Blazars as the Astrophysical Counterparts of the IceCube Neutrinos

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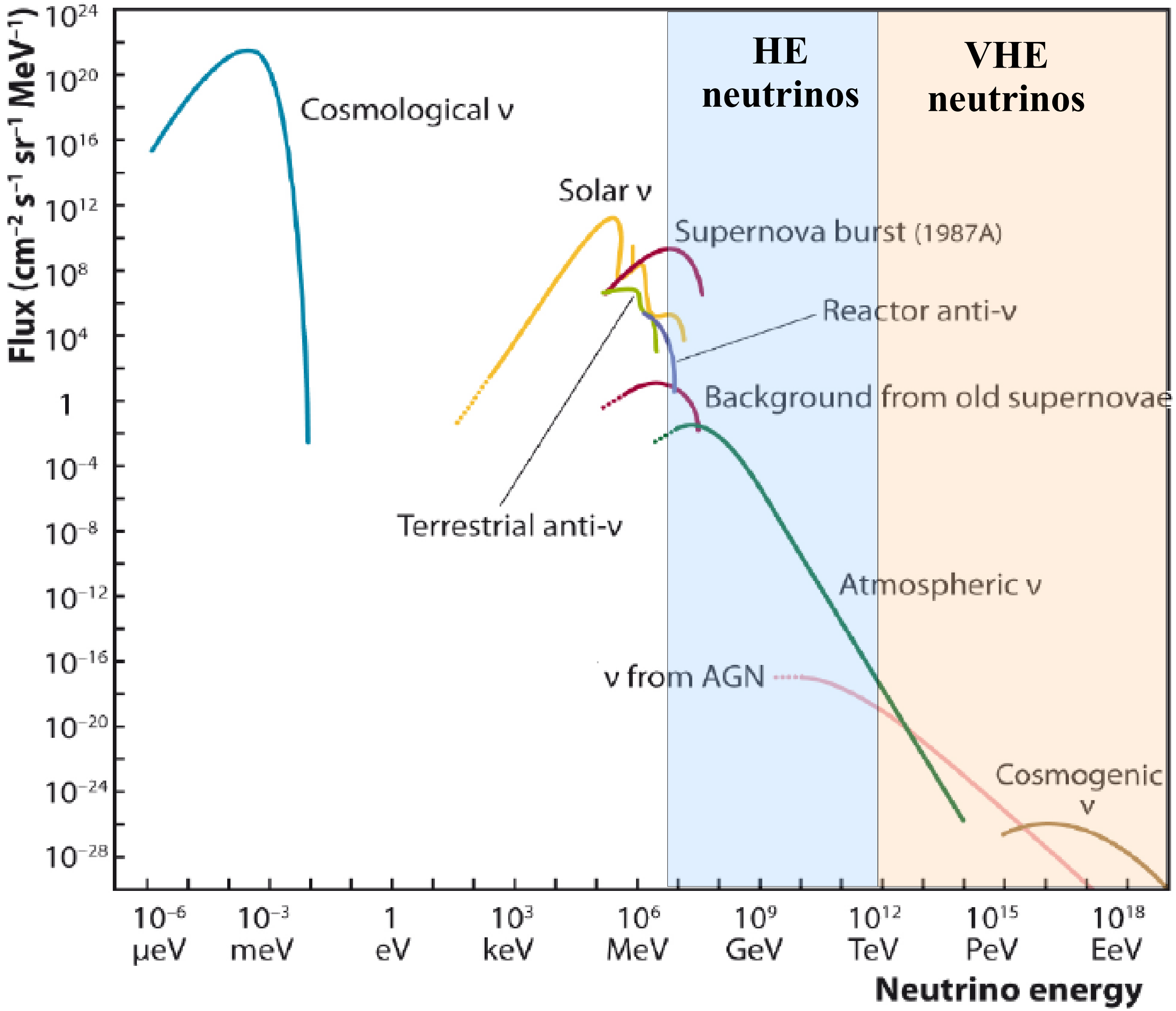
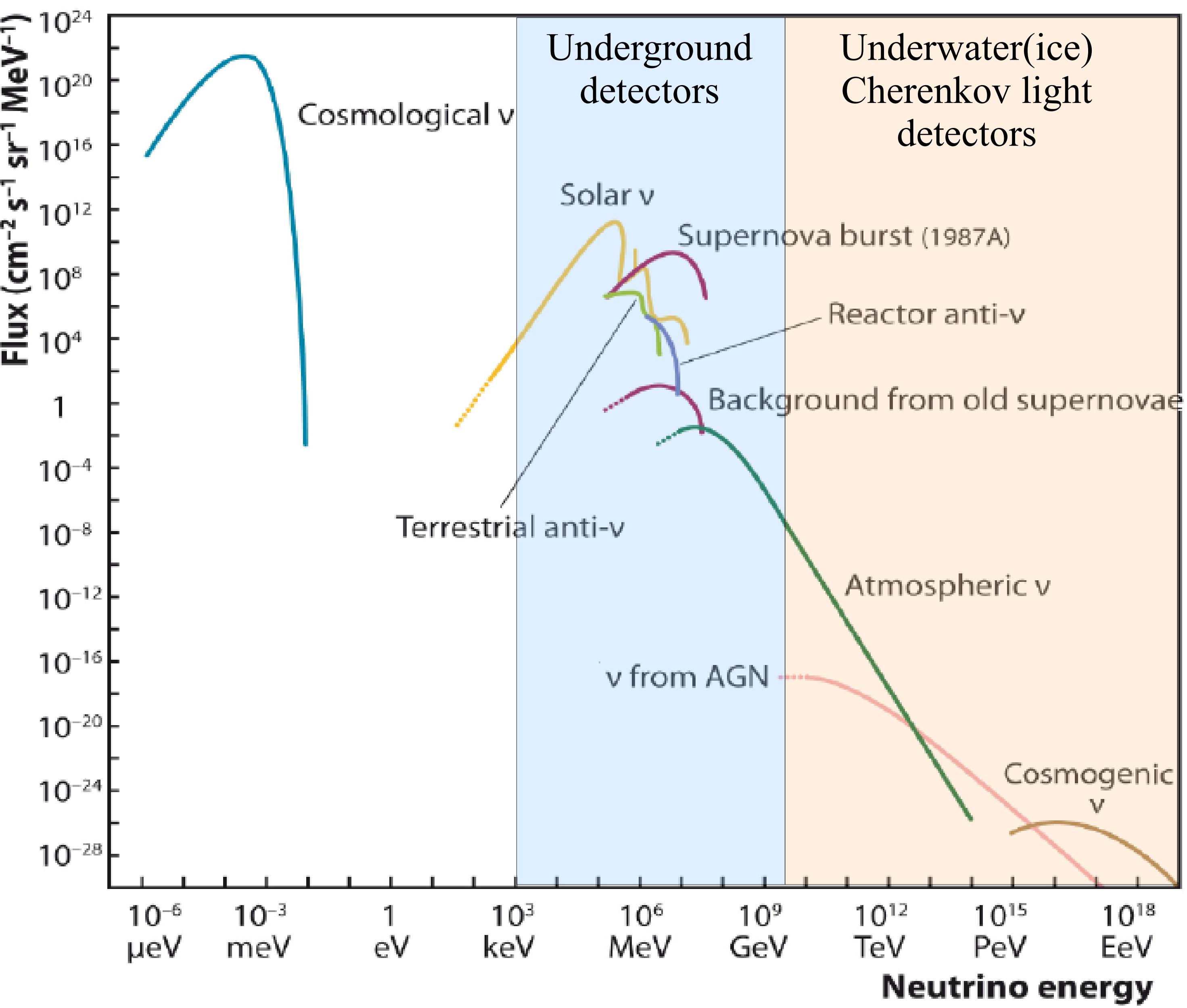
Talk outline

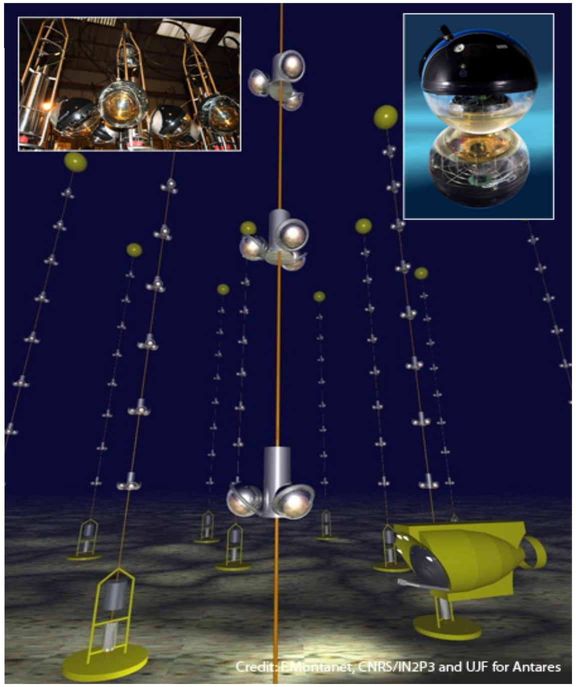
- Introduction
  - High energy (HE) vs. Very high energy (VHE) neutrinos
  - Overview of IceCube results
  - How are the VHE neutrinos produced?
- BL Lacs as probable astrophysical counterparts of IceCube neutrinos:
  - Emission from individual sources
  - Emission from the BL Lac population
  - Model predictions
- Summary

