The many faces of blazars in the context of hadronic models

Maria Petropoulou

Department of Physics & Astronomy,
Purdue University, West Lafayette, USA

In collaboration with:
S. Dimitrakoudis, P. Padovani, E. Resconi, P.Giommi,
A. Mastichiadis

14th Marcell Grossman Conference
Rome, 14.07.2015

Talk outline

- Introduction

- Two variants of hadronic models for blazar emission

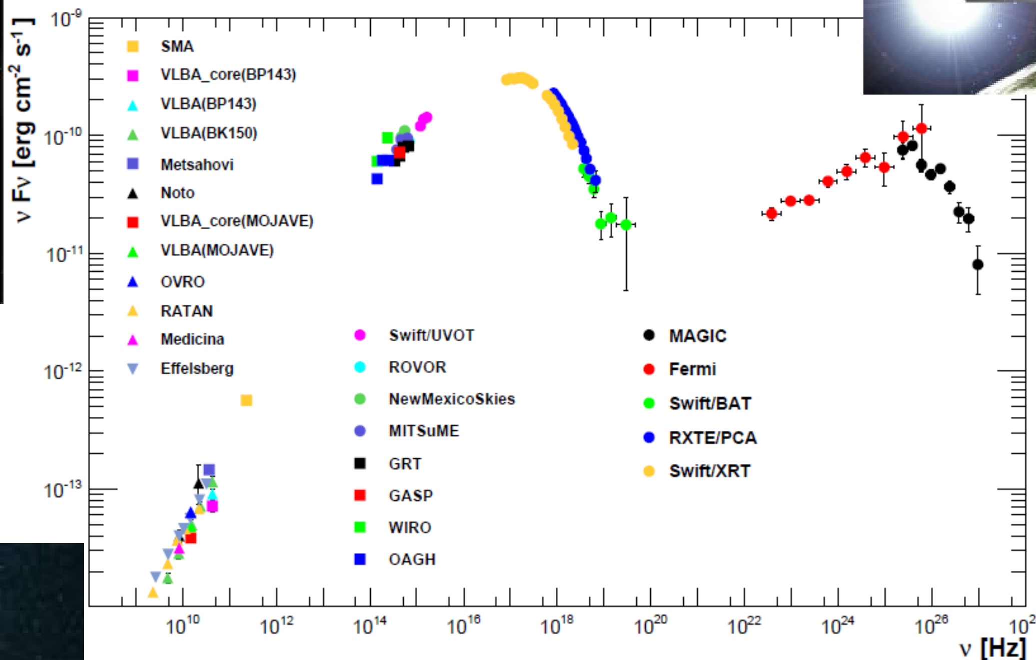
- Predictions of hadronic models for:
    1. Spectral Energy Distribution (SED)
    2. X-ray/γ-ray variability
    3. Cosmic Rays
    4. High-energy neutrinos

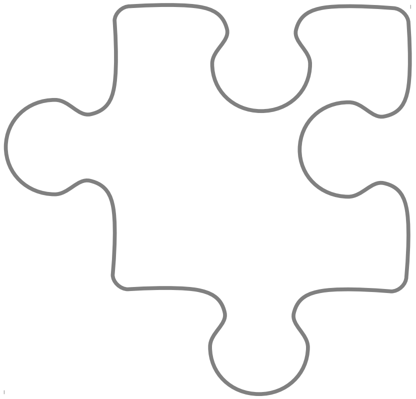
- BL Lacs as probable astrophysical counterparts of IceCube neutrinos

