# Neutrino emission from blazars in quiescence and flaring periods


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# Talk outline

- Introduction

- Neutrino emission from BL Lacs:
  **flaring states vs. quiescence**

  1. Motivation & Goals

  2. Application to Mrk 421

- Conclusions

*(Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115)*

# The first discovery of high-energy astrophysical ν from Icecube

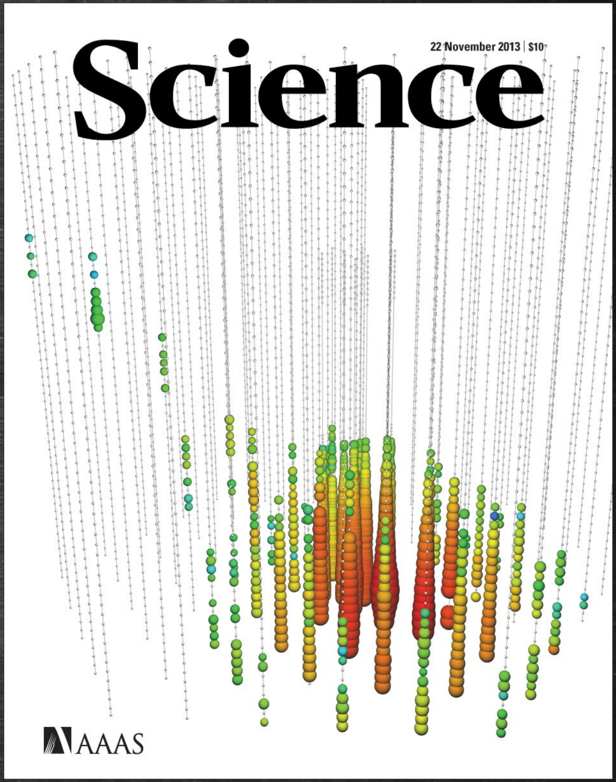
Q: What is their origin?

A: Not known yet.

Q: What is needed more?

A:

- More statistics



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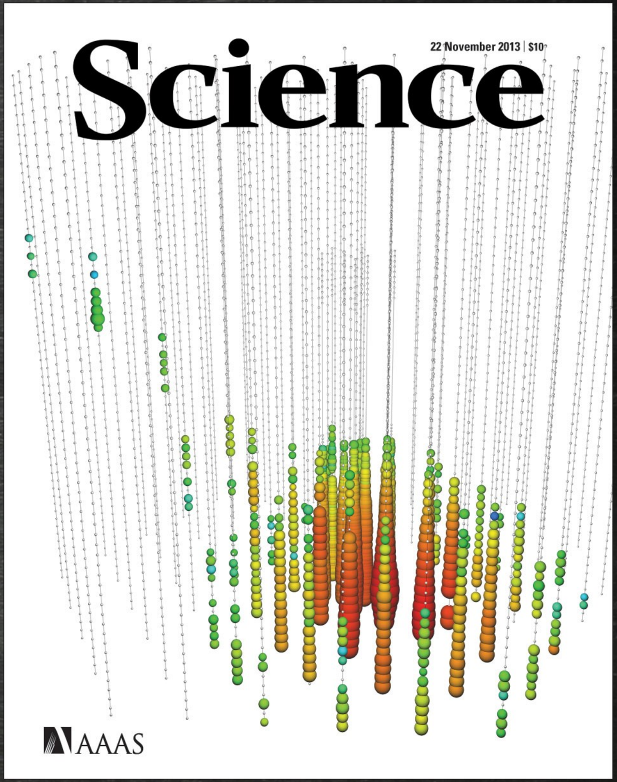


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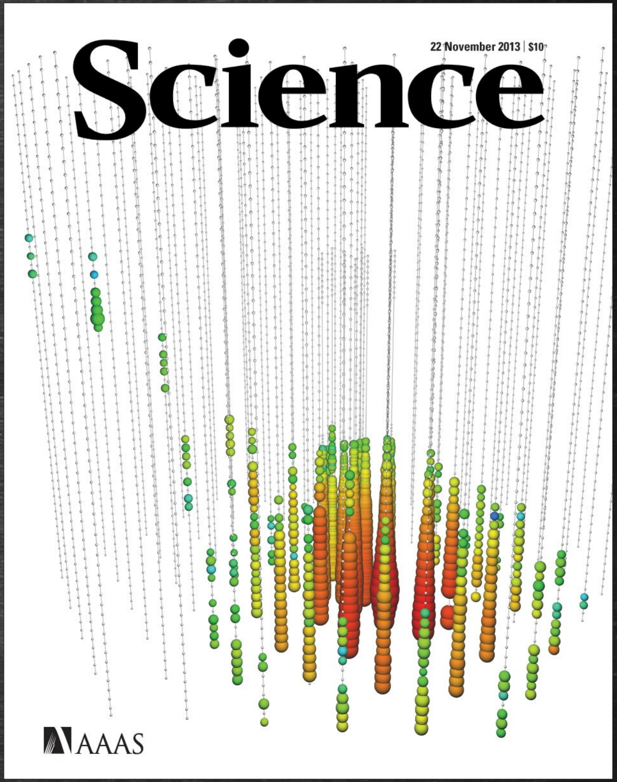



Q: What is their origin?

A: Not known yet.

Q: What is needed more?

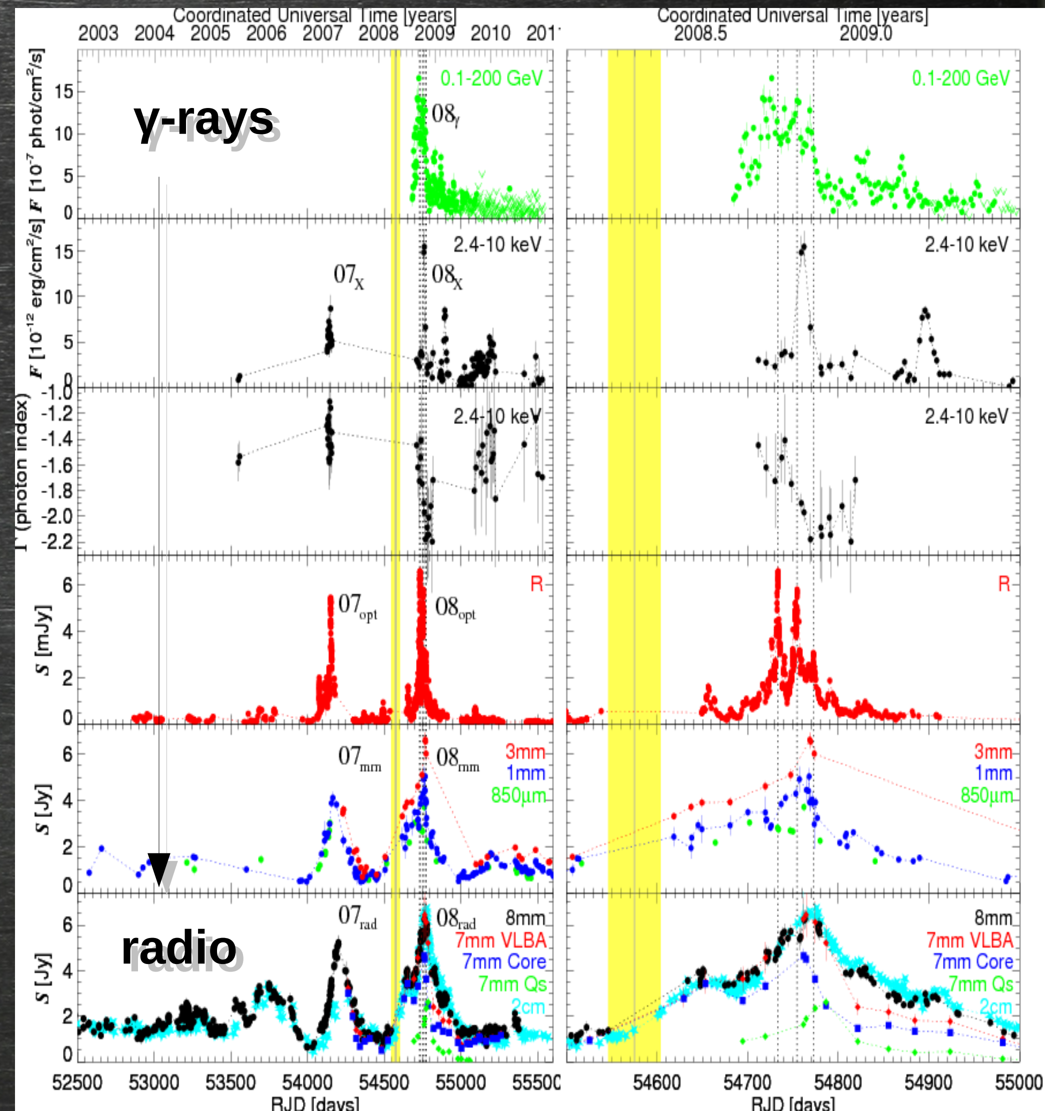
A:

- More statistics
- Model-independent searches of point sources
- Theoretical model predictions for particular types of sources.

# ν emission during flares and quiescence

## Motivation

- Blazars are variable sources across the electromagnetic spectrum !

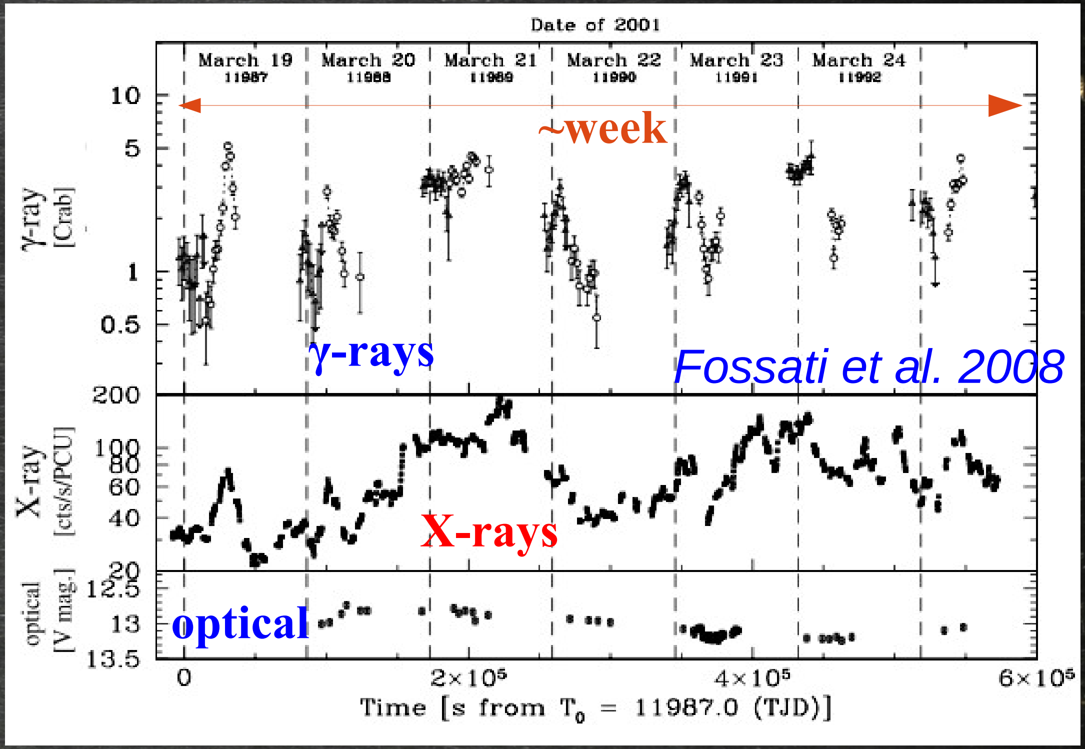



## Aims

- How does the ν flux correlate with the photon flux?
- Comparison between quiescence & flares
- What is the expected ν event rate from a ~day flare?
- What is the expected ν event number over the 5yr IceCube livetime?

# Mrk 421: an excellent lab for blazar models

Variable source in various energy bands & timescales!