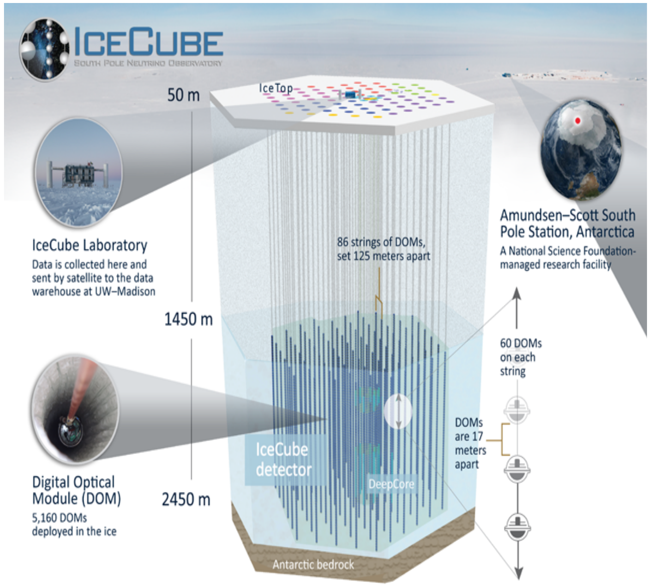
High energy vs. Very high energy ν



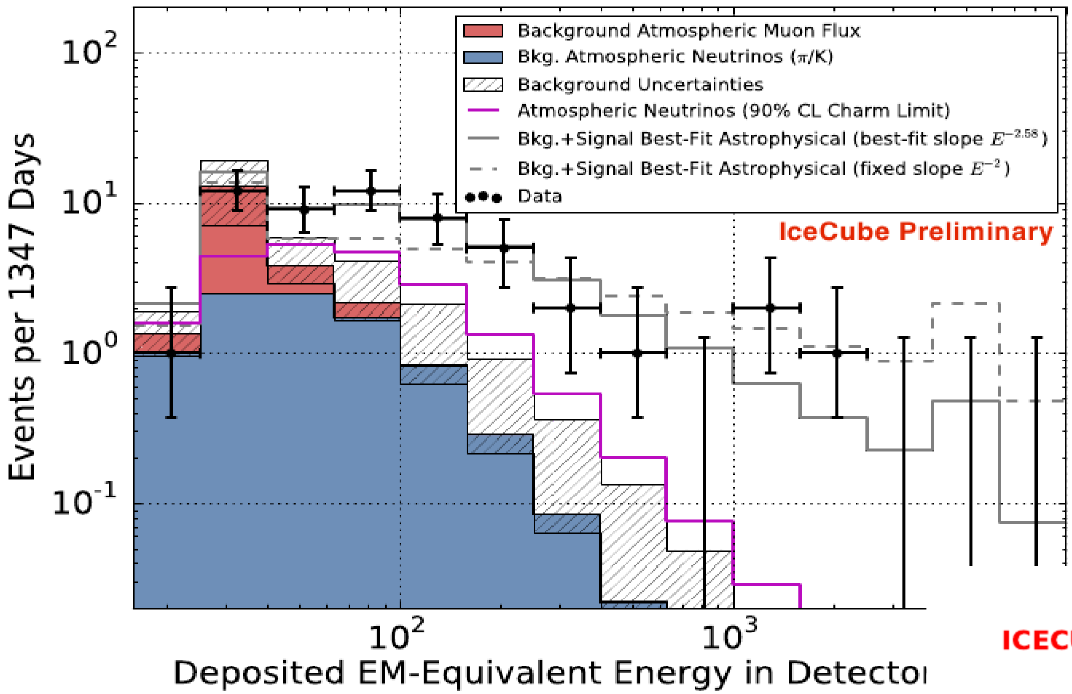
High energy vs. Very high energy ν



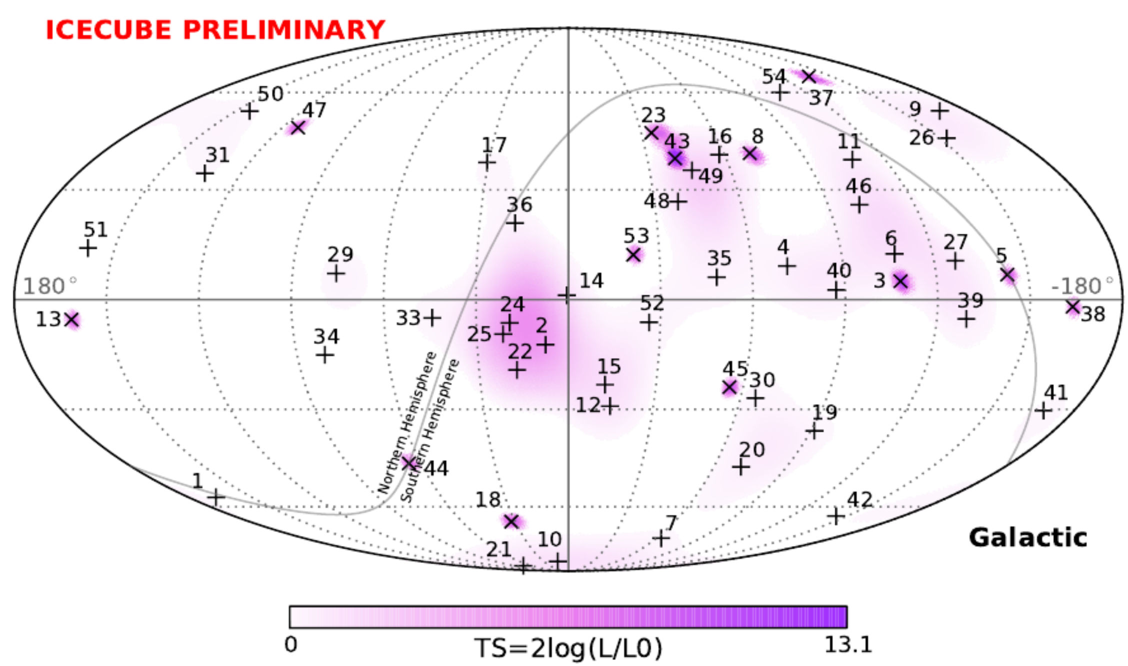




ICECUBE PRELIMINARY (ICRC 2015)



Left: Very high energy neutrino spectrum. In 4 years of data: 54 events in the range 30 TeV – 2 PeV. Spectral slope of astrophysical flux: γ=2.58

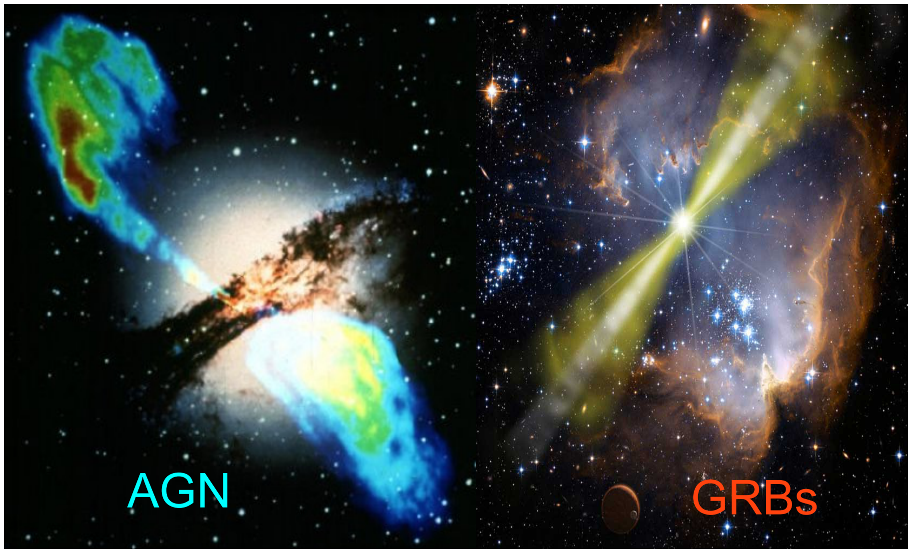


Right: Arrival directions of the 54 very high energy events found in IceCube using 4 years of data (2010–2014).

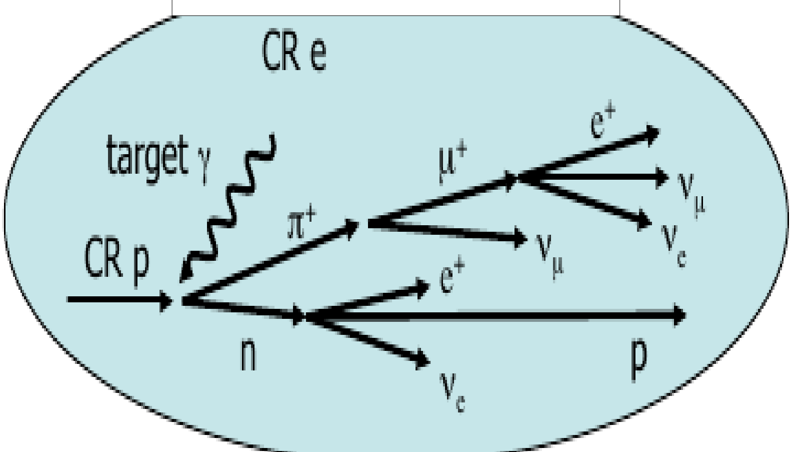
Not significant clustering found. Consistent with isotropy.

How are VHE ν produced?

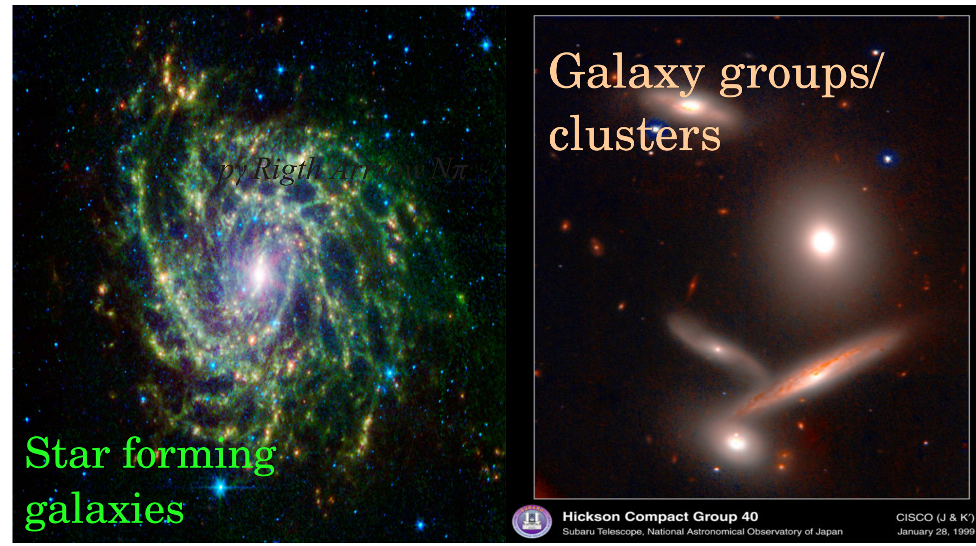
Jets as ν sources



$$p\gamma \rightarrow N\pi + X$$



CR reservoirs as ν sources



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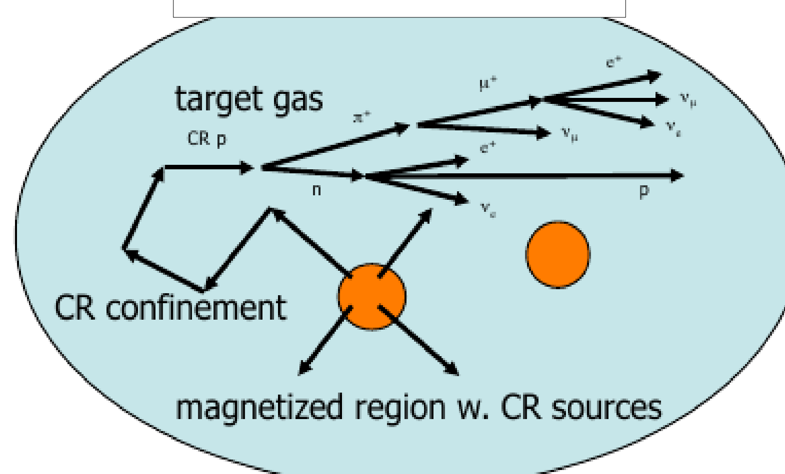
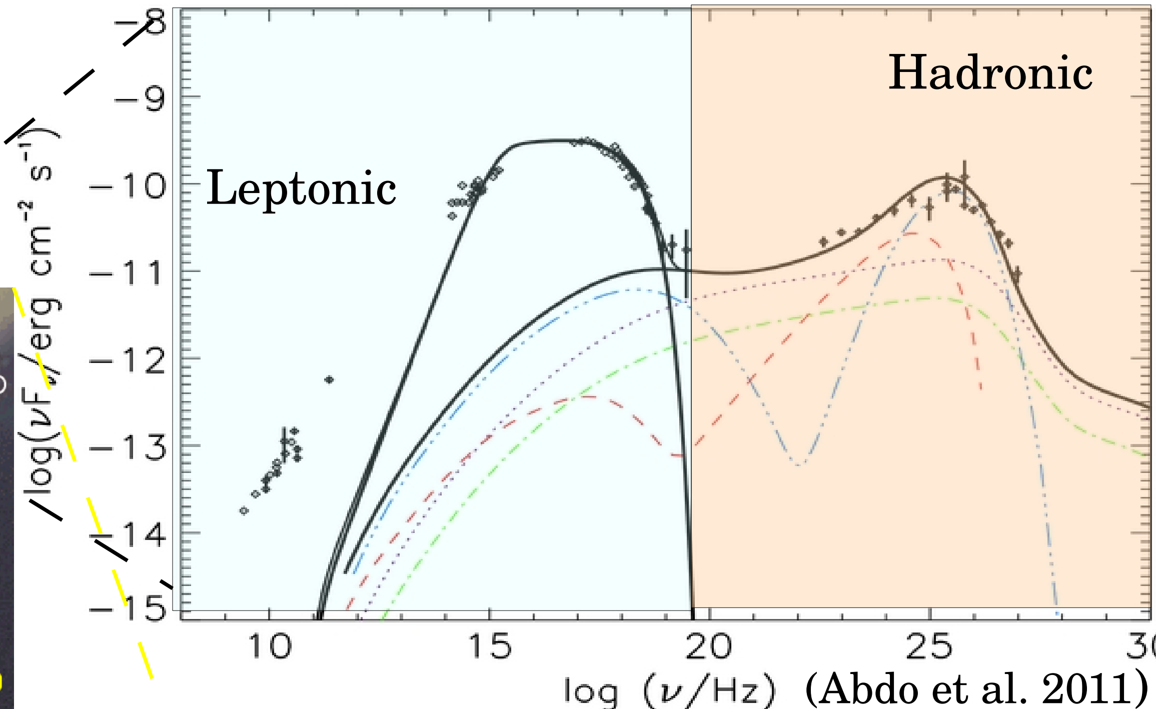