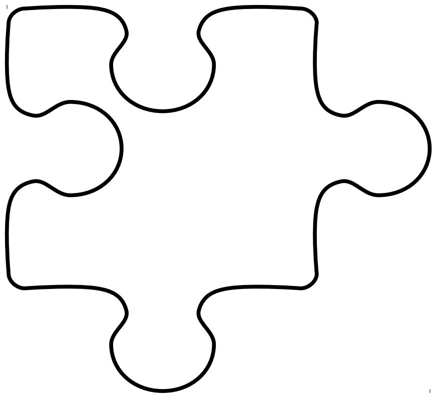
- Summary

Introduction

Blazars in the multi-messenger era

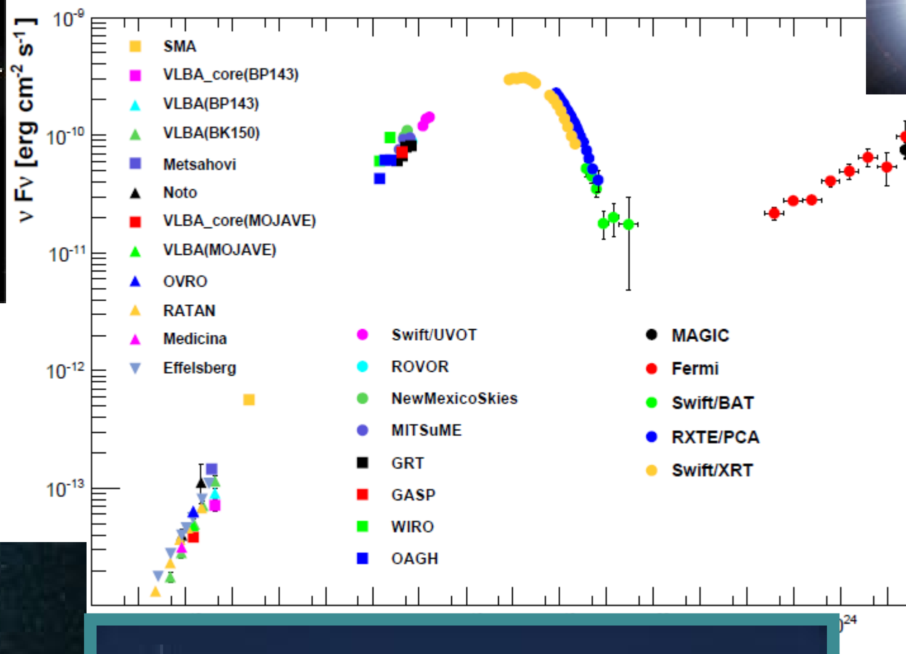


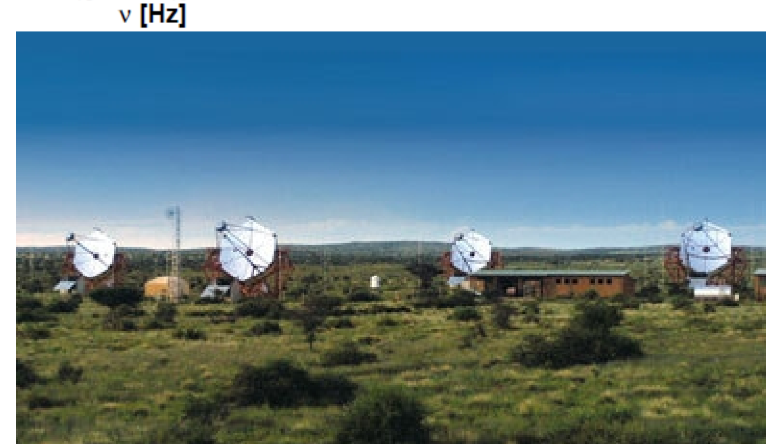




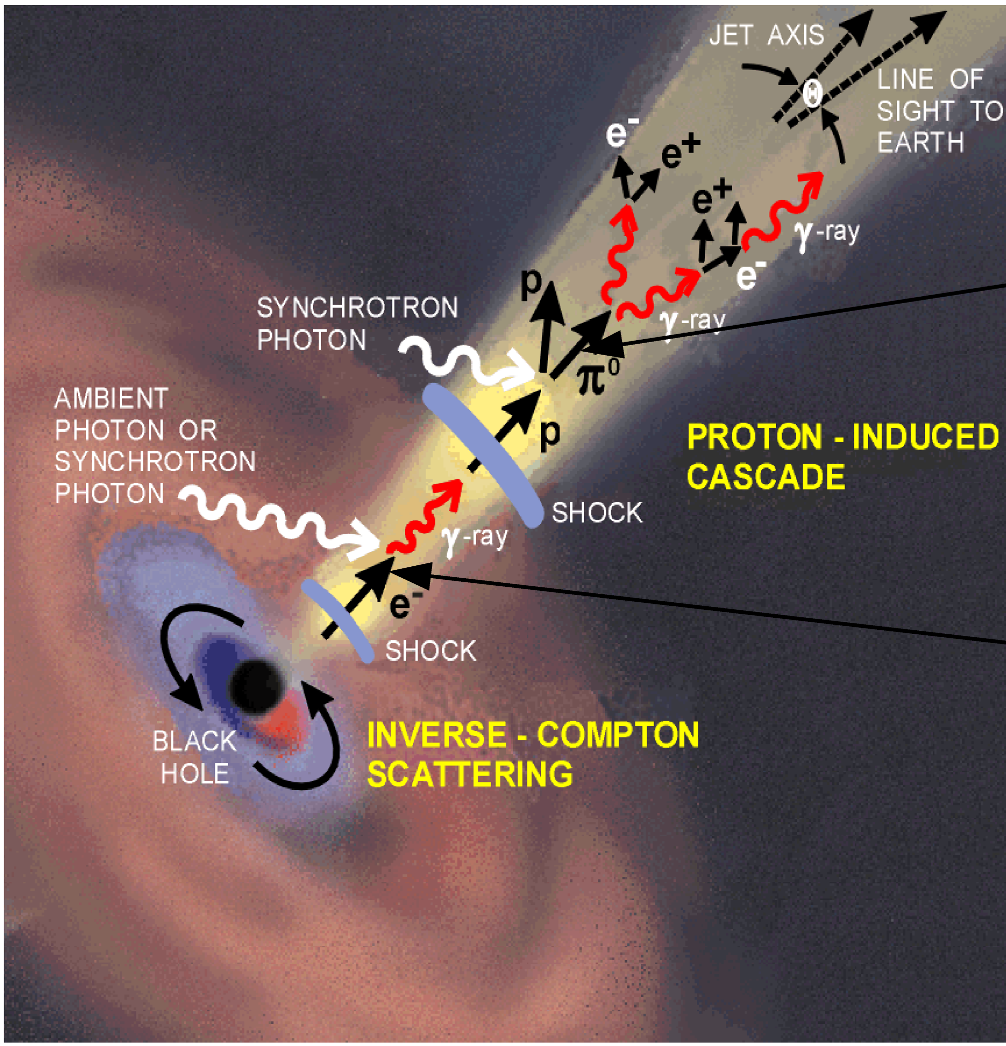
Introduction

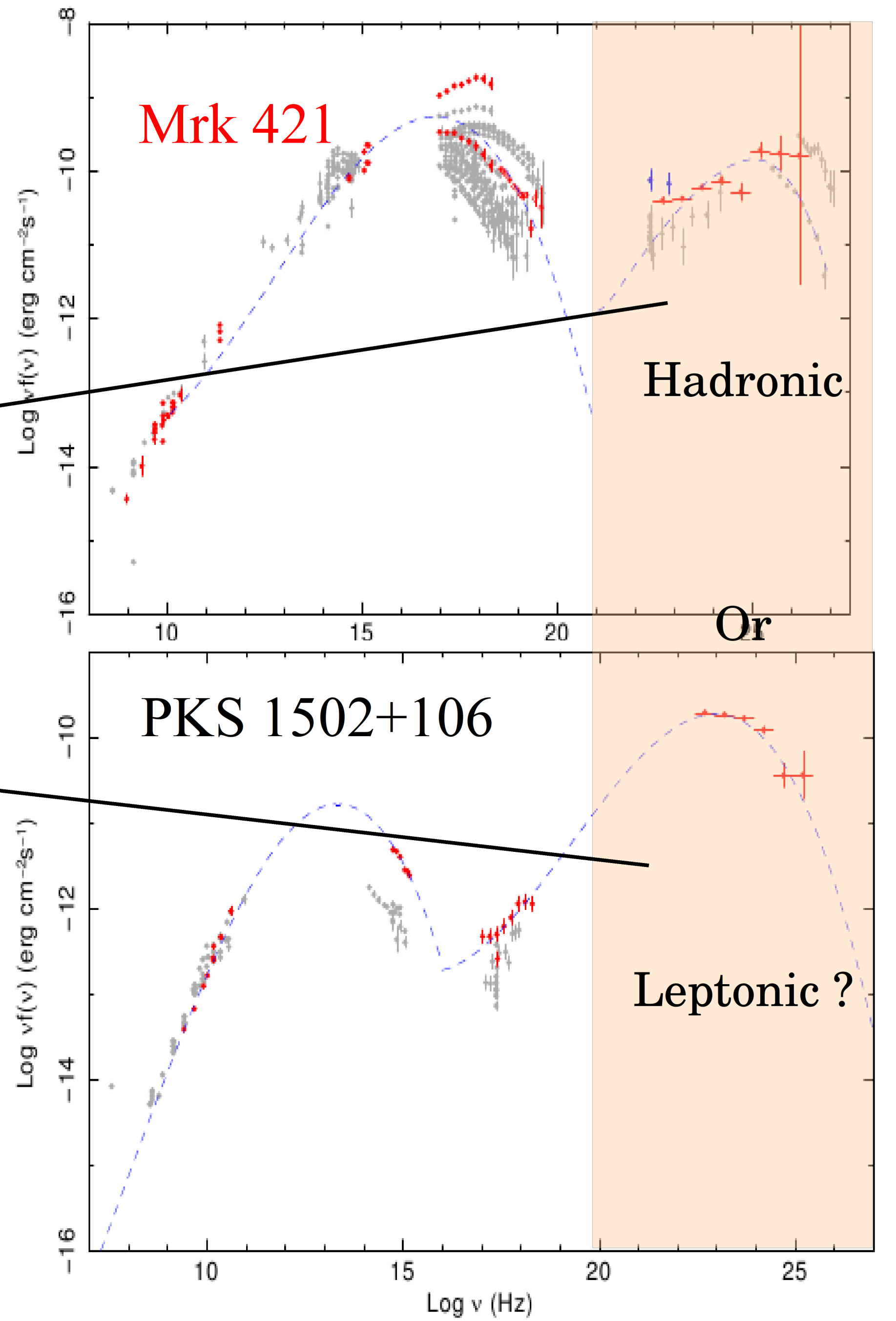
Blazars in the multi-messenger era





Blazar SED modeling

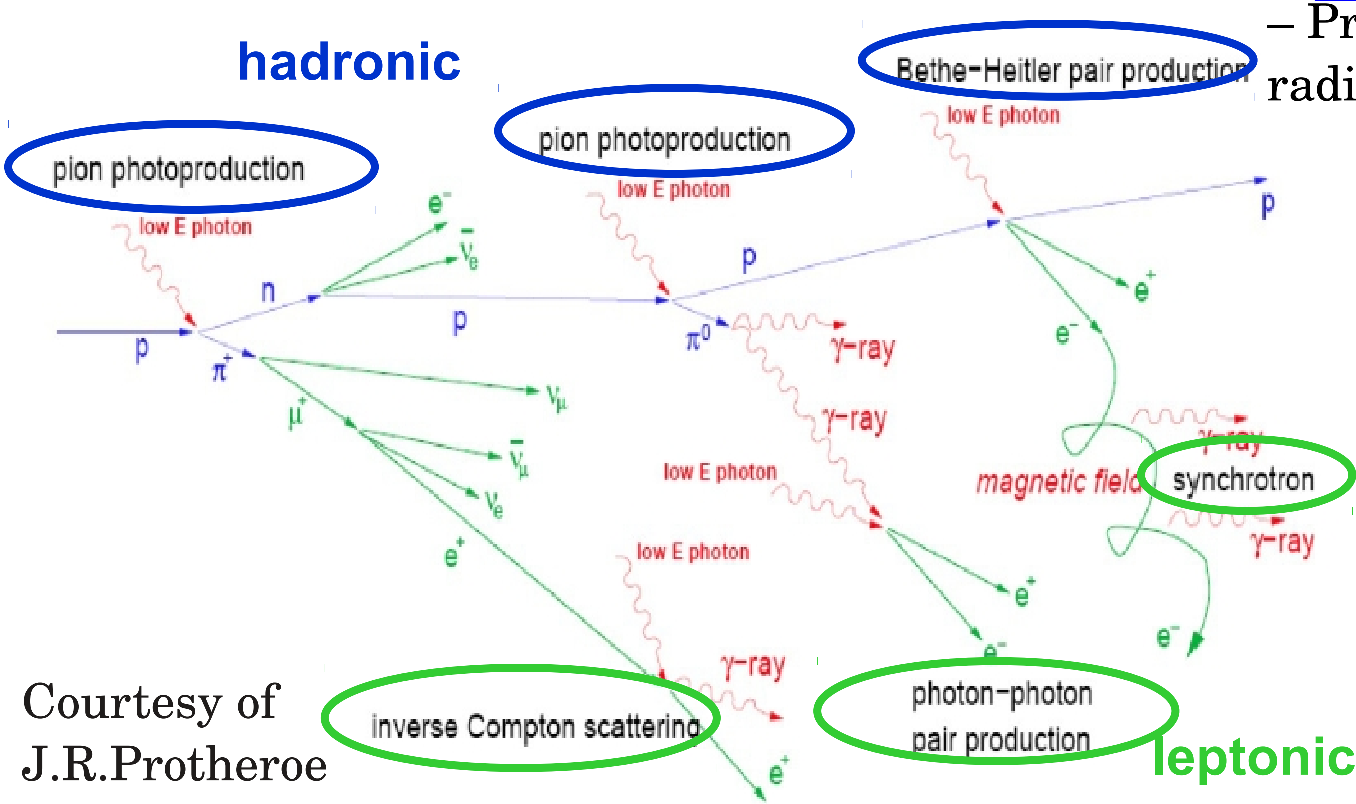




Hadronic models: processes in a nutshell

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

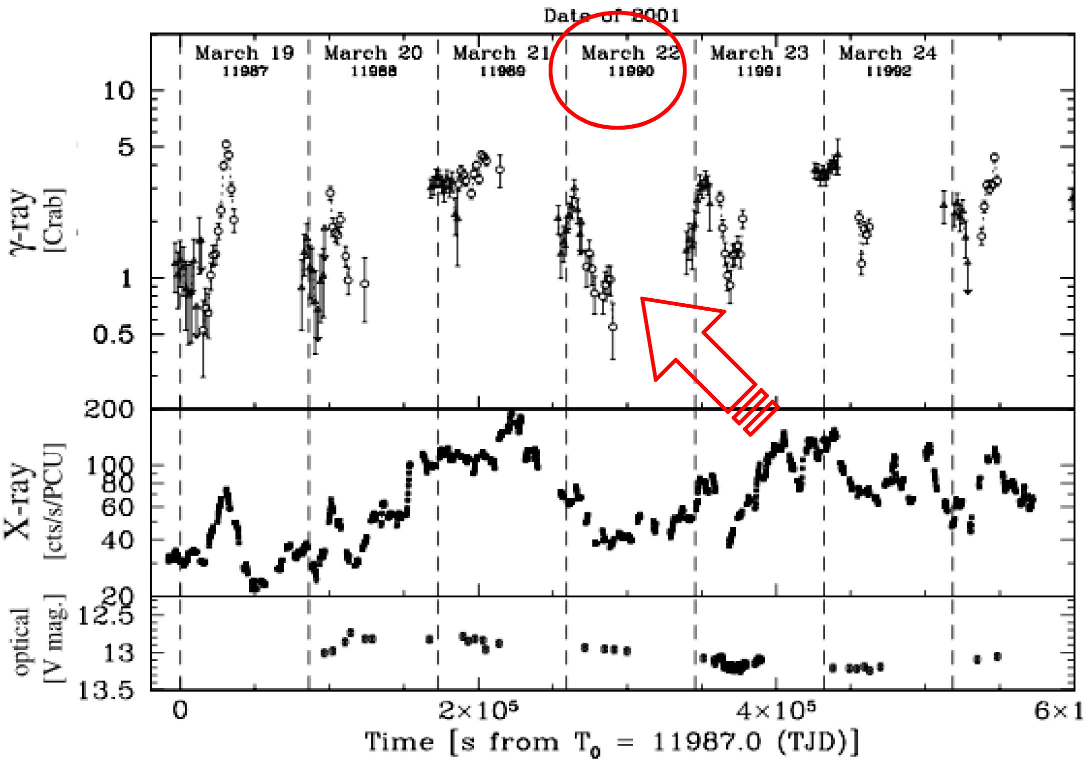
Hadronic emission models
– Proton-proton (pp) pion production
– Bethe-Heitler pair production
– Proton-photon pion production
– Neutron-photon pion production
– Neutral pion decay into γ-rays
– Charged pion decay into muons
– Muon decay into pairs
– Neutrino production
– Proton (+pion, muon) synchrotron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

