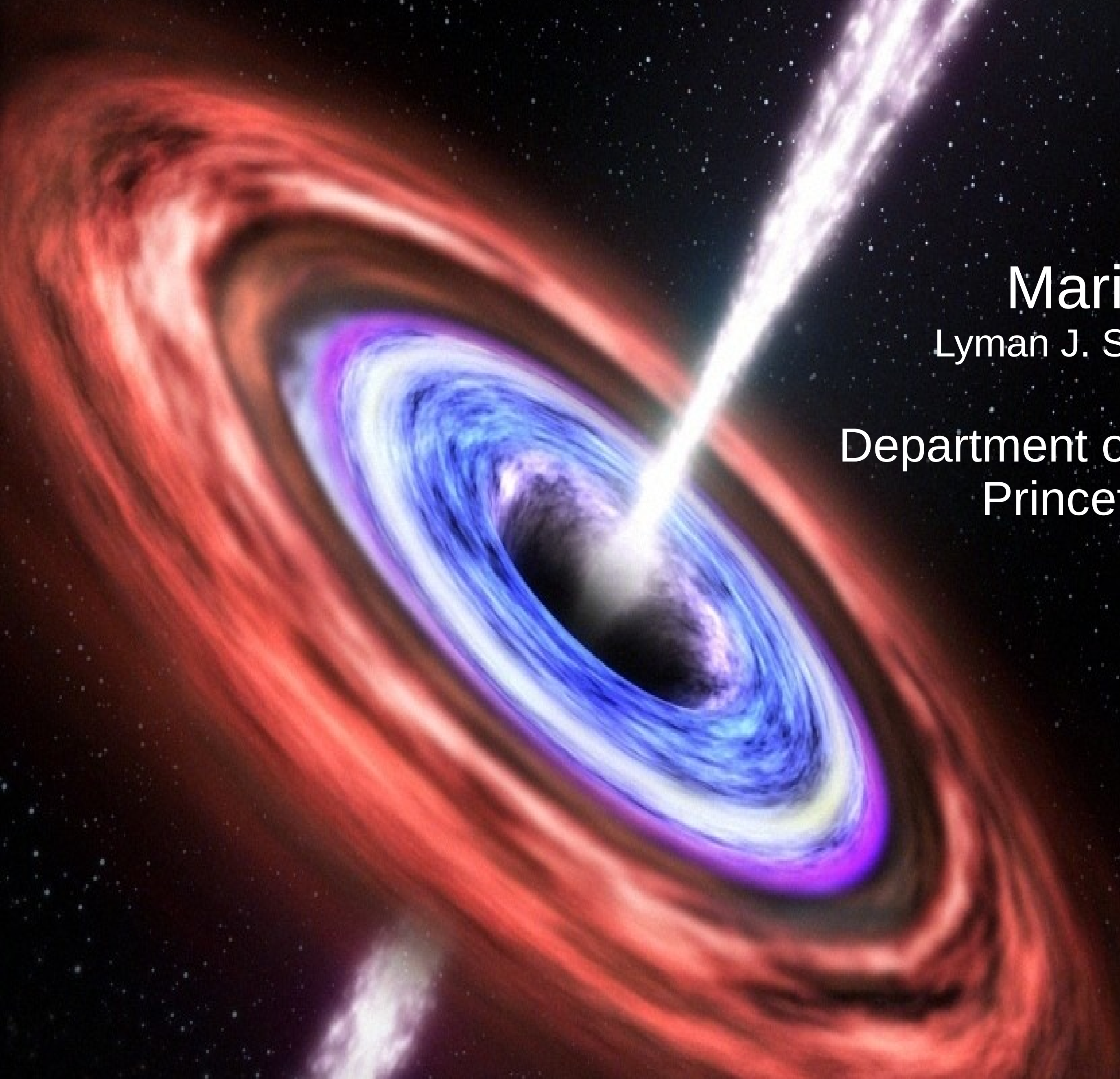
Blazars as sources of high-energy neutrinos



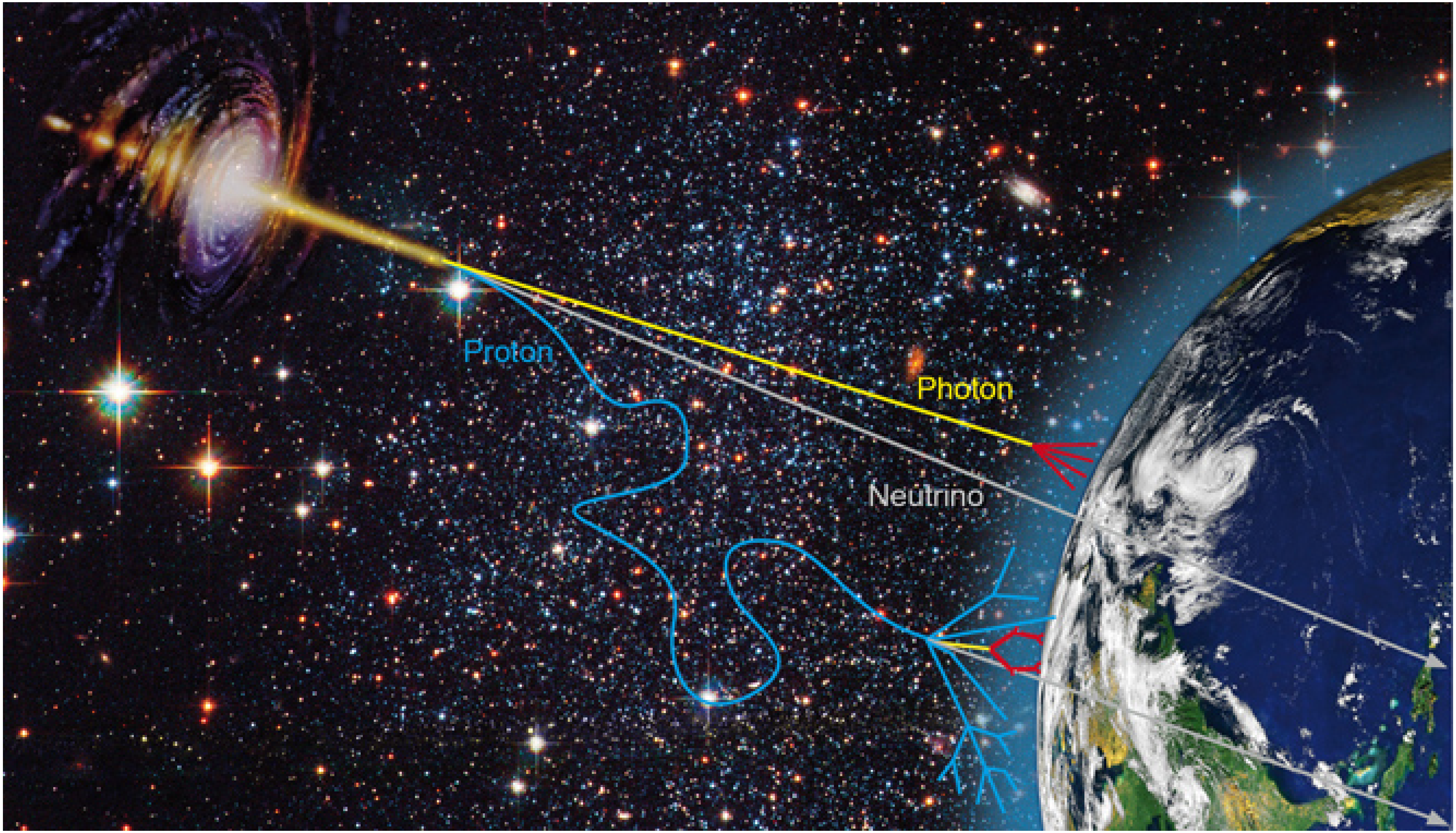
Maria Petropoulou
Lyman J. Spitzer Postdoctoral Fellow

Department of Astrophysical Sciences,
Princeton University, USA

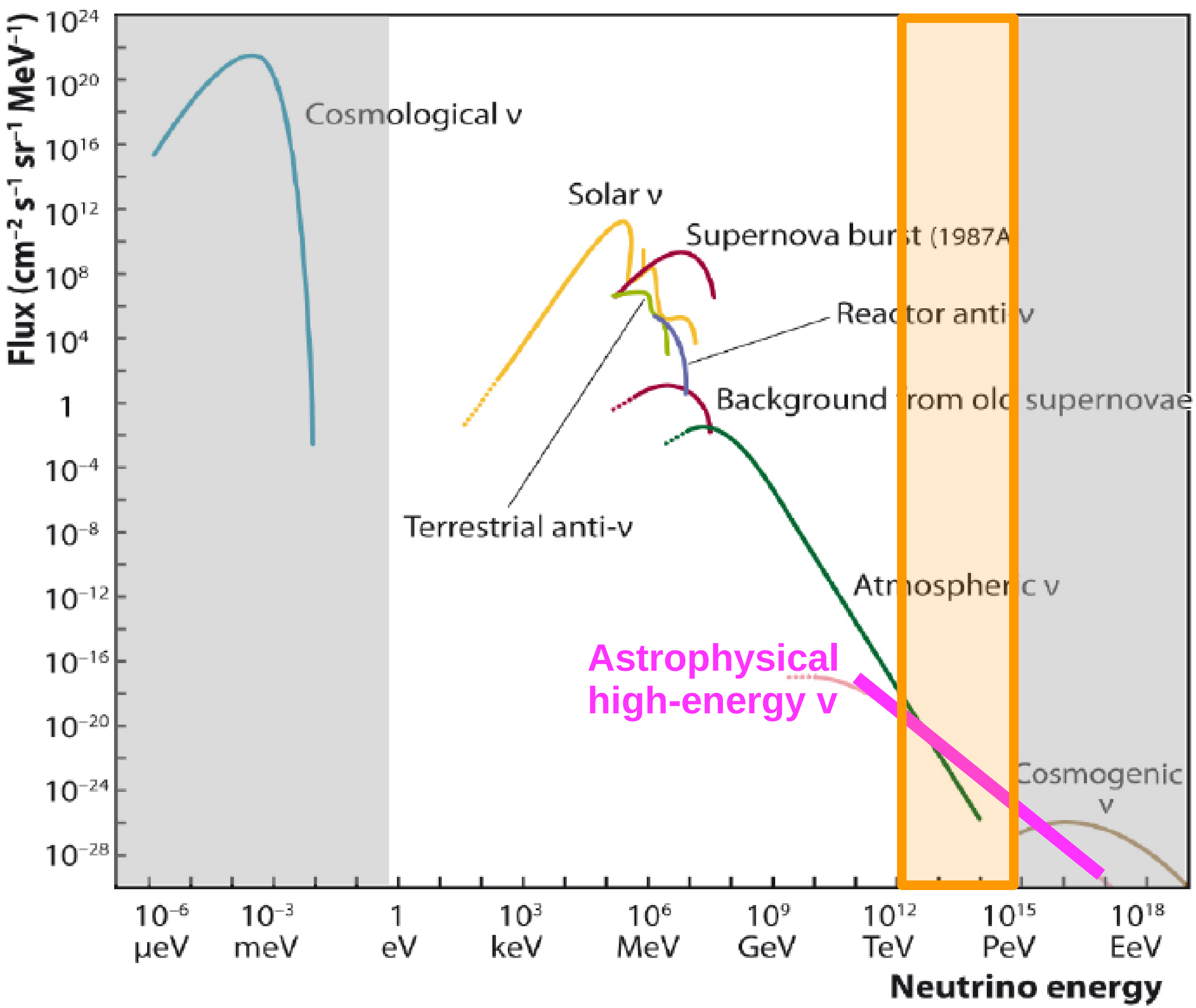
Torino, 14.06.2018

Fermi 10 Blazars and Beyond

Neutrinos (ν) as astrophysical probes



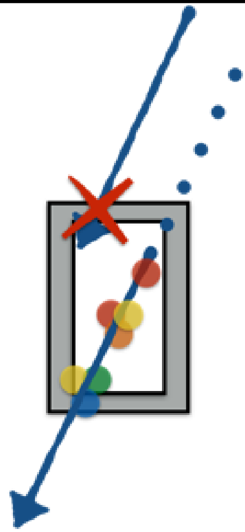
The ν energy spectrum

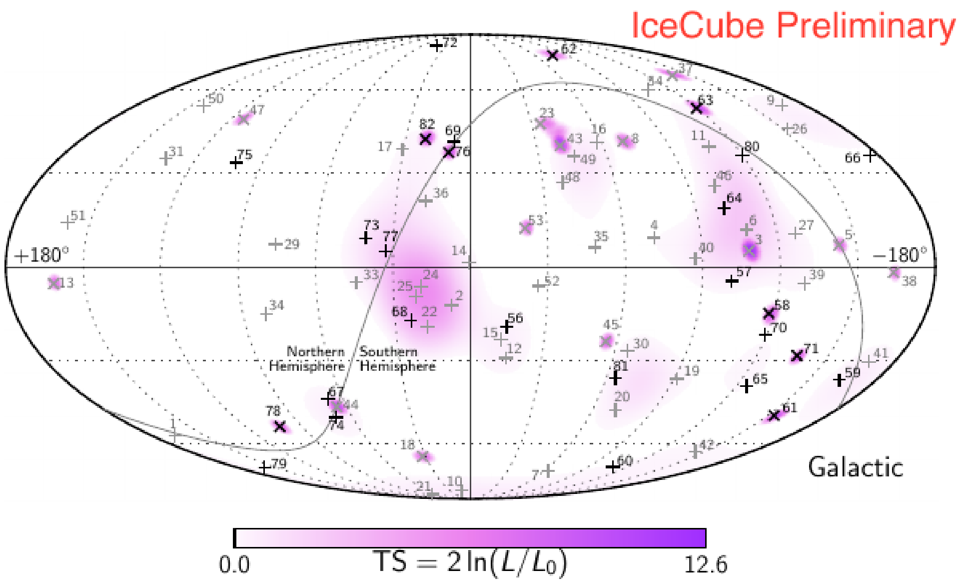


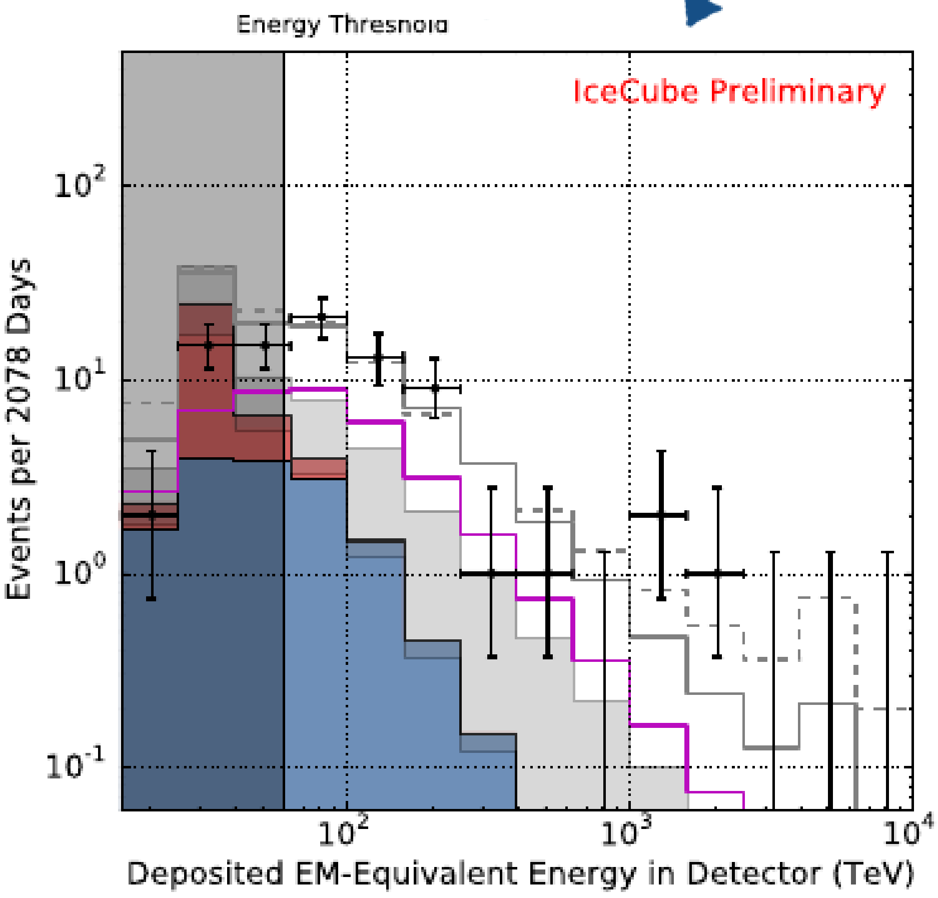
Observational status (in a nutshell)

High-Energy Starting Event sample (2010-2015):

- ~54 events with E_ν ~ 30 TeV – 2 PeV
- Background-only hypothesis rejected at ~8σ
- Spectrum still compatible with single power-law
- No significant clustering of events on the sky