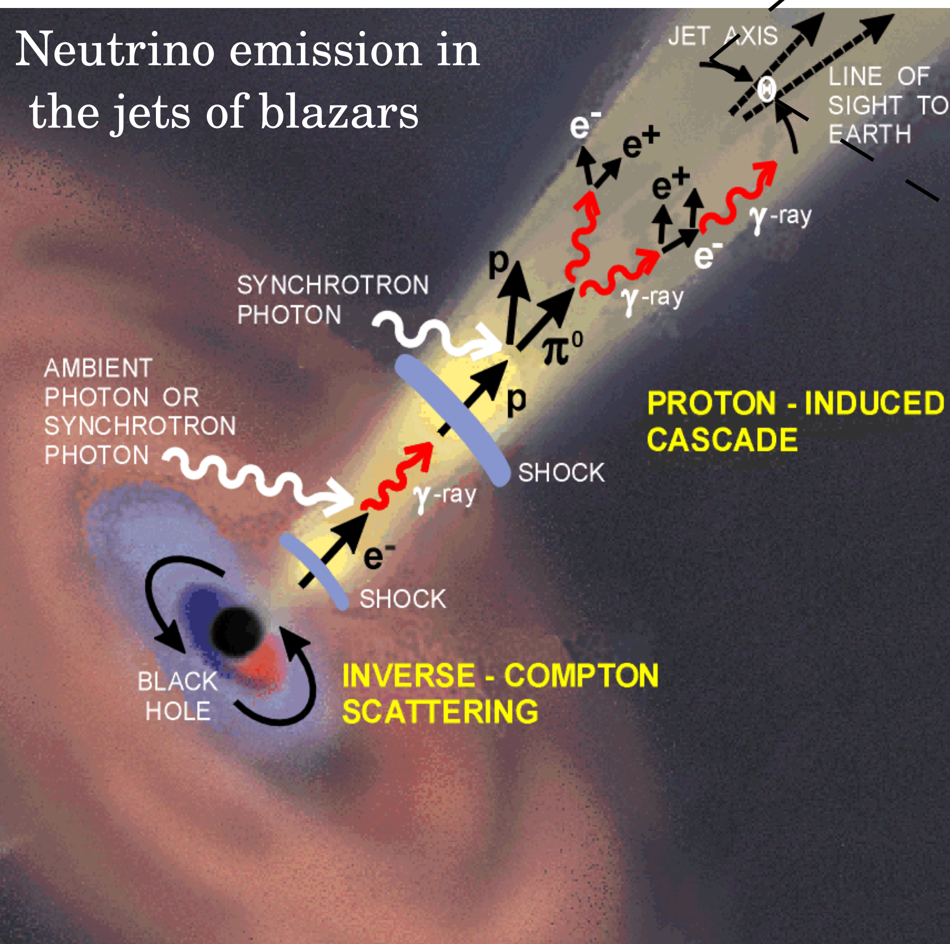
Neutrinos from blazars in a nutshell

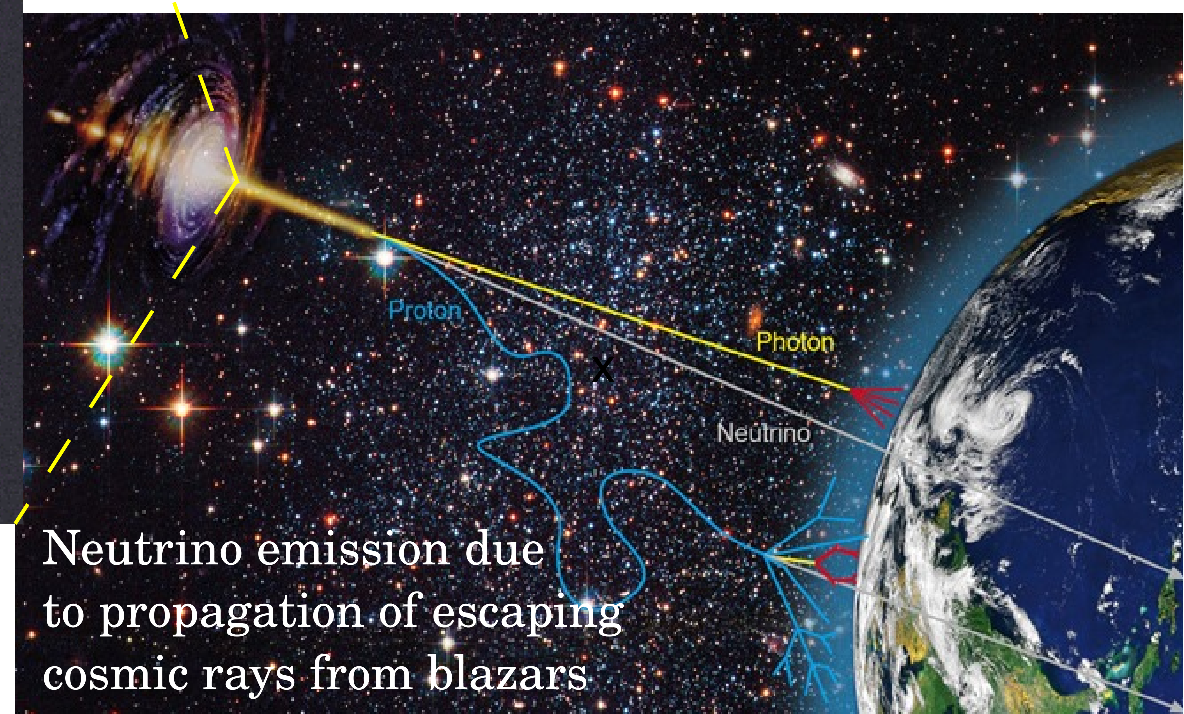
Multi-wavelength blazar emission



(Abdo et al. 2011)

Neutrino emission in the jets of blazars





Neutrino emission due to propagation of escaping cosmic rays from blazars

BL Lacs as counterparts of IceCube neutrinos

1. Cuts applied to the sample of 35 events:
   – E >60 TeV
   – median angular error < 20 deg
2. “Energetic” criterion: create “hybrid” γ-ν SEDs
3. All-sky γ-ray catalogs (GeV-TeV): TeVCat, WHSP, Fermi 1FHL.

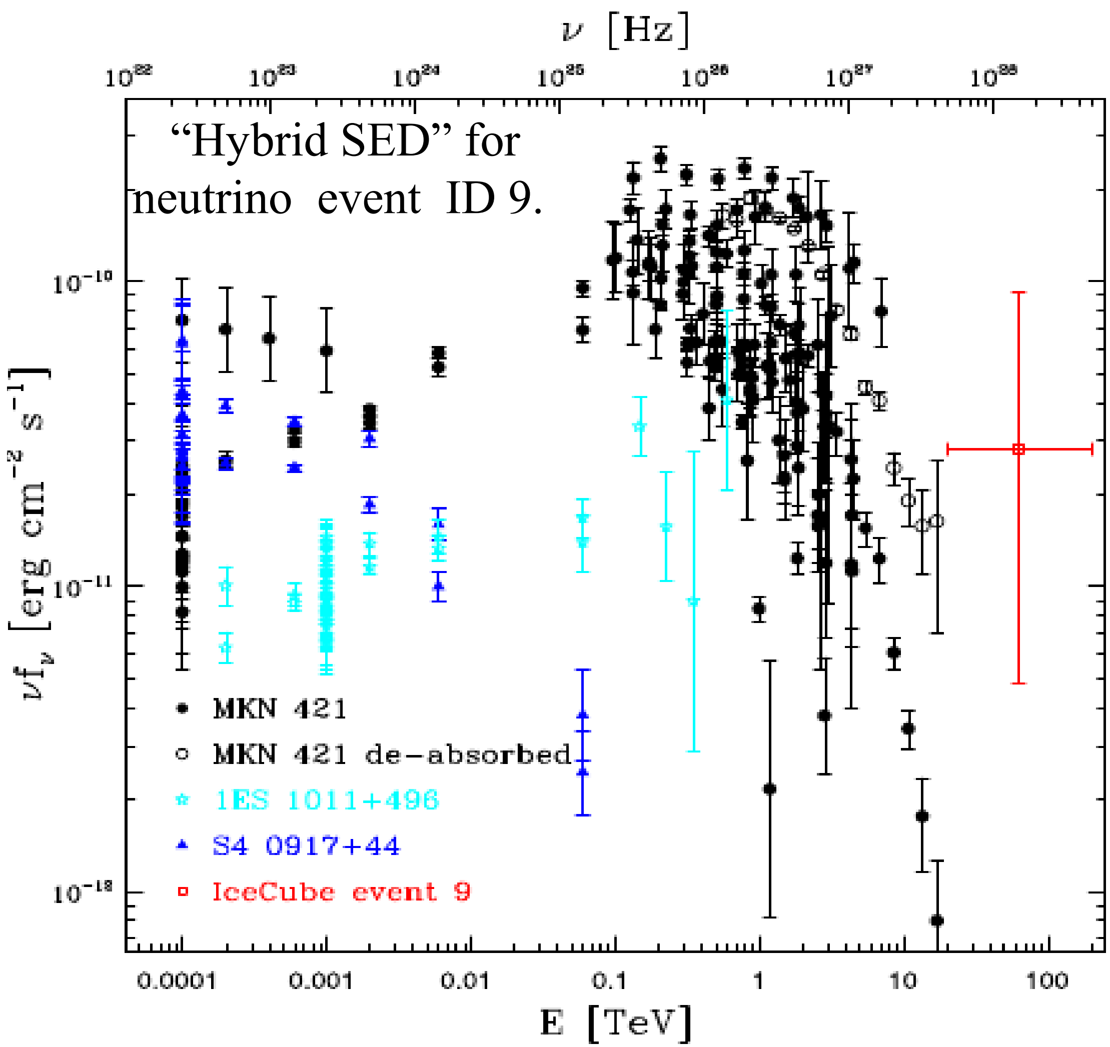
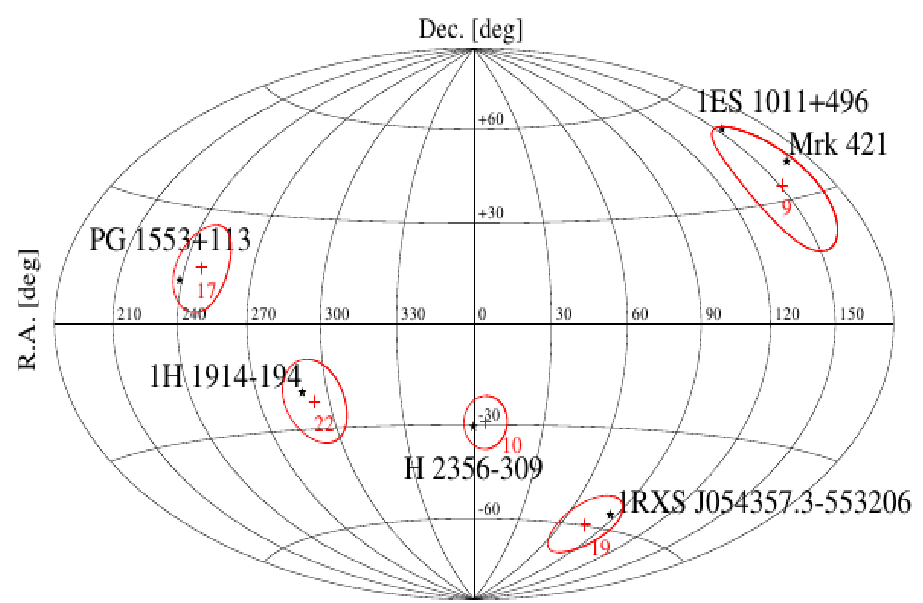


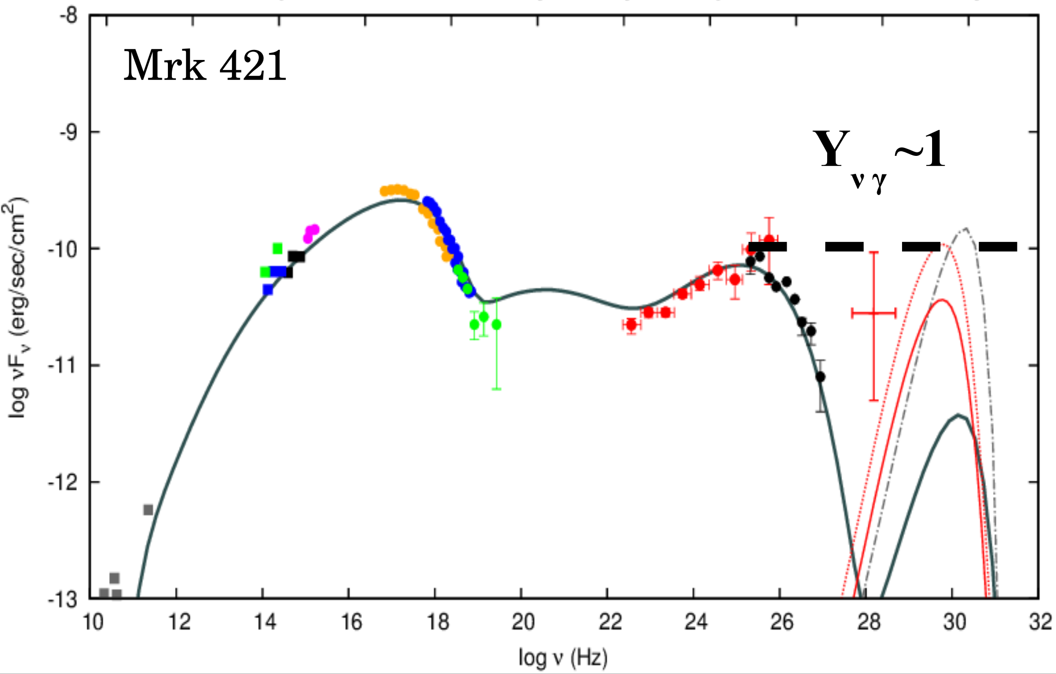
Table 4. List of most probable counterparts of selected IceCube high-energy neutrinos.

