Neutrino Production in AGN

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Basics of Neutrino Production

- $p + p\ (N) \rightarrow p + p\ (N) + \pi^0$
  or $p + n\ (N') + \pi^+$

$(\sigma_{pp} \sim 0.1$ mb$)$

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

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

$$\pi^0 \rightarrow 2\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau = 2.55\times10^{-8}\ \text{s}$$

$$\pi^- \rightarrow \mu^- + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad \tau = 2.2\times10^{-6}\ \text{s}$$

$$\mu^- \rightarrow e^- + \nu_\mu + \nu_e$$

Basics of Neutrino Production

- p + p (N) → p + p (N) + π^0
  or p + n (N') + π^+ (σ_{pp} ~ 0.1 mb)

- p + γ → p + π^0 (2/3) ($\sigma_{p\gamma}$ ~ 0.6 mb)
  or n + π^+ (1/3)

$$\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 3 \times 1012 \frac{L_{sy,44}}{\varepsilon_{-6}\,\delta_1^{\,4}\, Lj_{,46}}$$

$$n_{ph} \sim \frac{L_{sy}}{\delta^4 < \varepsilon > me\, c^2\, 4\pi\, R^2\, c} \sim 3 \times 1018\, \varepsilon_{-6}^{\;-1}\, R_{16}^{\;-2}\, Ls_{y,44}\, \delta_1^{\;-4}\, cm^{-3}$$

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

Basics of Neutrino Production

⇒ In AGN environments, pγ dominant over pp or pN, assuming that targets (γ, p) are internal to the jet

