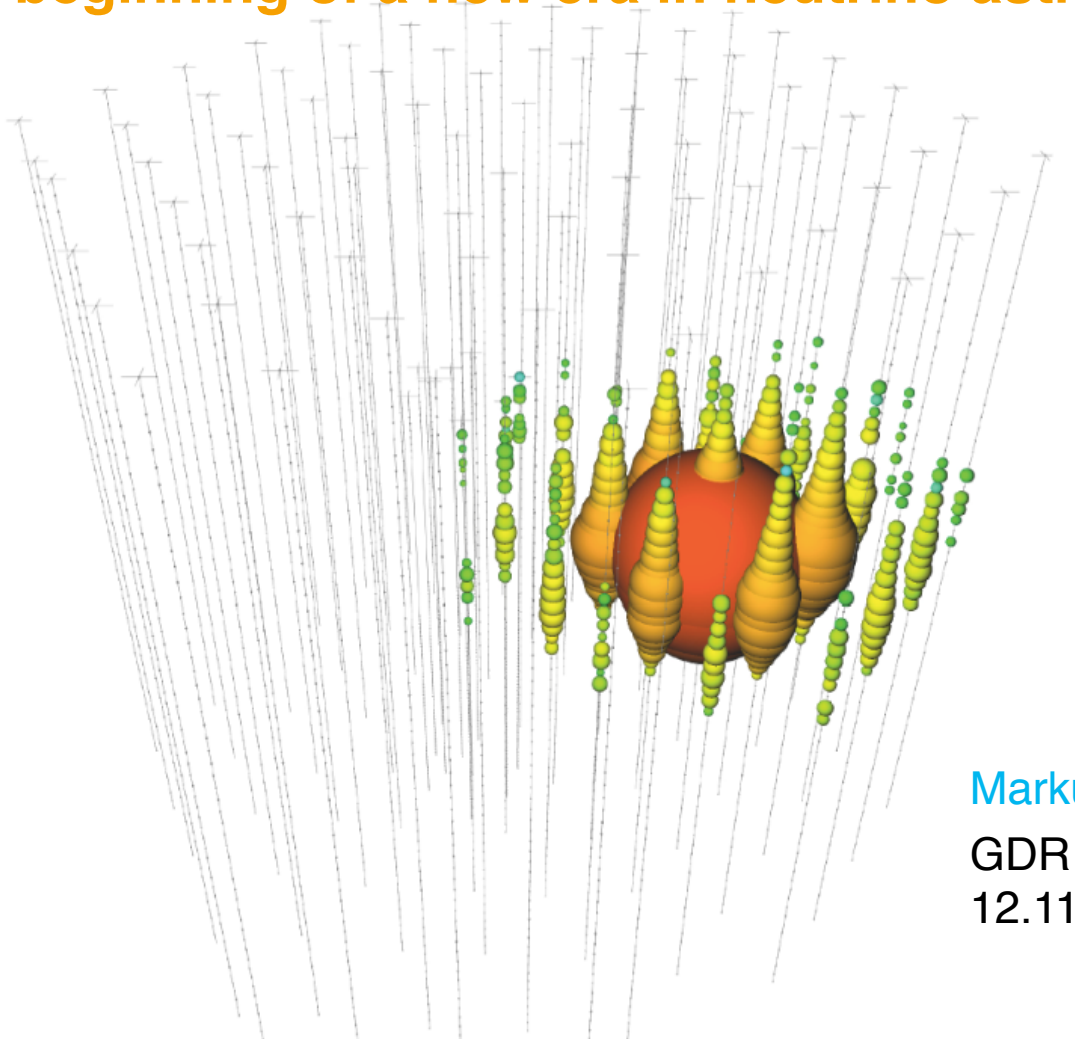
IceCube

the beginning of a new era in neutrino astrophysics.



Markus Ackermann

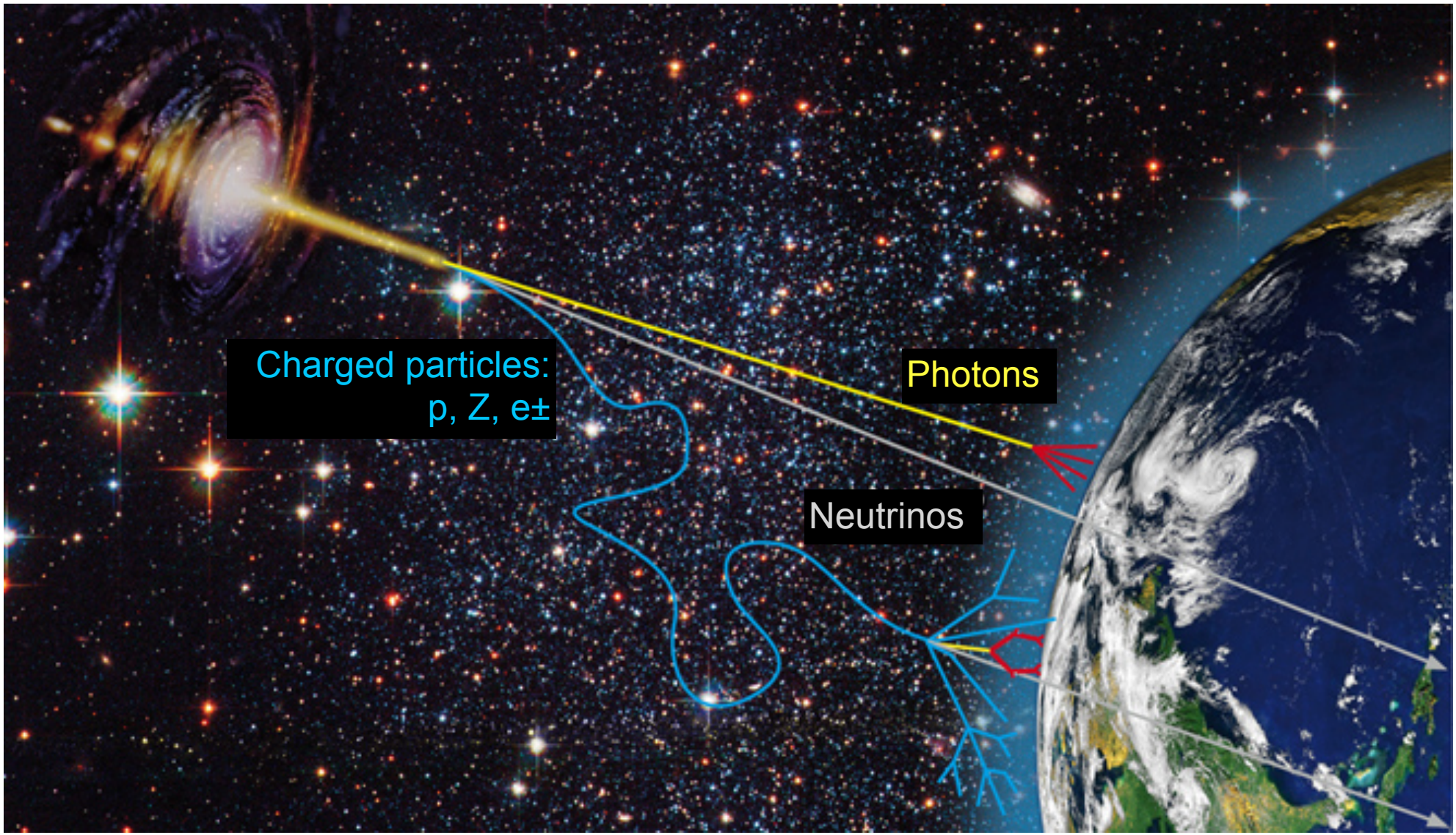
GDR Neutrino 2013
12.11.2013, IPNL, Lyon

HELMHOLTZ ASSOCIATION

DESY

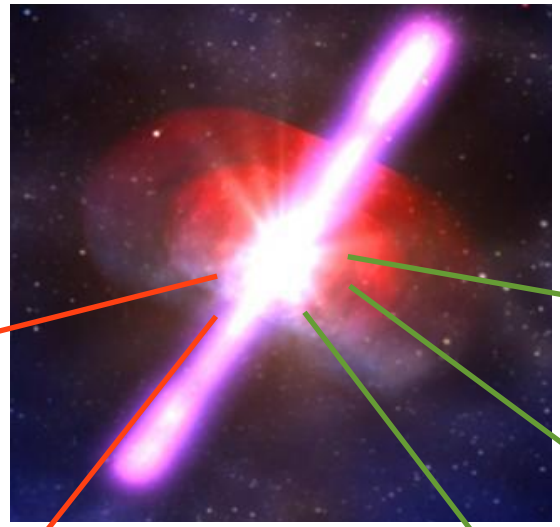
High-energy astrophysics

> 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.**



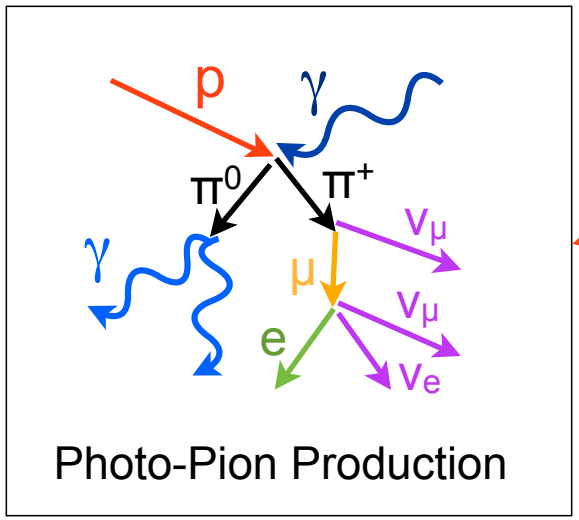
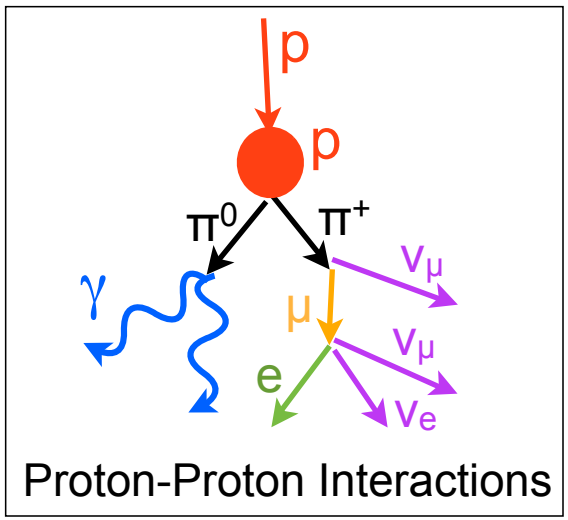
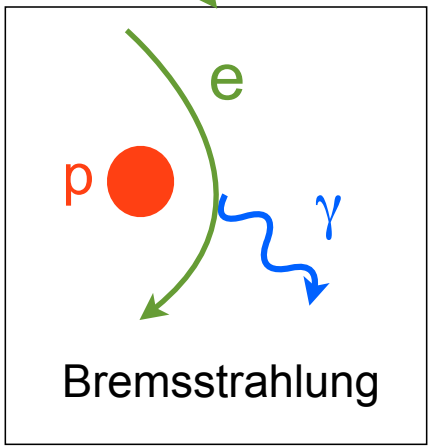


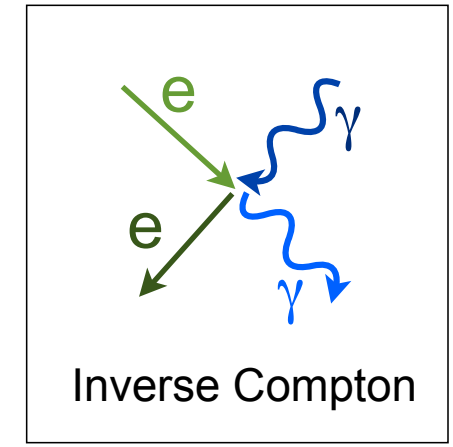
Photo-Pion Production



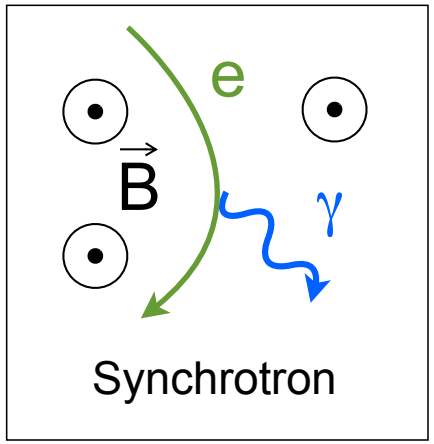
Proton-Proton Interactions



Bremsstrahlung



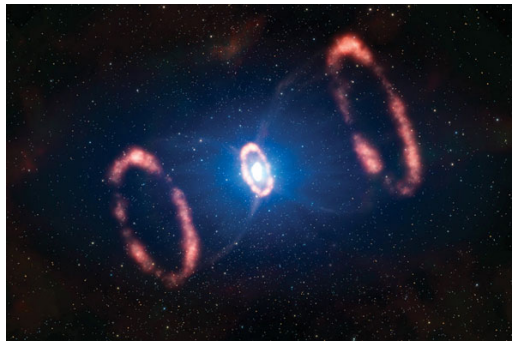
Inverse Compton



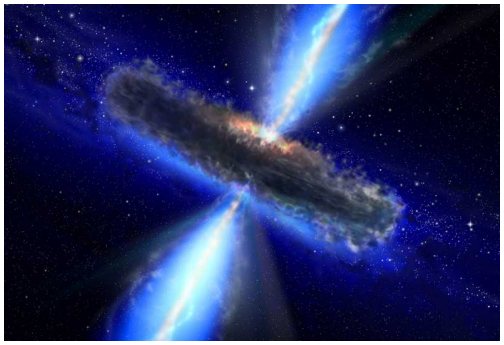
Synchrotron

The power of neutrino observations.

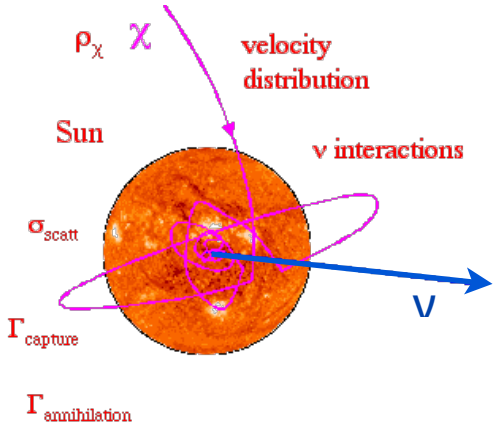
Neutrinos can **escape dense environments:**



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



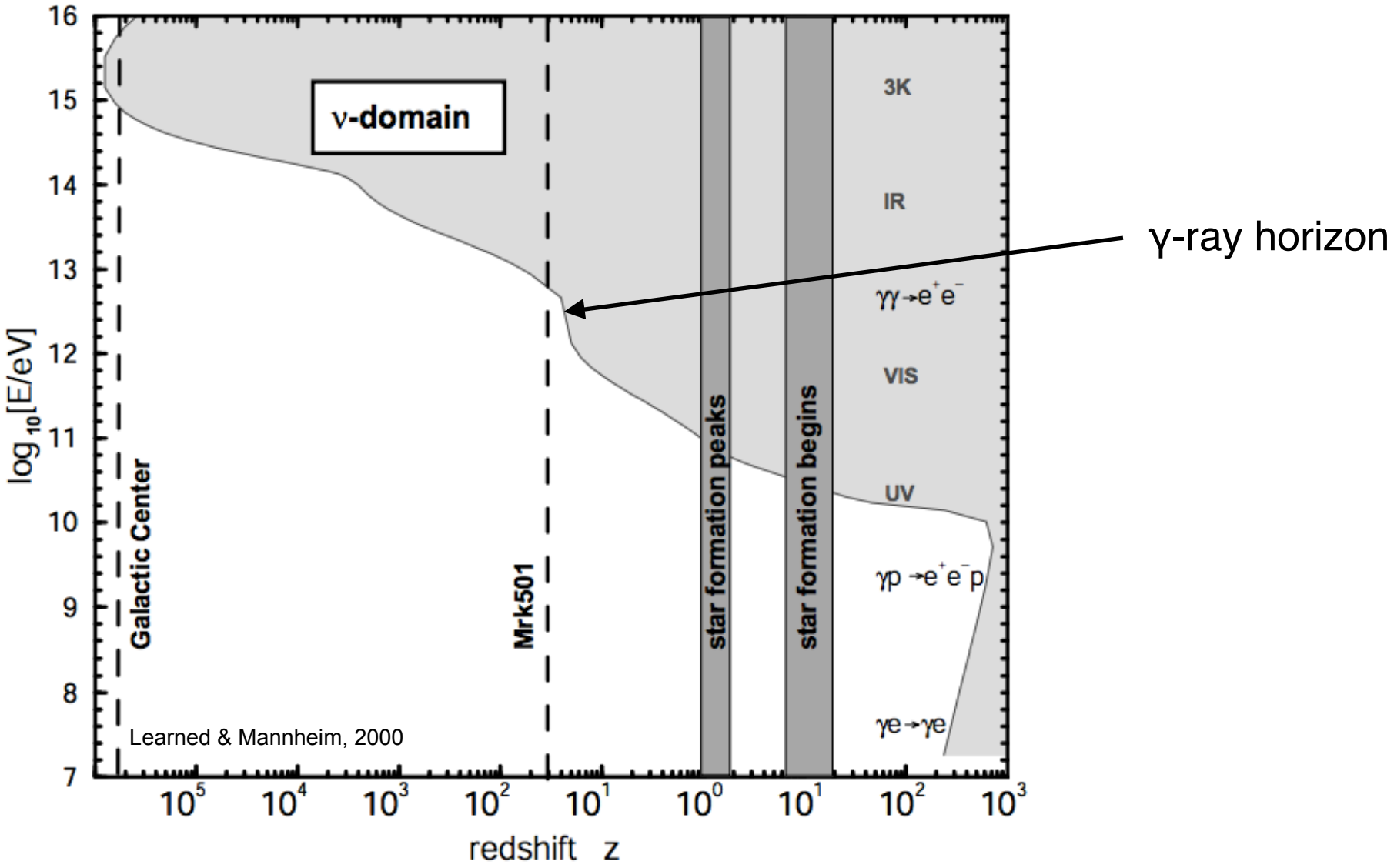
> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)



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

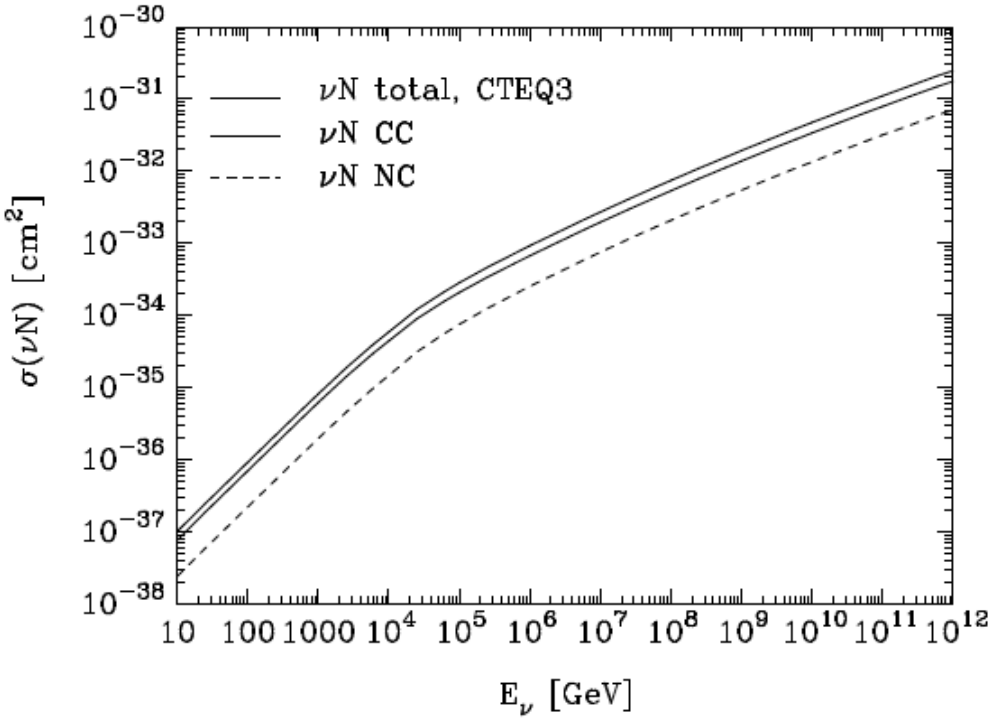
The neutrino domain: PeV astronomy.

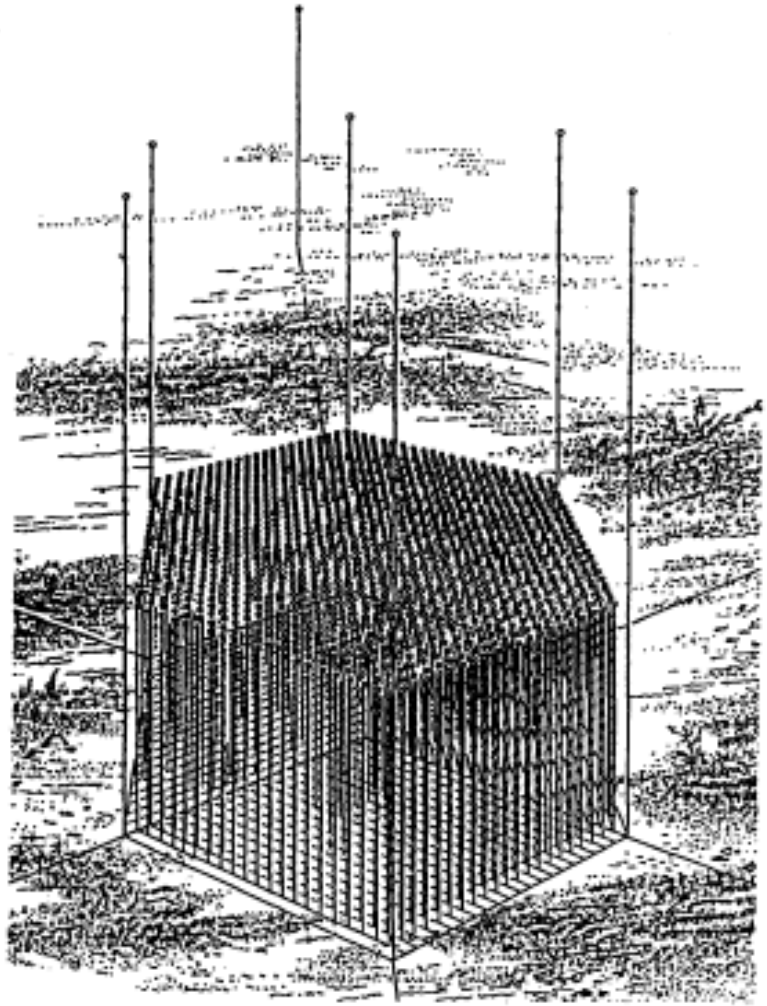
- Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.
- Only neutrino telescopes can do **PeV/EeV astronomy.**



Neutrino astrophysics.

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



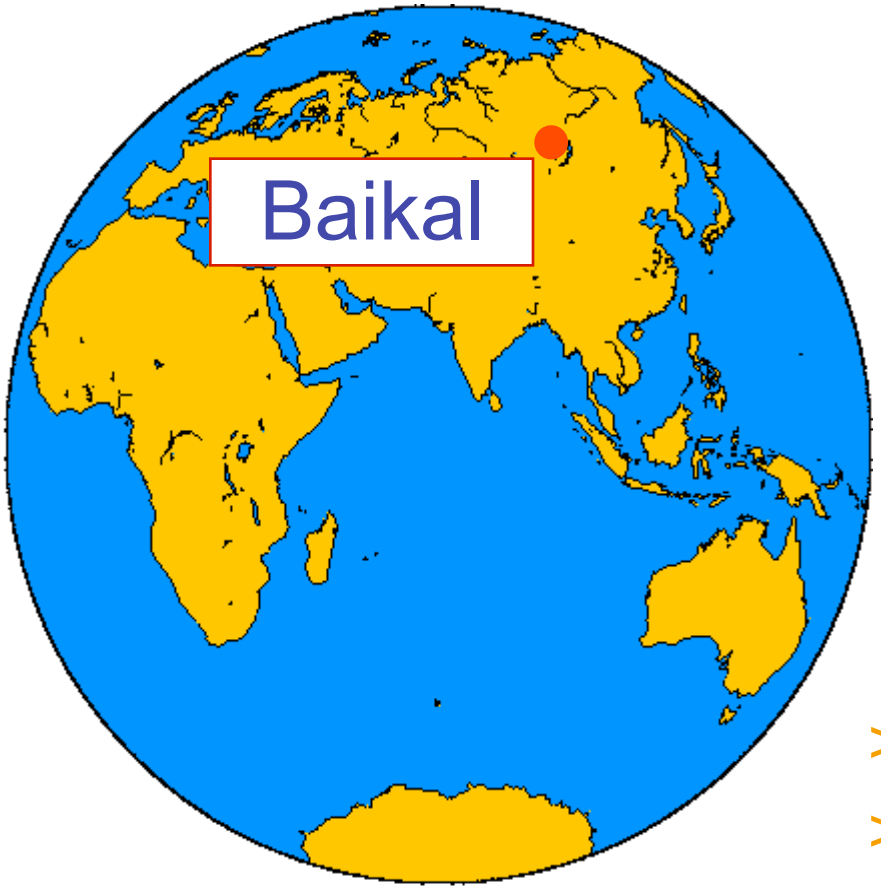


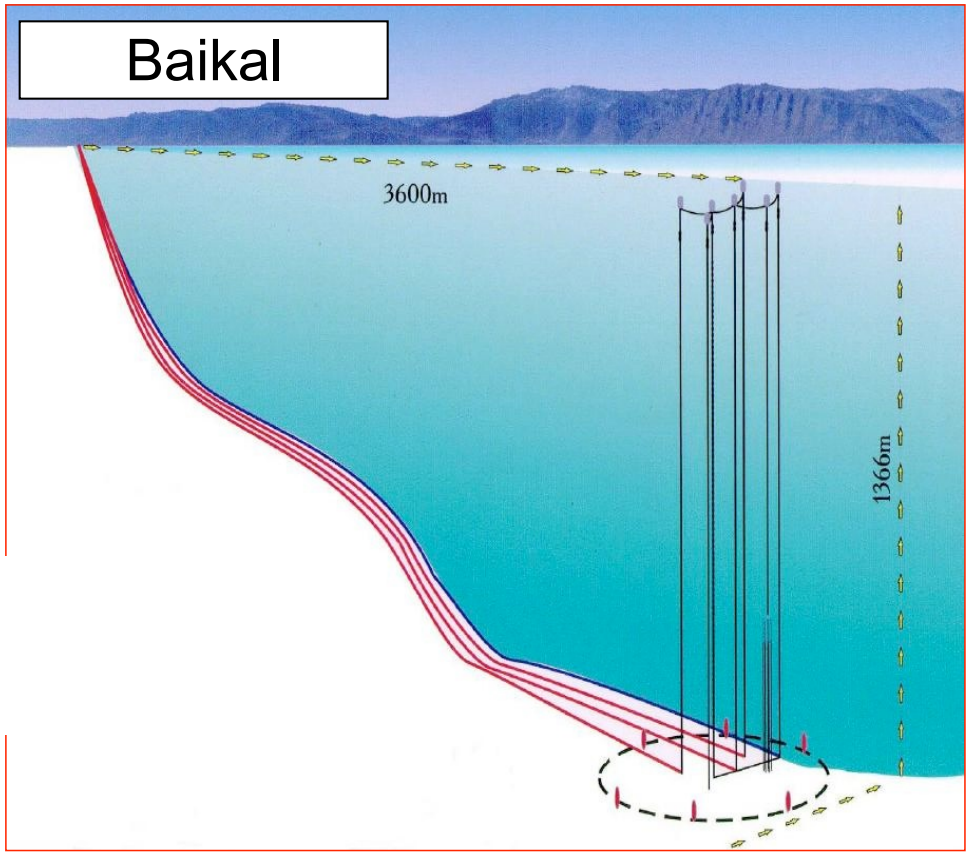
> **First design** of a **1 km^3** underwater detector already in 1978

