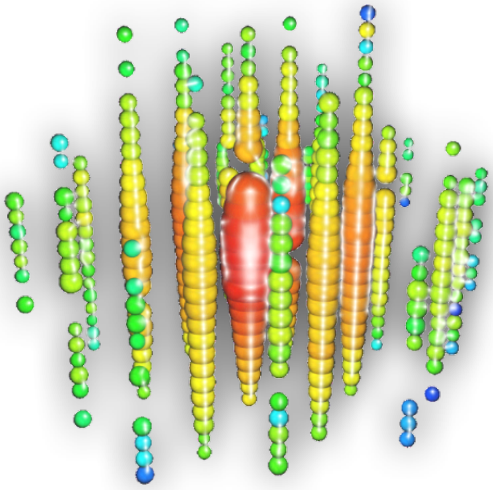
Neutrino astronomy

The IceCube view

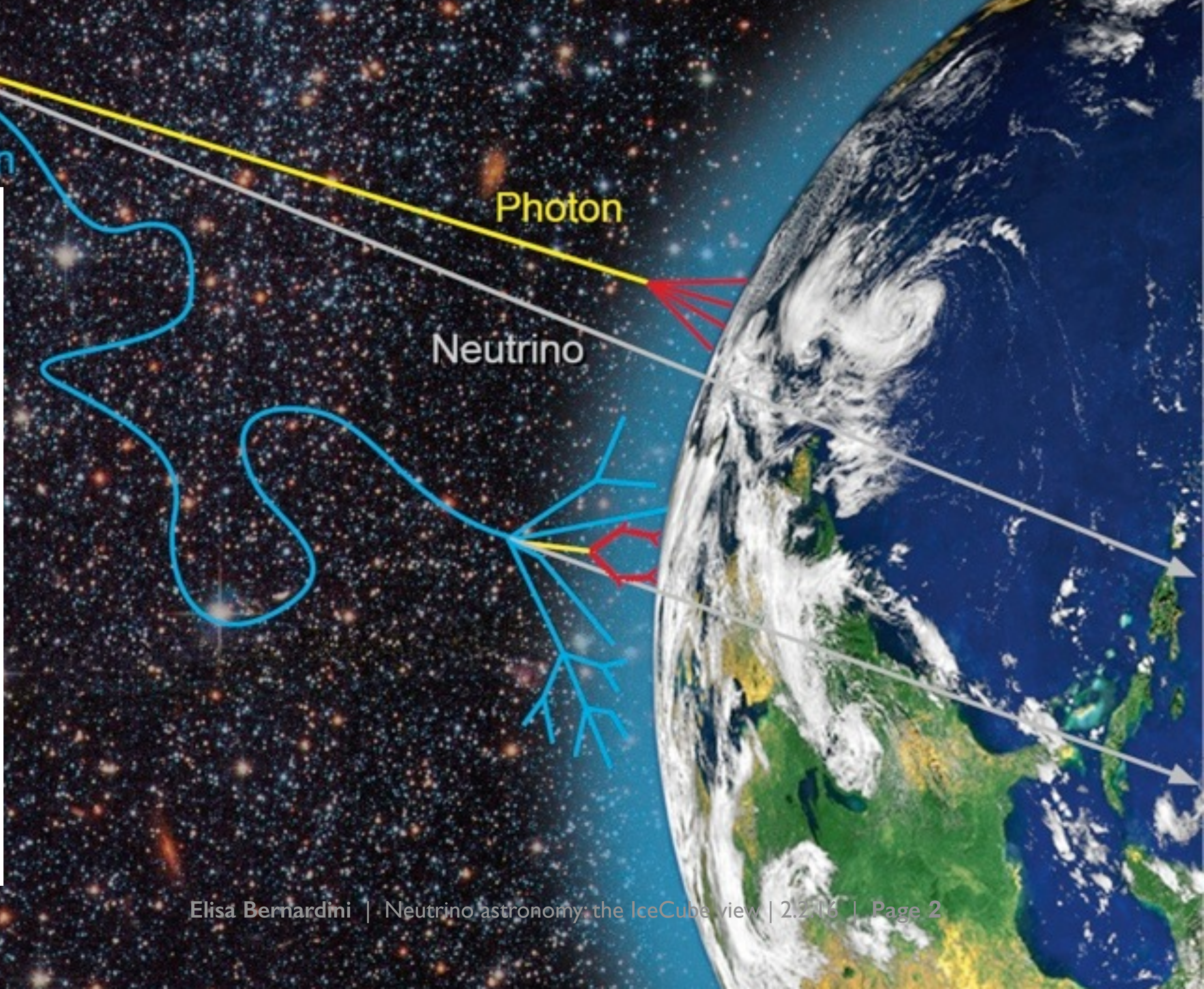


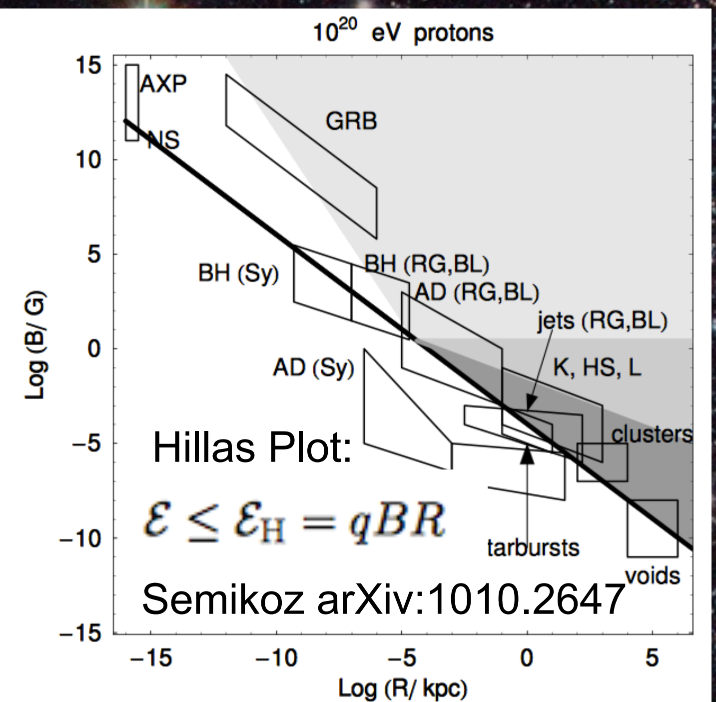
Elisa Bernardini
Università Federico II Napoli

2/2/2016

The generic source

- The origin of cosmic rays can be revealed only by astronomical means
- The messengers should be neutral and stable





Cosmic Rays gamma-rays and neutrinos

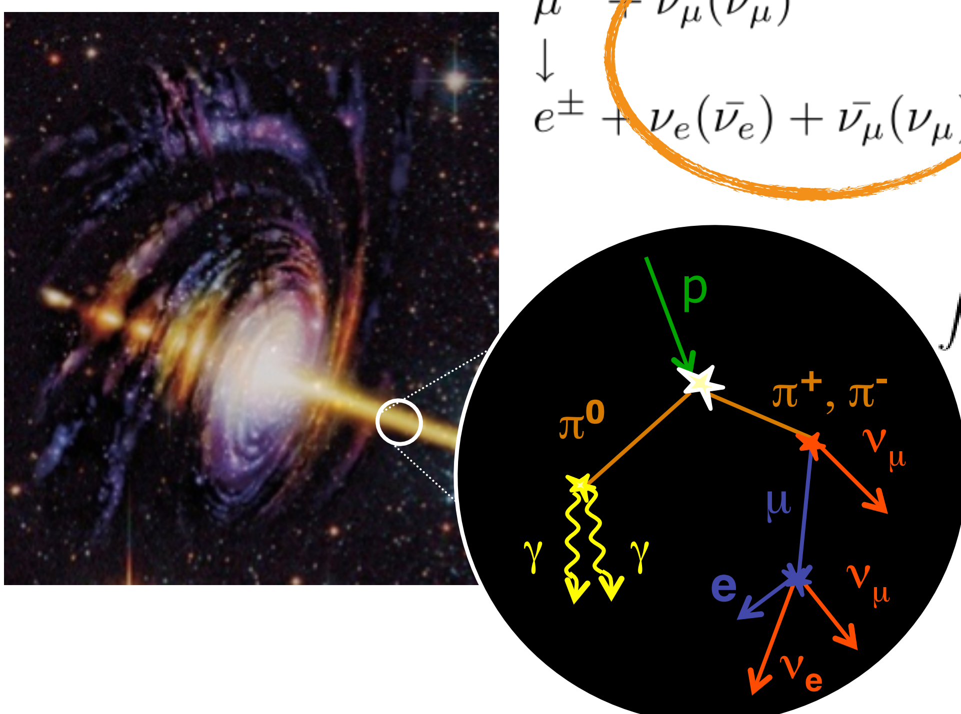
- If neutrinos are produced by cosmic accelerators:
  - 50% (20%) of CR energy is transferred to pions in pp (pγ) interactions
  - each neutrino carries 1/4 of the pion energy

$$pp \to pp(np, nn) + \quad n_1\pi^{\pm} + \qquad n_2\pi^0 + \quad (n_3K^{\pm} + n_4K^0 + \ldots.)$$

$$n_1\pi^{\pm} \downarrow \mu^{\pm} + \nu_\mu(\bar{\nu_\mu}) \downarrow e^{\pm} + \nu_e(\bar{\nu_e}) + \bar{\nu_\mu}(\nu_\mu)$$

$$n_2\pi^0 \downarrow \gamma\gamma$$

$$p\gamma \to \Delta \to \begin{array}{l} p + \pi^0 \ [2/3] \\ n + \pi^+ \ [1/3] \end{array}$$

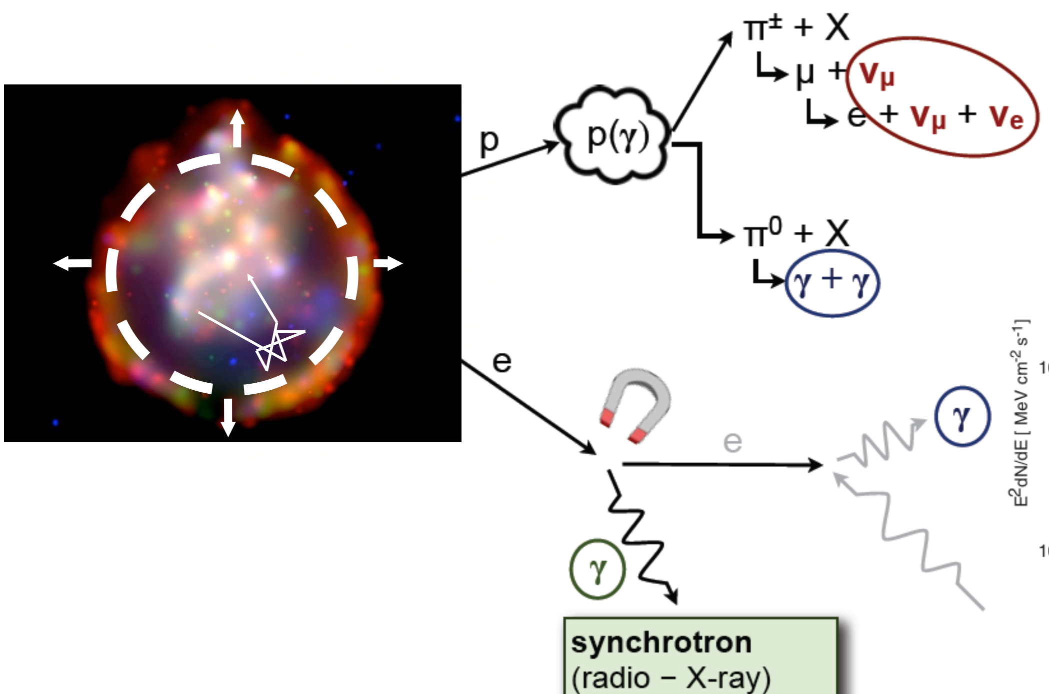


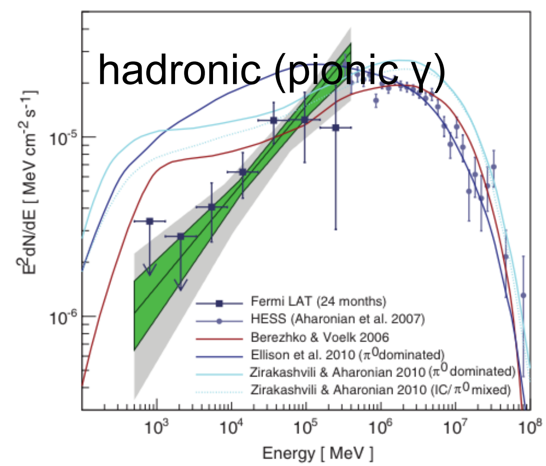
$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

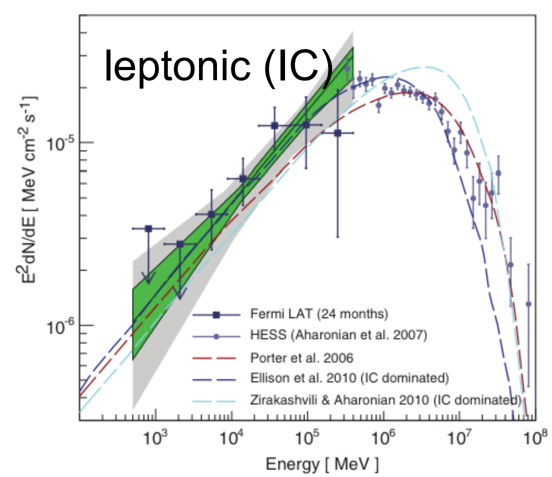
K=4 pγ
K=1 pp

Supernova Remnants

- SNR as sources of galactic CR:
  - Can SNR accelerate hadrons up to PeV energies?
  - How to distinguish hadronic/leptonic in gamma-rays?
- For strong Galactic sources:
  - neutrino flux 10^{-12}–10^{-11} TeV^{-1} cm^{-2} s^{-1} @ 1 TeV