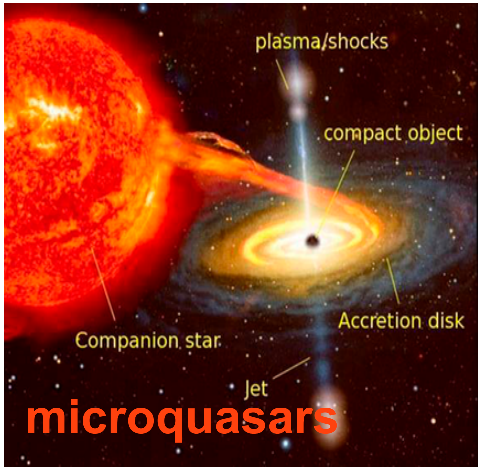






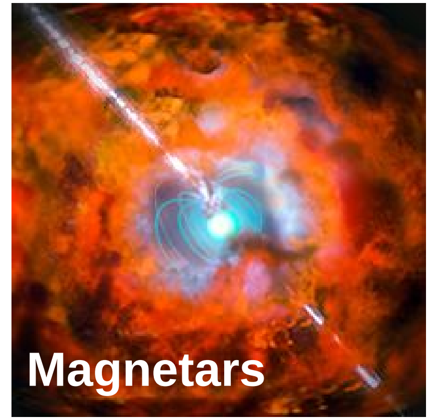
(ICRC 2017) arXiv:1710.01191

A zoo of astrophysical ν sources



(e.g. Guetta+2002, Torres+2005)

(e.g. Murase+2011, Zirakashvili & Ptuskin 2016, Petropoulou+2017)



(e.g. Fang & Metzger 2017)

(e.g. Metzger+2015)

(e.g. Loeb & Waxman 2006, Tamborra+2014, Bechtol+2017)

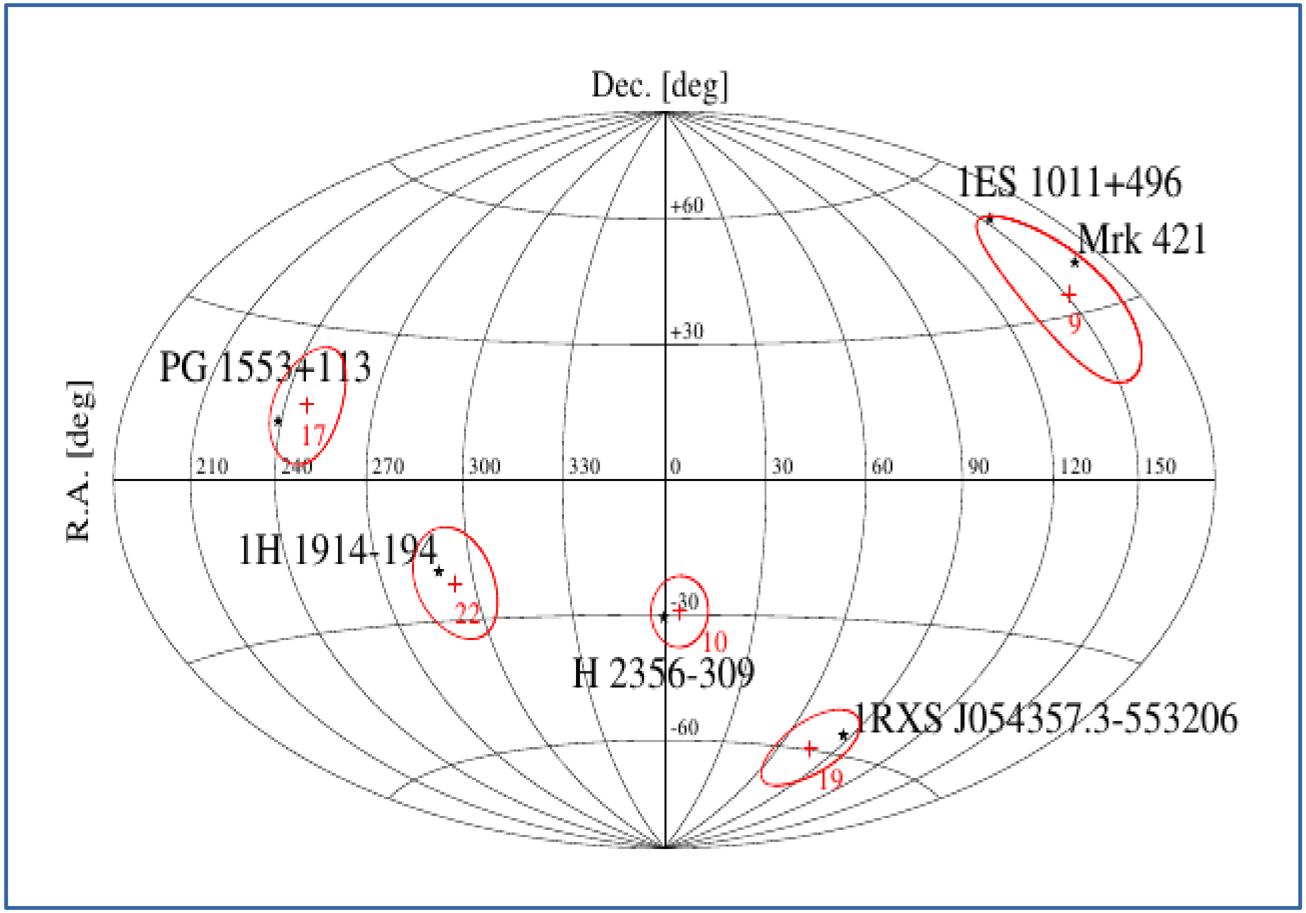
(e.g. Waxman & Bahcall 1999, Murase 2008, Hummer+2012, Petropoulou+2014)

(e.g. Mannheim 1995, Halzen & Zas 1997, Atoyan & Dermer 2001, Murase+2014, Petropoulou+2015)

(recent review by Ahlers & Halzen 2015)

Blazars as probable counterparts

(Padovani & Resconi 2014; Padovani, Resconi + 2016)



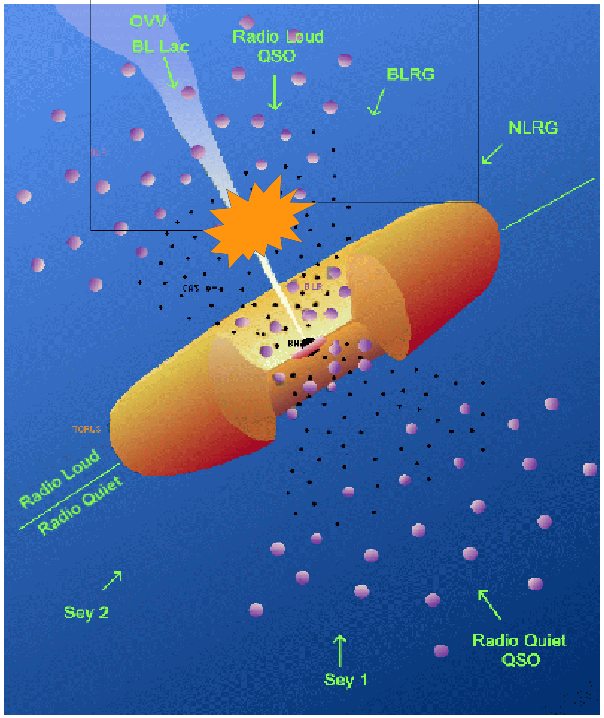
Can the physical processes in jets support the observed neutrino fluxes?

Modeling of ν and photon emission

- Synchrotron radiation
- Inverse Compton scattering
- Pair production
- Pair annihilation

...

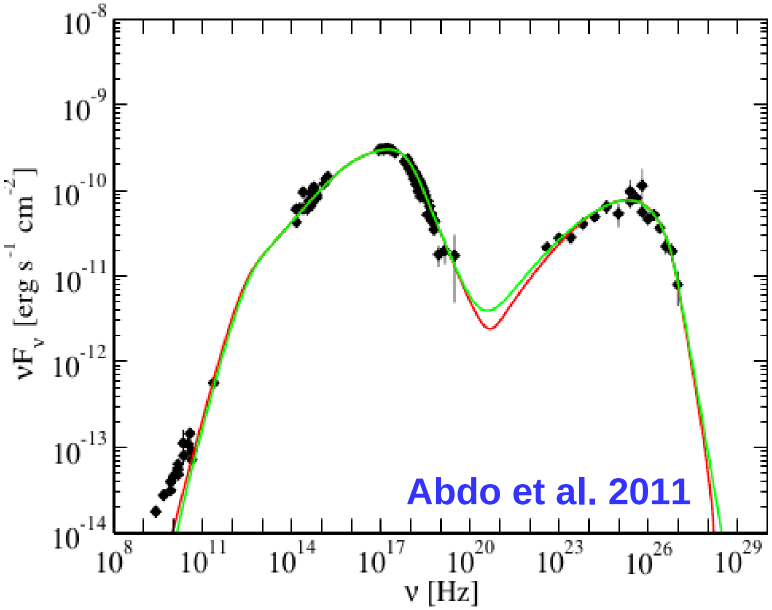
Leptonic models



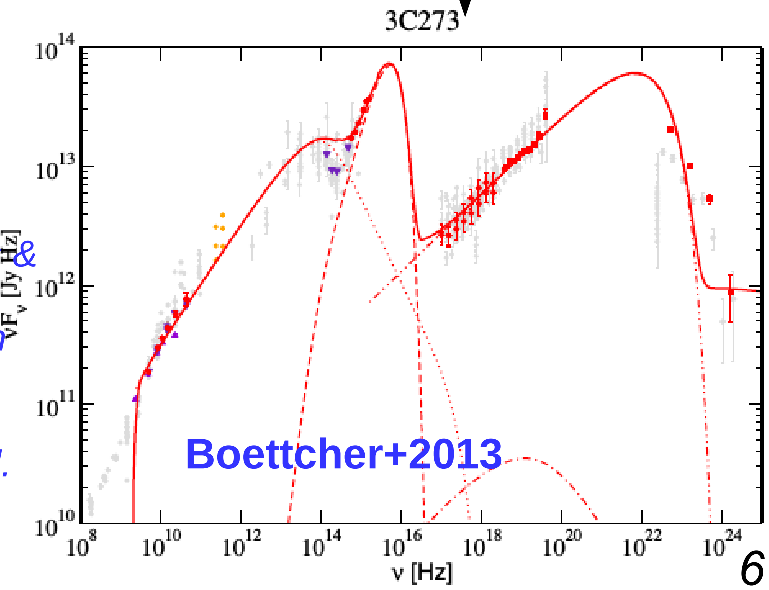
- Synchrotron radiation
- Inverse Compton scattering
- Pair production
- Pair annihilation
- **Photomeson production**
- **Photopair production**

...

Leptohadronic models



(e.g. *Sikora+1994, Dermer & Schlickeiser 1994, Mastichiadis & Kirk 1995, Bloom & Marscher 1996, Rieger +1998, Mannheim & Biermann 1992, Aharonian 2000, Atoyan & Dermer 2001, Muecke+2003, Boettcher et al. 2013, Cerruti+2015...)*



Numerical approach

PROTONS

$$\frac{\partial n_p}{\partial t} + \frac{n_p}{t_{p,esc}} + L_p^{BH} + L_p^{photopion} + L_p^{psyn} = Q_p^{inj} + Q_p^{photopion}$$

NEUTRINOS

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

μ, π, K synchrotron & decay **SHORT-LIVED MESONS**

ELECTRONS

$$\frac{\partial n_e}{\partial t} + \frac{n_e}{t_{e,esc}} + L_e^{IC} + L_e^{syn} + L_e^{ann} + L_e^{tpp} = Q_e^{inj} + Q_e^{BH} + Q_e^{IC} + Q_e^{\gamma\gamma} + Q_e^{photopion} + Q_e^{tpp}$$

PHOTONS

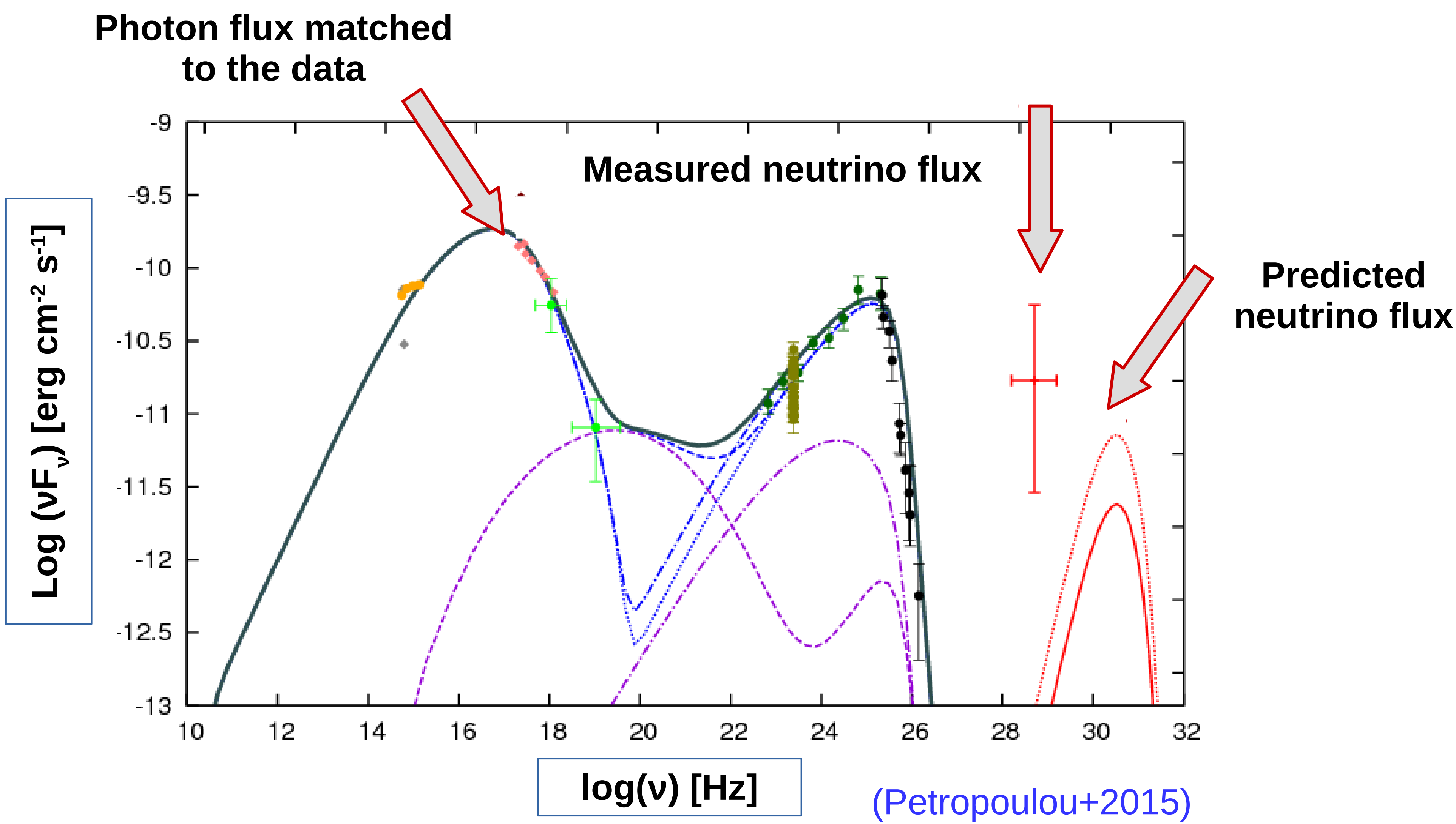
$$\frac{\partial n_\gamma}{\partial t} + \frac{n_\gamma}{t_{\gamma,esc}} + L_\gamma^{IC} + L_\gamma^{ssa} + L_\gamma^{\gamma\gamma} = Q_\gamma^{syn} + Q_\gamma^{psyn} + Q_\gamma^{msyn} + Q_\gamma^{IC} + Q_\gamma^{ann} + Q_\gamma^{photopion} + Q_\gamma^{ext}$$

NEUTRONS

$$\frac{\partial n_n}{\partial t} + \frac{n_n}{t_{n,esc}} + L_n^{photopion} = Q_n^{photopion}$$

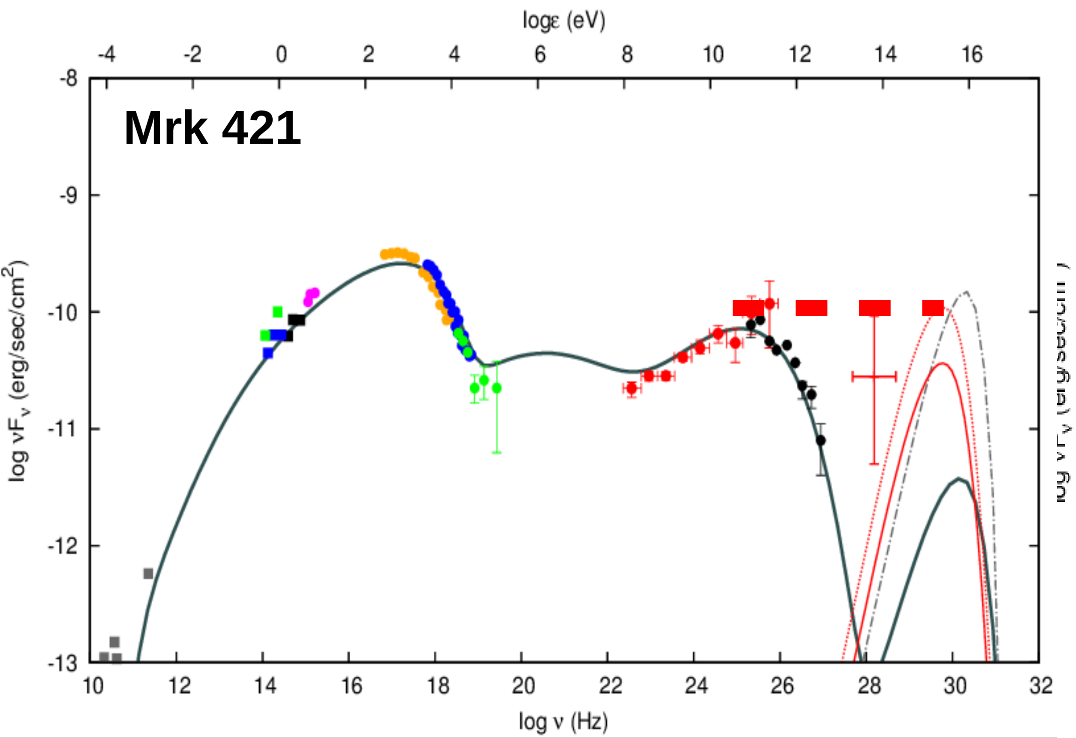
(Dimitrakoudis+2012)