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

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

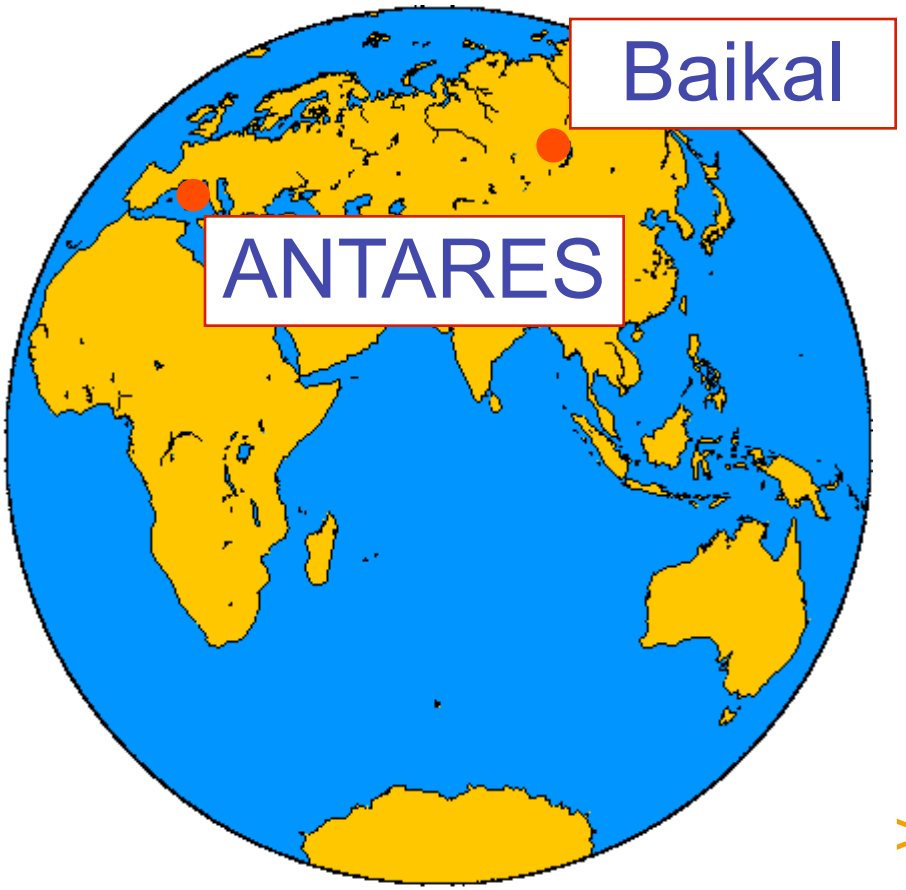
Operating neutrino telescopes: Baikal

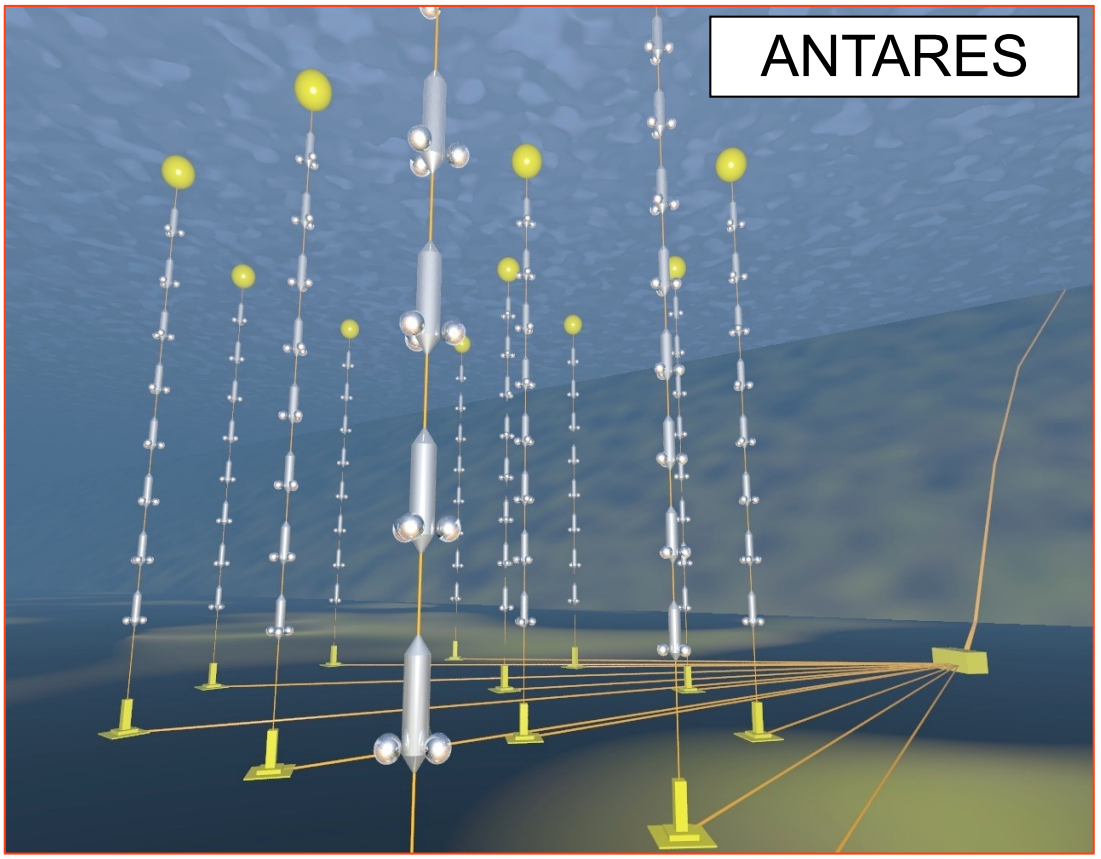




- ~ 4km off the shore of **Lake Baikal**
- **Completed** in **1998**
- 192 optical sensors on 8 strings (**10^{-4} km^3** instrumented volume)
- Upgraded to NT200+ configuration in 2007 (+18 sensors on 3 strings)

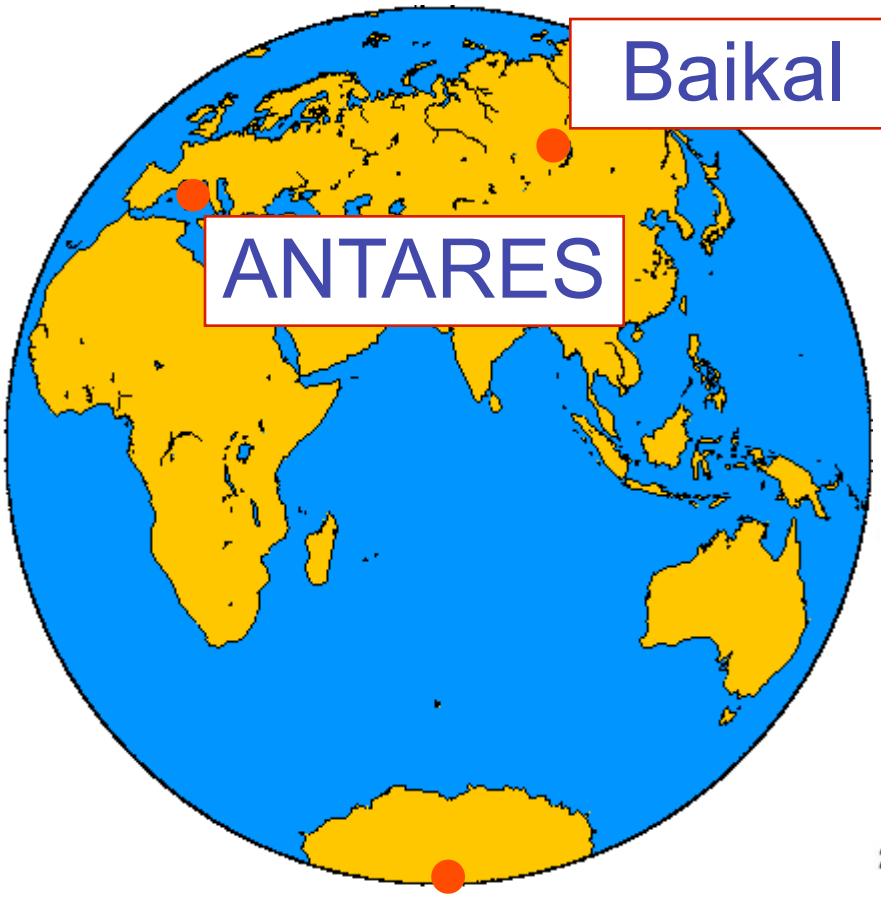
Operating neutrino telescopes: ANTARES

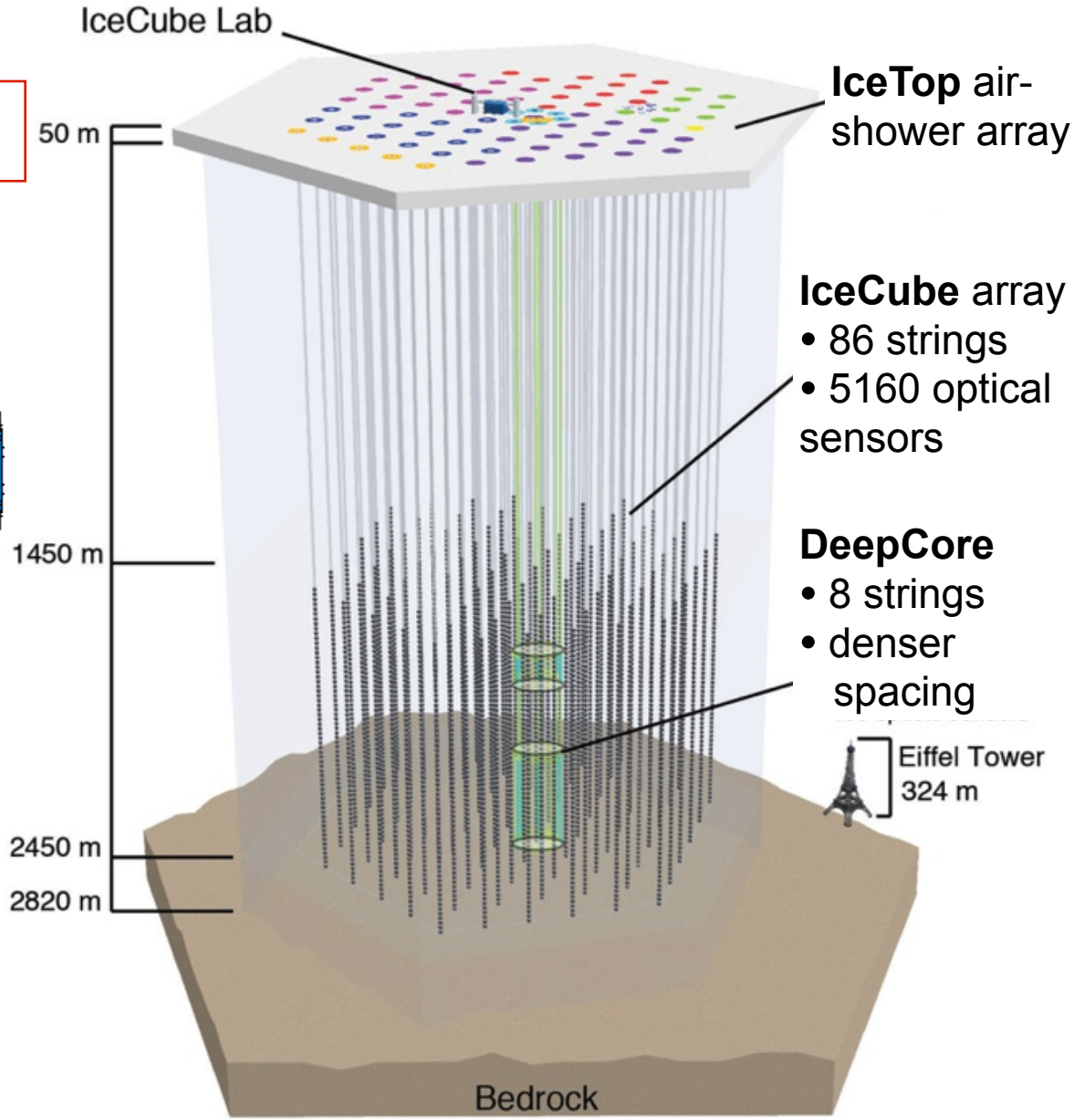




- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

Operating neutrino telescopes: IceCube

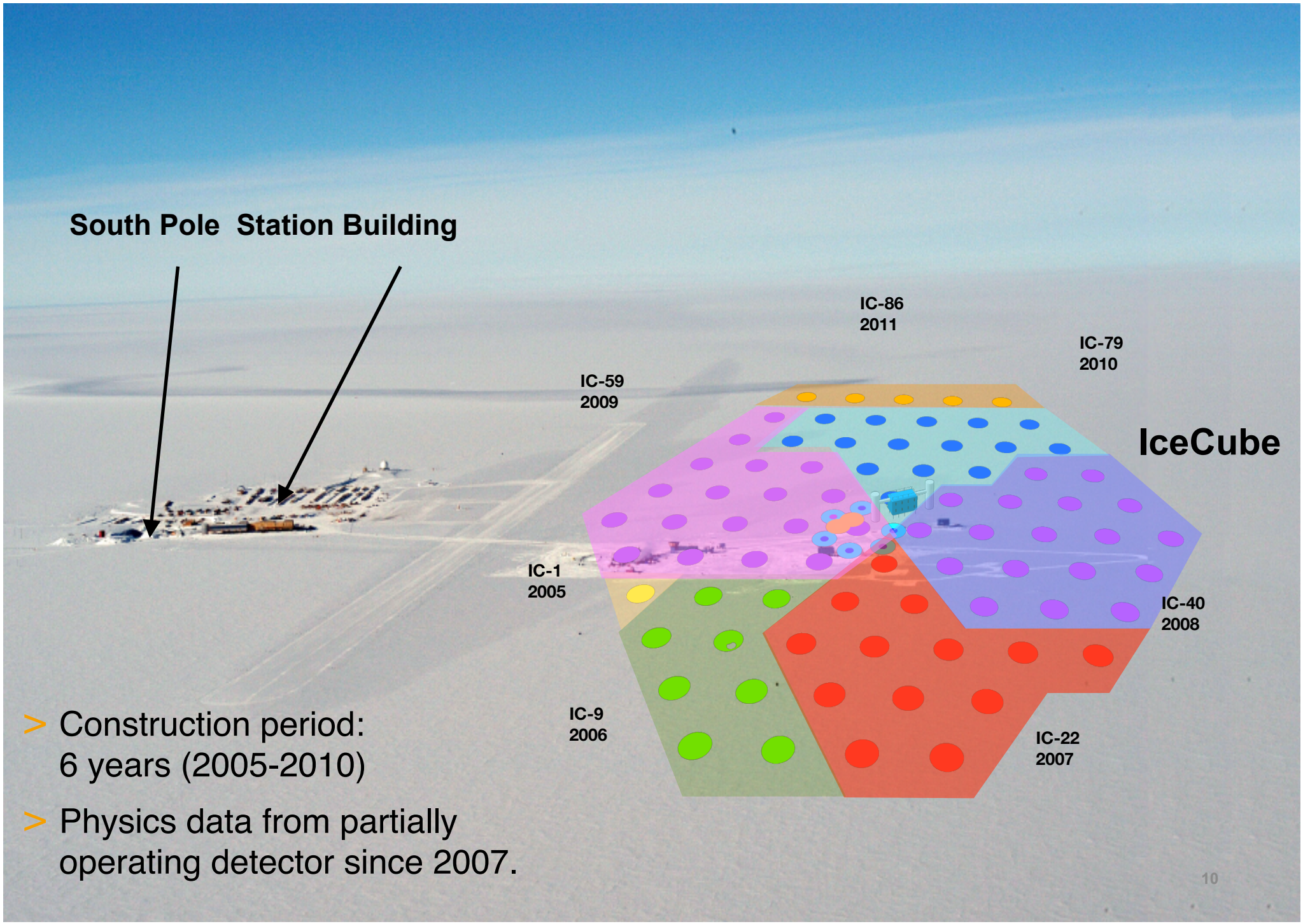




> **Completed** in Dec **2010**.

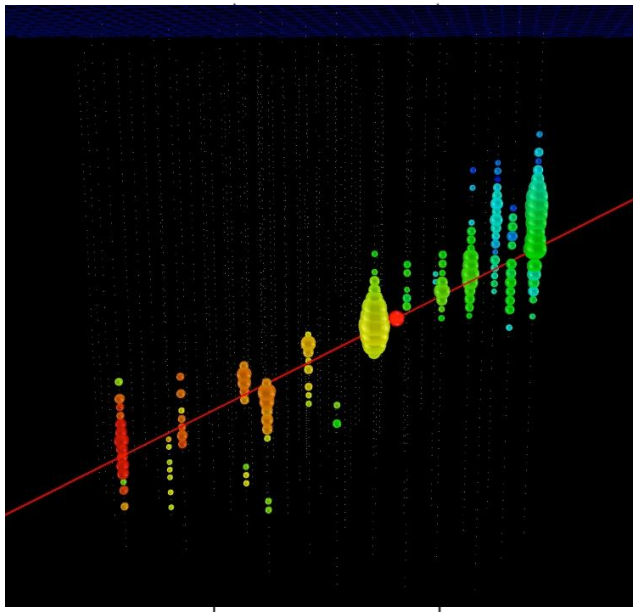
> Instrumented volume: **~ 1km^3**

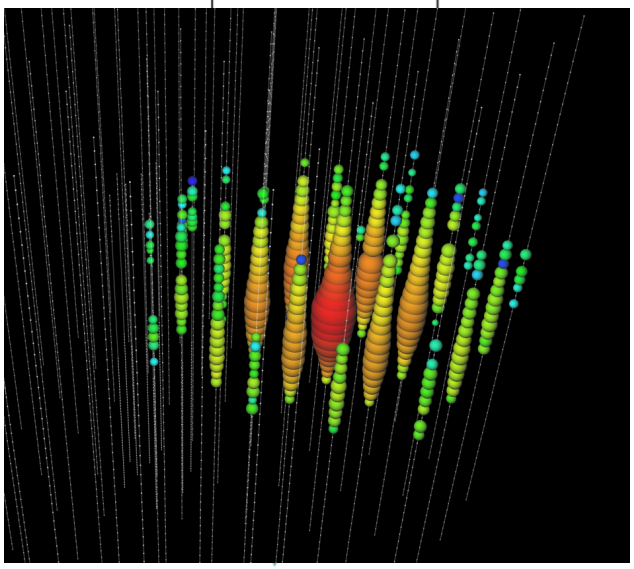
Construction of the IceCube observatory.



- Construction period: 6 years (2005-2010)
- Physics data from partially operating detector since 2007.

Detection of high-energy neutrinos.





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

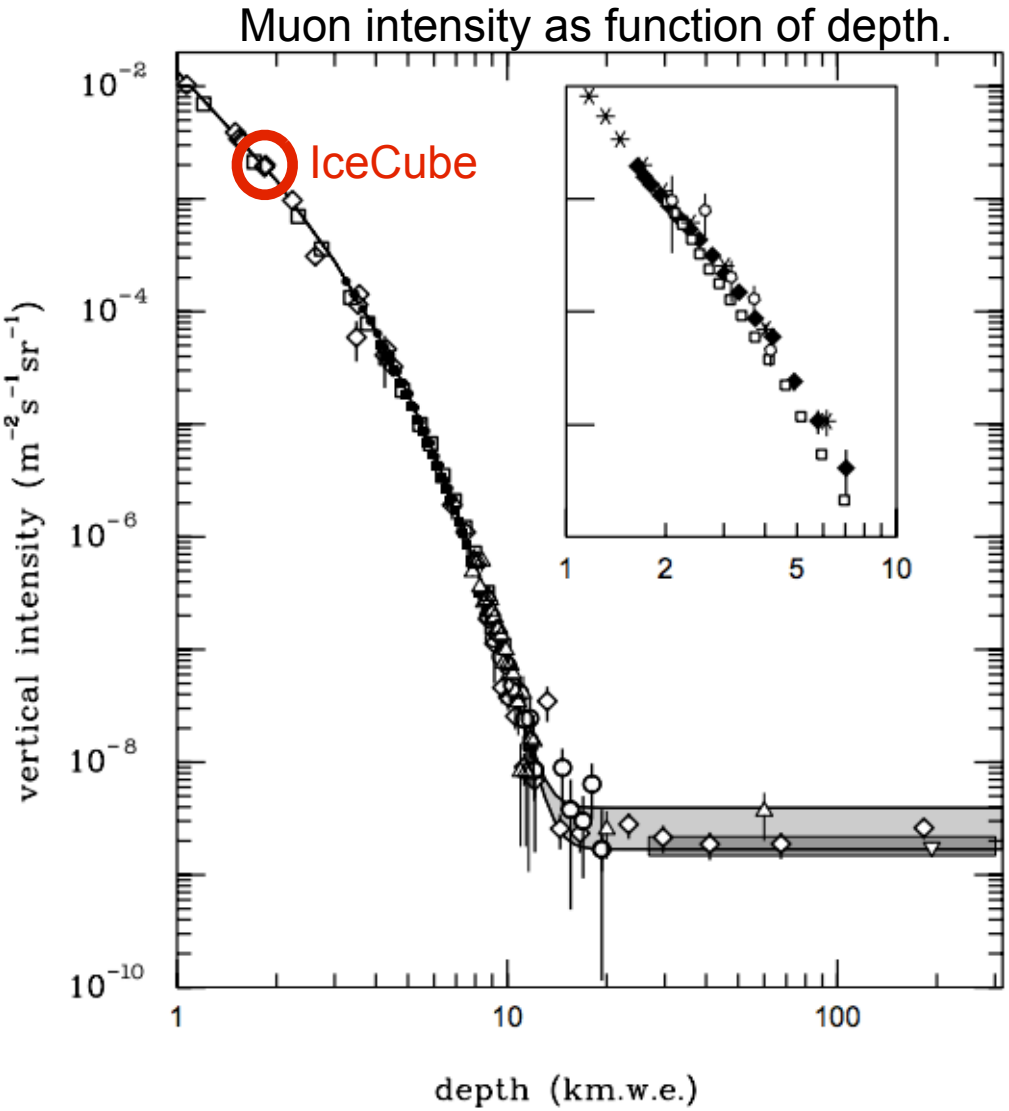
- **Angular** resolution: < 1°
- μ travels up to several km --> **interactions outside** the instrumented volume **visible**
- **Energy** resolution: dE/dx of the produced μ only.

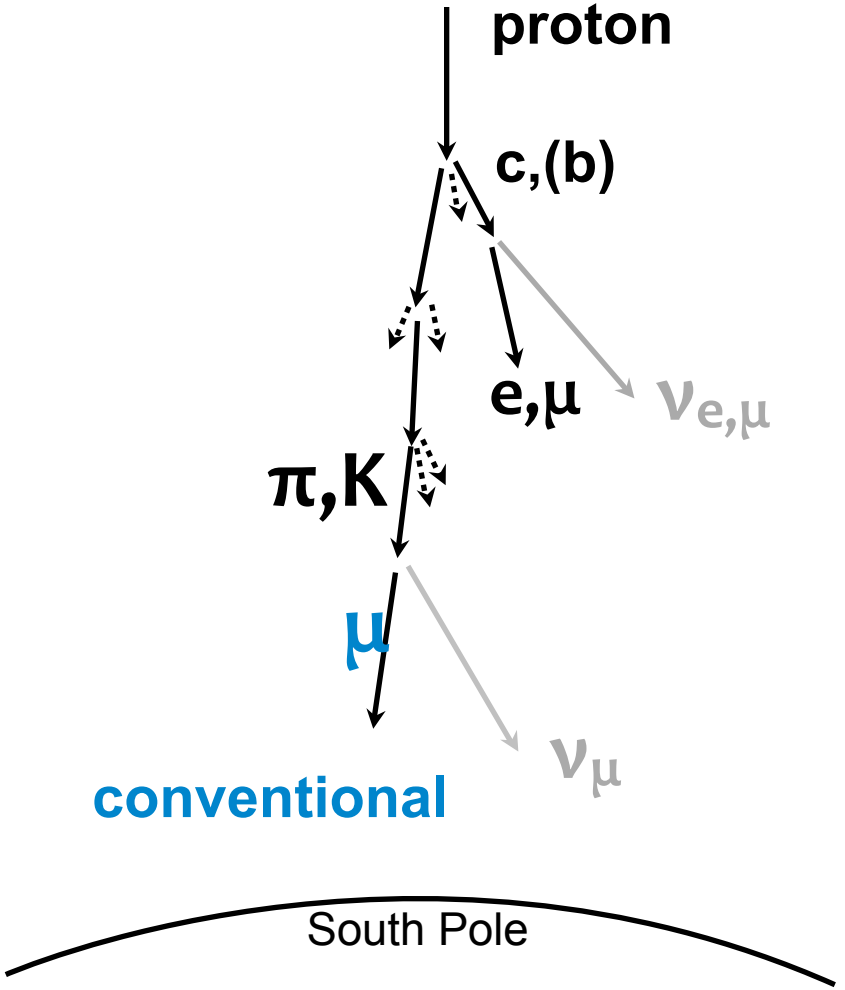
> **Shower-like event** signatures
(CC interactions of ν_e,ν_τ, NC interactions)

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

Backgrounds: Muons from CR air showers.

