Flaring Rate Distribution of Gamma-Ray Blazars and Implications for High-Energy Neutrino Emission

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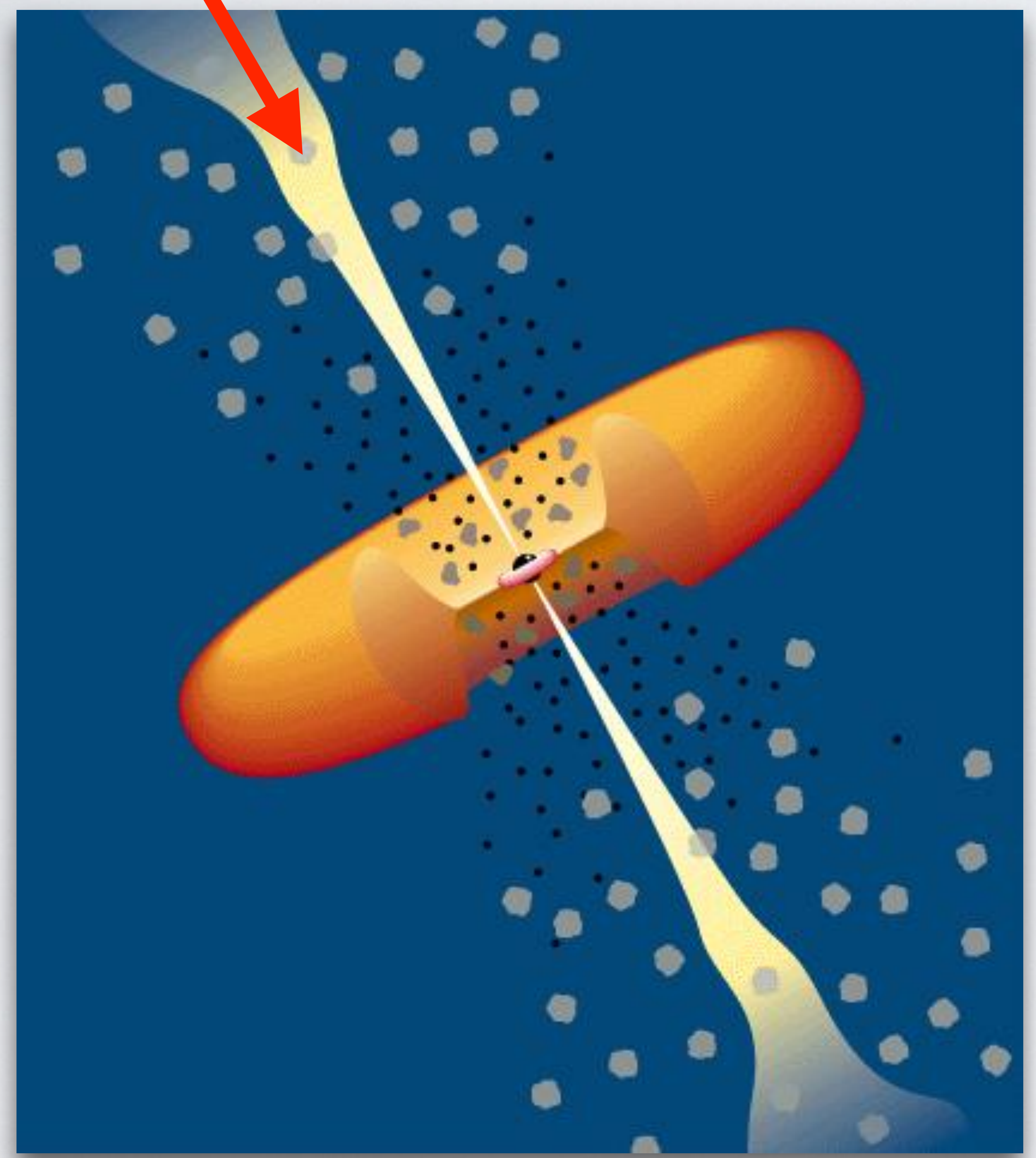
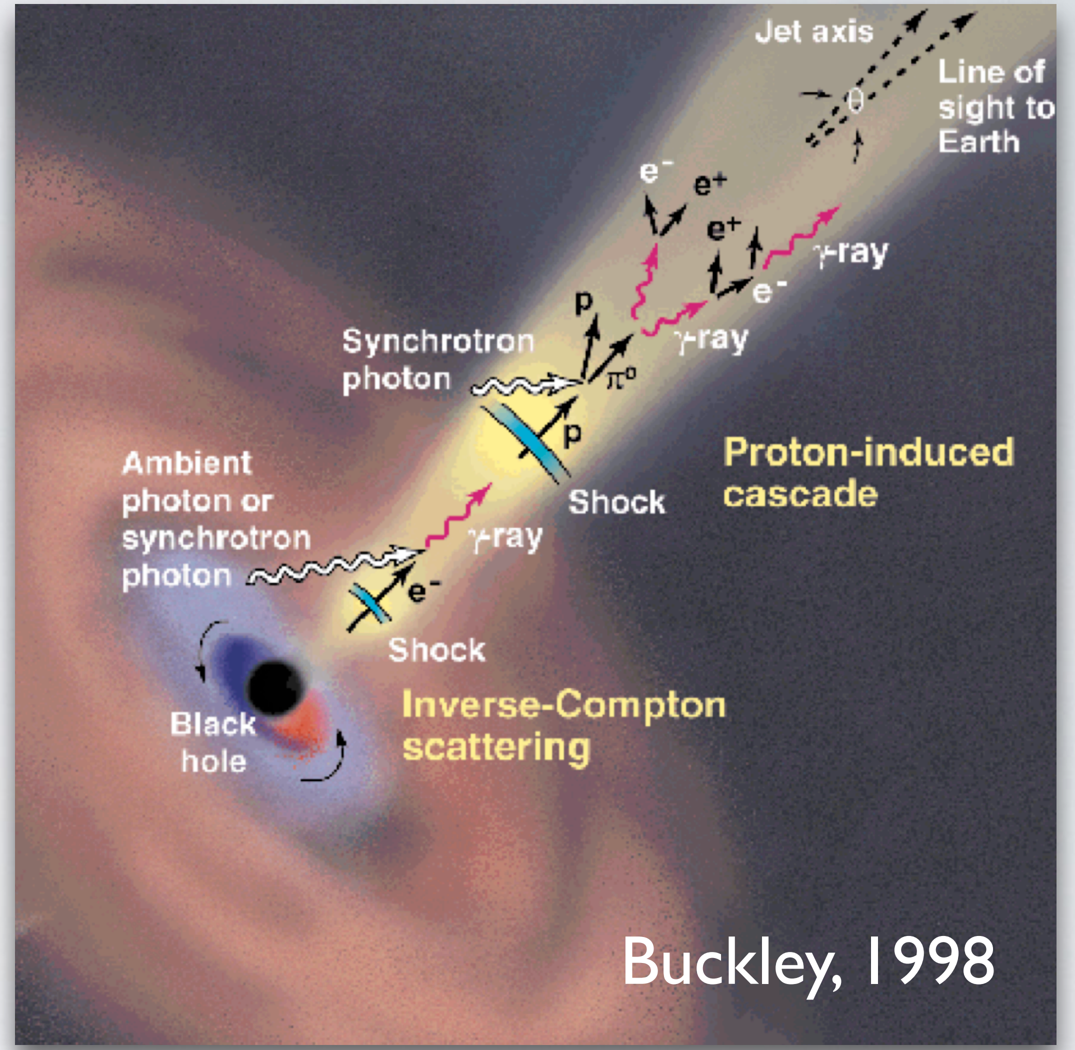
Blazars: the most "active" kind of AGNs

"Blazar"