See, however, Liu et al.: 1807.05113:
UHECR interactions with BLR clouds

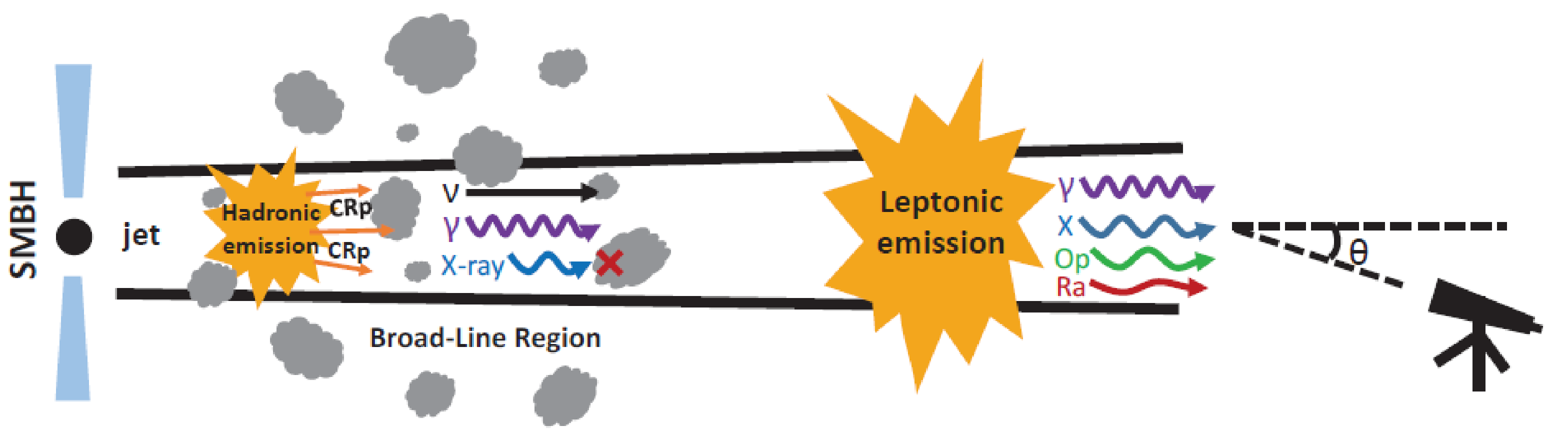
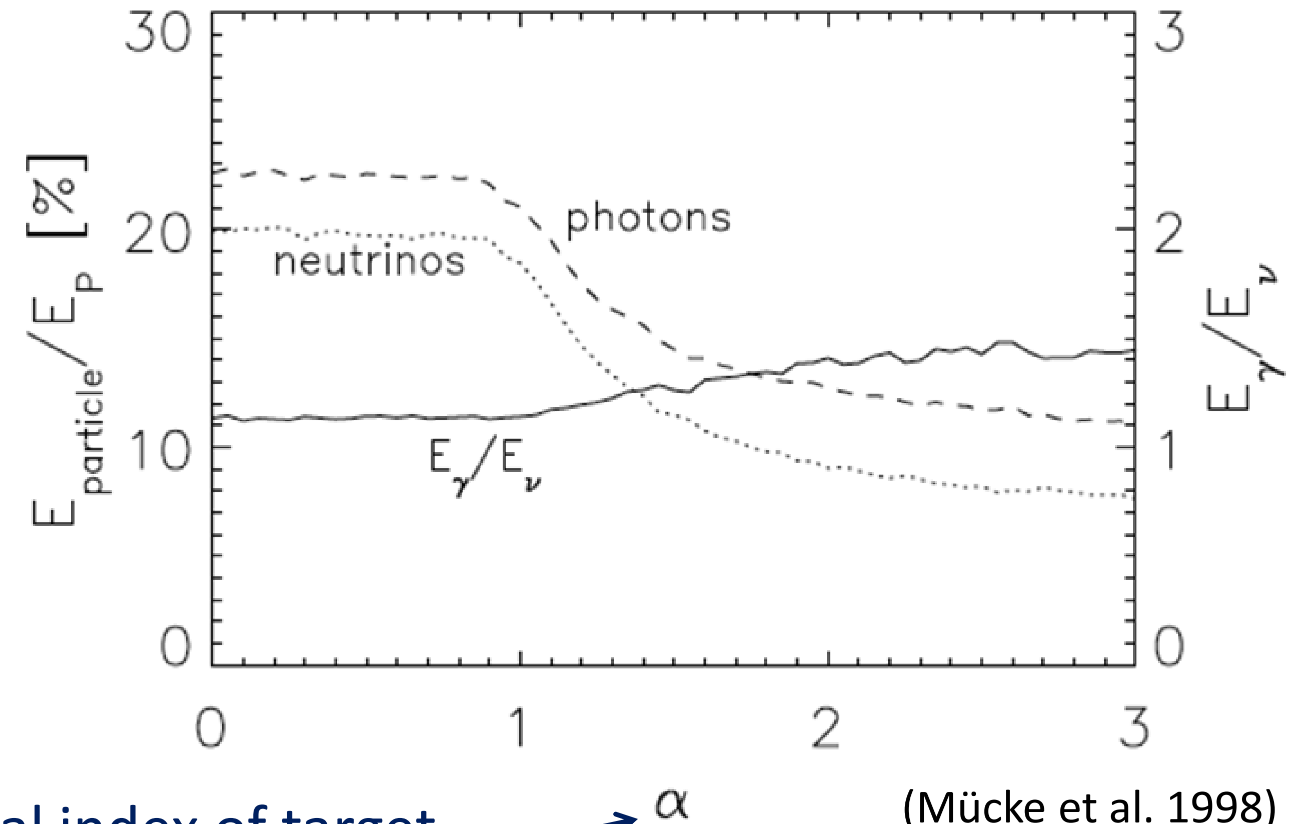


