Correlated neutrino & photon emission from Mrk 421 during flares

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In collaboration with

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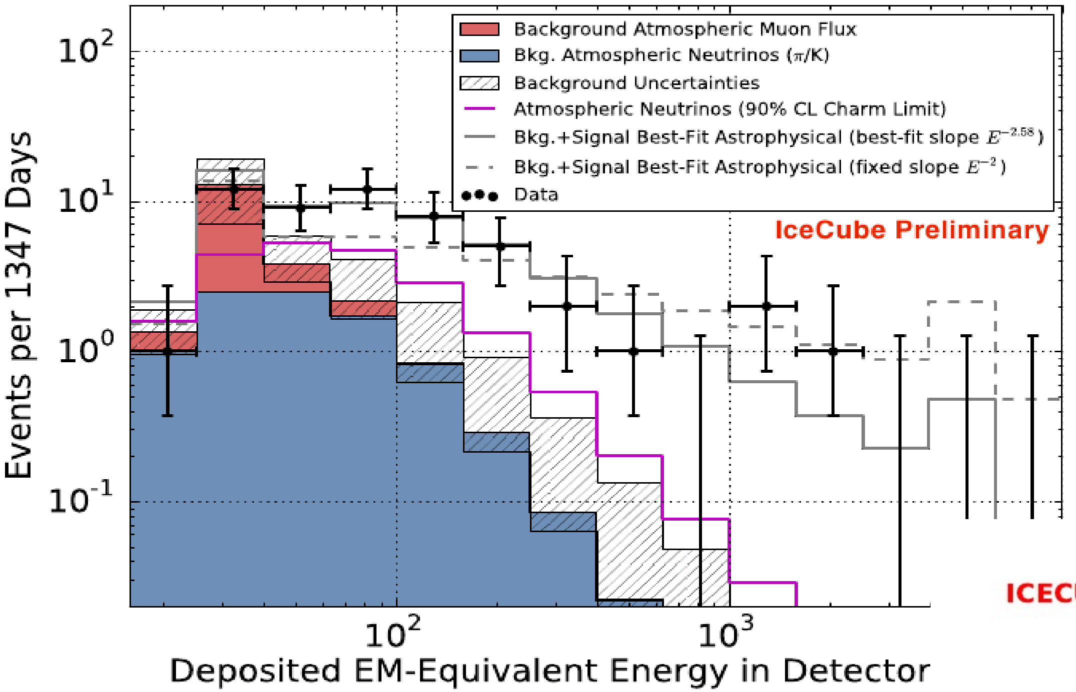
Context 1.

ICECUBE PRELIMINARY RESULTS (ICRC 2015)

High-Energy Starting Event (HESE) Sample

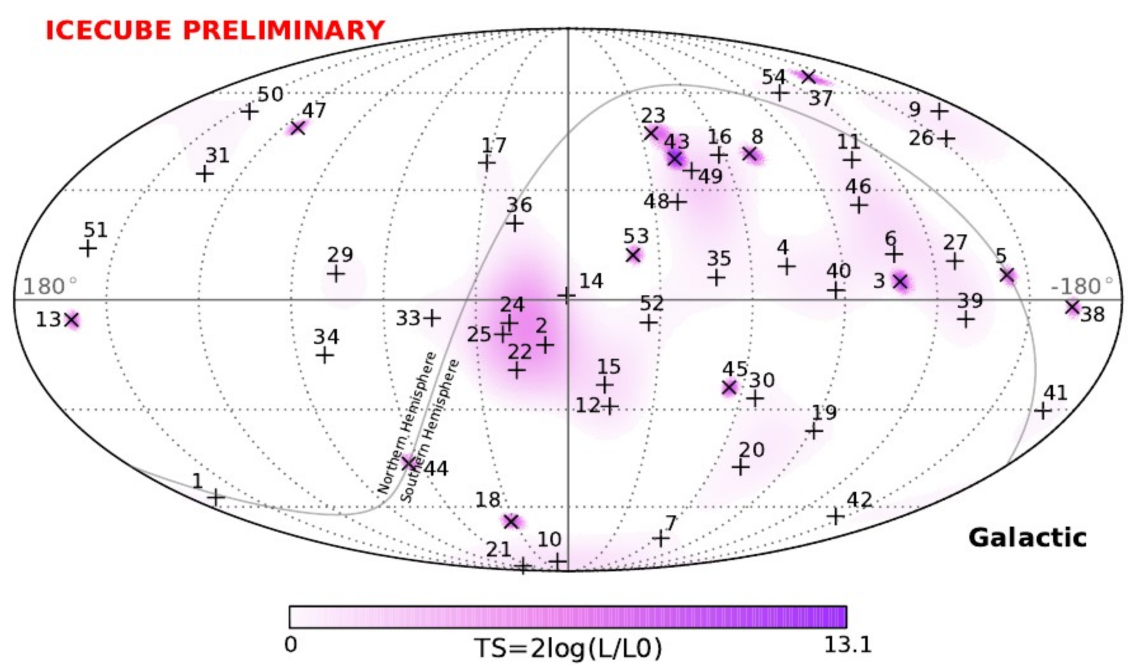


Left: Very high energy neutrino spectrum with 4 years of data:

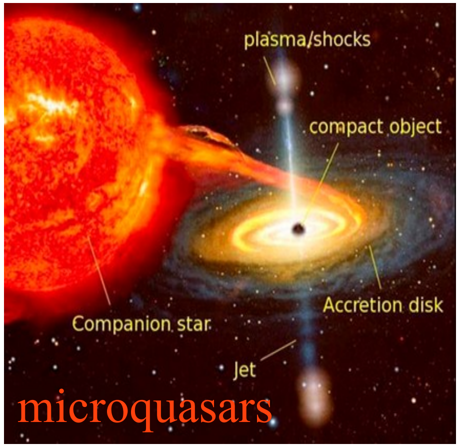
- 54 events in the energy range 30 TeV – 2 PeV.
- Spectral slope of astrophysical flux: γ=2.58

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.**

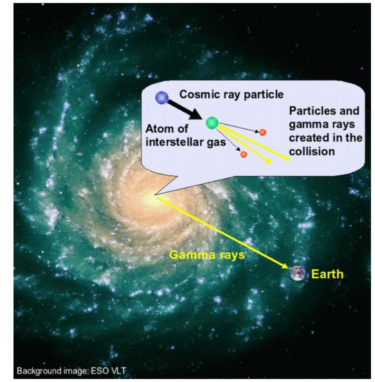


Astrophysical candidate sources



e.g. Guetta et al. 2002, Torres et al. 2005

e.g. Metzger et al. 2015



e.g. Kachelriess & Ostapchenko 2014

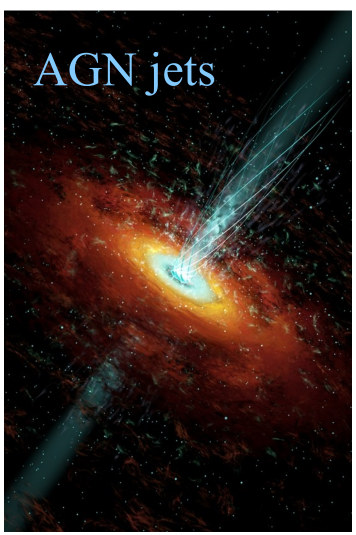
(see also Ahlers et al 2015 for a review)

e.g. Murase et al. 2011, Zirakashvili & Ptuskin 2015

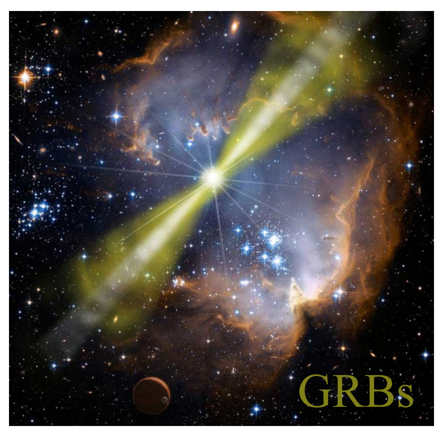
Galactic (full or partial contribution)?

High-energy neutrinos

Extragalactic ?



e.g. Mannheim 1995, Halzen & Zas 1997, Atoyan & Dermer 2001, 2003, Petropoulou et al. 2015



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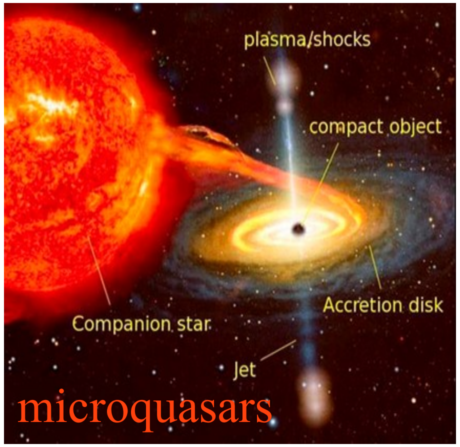
2.