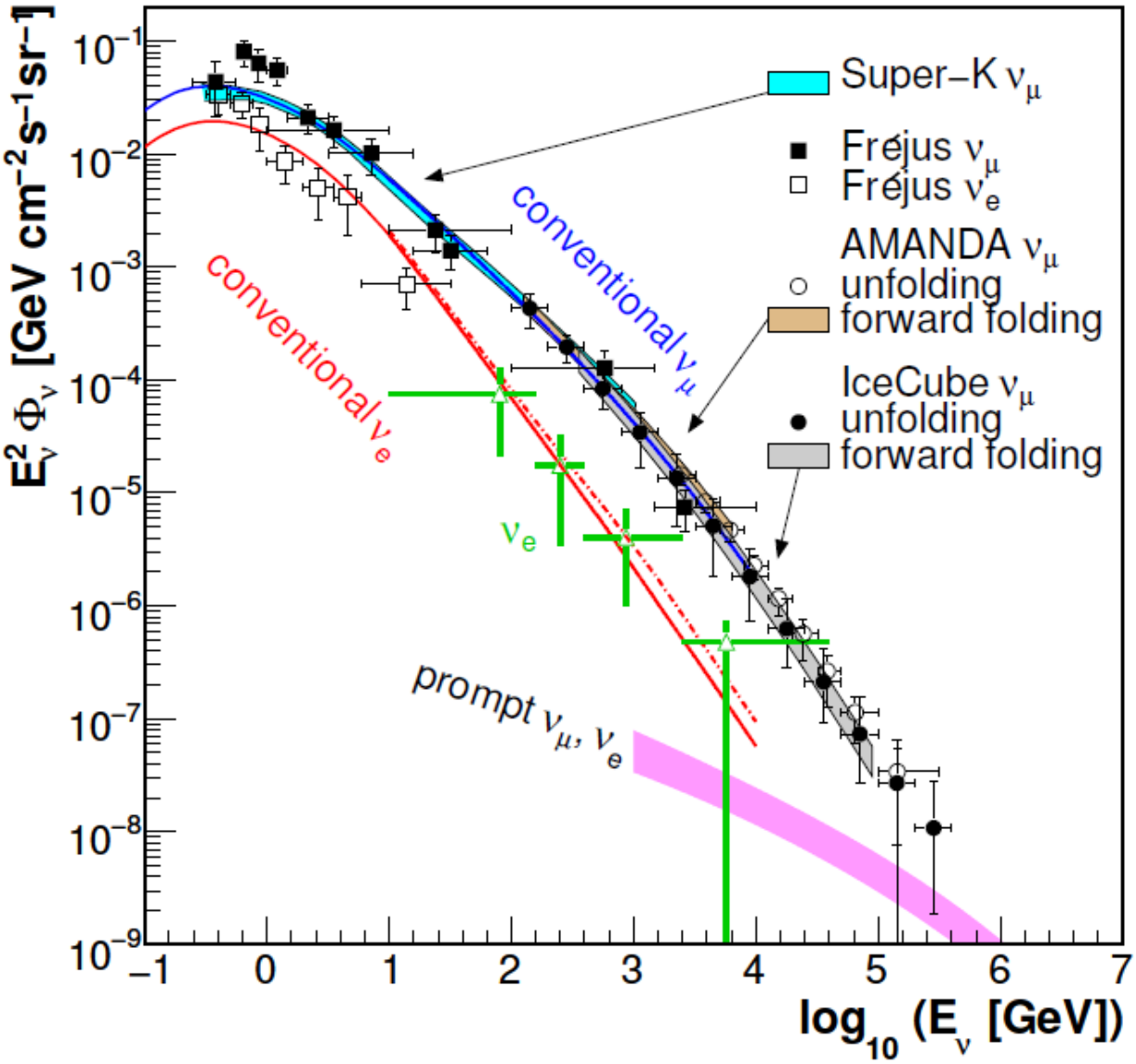
- **Muons from CR air showers** account for 99.9999% of all events seen by IceCube.
- Restricted to **Southern hemisphere.**

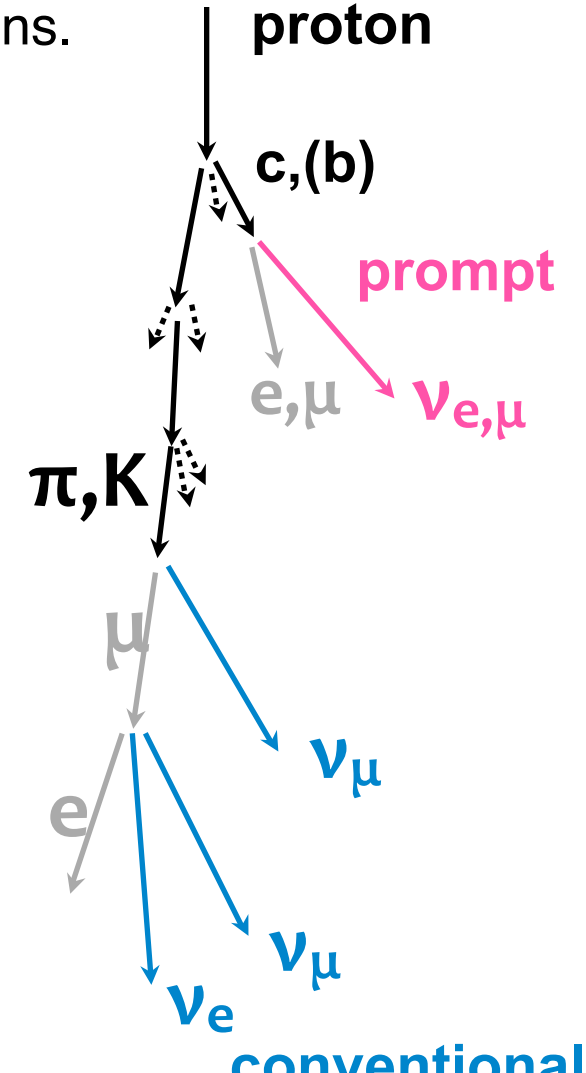




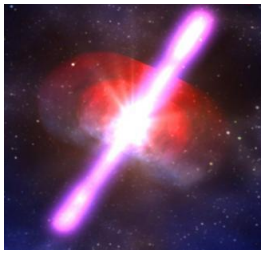
Backgrounds: Atmospheric neutrinos.

- **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.





Particle physics and astrophysics with IceCube.



> Search for **astrophysical sources** of high-energy **neutrinos**.

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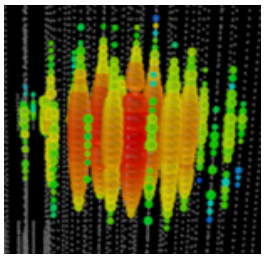
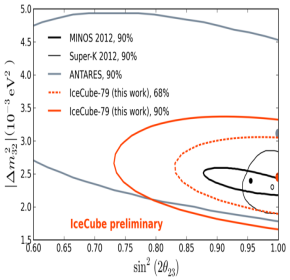


> Measurement of the **diffuse neutrino flux** from the universe

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

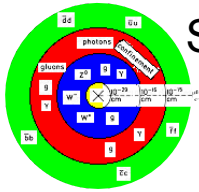


> Measurement of **neutrino properties** using atmospheric neutrinos

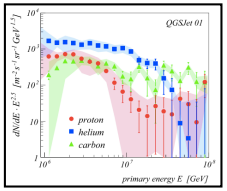
- Measurement of oscillation parameters
- Sensitivity to mass hierarchy with PINGU extension.

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

MeV neutrinos from SN

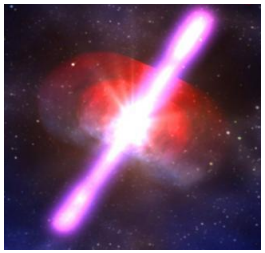


Search for exotic particles



CR physics ....

Particle physics and astrophysics with IceCube.



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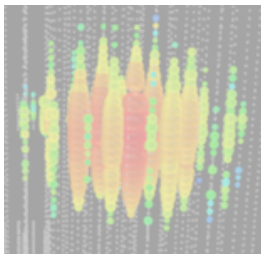

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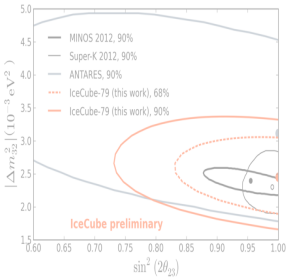

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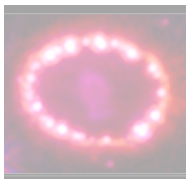
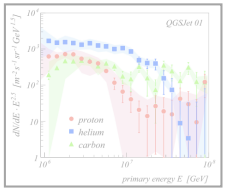


MeV neutrinos from SN

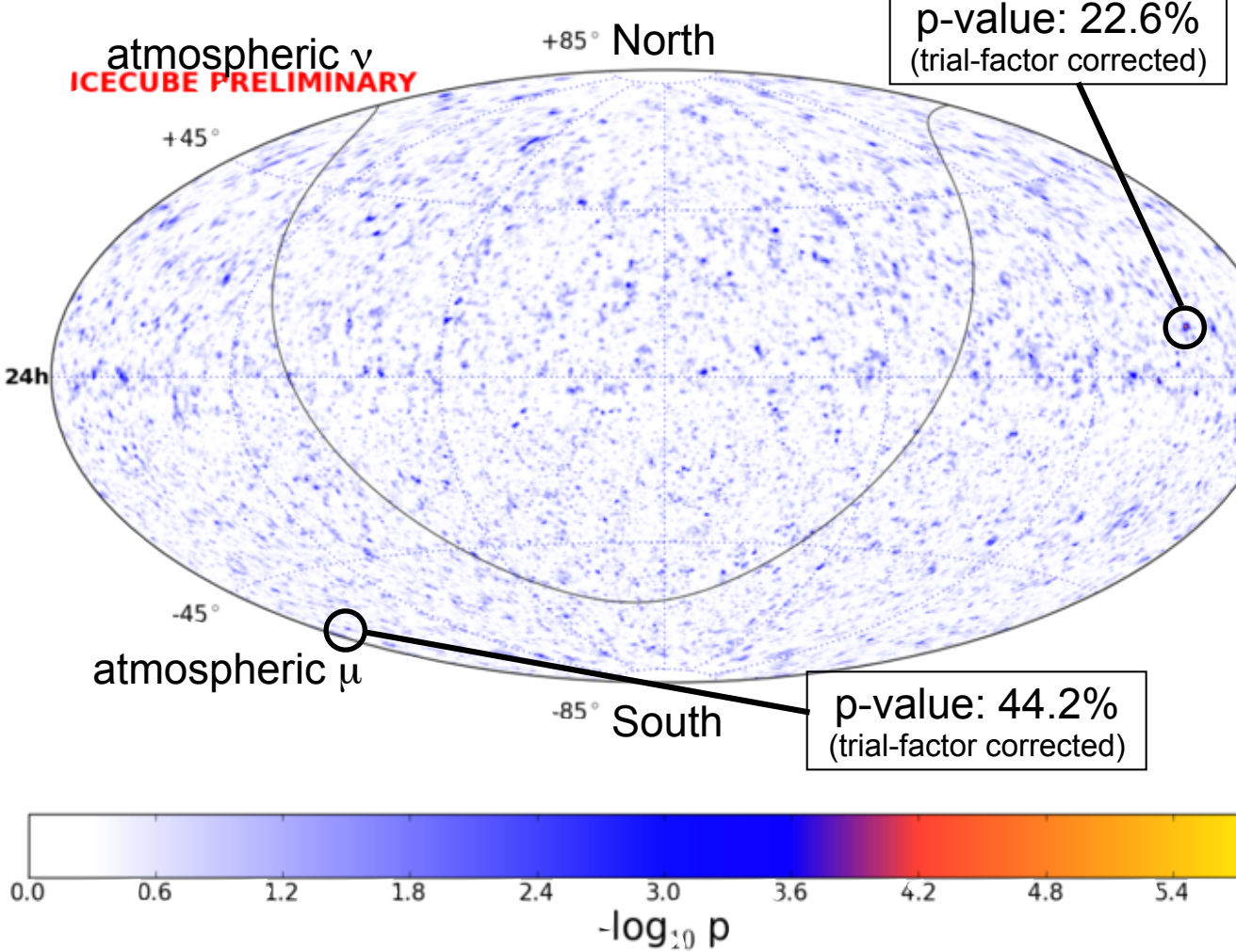
Search for exotic particles

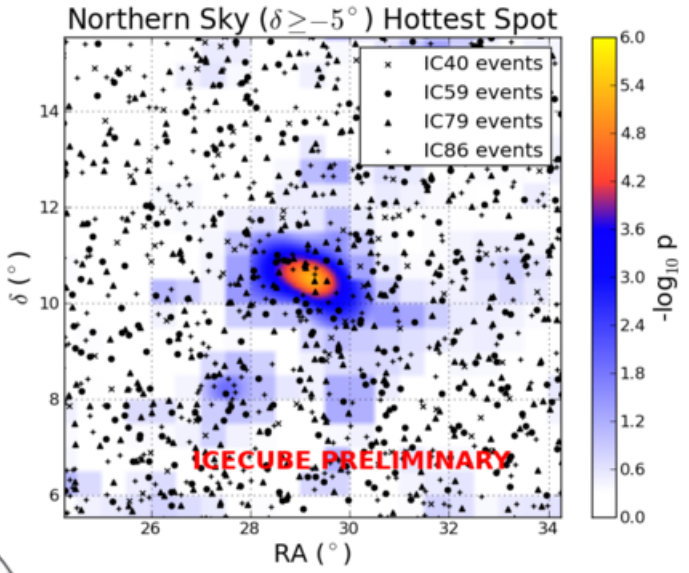


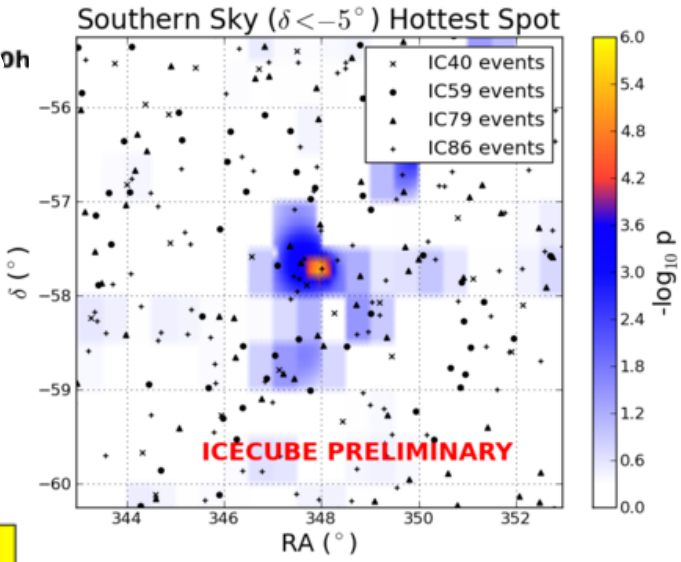
CR physics ....

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



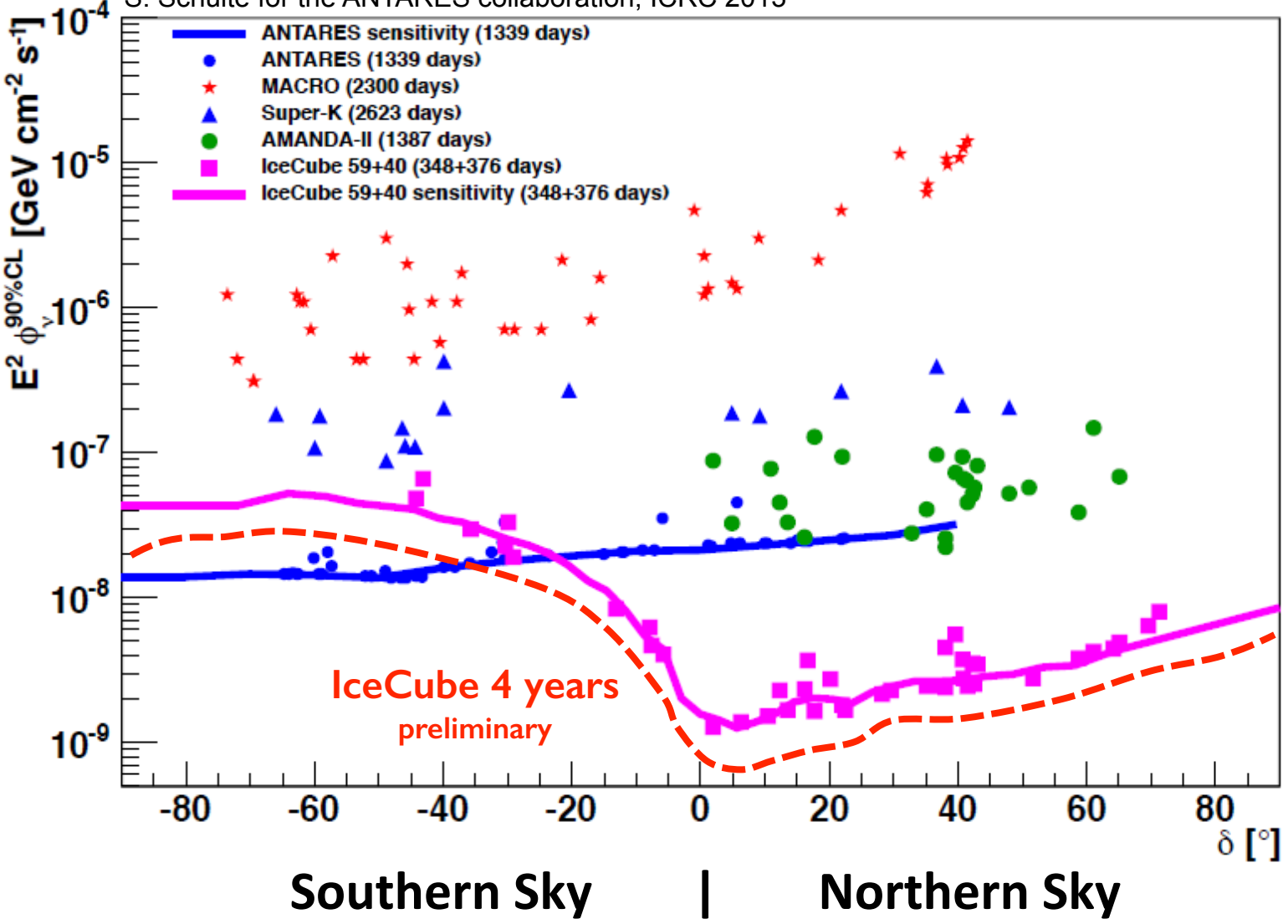




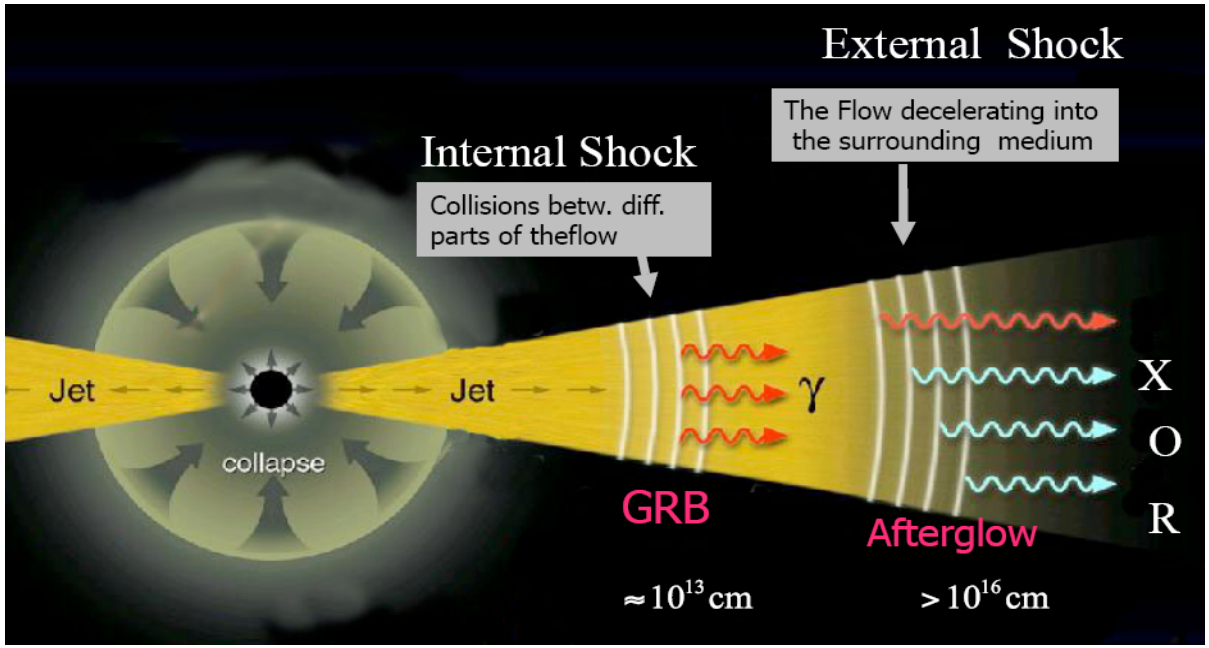
Upper limits on the neutrino flux from sources.

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

S. Schulte for the ANTARES collaboration, ICRC 2013

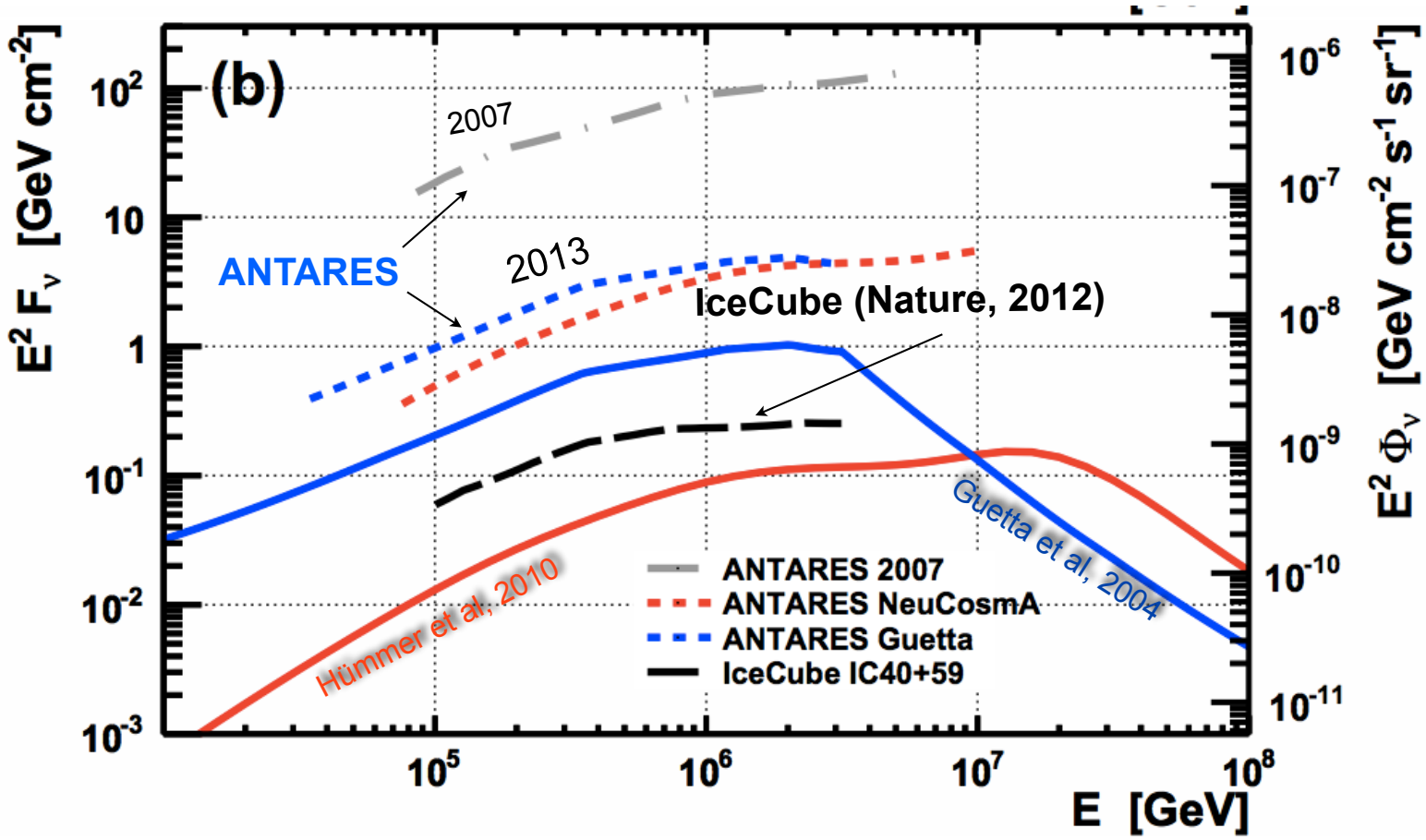


Search for neutrinos from transients: GRBs



- **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.



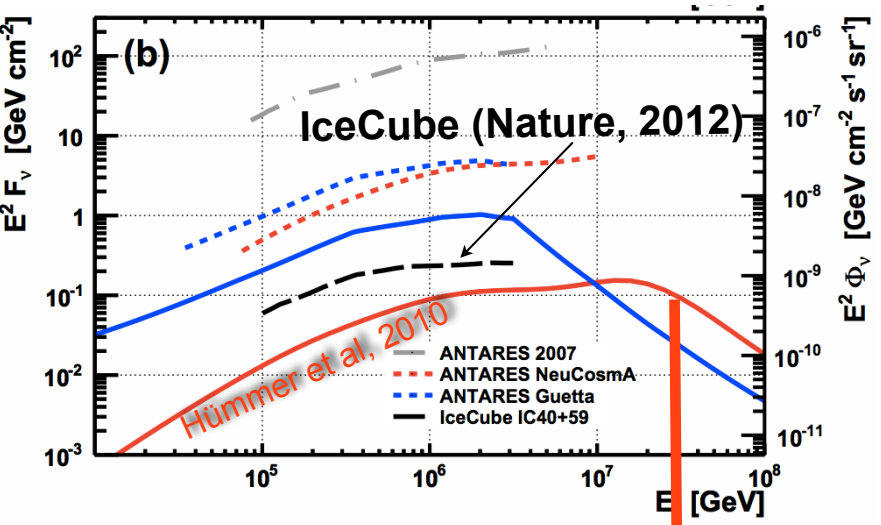
IceCube

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

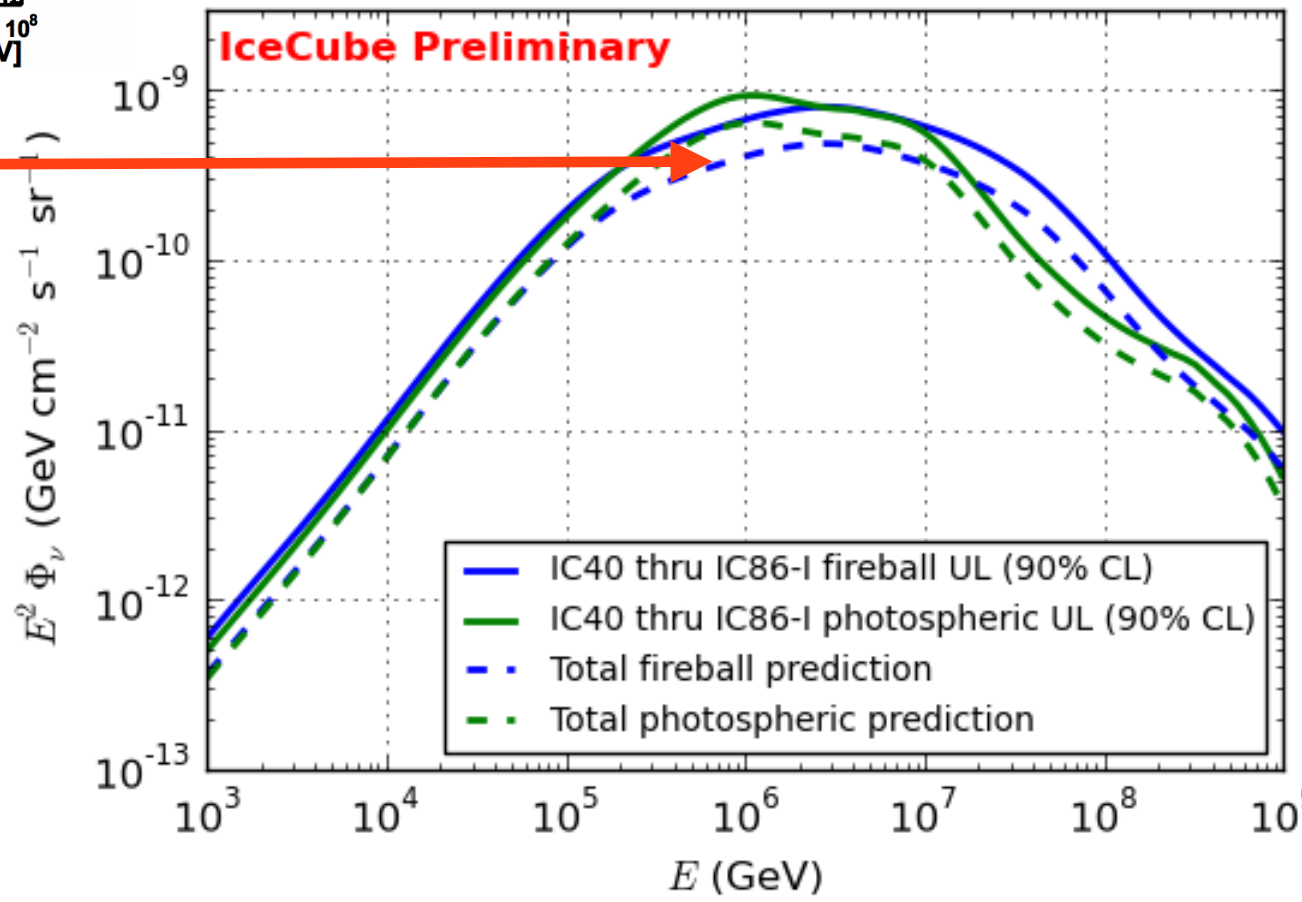
ANTARES

- **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 of **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**:

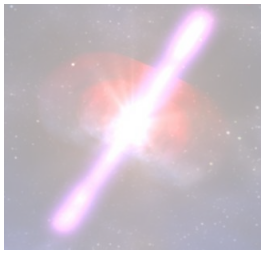
- Neutrino-triggered follow-up observations with optical telescopes.