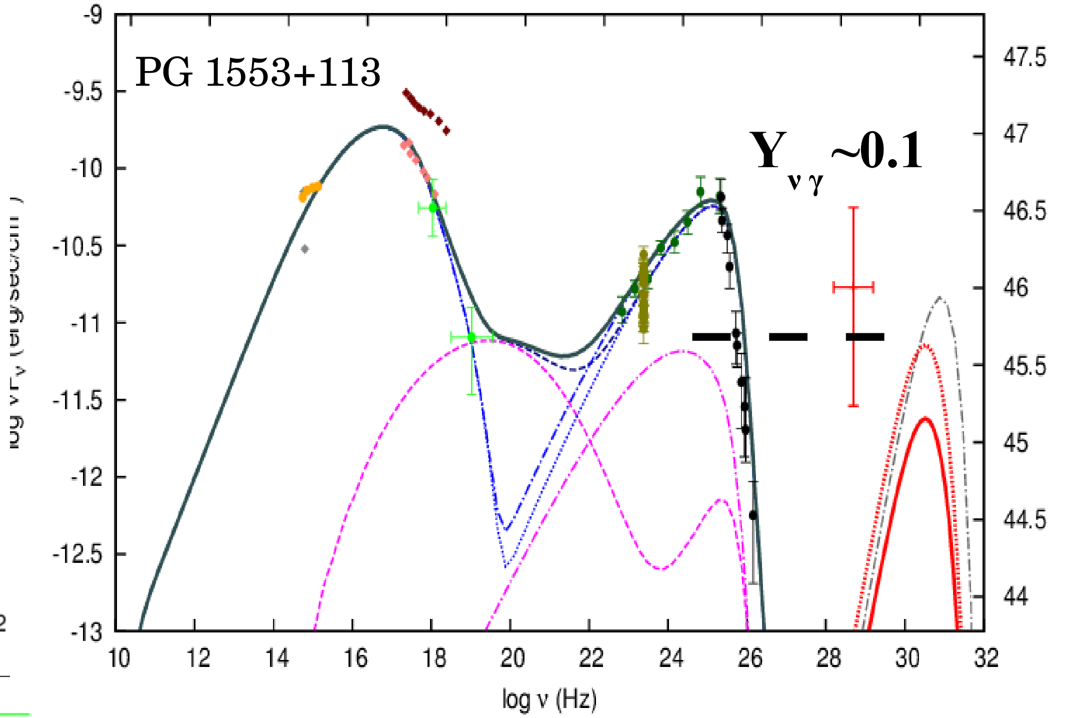
IceCube ID	Counterpart(s)	Class	Catalogue(s)
9	MKN 421	BL Lac (HSP)	TeVCat/WHSP
	1ES 1011+496	BL Lac (HSP)	TeVCat/WHSP
10	H 2356−309	BL Lac (HSP)	TeVCat/WHSP
14	HESS J1809−193	PWN	TeVCat
17	PG 1553+113	BL Lac (HSP)	TeVCat/WHSP
19	1RXS J054357.3−553206	BL Lac (HSP)	WHSP
20	SUMSS J014347−584550	BL Lac (HSP)	WHSP
22	1H 1914−194	BL Lac (HSP)	WHSP
27	PMN J0816−1311	BL Lac (HSP)	WHSP
33	MGRO J1908+06	PWN	TeVCat

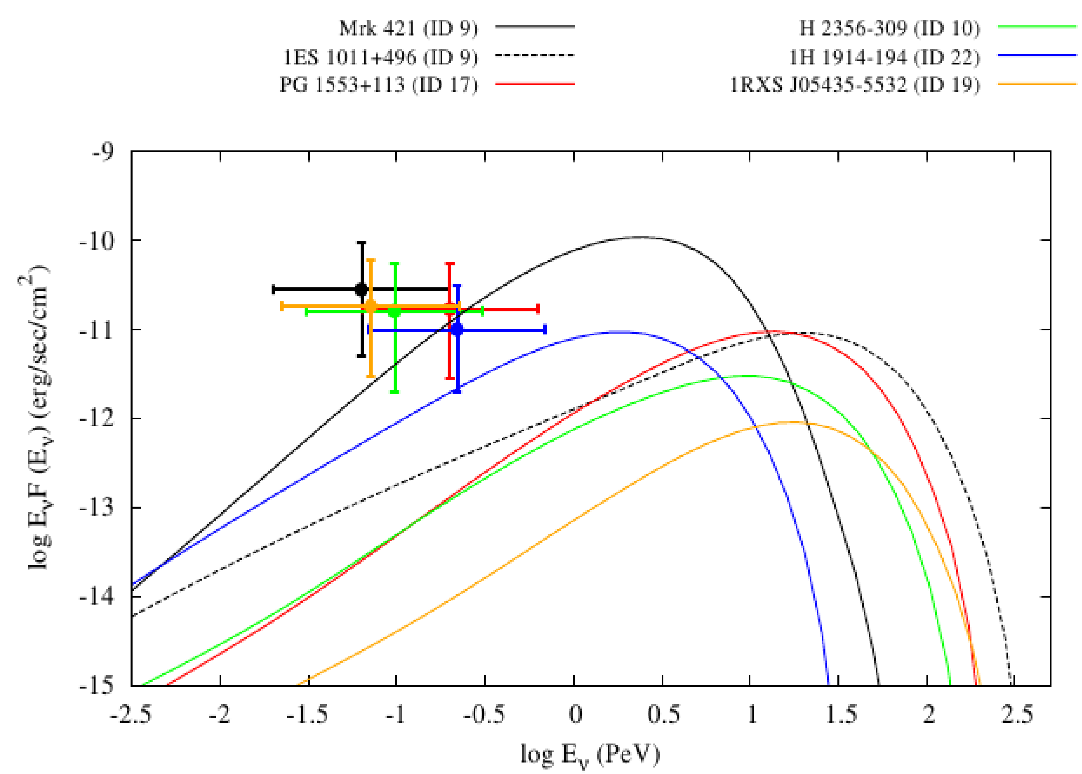


Padovani & Resconi 2014, MNRAS, 443

Neutrino emission from individual BL Lacs





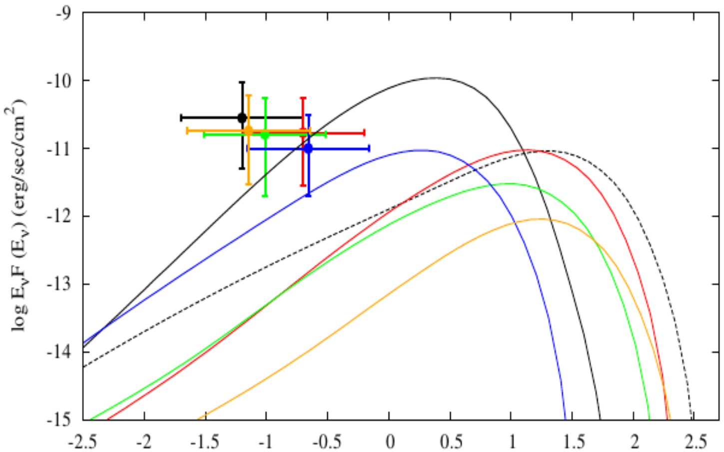


Mrk 421: possible positive detection of neutrinos might be achievable with some confidence (~3σ level) using preliminary discovery potentials based on 6 years IceCube life time

PG 1553+113: model prediction is much below the 3σ error bars. **Gamma-ray emission mostly from SSC**

Petropoulou et al. 2015, MNRAS, 448

Neutrino emission from *all* BL Lacs

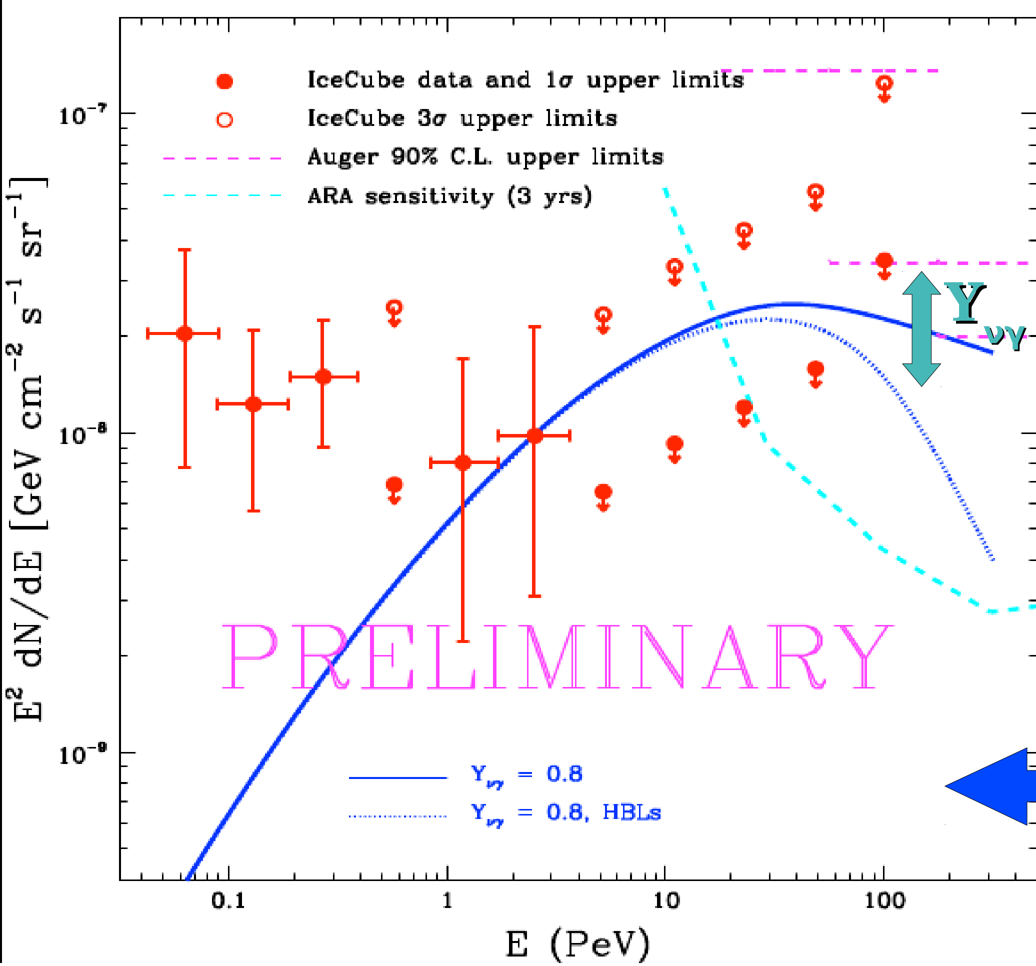


$$E_\nu F_\nu(E_\nu) = \frac{Y_{\nu\gamma} F_\gamma(>10\ \text{GeV})}{\int_{x_{\min}}^{\infty} dx\ x^{-s} e^{-x}} \left(\frac{E_\nu}{E_{\nu,p}}\right)^{-s+1} \exp\left(-\frac{E_\nu}{E_{\nu,p}}\right)$$

$$E_{\nu,p}(\delta, z, \nu^S_{\text{peak}}) \simeq \frac{17.5\ \text{PeV}}{(1+z)^2}\left(\frac{\delta}{10}\right)^2 \left(\frac{\nu^S_{\text{peak}}}{10^{16}\ \text{Hz}}\right)^{-1}$$

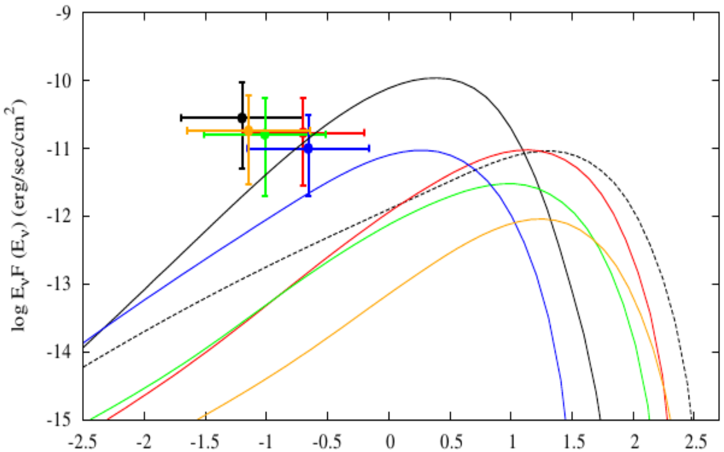
Monte-Carlo simulation for blazar population (Giommi & Padovani 2012 , 2013, 2015):

- Radio luminosity function & evolution
- Distribution of synchrotron peak ν (Hz)
- Redshift
- Distribution of Doppler factor
- γ-ray constraints



Padovani, Petropoulou et al. 2015, MNRAS, 452

Neutrino emission from *all* BL Lacs



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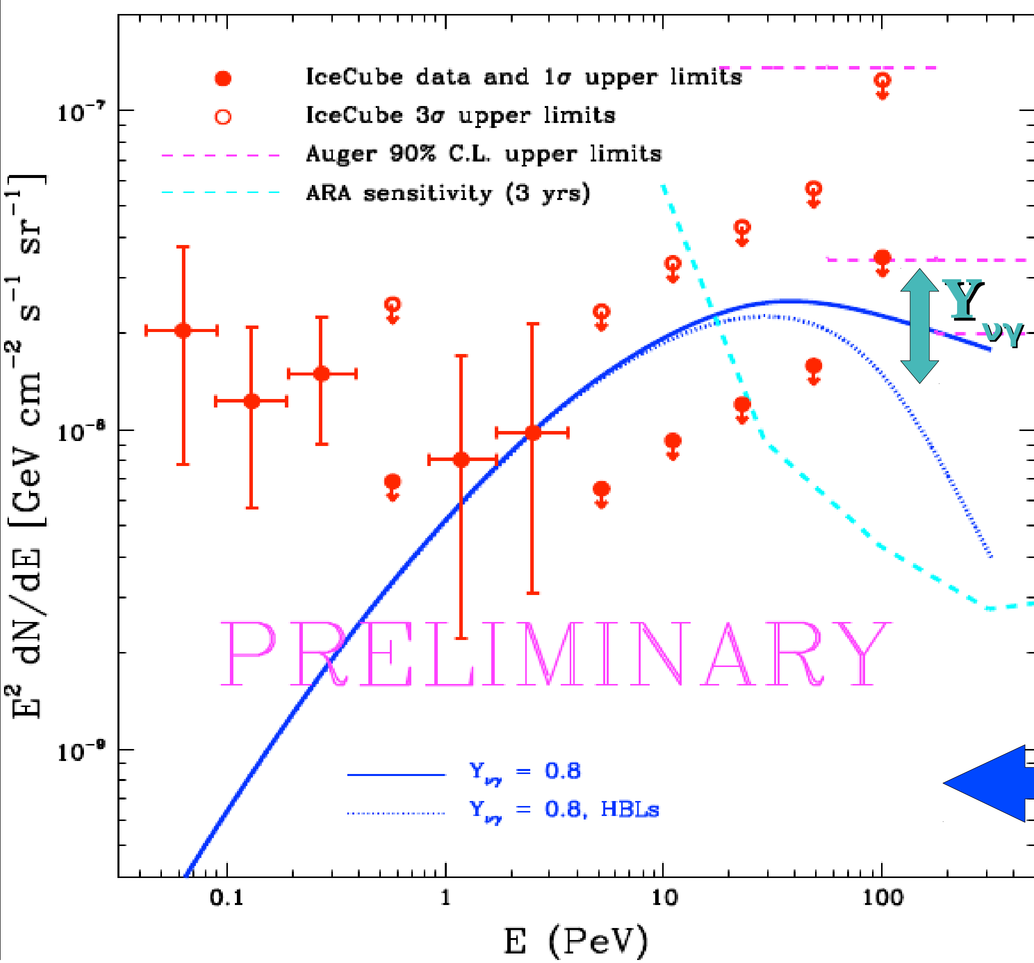