(see also Ahlers et al 2015 for a review)



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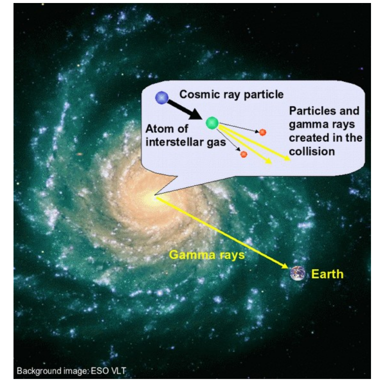

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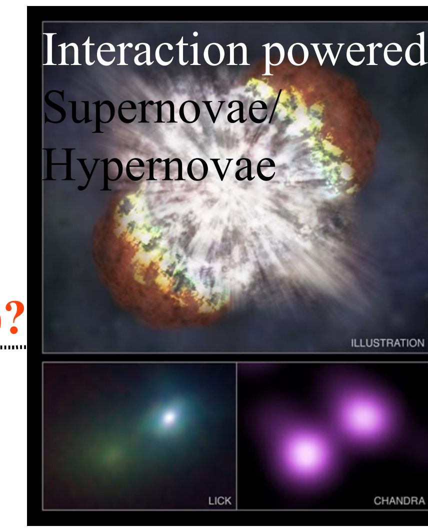

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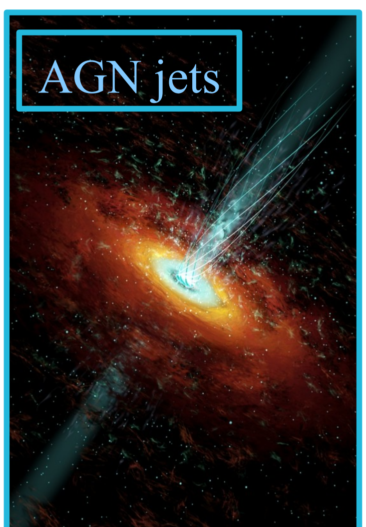

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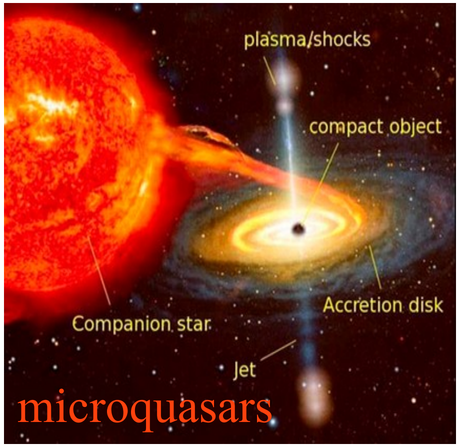

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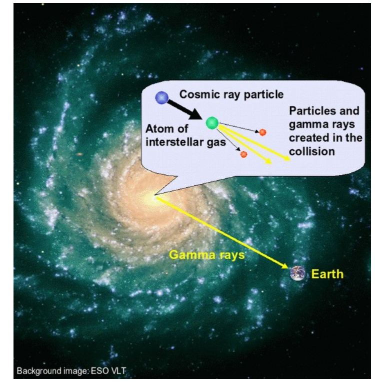

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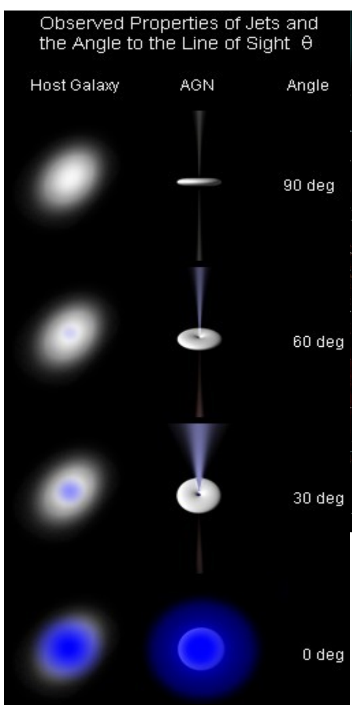
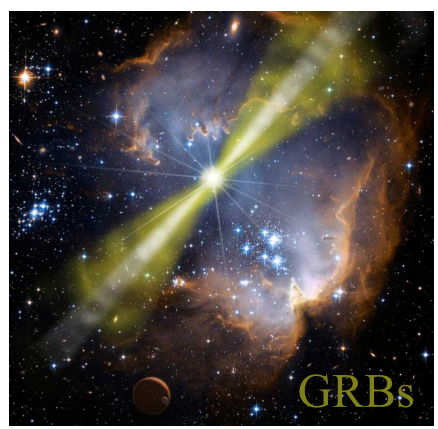


Blazars



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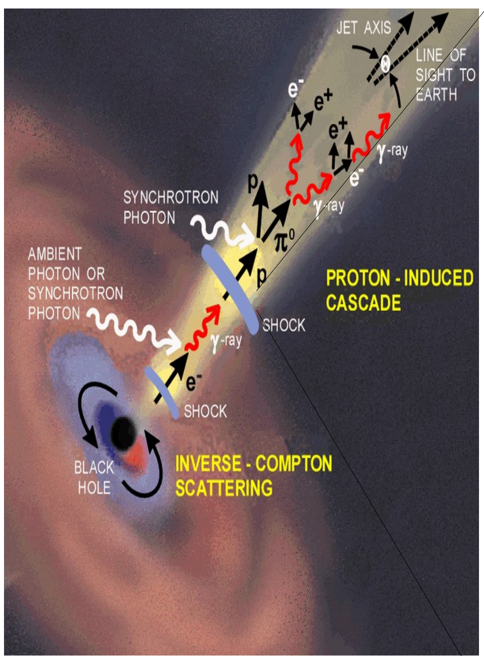
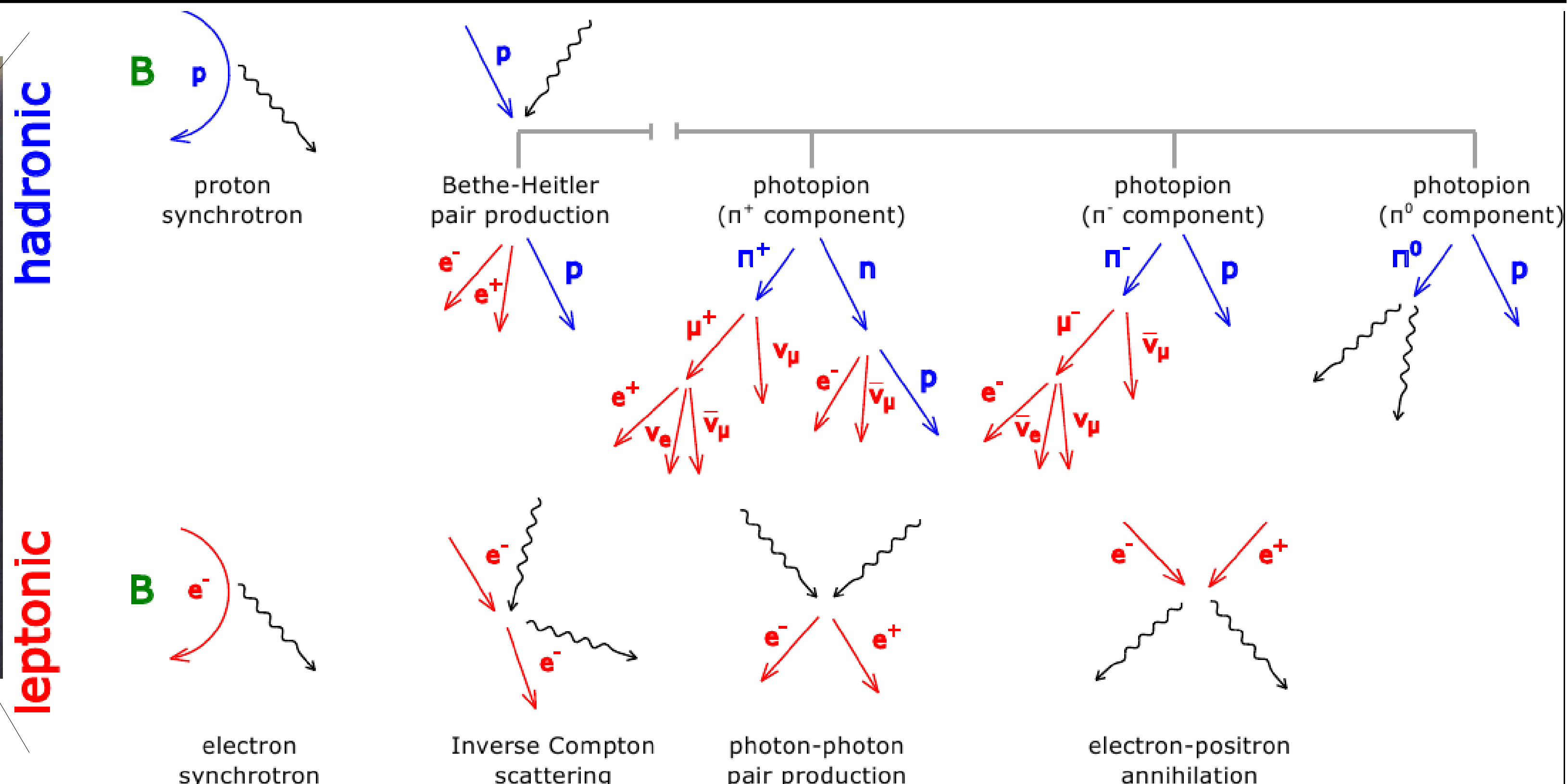
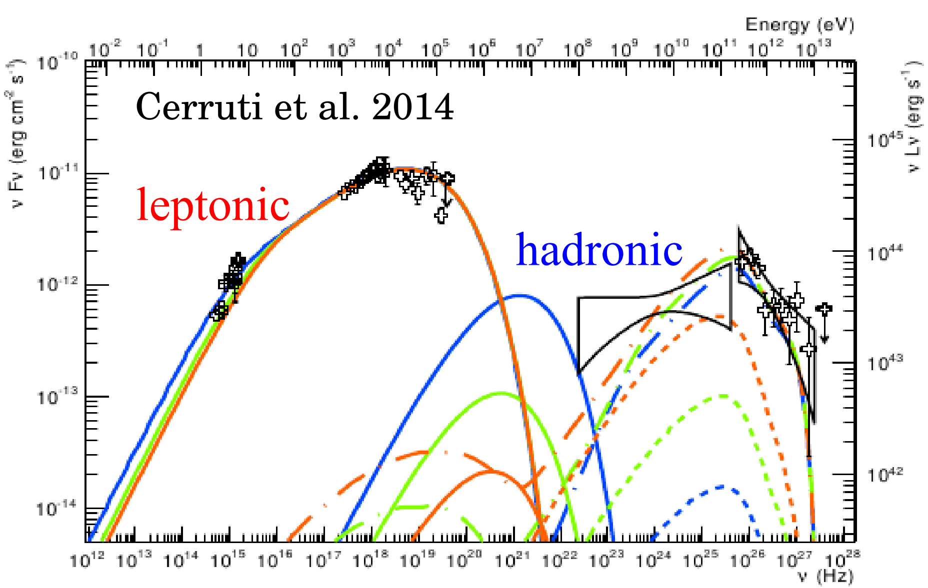
Neutrinos from blazars in a nutshell







Multi-wavelength photon spectrum

(e.g. Mannheim 1993, Aharonian 2000, Muecke & Protheroe 2001, Boettcher et al. 2013, Petropoulou & Dimitrakoudis 2015)

Mrk 421: a prototype blazar

Variable source in various energy bands & timescales!

