Mutiwavelength and Multimessenger Observations of Blazars and Theoretical Modeling:

Blazars as Astrophysical Neutrino Sources

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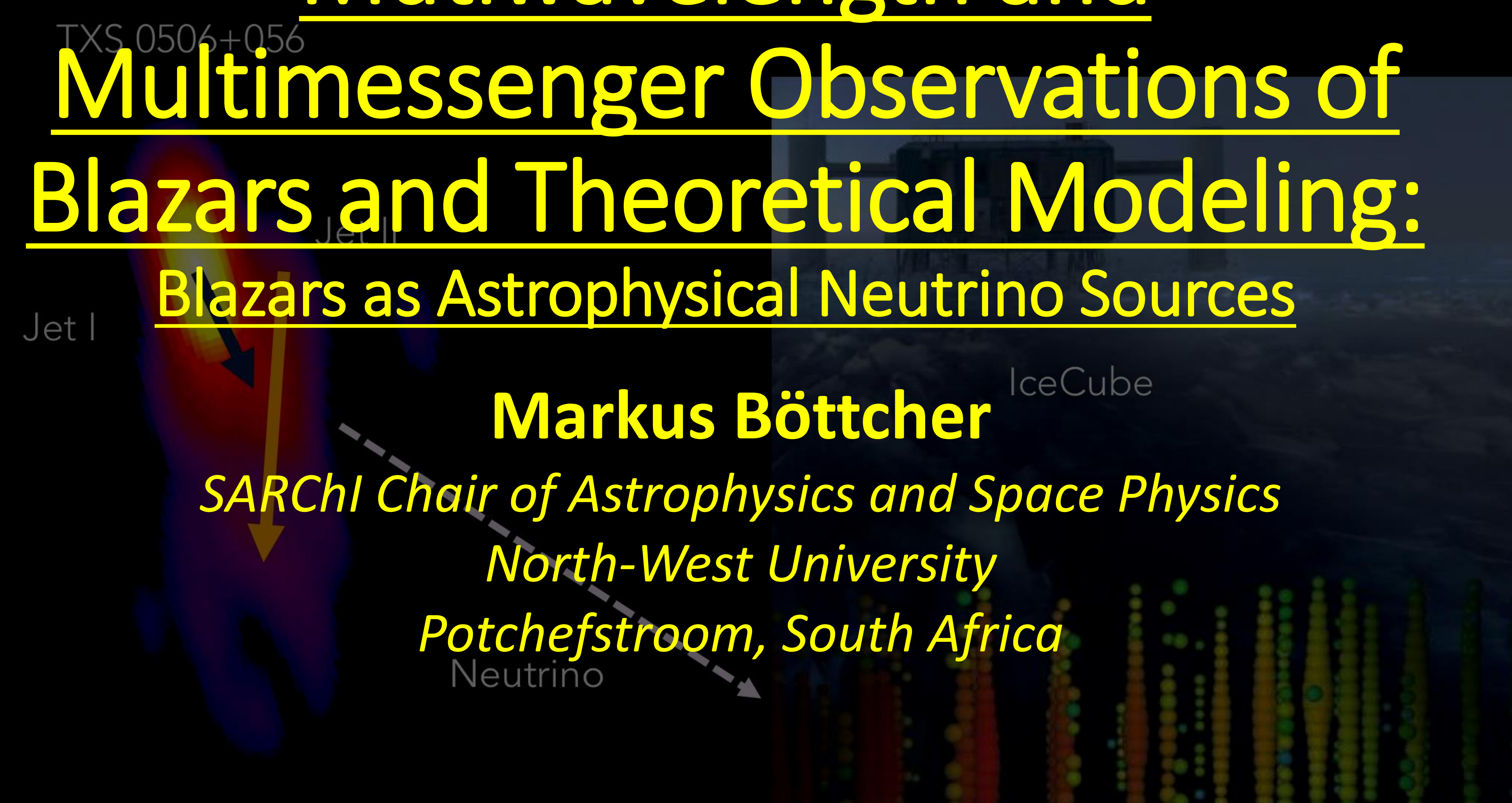

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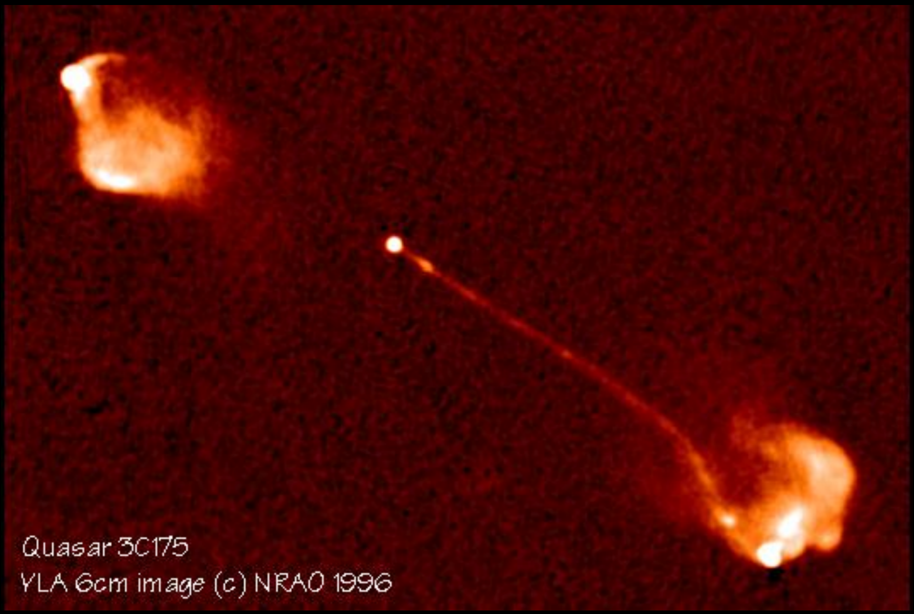
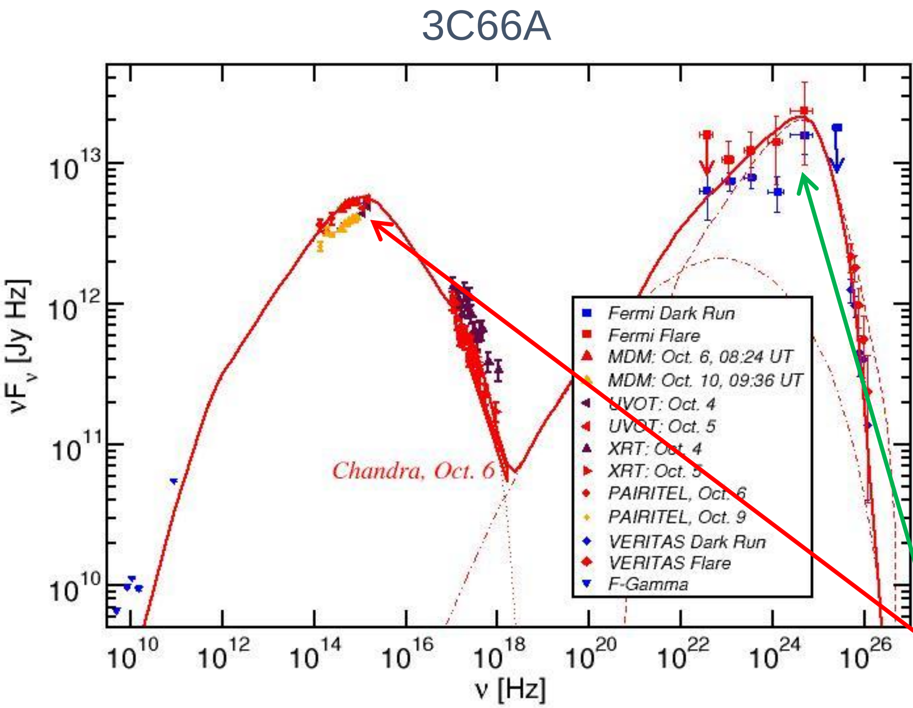
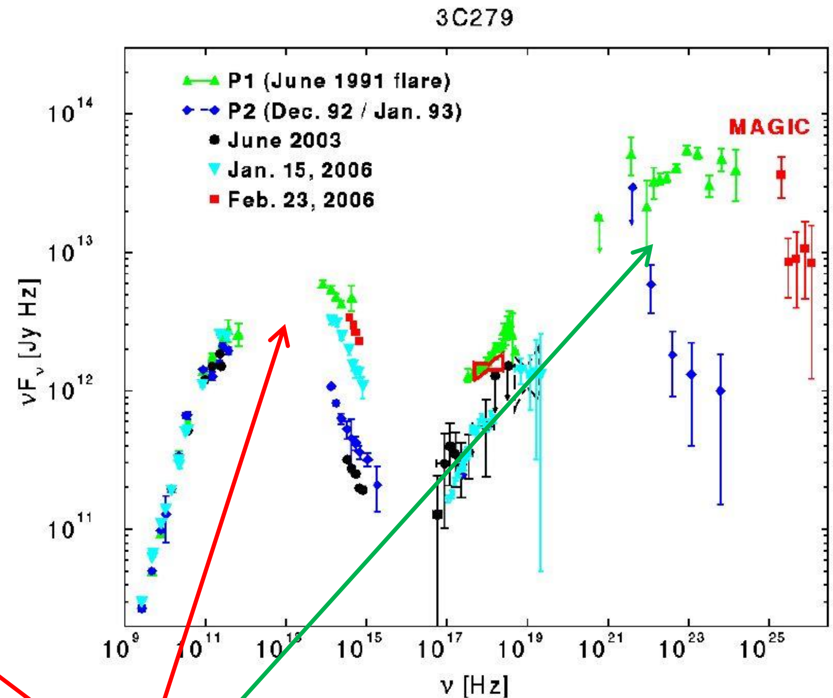
Blazars



- 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:

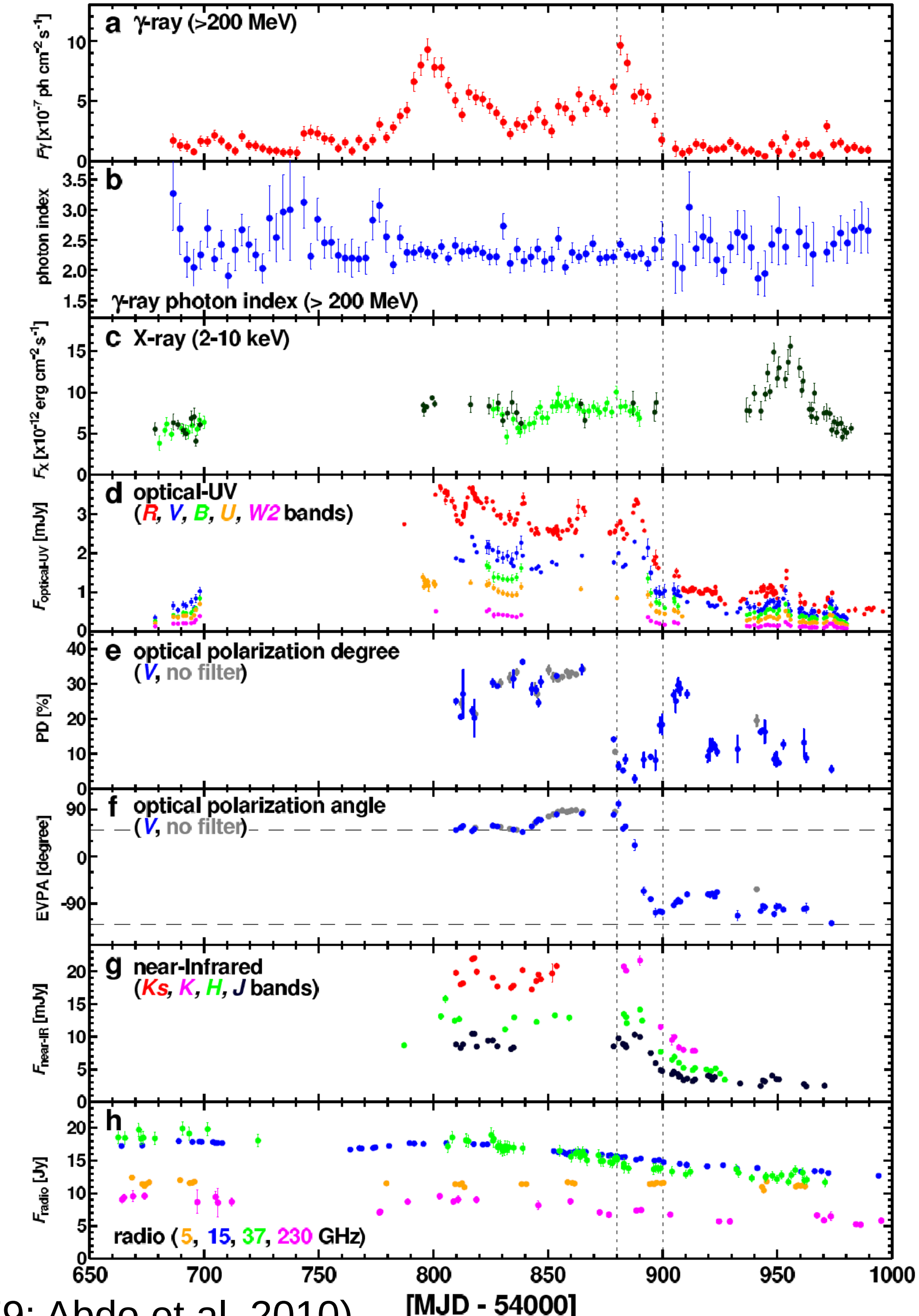
- Low-energy (electron synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

Blazar Variability

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

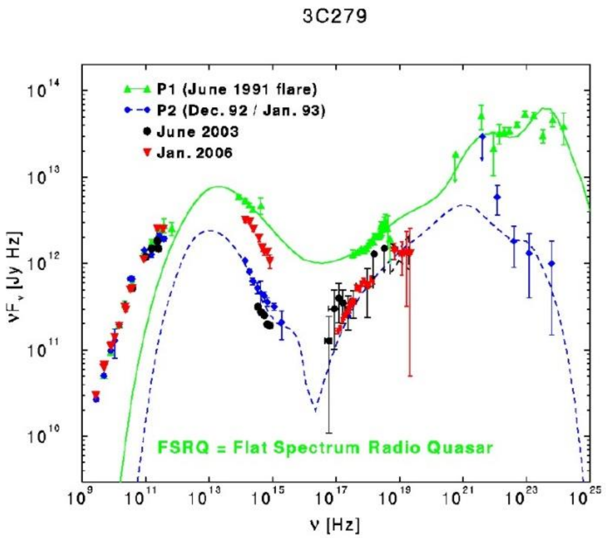
Observed optical polarization degrees
Π_{opt} <~ 30 %

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

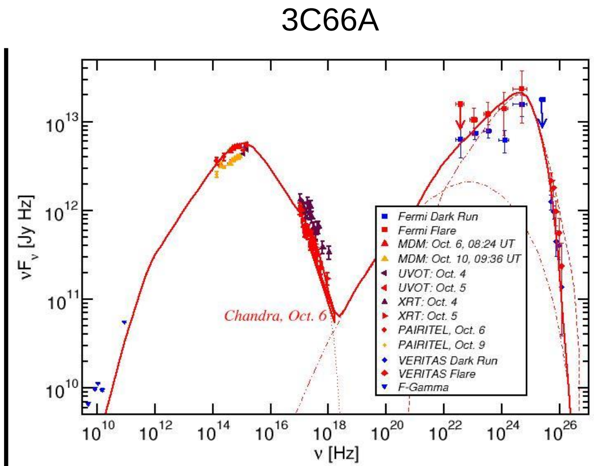


(3C279: Abdo et al. 2010)