Photo-Pion Production

Fractional energy output

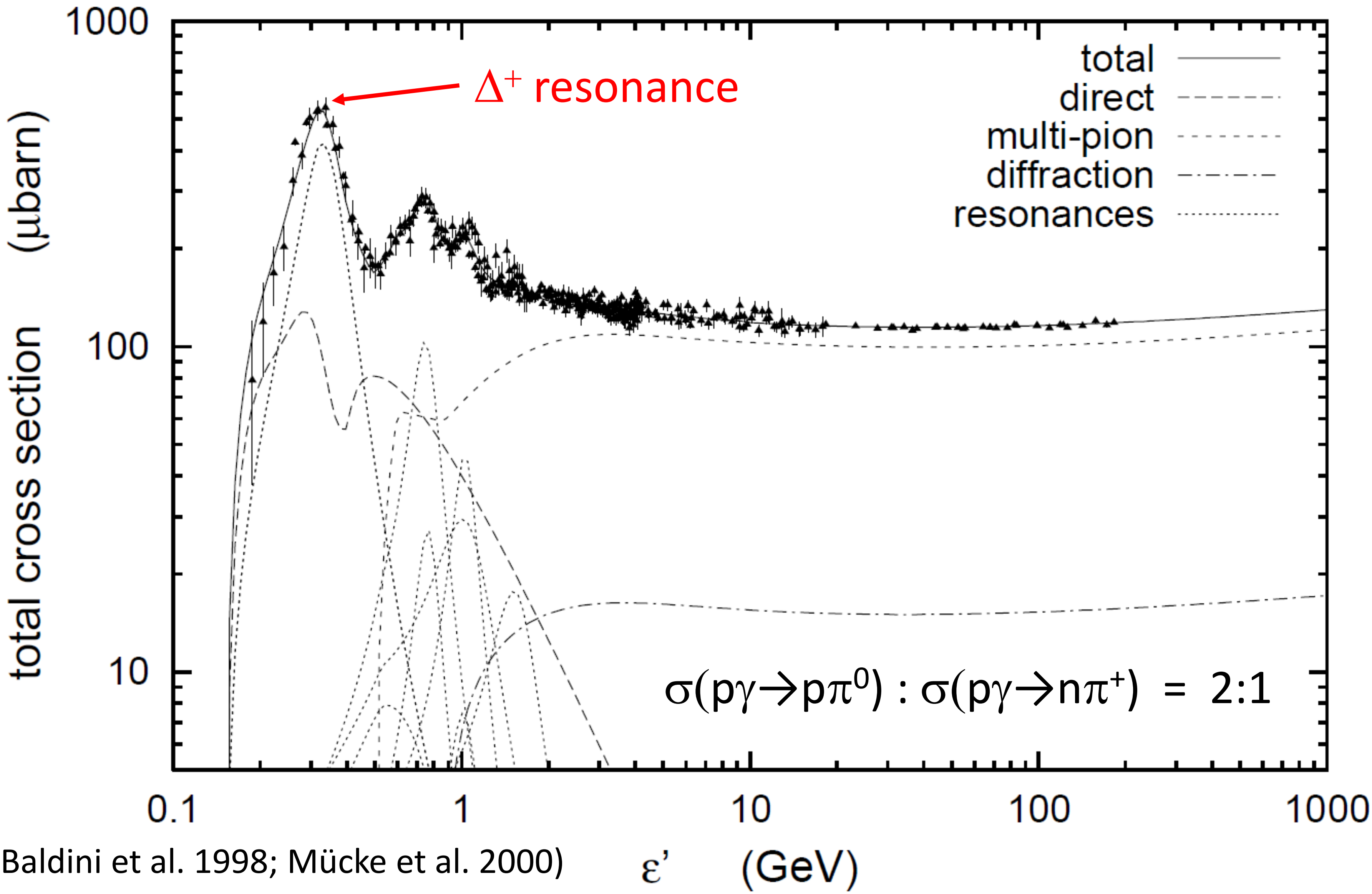


Spectral index of target photon field

(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 + $\mu^\pm$ + $\pi^\pm$).