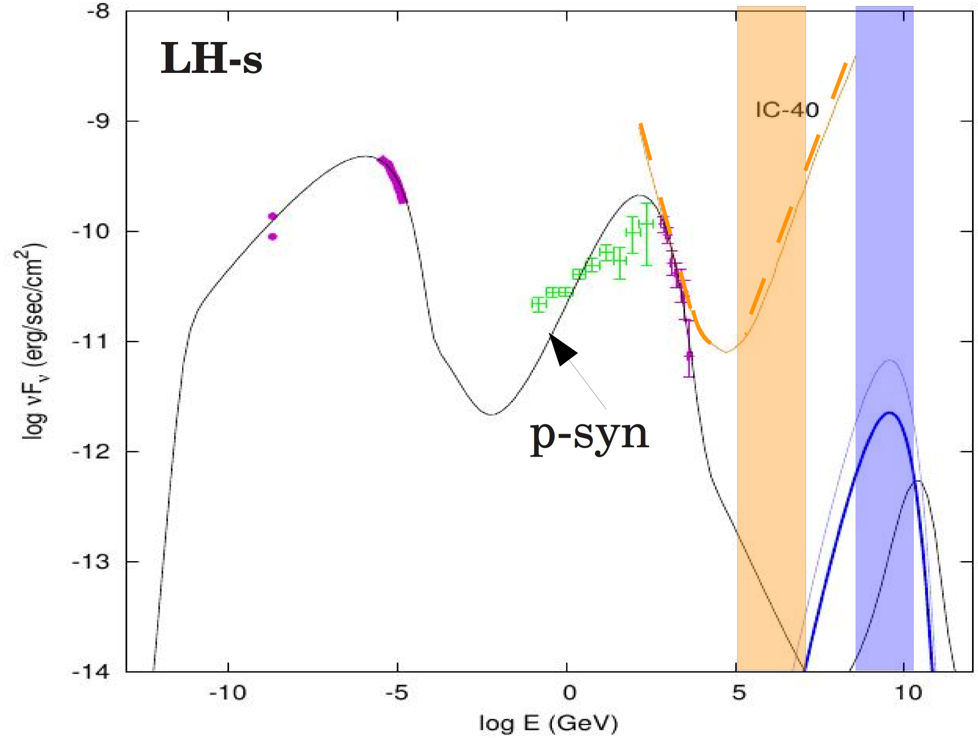


Courtesy of J.R.Protheroe

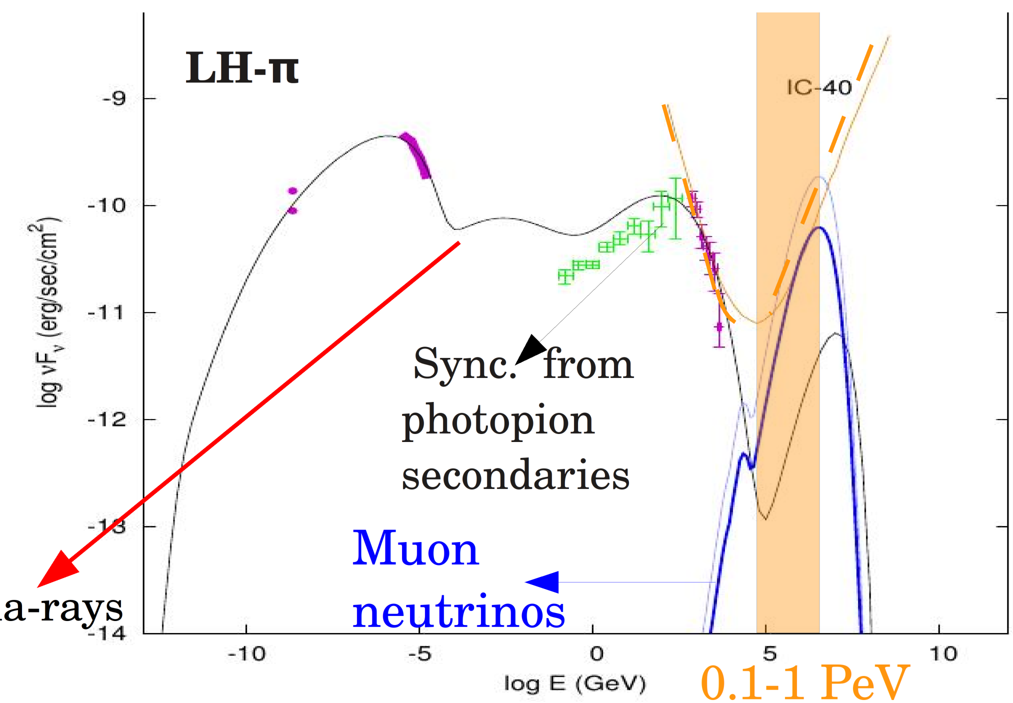
The case of Mrk 421: SED & ν

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





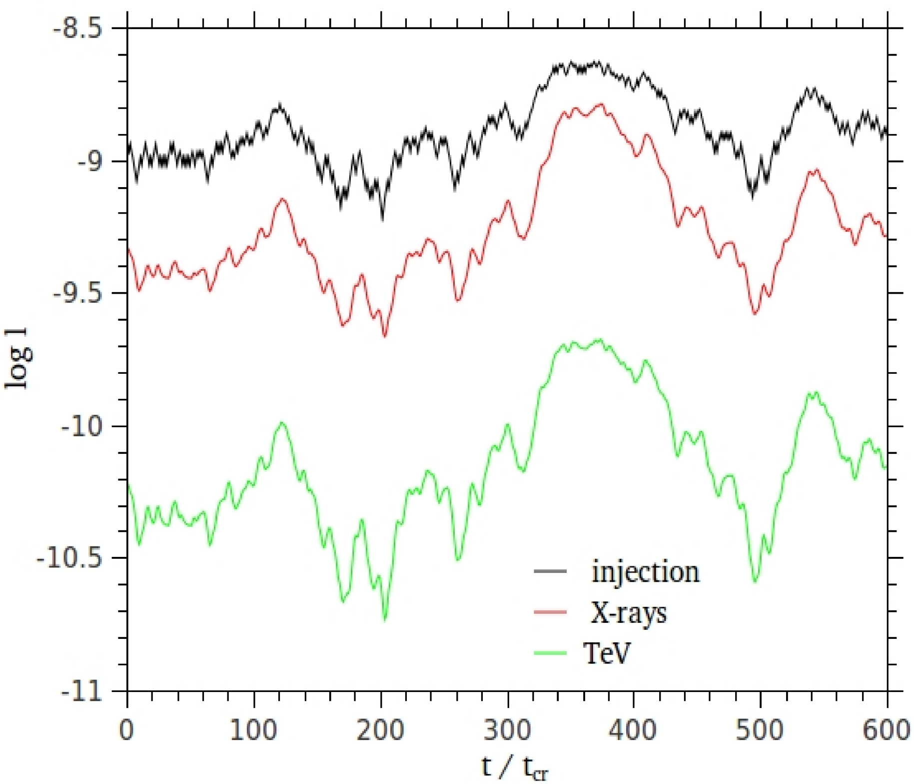
Dimitrakoudis et al., 2014, Aph, 54

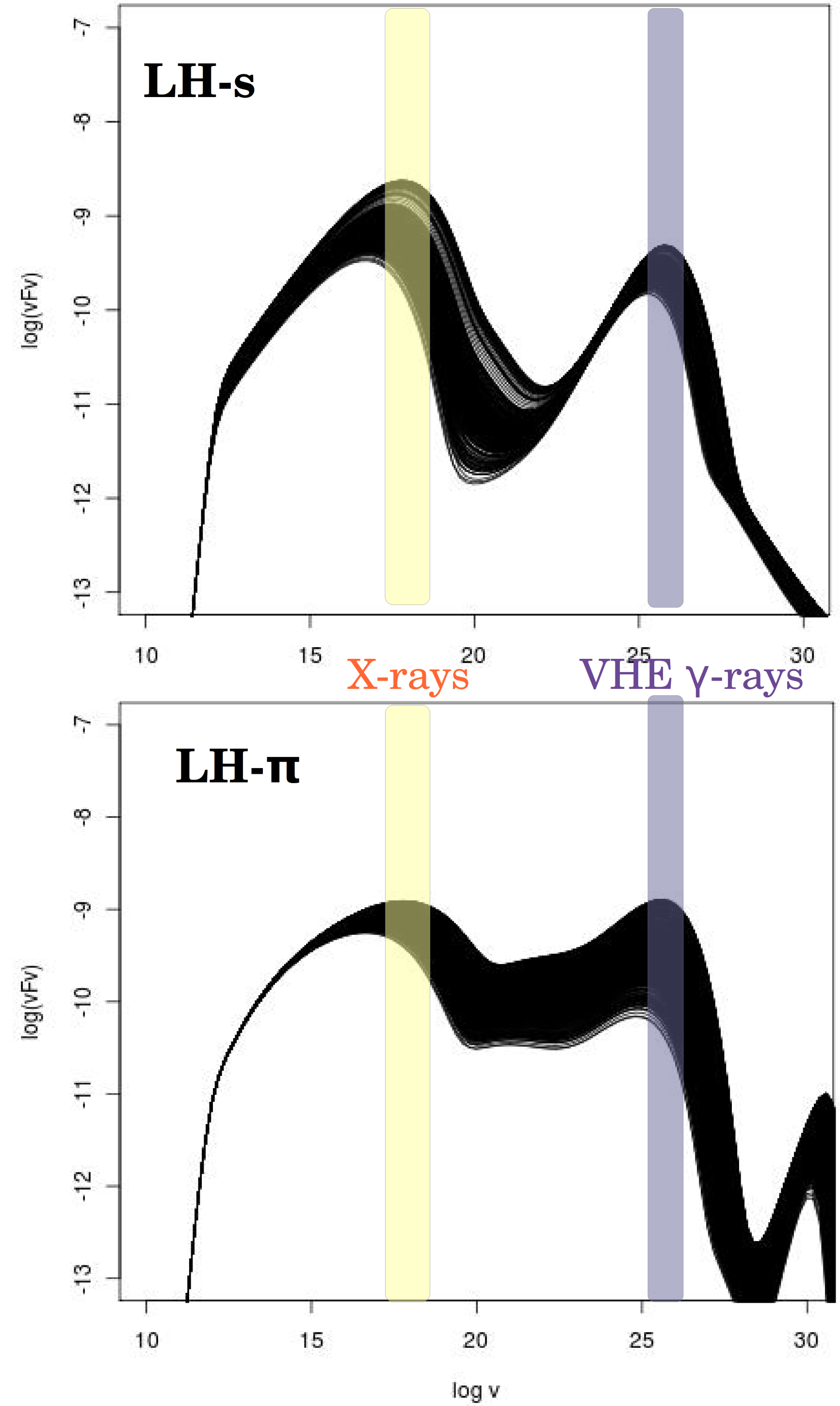


"Bethe-Heitler" component: a third hump in soft gamma-rays (Petropoulou & Mastichiadis 2015, MNRAS, 447)