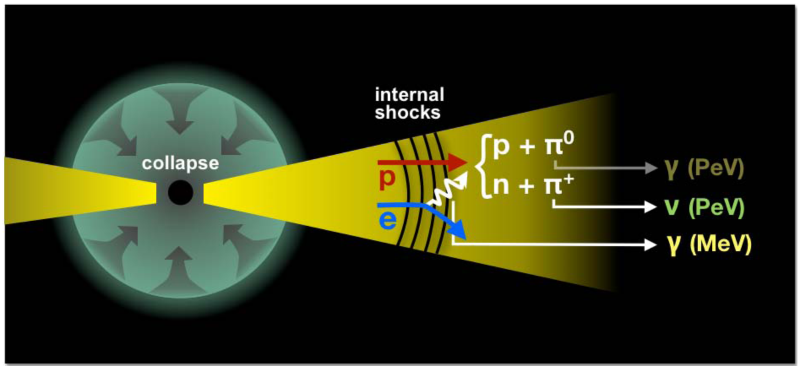


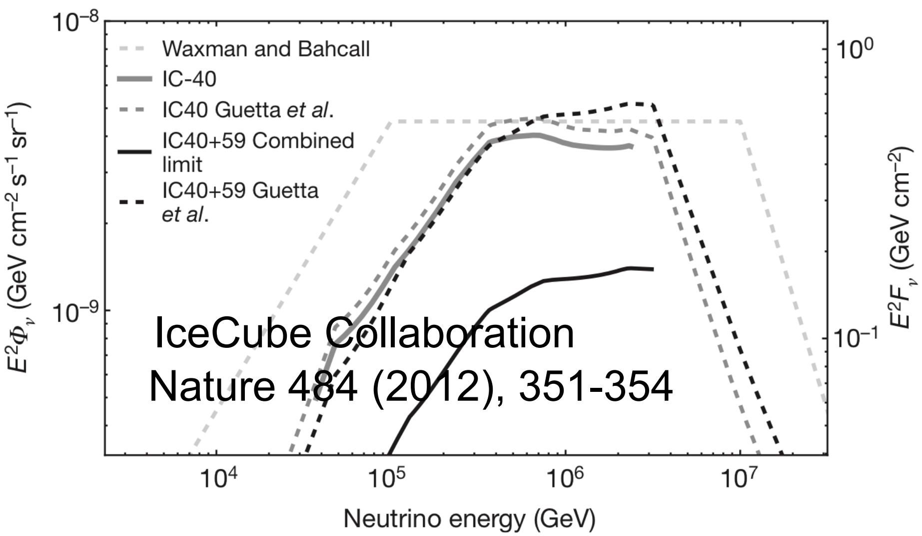




Gamma Ray Bursts

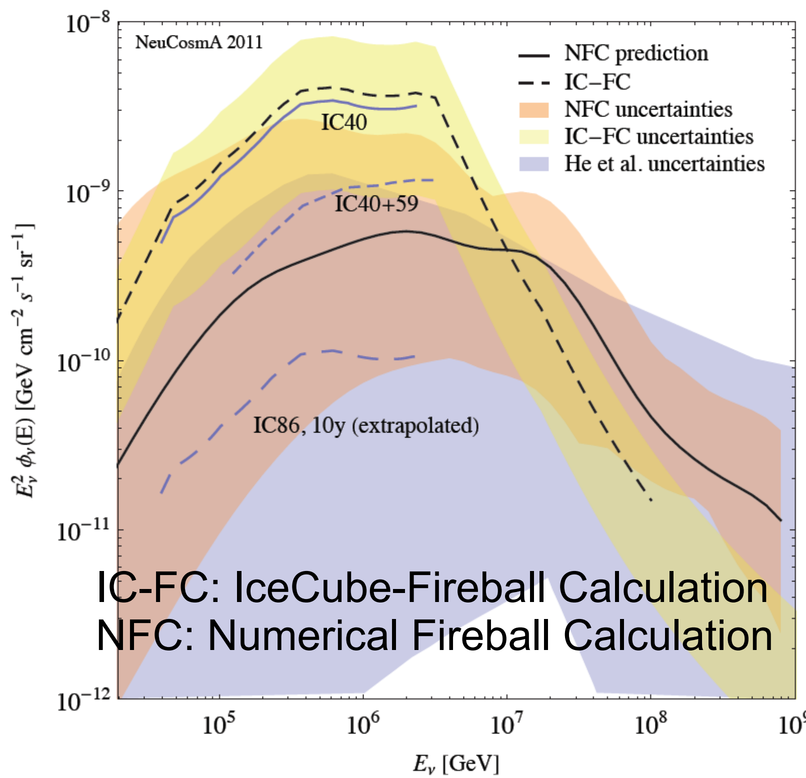
- Candidate sources for extra-galactic component: Gamma Ray Bursts





IceCube Collaboration
Nature 484 (2012), 351-354

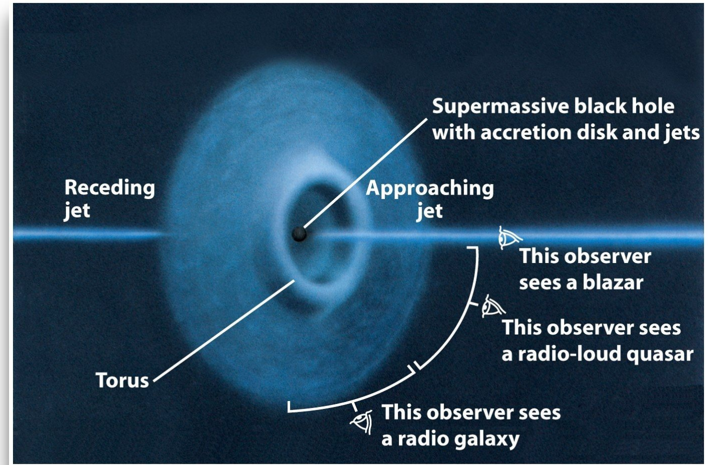
S. Hümmer, P. Baerwald, and W. Winter
Phys. Rev. Lett. 108, 231101 (2012)

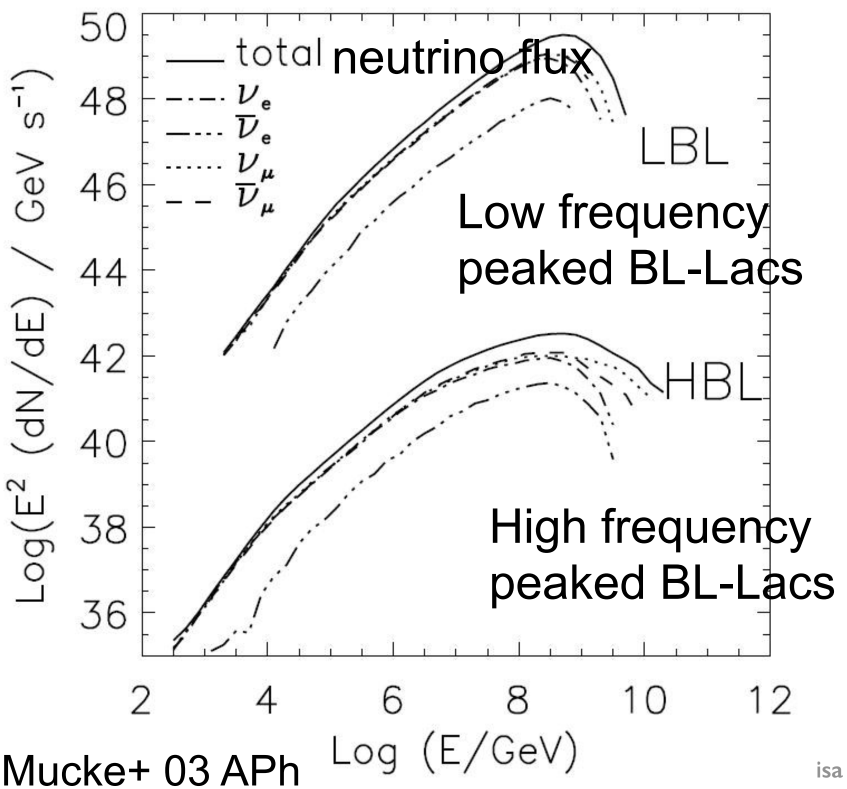


IC-FC: IceCube-Fireball Calculation
NFC: Numerical Fireball Calculation

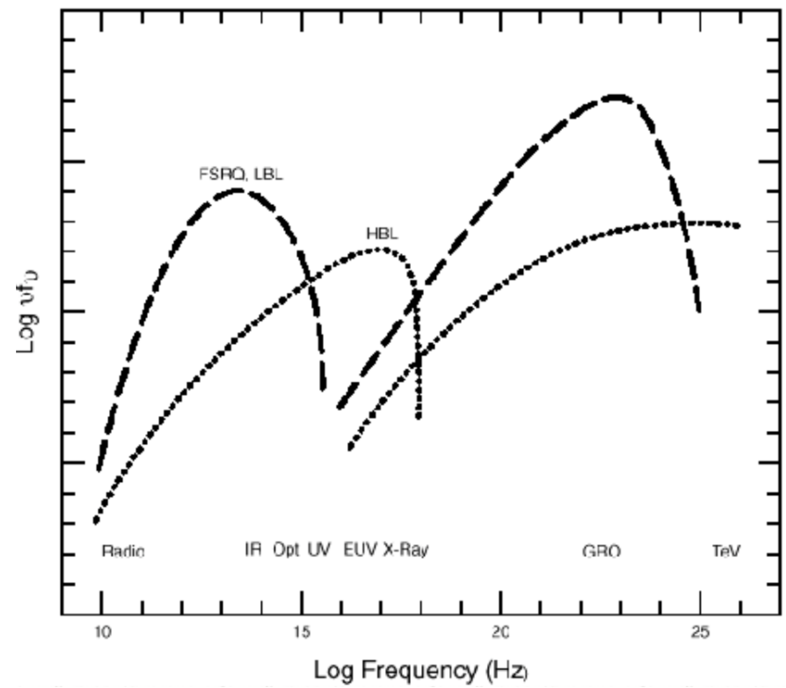
Active Galactic Nuclei

- Strong model dependence!
- Lower-peak blazars tend to have larger luminosities
- Lower-peak blazars → efficient ν (and γ) production (~ EeV neutrinos)

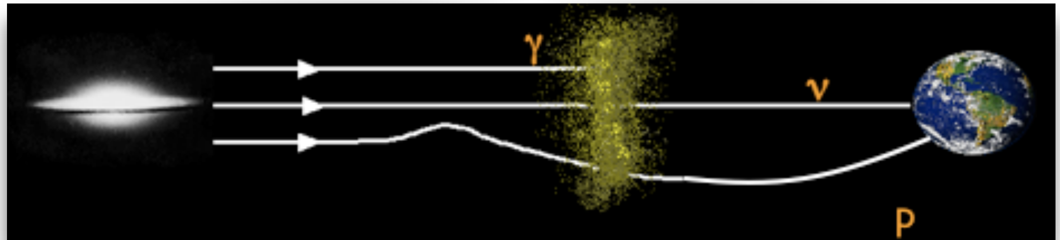


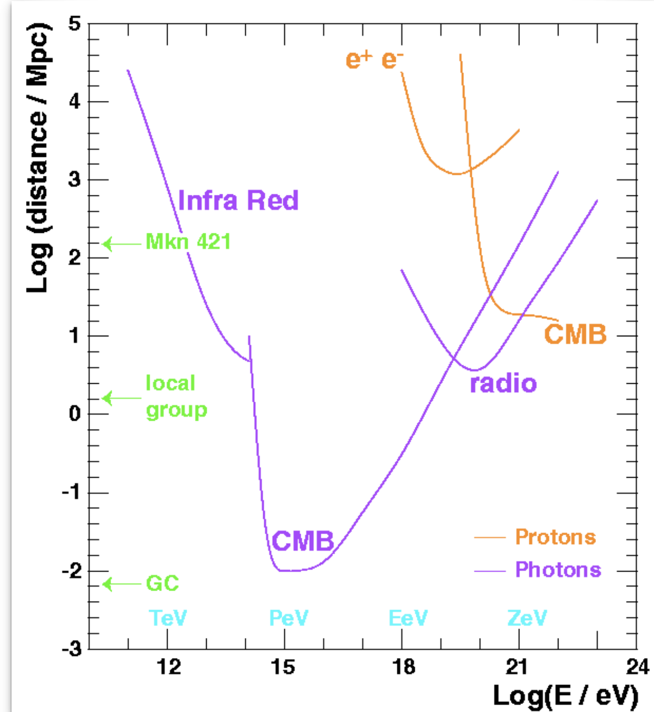


Mucke+ 03 APh



Rationale for neutrino astronomy



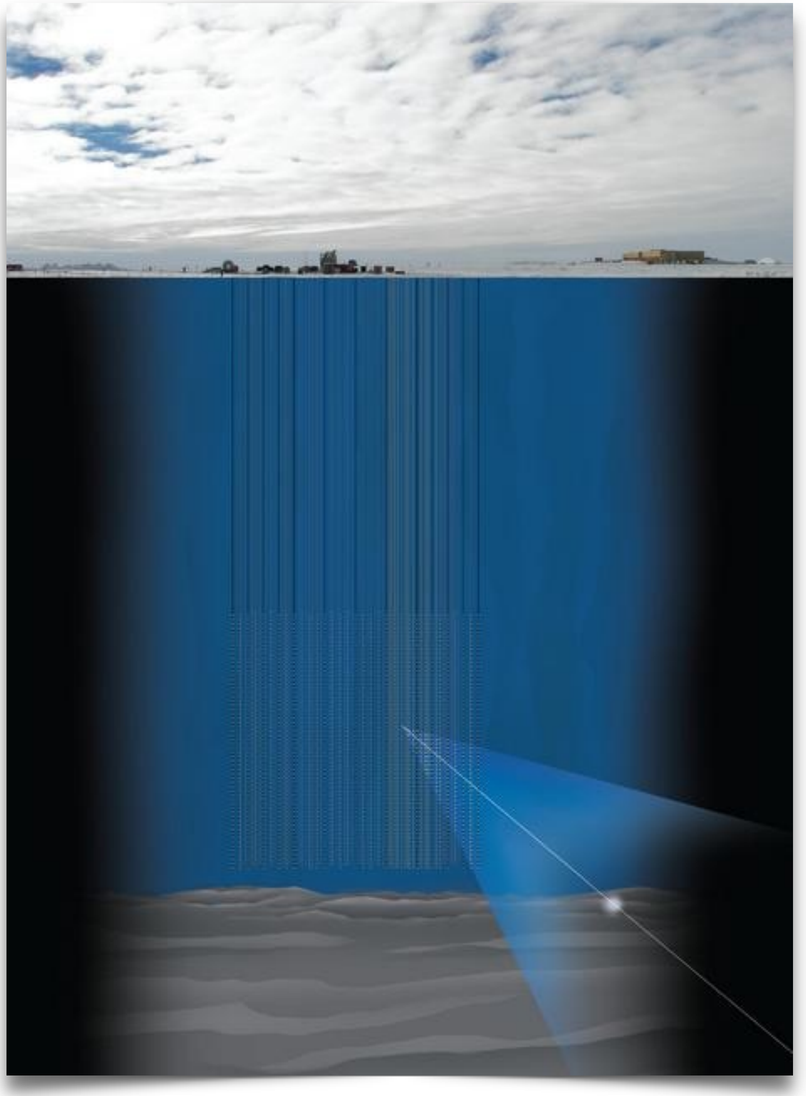


- Why neutrinos?
  - Mean free path of Very High Energy (VHE) photons is much less than the cosmological distance
  - Mean free path of VHE neutrinos is longer than cosmological distance
  - Neutrinos are the "smoking gun" for hadronic interactions

