Neutrino Astronomy results from IceCube

J.A. Aguilar for the IceCube collaboration

UNIVERSITÉ DE GENÈVE

5th Workshop on Air Shower Detection at High Altitude
28 May, 2014, Paris

OUTLINE

- Gamma-ray/Neutrino Connection
- The IceCube Observatory
- Point-like and Diffuse Neutrino Emission
- Other science: Cosmic Rays and Dark Matter
- Conclusions

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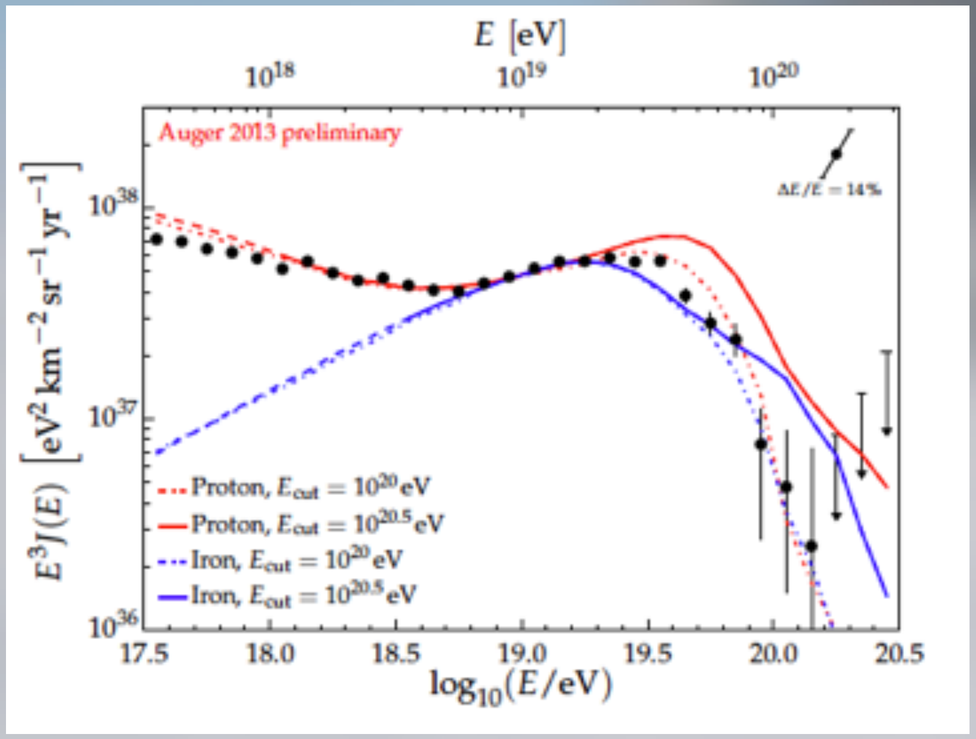
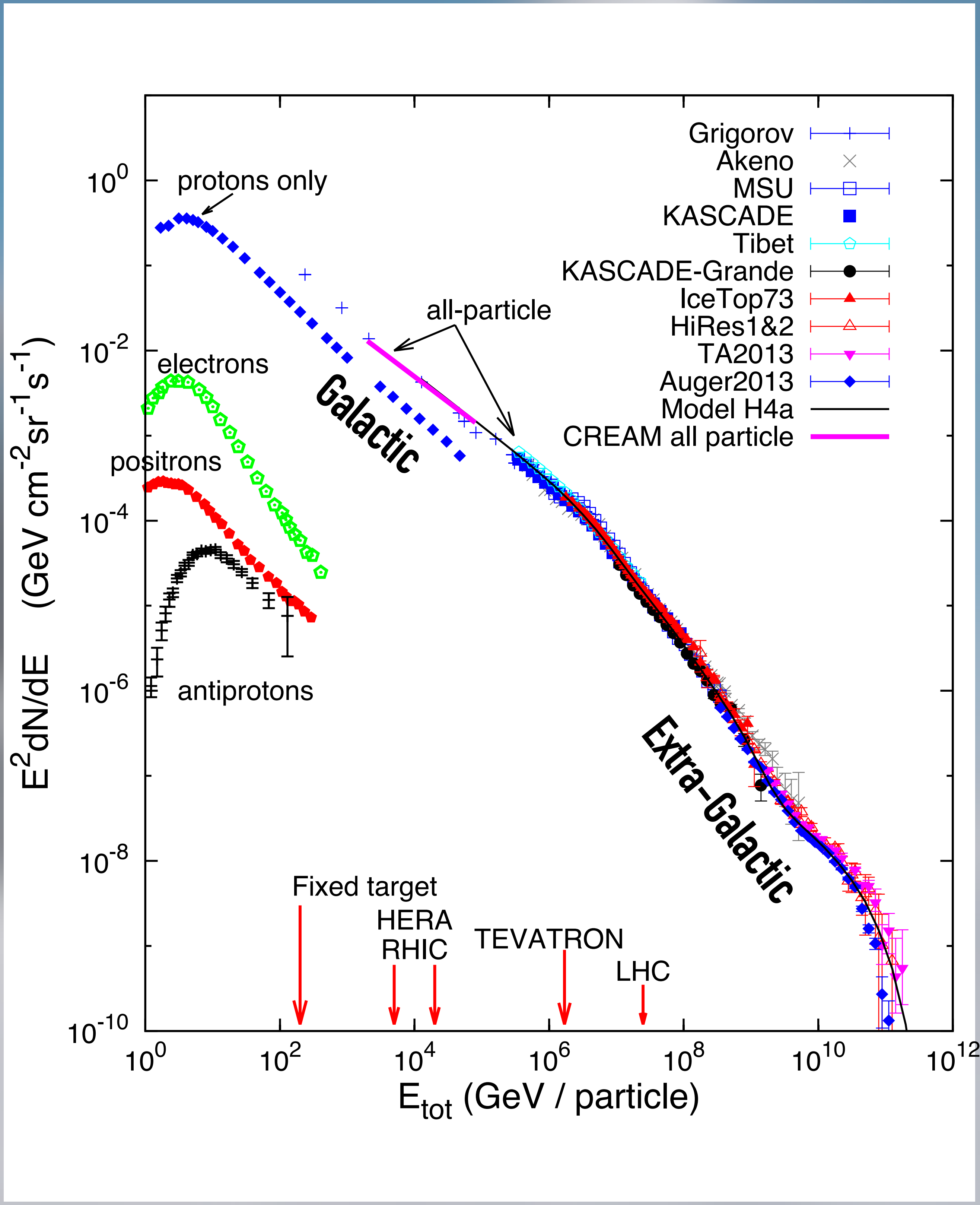
COSMIC RAYS

- Discovered by Victor Hess in 1912
- Cosmic Rays spectrum spans 10 decades of energy. Origin still unknown.
  - Galactic CRs: Supernova remnants?
  - Extra-Galactic CRs: AGNs, GRBs, magnetars?

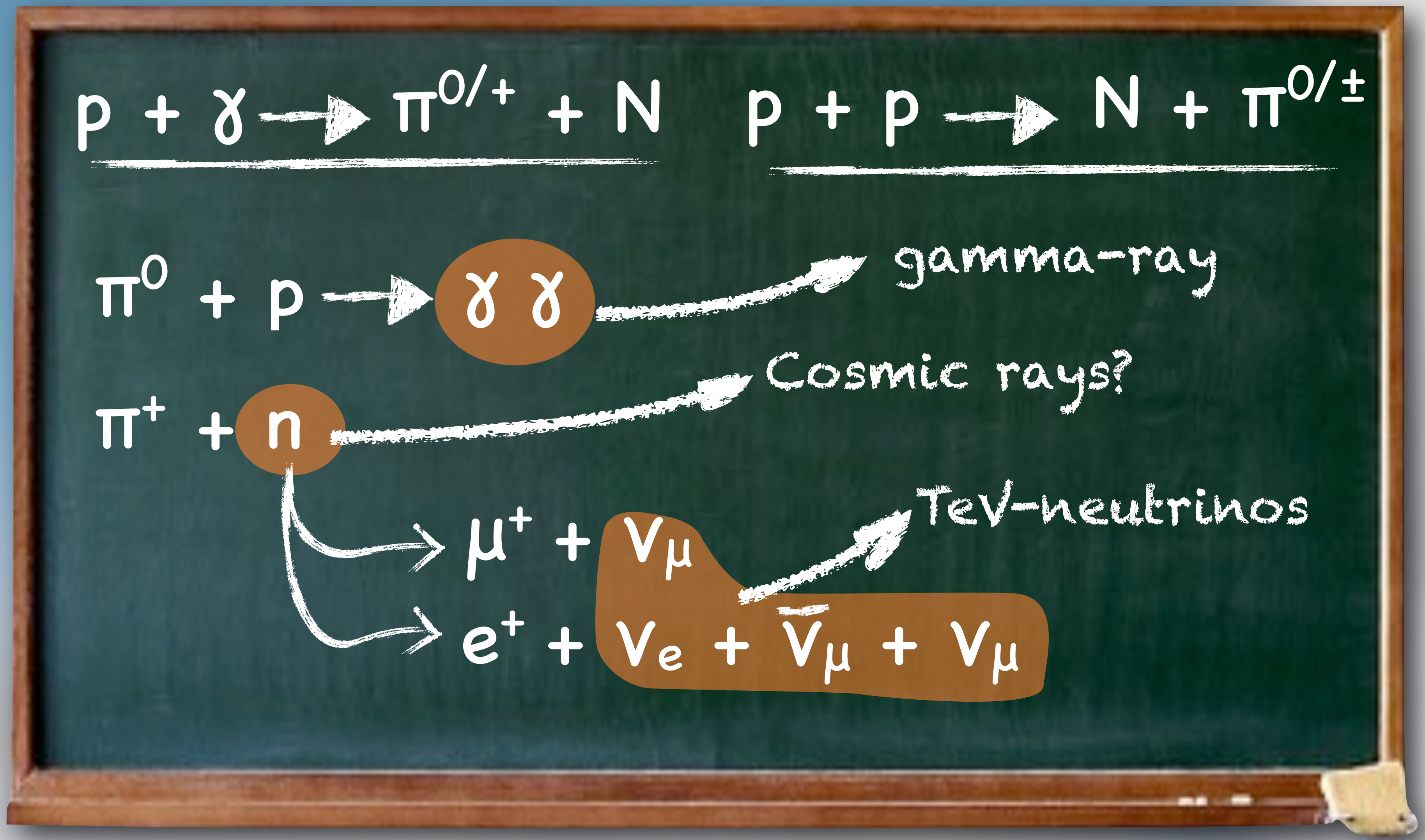


Pierre Auger ICRC 2013: arXiv:astroph/1107.4809



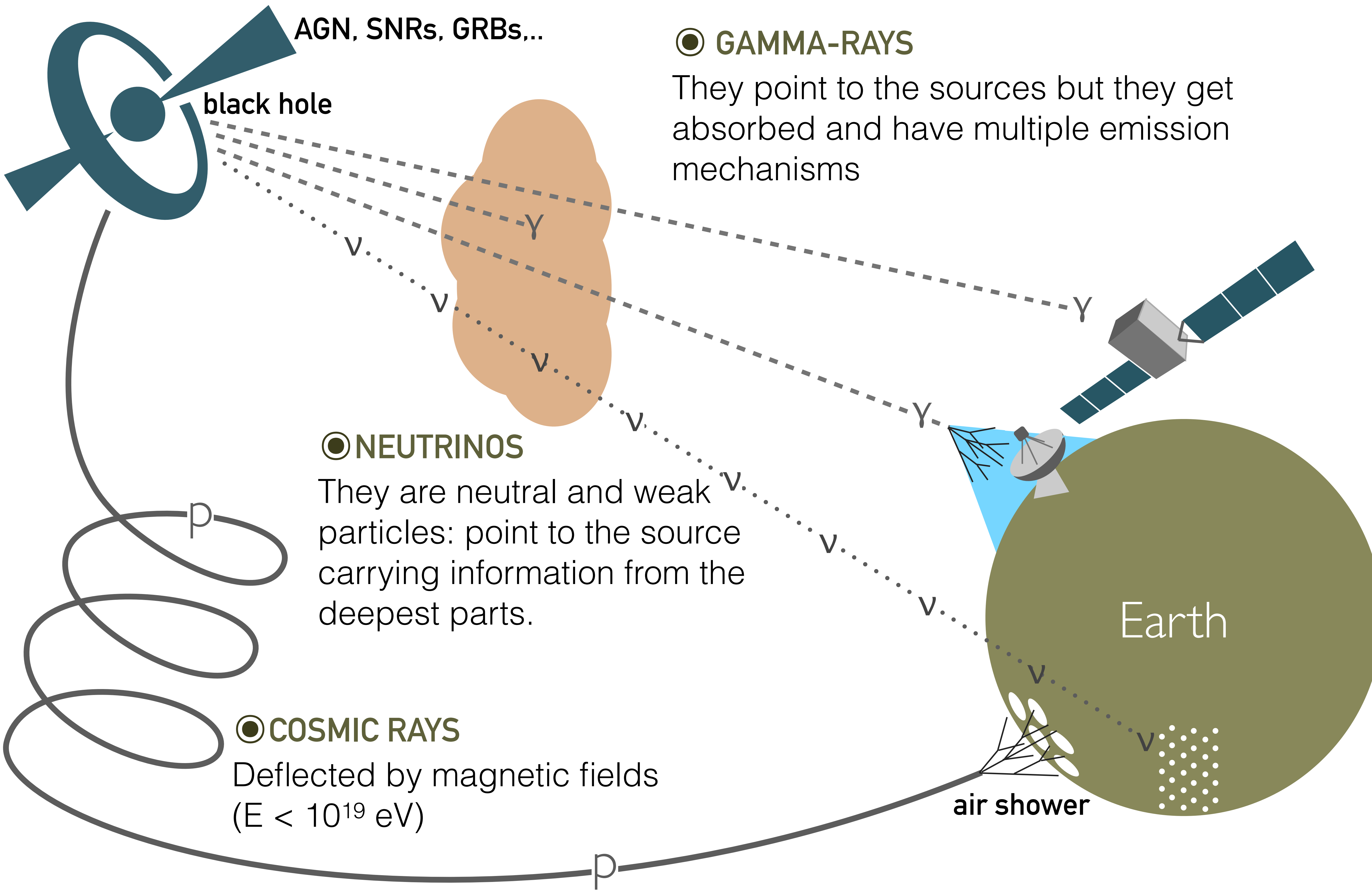
THE CR-ν-γ CONNECTION

- Cosmic rays can interact on the accelerator sites: SNR, AGNs, GRBs,...



...or they can interact in known targets: Earth's atmosphere, Interstellar matter in Galactic plane, cosmic microwave background.

Cosmic Messengers



◉ GAMMA-RAYS

They point to the sources but they get absorbed and have multiple emission mechanisms

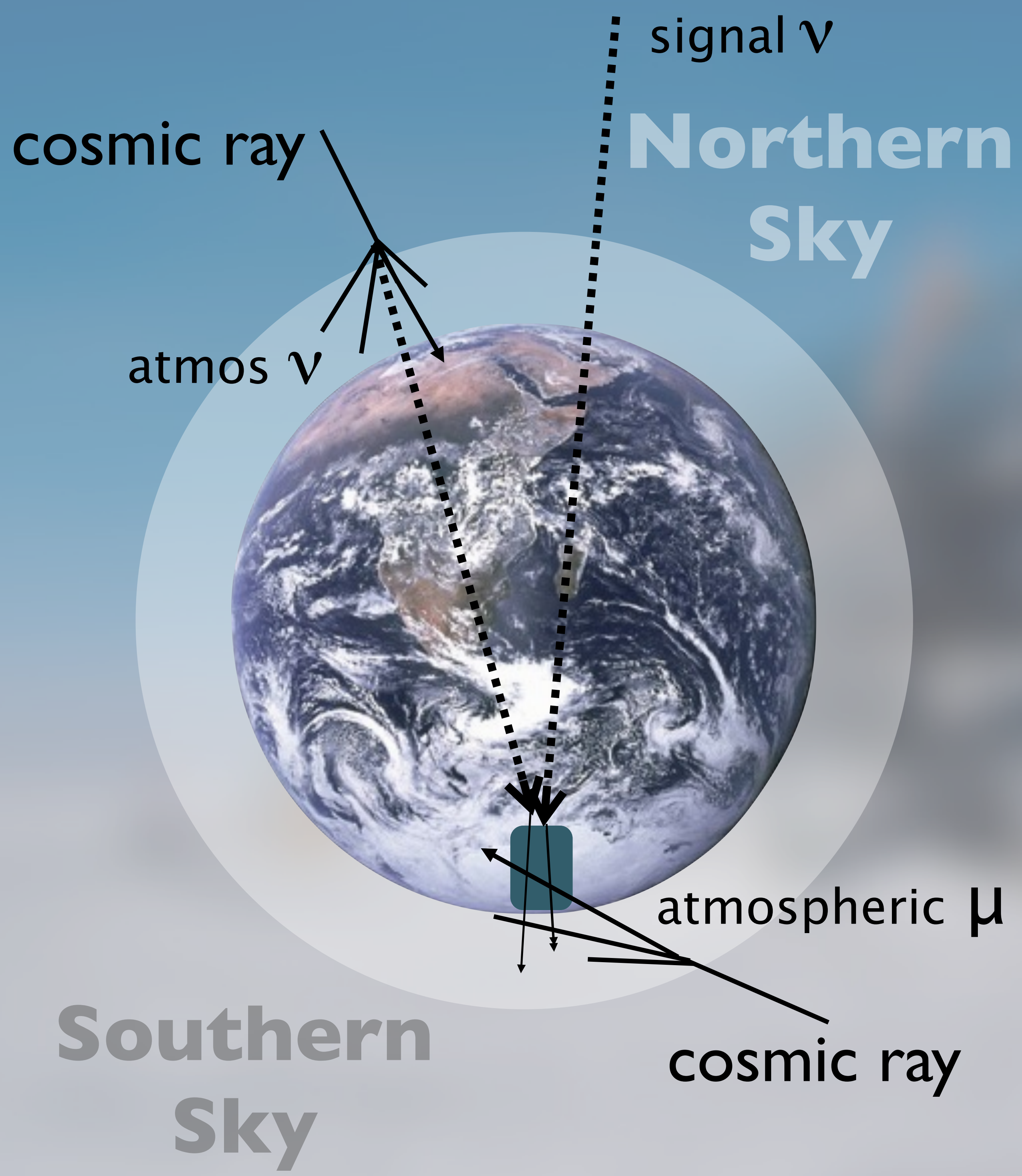
◉ NEUTRINOS

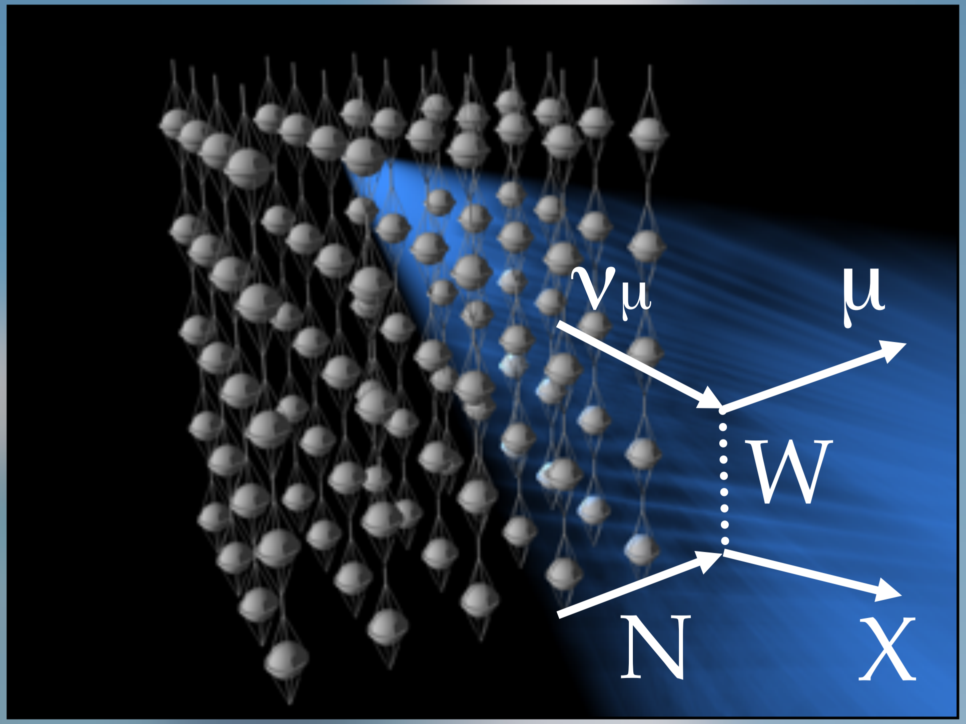
They are neutral and weak particles: point to the source carrying information from the deepest parts.