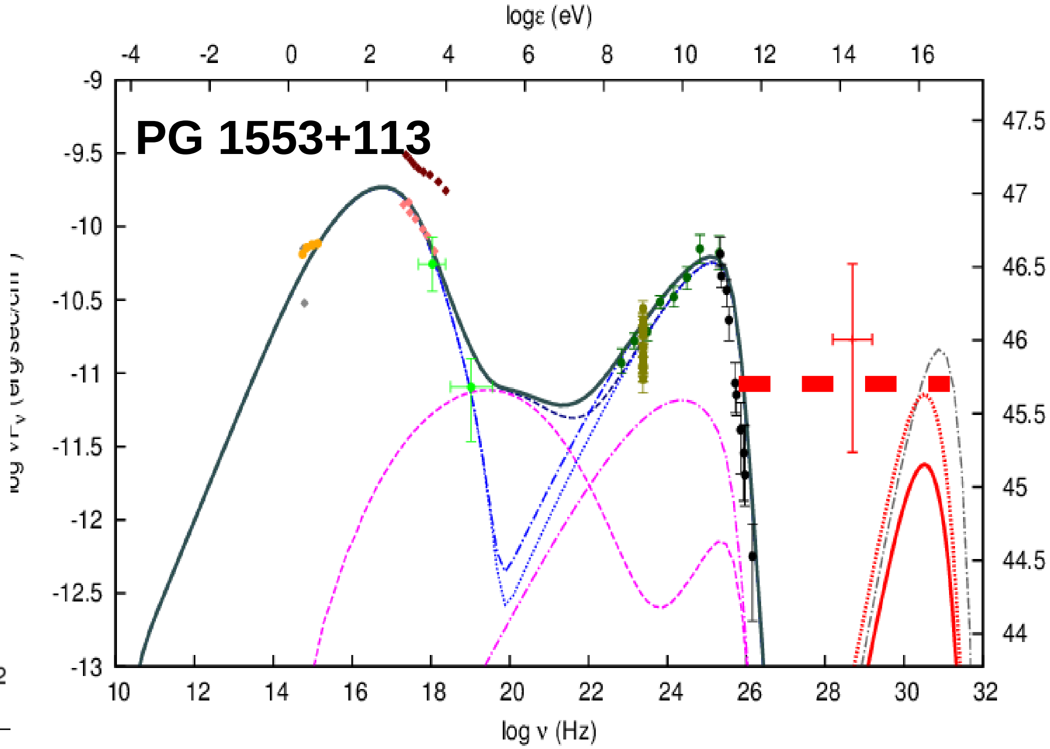
Self-consistent ν fluxes



(Petropoulou+2015)

Ratio of ν to γ-ray luminosities





Hadronic γ-rays ~ 1

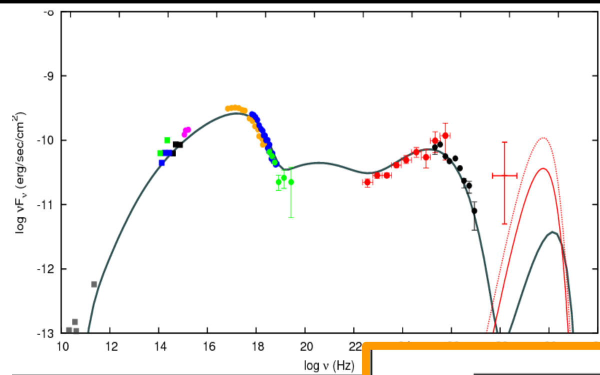
$$\boxed{Y_{\nu\gamma} = \frac{L_\nu}{L_\gamma(\varepsilon > 10\,GeV)}}$$

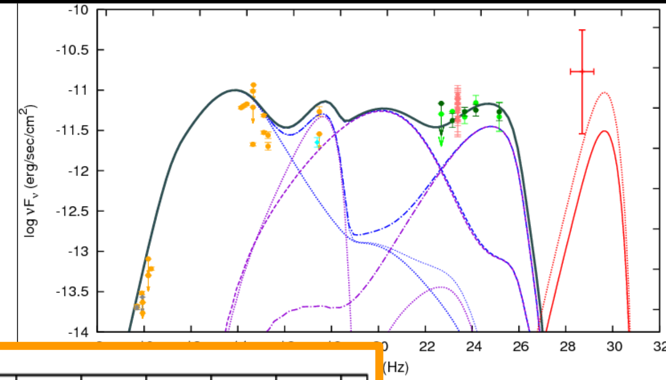
$\ll 1$ Leptonic γ-rays

Data do not always allow for solutions with $L_\nu \sim L_\gamma$

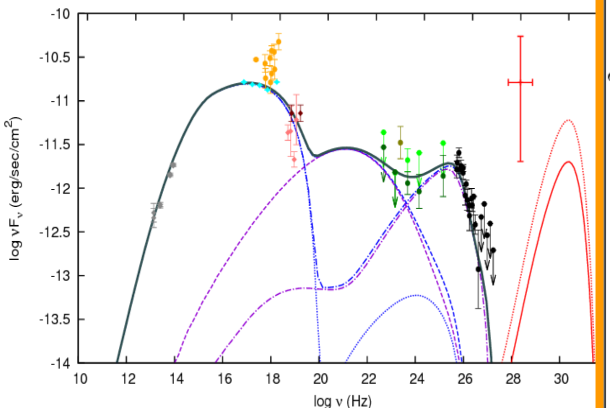
Self-consistent ν fluxes

Mrk 421

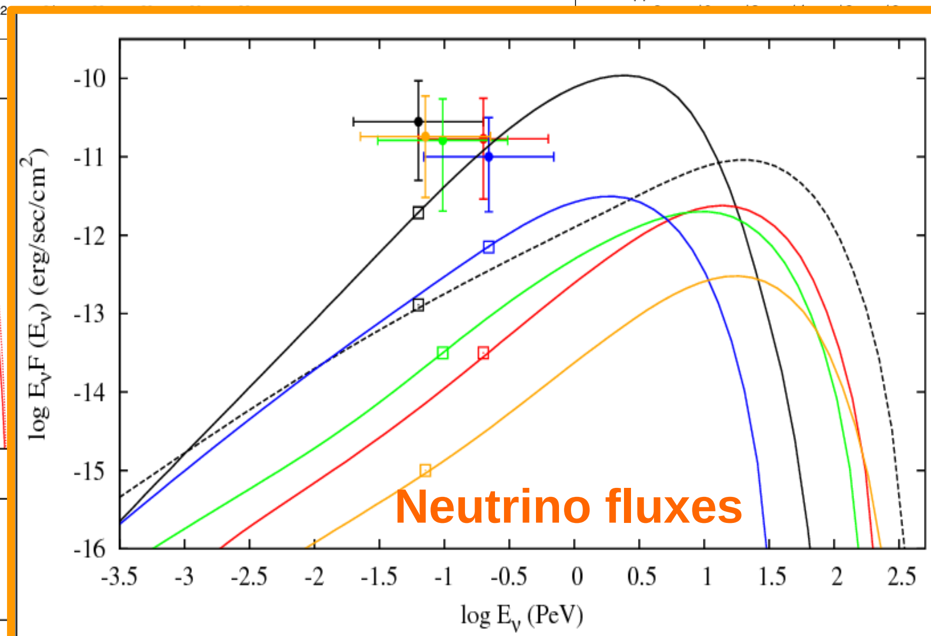


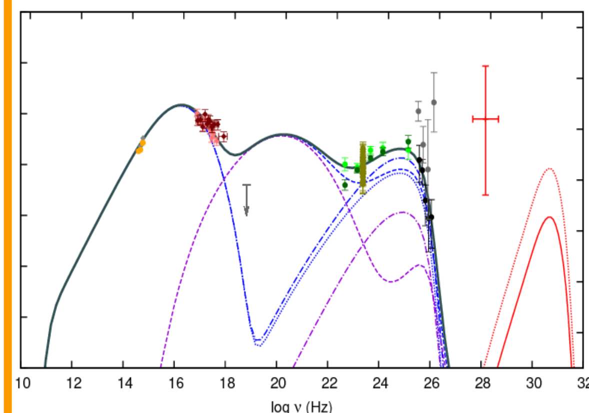


H 1914-194



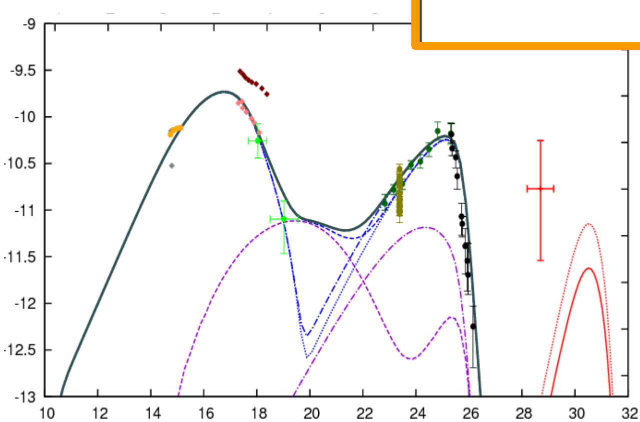
H 2356-309



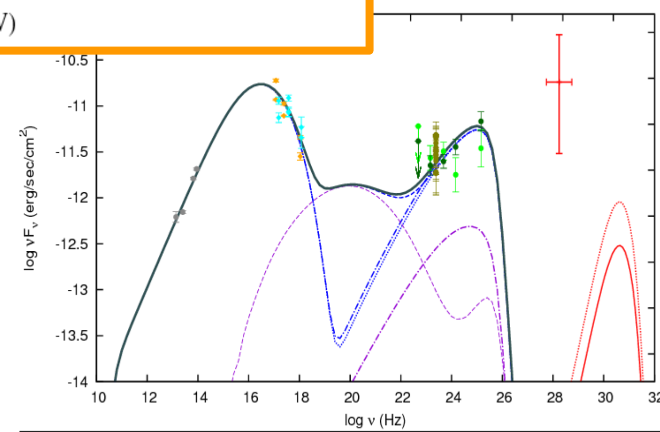


1ES 1011+496

(Petropoulou + 2015)

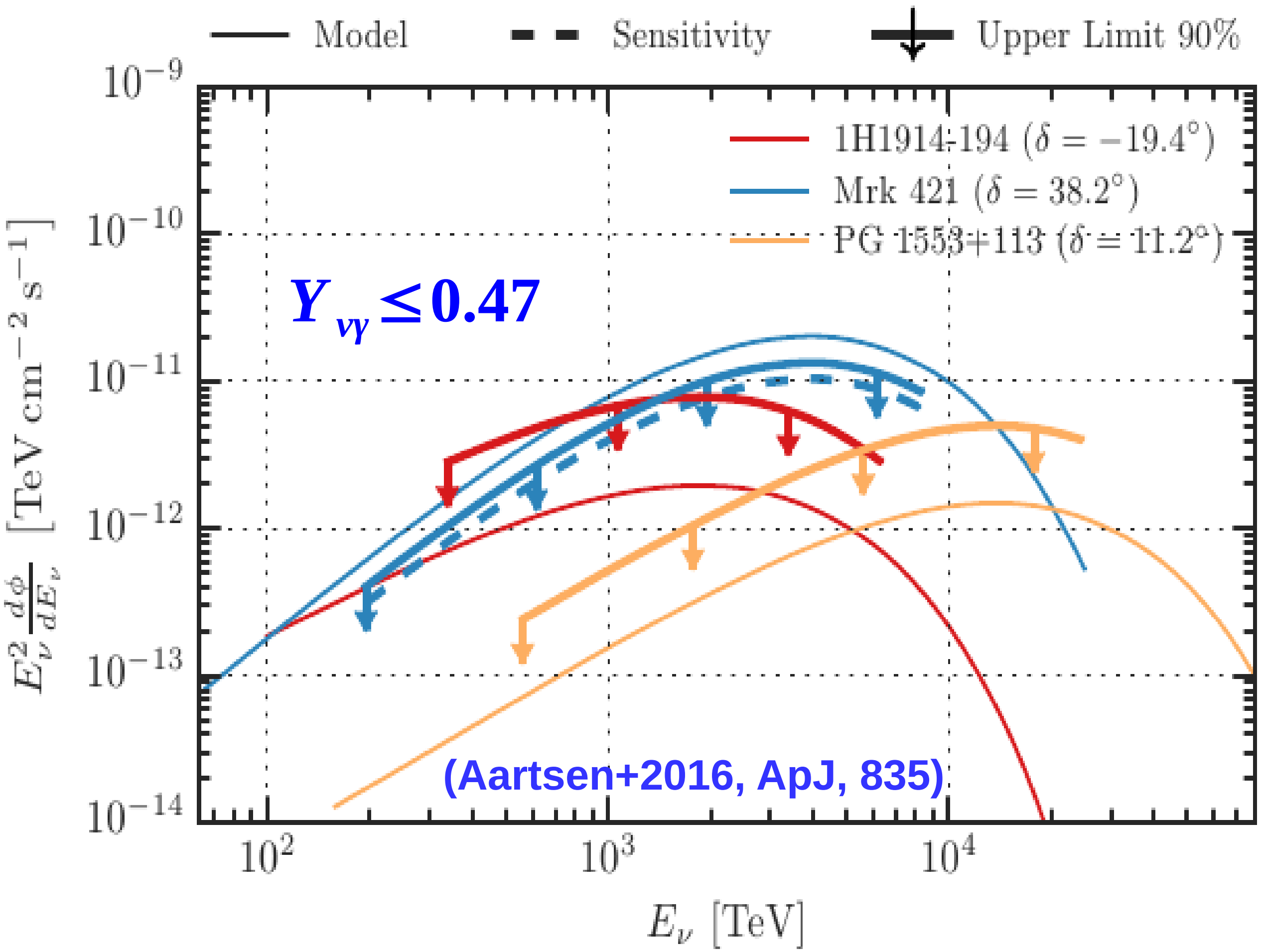


PG 1553+113



RXS J054357.3-553206

Constraints on single sources



<u>Constraints for Mrk 421:</u>

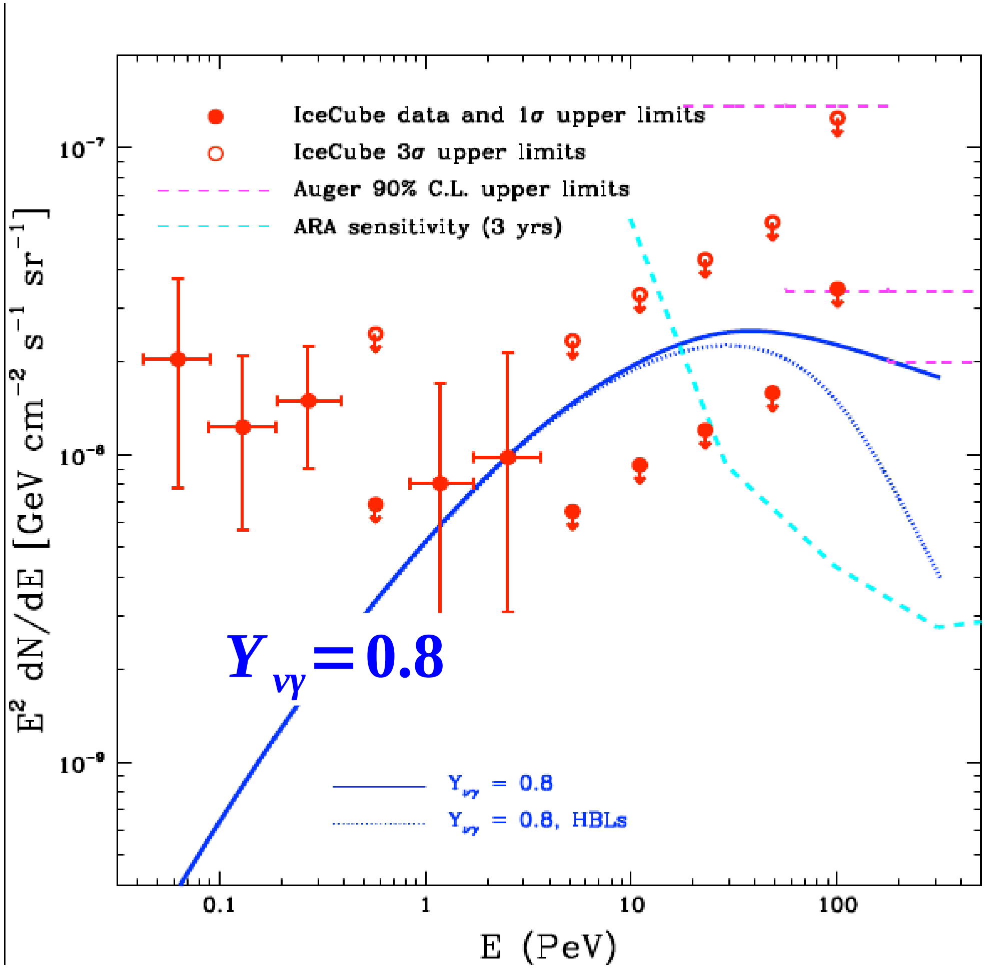
- $Y_{\nu\gamma} < 0.5$
- Neutrino flux $< 2 \times 10^{-10}$ erg s^{-1} cm^{-2}
- Power in relativistic protons $< 5 \times 10^{47}$ erg s^{-1}

The ν flux is assumed to be constant over time.