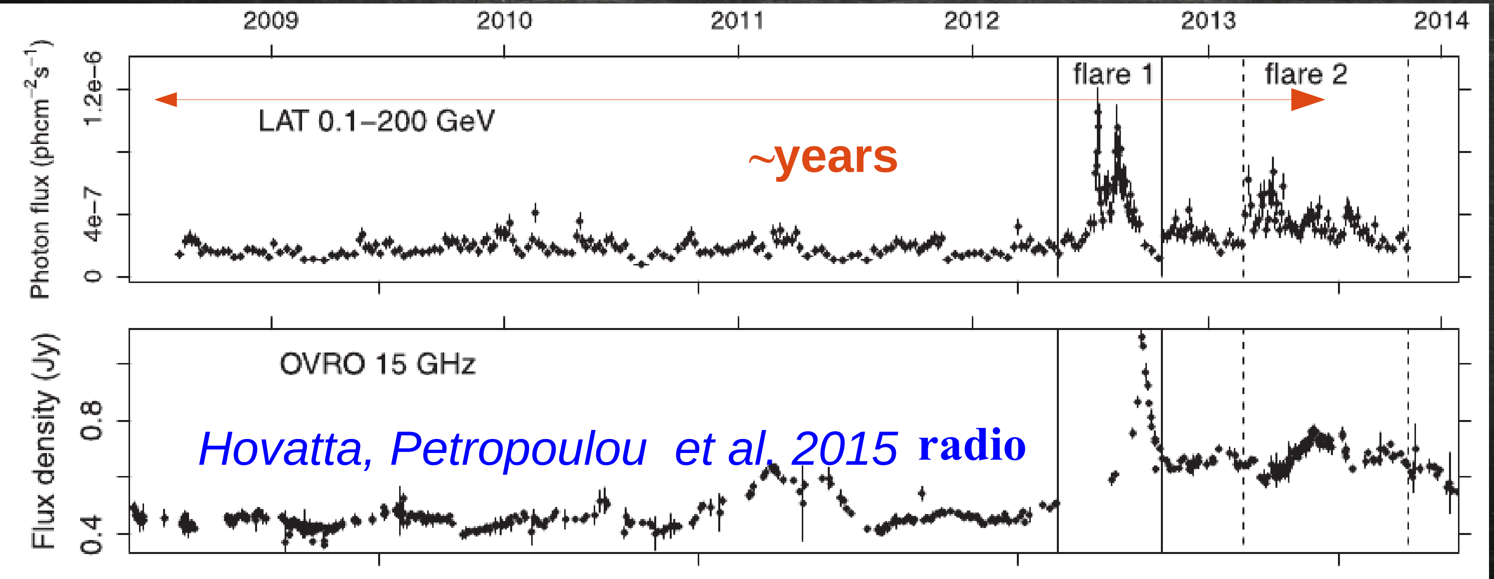



3 data sets used:

1) **~4 month-long data in 2009;** typical of the “quiescent” emission *(Abdo et al. 2011, ApJ, 736)*

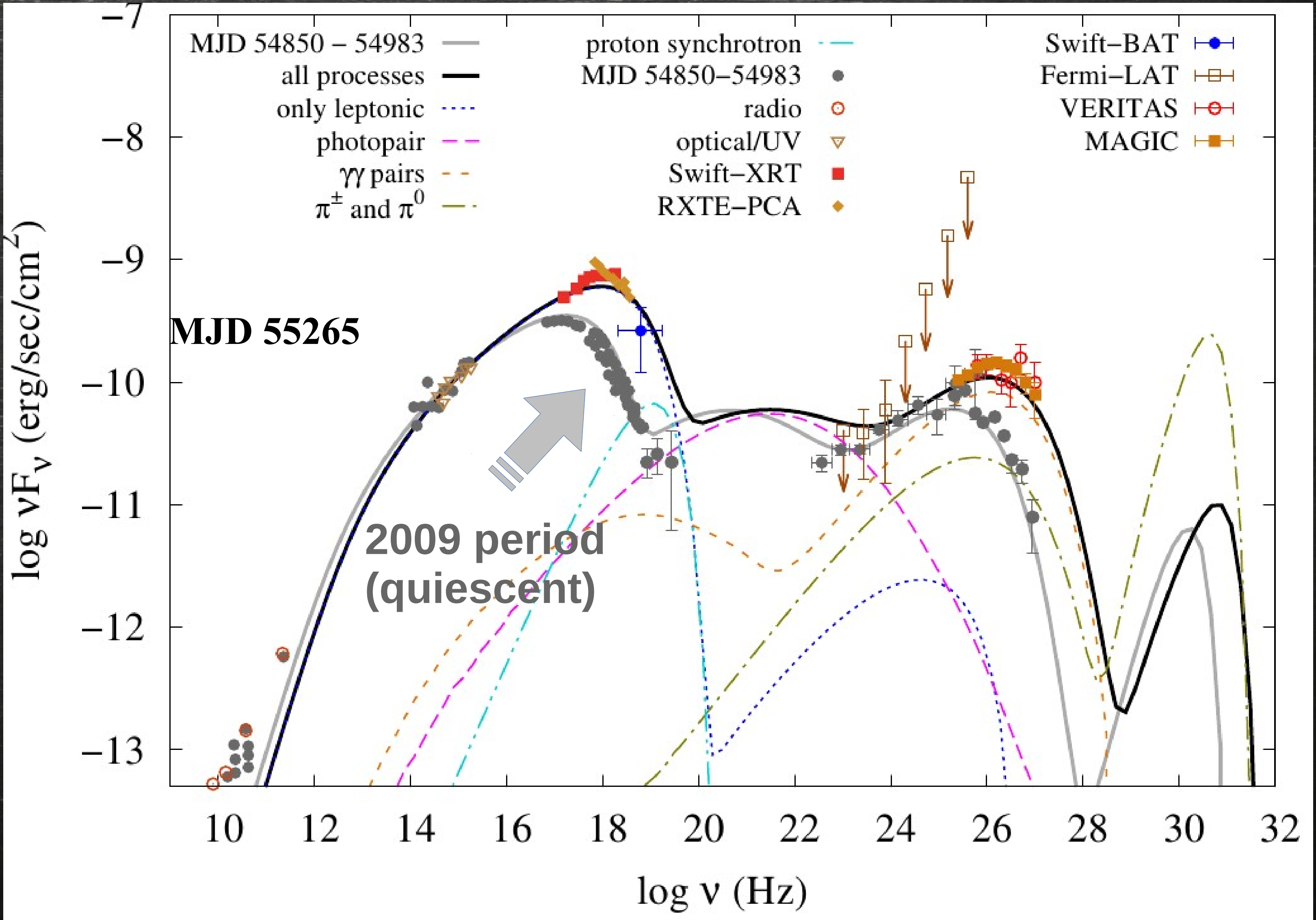
2) **13-day flare in 2010;** significant X-ray and VHE variability but ~constant GeV flux *(Aleksic et al. 2015, A&A, 578)*

3) **~7 yr-long Fermi-LAT data**



# SED modeling

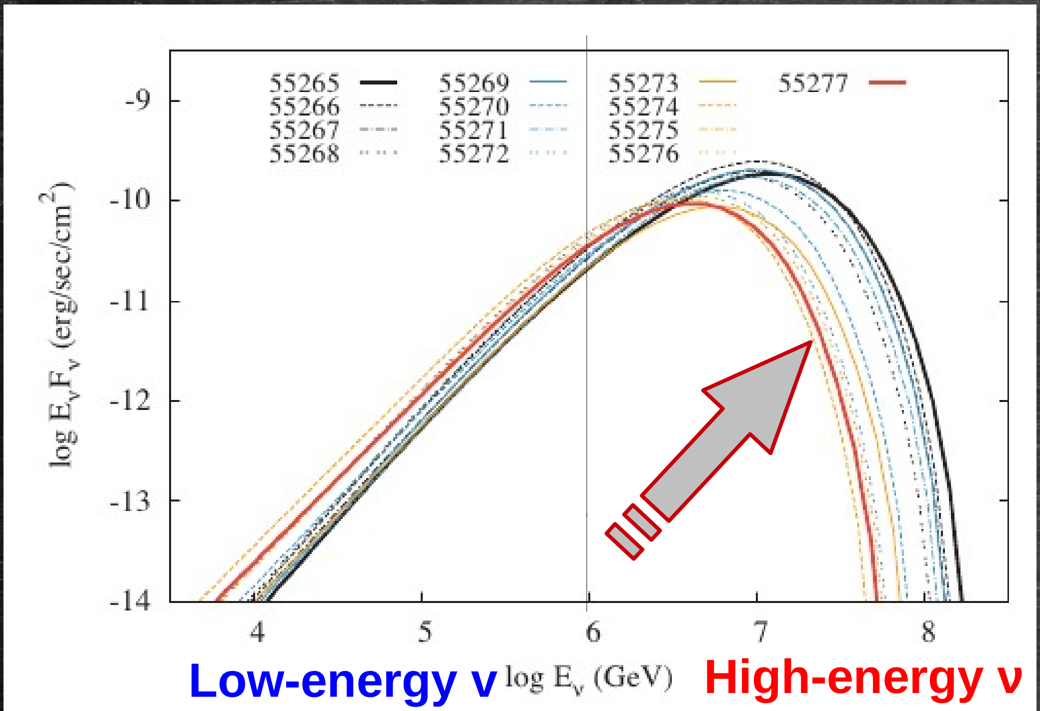
Unprecedented MW coverage & simultaneous obs. for MJD 55265-55277
(data are adopted from Aleksic et al. 2015)



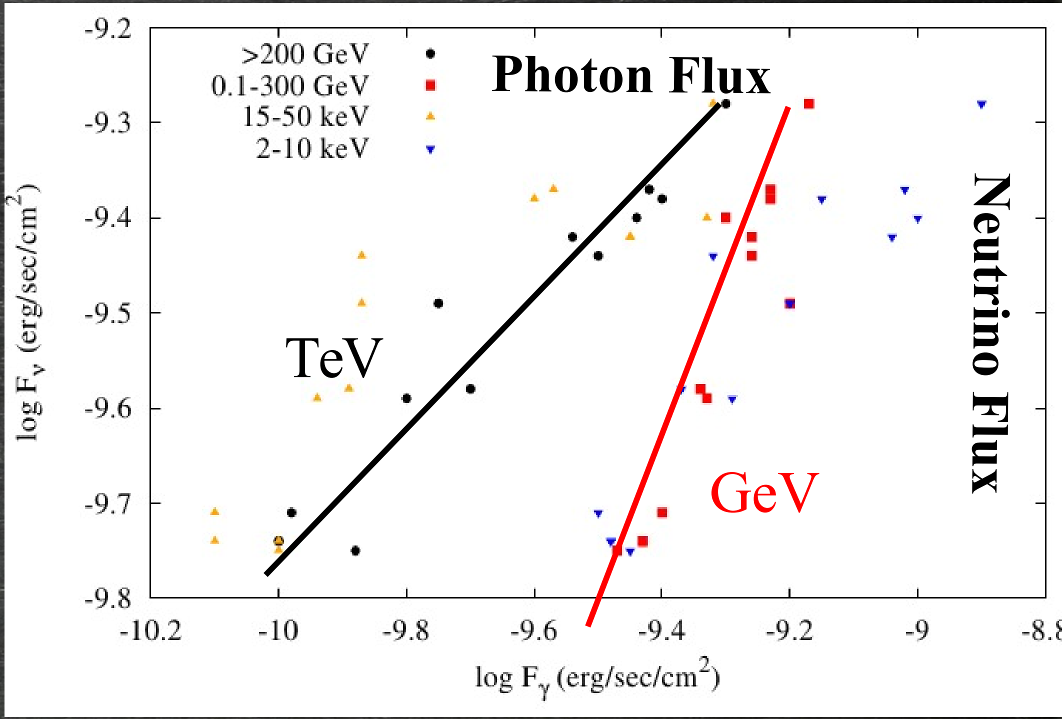

*Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115*

# Predicted ν emission

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

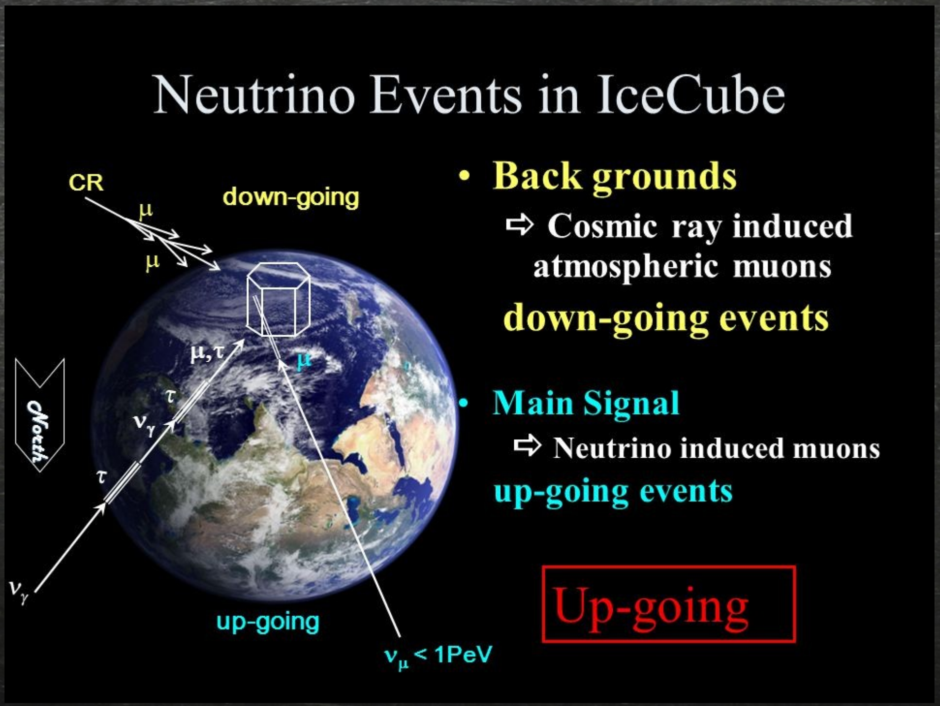
# Effective areas of the analyses

Up-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



# Comparison of event rates

Muon neutrino+anti-neutrino rate (evt / yr)