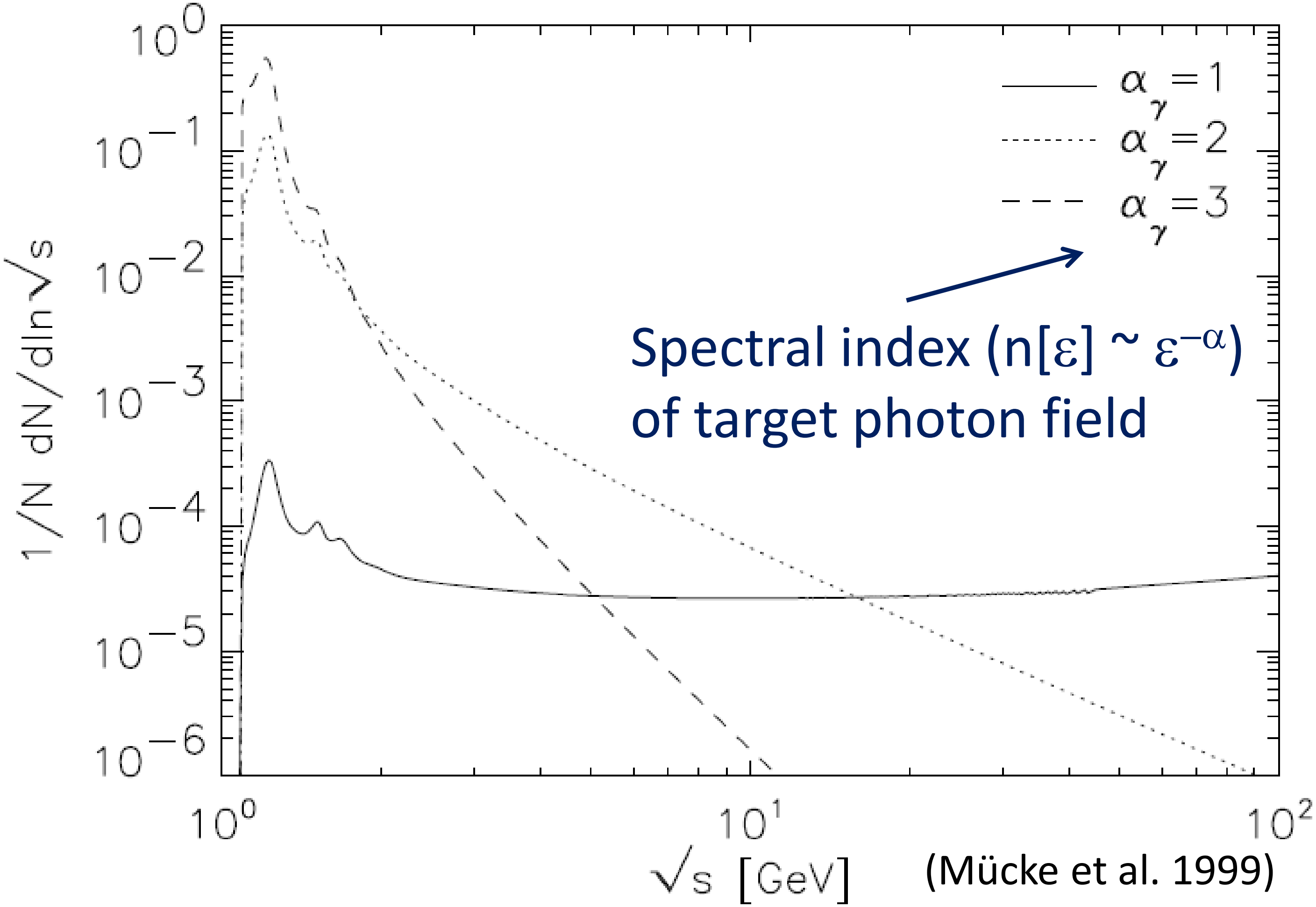
Photo-Pion Production



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

Photo-Pion Production

Interaction Probability



(Mücke et al. 1999)

Center-of-Momentum energy

For realistic target photon fields,
most interactions occur near threshold.

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 threshold: in center-of-momentum (c.m.) frame: all particles at rest

$\Rightarrow E_\nu^p \sim 1/3\,(m_\pi - m_\mu - m_e)\,c^2 \sim 10^7$ eV (in p rest frame)

$\Rightarrow E_\nu' = E_\nu/\delta \sim 10^7\,\gamma'_p$ eV (in emission-region rest frame)

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

Need protons with $E'_p \sim 10^{15}\,E_{14}\,\delta_1^{-1}$ eV => Not UHECRs!

and target photons with $E'_t \sim 170\,E_{14}^{-1}\,\delta_1$ eV => X-rays!

Photo-pion production - Energetics

- Protons with $E'_p \sim 10^{15}\, E_{14}\, \delta_1^{-1}$ eV

$\Rightarrow \gamma'_p \sim \gamma'_e \sim \gamma_\pi \sim 10^6\, E_{14}\, \delta_1^{-1} \equiv \gamma_6$

γ-ray production through:

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

b) secondary-electron Compton:

$\nu_{IC} \leq 10^{27}\, \delta_1\, \gamma_6$ Hz (~ 5 TeV)

Need an intense IR – optical target photon field with

$u'_{ph} >> u'_B \sim 400\, B_2^2$ erg/cm^3

Photo-pion production - Energetics

- Protons with $E'_p \sim 10^{15}\, E_{14}\, \delta_1^{-1}$ eV

$\Rightarrow \gamma'_p \sim \gamma'_e \sim 10^6\, E_{14}\, \delta_1^{-1} \equiv \gamma_6$