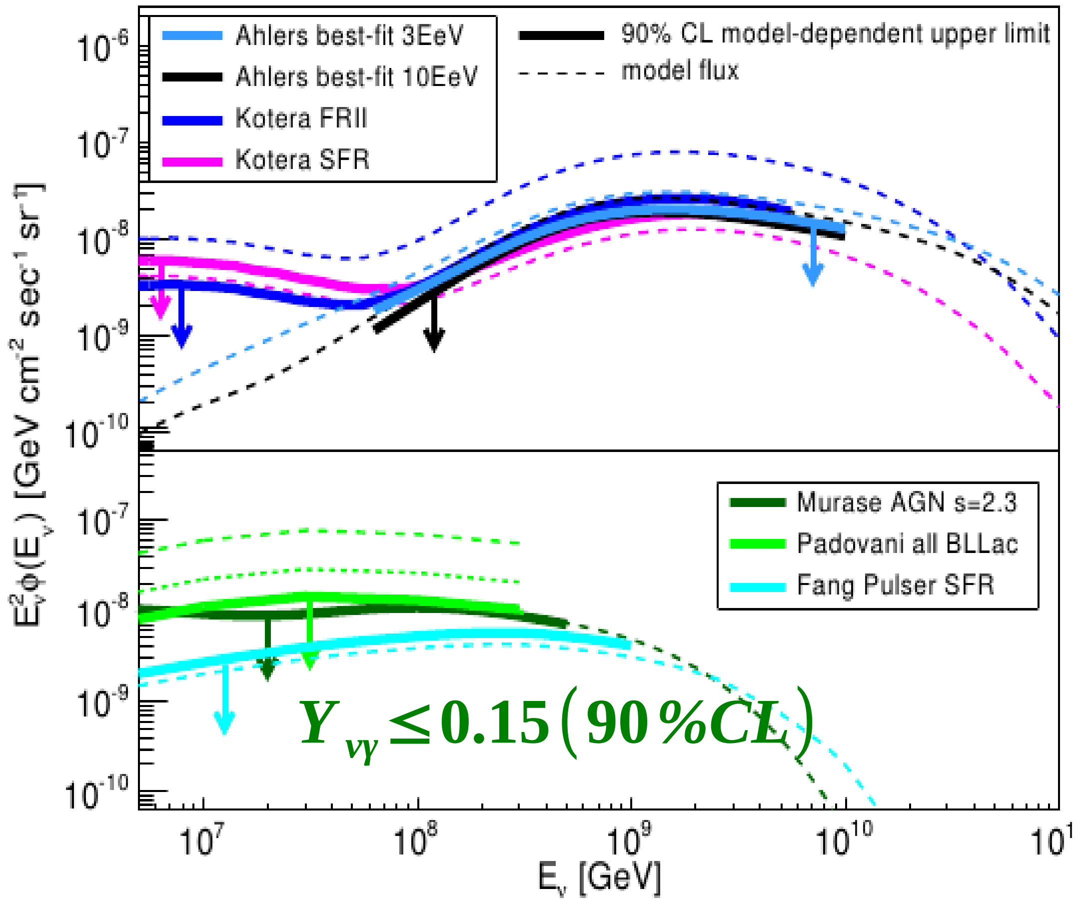
Diffuse ν emission from BL Lacs

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

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



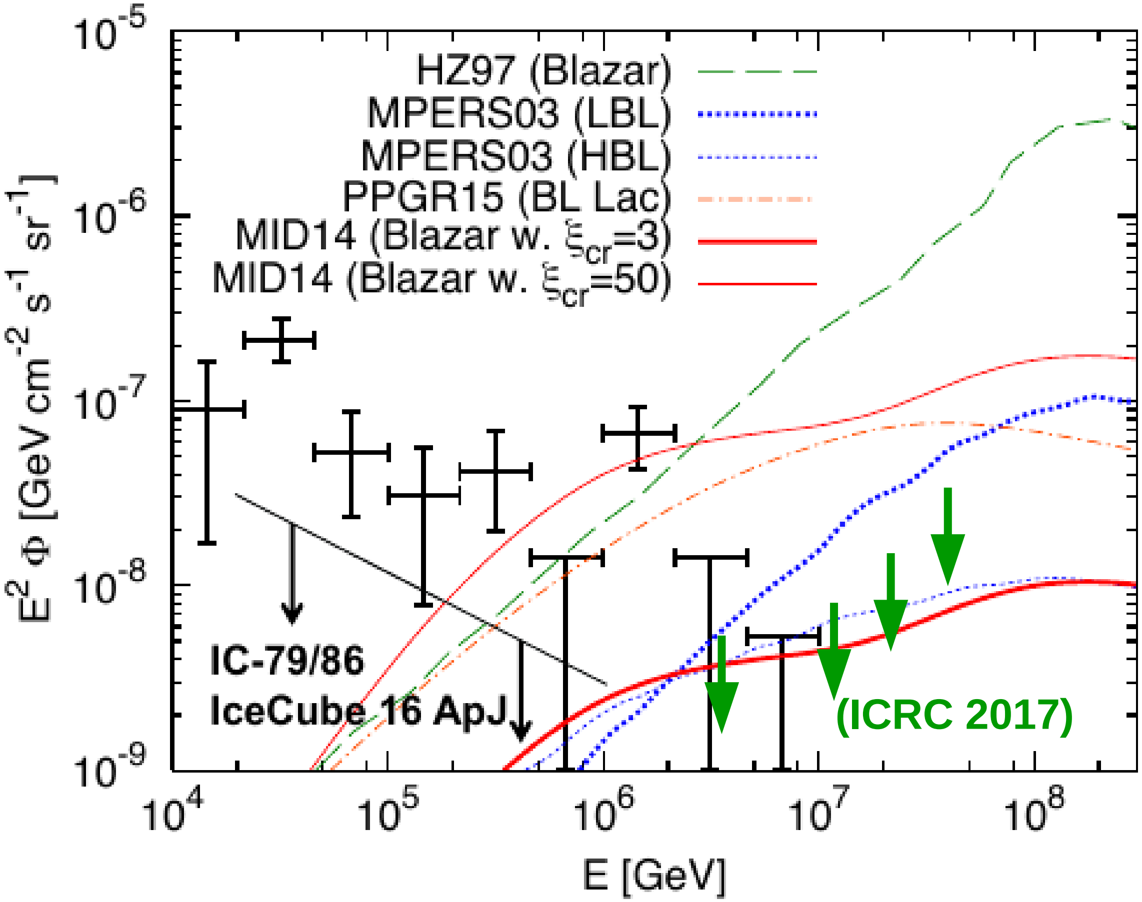
(Padovani, PM+2015)



(Aartsen+2016, arXiv:1607.05886)

What did we learn so far ?

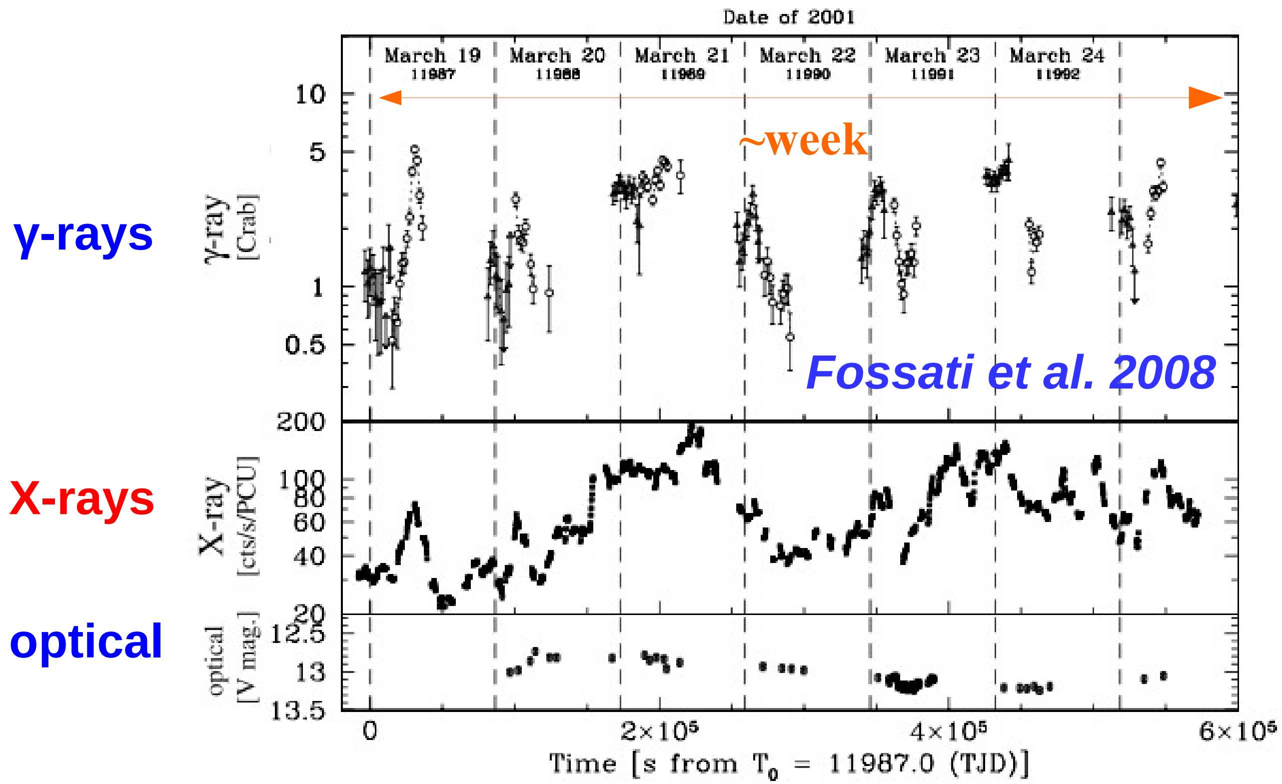
- Most blazar models predict hard spectra with a cutoff that depends on the maximum energy of the accelerated protons.
- Most blazar jet models cannot explain the IceCube ν flux at <100 TeV.
- The normalization of the neutrino spectra depends linearly on the proton luminosity, which can be constrained by IceCube.



(Murase 2015, arXiv:1511.01590)

The role of blazar flares

Blazars are variable sources across the electromagnetic spectrum!



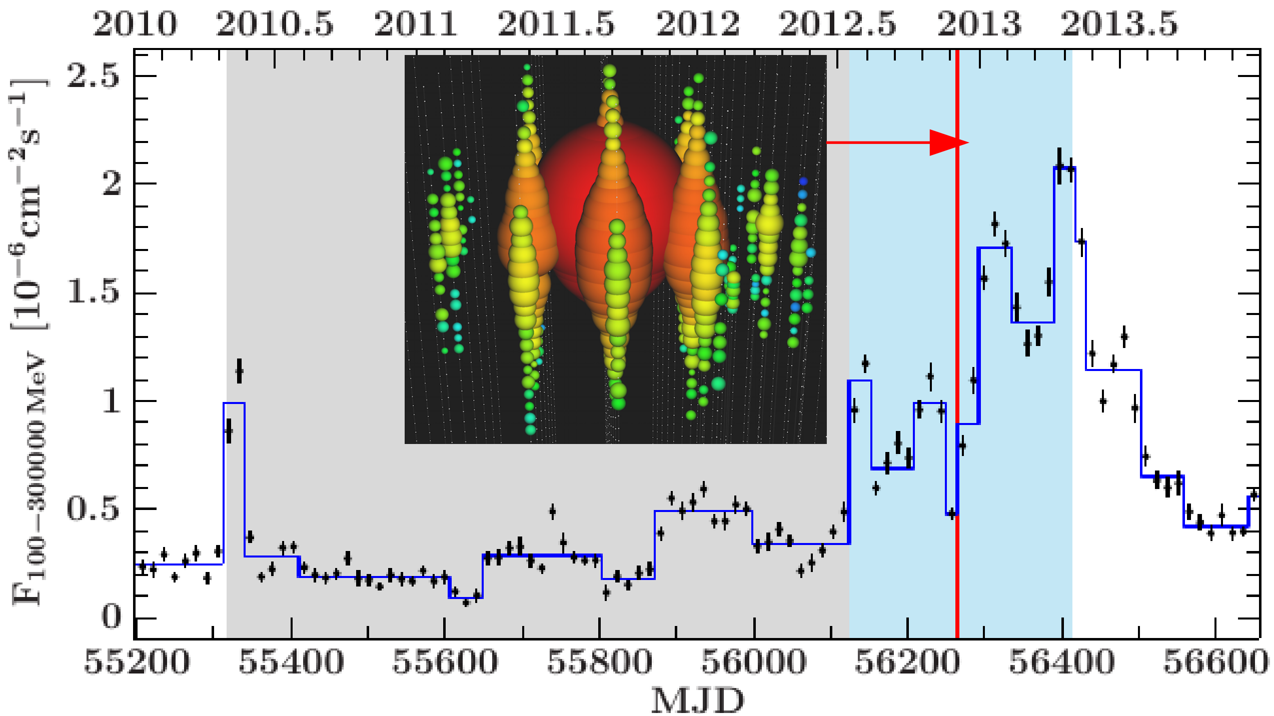
Neutrino luminosity can increase during flares.

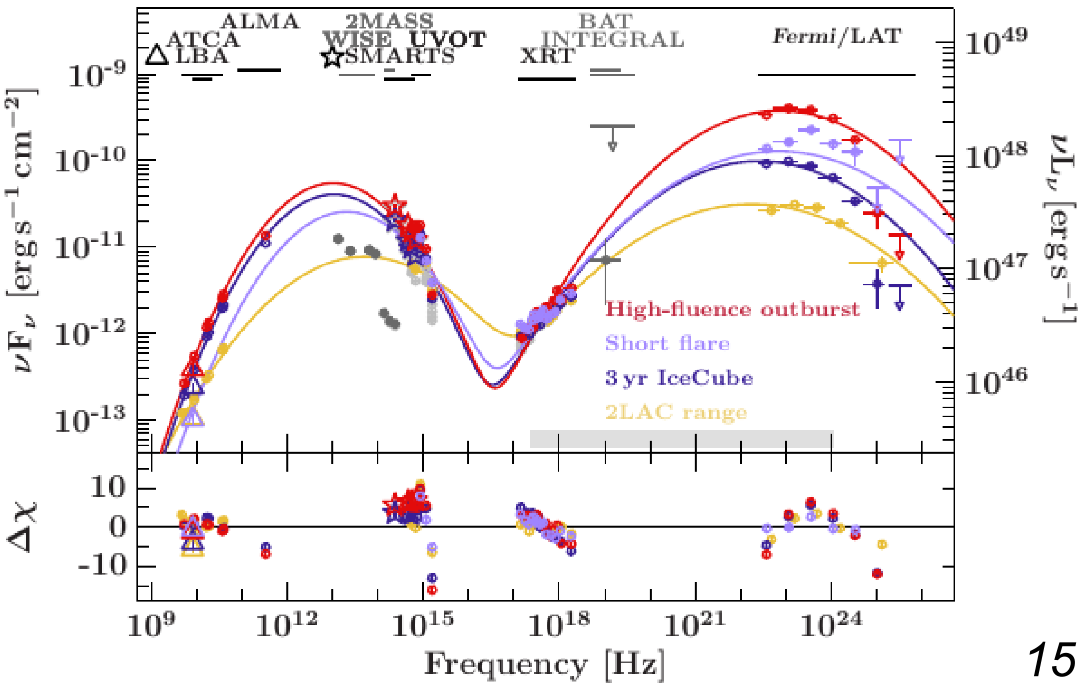
- If target photon luminosity increases, then: $\boxed{L_\nu \propto f_{p\gamma} L_p \propto \frac{L_{ph} L_p}{\epsilon_{ph} t_\nu \delta^4}}$

- If γ-rays flare and have a pionic origin, then: $\boxed{L_\nu \approx L_\gamma}$