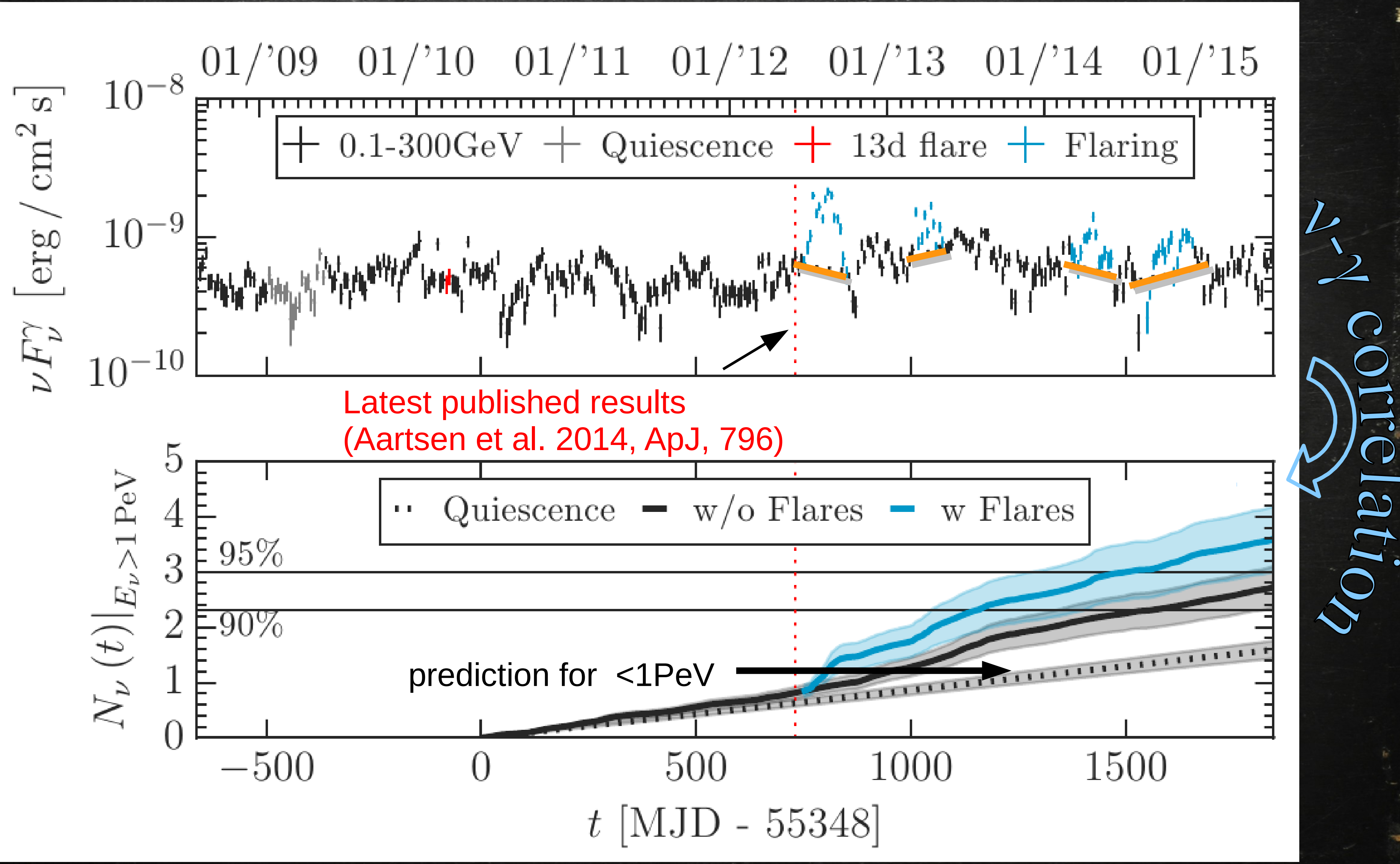
| | Mrk 421[a] | | Background[b] | |
|---|---|---|---|---|
| $E_\nu$ (TeV) | 13-day flare (55265-55277) | quiescent (54850-54983) | atmospheric | diffuse |
| $0.1 - 100$ | 0.023 | 0.019 | 7.371 | 0.010 |
| $100 - 10^3$ | 0.264 | 0.282 | $1.852 \times 10^{-3}$ | $2.203 \times 10^{-3}$ |
| $10^3 - 5 \times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

~0.57 evt/yr ~0.57 evt/yr Negligible

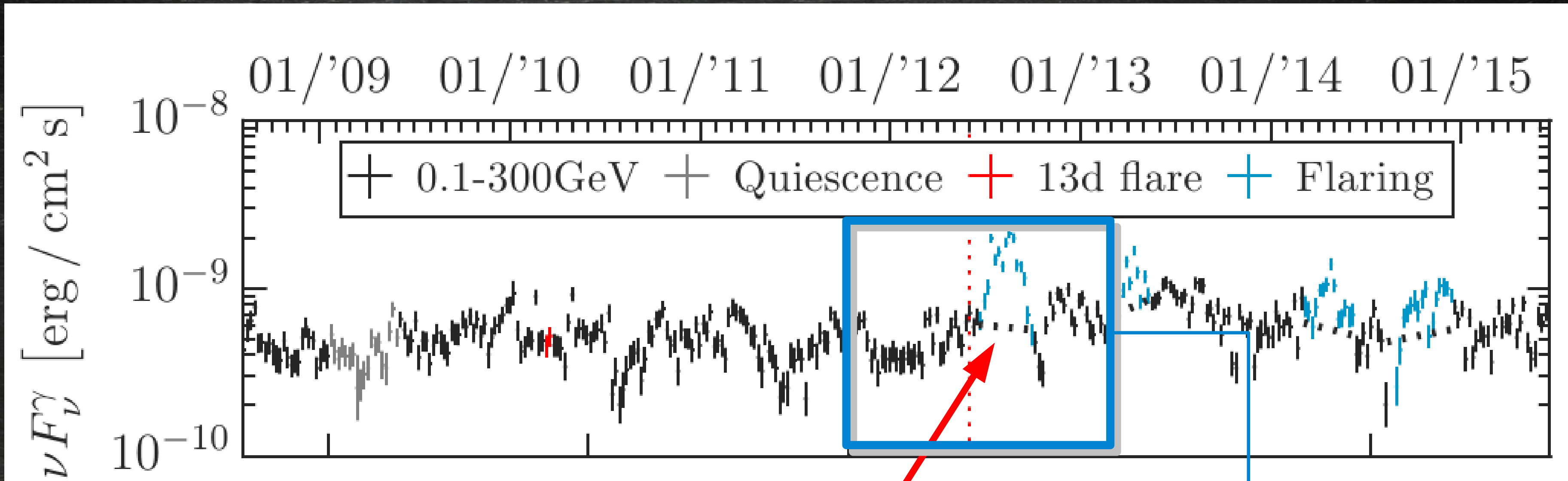
- Neutrinos (> 100 TeV) expected from the flare: 13 x 0.57/333 = 0.02
- Neutrinos (> 100 TeV) expected from quiescent period: 120 x 0.57/333 = 0.2
- Caution needed when associating a ν event with a flaring blazar lying in the error circle of ν detection
- An accumulation of many similar flares is required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

# The long-term γ-ray activity

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



# Predicted #ν in 5yr IceCube livetime




## Major GeV 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 GeV major flares

| Season | T (days) | $\nu_\mu + \bar{\nu}_\mu$ | $P_{N_\nu \geq 1}$(%)[†] |
|---|---|---|---|
| 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 IC Season 3
* Still <50%

# Constraining the model

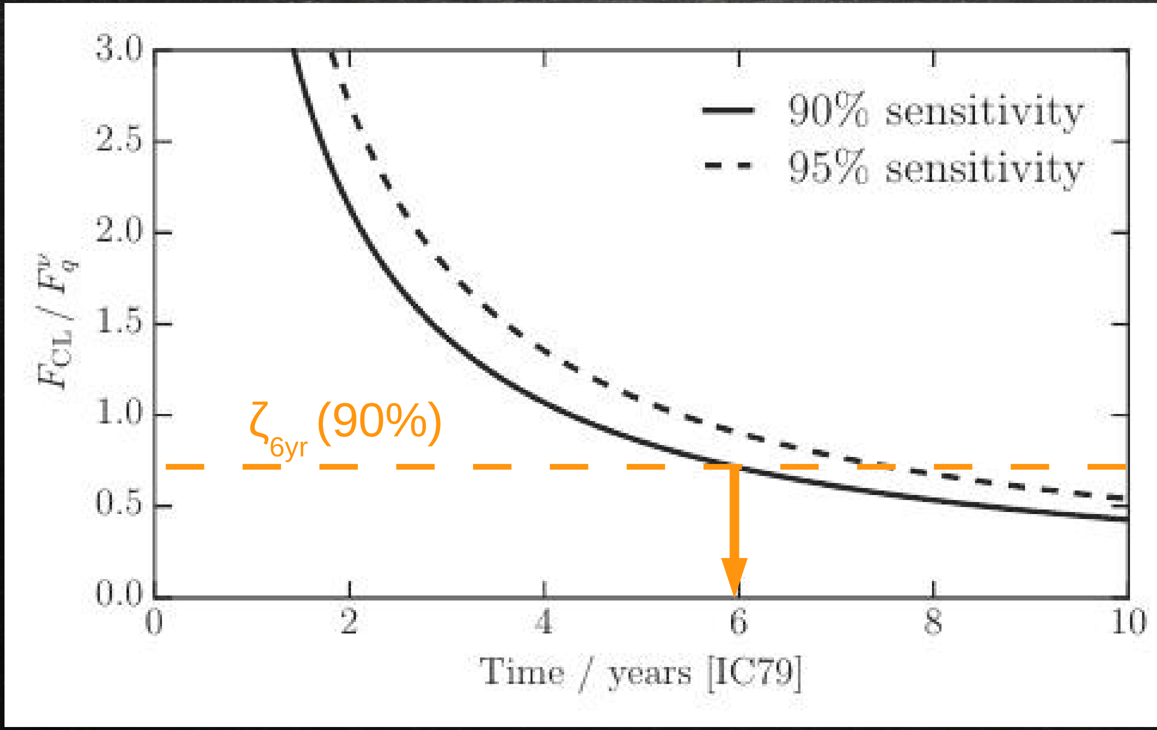
Q: What means a neutrino non-detection of Mrk 421?

A: Correlation between >1PeV ν and GeV γ-rays differs in major flares

**OR**

Much lower power is carried by CR in blazar jets

>100 TeV ν flux( normalized to 4e-10 erg/s/cm2) vs. T (yr) needed for IceCube ν detection at 90% (95%) CL



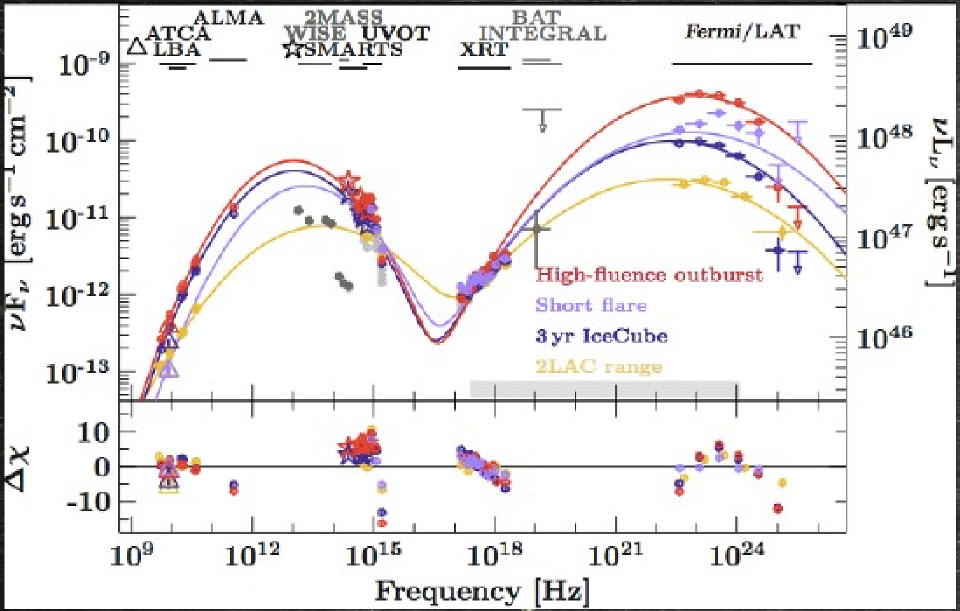

Upper limits on CR power given a non-detection (at 90%, 95% CL) of muon N (> 100 TeV) from Mrk 421 in X years.

| $X$ (yr) | $\zeta_X$ | | $L_{p,X}$ (erg/s) | |
|---|---|---|---|---|
| | 90% | 95% | 90% | 95 % |
| 6 | 0.71 | 0.9 | $6.2 \times 10^{47}$ | $7.8 \times 10^{47}$ |
| 8 | 0.53 | 0.68 | $4.6 \times 10^{47}$ | $5.9 \times 10^{47}$ |
| 10 | 0.43 | 0.54 | $3.7 \times 10^{47}$ | $4.7 \times 10^{47}$ |
| 20 | 0.21 | 0.27 | $1.8 \times 10^{47}$ | $2.3 \times 10^{47}$ |

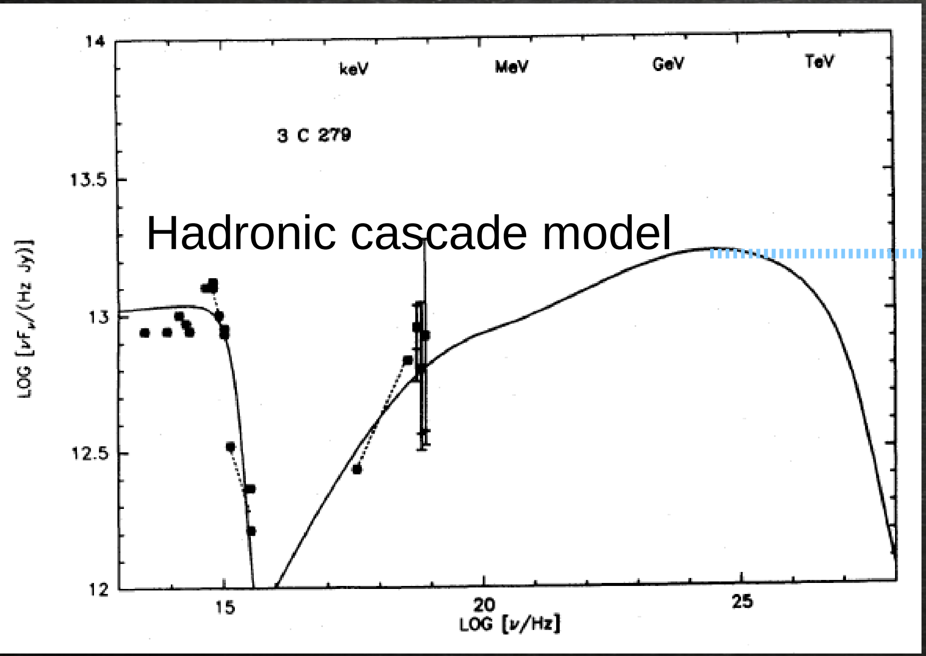
# What about FSRQ flares?