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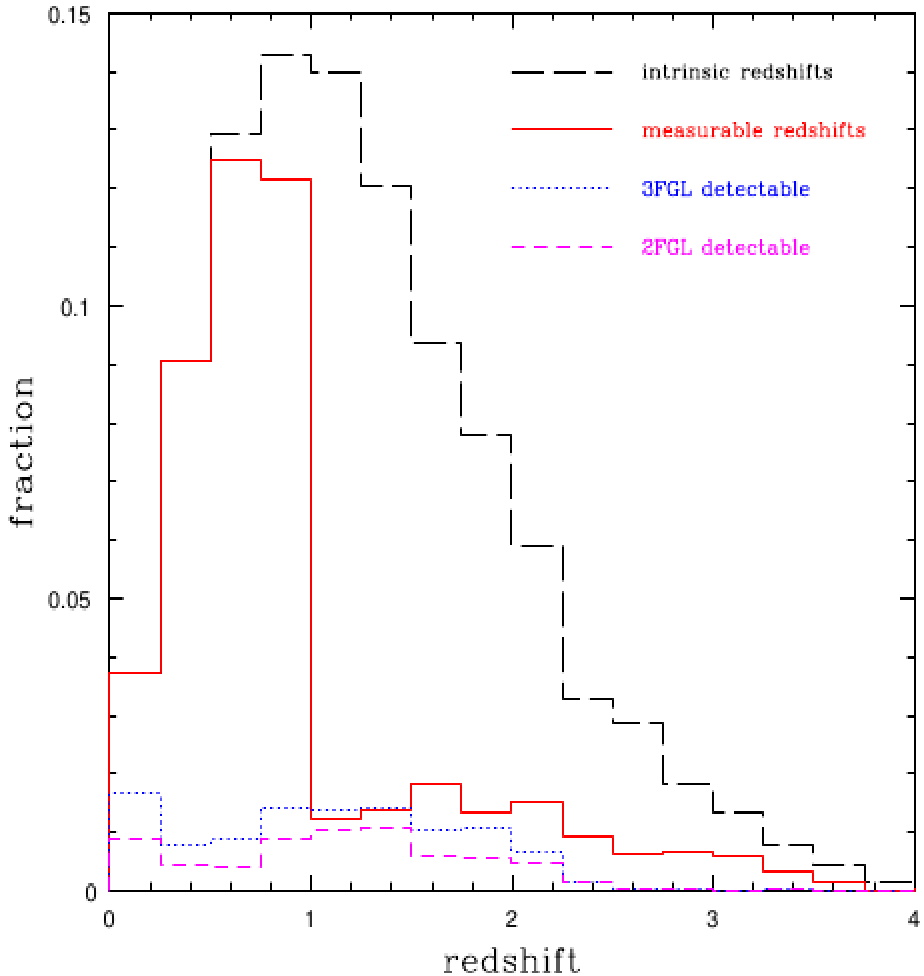
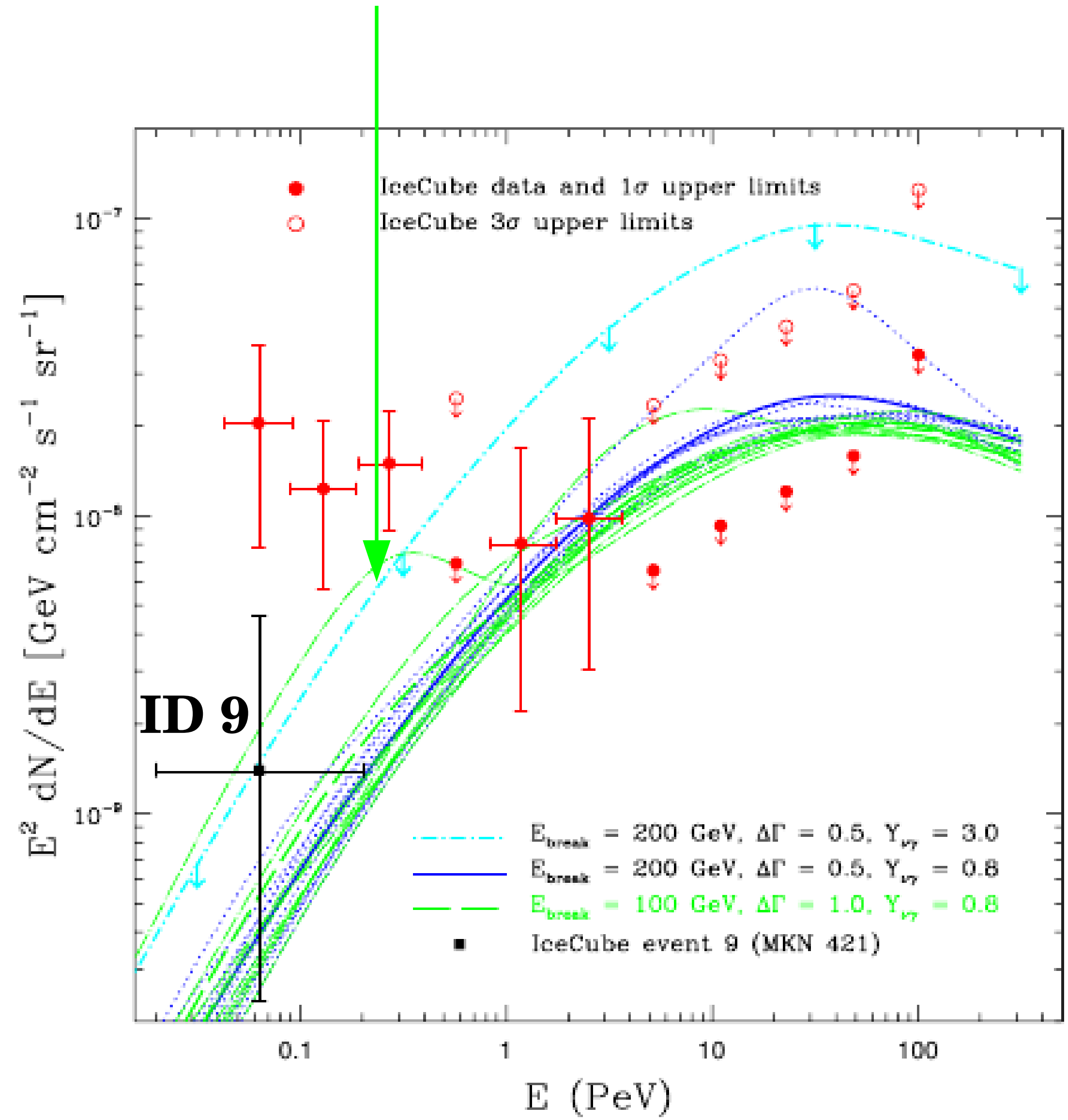
Padovani, Petropoulou et al. 2015, MNRAS, 452

Neutrino emission from *all* BL Lacs



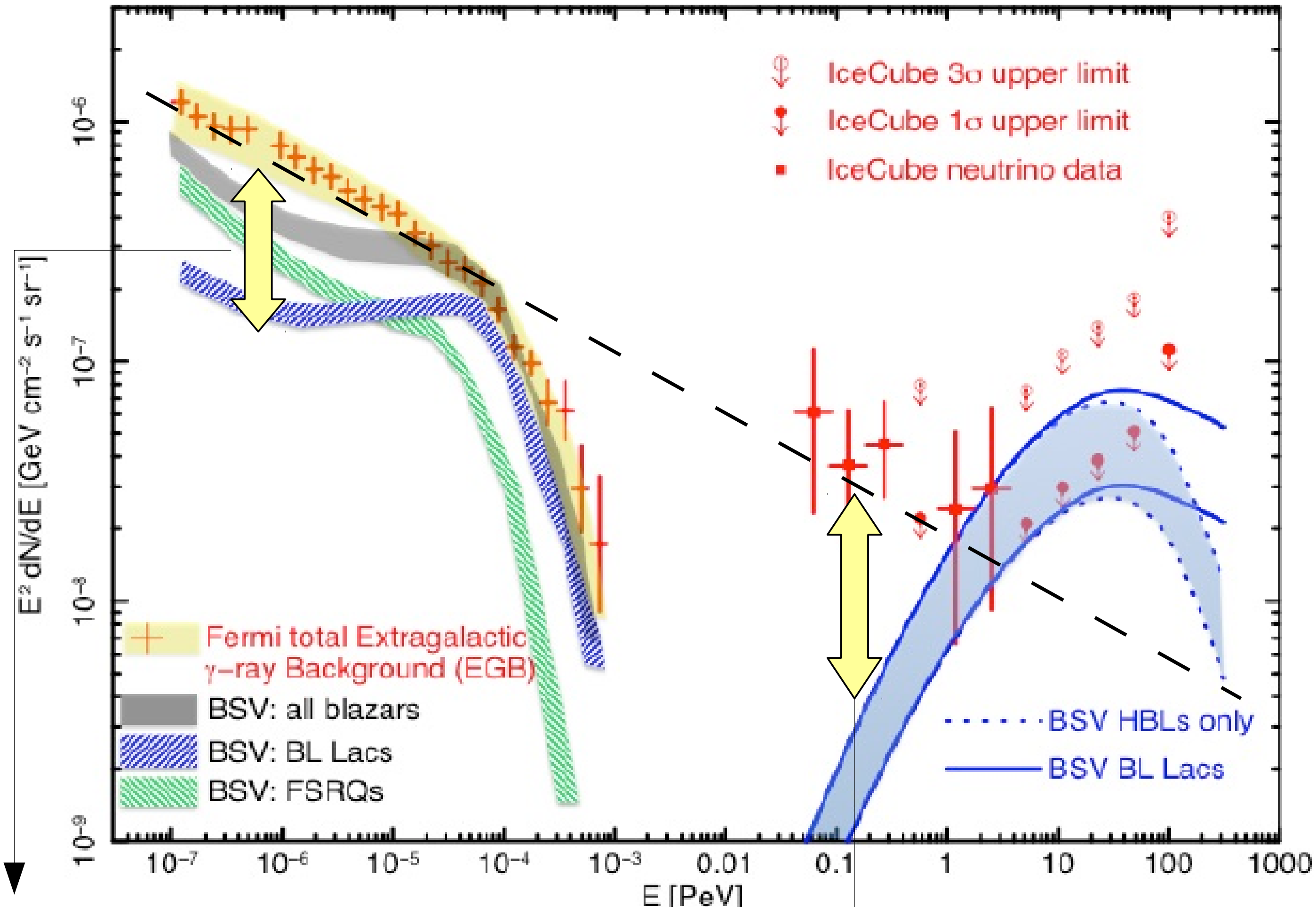
An "outlier" in the Monte Carlo simulation (a single bright source) mimics the neutrino emission from a point source!



Top left: Redshift distribution of ~0.5% of BL Lacs that make 95% of the NBG at 1 PeV.

Bottom right: Results from individual simulations showing the scatter in Monte Carlo simulations

Extragalactic backgrounds



– Another source population? (e.g. starburst galaxies: Lacki et al. 2014; Stecker 2007; galaxy clusters: talk by F. Zandanel)

– Another physical process? (e.g. pp collisions; Mannheim 1995, Ahlers et al. 2012)

– Contribution from individual BL Lacs ? (e.g. Mrk 421)

– Galactic contribution? (e.g. Padovani & Resconi 2014)

Predicted # of events

	With Glashow resonance	Without Glashow resonance
Y=0.8, Eγ=200GeV, ΔΓ=0.5	7 (2-10 PeV) 9-10 (2-100PeV)	4.6 (2-10 PeV) 6.6-7.6 (2-100 PeV)
Y=0.8, Eγ=100GeV, ΔΓ=1.0	~6 (2-10 PeV) ~8-9 (2-100PeV)	4 (2-10 PeV) 6-7 (2-100PeV)
Y=0.3, Eγ=200GeV, ΔΓ=0.5	2.6 (2-10 PeV) ~4 (2-100PeV)	1.7 (2-10 PeV) ~3 (2-100PeV)

6.6 is the 3σ upper limit for 0 events (Gehrels 1985)

Using the effective areas from IceCube (2013) in the range 2-10 PeV and extrapolating for the energy range 10-100 PeV.

