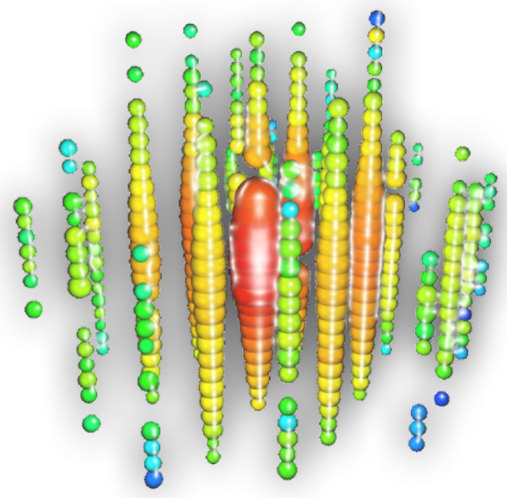
Neutrinos

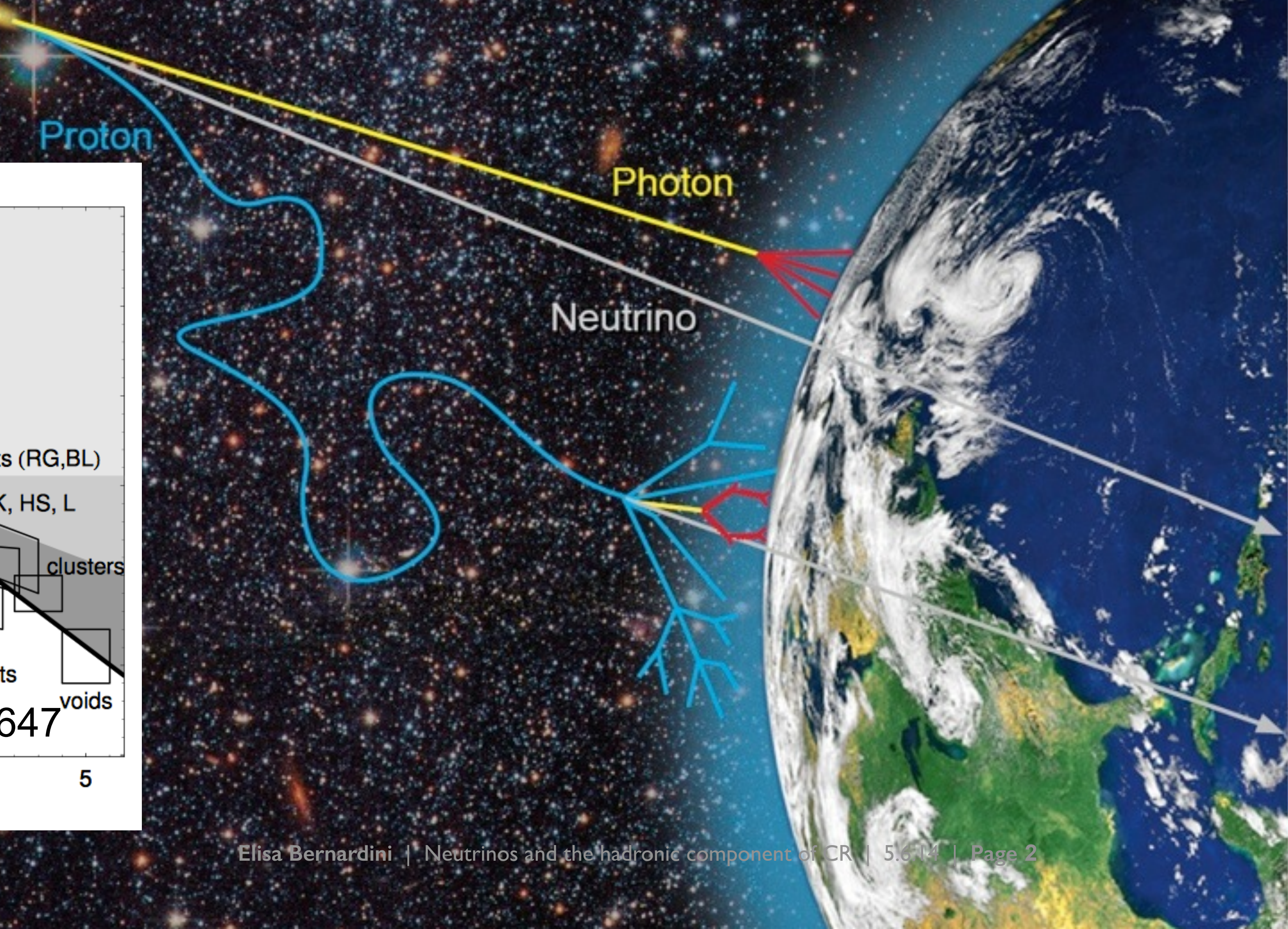
and the hadronic component of CR

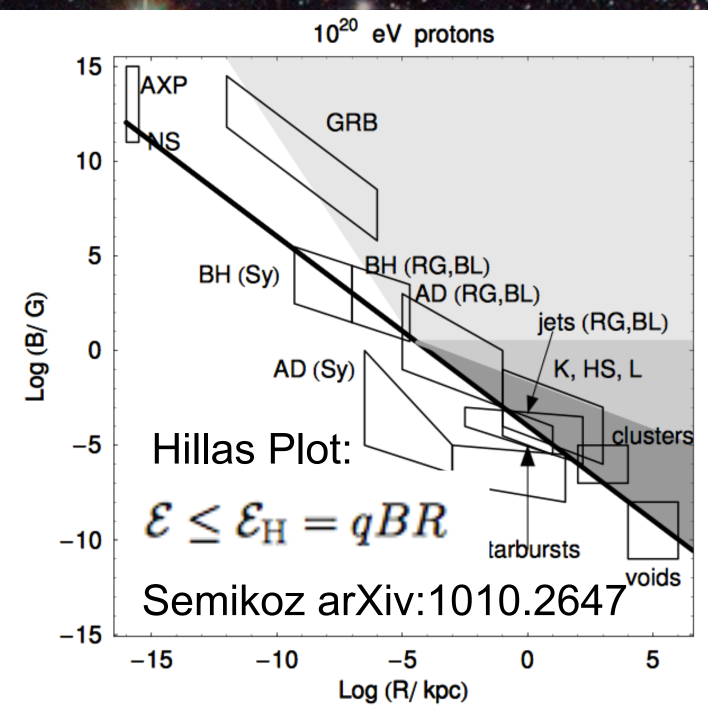


Elisa Bernardini
Scineghe 2014
Lisbon 5/6/2014

The generic source

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



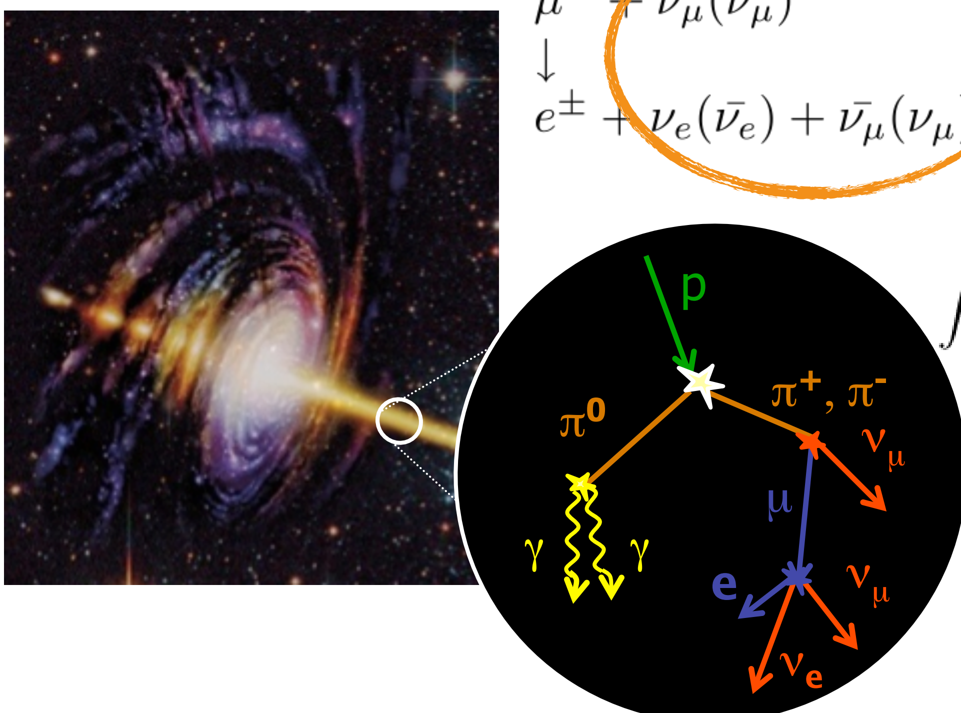


Cosmic Rays gamma-rays and neutrinos

- 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

$$\begin{array}{llll} pp \rightarrow pp(np, nn)+ & n_1\pi^{\pm}+ & n_2\pi^0+ & (n_3K^{\pm}+n_4K^0+....) \\ & \downarrow & \downarrow & \\ & \mu^{\pm}+\nu_\mu(\bar{\nu_\mu}) & \gamma\gamma & \\ & \downarrow & & \\ & e^{\pm}+\nu_e(\bar{\nu_e})+\bar{\nu_\mu}(\nu_\mu) & & \end{array}$$

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

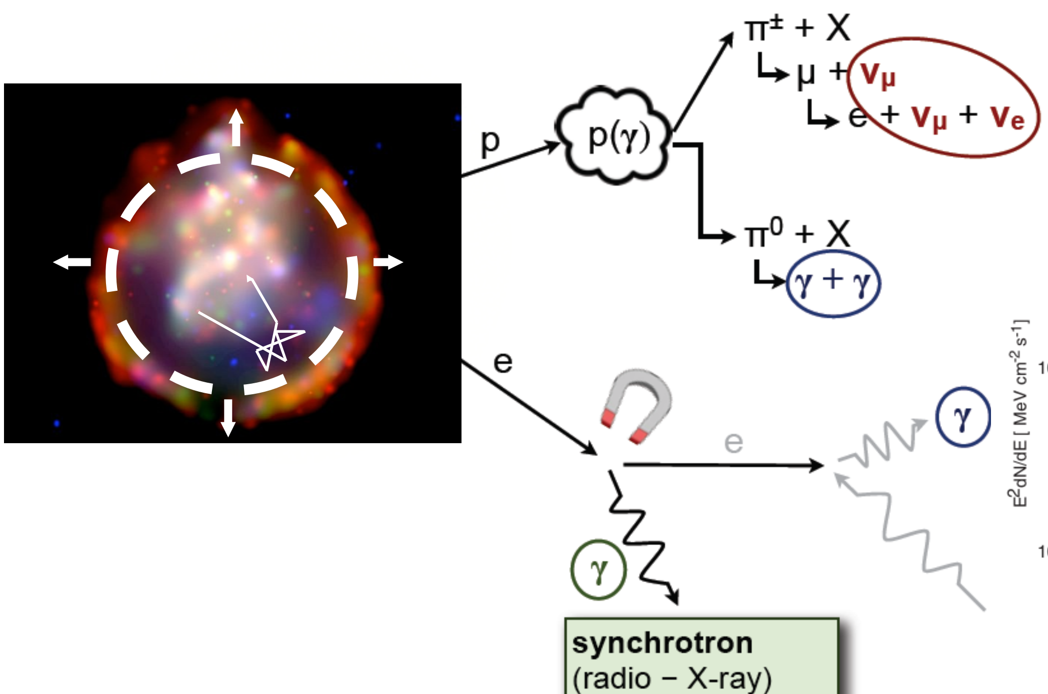


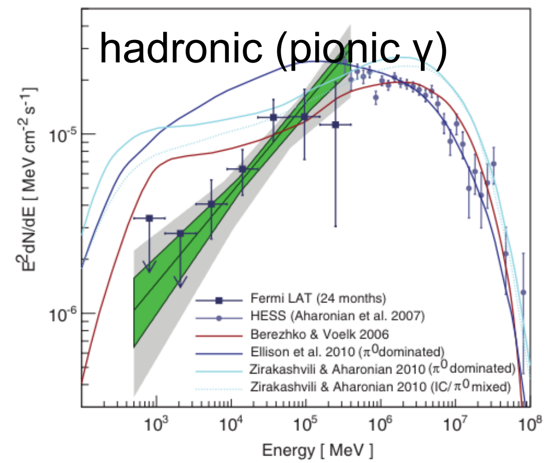
$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu$$