The case of Mrk 421: variability

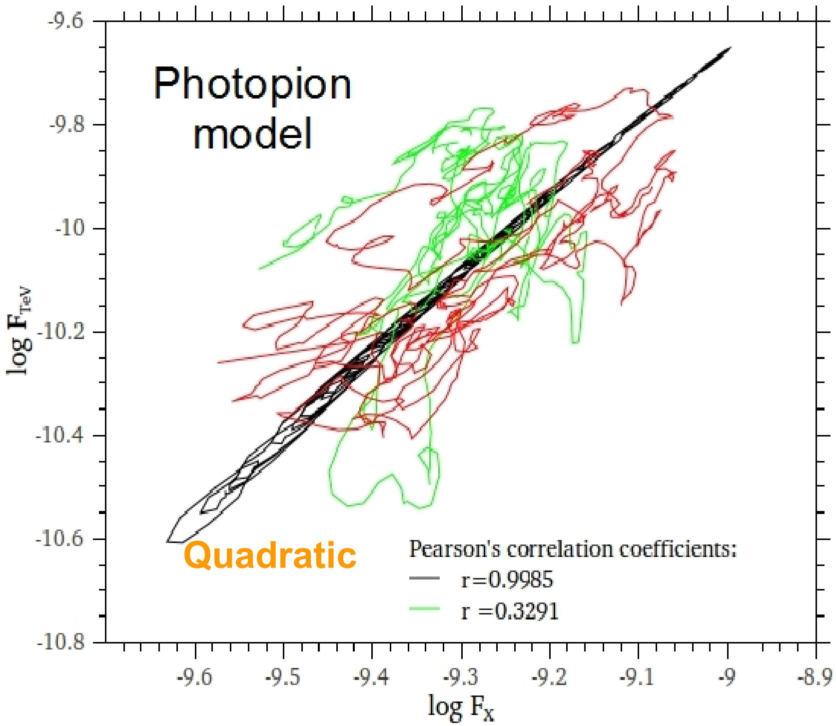
Small-amplitude random-walk variations in p and e *injection or maximum energy*

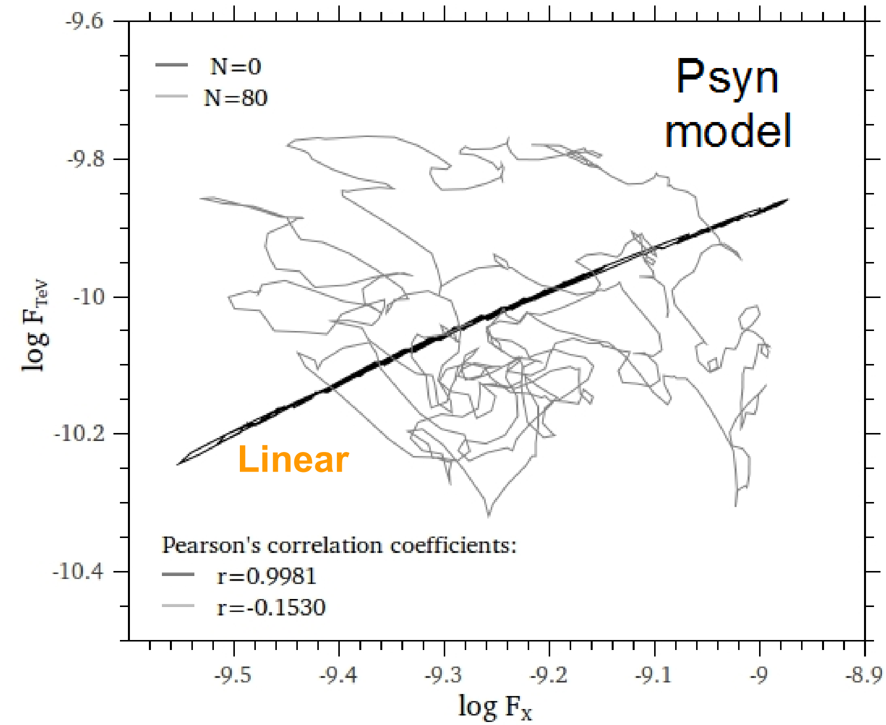




Masthichiadis et al., 2013, MNRAS

The case of Mrk 421: flux-flux correlations





Photopion (LH-π):

– If electrons-protons are correlated (no time lag) → TeV (hadronic) and X-rays (leptonic) vary quadratically

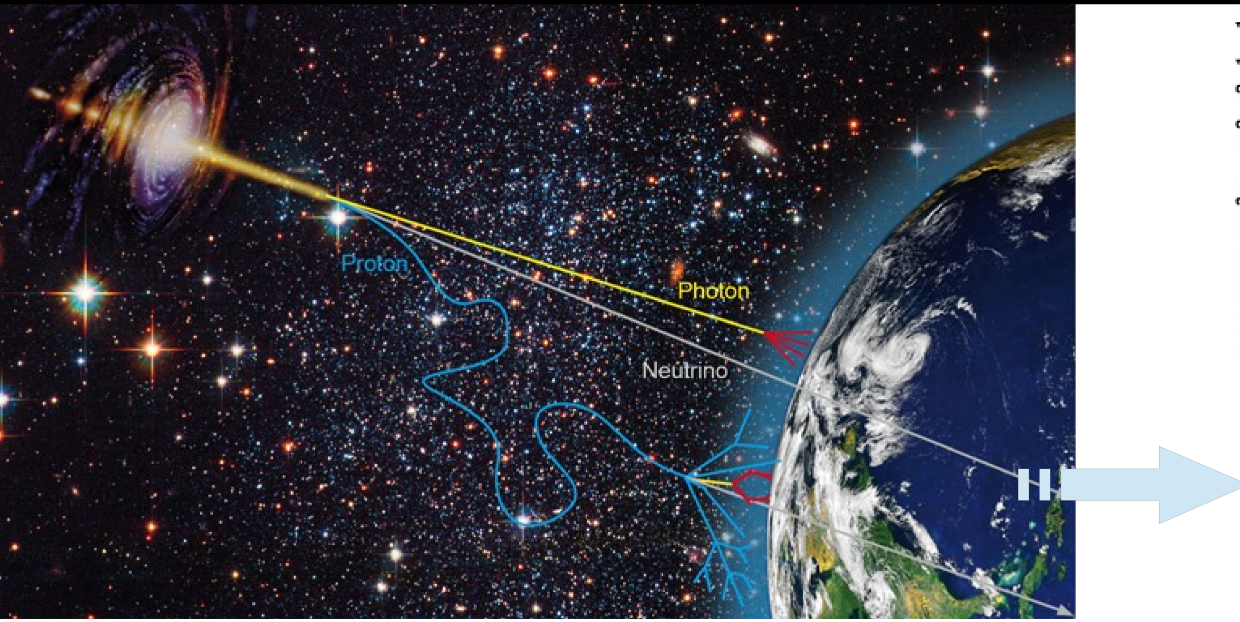
– Even if electrons-protons totally uncorrelated → X-ray and TeV retain some correlation

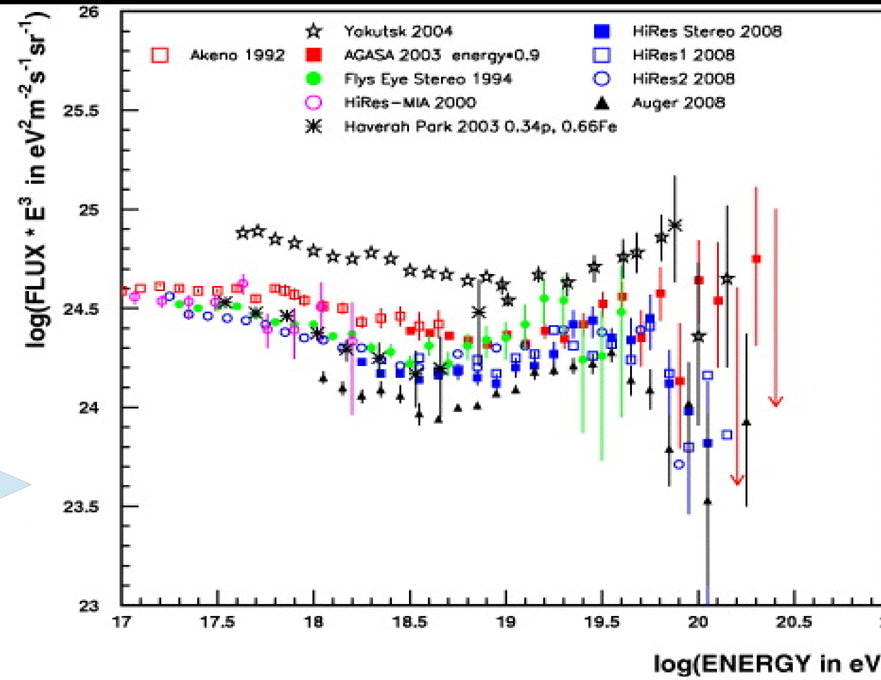
Proton synchrotron (LH-s):