The "Big Bird" and PKS B1424-418 flare

Kadler+2016

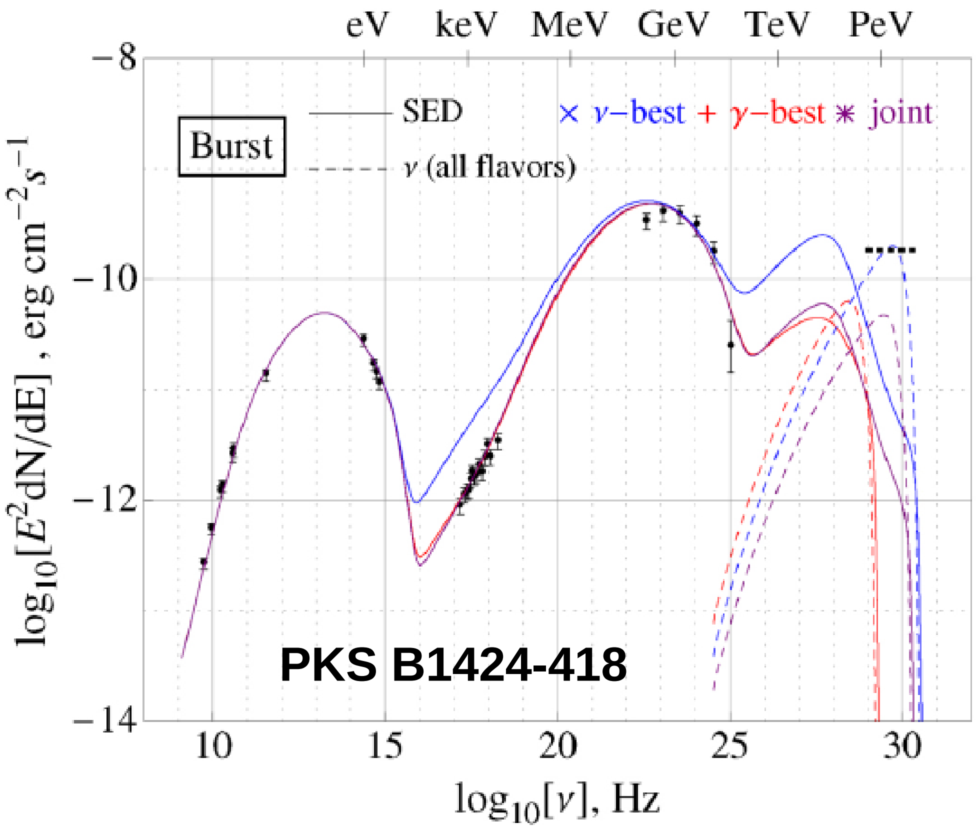




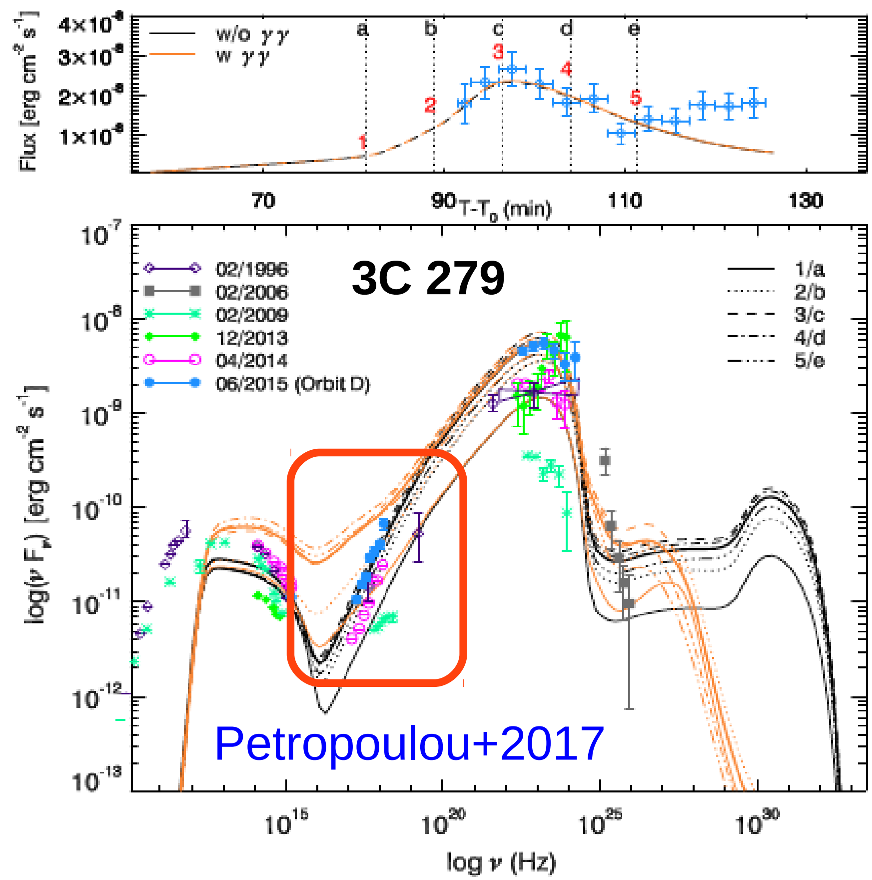
- Big Bird is a HESE event with E_ν~2 PeV
- PKS B1424-418 is an FSRQ at z=1.522
- Association of the HESE event with the flare can be explained only if: $\boxed{L_\nu \approx L_\gamma}$

SED modeling of flares is crucial

Gao+2017

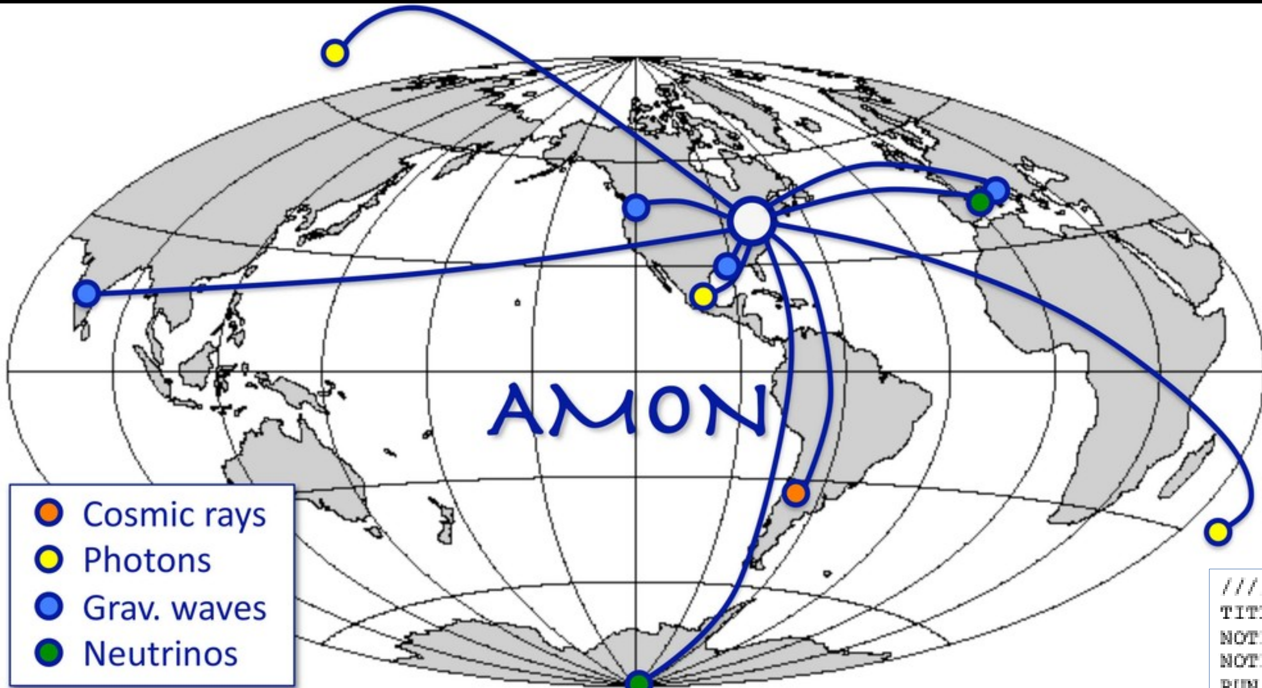


- Modeling of the PKS B1424-418 flare.
- The SED **cannot** be explained for parameters that lead to: $L_\nu \approx L_\gamma$



- Cascades initiated by the absorption of high-energy photons, redistributes their power to lower energies (e.g., X-rays).
- Cascades should not be neglected in the hadronic modeling of luminous flares.