$\Rightarrow$ Proton synchrotron at

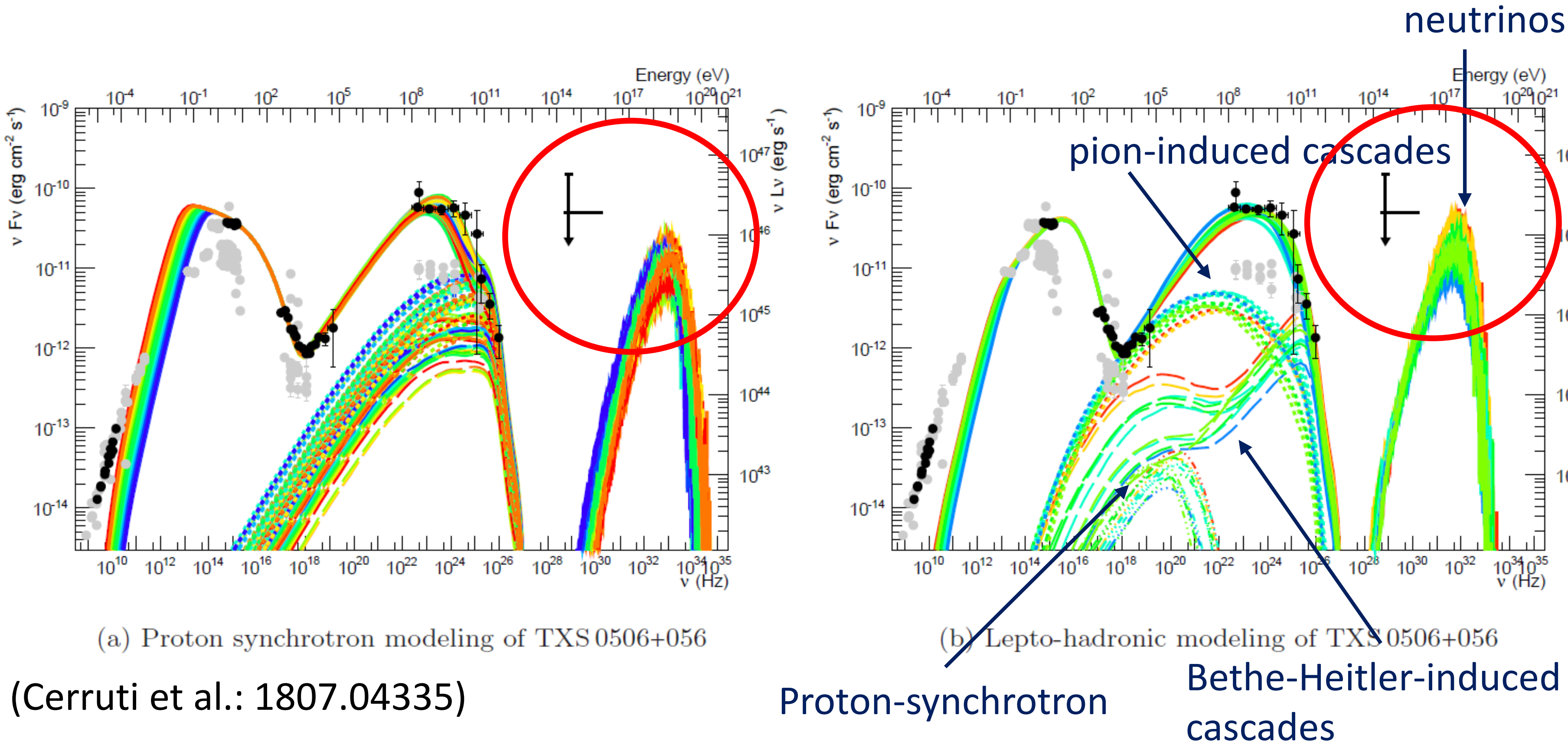
$\nu_{psy} \sim 2\times10^{18}\, \gamma_6^2\, B_2\, \delta_1$ Hz (~ 10 keV)

$\Rightarrow$ 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!