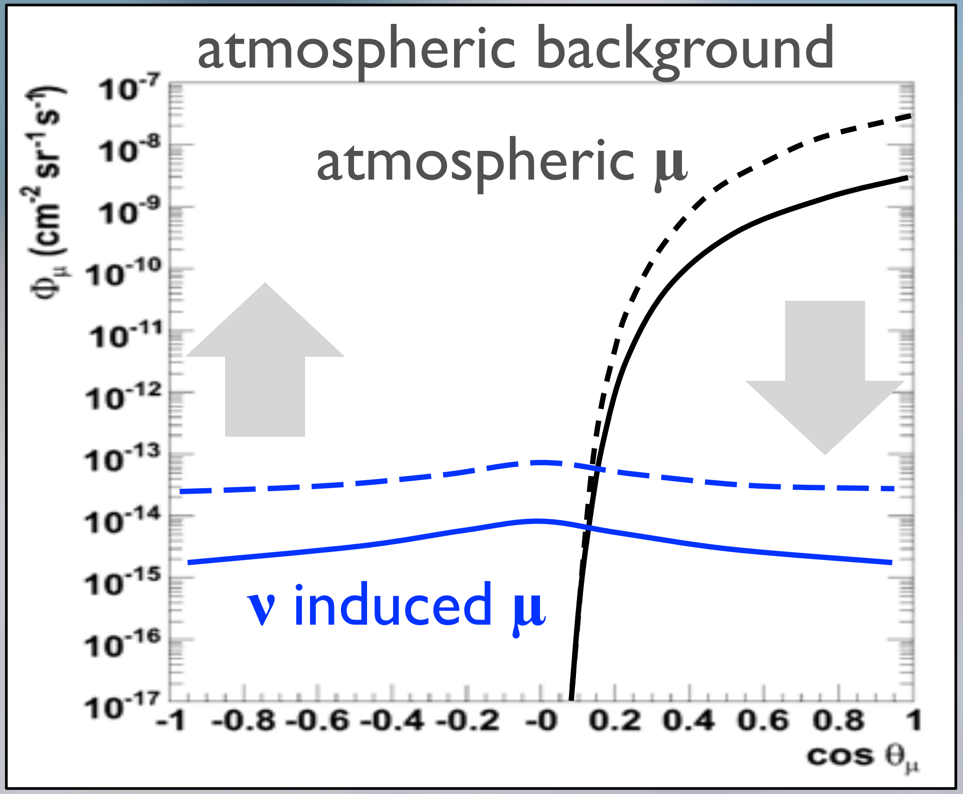
◉ COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)

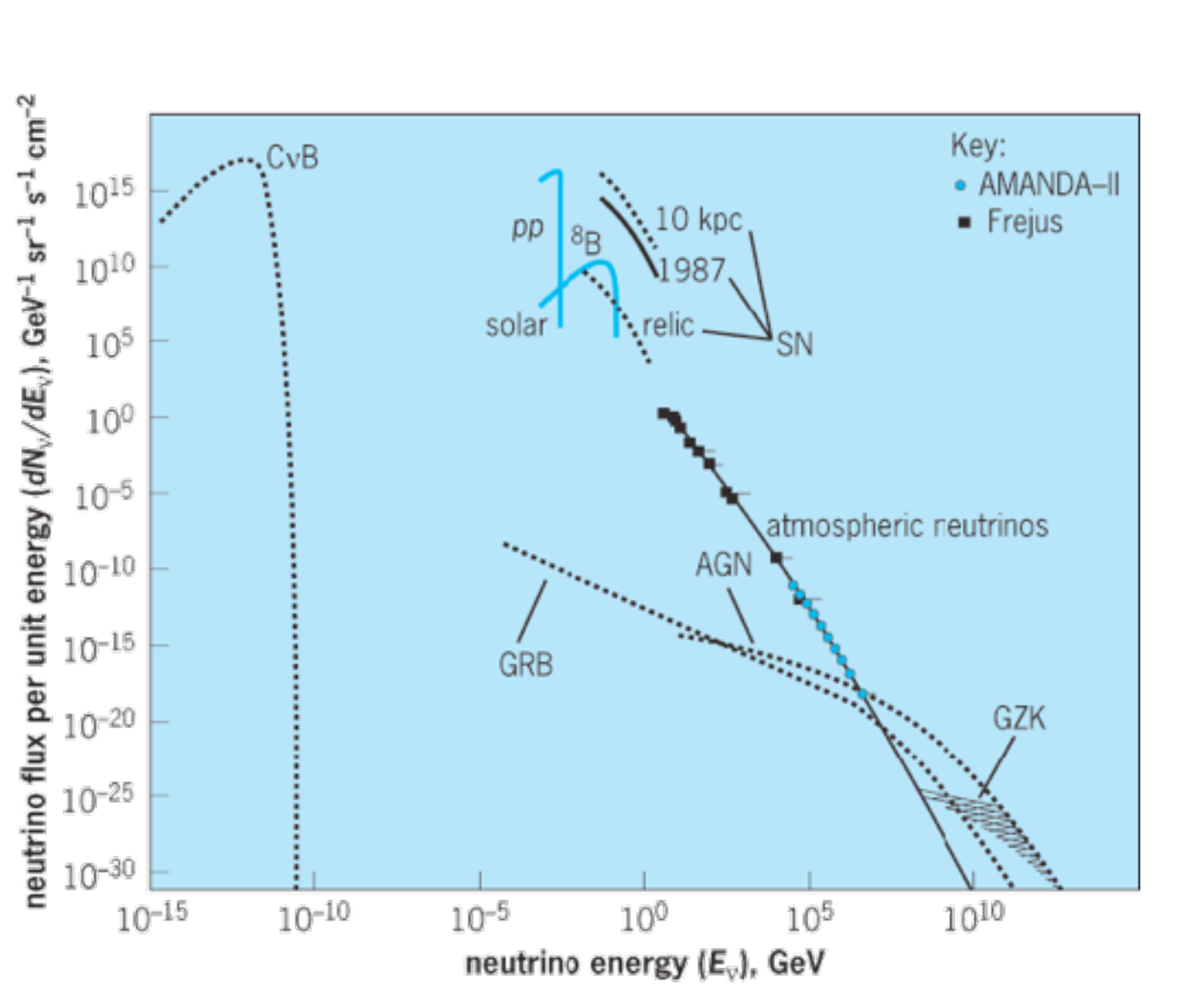
Detection Principle







The Neutrino Sky



- Atmospheric neutrinos (π/K)
  - dominant < 100 TeV
- Atmospheric neutrinos (charm)
  - "prompt" ~ 100 TeV
- Astrophysical neutrinos
  - maybe dominant > 100 TeV
- Cosmogenic neutrinos
  - > 10^6 TeV

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The IceCube Collaboration

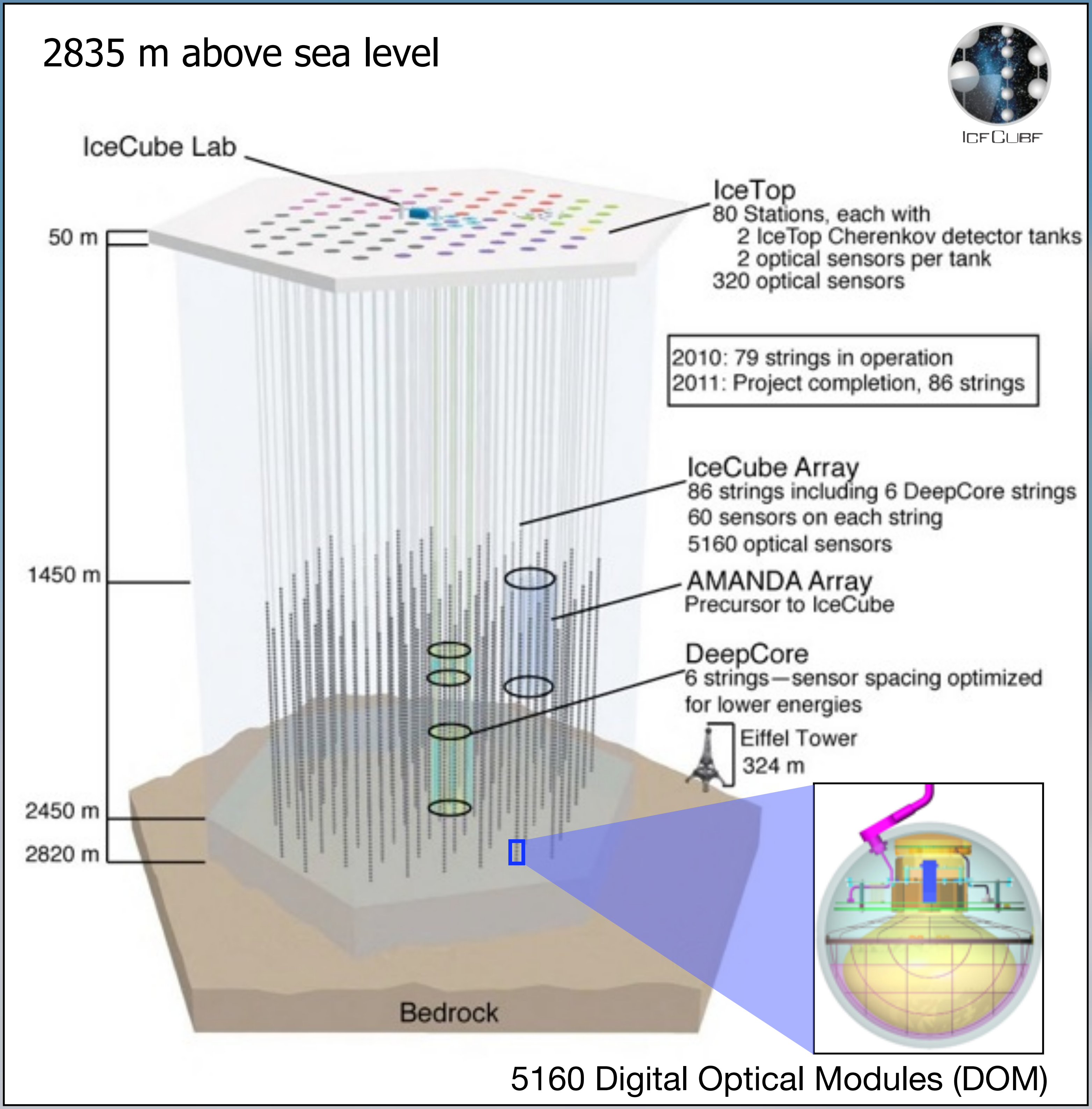
10 countries, 40 institutions, ~260 collaborators

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube observatory

IceCube Observatory



20 years of construction from AMANDA to IceCube

<u>IceCube phases:</u>

IceCube 1 (2004-5)

•
•
•

IceCube 40 (2008-9)

IceCube 59 (2009-10)

IceCube 79 (2010-11)

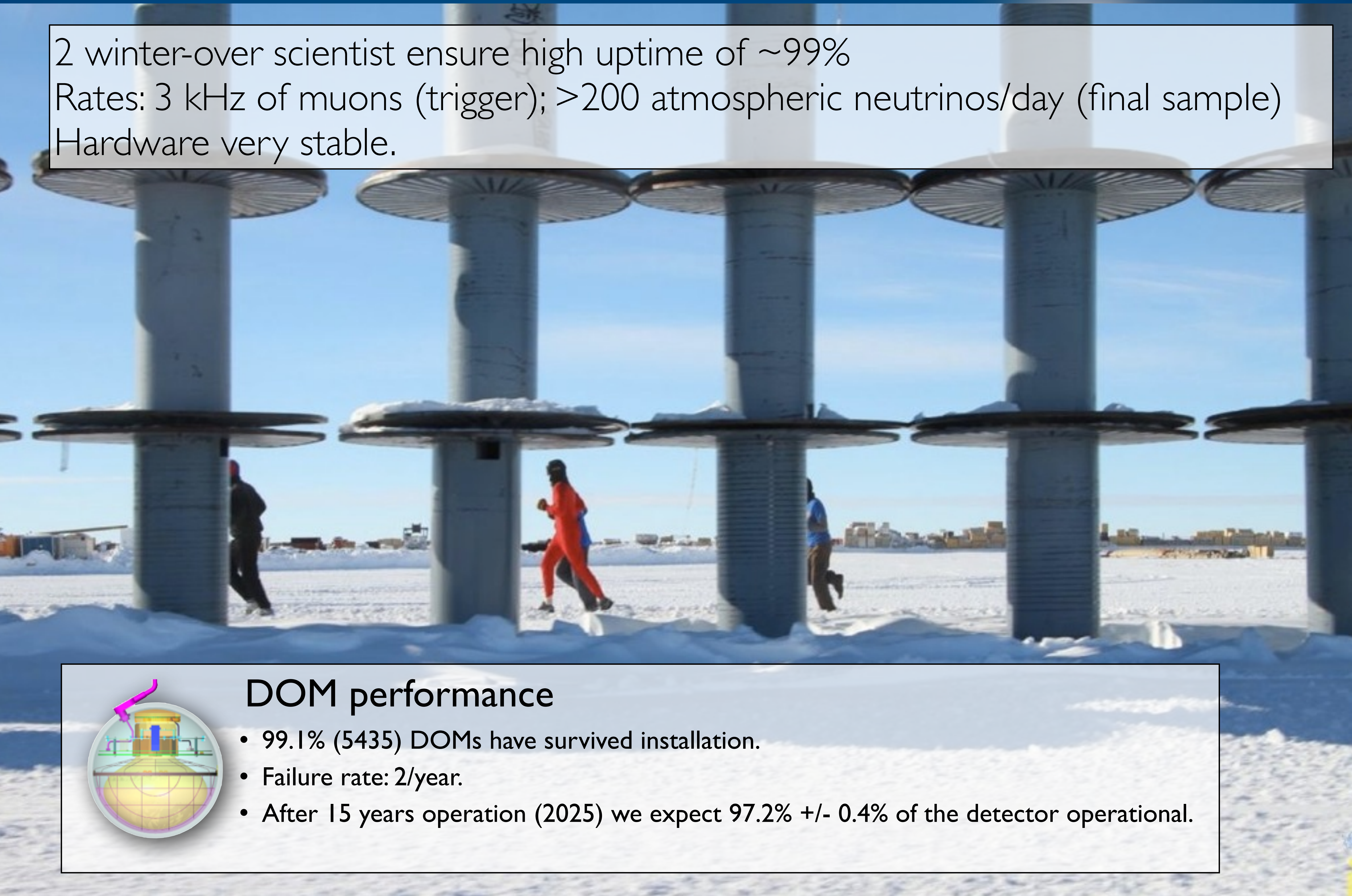
Completion with 86 strings in December 2010

IceCube 86-I (2011-12)

•
•
•

IceCube is running with high uptime …

2 winter-over scientist ensure high uptime of ~99%
Rates: 3 kHz of muons (trigger); >200 atmospheric neutrinos/day (final sample)
Hardware very stable.

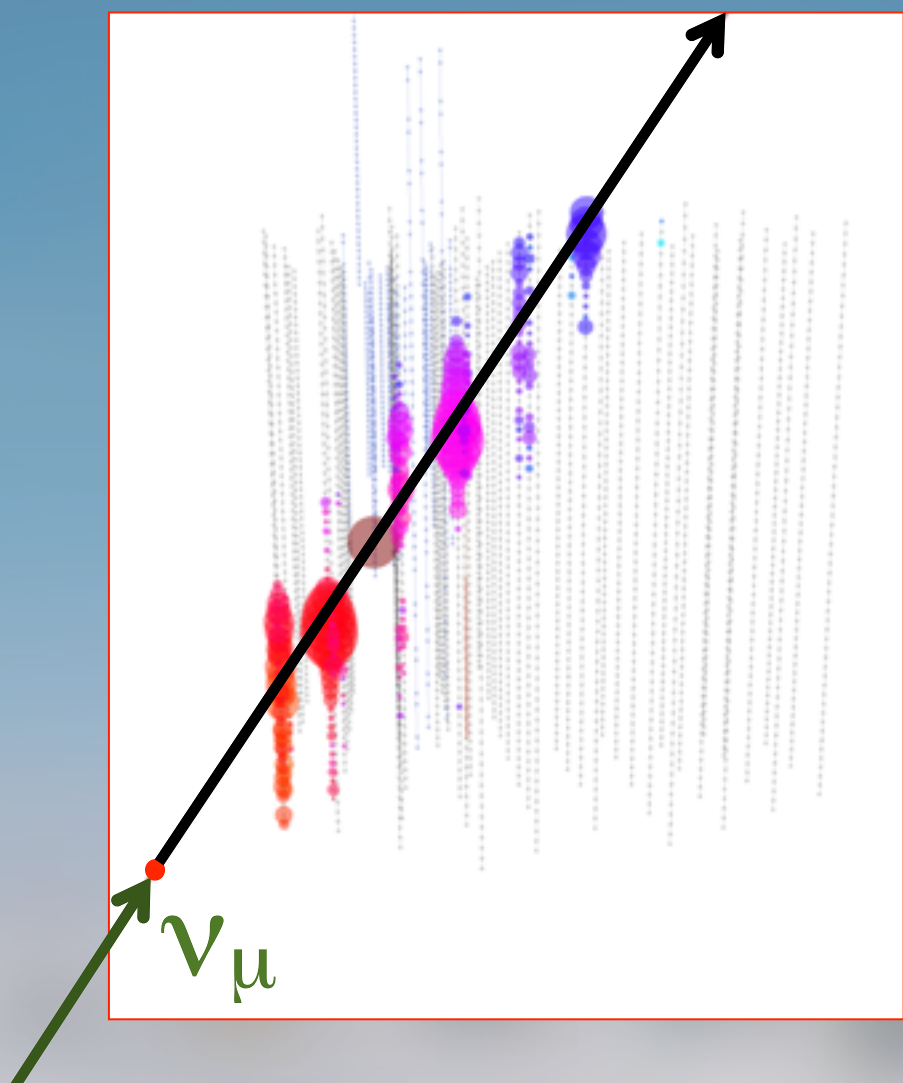


DOM performance

- 99.1% (5435) DOMs have survived installation.
- Failure rate: 2/year.
- After 15 years operation (2025) we expect 97.2% +/- 0.4% of the detector operational.

