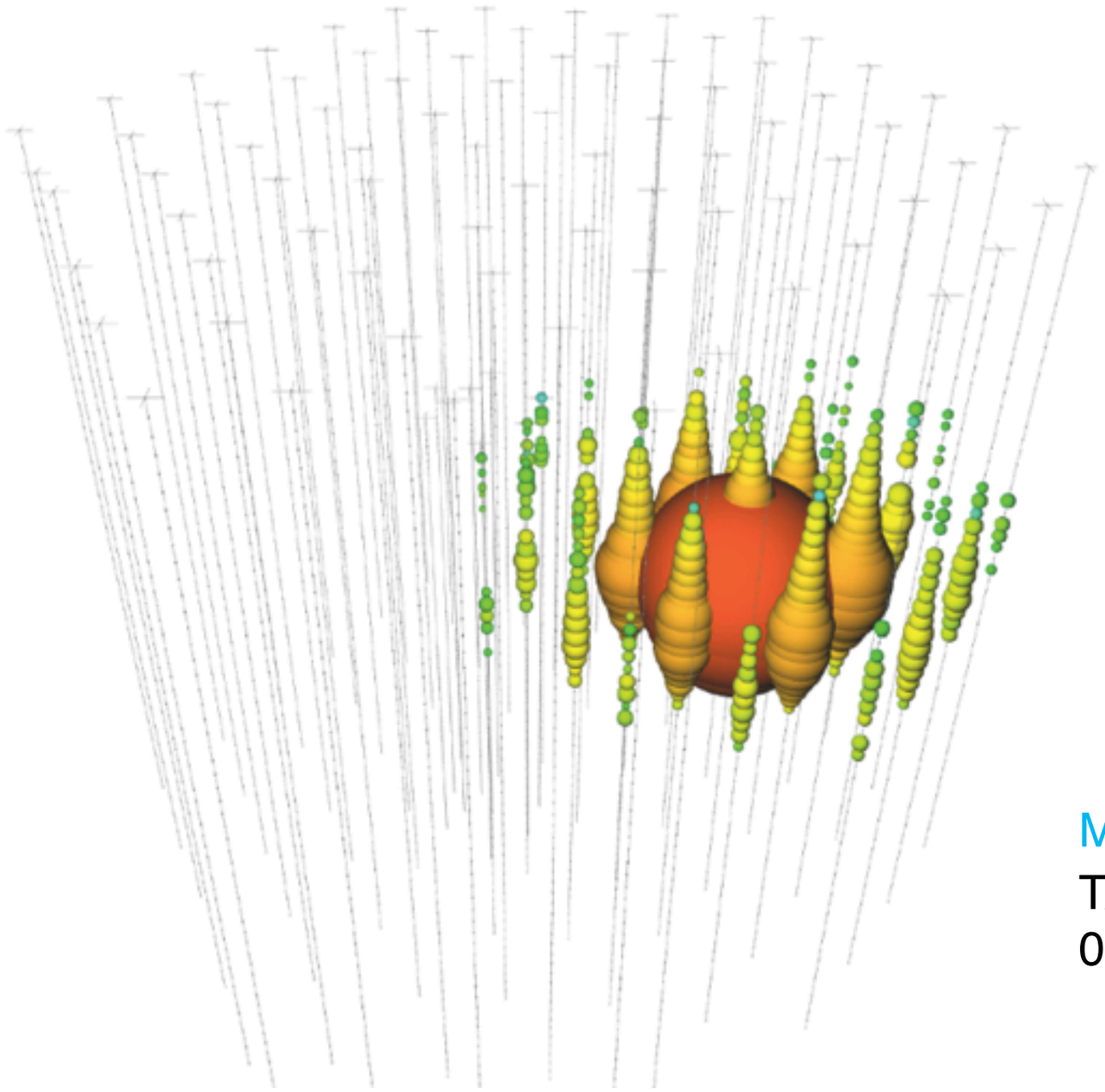
High-energy neutrino astronomy



Markus Ackermann

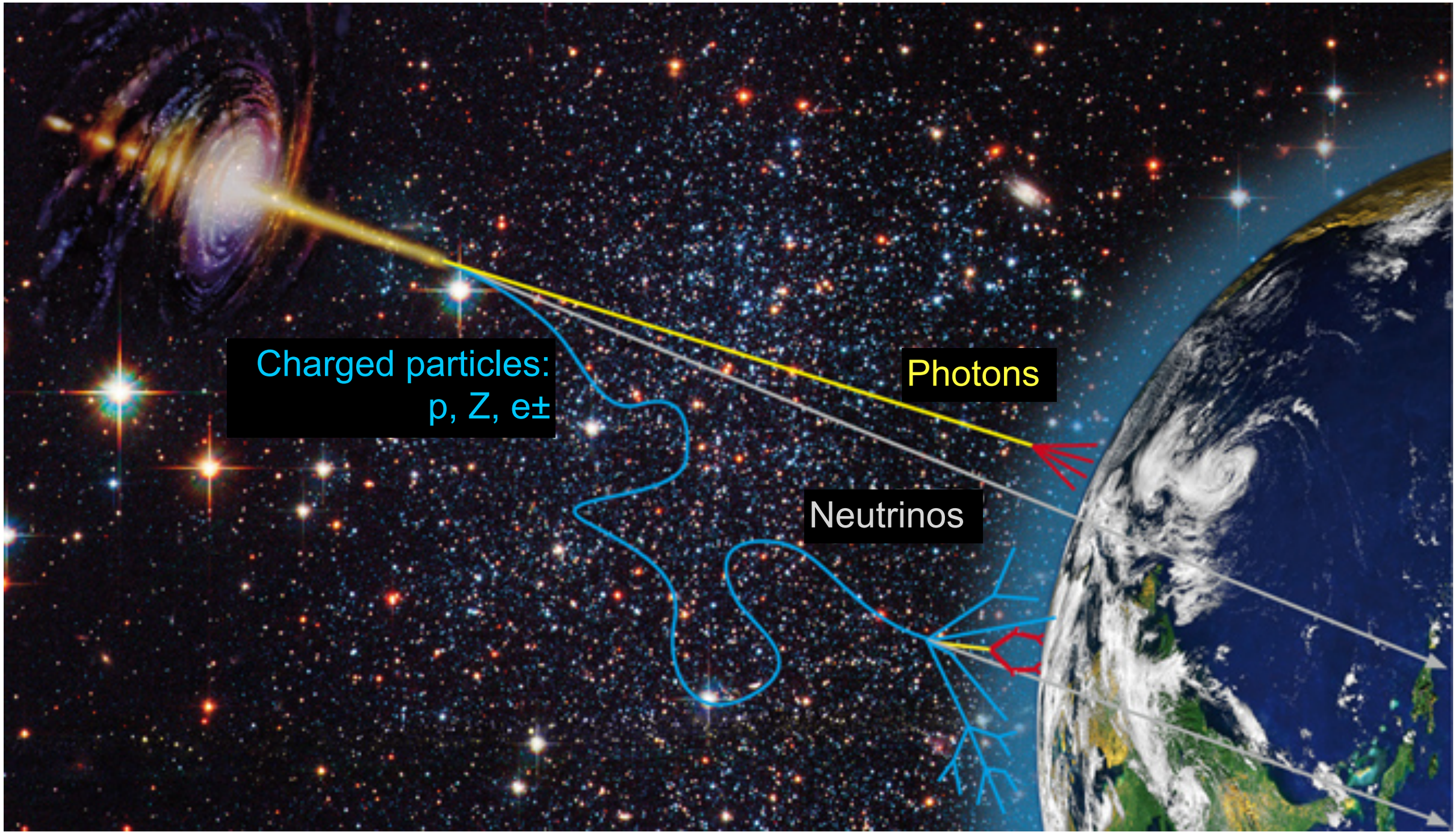
TAUP 2013, Monterey, California
09/13/2013

HELMHOLTZ ASSOCIATION

DESY

High-energy astrophysics

> Three messengers are available to study the non-thermal universe.



The power of neutrino observations.

> Neutrinos are a diagnostic of **hadronic acceleration sites and processes.**

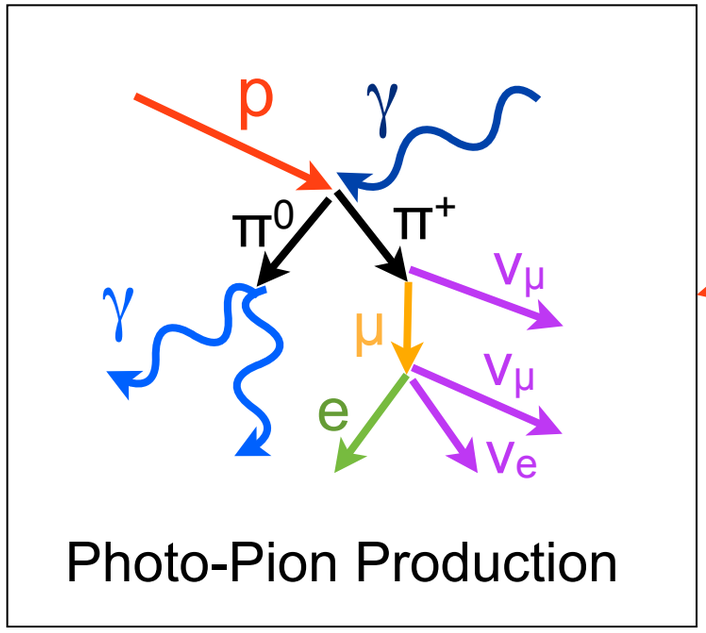
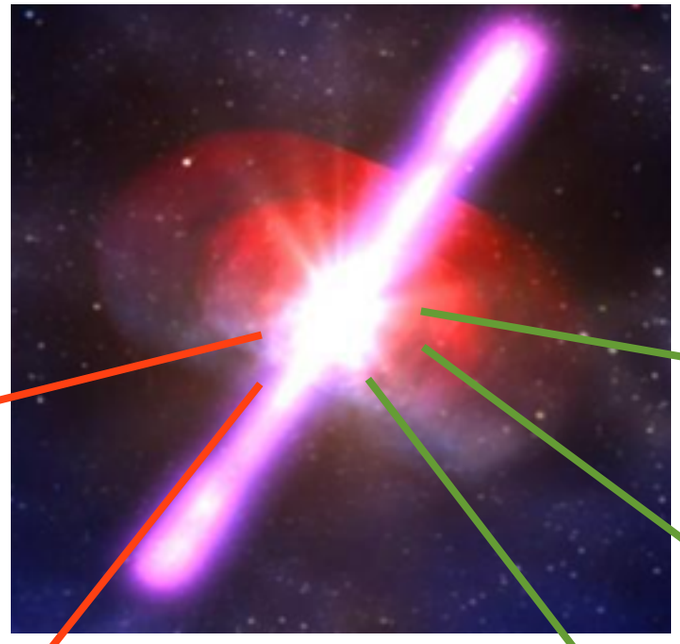
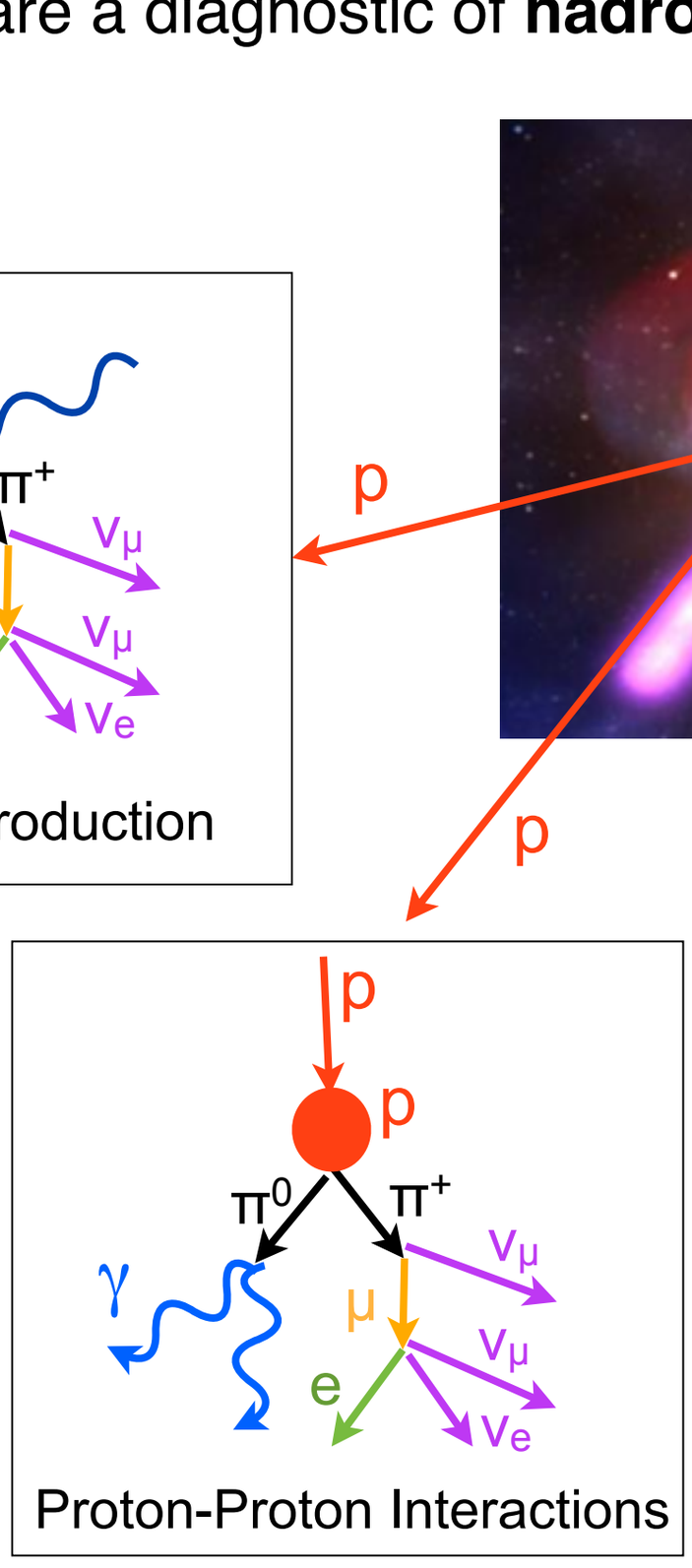
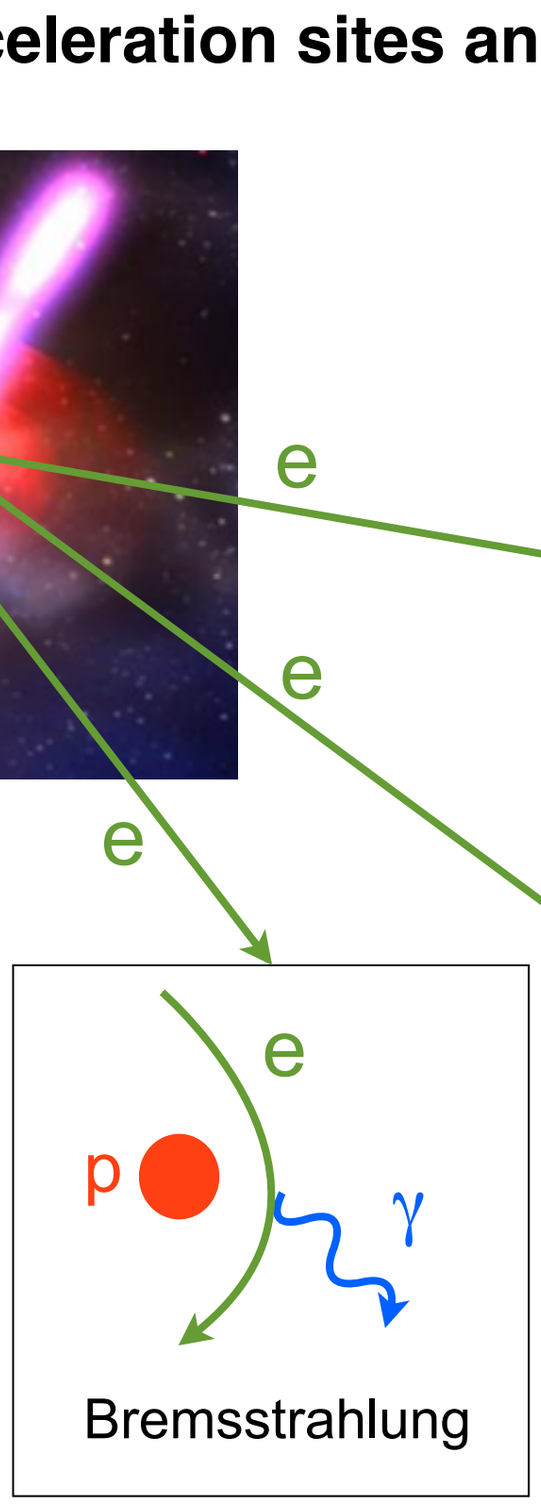


Photo-Pion Production

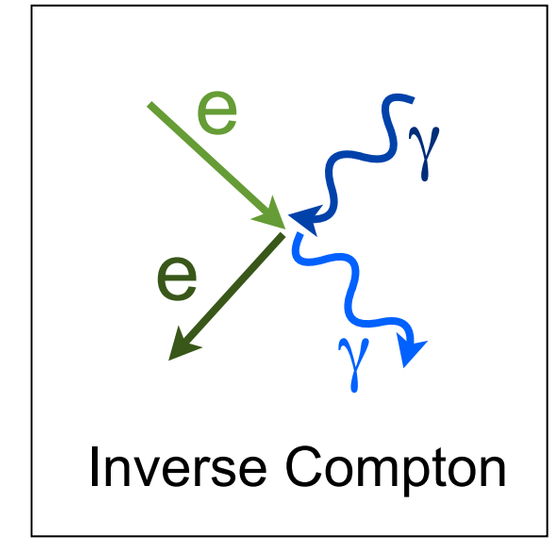




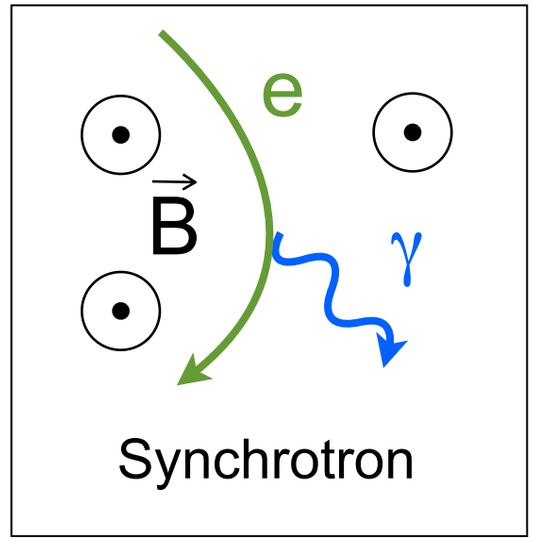
Proton-Proton Interactions



Bremsstrahlung



Inverse Compton



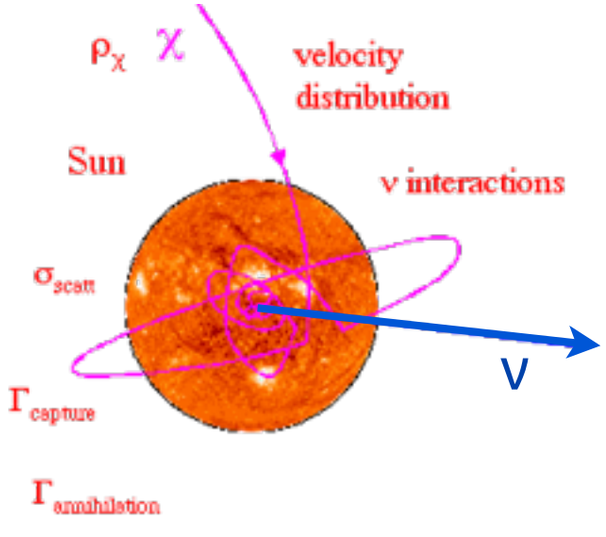
Synchrotron

The power of neutrino observations.

Neutrinos can **escape dense environments:**

> High-energy neutrinos from core-collapse SNe.
(e.g. Ando & Beacom, 2005)

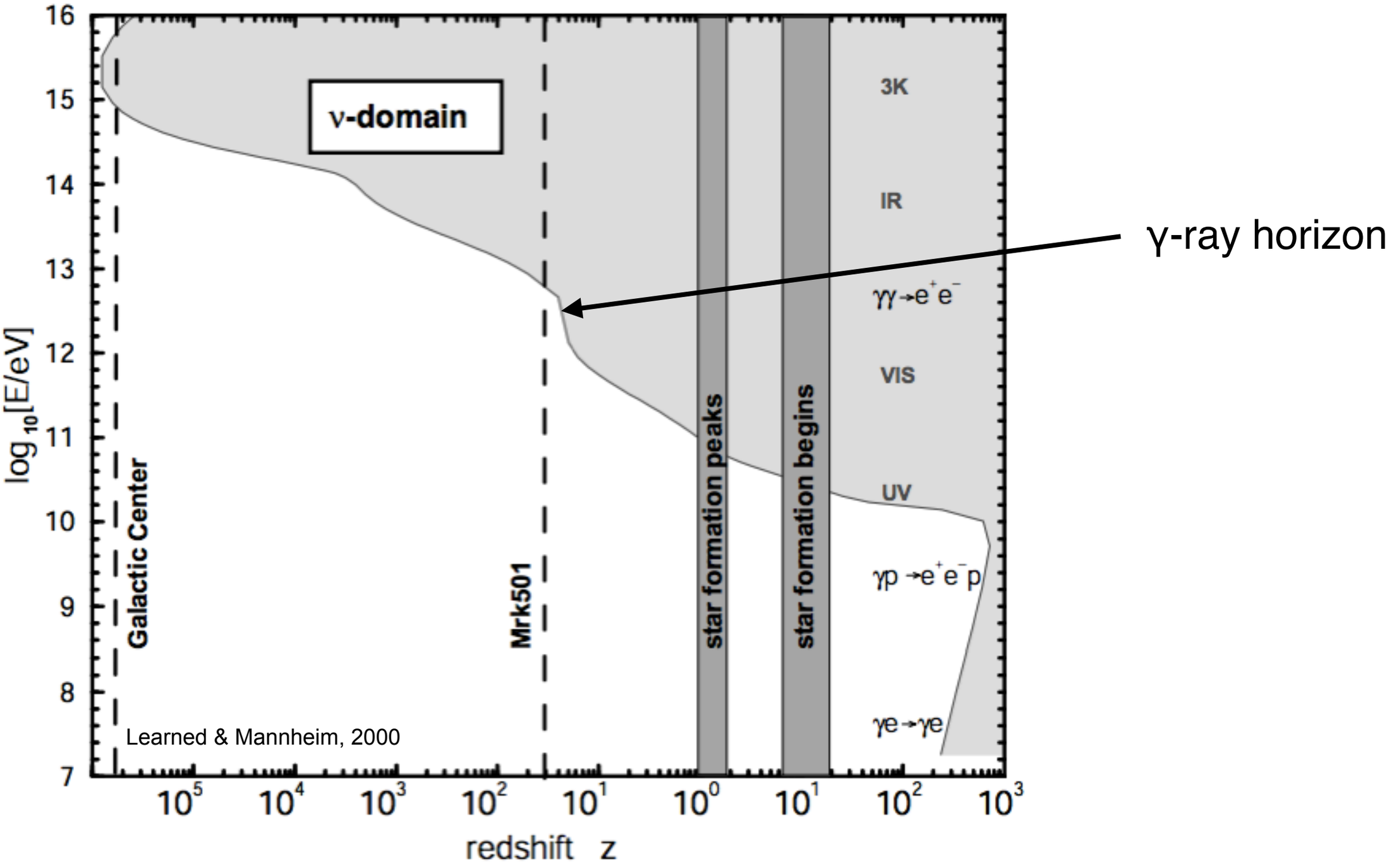
> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)



> High-energy neutrinos from dark matter annihilation in the sun.