> The **unexpected**:

- Search for space/time clustering of neutrino events.

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

Particle physics and astrophysics with IceCube.



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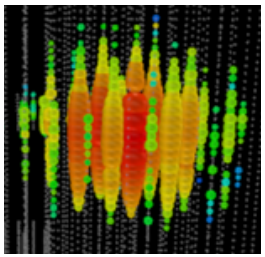

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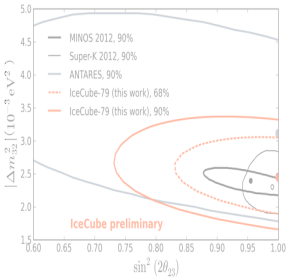

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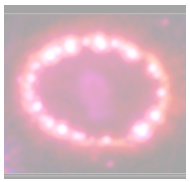
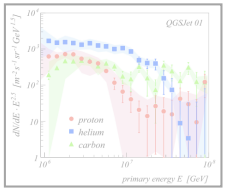
- Sensitivity to mass hierarchy with PINGU extension.

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



MeV neutrinos from SN

Search for exotic particles

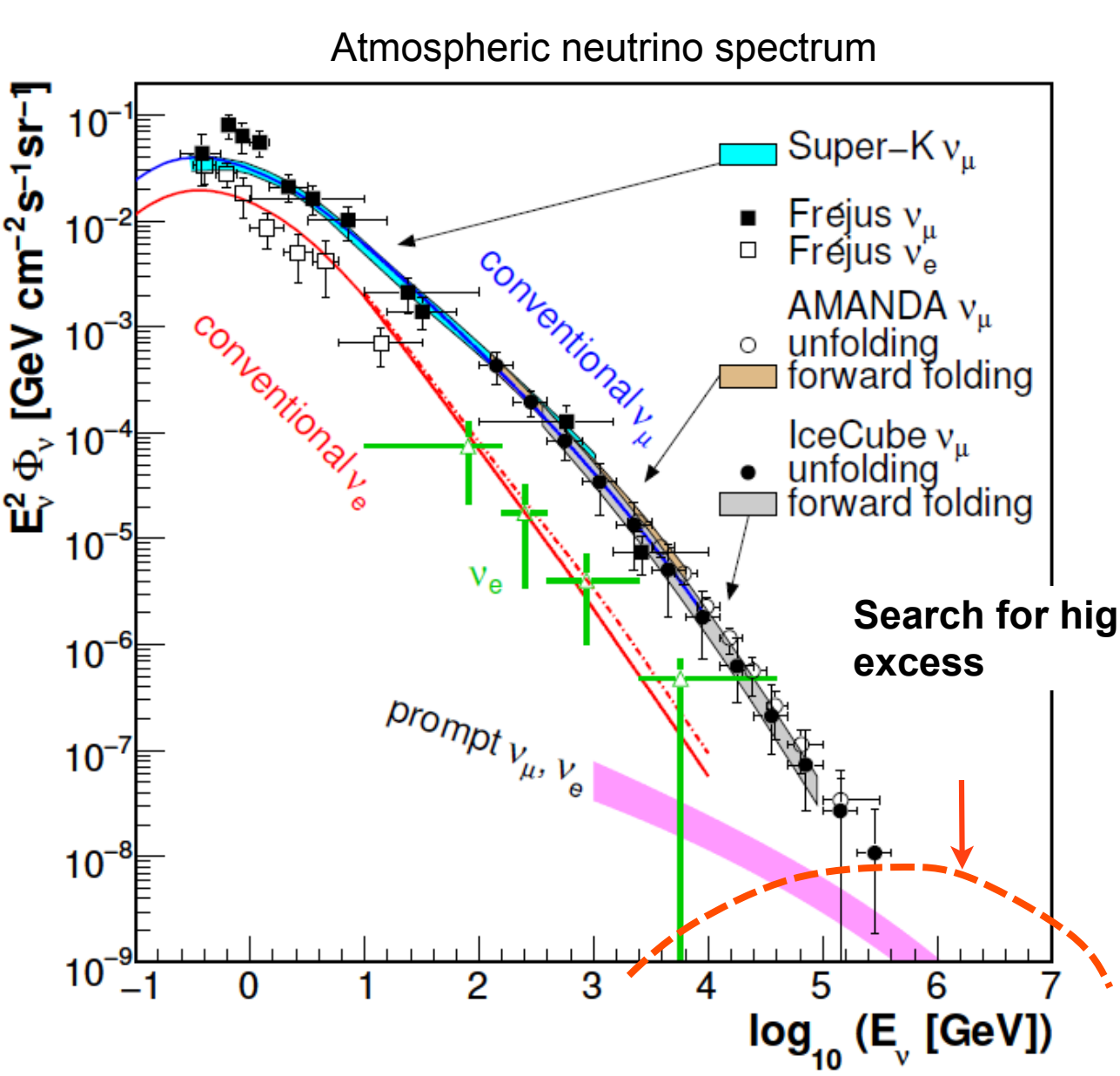


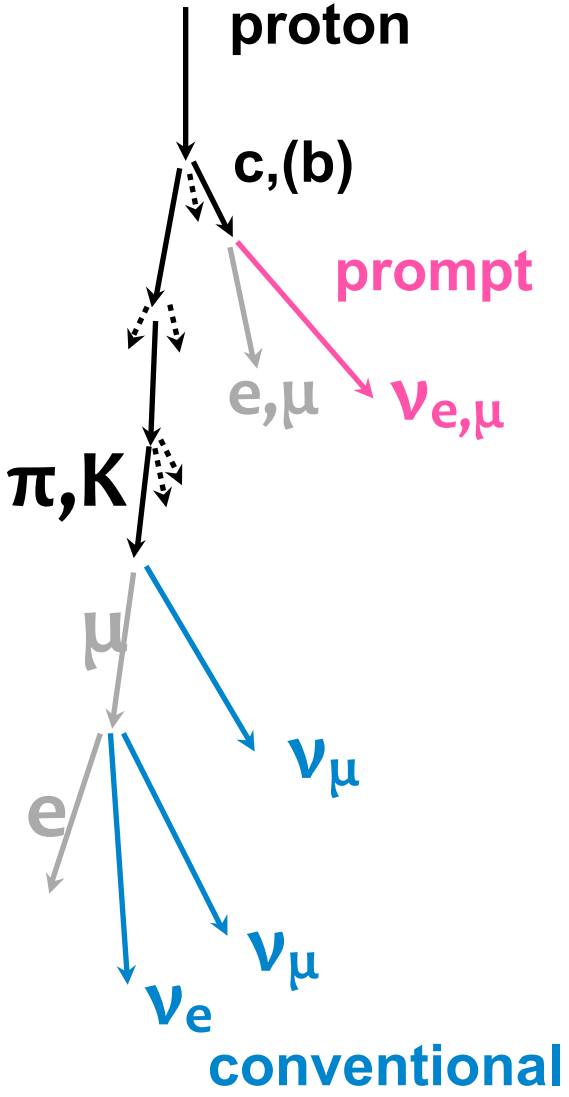
CR physics ....

Search for astrophysical neutrinos.

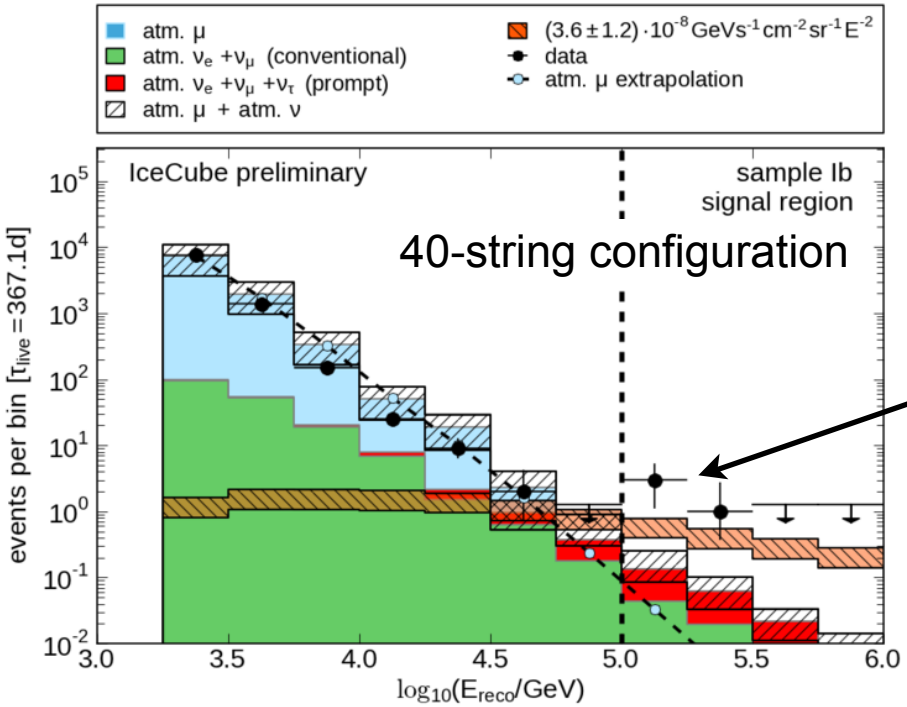
> **All neutrino sources** in the universe contribute to the astrophysical neutrino flux

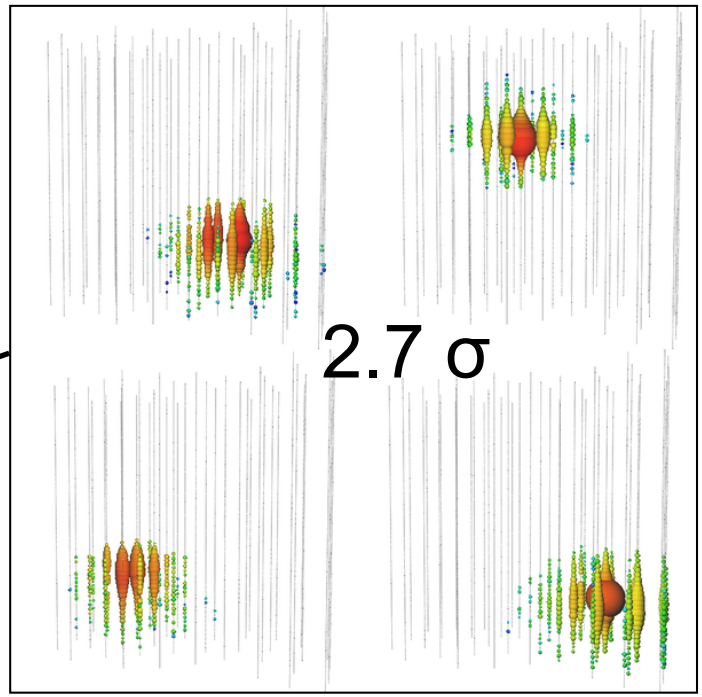
> **Harder spectrum** of astrophysical neutrinos than atmospheric background





Indications from construction phase data.

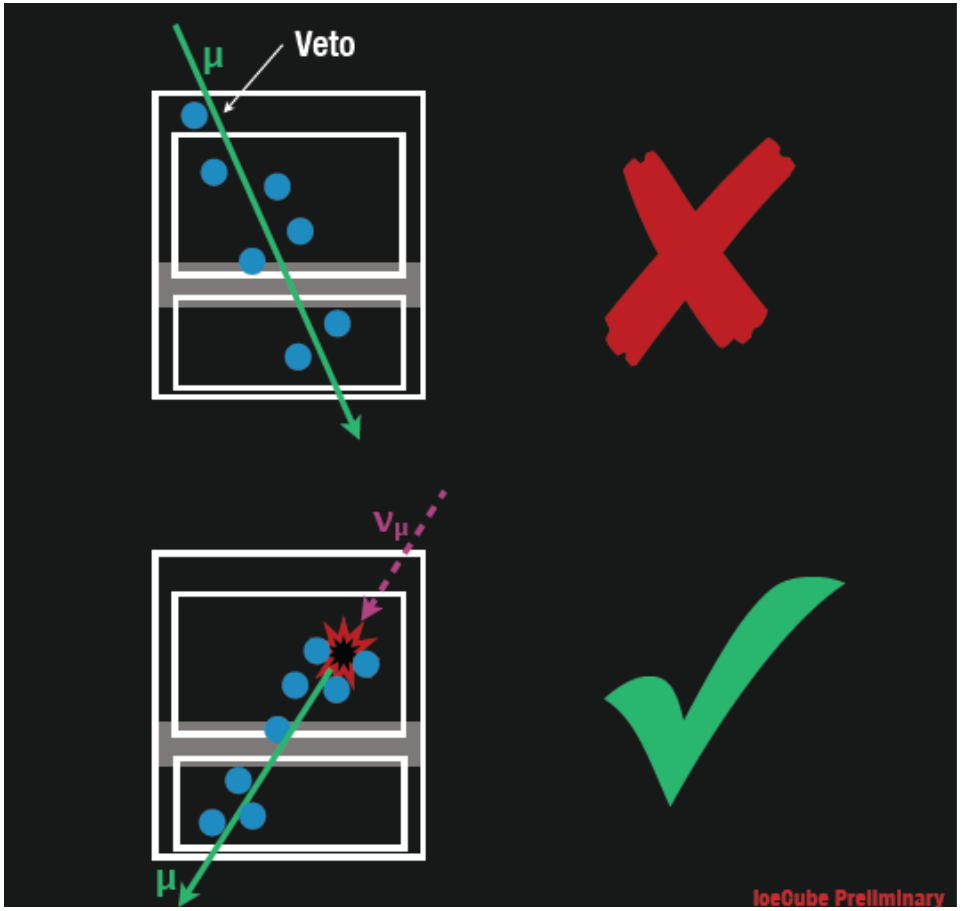


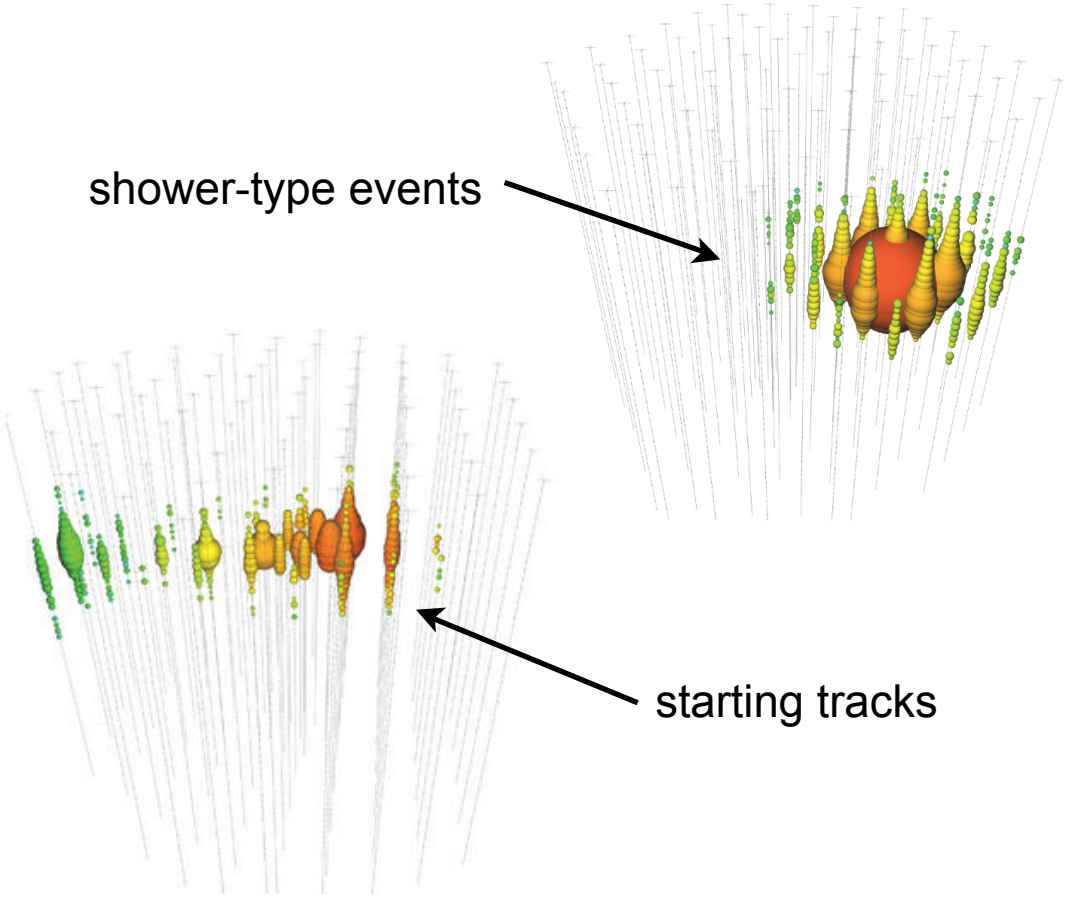


> **Excess events** observed in analysis of construction phase data.

> **Significance too weak** to exclude statistical background fluctuations.

Search for an astrophysical flux: The breakthrough.



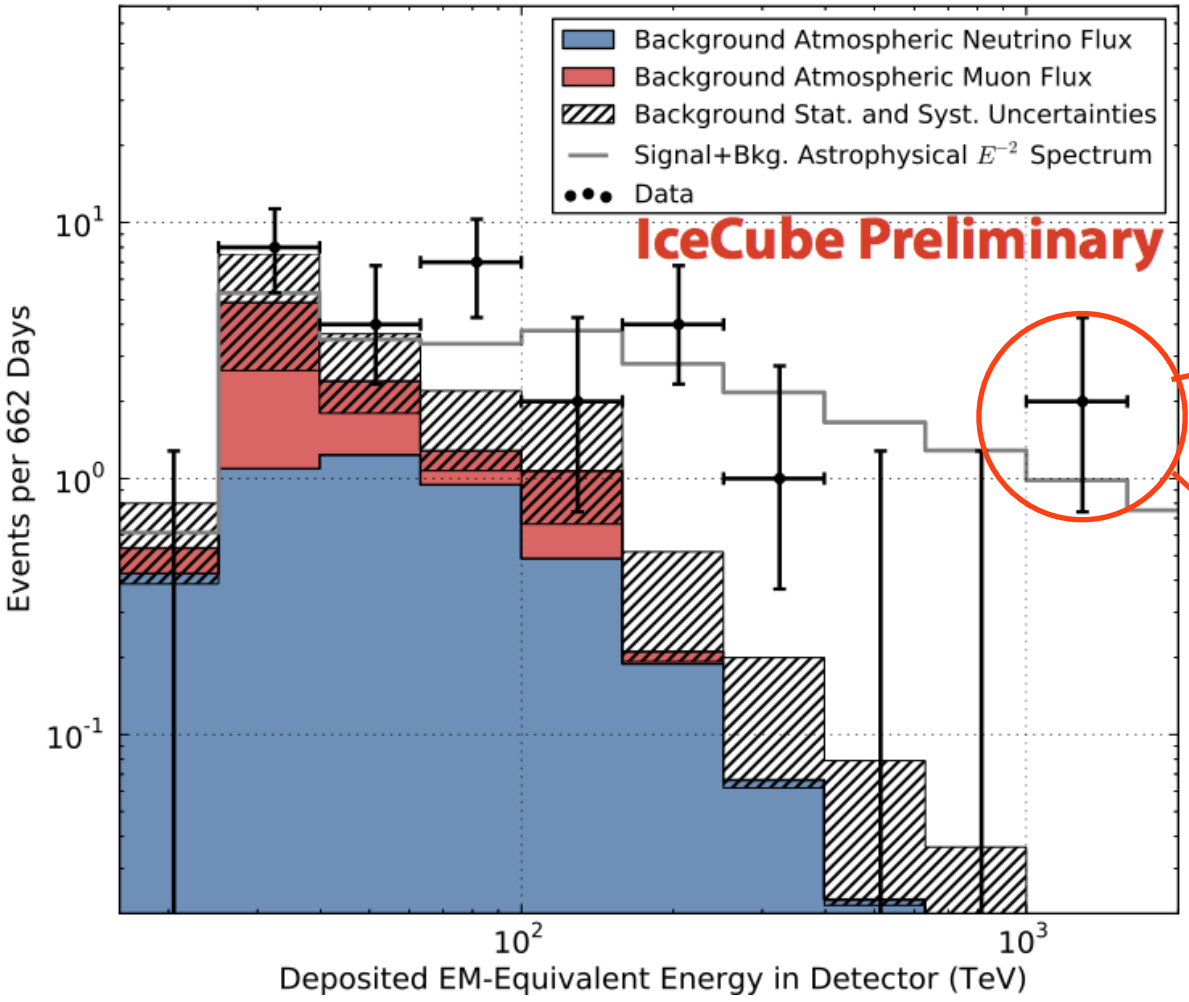


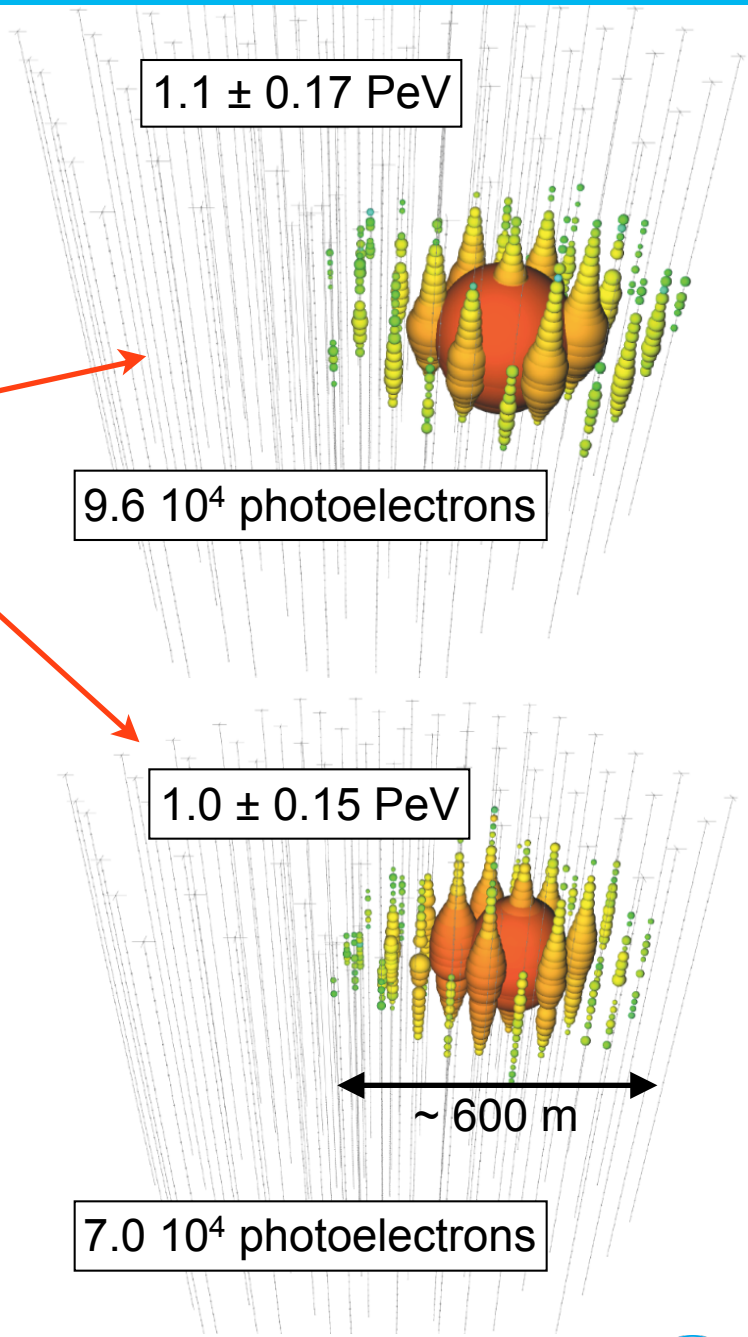
> **Search for contained and semi-contained** events with the full IceCube detector.

> **New strategy** to reject CR background (less simulation-dependent).

> Energy threshold: **~ 30 TeV** deposited energy.

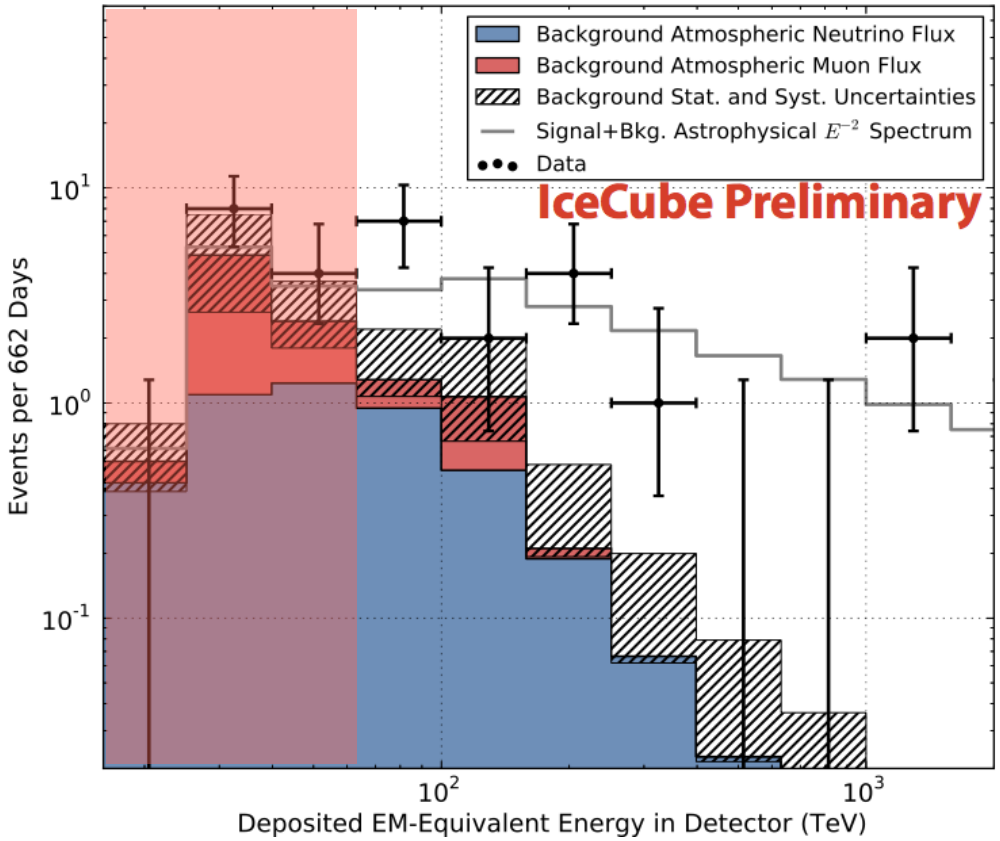
Evidence for an astrophysical neutrino flux.

