Neutrino Production in Blazar Jets

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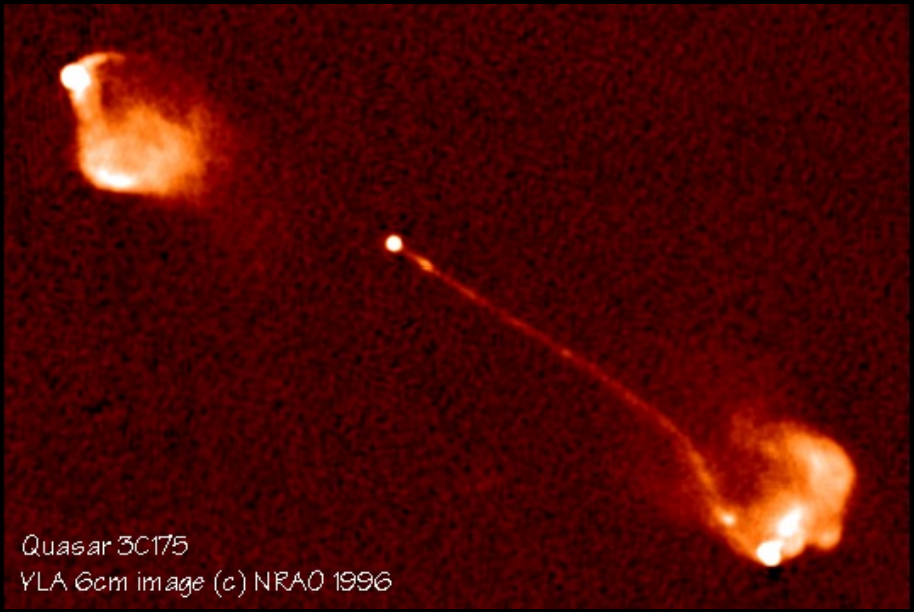
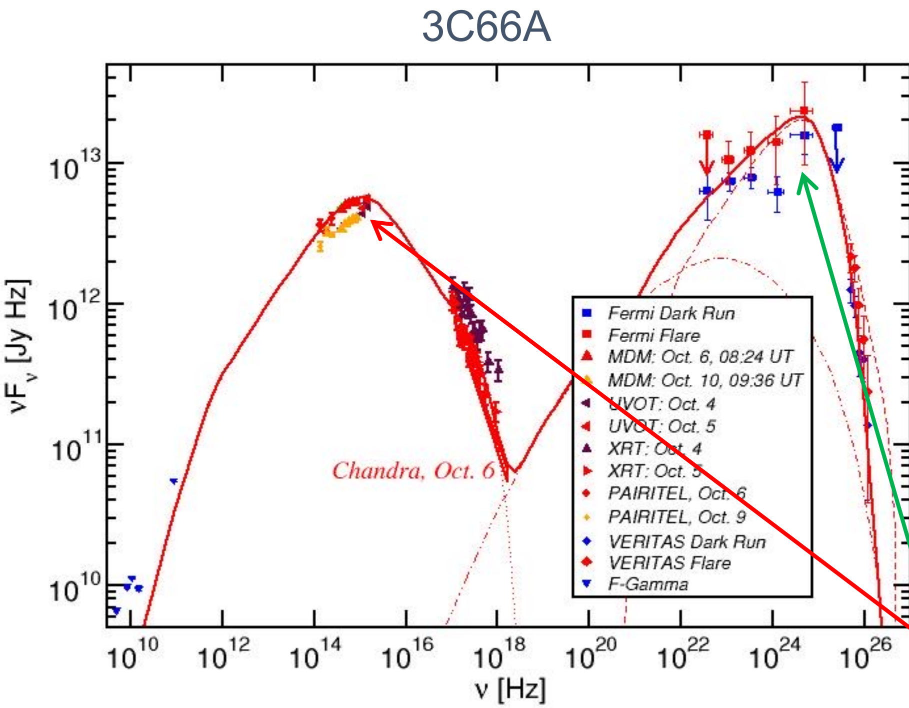
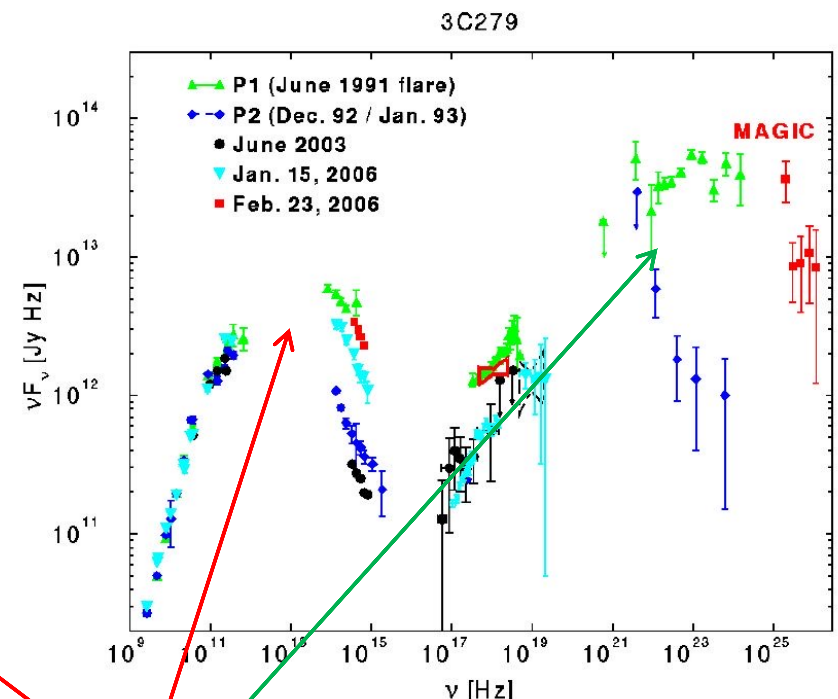
Blazars



- Class of AGN consisting of BL Lac objects and gamma-ray bright Flat Spectrum Radio Quasars (FSRQs)
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Often one-sided radio jets, superluminal motion
- Radio and optical polarization

Blazar Spectral Energy Distributions (SEDs)





Non-thermal spectra with two broad bumps:

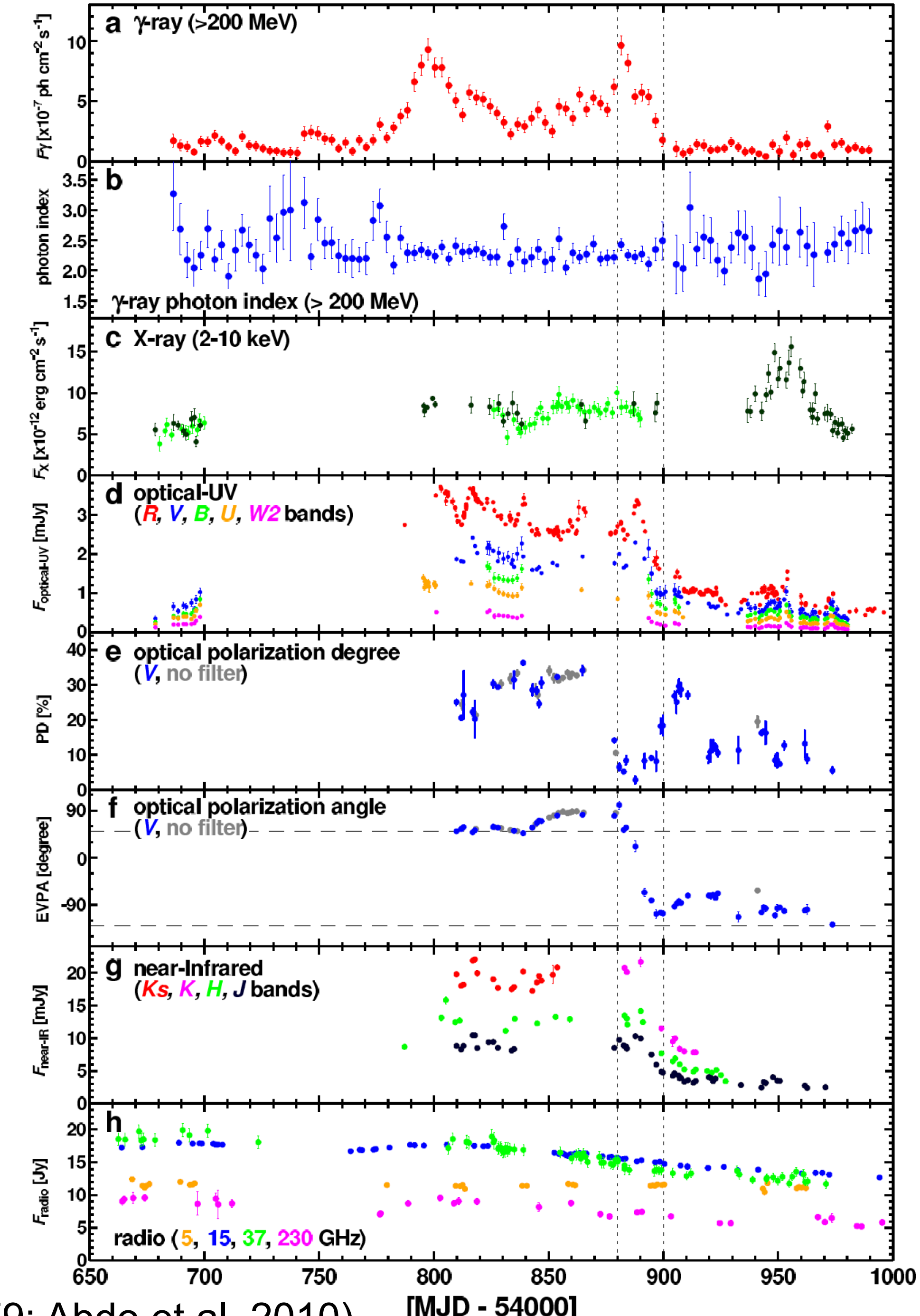
- Low-energy (electron synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

Blazar Variability

Multi-wavelength variability on various time scales (months – minutes)
Sometimes correlated, sometimes not

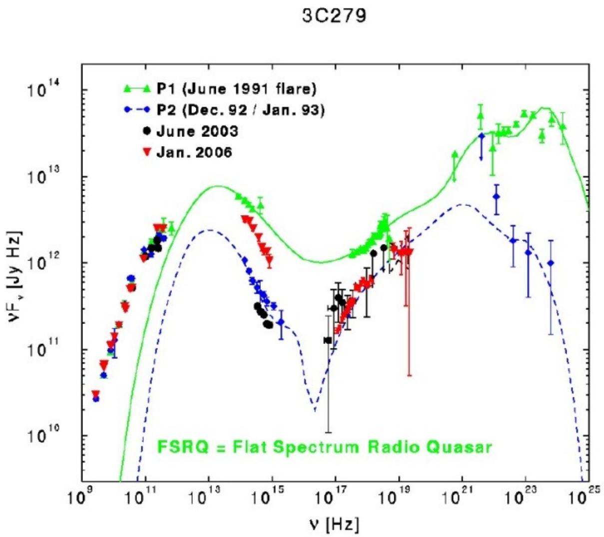
Observed optical polarization degrees
Π_{opt} <~ 30 %

Both degree of polarization and polarization angles vary.
Swings in polarization angle sometimes associated with high-energy flares!

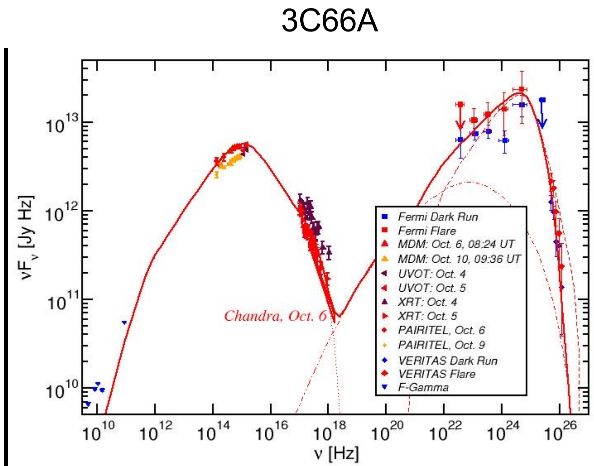


(3C279: Abdo et al. 2010)

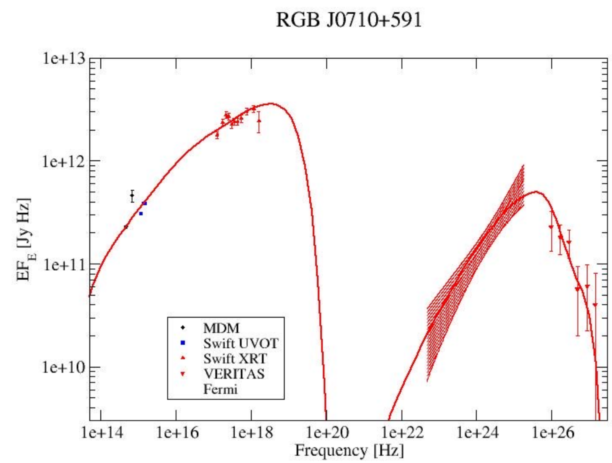
Blazar Classification



(Hartman et al. 2000)



(Abdo et al. 2011)



(Acciari et al. 2009)

Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/ Low-frequency peaked BL Lac Objects (LBLs)

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power

Intermediate-Synchrotron Peaked (ISP): Intermediate BL Lacs (IBLs):

Peak frequencies at IR/Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated

High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):

Low-frequency component from radio to UV/X-rays,

$\nu_{sy} > 10^{15}$ Hz

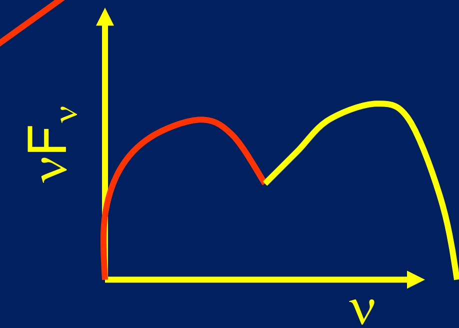
often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