The neutrino domain: PeV astronomy.

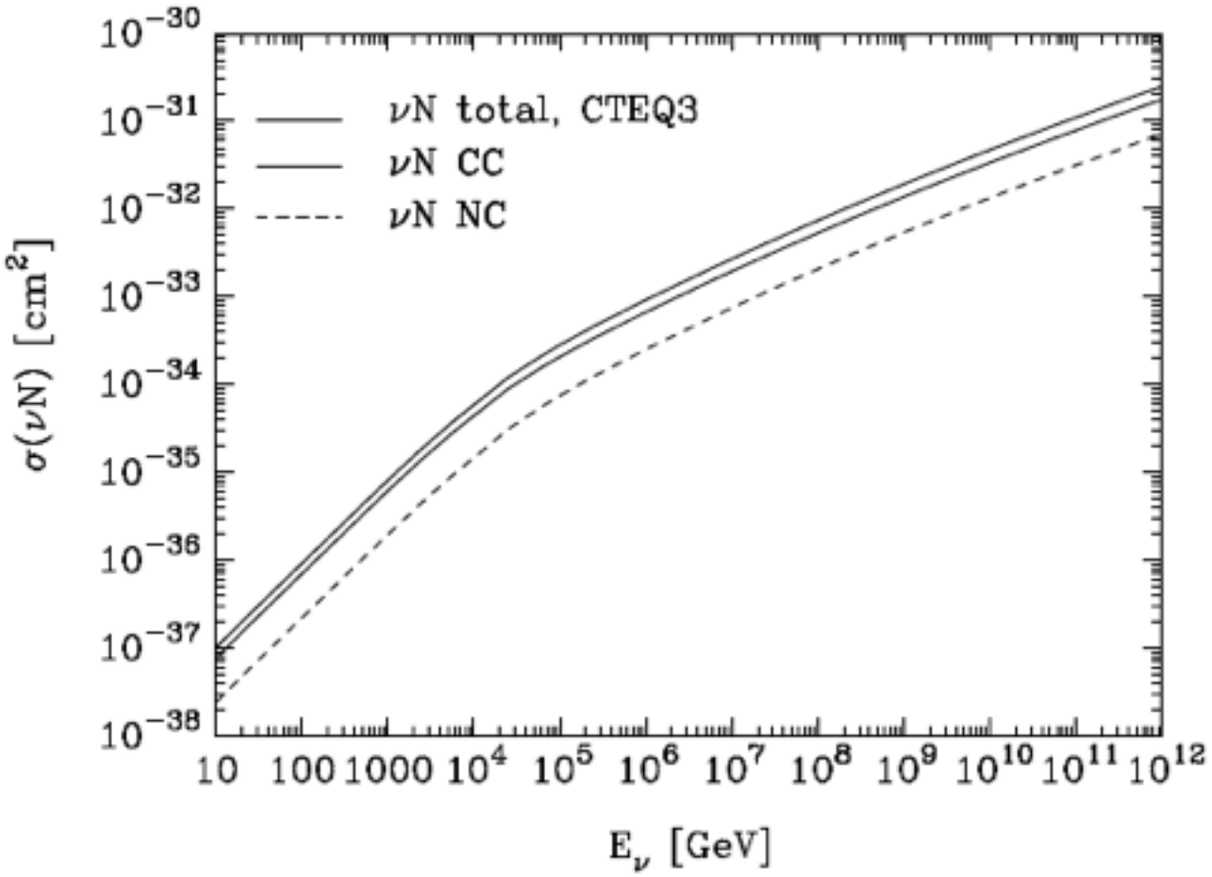
- Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.
- Only neutrino telescopes can do **PeV/EeV astronomy.**

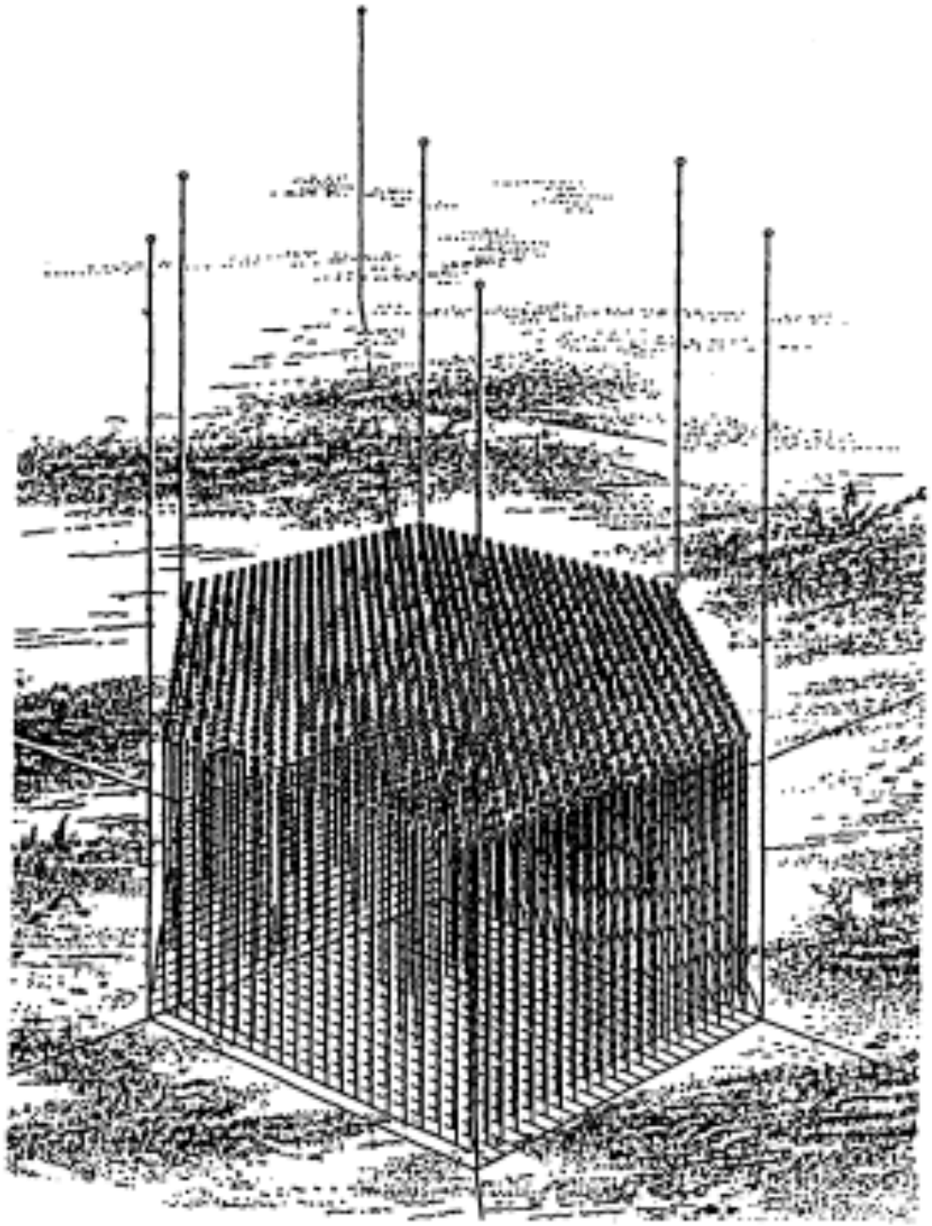


Learned & Mannheim, 2000

Neutrino astrophysics.

> **Small cross-section** of neutrinos requires **huge detectors.**



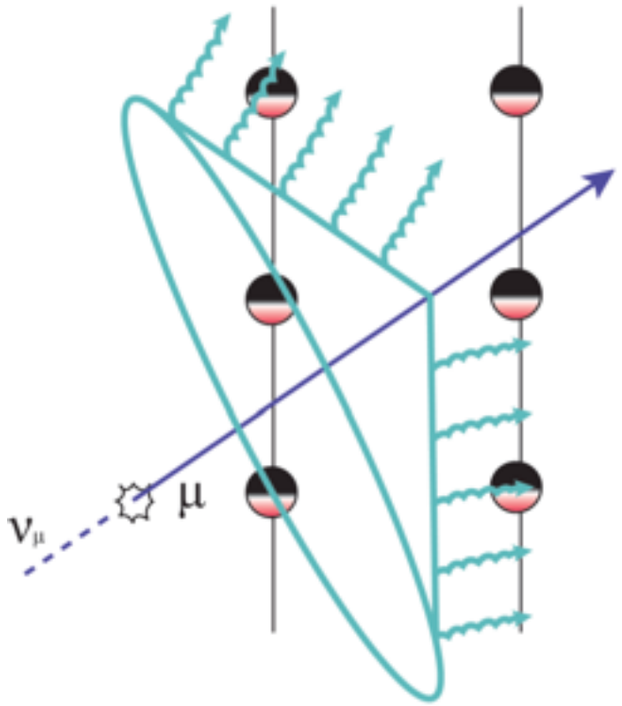


> **First design** of a **1 km^3** underwater detector already in 1978

- DUMAND array off the coast of Hawaii
- Never built after first test strings failed

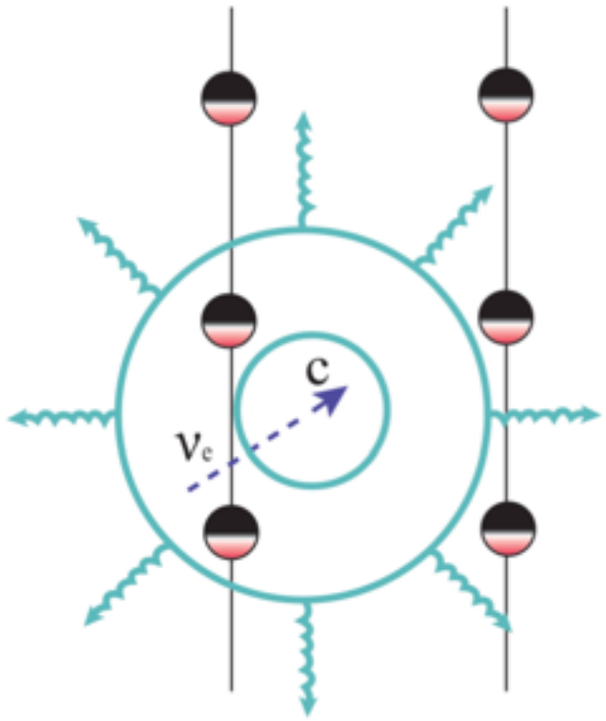
> **35 years later** we are finally there....

Detection of high-energy neutrinos.



> **Track-like event** signatures
(CC interactions of ν_μ)

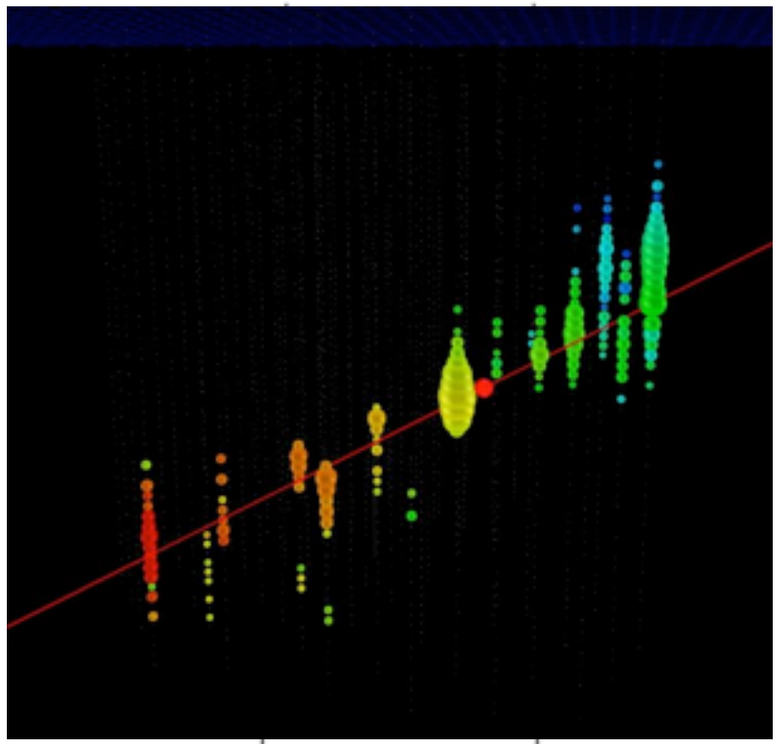
- **Angular** resolution: < 1°
- μ travels up to several km --> **interactions outside** the instrumented volume **visible**
- **Energy** resolution: dE/dx of the produced μ only.

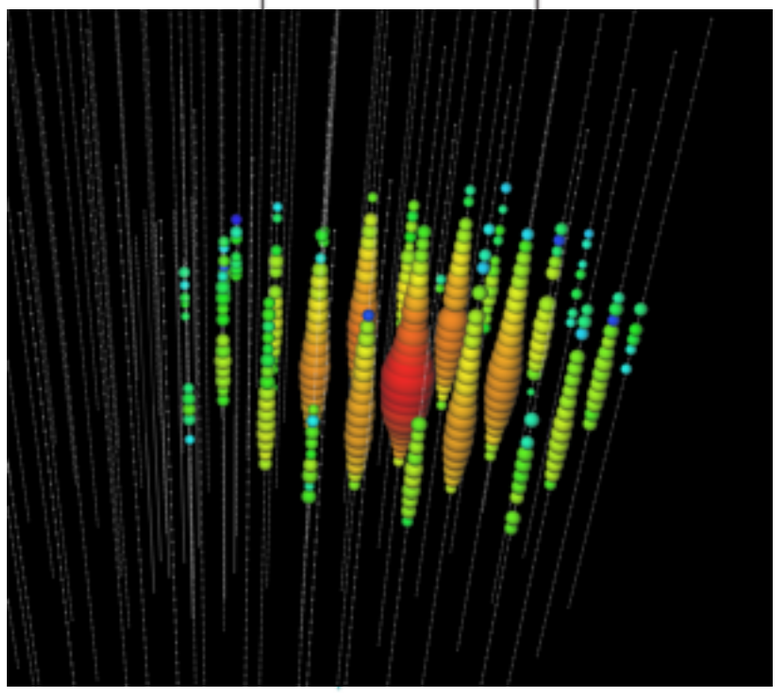


> **Shower-like event** signatures
(CC interactions of ν_e,ν_τ, NC interactions)

- **Angular** resolution: > 10°
- only **interactions inside** / close to the instrumented volume **visible**
- **Energy** resolution: up to 15% of neutrino energy.

Detection of high-energy neutrinos.





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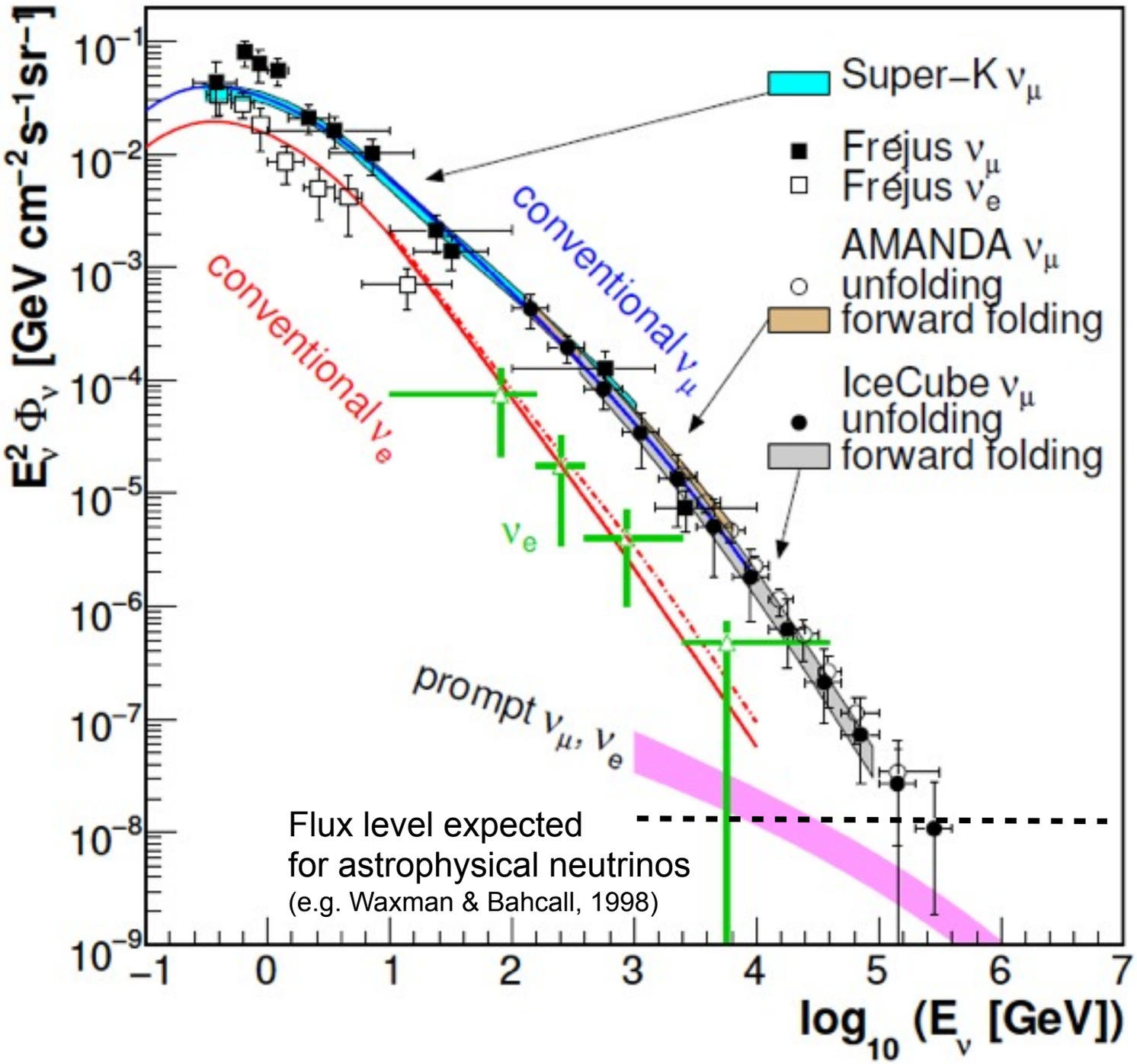
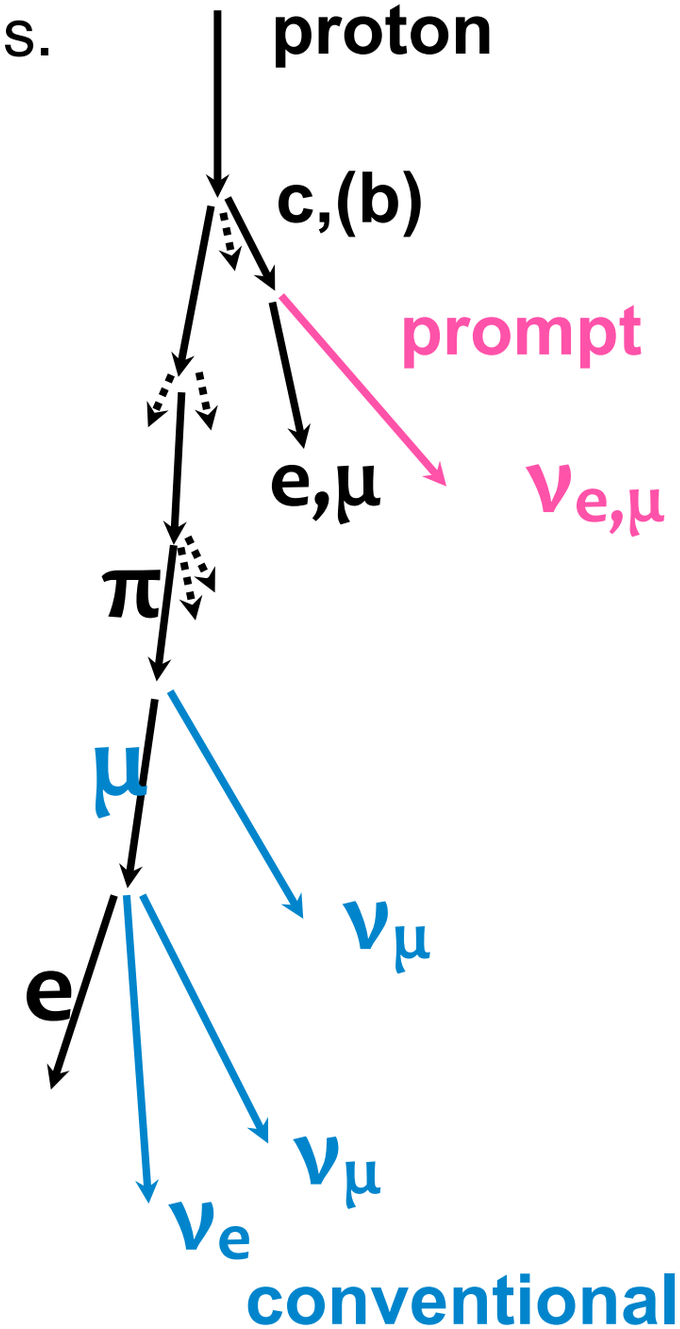
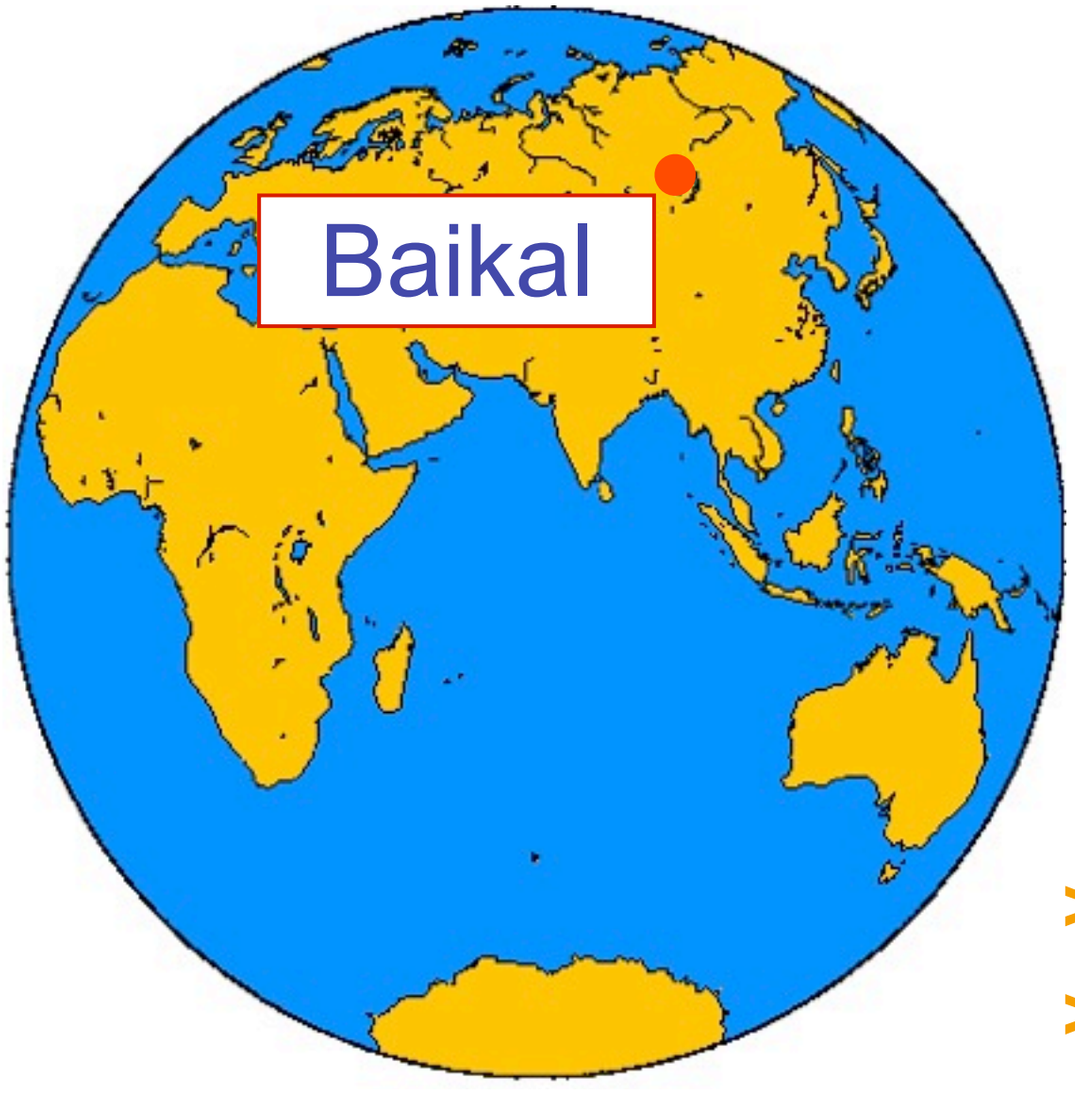
The atmospheric neutrino background.