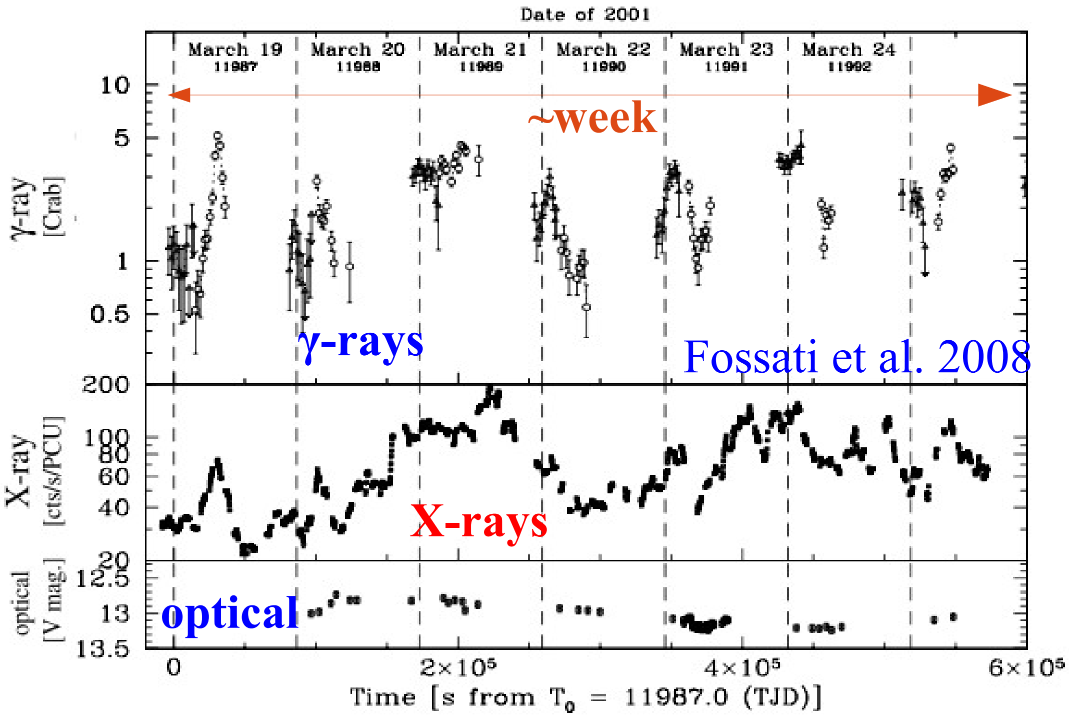
Type: Blazar (BL Lac) in the constellation of Ursa Major

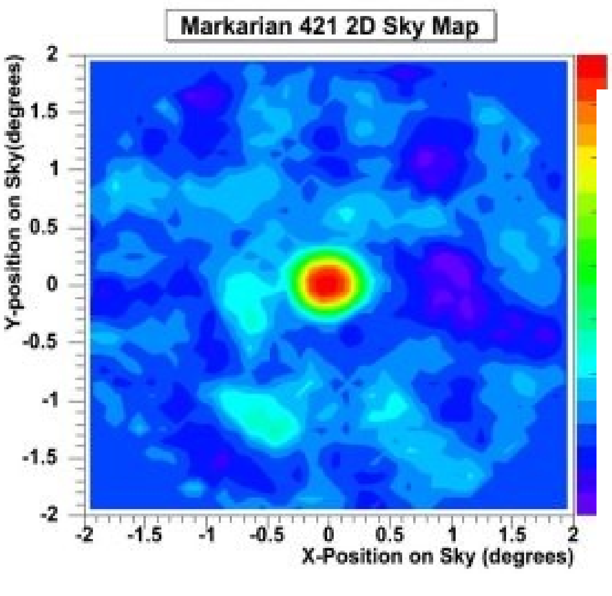
Redshift: $z=0.031$ (De Vacouleurs. et al. 1991)

Distance: ~ 135 Mpc

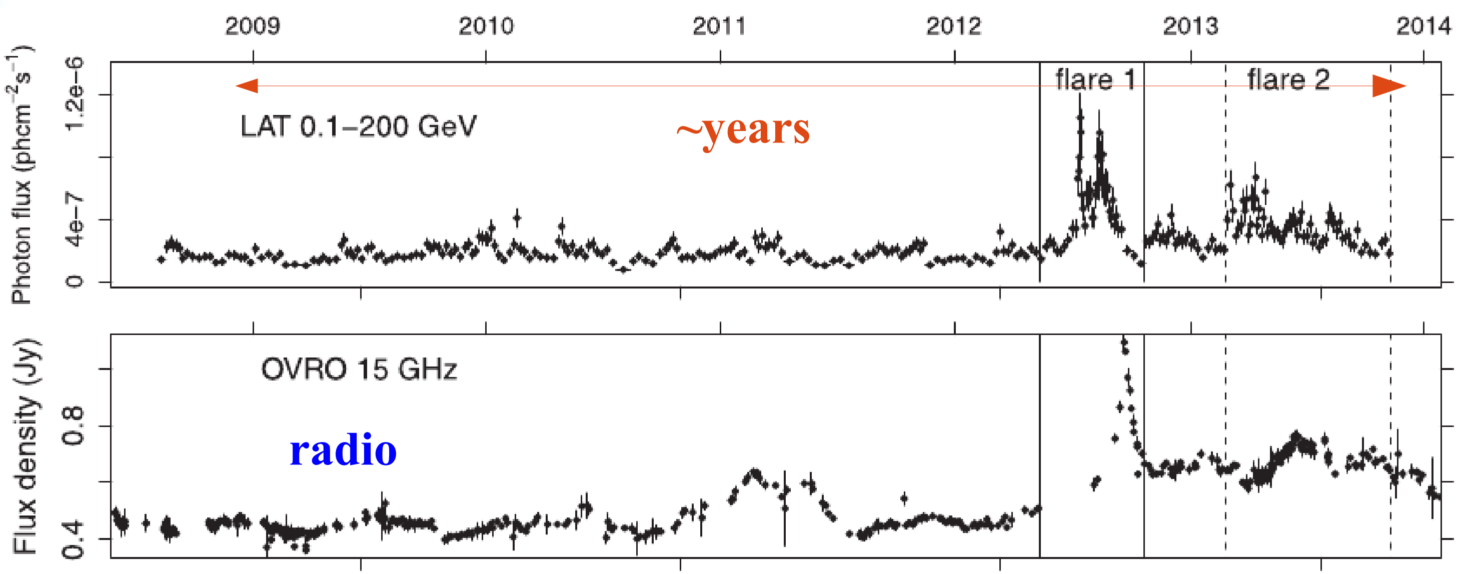
Declination: +38° 12′ 32″

Excellent laboratory for studying blazar emission physics





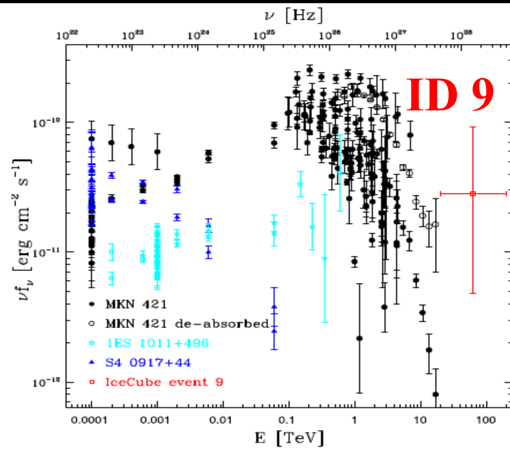
Hovatta et al. 2015



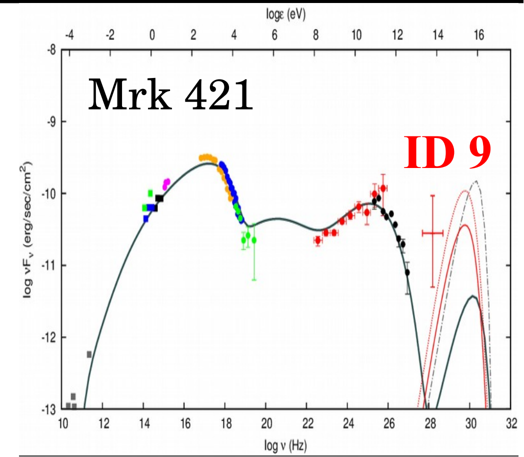
Mrk 421: as a neutrino point source

Motivation

- Mrk 421 was suggested as probable counterpart of neutrino event 9
- Predicted ν flux from its "quiescent"(=4 months with no strong flaring activity) state similar to that measured for ν ID 9