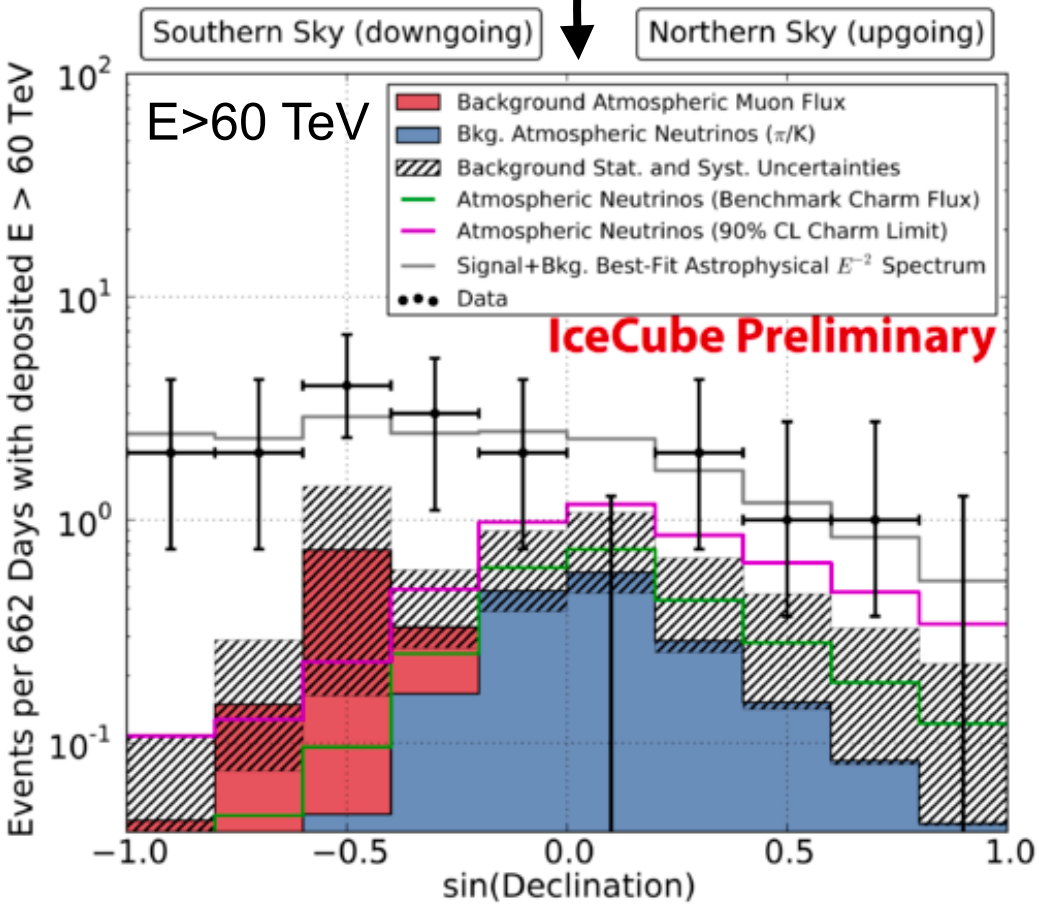




- **28 events** found in 2 years of full IceCube data
- **4.1σ excess** over expected backgrounds from atmospheric μ / ν

Spectral and angular distribution.



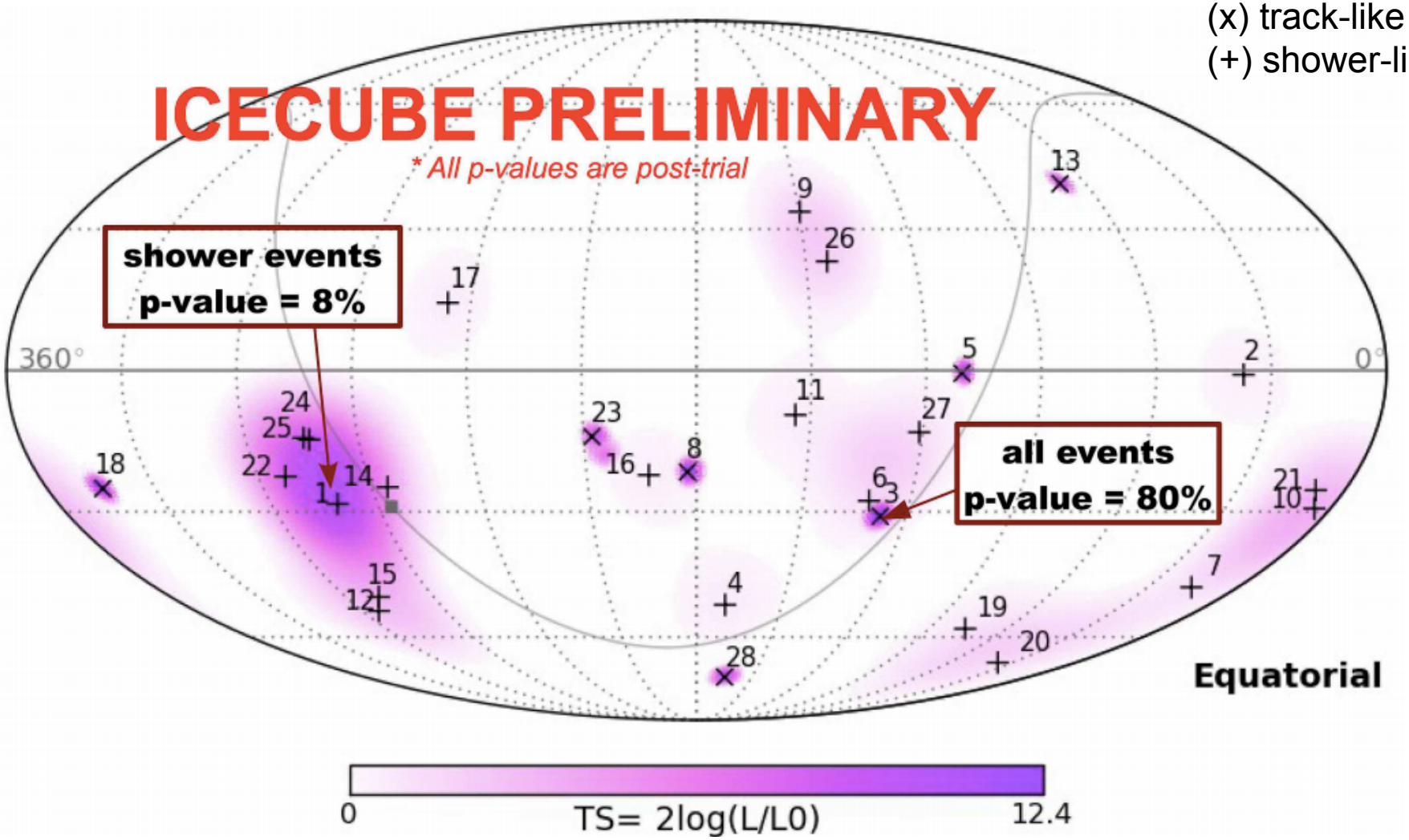


> **Spectrum** and **zenith distribution** compatible with:

- astrophysical flux
- power-law spectrum ($\Phi \sim E^{-2}$) between 60 TeV and 2 PeV.

Distribution of high-energy neutrinos on the sky.

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

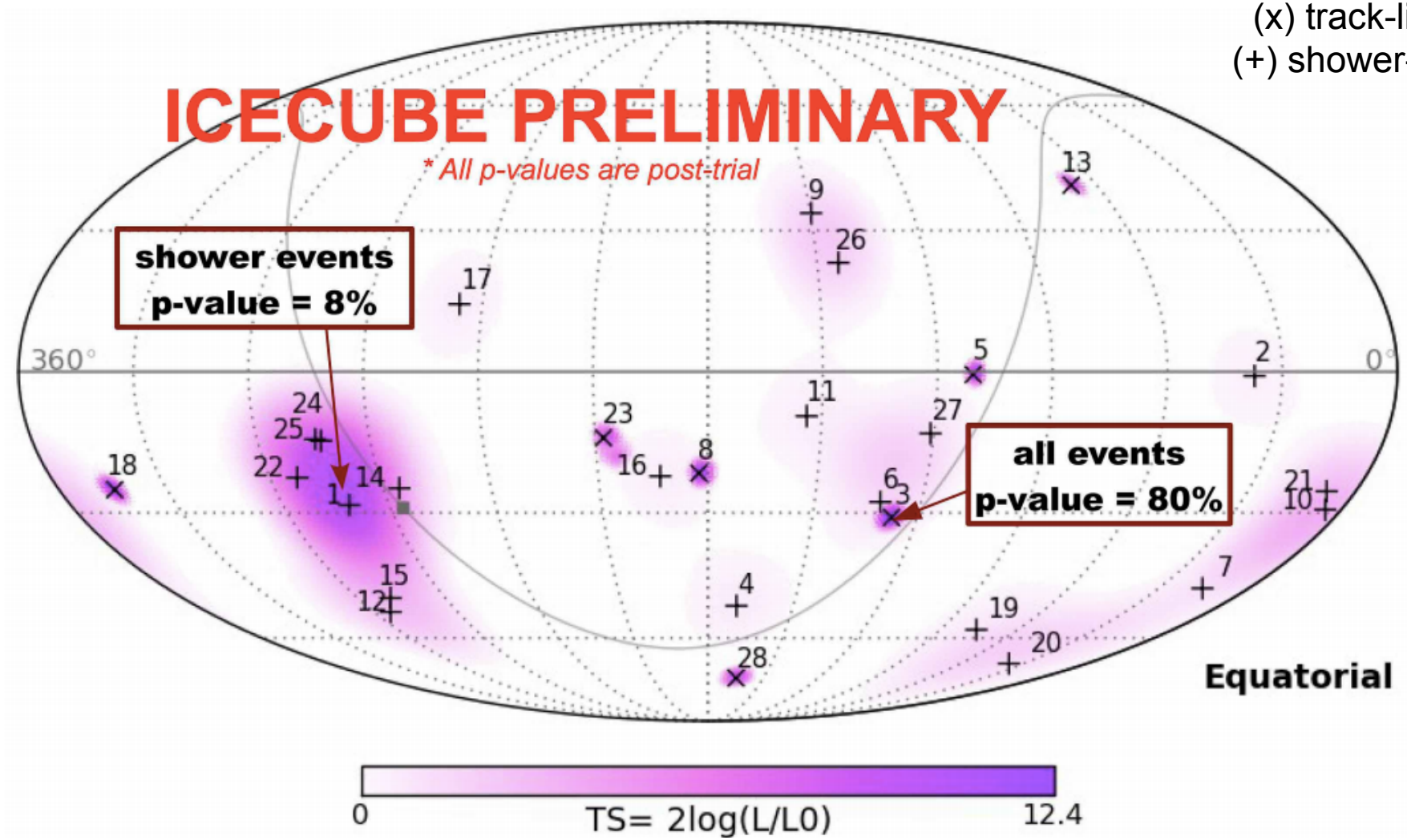


> **21 shower-like** events, **7 track-like** events.

> **Dominance of shower-like events** expected from astrophysical neutrinos due to flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

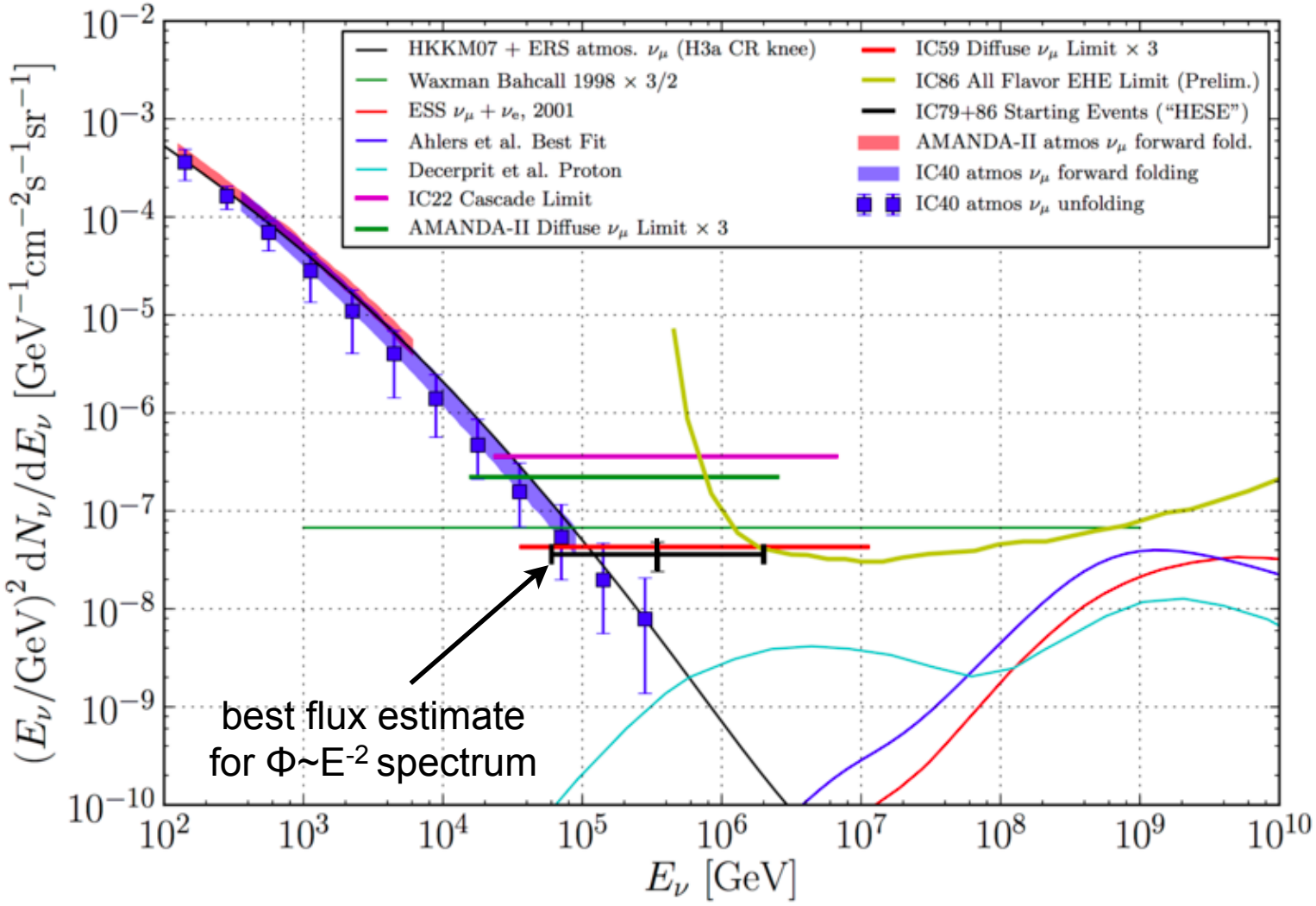
Distribution of high-energy neutrinos on the sky.

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



- **Event distribution** compatible with expectations from background + isotropic astrophysical flux.
- **Publication** accepted by Science.

Evidence for astrophysical neutrinos.



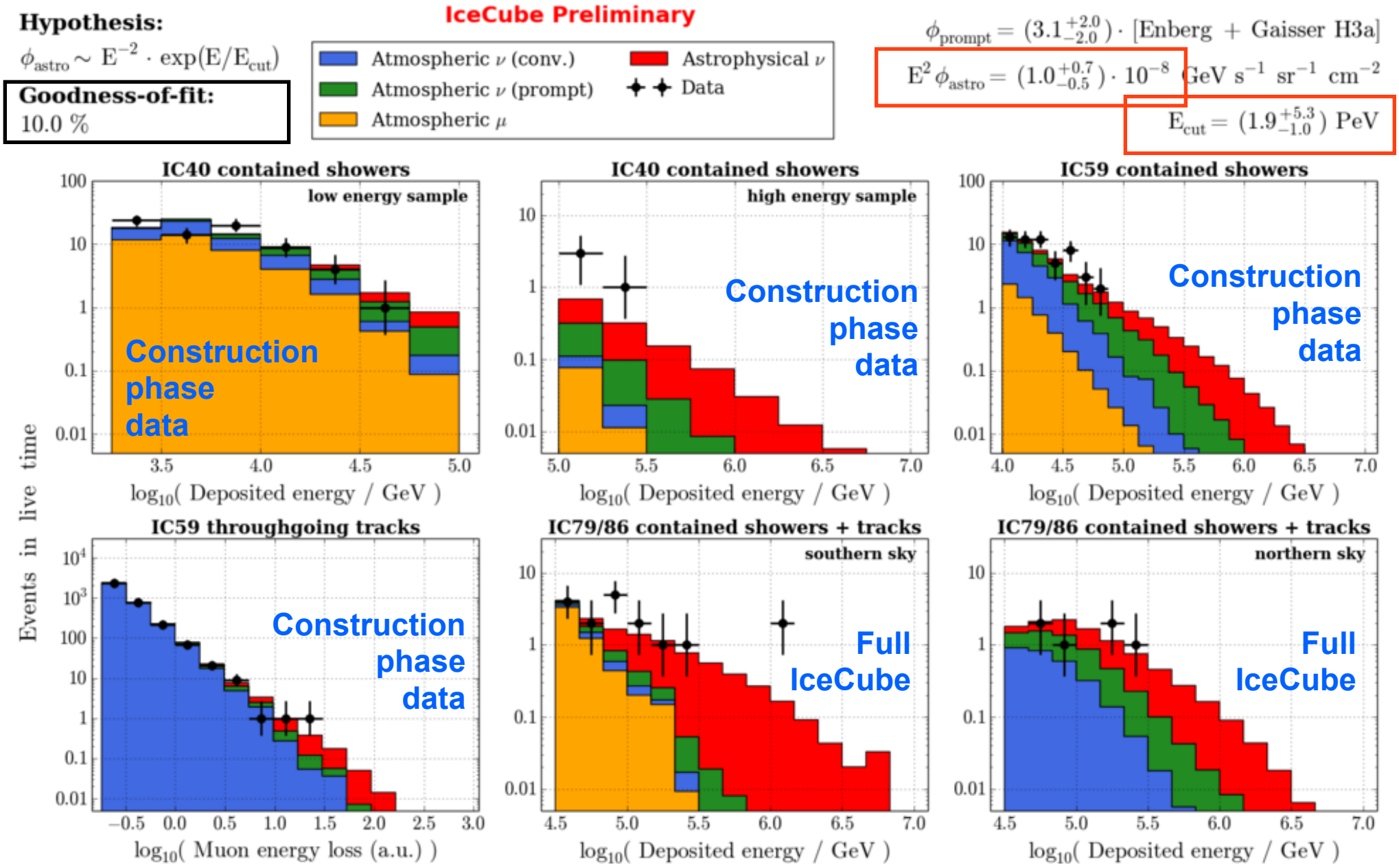
> After decades of limits: The **first ever flux point** on the diffuse astrophysical neutrino spectrum.

A global spectral fit to all IceCube data.

Hypothesis:

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

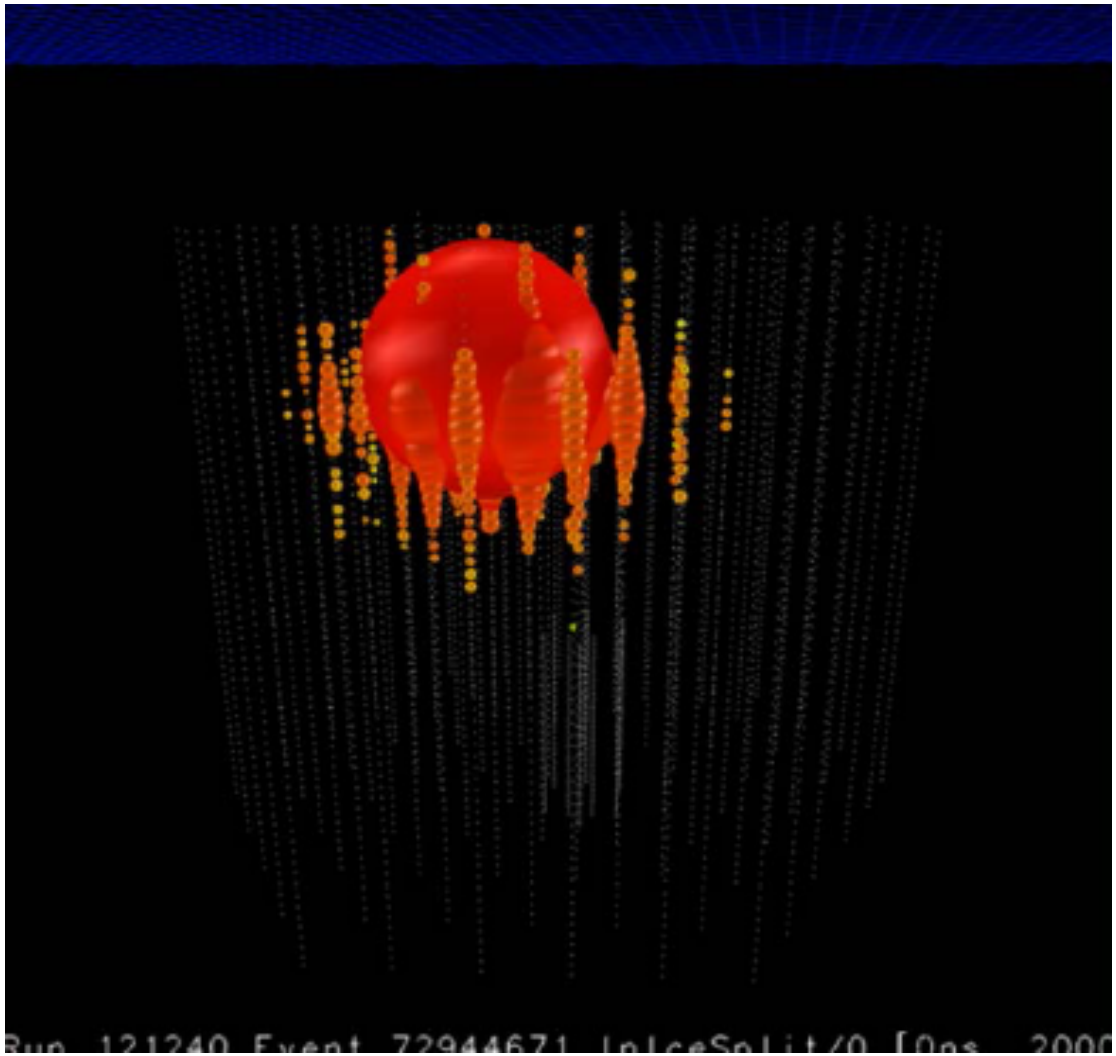
Goodness-of-fit:
10.0 %



> **Astrophysical interpretation consistent** with all IceCube data.

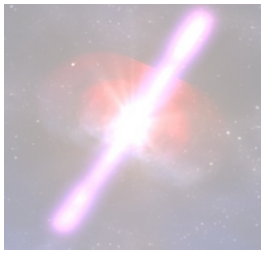
More results expected soon.

- Analysis of **2012/2013** IceCube data
  (run period from May 2012 - Apr 2013).
- **Better constraints** on prompt atmospheric neutrino fluxes from below 30 TeV data.
- Search for **excess events** in through-going tracks with IC-79/IC-86



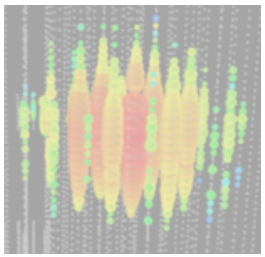
Another PeV neutrino in pre-scaled 2012/2013 data sample used for analysis development (10% of available data).

Particle physics and astrophysics with IceCube.



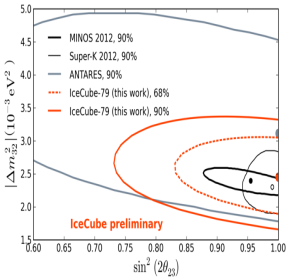
> Search for **astrophysical sources** of high-energy **neutrinos**.

- Galactic and extragalactic sources.
- Transients (Gamma-ray bursts, flares of AGNs, periodic emission from binaries).
- Neutrinos from WIMP annihilation in the sun.



> Measurement of the **diffuse neutrino flux** from the universe

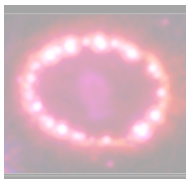
- from unresolved sources
- from the interactions of ultra-high-energy CR.



> Measurement of **neutrino properties** using atmospheric neutrinos

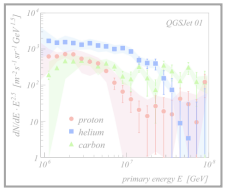
- Measurement of oscillation parameters
- Sensitivity to mass hierarchy with PINGU extension.

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



MeV neutrinos from SN


photons
gluons
Z0
W+
W-
Search for exotic particles



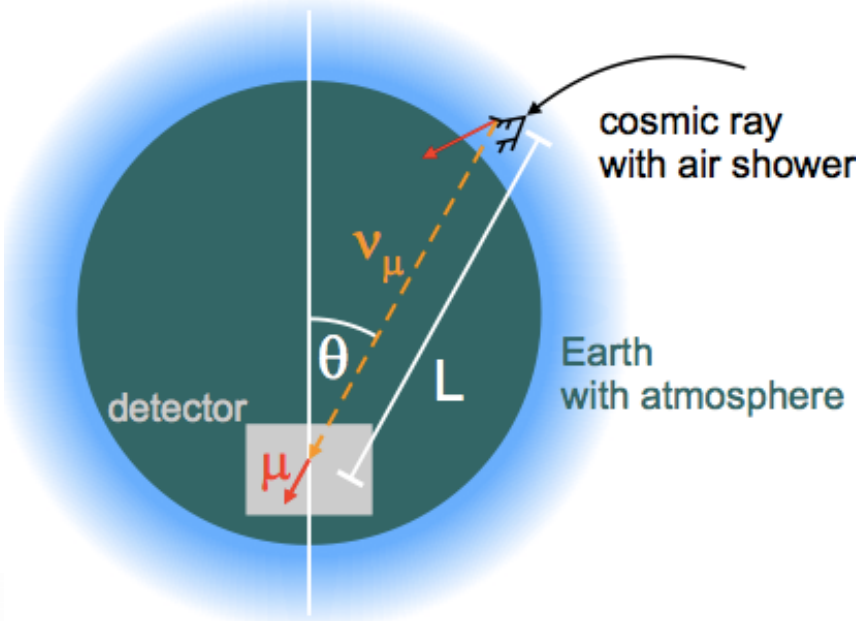
CR physics ....