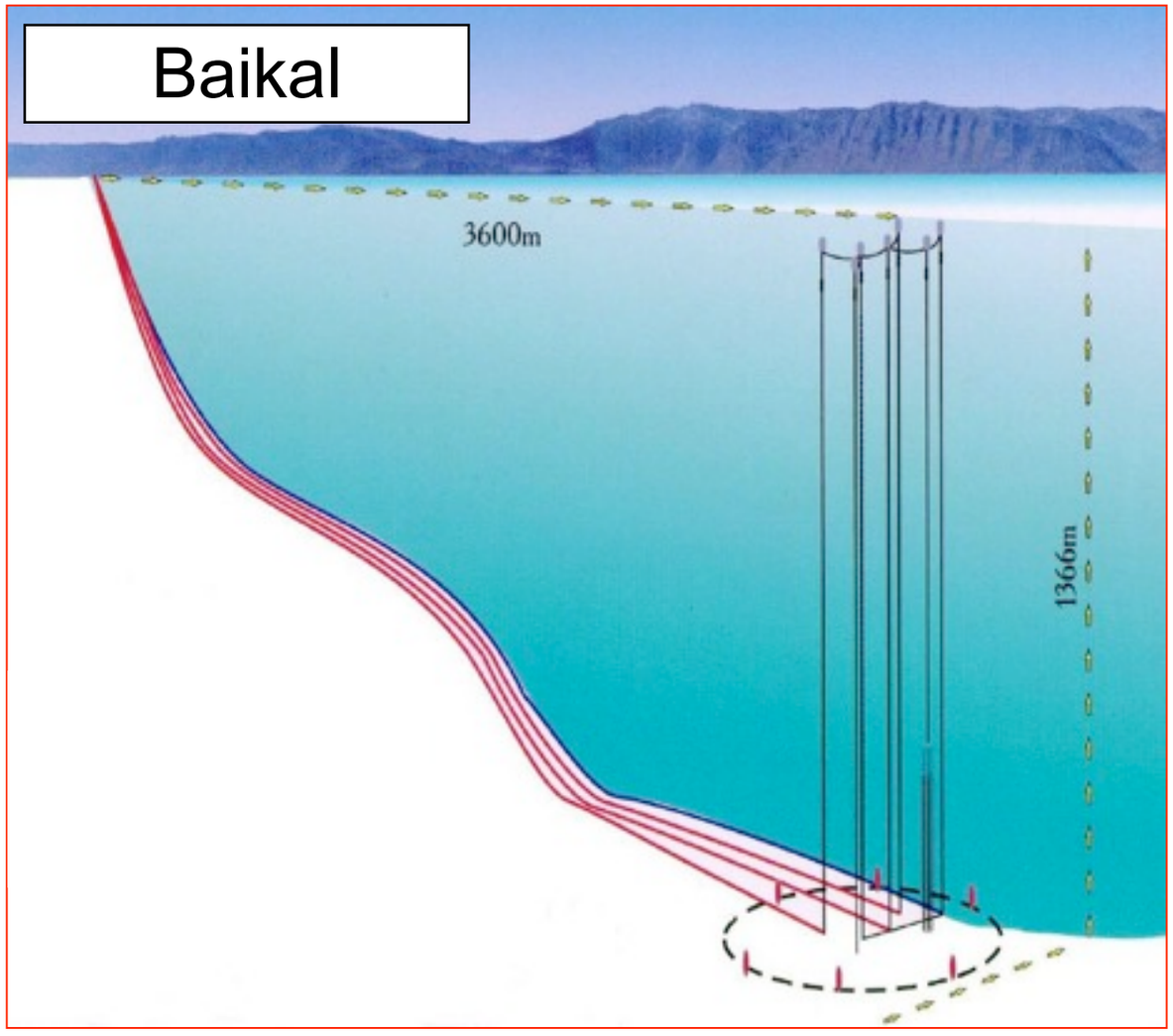
- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Atmospheric-ν are produced in **CR air shower interactions**.
- **"Prompt" component** from the decay of charm mesons.





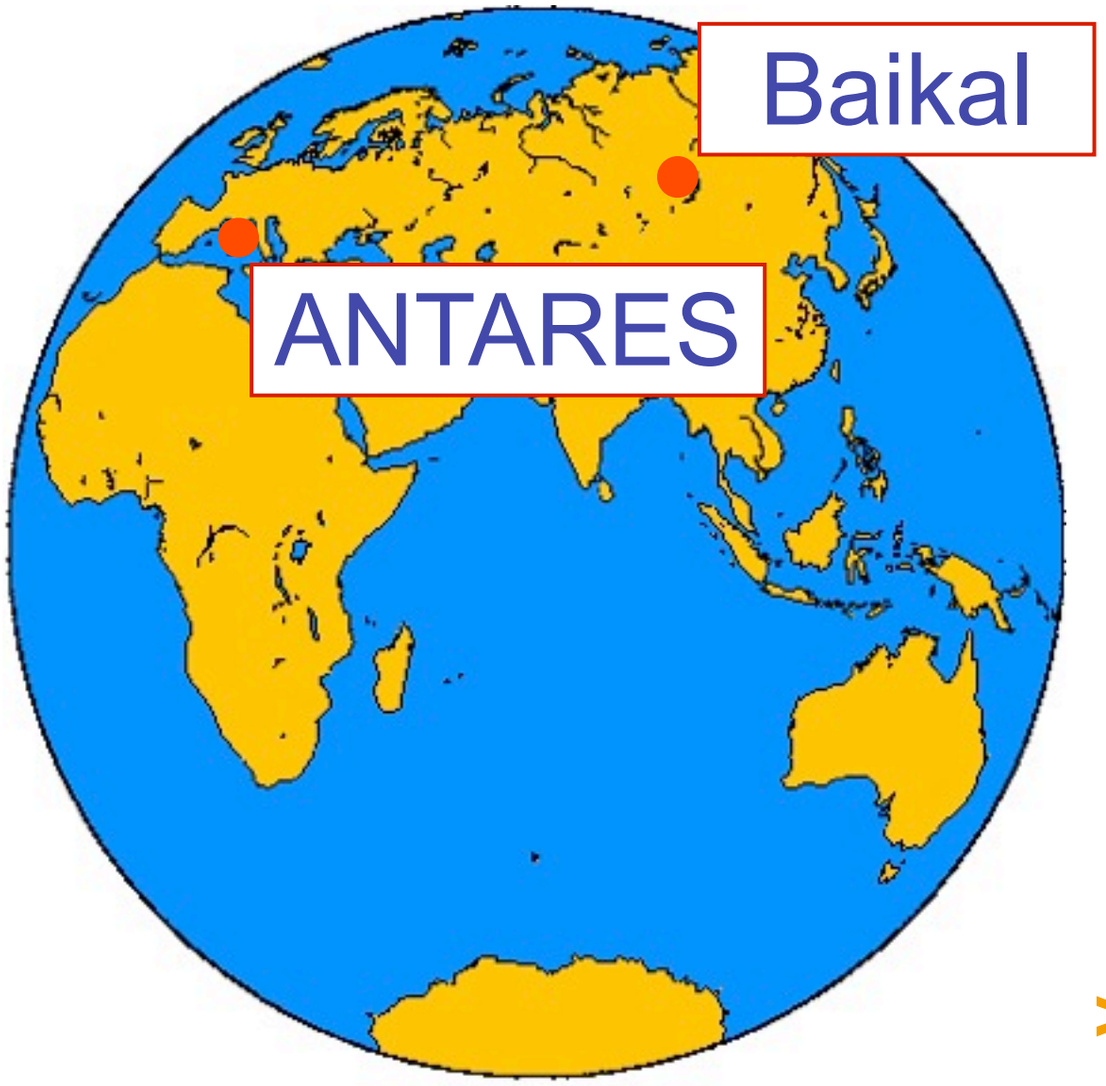
Operating neutrino telescopes: Baikal

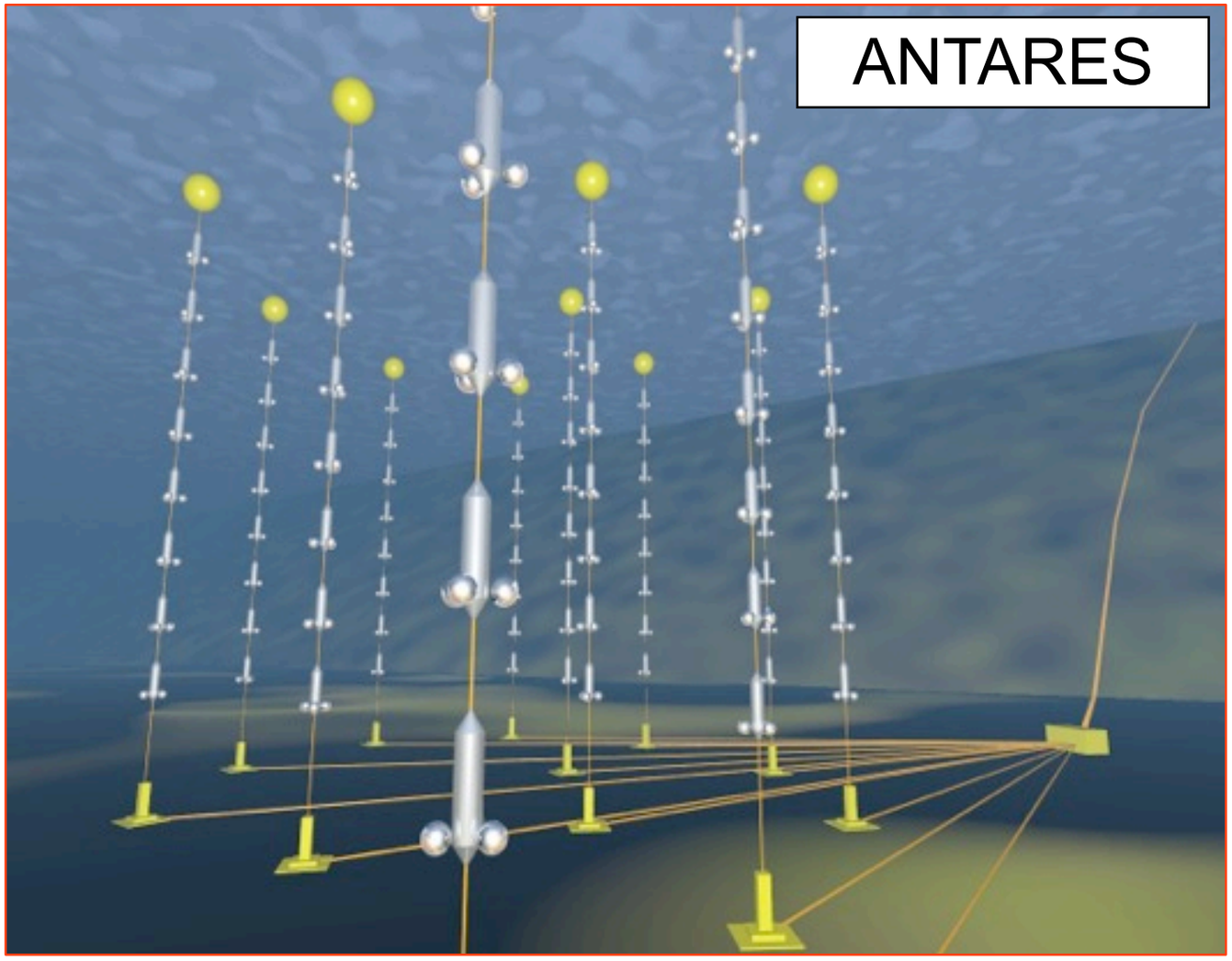




- ~ 4km off the shore of **Lake Baikal**
- **Completed** in **1998**
- 192 optical sensors on 8 strings
  (**10^{-4} km³** instrumented volume)
- Upgraded to NT200+ configuration in 2007
  (+18 sensors on 3 strings)

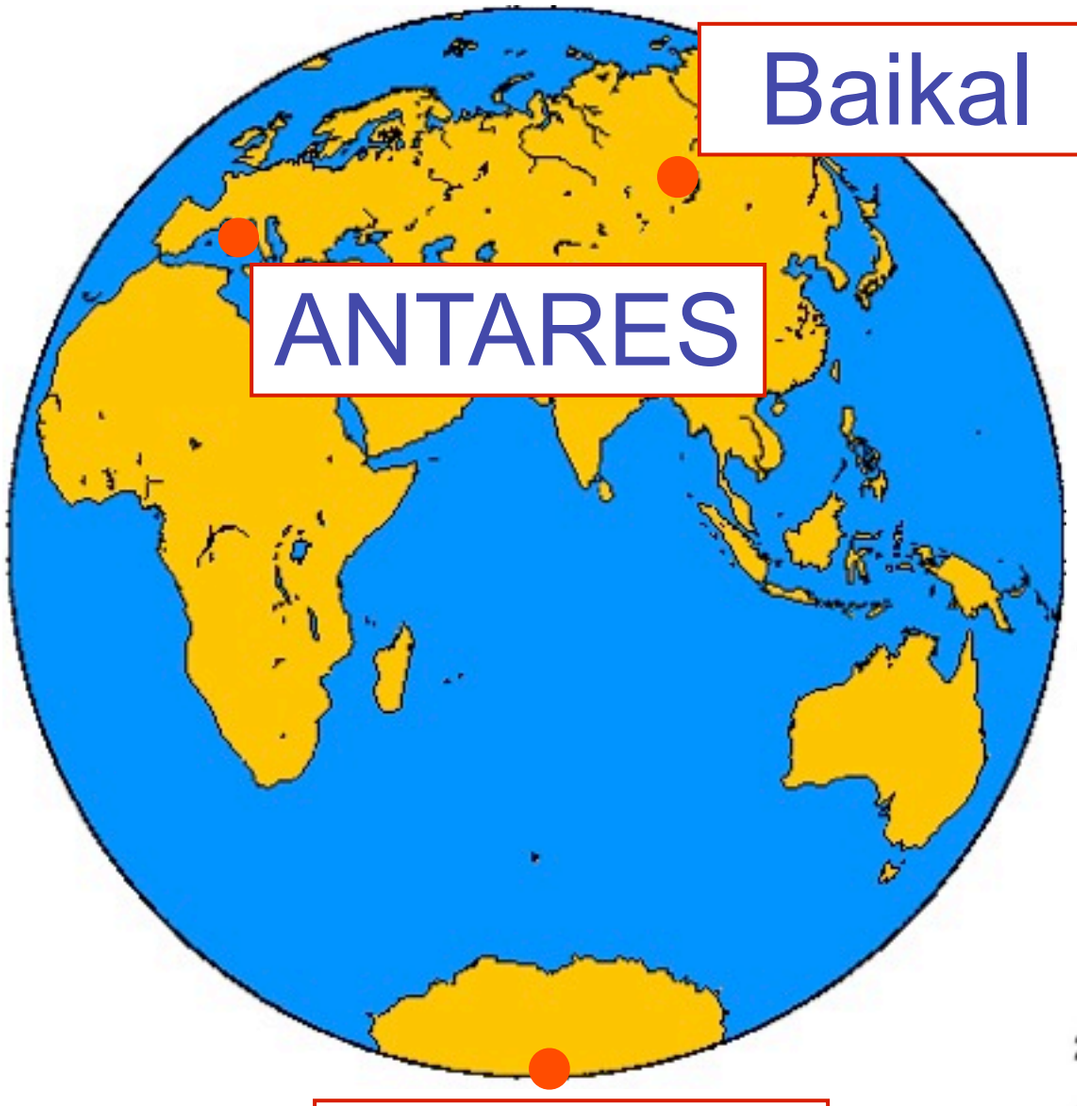
Operating neutrino telescopes: ANTARES

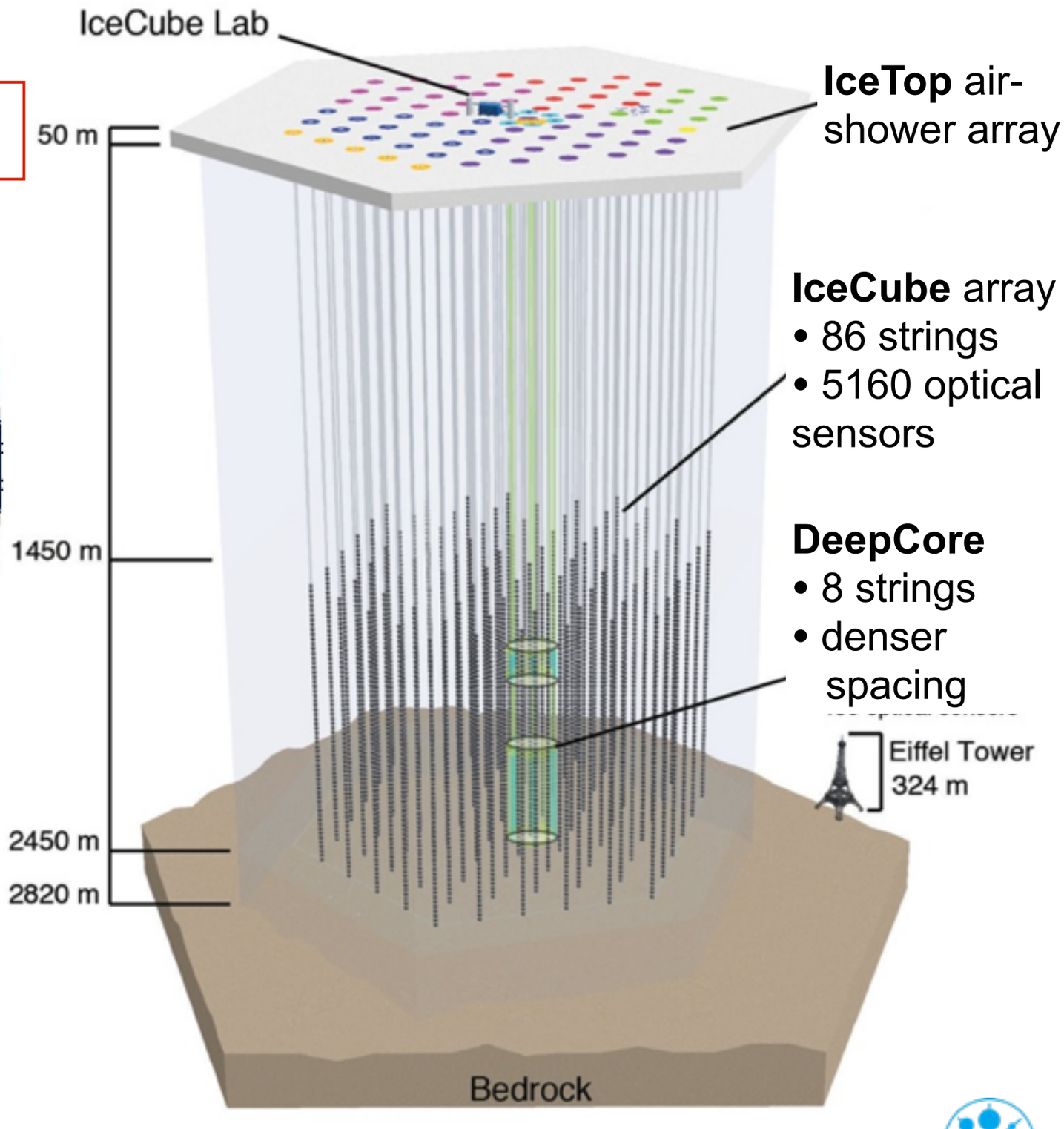




- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

Operating neutrino telescopes: IceCube



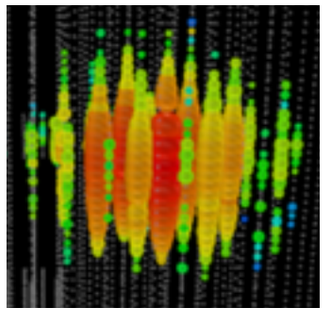


- **Completed** in Dec **2010**.
- Instrumented volume: **~ 1km^3**

High-energy neutrino astrophysics.