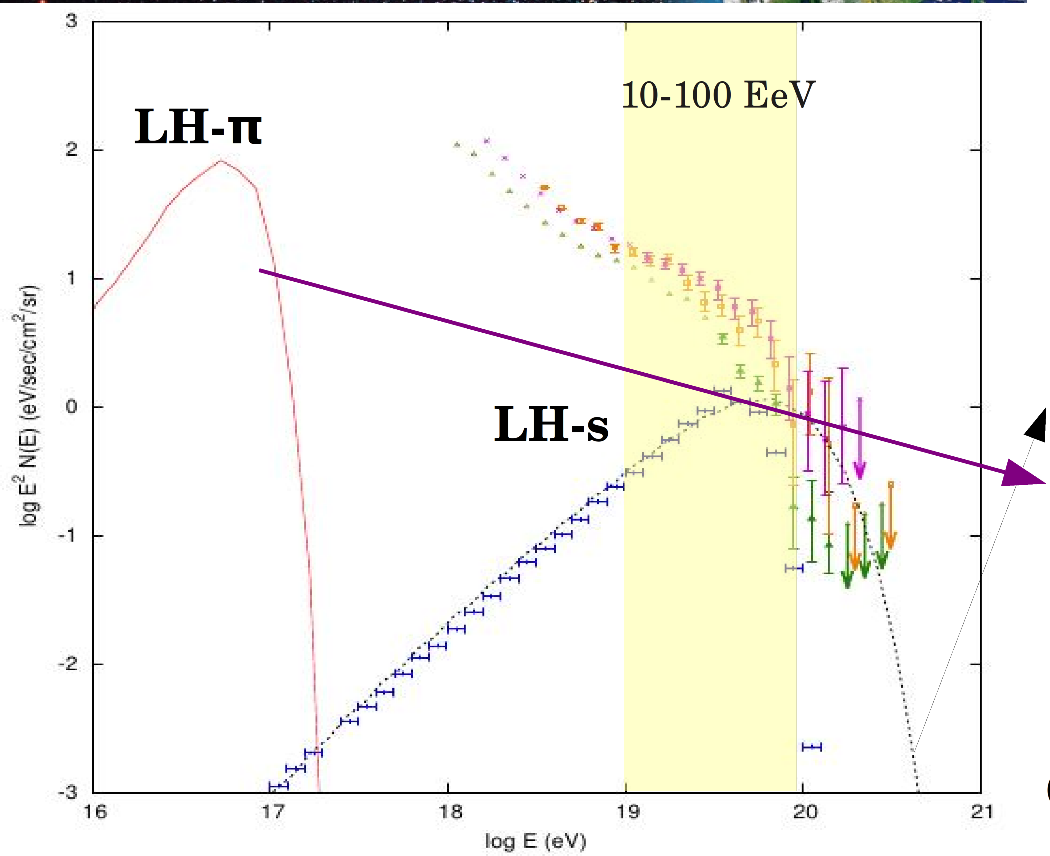
– If electrons-protons totally correlated (no time lag) → X-rays (leptonic) and TeV (hadronic) vary linearly

– If electrons-protons totally uncorellated → the X-ray/TeV correlation is lost.

The case of Mrk 421: Cosmic-rays







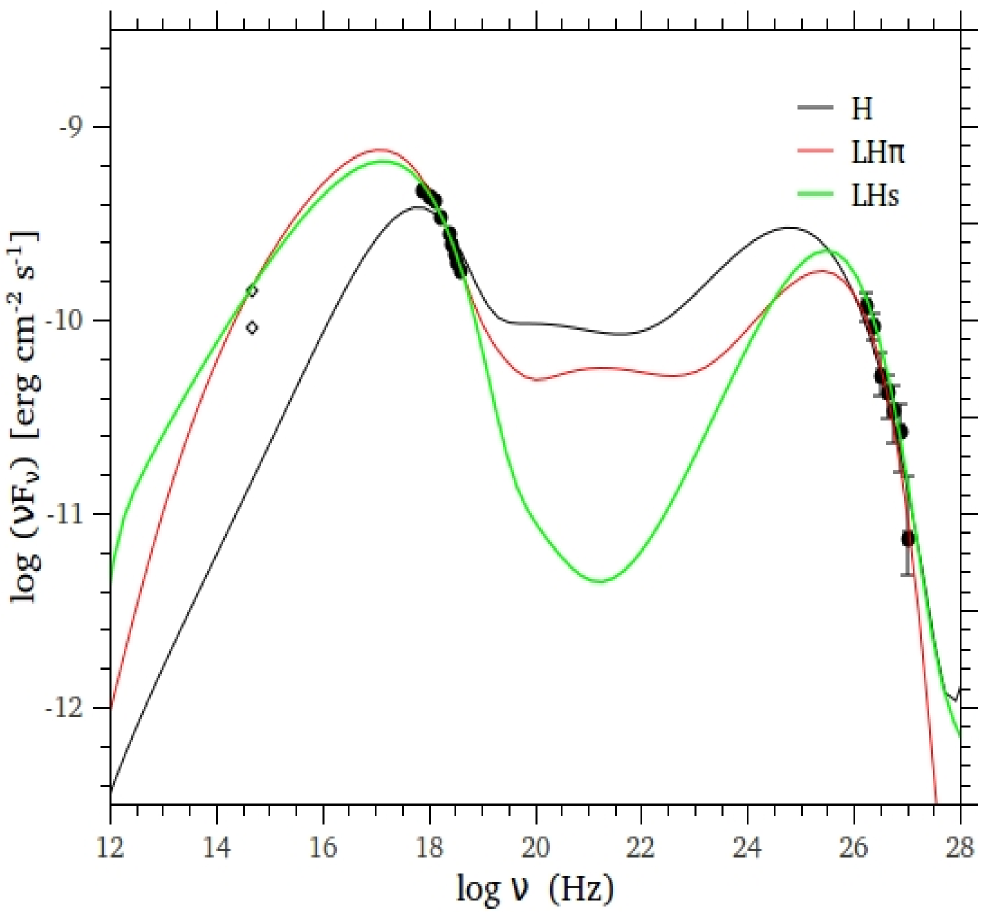
$n \rightarrow p + e^{-} + \bar{\nu}_e$ Neutron decay

$p + CMB \rightarrow \ldots \textit{cosmogenic}\ \nu$ Proton losses

$p + B \rightarrow \ldots \textit{deflection}$

(Propagation was made using CRPropa 2.0)

The case of Mrk 421: Model comparison



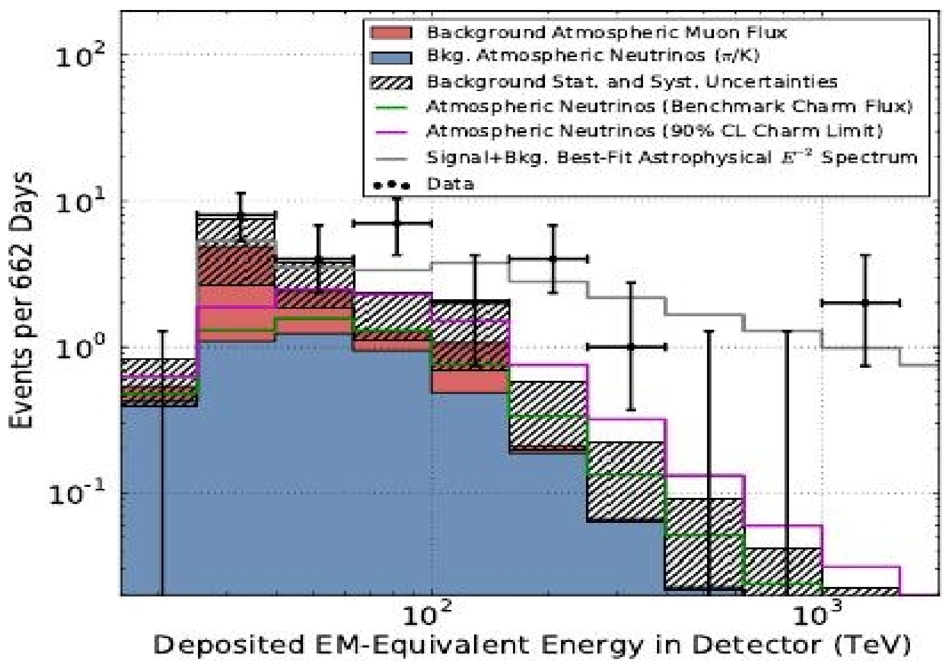
	UV/X-rays	*γ-rays*
LH-π model	e-syn	e-syn from photopion
LH-s model	e-syn	p-syn

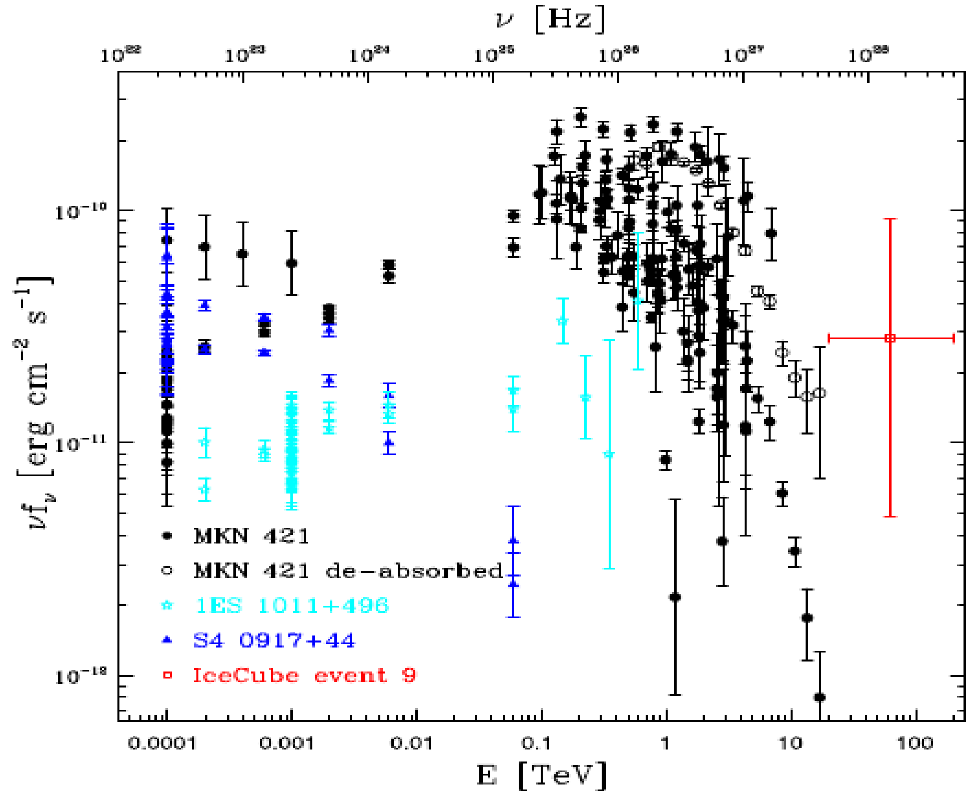
	LH-π	**LH-s**
Dominant energy density	Protons	B-field
Jet power	~ 1e48 erg/s	~ 1e46 erg/s
Maximum proton energy	~ 20 PeV	~20 EeV
Peak neutrino energy	~PeV	~ EeV
X-ray/TeV γ-ray correlations	quadratic	linear