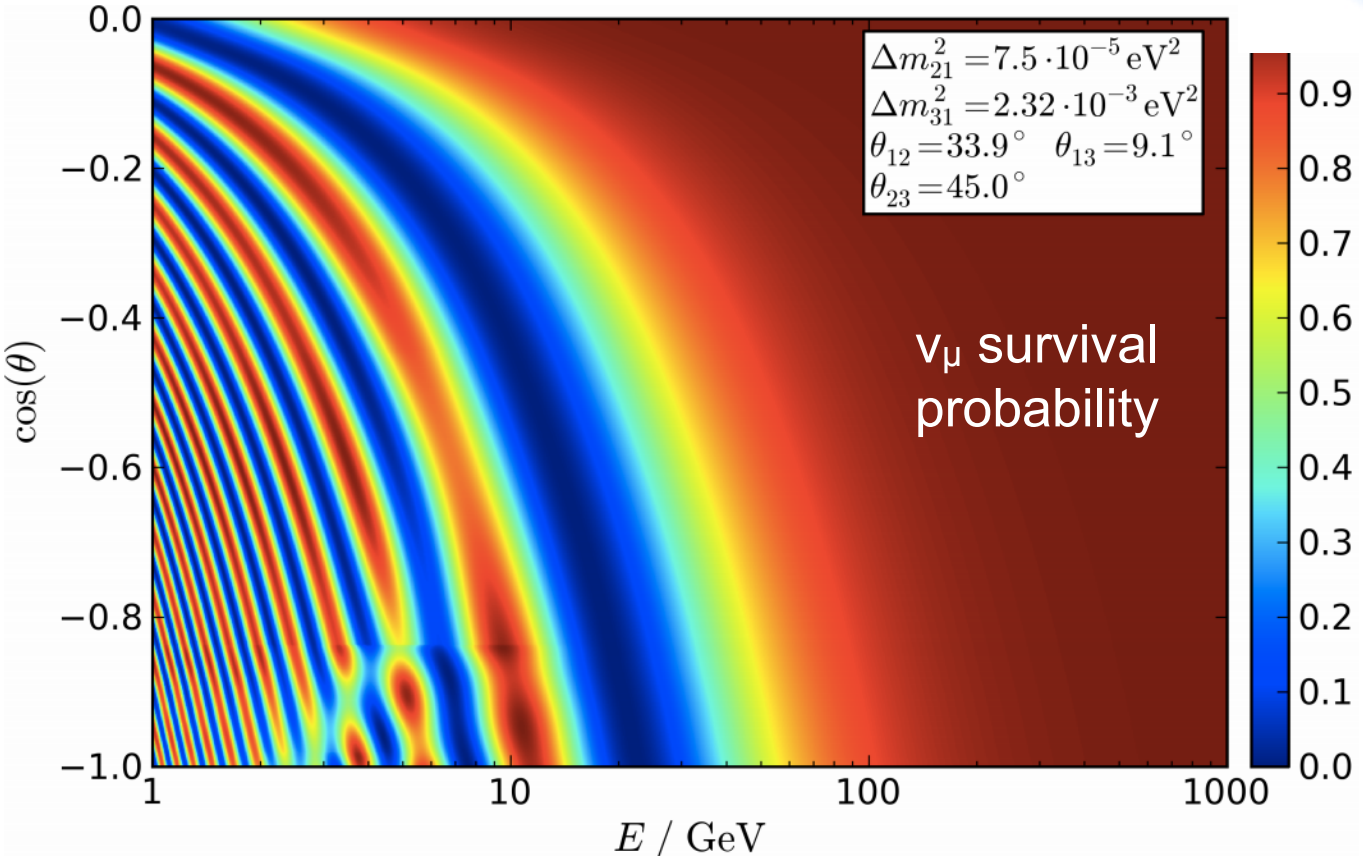
Studies of neutrino properties with IceCube.

> Measurement of **Δm^2_{23}** and **$\sin^2(2\theta_{23})$** using **DeepCore** sub-detector (~10 GeV threshold).

> For vertical events: ν_μ **survival probability** minimum **~ 25 GeV**.

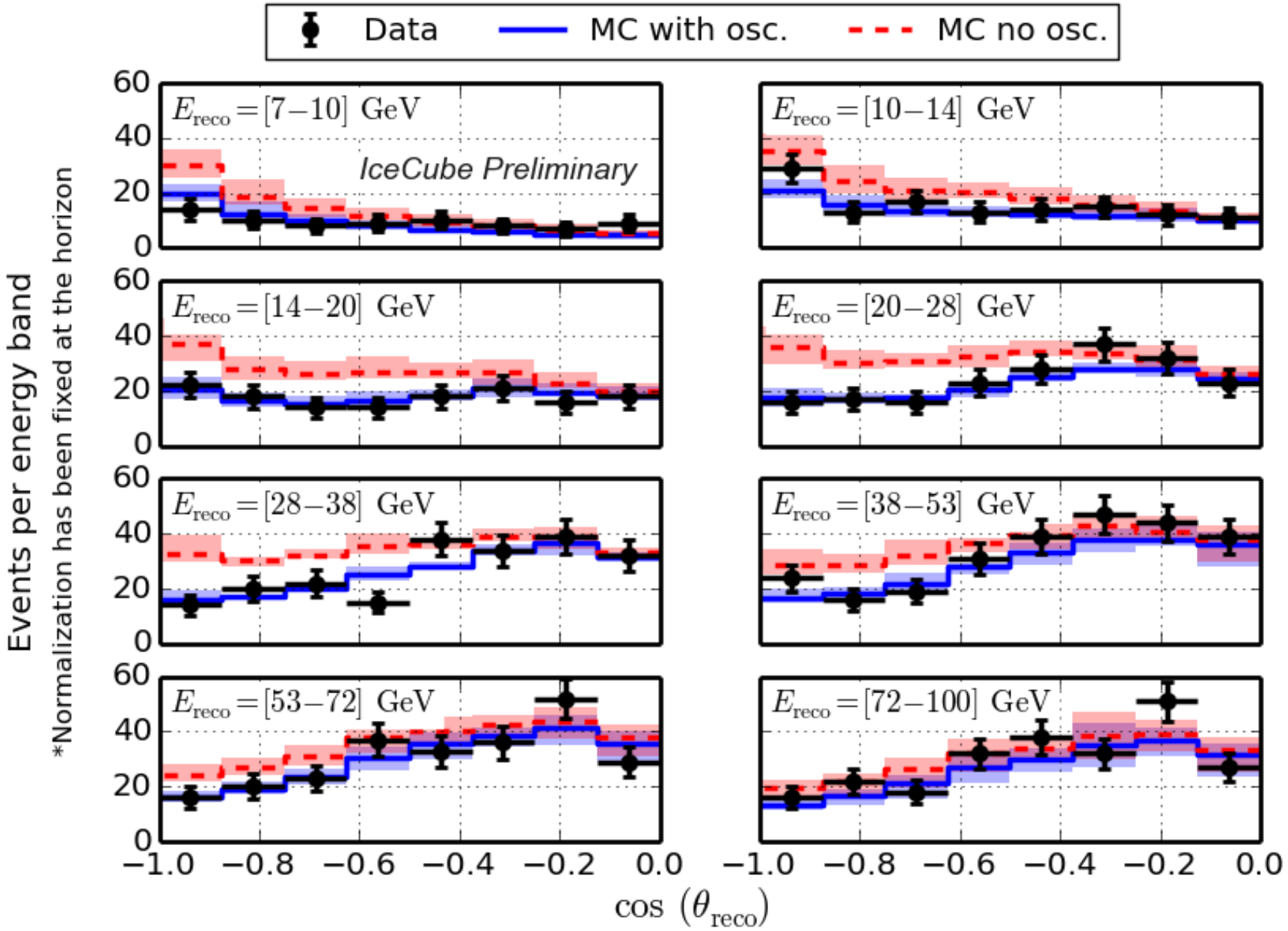
$$P(\nu_\mu \to \nu_\tau) = sin^2(2\theta_{atm}) sin^2(1.27 \Delta m^2_{atm} \frac{L}{E_\nu})$$





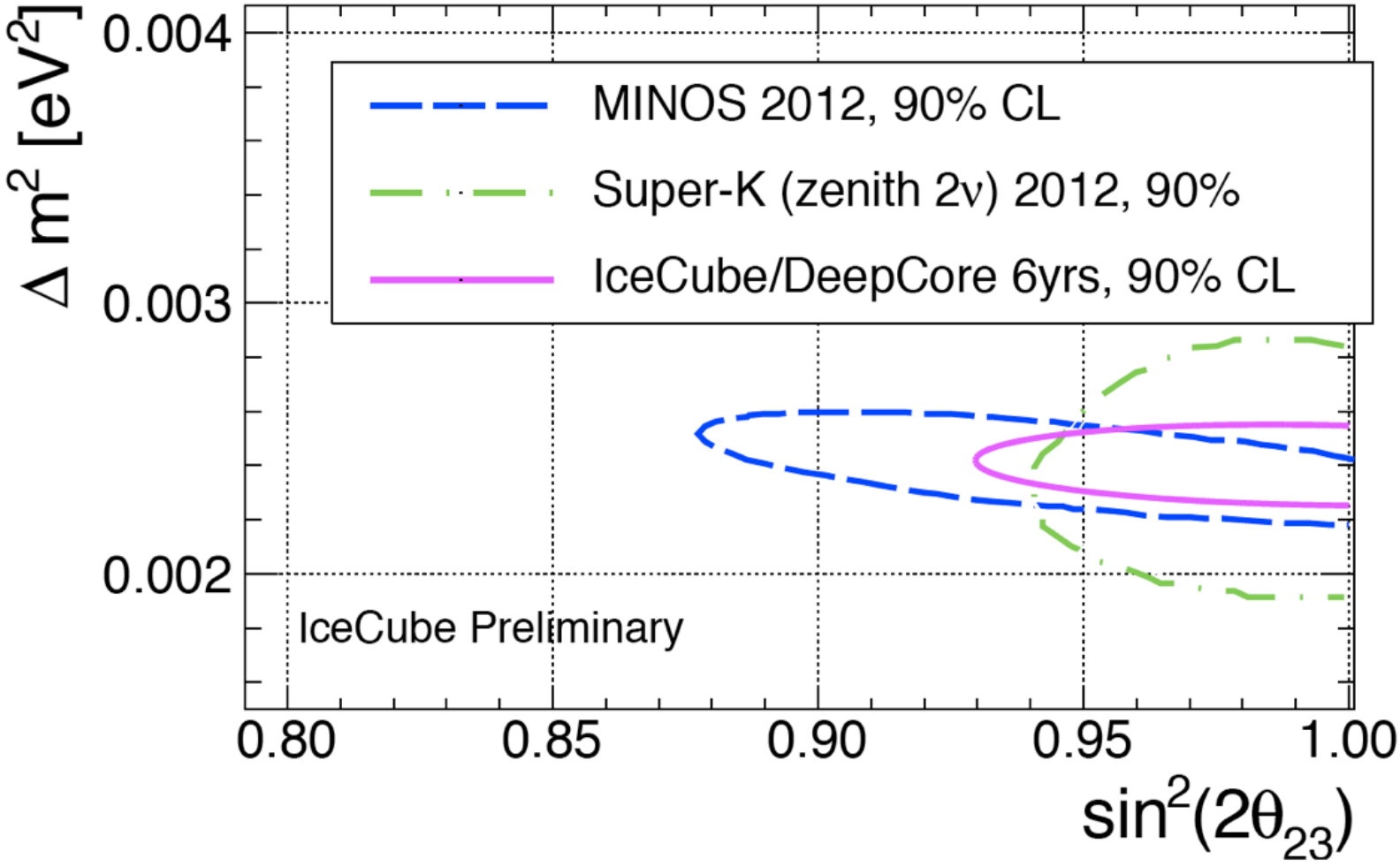
> High-energy events can be used to **control systematics**.

Studies of neutrino properties with IceCube.



> Analysis performed using **one year** of available full **IceCube** data.

Constraints on oscillation parameters.

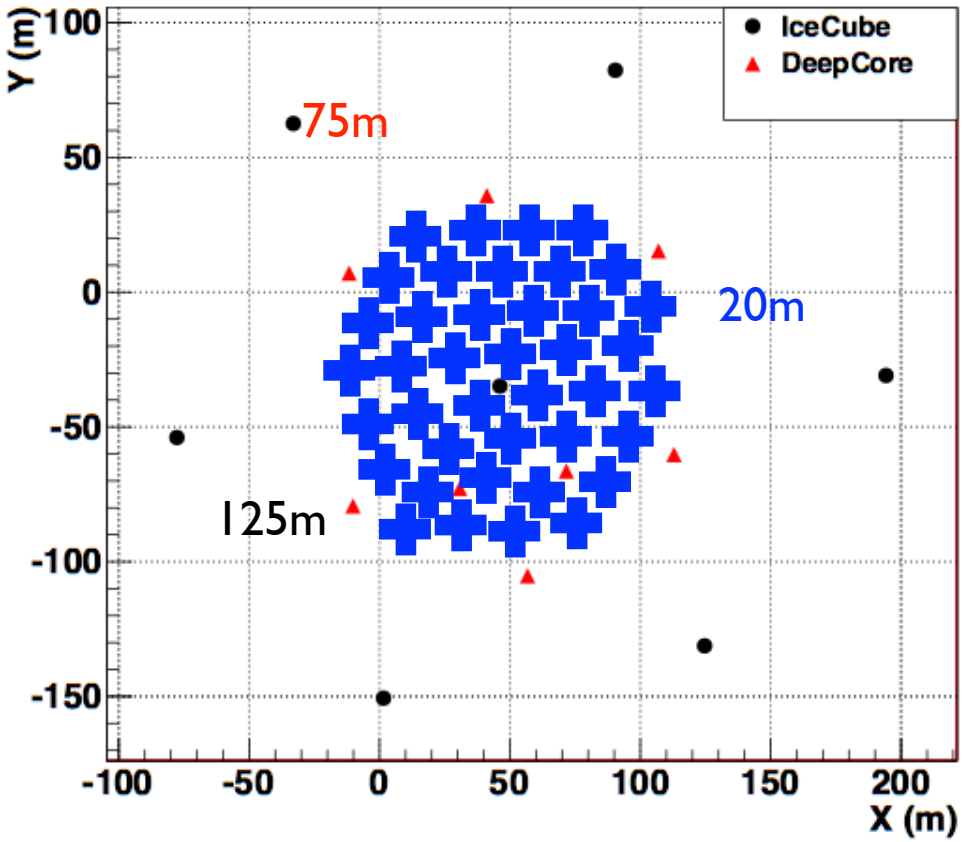


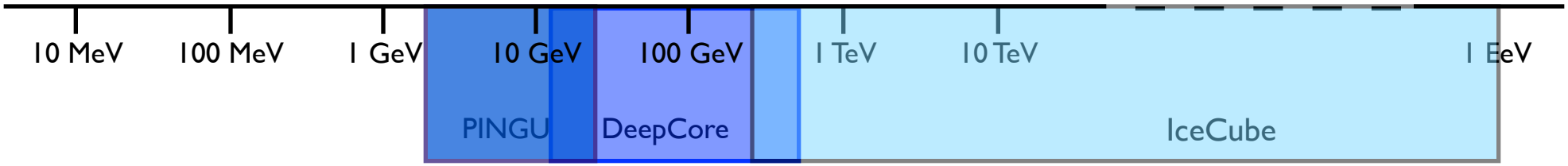
- **Promising constraints** on oscillation parameters from analysis.
- Uncertainty band **dominated by statistics** → Competitive constraints from multi-year dataset.

PINGU.

- IceCube: 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- DeepCore: +8 strings
  - 75m string spacing
  - 7m DOM spacing
- **PINGU** (baseline design)**: +40 strings**
  - **20m string spacing**
  - **5m DOM spacing**

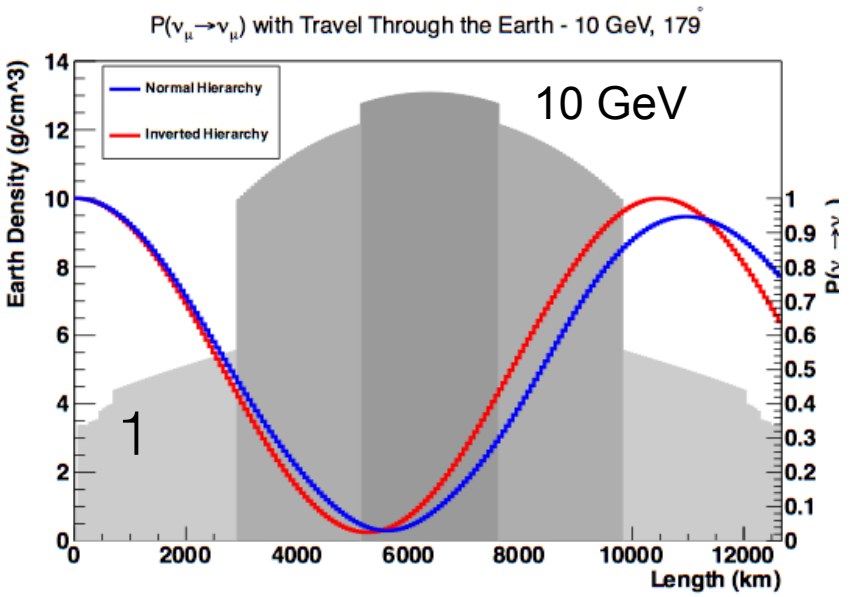
IceCube-DeepCore-PINGU top view

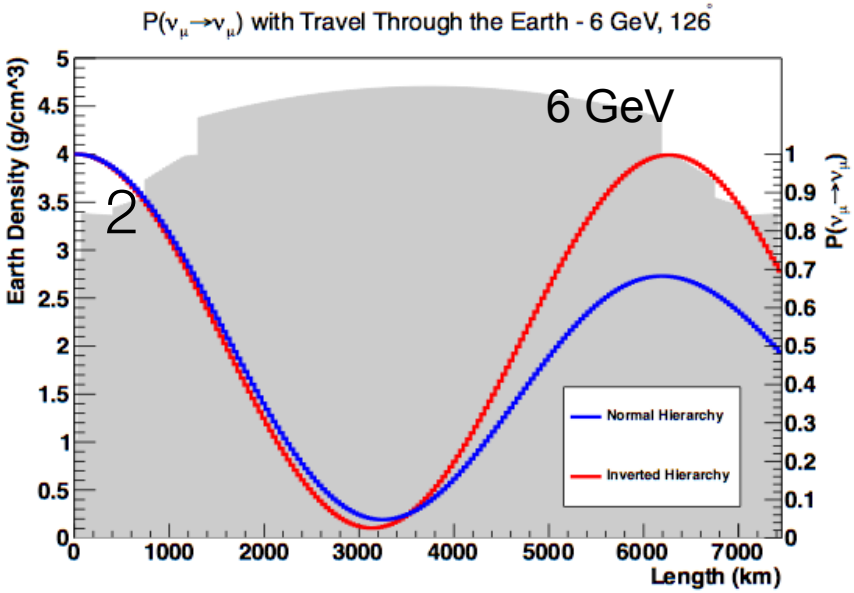


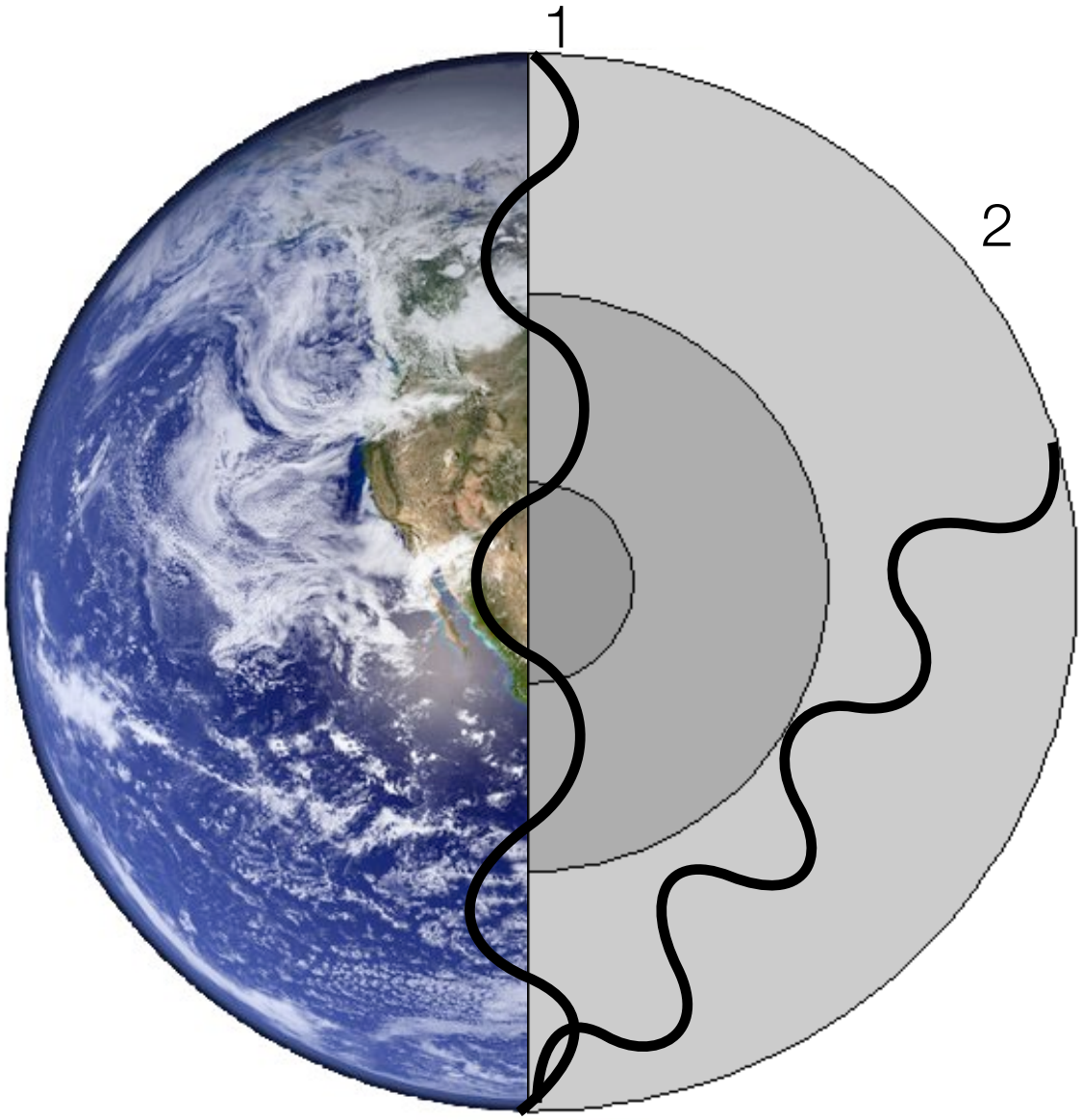


Measurement of neutrino mass hierarchy with PINGU.

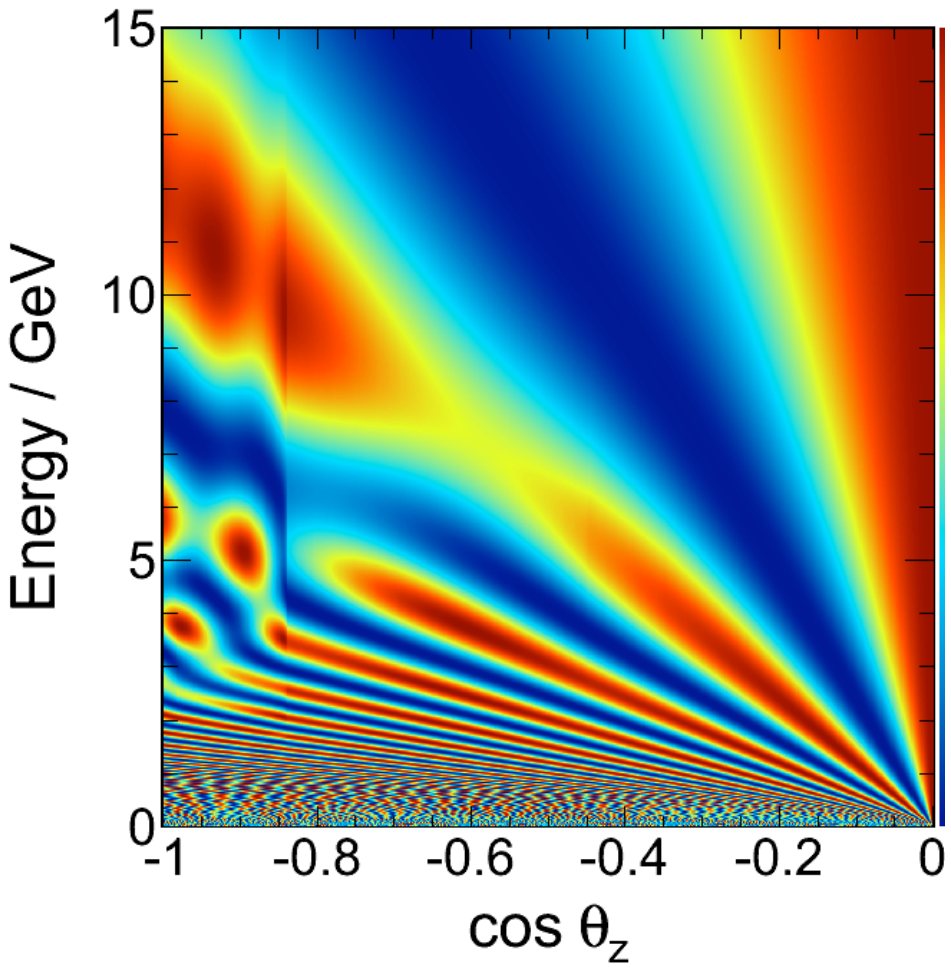
> **Up to 20% differences** in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy

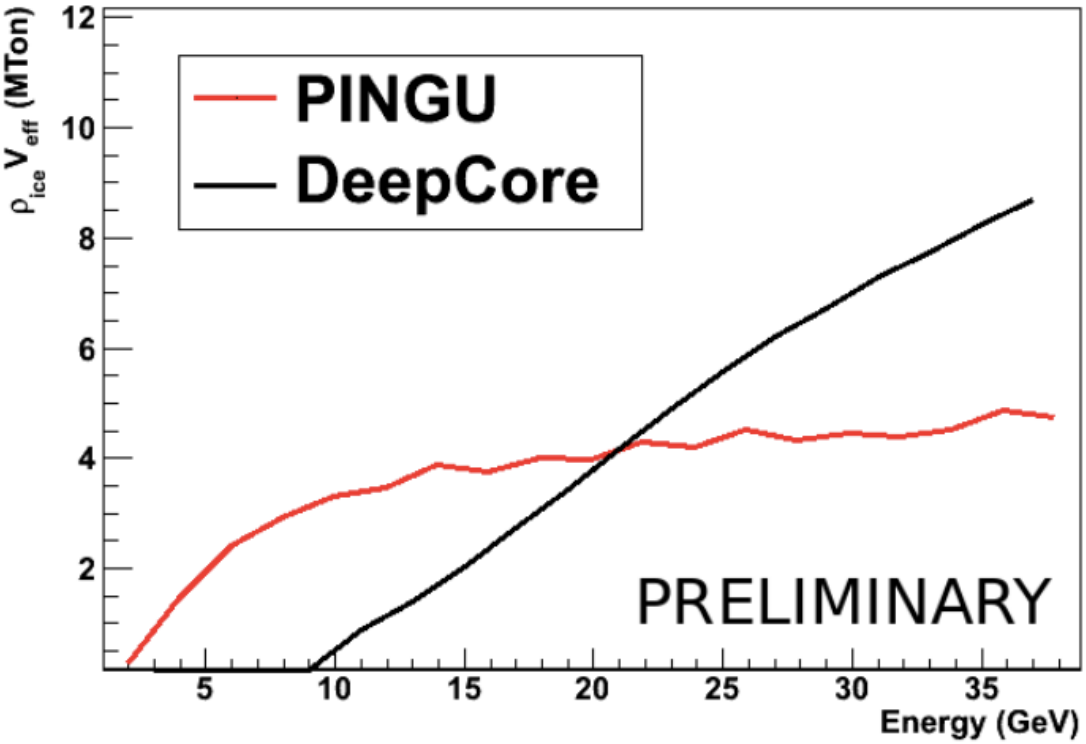






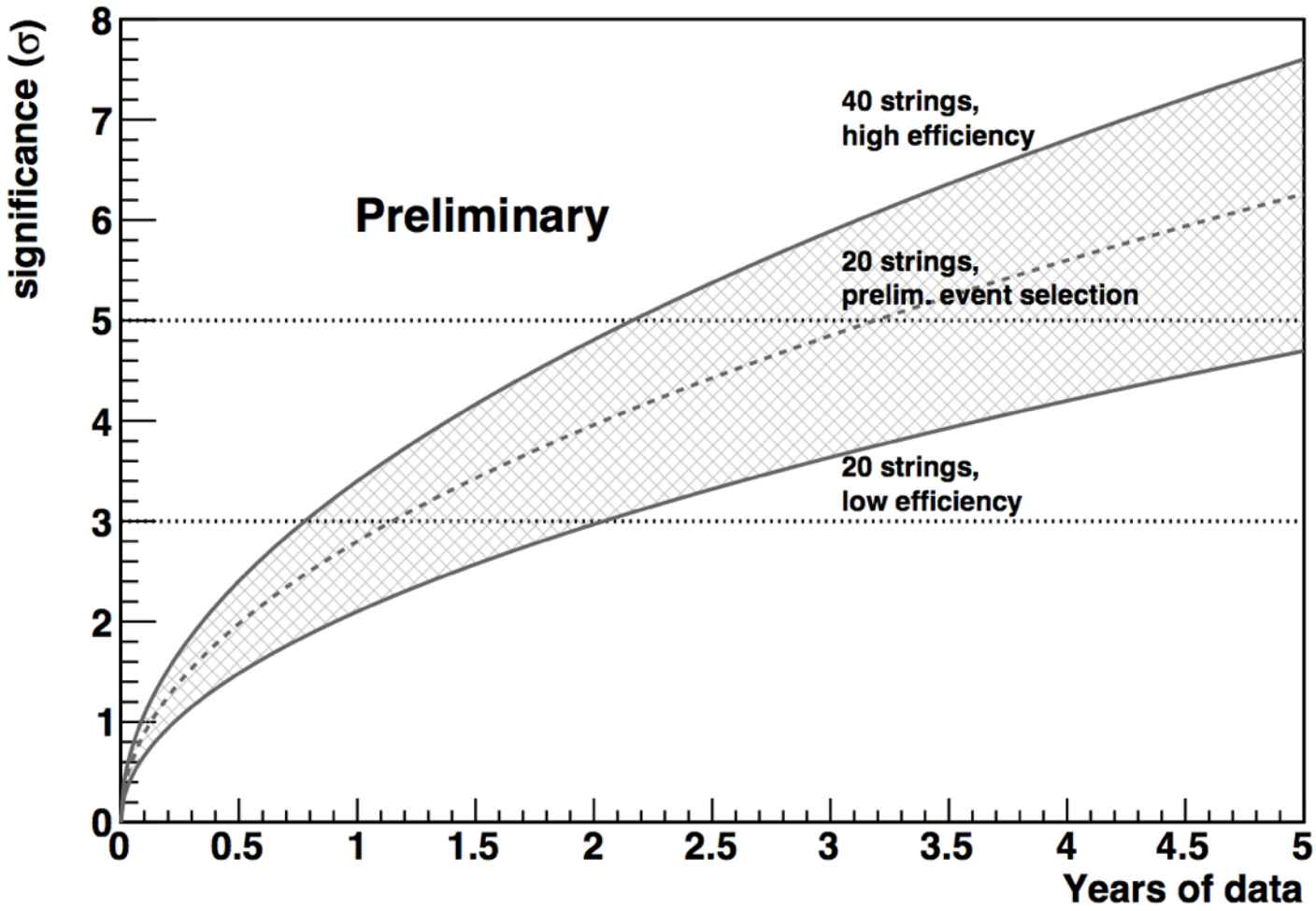
Measurement of neutrino mass hierarchy with PINGU.