> Search for the **sites of hadronic acceleration.**

- Galactic and extragalactic sources.
- Transients (Gamma-ray bursts, flares of AGNs, periodic emission from binaries)

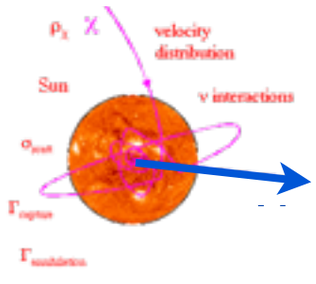


> Search for a **diffuse neutrino flux** from throughout the universe

- from unresolved sources
- from the interactions of ultra-high-energy CR

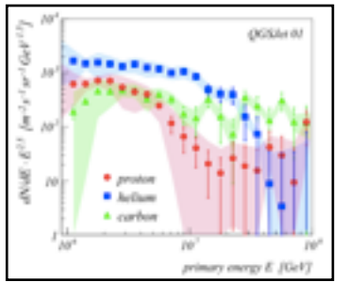
NOT covered in this talk: all the other great science with neutrino telescopes....

MeV neutrinos from SN

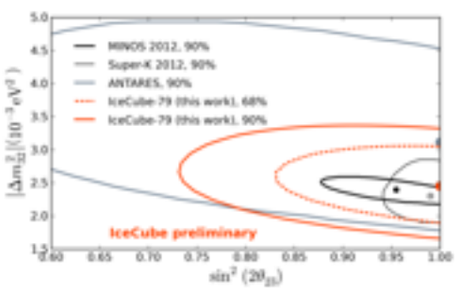


Search for WIMP annihilations

Search for exotic particles



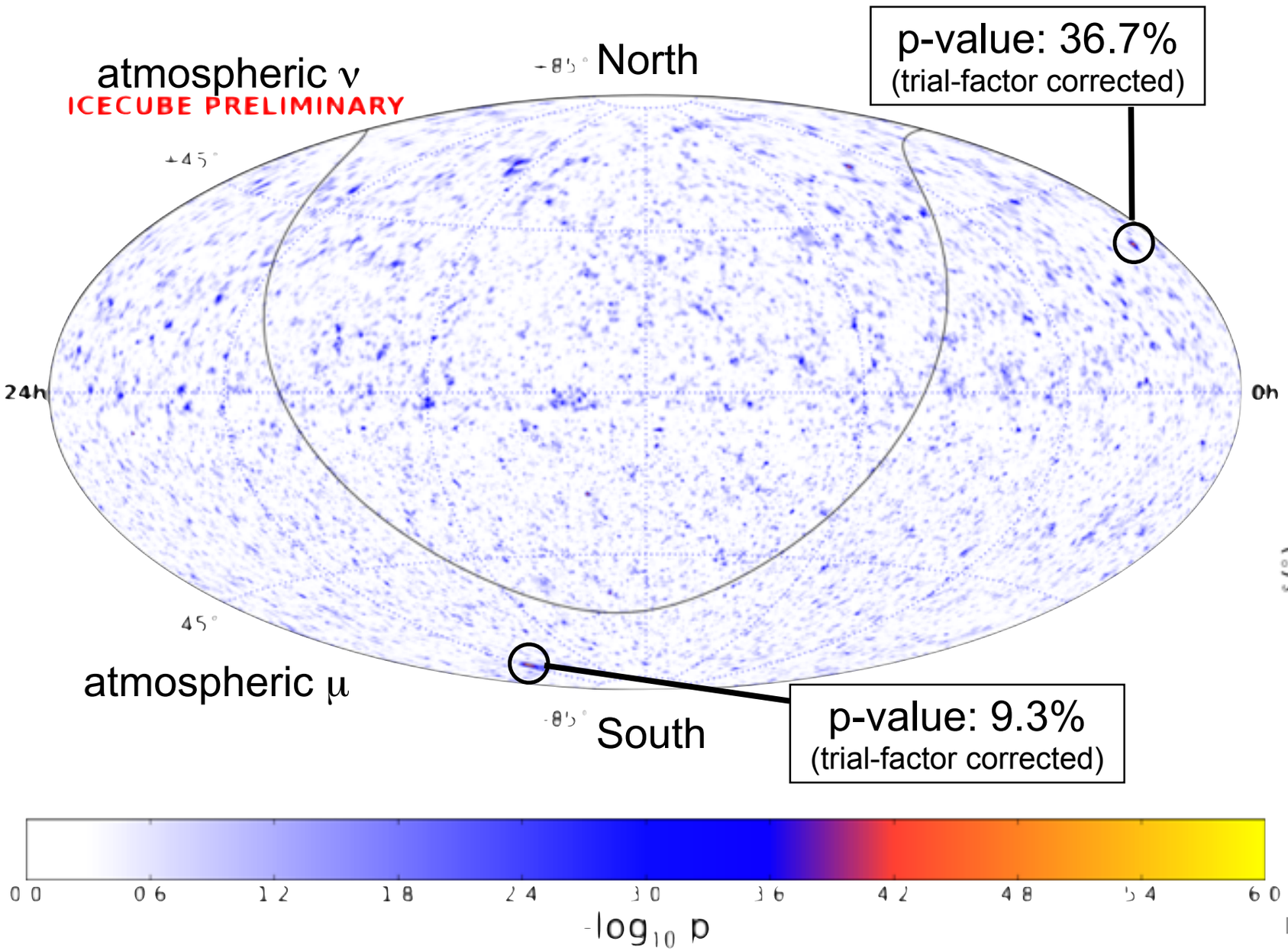
CR physics

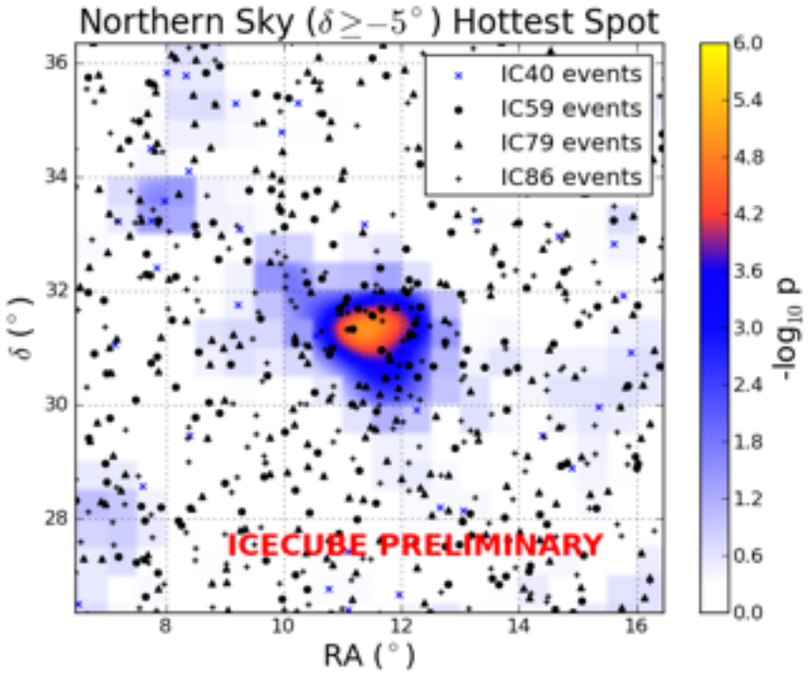


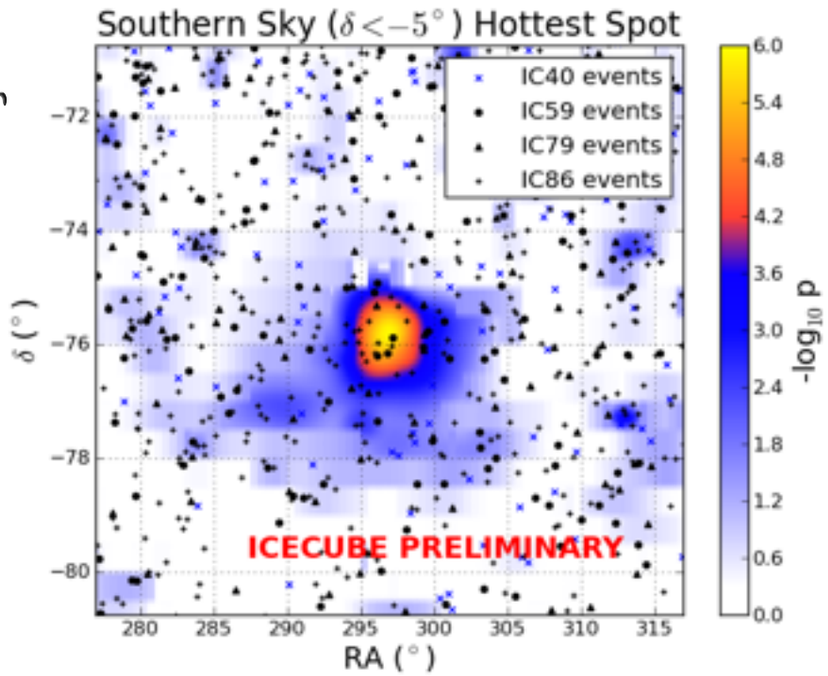
Neutrino properties

Search for individual neutrino sources: IceCube

- **4 years** of IceCube data (construction phase + full array)
- 1371 days of livetime, **394,000 events** total
  - **178,000 neutrino** candidates in the North
  - **216,000 atmospheric muons** in the South

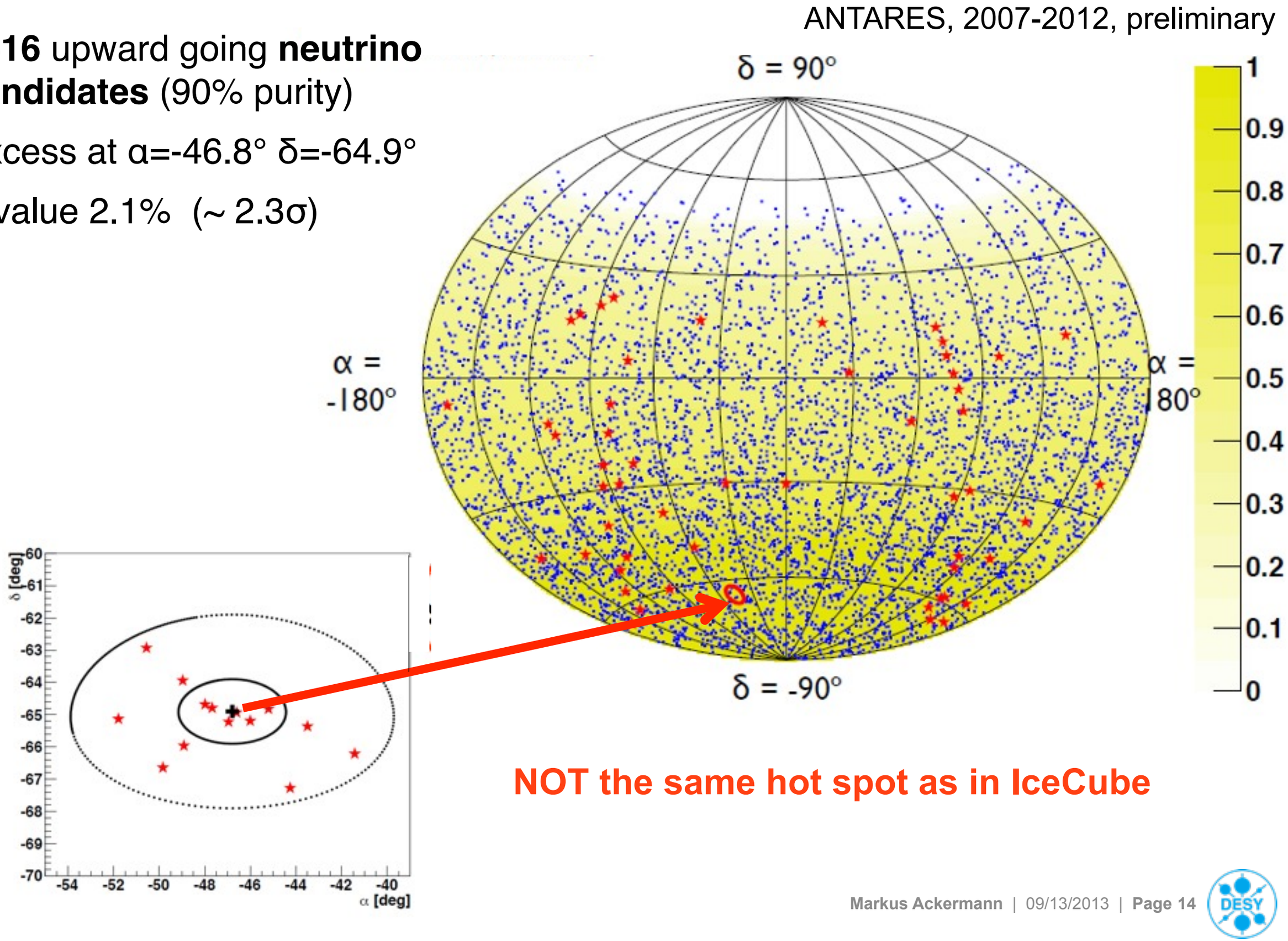






Search for individual neutrino sources: ANTARES

- **5516** upward going **neutrino candidates** (90% purity)
- Excess at α=-46.8° δ=-64.9°
- p-value 2.1% (~ 2.3σ)

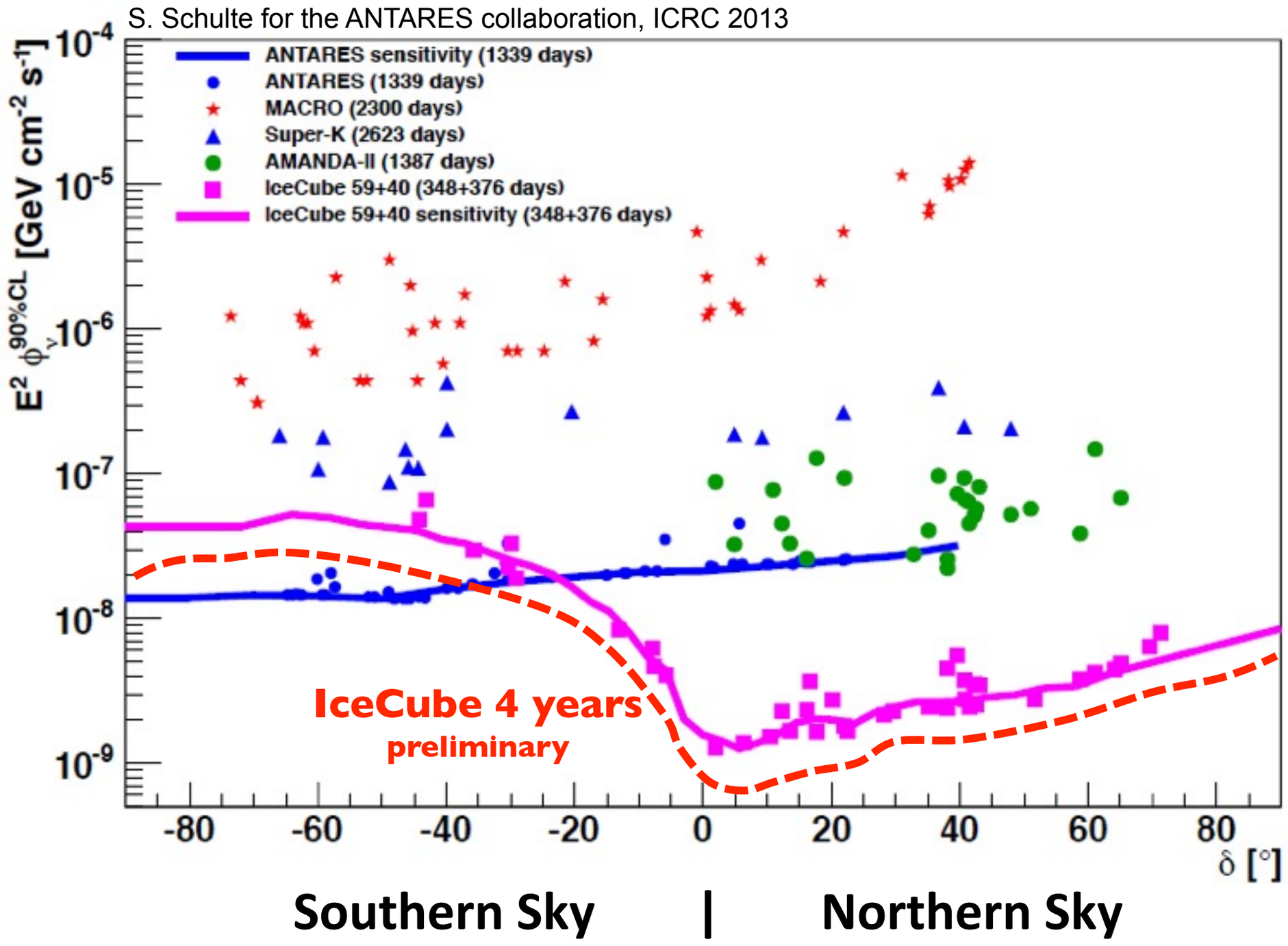


NOT the same hot spot as in IceCube

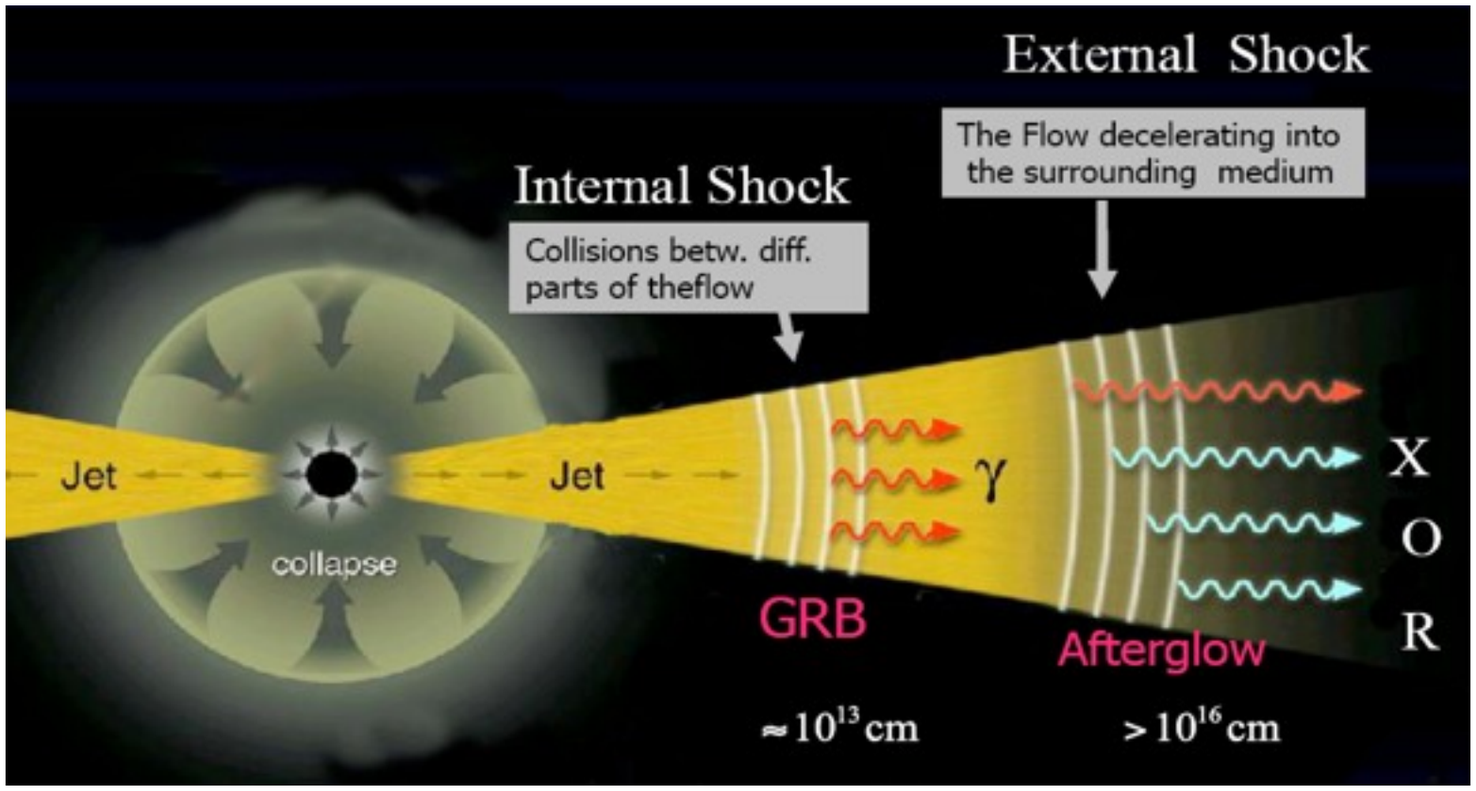
Upper limits on the neutrino flux from sources.