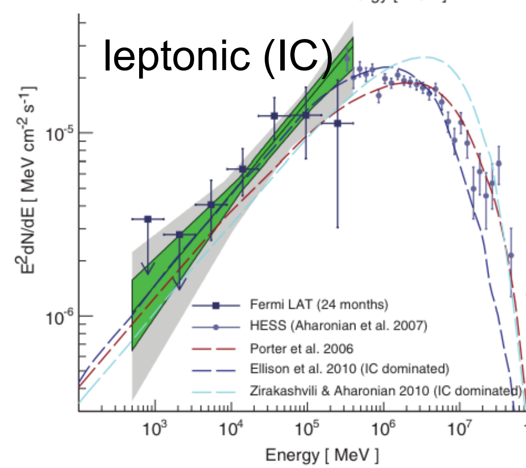
K=4 pγ
K=1 pp

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







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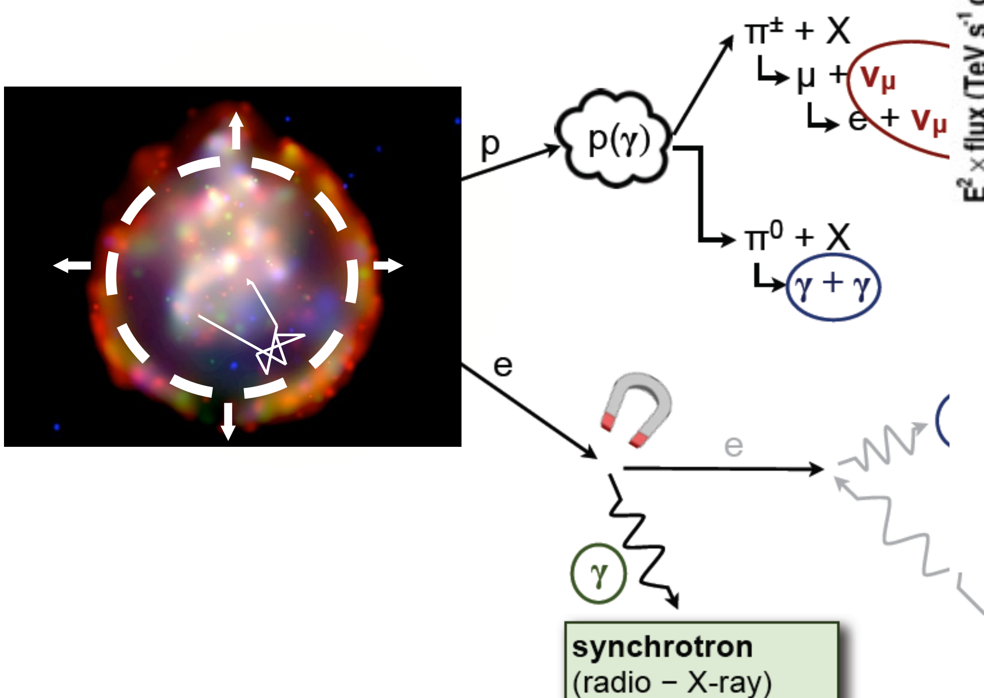
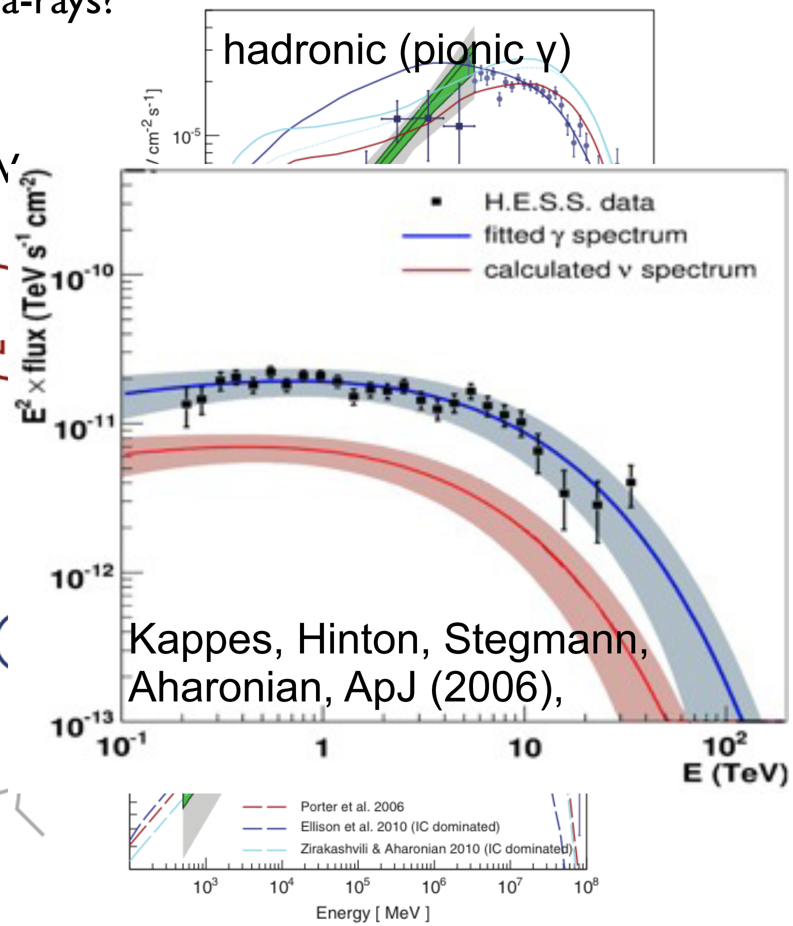
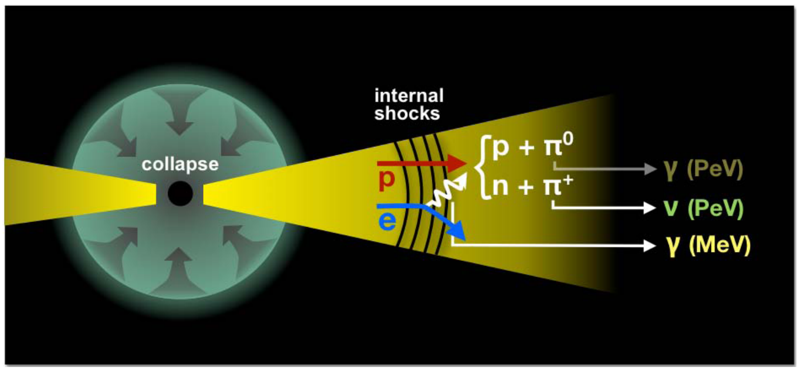
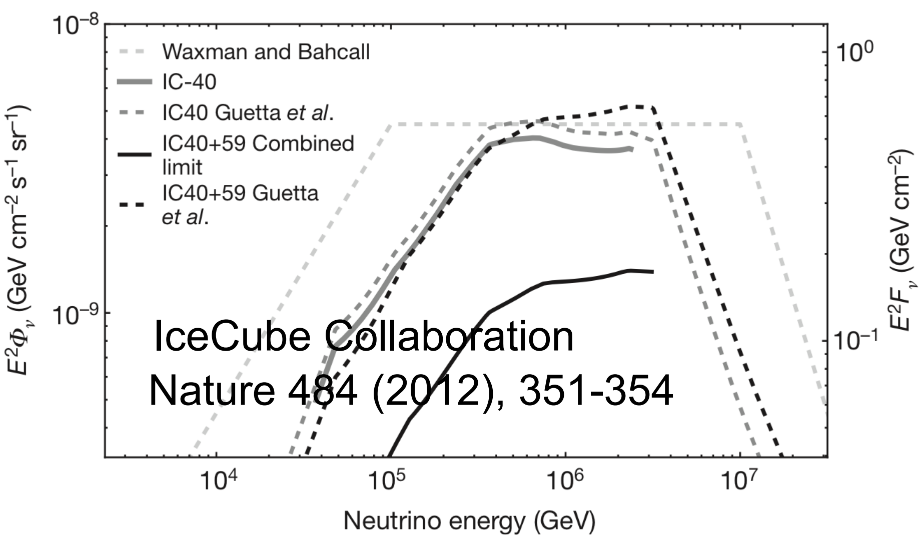




Gamma Ray Bursts

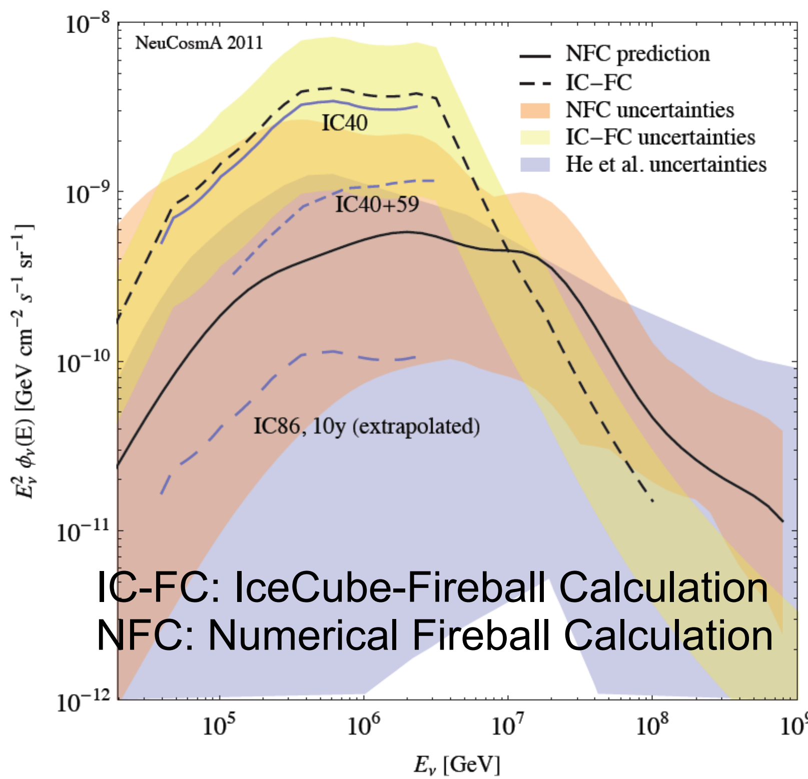
- Candidate sources for extra-galactic component: Gamma Ray Bursts





IceCube Collaboration
Nature 484 (2012), 351-354

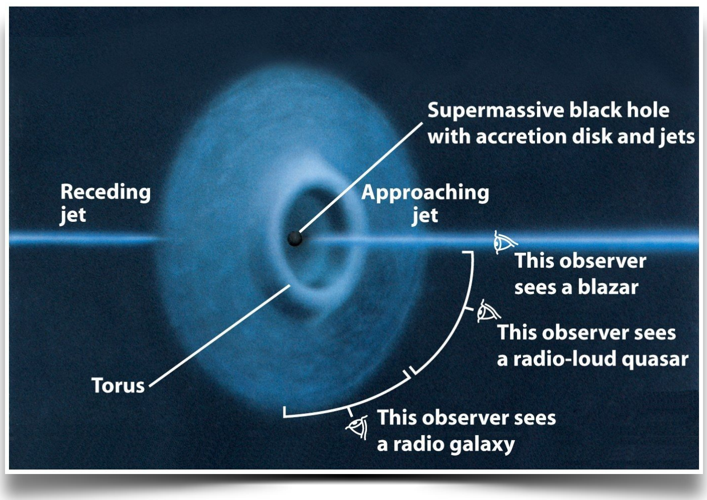
S. Hümmer, P. Baerwald, and W. Winter
Phys. Rev. Lett. 108, 231101 (2012)