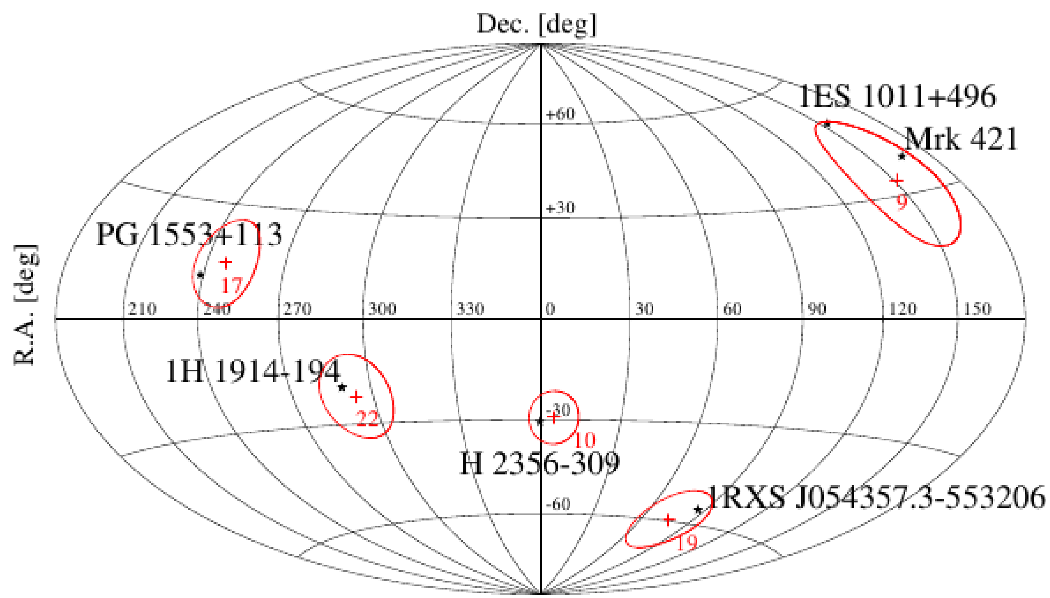
Masthichiadis et al., 2013, MNRAS

BL Lacs as counterparts of IceCube neutrinos

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





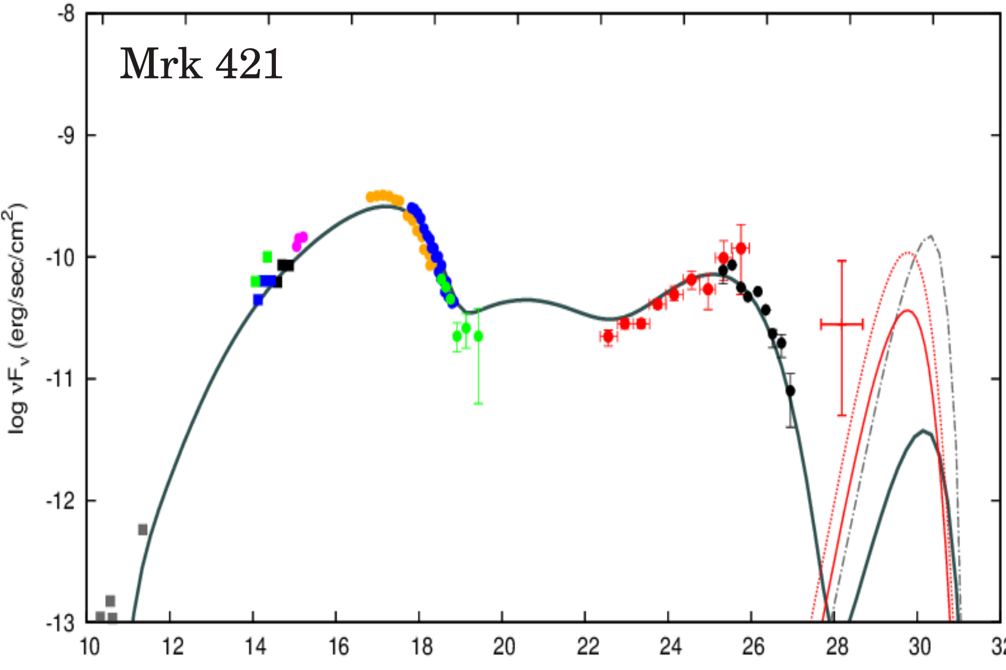


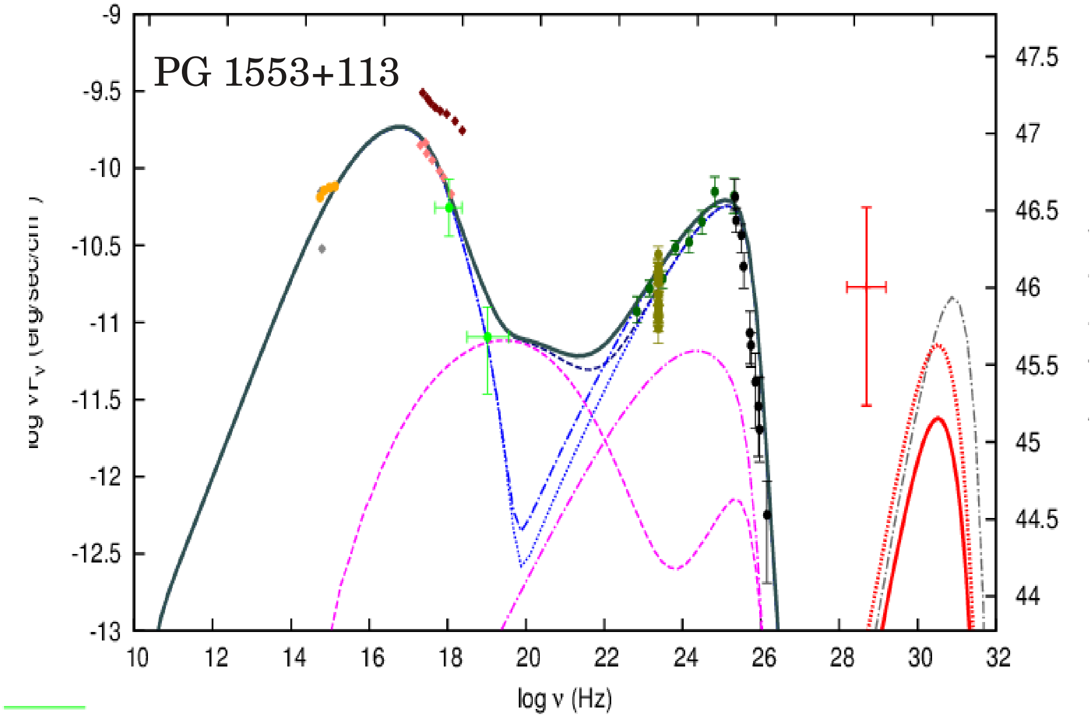
Top left: muon ν spectrum (28 events)

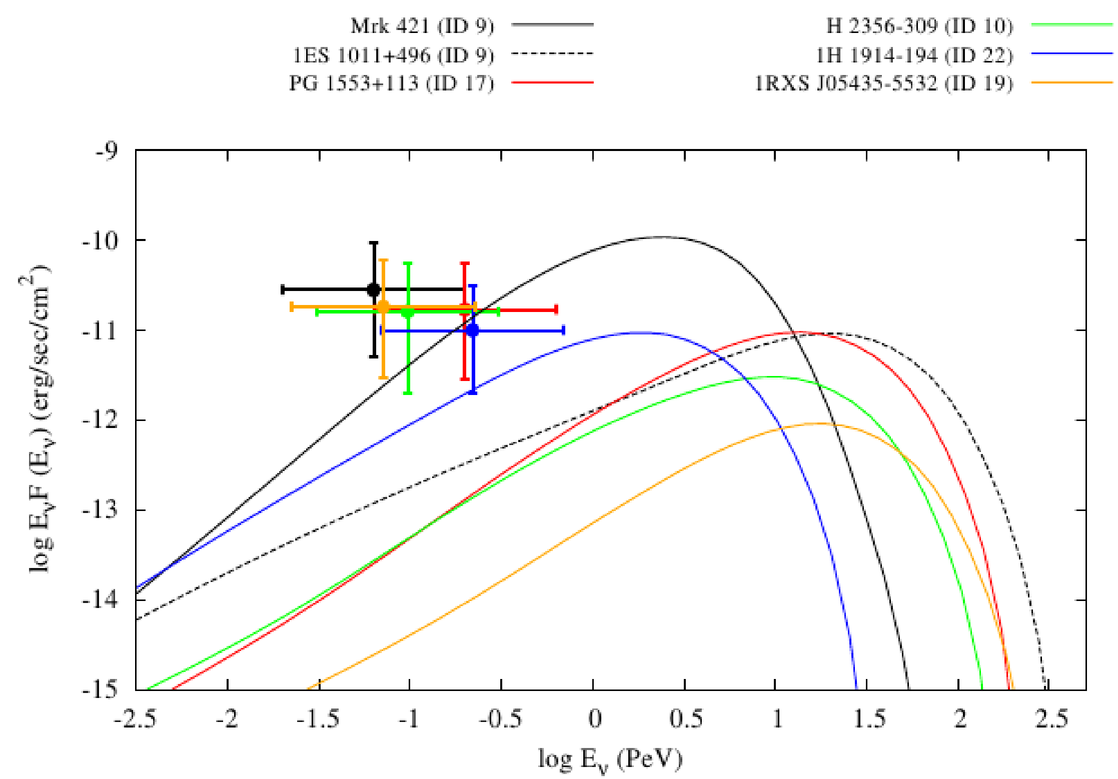
Top right: “hybrid SED” from Padovani & Resconi, 2014, MNRAS, 443