- **Factor 1000 increase** in sensitivity over 13 years.
- **No detections.**
- **ANTARES and IceCube** observations are **complementary**.

S. Schulte for the ANTARES collaboration, ICRC 2013

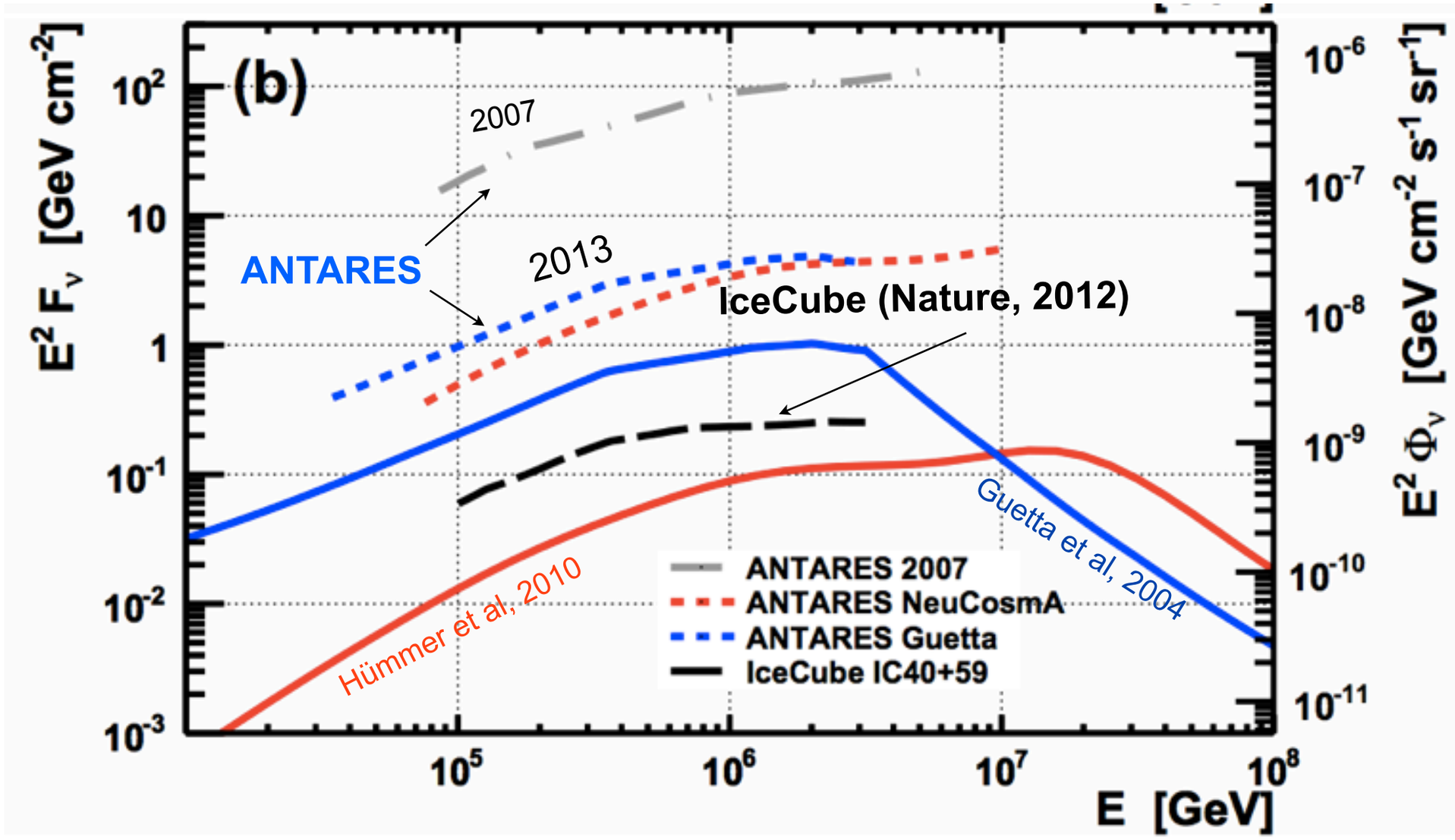


Search for neutrinos from transients: GRBs



- **GRBs** have been proposed as the **dominant acceleration site** for CRs up to energies > 10^{20} eV.
- Accompanying **neutrino emission** should be **visible in km³-sized** neutrino telescopes in a wide variety of scenarios.
- Search for **cumulative signal** from all observable bursts.

Search for neutrinos from GRBs.



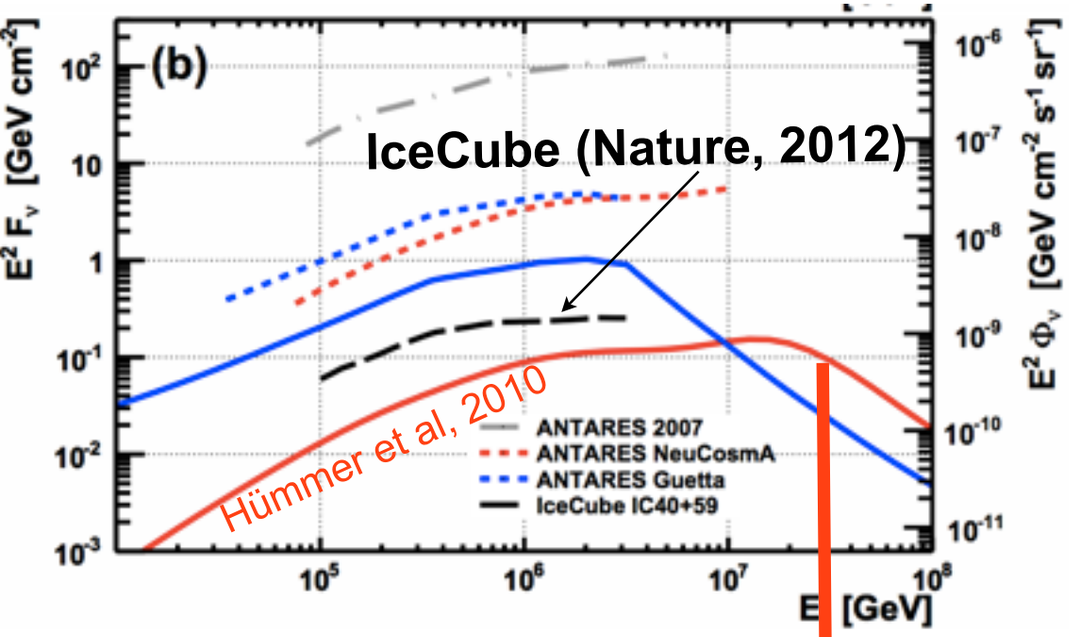
IceCube

- **225 GRB** at Northern sky
- 2 years of IceCube construction phase data
- No significant correlation found between IceCube events and GRBs.

ANTARES

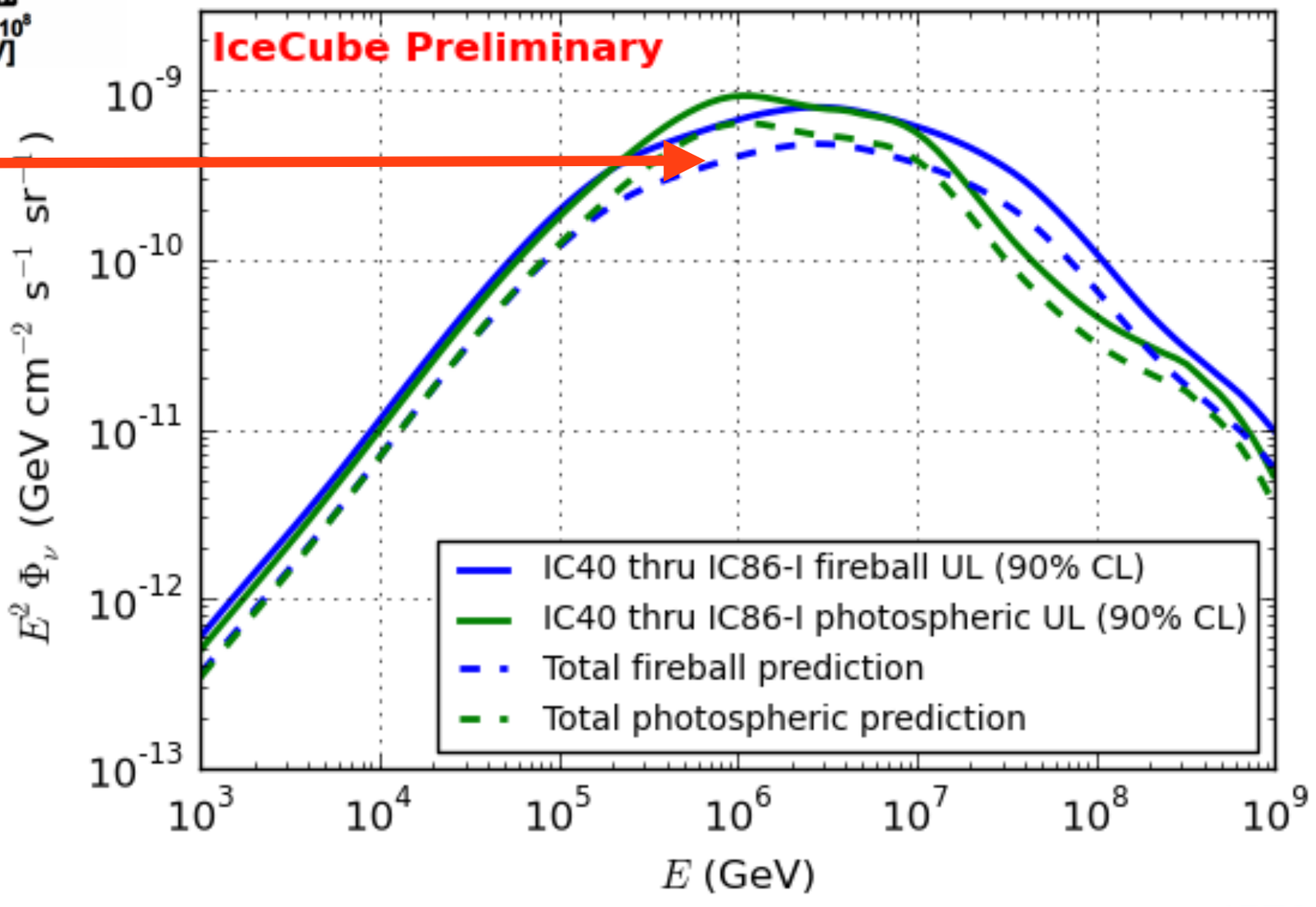
- **296 GRB at** Southern sky
- No ANTARES event in time and direction coincidence (arXiv:1307.0304)

Search for neutrinos from GRBs.



- Neutrino flux prediction is individually modeled for each GRB
- More sophisticated calculations of neutrino production in GRBs lead to a lower flux prediction.

- **New upper limits** from the analysis of 568 GRBs (4 years of IceCube data)
- Limits close **to corrected flux** predictions.



Searches for other transients.

- Specific searches for transient enhance the sensitivity through improving signal/noise.

- Flares o**f Active Galactic Nuclei**:
  - Correlation with Fermi light curves
  - ToO observation program with IACTs.

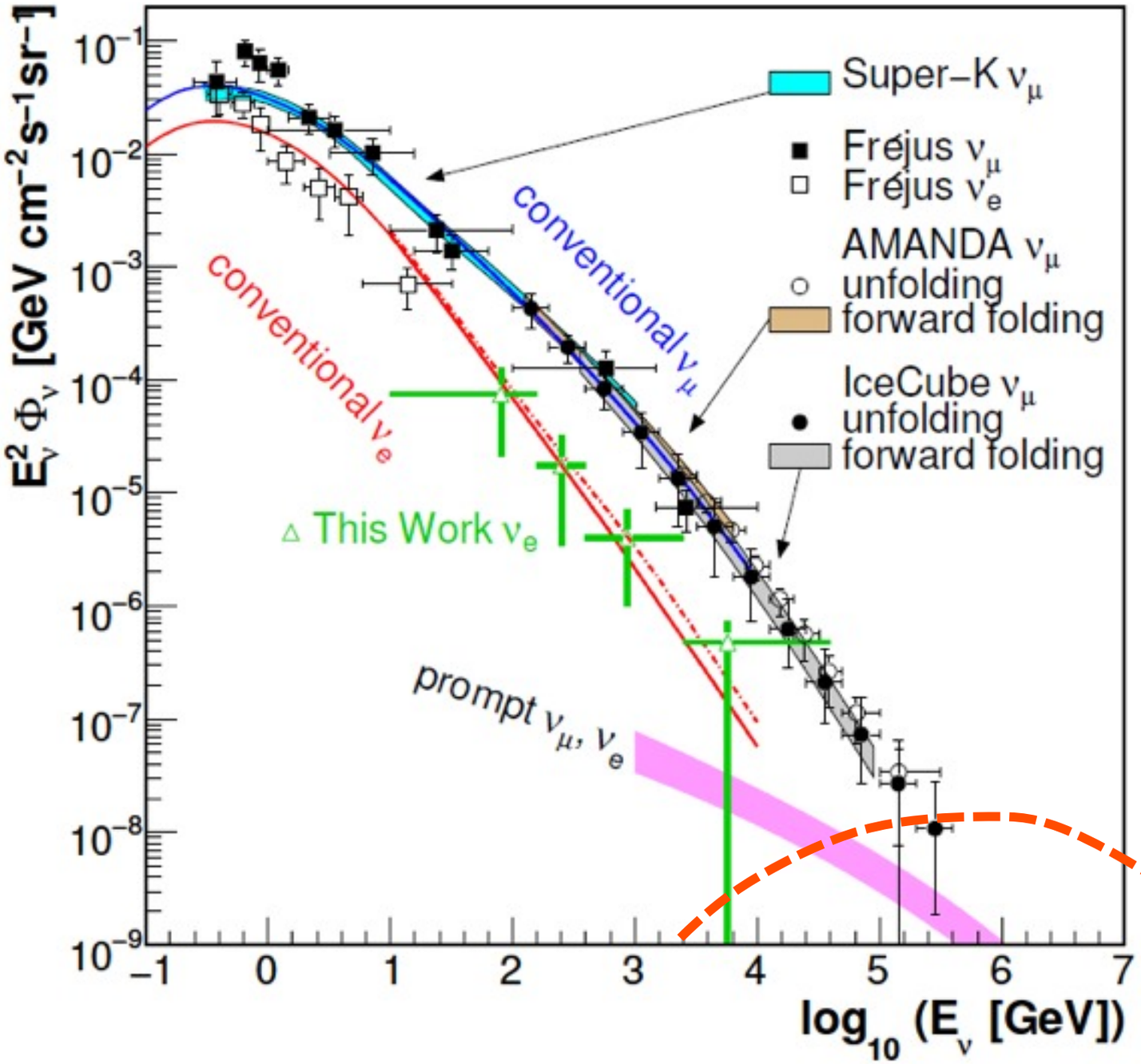
- **Periodic sources** / Binaries:
  - Phase resolved analysis of neutrino events from periodic sources.

- GeV/TeV neutrinos from **extragalactic SNe**:
  - Neutrino-triggered follow-up observations with optical telescopes.

- The **unexpected**:
  - Search for space/time clustering of neutrino events.

- **No significant detection** yet in any of these searches.

Search for diffuse astrophysical neutrinos.



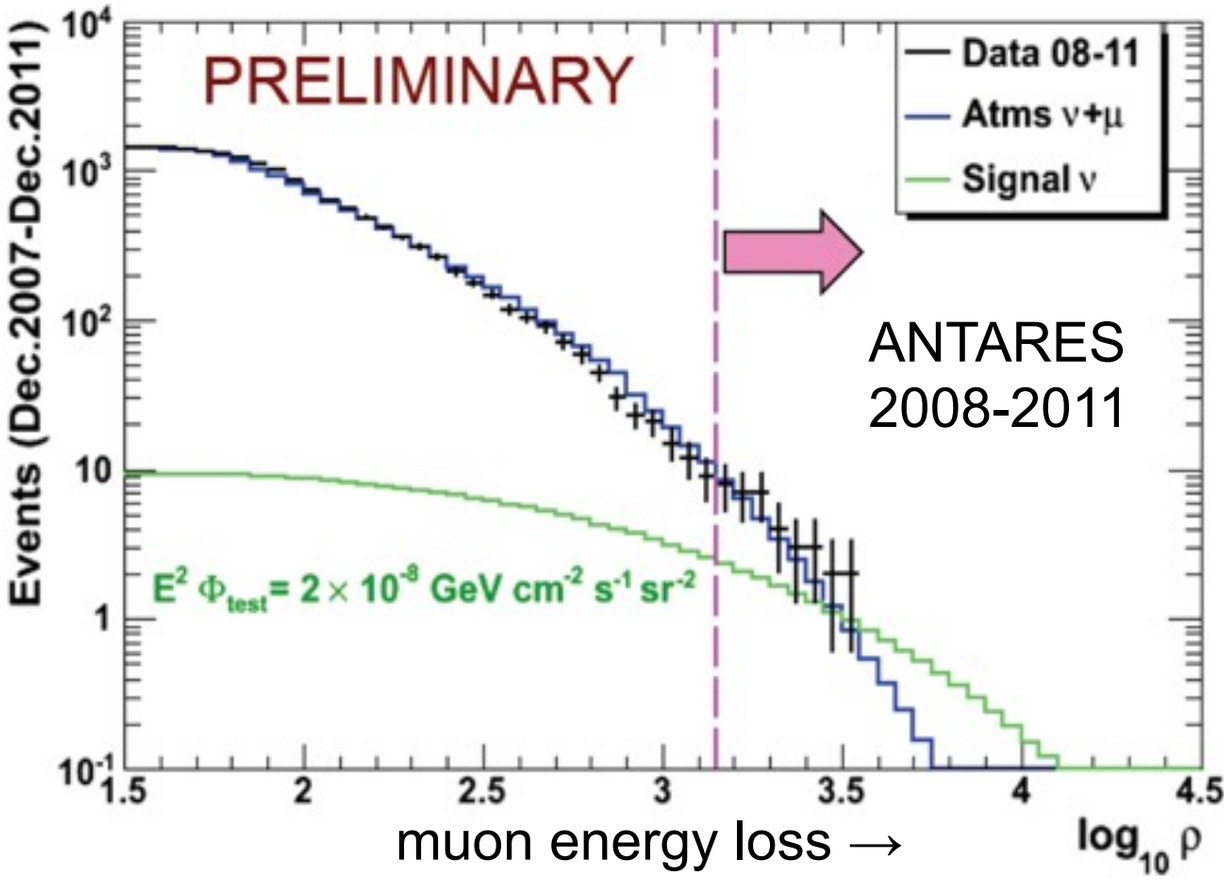
> Search for a **diffuse excess** of neutrinos over background from atmosphere at high energies.

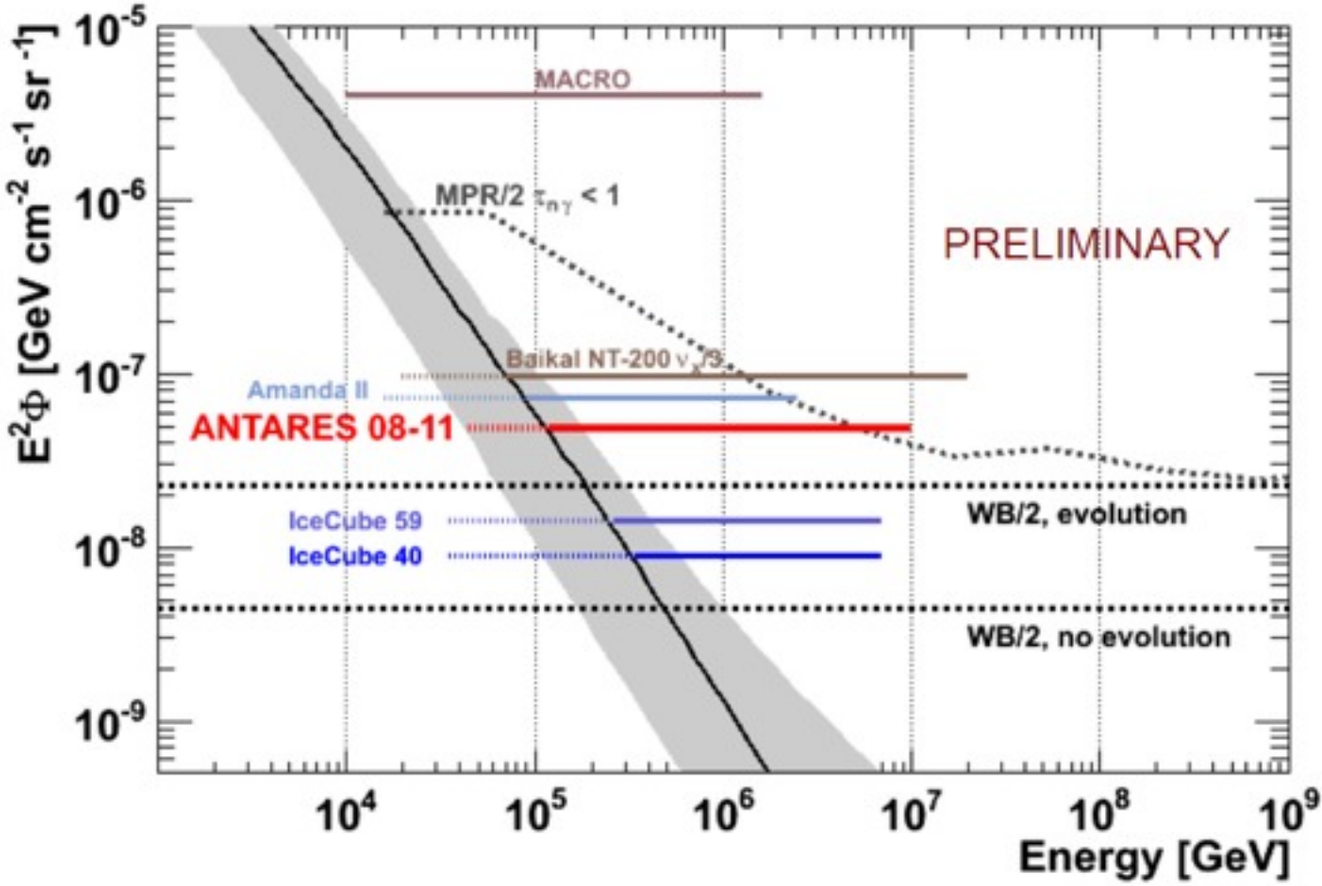
- From unresolved neutrino sources
- From the interactions of CR with the extragalactic background light

> **Lower** atmospheric **background** for **shower-type** events (ν_e + NC ν_μ only)

extraterrestrial neutrinos ?