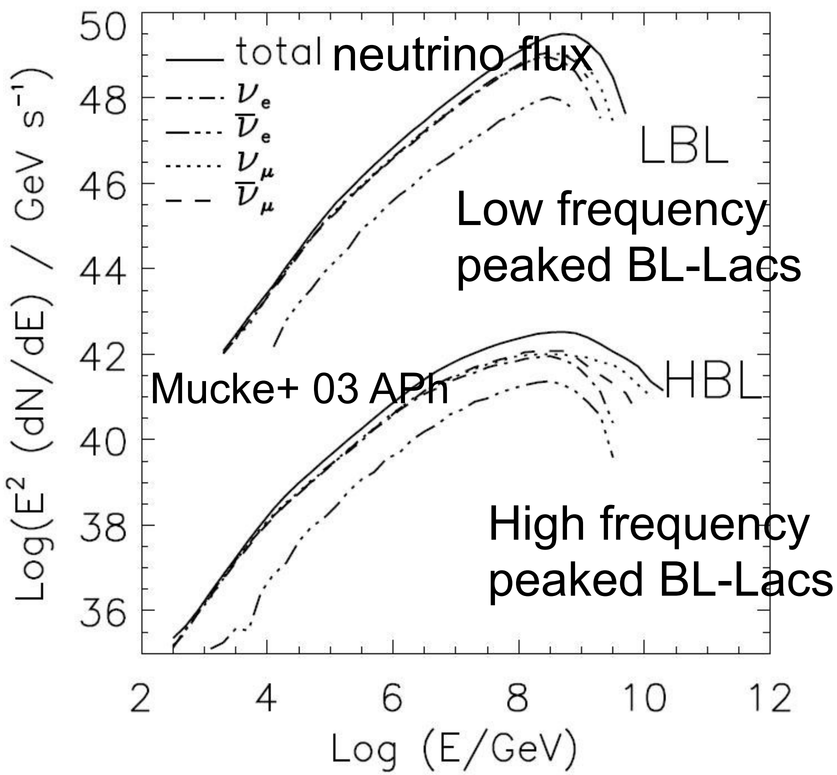


IC-FC: IceCube-Fireball Calculation
NFC: Numerical Fireball Calculation

Active Galactic Nuclei

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

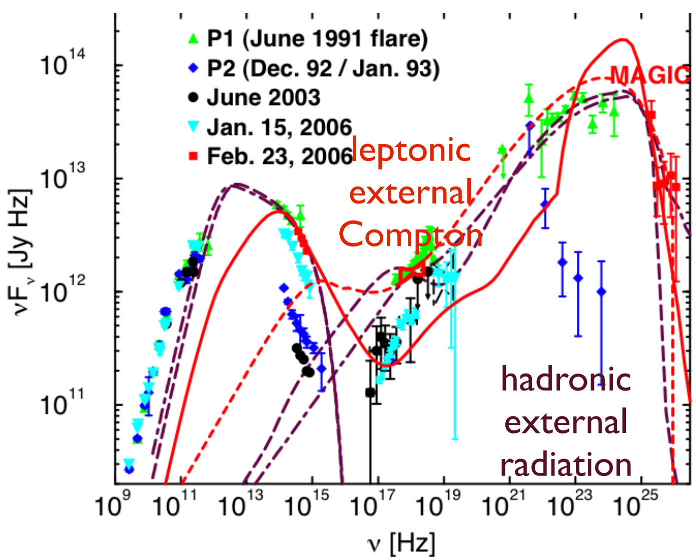




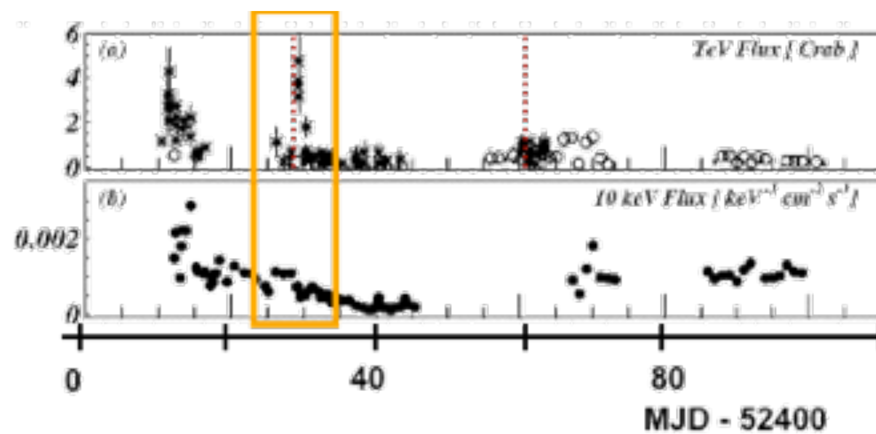
Active Galactic Nuclei: leptonic versus hadronic in gamma-rays

- Hadronic as well as leptonic models represent SEDs satisfactorily
- Variability information required for unambiguous model fits
- Spectral behaviour @GeV-TeVs differ for leptonic & hadronic models
- Hadronic-models tend to predict (sub)TeV-emission from LBLs
- Leptonic models prefer a cutoff below 100 GeV

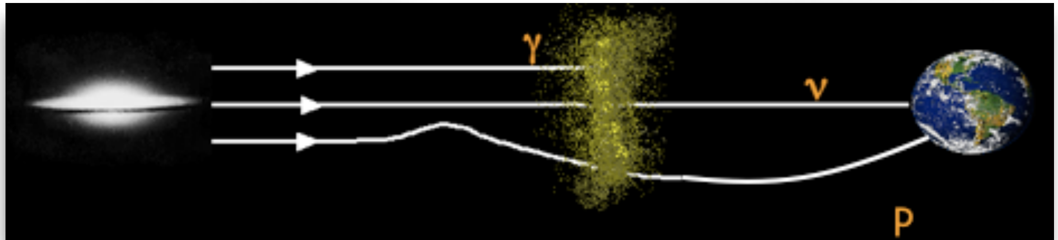
Böttcher, Reimer & Marscher 2008

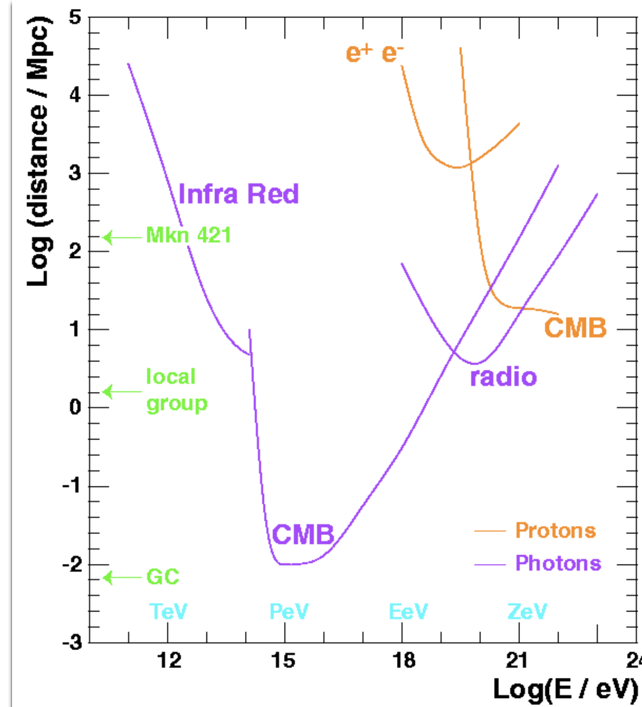


1ES 1959+650 orphan flare in 2002
associated neutrinos likely background



Rationale for neutrino astronomy



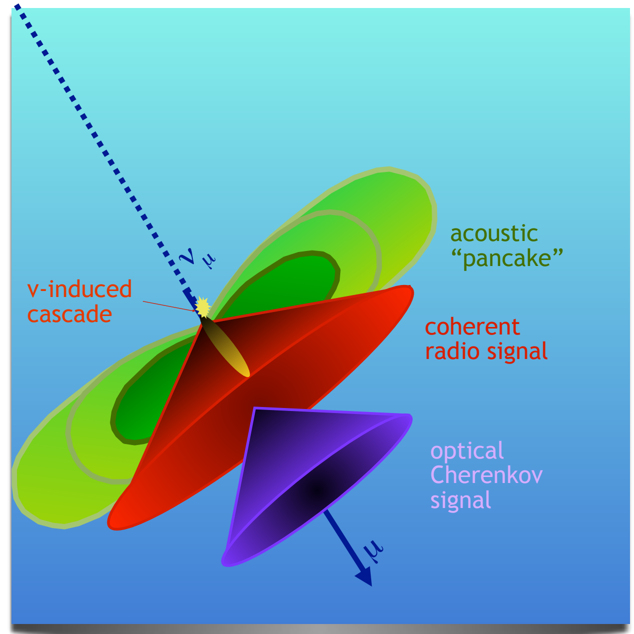


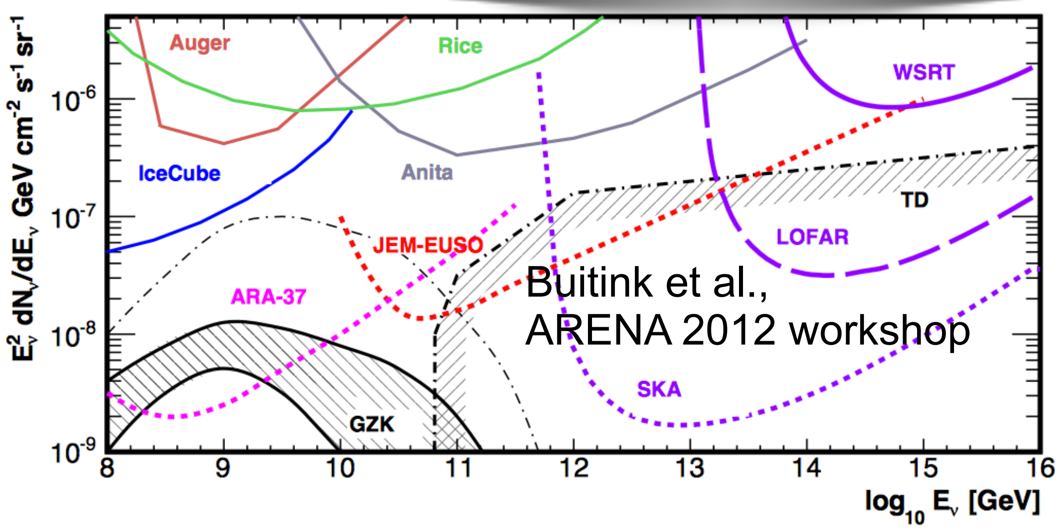
- Why neutrinos?
  - Mean free path of Very High Energy (VHE) photons is much less than the cosmological distance
  - Mean free path of VHE neutrinos is longer than cosmological distance
  - Neutrinos are the "smoking gun" for hadronic interactions

	process	cut-off	mean free
γ-rays	γ	>100 TeV	10 Mpc
proton	p+	>50 EeV	50 Mpc
neutrinos	ν	>40 ZeV	40 Gpc

Neutrino Detection at high energies

- 10^9 eV to 10^{16} eV
  - Cherenkov photons in water/ice
- 10^{17} eV to $>10^{23}$ eV
  - Coherent radio pulses in ice, salt and Moon regolith
- $> 10^{19}$ eV
  - Acoustic waves in water/ice and salt
- 10^{17} to 10^{19} eV
  - Extensive air showers

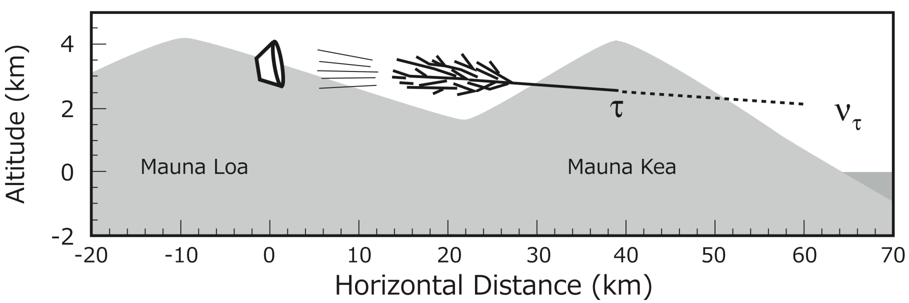


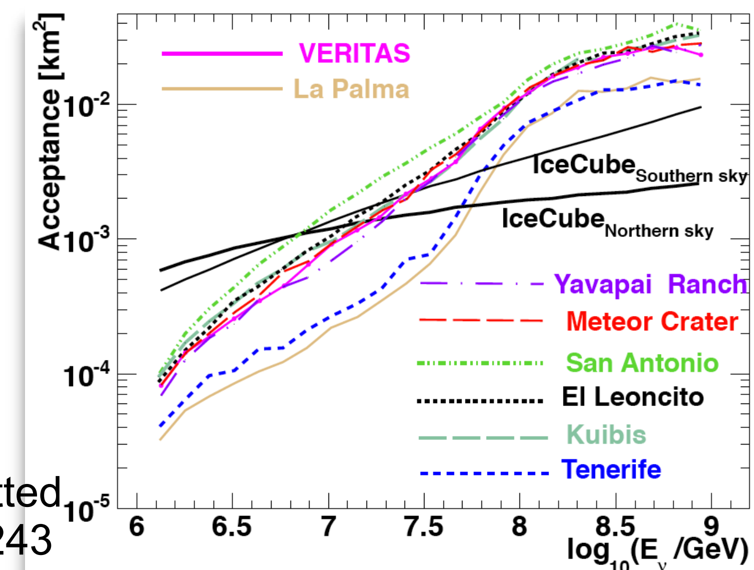


Detecting neutrinos with Cherenkov detectors

- At EeV energies the range of leptons is *O*(km)
- Emerging from the Earth the lepton can produce a detectable EAS [D. Fargion, Astr.J. 570, 909 (2002), X. Bertou et al., Astr. Phys. 17, 183 (2002), E. Zas, New J.Phys. 7, 130 (2005)]
- All-sky Survey High Resolution Air-shower detector (Ashra) reported limits on GRBs
- At energies above ~ 5 10^{17} eV the acceptance of Cherenkov telescopes surpasses that of IceCube

Y.Asaoka, M.Sasaki, Astropart. Phys. 41 (2013)