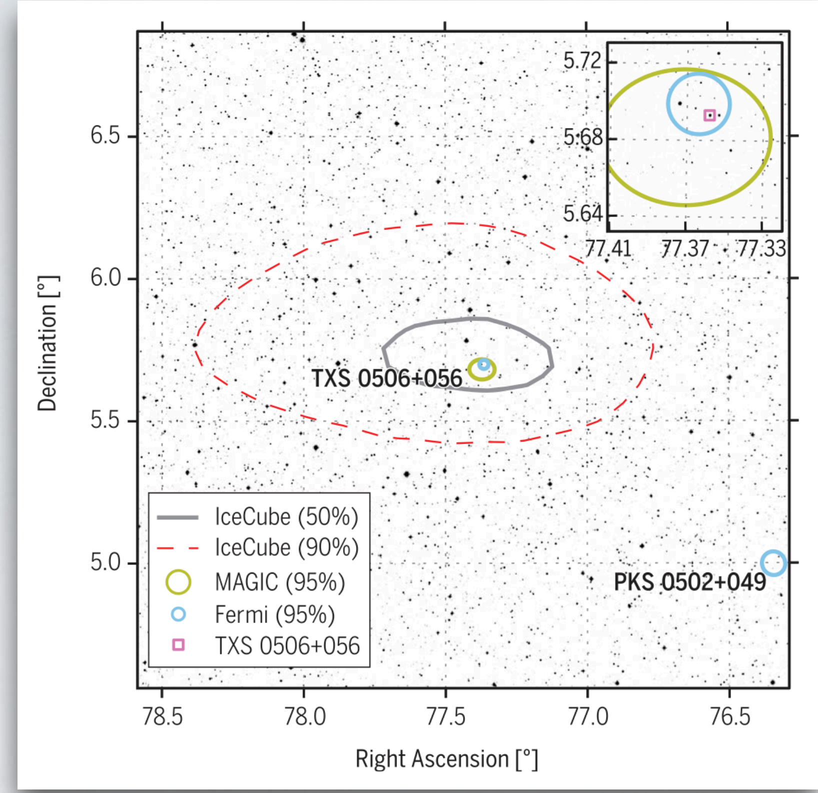
Urry & Padovani, 1995



A candidate of the origin of Ultra High Energy Cosmic rays and/or High Energy Neutrinos

High Energy Astrophysical Neutrinos

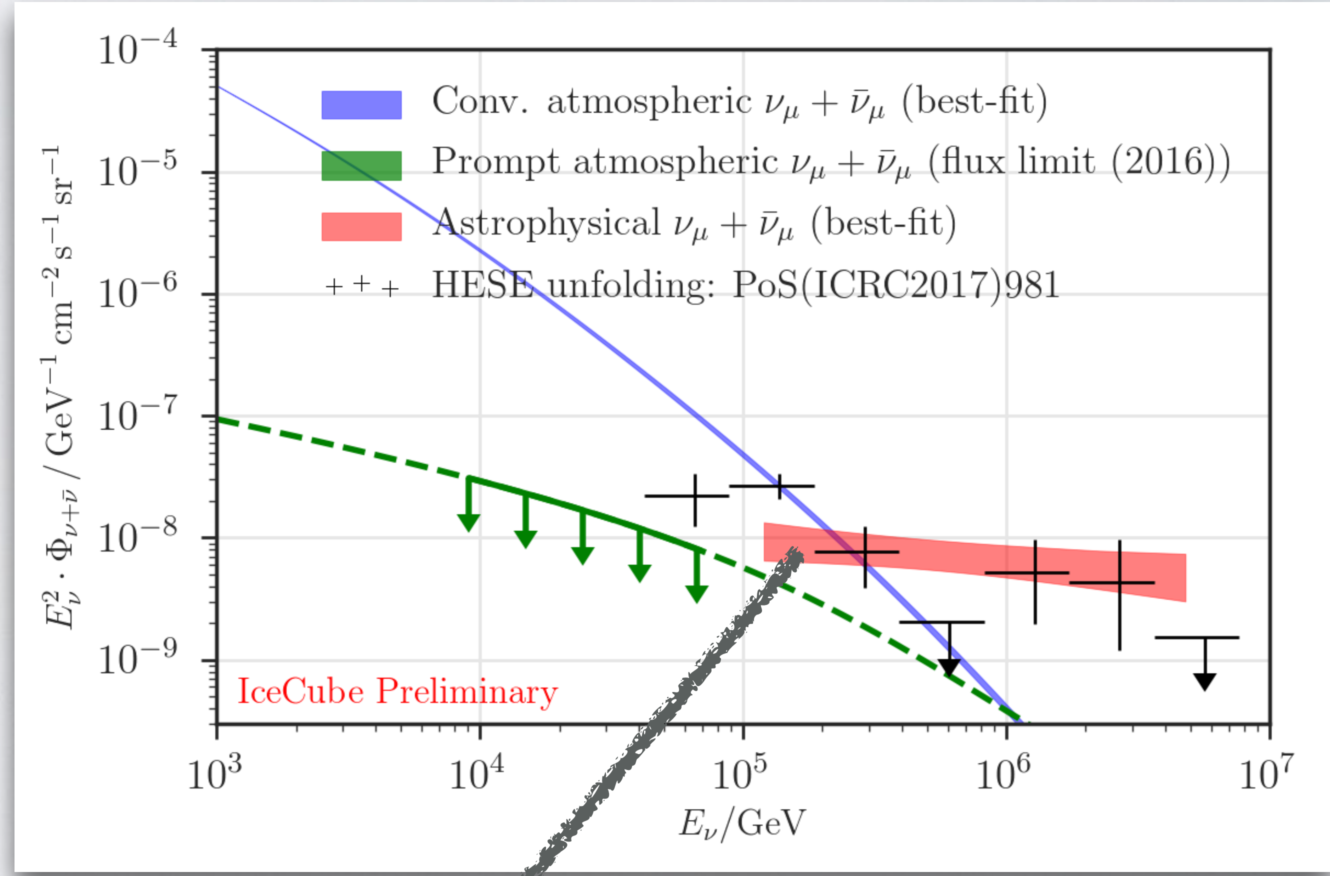
Coincidence of a sub-PeV muon neutrino with a gamma-ray flare of Blazar TXS 0506+056



IceCube Collaboration et al., (2018)

The isotropic high-energy astrophysical neutrino background

IceCube Collaboration, ICRC 2017



The Isotropic Neutrino Background: Neutrinos produced by a large number of extra-galactic sources

In This Work

- Analysis of flares of gamma-ray blazars
- Estimation of high-energy neutrino emission of blazar flares
- Discussion of the contribution of bright gamma-ray blazar flares to the Isotropic Neutrino Background

Data Sets

- Public Fermi-LAT Monitored Source List:
  - Weekly-binned and decade-long gamma-ray light curves of 142 blazars in 0.1–300 GeV
  - 100 FSRQs, 32 BL Lacs, and 10 blazars of uncertain type
- Open Universe for Blazars:
  - Blazar X-ray light curves in 0.3–10 keV based on 14 years of Swift-XRT data

http://fermi.gsfc.nasa.gov/ssc/data/policy/LAT_Monitored_Sources.html.

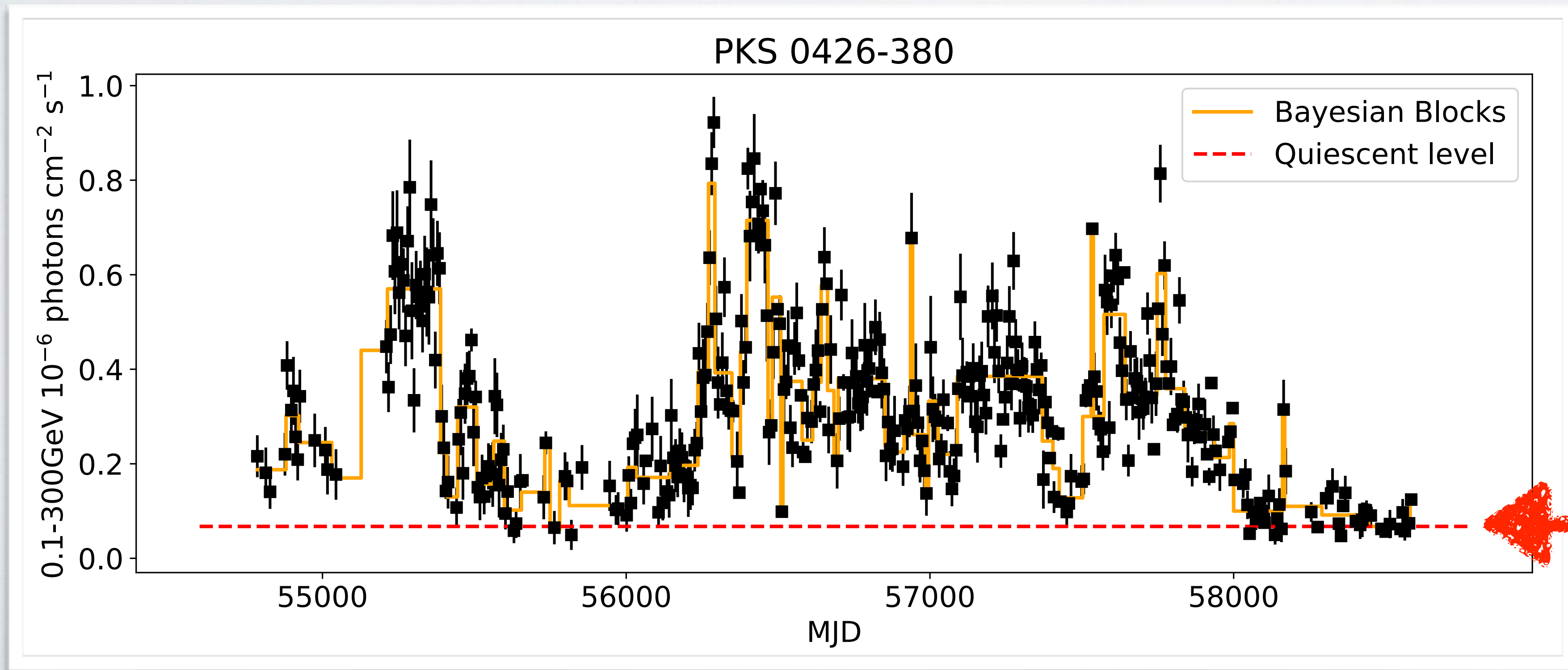
P. Giommi et al. (2019)