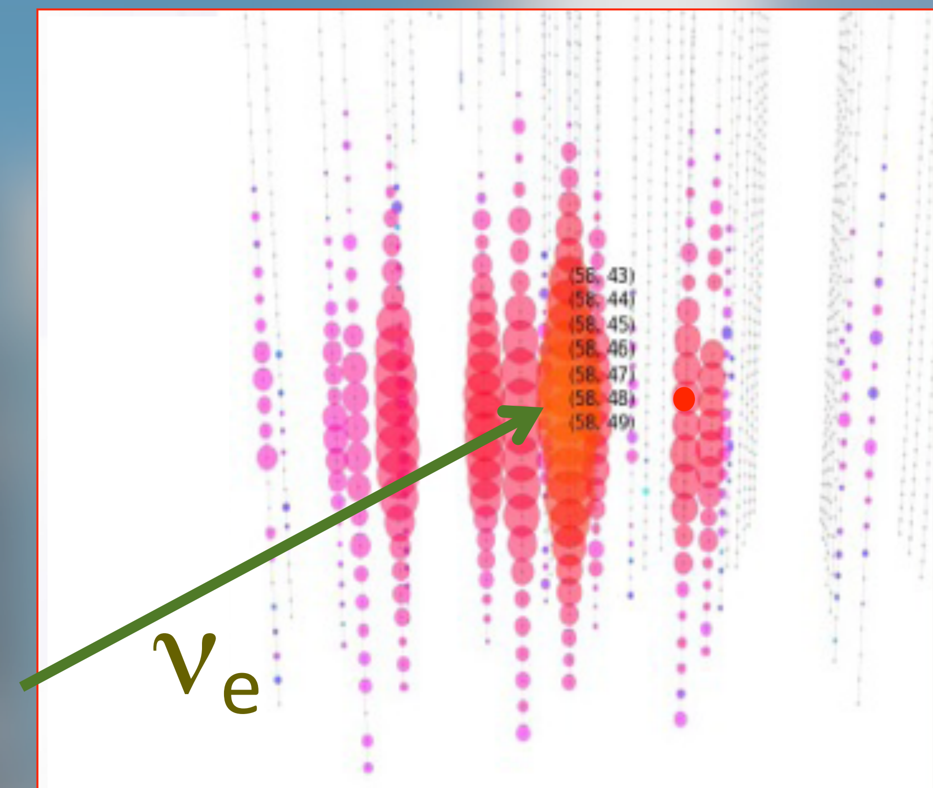
In-ice Signatures

through-going muons → ν_μ



- Good angular resolution: **Neutrino Astronomy**
- Vertex can outside the detector: **Increased effective volume!**

cascade → all flavors



- **νe, $\nu\tau$** and all-flavor neutral current
- Fully active calorimeter: **High energy resolution**
- Angular reconstruction above ~50 TeV

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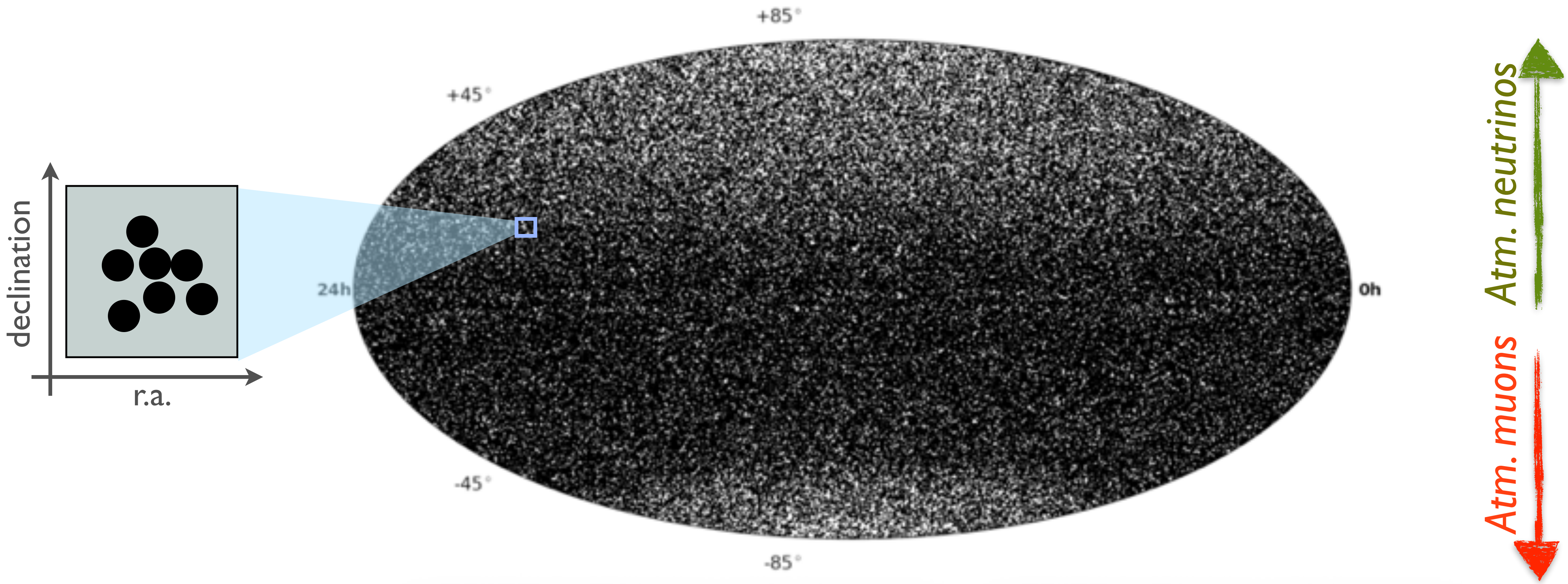
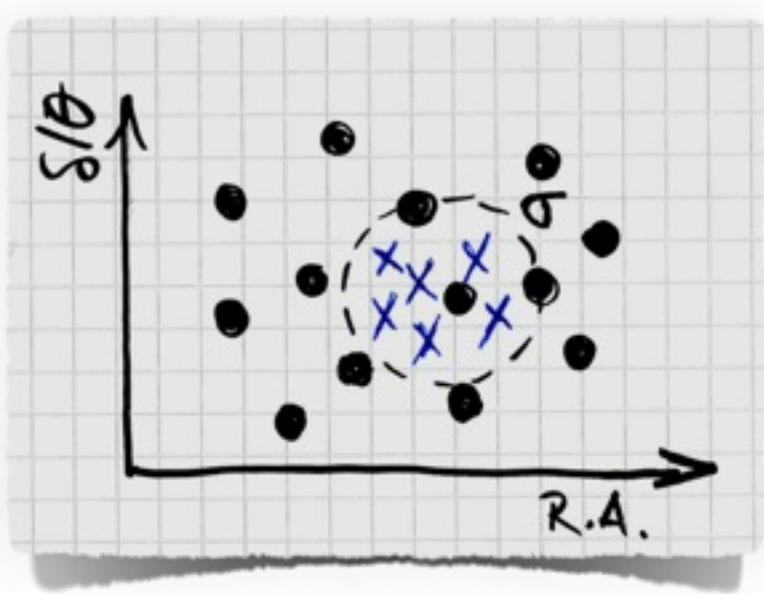
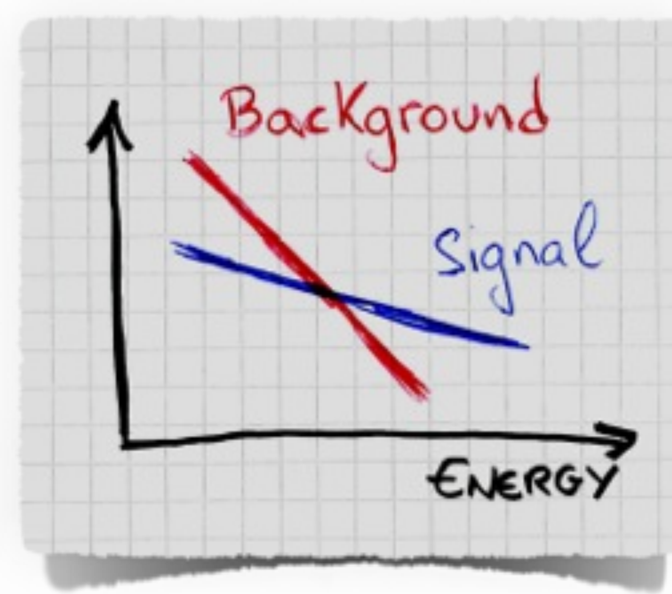
Search for Point Sources of Emission

- Neutrinos are not deviated by magnetic fields.
- Scattering due to **ν-μ** kinematics and detector Point Spread Function.



Ingredients:

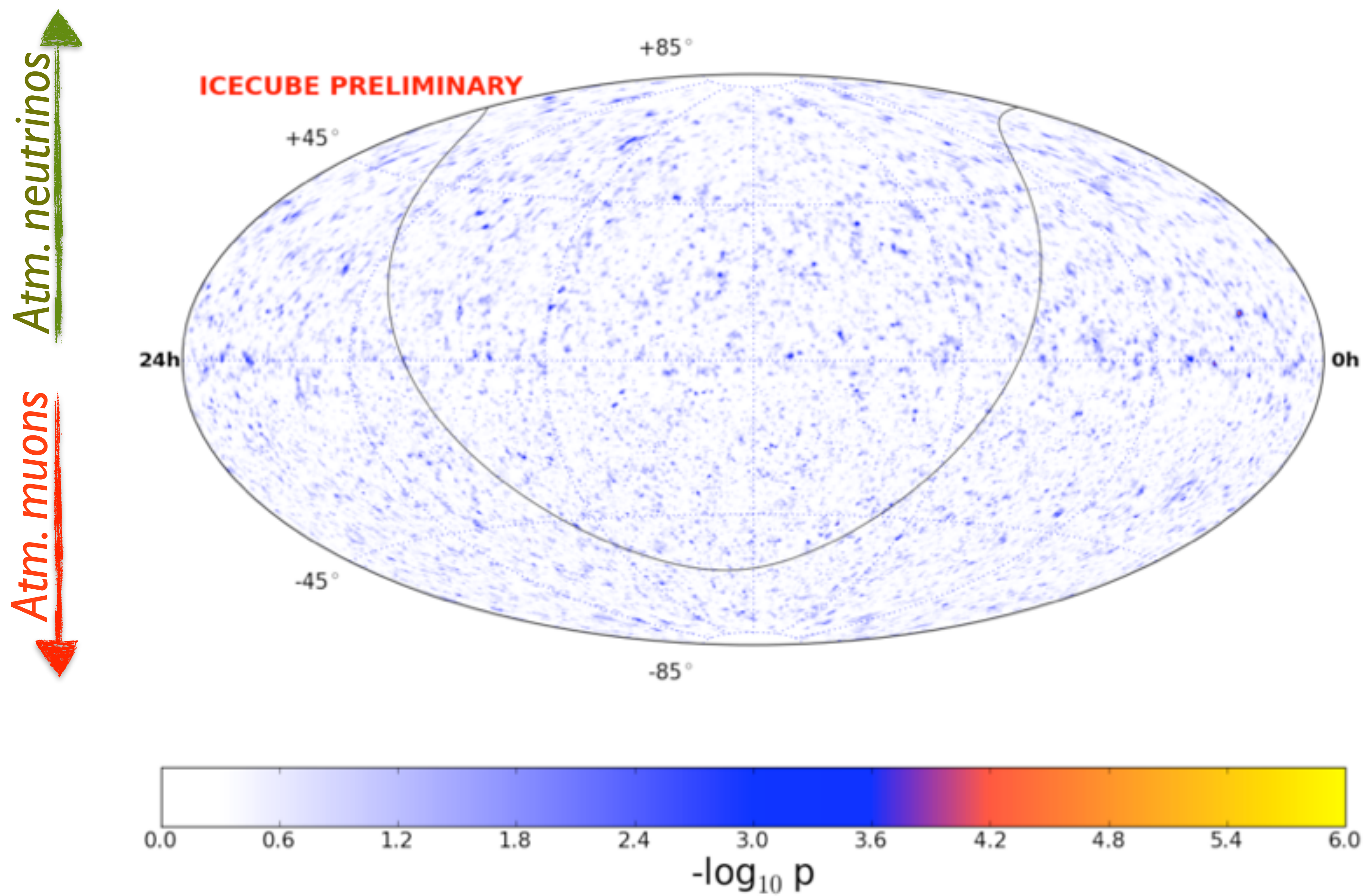




Point Source Search Skymap

- Total events: **394,000** (178k upgoing + 216k downgoing)
- Livetime: **1371 days**

4 years



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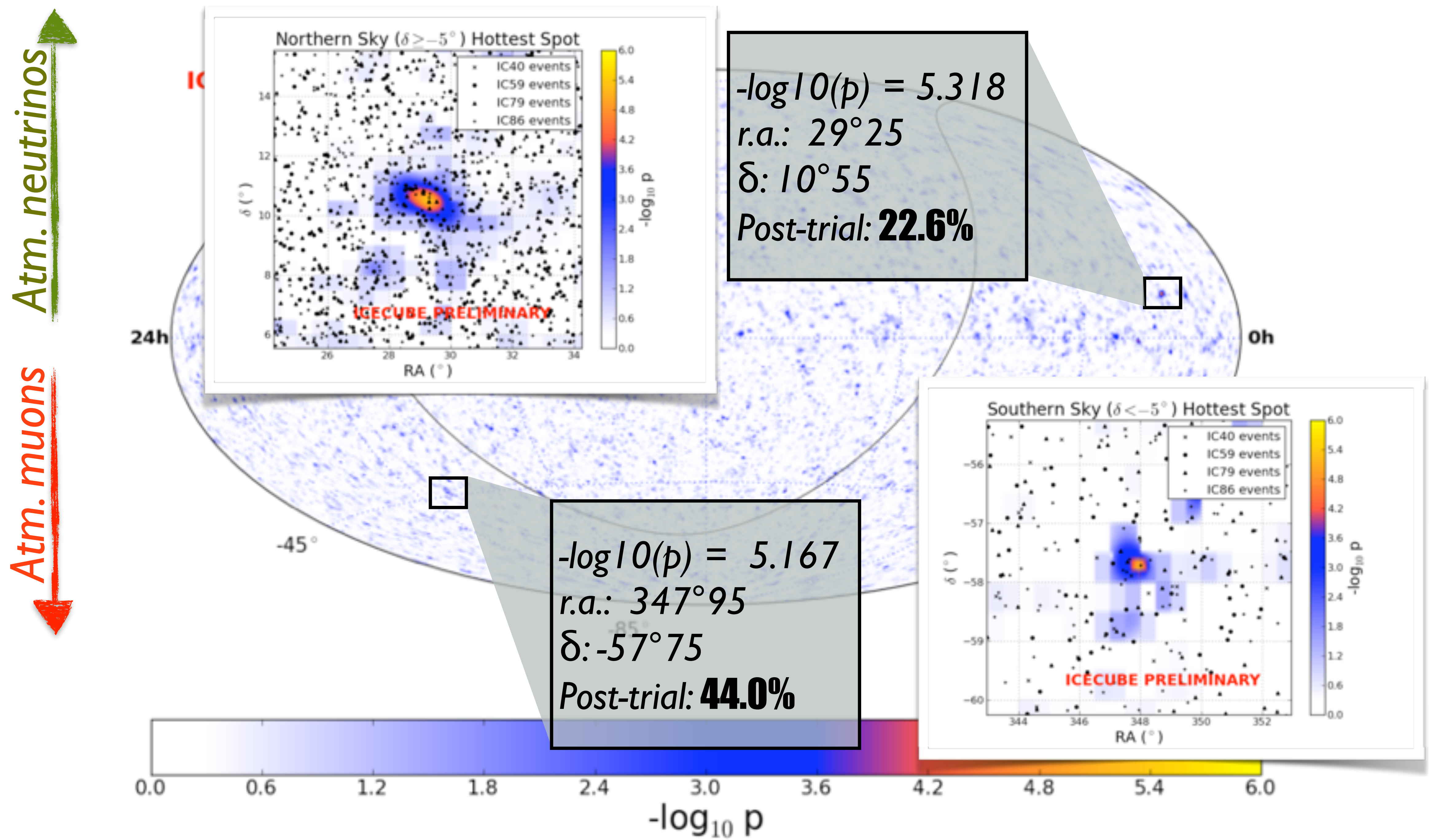
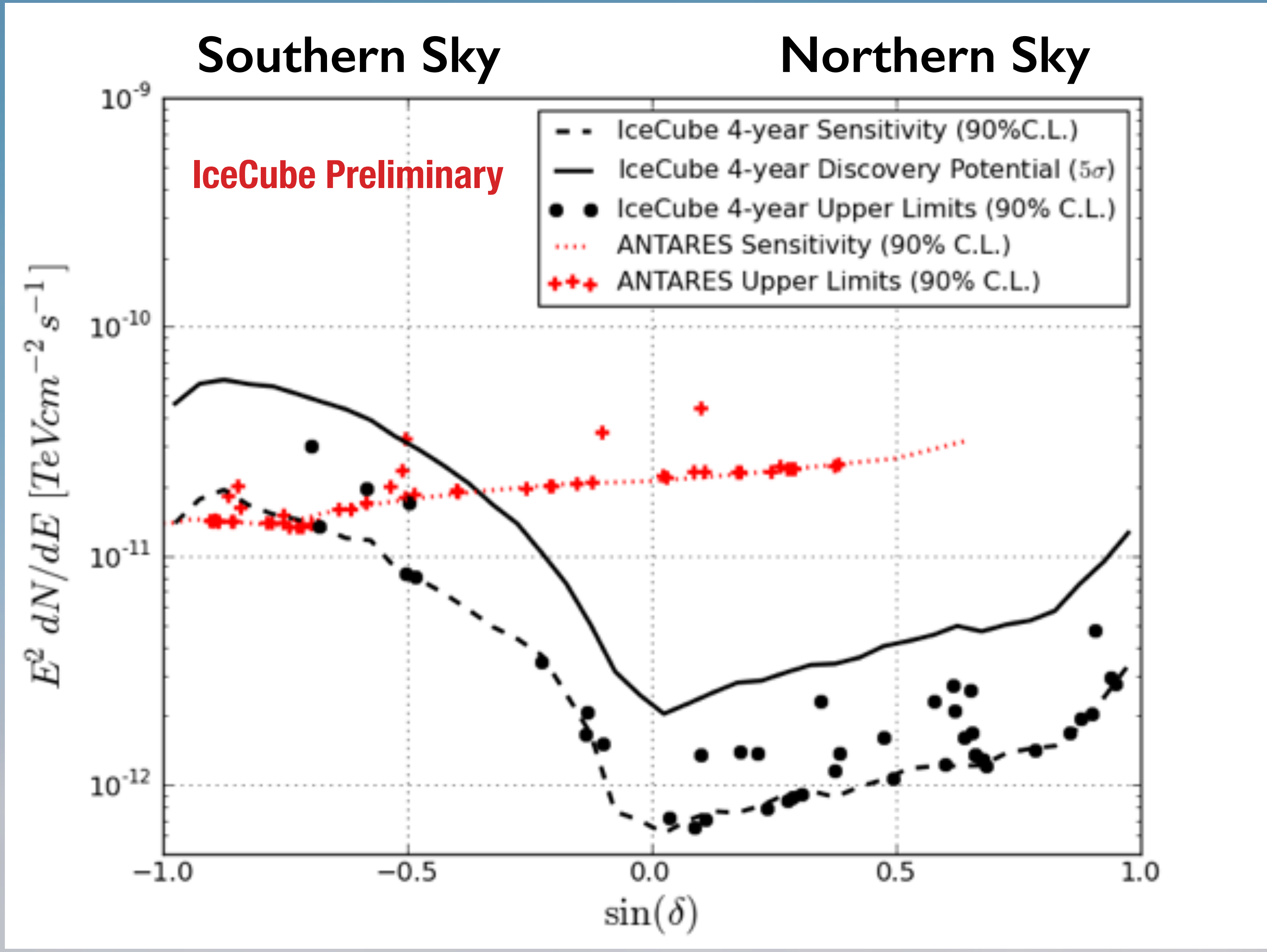
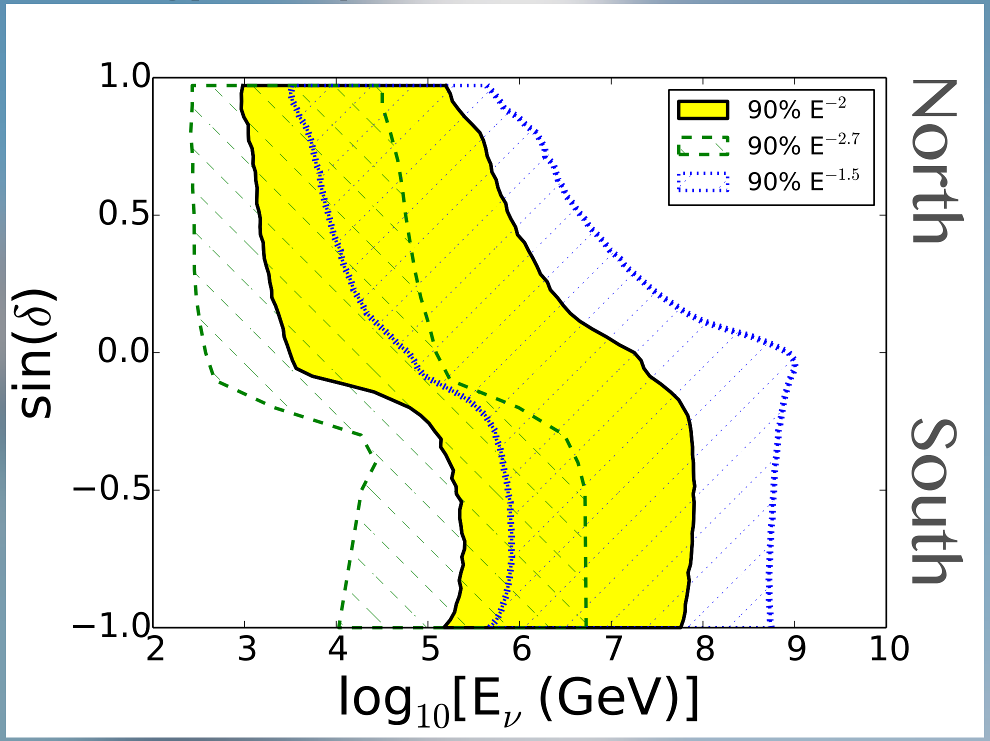