Bottom left: Sky map of 5 neutrino events and BL Lac counterparts from Petropoulou et al. 2015, MNRAS, 448

Neutrino emission from individual BL Lacs





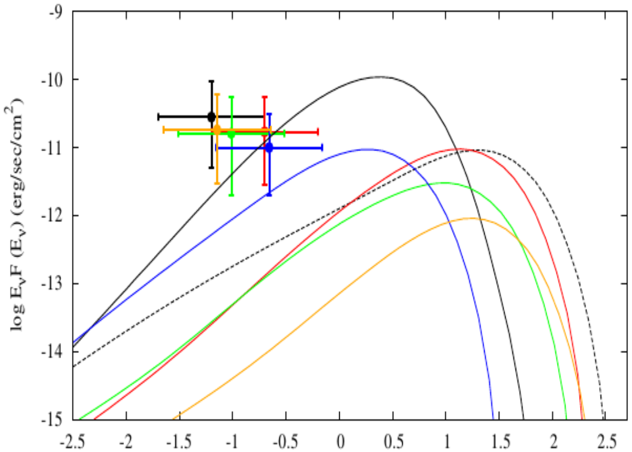


Mrk 421: possible positive detection of neutrinos might be achievable with some confidence (~3σ level) using preliminary discovery potentials based on 6 years IceCube life time

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

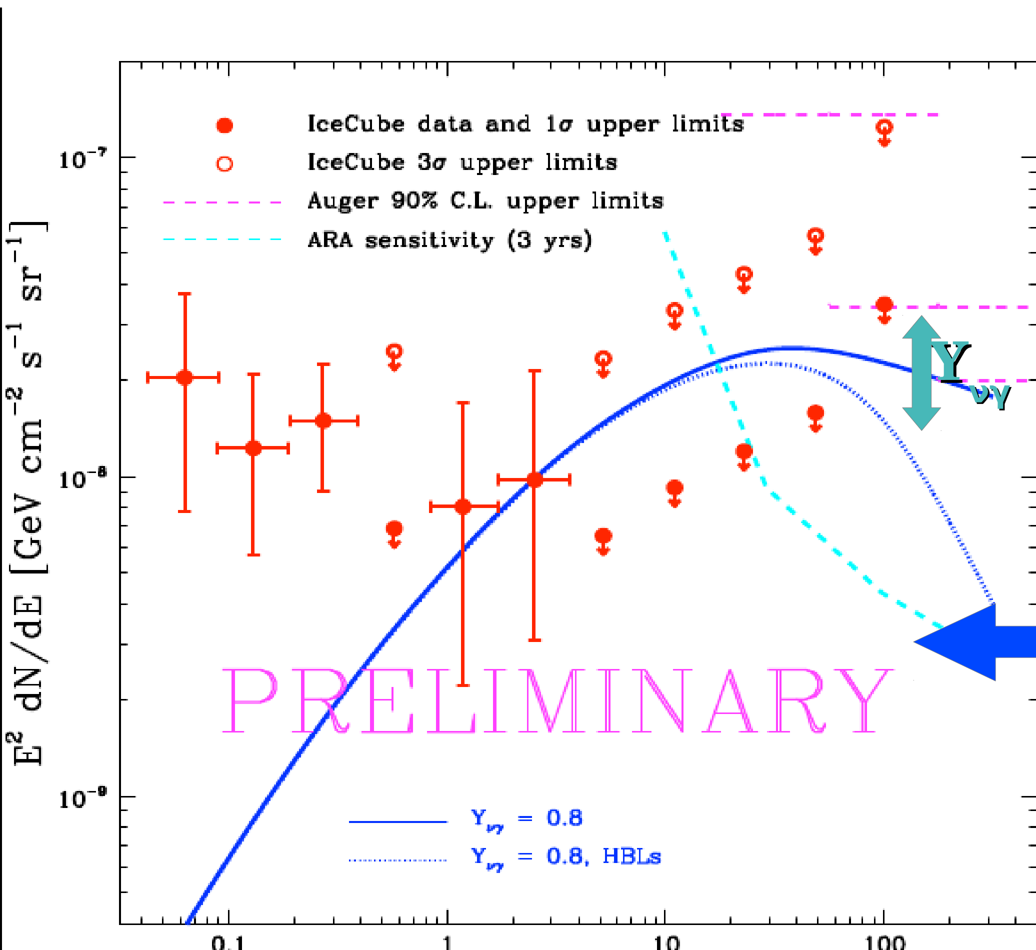


$$E_\nu F_\nu(E_\nu) = \frac{Y_{\nu\gamma} F_\gamma(> 10\ \mathrm{GeV})}{\int_{x_{\rm min}}^{\infty} dx\, x^{-s} e^{-x}} \left(\frac{E_\nu}{E_{\nu,p}}\right)^{-s+1} \exp\left(-\frac{E_\nu}{E_{\nu,p}}\right)$$

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

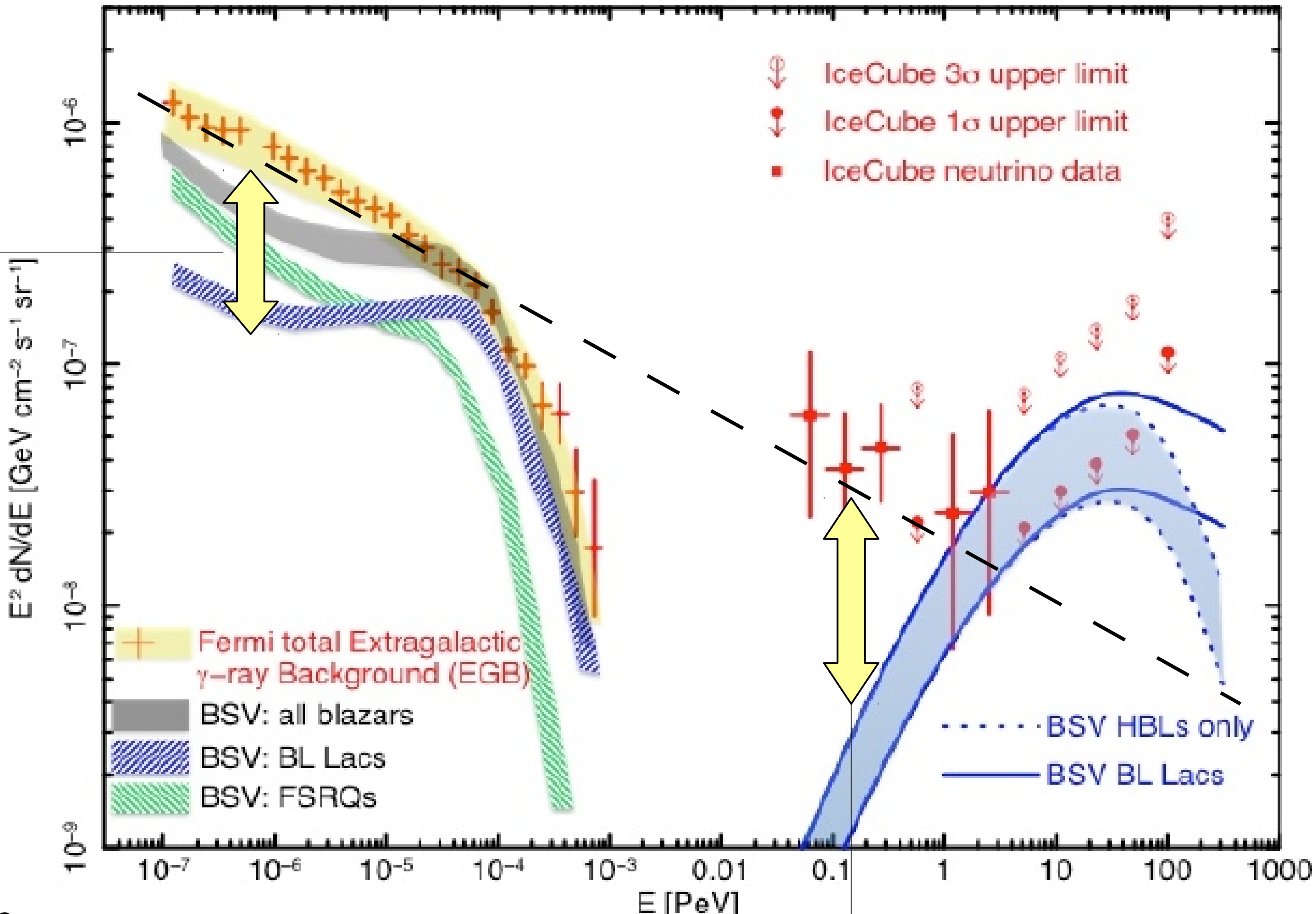
Monte-Carlo simulation for blazar population (Giommi & Padovani 2012, …):

– γ-ray fluxes
– Distribution of synchrotron peak frequency
– Redshift
– Distribution of Doppler factor δ
– etc…



Padovani et al. 2015, accepted in MNRAS

Extragalactic backgrounds



– Another source population? (e.g. starburst galaxies; Lacki et al. 2014; Stecker 2007)
– 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)

Summary

Lessons learned from Mrk 421:

– SED modeling of blazars is an important tool for understanding the physical conditions in the source

– Two variants of hadronic models can fit the SED of Mrk 421 (22nd/23rd March 2001)

- LH-π : γ-rays from photopion + EM cascade (more energetically demanding)
- LH-s : γ-rays from proton synchrotron (requires higher proton energies

– both fit equally well the MW spectra

– the LH-π predicts a Bethe-Heitler hump at MeV energies

– the LH-π model predicts neutrinos at ~2-20 PeV

BL Lac - IceCube neutrino events correlations:

– successful MW fits using the LH-π model of 6 sources (with different z, SEDs etc)!