Quiescent Flux Level

We assume that the quiescent state has a relatively low and stable flux.

A procedure to derive the quiescent flux level:

- Apply a Bayesian blocks algorithm to each gamma-ray light curve (p0 = 0.075).
  - The fluxes during the partitioned interval are regarded to be constant.
- The average flux of each Bayesian block => An optimal step-function light curve
- Derive the minimum block flux as the quiescent level, on the condition that the number of data points of the block is equal to or larger than the average number.



An example of a weekly-binned blazar gamma-ray light curve with a Bayesian blocks algorithm

Quiescent Flux Level

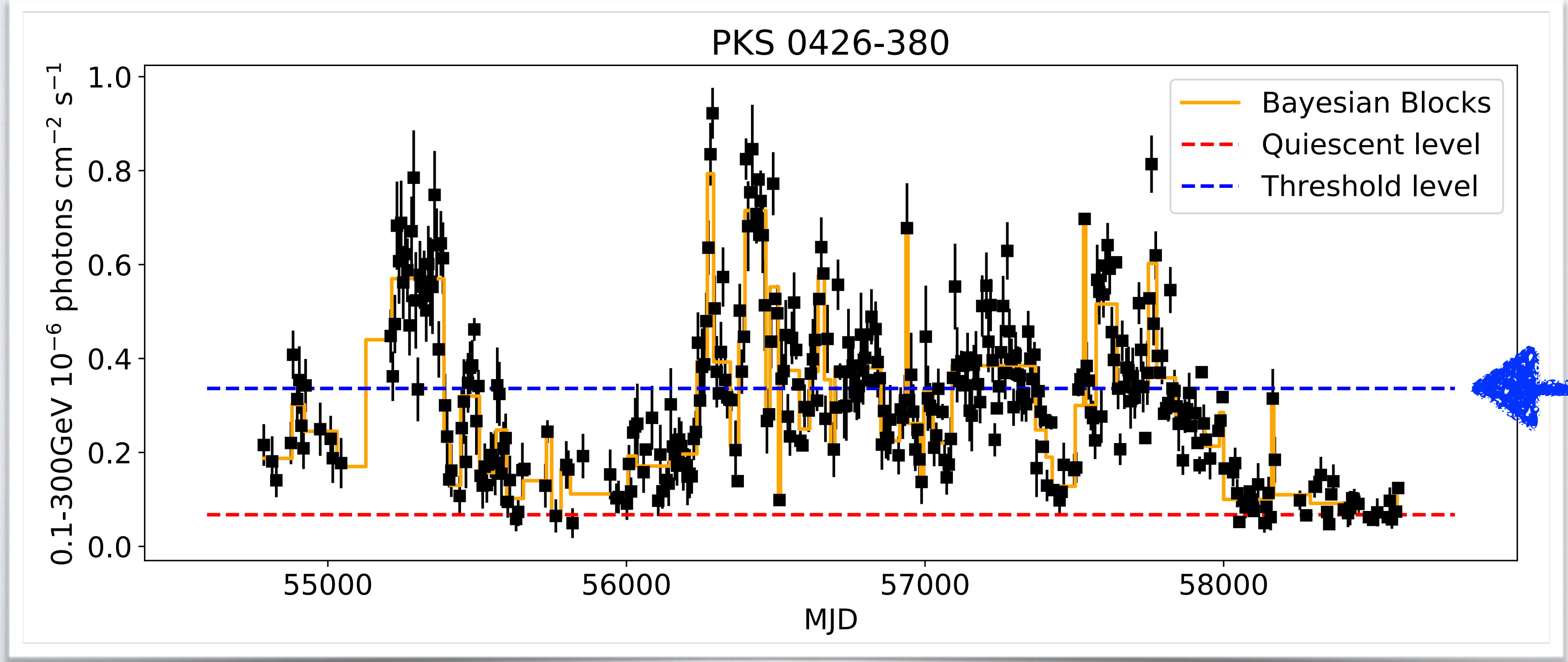
Flaring Threshold Level

The weekly-binned gamma-ray flux over the threshold level
=> Defined as a gamma-ray flare flux (e.g. Resconi et al. 2009)

Flaring Threshold Level: $F_\gamma^{th} = F_\gamma^{q} + s\langle F_\gamma^{err} \rangle$

Unless otherwise noted, s =6

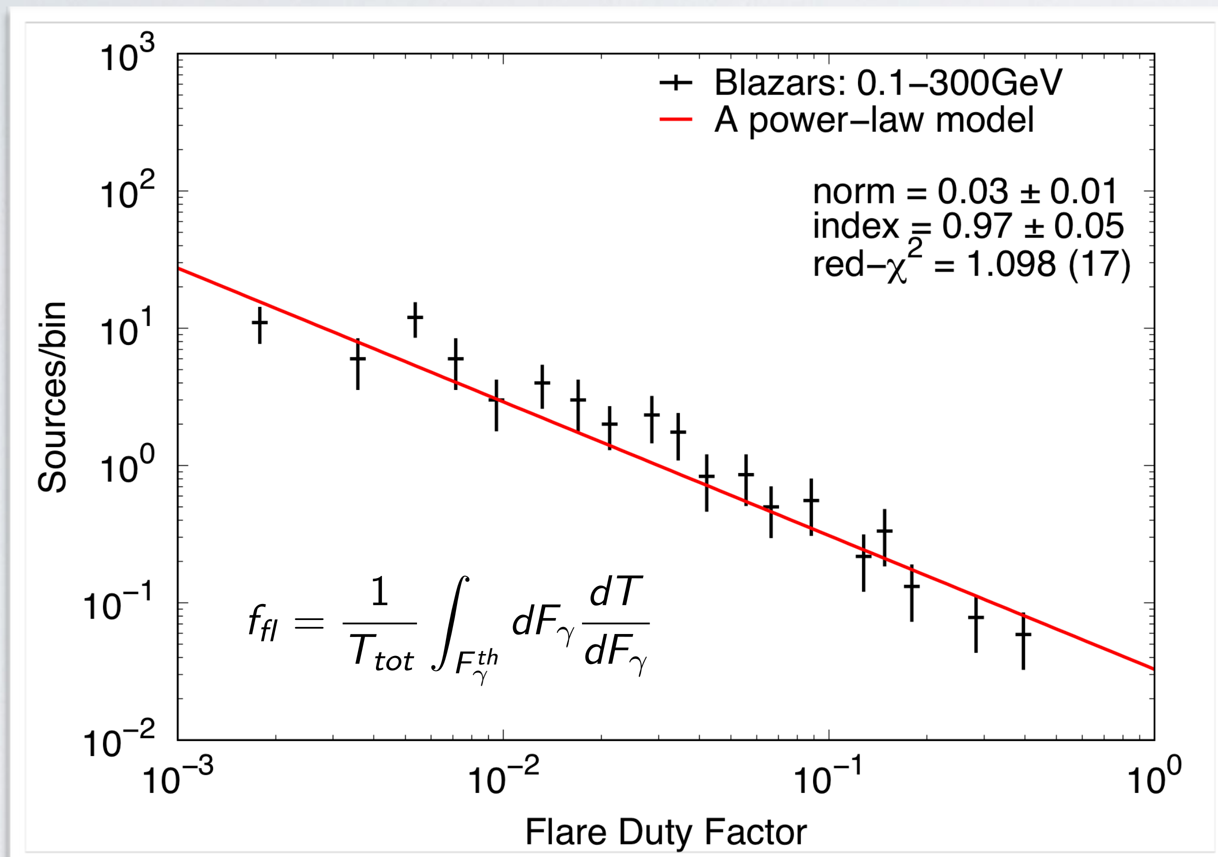
F_γ^{q}: the gamma-ray quiescent level
$\langle F_\gamma^{err} \rangle$: an average error of the gamma-ray light curve
s: the significance above the quiescent level in units of σ