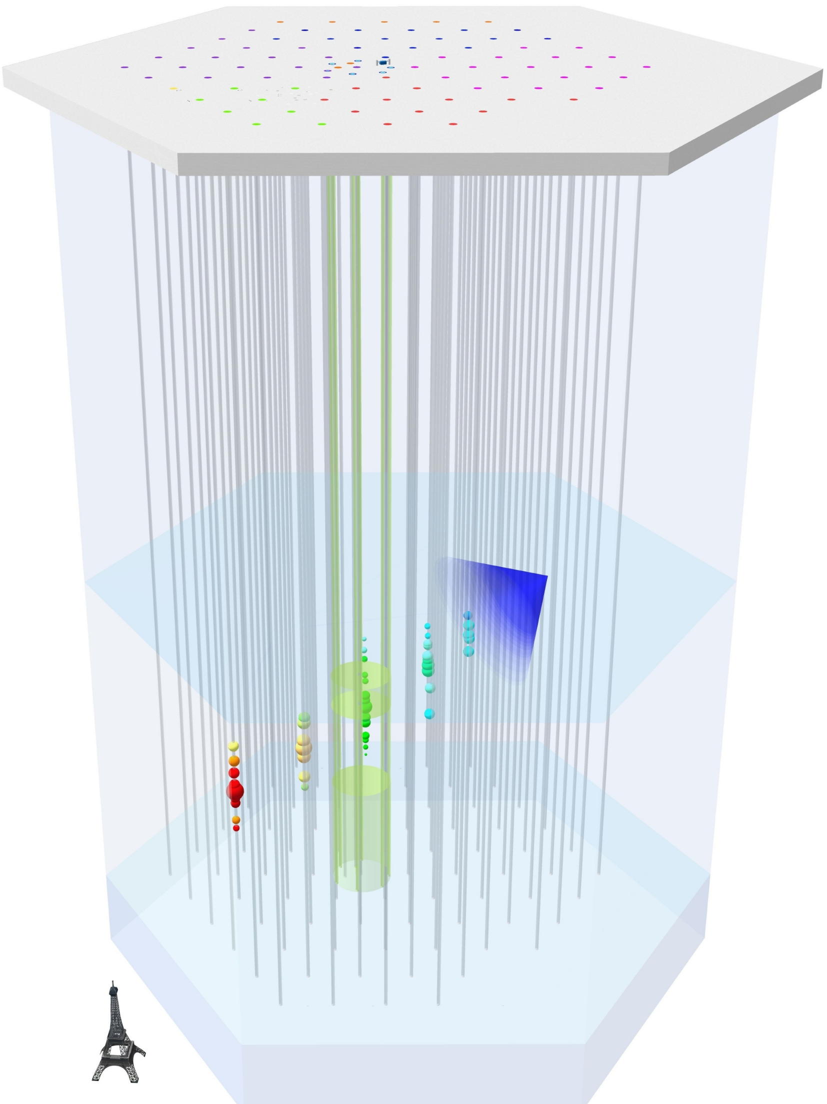
	process	cut-off	mean free
γ-rays	$\gamma+\gamma_{2.7°K}$	>100 TeV	10 Mpc
proton	$p+\gamma_{2.7°K}$	>50 EeV	50 Mpc
neutrinos	$\nu+\nu_{1.95°K}$	>40 ZeV	40 Gpc

Neutrino telescopes: the detection principle

- A neutrino interacts with prob. $O(10^{-11})$ with an ice/water nucleus
- A lepton and/or cascade is produced
- The arrival time of the Cherenkov photons is measured at a grid of PMTs
- Get information on incoming particles':
  - direction
  - energy
- The background from non-Cherenkov photons is low
- Stable operating conditions:
  - full-time operation
  - full-sky detector (energy dependent)

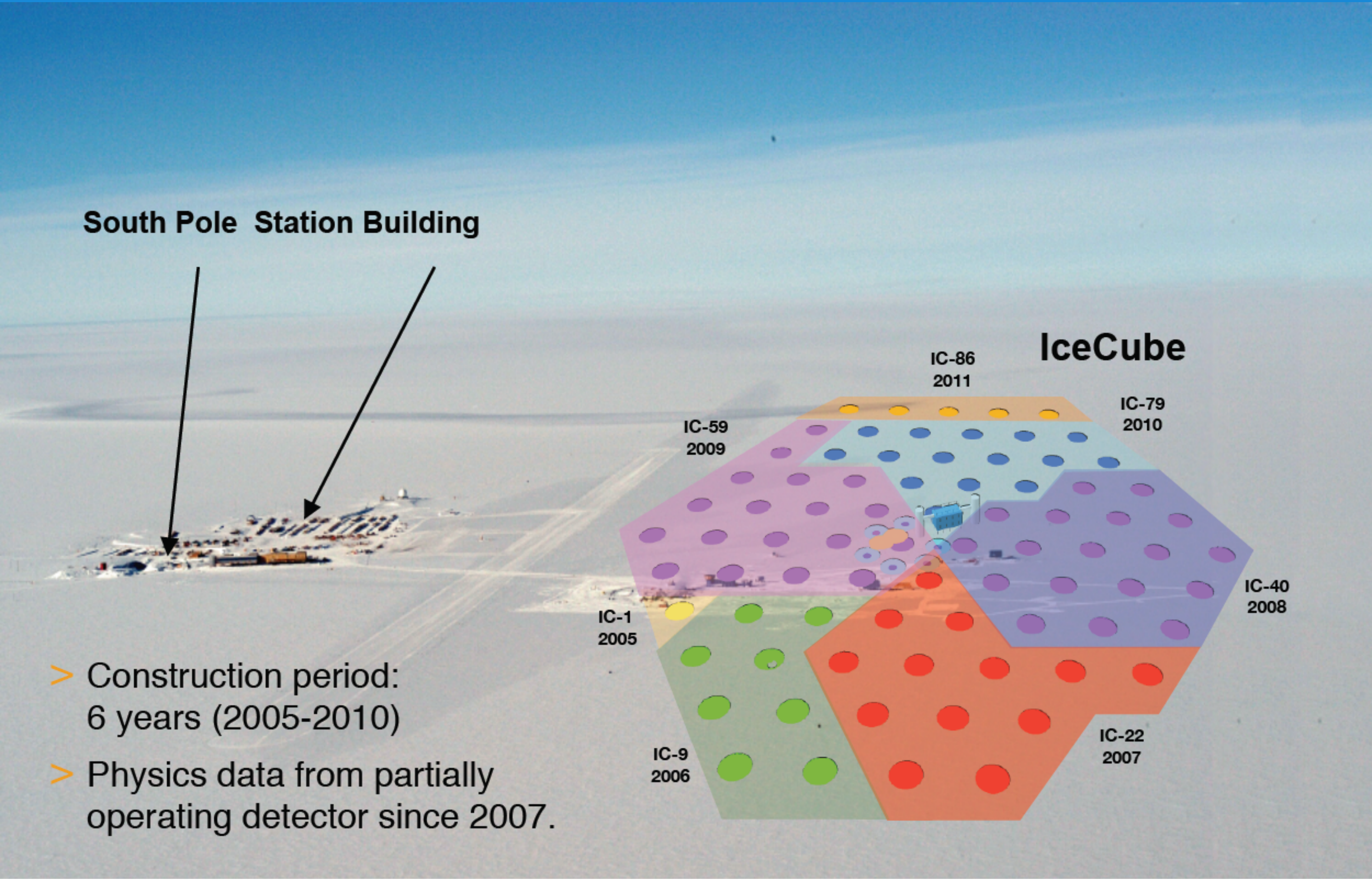


IceCube Observatory



- 5160 sensors on 86 strings
- Higher density DeepCore
- 1 km^3 sensitive volume
- ~98% of all sensors working after deployment
- Failure rate <0.1% per year
- ~99% data taking efficiency

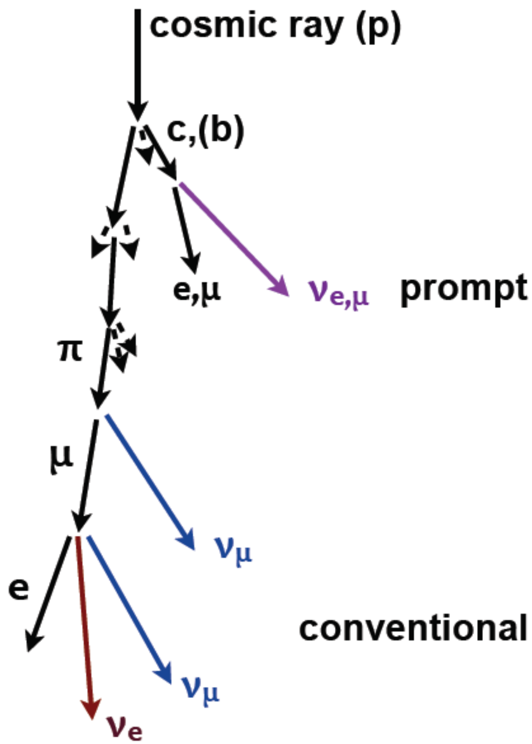
IceCube construction

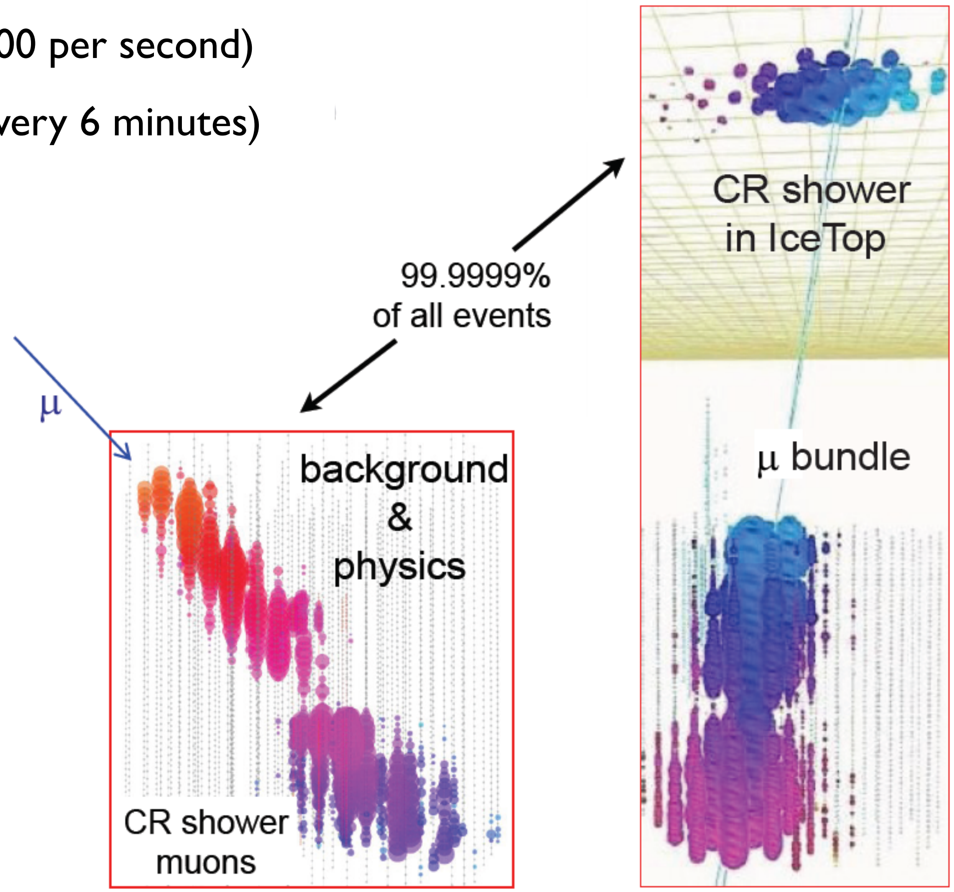


- Construction period: 6 years (2005-2010)
- Physics data from partially operating detector since 2007.

Signal and background

- Expected signals are weak and mimicked by irreducible backgrounds
- Event rates in IceCube (year^{-1}):
  - atmospheric muons 7 x 10^{10} (2000 per second)
  - atmospheric neutrinos 5 x 10^4 (1 every 6 minutes)
  - astrophysical O(10)

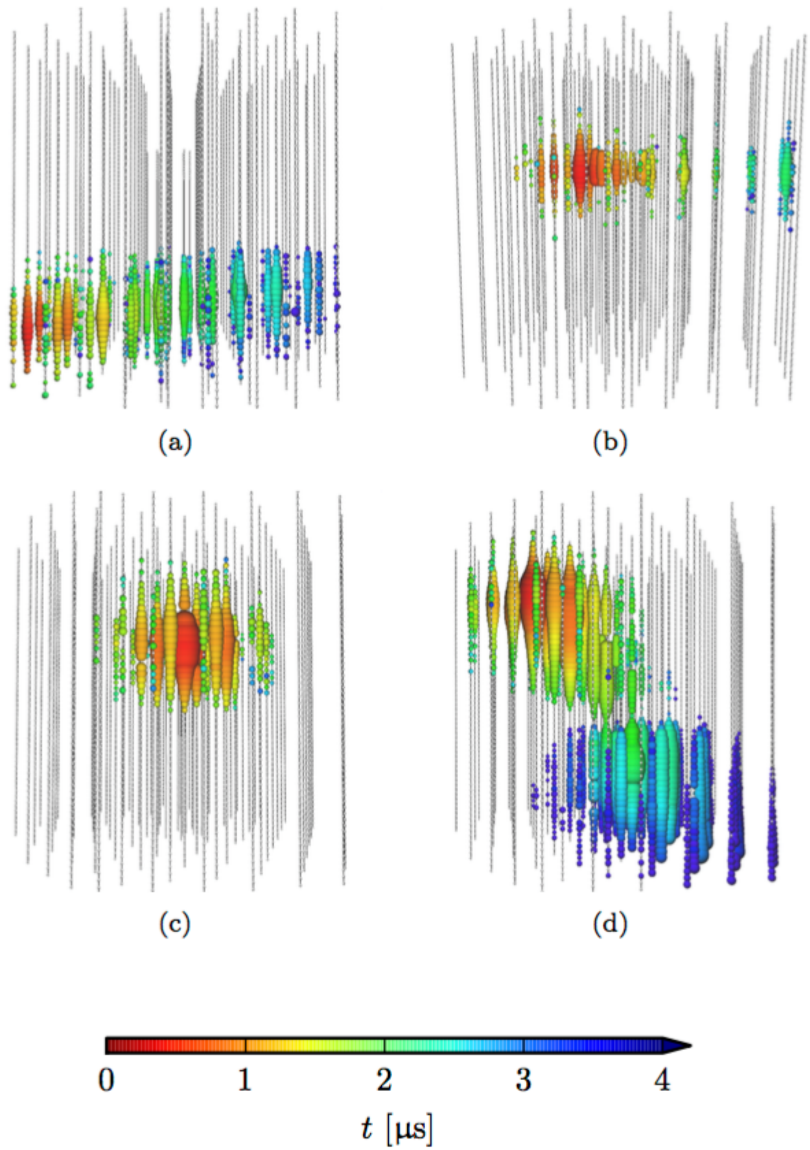




Neutrino signatures

Through-going track (ν_μ)
angular resolution $< 1^o$
only dE/dx

Starting track (ν_μ)
angular resolution $< 1^o$
dE/dx + energy & position at vertex