No physical model for the flare of PKS B1424-418

*Kadler et al. 2016, Nature Physics (arXiv:1602.02012)*



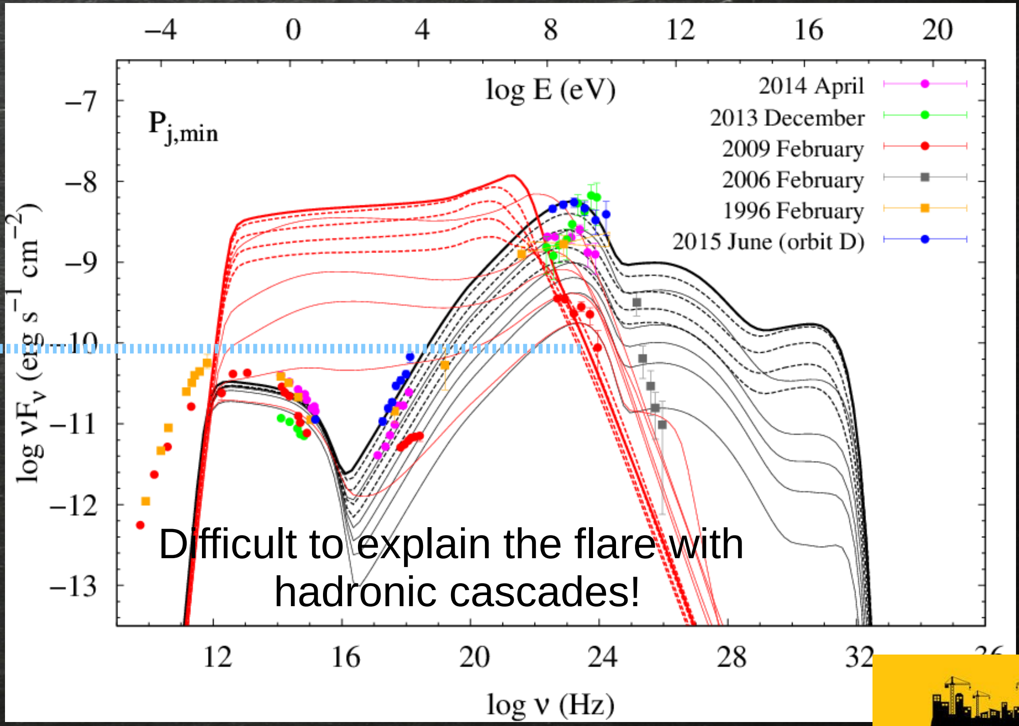

3C 279 then…




Hadronic cascade model

*Mannheim & Biermann, A&A, 1992*

And now… minute-timescale Fermi-LAT flare




Difficult to explain the flare with hadronic cascades!

*Petropoulou, Nalewajko, Hayashida, in prep.*
*Petropoulou & Murase, in prep.*

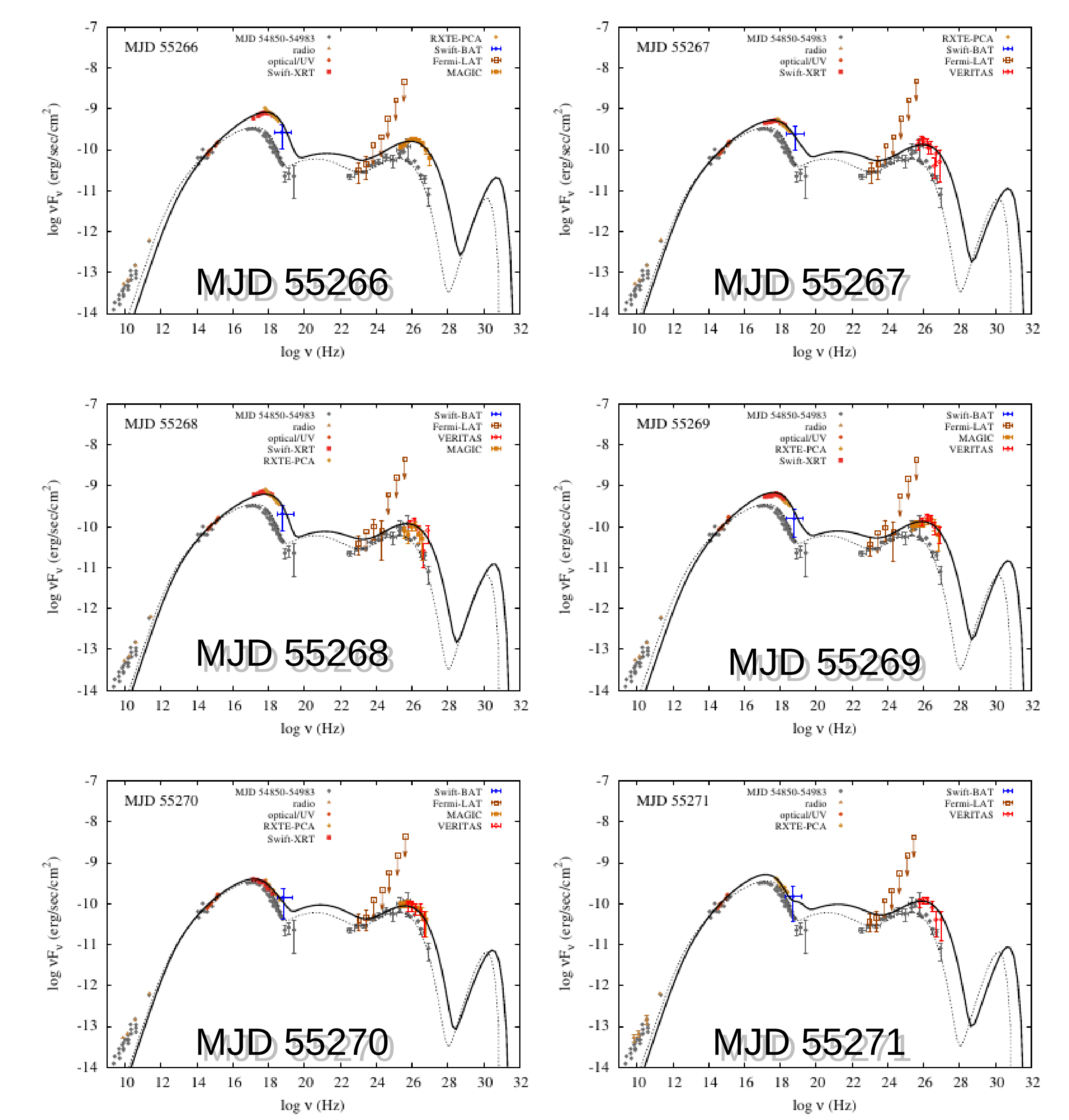
# Conclusions

- Hadronic SED modeling is a powerful tool for neutrino calculations!
- Accumulation of many week-duration flares necessary for the detection of at least 1 neutrino from Mrk 421
- Neutrino flux >1 PeV correlates with X-ray and γ-ray fluxes
- Major flares (long duration & large flux increase) have a significant impact on the # ν 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 set upper limits on the CR power of the blazar.

Thank you!

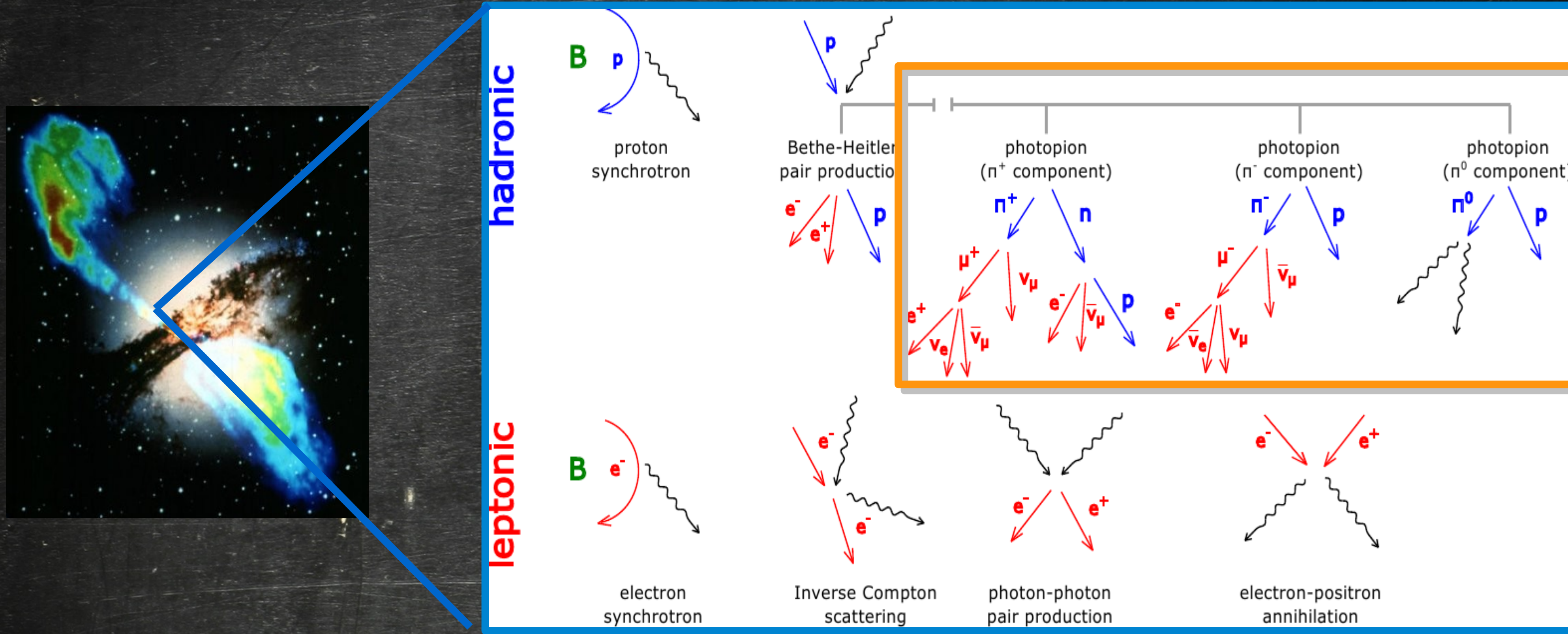
# Back-up Slides

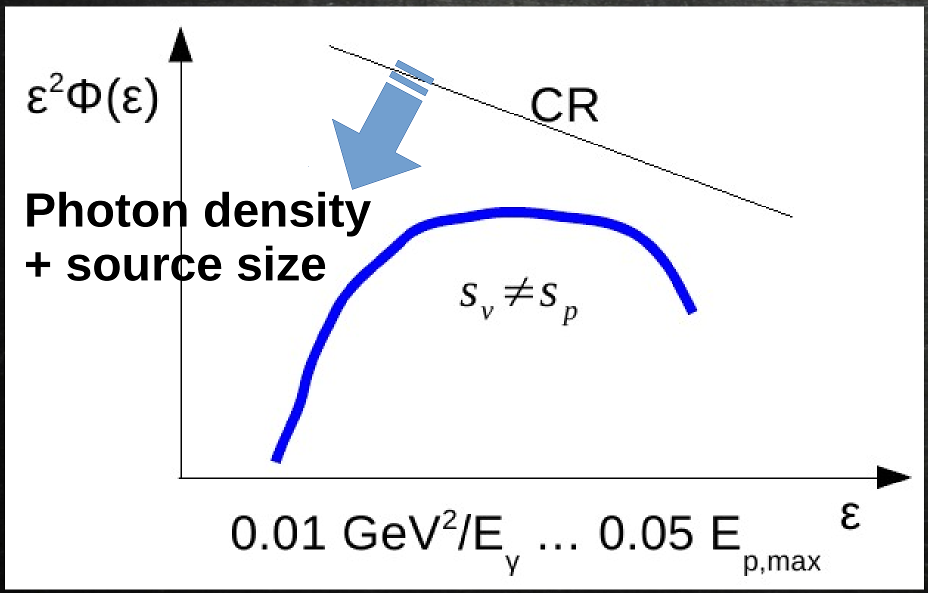
# SED modeling

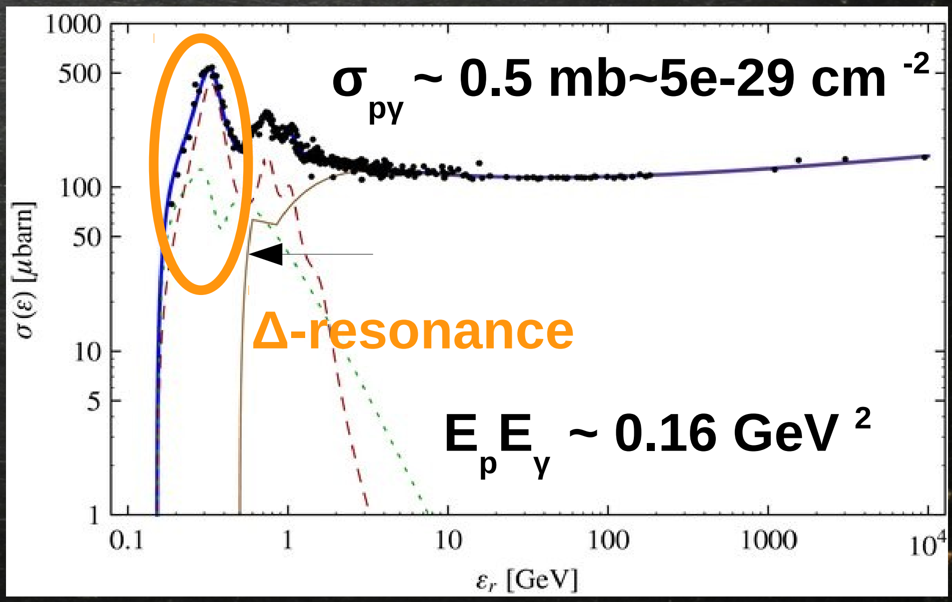



- Successful hadronic fits to all 13 days.
- Small changes (~2-3) of the parameter values.
- Calculation of daily ν spectra.