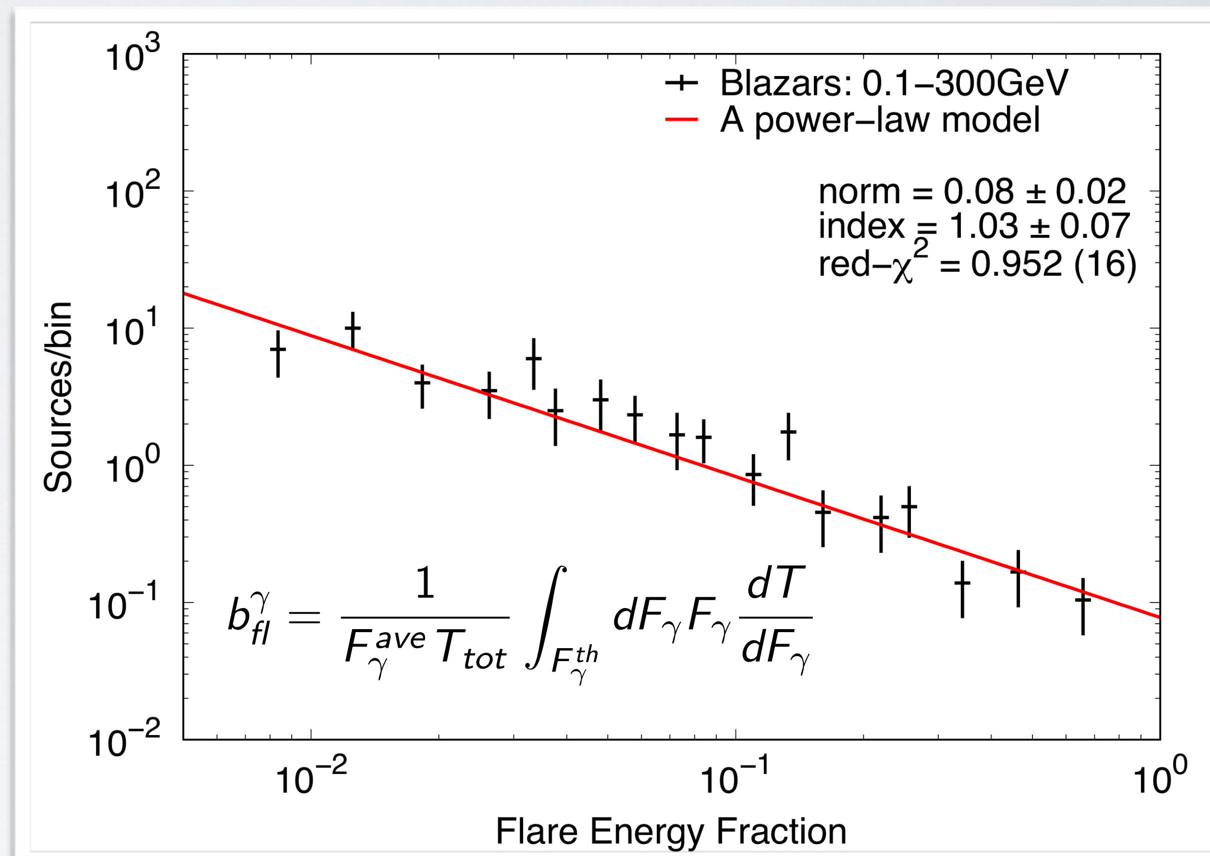
Flaring Threshold Level with s=6

Flare Duty Factor and Flare Energy Fraction for 0.1–300GeV gamma ray light curves of flaring blazars

Flare Duty Factor
= (Flaring Time)/(Total Observation Time)



Flare Energy Fraction
= Fraction of Energy Emitted in the Flaring State



Their distributions are well represented by a power-law function with the index of -0.97 and -1.03, respectively.

A Simple Scaling Relation between the Gamma-ray and Neutrino Fluxes

- Different models of blazar gamma-ray emission
  => A relation between the gamma-ray and neutrino flux:

$$\boxed{F_\nu \propto F_\gamma^\gamma} \qquad \boxed{\gamma = 1.5 - 2.0}$$

e.g. Murase, Oikonomou, Petropoulou (2018)

- The X-ray quiescent level in 0.3–10 keV
  => A rough upper limit to the muon neutrino quiescent flux
  in the 100TeV—PeV range

e.g. Murase, Oikonomou, Petropoulou (2018), Padovani et al. (2019)

Optimistically, we assume : $\boxed{\epsilon_\nu F^q_{\nu_\mu} = \epsilon_X F^q_X}$

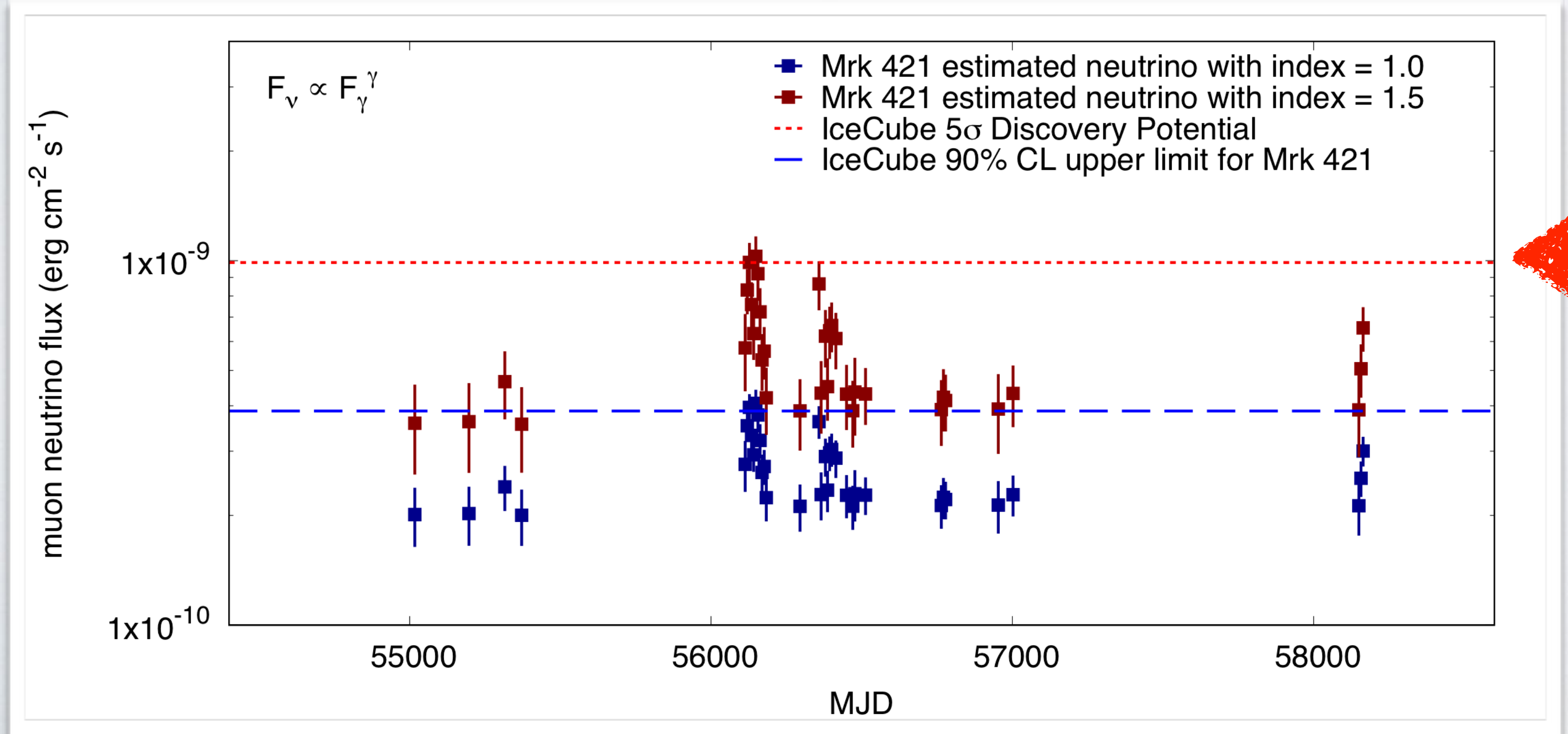
$\epsilon_\nu F^q_{\nu_\mu}$: Muon neutrino quiescent level
$\epsilon_X F^q_X$: X-ray quiescent level