Summary

Neutrino emission from individual BL Lacs :

– successful leptohadronic fits to the Spectral Energy Distribution (SED) of 6 sources (with different z, SEDs etc)!

– Mrk 421 (z=0.031) and 1H 1914-194 (z=0.137) potential point sources of neutrinos

– the ratio Y of the ν luminosity to the γ-ray (>10 GeV) luminosity is a measure of the hadronic "contamination" to the blazar SED

Neutrino emission from all BL Lacs :

– the NBG from BL Lacs explains the 1-2 PeV flux but requires another population for the sub-PeV neutrino flux

– only 0.5% of all BL Lacs is responsible for 95% of the NBG at 1 PeV

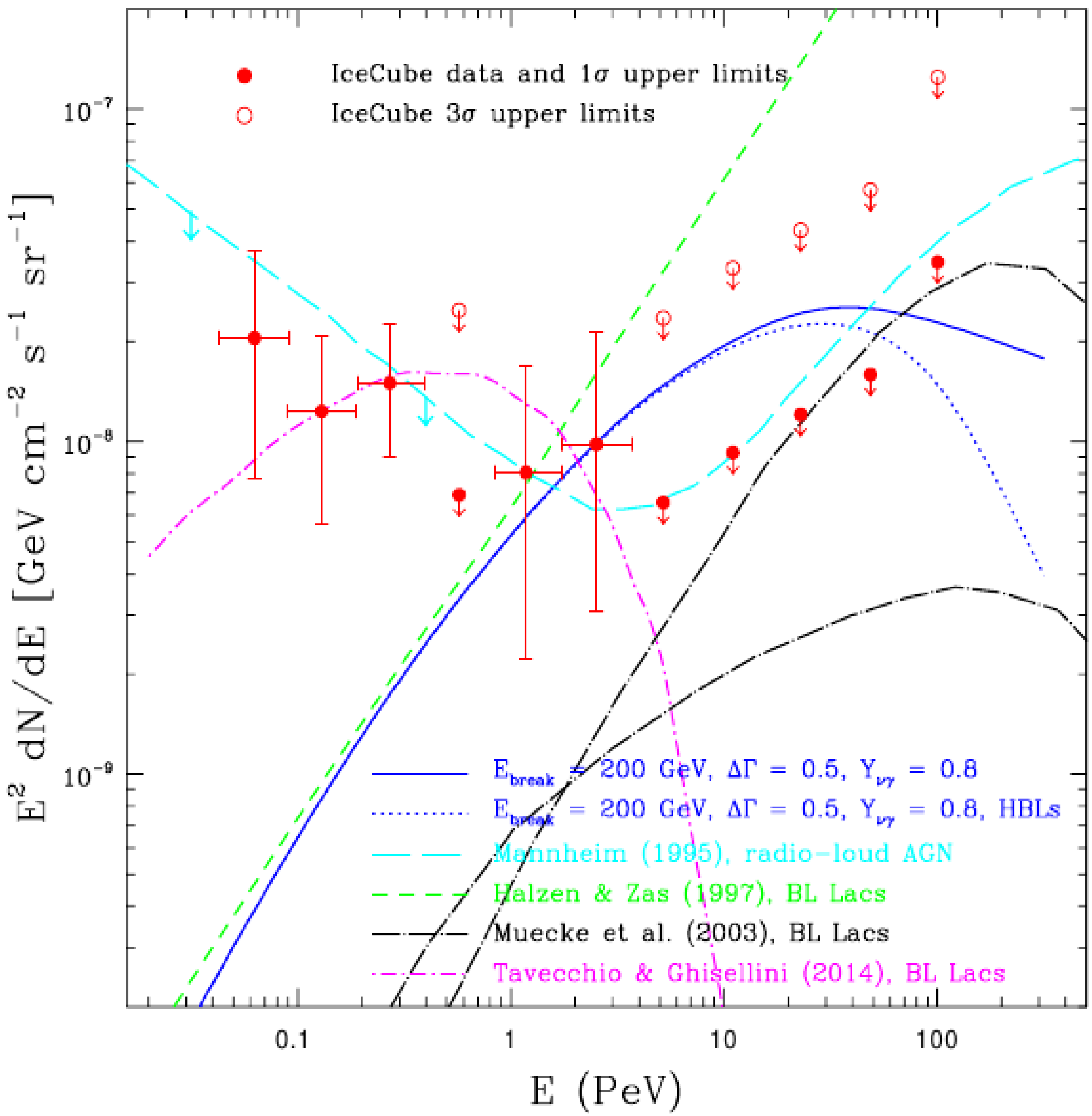
– only 11% of 0.5% of all BL Lacs would be detectable by the 3FGL Fermi catalog

– future non-detections above 2~PeV may be used to constrain the average Y value of BL Lacs

THANK YOU

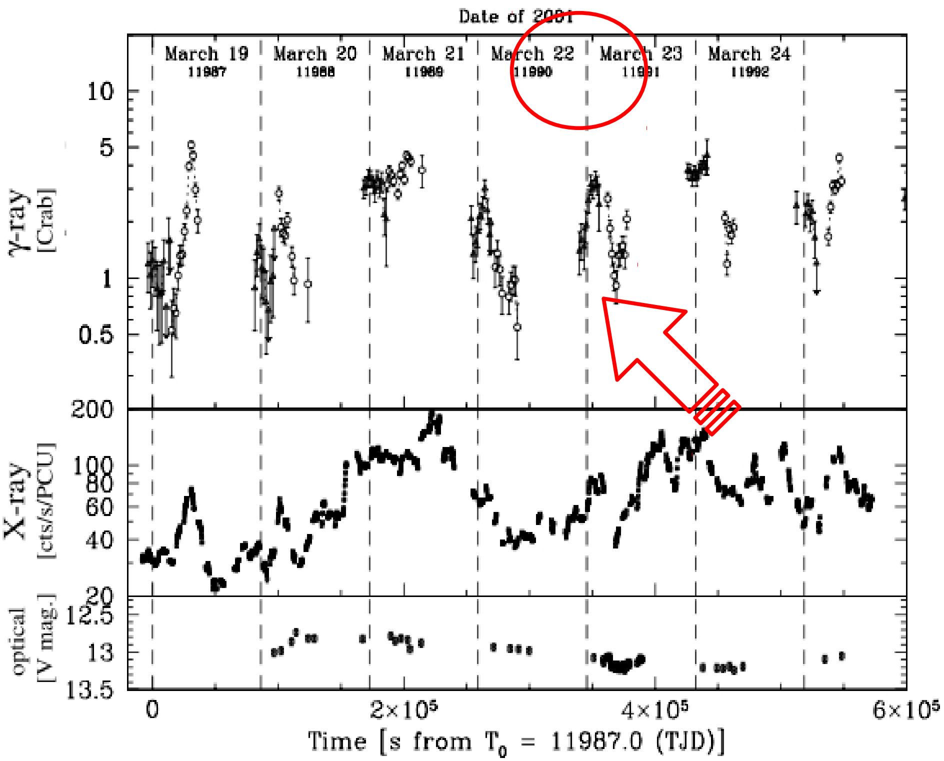
Back-up slides

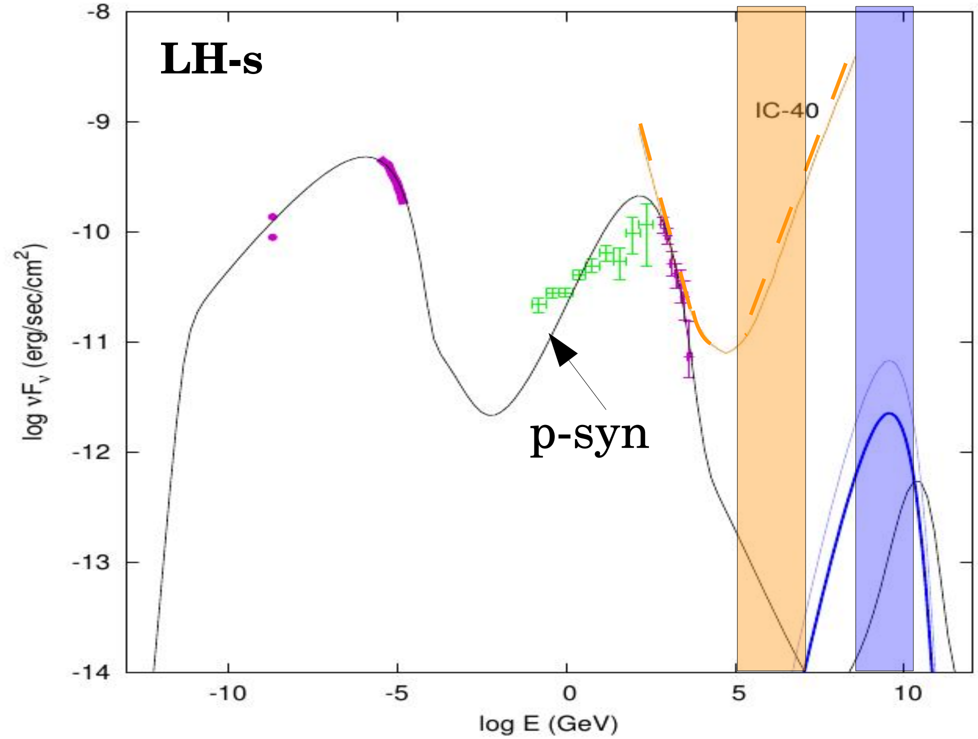
Model comparison



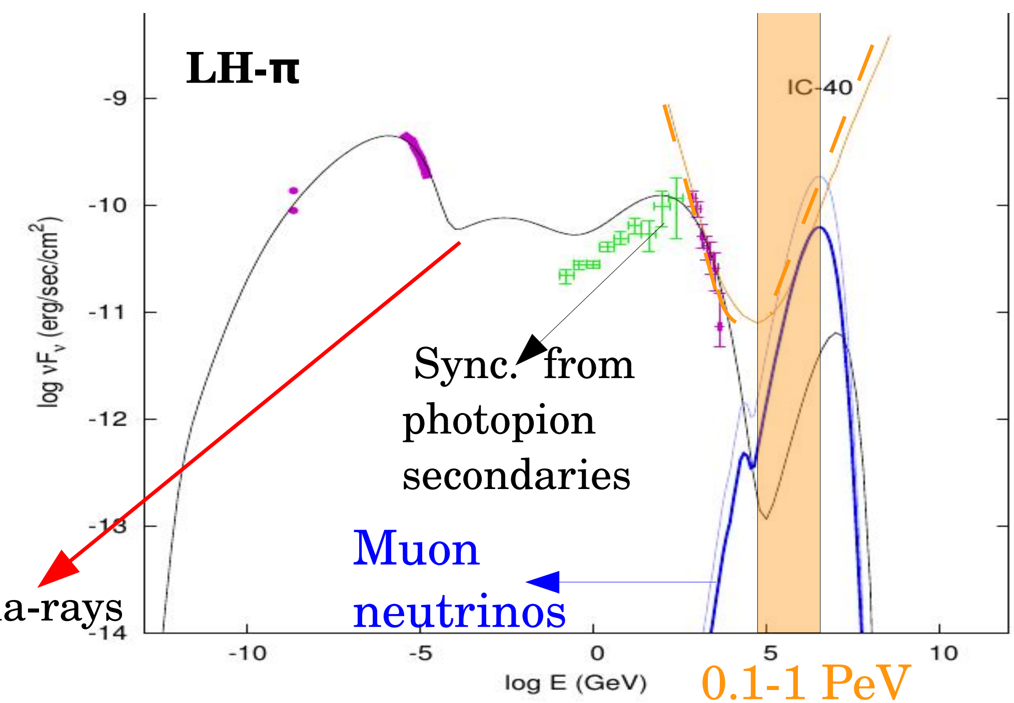
The case of Mrk 421: SED & ν

The 2001 MW campaign (Fossati et al. 2008, ApJ, 677)