Point Source Search Neutrino Upper Limits



IceCube sensitivity dominant in the whole sky (for an unbroken E^{-2} spectrum)

Energy response North/South

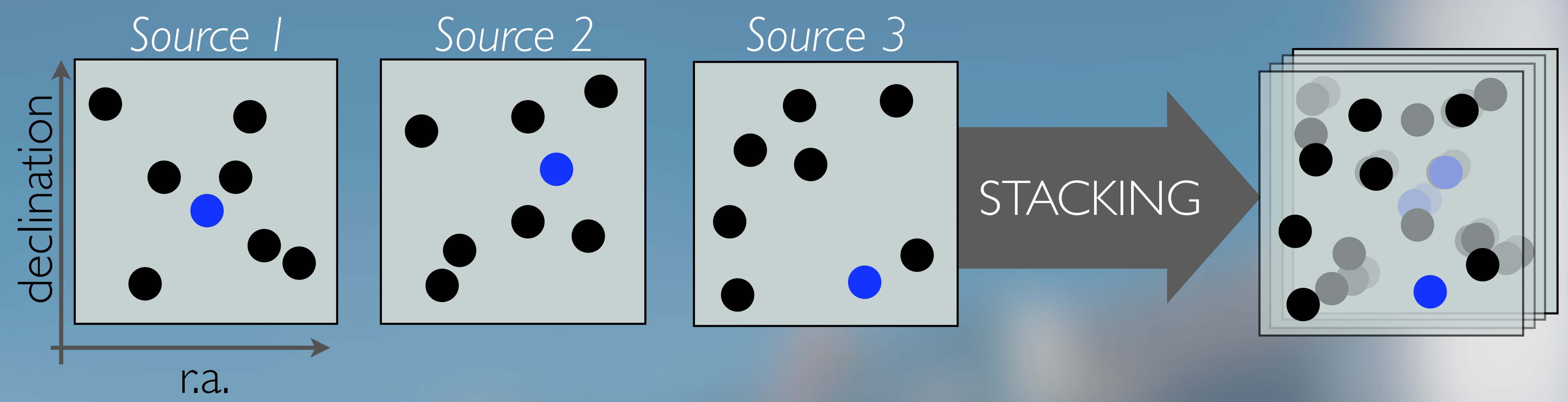


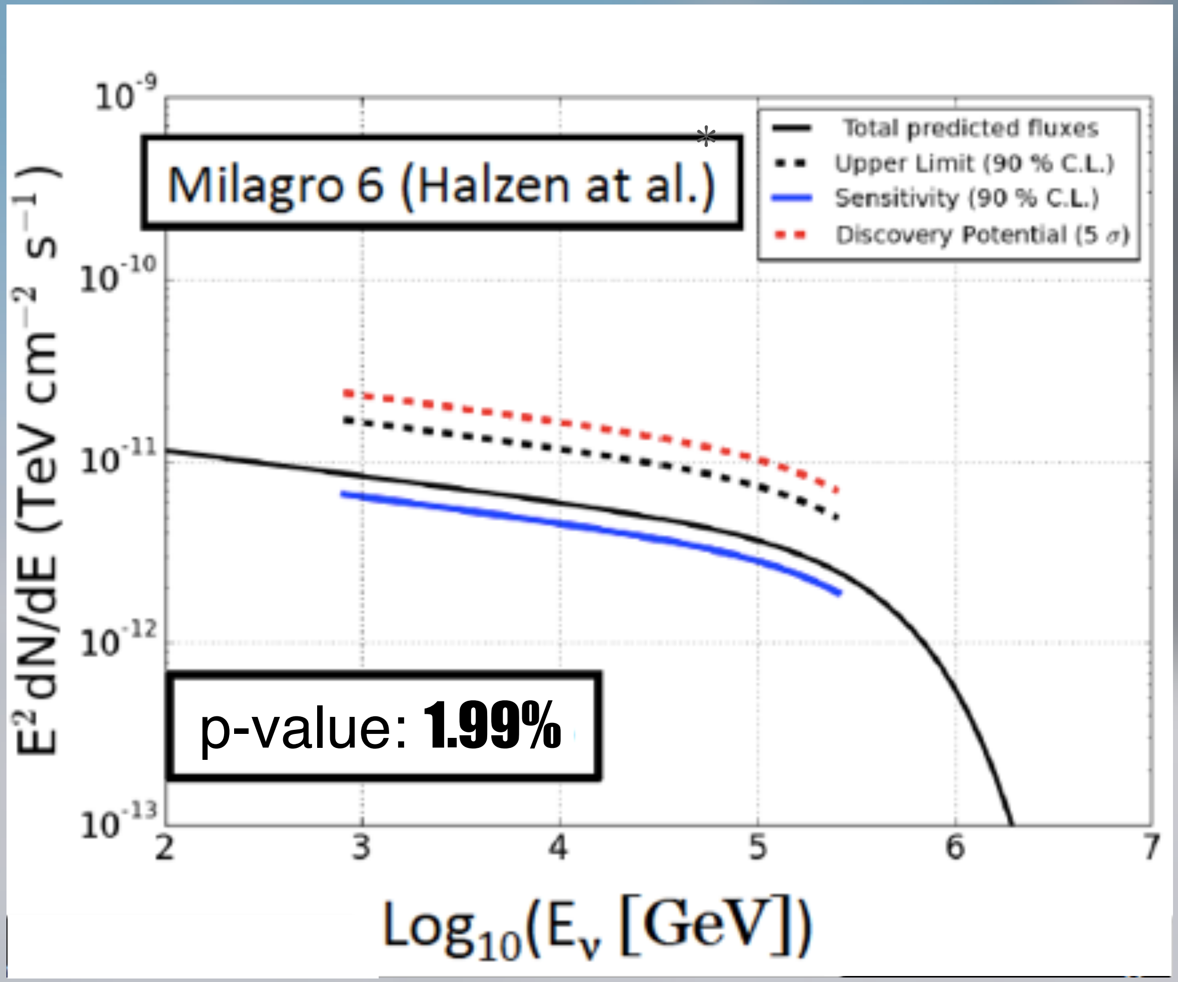
Energy range for E^{-2} muon neutrino upper limits:

1 TeV - 1 PeV North

10^2 TeV - 10^2 PeV South

Stacking Searches





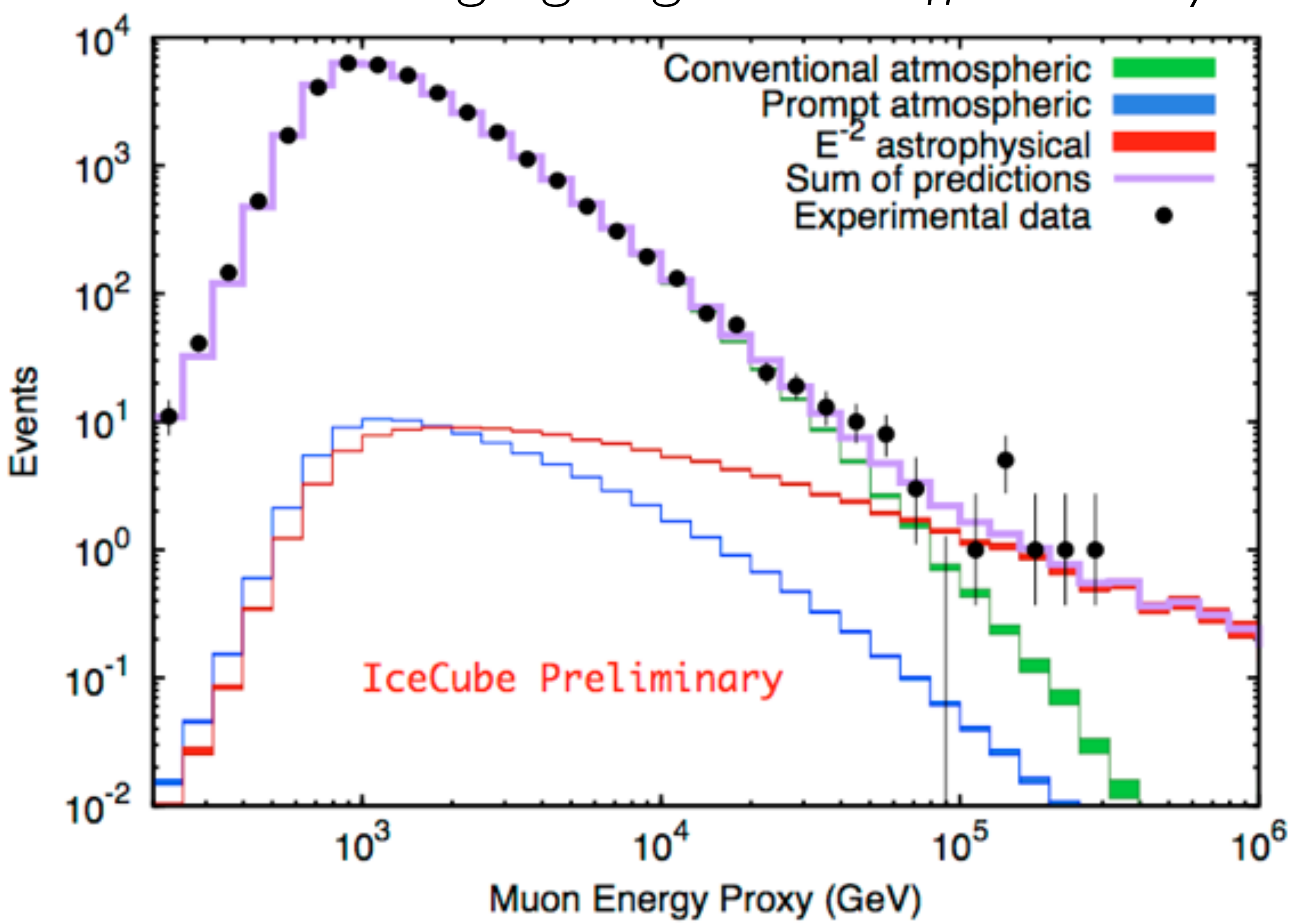
- 6 TeV associations with supernova remnants based on **Milagro observations**. Models from Halzen et al.
- p-value of 2% *a posteriori* in IC40.
- Evolved from under-fluctuation in IC59 and 20% in IC59+IC79.
- p-value in IC86+IC79+IC59: **1.99%**

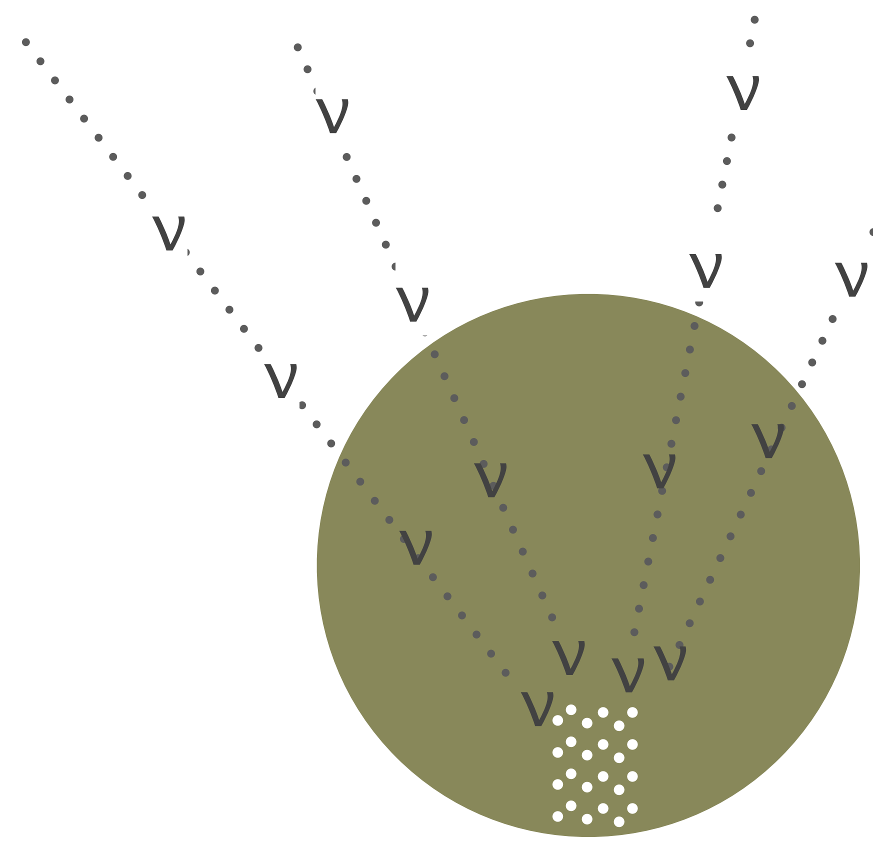
*F. Halzen, A. Kappes and A. O'Murchadha (Phys. Rev. D78:063004, 2008)

Search for Diffuse Emission

- Sources may be numerous and faint: **hard to resolve individually**

Standard through going-muon diffuse analysis





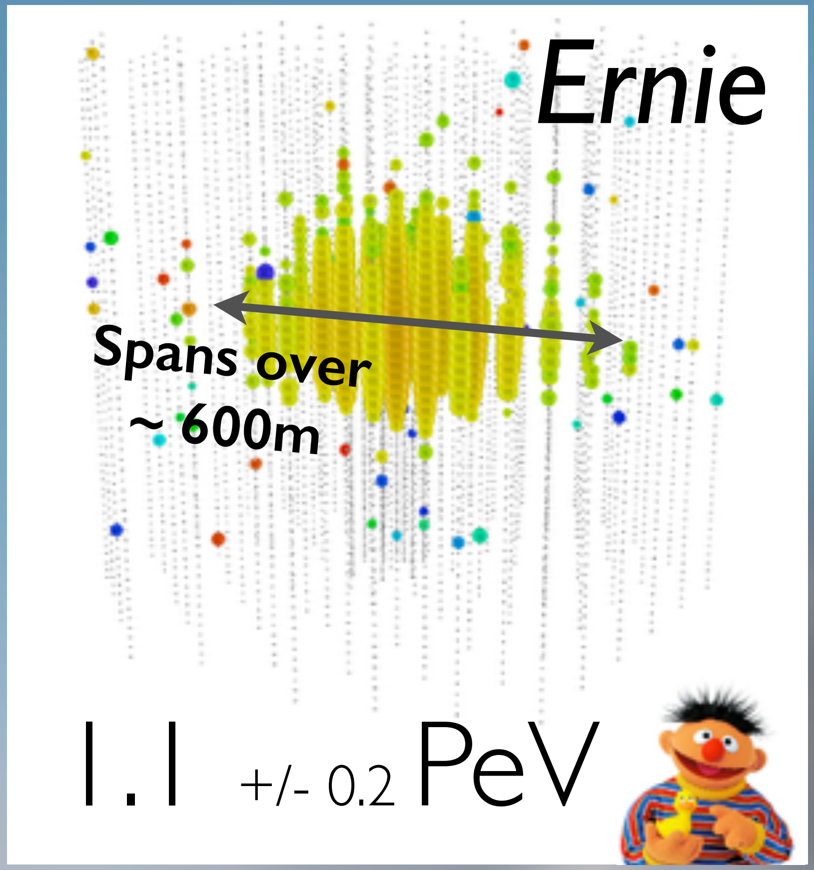
- The best-fit astrophysical flux:

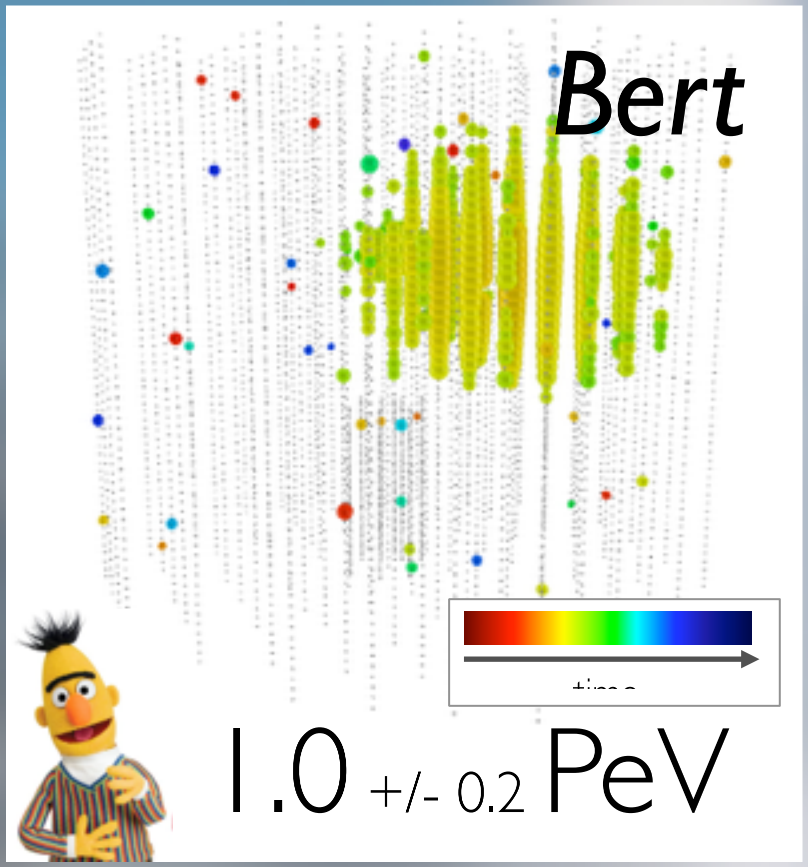
$1.01 \times 10^{-8}\, E^{-2}\, \mathrm{GeV\, cm^{-2}\, s^{-1}\, sr^{-1}}$

- The bkg-only hypothesis is disfavored: **3.9σ**

High Energy Starting Events: the First PeV Neutrinos

- Two very interesting cascade events found in IceCube (IC79/IC86)





- Analysis targeting much higher energy neutrinos (related to GZK cutoff)
- Expected background: 0.08 ± 0.05
- Significance: **2.8σ**

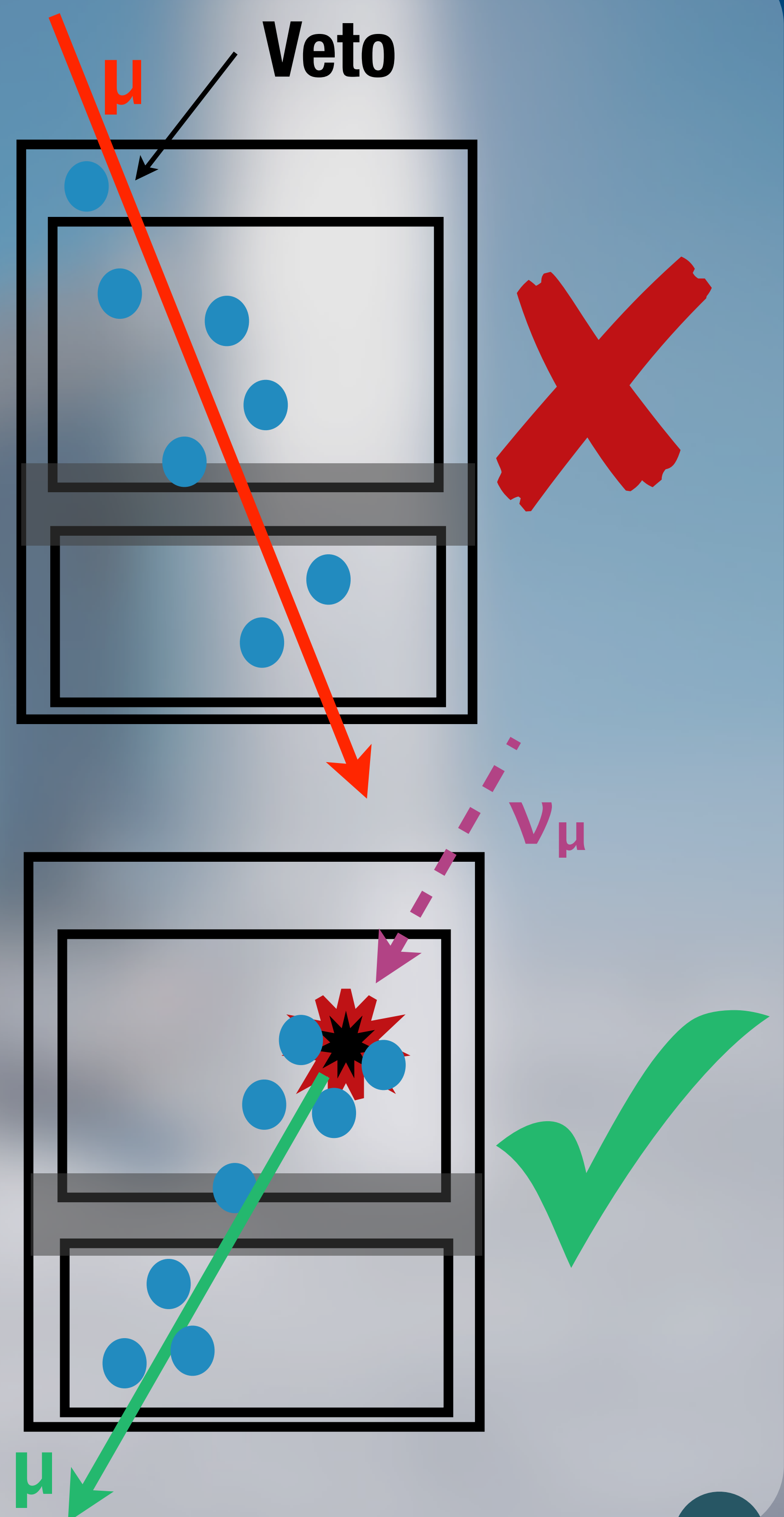
Too low in energy for GZK

Too high in energy for atmospheric

High Energy Starting Events

Analysis of 3 years of data

- Golden channel: "down-going starting events"
  - **High energies events: Qtot > 6000 p.e.**
  - **Use out layer of detector as veto**
- Sensitive to all flavors in region above 60 TeV.
- Veto rejects **atmospheric muons** and **down-going atmospheric neutrinos** (the muons produced in the same shower will likely not have ranged out at IceCube)



High Energy Starting Events: 2 YEARS

28 EVENTS

7 track-like events

1° ang. resolution

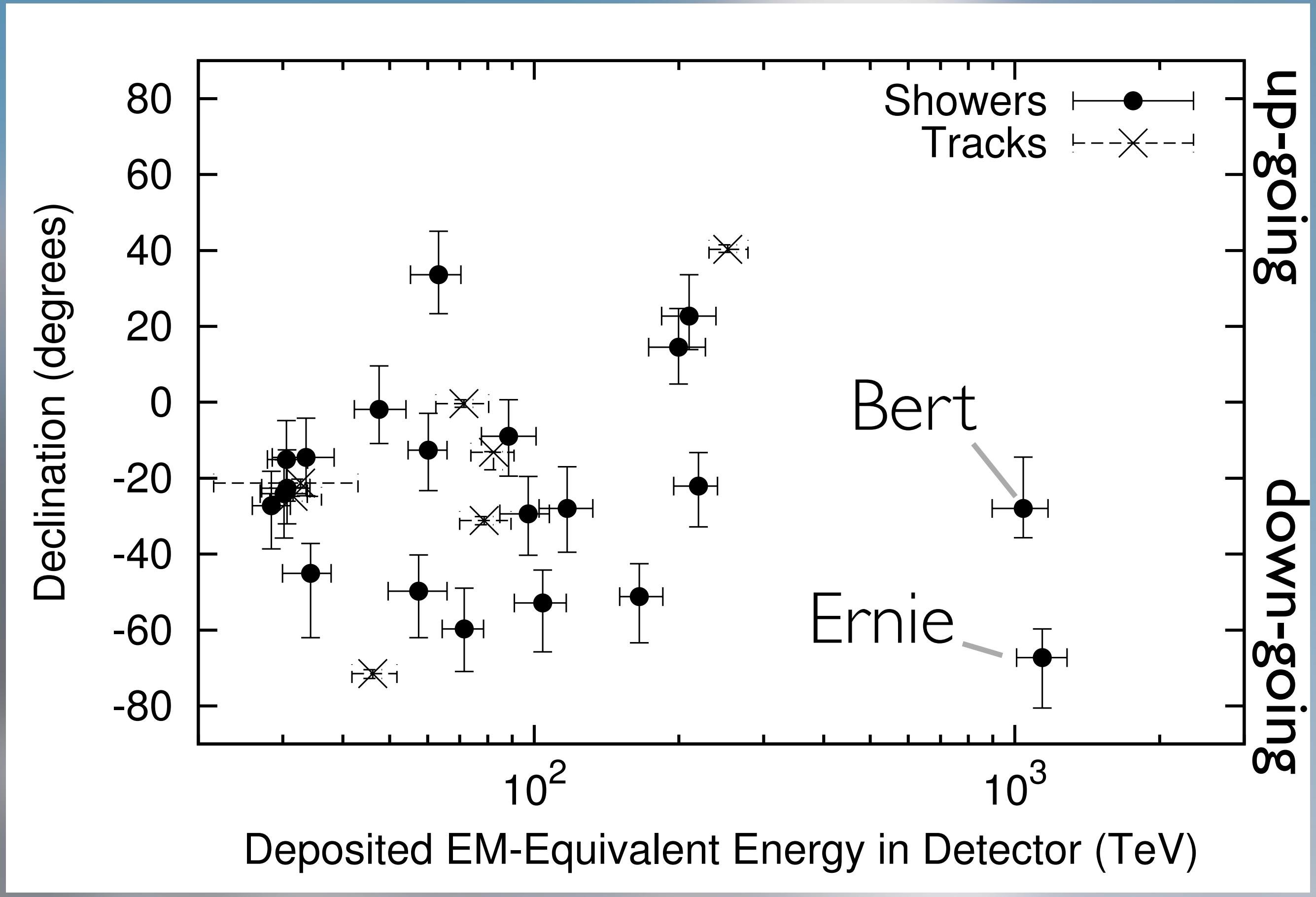
Muon takes some energy away

21 cascade-like events

10° – 45° ang. resolution

15% visible energy resolution

IceCube, Science, 342, 1242856 (2013)



Estimated background:

- $4.6^{+3.7}_{-1.2}$ atm. neutrinos
- 6.0±3.4 atm. muons

3.3σ significance w.r.t. reference bkg. model (26 events)

4.1σ combining with 2.8σ from GZK results (26 + 2 events)

4.1σ full likelihood fir of all components (28 events)

High Energy Starting Events: 3 YEARS

37 EVENTS

9 track-like events

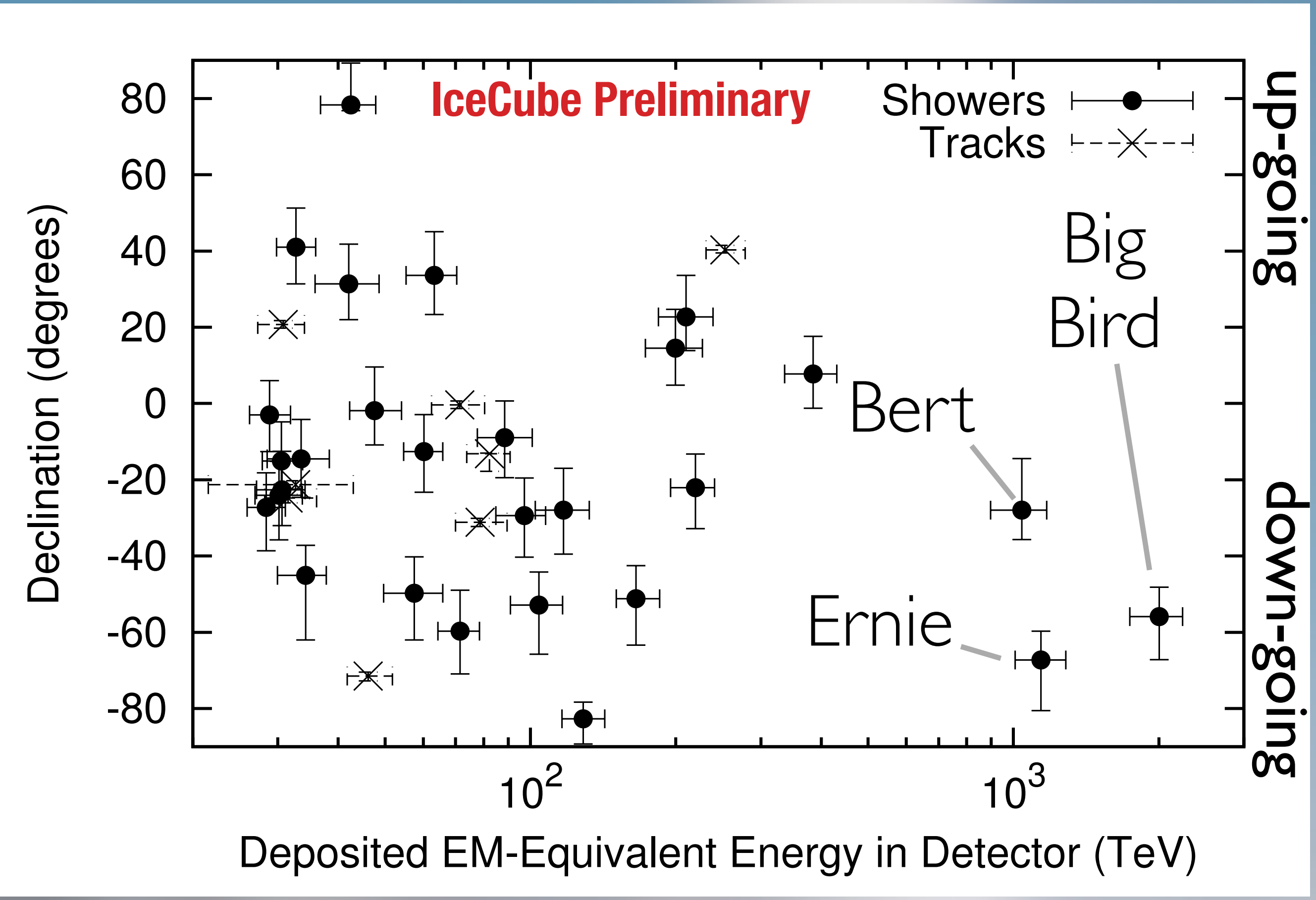
1° ang. resolution

Muon takes some energy away

28 cascade-like events

10° – 45° ang. resolution

15% visible energy resolution



Estimated background:

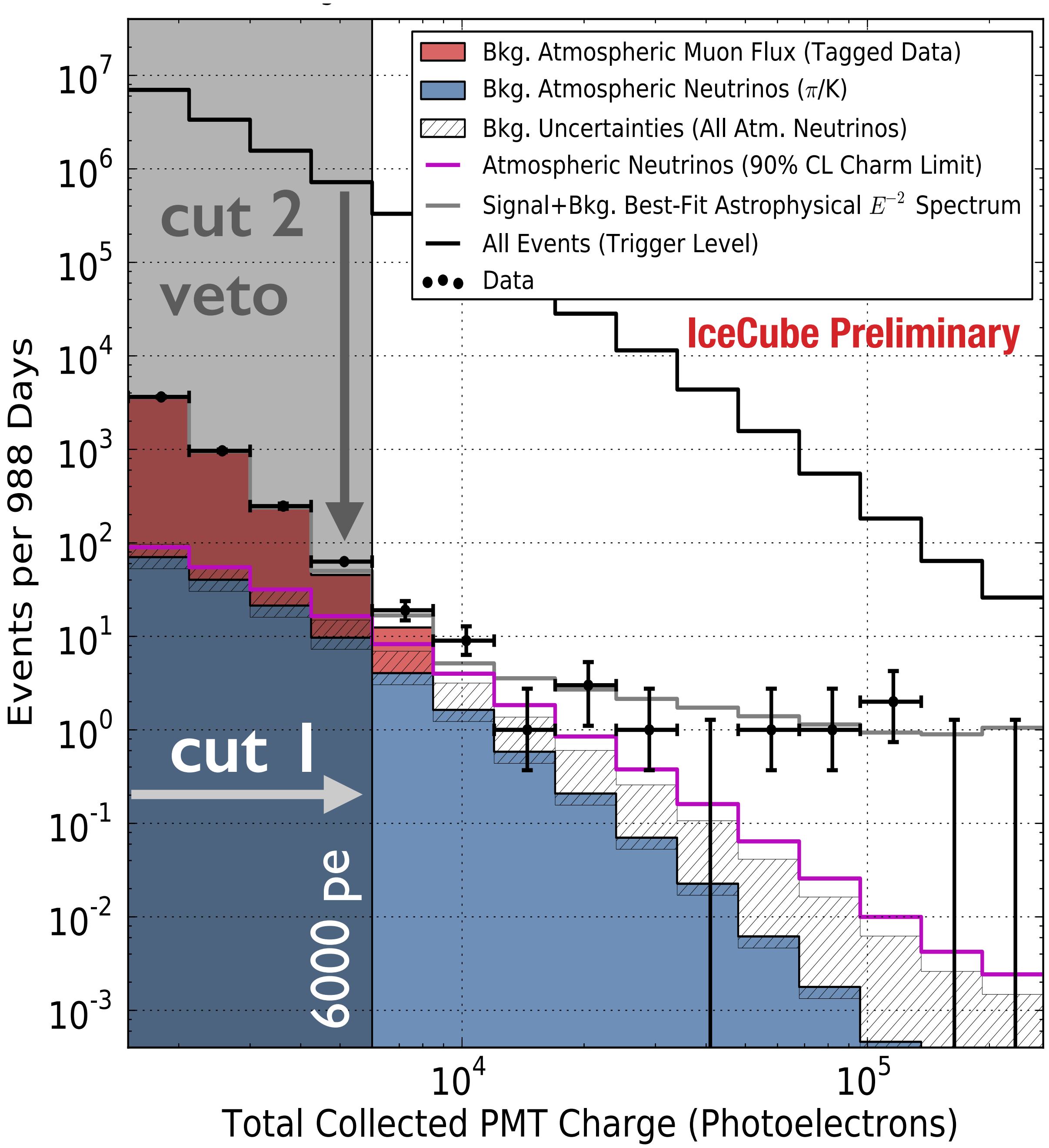
- $6.6^{+5.9}_{-1.6}$ atm. neutrinos
- 8.4±4.2 atm. muons