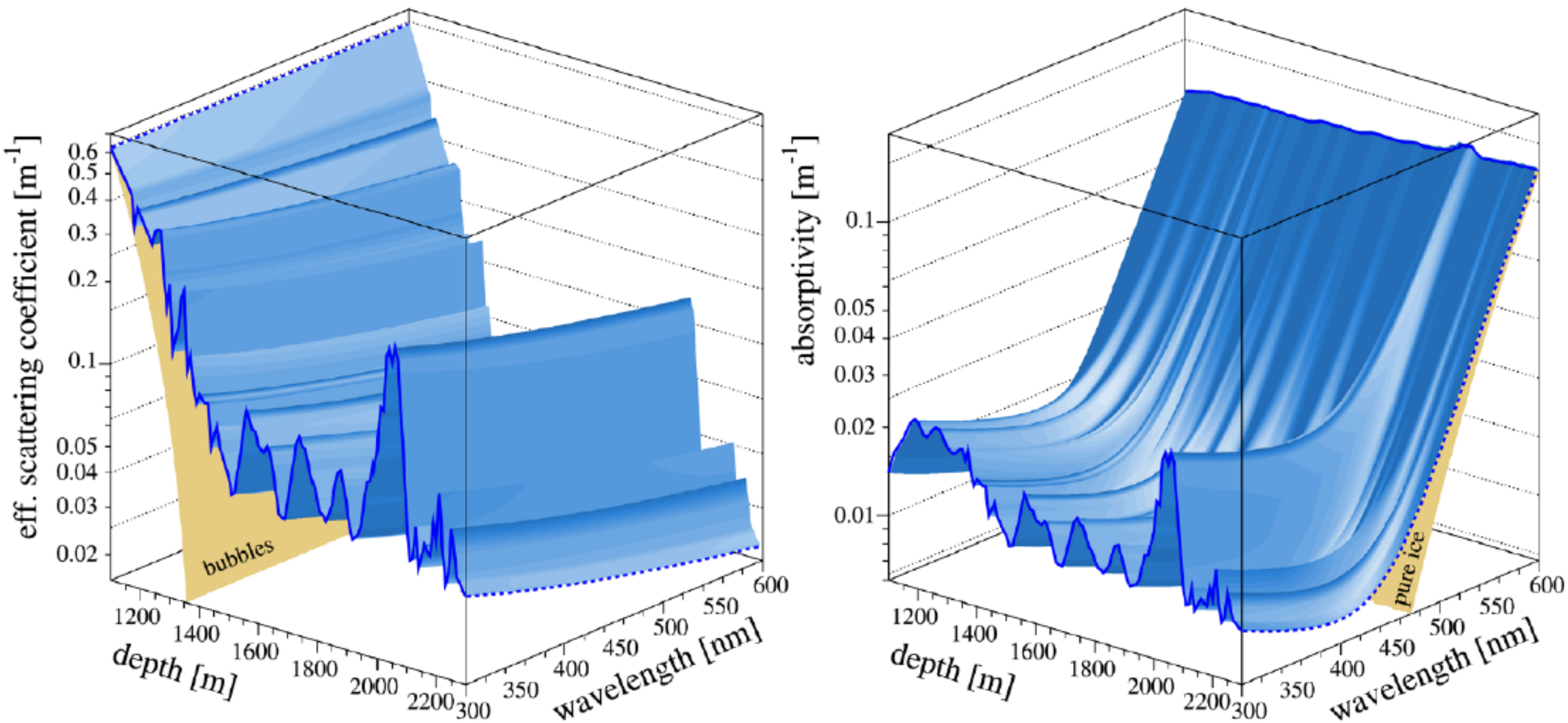


Cascade (ν_e, ν_μ, ν_τ)
angular resolution $> 10^o$
energy resolution ~ 15%

Double-Bang (ν_τ)
E > *O*(PeV)
not observed yet!

Picture: Lars Mohrmann (2015)

Ice optical properties



Neutrino fluxes

- Expected signals are weak and mimicked by irreducible backgrounds
- Event rates in IceCube ($year^{-1}$):
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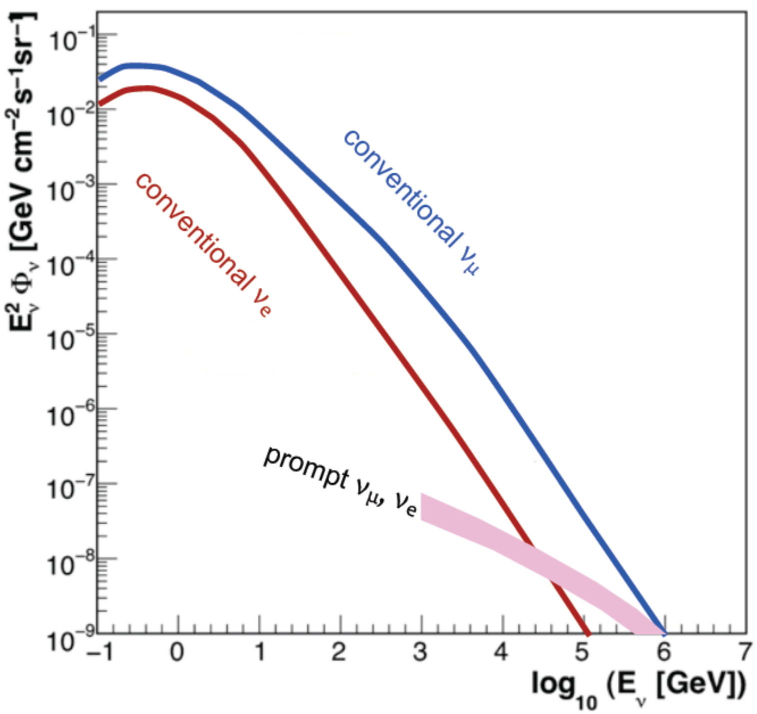
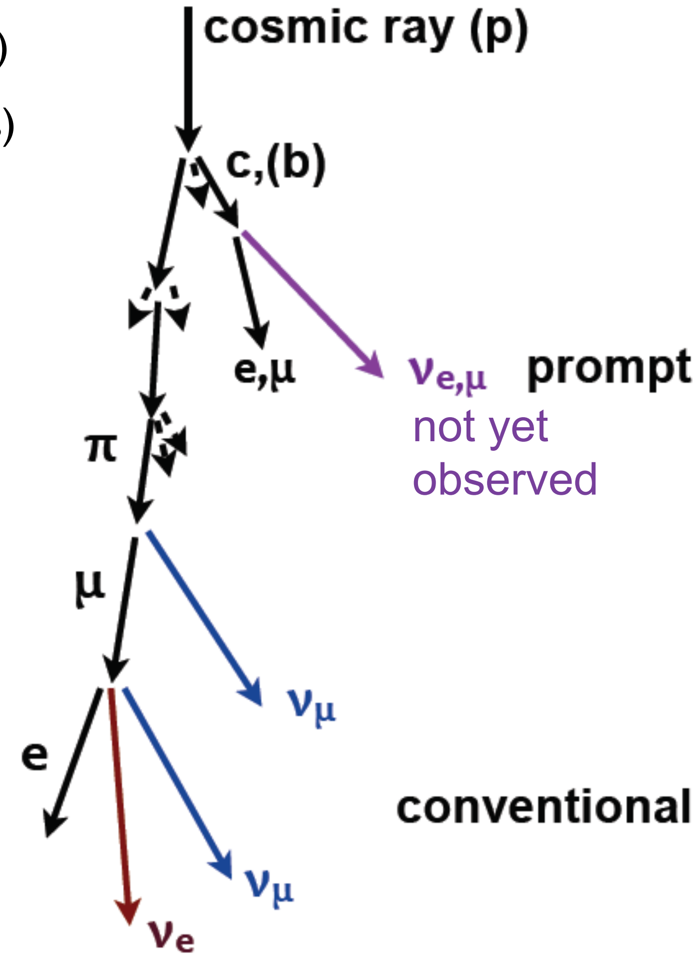
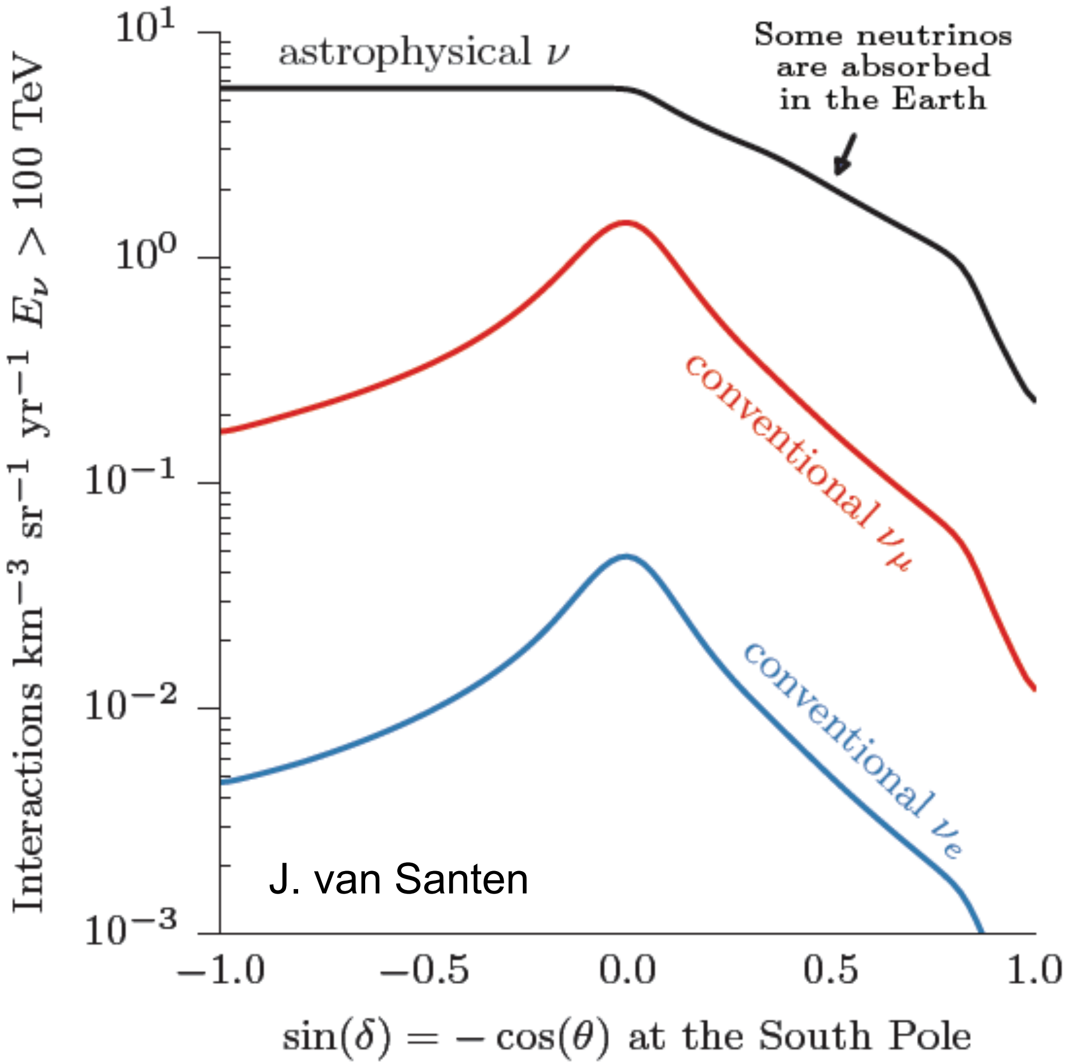
  - atmospheric neutrinos 5×10^4 (1 every 6 minutes)
  - astrophysical *O*(10)



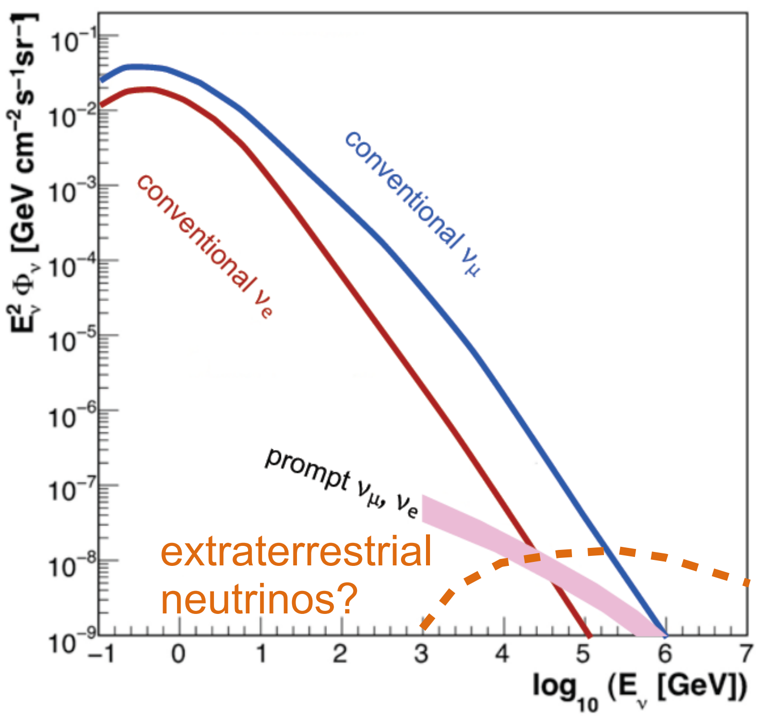


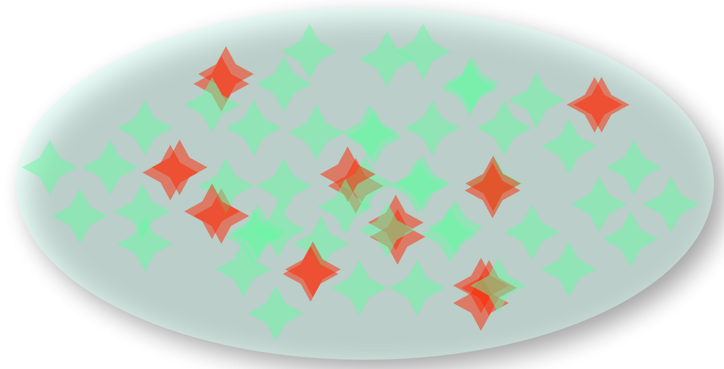
Atmospheric versus astrophysical neutrinos