IC170922A & TXS 0506+056



- IC170922A is a track with E_ν~300 TeV (ang.res. < 1deg)
- AMON circulated GCN ~43 s after its detection

```
//////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

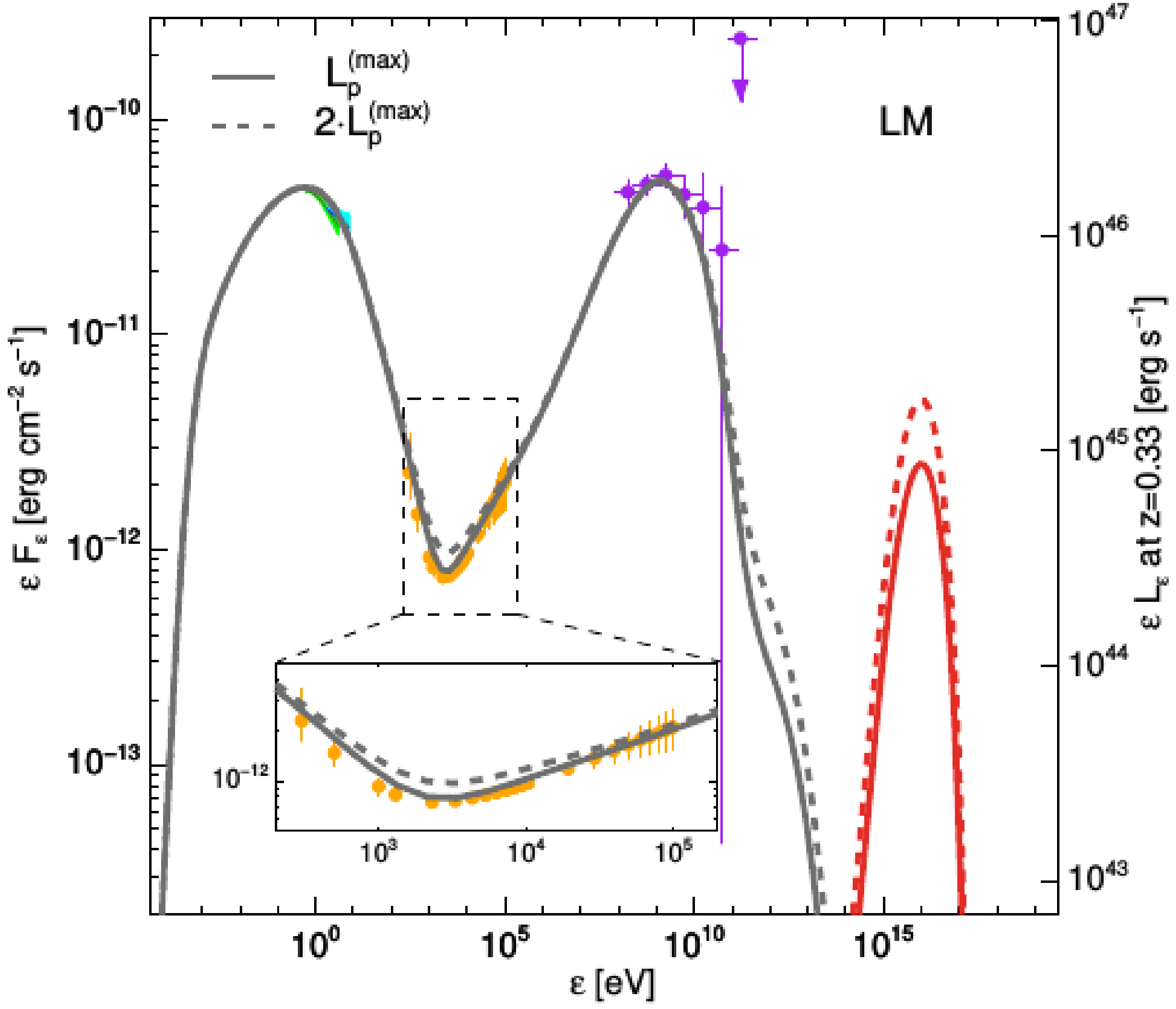
- *Swift* observations (Keivani+): GCN #21930, Atel #10942 (26/09/17)
- NuSTAR observations (Fox+): Atel #10861 (12/10/17)
- *Swift* detected initially several sources among them the blazar TXS 0506+056
- *Fermi* reported that TXS 0506+056 was in a flaring state: Atel #10781

Modeling of the TXS 0506+056 flare

Leptonic model with a sub-dominant hadronic component

Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Analysis of *Swift*/UVOT, X-SHOOTER, *Swift*/XRT, NuSTAR, Fermi-LAT data.
- UVOT + X-SHOOTER show that $\nu_{pk}<10^{14}$ Hz (ISP).
- External Compton explains γ-rays.
- SSC contribution to NuSTAR band.
- Hadronic cascade should not exceed X-ray data. → Upper limits on ν and baryon loading



Modeling of the TXS 0506+056 flare

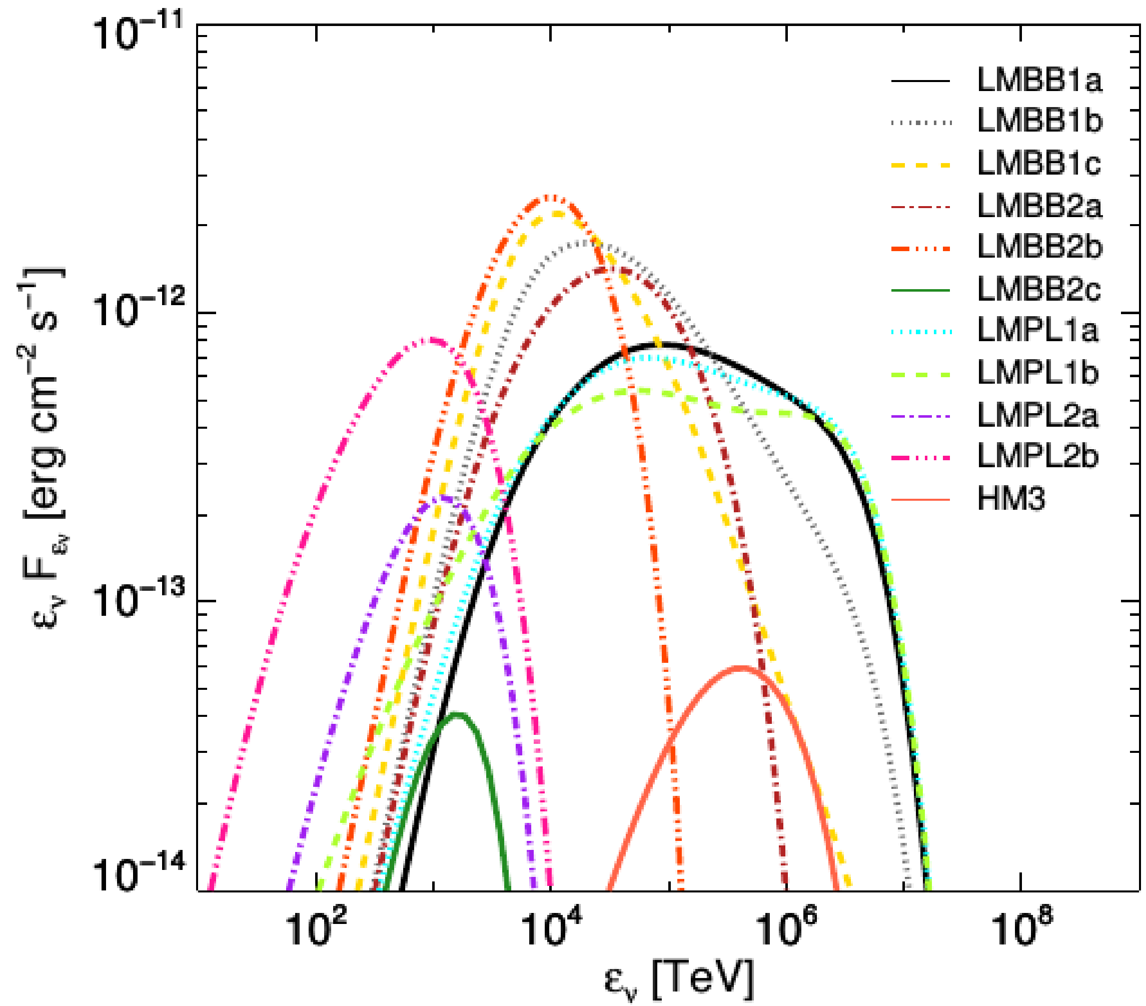
Leptonic model with a sub-dominant hadronic component

Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Upper limits on ν fluxes for many model parameters.
- ~0.01 events for a flare T=10^7 s or ~1% probability to see 1 event.

	$F_\nu^{\rm UL}$ [erg cm^{-2} s^{-1}]		$\mathcal{N}_\nu$
	100 TeV - 1 PeV	100 TeV - 10 PeV	$\leq$ 10 PeV
LMBB1a	1.6×10^{-14}	4.5×10^{-13}	1×10^{-3}
LMBB1b	5.2×10^{-14}	1.7×10^{-12}	4×10^{-3}
LMBB1c	9.1×10^{-14}	2.7×10^{-12}	6×10^{-3}
LMBB2a	4.5×10^{-14}	1.1×10^{-12}	3×10^{-3}
LMBB2b	1.8×10^{-13}	3.6×10^{-12}	8×10^{-3}
LMBB2c	2.5×10^{-14}	7.3×10^{-14}	2×10^{-4}
LMPL1a	3.1×10^{-14}	5.2×10^{-13}	1×10^{-3}
LMPL1b	9×10^{-14}	6.3×10^{-13}	1×10^{-3}
LMPL2a	2.5×10^{-13}	5.2×10^{-13}	5×10^{-3}
LMPL2b	1.2×10^{-12}	2×10^{-12}	1×10^{-2}
HM3	1.6×10^{-16}	2×10^{-15}	4×10^{-6}

Neutrino fluxes for different model variants

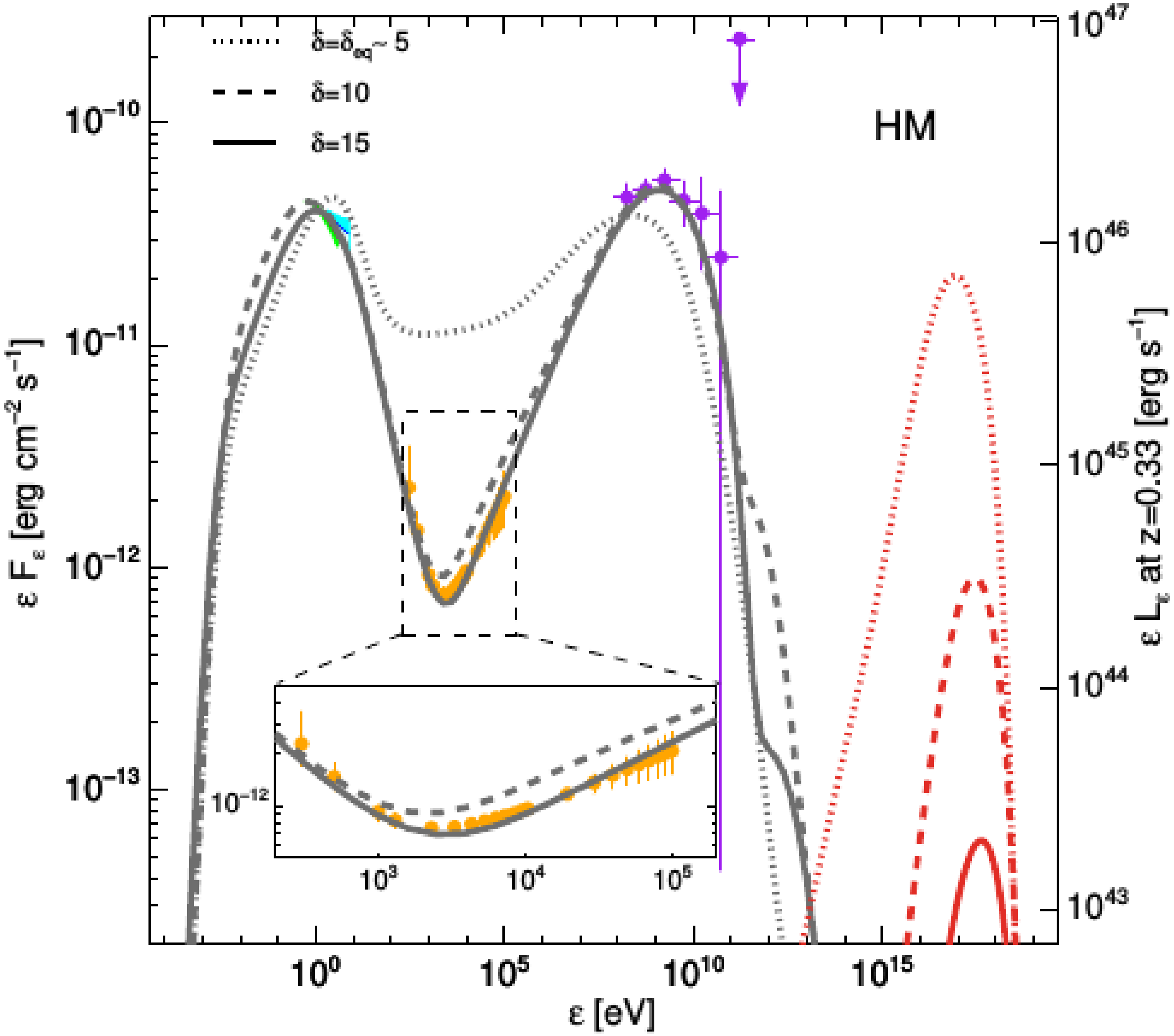