Upper limits on the diffuse flux of atmospheric neutrinos.



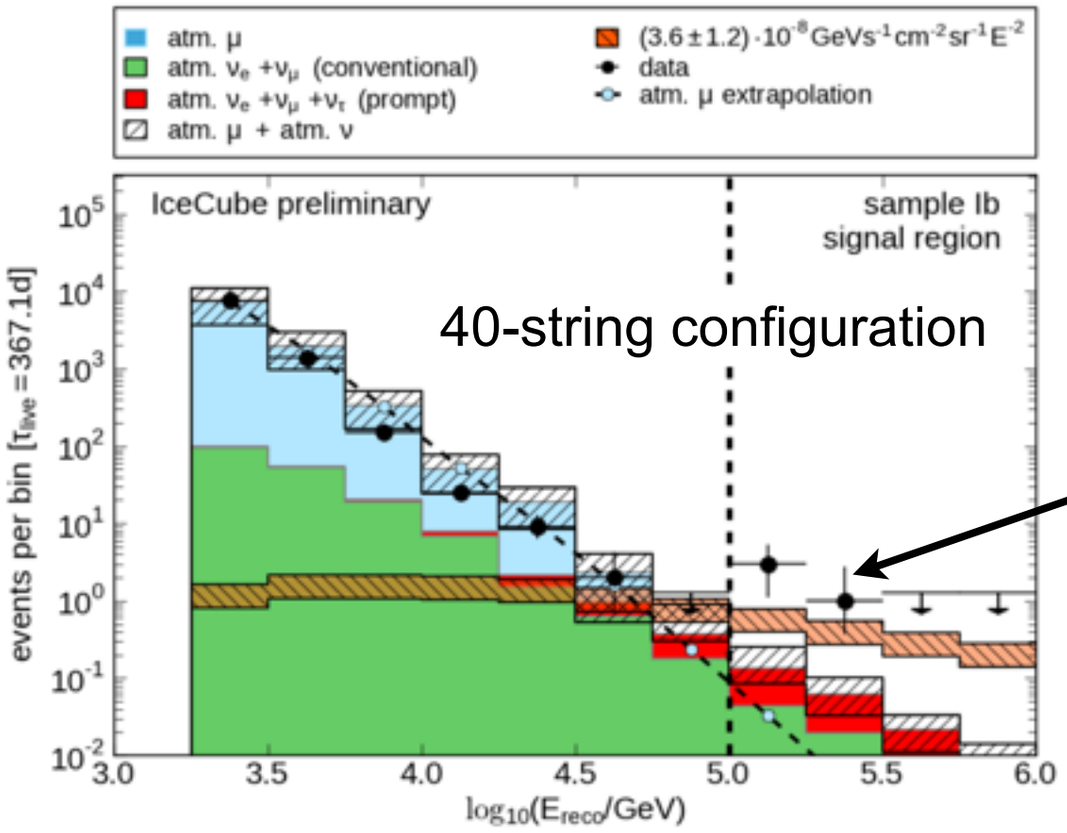


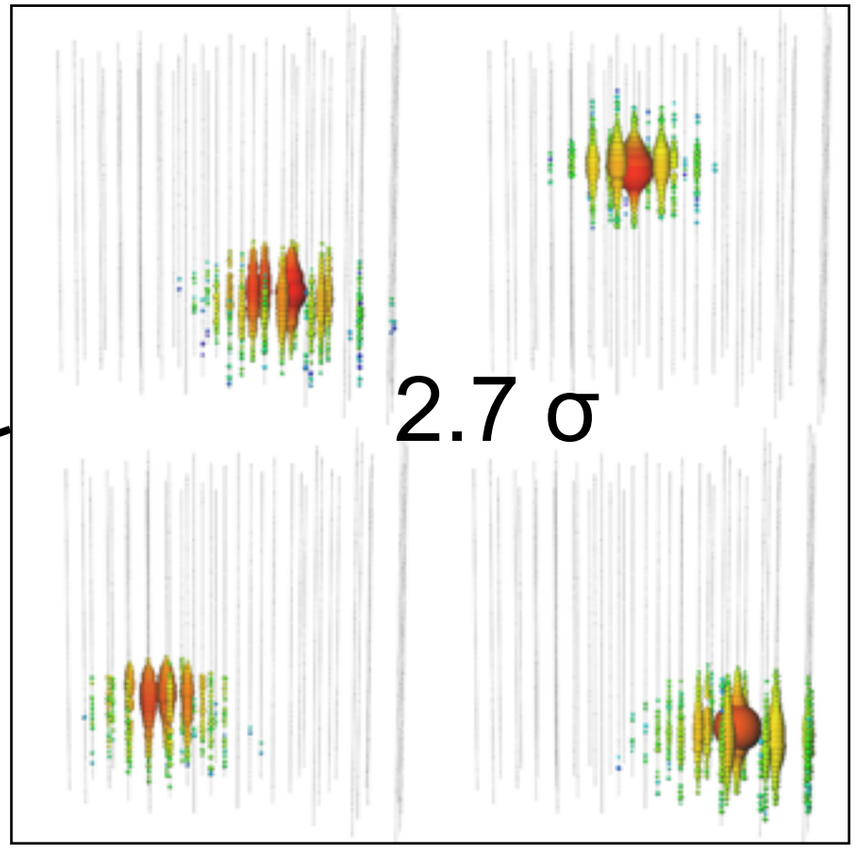
- Search for high-energy excess in the muon energy loss spectrum.

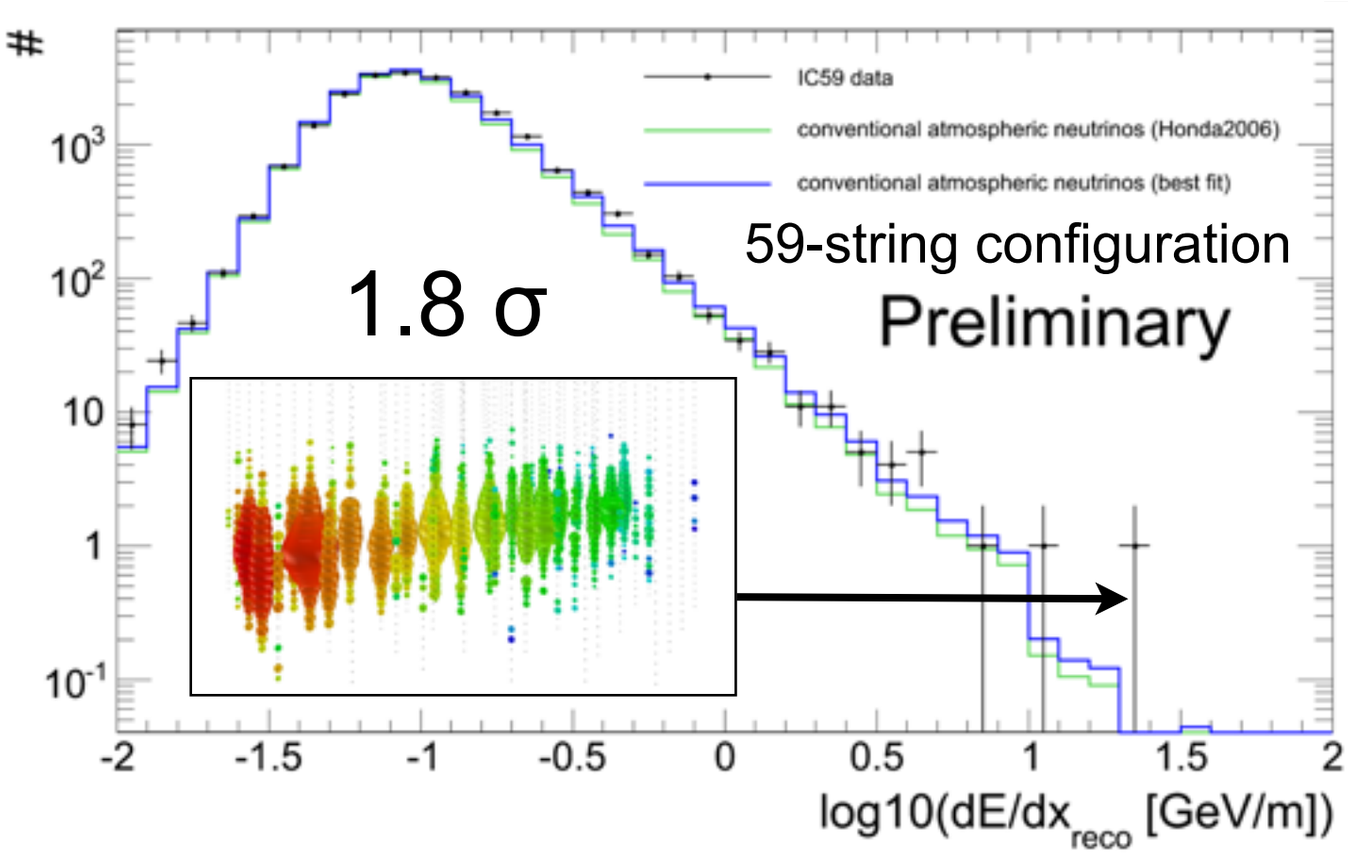
- Upper limits on astrophysical flux:
  - ANTARES (2008 - 2011)
  - IceCube construction phase

see talks by M. Spurio, J. Schnabel

Indications for excess from IceCube construction phase data.



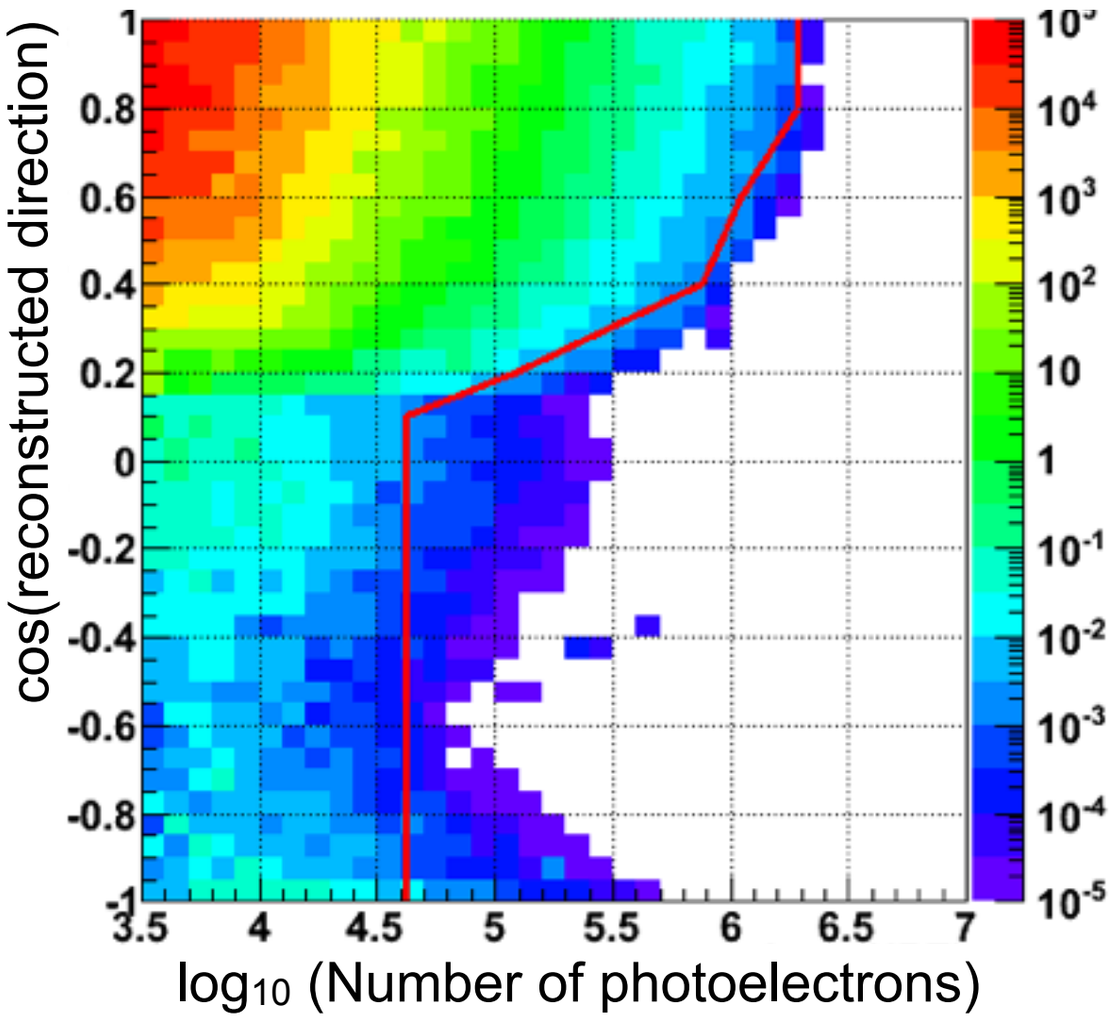


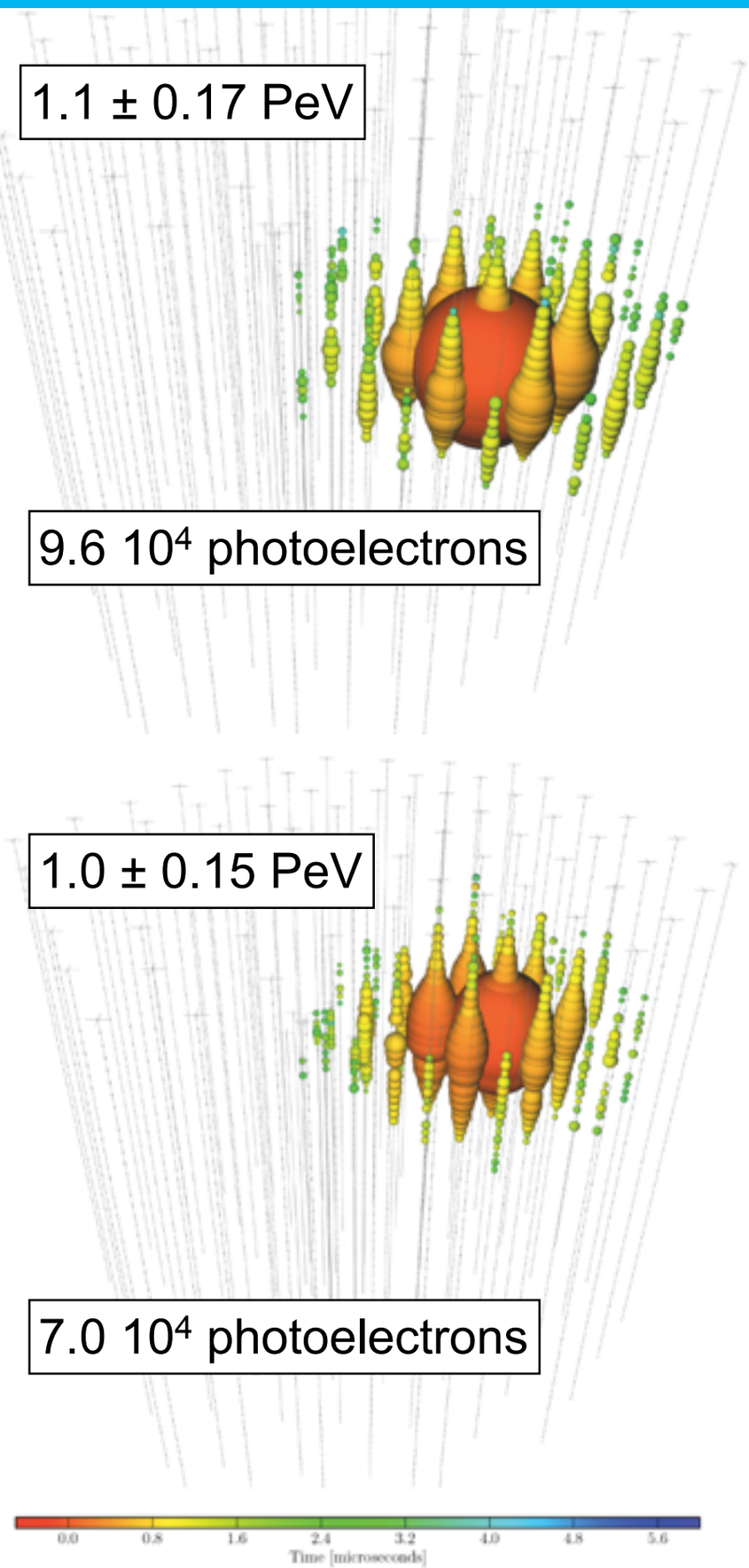


- **Excess events** observed in analysis of **construction phase** data
  - 4 shower-type events observed above 100 TeV.
  - ~ 200 TeV neutrino-induced muon.
- **Low significance** → Could be background fluctuation or emerging signal.

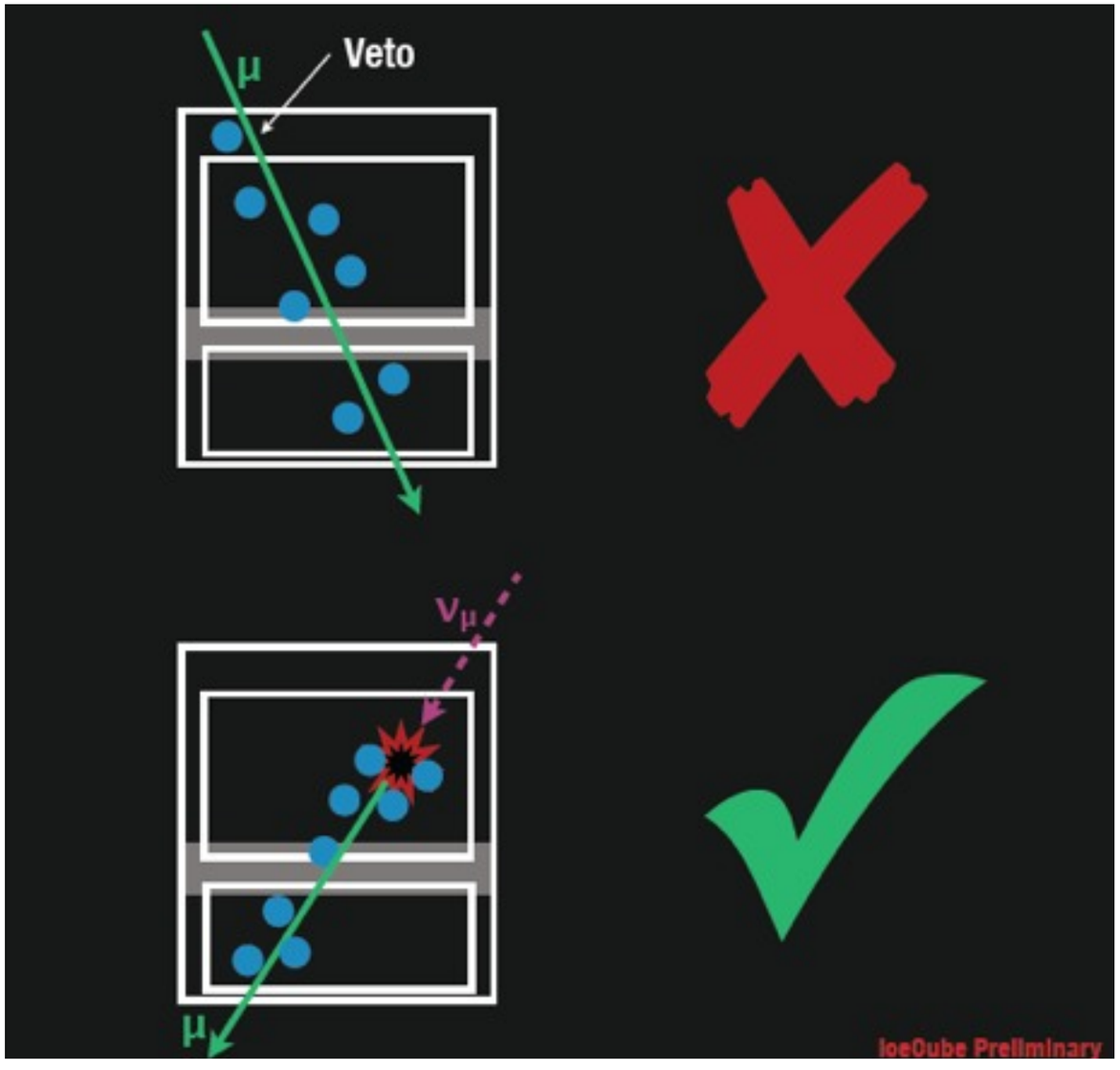
Search for bright events with 2 years of IceCube data.