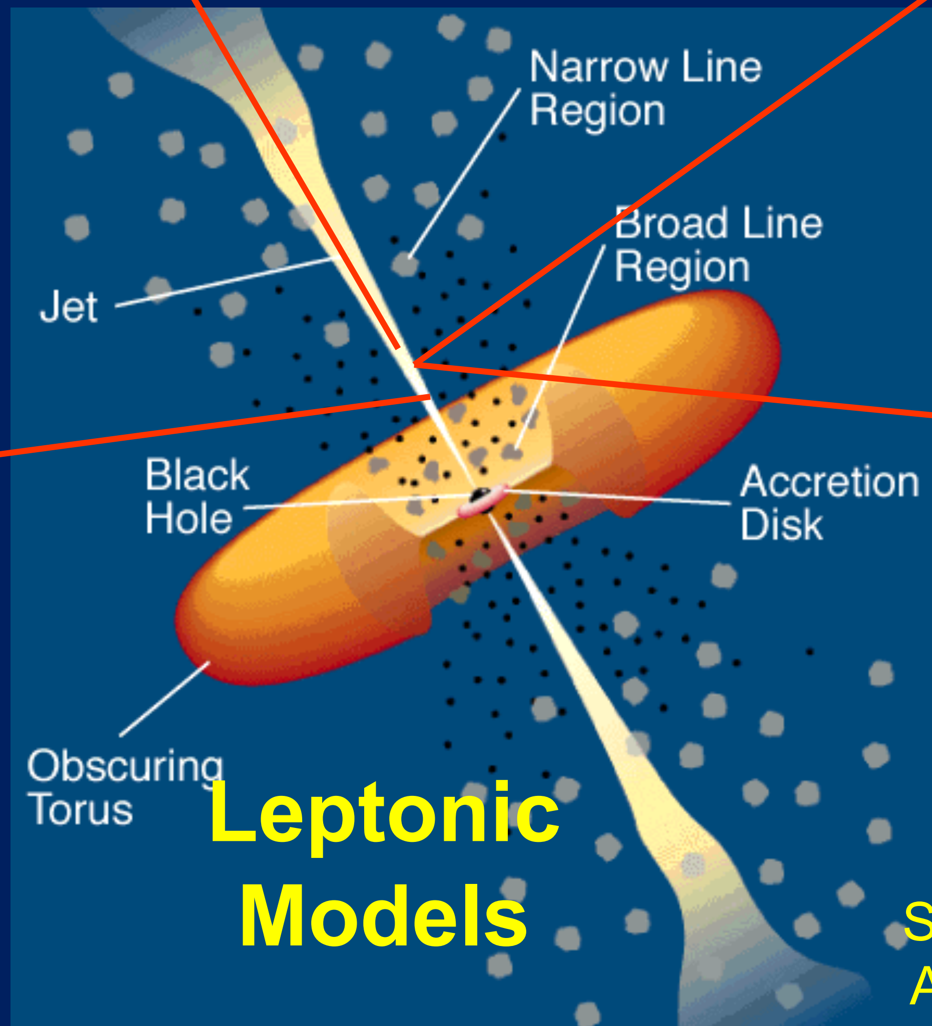
Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$

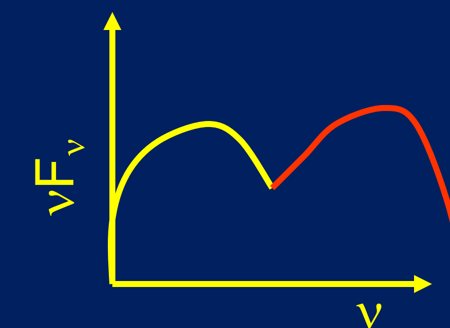
Synchrotron emission

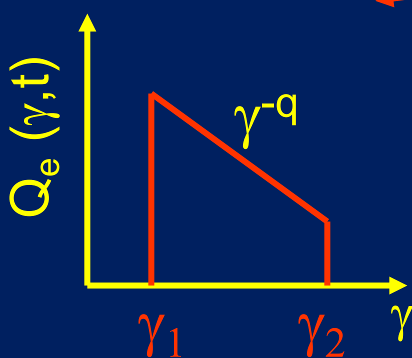


Injection, acceleration of ultrarelativistic electrons



Compton emission





Leptonic Models

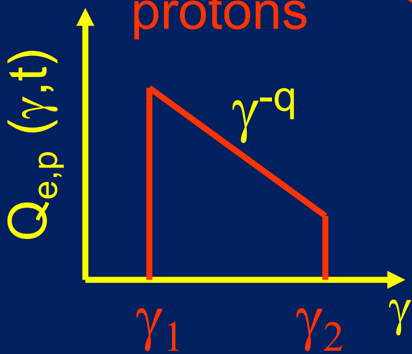
Seed photons:

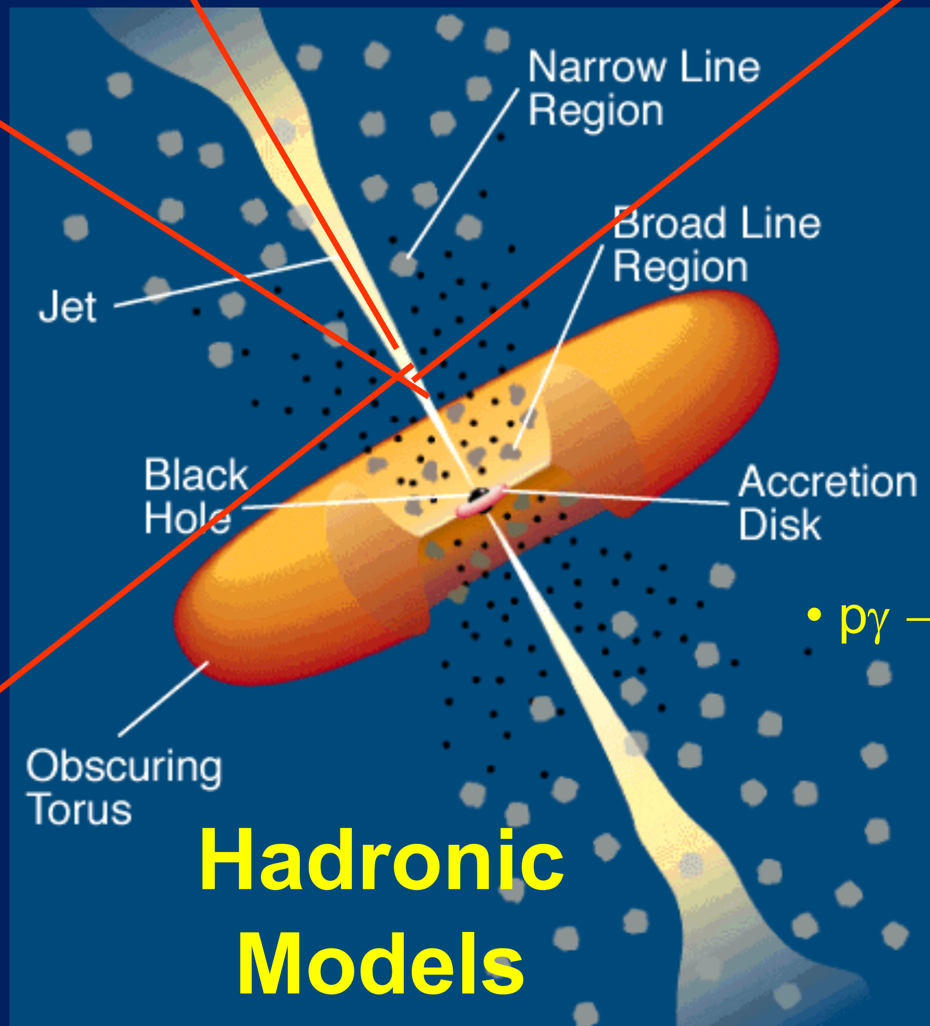
Synchrotron (SSC), Accr. Disk + BLR + dusty torus + …

Blazar Models

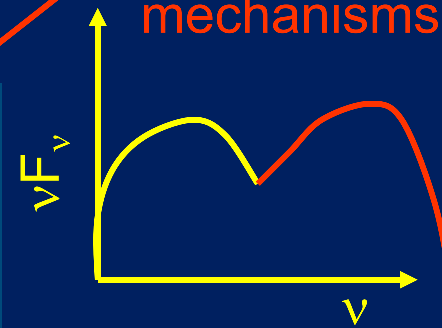
Relativistic jet outflow with $\Gamma \approx 10$

Injection, acceleration of ultrarelativistic electrons and protons



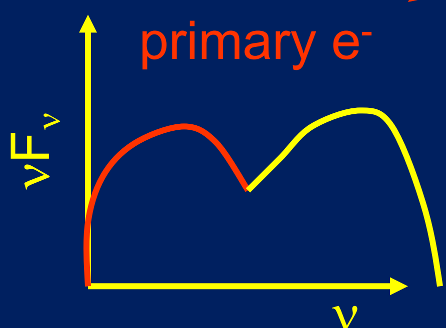


Proton-induced radiation mechanisms:



- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Synchrotron emission of primary e^-



Basics of Neutrino Production in Blazar Jets

- $p + \gamma \rightarrow p + \pi^0$

  or $n + \pi^+$

($\sigma_{p\gamma} \sim 0.6$ mb)

$\pi^0 \rightarrow 2\gamma$

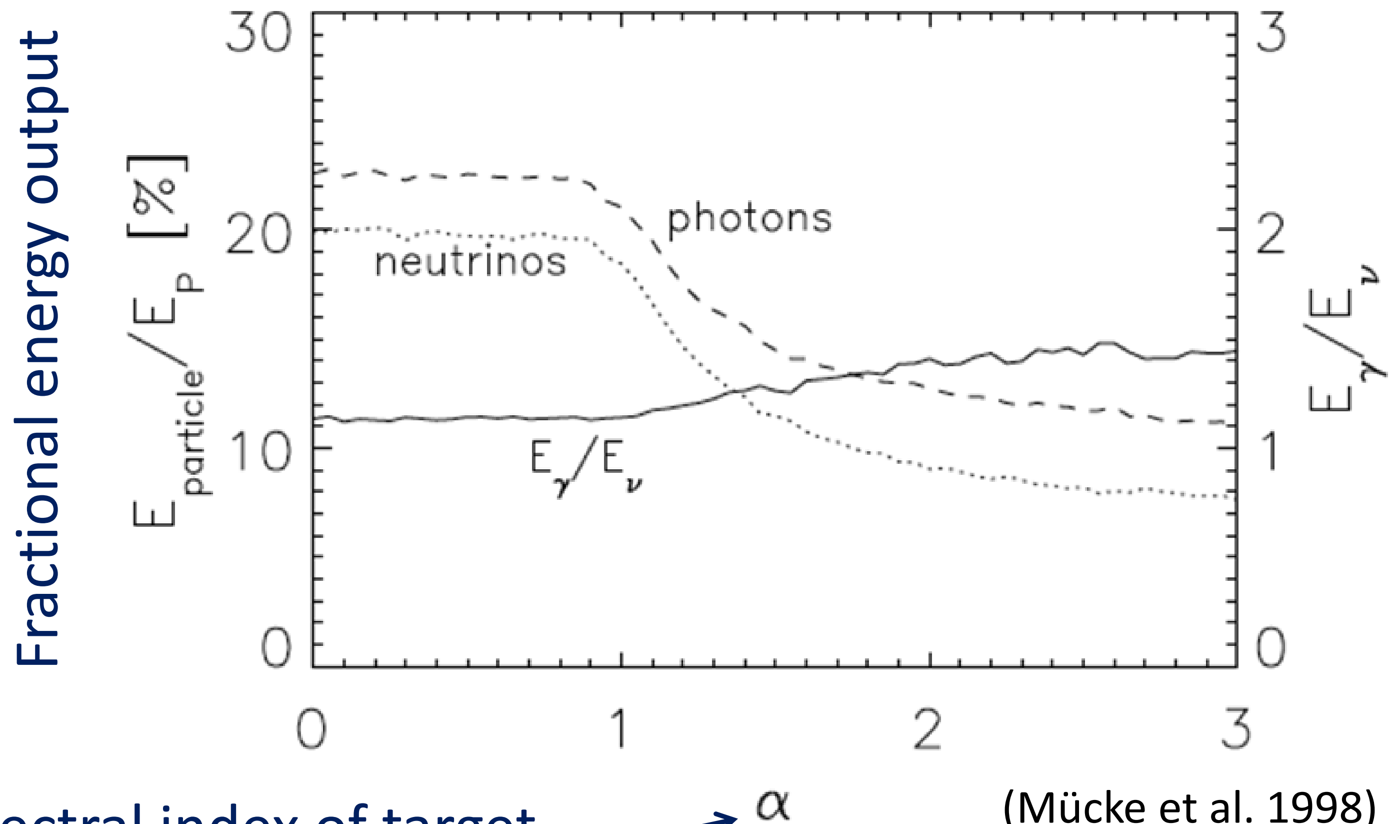
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\tau = 2.55 \times 10^{-8}$ s

$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$

$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$ $\tau = 2.2 \times 10^{-6}$ s