Modeling of the TXS 0506+056 flare

Leptohadronic model

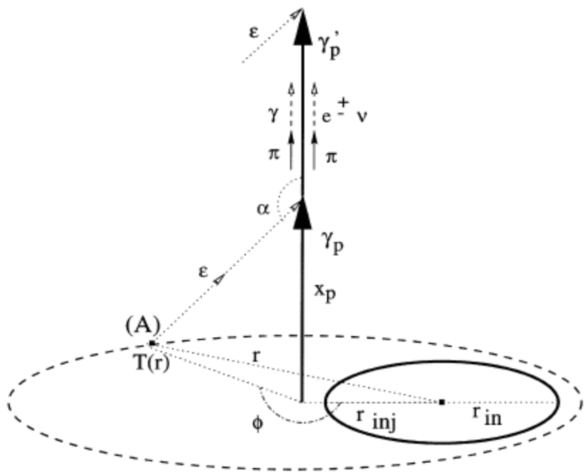
Keivani, Murase, Petropoulou, Fox+, 2018, sub.

- Model with γ-rays coming from pion-induced cascade ($L_\gamma - L_\nu$) is ruled out.
- Model with γ-rays from proton synchrotron leads to EeV neutrinos with very low luminosities.
- IC-170922A cannot be explained in this scenario.

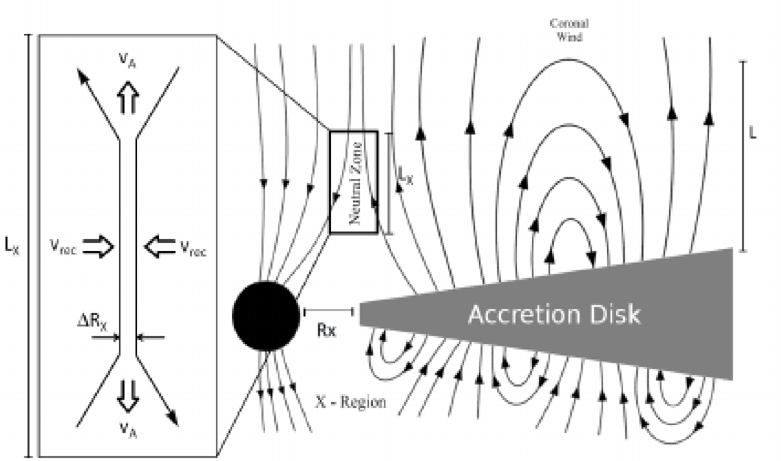


The revival of the hadronic cascade model

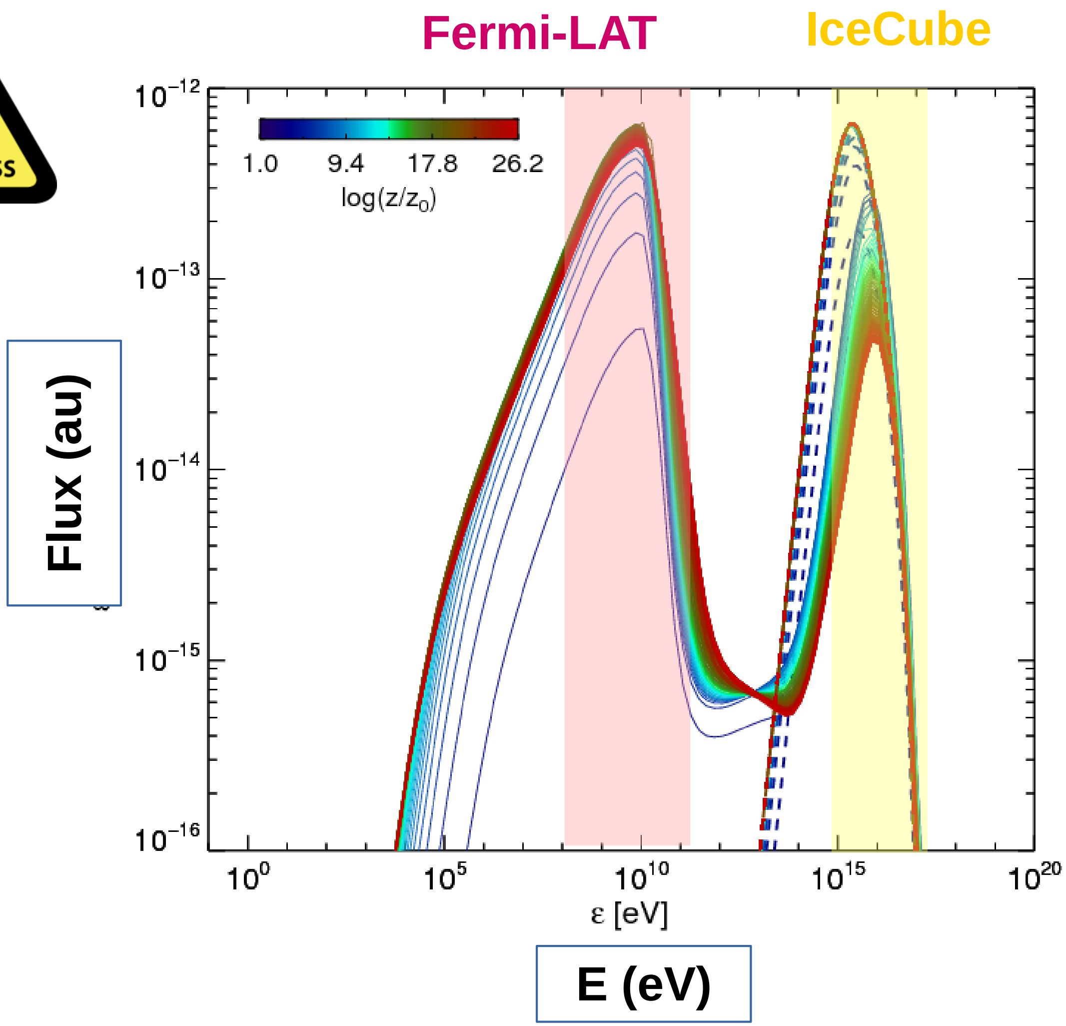
Gamma-ray & neutrino flare from hadronic cascades



(Bednarek & Protheroe 1999)



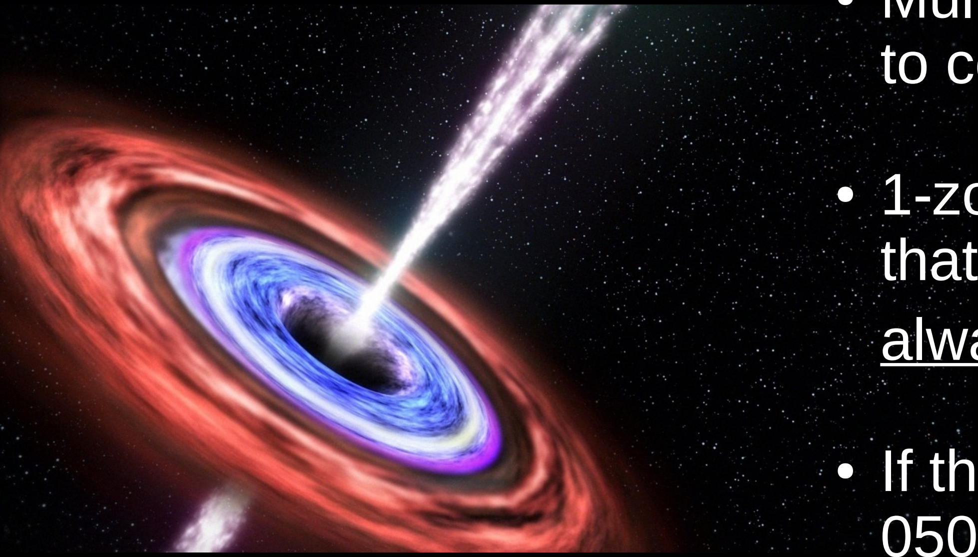
(Khiali+2015)



Mastichiadis & Petropoulou, in prep.

Summary

- It is unlikely that blazars are the dominant contributors to the IceCube neutrino flux.
- IceCube places strong constraints on many blazar models for neutrinos. Still, these are derived assuming constant neutrino fluxes.
- Neutrino emission can be enhanced during blazar flares. A flaring blazar could be detected as a neutrino point source.



- Multi-wavelength data during flares is crucial to constrain emission models.
- 1-zone SED modeling of blazar flares shows that the naive expectation $L_\nu \sim L_\gamma$ is almost always ruled out.
- If the association of IC 170922A and TXS 0506+056 is physical, then we should start thinking beyond the 1-zone models.

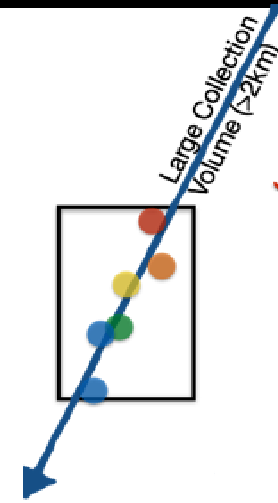
THANK YOU!

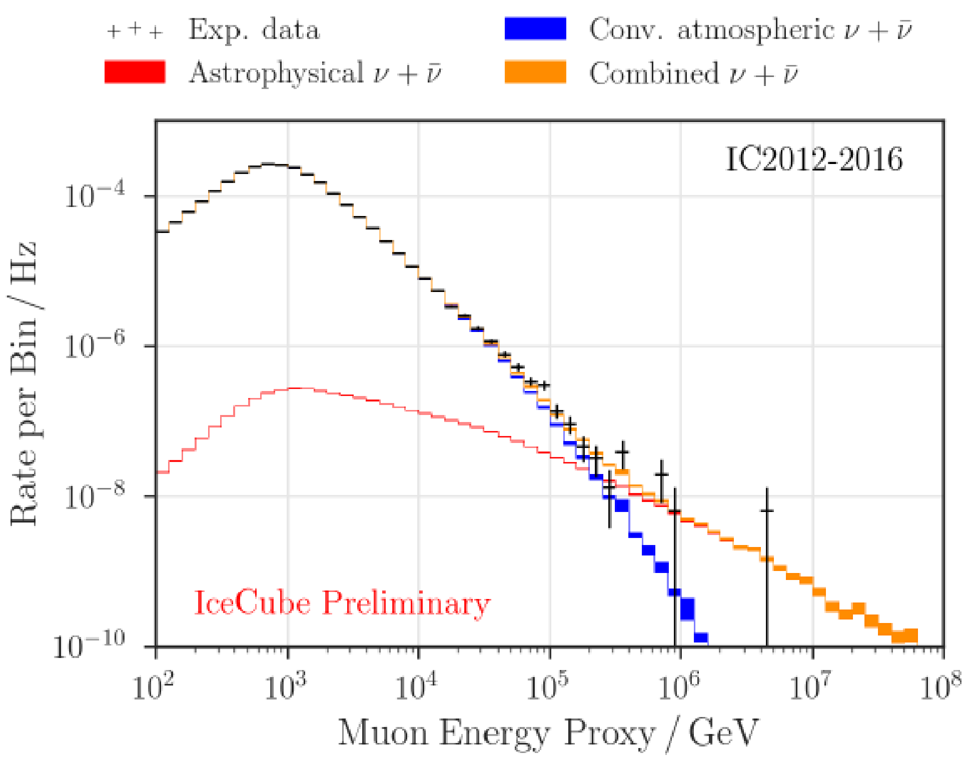
Back-up slides

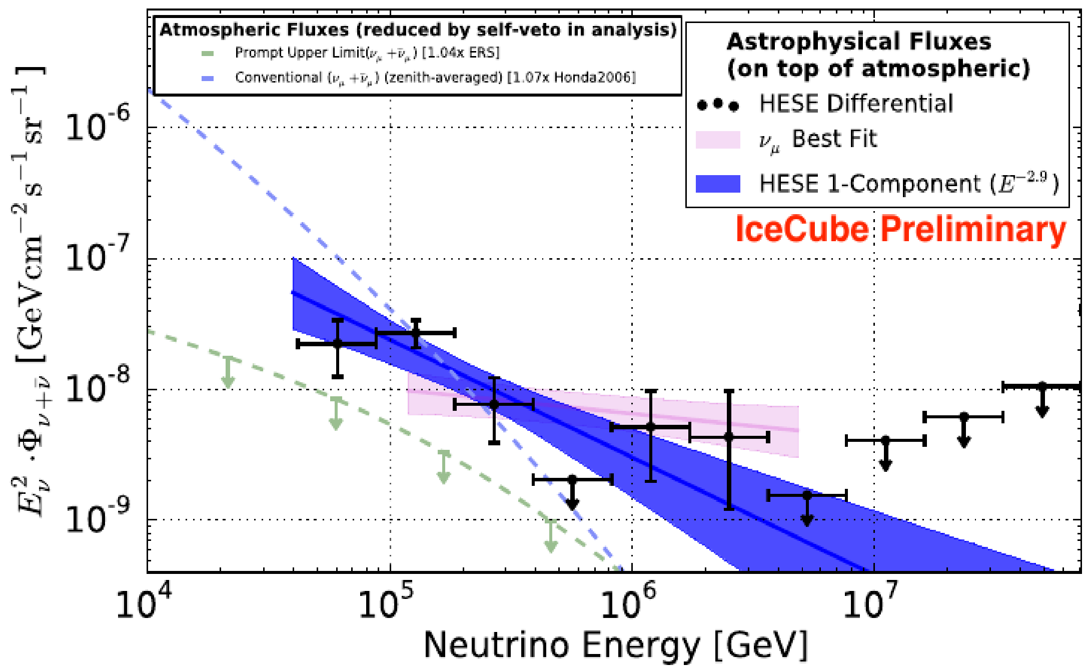
High-energy ν observations

Through-going muon sample (2009-2017):

- ~10³ astrophysical neutrinos
- Spectrum compatible with single power-law.
- No correlation of events [E_ν>200 TeV] with astrophysical sources







(ICRC 2017) arXiv:1710.01191

Blazars as probable counterparts

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

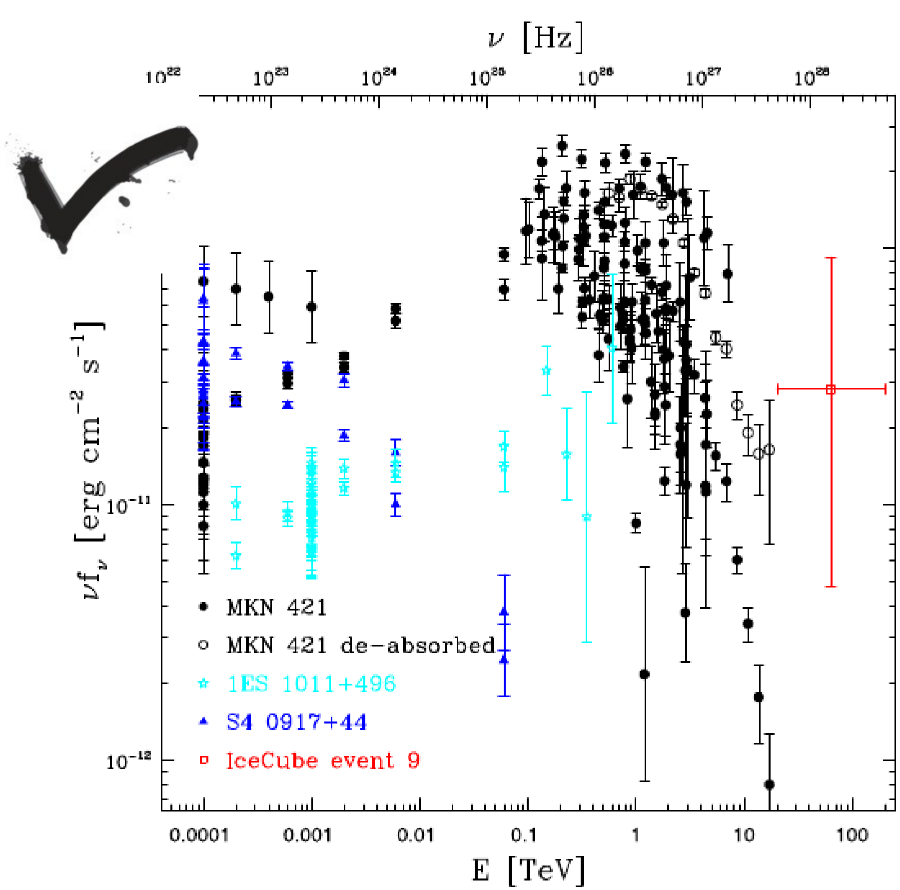
* “Energetic” criterion

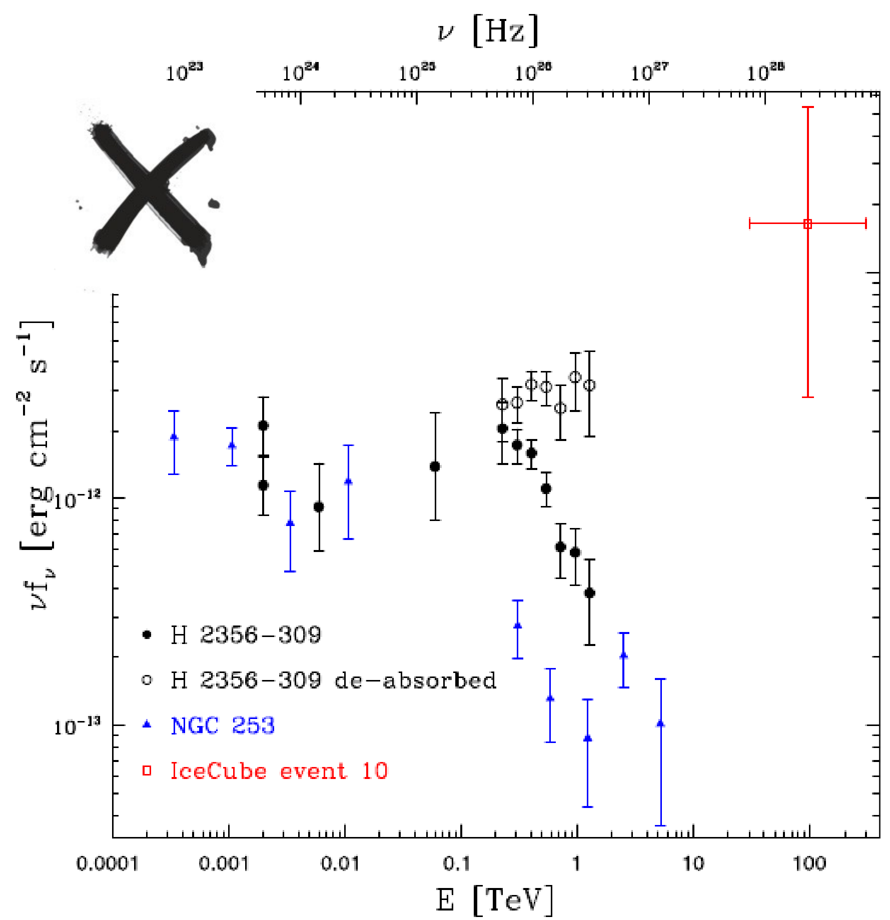