4.8σ combining with 2.8σ from GZK results (35 + 2 events)

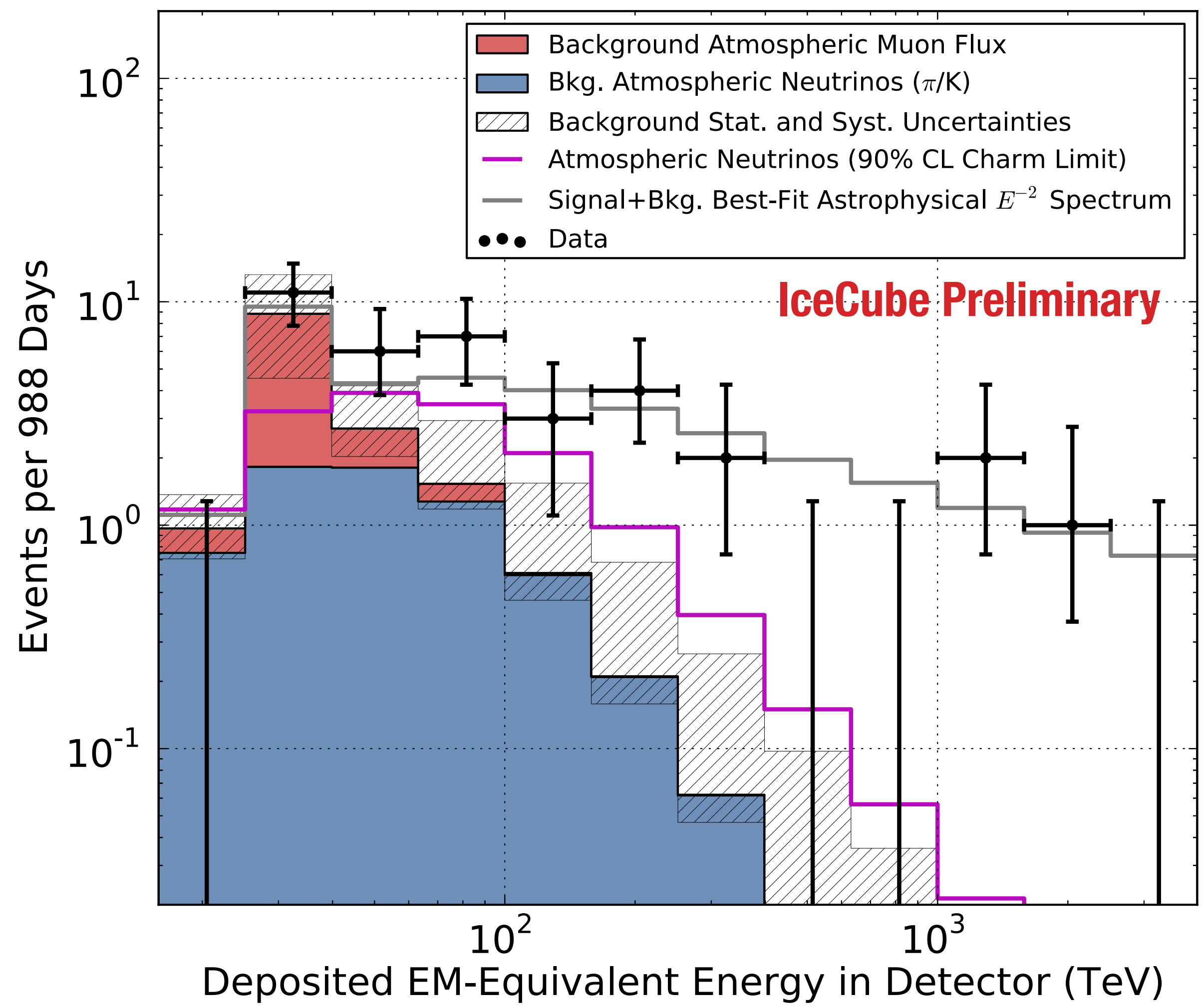
5.7σ full likelihood fir of all components (36 + 1 events)

Charge and Energy Distribution

Charge



Energy

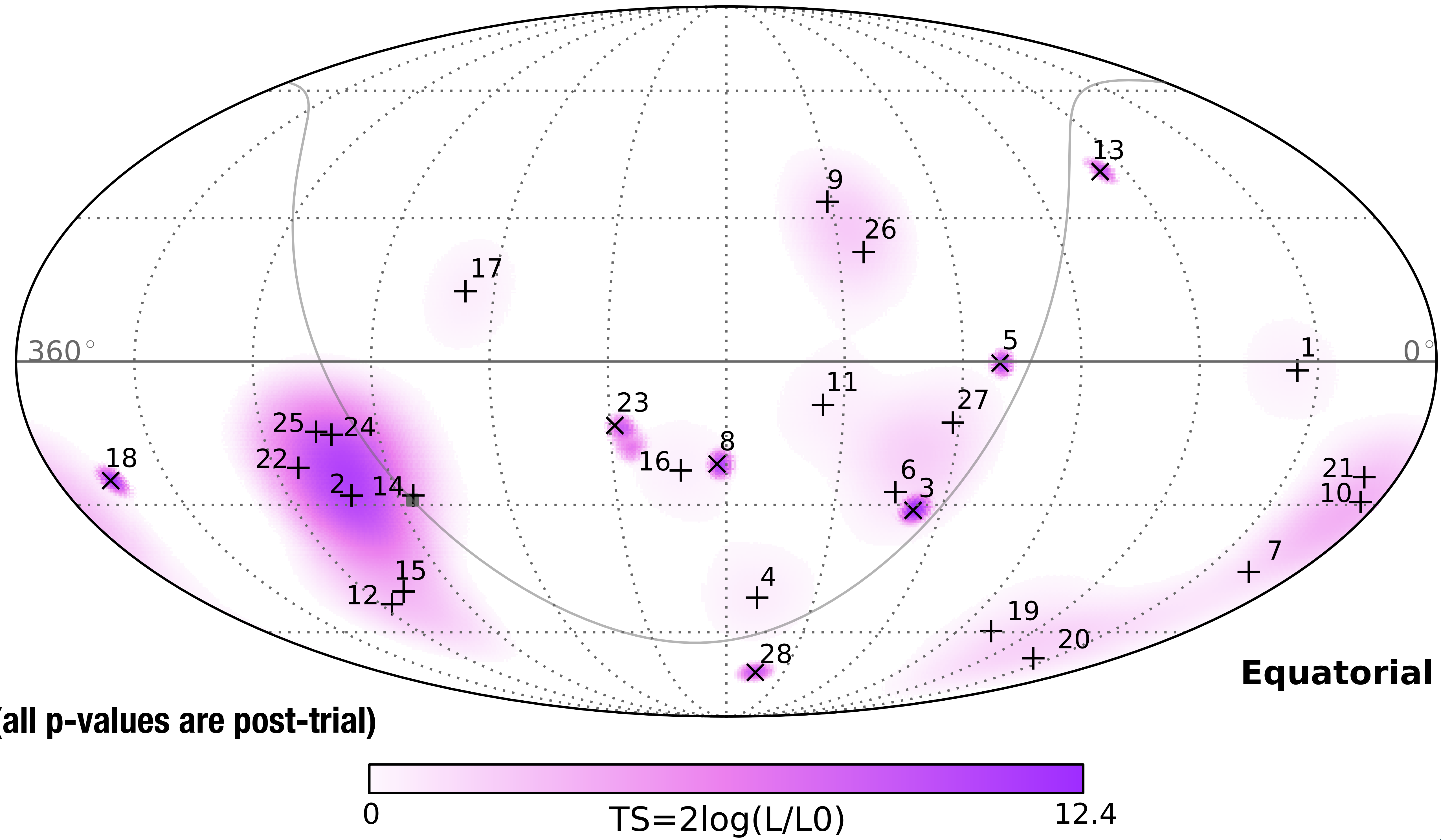


Harder than any expected atmospheric background. Best fit (per flavor):

$$0.95 \pm 0.3 \times 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

Looking for Clustering

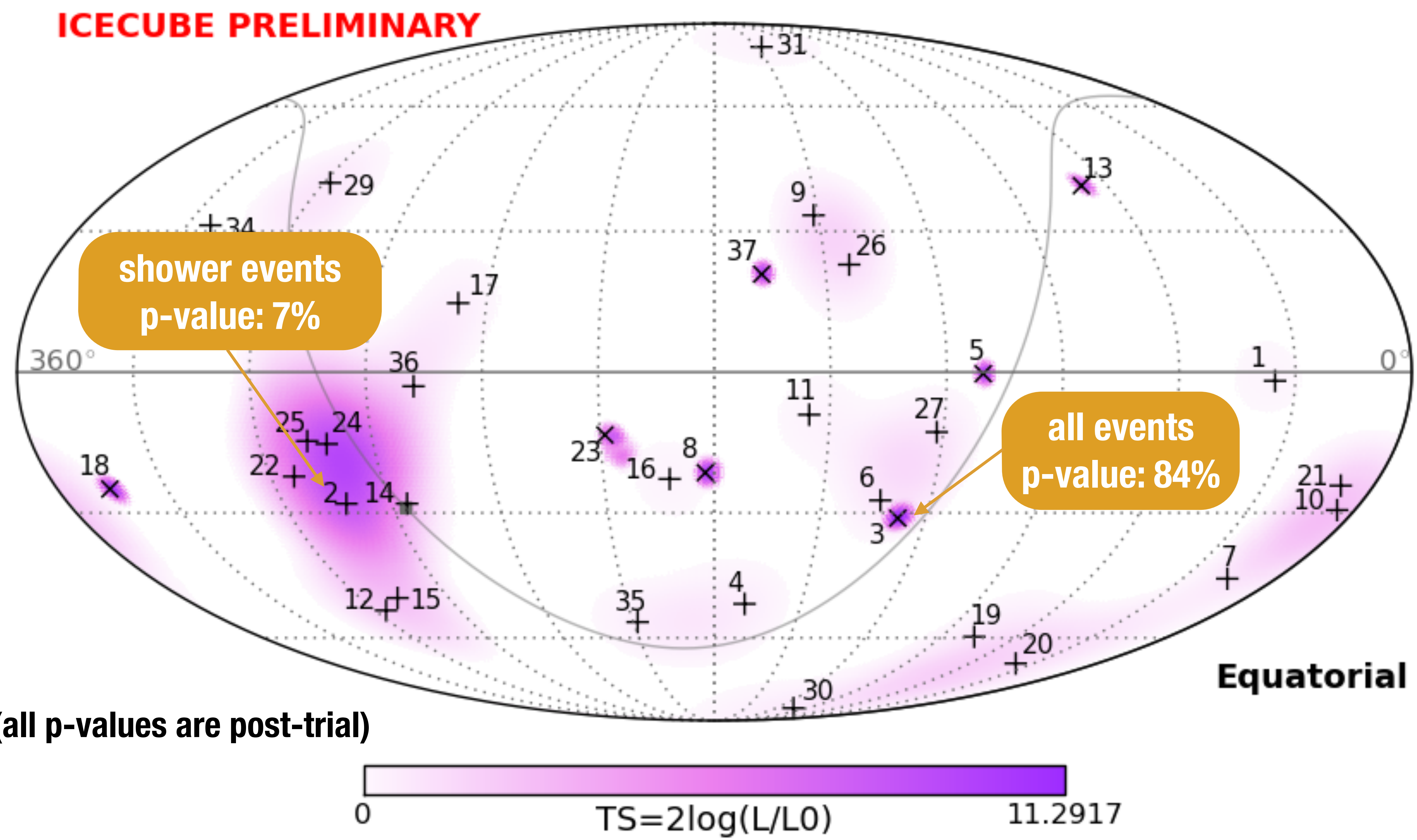
No significant clustering observed **2 years**



(all p-values are post-trial)

Looking for Clustering

No significant clustering observed **3 years**



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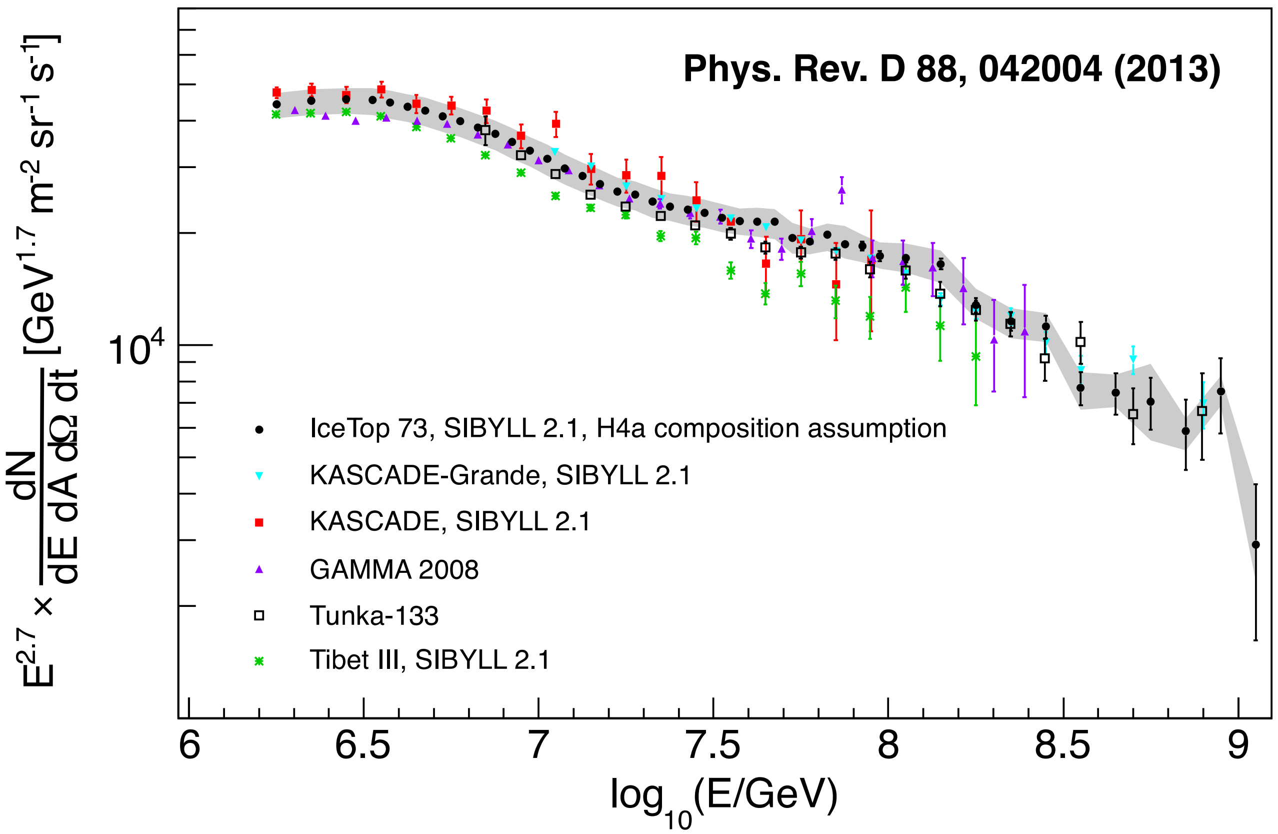
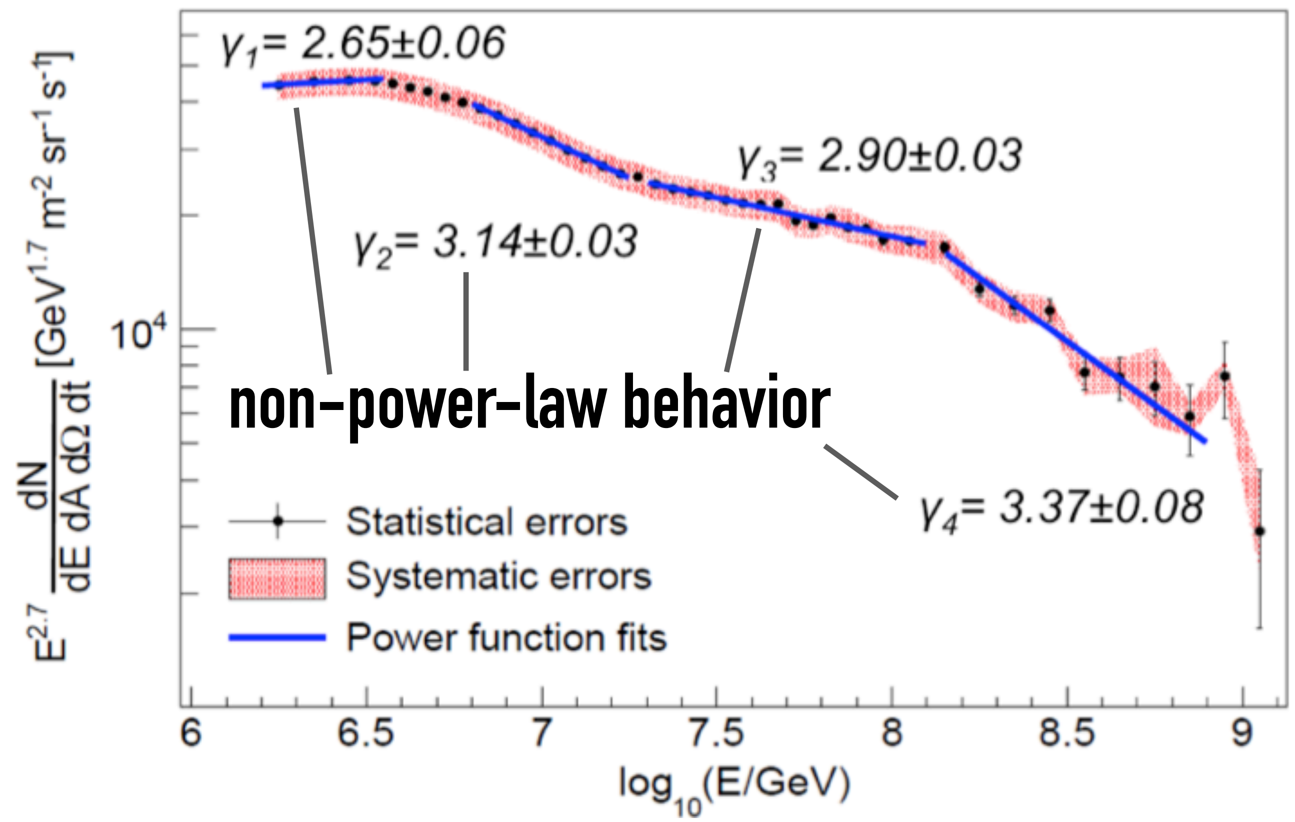
Cosmic-Rays in IceTop