$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu_e}$

Photo-Pion Production

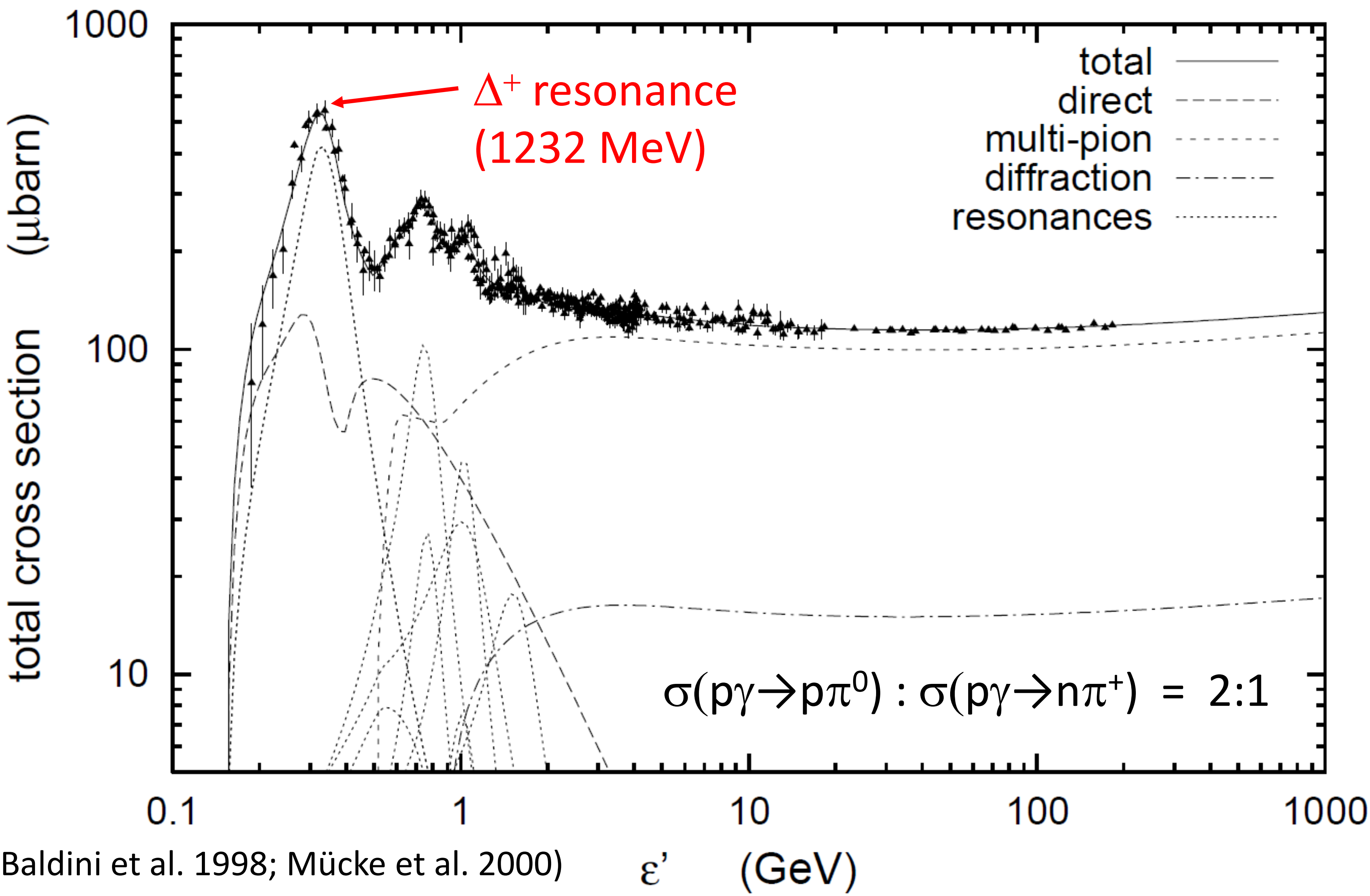


Spectral index of target photon field

(Mücke et al. 1998)

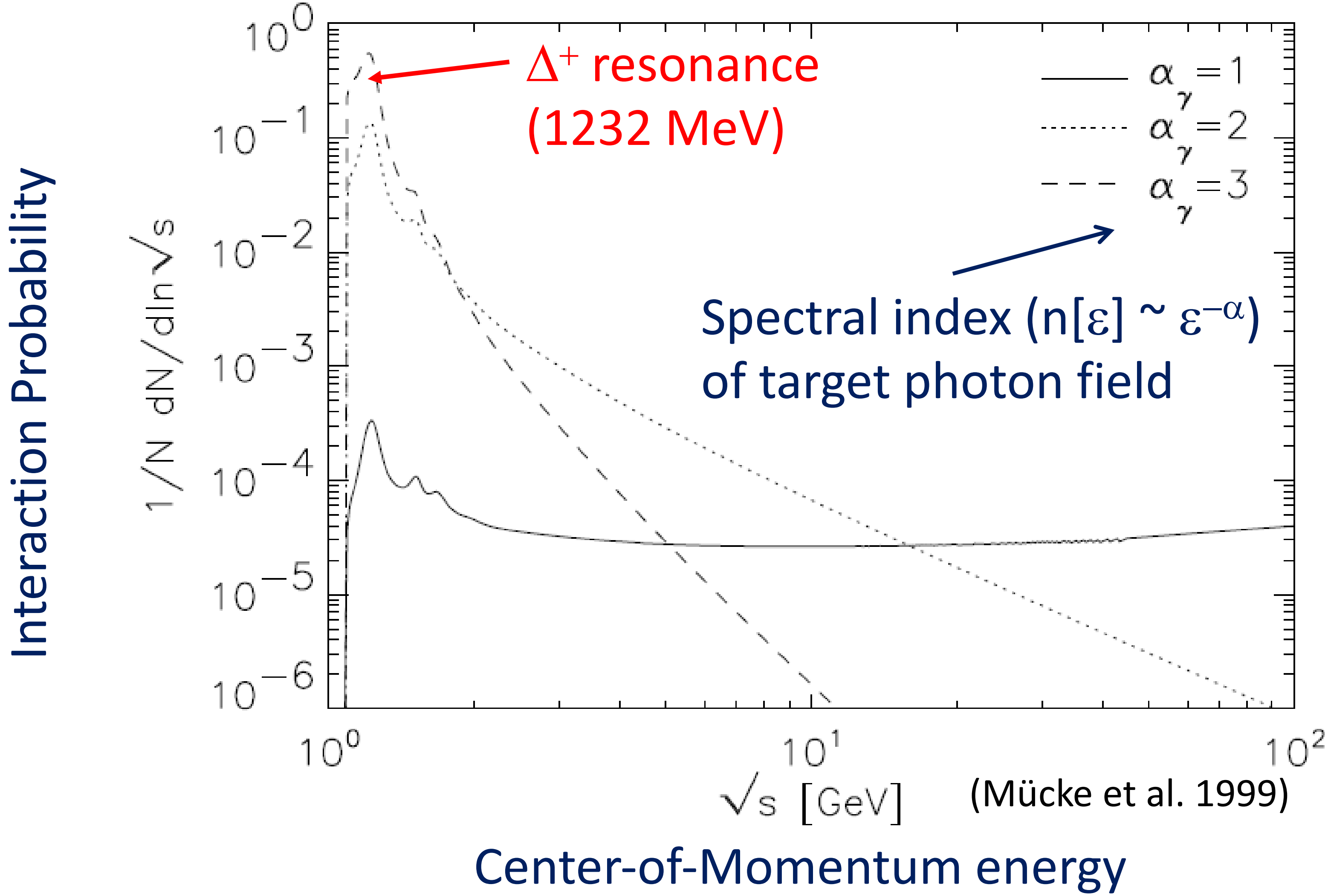
Total energy output in neutrinos is ~ approx. equal to energy output in photons (from π^0 decay + radiative losses of secondary electrons + $\mu^\pm$ + $\pi^\pm$).

Photo-Pion Production



(Baldini et al. 1998; Mücke et al. 2000)

Photo-Pion Production



For realistic target photon fields, most interactions occur near threshold (at Δ^{+} resonance).

Photo-pion production - Energetics

p-γ threshold: $$E_p^{\rm thr} = \frac{m_p\, m_\pi\, c^4}{2\, E_{\rm ph}} \left(1 + \frac{m_\pi}{2\, m_p}\right) \sim 10^{17}\ \mathrm{eV}\ E_{t,eV}^{-1}$$

At Δ^+ resonance:

$$s = E_p'\, E_t'\, (1 - \beta_p'\, \mu) = E_{\Delta^+}^2 = (1232\ \mathrm{MeV})^2$$

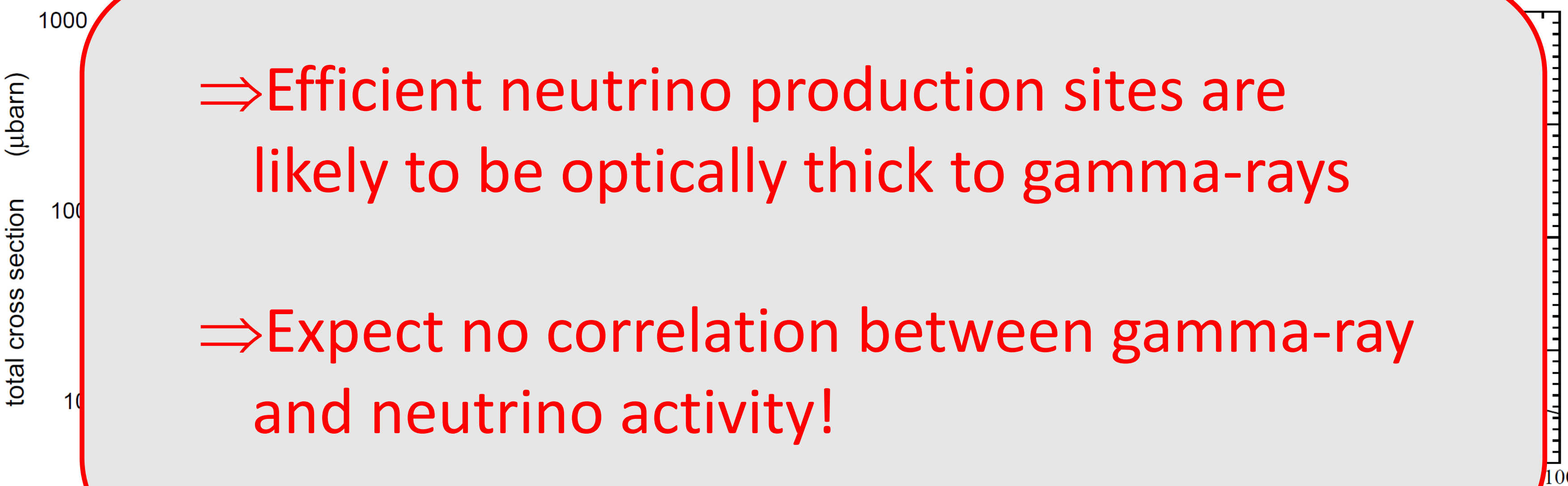
Each neutrino takes about ~ 5 % of the proton's energy

$\Rightarrow$ To produce IceCube neutrinos (~ 100 TeV $\rightarrow$ $E_\nu = 10^{14}\, E_{14}$ eV):

Need protons with	$E'_p \sim 200\, E_{14}\, \delta_1^{-1}$ TeV
and target photons with	$E'_t \sim 1.6\, E_{14}^{-1}\, \delta_1$ keV

The pγ Efficiency Problem

- Efficiency for protons to undergo pγ interaction ~ $\tau_{p\gamma} = \ell_{esc}\, \sigma_{p\gamma}\, n_{ph}$
- Likelihood of γ-ray photons to be absorbed ~ $\tau_{\gamma\gamma} = R\, \sigma_{\gamma\gamma}\, n_{ph}$



⇒Efficient neutrino production sites are likely to be optically thick to gamma-rays

⇒Expect no correlation between gamma-ray and neutrino activity!

$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\, \ell_{esc}}{\sigma_{\gamma\gamma}\, R} \approx \frac{1}{300} \frac{\ell_{esc}}{R}$$

ℓ_{esc} = average length travelled by protons until escape

at $E_\gamma \sim \frac{m_e^2 c^4}{E_t} \sim 3.3 \times 10^{-5} E_\nu$ ← ~ GeV – TeV γ-rays

Photo-pion production – Origin of Target Photons

To produce IceCube neutrinos (~ 100 TeV $\rightarrow E_\nu = 10^{14} E_{14}$ eV):

Need protons with $E'_p \sim 200\, E_{14}\, \delta_1^{-1}$ TeV

and target photons with $E'_t \sim 1.6\, E_{14}^{-1}\, \delta_1$ keV => X-rays!

(At least) two possible scenarios:

a) Target photons co-moving with the emission region

$\Rightarrow E_t^{obs} \sim 16\, E_{14}^{-1}\, \delta_1^2/(1+z)$ keV

$\Rightarrow$ Observed as Doppler-boosted hard X-rays

Tightly constrained by observed hard X-ray flux -> Energetics constraints.

b) Target photons stationary in the AGN frame

$\Rightarrow E_t^{obs} \sim 160\, E_{14}^{-1}/(1+z)$ eV

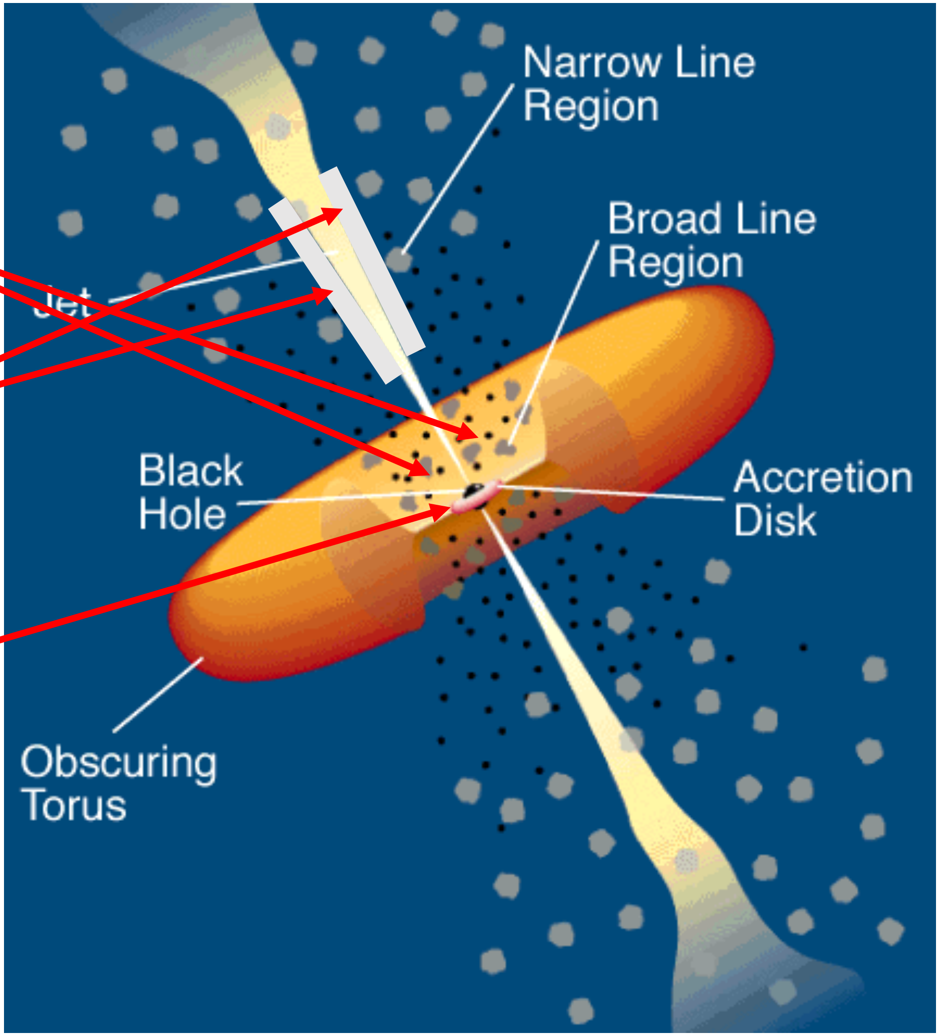
$\Rightarrow$ Observed as UV / soft X-rays, Doppler boosted into the emission-region frame

Much more relaxed energetics constraints.

