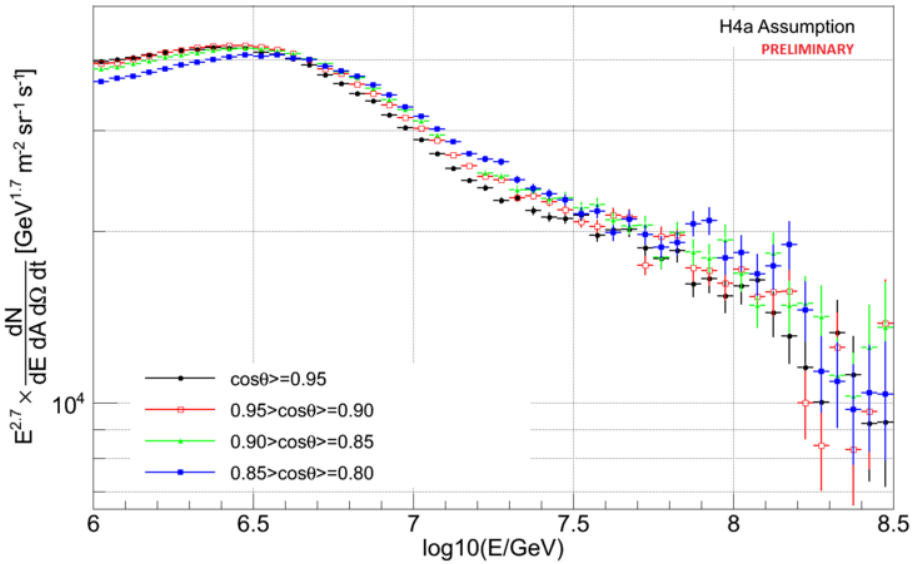
- p_0, p_1 and p_2 are fixed by MC studies and depend on **zenith angle** and **primary mass**