- 79-string and 86-string configurations.
- **Optimized** for **cosmogenic neutrinos** of EeV energies.
  Cosmogenic = produced in interactions of ultrahigh-energy CR with the CMB/background light.
- **2 events** just above threshold.
- **2.8σ excess** above expected atmospheric-ν flux.

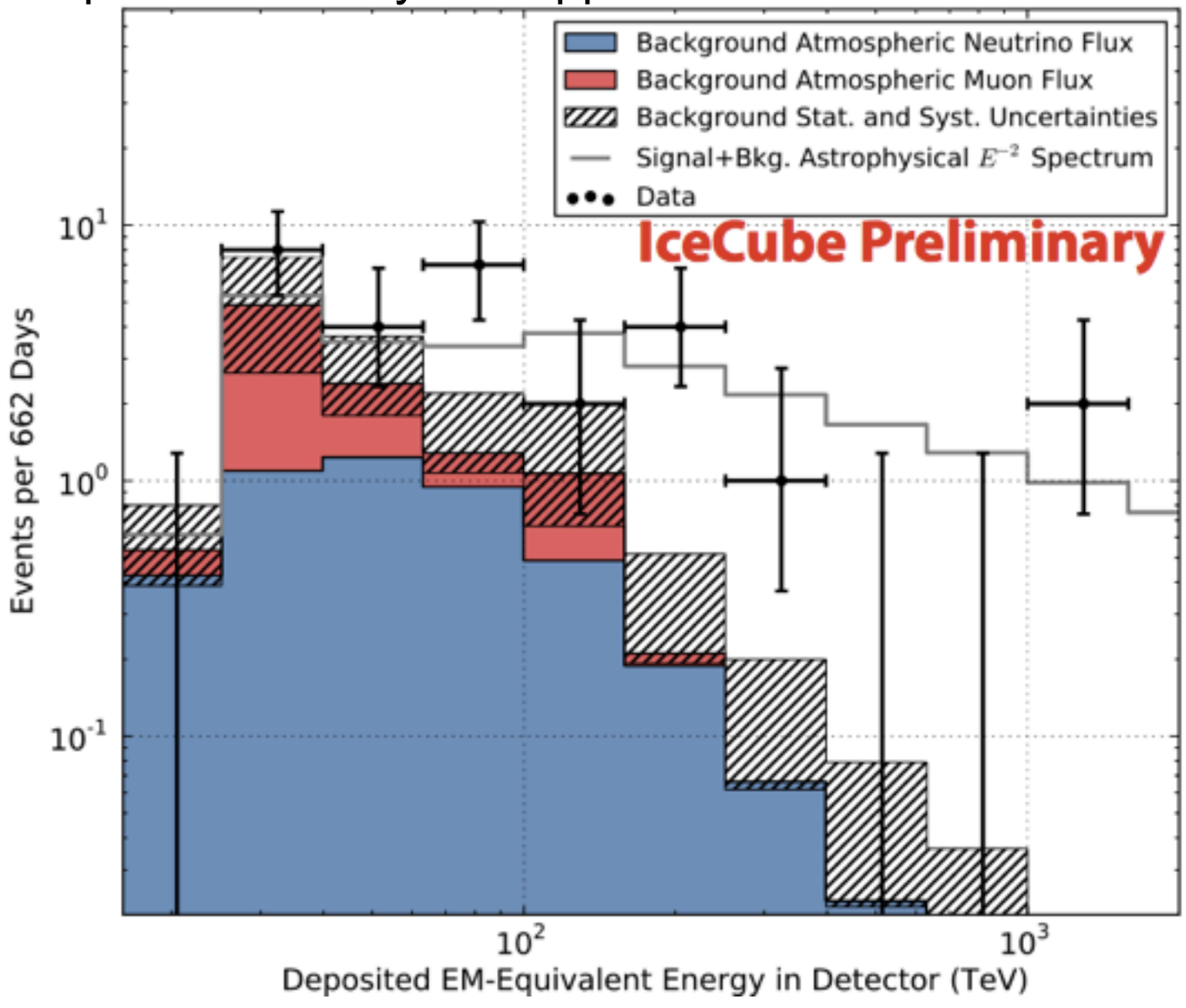




Search for a diffuse astrophysical flux.



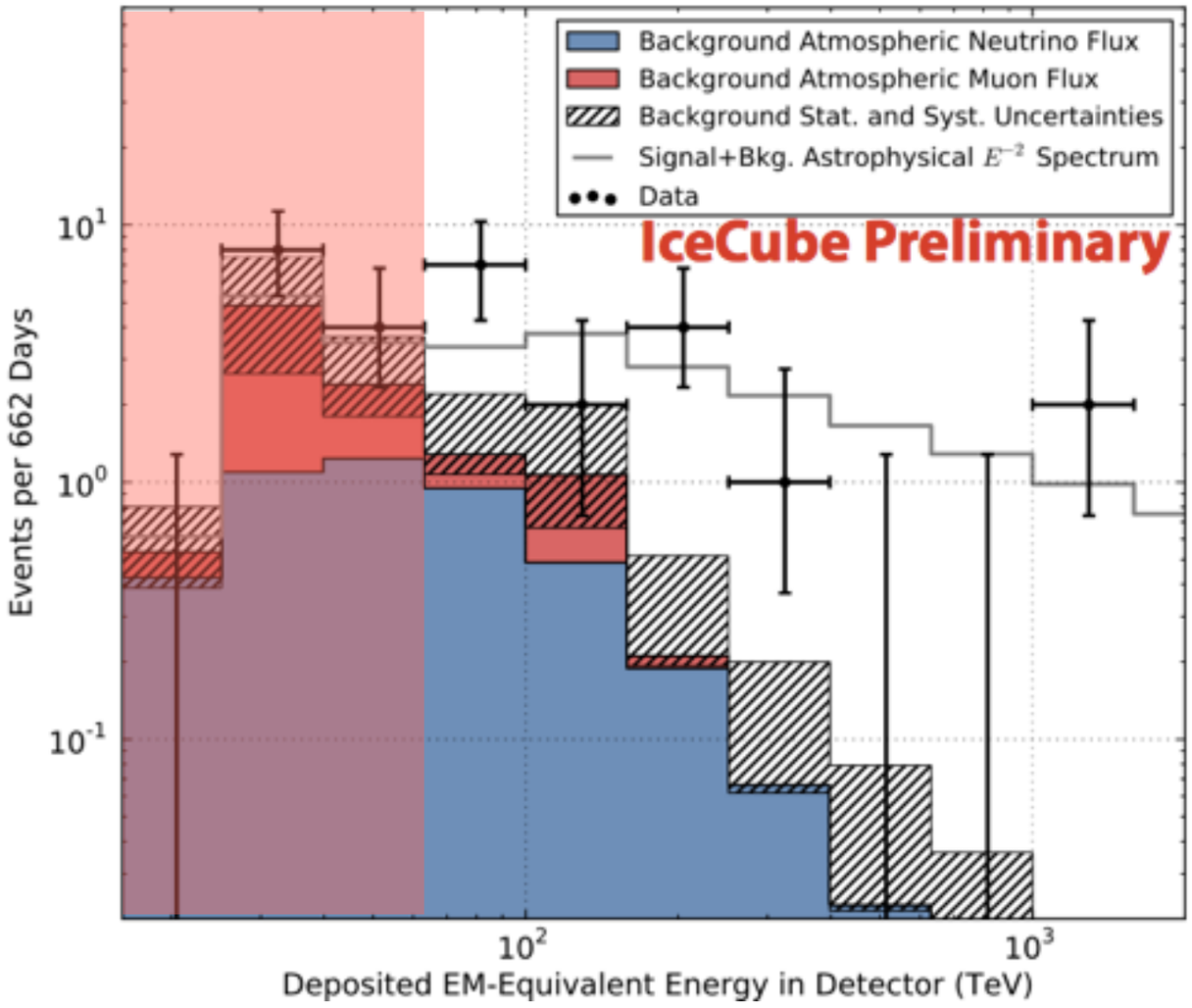
see presentation by C. Kopper



- **Extension** of previous search to **lower energies** (~ 30 TeV energy threshold)
- **New strategy** to reject CR background.
- **28 events** found in 2010-2012 dataset.
- **4.1σ excess** over expected backgrounds from atmospheric μ / ν

Spectral and angular distribution.

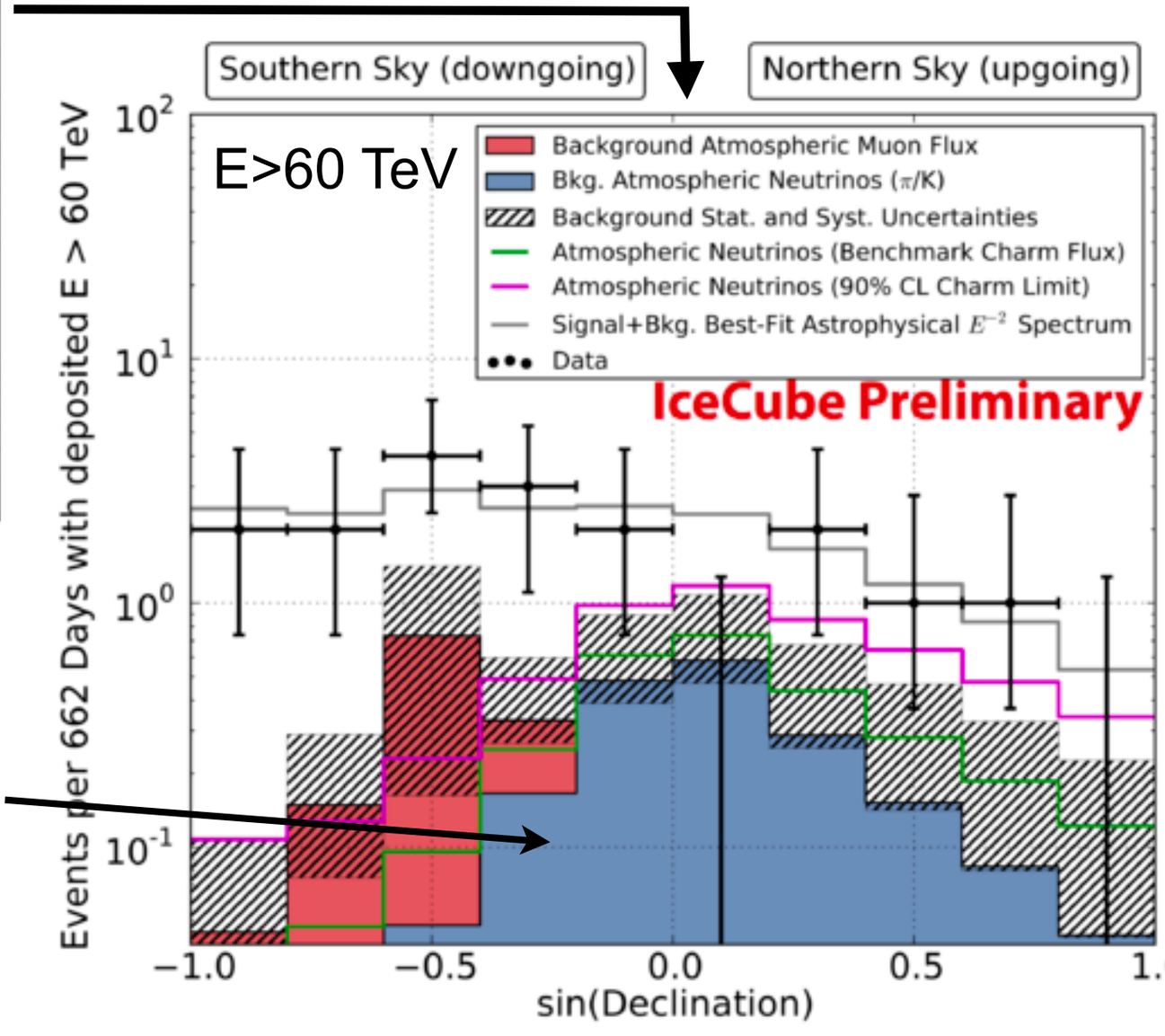
see presentation by C. Kopper



> **Spectrum** and **zenith distribution** compatible with an astrophysical flux with a power-law spectrum ($\Phi \sim E^{-2}$) between 60 TeV and 2 PeV.

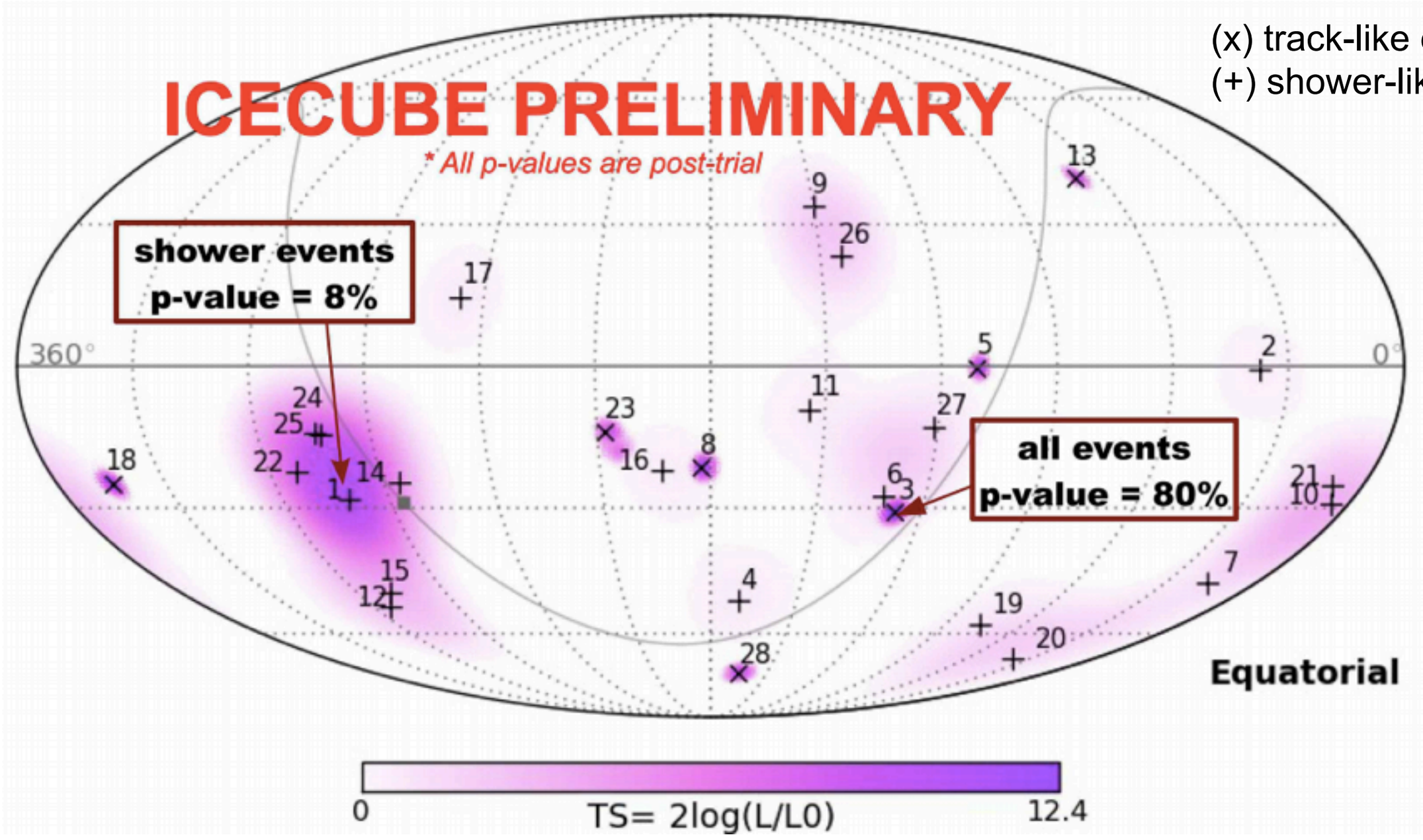
Atmospheric neutrinos on southern hemisphere suppressed by "self-veto":

- p + air → X + ν_μ + ν_e + ... + μ
- high-energy μ from shower triggers veto



Distribution of high-energy neutrinos on the sky.

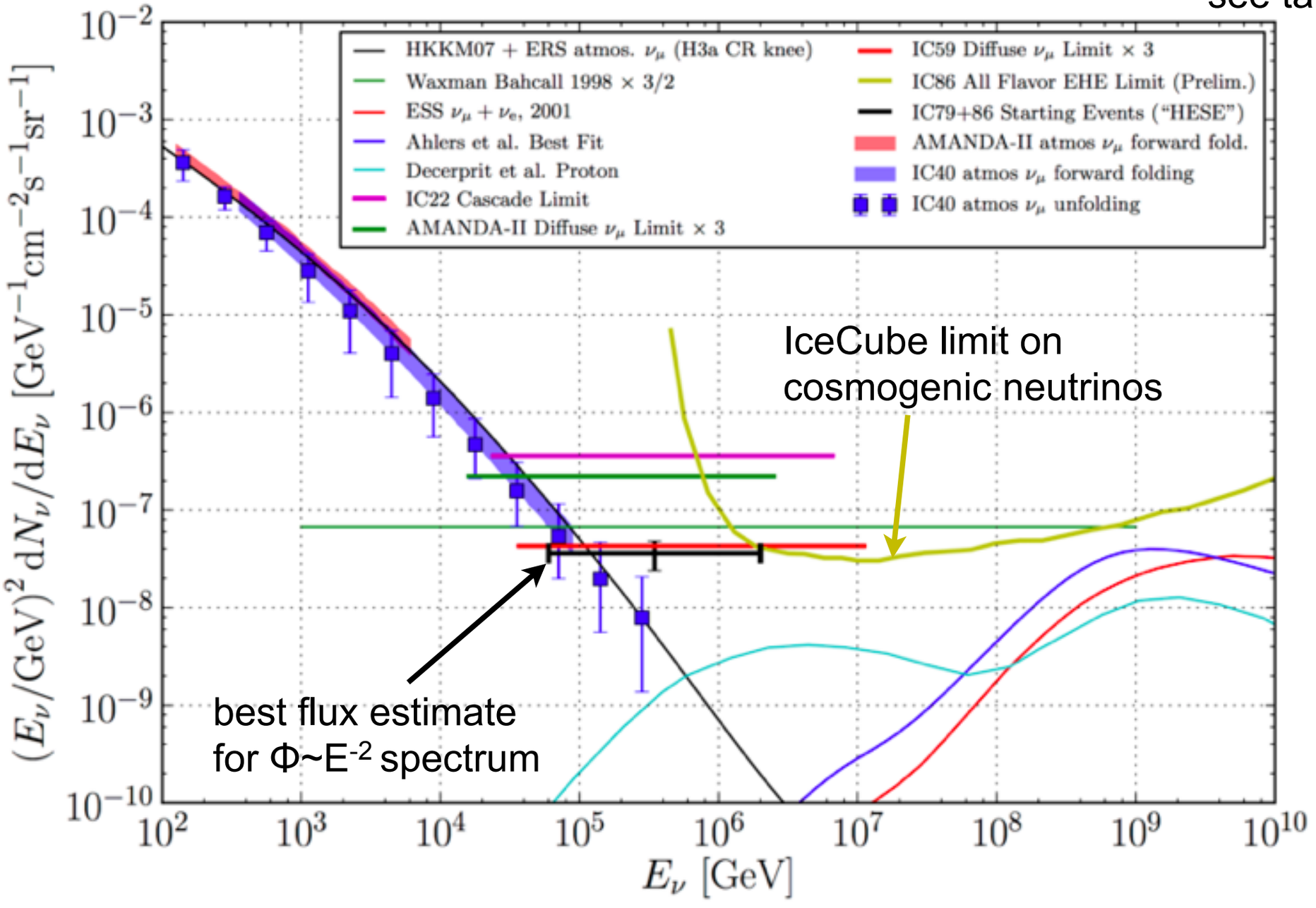
(x) track-like event
(+) shower-like event



- **Event distribution** compatible with expectations from background + isotropic astrophysical flux.
- **No significant correlation** in space/time with GRBs found.
- **More statistics needed** to distinguish different hypotheses of astrophysical origin.

Searches for diffuse astrophysical and cosmogenic neutrinos.

see talk by M. Ahlers



- Observed excess is **too low in energy** to be of **cosmogenic** origin.
- IceCube starts to probe the phase space of cosmogenic neutrino models.