Photo-pion production – Origin of Target Photons

Possible sources of external UV / soft X-ray target photons:

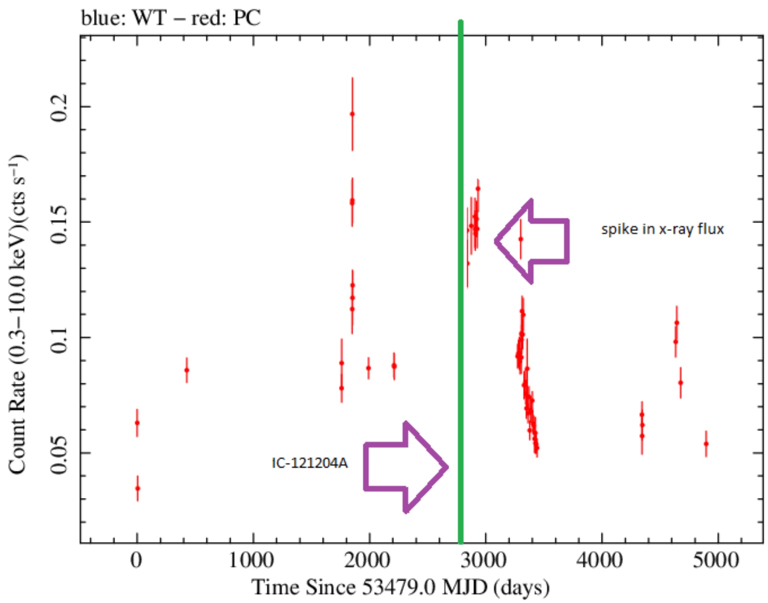
- Broad Line Region?
  (Padovani et al. 2019)
- Slow-moving sheath
  (Tavecchio & Ghisellini 2005)
- Accretion flow (RIAF)
  (Righi et al. 2019)

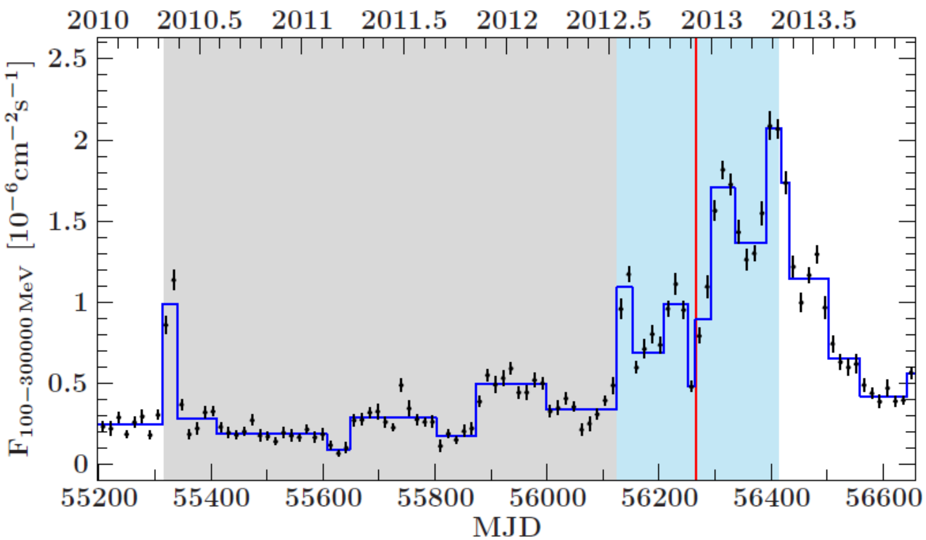


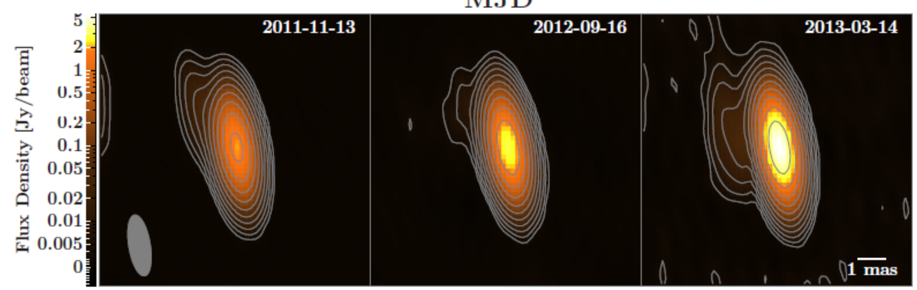
Tentative Associations of IceCube Neutrinos with Blazars

- IC-35 ("Big Bird", 2012) – PKS 1424-418 (Kadler et al. 2016)

- 2 PeV neutrino (HESE) on 4 Dec. 2012
- Poorly reconstructed arrival direction
- FSRQ at z = 1.522
- Year-long γ-ray, X-ray, optical, and radio outburst, dominated by core-flux increase.

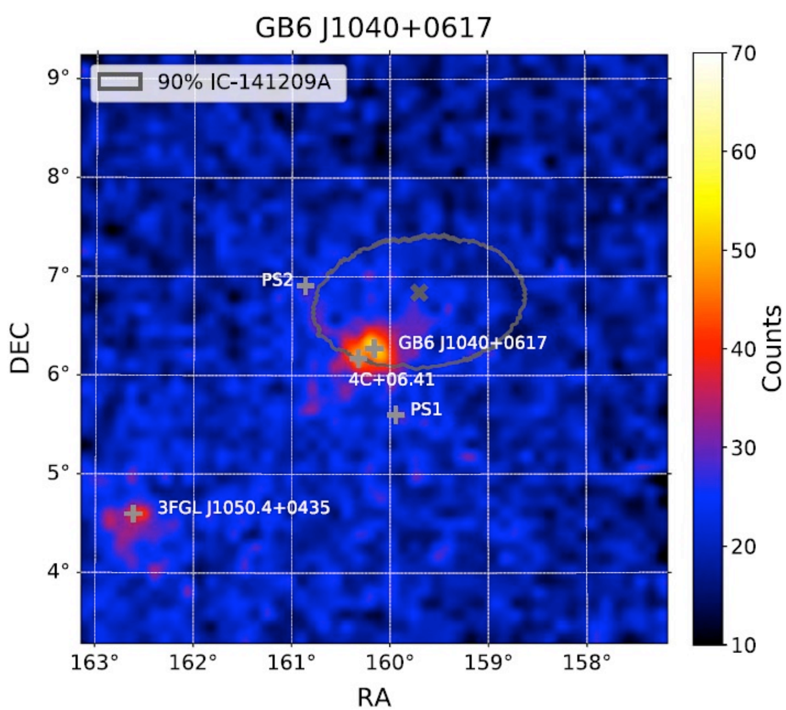


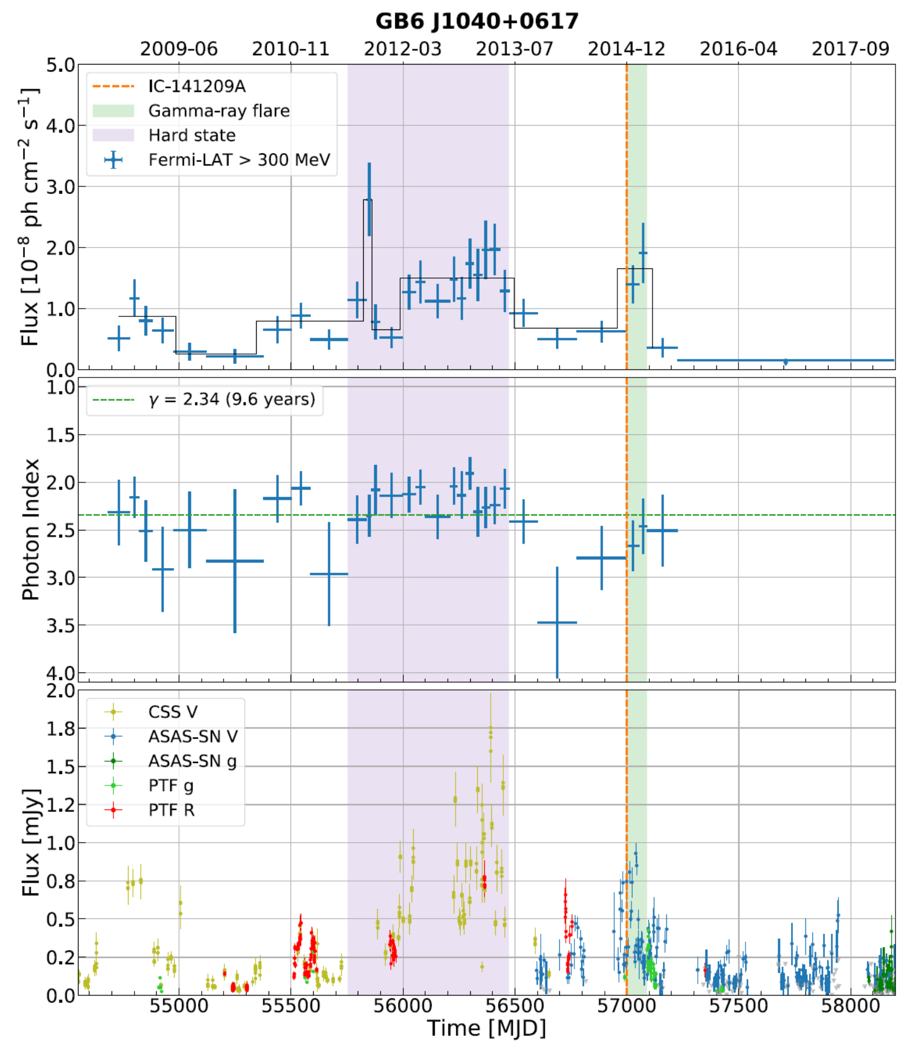




Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-141209A – GB6 J1040+0617 (Garrappa et al. 2019)
  - ~ 100 TeV HESE neutrino
  - BL Lac object at z = 0.735
  - γ-ray flux increase at the time of IceCube 141209A

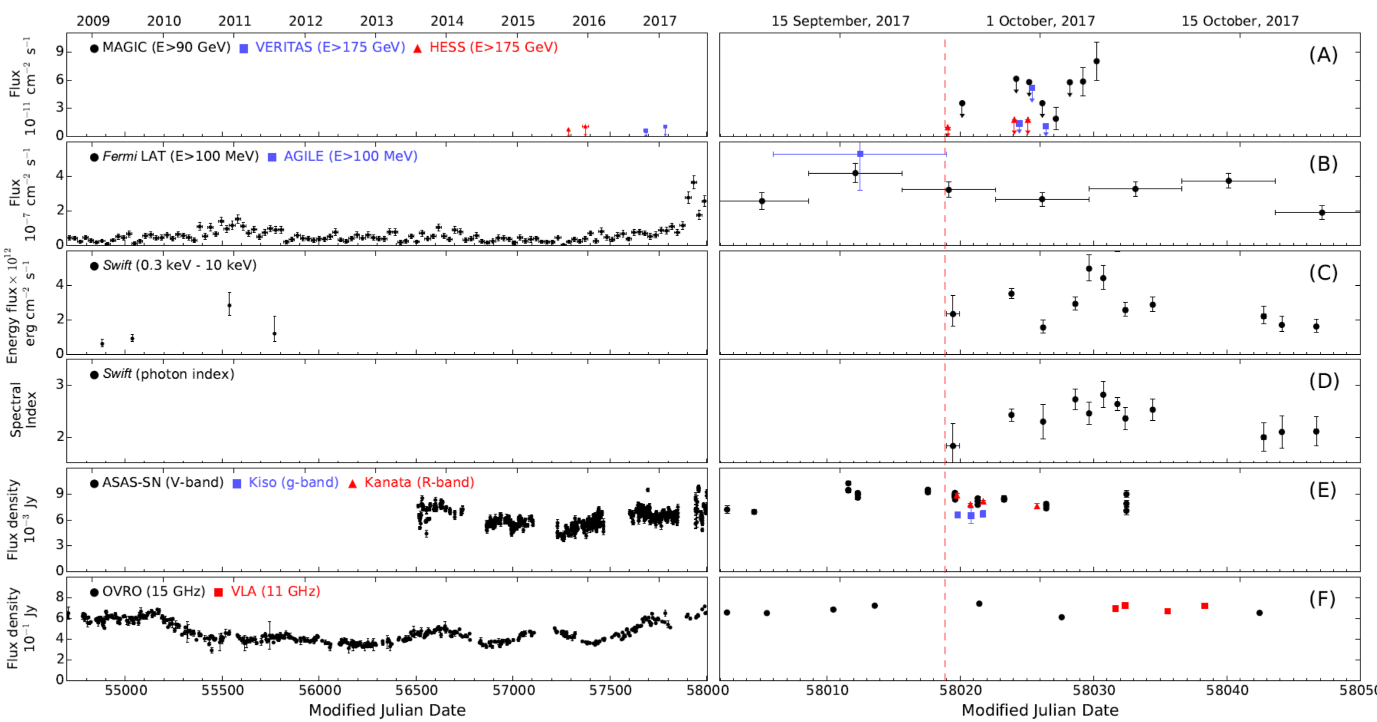




Tentative Associations of IceCube Neutrinos with Blazars

- <u>IceCube-170922A – TXS 0506+056 (IceCube Collaboration et al. 2018a; Garrappa et al. 2019; Padovani et al. 2019; …)</u>

- 290 TeV neutrino
- "Masquerading" BL Lac object at z = 0.3365 with weak BLR emission (Padovani et al. 2019)
- Neutrino event coincident with 4-week-long γ-ray high state
- Highest-confidence association and most well-studied potential neutrino-emitting blazar so far



Tentative Associations of IceCube Neutrinos with Blazars

- 2014 – 15 Neutrino Flare – TXS 0506+056 or PKS 0502+049 (IceCube Collaboration et al. 2018b; Britzen et al. 2019; Sumida et al. 2022; …)
  - Search in archival data => Evidence for ~ 13 excess neutrinos from the direction of TXS 0506+056 in 2014 – 2015 (~ 4 months around December 2014).
  - No evidence for γ-ray activity from TXS 0506+056 during the neutrino flare.