Estimation of Muon Neutrino Flux

A simple scaling relation between the gamma-ray and neutrino flux, Independent of the details of neutrino production

$$\epsilon_\nu F^{fl}_{\nu_\mu} = \epsilon_X F^q_X \left(\frac{F^{fl}_\gamma}{F^q_\gamma}\right)^\gamma$$

F^q_γ: Gamma-ray quiescent level
F^{fl}_γ: Gamma-ray flaring flux
$\epsilon_X F^q_X$: X-ray quiescent level (erg cm^{-2} s^{-1})

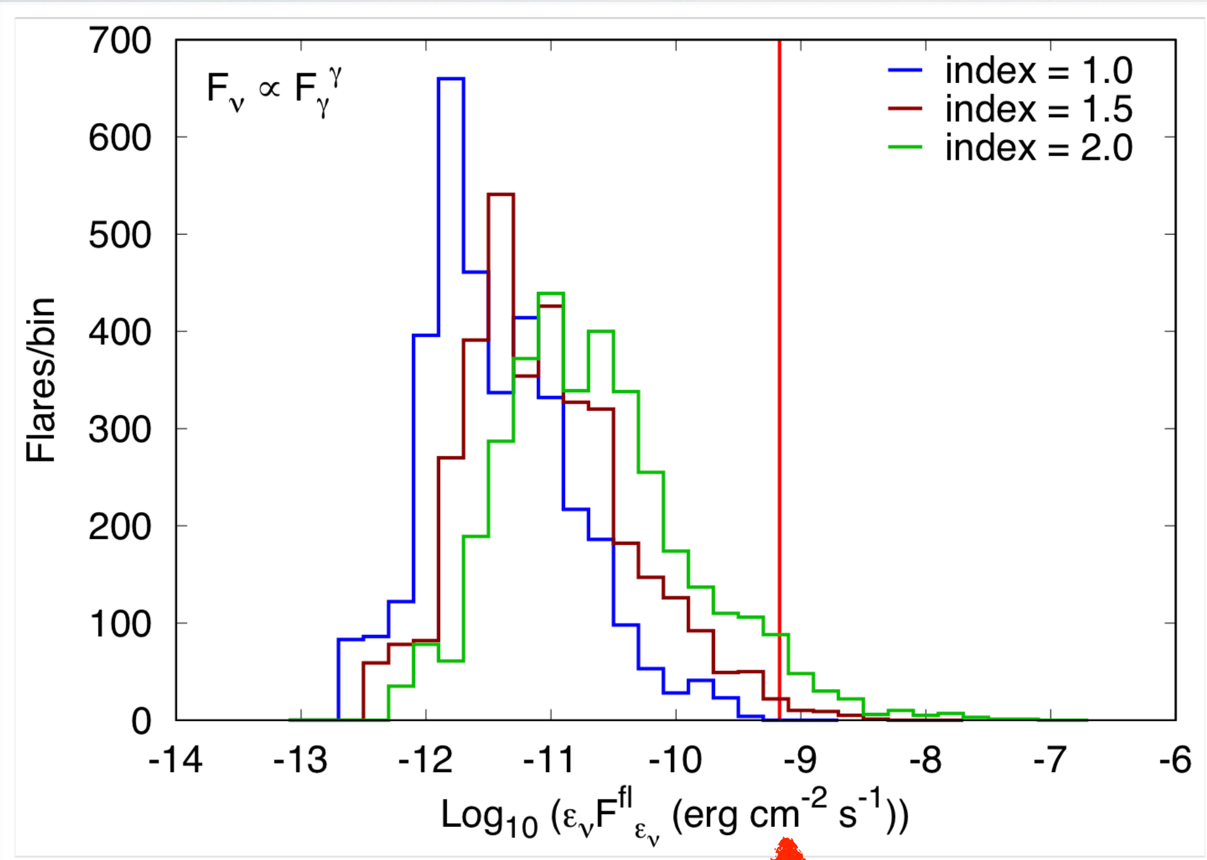


The IceCube 5σ discovery potential scaled to a week

An example of time history of muon neutrino flux with γ=1.0 and γ=1.5 (Mrk 421)

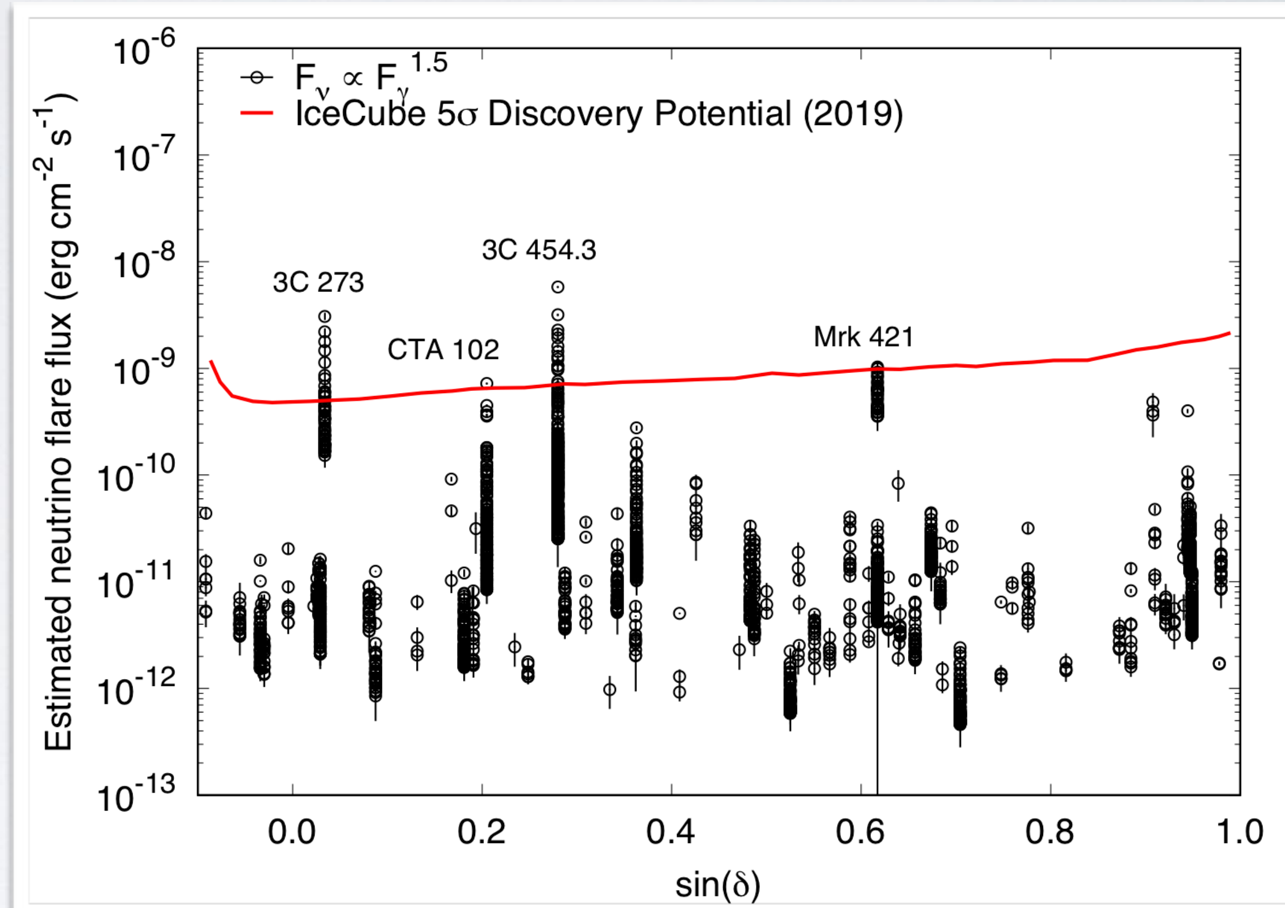
Estimated Neutrino Flare Fluxes from Gamma-ray Blazars