IceTop 73 energy spectrum 1.6 PeV to 1.3 EeV





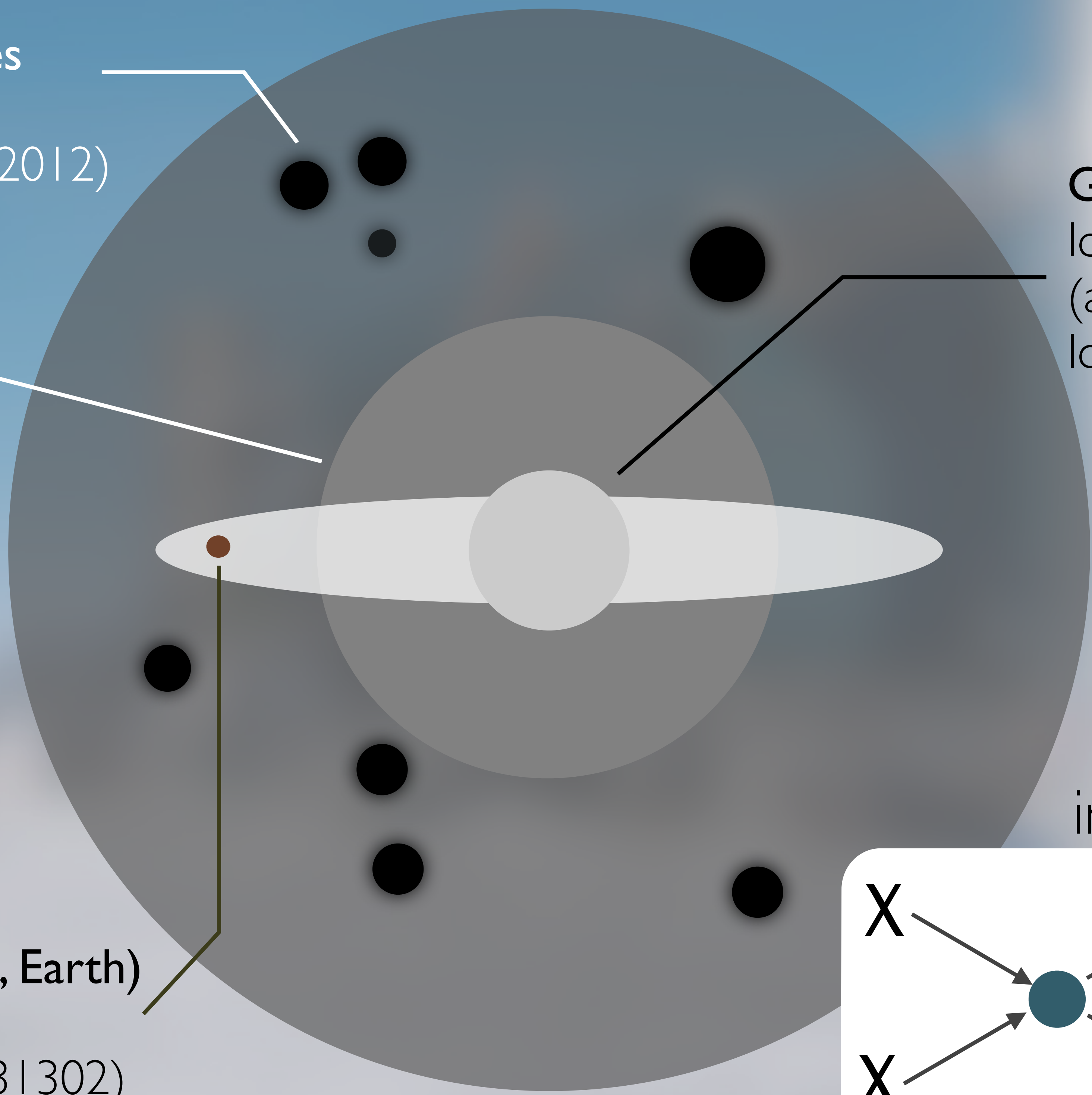
- CR physics is related to neutrino astrophysics:
  - the cosmic settings which generate CRs also produce ν's
  - CRs interacting in Earth's atmosphere produce the bkg for astrophysical ν's - atm. ν's and atm. μ's

Dark Matter Searches in IceCube

Dwarf spheroidal Galaxies
IceCube-59 limits

Cluster of Galaxies
IceCube-59 limits
(arXiv: 1210.3557 2012)

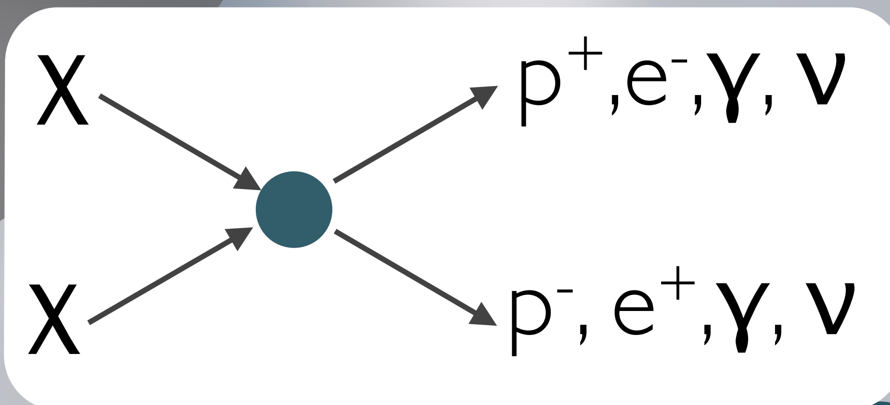
Galactic Halo
IceCube-22 limits
(PDR 84 (2011) 022004)



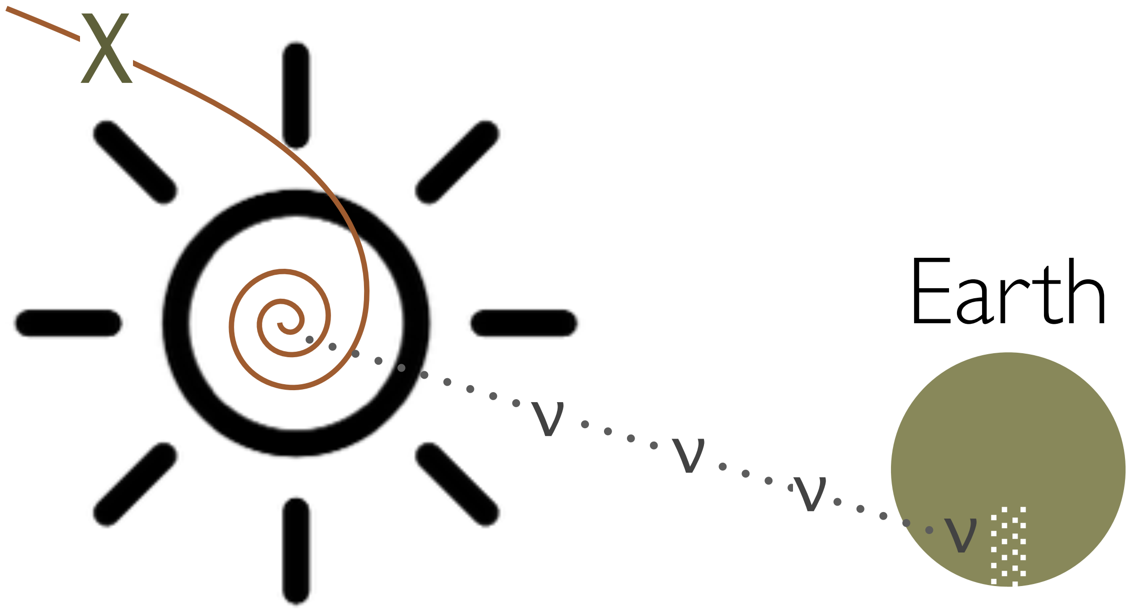
Galactic Center
IceCube-40 limits
(arXiv:1210.3557 2012)
IceCube-59 sens.

Local Sources (Sun, Earth)
IceCube-79 limits
(PLR 110 (2013) 131302)

indirect searches



WIMP Searches From the Sun

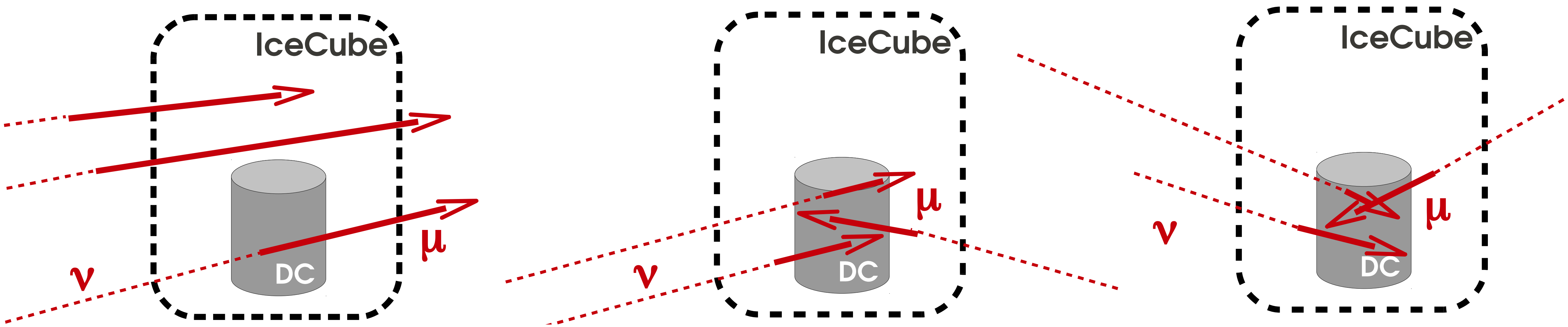


- Sun is a **down-going** source during austral summer
- Sun is an **up-going** source during austral winter

- ***Up-going*** ①
- No containment

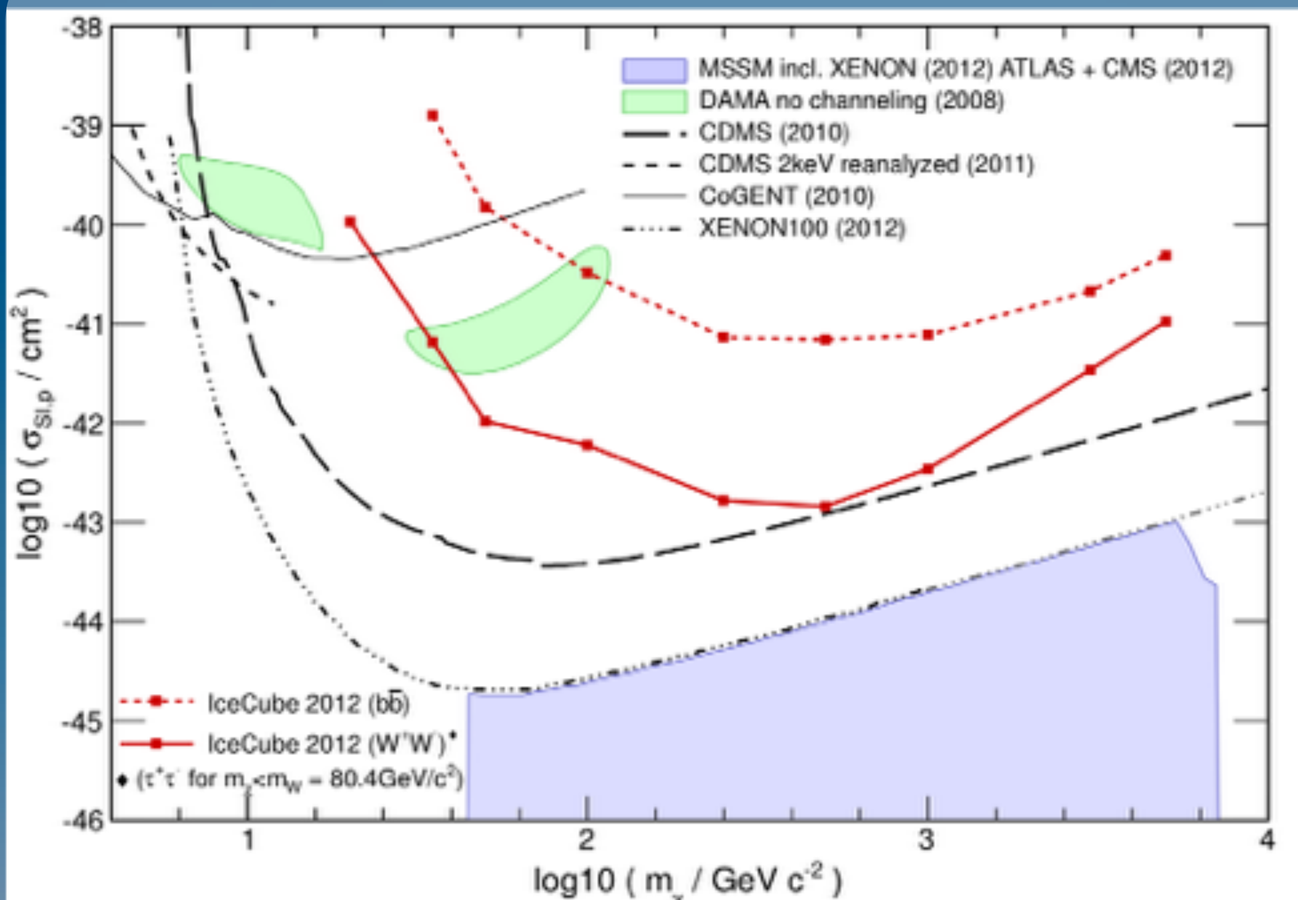
- ***Up-going*** ②
- strong containment

- ***Down-going*** ③
- strong containment

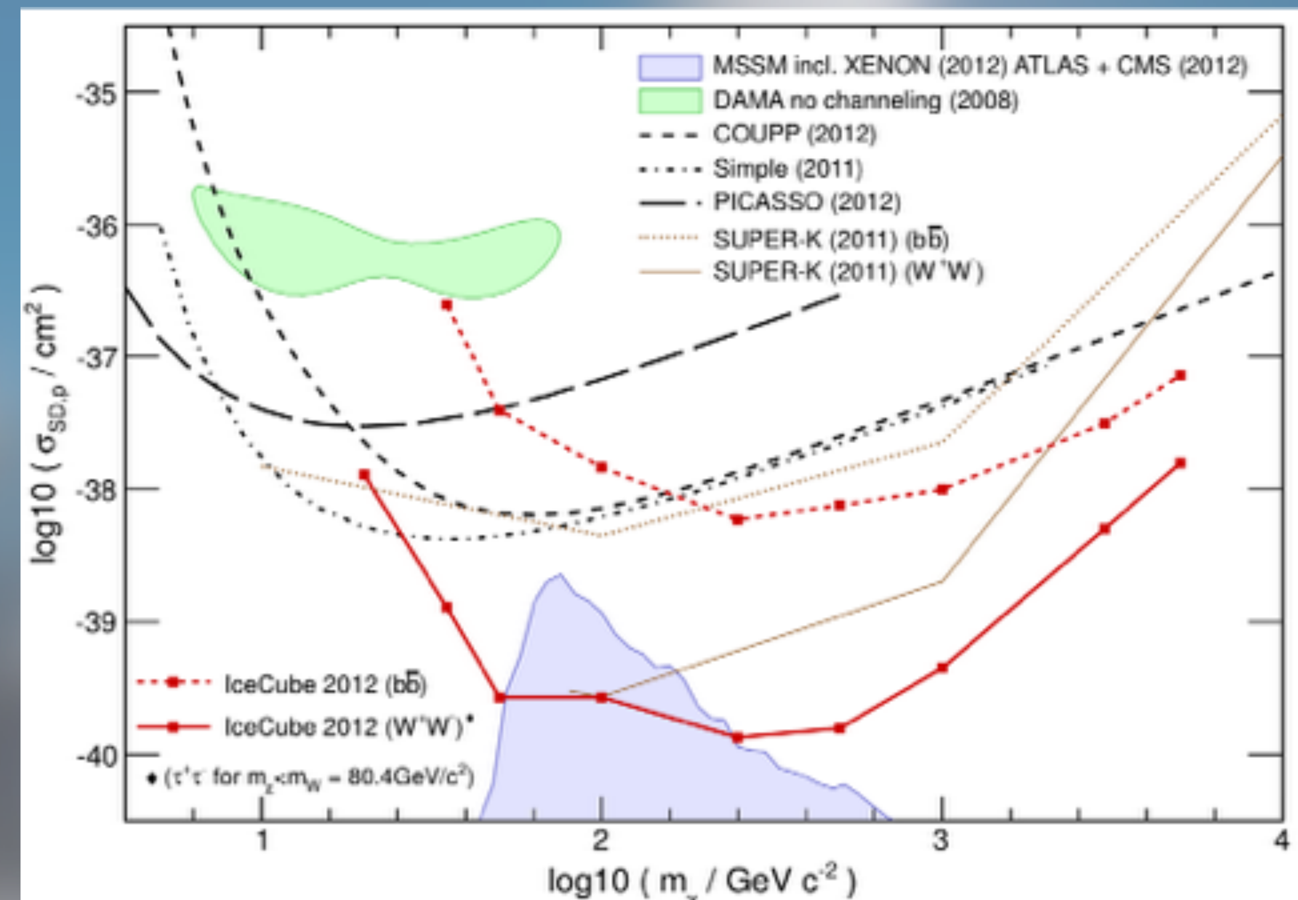


317 days of livetime, down to neutrino energies of ~10GeV!