Photo-Pion Models for TXS 0506+056



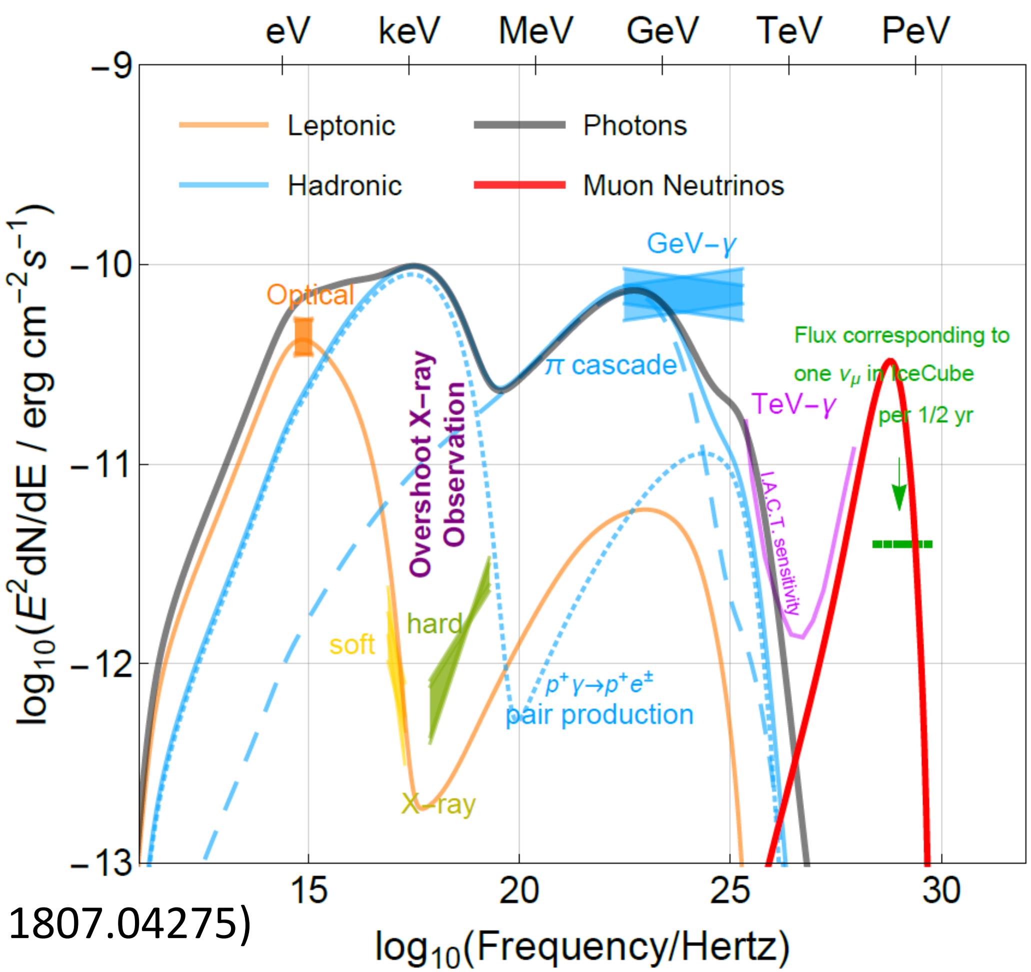
(a) Proton synchrotron modeling of TXS 0506+056

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

(Cerruti et al.: 1807.04335)