Estimated neutrino flare flux distributions



IceCube 8yr typical discovery potential of 1.0×10^{-12} TeV cm^{-2} s^{-1} (scaled to a week)

Estimated muon neutrino flare fluxes with γ=1.5 as a function of sinδ (δ= declination)



Four sources are close to or above the IceCube 5σ discovery potential

$$\epsilon_\nu F^q_{\nu_\mu} \ll \epsilon_X F^q_X \quad or \quad \gamma < 1.5$$

Contribution of Blazar Flares to the Isotropic Neutrino Background in Accordance with Stacking/Clustering Constraints

$$E_\nu^2 \Phi_\nu \lesssim 3.8\times10^{-10}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}} \left(\frac{\xi_z}{0.7}\right)\left(\frac{0.05}{f_{fl}}\right)^{1/2}\left(\frac{b_{fl}^\nu}{1.0}\right)^{1/2}\left(\frac{10^{46}\mathrm{erg s^{-1}}}{\epsilon_\nu L^{fl}_{\epsilon_{\nu_\mu}}}\right)^{1/2}$$

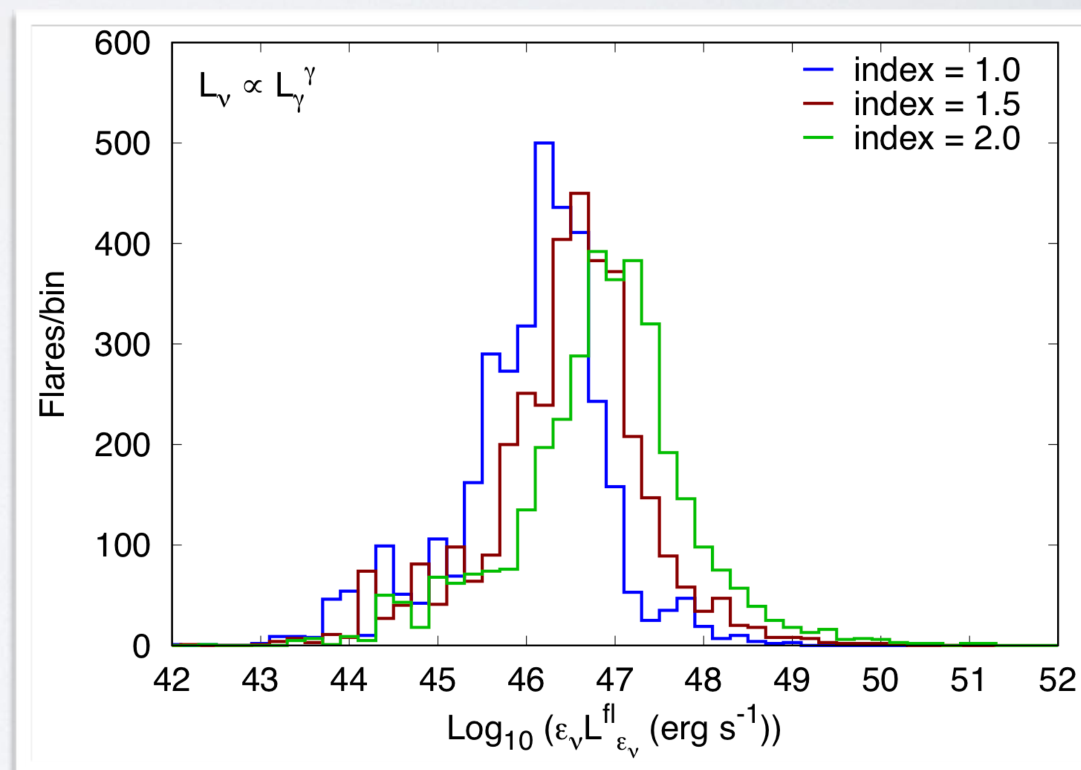
A dimensionless parameter depending on the z evolution of blazars

$\xi_z = 0.68$ for BL Lacs
$\xi_z = 8.4$ for FSRQs

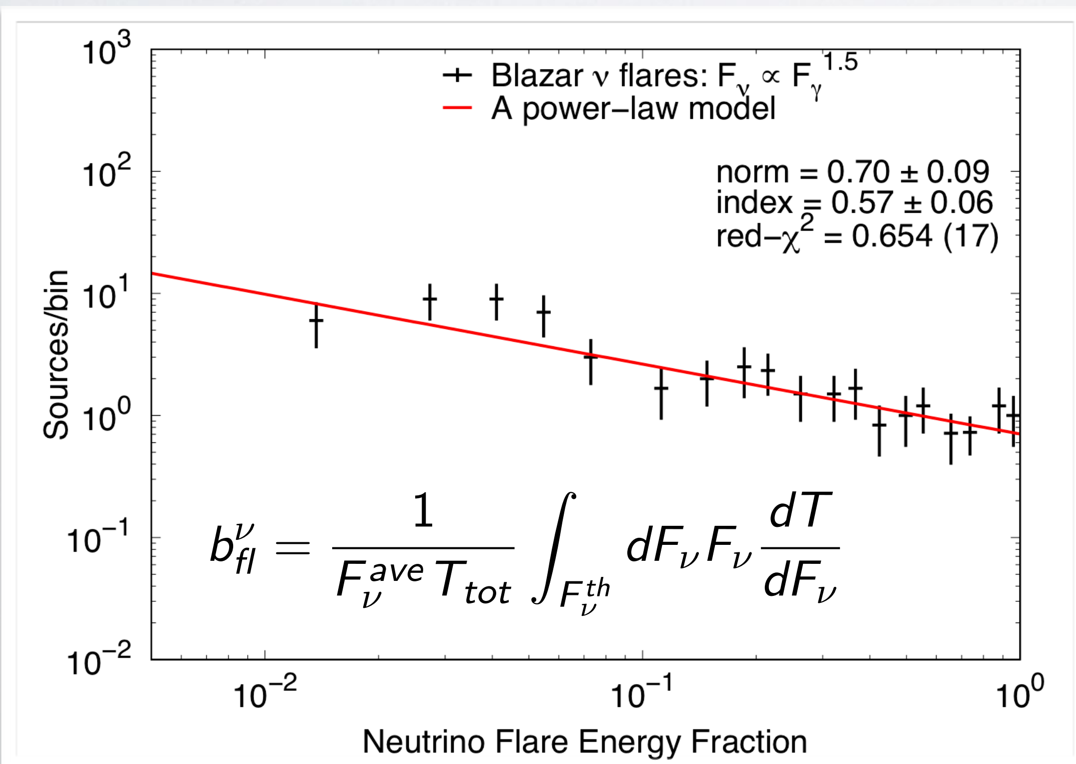
Flare Duty Factor

Murase, Oikonomou, Petropoulou (2018)