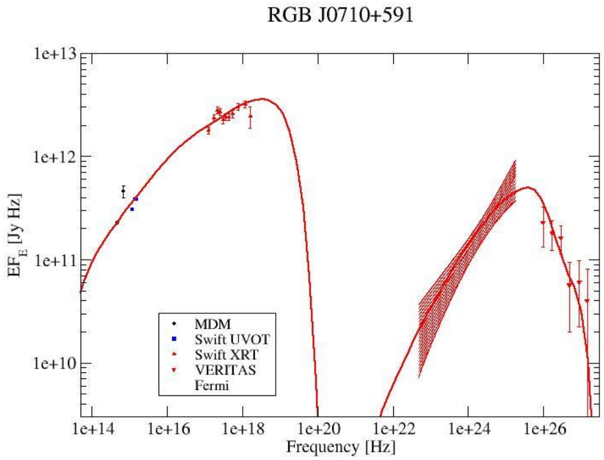
Blazar Classification



(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

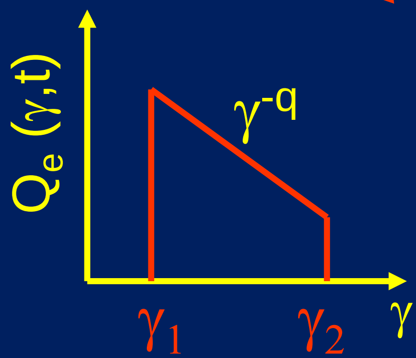
often dominating the total power

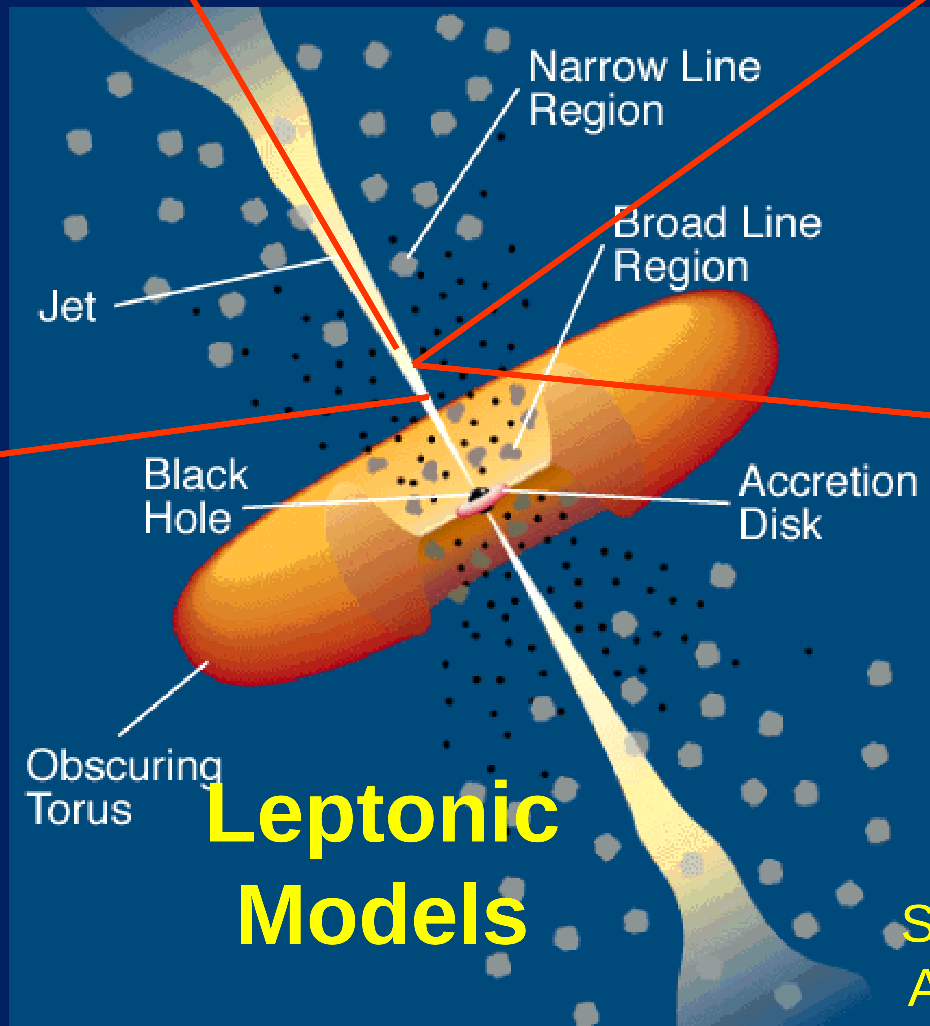
High-frequency component from hard X-rays to high-energy gamma-rays

Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$

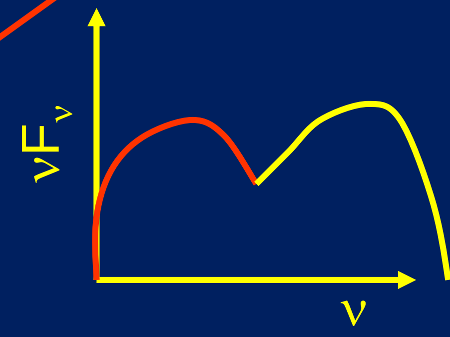
Injection, acceleration of ultrarelativistic electrons



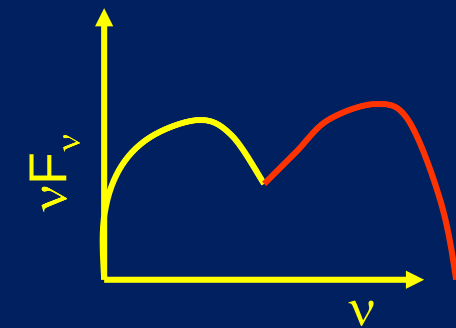


Leptonic Models

Synchrotron emission



Compton emission

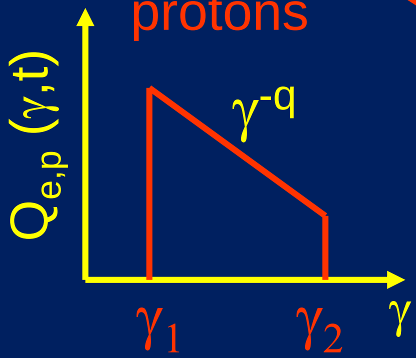


Seed photons:

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

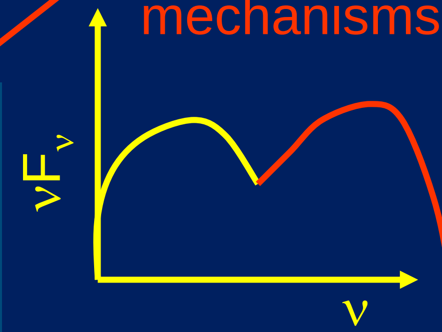
Blazar Models

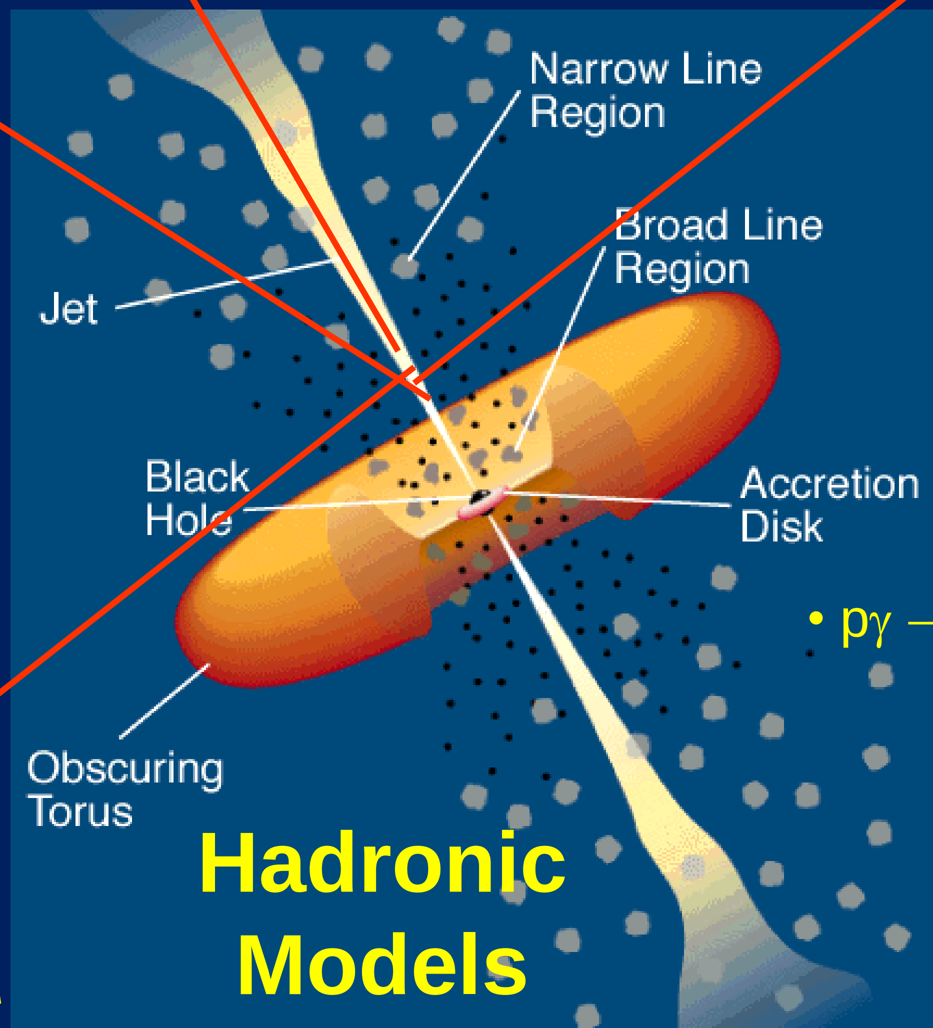
Injection, acceleration of ultrarelativistic electrons and protons



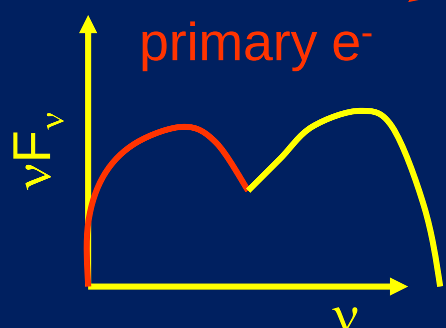
Relativistic jet outflow with $\Gamma \approx 10$

Proton-induced radiation mechanisms:





Synchrotron emission of primary e^-



- 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 …

Basics of Neutrino Production in Blazar Jets

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

  or $n + \pi^+$

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

$\pi^0 \rightarrow 2\gamma$

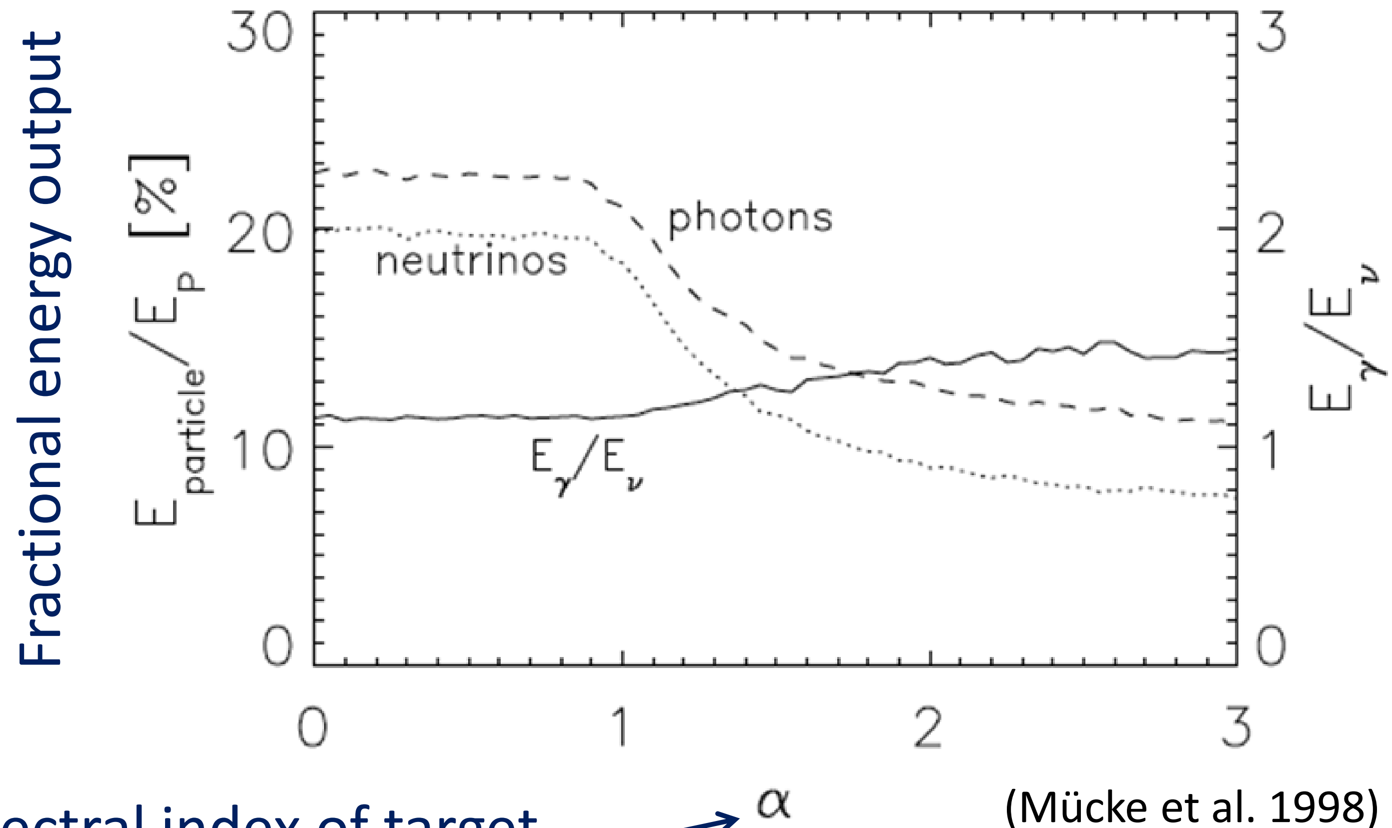
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\quad \tau = 2.55 \times 10^{-8}$ s