# Radiative processes in a nutshell



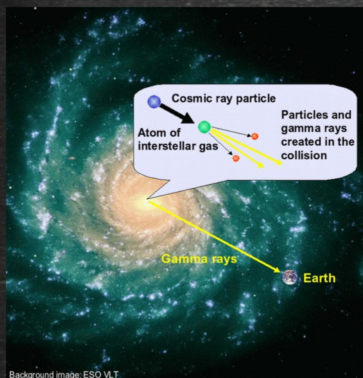



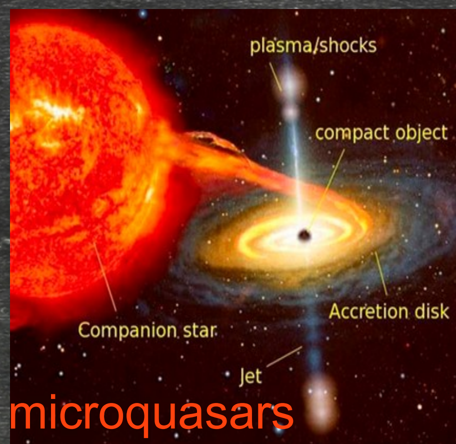
# A zoo of candidate sources



e.g. Kachelriess & Ostapchenko 2014




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




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

e.g. Waxman & Bahcall 1999, Murase 2008, Hummer et al. 2012, Petropoulou et al 2014


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


e.g. Metzger et al. 2015

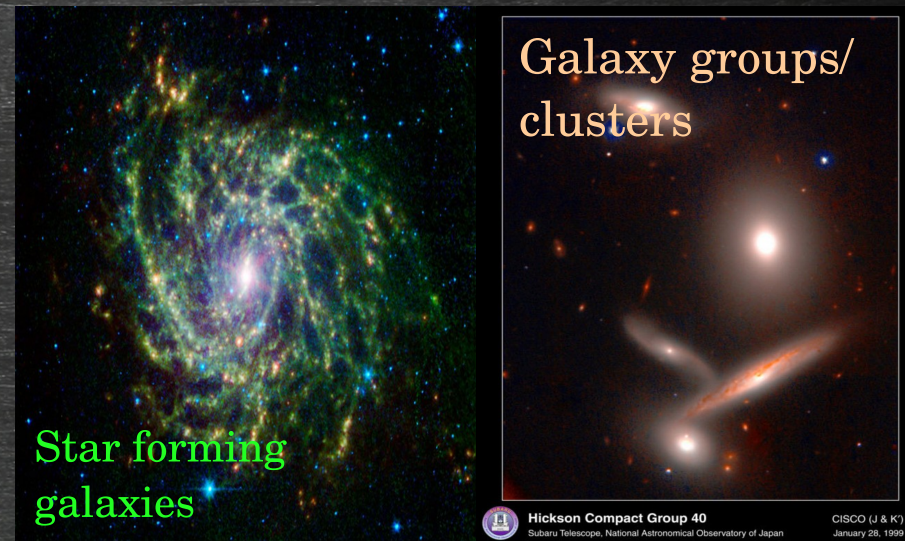

e.g. Tamborra et al. 2014, Loeb & Waxman 2006

*(Review by Ahlers et al 2015)*

# ν production processes

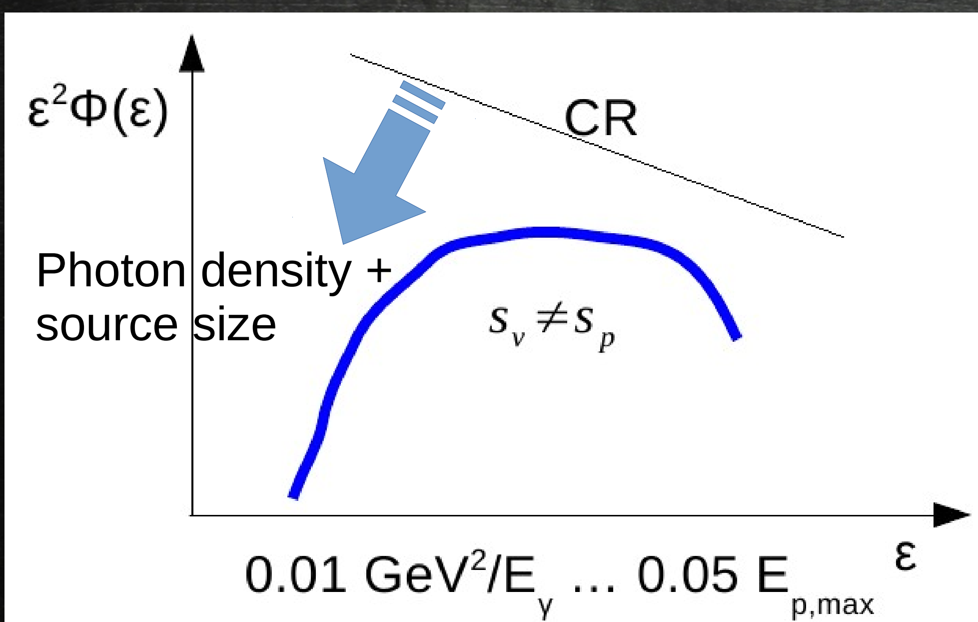
## Jets as ν sources

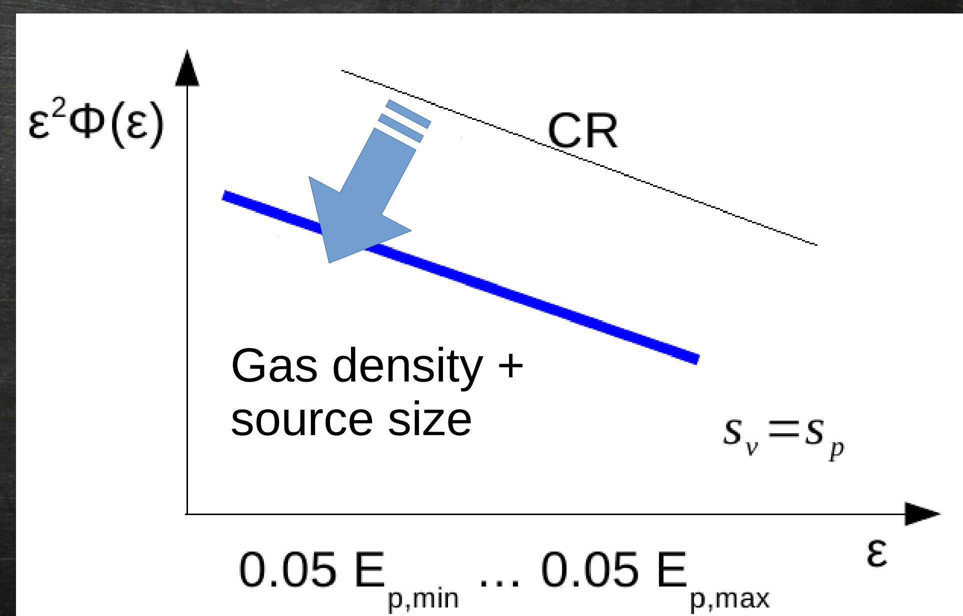

## CR reservoirs as ν sources




### PHOTOHADRONIC INTERACTIONS

### INELASTIC pp COLLISIONS

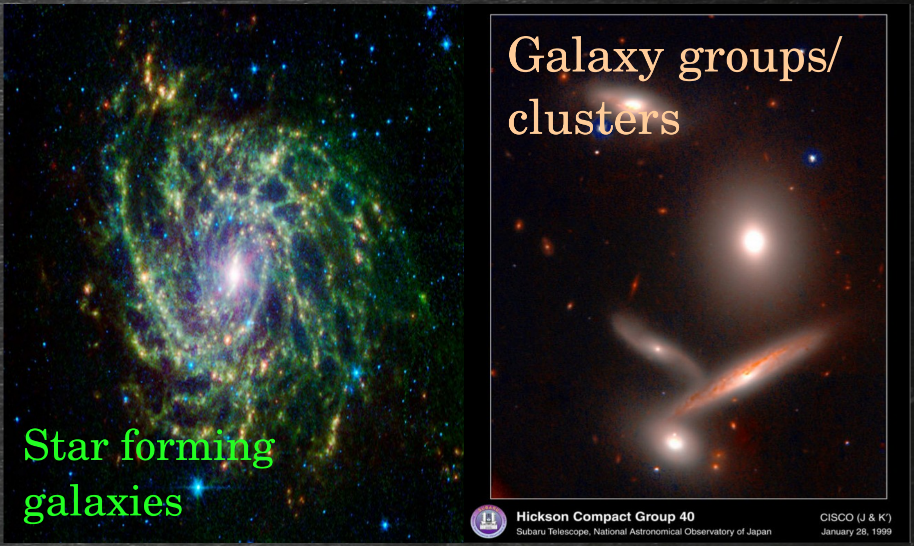


# Introduction: ν production processes

## Jets as ν sources


## CR reservoirs as ν sources

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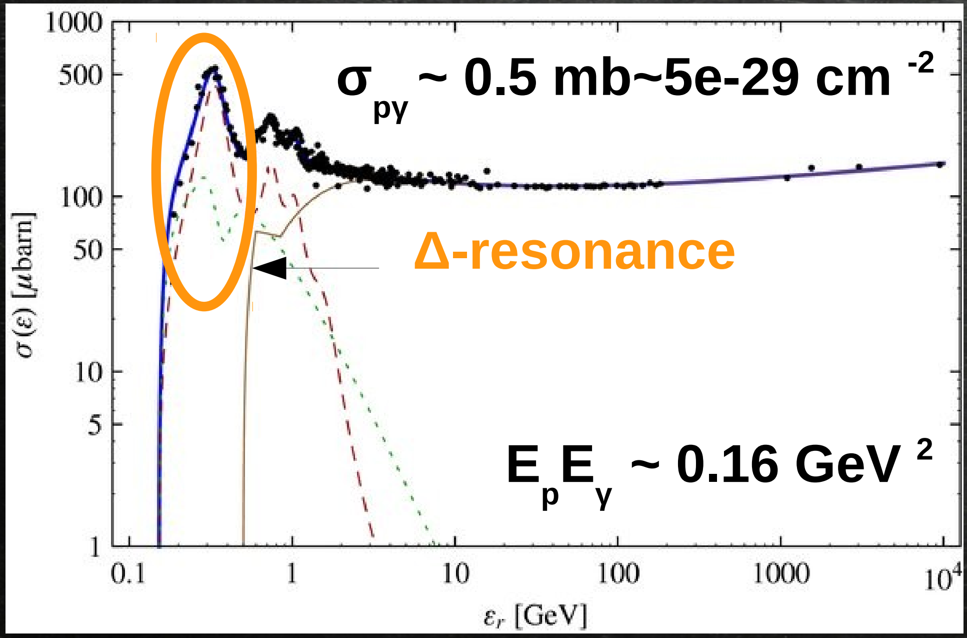


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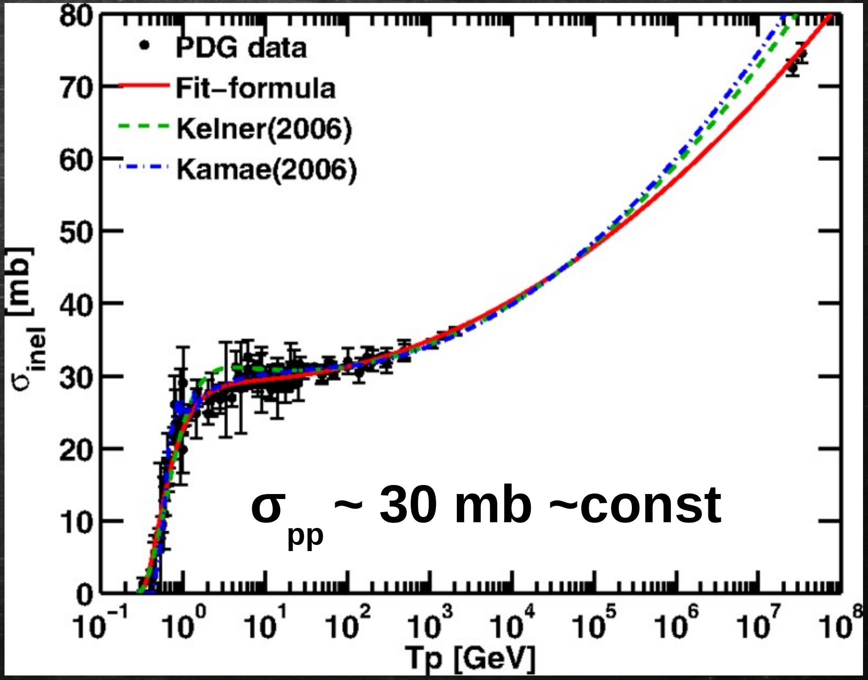


# Numerical treatment

## Kinetic equation approach (Dimitrakoudis et al. 2012)

Protons:

$$\frac{\partial n_{\mathrm{p}}}{\partial t} + L_{\mathrm{p}}^{\mathrm{BH}} + L_{\mathrm{p}}^{\mathrm{photopion}} + L_{p}^{\mathrm{psyn}} + \frac{n_{\mathrm{p}}}{t_{\mathrm{p,esc}}} = Q_{\mathrm{p}}^{\mathrm{inj}} + Q_{\mathrm{p}}^{\mathrm{photopion}}$$

Electrons:

$$\frac{\partial n_{\mathrm{e}}}{\partial t} + L_{\mathrm{e}}^{\mathrm{syn}} + L_{\mathrm{e}}^{\mathrm{ics}} + L_{\mathrm{e}}^{\mathrm{ann}} + L_{\mathrm{e}}^{\mathrm{tpp}} + \frac{n_{\mathrm{e}}}{t_{\mathrm{e,esc}}} = Q_{\mathrm{e}}^{\mathrm{ext}} + Q_{\mathrm{e}}^{\mathrm{BH}} + Q_{\mathrm{e}}^{\gamma\gamma} + Q_{\mathrm{e}}^{\mathrm{photopion}} + Q_{\mathrm{e}}^{\mathrm{tpp}}$$

Photons:

$$\frac{\partial n_{\gamma}}{\partial t} + \frac{n_{\gamma}}{t_{\gamma,\mathrm{esc}}} + L_{\gamma}^{\gamma\gamma} + L_{\gamma}^{\mathrm{ssa}} = Q_{\gamma}^{\mathrm{syn}} + Q_{\gamma}^{\mathrm{psyn}} + Q_{\gamma}^{\mathrm{ics}} + Q_{\gamma}^{\mathrm{ann}} + Q_{\gamma}^{\mathrm{photopion}}$$

Neutrinos:

$$\frac{\partial n_{\nu}}{\partial t} + \frac{n_{\nu}}{t_{\mathrm{esc}}} = Q_{\nu}^{\mathrm{photopion}}$$

Neutrons:

$$\frac{\partial n_{n}}{\partial t} + L_{n}^{\mathrm{photopion}} + \frac{n_{n}}{t_{\mathrm{esc}}} = Q_{n}^{\mathrm{photopion}}$$

Pion, muon & kaon decay is modeled using results of MC code SOPHIA (Muecke et al. 2000)

Synchrotron cooling of the above is also included.