A global spectral fit to all IceCube data.

see talk by L. Mohrmann

Hypothesis:

$\phi_{astro} \sim E^{-2} \cdot \exp(E/E_{cut})$

Goodness-of-fit:
7.8 %

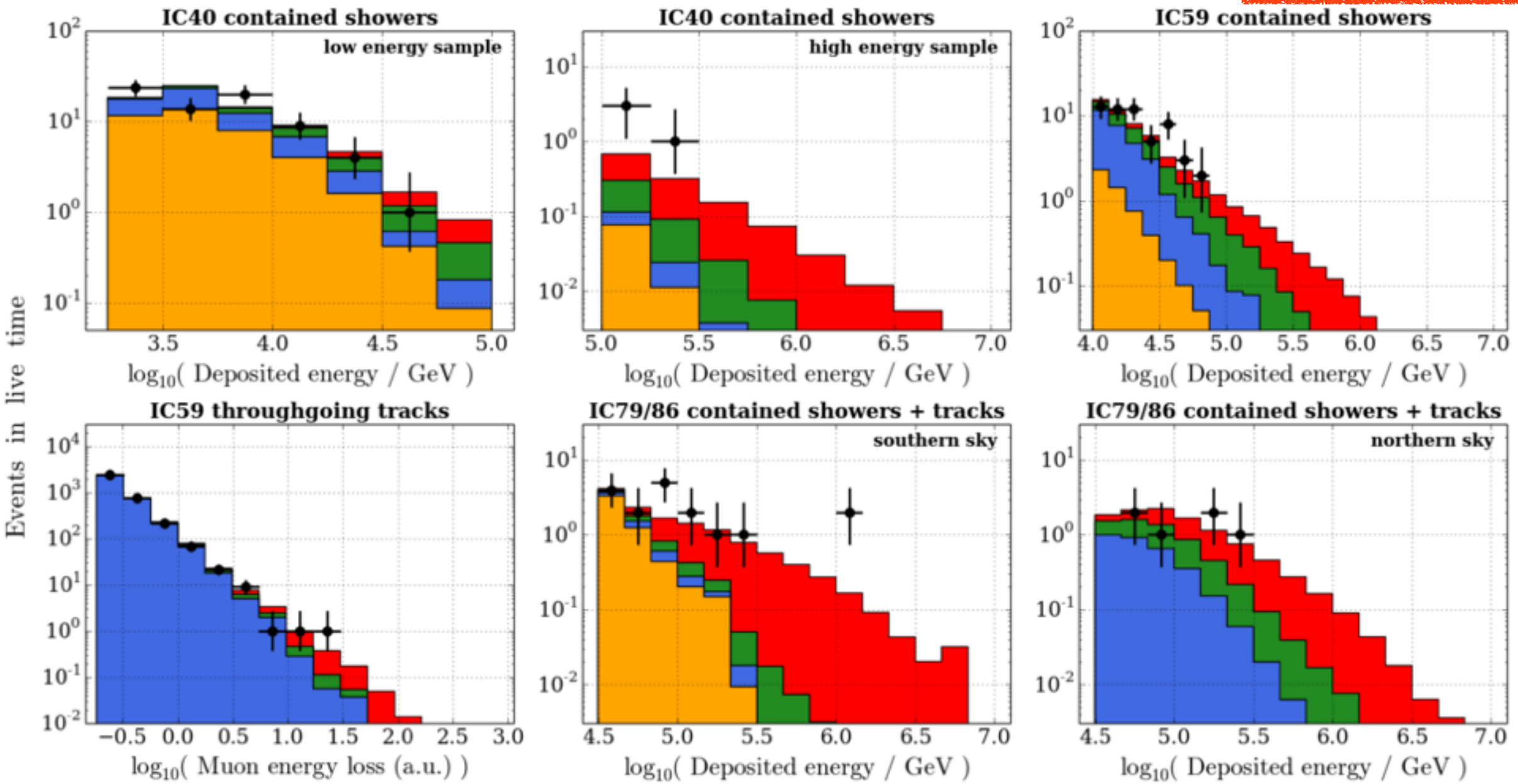
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$\phi_{prompt} = (2.8^{+2.0}_{-2.0}) \cdot$ [Enberg + Gaisser H3a]

$E^2 \phi_{astro} = (1.0^{+0.8}_{-0.5}) \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

$E_{cut} = (1.8^{+5.0}_{-1.0})$ PeV



> **Hard spectrum** with cutoff: $\Phi \sim E^{-2} \exp(-E/E_{cut})$

A global spectral fit to all IceCube data.

see talk by L. Mohrmann

Hypothesis:

$\phi_{\text{astro}} \sim E^{-\gamma}$

Goodness-of-fit:

10.0 %

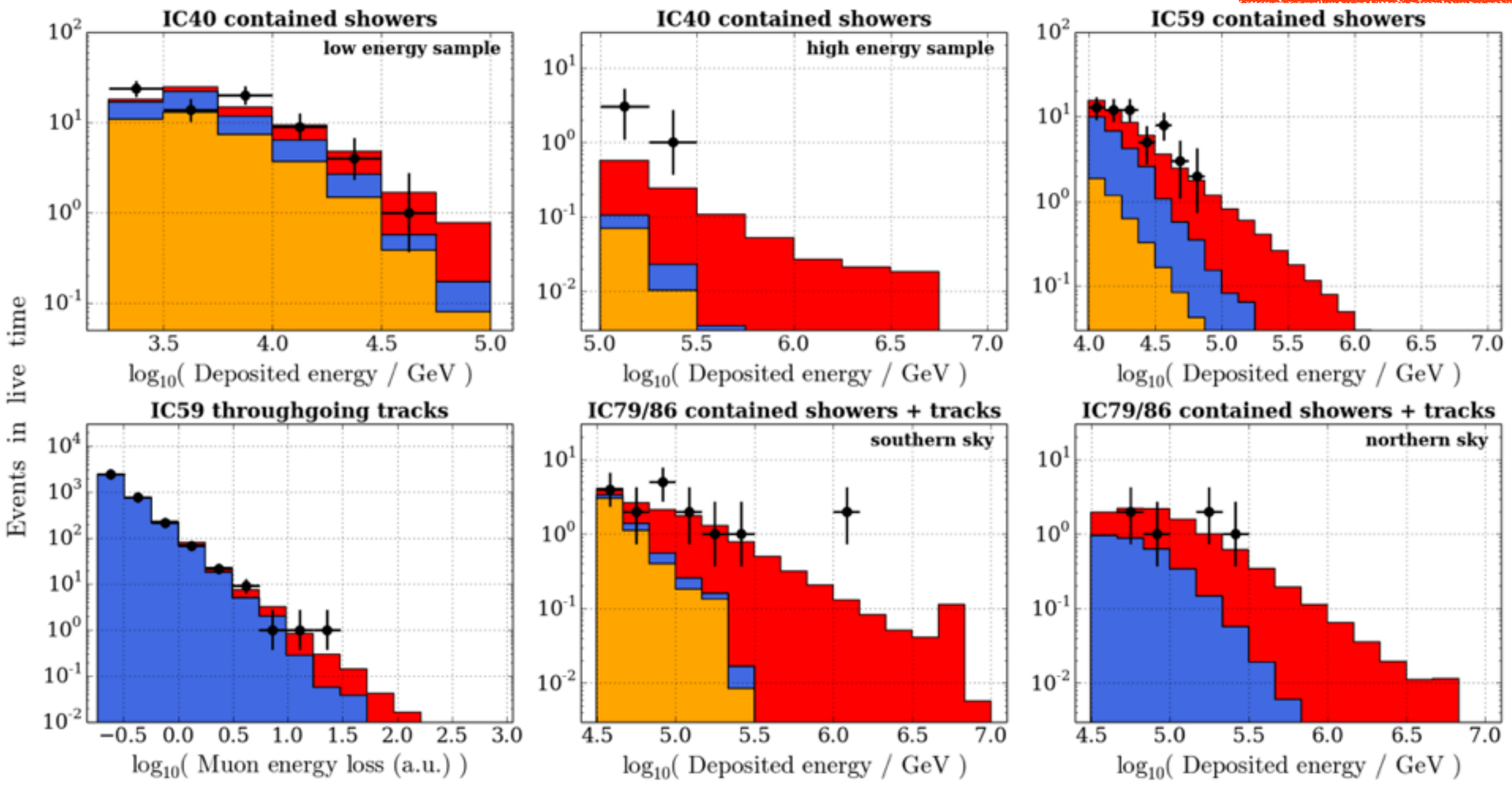
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$\phi_{\text{prompt}} = (0^{+1.6}_{-0.0}) \cdot$ [Enberg + Gaisser H3a]

$E^{2.7}\,\phi_{\text{astro}} = (6.8^{+1.8}_{-1.8}) \cdot 10^{-5}\,\text{GeV}^{1.7}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$

$\gamma_{\text{astro}} = (2.7^{+0.2}_{-0.2})$



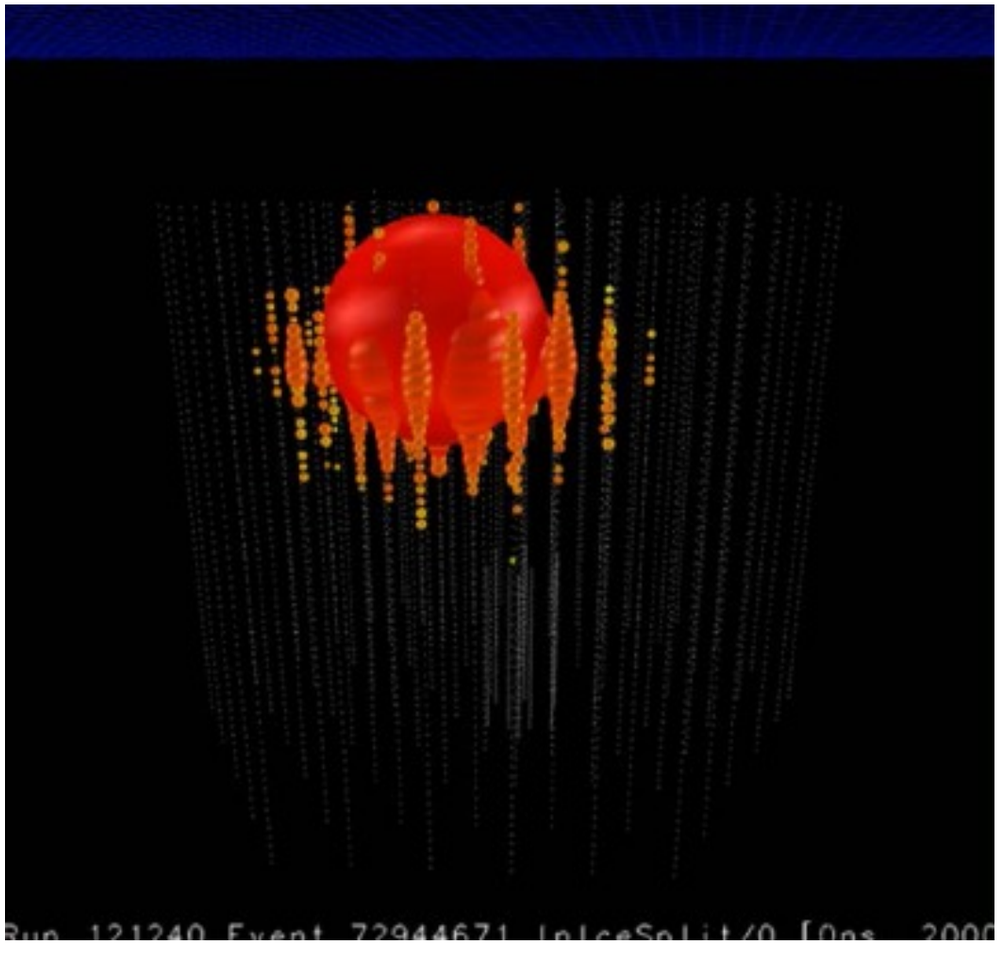
> **Pure power-law** with unknown index: $\Phi \sim E^{-\gamma}$

More results expected soon.

- Analysis of **2012/2013** IceCube **data** (run period from May 2012 - Apr 2013).

- **Better constraints** on atmospheric neutrino fluxes from **low-energy** contained/semi-contained events (see talk by J. van Santen).

- Search for **excess events** in the **dE/dx spectrum** of through-going tracks (see talk by C. Weaver)

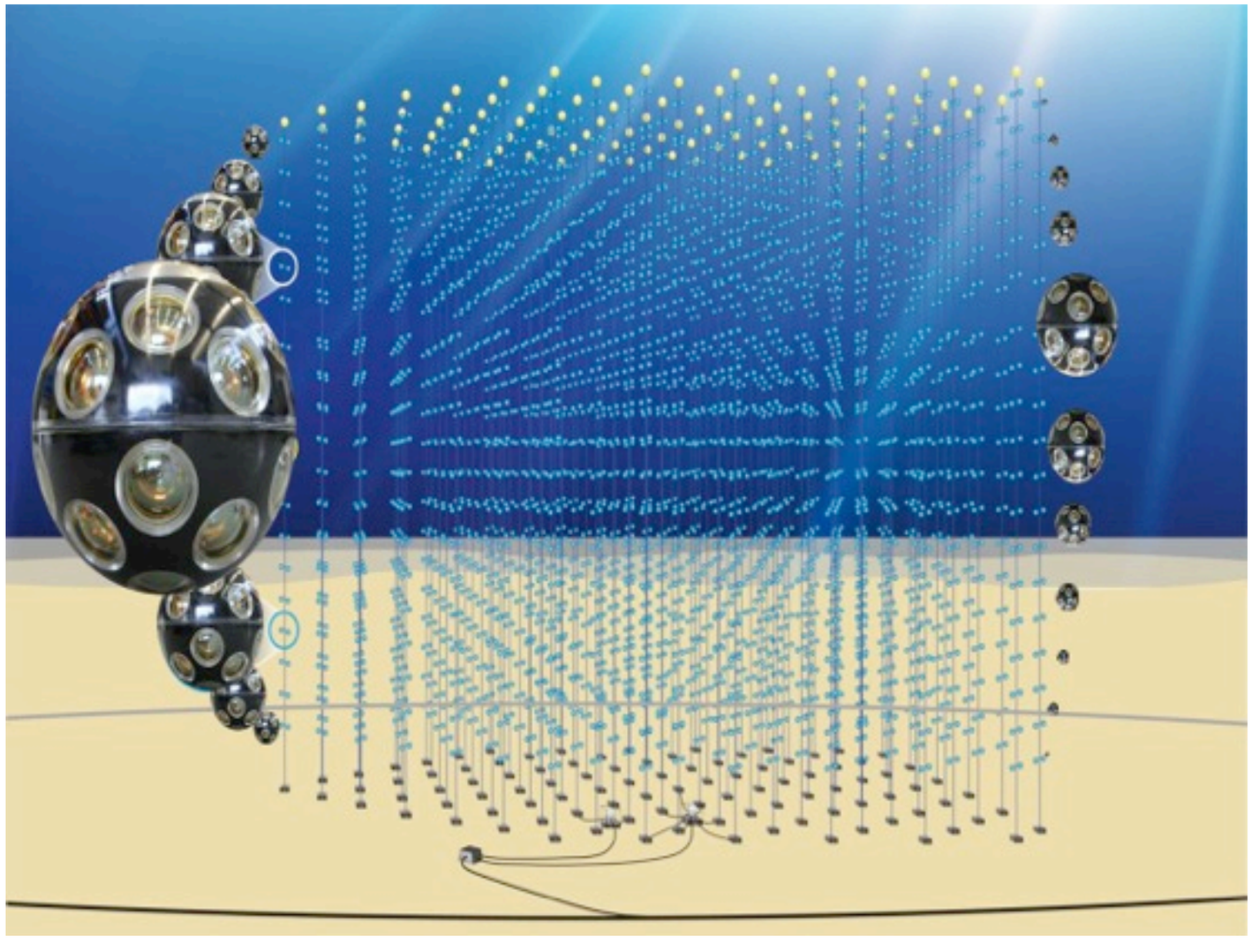


Another PeV-class neutrino in pre-scaled 2012/2013 data sample used for analysis development (10% of available data).

Future neutrino telescopes.

- A **gigaton detector** is the **scale needed** to observe astrophysical neutrinos
- Need to go **beyond** the **gigaton scale** for “precision neutrino astronomy”.

- KM3NeT is the most advanced project to build a multi-gigaton neutrino telescope array.



KM3NeT

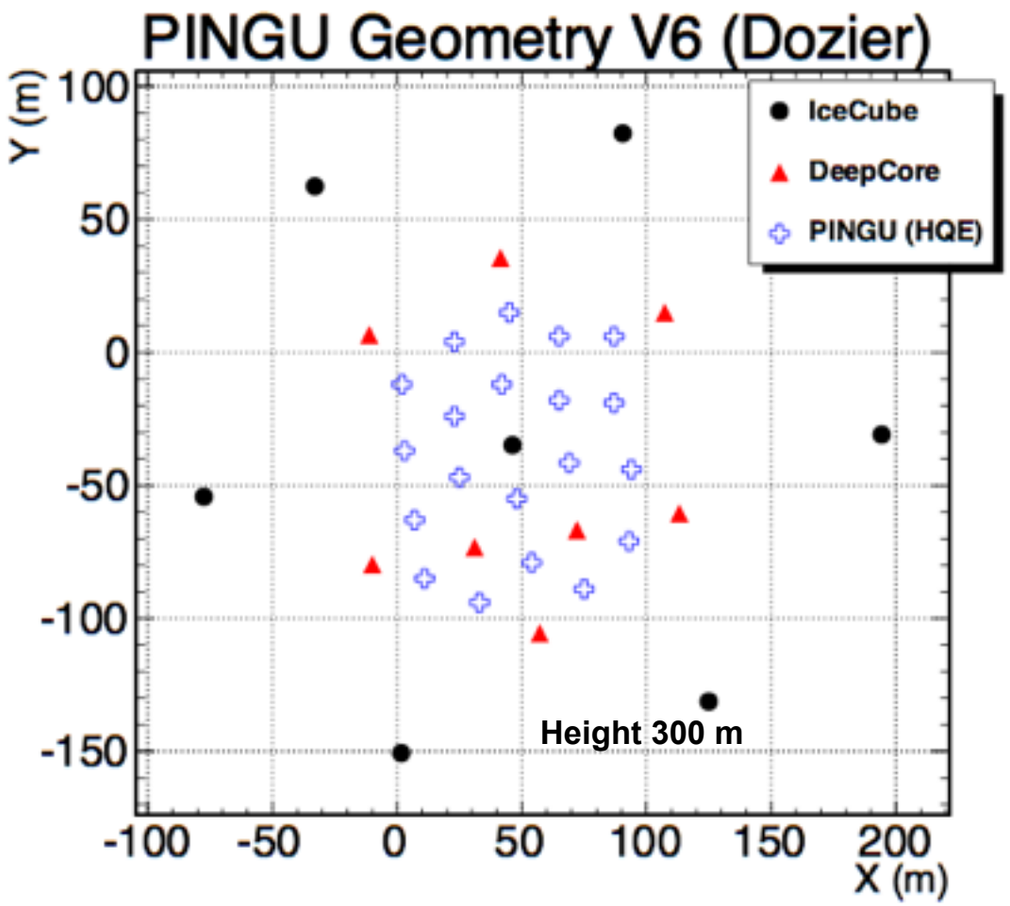
- **Distributed infrastructure** for underwater neutrino telescopes.
- **Detector sites** off the coast of France, Italy, and Greece.
- Instrumented volume: 1-2 km³ (**~5 km³** total)
- **1 TeV** energy threshold.
- **40 M€** funding for phase-I available

Beyond IceCube.

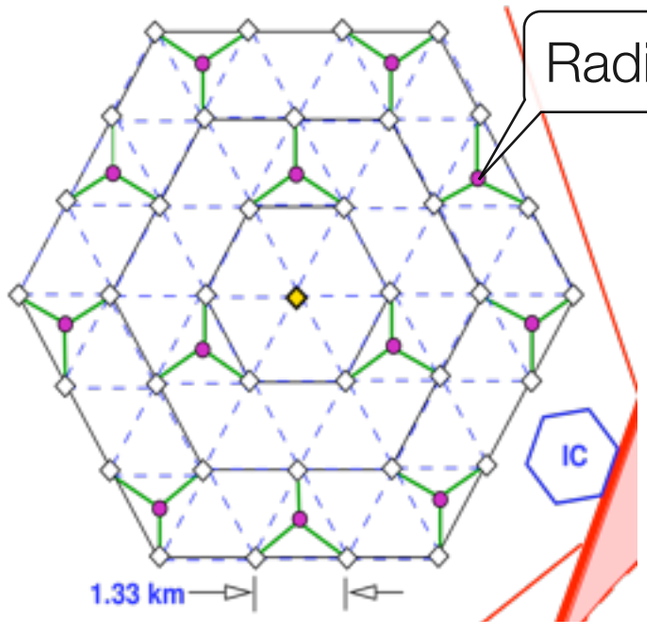
Increase of core density

PINGU

- 20-40 new strings inside the DeepCore volume.
- Energy threshold reduced to 1 GeV.
- Focus on measurement of fundamental neutrino properties (mass hierarchy)

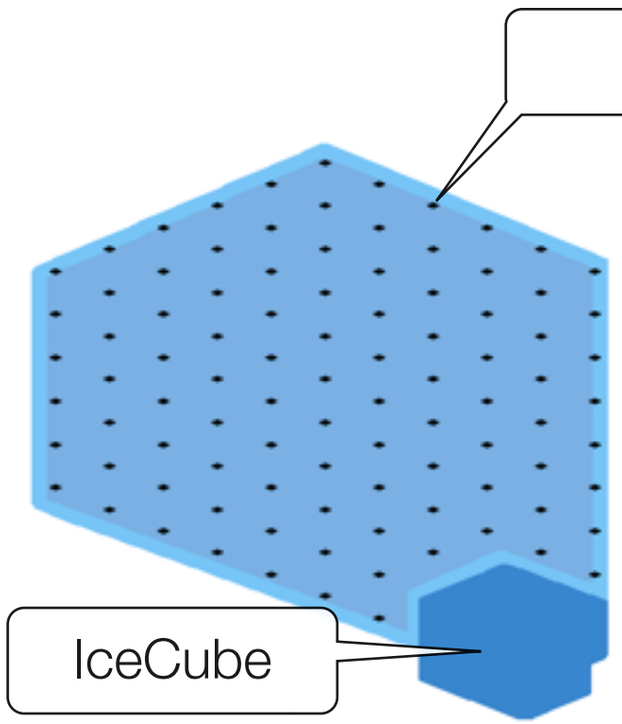


Extensions to larger volumes



Askarian Radio Array (ARA)

- InIce Radio array for >30 PeV neutrinos
- several tens of km^2 surface area



IceCube ++

- IceCube extension with larger string spacing
- Large increase in effective area above 10 TeV

Summary.

- IceCube is the first **gigaton scale** neutrino telescope in operation.
- ANTARES complements the observations on the Southern hemisphere.
- Neutrino telescopes have improved the sensitivity for observations of astrophysical neutrinos by a factor of 1000 in 13 years.
- So far **no discovery** of an individual neutrino source.
- IceCube observes the **first strong evidence** for **astrophysical neutrinos:**
  - Data incompatible with atmospheric expectations on the > 4σ level.
  - Compatible with a diffuse & isotropic astrophysical flux (no significant clustering observed).
  - Additional studies and data needed to constrain the spectral parameters of this flux.
  - Such studies are in an advanced stage with results expected soon.