WIMP Searches From the Sun



90% CL χ-p cross-section (spin-independent)



90% CL χ-p cross-section (spin-dependent)

- Complementary to direct detection search efforts
  - fills out WIMP picture by testing other properties
- Most stringent SD cross-section limit for most models

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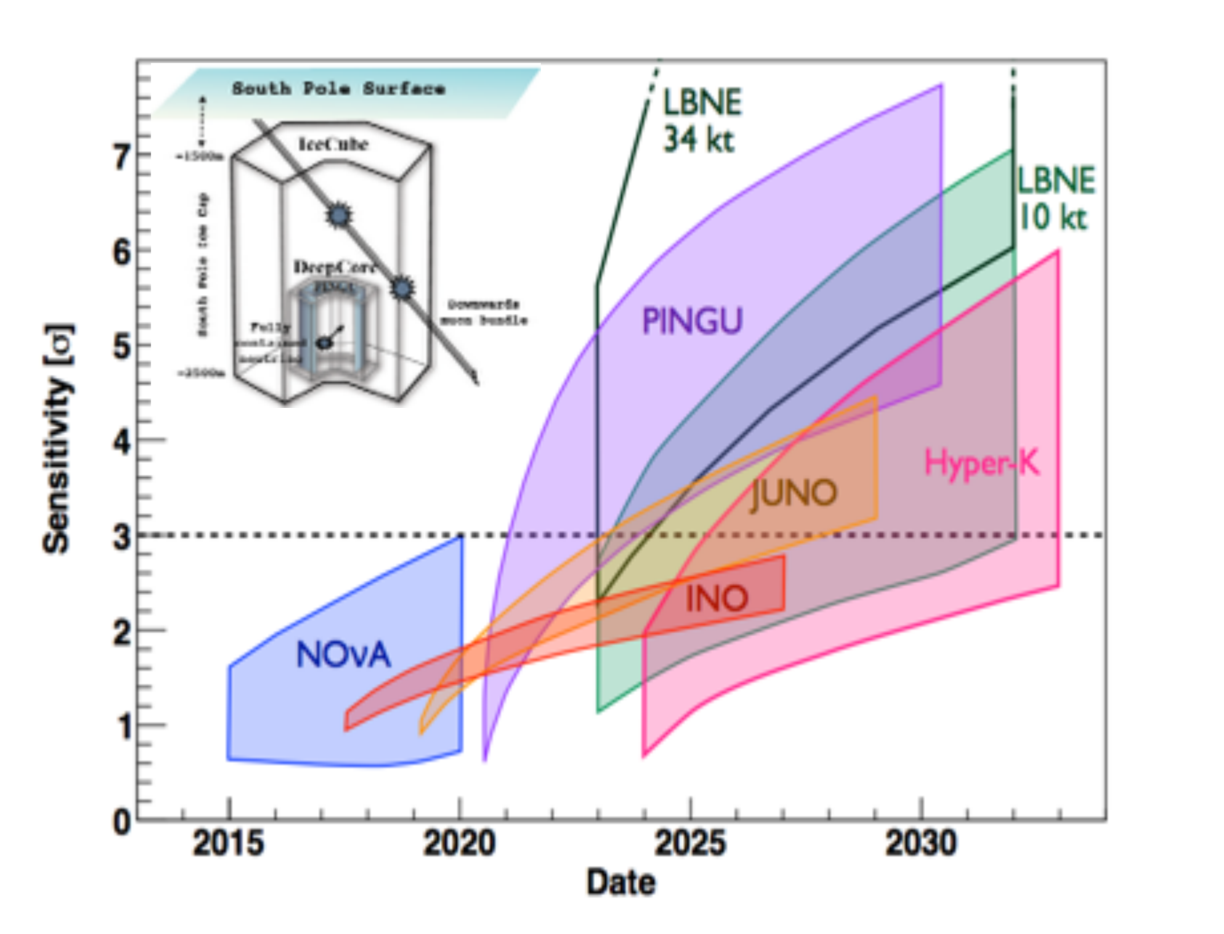
The FUTURE

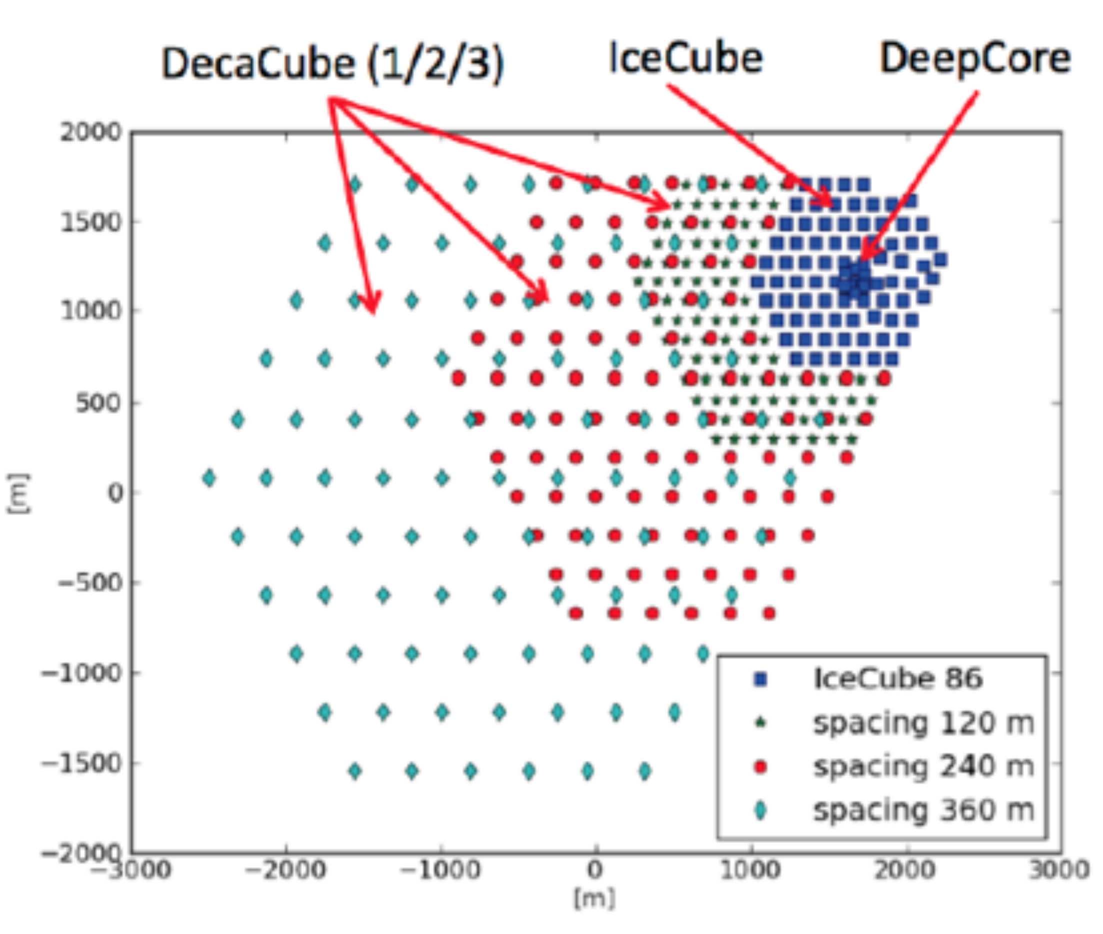
PINGU

Further in-fill of deep core.
Lower the energy threshold few GeV
Oscillations and Neutrino Mass Hierarchy

High Energy Extension

Extension of IceCube array
Look for high-energy events
GZK and astrophysical neutrinos





Conclusions

No evidence yet of neutrino point and extended sources…

…but increasing evidence for a diffuse high-energy component beyond the atmospheric spectrum.

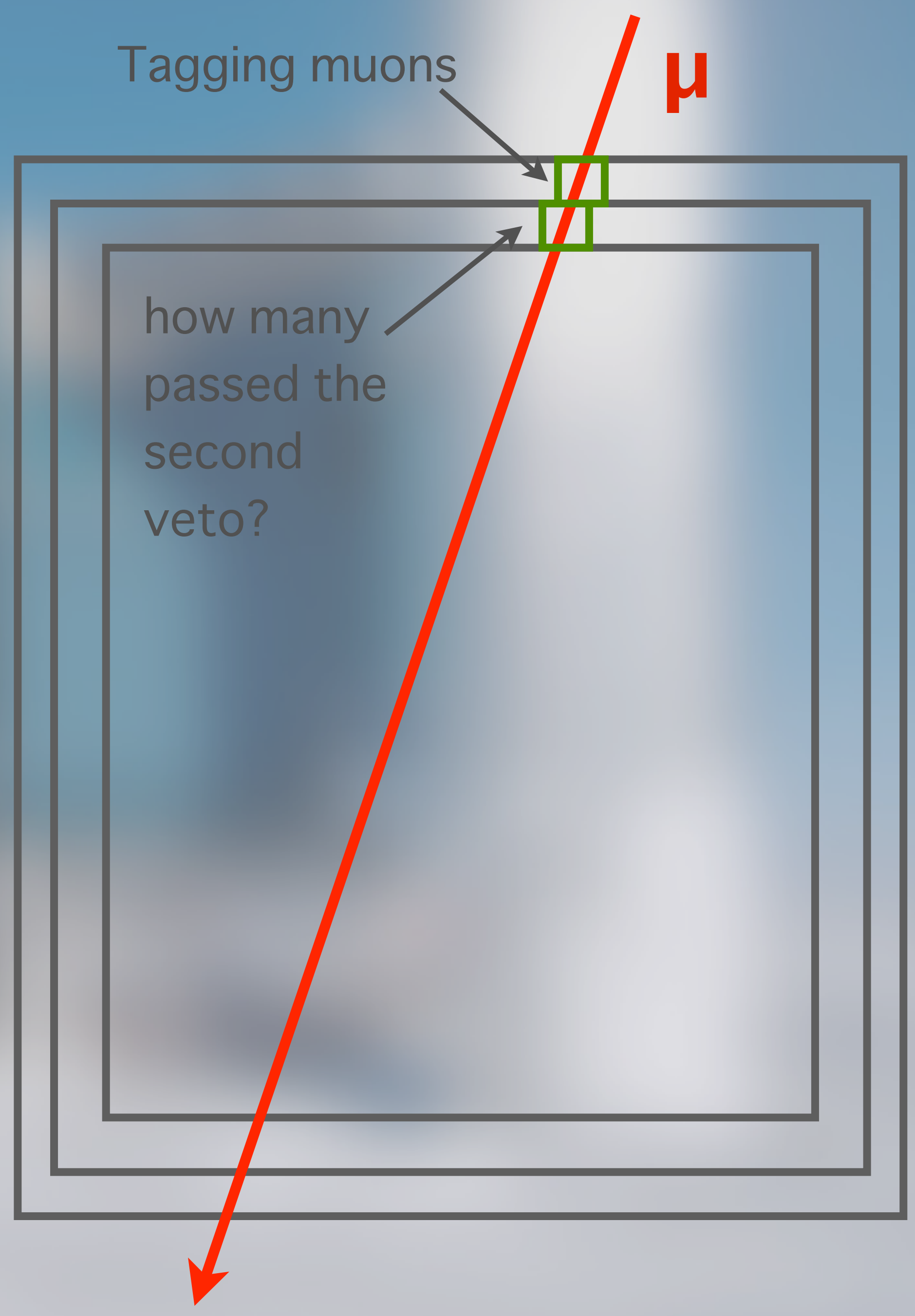
- IceCube has paved the road for neutrino astrophysics.
- More data will resolve the origin of these neutrinos.
- Other scientific topics like Cosmic-ray spectrum and dark-matter are also possible with IceCube.
- Future extensions of IceCube will enlarge the energy range and widen the physics goals.

BACKUP

Atm. Muon Background

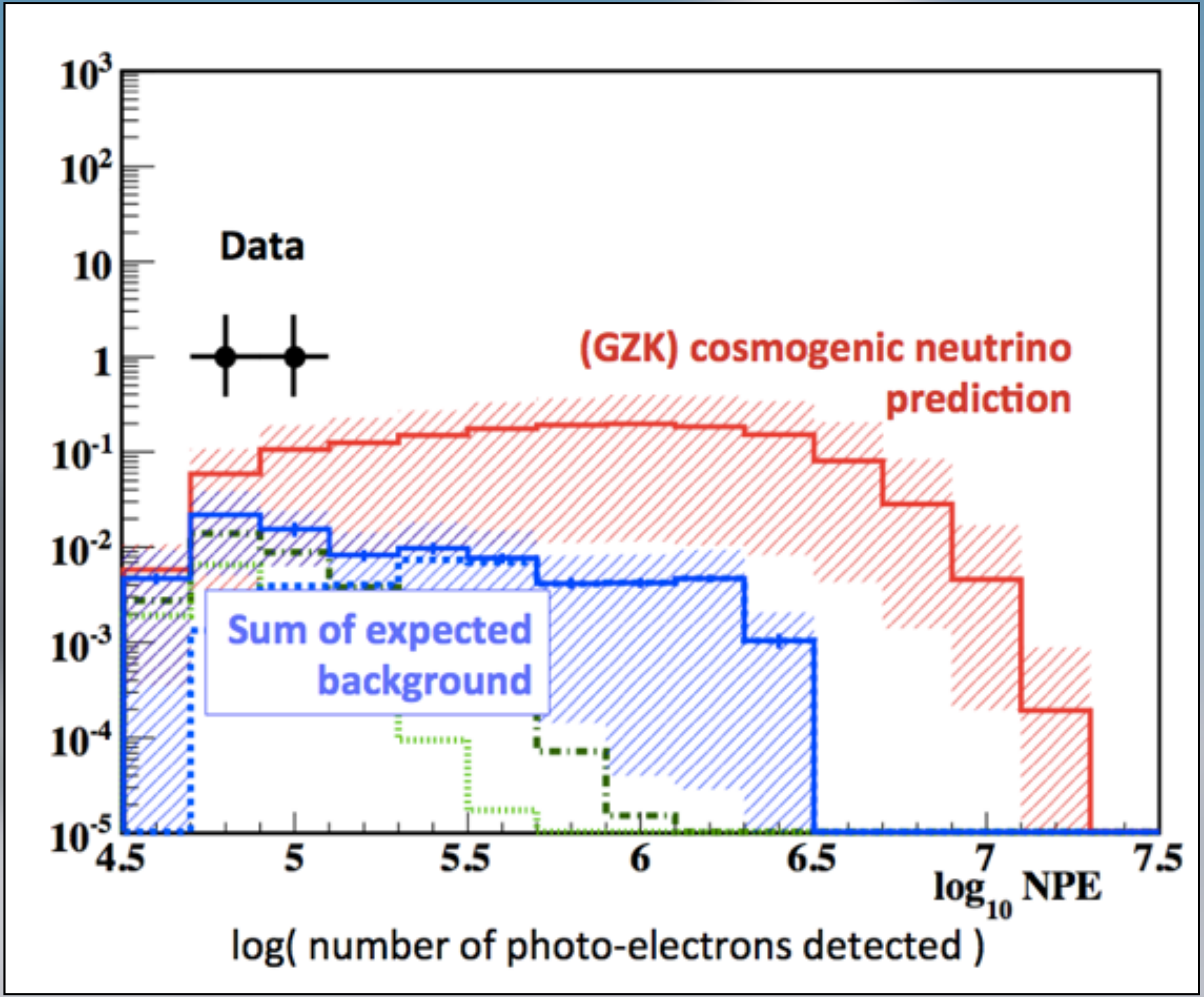
- Muons can (rarely) penetrate veto region
- Control sample available: tag muons with part of detector and see what fraction vetoed by another.
- Expected background (2 years):

6 ± 3.4



First PeV Neutrinos

Physical Review Letters 111 (2013) 021103: arXiv:1304.5356



- Analysis targeting much higher energy neutrinos (related to GZK cutoff)
- Expected background:

  0.08 ± 0.05
- Significance:

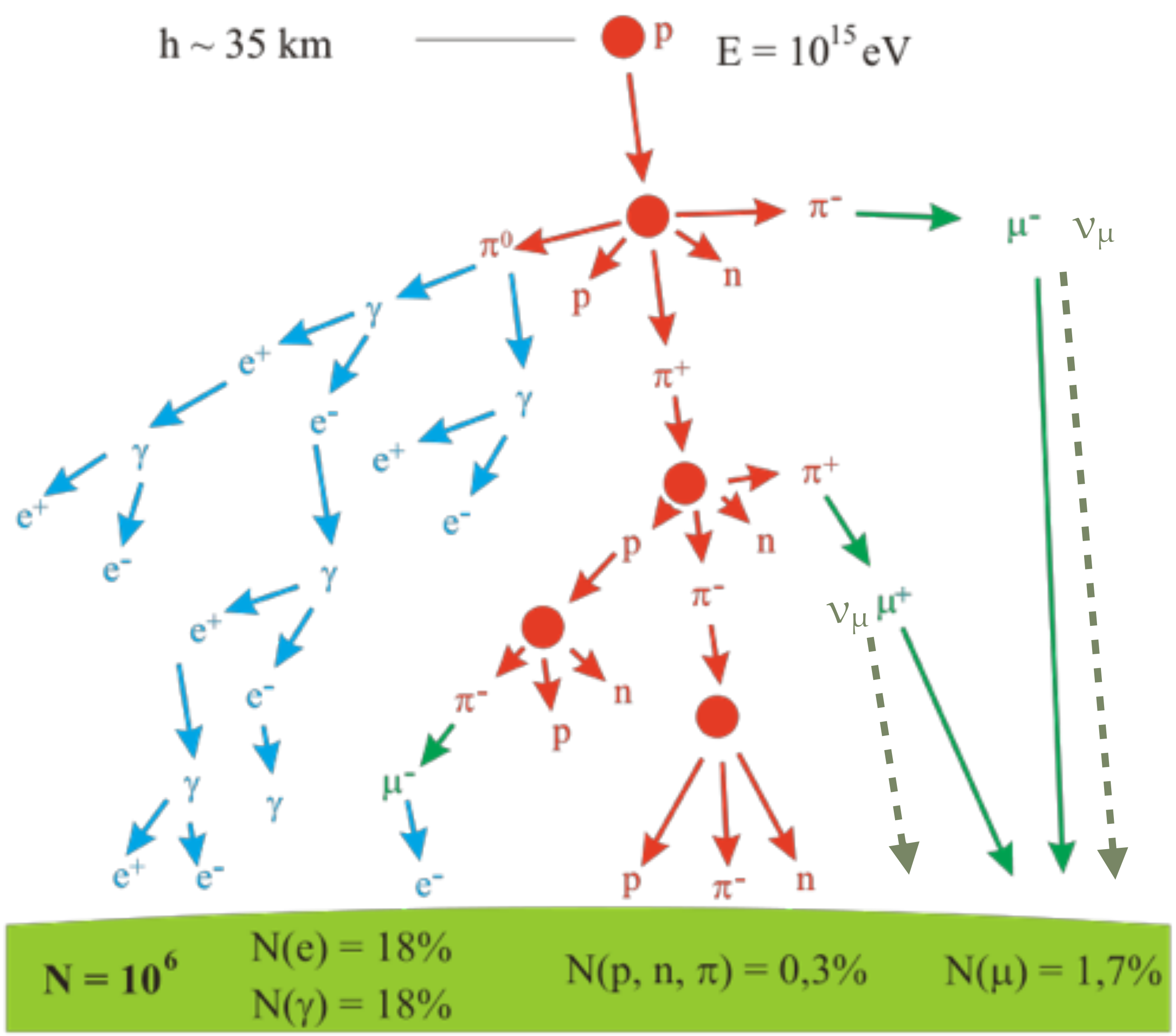
  2.8σ

Too low in energy for GZK
Too high in energy for atmospheric

Atm. Neutrino Background

- Down-going atmospheric neutrinos will be accompanied by muons from the same shower.
- Down-going events that start in the detector are ***extremely*** unlikely to be atmospheric.
- Expected background (2 years):

  $\mathbf{4.6^{+2.9}_{-1.9}}$



Gaisser et al. arXiv:0812.4308