$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

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

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

Photo-Pion Production

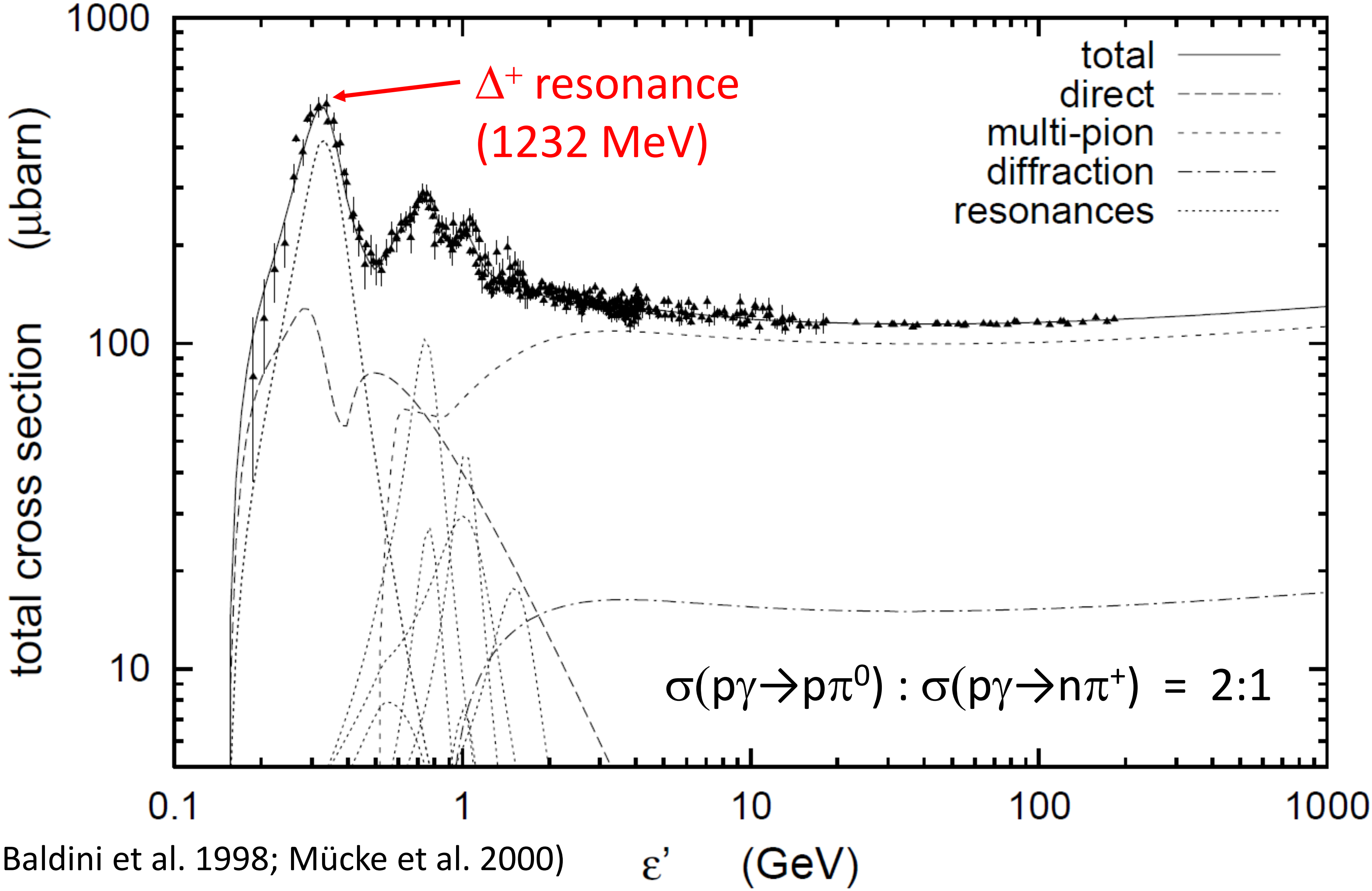


(Mücke et al. 1998)

Spectral index of target photon field

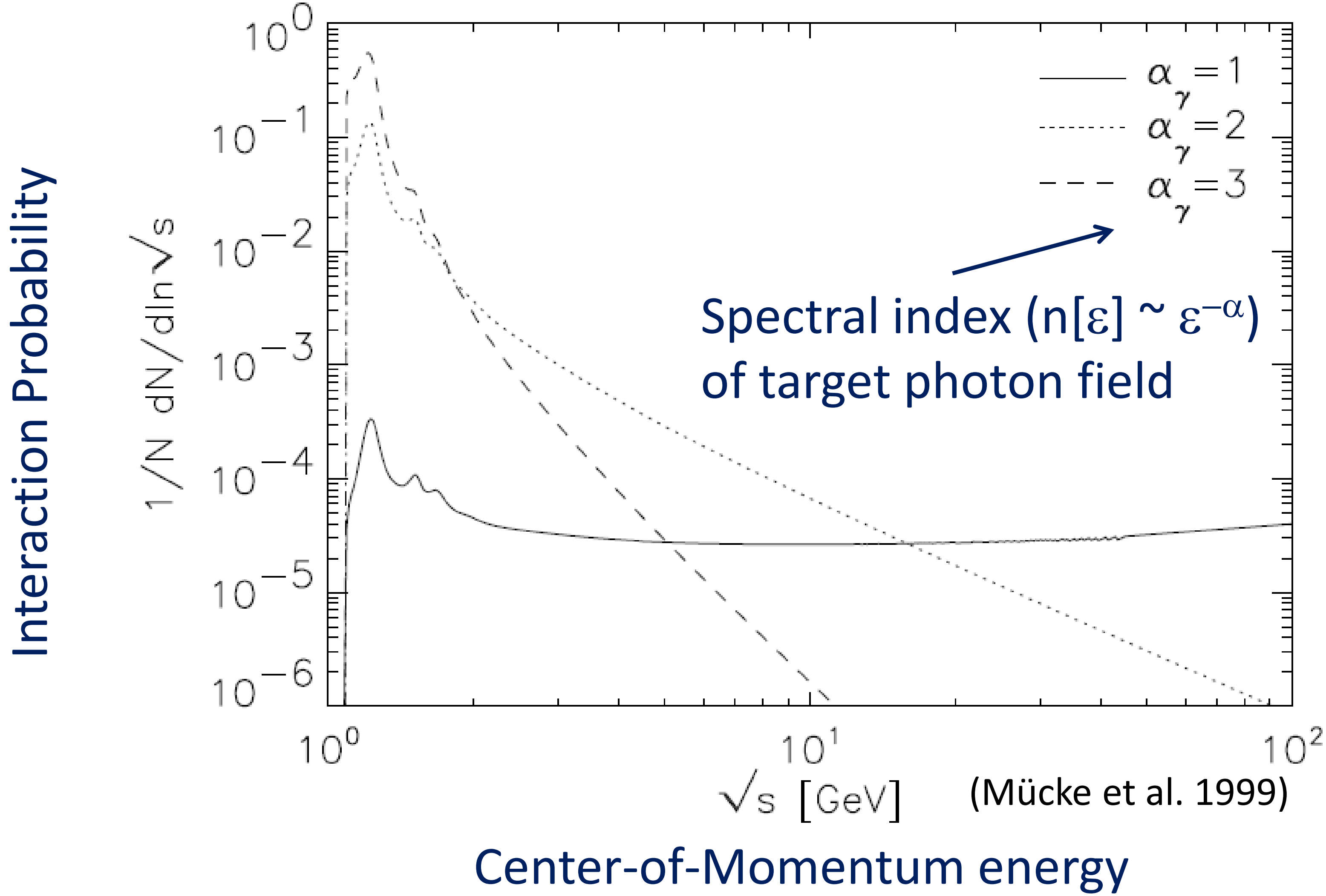
Total energy output in neutrinos is ~ approx. equal to energy output in photons (from π^0 decay + radiative losses of secondary electrons + $\mu^\pm$ + $\pi^\pm$).

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

At Δ^+ resonance:

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

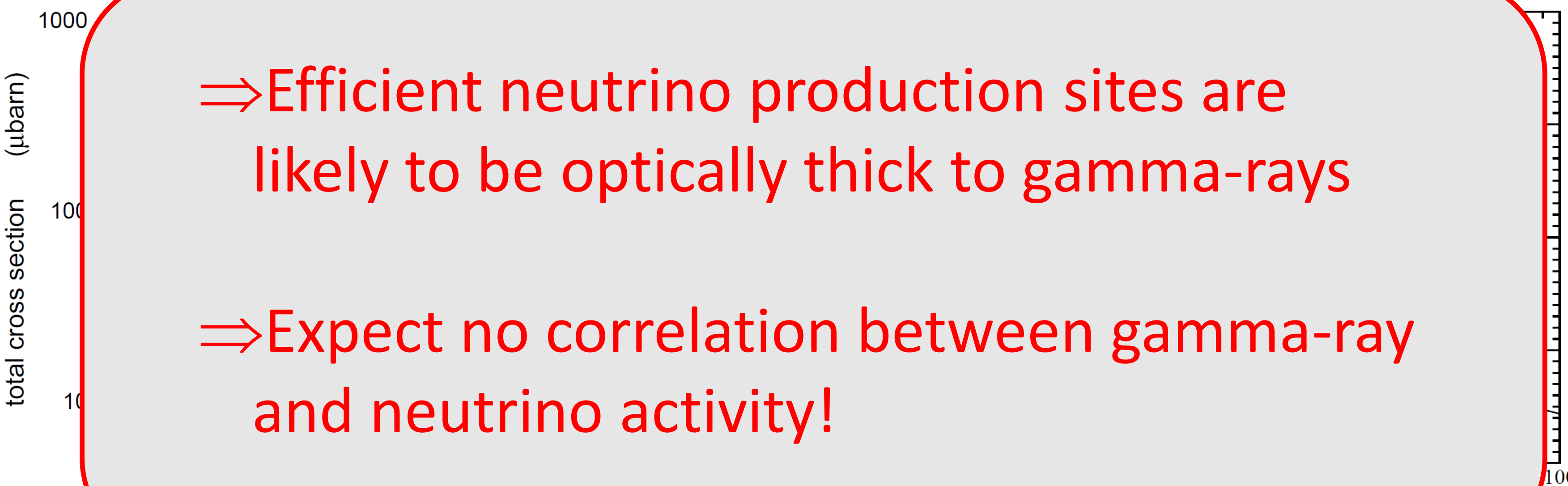
Each neutrino takes about ~ 5 % of the proton's energy

⇒ To produce IceCube neutrinos (~ 100 TeV → $E_\nu = 10^{14}\, E_{14}$ 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 → $E_\nu = 10^{14}\, E_{14}$ 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

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

⇒ 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

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

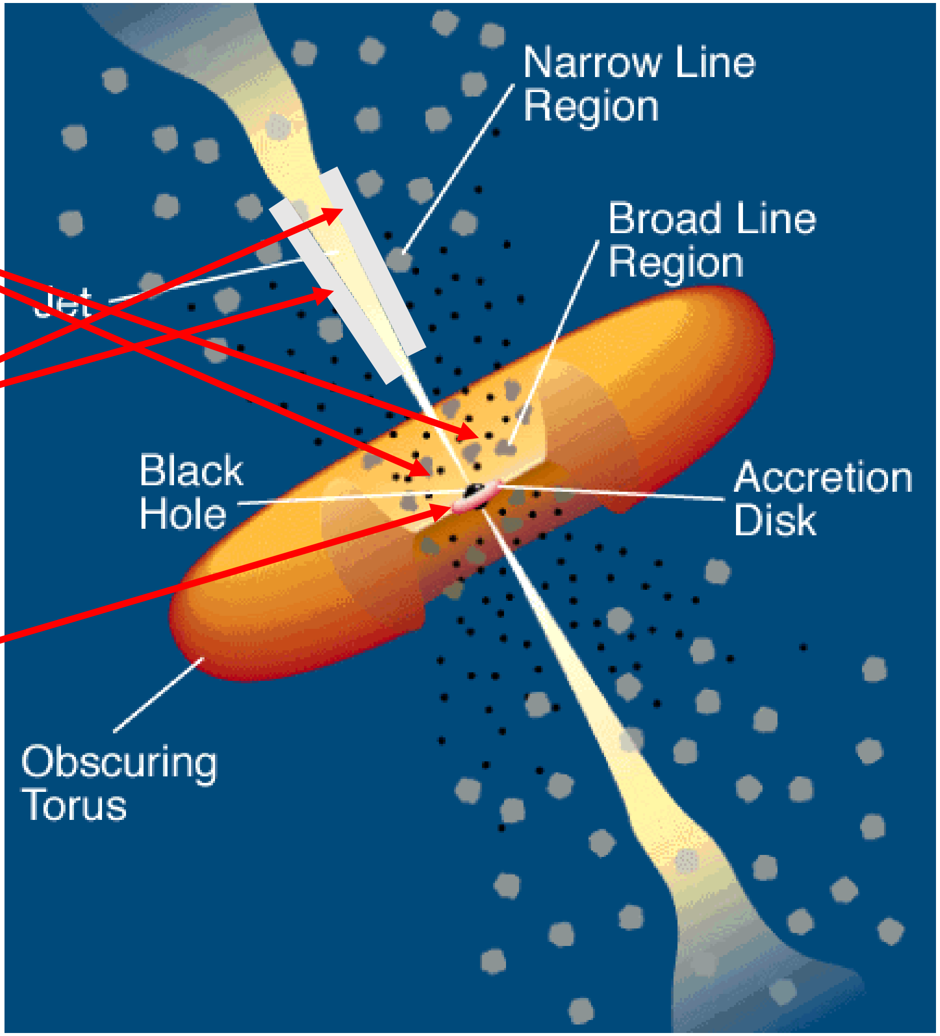
⇒ Observed as UV / soft X-rays, Doppler boosted into the emission-region frame

Much more relaxed energetics constraints.

Photo-pion production – Origin of Target Photons

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

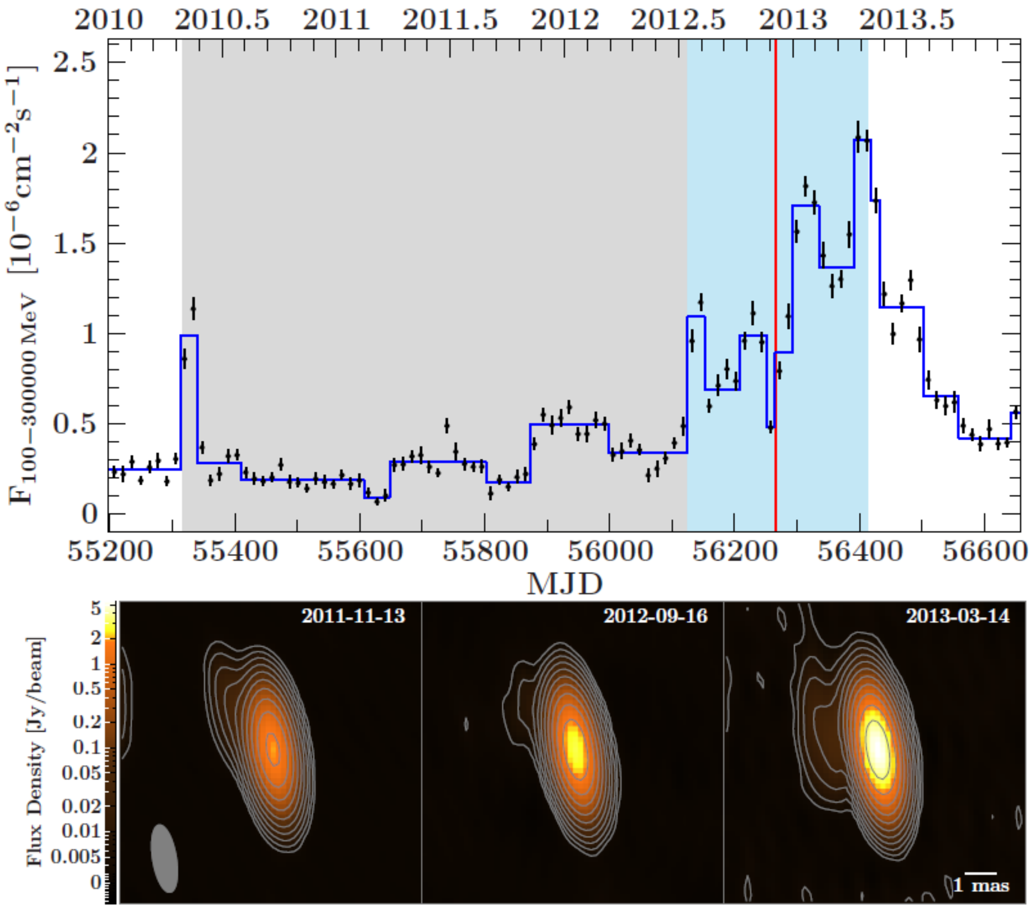
- Broad Line Region? (Padovani et al. 2019)
- Slow-moving sheath (Tavecchio & Ghisellini 2005)
- Accretion flow (RIAF) (Righi et al. 2019)