# BL Lacs as counterparts of IceCube neutrinos

PR 2014

* Catalogs used:

- TeVCat (VHE detected)
- 1WHSP (~1000 VHE candidates)
- 1FHL (>10 GeV)

* Cuts applied to the sample of 35 events:

- E >60 TeV
- median angular error < 20 deg

* "Energetic" criterion

PR etal 2016

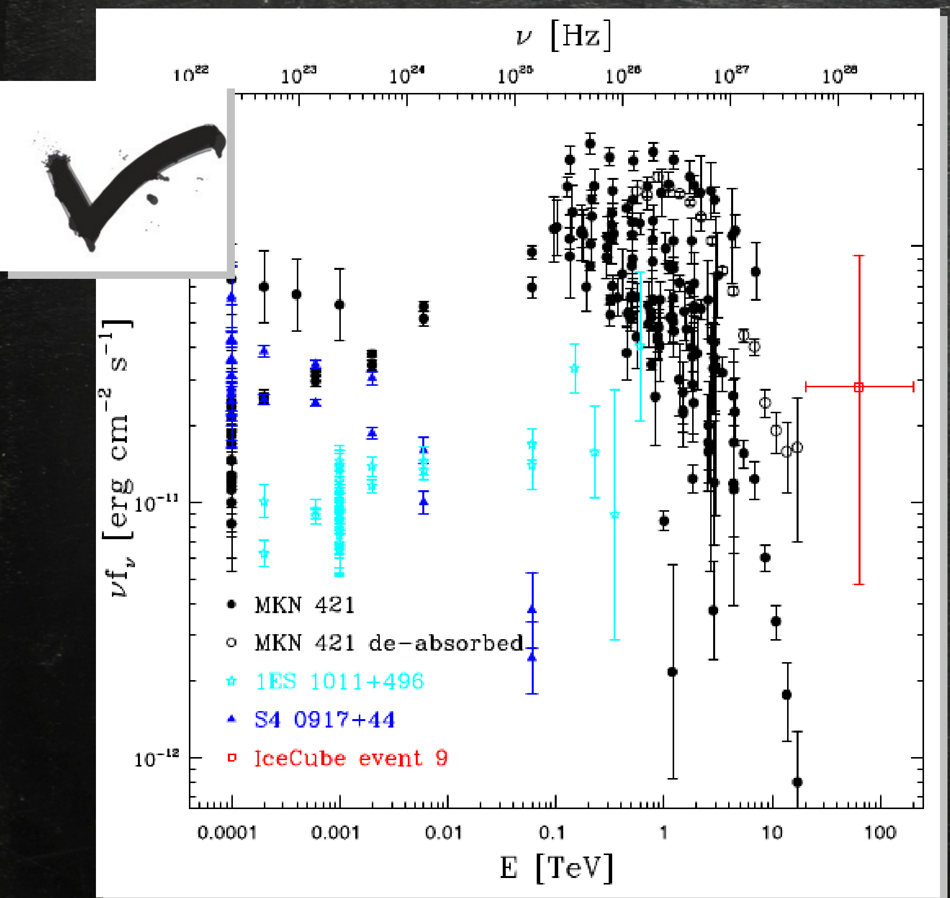
* Catalogs used:

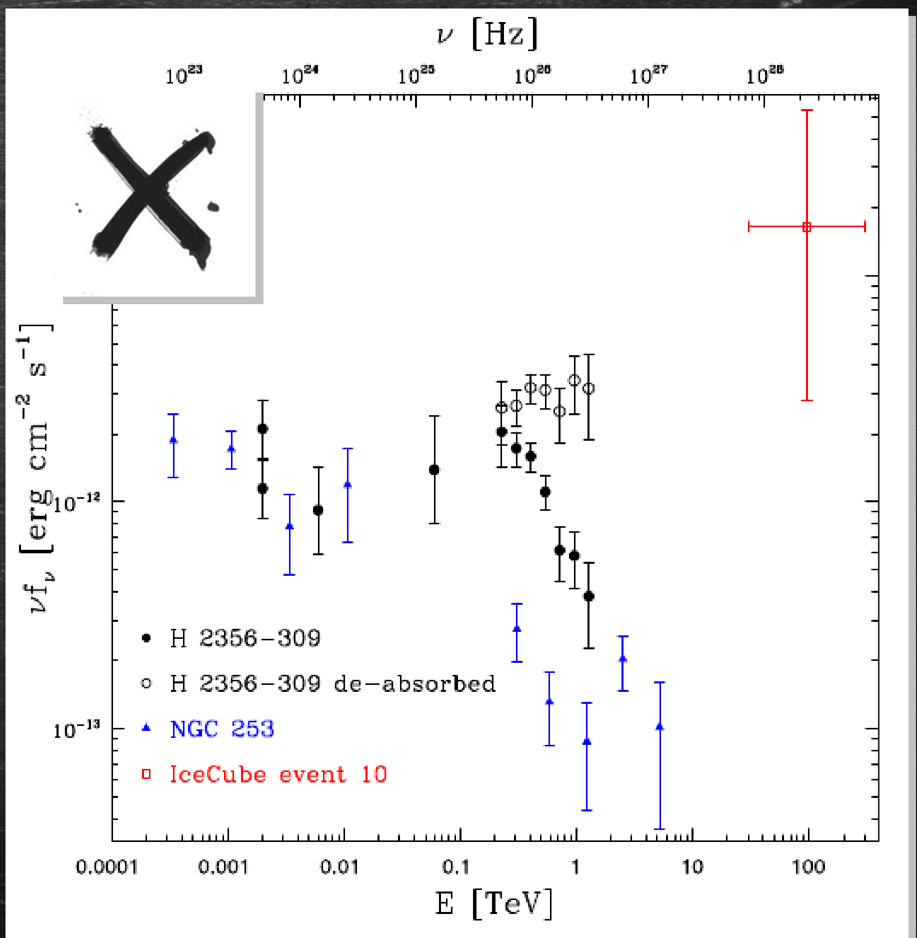
- 3LAC (>100 MeV)
- 2WHSP (~1700 VHE candidates)
- 2FHL (>50 GeV)

* Cuts applied to the sample of 51 events:

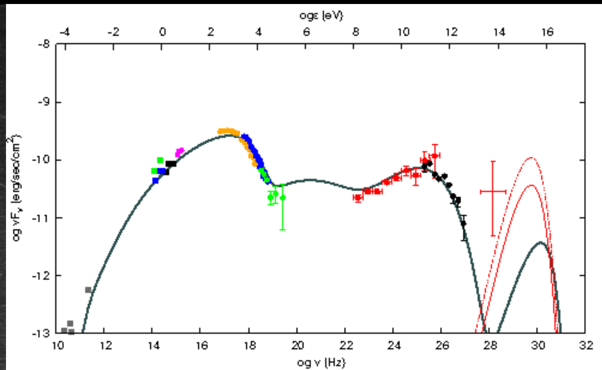
- E >60 TeV
- median angular error < 20 deg

* "Energetic" criterion

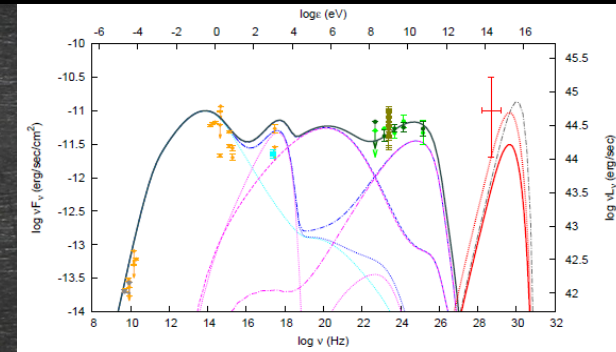


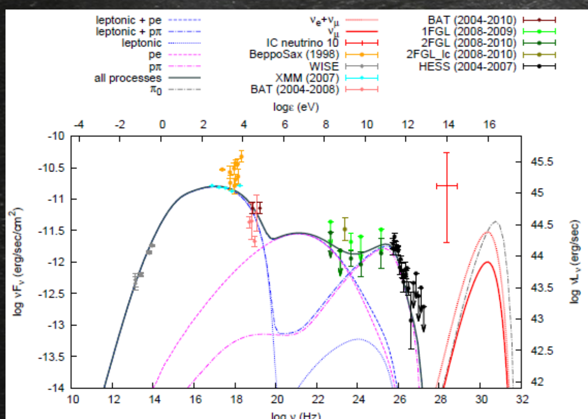
# BL Lacs as counterparts of IceCube neutrinos