Estimated neutrino flare luminosities



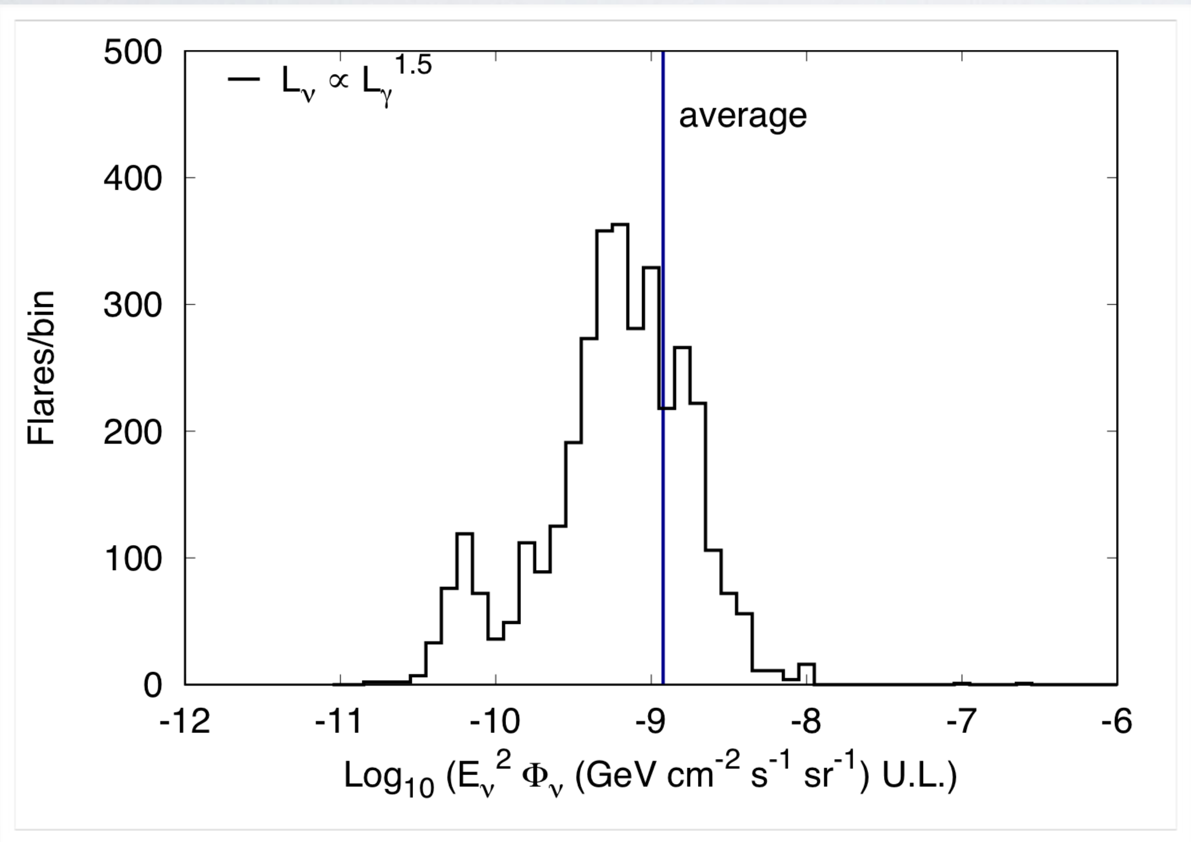
Neutrino Flare Energy Fraction



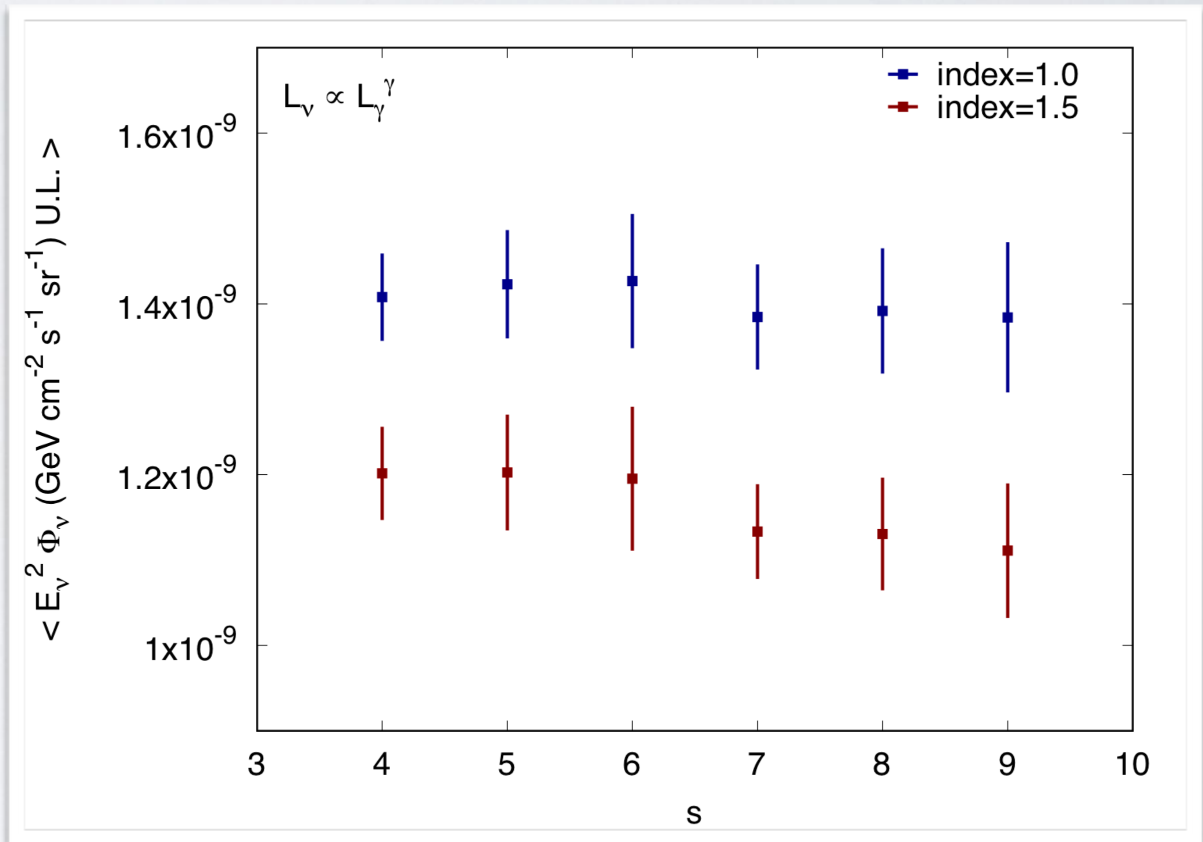
Contribution of Flaring Bright Blazars of this Sample to the Isotropic Neutrino Background

Estimated by summing up the individual contributions divided by their number

Distribution of $E_\nu^2\Phi_\nu$ U.L. for the individual flares with γ=1.5



< $E_\nu^2\Phi_\nu$ U.L. > as a function of the flare significance s

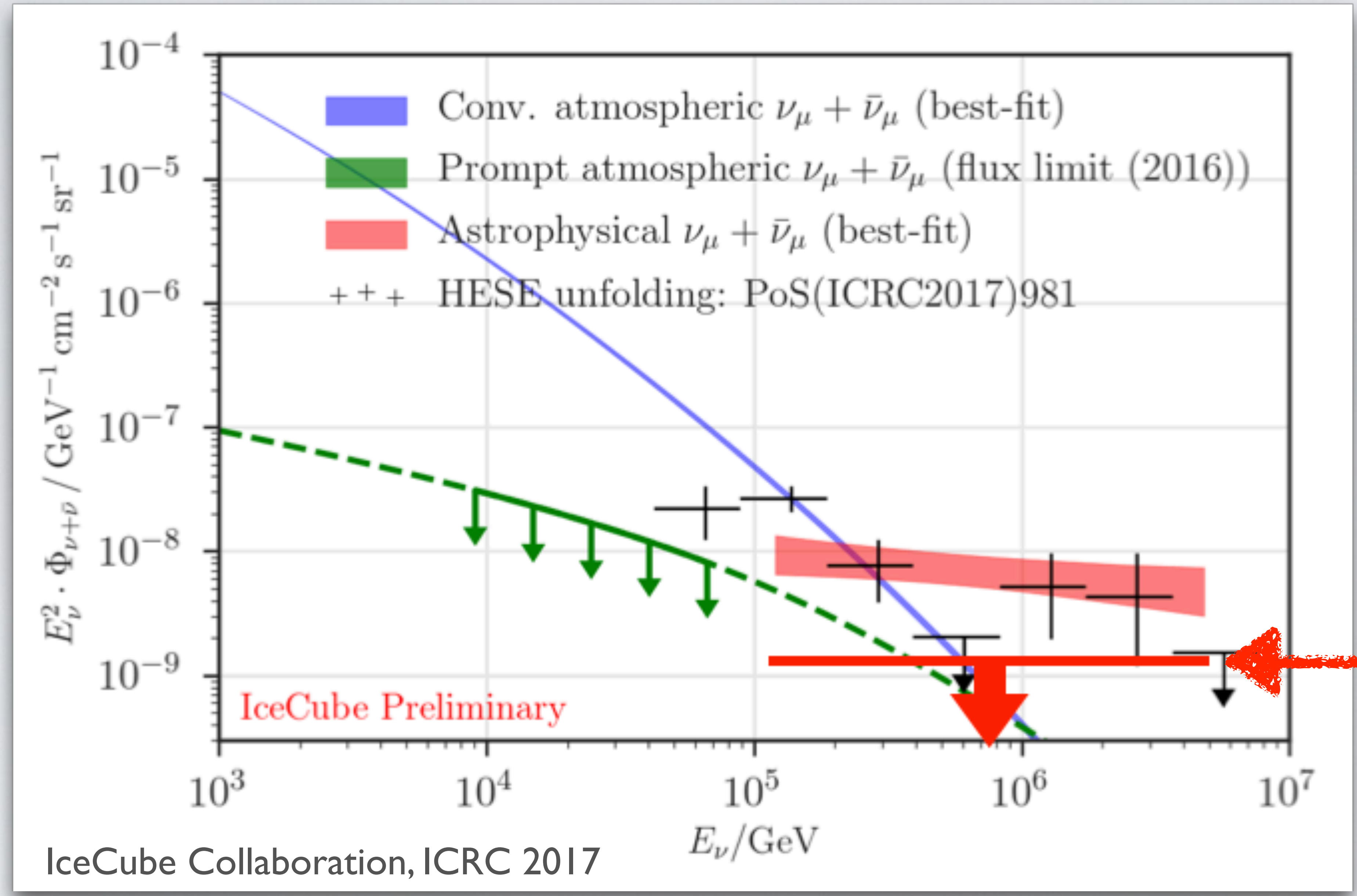


$< E_\nu^2\Phi_\nu \mathrm{U.L.} >$ (GeV cm^{-2} s^{-1} sr^{-1})

$(0.96\pm0.08)\times10^{-9}$ for $\gamma = 2.0$
$(1.20\pm0.08)\times10^{-9}$ for $\gamma = 1.5$
$(1.43\pm0.08)\times10^{-9}$ for $\gamma = 1.0$

The estimated contribution of blazar flares to the isotropic neutrino background: almost independent of s.