Tentative Associations of IceCube Neutrinos with Blazars

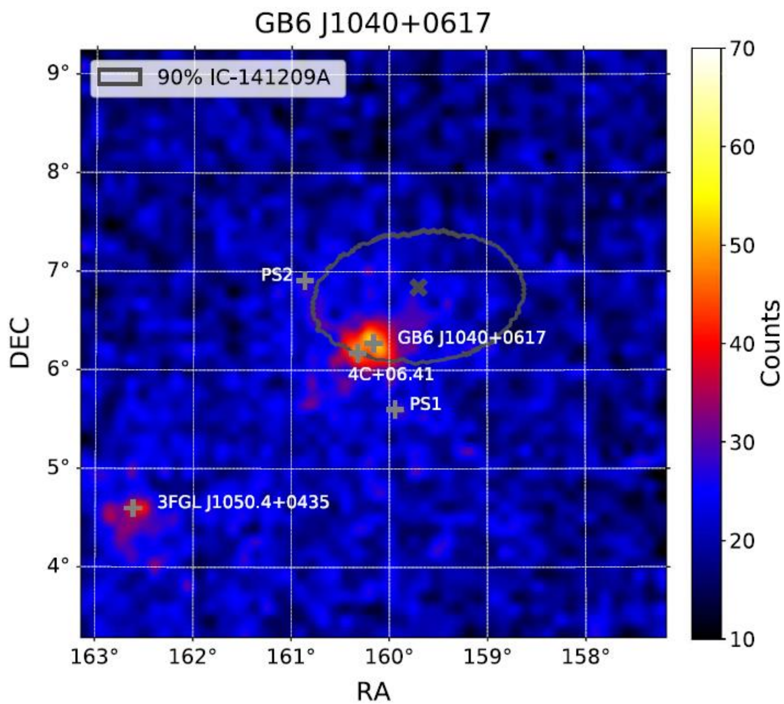
- IC-35 ("Big Bird", 2012) – PKS 1424-418 (Kadler et al. 2016)

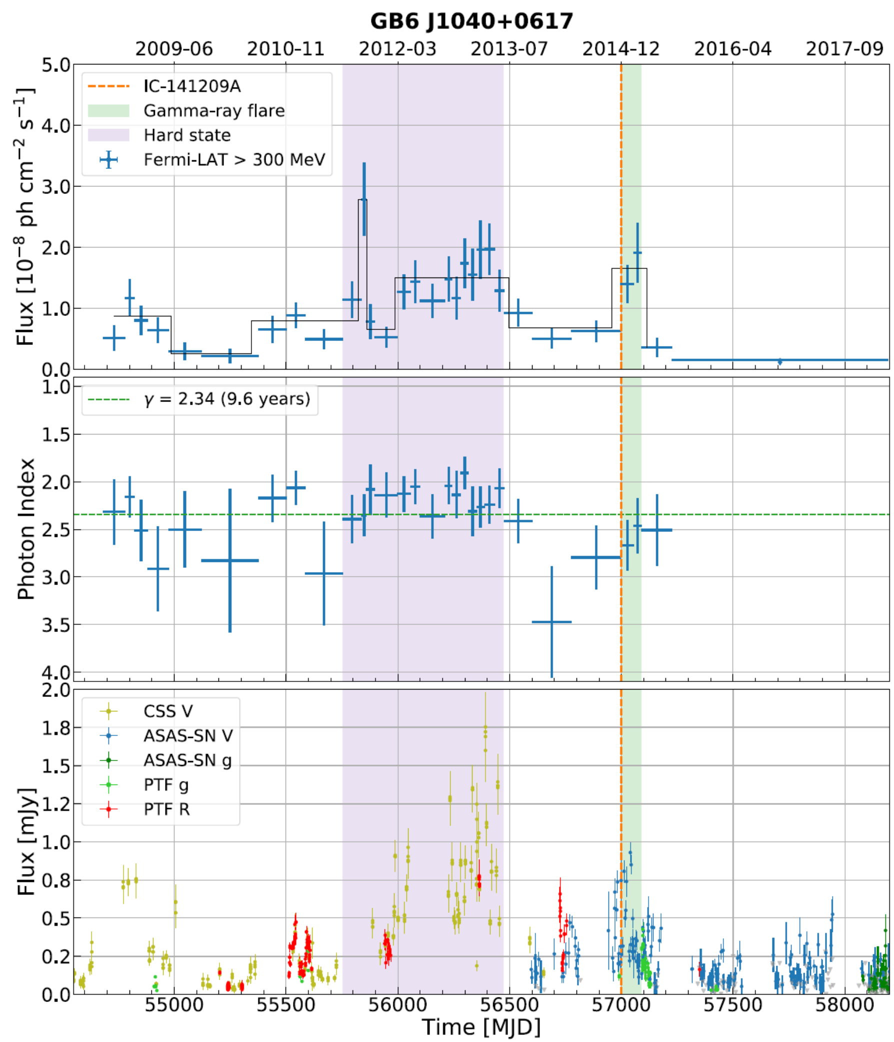
  - 2 PeV neutrino (HESE) on 4 December 2012
  - Poorly reconstructed arrival direction
  - FSRQ at z = 1.522
  - Year-long γ-ray, X-ray, optical, and radio outburst.
  - Radio outburst dominated by core-flux increase



Tentative Associations of IceCube Neutrinos with Blazars

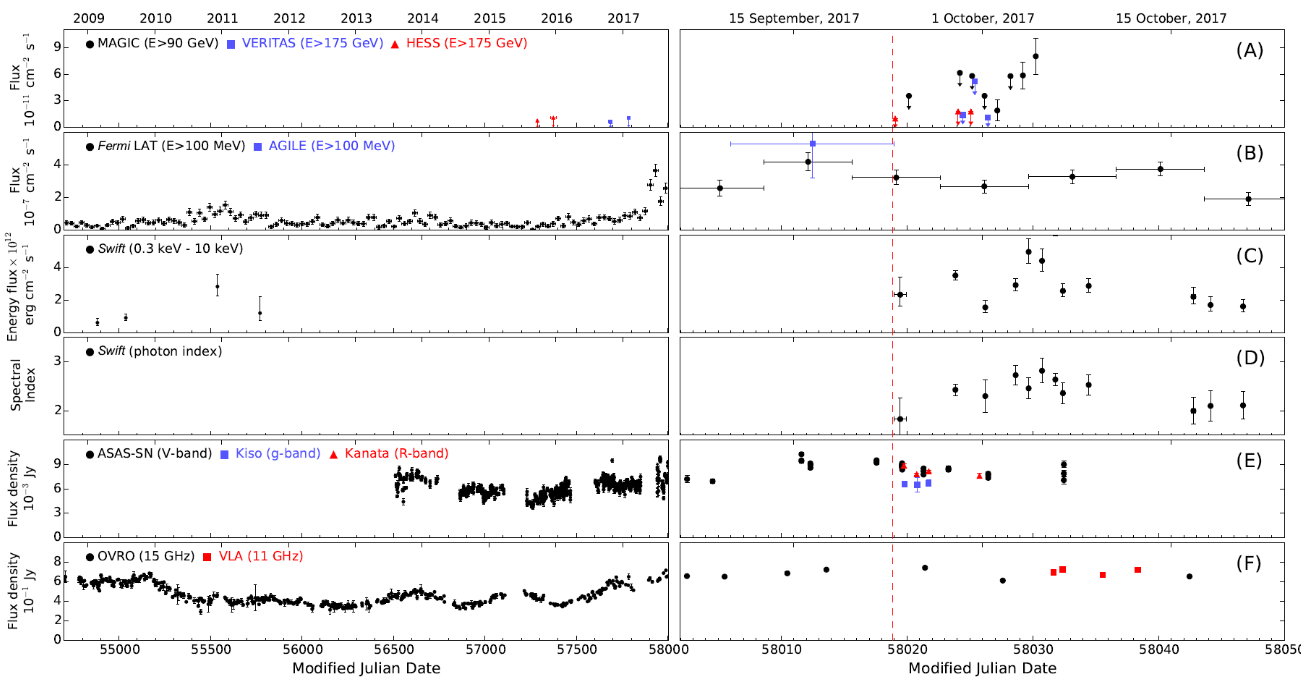
- IceCube-141209A – GB6 J1040+0617 (Garrappa et al. 2019)
  - ~ 100 TeV HESE neutrino
  - BL Lac object at z = 0.735
  - γ-ray flux increase at the time of IceCube 141209A





Tentative Associations of IceCube Neutrinos with Blazars

- IceCube-170922A – TXS 0506+056 (IceCube Collaboration et al. 2018a; Garrappa et al. 2019; Padovani et al. 2019; …)
  - 290 TeV neutrino
  - “Masquerading” BL Lac object at z = 0.3365 with weak BLR emission (Padaovani 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.

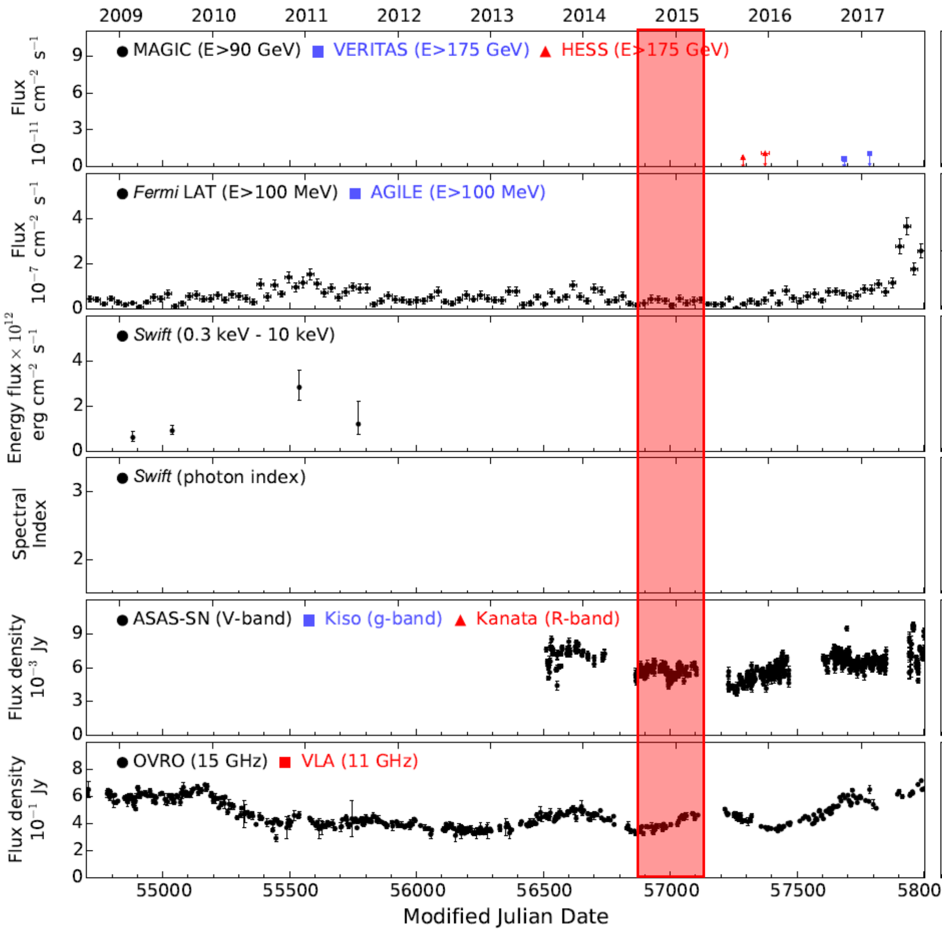
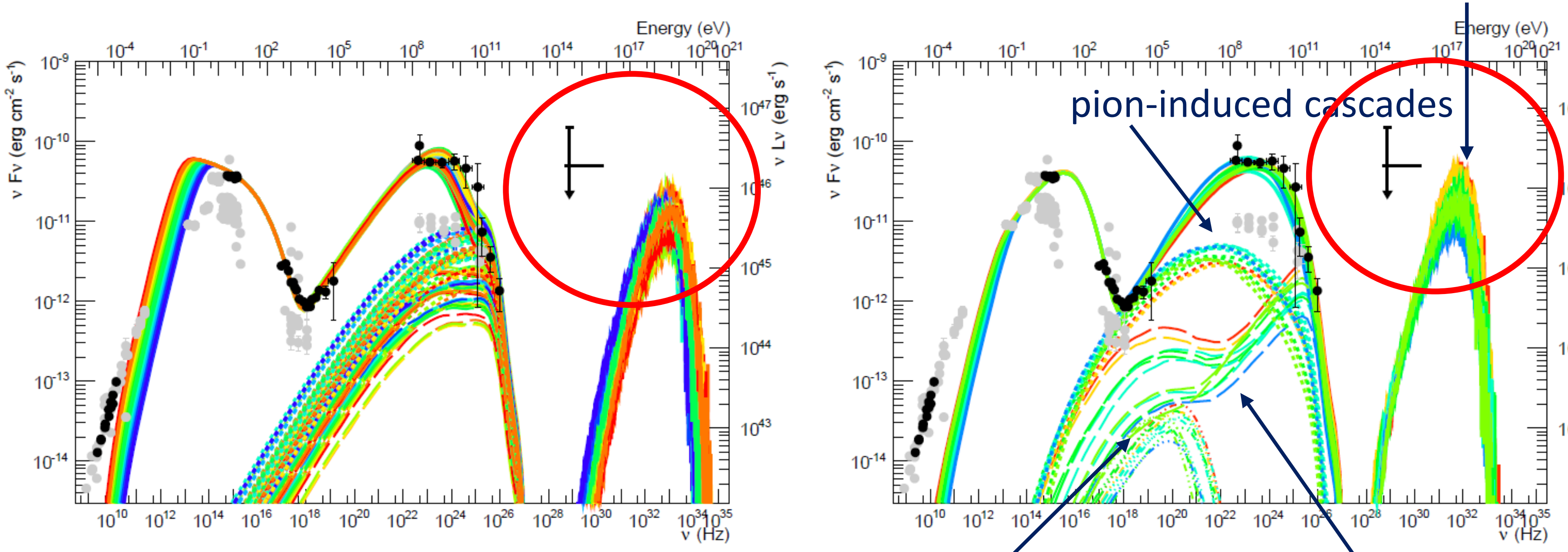