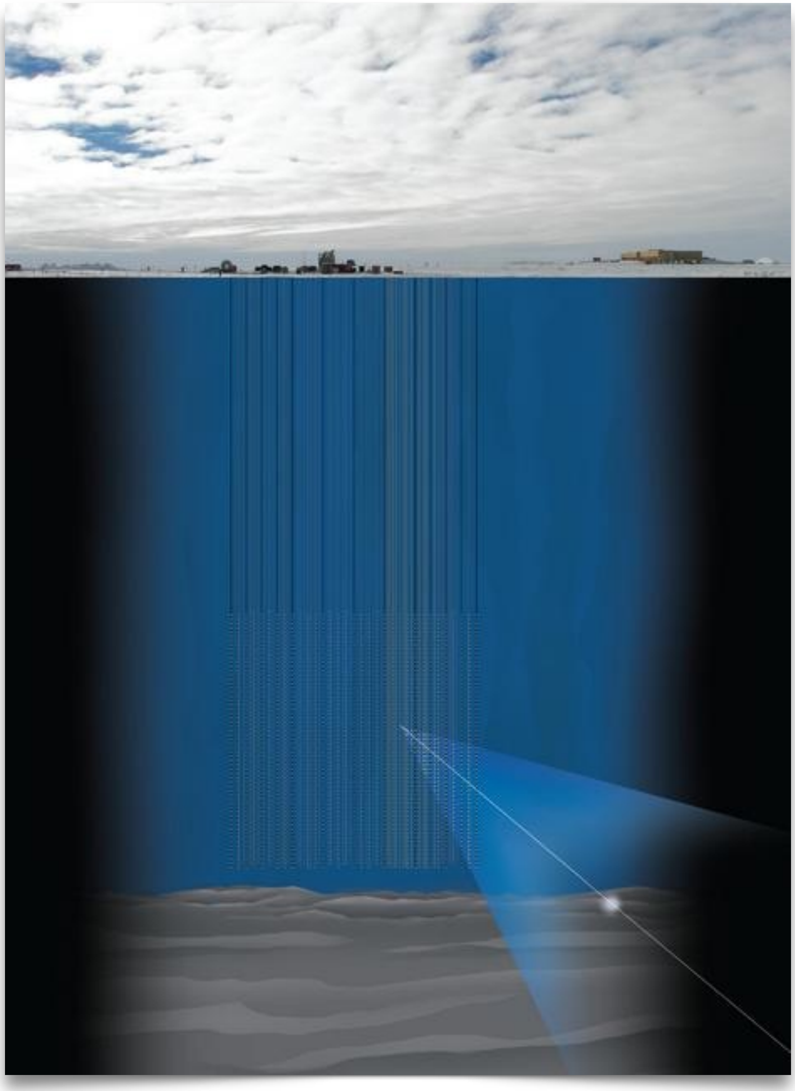




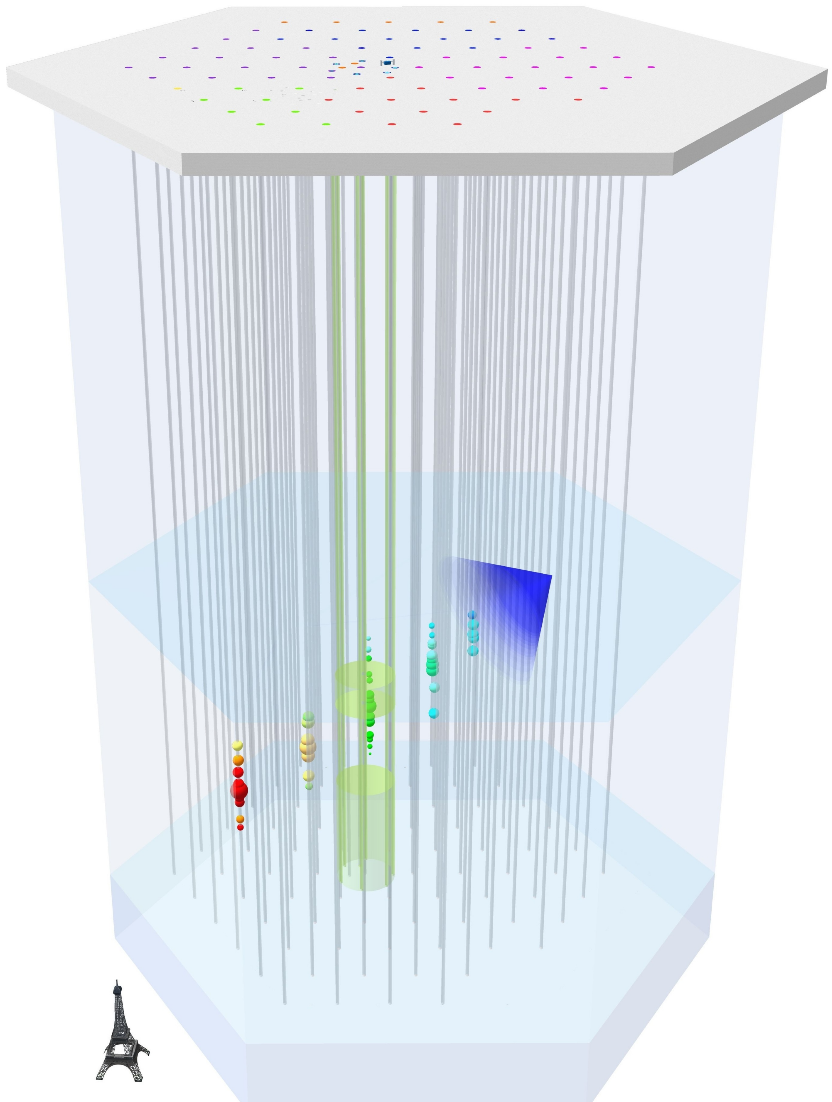
D. Gora, E.B., A. Kappes, submitted to Astropart. Phys. arXiv:1402.4243

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)

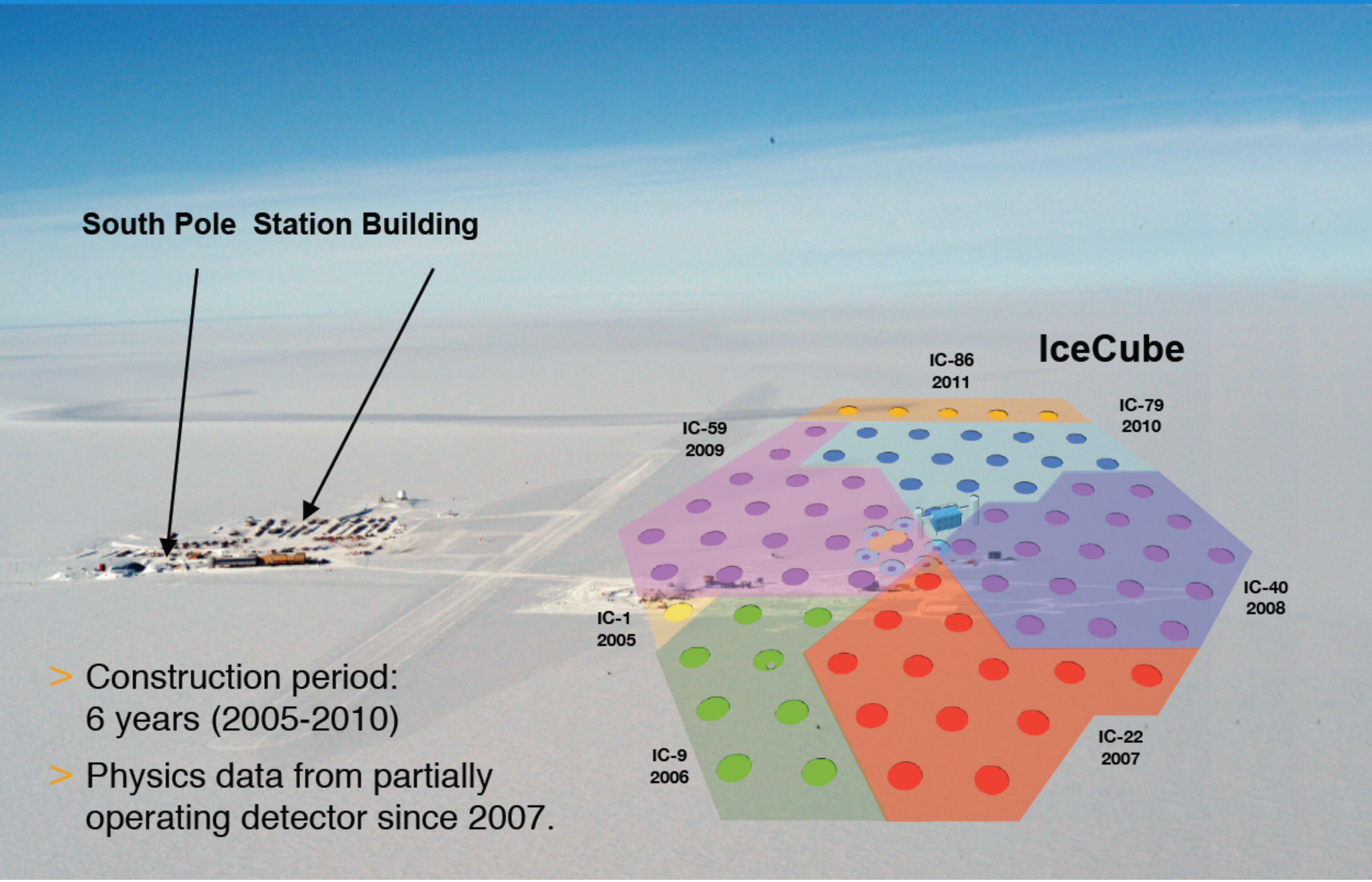


IceCube Observatory



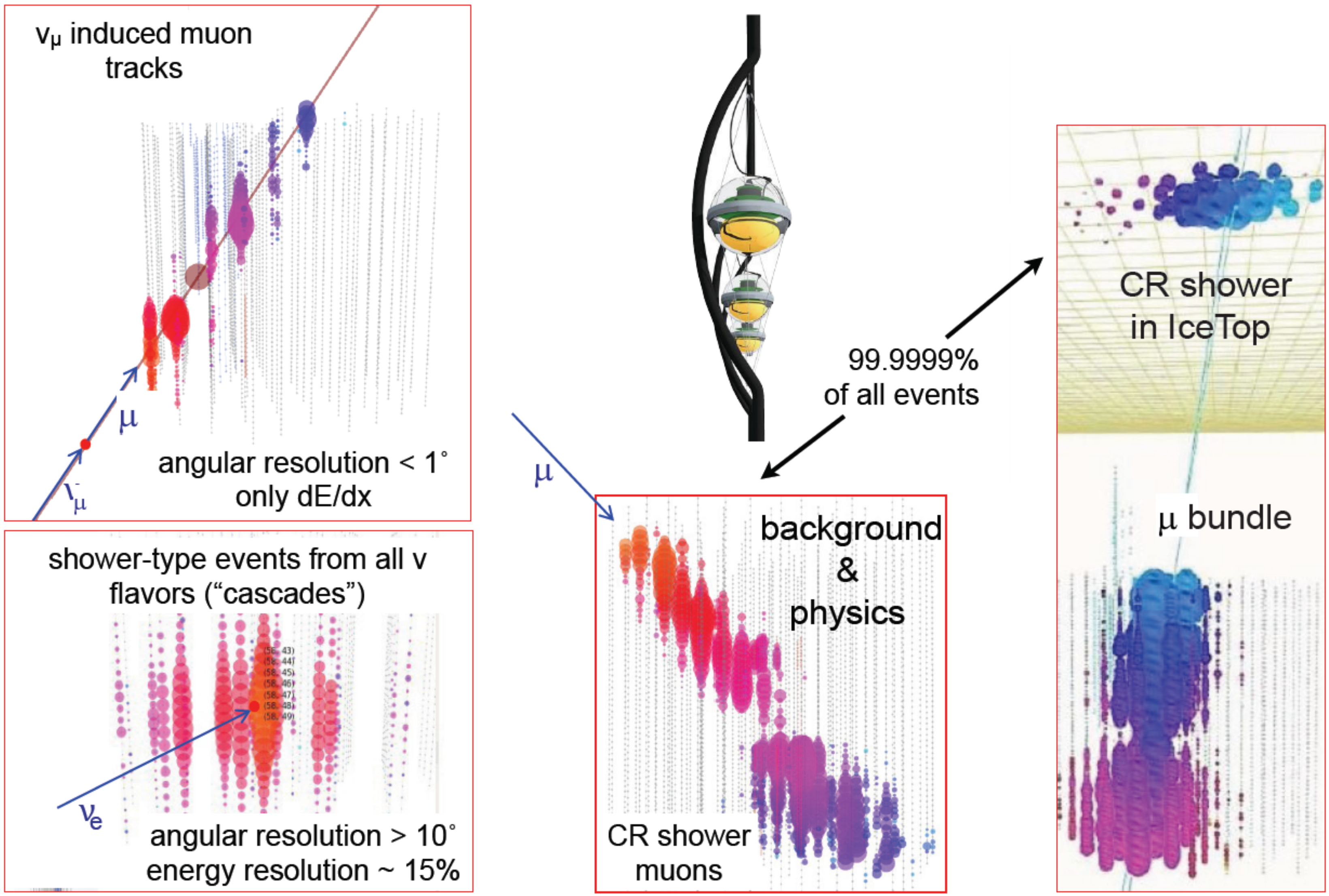
- 5160 sensors on 86 strings
- Higher density DeepCore
- 1 km^3 sensitive volume
- ~98% of all sensors working after deployment
- Failure rate <0.1% per year
- ~99% data taking efficiency