Padovani & Resconi 2014



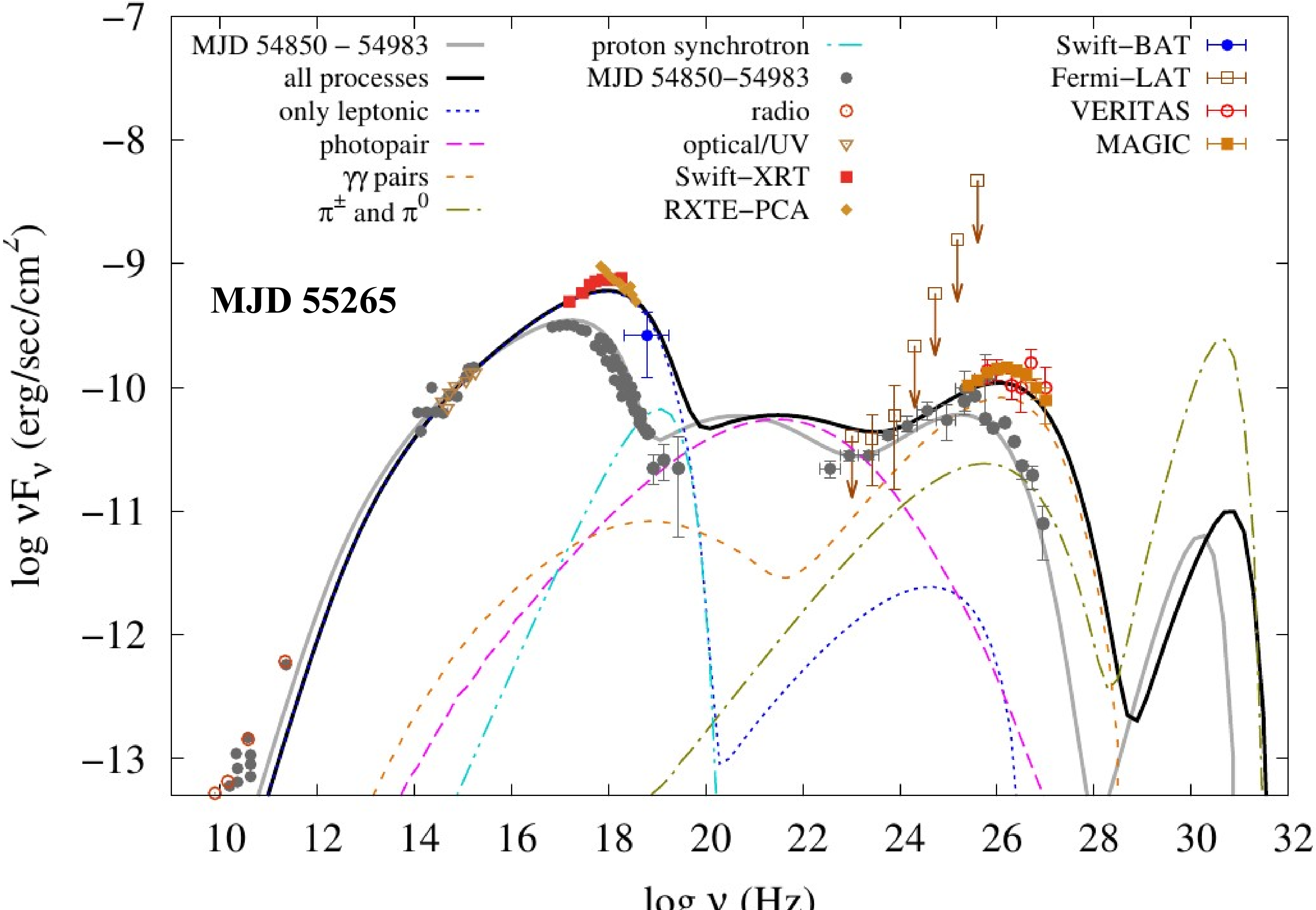
Petropoulou et al. 2015

Aims

- Can the hadronic model explain flaring activity?
- How does the neutrino flux correlate with the photon flux?
- What is the expected neutrino event rate from a ~**day flare**?
- What is the expected neutrino event number over the **5yr IceCube livetime**?

The 13-day flare of 2010

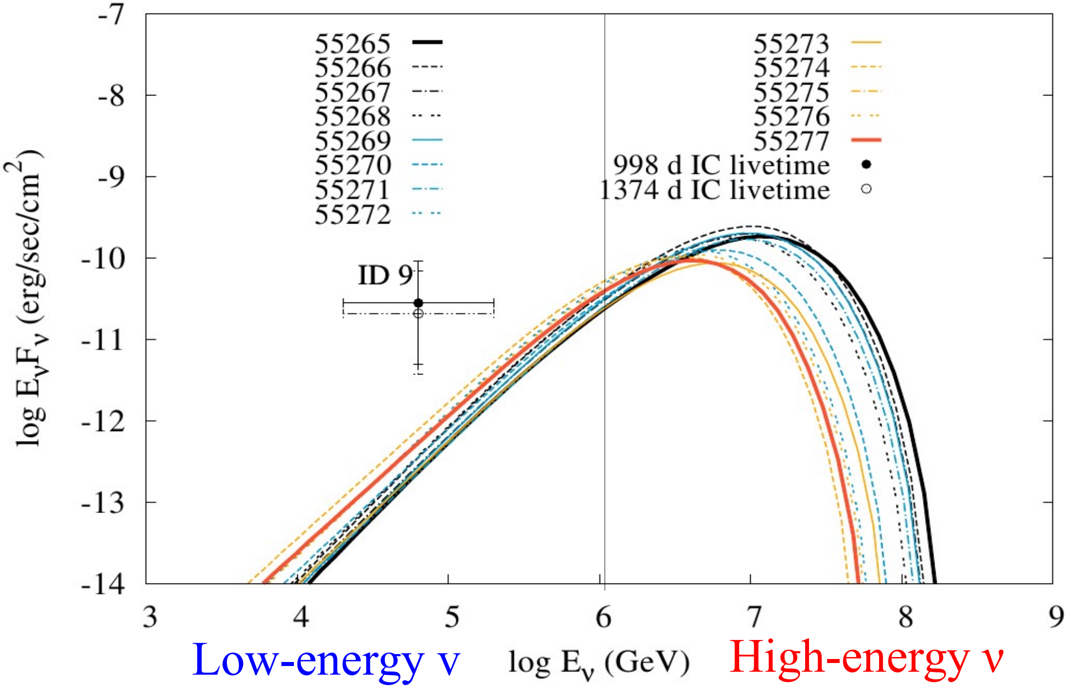
Unprecedented MW coverage & simultaneous observations for MJD 55265-55277
(data are adopted from Aleksic et al. 2015)



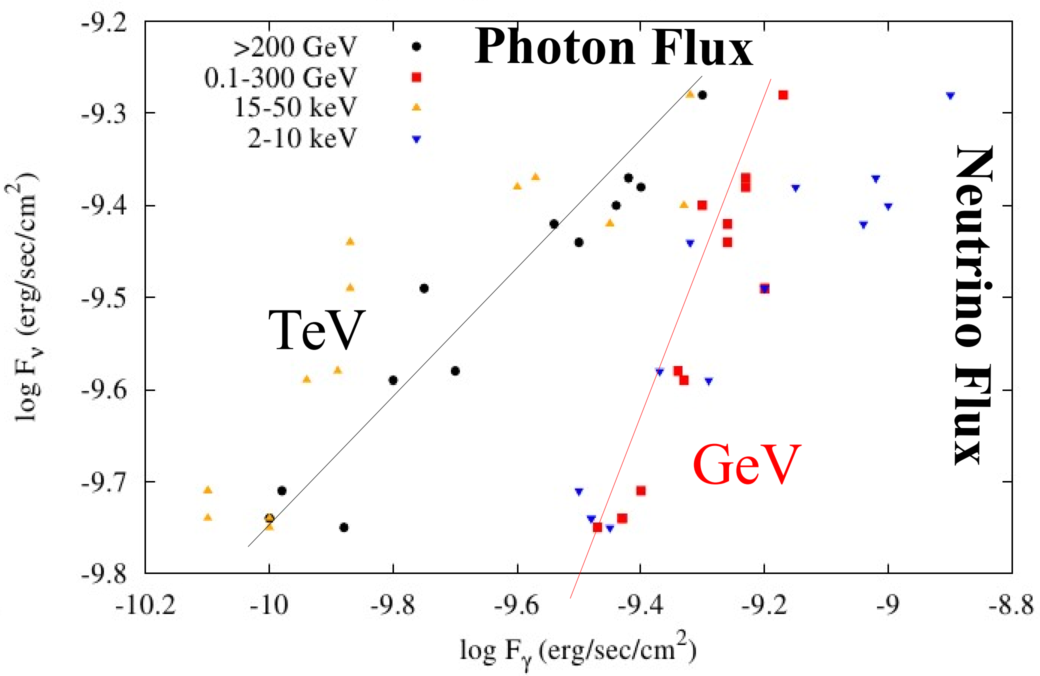
Petropoulou, Coenders, Dimitrakoudis, Aph submitted

The 13-day flare of 2010

Daily all-flavor ν flux spectra



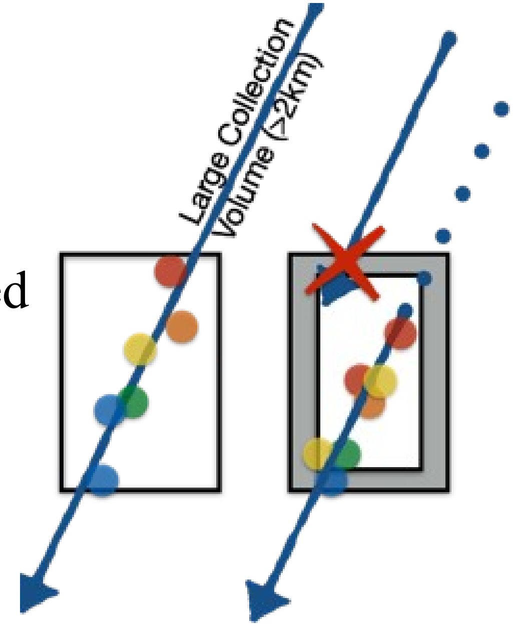
High-energy ν flux vs. photon flux



- < 1 PeV neutrino flux is ~ constant
- \> 1 PeV neutrino flux varies
- \> 1 PeV neutrino flux is correlated with X-rays and γ-rays
- \>1 PeV ν - GeV γ-ray correlation will be applied to the long-term Fermi/LAT light curve