Photo-Pion Models for TXS 0506+056



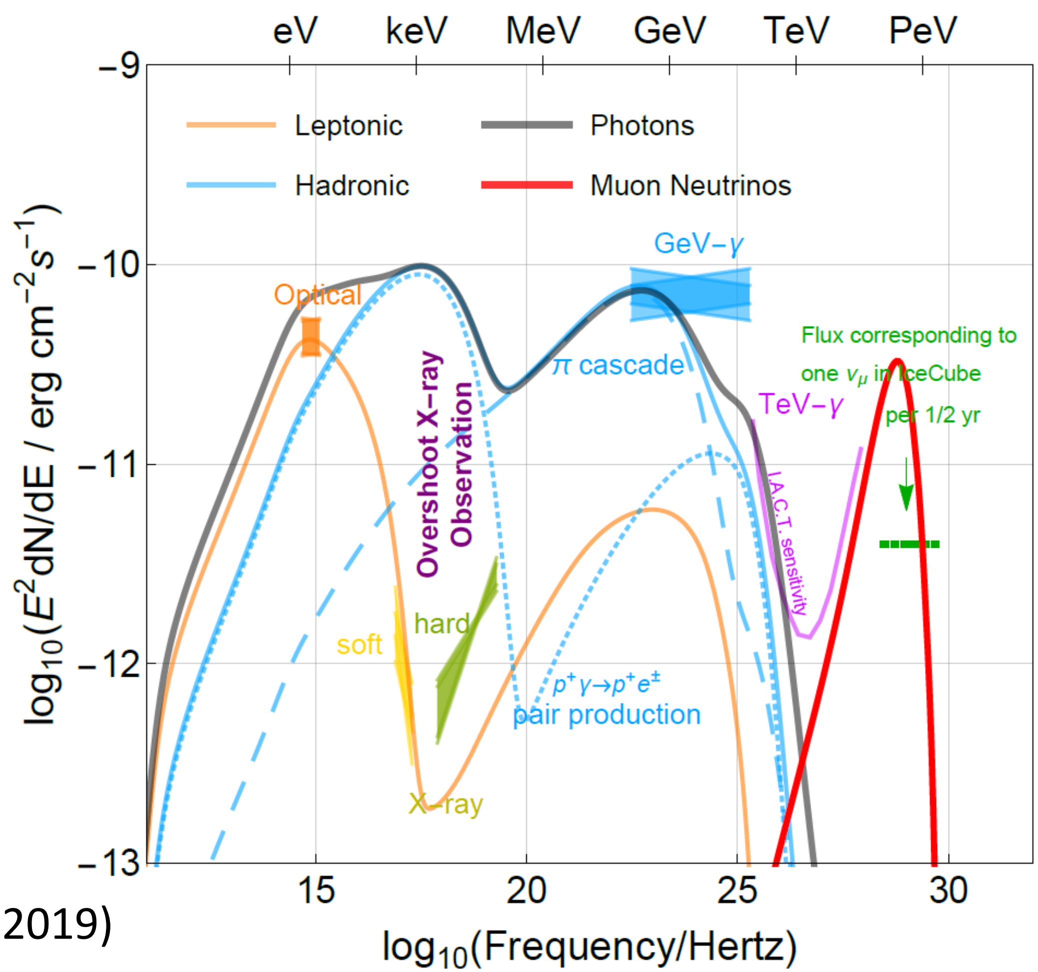
(a) Proton synchrotron modeling of TXS 0506+056

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

(Cerruti et al. 2019)

Models producing neutrinos and γ-rays by the same proton population, predict too high neutrino energies!

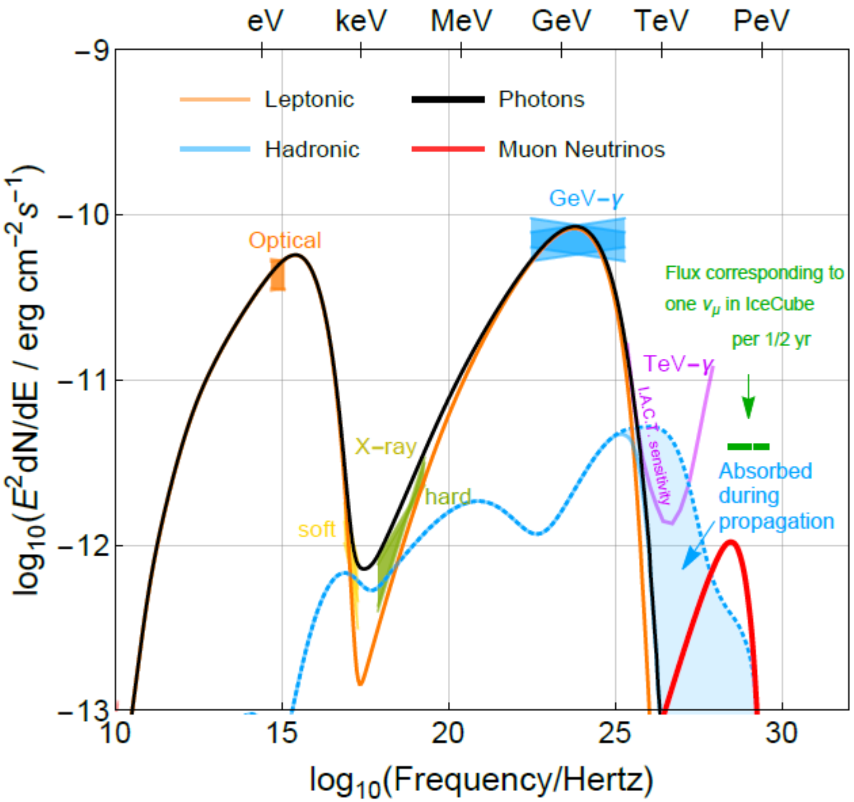
Photo-Pion Models for TXS 0506+056



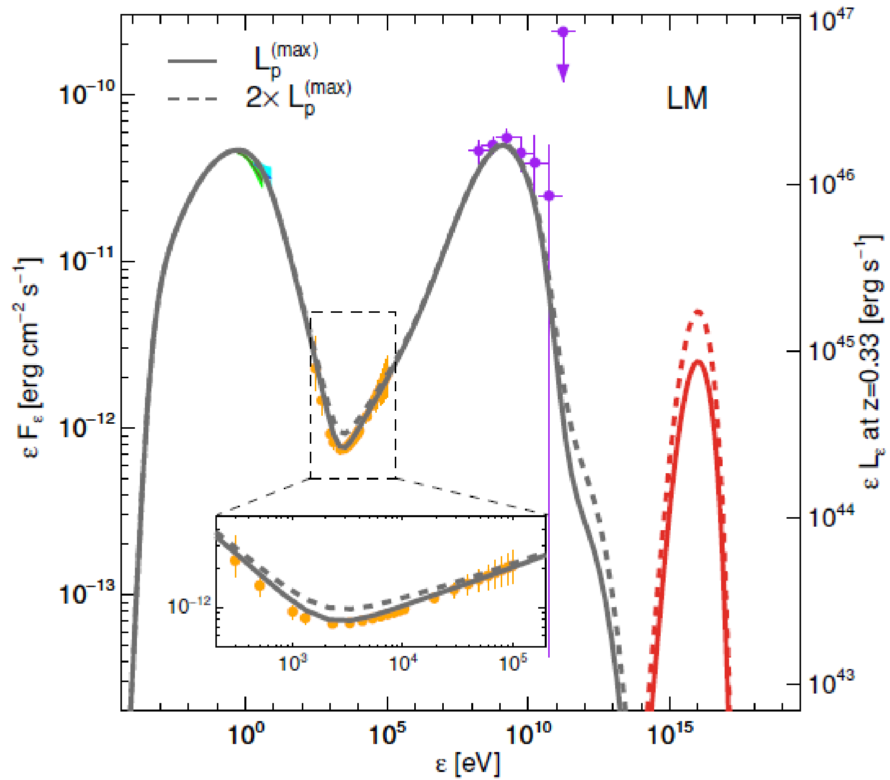
(Gao et al. 2019)

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)

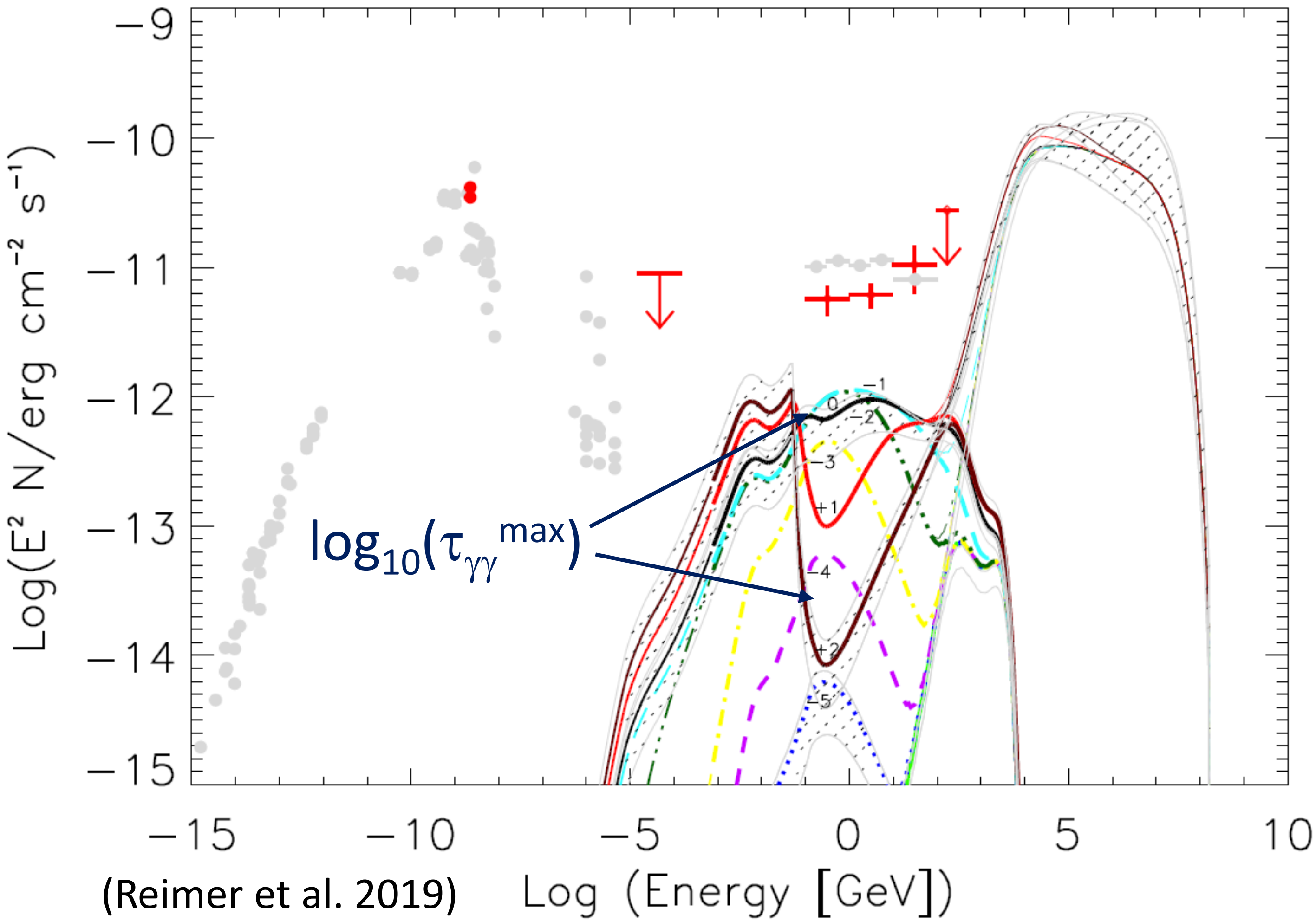


(Keivani et al. 2018)

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, $u_t' \gg u_B'$.

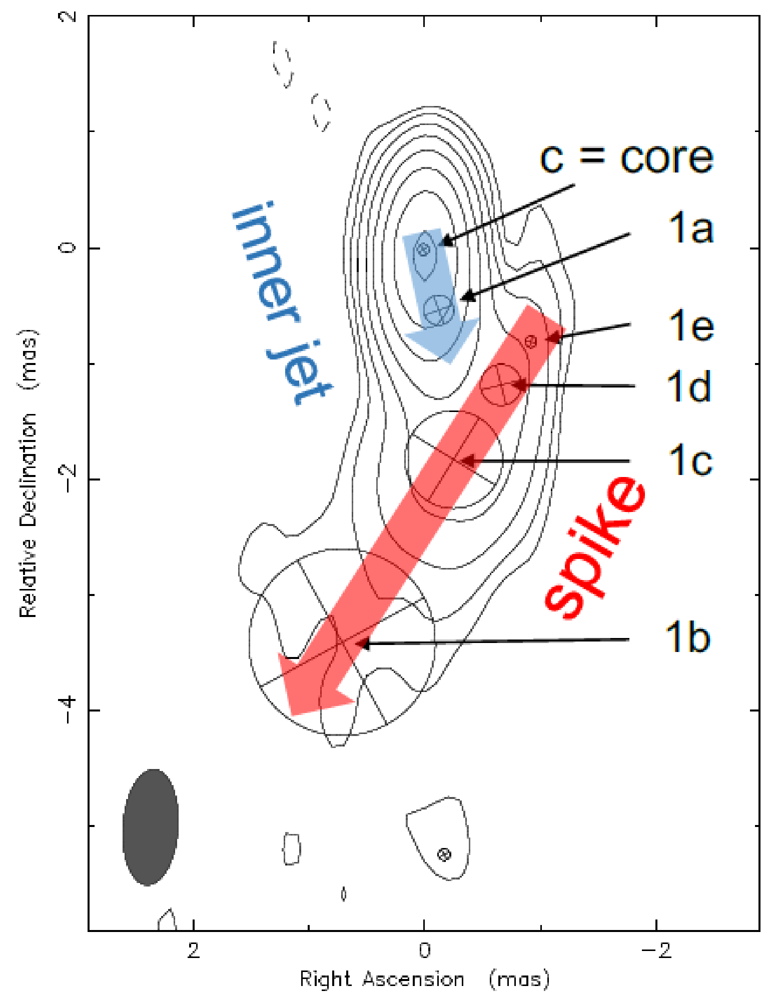
$\gamma\gamma$-absorption + Compton-supported cascades produce X-ray – γ-ray flux well below observed levels.

=> 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; …)

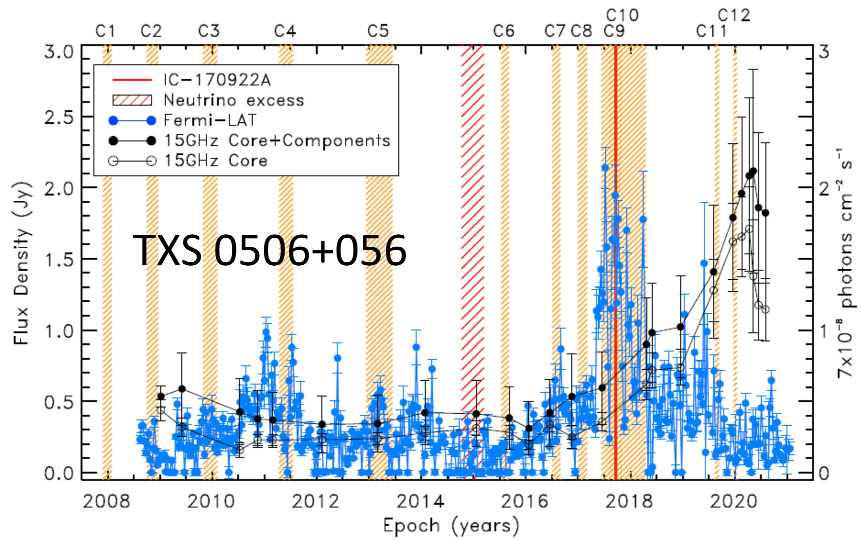
  - Radio jet structure seems reveal two, possibly radiatively interacting jets.
  - Neutrino-flare flux can be produced in case of vastly different jet speeds.