Upper Limit of the Contribution of Flaring Bright Gamma-ray Blazars of this Sample to the Isotropic Neutrino Background



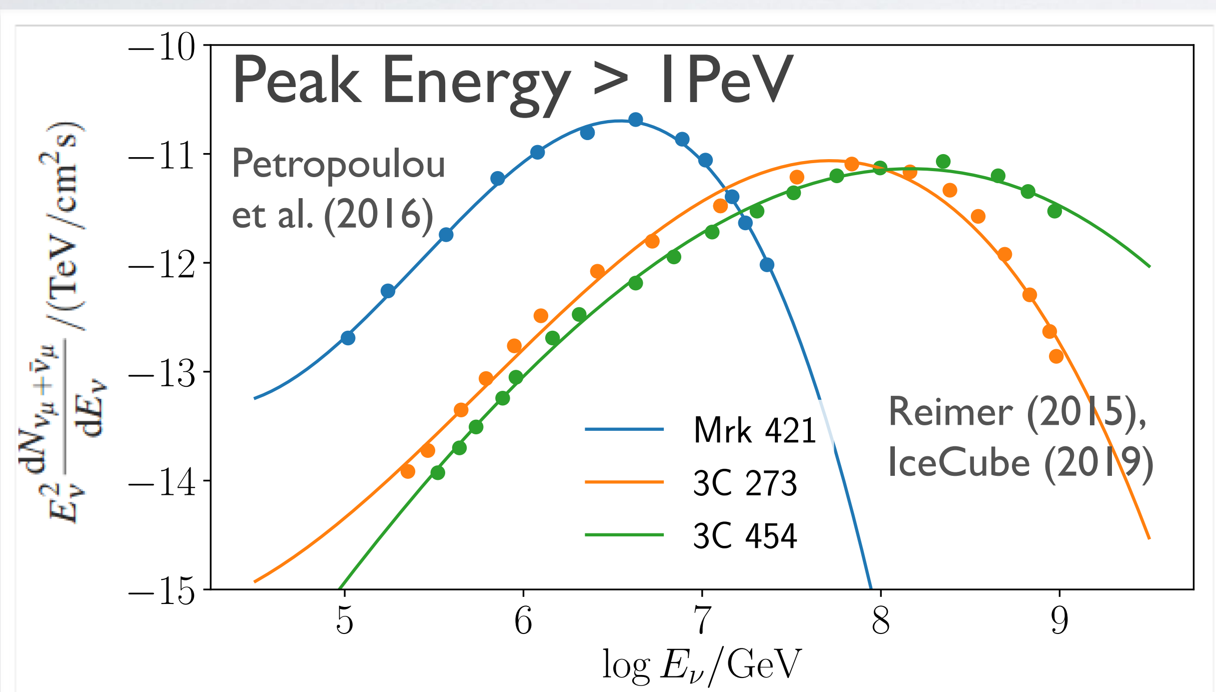
- ~12–14% of the Isotropic Neutrino Background
- But, fainter blazar flares could make a larger contribution.

Neutrino Flare Flux Estimation using Theoretical Neutrino Spectra

So far, we assumed a flat E_ν^{-2} spectrum

$$\epsilon_\nu F^q_{\nu_\mu} = \epsilon_X F^q_X$$ in quiescent state

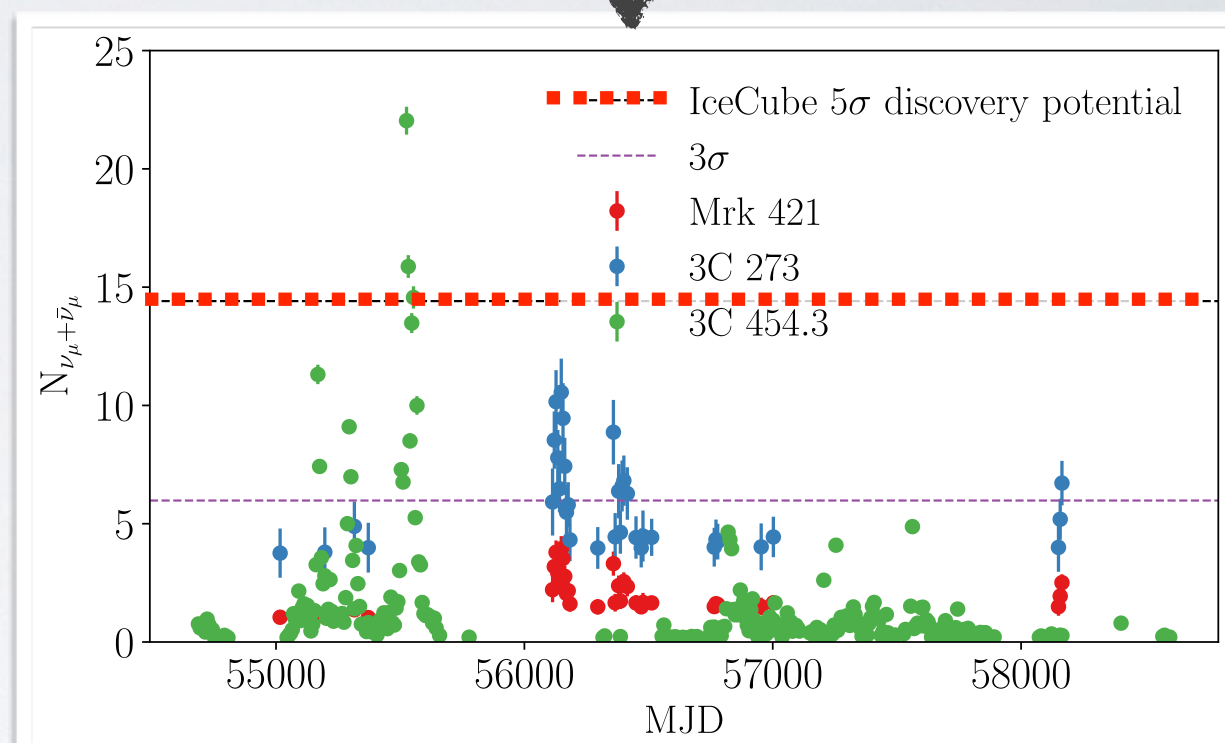
Alternatively, we use theoretical neutrino spectra in quiescent state for Mrk 421, 3C 273, 3C 454.3.



$$E_\nu^2 \frac{dN_\nu}{dE_\nu} = \left(E_\nu^2 \frac{dN_\nu}{dE_\nu}_{\,model}\right) \cdot \left(\frac{F_\gamma^{fl}}{F_\gamma^q}\right)^{1.5}$$

\+

IceCube effective area and exposure



The expected number of neutrinos is almost below the IceCube sensitivity.

For these sources, a soft neutrino spectrum peaking < 1PeV can be ruled out more readily.

Summary

- Combining bright gamma-ray blazar data with X-ray data, we estimated neutrino flare fluxes of blazars using a model-independent method.
- Estimated neutrino flare fluxes for 3C 273, CTA 102, 3C 454.3, and Mrk 421 are close to or above the IceCube 5σ discovery potential.
  - The lack of neutrino detection of these sources suggests that
    - the neutrino quiescent level is much lower than the X-ray quiescent level or
    - the index γ of the scaling method is less than 1.5
- The upper limit of the contribution of bright gamma-ray flaring blazars of this sample is ~12-14% of the isotropic neutrino background.
  - Fainter gamma-ray blazar flares could make a larger contribution.