IceCube construction



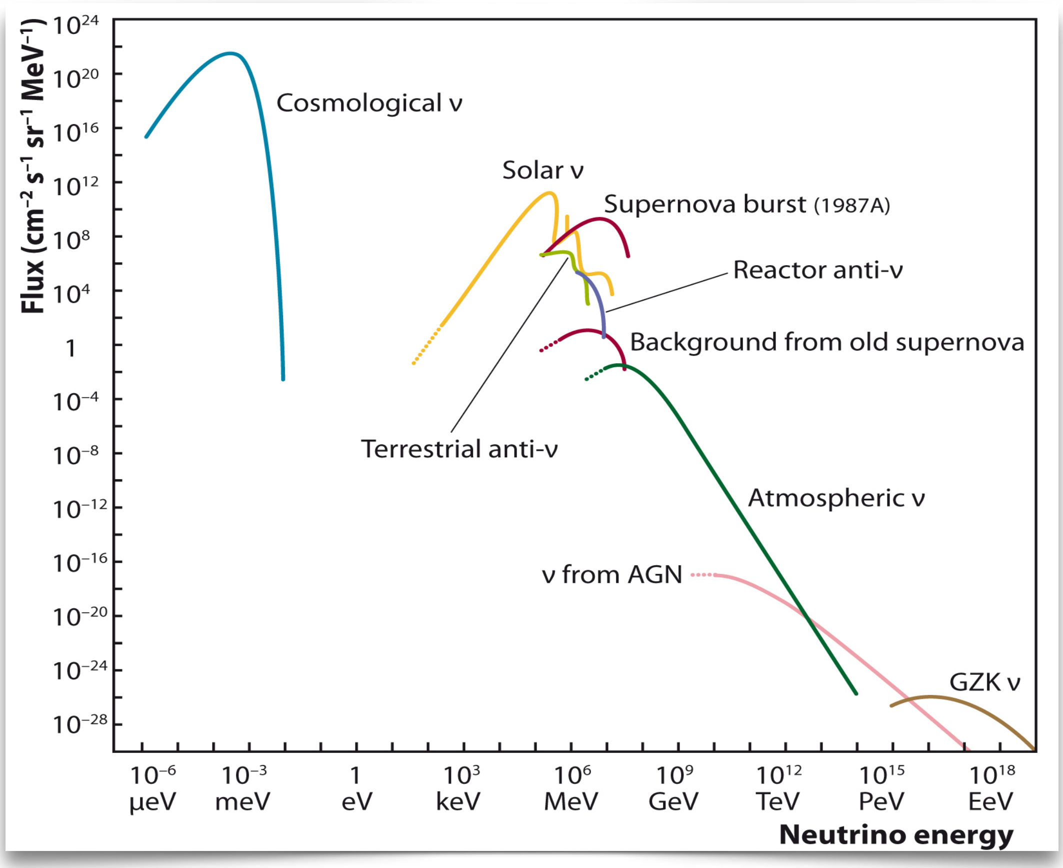
- Construction period: 6 years (2005-2010)
- Physics data from partially operating detector since 2007.

Event signatures in IceCube



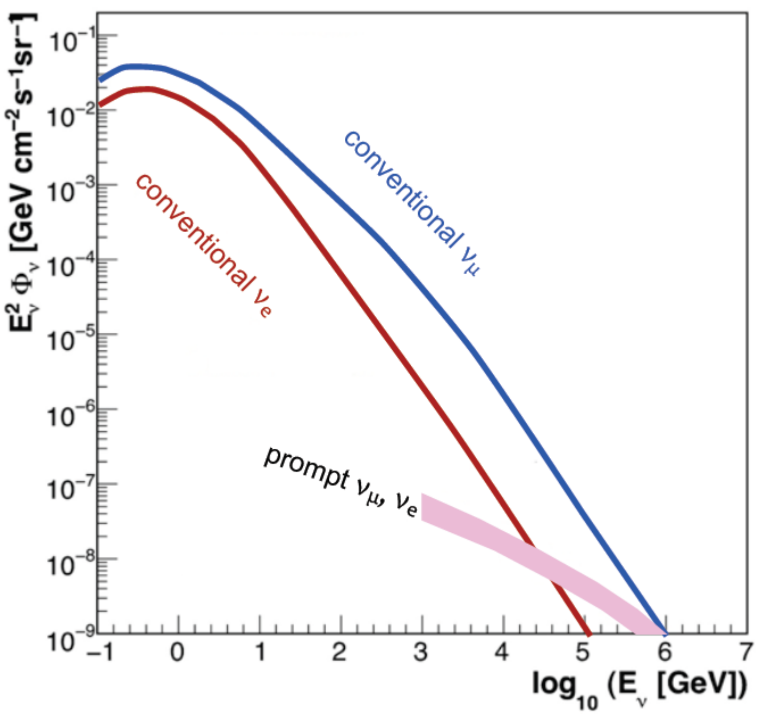
Neutrino fluxes

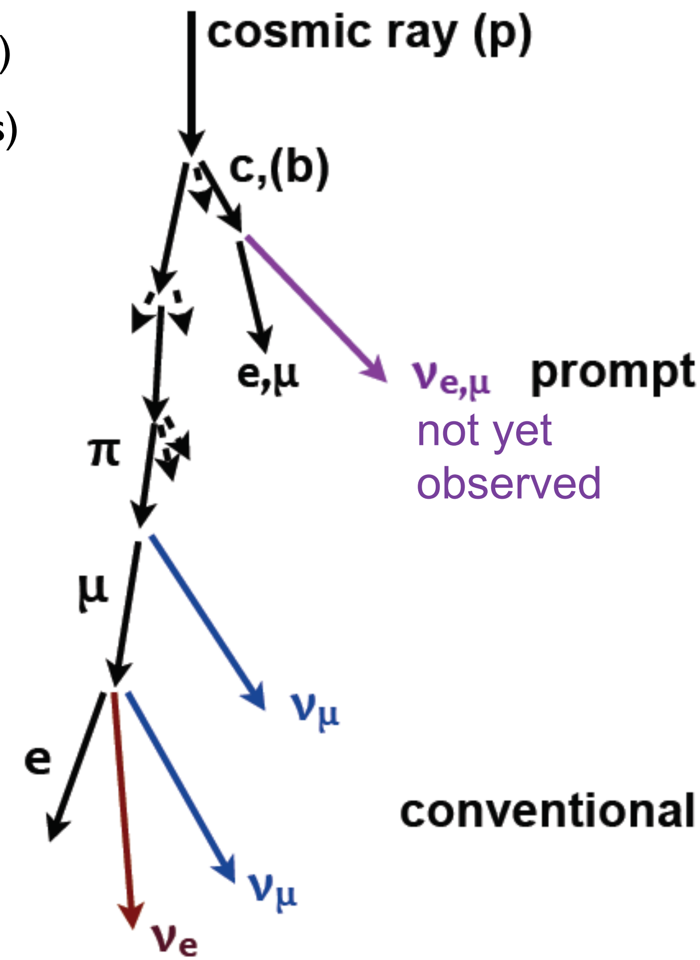
- Expected signals are weak and mimicked by irreducible backgrounds
- Most neutrinos seen by neutrino telescopes are of atmospheric origin, i.e. produced in CR air shower interactions



Neutrino fluxes

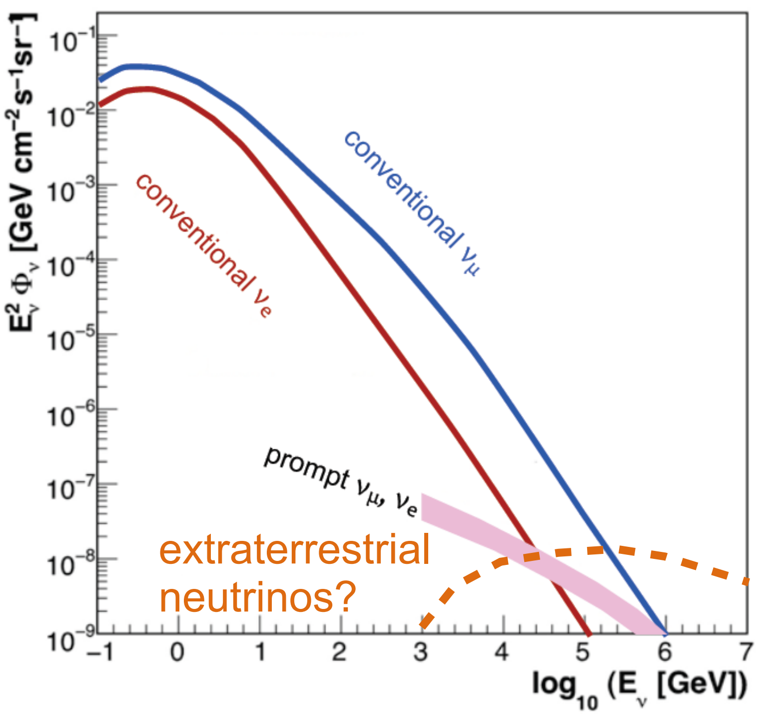
- Expected signals are weak and mimicked by irreducible backgrounds
- Event rates in IceCube (year^{-1}):
  - atmospheric muons 7×10^{10} (2000 per second)
  - atmospheric neutrinos 5×10^4 (1 every 6 minutes)
  - astrophysical *O*(10)

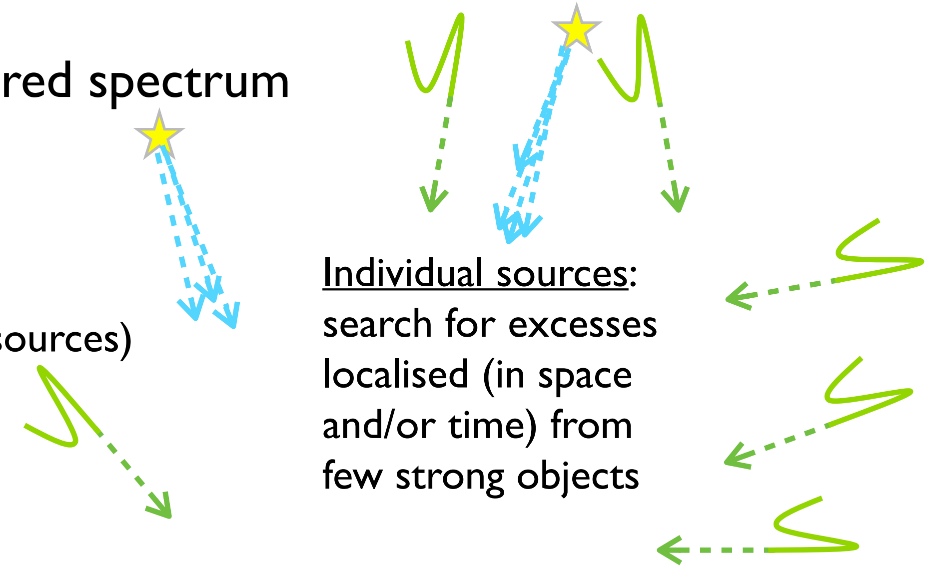




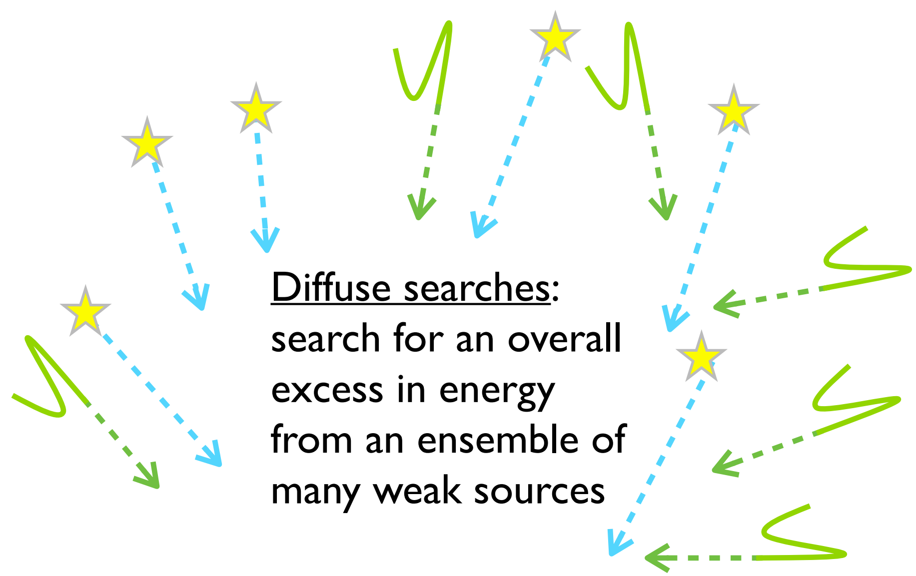
Searching for cosmic neutrinos

- 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)