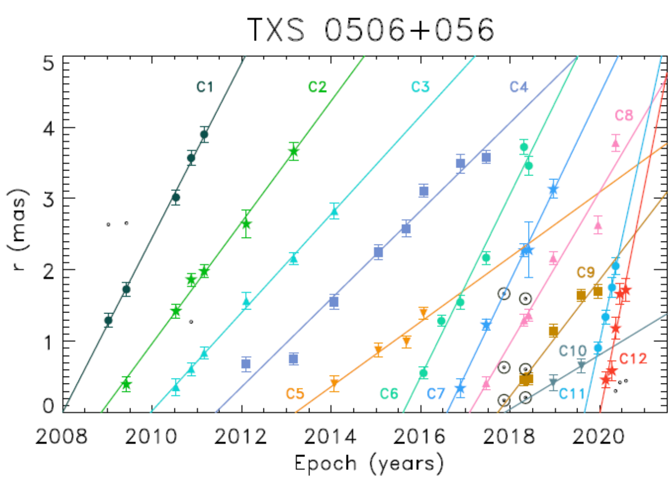


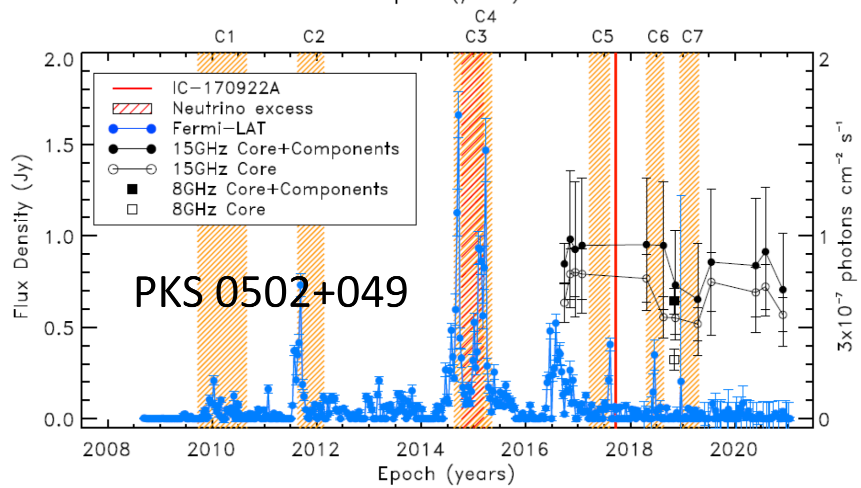
(Britzen et al. 2019)

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;

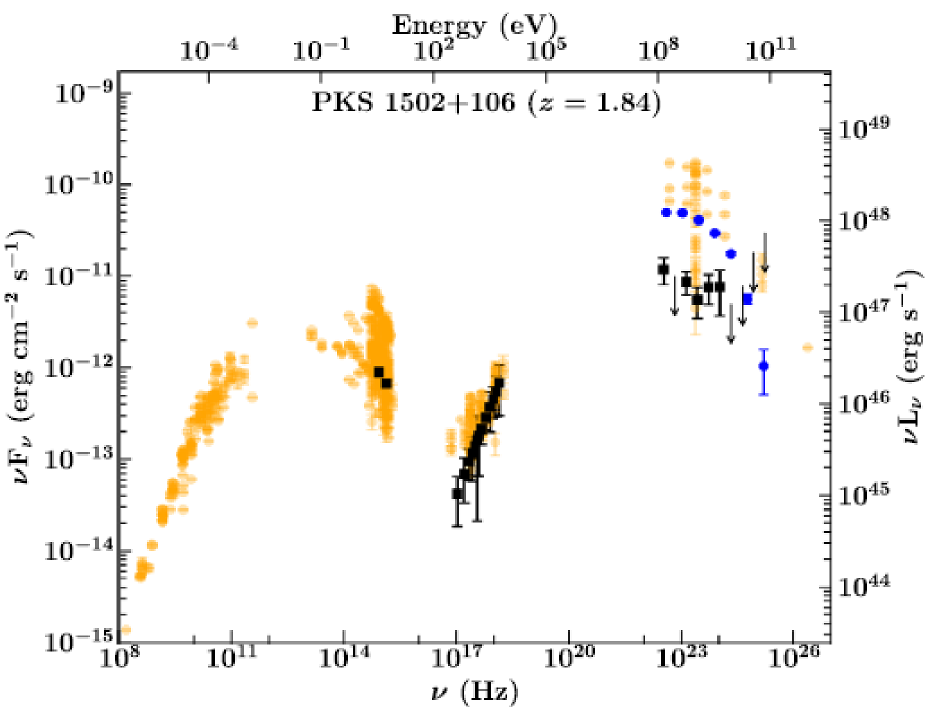
  4FGL J1750.4-1721: Unassociated.

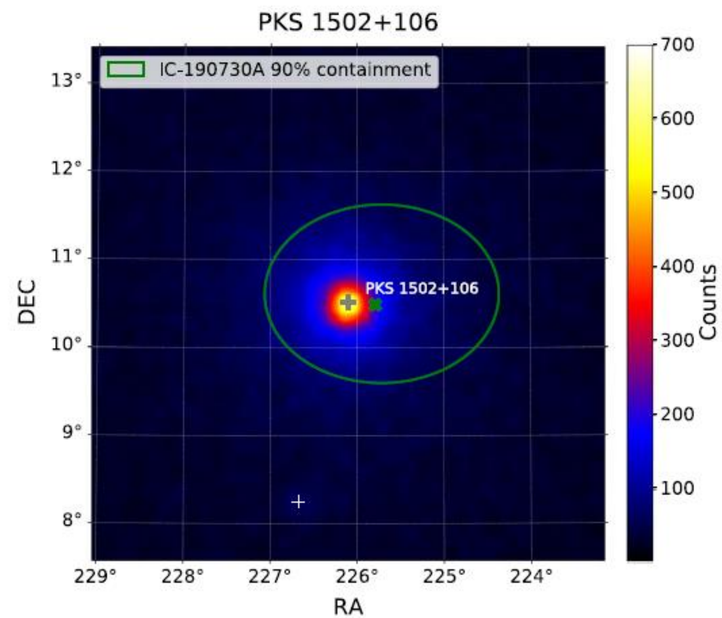
- IceCube-211208A – PKS 0735+17 (?) (Santander et al. 2021; Kadler et al. 2021; Zhirkov et al. 2021; …)

  ISP blazar at z = 0.450, high state in radio, optical, X-rays and γ-rays during the neutrino event; slightly outside the 90 % error region of IceCube-211208A.

Tentative Associations of IceCube Neutrinos with Blazars

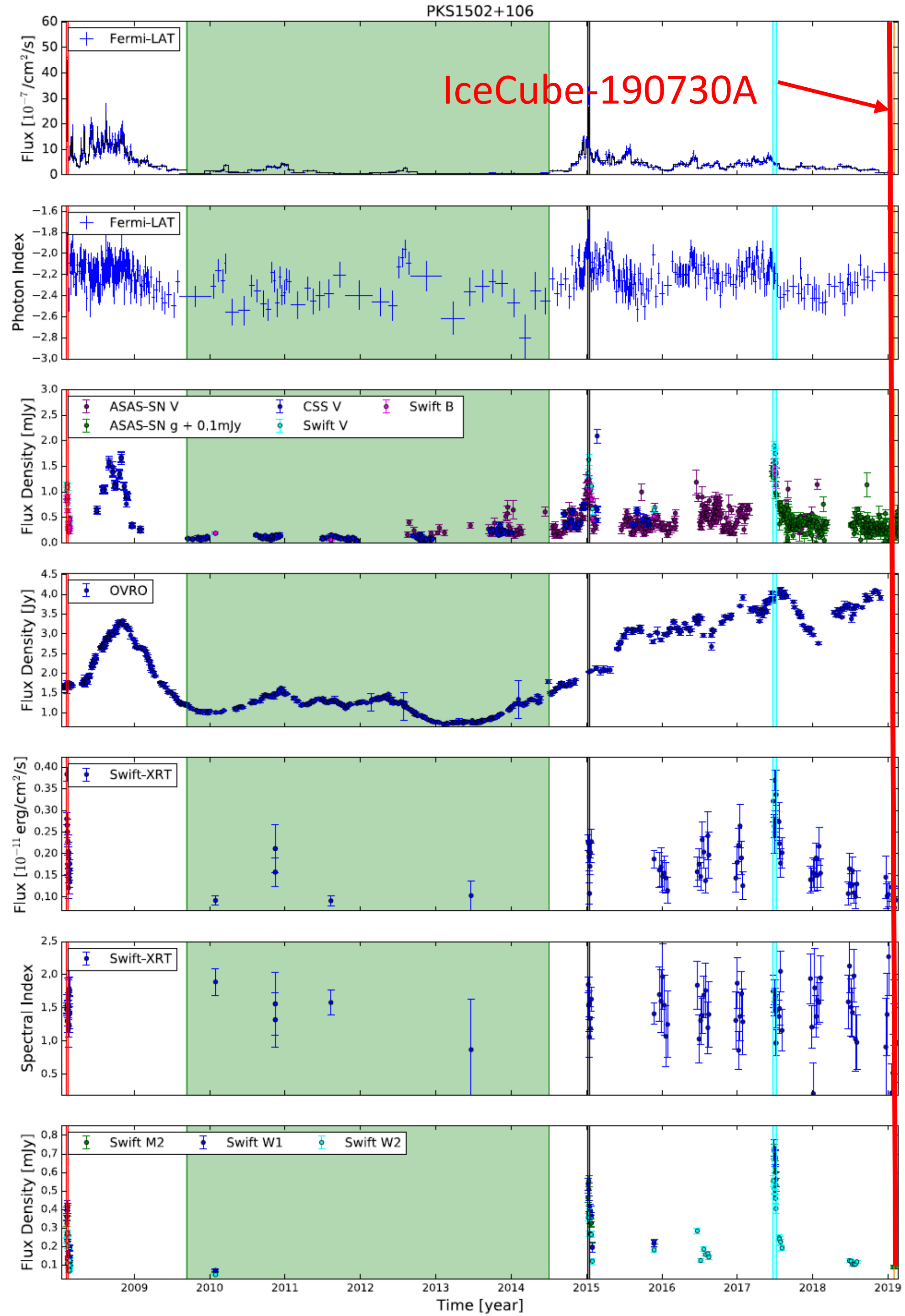
- IceCube-190730A – PKS 1502+106 (IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)
  - FSRQ at z = 1.84
  - E_ν ~ 300 TeV
  - Signalness = 67 %
  - 15th-brightest 4LAC source





(Franckowiak et al. 2020)

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



- Neutrino event during a long-term radio outburst

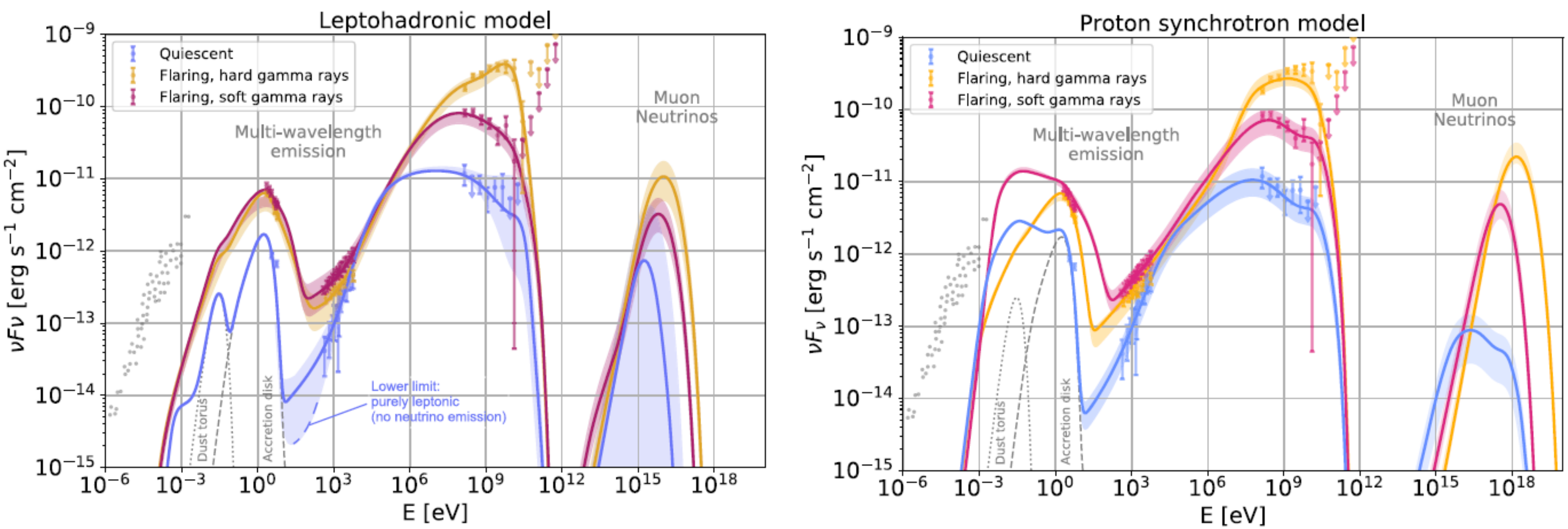
  (started 2014), but low

  γ-ray activity

(Franckowiak et al. 2020)

Tentative Associations of IceCube Neutrinos with Blazars

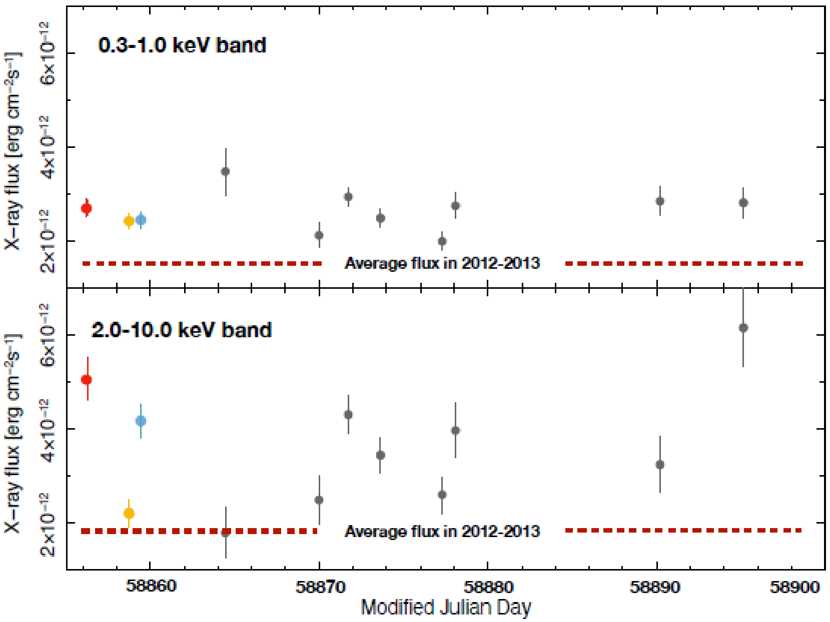
- IceCube-190730A – PKS 1502+106 (IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)
  - Study of different hadronic and lepto-hadronic models of multi-messenger emission of PKS 1502+106 by Rodrigues et al. (2021):
  - Models with hadronically dominated X-ray / γ-ray emission consistent with detection of 1 neutrino during the quiescent γ-ray state.