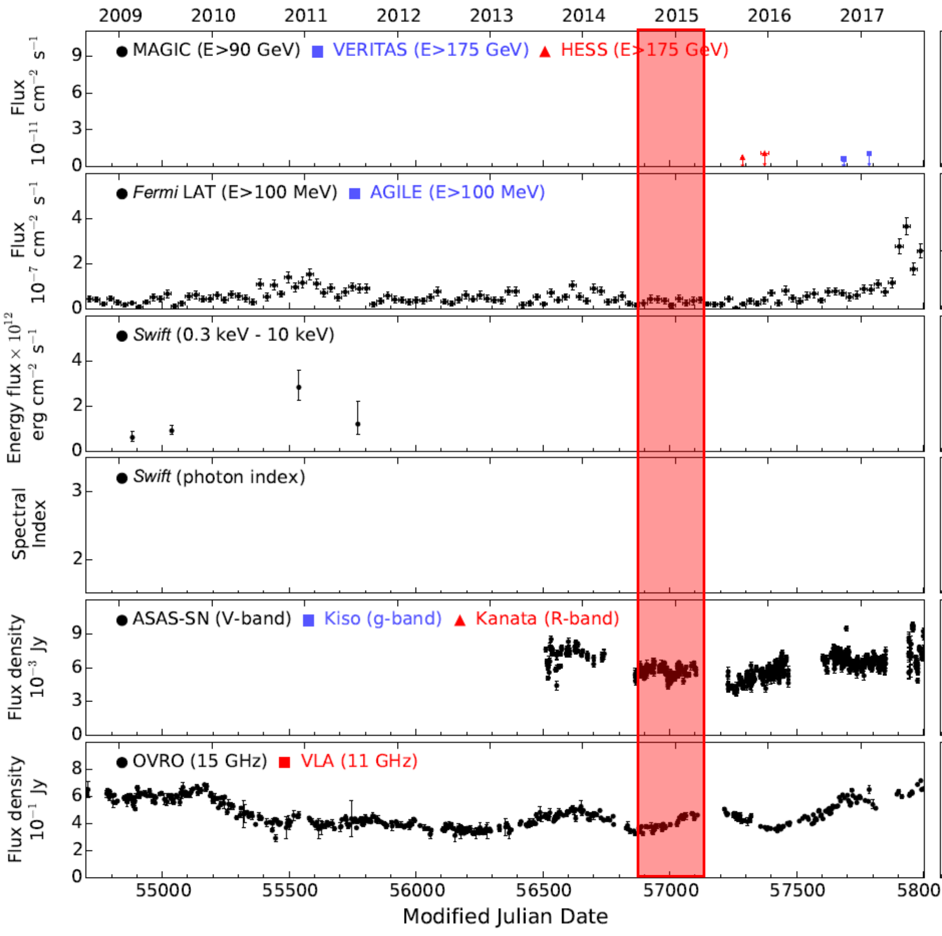
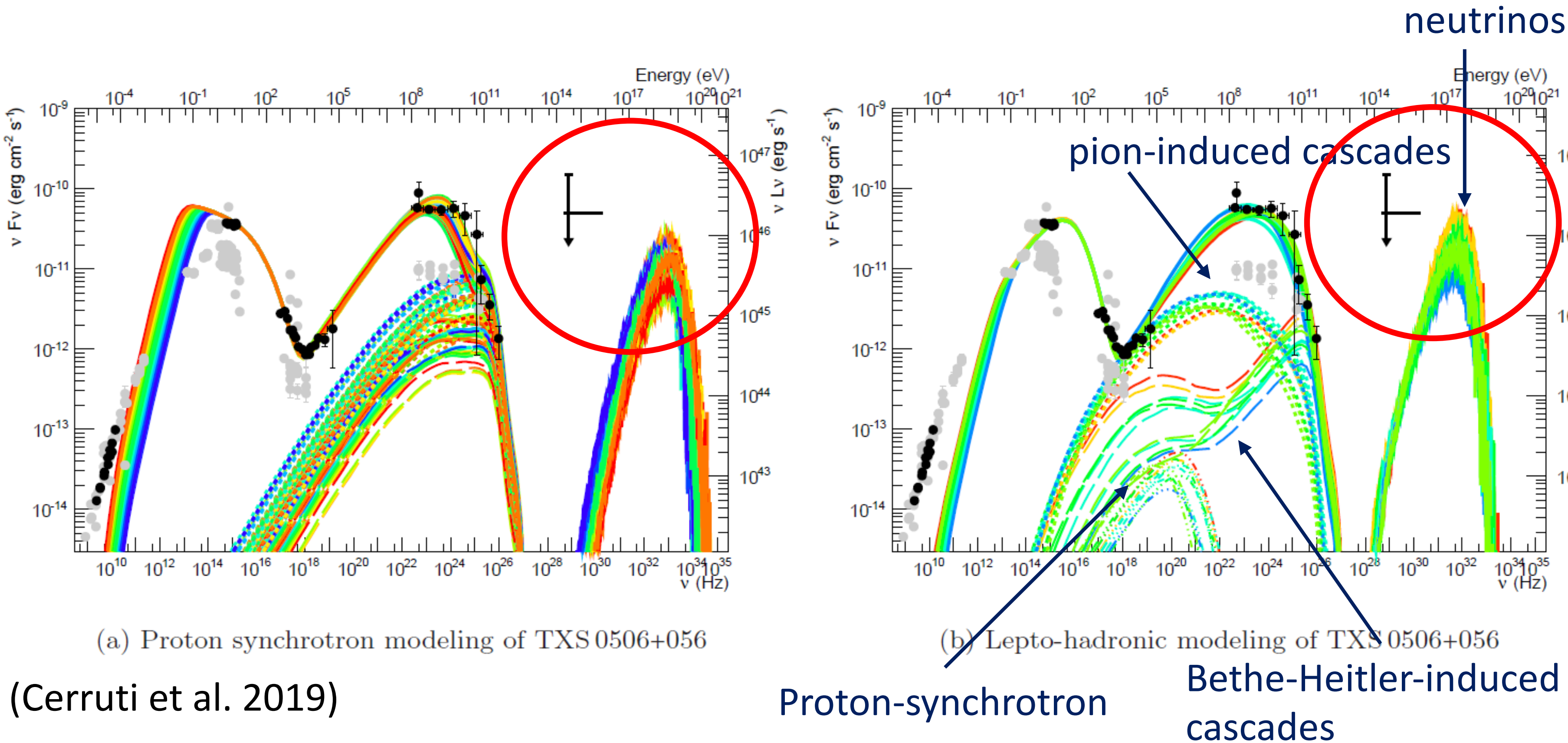


Photo-Pion Models for TXS 0506+056



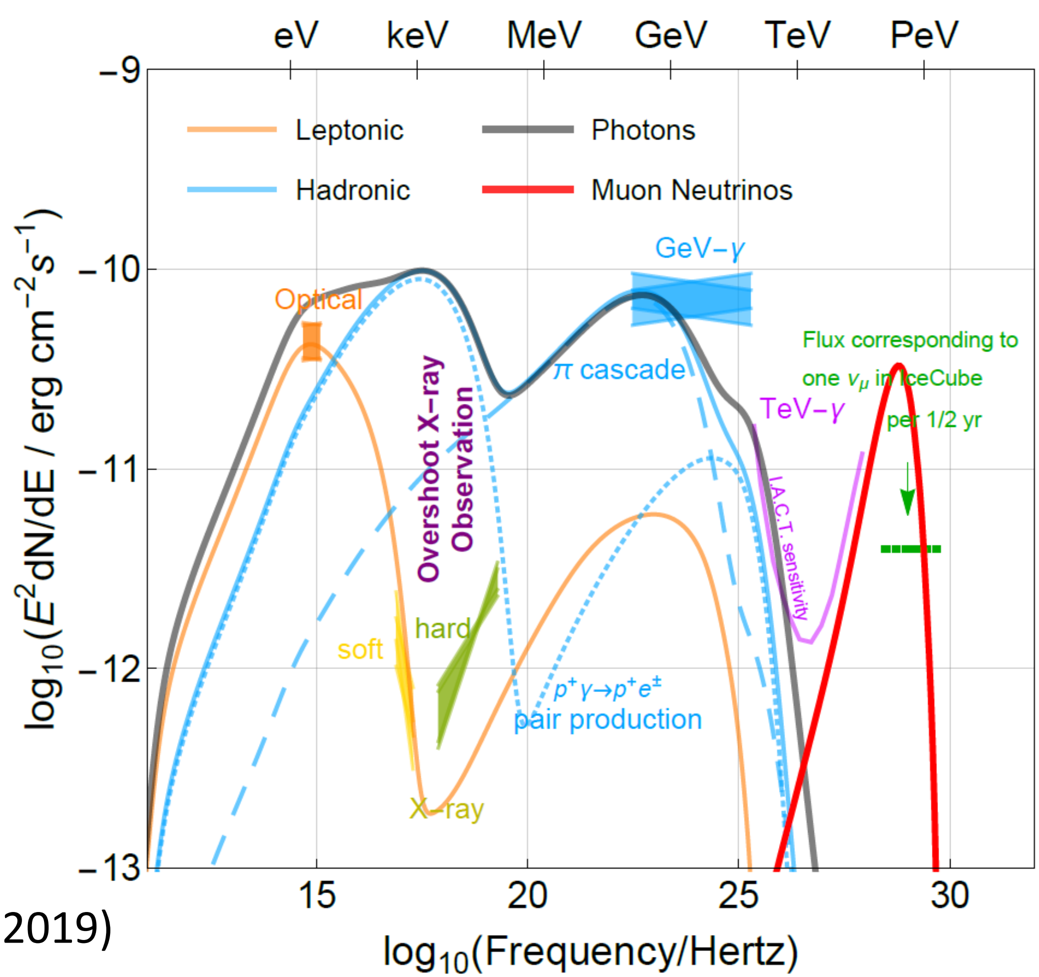
(a) Proton synchrotron modeling of TXS 0506+056

(b) Lepto-hadronic modeling of TXS 0506+056

(Cerruti et al. 2019)

Models producing neutrinos and γ-rays by photo-pion production on synchrotron photons, predict too high neutrino energies!

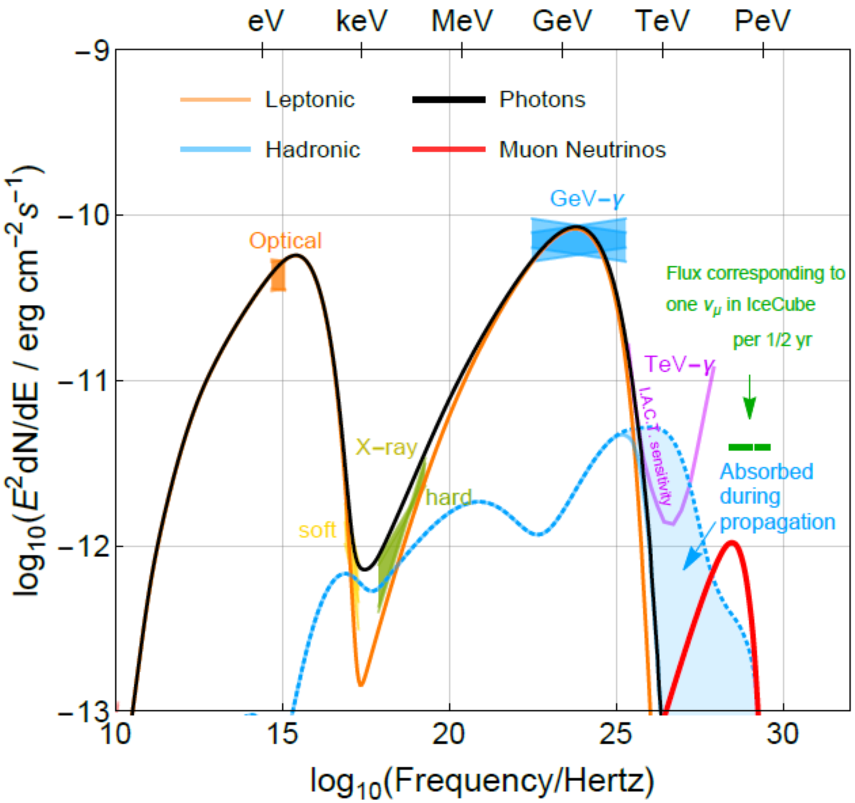
Photo-Pion Models for TXS 0506+056



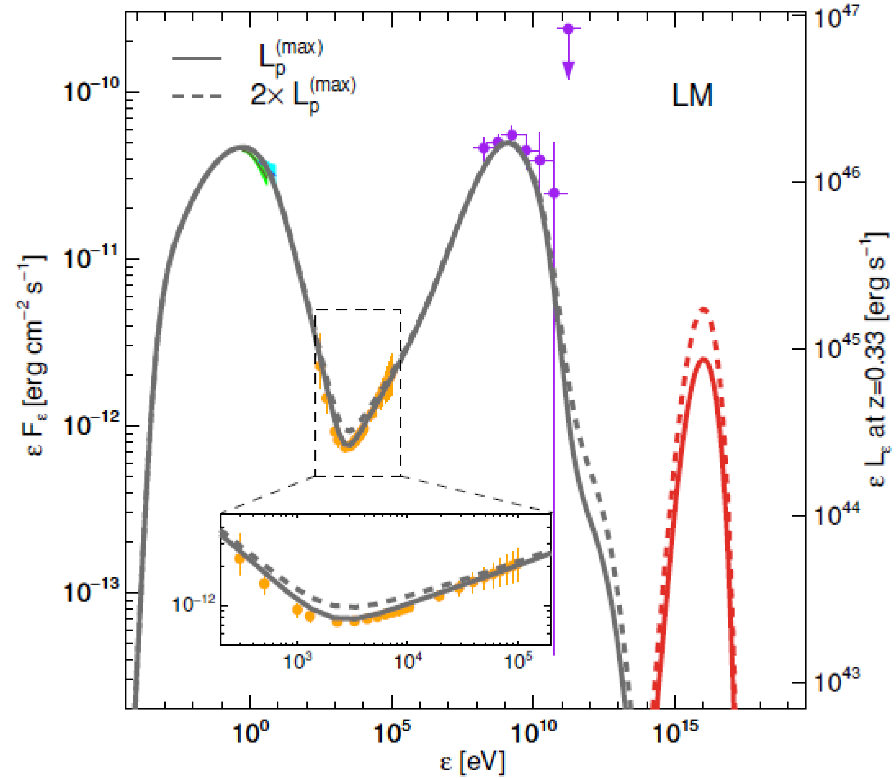
(Gao et al. 2019)

Models with p-γ induced γ-ray emission over-produce X-rays due to cascades!