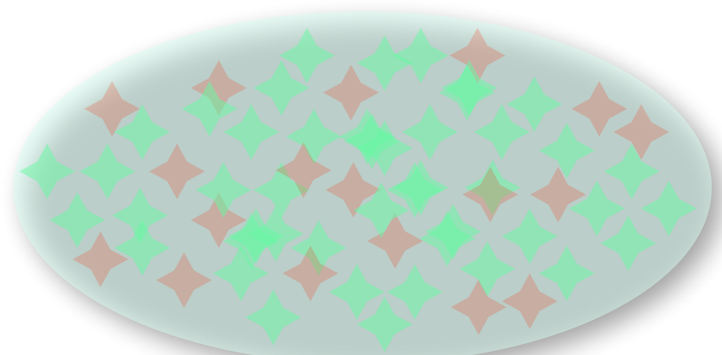
Searching for cosmic neutrinos

- The signal is expected to exhibit a differed spectrum
- Search for deviations from background
  - in energy (diffuse-like searches)
  - in energy and direction (look for individual sources)



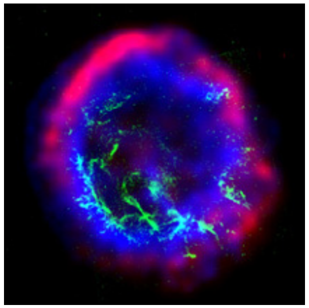


Individual sources: search for excesses from few strong objects. Localised (in space and/or time)

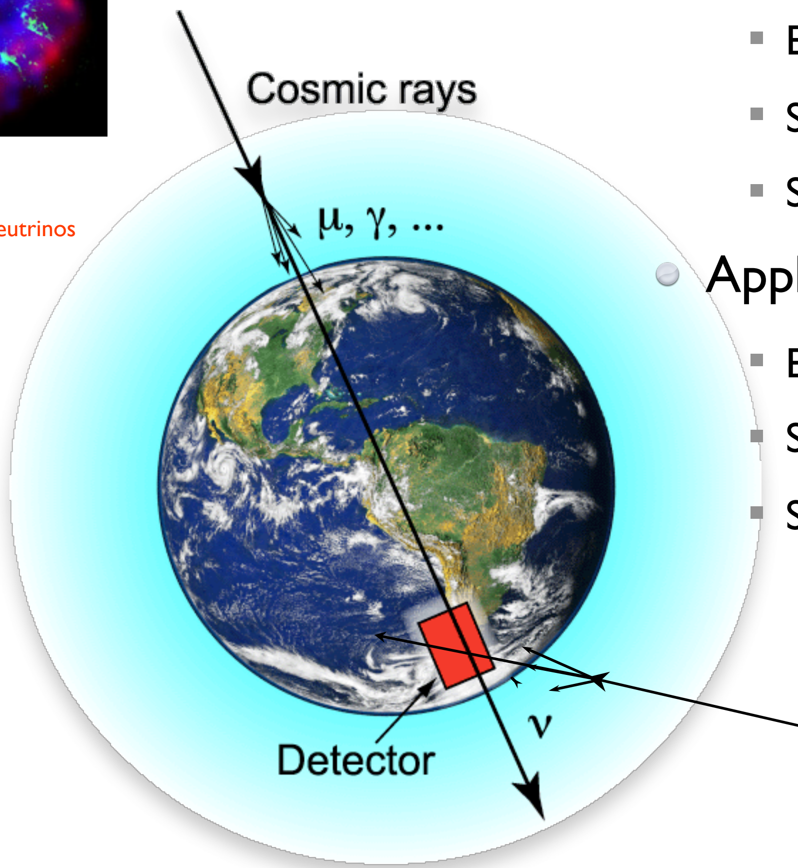


Diffuse searches: search for an overall excess from an ensemble of many weak sources. Deviation in energy spectrum

Isolating neutrino events: through-going muons



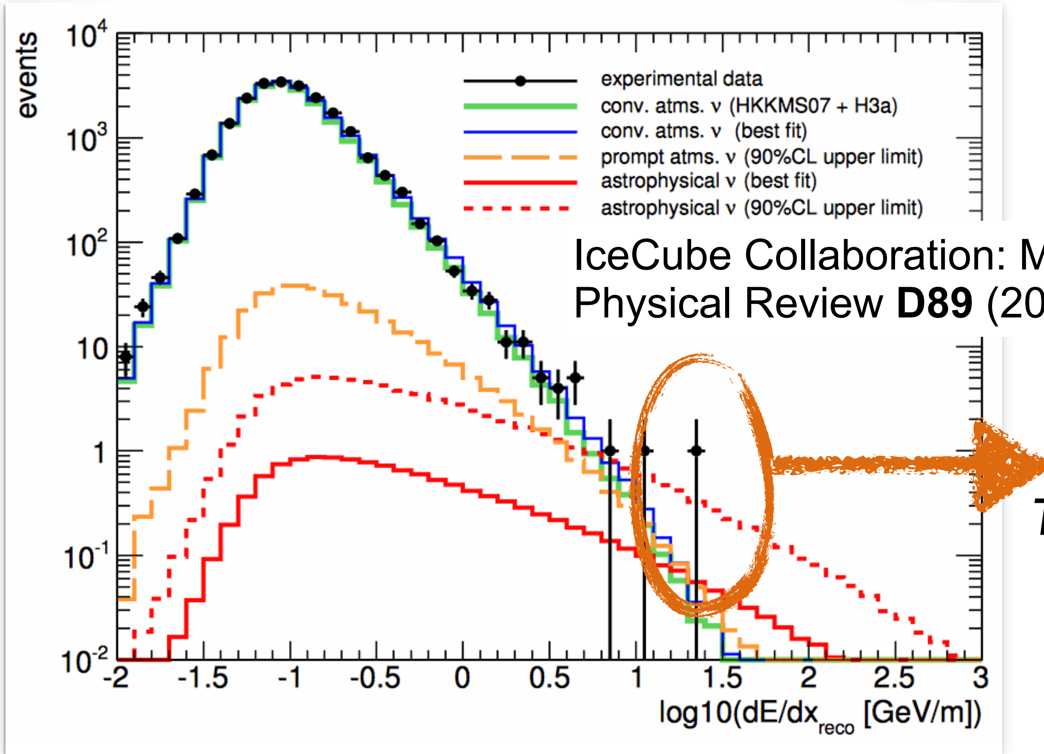
Cosmic neutrinos



- Earth stops penetrating muons
  - Effective volume larger than detector
  - E > O(100 GeV)
  - Sensitive to ν_μ only
  - Sensitive to "half" the sky (the North)
- Apply strong energy cuts
  - E>O(PeV)
  - Sensitive to ν_μ only
  - Sensitive to the South (mostly at horizon)

Diffuse searches with up-going muons

- Energy density of extragalactic CR ~10^{44} erg/yr/Mpc^3
- Compare to extragalactic diffuse background light [E.Waxman and J.Bahcall, Phys. Rev. D 59, 023002 (1999), K. Mannheim, R.J. Protheroe, J.P. Rachen , Phys.Rev. D63 (2001) 023003, E. Waxman (2011)]



IceCube Collaboration: M. G. Aartsen et al Physical Review **D89** (2014) 062007

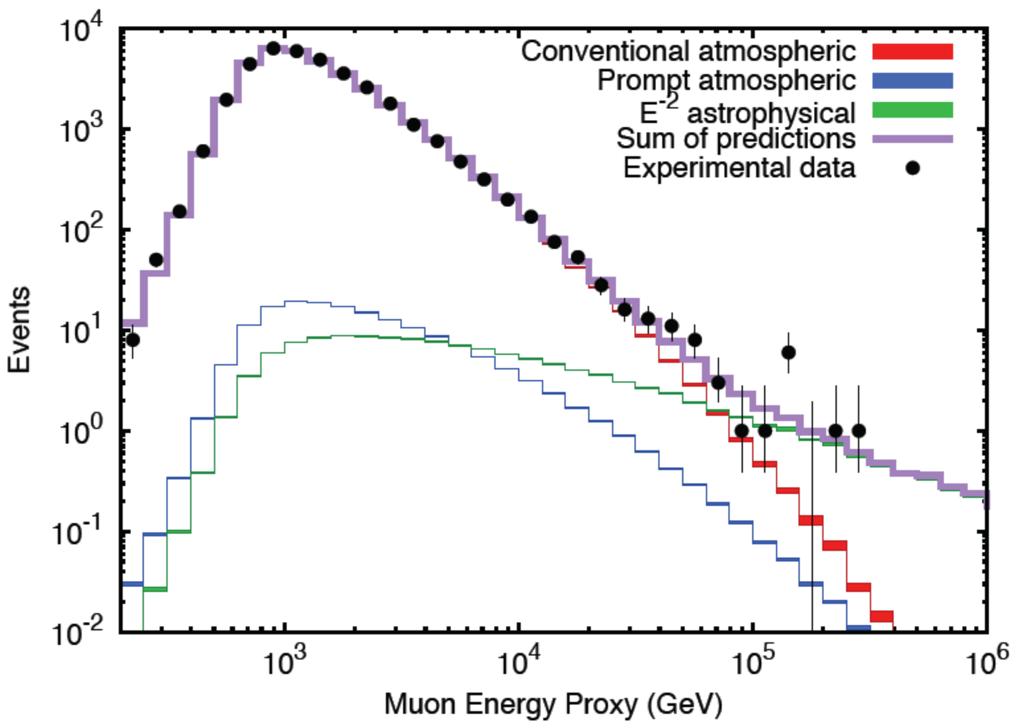
One excess muon E ~ 200 TeV significance 1.8 σ

The best fit yields an astrophysical signal flux of $E^2 \cdot \Phi(E) = 0.25 \cdot 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Diffuse searches with up-going muons

- Significant astrophysical neutrino flux ν_μ-based and northern sky-dominated
- Significance at 3.7σ
- Best fit has spectral index 2.2
- Normalization for E^{-2}: $0.99^{+0.4}_{-0.3}$ 10^{-8} E^{-2} GeV cm^{-2} s^{-1} sr^{-1}

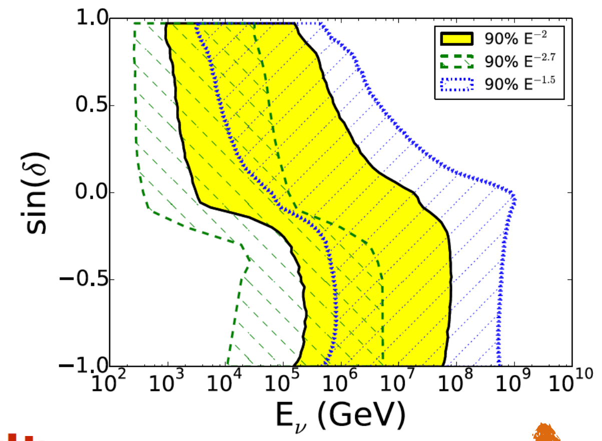
accepted by PRL,
arXiv:1507.04005



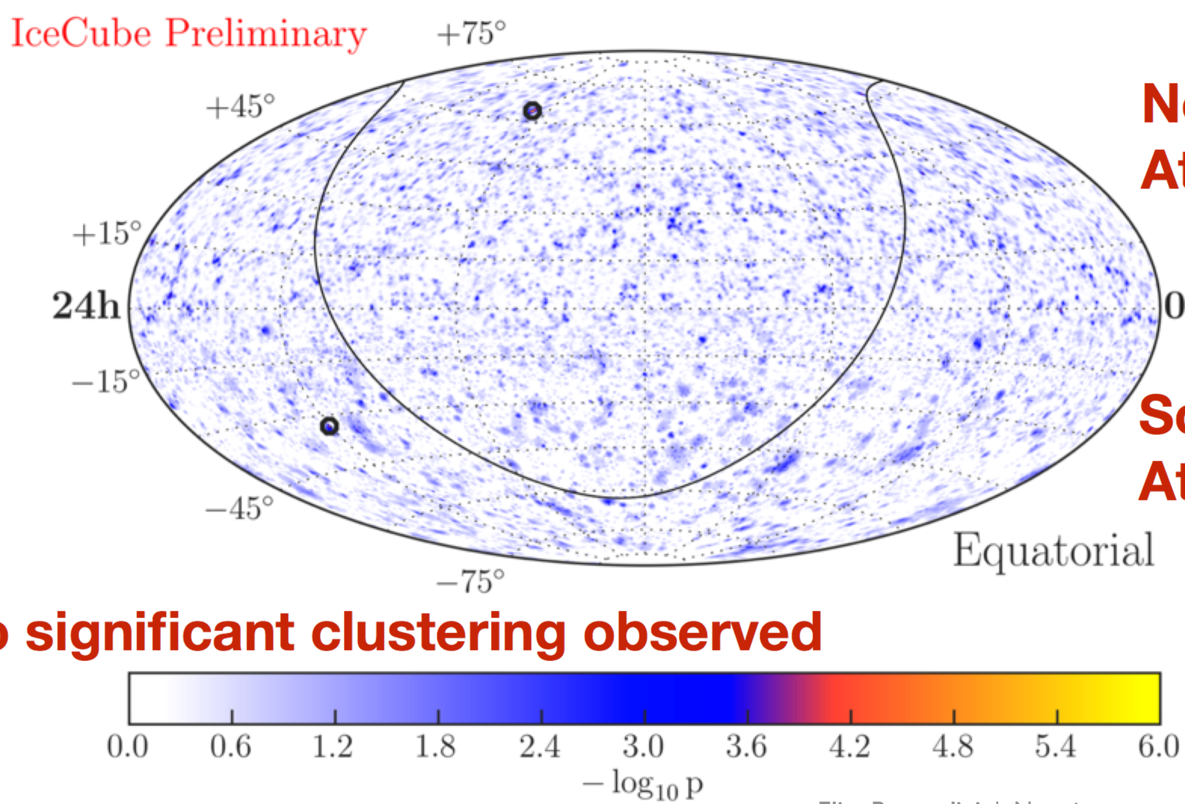
Are there individual sources?