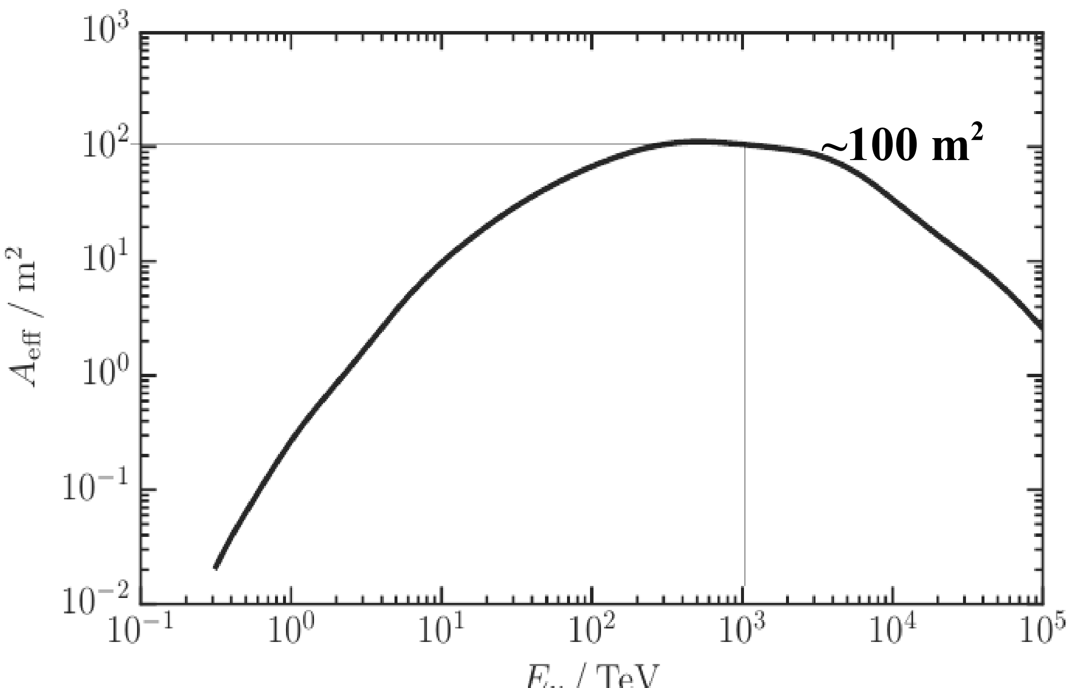
Effective areas for different analyses

Through-going events
- Larger statistical sample
- Larger effective volume
- Atm. background not removed
- Poorer energy determination

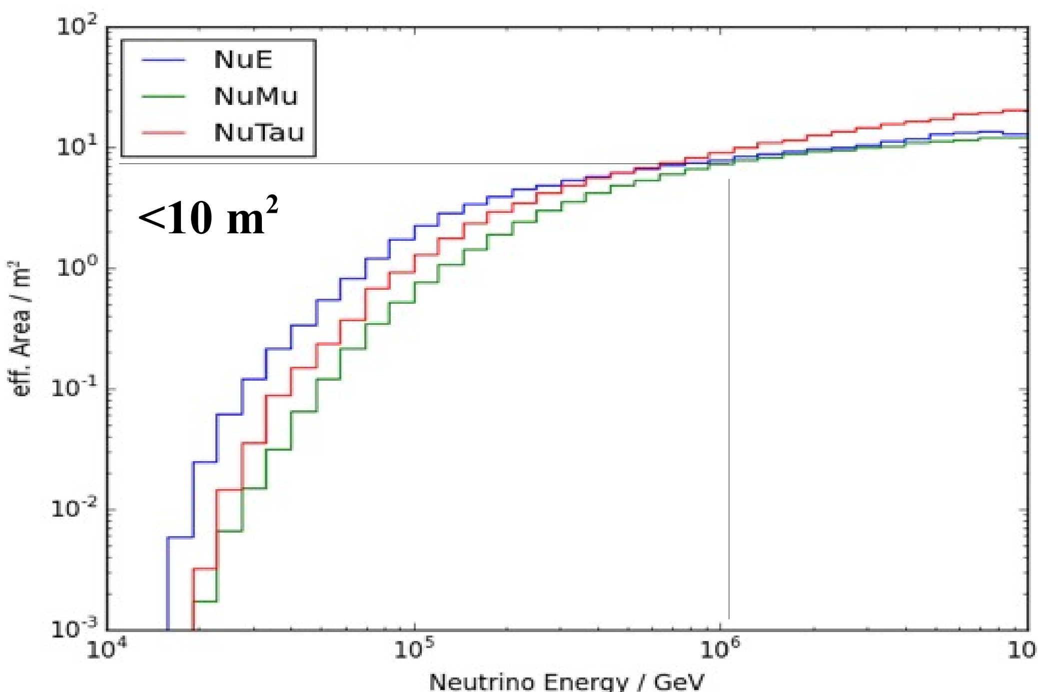


High-energy starting events (HESE)
- Smaller statistical sample
- Smaller effective volume
- Atm. Background removed
- Accurate energy determination

Effective area for through-going muons at the position of Mrk 421



Effective Area for HESE over the northern hemisphere



The 13-day flare of 2010

Muon neutrino+antineutrino rate (evt / yr)

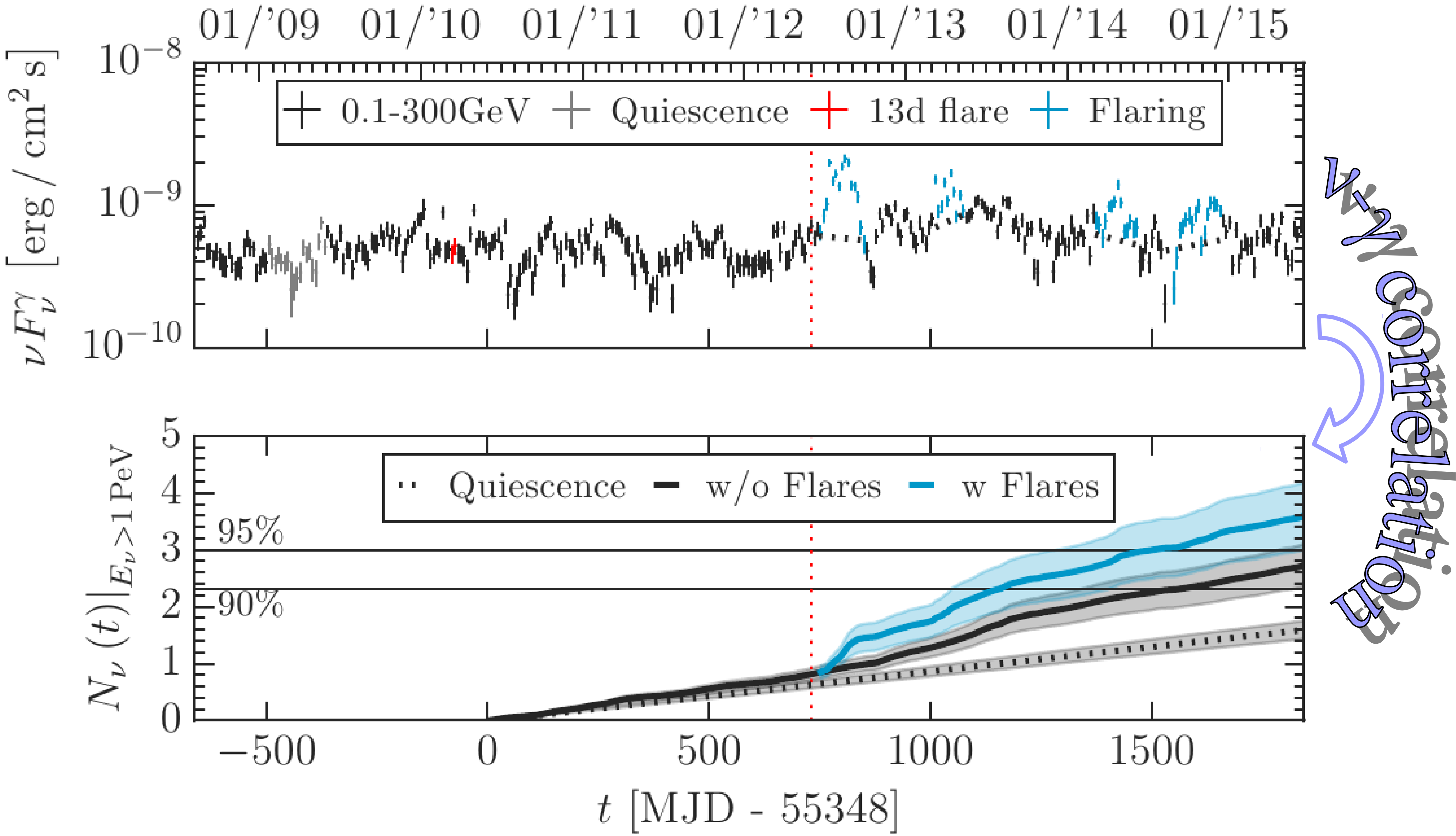
	Mrk 421[a]		Background[b]	
E_ν (TeV)	13-day flare (55265-55277)	quiescent (54850-54983)	atmospheric	diffuse
0.1 – 100	0.023	0.019	7.371	0.010
100 – 10^3	0.264	0.282	1.852×10^{-3}	2.203×10^{-3}
10^3 – 5×10^4	0.306	0.288	4.554×10^{-6}	2.236×10^{-4}

|| ~0.57 evt/yr || ~0.57 evt/yr   Negligible

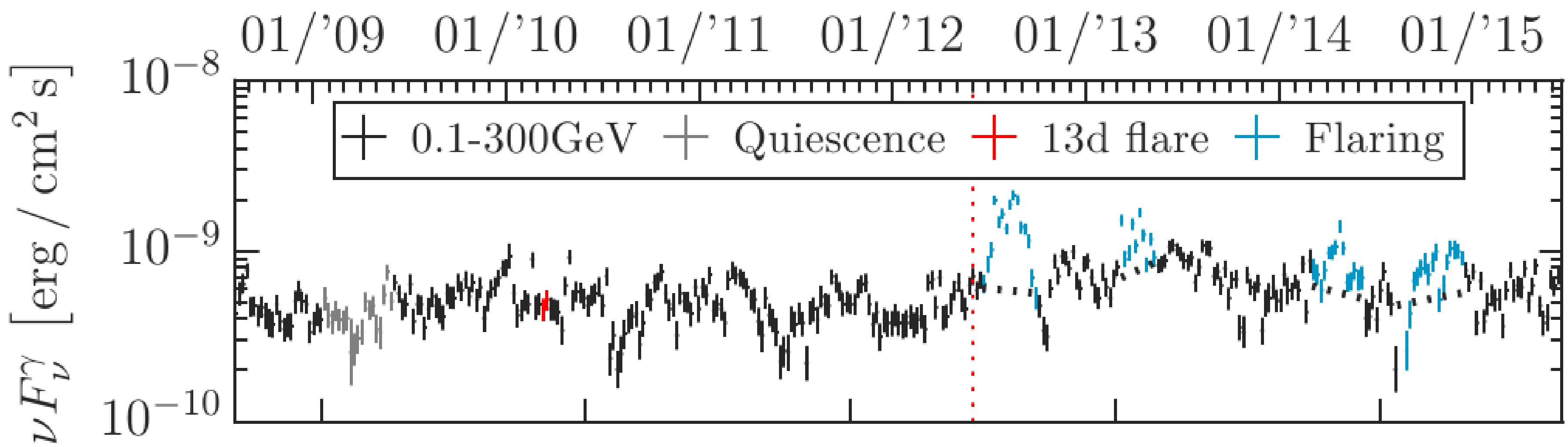
- Neutrinos (> 100 TeV) expected from the flare: 13 x 0.57/333 = 0.02
- Neutrinos (> 100 TeV) expected from quiescent period: 120 x 0.57/333 = 0.2
- Caution needed when associating a ν event with a flaring blazar lying in the error circle of ν detection