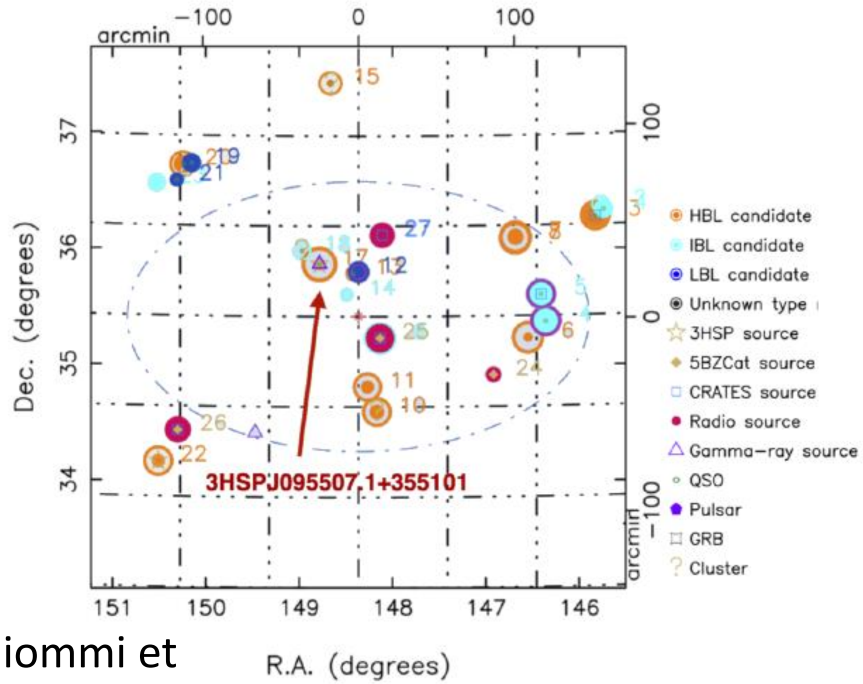


(Rodrigues et al. 2021)

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)

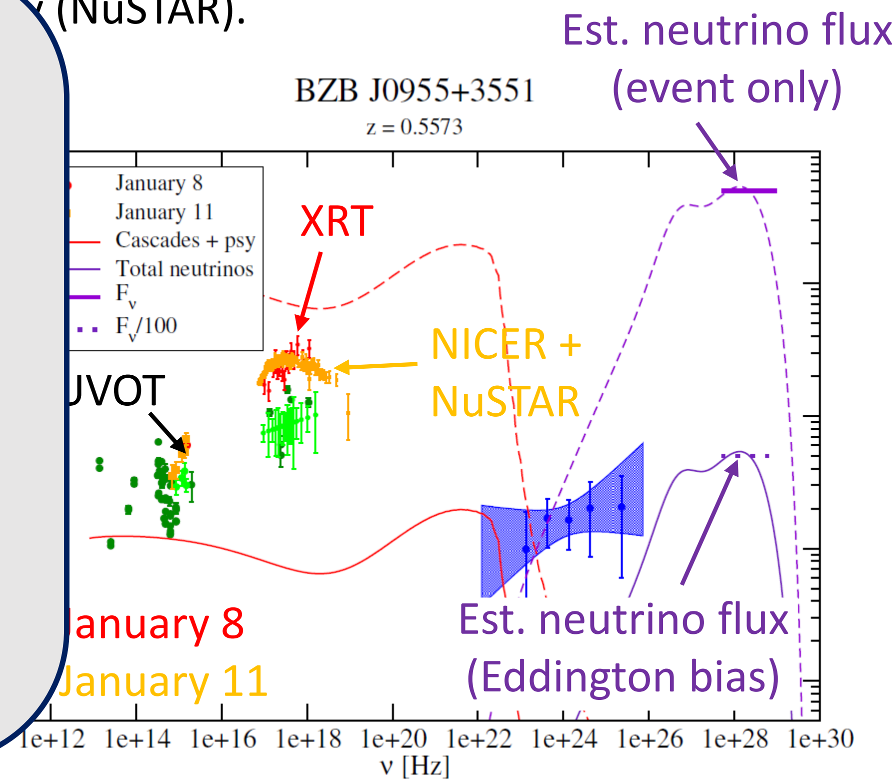
- One other γ-ray blazar in the 90 % uncertainty region: 4FGL J0957.8+3423, but no flux enhancement in any band. (Krauss et al. 2020)

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.

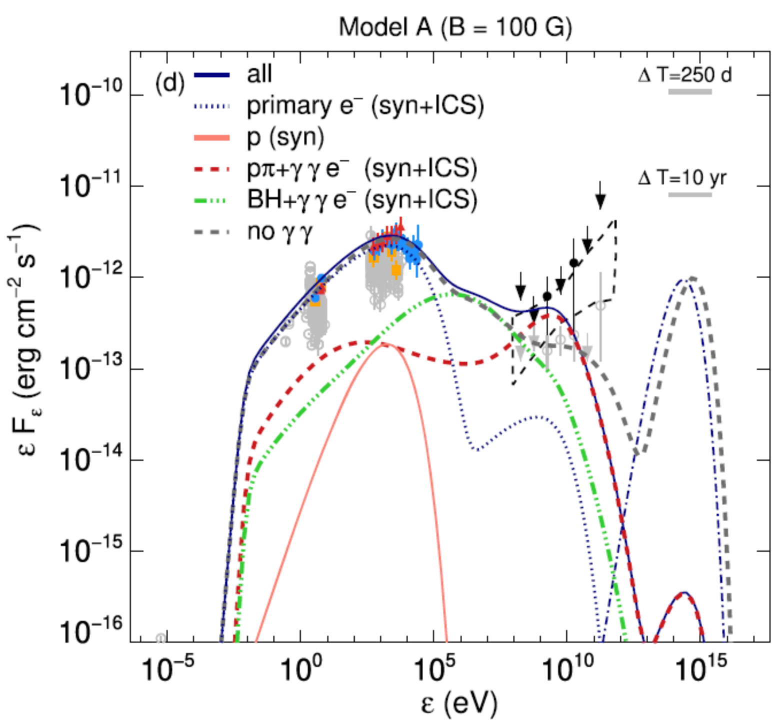
N ~ 100 for a 3HSP J09907.9+35510 like source (Franckowiak et al. 2020).



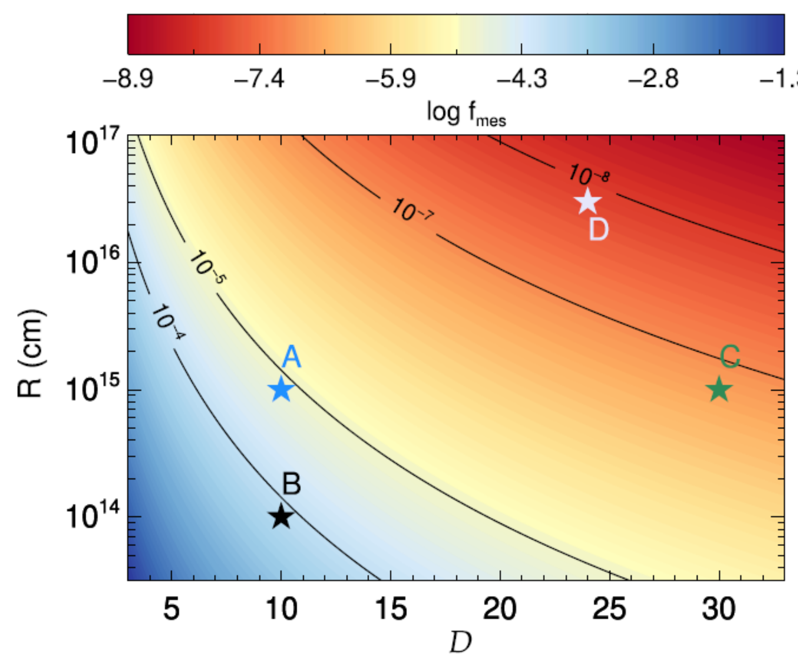
(Paliya et al. 2020)

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



$f_{mes} = t_{lc}/t_{p\gamma}$



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

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.

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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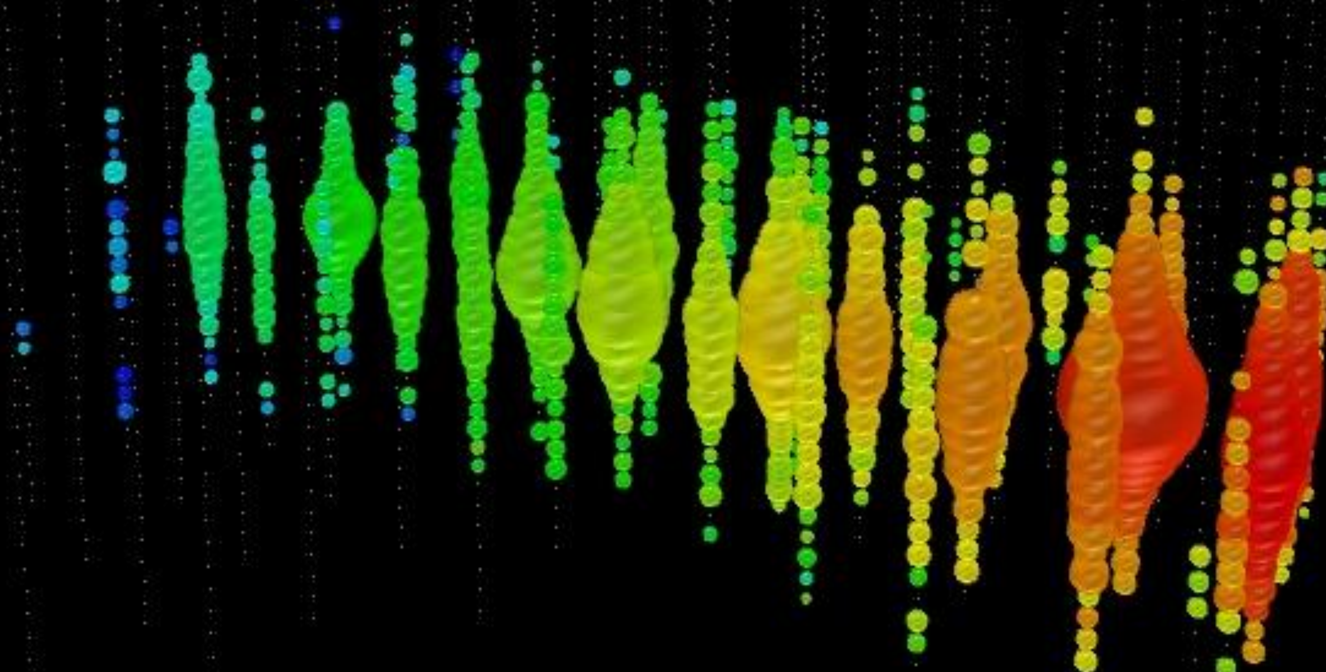
Thank you!



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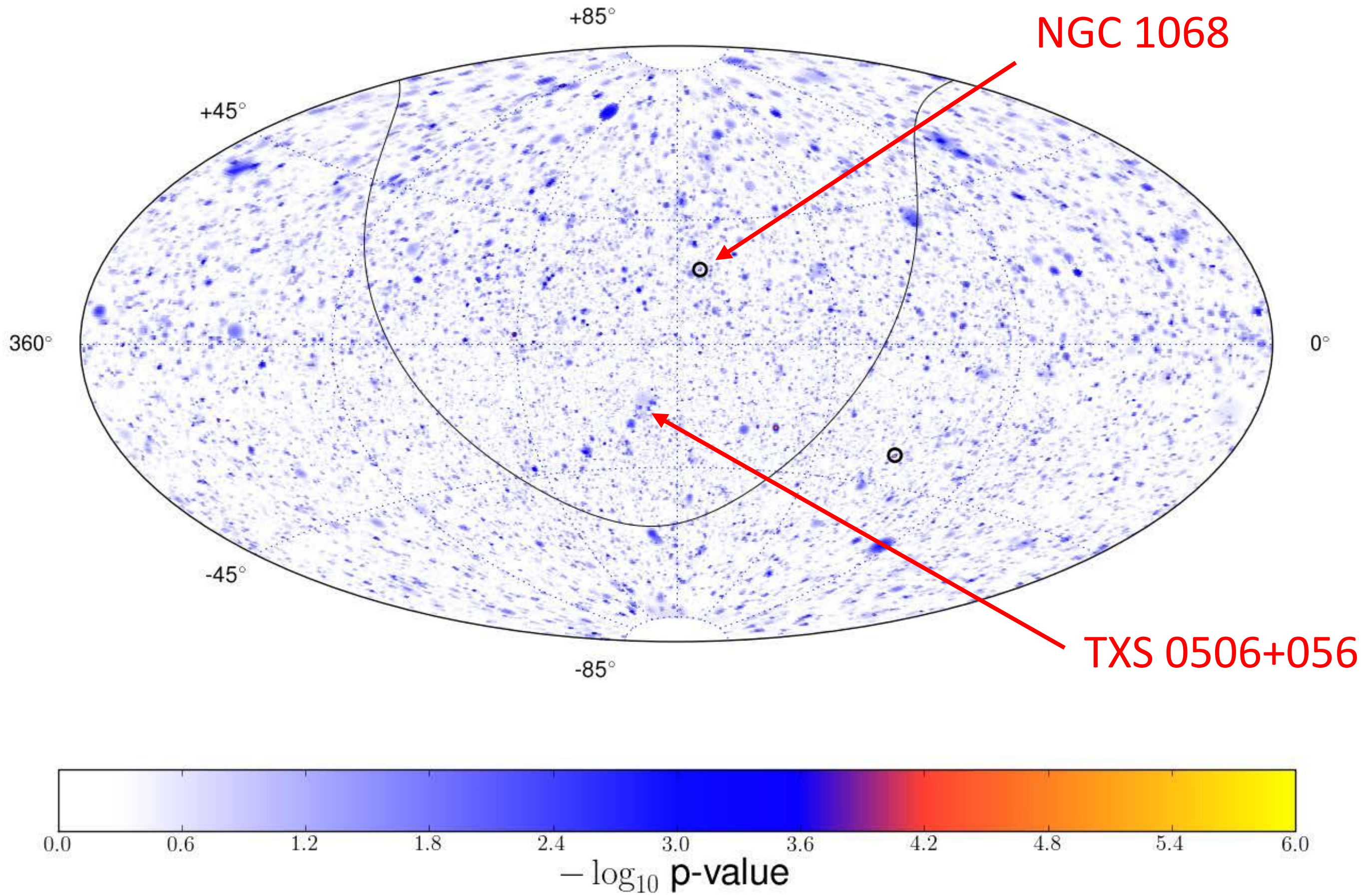
Backup Slides

IceCube-Detected Neutrinos

All-Sky Map



3.3 σ evidence of a cumulative excess of events from 110 potential sources, primarily driven by 4 active galactic nuclei (AGN):

NGC 1068 (Seyfert),

TXS 0506+056, PKS 1424+240, GB6 J1542+6129 (blazars)

Basics of Neutrino Production

- $p + p\ (N) \rightarrow p + p\ (N) + \pi^0$
  or $p + n\ (N') + \pi^+$ $\quad (\sigma_{pp} \sim 0.1\ \mathrm{mb})$

- $p + \gamma \rightarrow p + \pi^0 \quad (2/3)$
  or $n + \pi^+ \quad (1/3)$ $\quad (\sigma_{p\gamma} \sim 0.6\ \mathrm{mb})$

$$\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 3 \times 10^{12} \frac{L_{sy,44}}{\varepsilon_{-6}\, \delta_1^4\, L_{j,46}}$$

$$n_{ph} \sim \frac{L_{sy}}{\delta^4 < \varepsilon > m_e c^2\, 4\pi R^2 c} \sim 3 \times 10^{18}\, \varepsilon_{-6}^{-1} R_{16}^{-2} L_{sy,44}\, \delta_1^{-4}\, cm^{-3}$$

$$n_p \leq \frac{L_j}{m_p c^2 \pi R^2 c} \sim 10^6 R_{16}^{-2} L_{j,46}\, cm^{-3}$$

In AGN jets, p-γ interactions strongly dominate over p-p.