- IceCube 6-year though-going muon point source search
- Northern-sky muons: 35% chance probability
- > PeV southern-sky muons: 87%

The Astrophys. J., 779 (2013)



the 90% central signal containment region for three different power law neutrino spectra



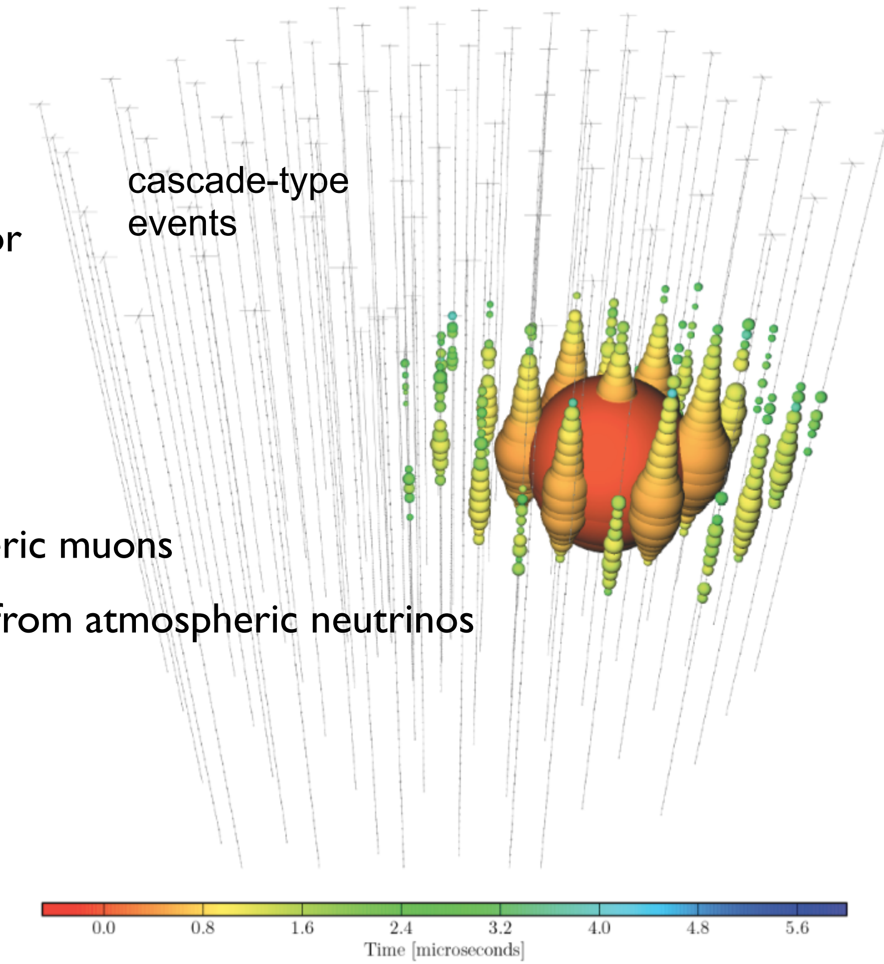
North Atm. ν

South Atm. μ

No significant clustering observed

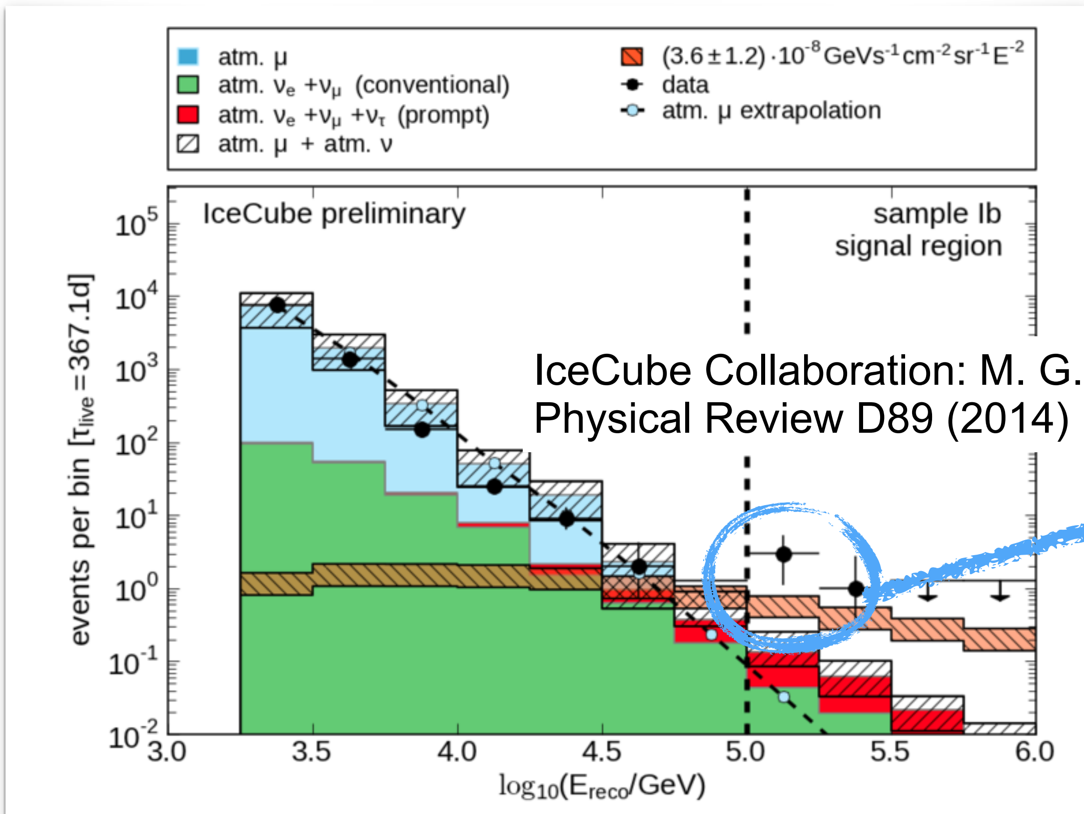
Isolating neutrino events: showers

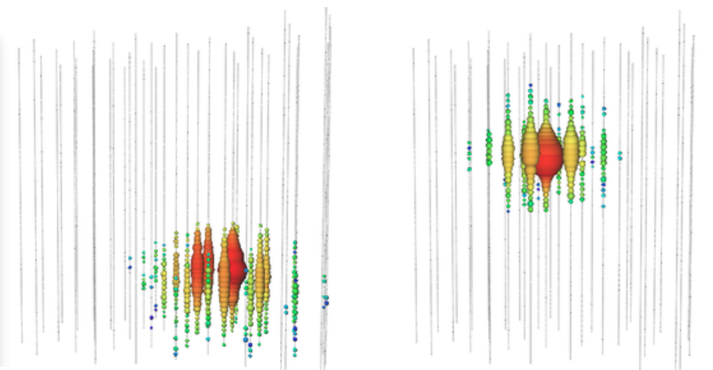
- Looking for cascades
- Earth stops penetrating muons
  - Effective volume smaller than detector
  - E > O(30 TeV)
  - Sensitive to all flavours (more signal!)
  - Sensitive to full sky
  - no direct background from atmospheric muons
  - order of magnitude less background from atmospheric neutrinos



IceCube results: diffuse searches with showers

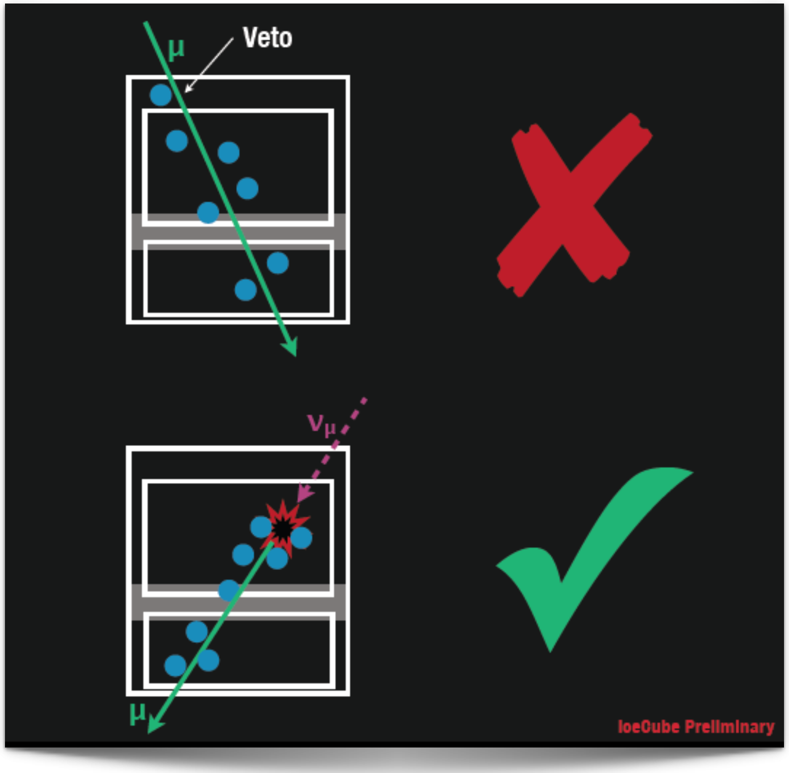
- 3 (+1 in control sample) cascades found > 100 TeV, muon background $0.04^{+0.06}_{-0.02}$, atmospheric neutrino background 0.21, significance 2.7 σ

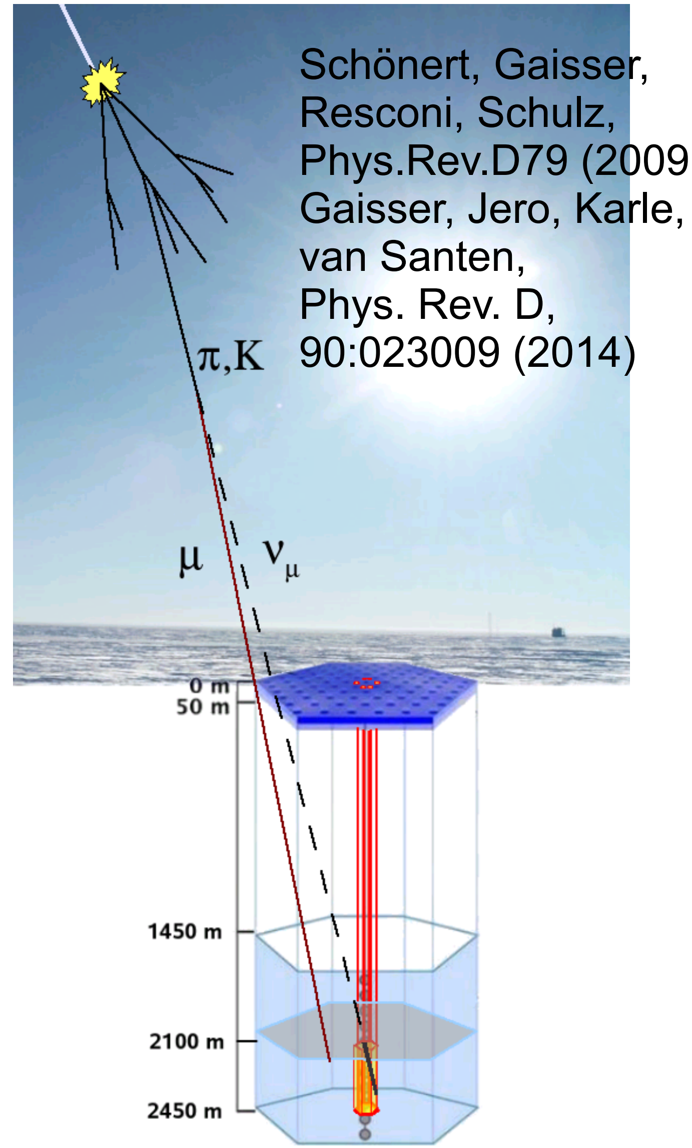




IceCube Collaboration: M. G. Aartsen et al
Physical Review D89 (2014) 102001

How to veto down-going atmospheric neutrinos

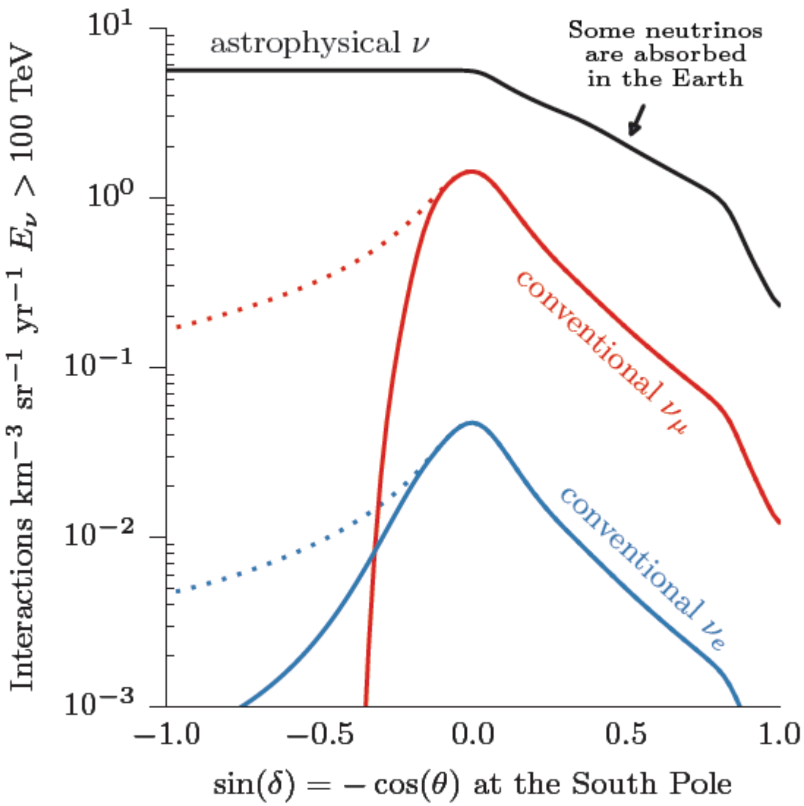


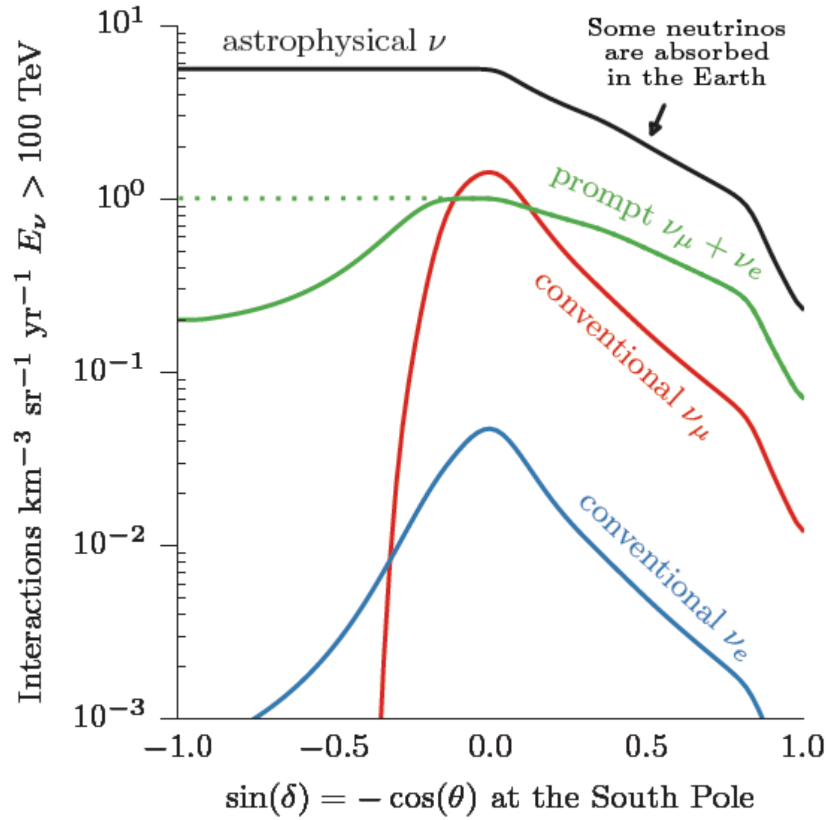


- Atmospheric neutrinos will, in general, be accompanied by muons produced in the same parent air shower
- Golden channel: "down-going starting events"