- **Mass hierarchy** is one of the last unknown fundamental properties of the neutrino sector.
- Need to be **sensitive** to energies down to **5 GeV** for measurement.
- **PINGU**: > megaton effective volume above a few GeV.

Expected PINGU performance.



> **Expected significance** from likelihood analysis of oscillation patterns.

> **Letter-of-Intent** prepared in the collaboration.

- To be released to the public before the end of the year.

Summary.

> IceCube is the first **gigaton scale** neutrino telescope in operation.

> 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.

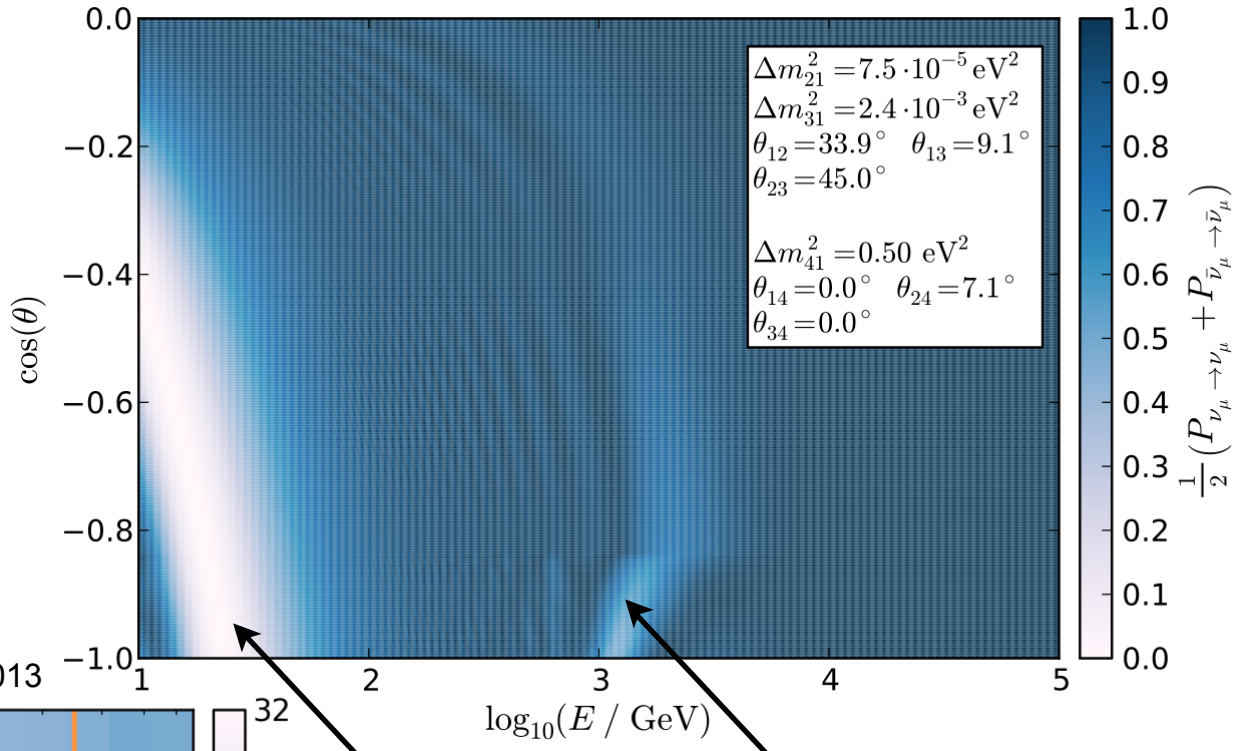
> IceCube is a **unique infrastructure** to study **neutrino properties.**

- Competitive studies of standard oscillation parameters with DeepCore.
- In the future: Mass hierarchy with PINGU.

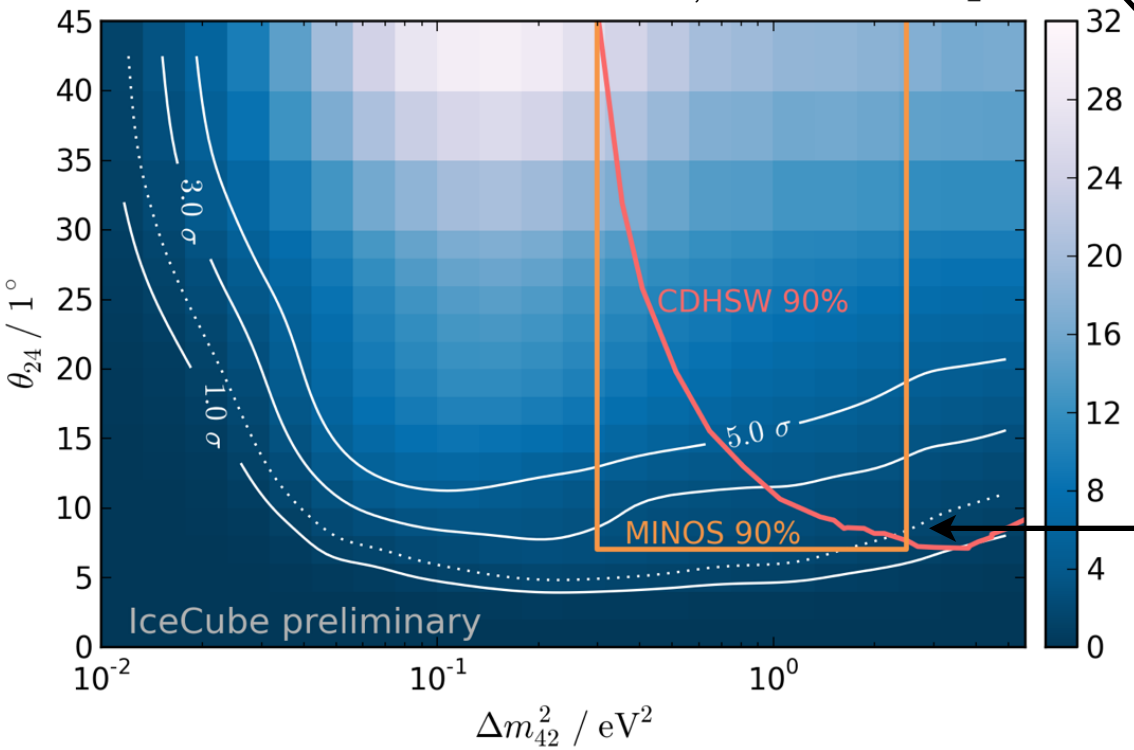
Click to add title.

Sensitivity to sterile neutrinos.

- IceCube is sensitive to **O(eV) sterile neutrinos.**
- Search for **oscillation** patterns of **TeV neutrinos.**
- **Competitive limits** expected from full IceCube array.



M. Walraff for the IceCube collaboration, ICRC 2013

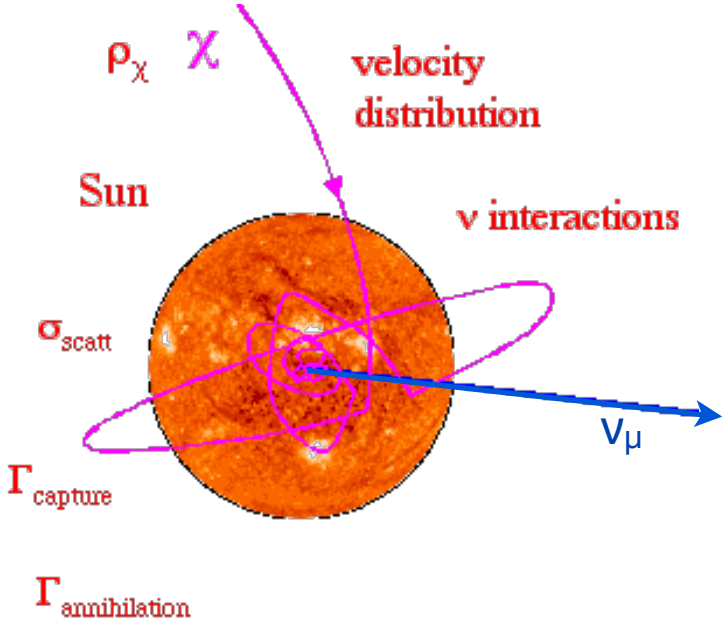


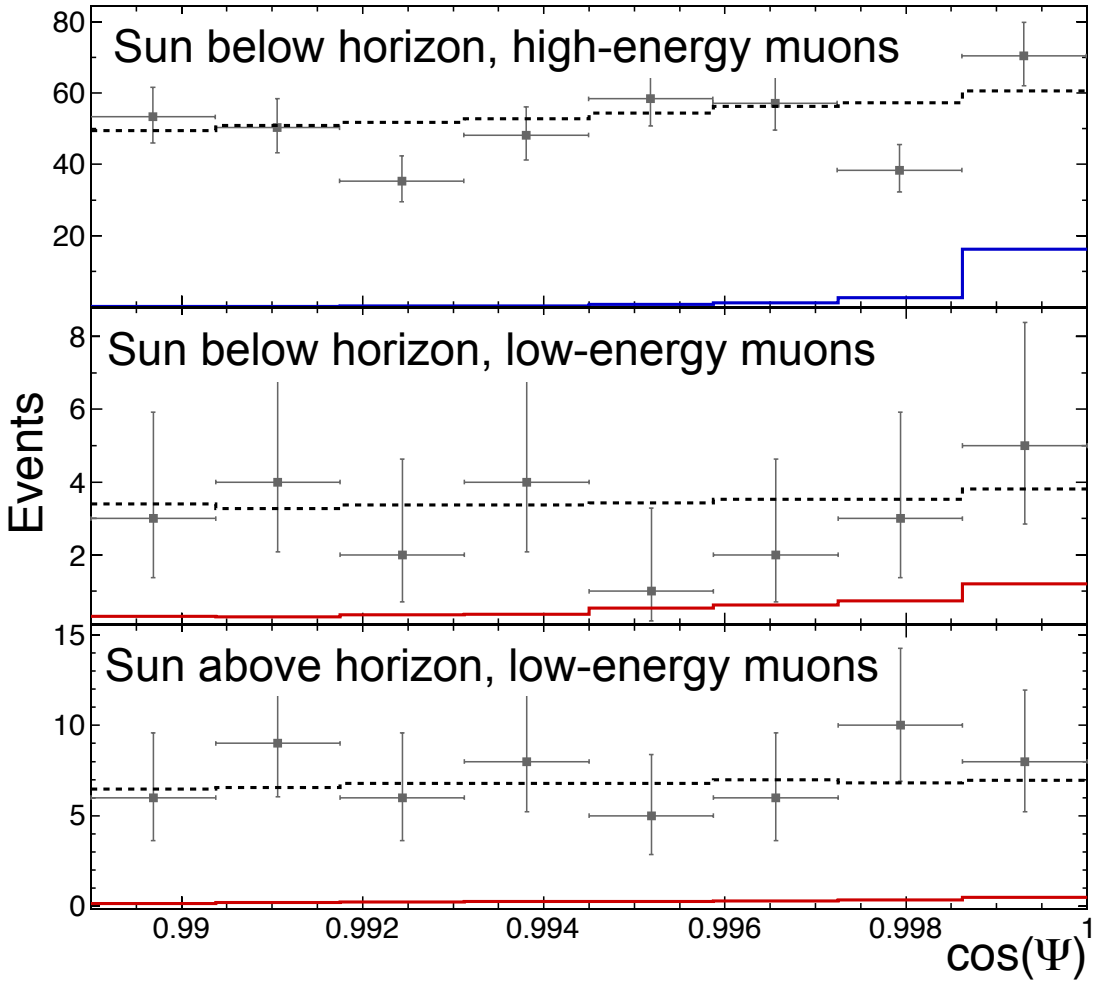
Standard oscillations

Sterile neutrino oscillations

IceCube 5-year 90% exclusion sensitivity

Search for neutrino annihilations in the sun.

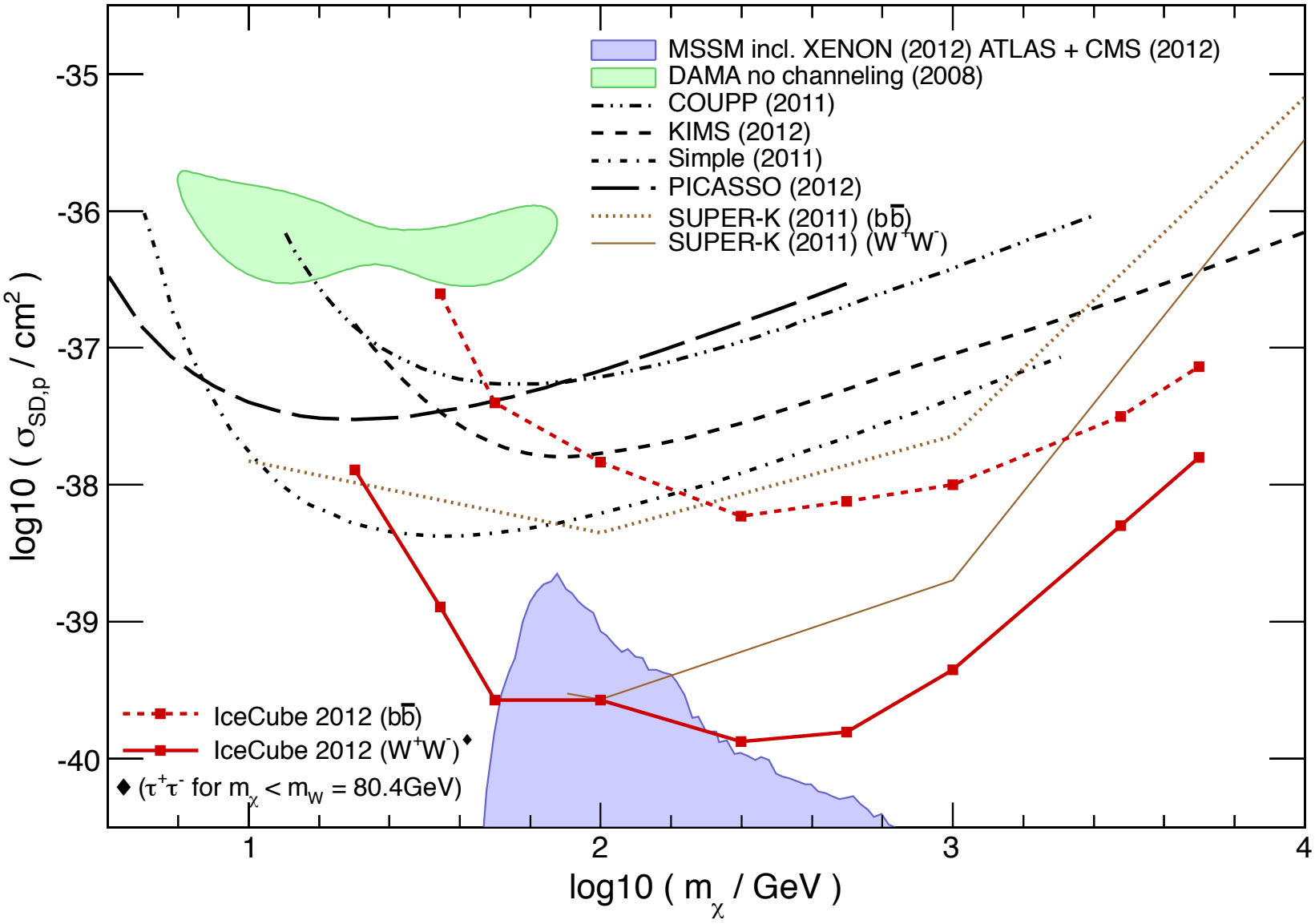




- DM particles **get captured** by scattering off atoms **in the Sun**.
- **Annihilation** of accumulated **WIMPs** produces neutrinos.
- In equilibrium: **Neutrino flux** depends only on **scattering cross section.**

Search for neutrino annihilations in the sun.

- Mass of sun is dominated by **hydrogen atoms**.
- World's best limits on **spin-dependent** scattering **cross-section** from IceCube.



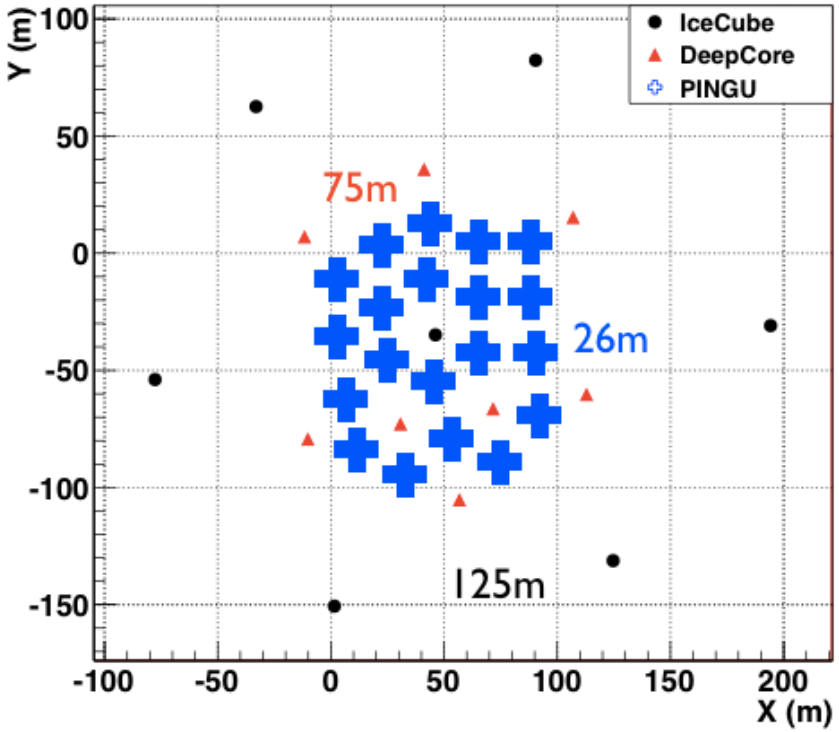
Beyond IceCube.

Increase of core density

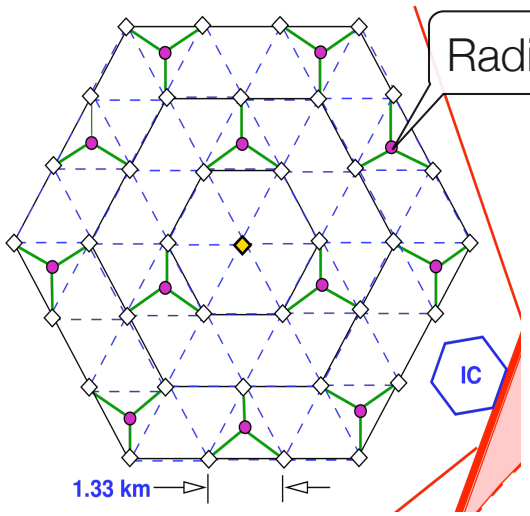
PINGU

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

IceCube-DeepCore-PINGU top view

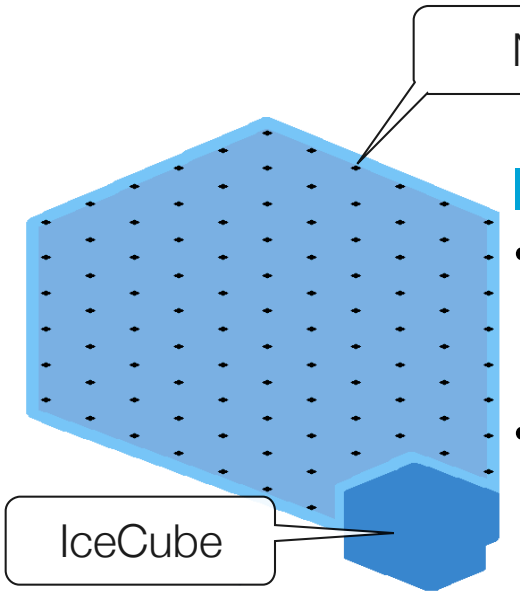


Extensions to larger volumes



Askarian Radio Array (ARA)

- InIce Radio array for **>30 PeV** neutrinos
- several **tens of km²** surface area

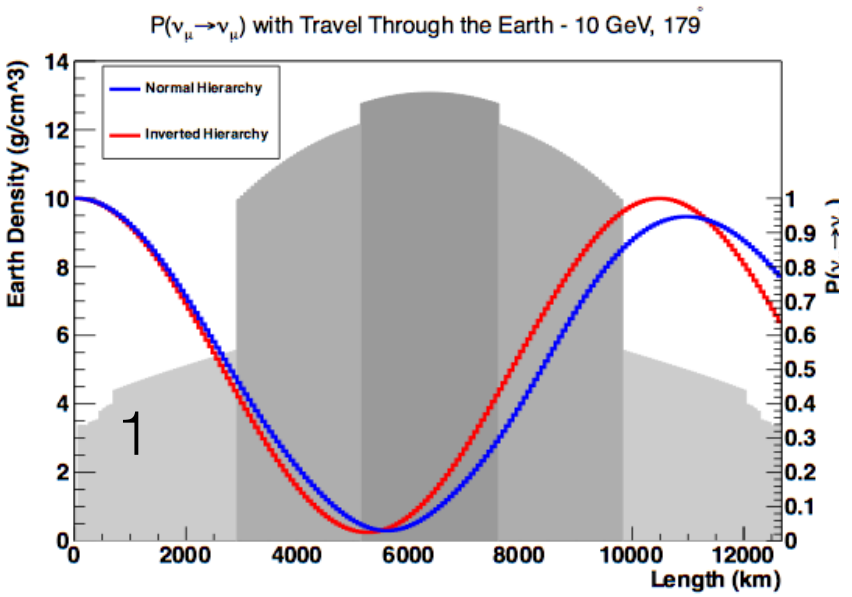


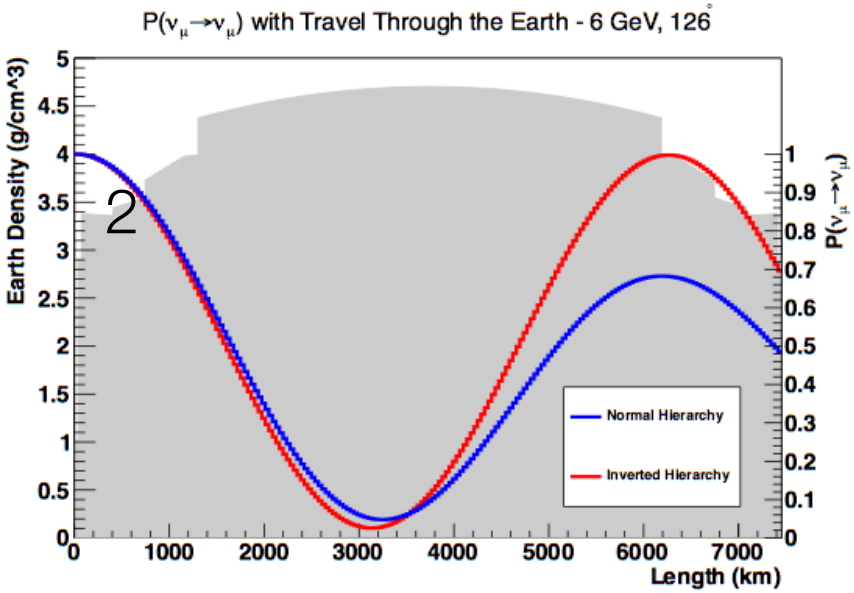
IceCube ++

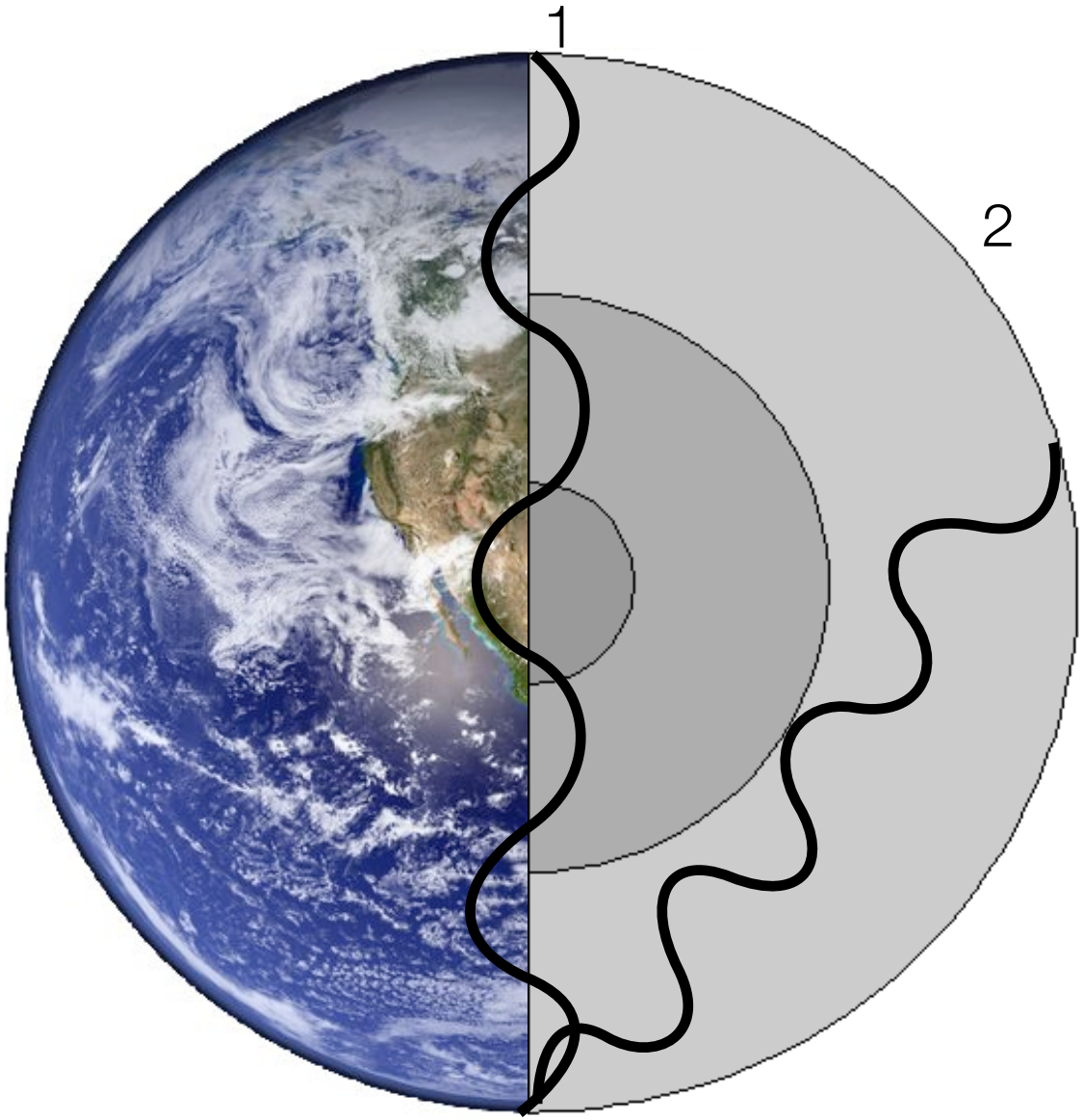
- IceCube extension with **larger string spacing**
- Large **increase in effective area** above 10 TeV

Measurement of neutrino mass hierarchy with PINGU.