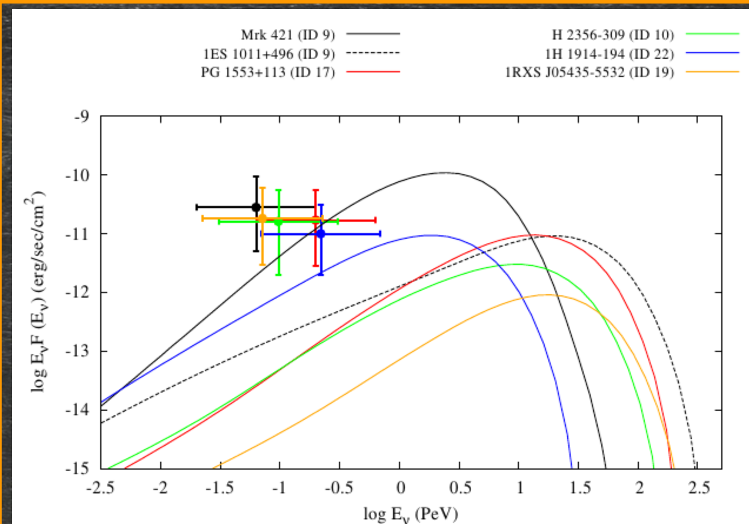
Mrk 421

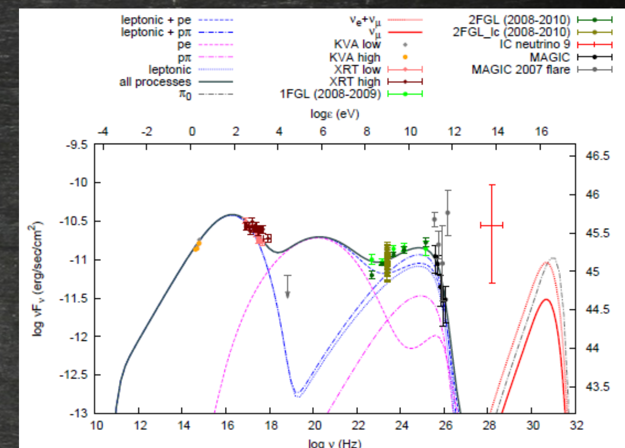


H 1914-194

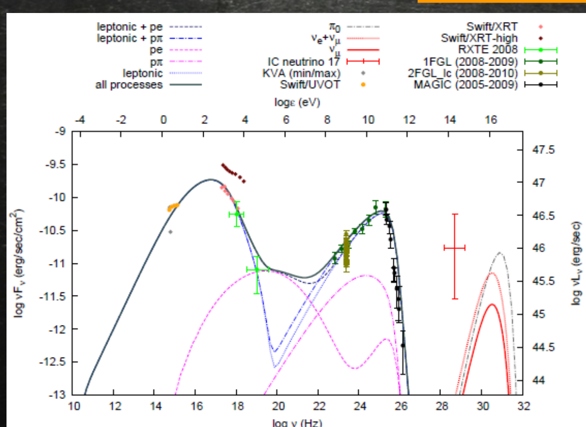


H 2356-309

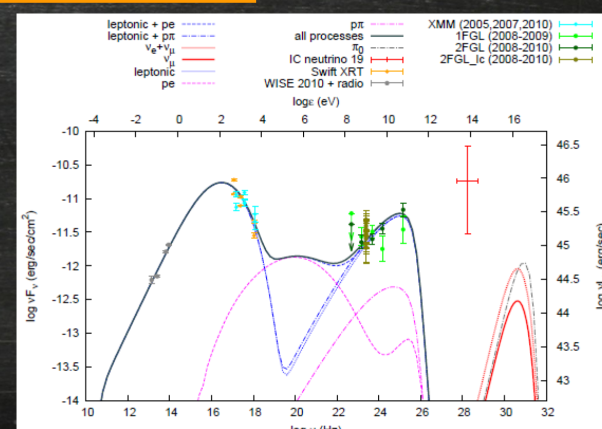


1ES 1011+496



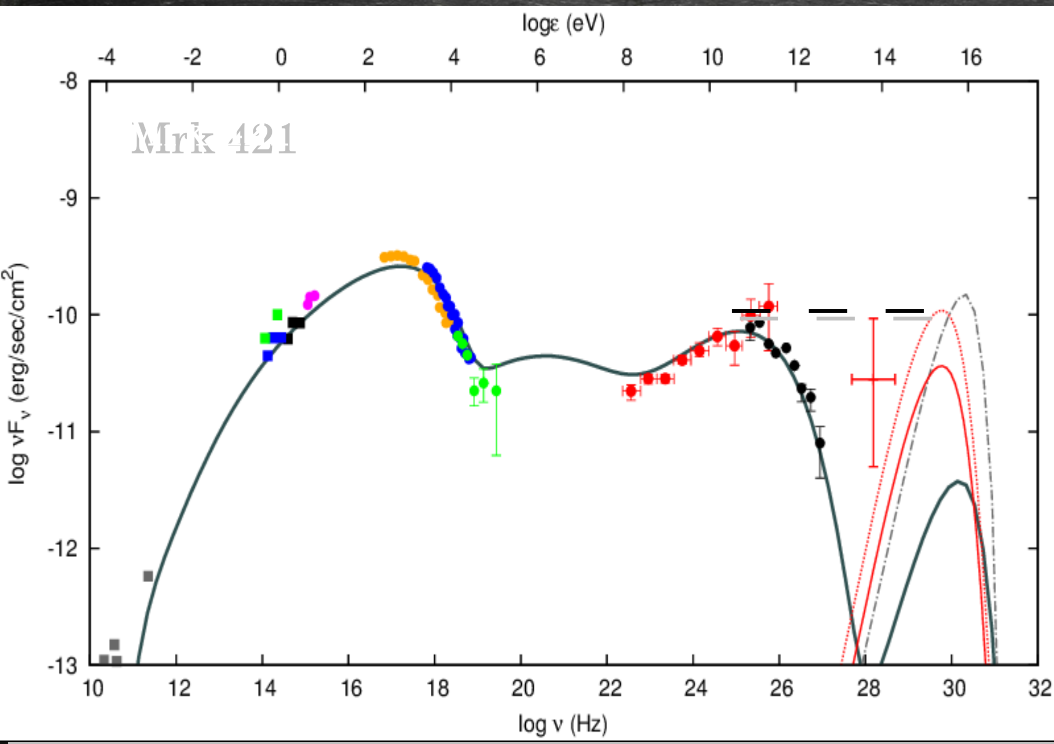
PG 1553+113

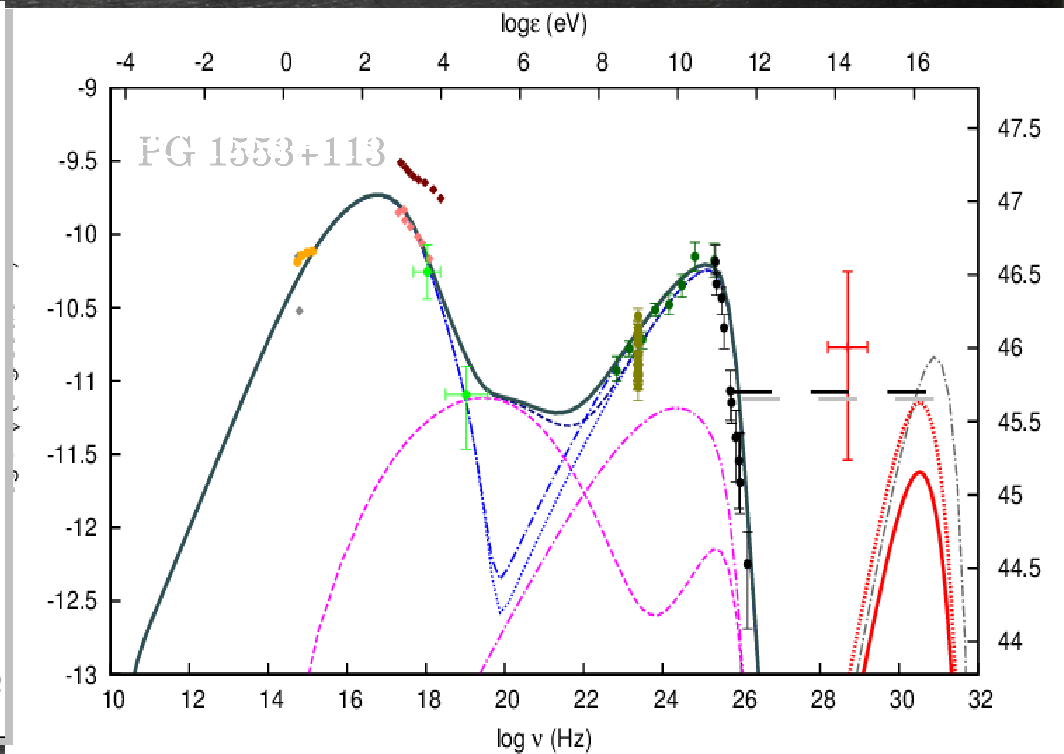


1 RXS J054357.3-553206

Petropoulou et al 2015

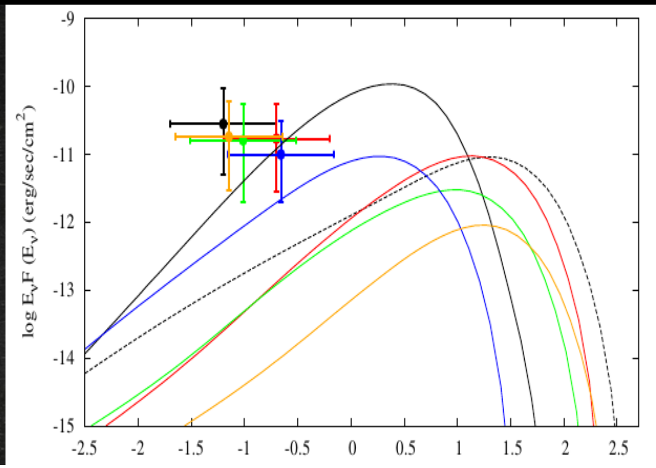
# BL Lacs as counterparts of IceCube neutrinos



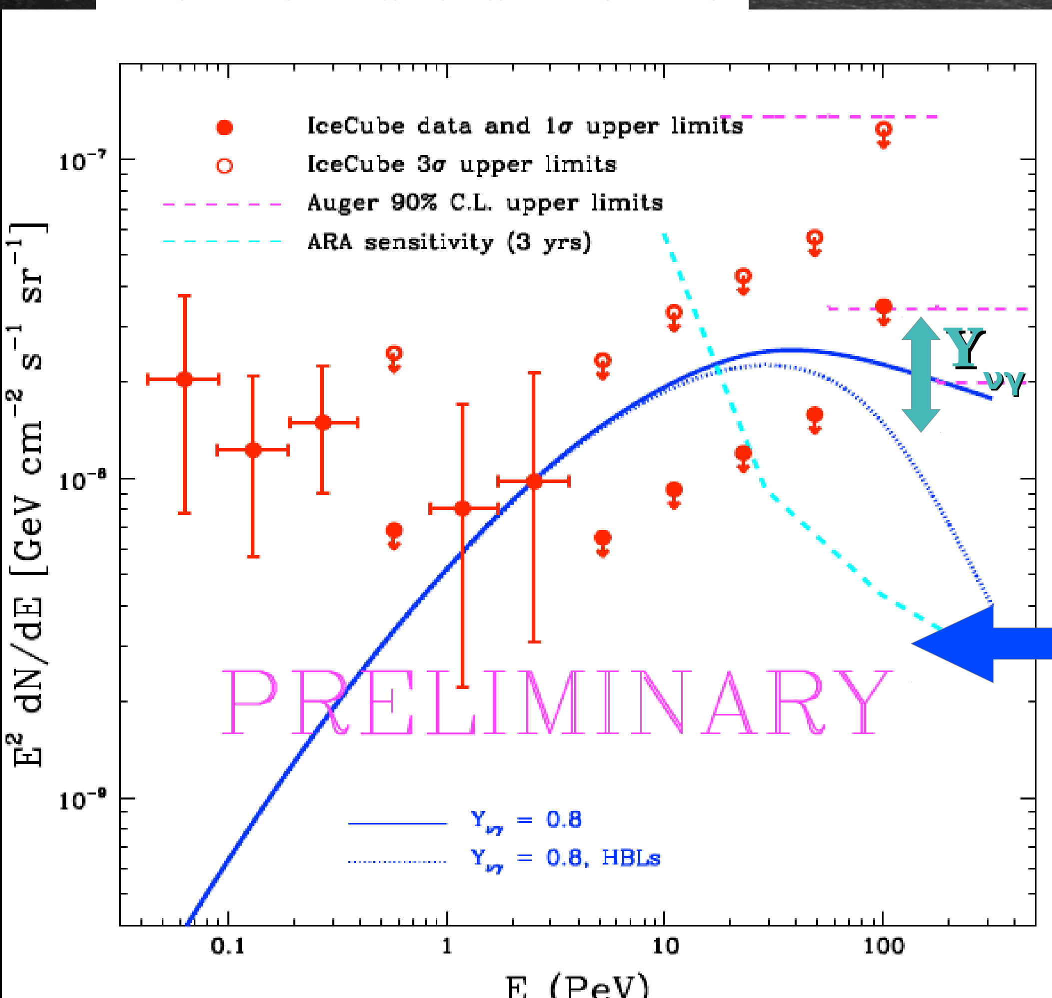

Hadronic γ-ray emission $\sim 1$ ⟵ $$Y_{\nu\gamma} = \frac{L_{\nu}^{(all)}}{L_{>10\,GeV}}$$ ⟶ $\ll 1$ Leptonic γ-ray emission