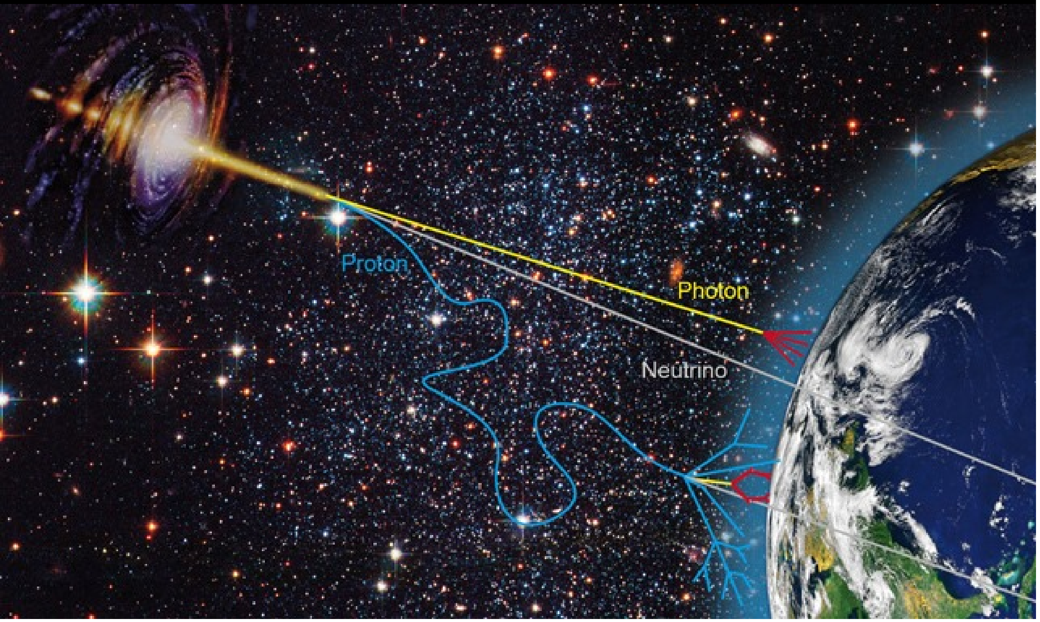


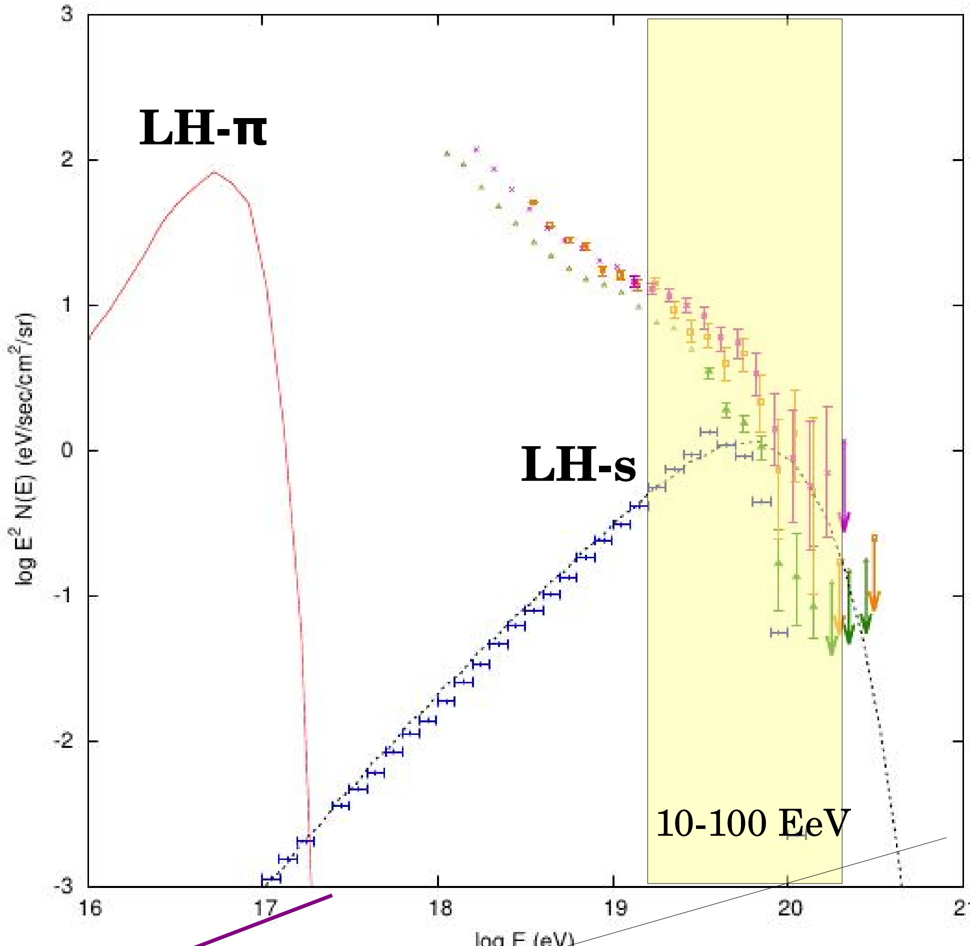
Dimitrakoudis et al., 2014, Aph, 54



"Bethe-Heitler" component: a third hump in soft gamma-rays (**Petropoulou & Mastichiadis 2015, MNRAS, 447**)

The case of Mrk 421: Cosmic-rays





$n \rightarrow p + e^{-} + \bar{\nu}_e$ Neutron decay

$p + CMB \rightarrow \ldots cosmogenic\ \nu$ Proton losses

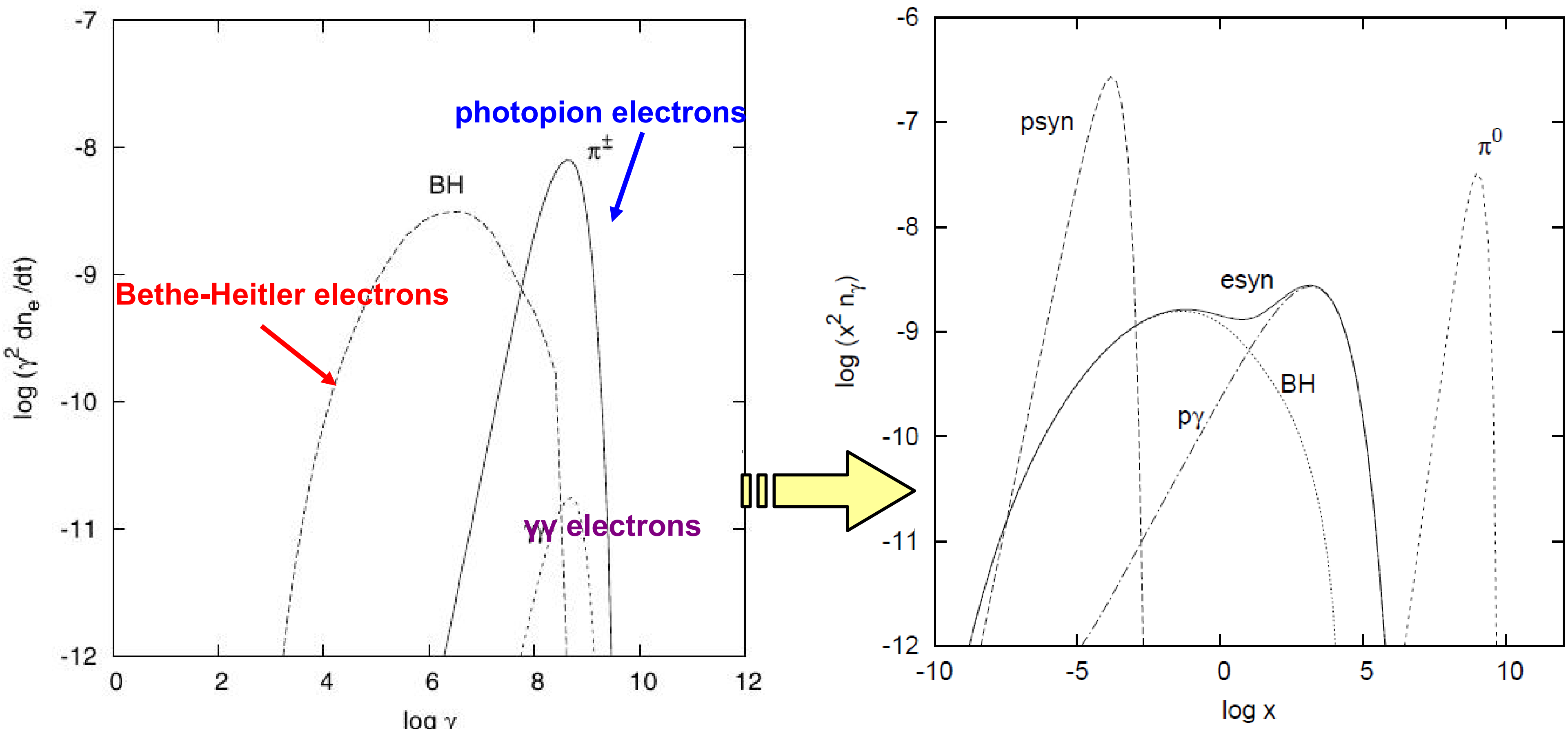
$p + B \rightarrow \ldots deflection$

(Propagation was made using CRPropa 2.0)

Example of a SED

Secondary electrons

Photons



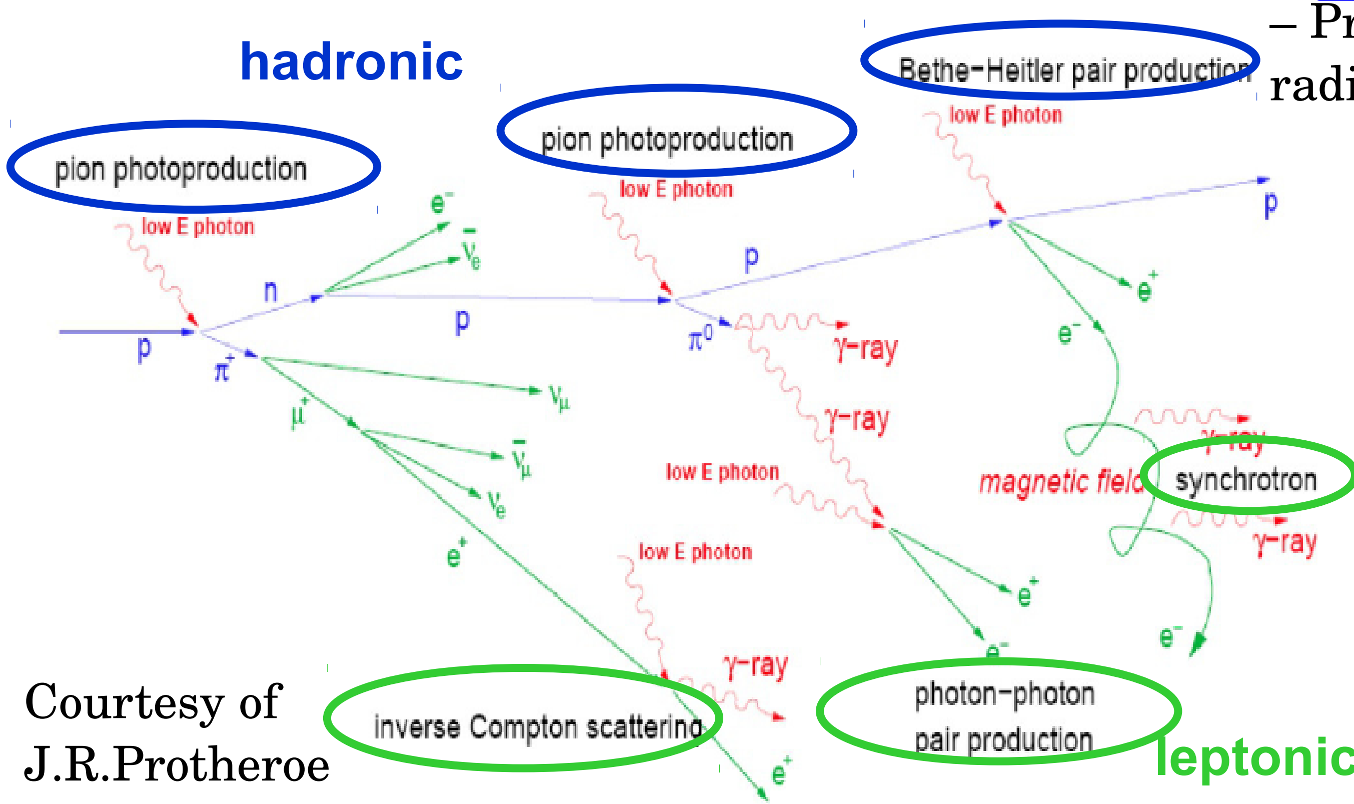
Dimitrakoudis et al. 2012

$$R = 3\times10^{16}cm$$
$$B = 1\mathrm{G}$$
$$E'_p = 2\times10^{15}eV$$

Hadronic models: processes in a nutshell

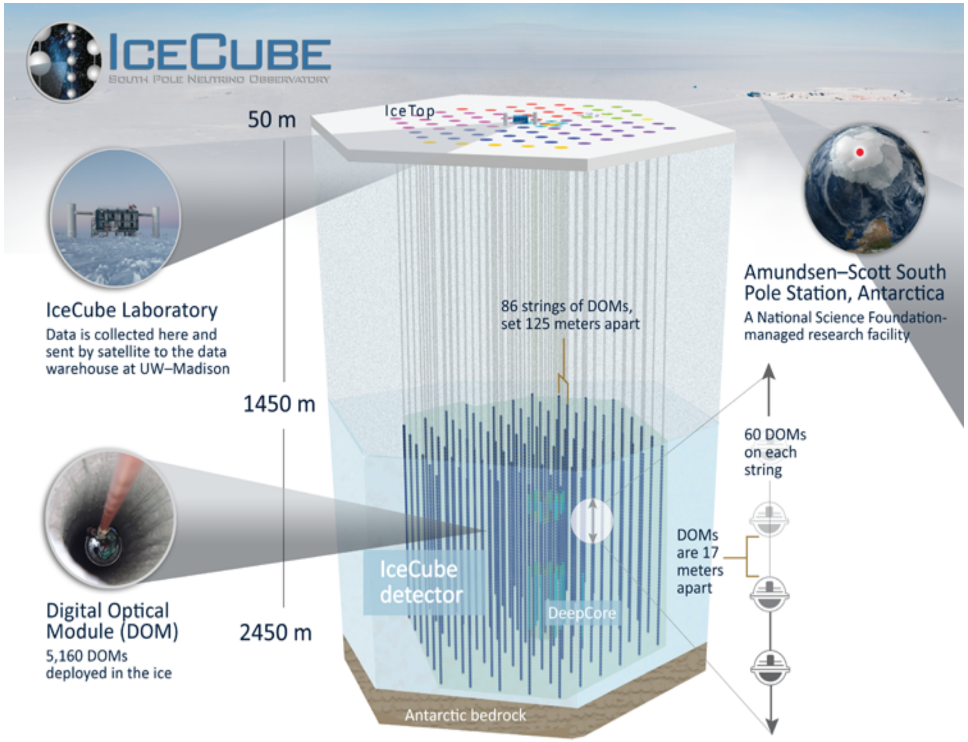
Leptonic emission models
– Synchrotron radiation
– Inverse Compton scattering
– Photon-photon absorption
– Synchrotron self-absorption