Photo-pion production - Energetics

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

$\Rightarrow \gamma'_p \sim \gamma'_e \sim \gamma_\pi \sim 2\times10^5\ E_{14}\ \delta_1^{-1} \equiv 10^6\ \gamma_6$ ($\gamma_6 > 0.2$)

<u>γ-ray production through:</u>

a) π^0 decay: $\nu_{\pi 0} \sim 1.7\times10^{29}\ \delta_1\ \gamma_6$ Hz (~ 700 TeV)

b) Proton synchrotron at

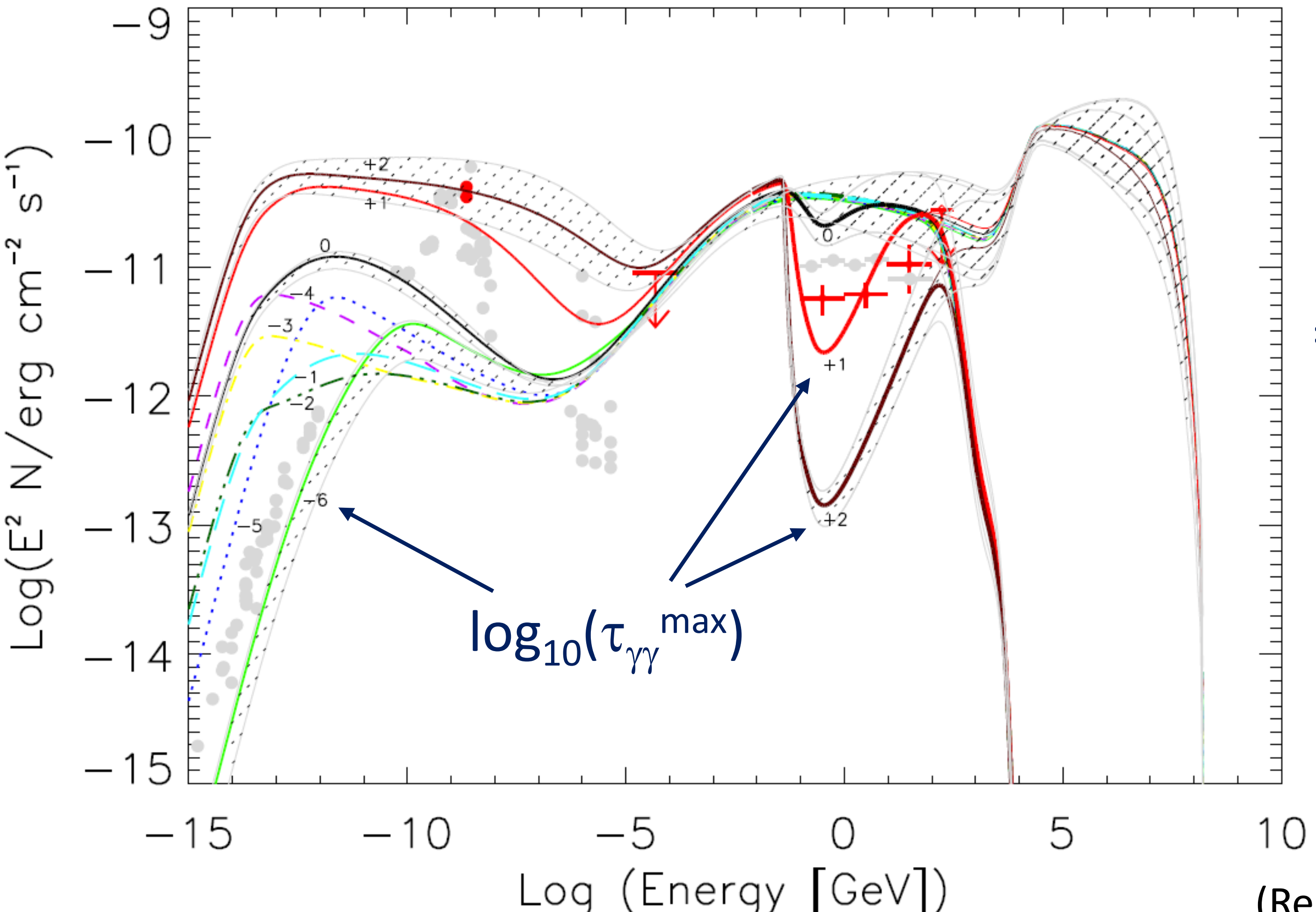
$\nu_{psy} \sim 2\times10^{18}\ \gamma_6^2\ B_2\ \delta_1$ Hz (~ 10 keV)

c) Secondary electron synchrotron at

$\nu_{esy} \sim 4\times10^{21}\ \gamma_6^2\ B_2\ \delta_1$ Hz (~ 20 MeV)

$\Rightarrow$ Protons producing IceCube neutrinos will not produce gamma-rays through proton synchrotron or secondary-electron synchrotron!

Synchrotron Supported Cascades



Need
$u_t' \ll u_B'$
$= 4\ B_1^2$ erg / cm^3

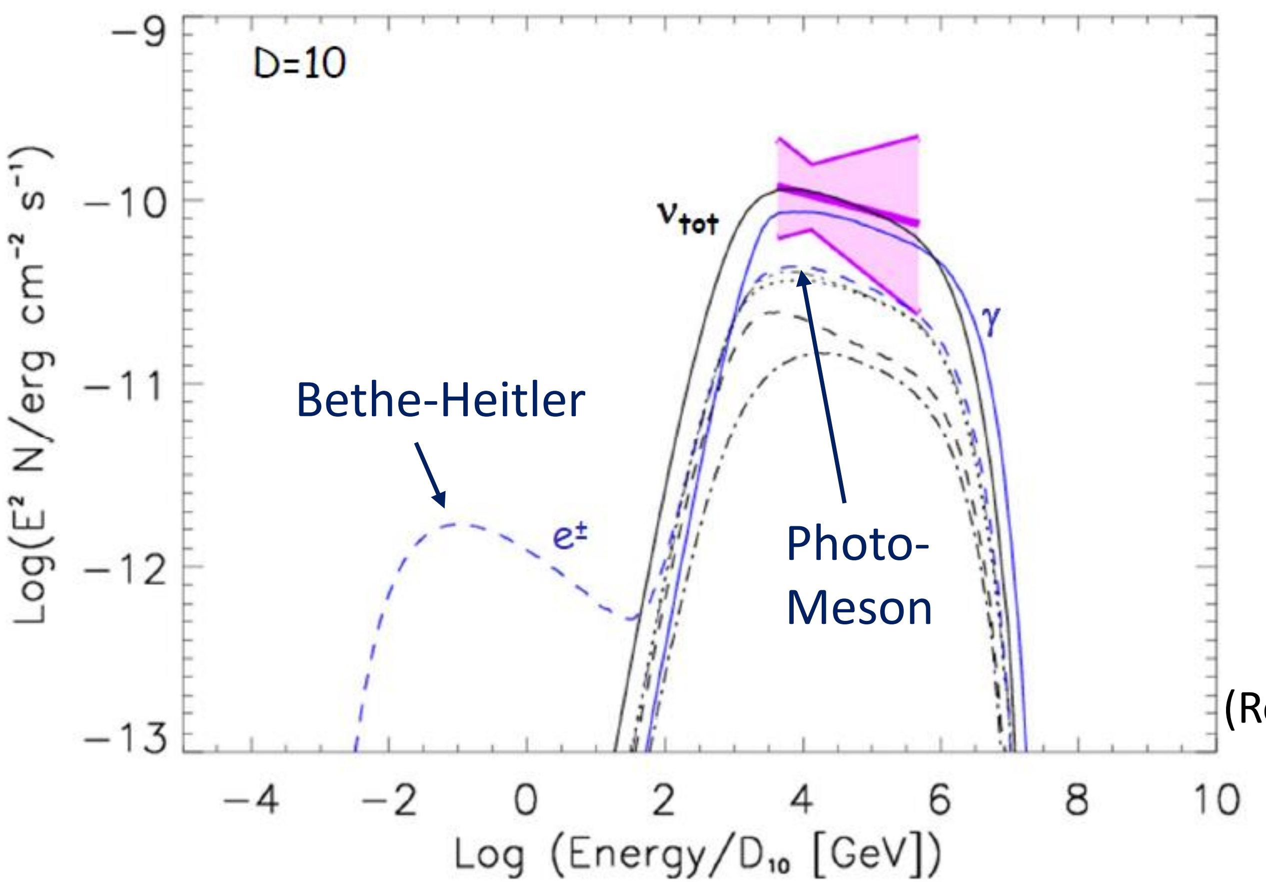
(Reimer et al. 2019)

Ruled out by MWL spectra

(over-predicting either Fermi-LAT or X-ray / radio fluxes)

Constraints from Cascades

1) Find mimimum target photon fields + proton spectra to produce IceCube neutrino flux from TXS 0506+056 neutrino flare.



(Reimer et al. 2019)

- Target photons: $n_{ph}(\varepsilon) \sim \varepsilon^{-\alpha}$, ε_{min} = 10 keV, ε_{max} = 60 keV, α = 1
- Proton spectrum: n_p (E) ~ $E^{-\alpha_p}$, E_{max} = 30 PeV, α_p = 2.0

Spectral Energy Distribution of TXS 0506+056

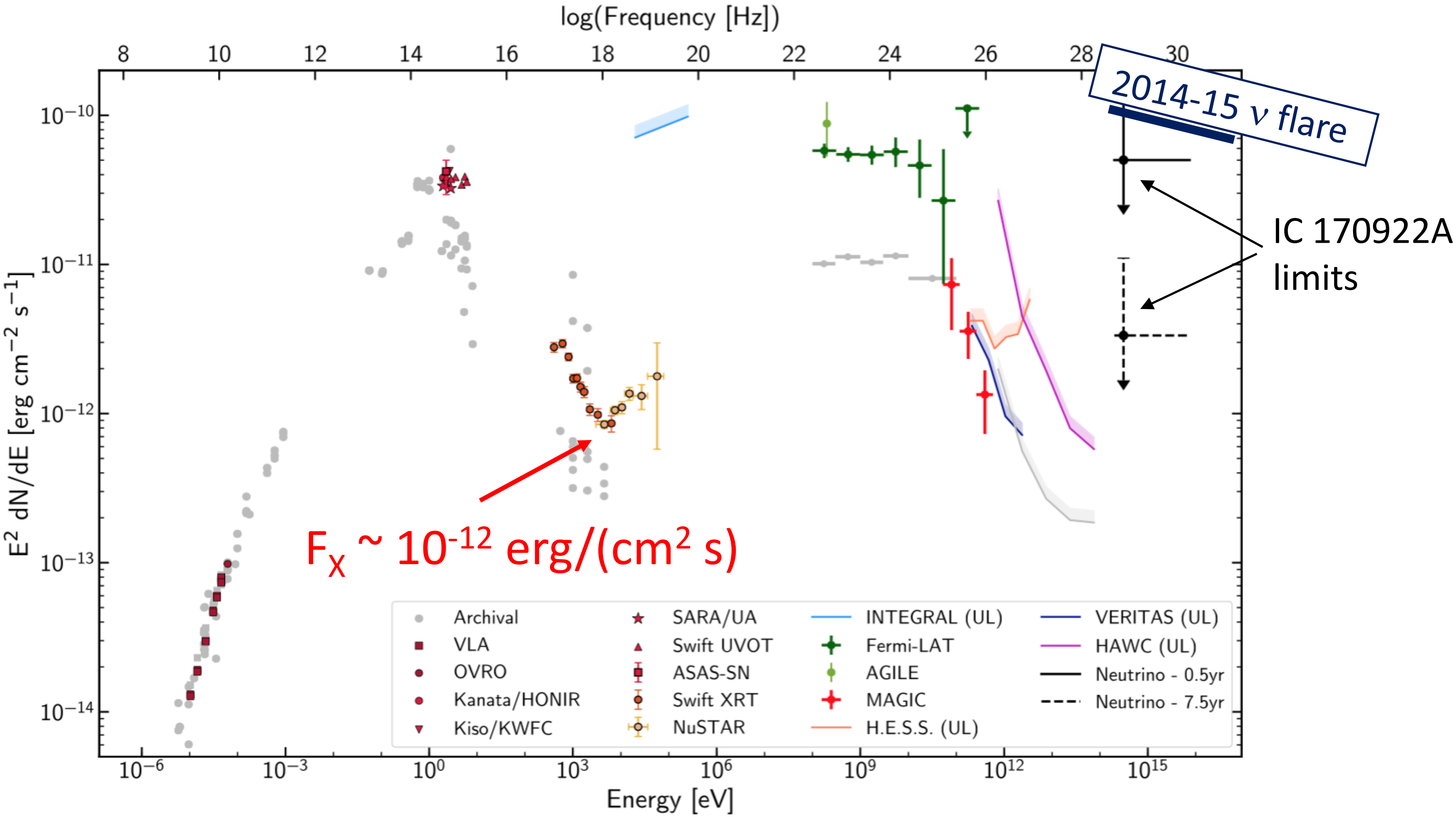


Photo-pion production – Origin of Target Photons

Constrain target photon luminosity and required proton power from

- observed neutrino luminosity ($L'_\nu \sim 1.7\times10^{42}\, \delta_1^{-4}$ erg/s for 2014 – 15 neutrino flare)
- limit on observed UV / X-ray flux ($F_x \sim 10^{-12}$ erg cm^{-2} s^{-1} for TXS 0506+056)

$$L'_\nu \approx \frac{1}{2} N_0\, m_p c^2 \int_{\gamma_1}^{\gamma_2} \gamma_p^{-\alpha_p}\, |\dot{\gamma}_{\mathrm{p,p}\gamma}|\, d\gamma_p \approx 1.3\times10^{-14}\, N_0\, u'_t\, \mathrm{cm}^3\, \mathrm{s}^{-1}$$

$N_0 u'_t \rightarrow L_{kin,p}$

$$\dot{\gamma}_{p,\,p\gamma} \approx -c \underbrace{<\sigma_{p\gamma} f>}_{\approx 10^{-28}\,\mathrm{cm}^2} \frac{u_t{}'}{m_e\, c^2}\, \gamma_p$$

$u_t{}' \rightarrow F_{X/UV} = \dfrac{u_t{}'\, R^2\, \delta^4\, c}{d_L{}^2}$

Photo-pion production – Origin of Target Photons

a) Co-moving target photon field

X-ray flux limit => $u'_t < 9\times10^{-4}\ R_{16}^{-2}\ \delta_1^{-4}$ erg cm^{-3}

$\Rightarrow$ Synchrotron-supported cascades (already ruled out)

$L_{p,kin} \sim 1.6\times10^{54}\ R_{16}\ \Gamma_1^{2}$ erg/s

$\Rightarrow$ Unrealistically large kinetic power;
requires very low B-field (B < 1 G) to suppress proton synchrotron below X-ray flux limit

=> Ruled out!

Photo-pion production – Origin of Target Photons

b) Stationary target photon field

From UV / X-ray flux: $u'_t < 100\ \Gamma_1^2\ R_{t,17}^{-2}$ erg cm^{-3}

$\Rightarrow$ Compton dominated cascades for B << 100 G 

$L_{p,kin} \sim 1.5\times10^{49}\ \delta_1^{-4}\ R_{t,17}^{2}\ R_{16}^{-1}$ erg/s

Below Eddington limit for $M_{BH} > 10^9\ M_0$ => plausible.

Can suppress p-sy below UV/X-ray limit for B ~ 10 G.

$\Rightarrow$ Plausible!

$\Rightarrow$ Stationary UV / soft X-ray target photon field external to the jet is plausible!