The long -term γ-ray activity

The 6.9 yr Fermi light curve (0.1-300 GeV) overlaps with the 5yr IceCube livetime



Expected ν in the 5yr IceCube livetime



Major flares

No.	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)$
Flares 1a+1b	105	0.61 ± 0.16	46 ± 8
Flare 2	70	0.32 ± 0.07	27 ± 5
Flare 3	98	0.26 ± 0.05	23 ± 4
Flares 4a+4b	112	0.26 ± 0.05	23 ± 4
∑ Flares	385	1.46 ± 0.32	77 ± 7

Without major flares

Season	T (days)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)^\dagger$
06/2010-05/2011	364	0.43 ± 0.06	34 ± 4
06/2011-05/2012	364	0.38 ± 0.05	32 ± 3
06/2012-05/2013	371	0.71 ± 0.11	51 ± 5
06/2013-05/2014	364	0.70 ± 0.11	50 ± 5
06/2014-05/2015	350	0.47 ± 0.06	38 ± 4
∑ w/o Flares	1834[a]	2.73 ± 0.38	94 ± 2
∑ w Flares	1834	3.59 ± 0.60	97 ± 2

Similar probability for detecting at least 1 neutrino from the 2012 flare alone and the whole IceCube Season 3

Summary

- The neutrino event rate from the 13-day flare from Mrk 421 is 0.57 evt/yr and similar to the rate from a 4-month period of no flaring activity
- 1 γ-ray flare from Mrk 421 does not necessarily lead to 1 neutrino event
- Accumulation of many week-duration flares necessary for the detection of at least 1 neutrino
- Neutrino flux above 1 PeV correlates with X-ray and γ-ray fluxes
- Major flares (long duration & large flux increase) have a significant impact on the neutrino count over time
- Utilizing the >1 PeV ν-GeV γ-ray correlation and Fermi/LAT light curve of Mrk 421 we expect: **~3.6 ν with flares and ~2.7 ν without flares included.** These exceed the threshold value for detection of at least 1 neutrino at **95% CL and 90% CL** respectively
- No high-energy ν detection would suggest that the correlation does not hold during major flares or/and the hadronic contribution to blazar emission is smaller
- Neutrino-photon flux correlations are model-dependent but important for optimizing time-dependent neutrino searches

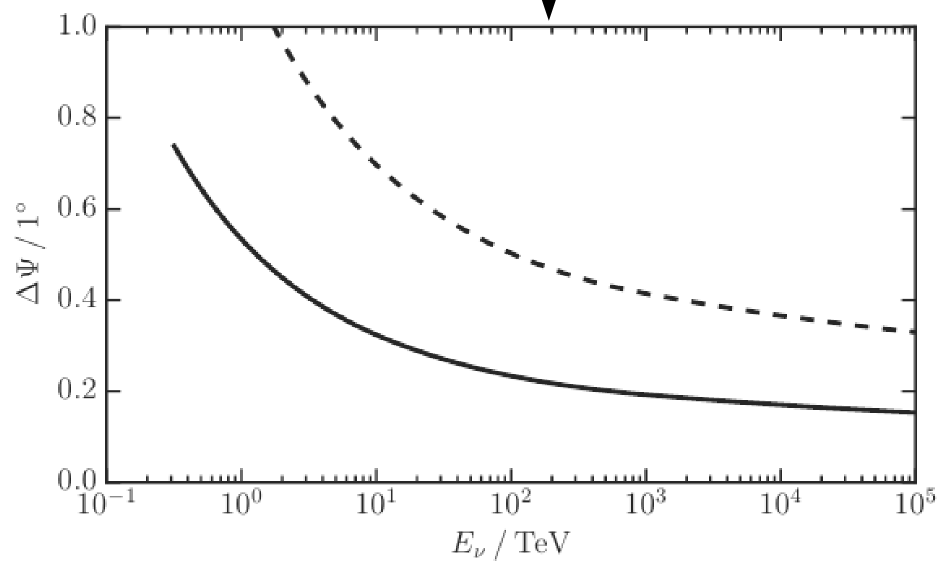
THANK YOU

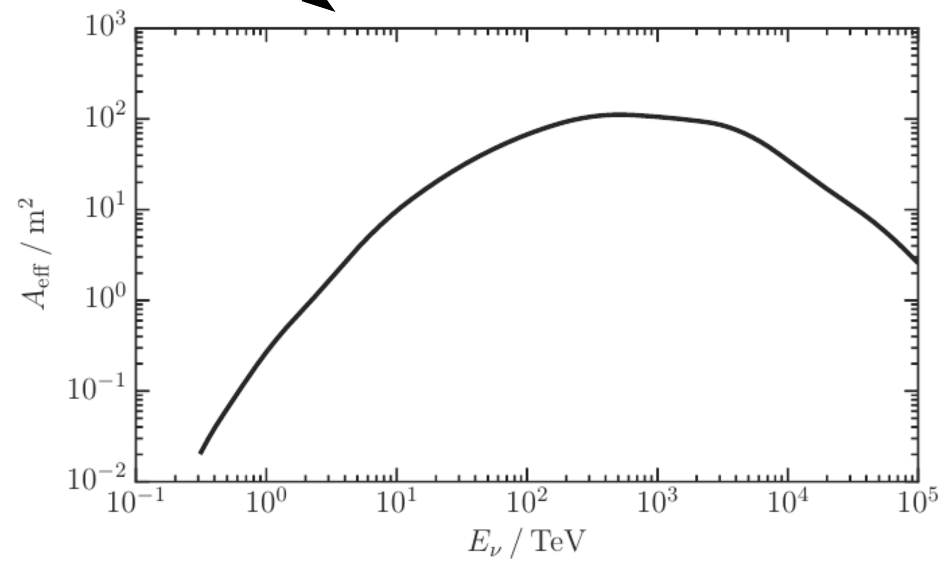
Back-up Slides

Calculation of muon neutrino number

$$N_\nu = T \int_{E_{\nu,\mathrm{min}}}^{E_{\nu,\mathrm{max}}} dE_\nu \int_{\Delta\Omega(E_\nu)} \mathrm{d}\Omega \, A_{\mathrm{eff}}(E_\nu, \vec{x}) \sum_i \frac{\partial^2 F_{\nu,i}}{\partial\Omega \partial E_\nu}$$

1) Atmospheric background
2)Diffuse Astrophysical Flux
3)Point source flux





Point source searches with IceCube

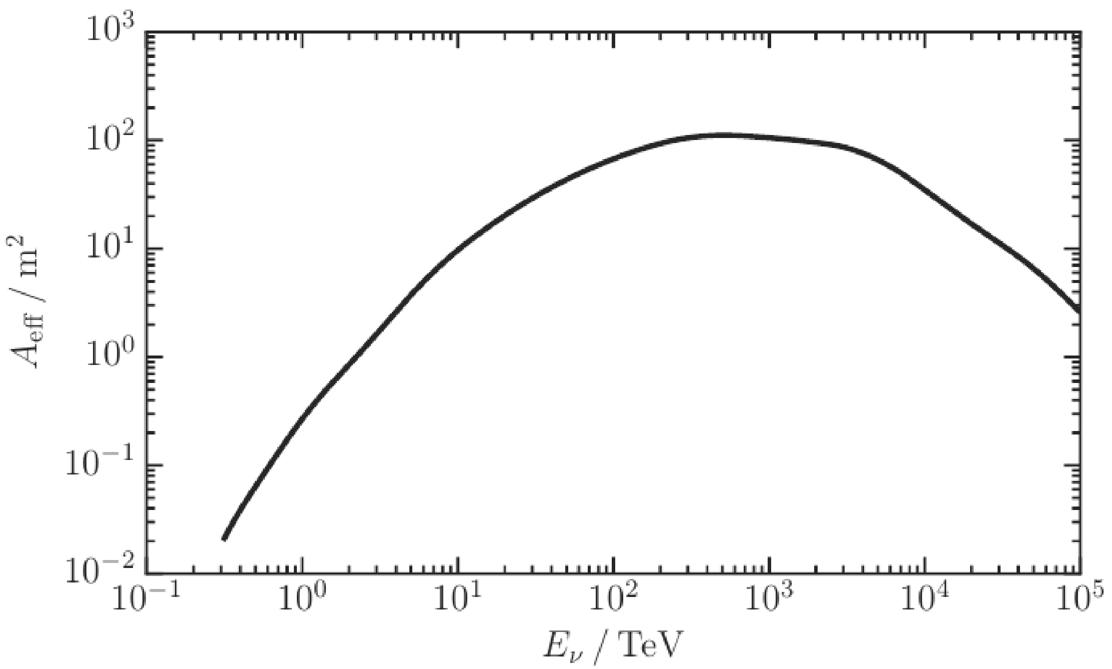
Advantages of using track-like events of charged μ:

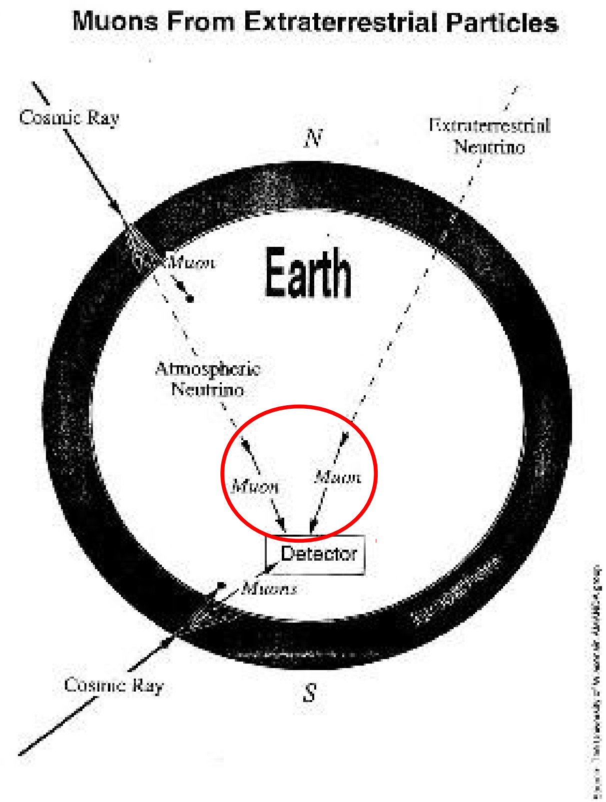
- Angular resolution < 1 degree
- Good angular reconstruction reduces the background to a small area on the sky
- Large distances traveled in the detector → large effective volume

\+ CR μ background reduced due to Earth absorption

– neutrino E difficult to be determined with accuracy

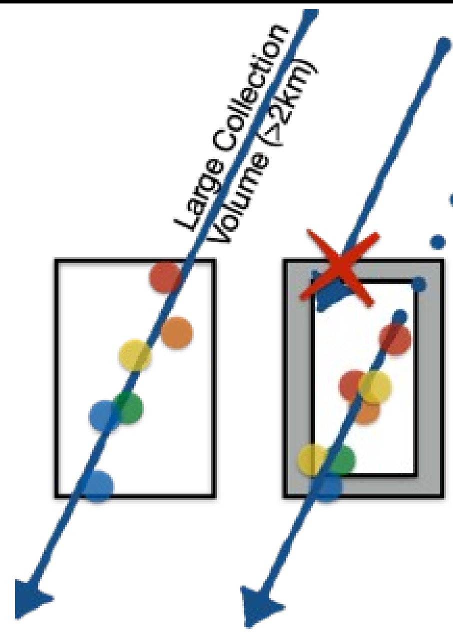
– Earth absorption reduces neutrinos > 1 PeV





Effective areas

Through-going events



High-energy starting events (HESE)

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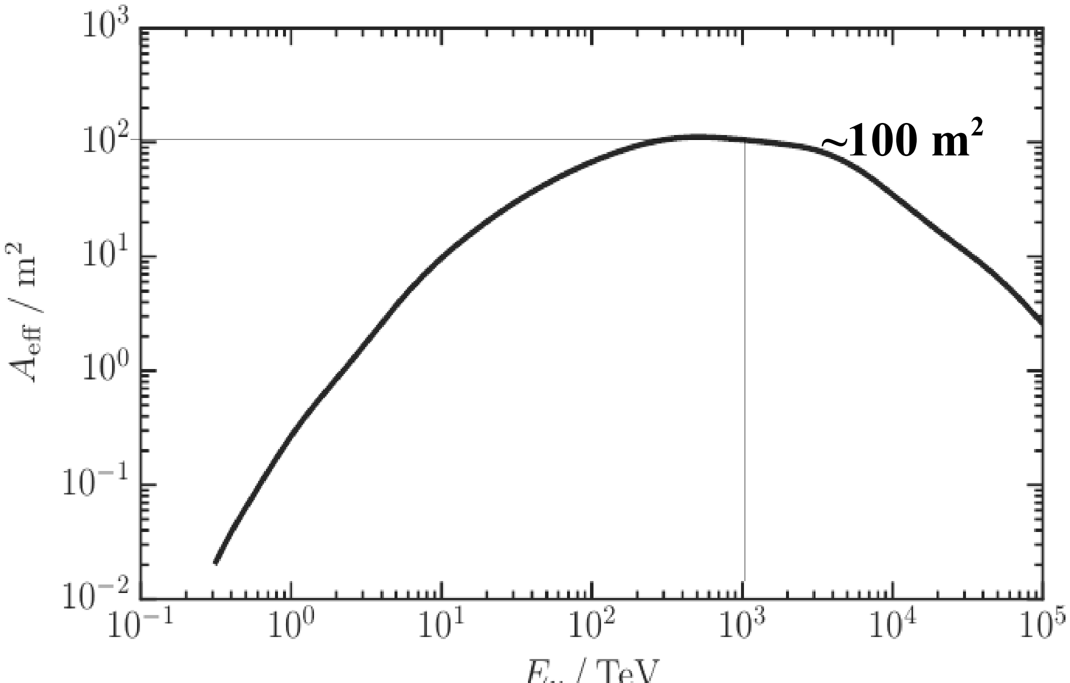

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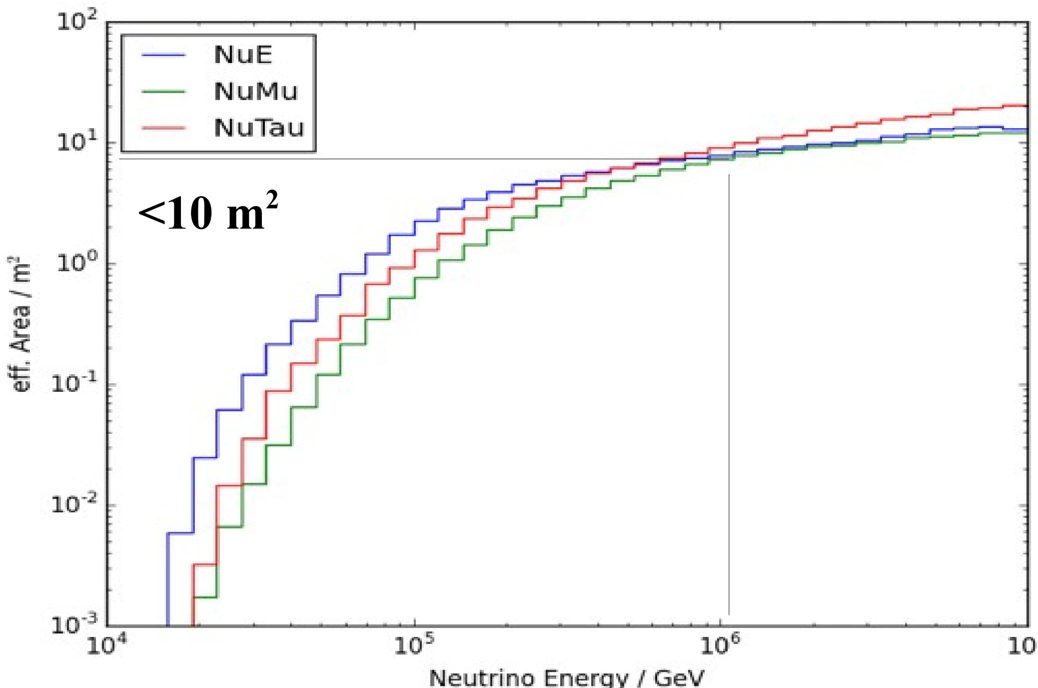
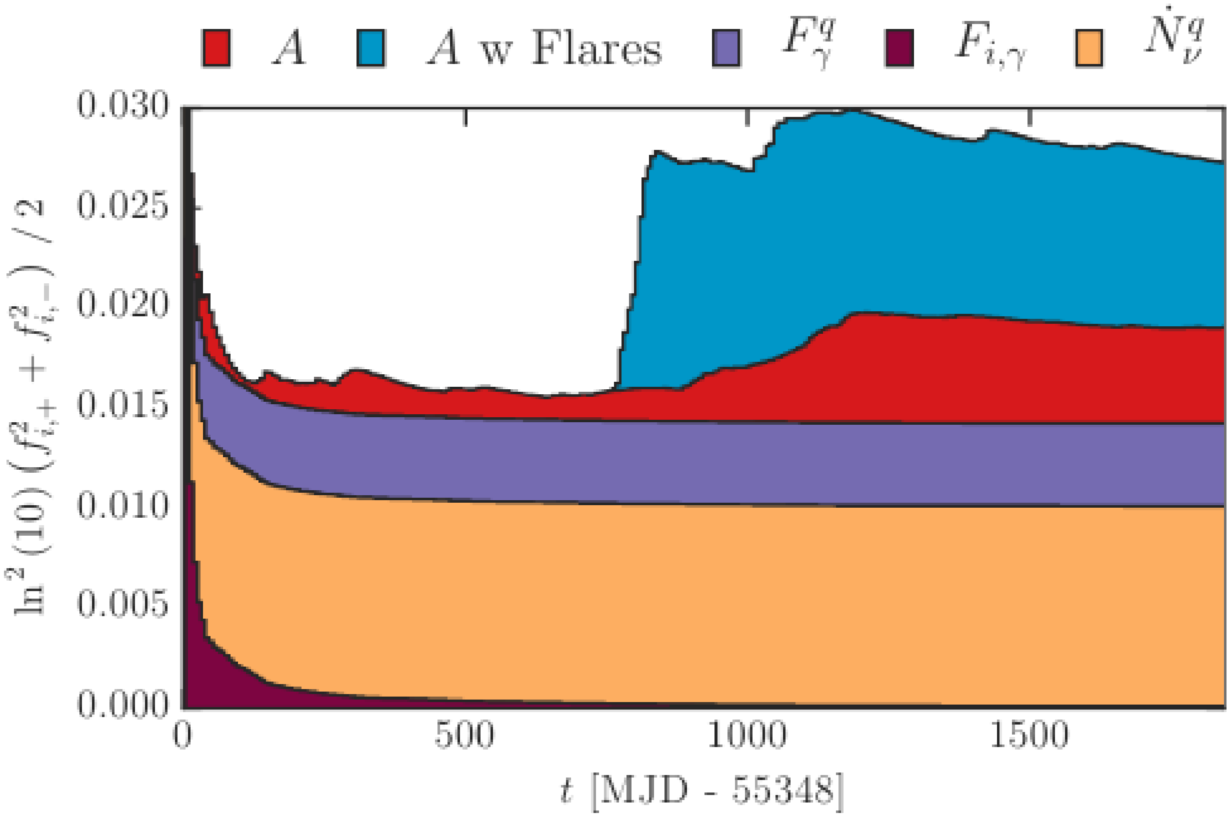