Hadronic emission models
– Proton-proton (pp) pion production
– Bethe-Heitler pair production
– Proton-photon pion production
– Neutron-photon pion production
– Neutral pion decay into γ-rays
– Charged pion decay into muons
– Muon decay into pairs
– Neutrino production
– Proton (+pion, muon) synchrotron radiation

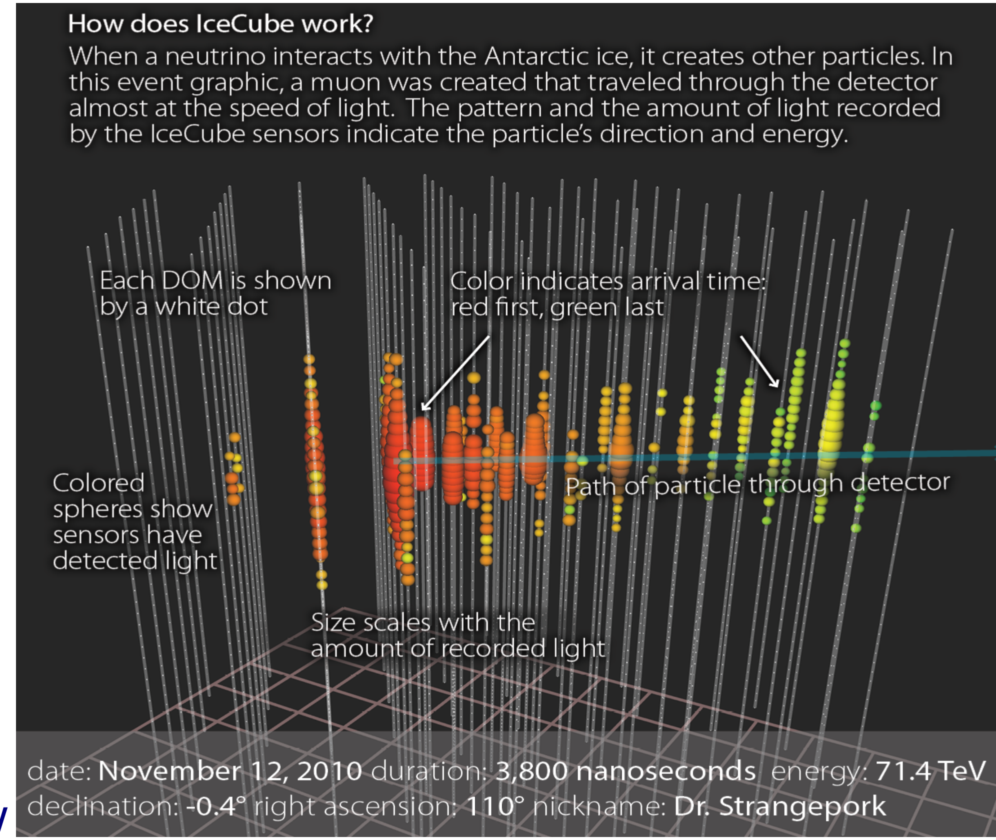


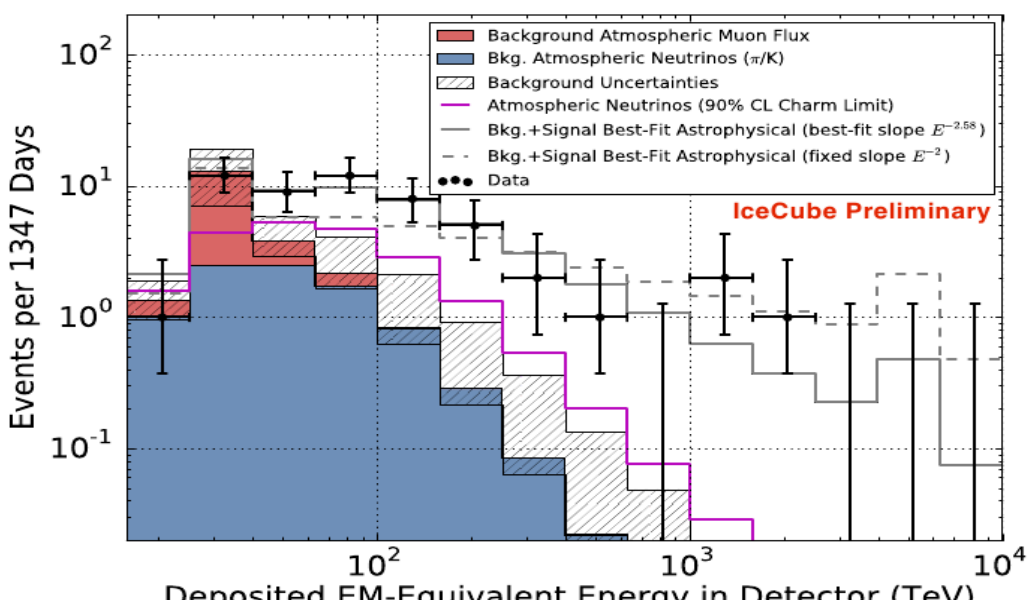
Courtesy of J.R.Protheroe

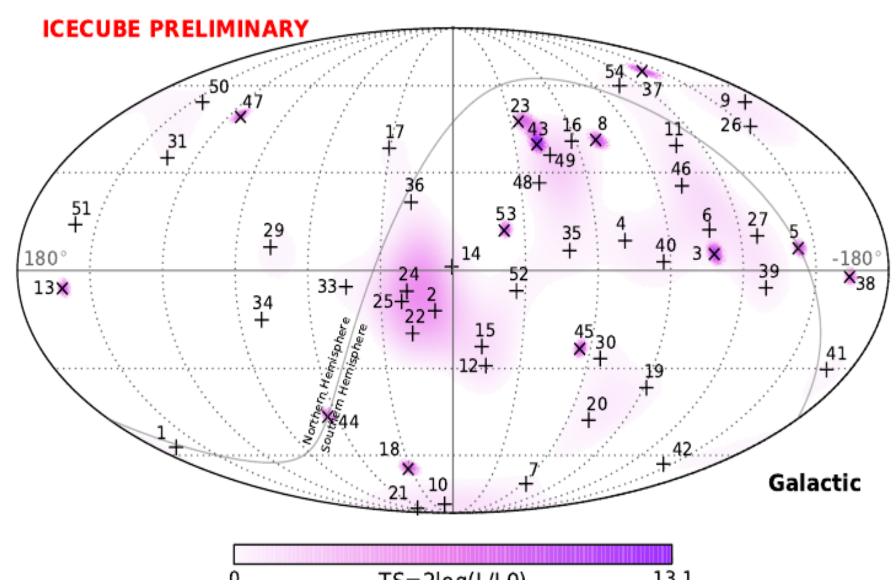
An introductory slide



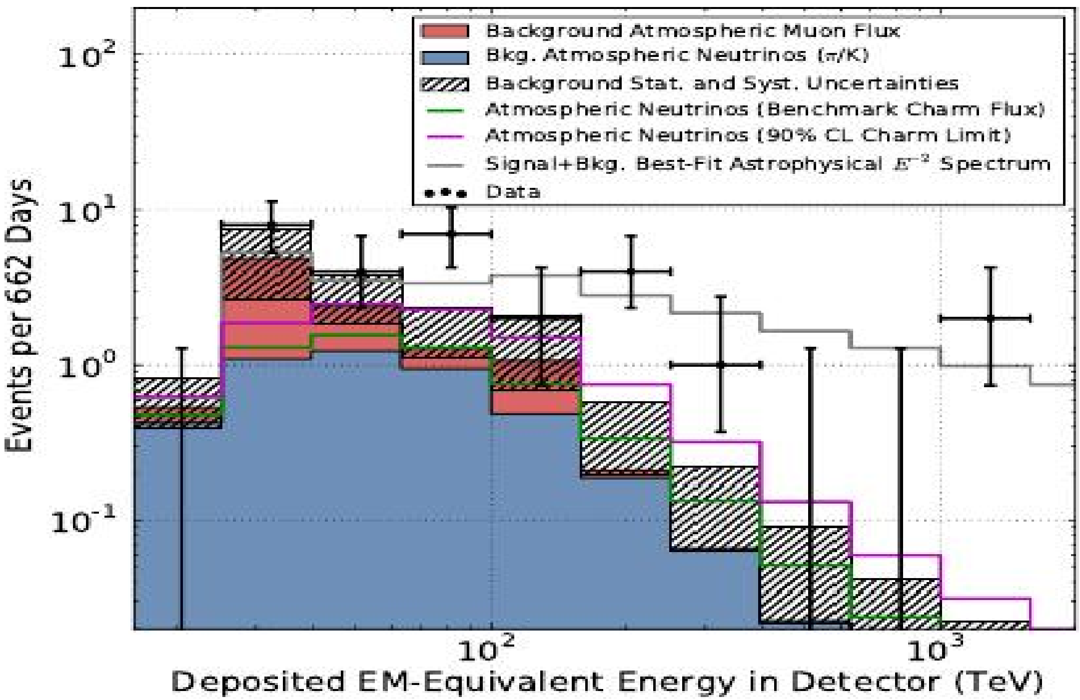
https://www.youtube.com/watch?v=3PZgfPHULHw



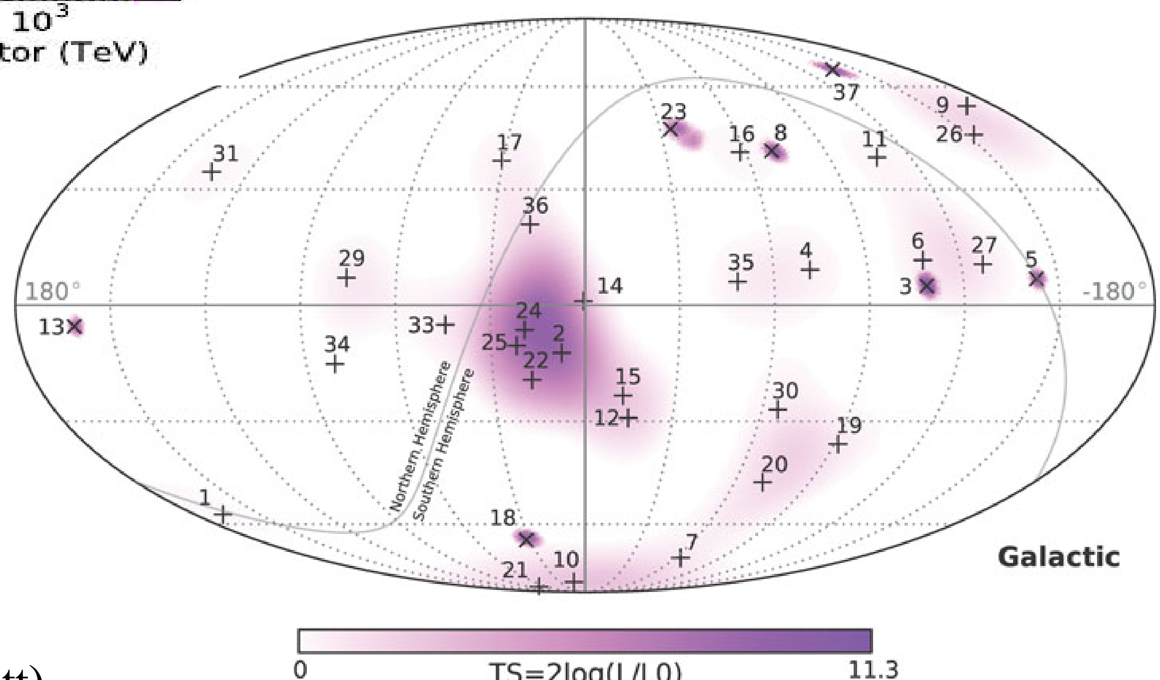




Overview of IceCube results



Left: Very high energy neutrino spectrum. In 3 years of data: 37 events in the range 30 TeV – 2 PeV.
Spectral slope of astrophysical flux: γ=2.3
(PRELIMINARY: in 4-year data 54 events; Spectral slope of astrophysical flux: γ=2.58)



Right: Arrival directions of the 37 very high energy events found in IceCube using 3 years of data (2010–2013).
Not significant clustering found.
Consistent with isotropy.

(The IceCube collaboration,2014, Phys.Rev.Lett)