Vetoing atmospheric neutrinos

- The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different

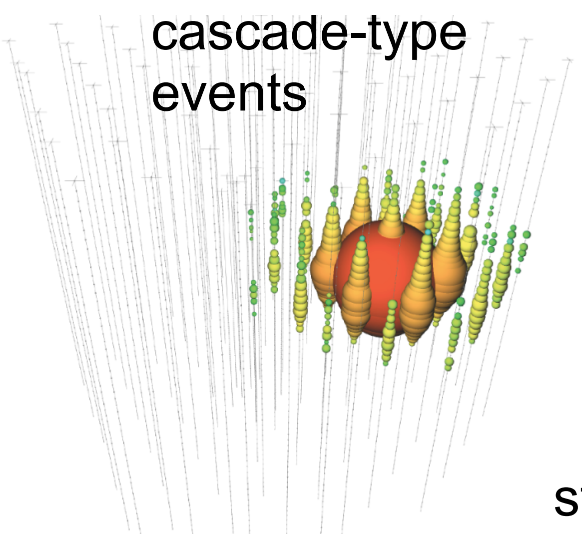


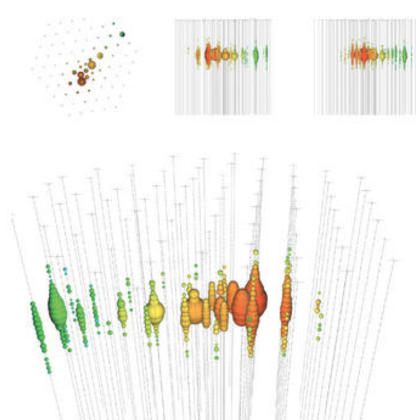


Pictures: J. van Santen

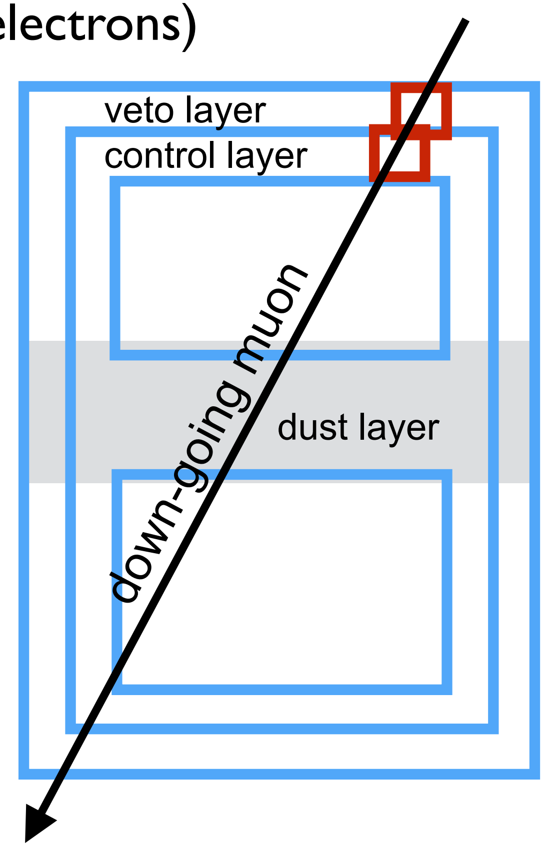
The breakthrough

- Search for well reconstructed contained and semi-contained events
- Veto atmospheric muons and neutrinos
- Use data to measure muon background (inner veto layer)
- Only study very high energies (> 4000 photo-electrons)
- Energy threshold: ~ 30 TeV



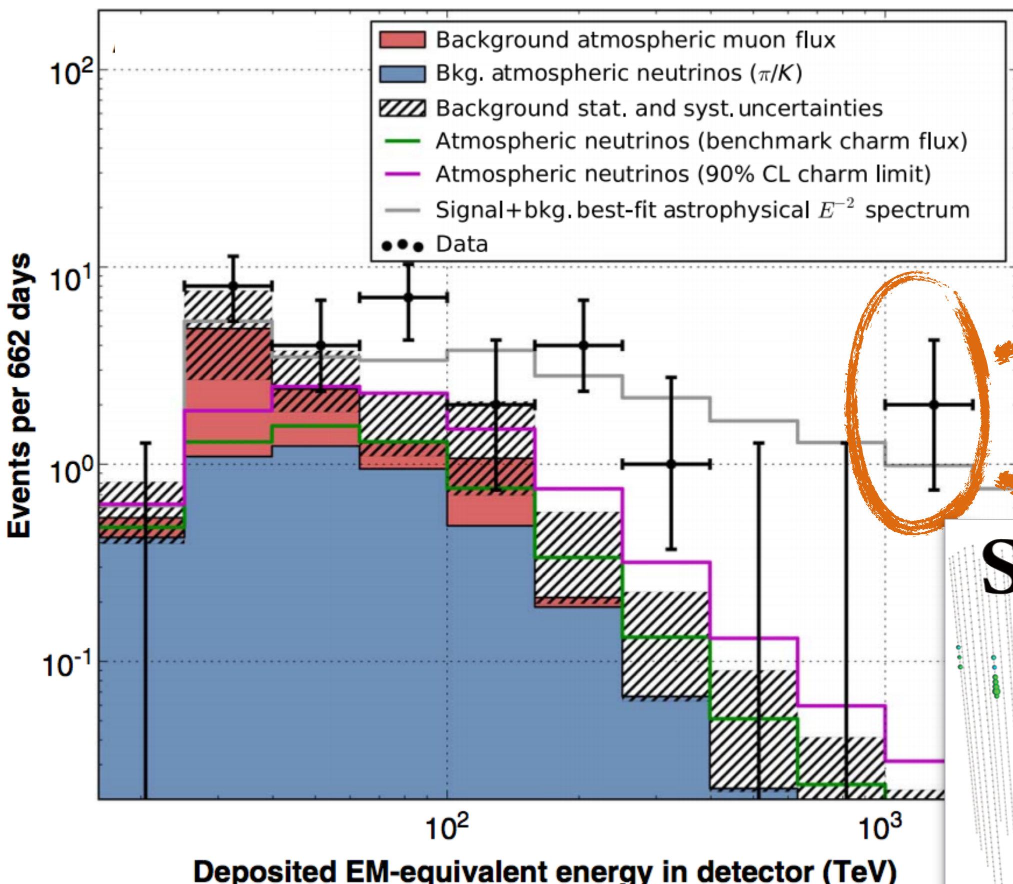


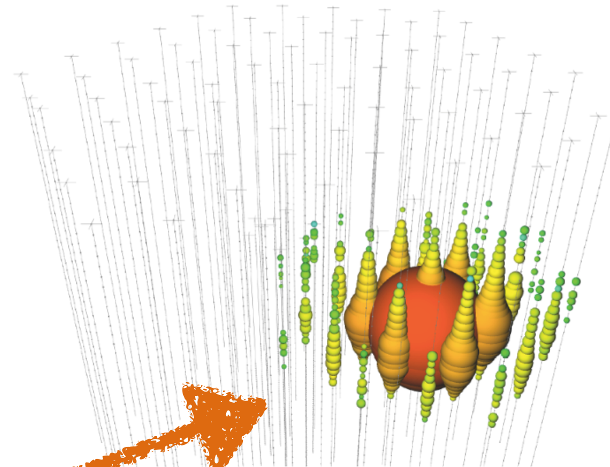
starting tracks



First clear evidence for extraterrestrial neutrinos

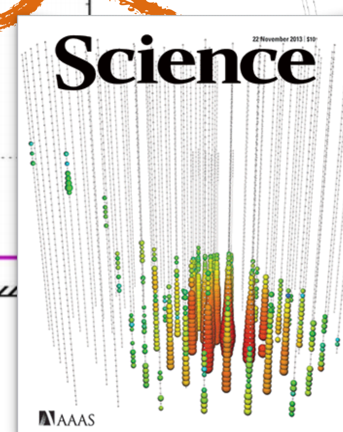
- 28 events found above 30 TeV, muon background 6.(
  neutrino background $4.6^{+3.7}_{-1.2}$, significance 4.1 σ

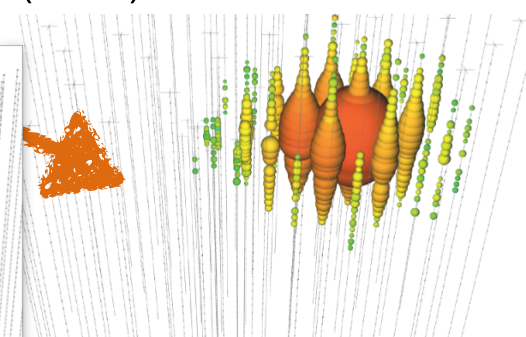




1.1 ± 0.17 PeV

IceCube Collaboration: M. G. Aartsen et al
Science 342 (2013) 1242856

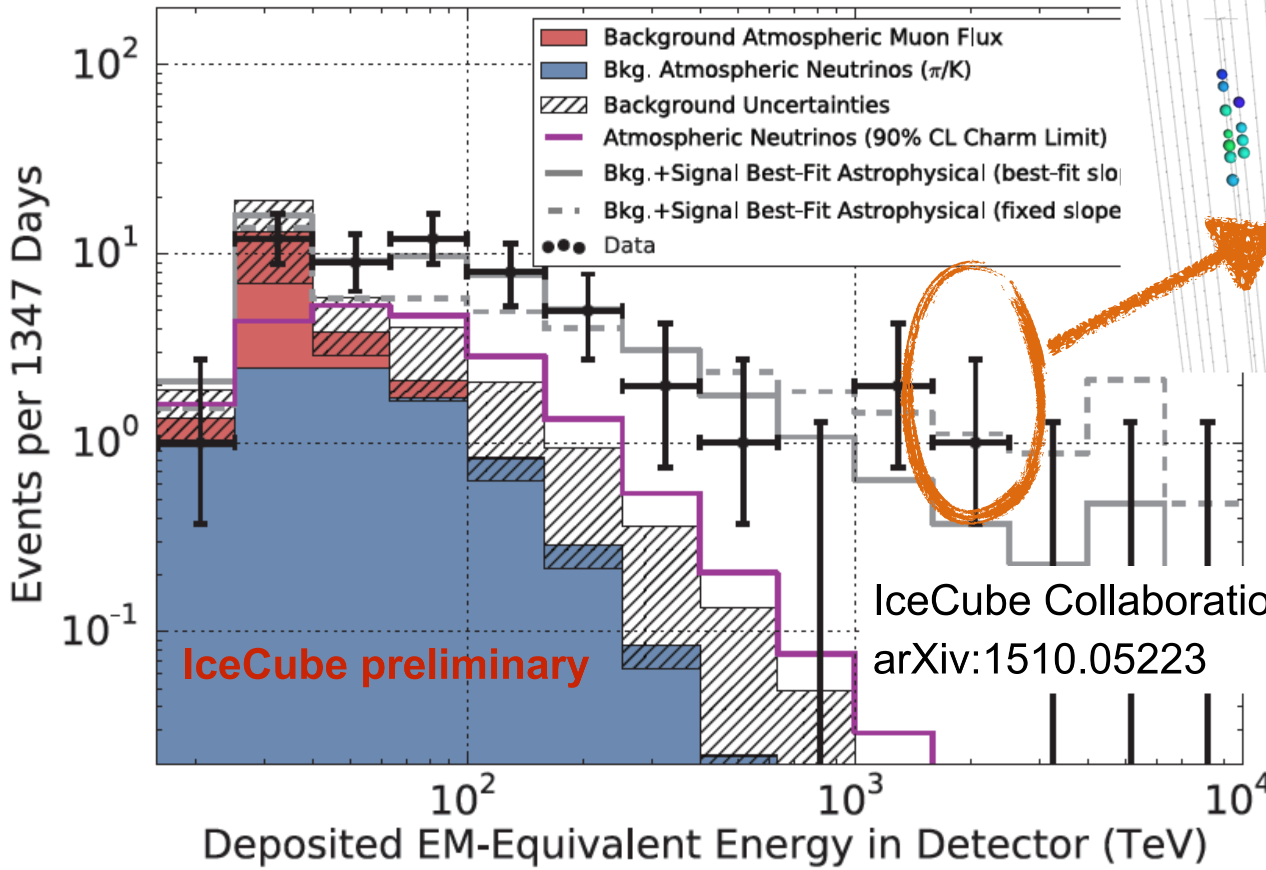


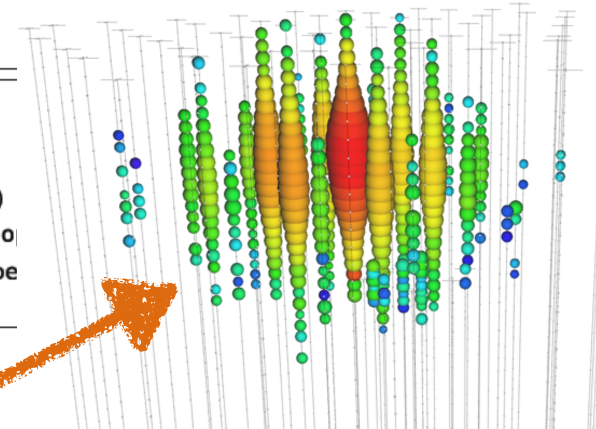


1.0 ± 0.15 PeV

Four years of (full) IceCube data

- 54 events found, muon background $12.6^{+5.1}_{-5.1}$, atmospheric neutrino background $9.0^{+8.0}_{-1=2.2}$
- 39 cascades, 13 tracks, 2 likely background