Photo-Pion Models for TXS 0506+056



(Gao et al. 2019)

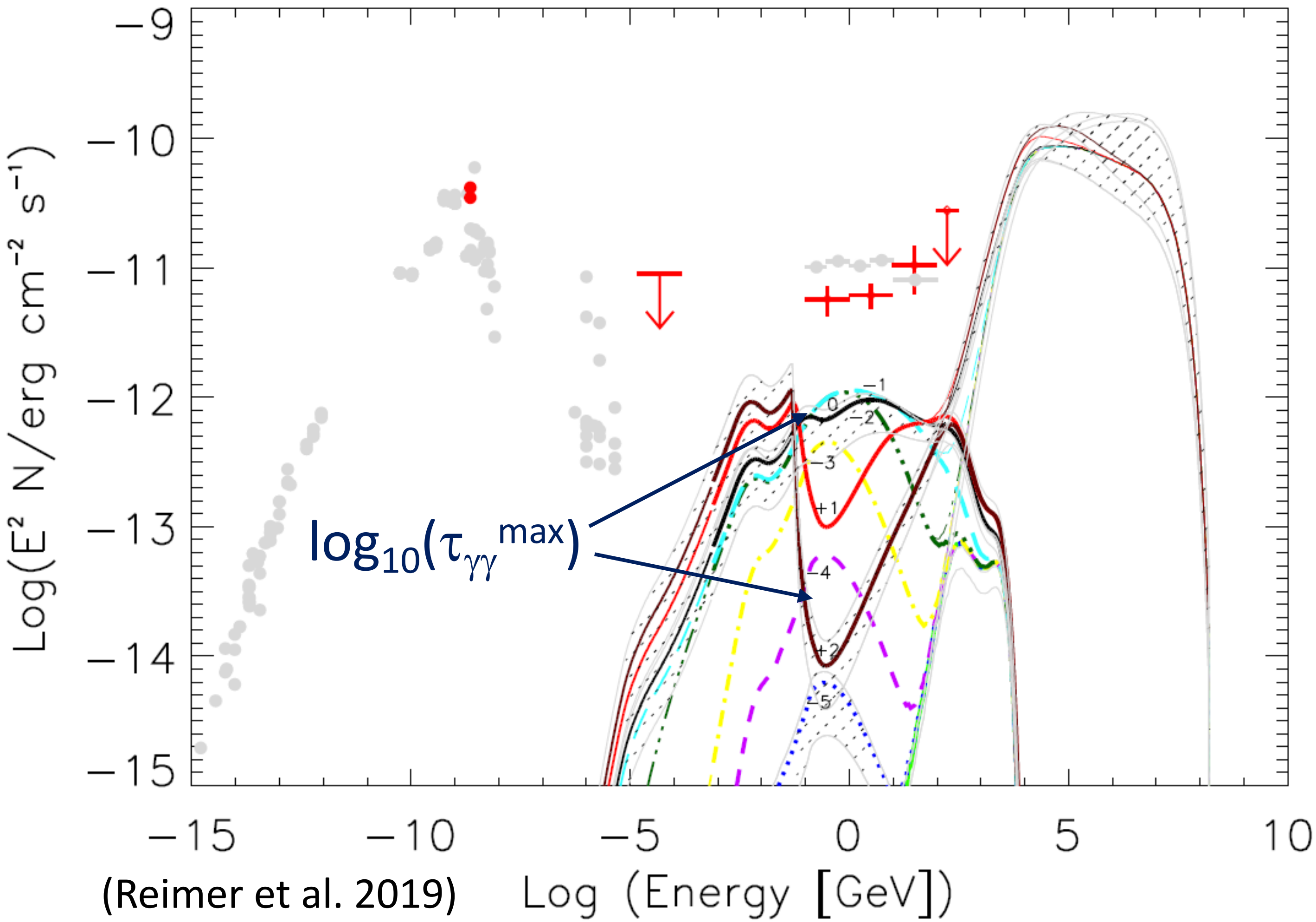


(Keivani et al. 2018)

Most models producing neutrinos and γ-rays require leptonic-dominated γ-ray production!

Photo-Pion Models for TXS 0506+056

Constraints from cascades



(Reimer et al. 2019)

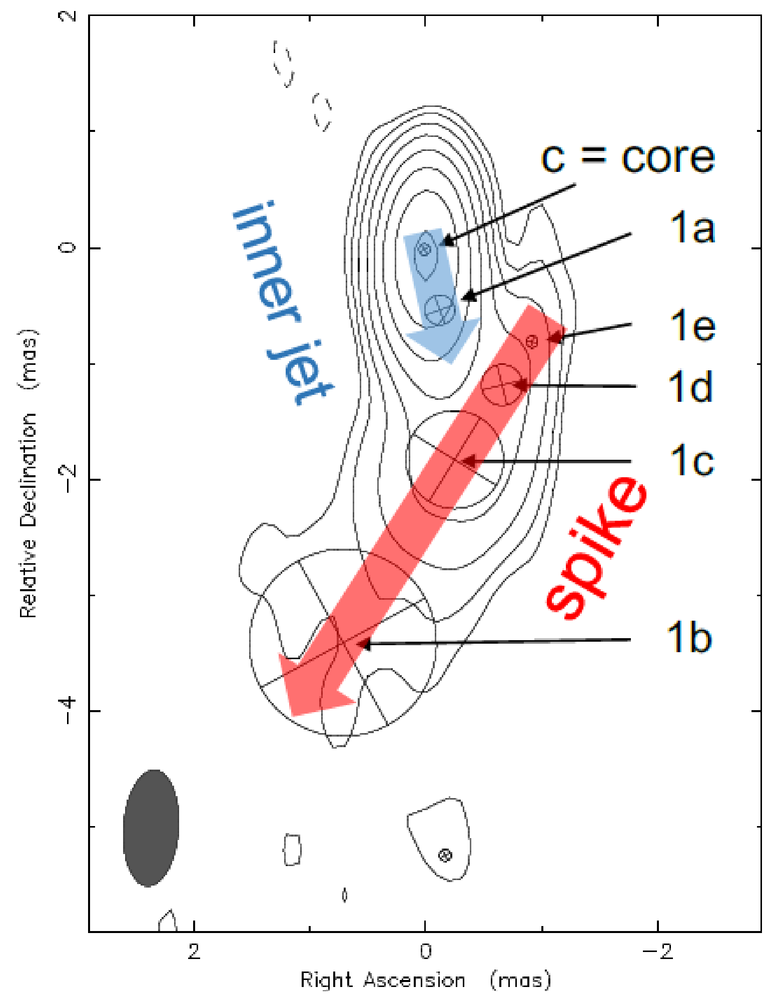
Neutrino-flare flux can be produced with moderate power requirements in the presence of dense external radiation field, $u_t' \gg u_B'$.

$\gamma\gamma$-absorption + Compton-supported cascades produce X-ray – γ-ray flux well below observed levels.

=> No neutrino – γ-ray correlation expected!

Tentative Associations of IceCube Neutrinos with Blazars

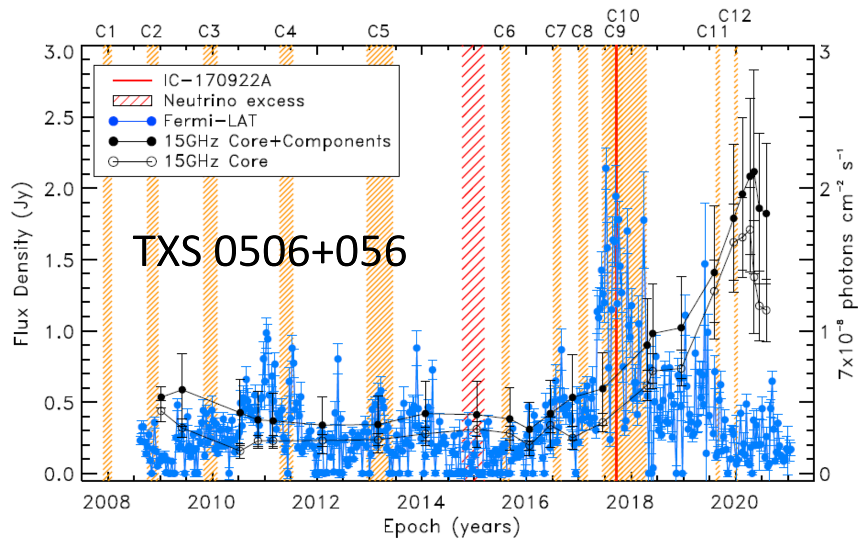
- 2014 – 15 Neutrino Flare – TXS 0506+056 or PKS 0502+049 (IceCube Collaboration et al. 2018b; Britzen et al. 2019; Sumida et al. 2022; …)
  - Radio jet structure seems reveal two, possibly radiatively interacting jets.
  - Neutrino-flare flux can be produced in case of vastly different jet speeds.

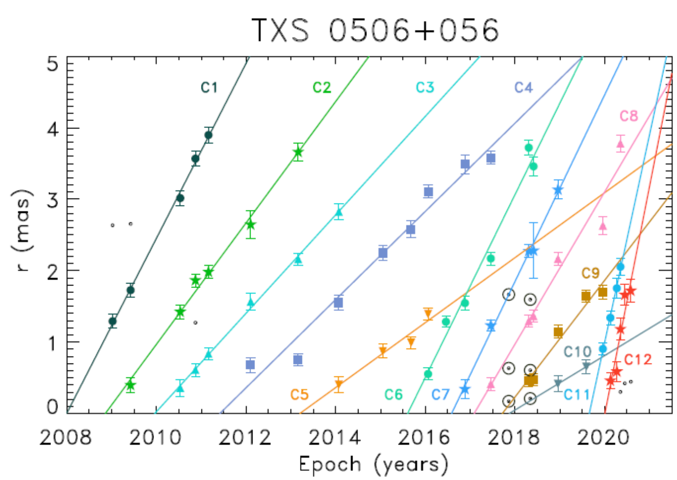


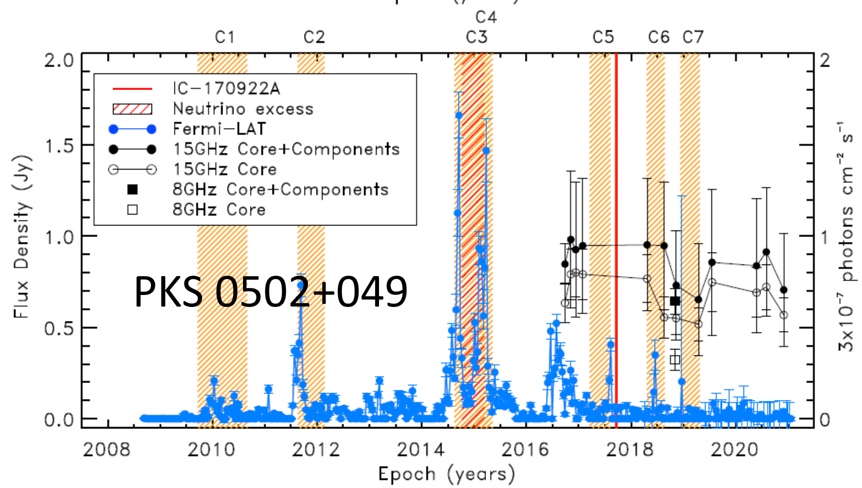
(Britzen et al. 2019)

Tentative Associations of IceCube Neutrinos with Blazars

- 2014 – 15 Neutrino Flare – TXS 0506+056 or PKS 0502+049 (IceCube Collaboration et al. 2018b; Britzen et al. 2019; Sumida et al. 2022; …)
  - Claim of coincidence of neutrino events with ejection of new radio components (Sumida et al. 2022):
  - TXS 0506+056 – IceCube-170922A
  - PKS 0502+049 – 2014 – 15 neutrino flare







Tentative Associations of IceCube Neutrinos with Blazars

- IC-150926A – 4FGL J1258.7-0452 (Franckowiak et al. 2020)

  BL Lac object at z = 0.586

- IceCube-161103A – GB6 J0244.7+1320 (Franckowiak et al. 2020)

  BCU, unknown redshift

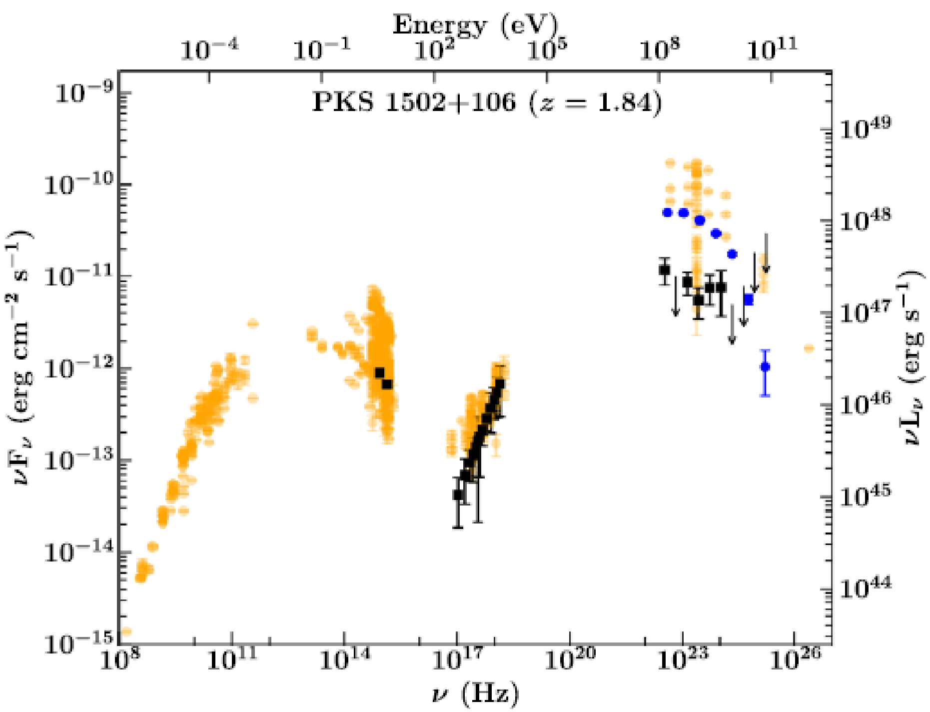
- IceCube-190221A – AT20G J175841-161703 / 4FGL J1750.4-1721 (Franckowiak et al. 2020)

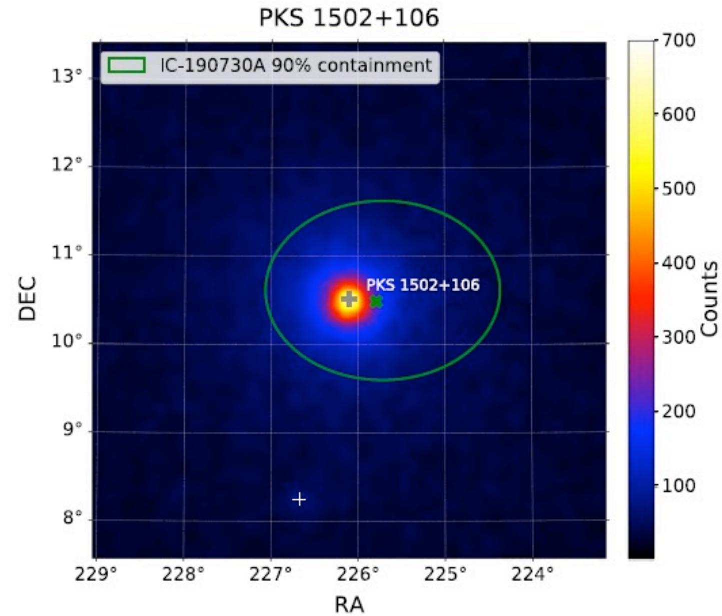
  AT20G J175841-161703: BCU, unknown redshift;

  4FGL J1750.4-1721: Unassociated.