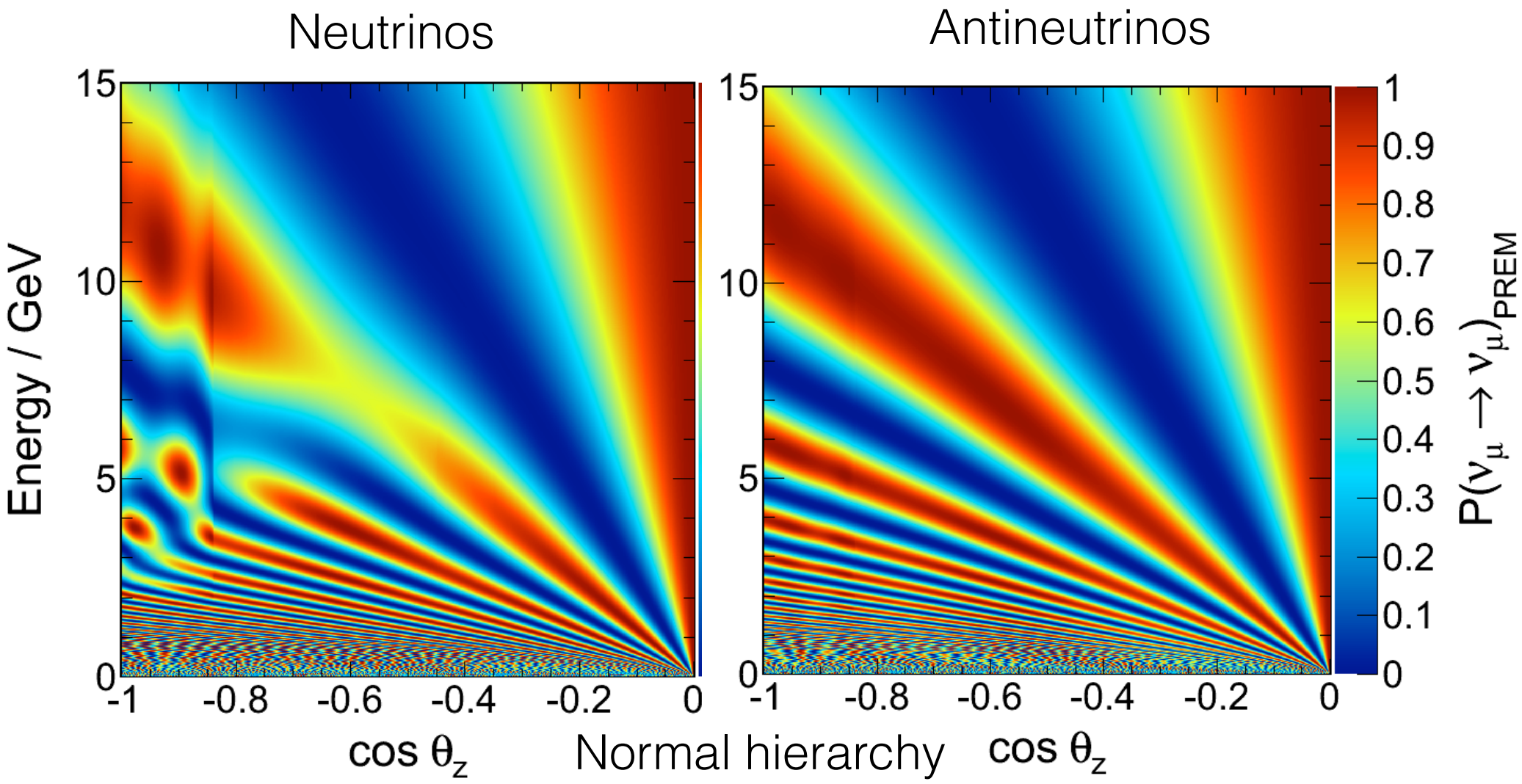
> **Up to 20% differences** in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy





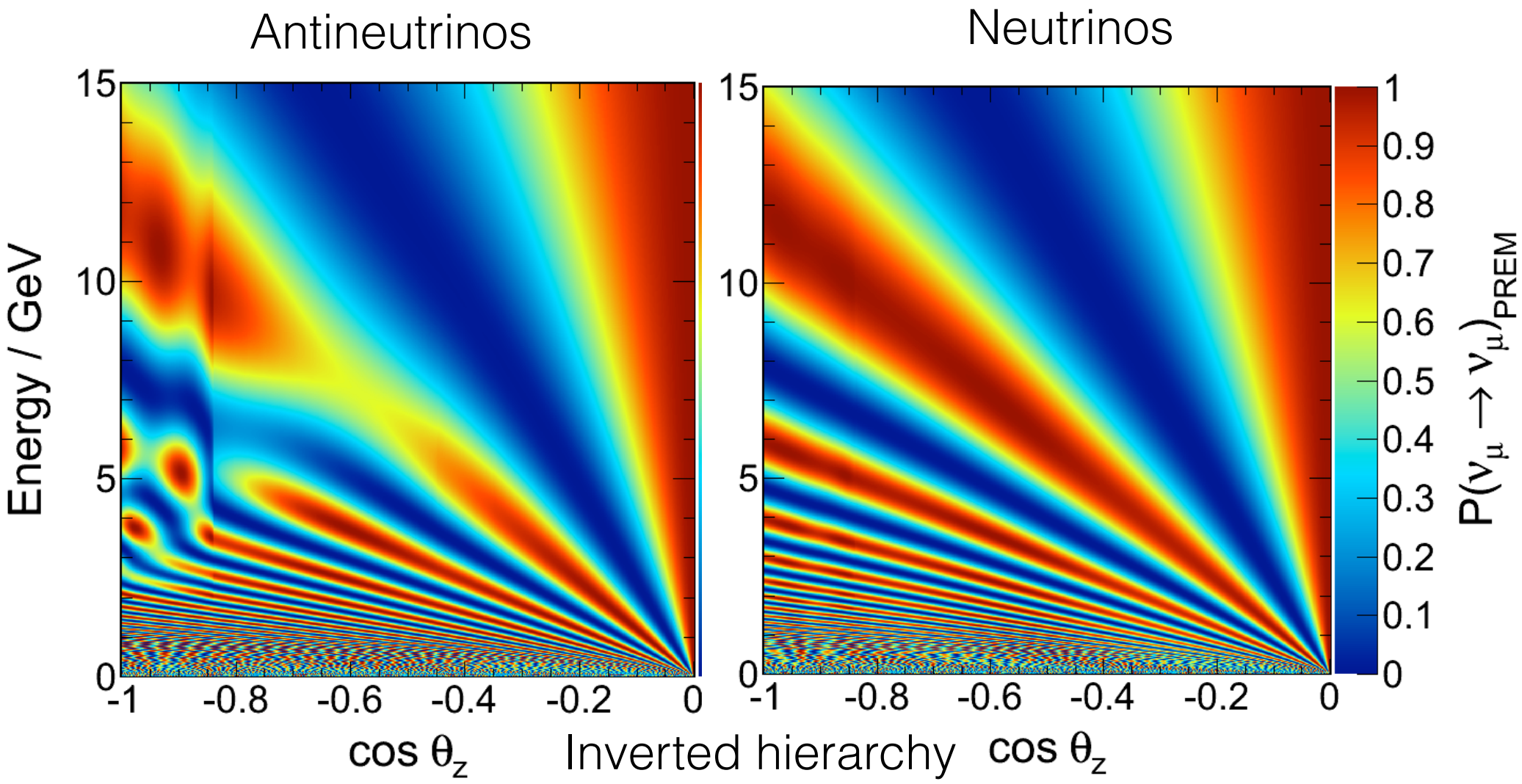


Muon neutrino survival probabilities for normal hierarchy.



> Survival properties for neutrinos and anti-neutrinos.

Muon neutrino survival probabilities for inverted hierarchy.



- **Survival probabilities switched** for neutrinos/anti-neutrinos in inverted hierarchy
- **PINGU cannot distinguish** neutrinos from anti-neutrinos ....
- ...but **rates** are **not the same**.

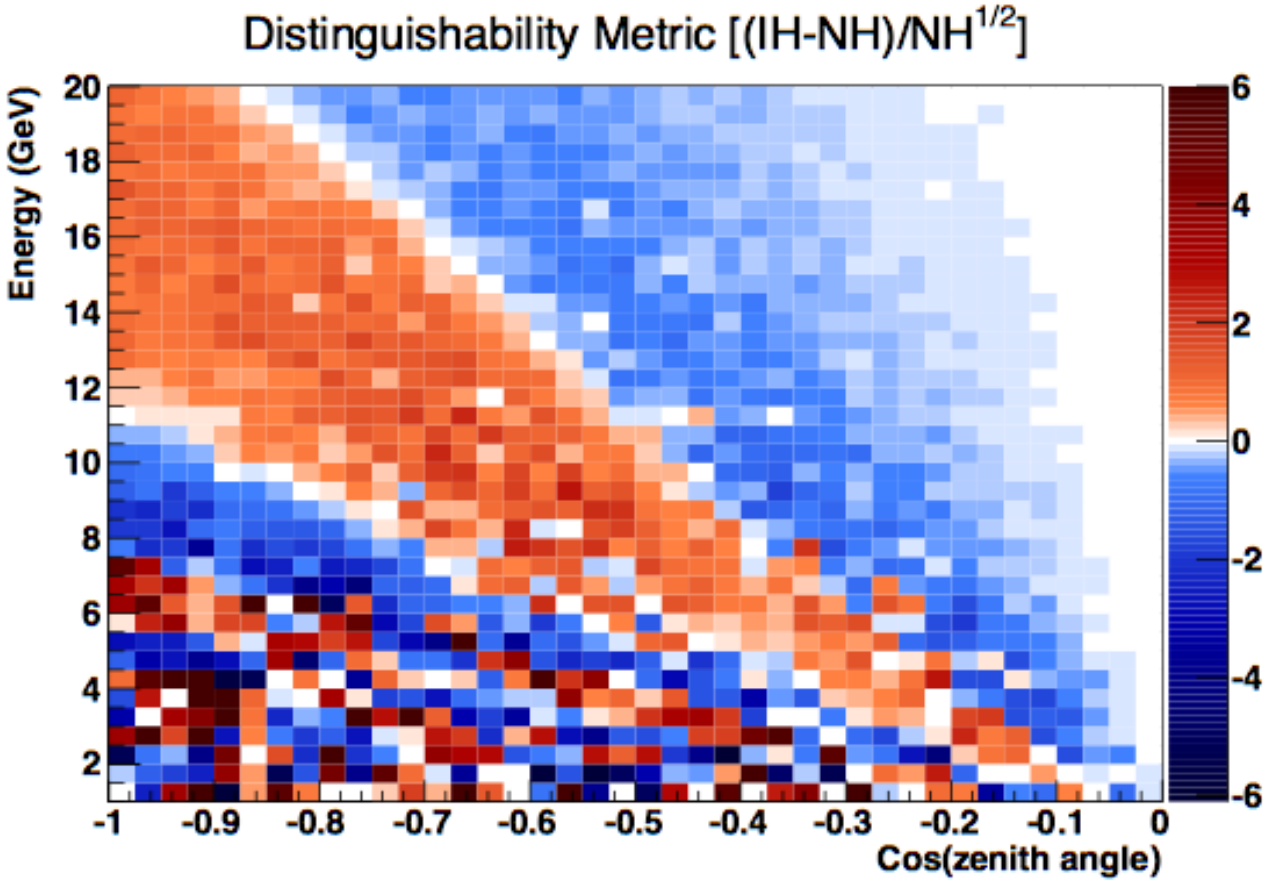
Measurement of mass hierarchy with PINGU.

> Need to measure **complicated pattern** in 2-dim distribution (E, cos(zenith))

> Good way to **visualize signature** of mass hierarchy:

- **Distinguishability metric** (Akhmedov, Razzaque & Smirnov (arXiv:1205.7071)):

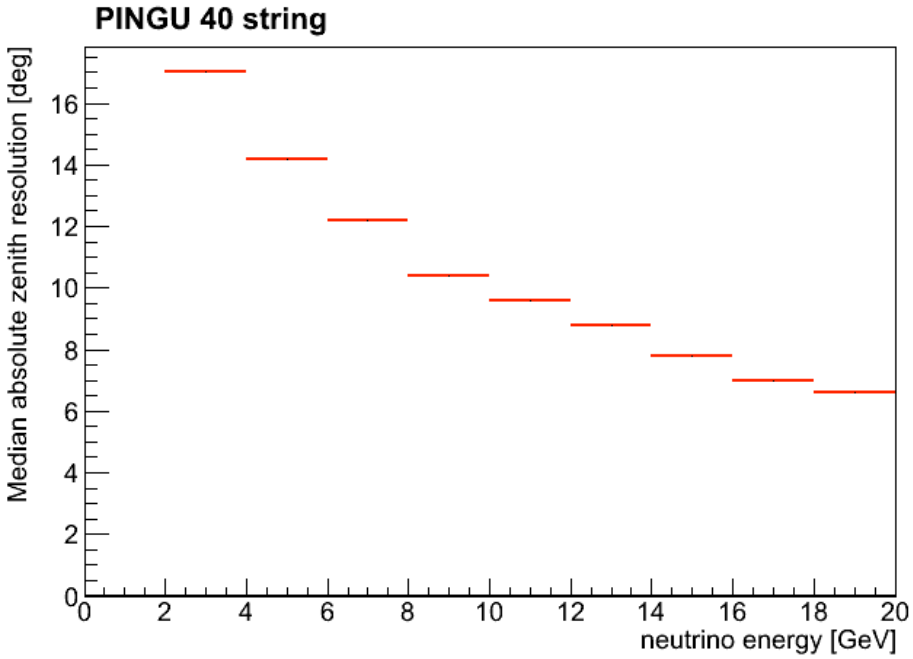
$$\frac{N_{obs,IH} - N_{obs,NH}}{\sqrt{N_{obs,NH}}}$$

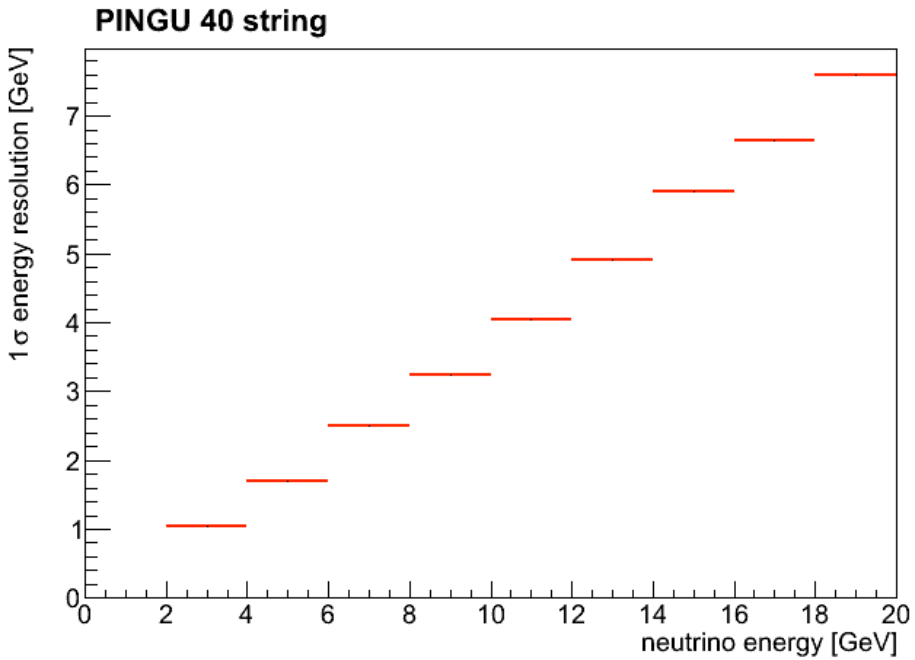


> Expected signal from inverted hierarchy in a **perfect detector.**

> Real detector will have **finite energy and zenith resolution**.

Performance studies for PINGU.





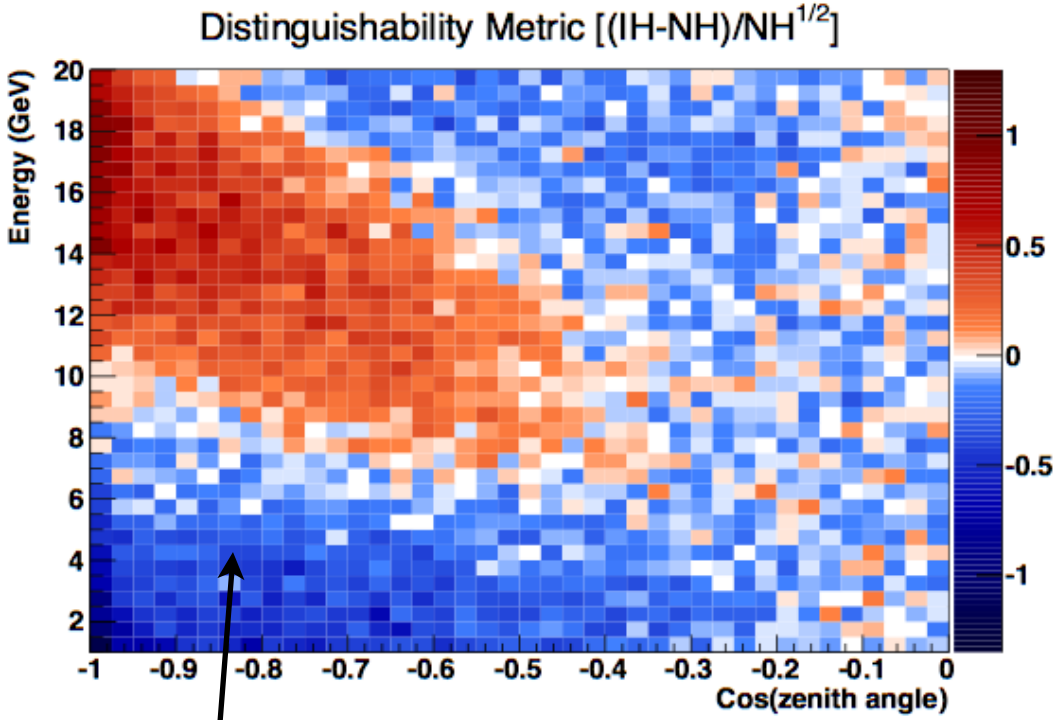
> Currently using **DeepCore algorithms** for reconstruction.

> **Systematics** studied so far:

- θ_{23}, θ_{13}, Δm^2_{atm}, δ_{CP} within world average ±2σ ranges
- Efficiency errors (30%)
- Atmos. ν spectral index (±0.05)
- Energy calibration (10% bias)
- Pointing accuracy (10% bias)
- Energy resolution (10% error)
- Angular resolution (10% error)
- Further studies underway now.

Measurement of mass hierarchy with PINGU.

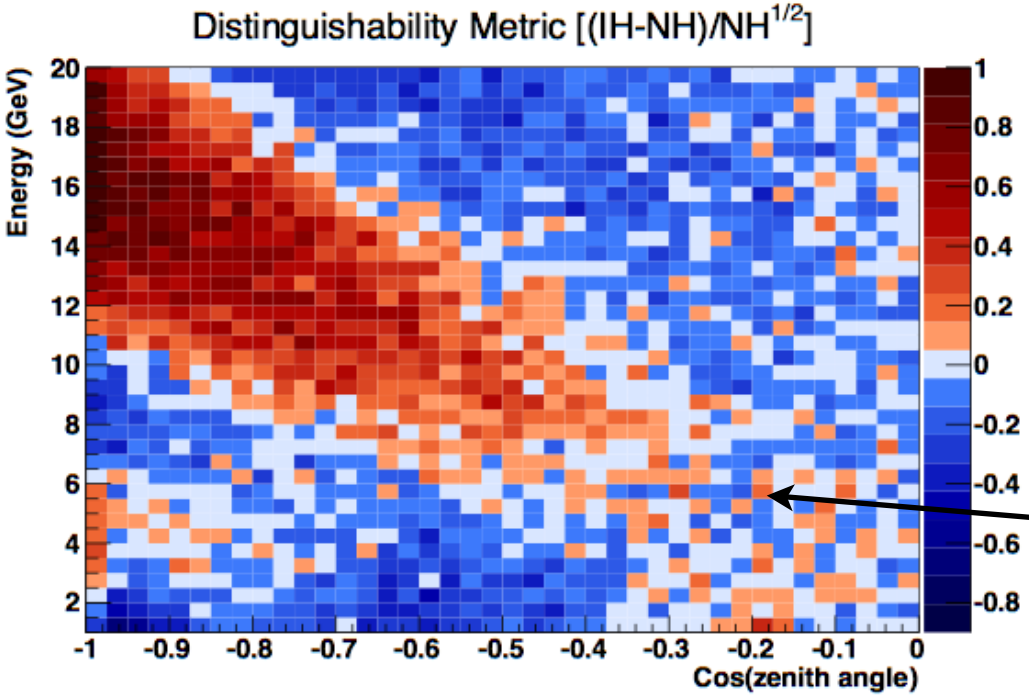
> Good **identification of mass hierarchy** possible with realistic experimental resolution.



Zenith resolution: 12.5°
Energy resolution 3 GeV

conservative scenario

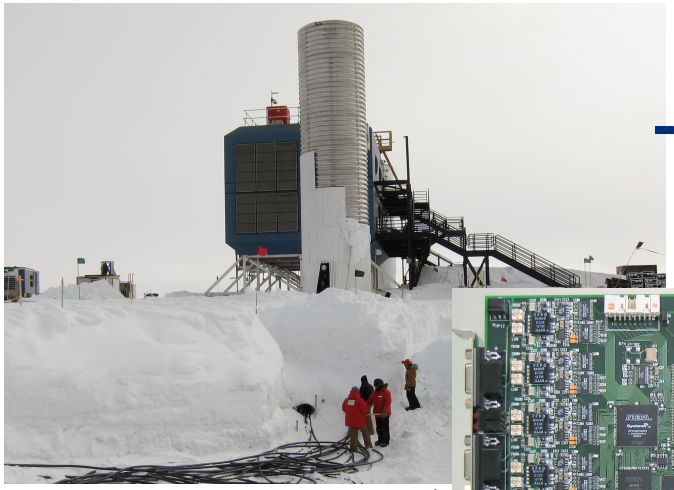
optimistic scenario

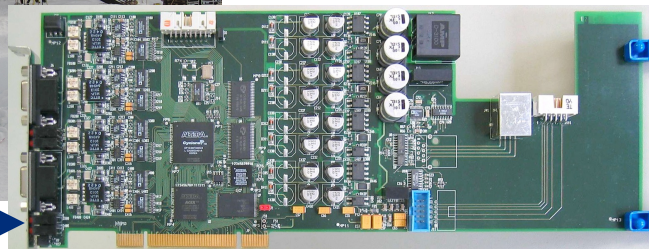


Zenith resolution: 10°
Energy resolution 1 GeV

IceCube detector elements.

IceCube Laboratory
DAQ
Online filtering
Transfer
Storage



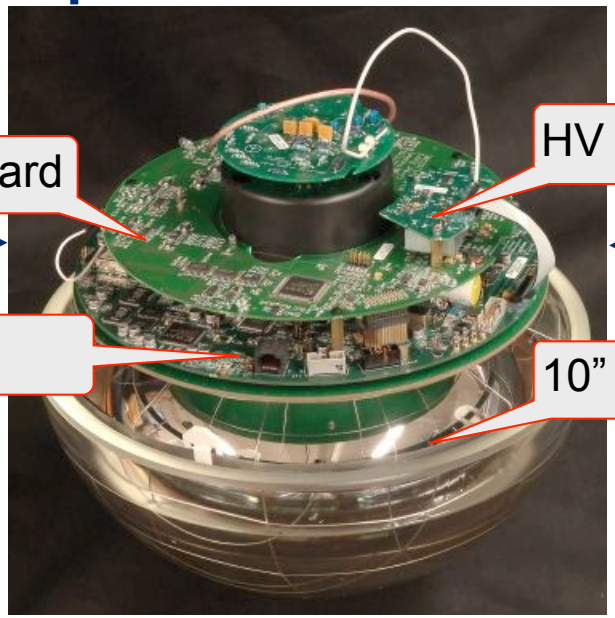


DOM receiver card

South Pole link to TDRSS satellite network

InIce Array
86 strings
60 DOMs per string

Digital optical module (DOM)



IceTop Array
81 stations
2 tanks per station
2 DOMs per tank