Calculation of uncertainties

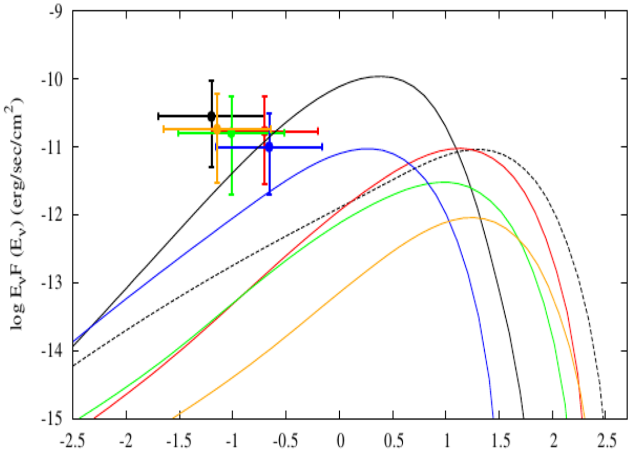
$$N_\nu \equiv \dot{N}_\nu T = \frac{\dot{N}_\nu^q}{F_\nu^q} \int_T dt\, F_\nu(t) = \dot{N}_\nu^q \int_T dt \left(\frac{F_\gamma(t)}{F_\gamma^q} \right)^A$$

$$\sigma_{n_\nu}^2 = f_{\dot{N}_\nu^q}^2 + f_{F_{\gamma,i}}^2 + f_{F_\gamma^q}^2 + f_{\mathrm{A}}^2$$



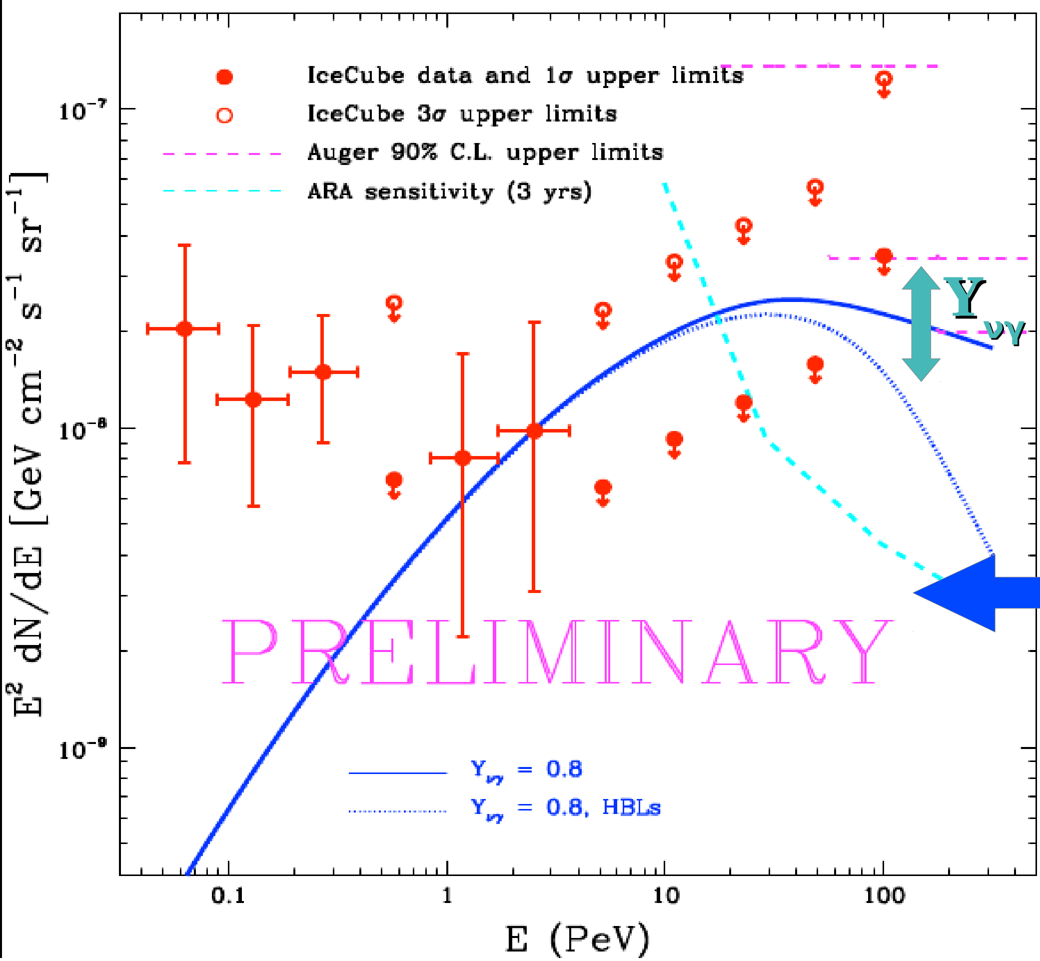
Stacked contributions of various sources of uncertainty to the total one

Neutrino emission from *all* BL Lacs



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

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



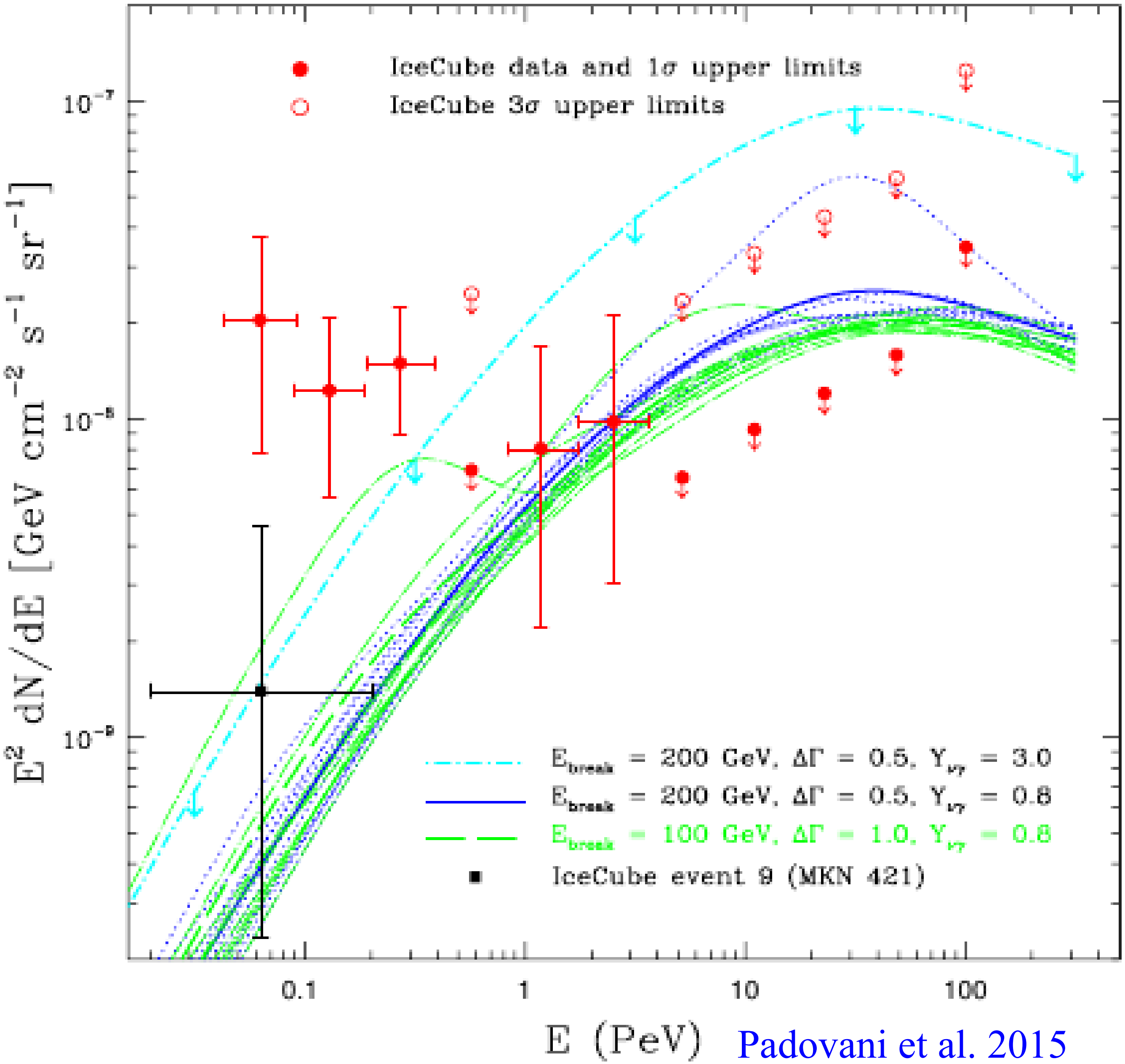
Monte-Carlo simulation for blazar population (Giommi & Padovani 2012 , 2013, 2015):

– Radio luminosity function & evolution
– Distribution of synchrotron peak frequency
– Redshift
– Distribution of Doppler factor
– γ-ray constraints

Padovani et al. 2015

Point source & diffuse ν signal

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



Padovani et al. 2015