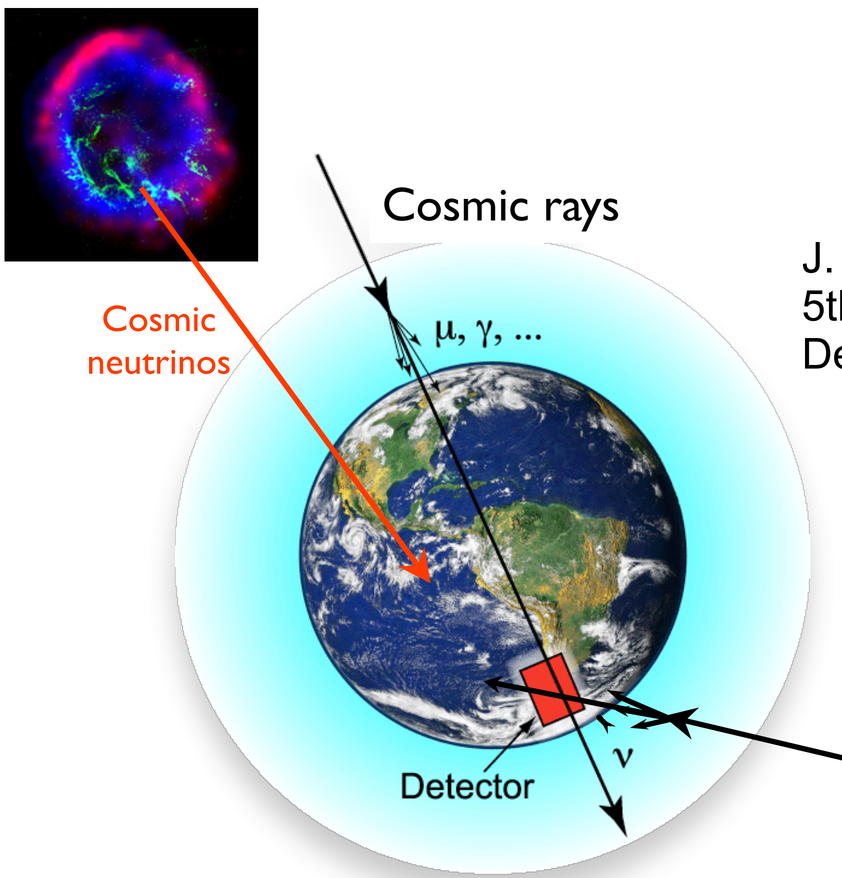
Individual sources: search for excesses localised (in space and/or time) from few strong objects



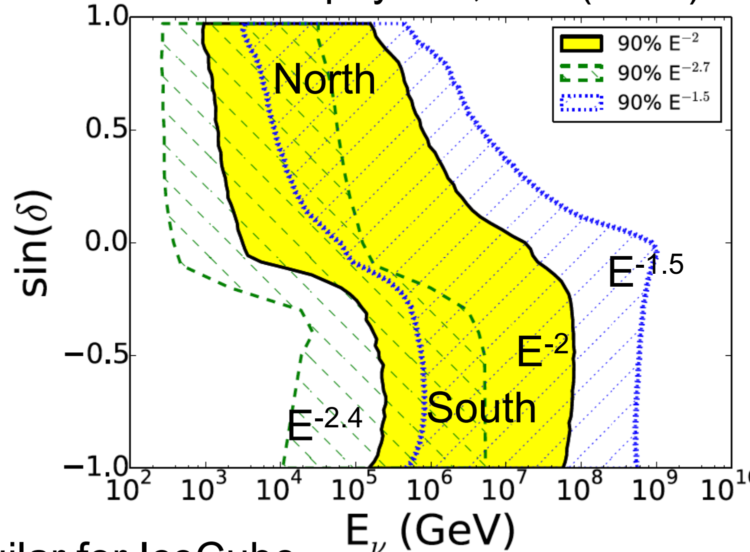
Diffuse searches: search for an overall excess in energy from an ensemble of many weak sources

IceCube results: limits on point sources

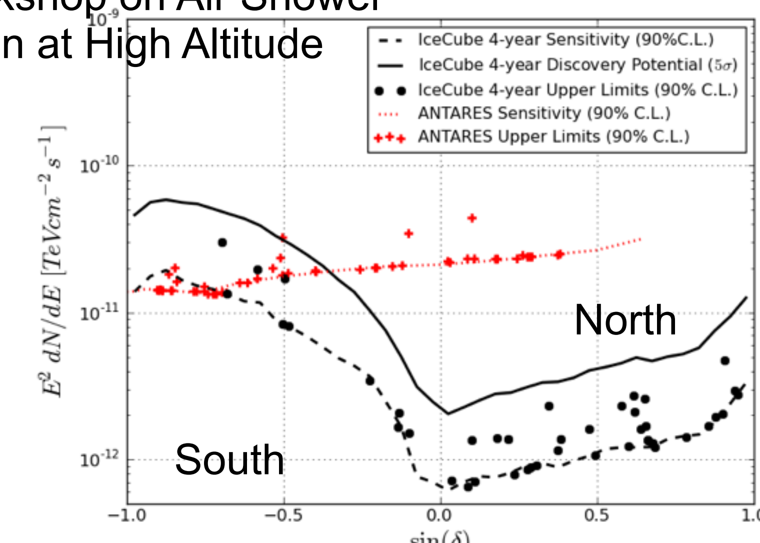
- Cosmic muons are filtered:
  - by the Earth if from the North
  - using energy cuts if from the South



The Astrophys. J., 779 (2013)



J. A. Aguilar for IceCube
5th Workshop on Air Shower
Detection at High Altitude



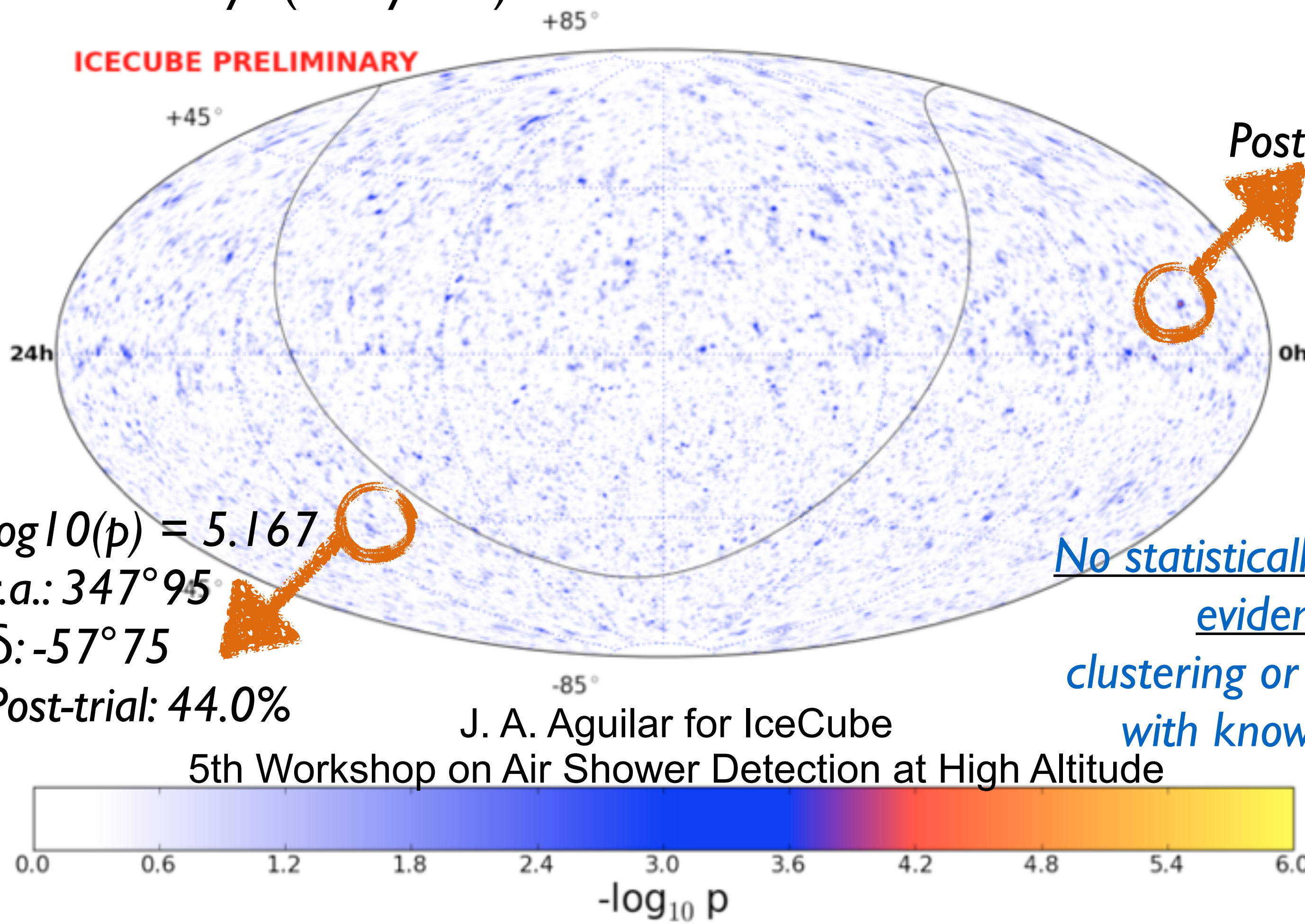
IceCube results: point sources

- Total events: 394,000 (178k upgoing + 216k downgoing)
- Livetime: 1371 days (in 4 years)

-log10(p) = 5.318
r.a.: 29°25
δ: 10°55
Post-trial: 22.6%

Up-going

Down-going

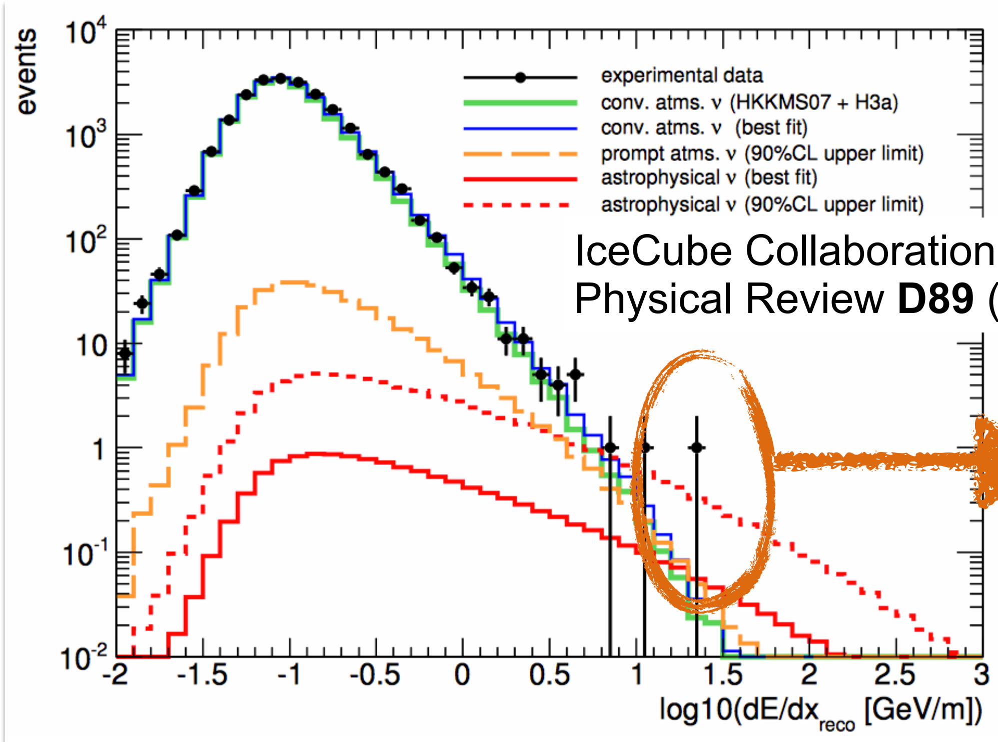


log10(p) = 5.167
r.a.: 347°95
δ: -57°75
Post-trial: 44.0%

<u>No statistically significant</u>
<u>evidence</u> of either
clustering or correlations
with known directions

IceCube results: diffuse searches I

- 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)]



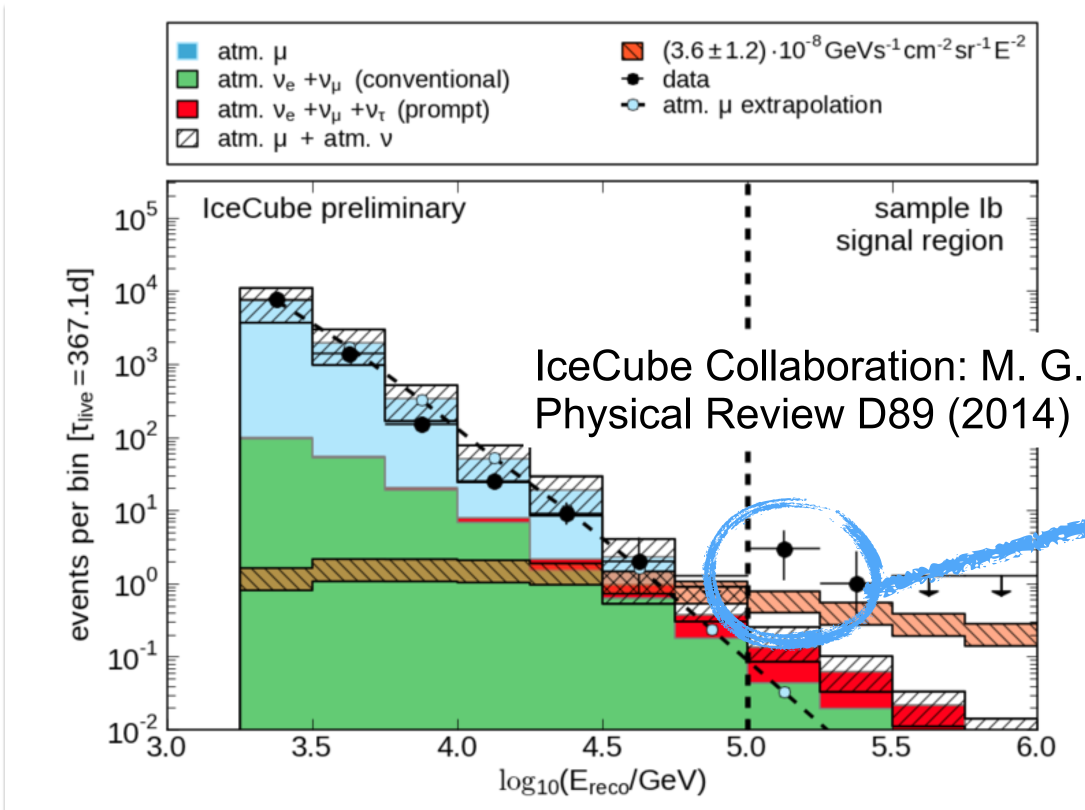
IceCube Collaboration: M. G. Aartsen et al
Physical Review **D89** (2014) 062007