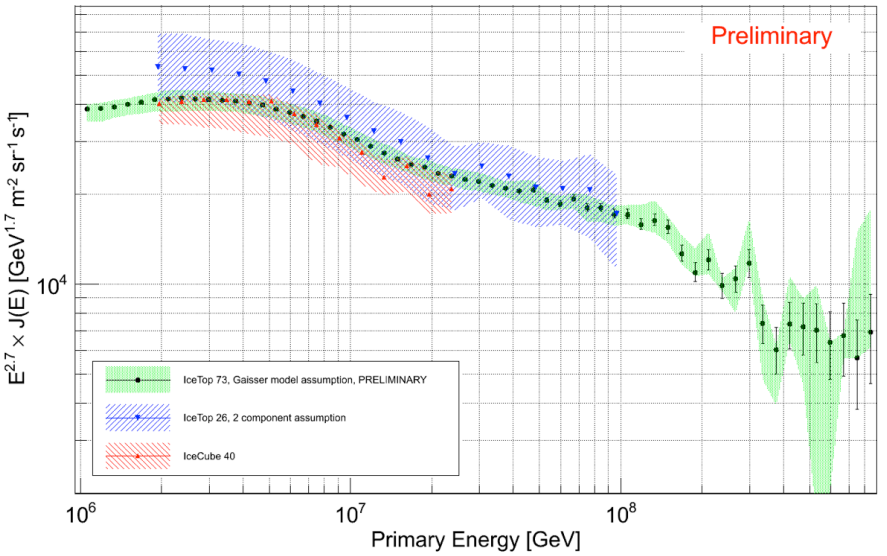


Cosmic ray flux and composition

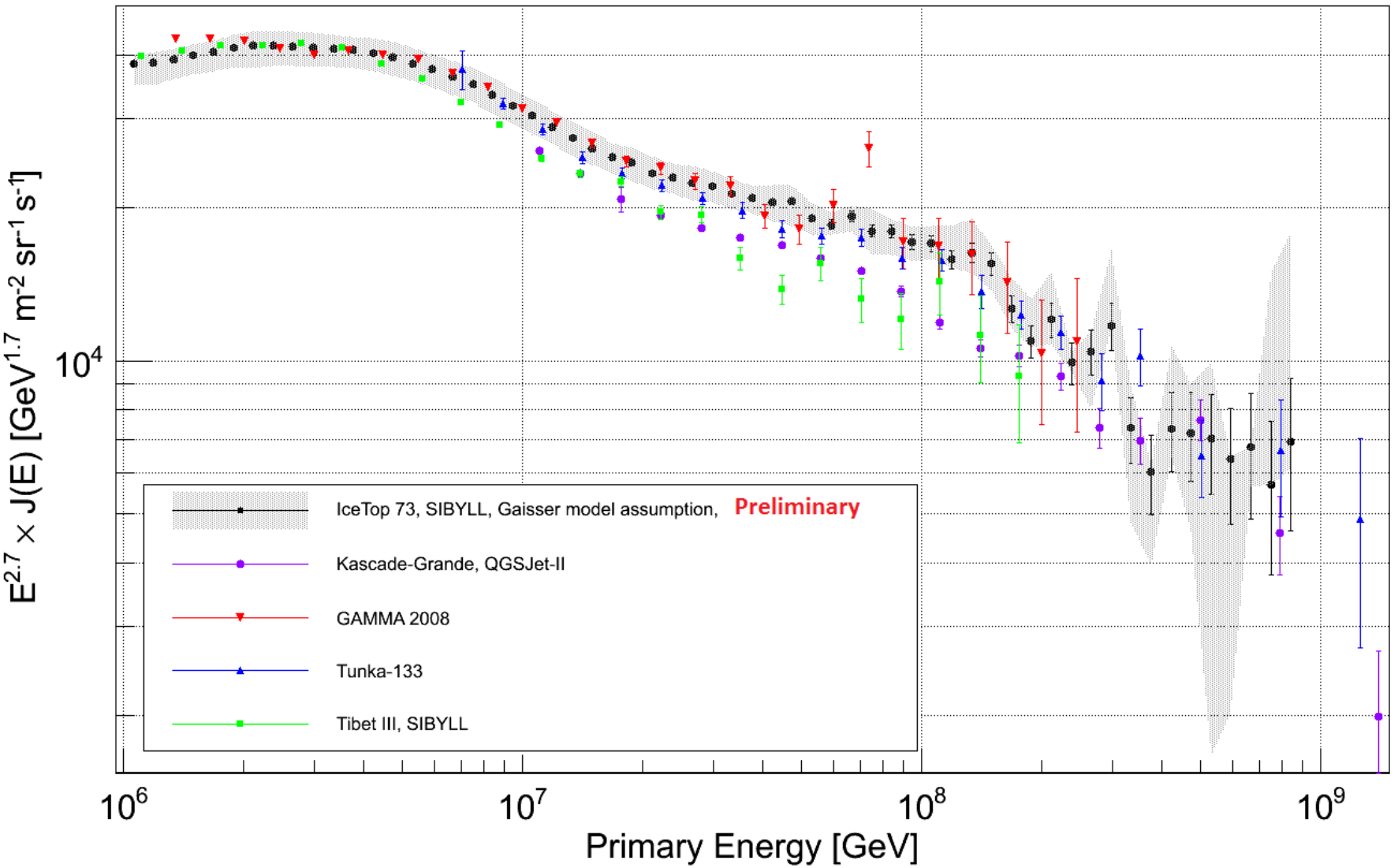
- **composition analysis** via zenith-dependence (**IT-73**)
  - *e.g.*, mixed composition model ("H4a") with five CR mass groups [Gaisser'12]







Cosmic ray flux and composition



Summary

- The **fully-instrumented** IceCube observatory has been running smoothly for more than two years.
- The **IceTop**, **IceCube** and **DeepCore** sub-detectors have mutual benefits and enable a large scientific program.
- Actually, *too large* for this talk:
  - indirect dark matter detection (**IC-79** solar, **IC-59** dwarf gal./gal.clusters)
  - atmospheric neutrino oscillations (**IC-79**)
  - search for exotic particles (**IC-86**)
  - Earth core analysis with atmospheric neutrinos (**IC-40**)
  - Galactic supernova (**SN trigger**)
  - ...
- A recent highlight: observation of two PeV cascades in **IC-79+86**
- Follow-up analysis of these "background events" and dedicated searches for high-energy contained events in IceCube are under way. (➜ talk by Keiichi)