Padovani+2016

* 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

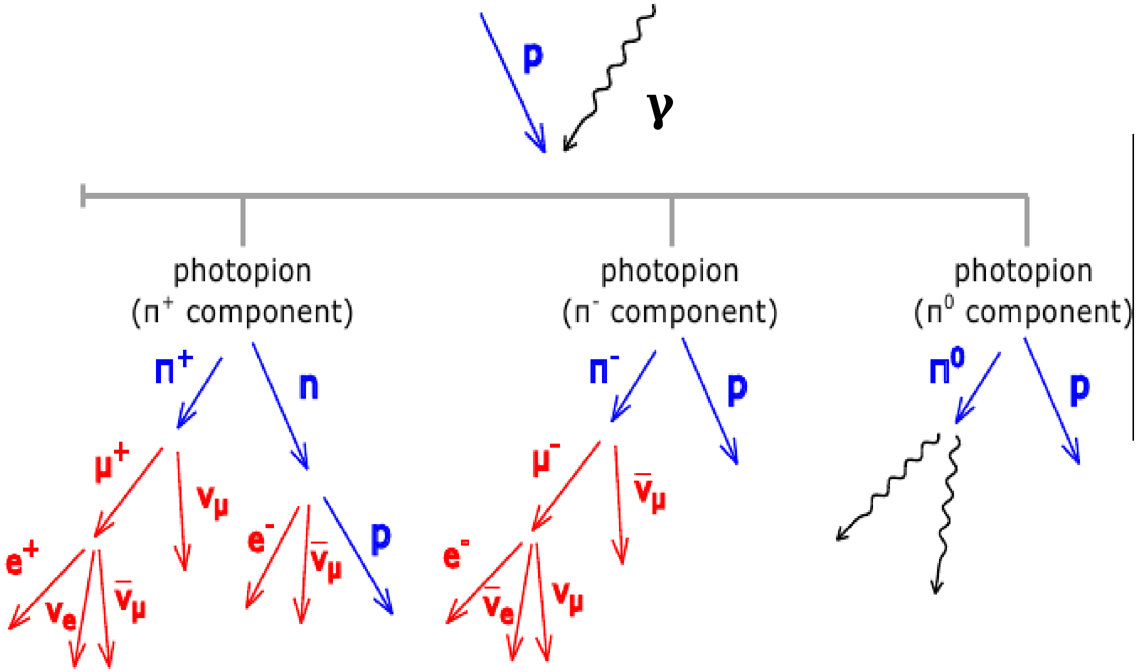
* “Energetic” criterion





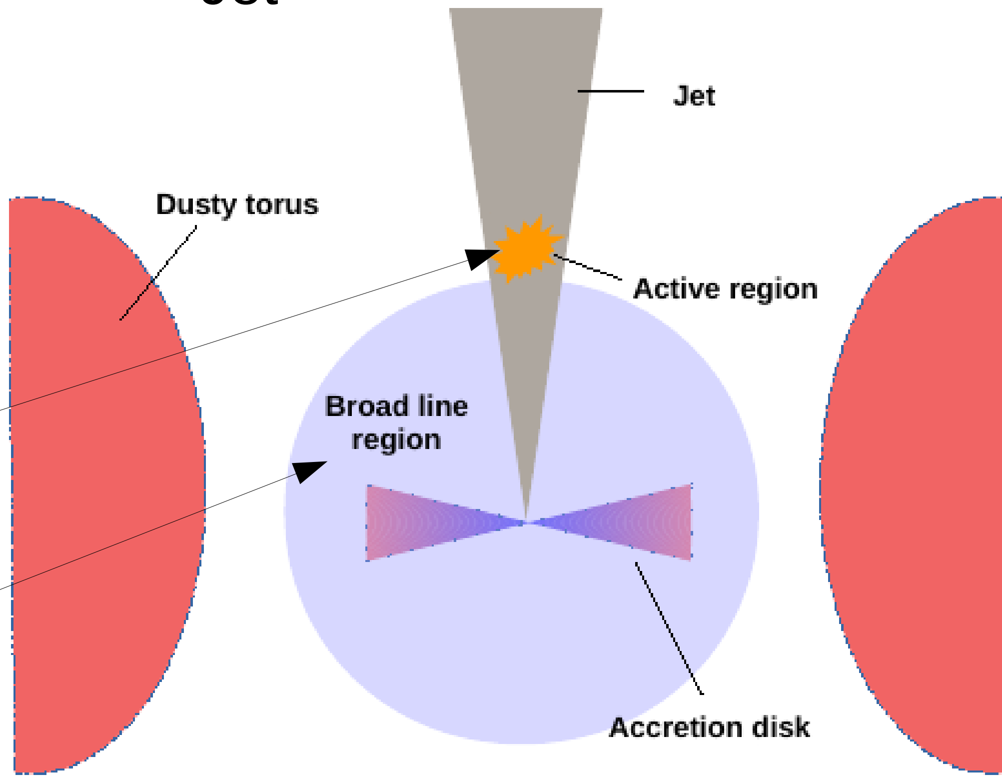
Neutrino production in blazars

Photomeson production



Target photons from:

- Accretion disk
- Broad line region (BLR)
- Dusty torus
- Jet



Typical neutrino energies

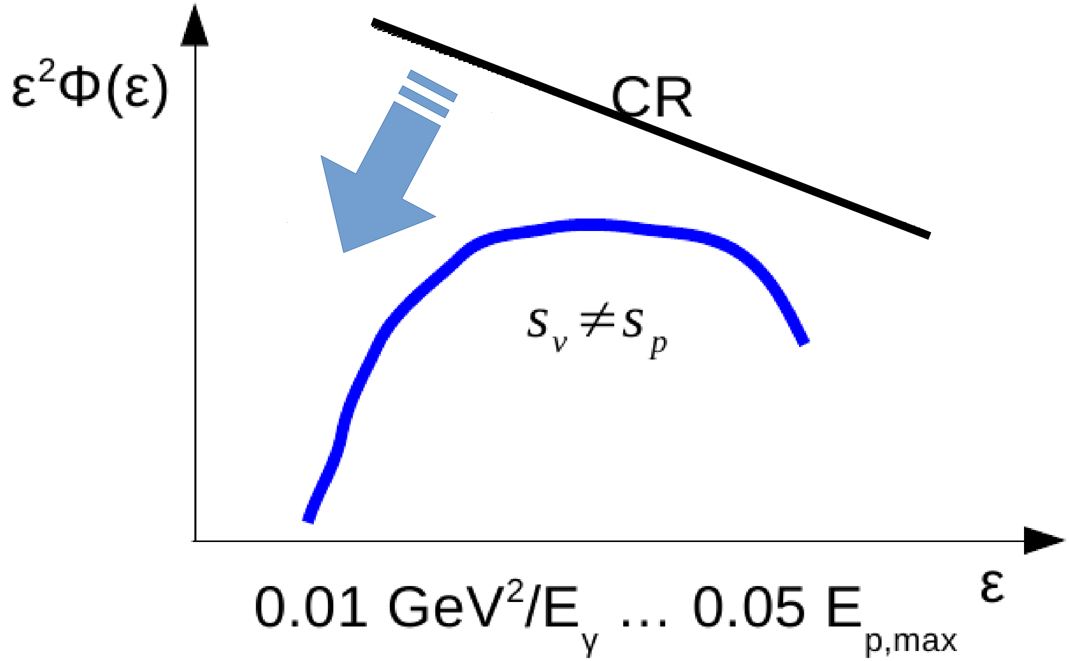
$$E_\nu \approx 0.05\, E_p \geqslant 90\, PeV\, \Gamma_1^2 \left(\varepsilon_s / 10\, eV\right)^{-1}$$

$$E_\nu \approx 0.05\, E_p \geqslant 0.9\, PeV \left(\varepsilon_{BLR} / 10\, eV\right)^{-1}$$

Neutrino production in blazars

Neutrino spectrum depends on:

- Density of target photons & size of the souce
- Spectrum of target photons



Photomeson production efficiency

Jet photons: $$f_{p\gamma} \propto \frac{L_{ph}}{\varepsilon_{ph} R \delta^3} \propto \frac{L_{ph}}{\varepsilon_{ph} t_v \delta^4}$$

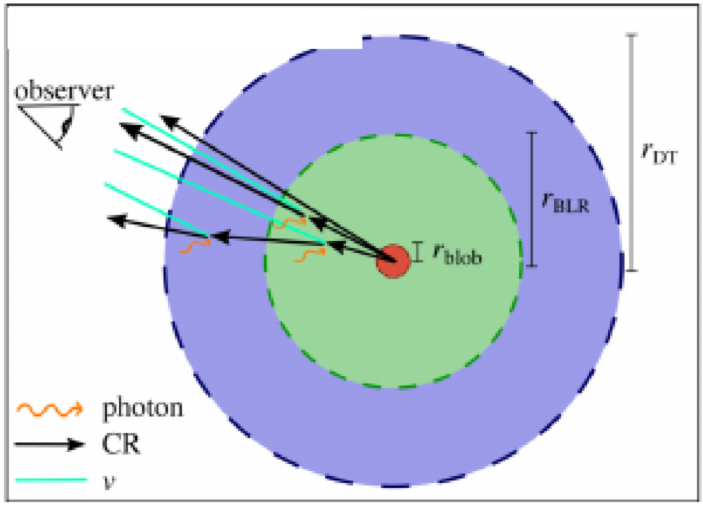
- Strong dependence on the beaming.

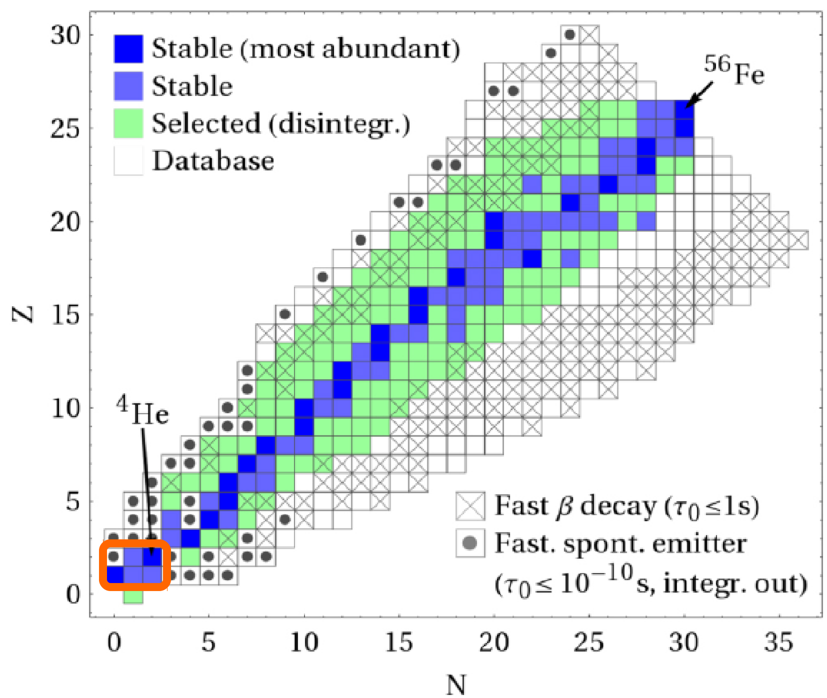
BLR photons: $$f_{p\gamma} \propto \frac{L_{BLR}}{\varepsilon_{BLR} R_{BLR}}$$

- No dependence on the beaming.

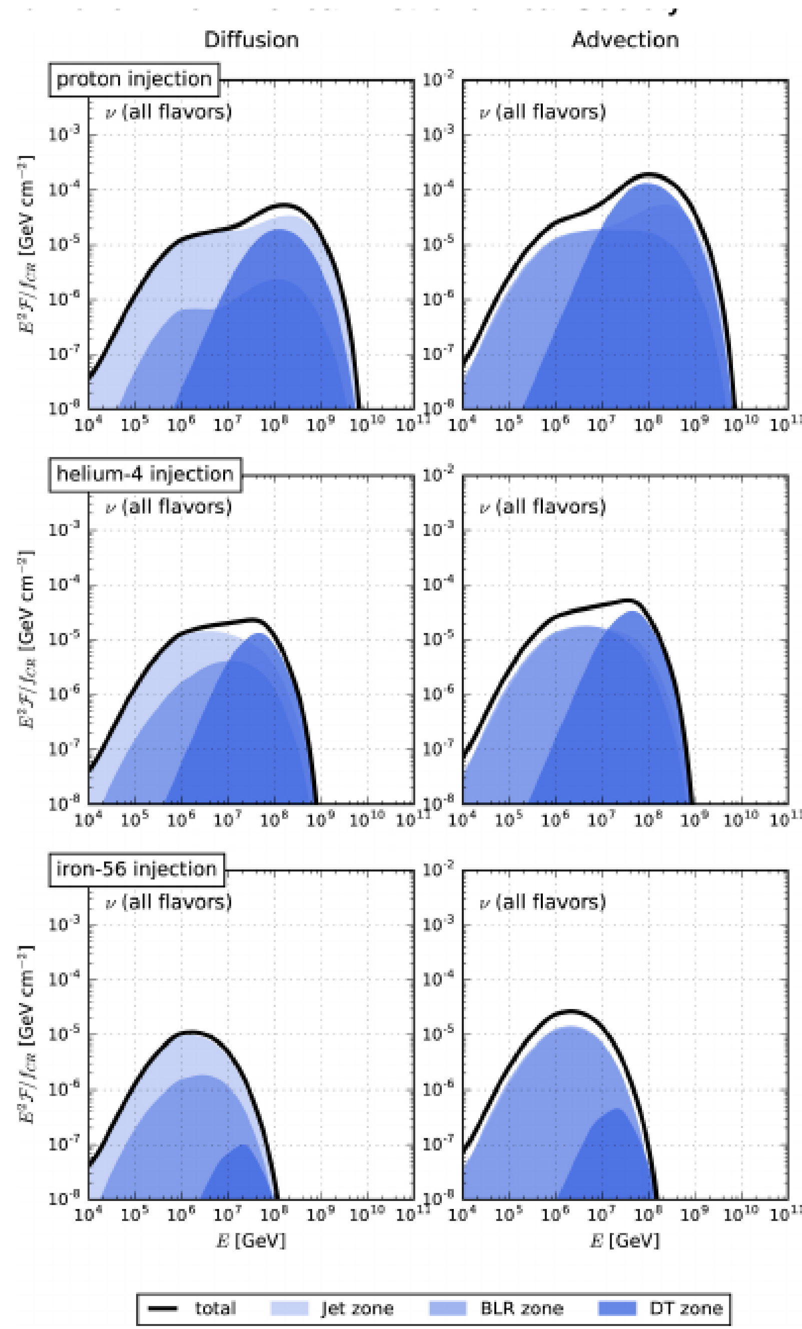
Nuclei in blazar jets

Rodriguez+2018

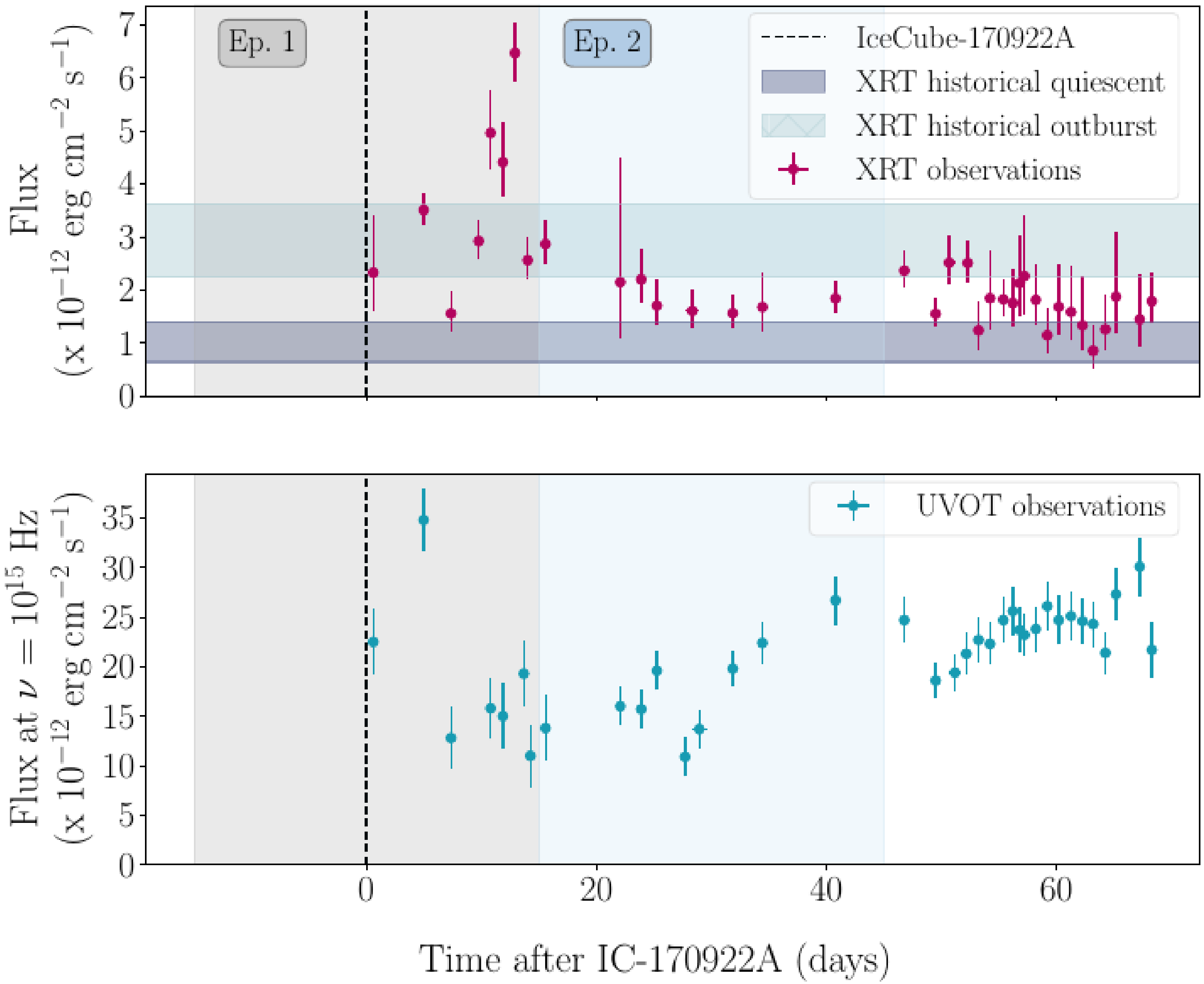




Neutrino fluence for a pre-assumed FSRQ SED



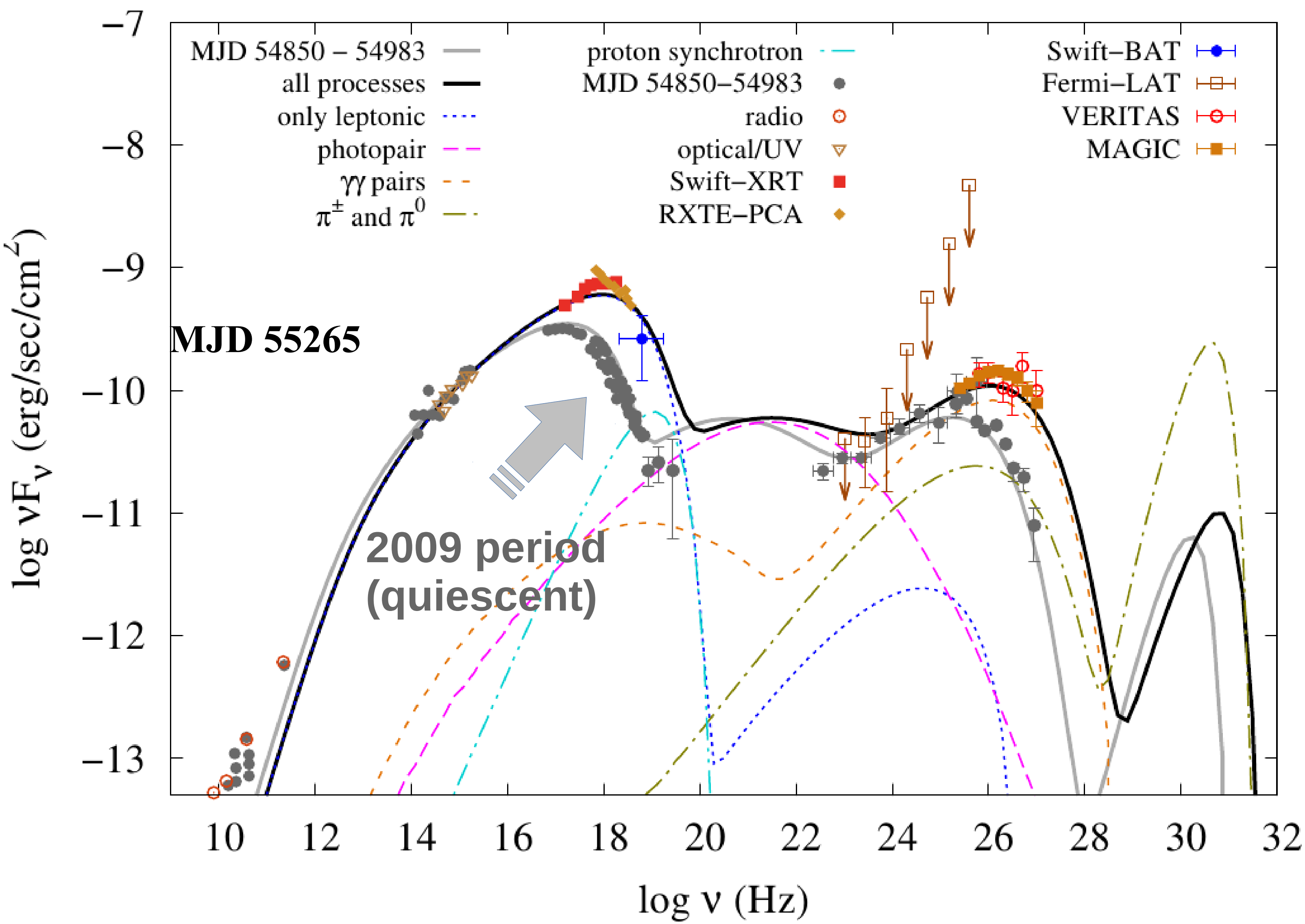
X-ray/UVOT light curves of TXS 0506+056



Keivani, Murase, Petropoulou, Fox+, 2018, sub.

The 13-day flare of 2010

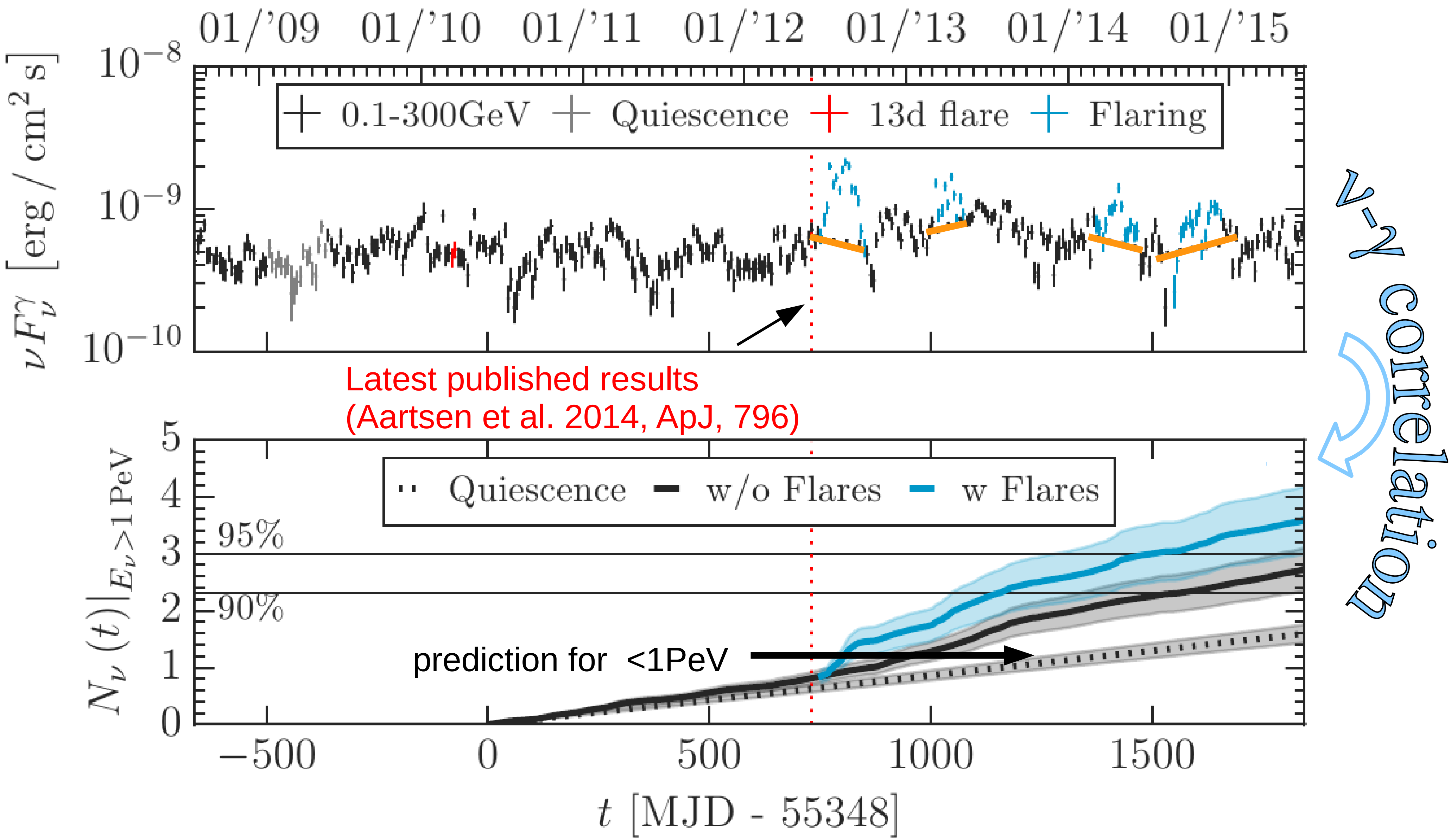
Unprecedented MW coverage & simultaneous observations for MJD 55265-55277
(data are adopted from *Aleksic et al. 2015*)



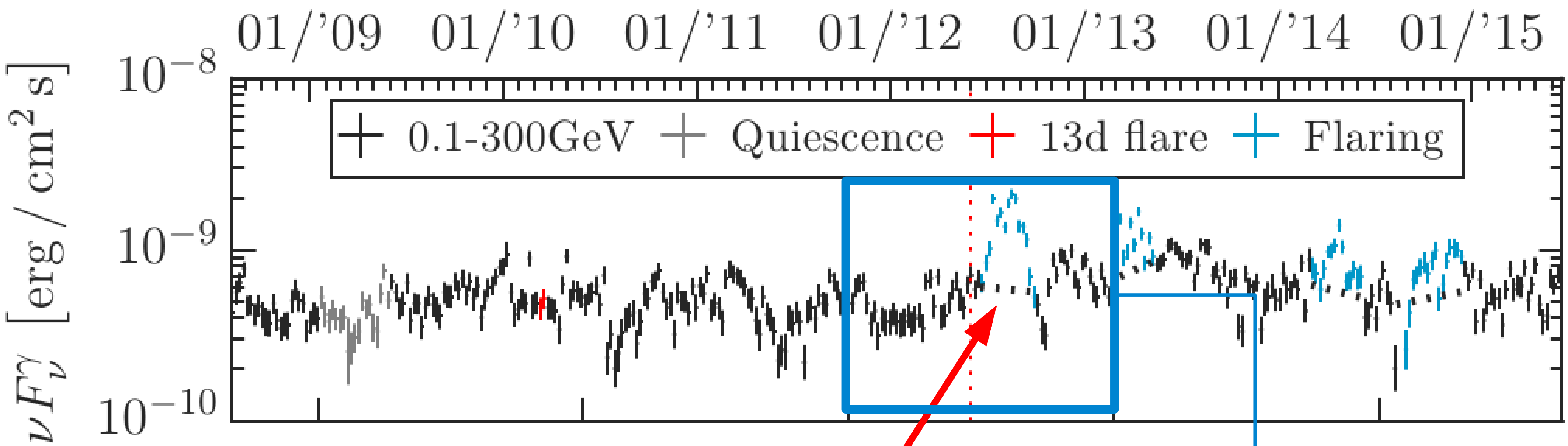
Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115

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)	$\nu_\mu + \bar{\nu}_\mu$	$P_{N_\nu \geq 1}(\%)^{\dagger}$
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 IC Season 3

* Still <50%