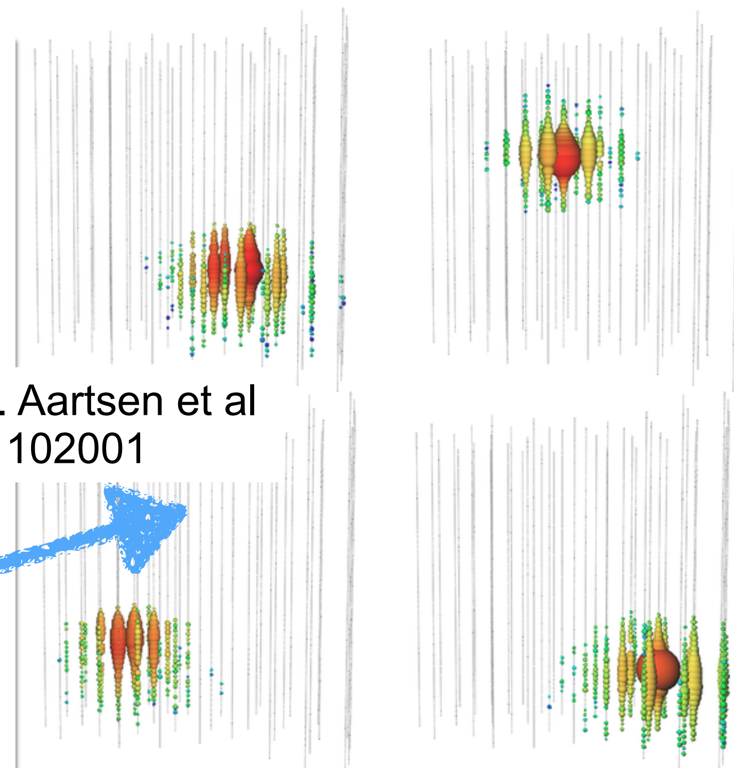
One excess muon E ~ 200 TeV significance 1.8 σ

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}

IceCube results: diffuse searches II

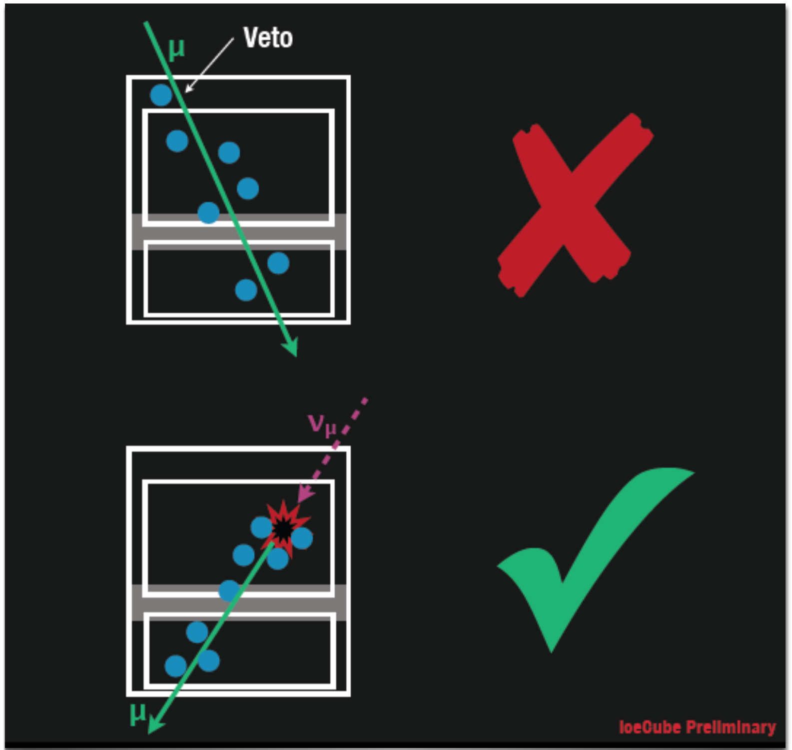
- 3 (+1 in control sample) cascades found > 100 TeV, muon background $0.04^{+0.06}_{-0.02}$, atmospheric neutrino background 0.21, significance 2.7 σ

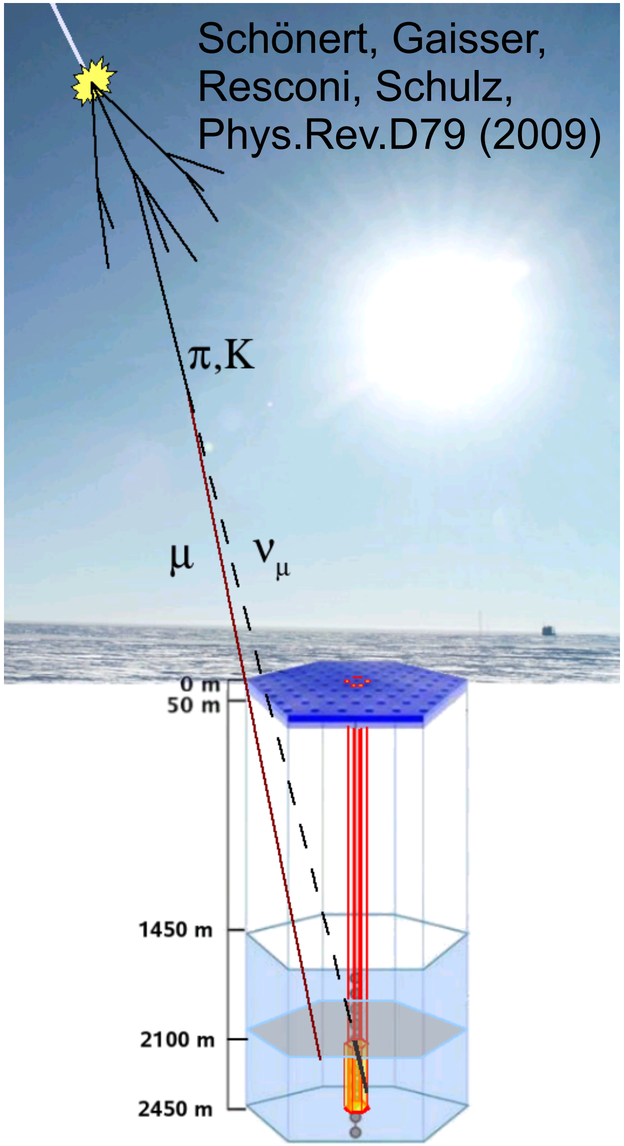




IceCube Collaboration: M. G. Aartsen et al Physical Review D89 (2014) 102001

How to veto down-going atmospheric neutrinos

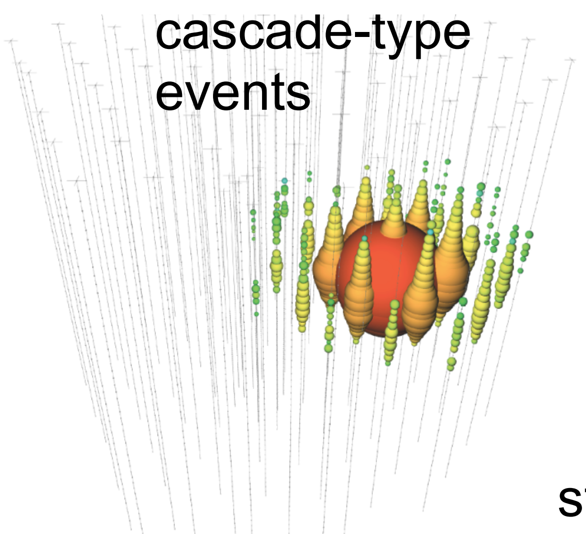


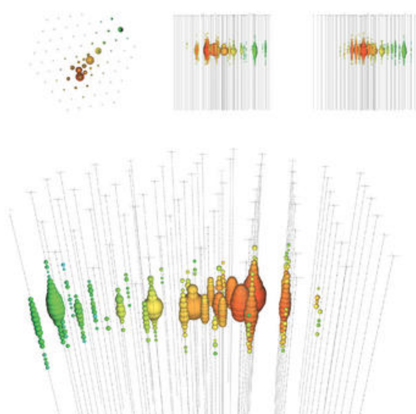


- Atmospheric neutrinos will, in general, be accompanied by muons produced in the same parent air shower
- Golden channel: "down-going starting events"

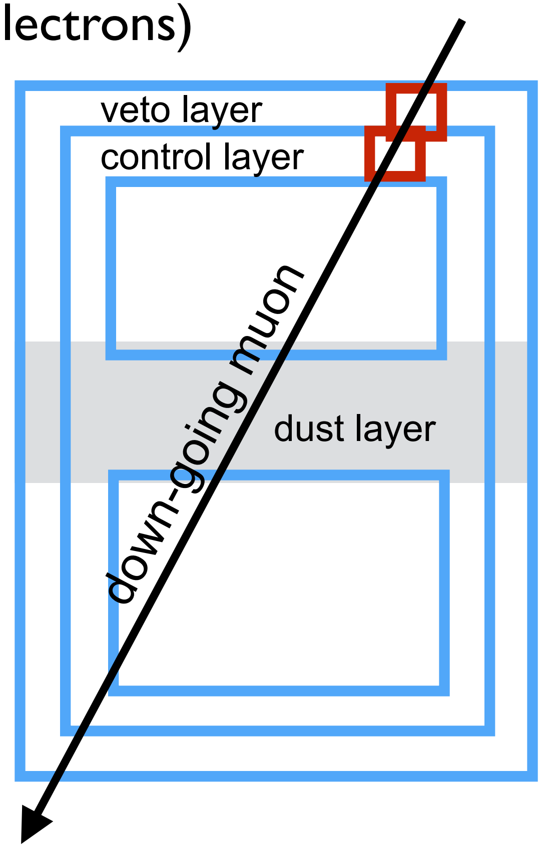
The breakthrough

- 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



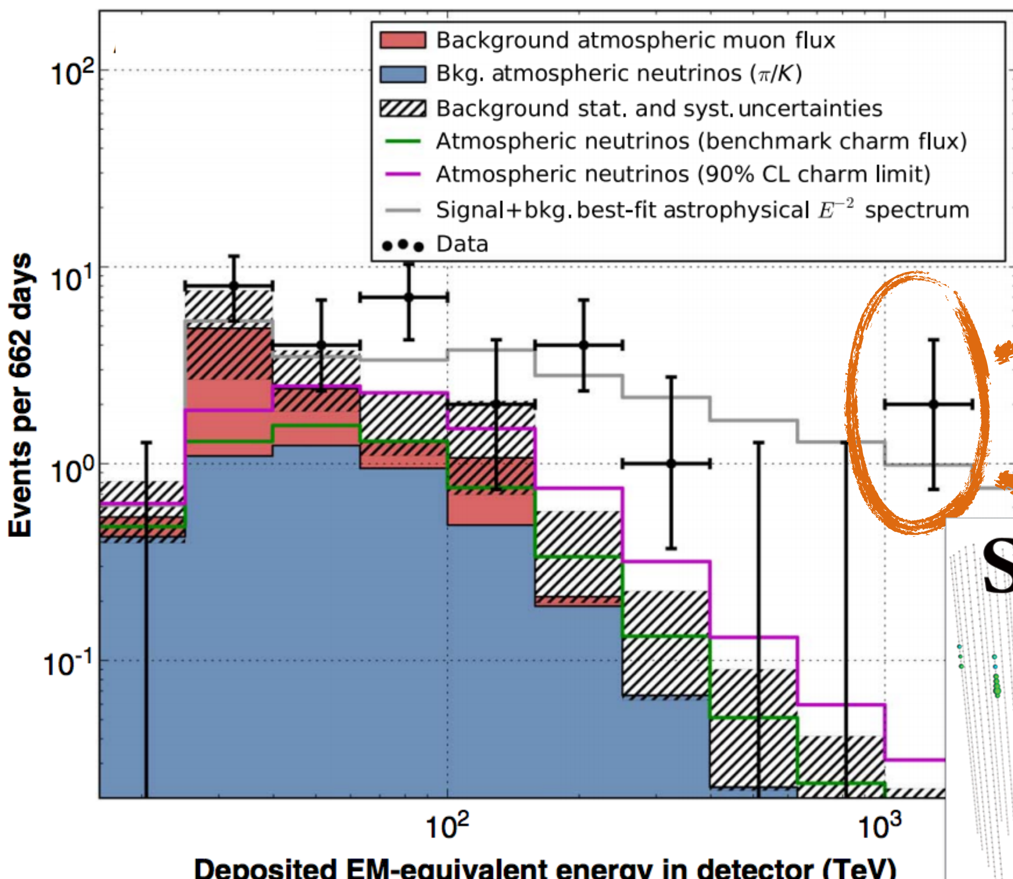


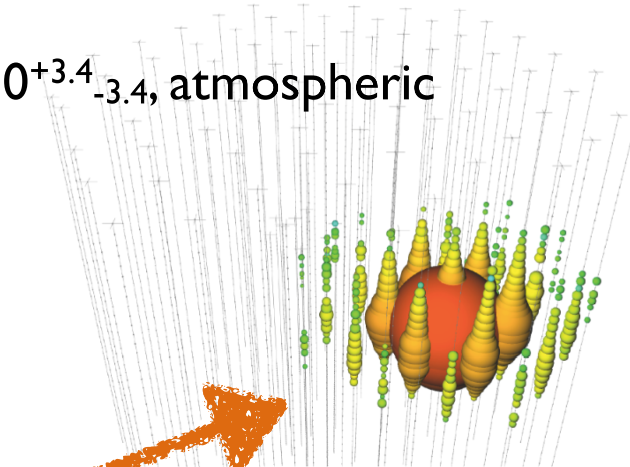
starting tracks



First clear evidence for extraterrestrial neutrinos (2013)