Tentative Associations of IceCube Neutrinos with Blazars

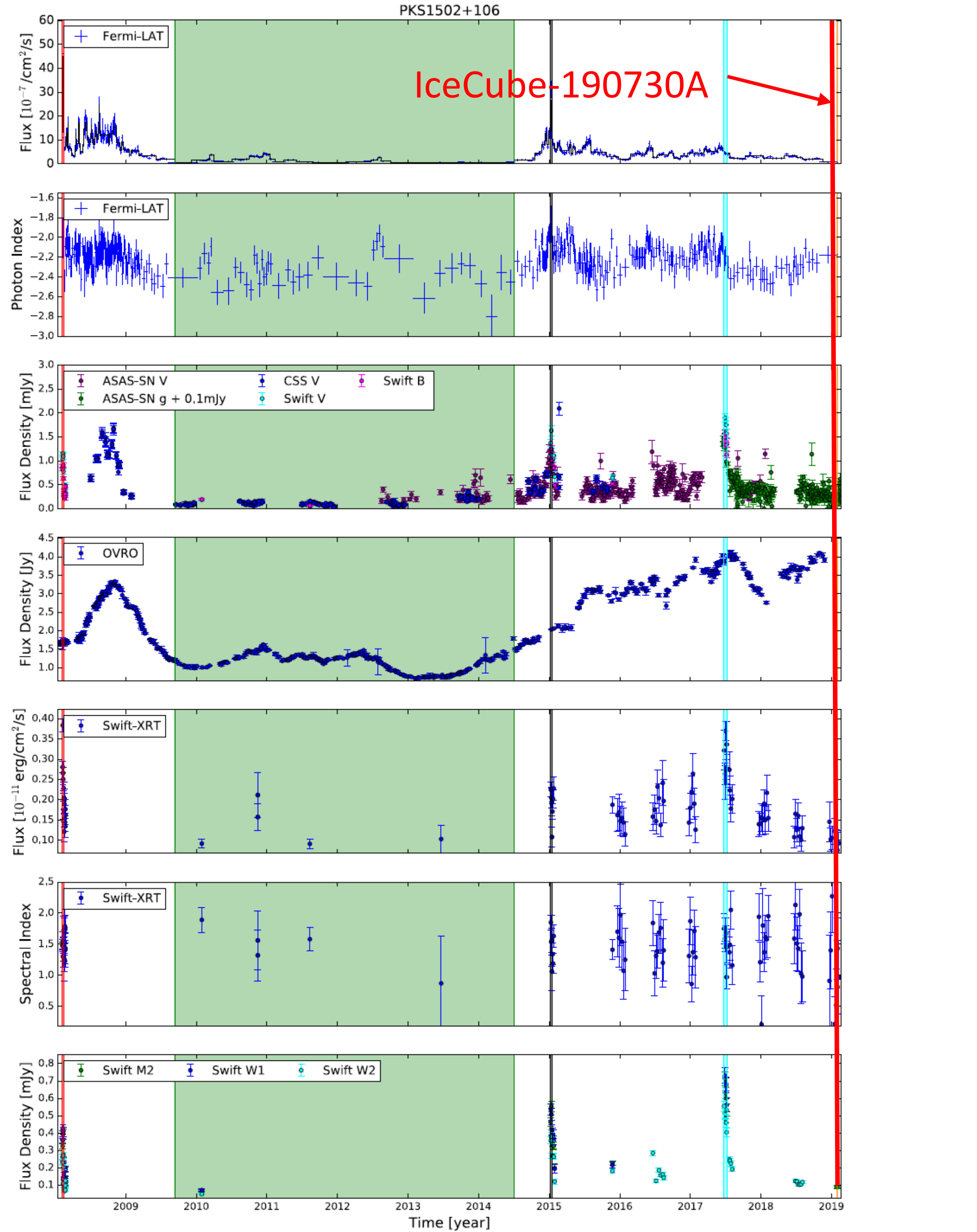
- IceCube-190730A – PKS 1502+106 (IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)
  - FSRQ at z = 1.84
  - E_ν ~ 300 TeV
  - Signalness = 67 %
  - 15th-brightest 4LAC source





(Franckowiak et al. 2020)

- <u>IceCube-190730A – PKS 1502+106 (IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)</u>



- Neutrino event during a long-term radio outburst (started 2014).
- Low γ-ray activity, but moderate X-ray activity.

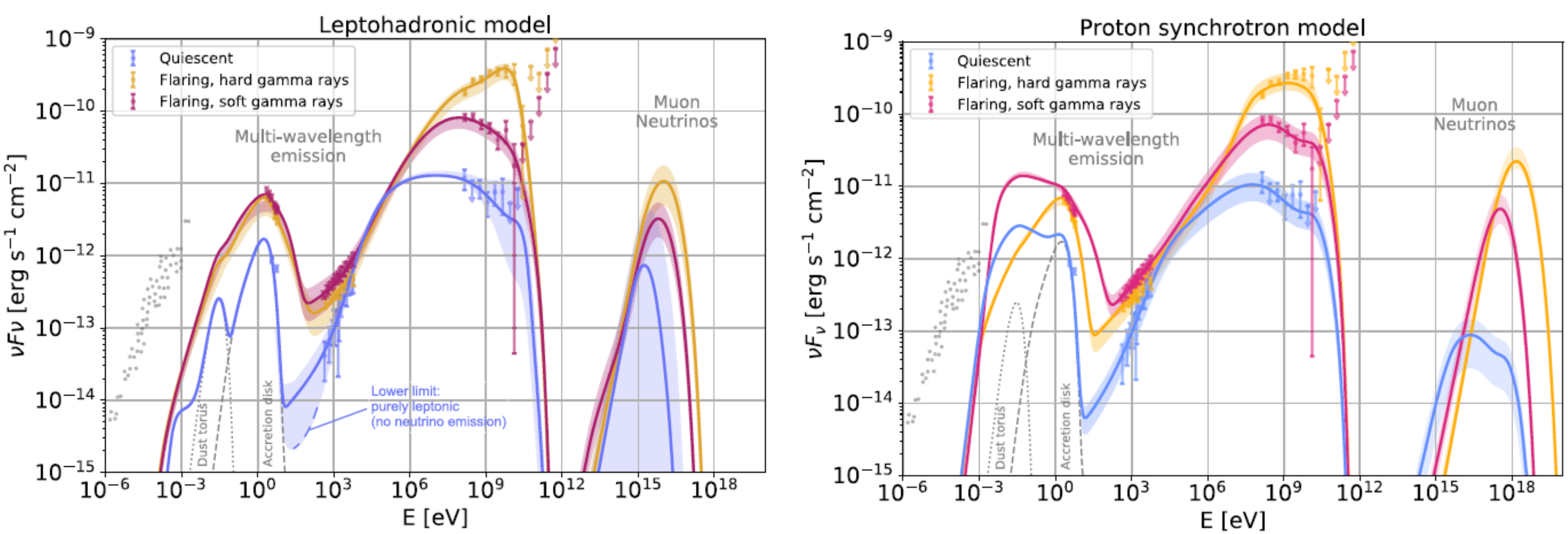
(Franckowiak et al. 2020)

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-190730A – PKS 1502+106 (IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)

  - Study of different hadronic and lepto-hadronic models of multi-messenger emission of PKS 1502+106 by Rodrigues et al. (2021):

  - Models with hadronically dominated X-ray / γ-ray emission consistent with detection of 1 neutrino during the quiescent γ-ray state.

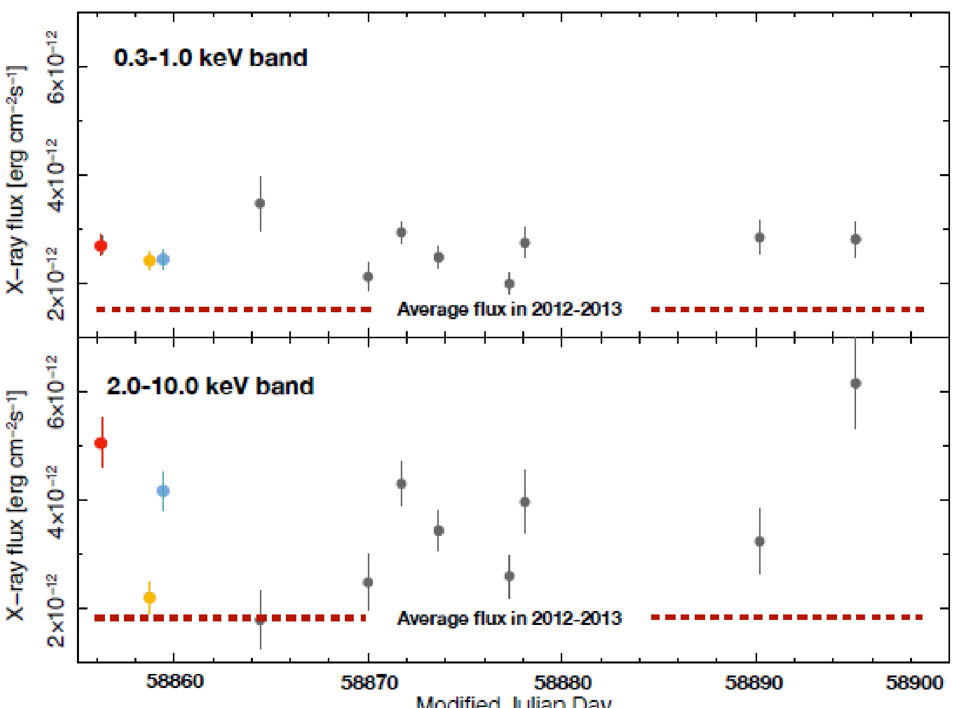


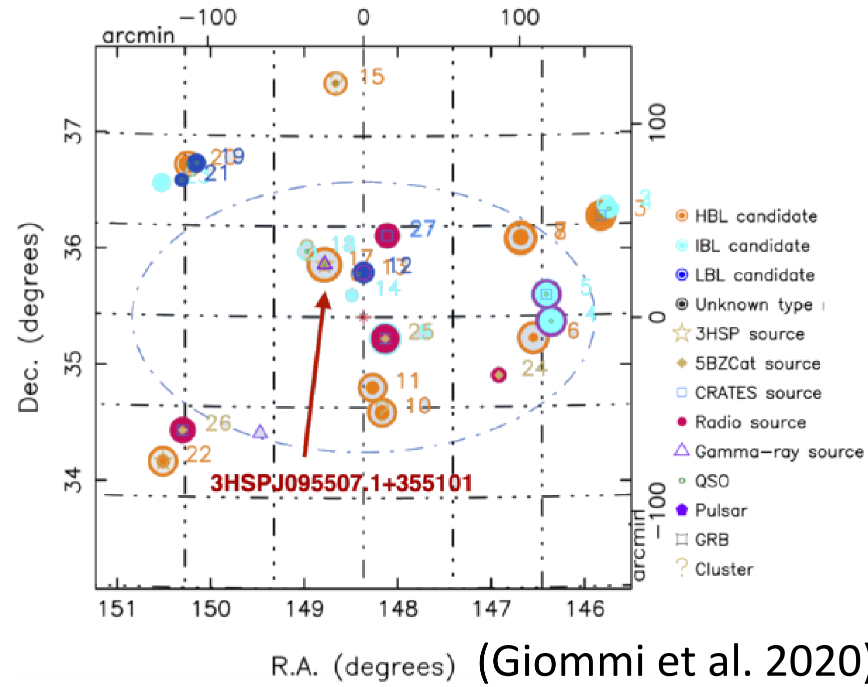
(Rodrigues et al. 2021)

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-200107 – 3HSP J095507.9+35510 (Giommi et al. 2020; Paliya et al. 2020; Krauss et al. 2020; Petropoulou et al. 2020)

- HBL at z = 0.5573 (Paiano et al. 2020; Paliya et al. 2020)
- HESE with uncertain energy ($E_\nu \sim 330^{+2230}_{-270}$ TeV)
- Bright X-ray flare on the day after the neutrino event (Swift ToO), but no γ-ray flare.





(Giommi et al. 2020)

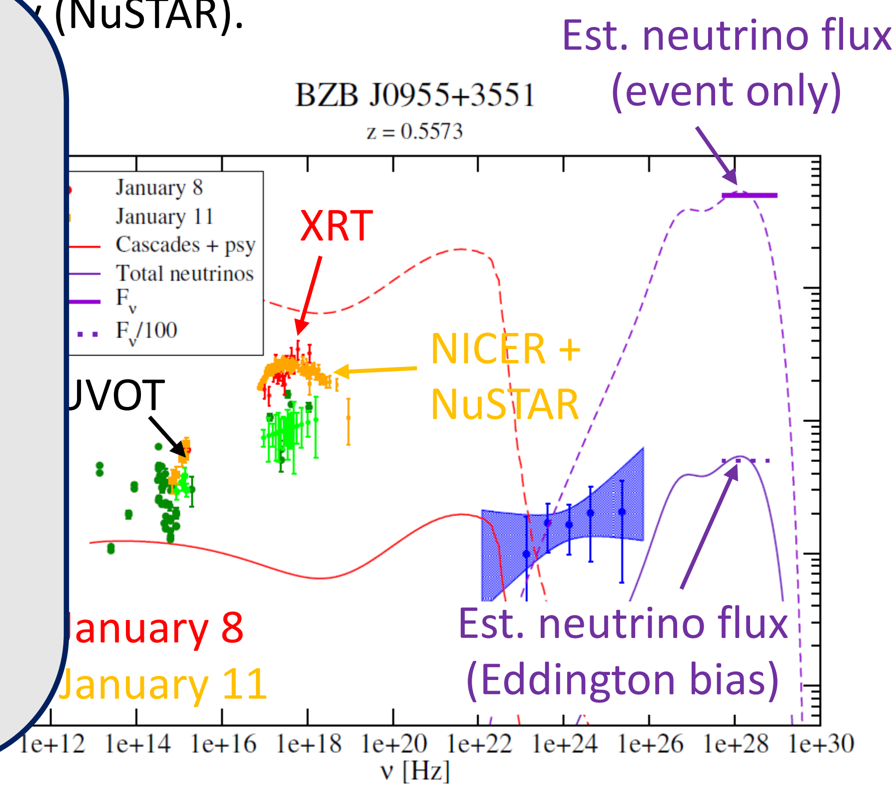
- One other γ-ray blazar in the 90 % uncertainty region: 4FGL J0957.8+3423, but no flux enhancement in any band. (Krauss et al. 2020)

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-200107 – 3HSP J095507.9+35510 (Giommi et al. 2020; Paliya et al. 2020; Krauss et al. 2020; Petropoulou et al. 2020)
  - Extensive MWL campaign, including DDT NuSTAR + Swift ToO observations + GTC optical spectroscopy (Paliya et al. 2020); NICER DDT simultaneous with NuSTAR.
  - (NuSTAR).