– Mrk 421 potential point source of neutrinos

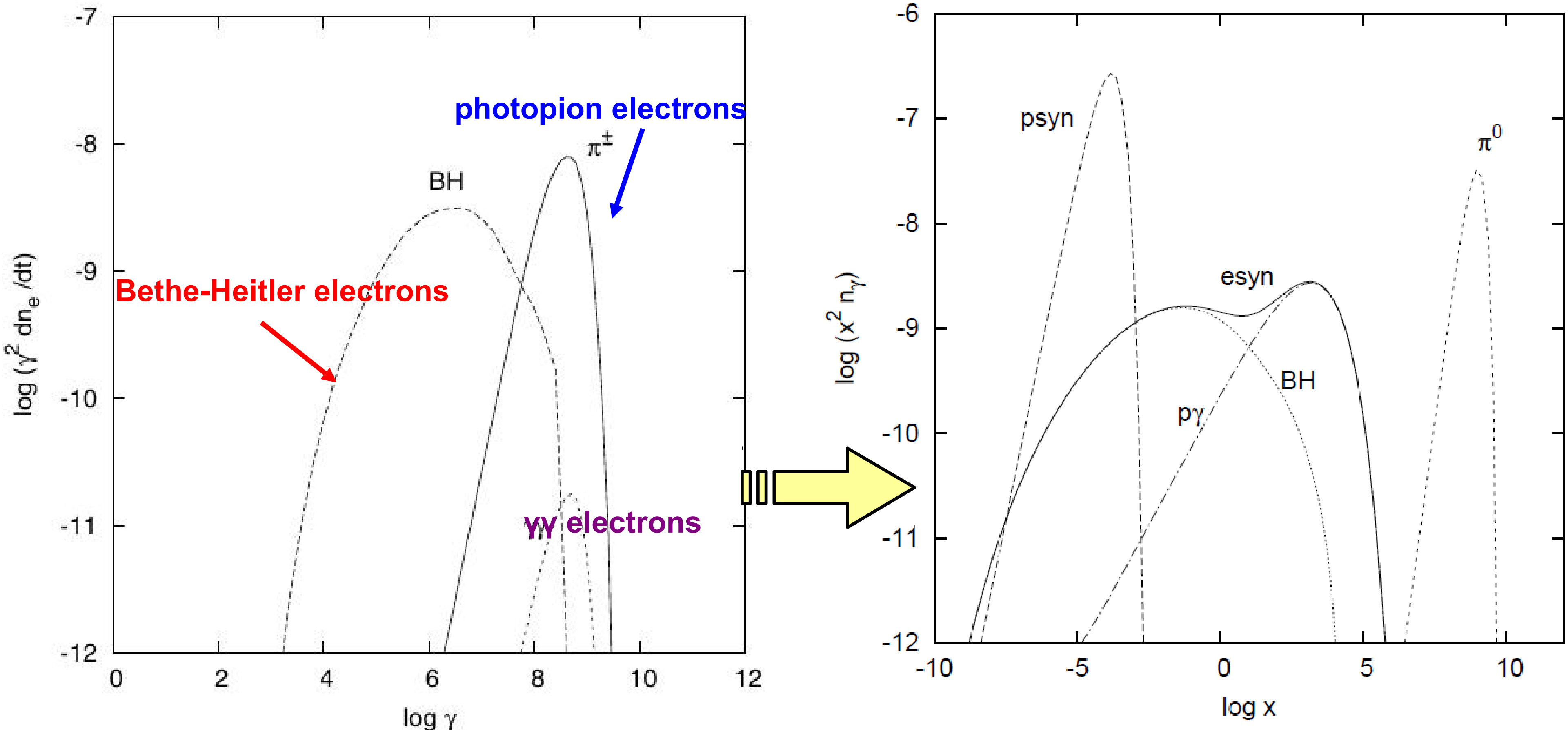
– the NBG from BL Lacs explains the 1-2 PeV flux but requires another population for the sub-PeV neutrino flux

THANK YOU

Example of a SED

Secondary electrons

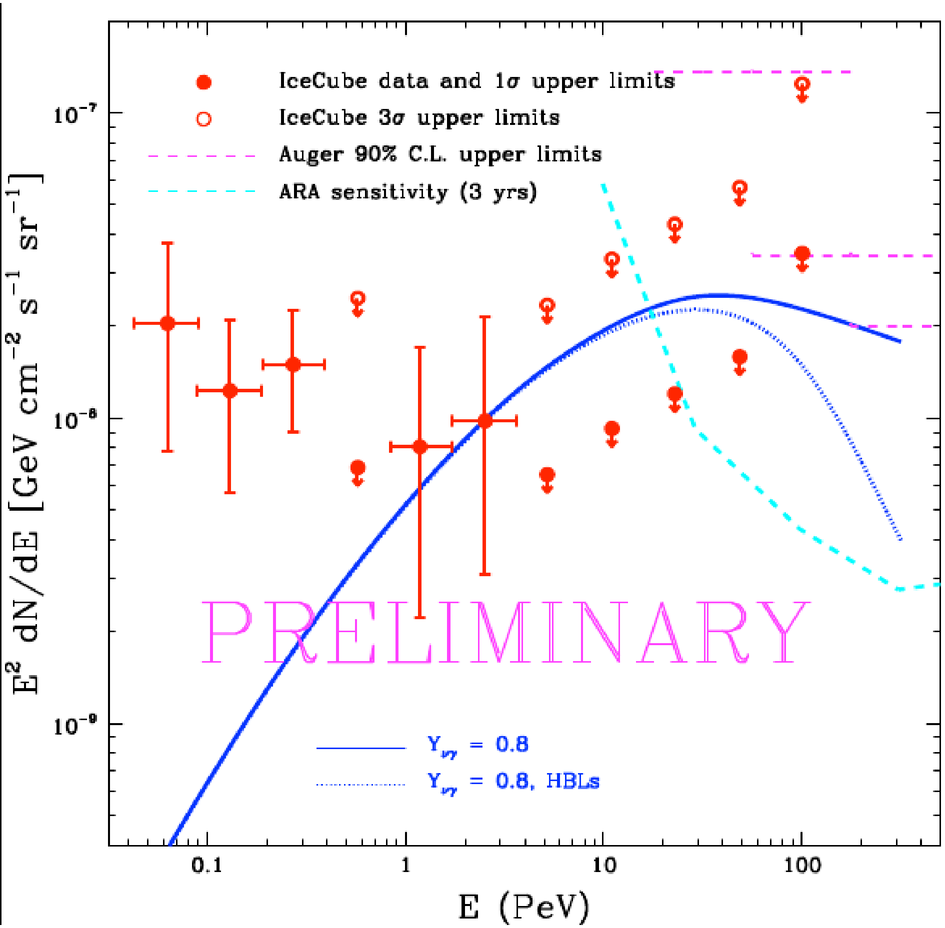
Photons



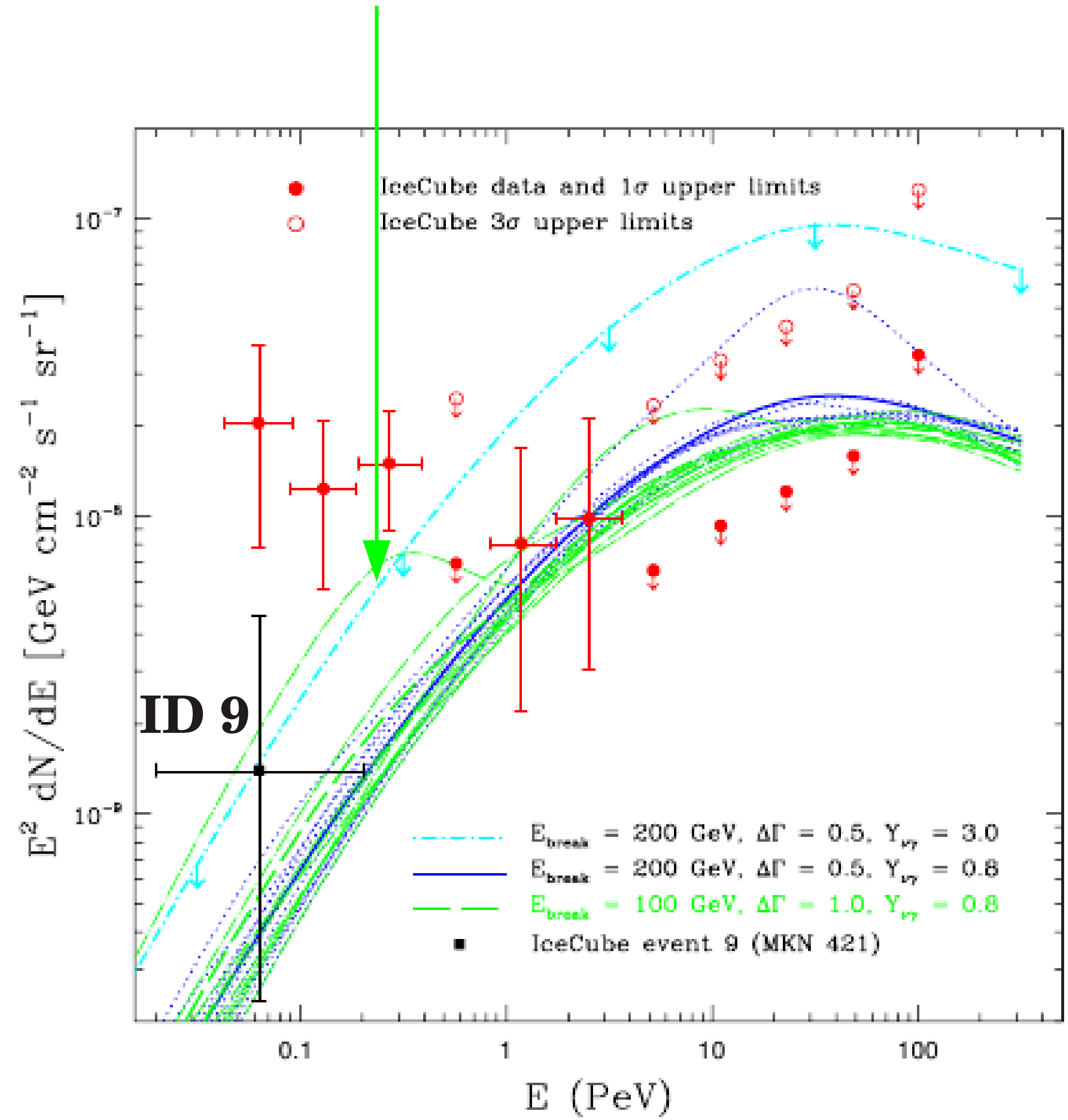
Dimitrakoudis et al. 2012

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

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: Mean of 10 Monte Carlo simulations

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