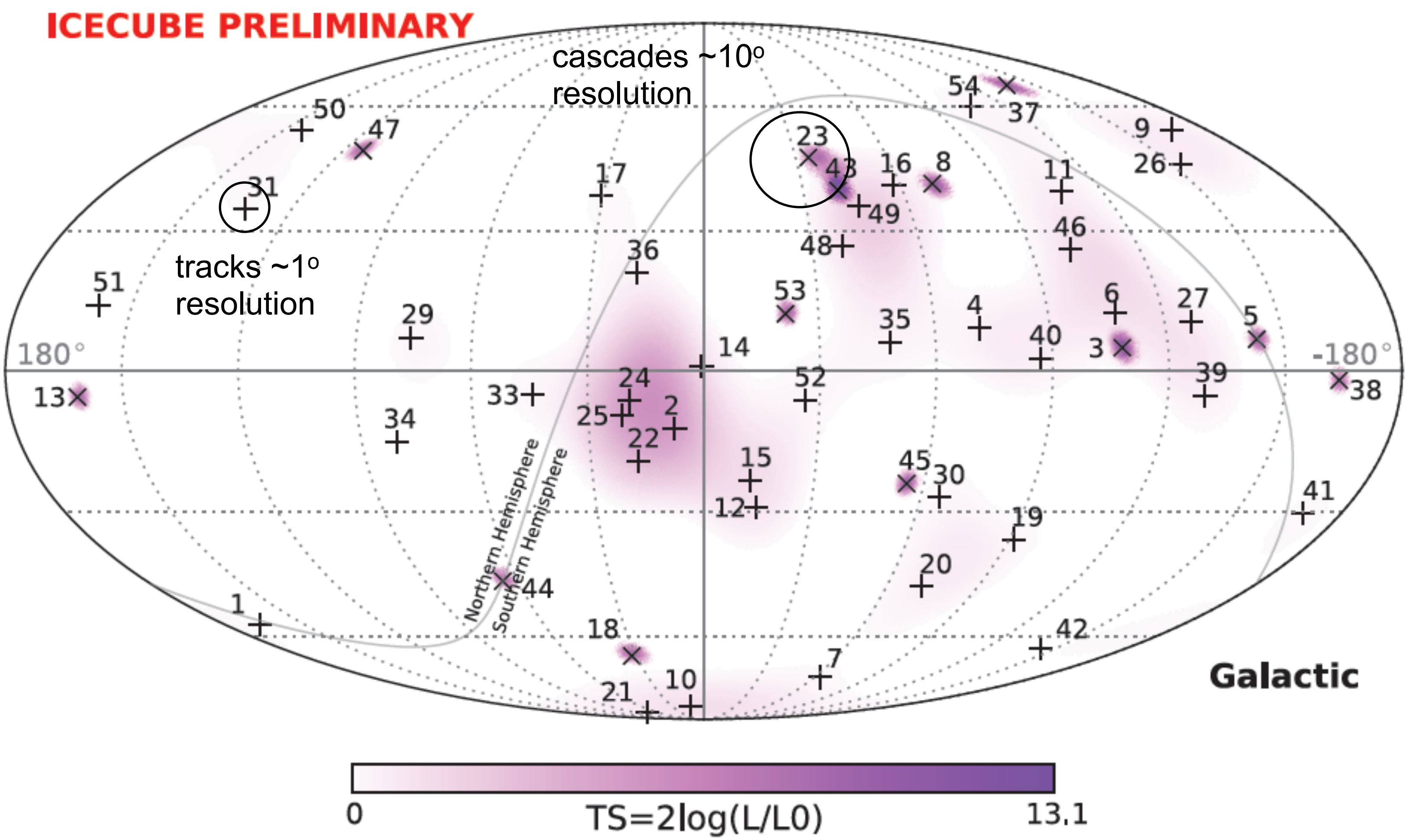




$2.0^{+0.26}_{-0.24}$ PeV

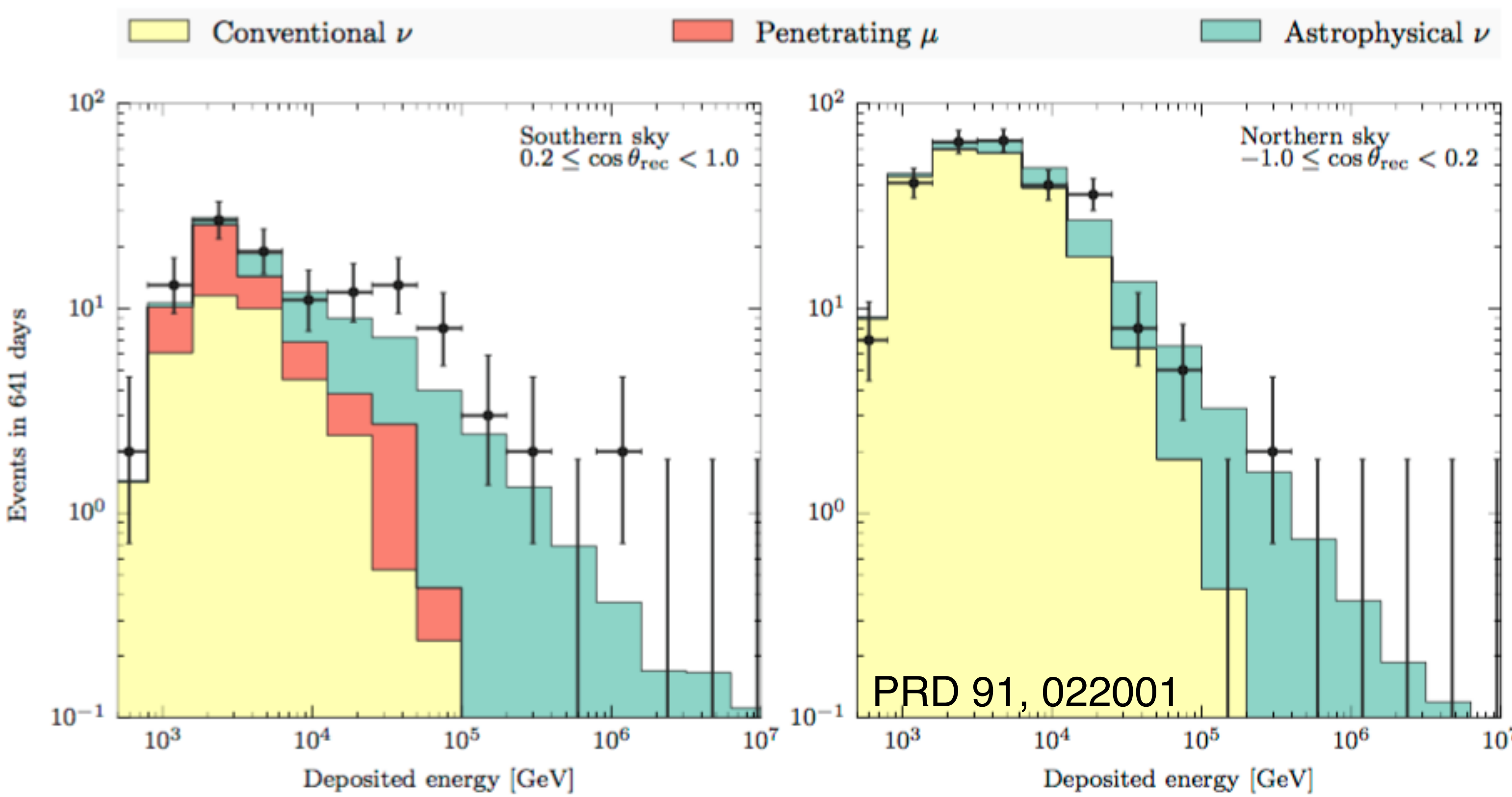
IceCube Collaboration: M. G. Aartsen et al arXiv:1510.05223

Extragalatic origin of cosmic neutrinos?



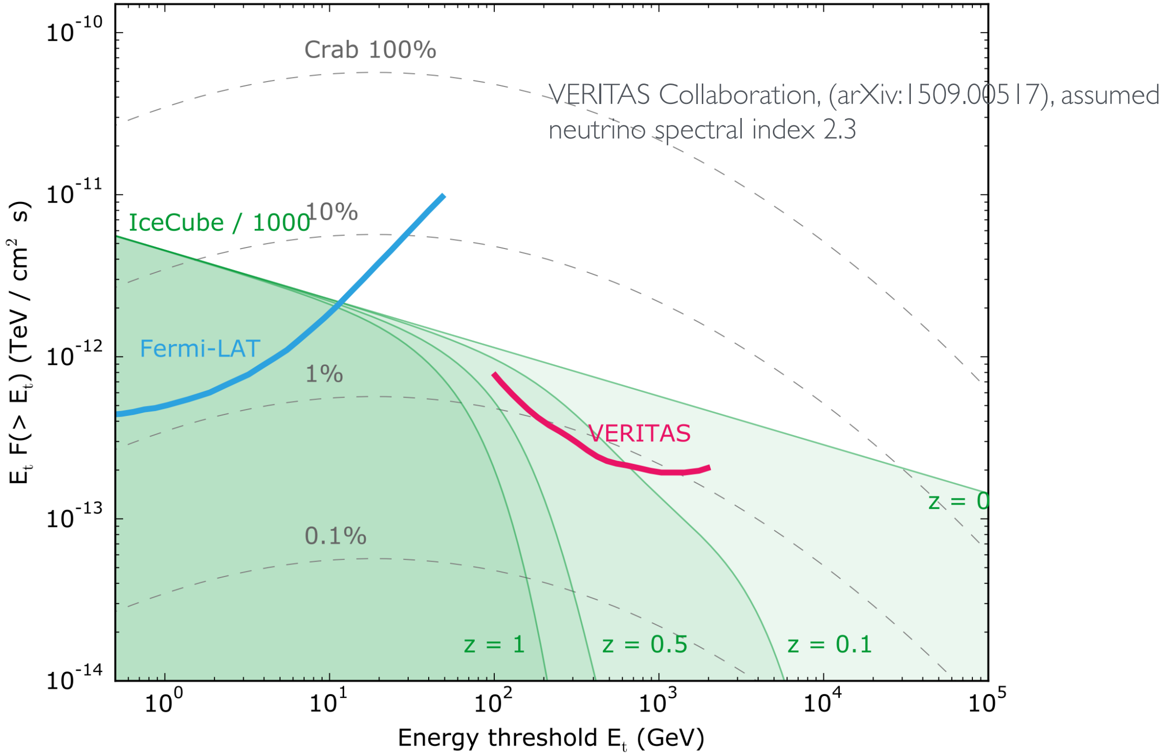
Lowering the energy threshold

- Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance
- Best fit spectral index: 2.46 ± 0.12



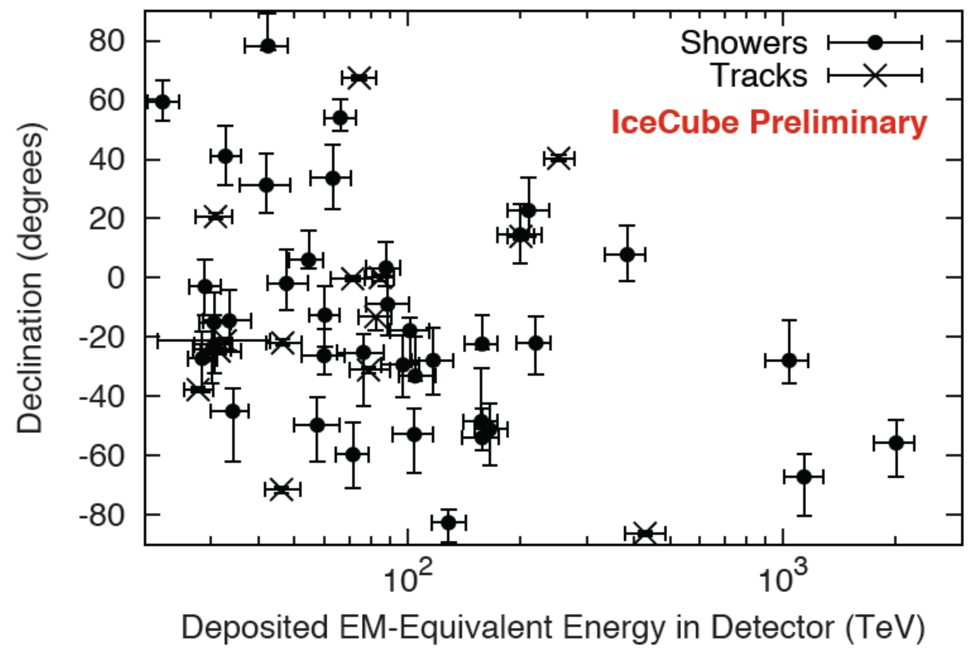
Looking for gamma-ray counterparts of IceCube HESE

- No significant correlation between contained track and Fermi sources (arxiv/1505.00935)
- Steady sources seem to be ruled out (z<0.2)
- If neutrinos are extragalatic, counterparts in gamma-ray may be hard to find!



What do we know

- Data suggest some extra-galactic component
- Data deviates from an unbroken E^{-2} spectrum
- Few bright sources are disfavoured by point source searches
- Protons interacting with radiation seem to be favoured
- Dedicated studies:
  - Star forming galaxies can account up to 28%, arxiv/1511.00688
  - Gamma-ray blazars can account for < 20%, arxiv/1502.03104
  - GRBs for less than 1%, arxiv/1412.6510



The dawn of Neutrino Astronomy

- IceCube has paved the road for neutrino astrophysics!
- No evidence yet of neutrino point and extended sources
- The sources of IceCube neutrinos are not readily traced by extragalactic gamma-ray emitters
- Large number of weak sources or transients?