Eddington bias:
N potential sources with probability 1/N to detect 1 neutrino => Expect 1 neutrino from ~ 1 of the sources.

N ~ 100 for a 3HSP J09907.9+35510 like source (Franckowiak et al. 2020).



(Paliya et al. 2020)

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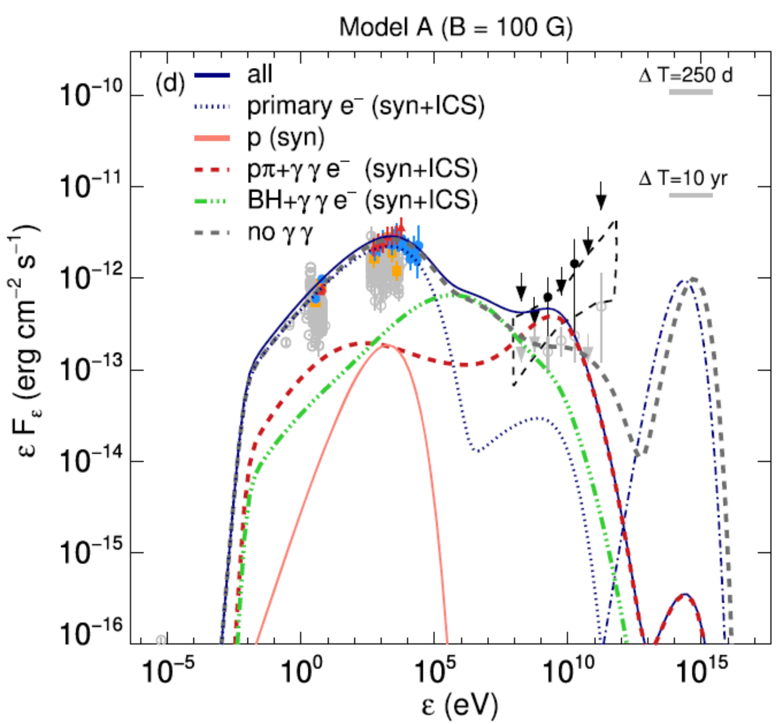
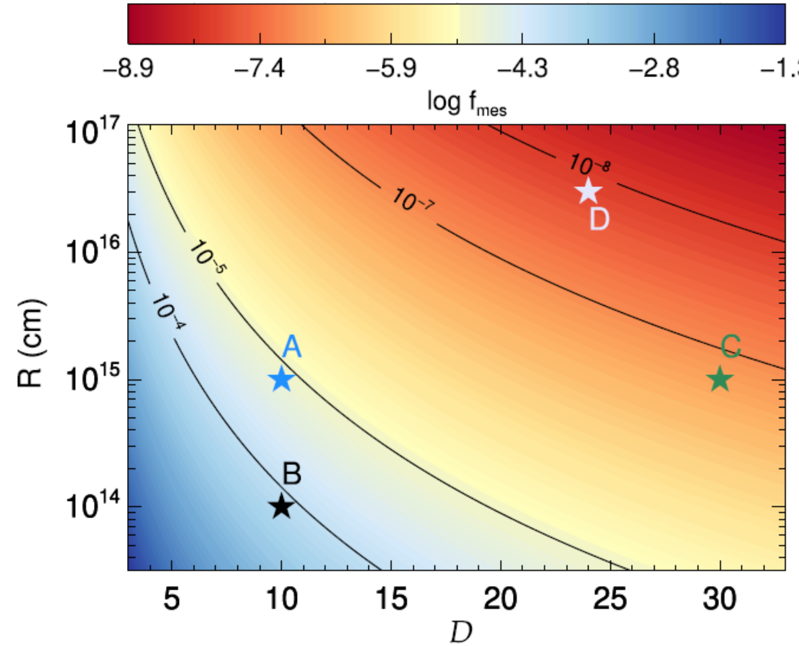
  - Detailed study of various lepto-hadronic scenarios by Petropoulou et al. (2020):





Single-zone models with co-moving (synchrotron) target photon field: Hadronically dominated high-energy emission, but systematically under-predicting Fermi-LAT spectrum.

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-200107 – 3HSP J095507.9+35510 (Giommi et al. 2020; Paliya et al. 2020; Krauss et al. 2020; Petropoulou et al. 2020)
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Table 3

Yearly Rate of Muon and Antimuon Neutrinos Expected to Be Detected by IceCube, and Poisson Probability to Detect a Single Muon (or Antimuon) Neutrino with Energy Exceeding 100 TeV with the Alert (Point Source) Search for the Leptohadronic Models Studied in This Section

Model	$\dot{N}_{\nu_\mu+\bar{\nu}_\mu}(>100\ \mathrm{TeV})$ $(\times 10^{-4}\ \mathrm{yr}^{-1})$ Alert (Point Source)	$\mathcal{P}\|_{1\ \nu_\mu\ \mathrm{or}\ \bar{\nu}_\mu}(>100\ \mathrm{TeV})$ Alert (Point Source)
$A_{(B'=15\mathrm{G})}$	17 (190)	0.02 (0.2)%
$A_{(B'=30\mathrm{G})}$	50 (540)	0.06 (0.7)%
$A_{(B'=100\mathrm{G})}$	45 (490)	0.05 (0.6)%
B	18 (200)	0.02 (0.2)%
C	25 (100)	0.03 (0.1)%
D	40 (210)	0.05 (0.3)%

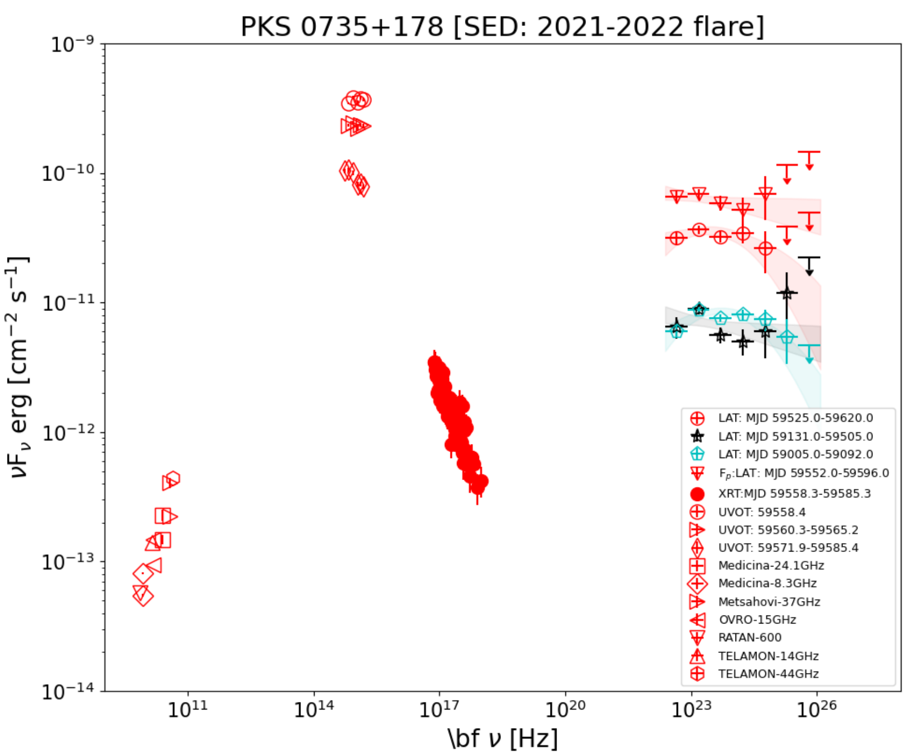
All models predict << 1 neutrino during the flare – consistent with Eddington bias.

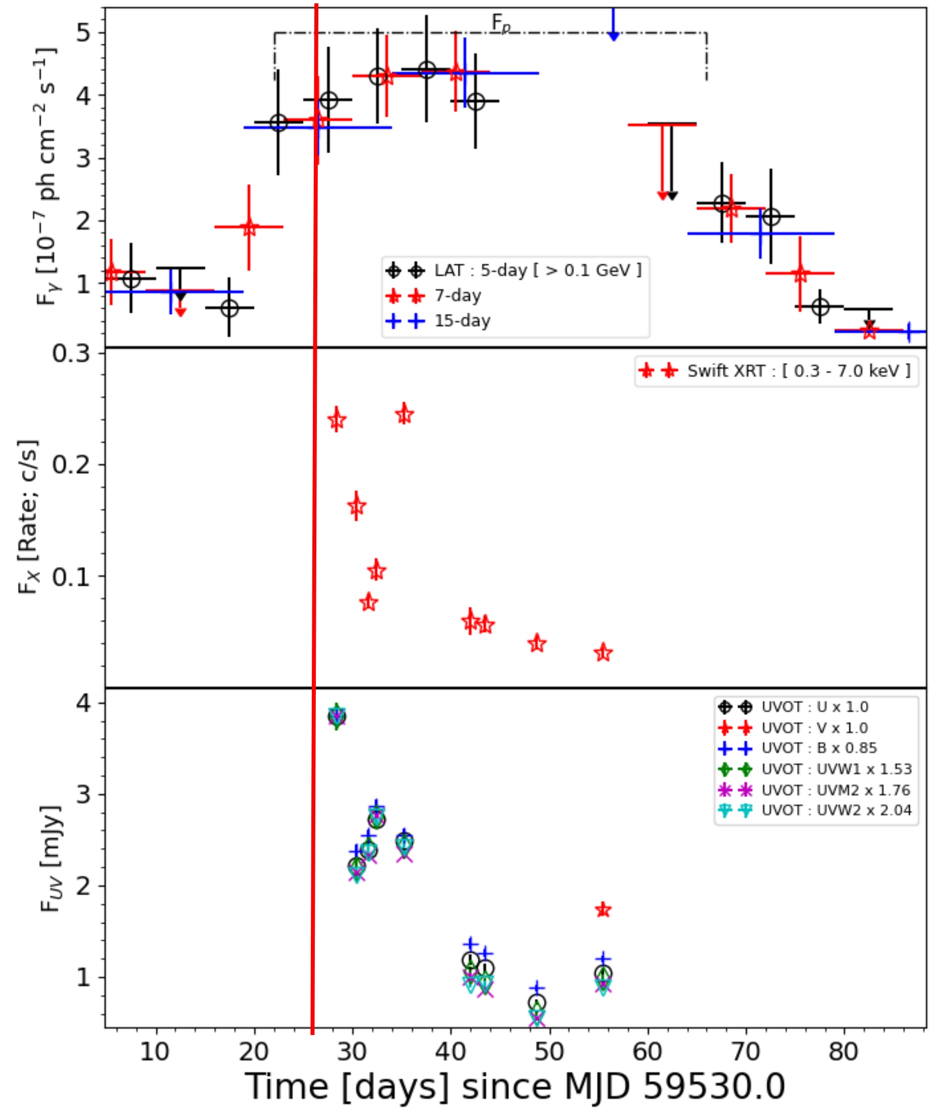
Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-211125 –AT2021afpi / 4FGL J0258.1+2030
  - Neutrino of E ~ 117 TeV; 39 % probability of being astrophysical.
  - Two potential counterparts:
    - AT2021afpi:
      - Young, narrow-line He-rich Nova detected by MASTER (Zhirkov et al. 2021; Stein et al. 2021; Taguchi et al. 2021);
      - X-ray outburst at the time of the neutrino event (Paliya 2021).
    - 4FGL J0258.1+2030:
      - Blazar of unknown type (uncertain z = 2.2, little other information available);
      - also potential counterpart of IceCube-191231A: **First potential counterpart to two neutrinos!**
      - Enhanced radio state (Kadler 2021);
      - Poorly covered by Fermi-LAT; no detections in VHE gamma-rays; no information about X-ray state.

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-211208 – PKS 0735+17
  - FSRQ at z = 0.45
  - Multi-wavelength flare, including X-rays and γ-rays, during and after the neutrino event





Chandra et al. (2022), in prep.

Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-2200225 – PKS 0215+015 / PKS 0205-010 (Garrappa et al. 2022; Kadler et al. 2022; Plavin et al. 2022; Nesci 2022)
  - 2 blazars in the vicinity of the neutrino event (Garrappa et al. 2022):
    - FSRQ PKS 0215+015 (z = 1.715), ~1.75^{o} from best-fit neutrino position. Long-term gamma-ray high state since mid-2021; long-term radio outburst (Kadler et al. 2022; Plavin et al. 2022); optical high state (Nesci 2022). No information on X-ray activity. Favoured as potential neutrino source.
    - PKS 0205-010 (z uncertain), ~2.7^{o} away. No significant activity reported in band.
- IceCube-220304 – TXS 0310+022 (Kadler et al. 2022a,b)
    - FSRQ at z = 0.994. Several-months-long radio flare in 2021, and strongly inverted radio spectrum during neutrino event.

Summary

- Blazars are likely sources of very-high-energy neutrinos. Number of tentative associations steadily increasing.

- Production of IceCube neutrinos requires
  - Protons of ~ PeV energies
  - Target photons of co-moving UV / X-ray energies, most plausibly from outside the jet

- In many cases, models require leptonically dominated high-energy emission, with sub-dominant hadronic component.

- No correlation between γ-ray and neutrino activity necessarily expected. Many observed associations during γ-ray low states, but elevated states at lower energies.

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Thank you!