# Neutrino emission from *all* BL Lacs




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

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




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

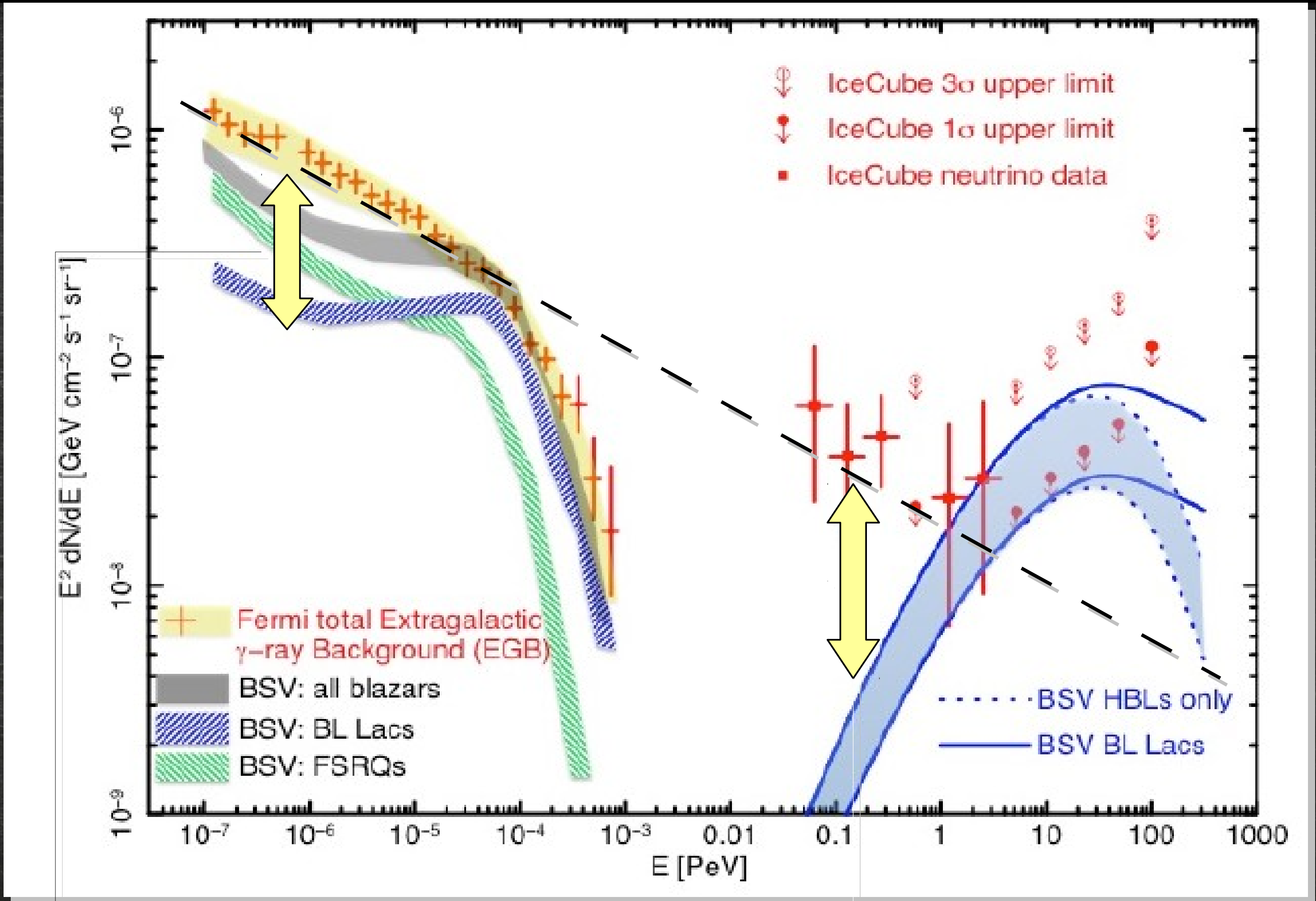
# Predicted # of events

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

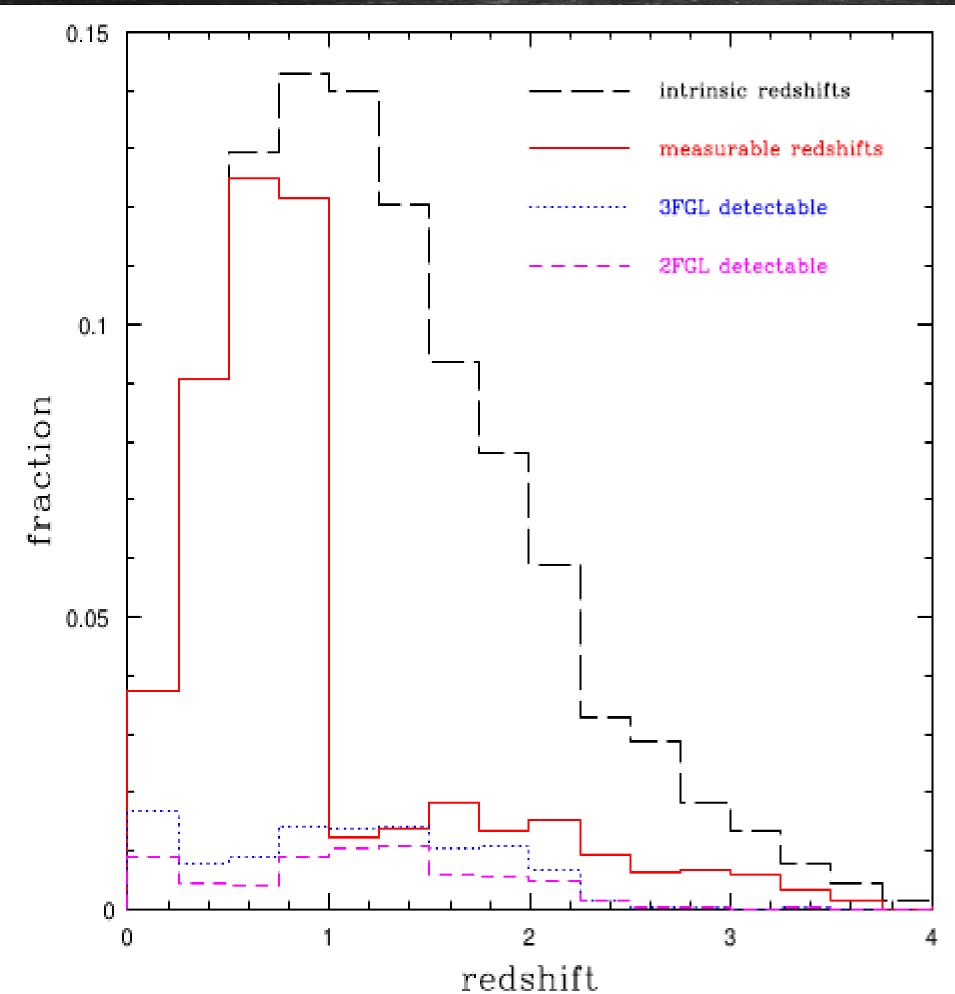
# Extragalactic backgrounds



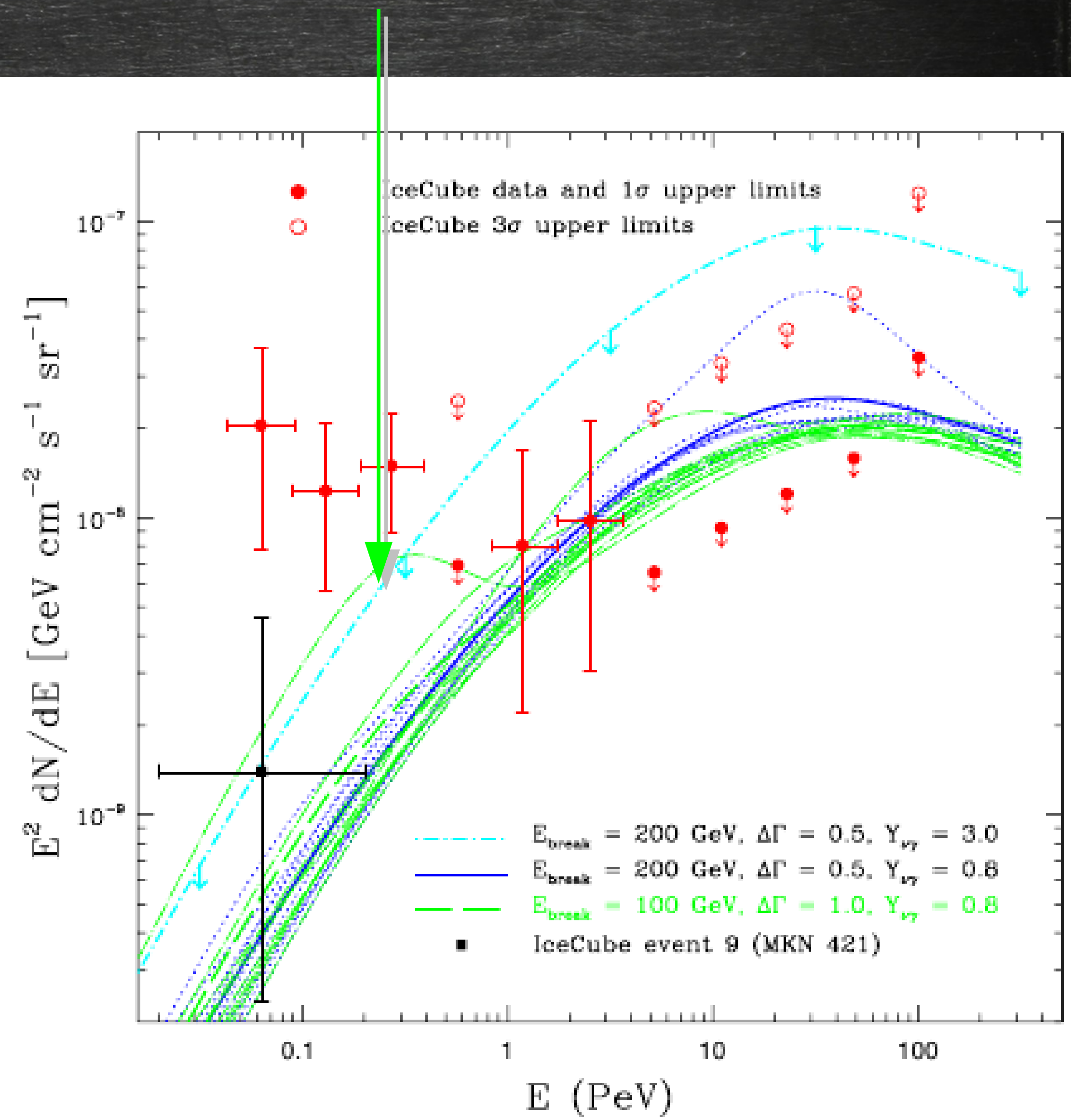

– Another source population? (e.g. starburst galaxies: Lacki et al. 2014; Stecker 2007)
– Another physical process? (e.g. pp collisions; Mannheim 1995, Ahlers et al. 2012)

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

# 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!



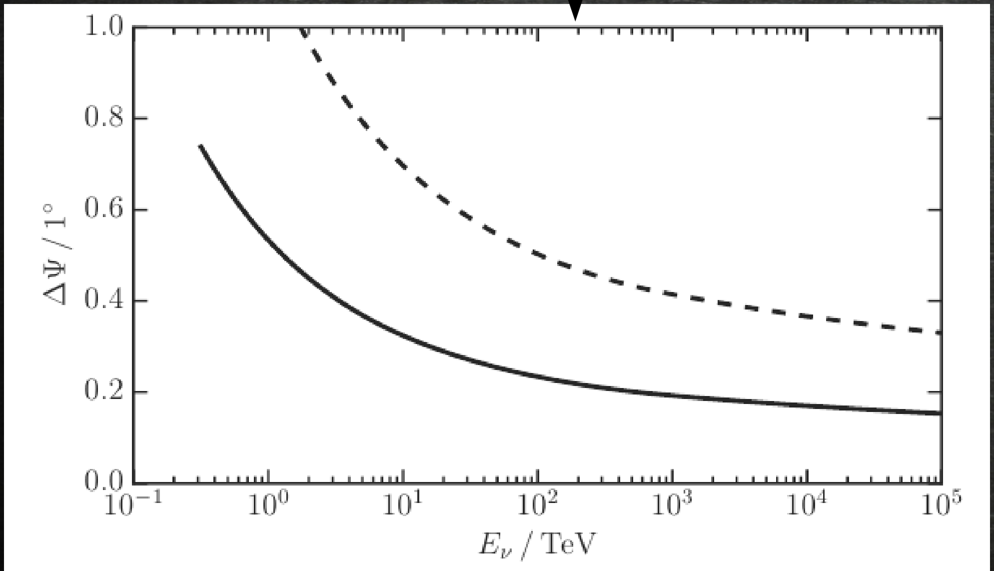

Top left: Redshift distribution of ~0.5% of BL Lacs that make 95% of the NBG at 1 PeV.

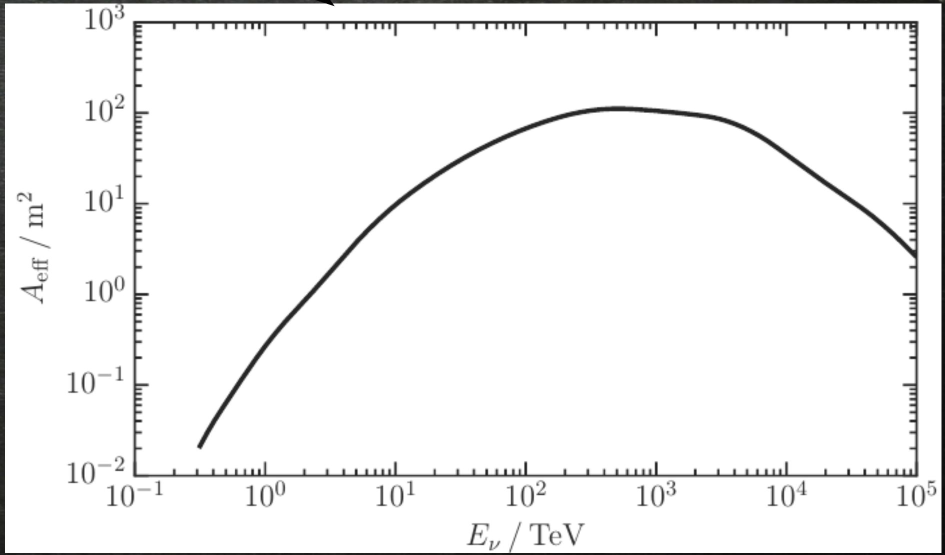
Bottom right: Results from individual simulations showing the scatter in Monte Carlo simulations

# Calculation of muon neutrino number

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

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

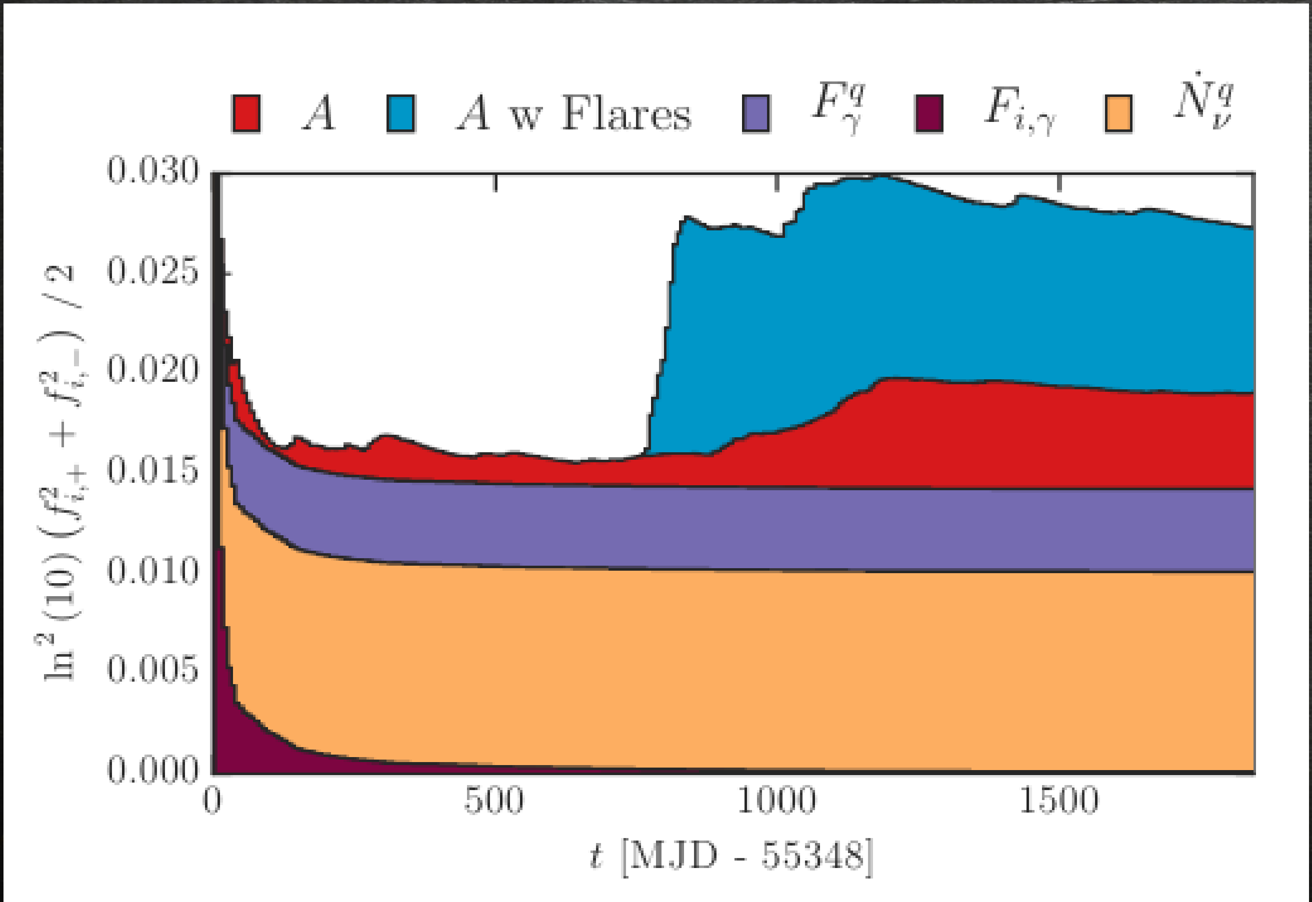


# Calculation of uncertainties

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

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




Stacked contributions of various sources of uncertainty to the total one