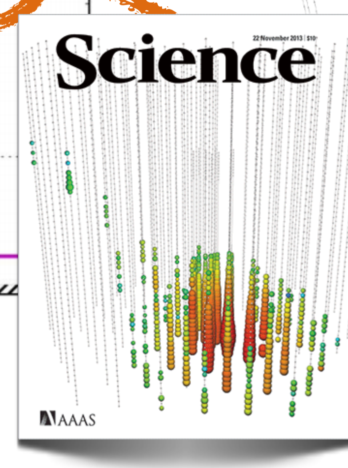
- 28 events found above 30 TeV, muon background $6.0^{+3.4}_{-3.4}$, atmospheric neutrino background $4.6^{+3.7}_{-1.2}$, significance 4.1 σ

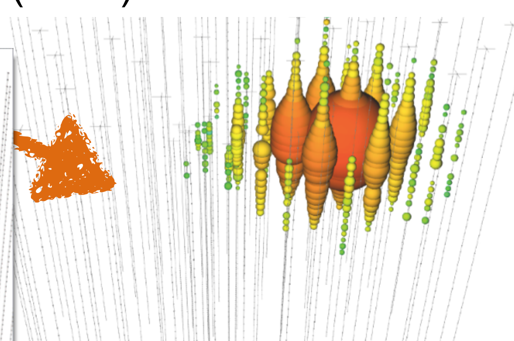




1.1 ± 0.17 PeV

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

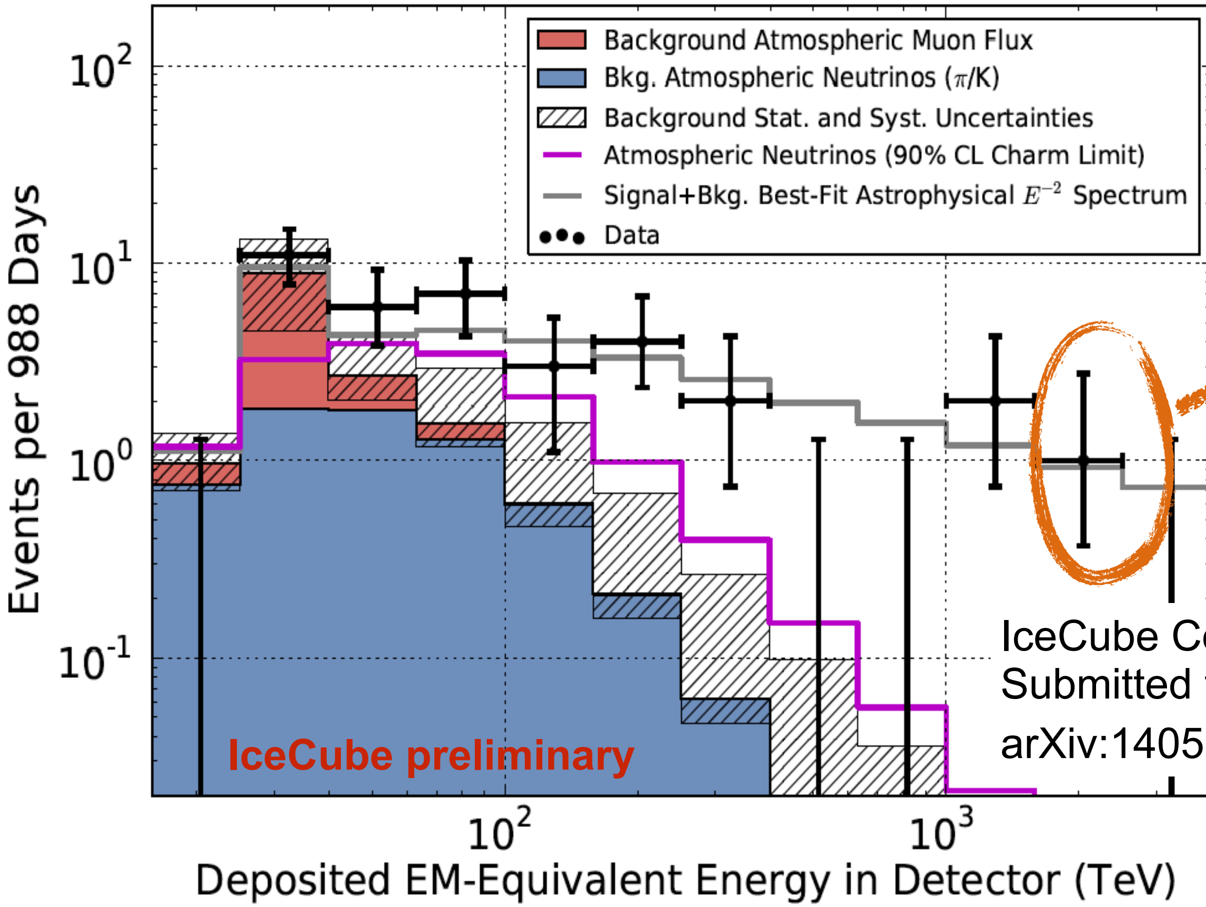


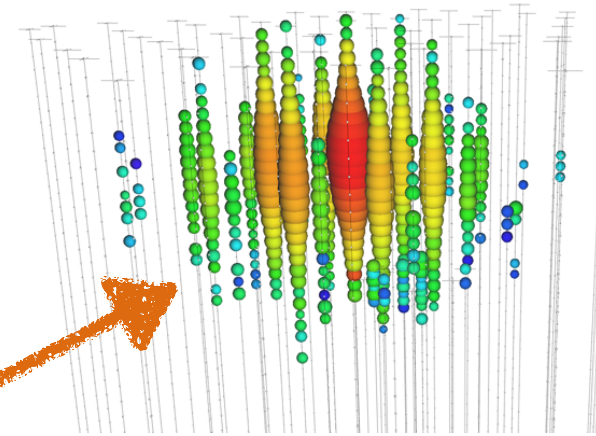


1.0 ± 0.15 PeV

Three years of (full) IceCube data

- 37 events found, muon background $8.4^{+4.2}_{-4.2}$, atmospheric neutrino background $6.6^{+5.9}_{-1.6}$, significance 5.7 σ



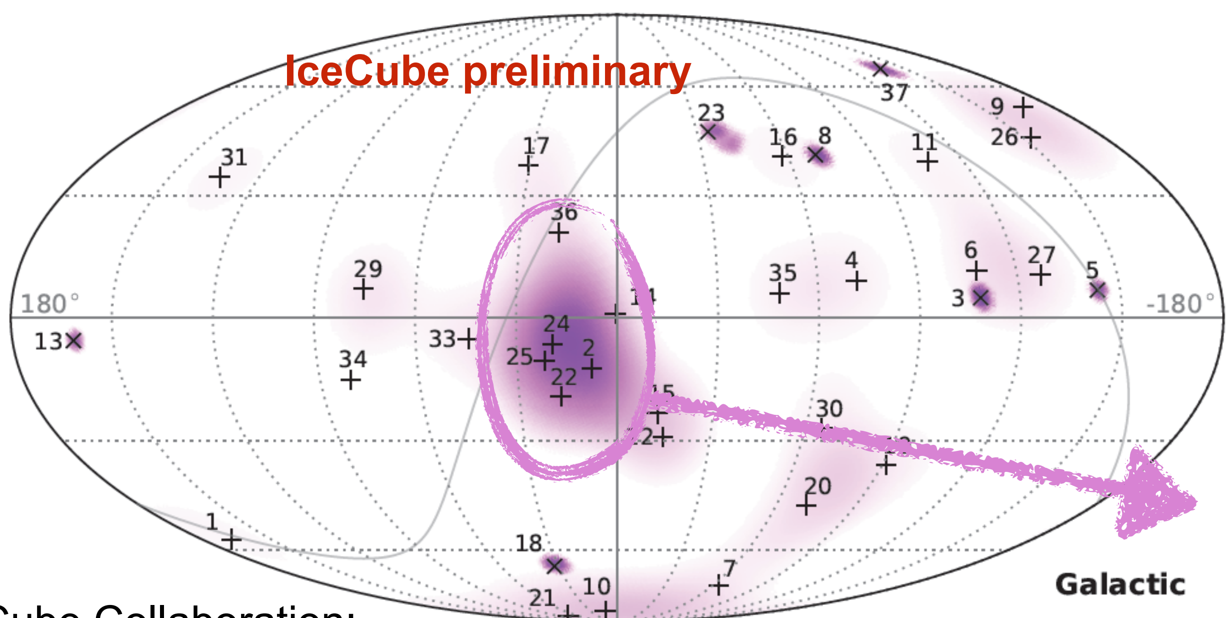


$2.0^{+0.26}_{-0.24}$ PeV

IceCube Collaboration: M. G. Aartsen et al
Submitted to PRL
arXiv:1405.5303

Trying to pin point the sources: time integrated tests

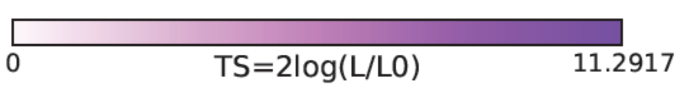
- Cluster of a point source contribution above background using directional uncertainty map for each event
- Search for correlations with known gamma-ray sources



No statistically significance evidence of either clustering or correlations

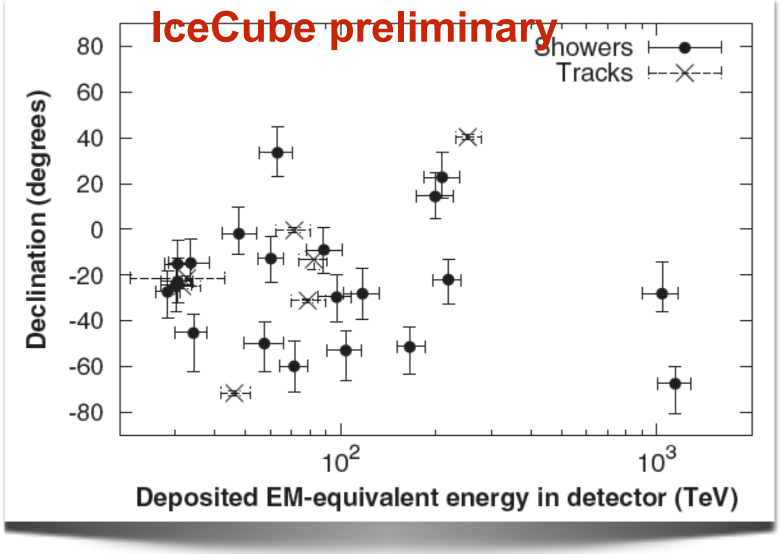
28% of scrambled datasets yield a test statistic greater than or equal to this spot

IceCube Collaboration:
M. G. Aartsen et al
Submitted to PRL
arXiv:1405.5303



What do we know about the origin of the IceCube events?

- Data suggest some extra-galactic component
- Data tend to deviate from an unbroken E^{-2} spectrum
- Few bright sources are disfavoured by point source searches (especially in the North) and limits on GRBs
- Protons interacting with radiation seems to be favoured
- In case of AGNs PeV data can be described, but not lower energies
- CR interactions with gas?



IceCube Collaboration:
M. G. Aartsen et al
Submitted to PRL
arXiv:1405.5303

The dawn of Neutrino Astronomy

- 2013: First clear evidence for extraterrestrial neutrinos
- IceCube has paved the road for neutrino astrophysics!
- No evidence yet of neutrino point and extended sources
- More data will resolve the origin of these neutrinos
  - measure the energy spectrum
  - single-out sources?
  - establish connection to Cosmic Rays