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

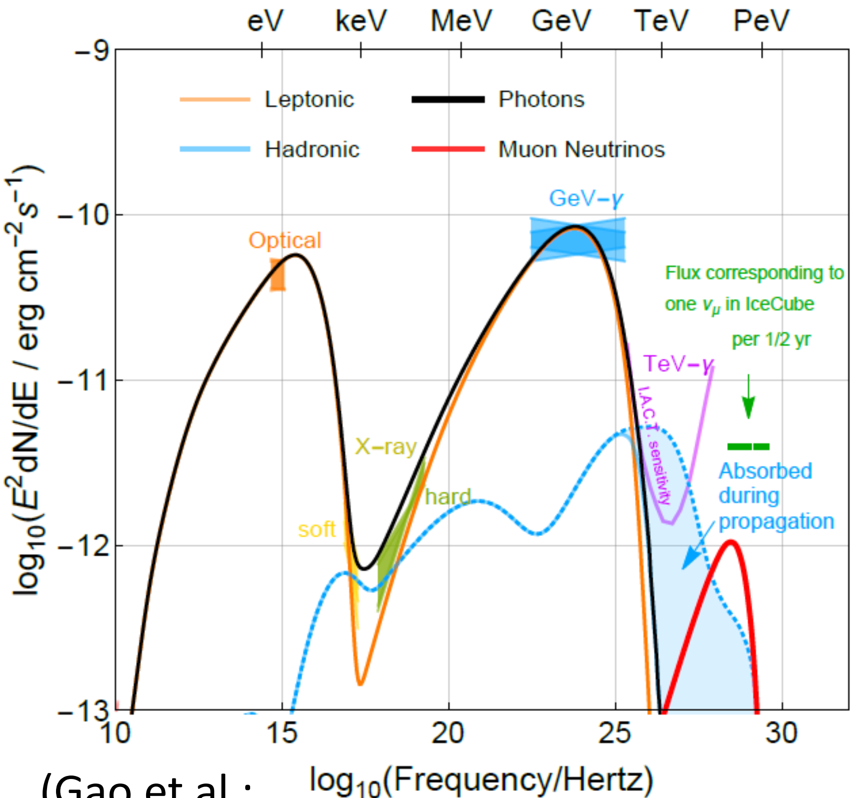
Photo-Pion Models for TXS 0506+056



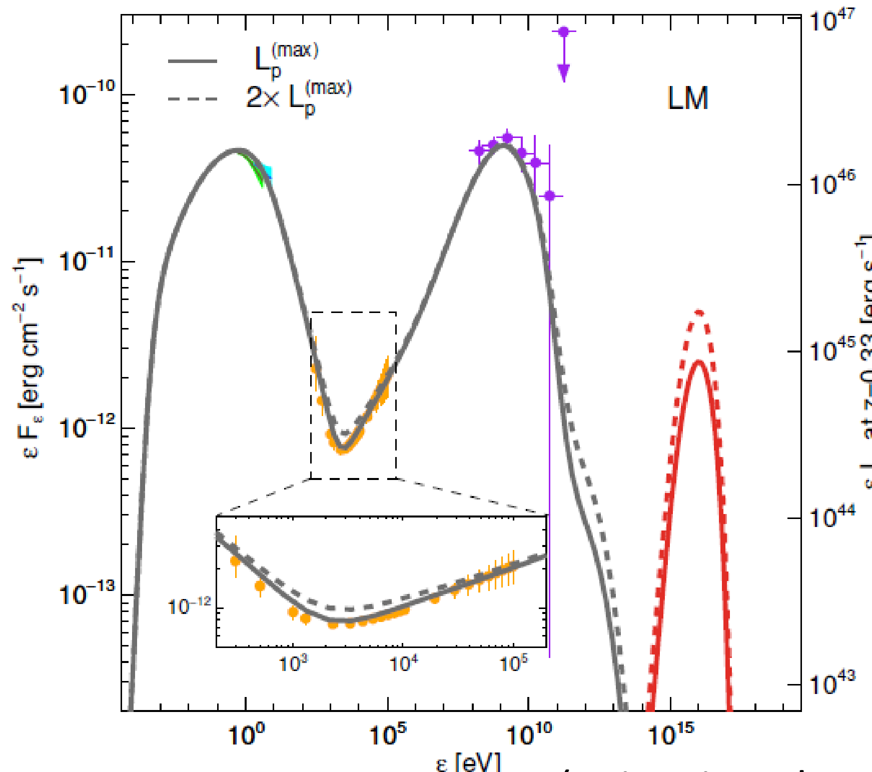
(Gao et al.: 1807.04275)

Models with p-γ induced γ-ray emission over-produce X-rays due to cascades! -> A. Reimer's talk

Photo-Pion Models for TXS 0506+056



(Gao et al.: 1807.04275)



(Keivani et al.: 1807.04537)

Models producing neutrinos and gamma-rays require leptonic-dominated gamma-ray production!

Photo-pion production – Origin of Target Photons

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

Need protons with $E'_p \sim 10^{15}\, E_{14}\, \delta_1^{-1}$ eV => Not UHECRs!

and target photons with $E'_t \sim 170\, E_{14}^{-1}\, \delta_1$ eV => X-rays!

(At least) two possible scenarios:

a) Target photons co-moving with the emission region

$\Rightarrow E_t^{obs} \sim 1.7\, E_{14}^{-1}\, \delta_1^2/(1+z)$ keV

$\Rightarrow$ Observed as X-rays

b) Target photons stationary in the AGN frame

$\Rightarrow E_t^{obs} \sim 17\, E_{14}^{-1}/(1+z)$ eV

$\Rightarrow$ Observed as UV

Spectral Energy Distribution of TXS 0506+056

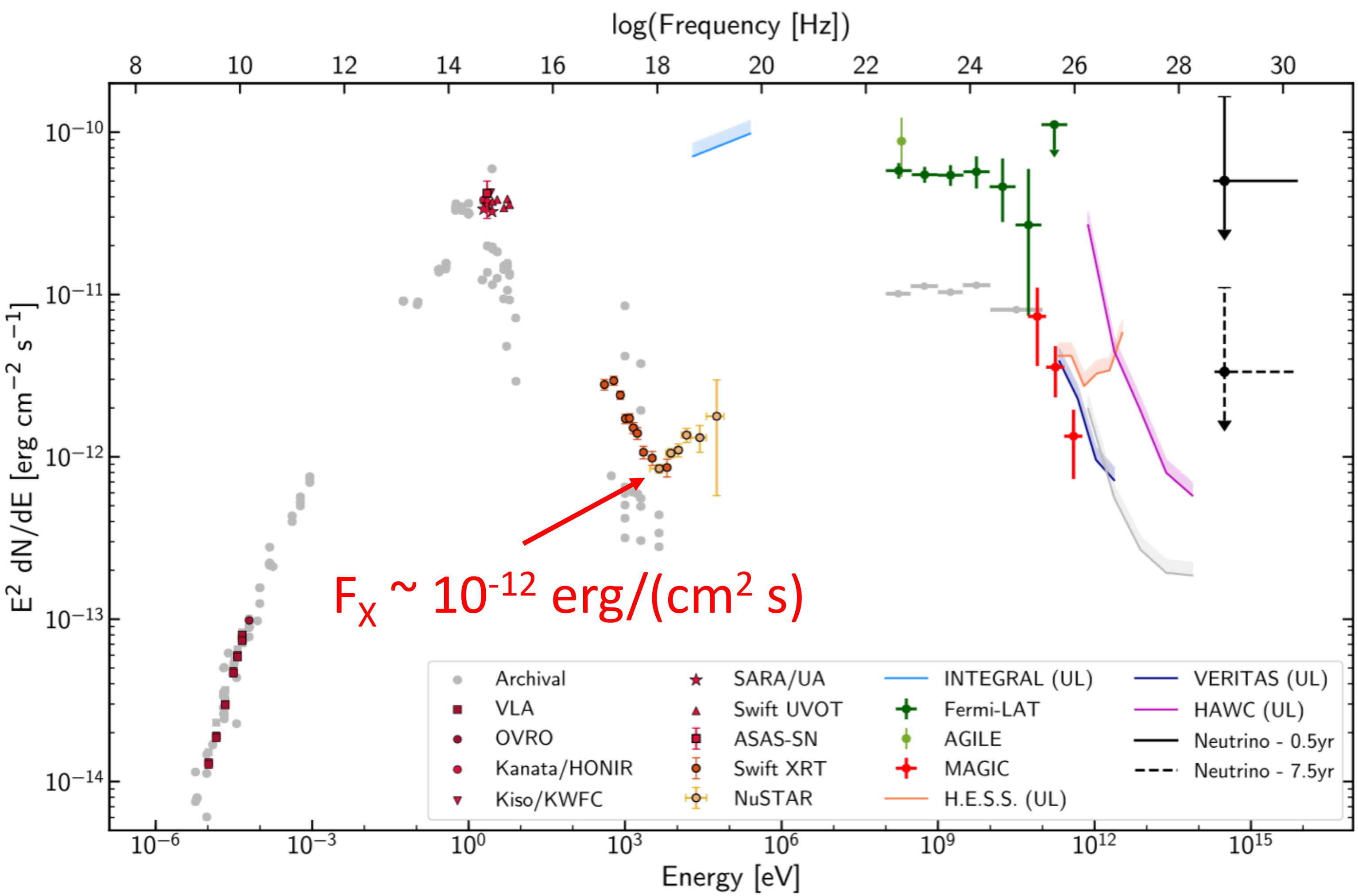


Photo-pion production – Origin of Target Photons

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)

$$L'_\nu \approx \frac{1}{2} m_p c^2 \int d\gamma_p \, N_p(\gamma_p)\,|\dot{\gamma}_{p,\,p\gamma}| \longrightarrow E_{kin,p}\,,\ L_{kin,p}$$

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

$$u'_{ph} \longrightarrow F_{X/UV} = \frac{u'_{ph} R^2 \delta^4 c}{d_L^{\,2}}$$

Photo-pion production – Origin of Target Photons

a) Co-moving target photon field

$$u'_t < 9\times10^{-4}\, R_{16}^{-2}\, \delta_1^{-4}\ \mathrm{erg\ cm^{-3}}$$

$$E_{kin,\,p} > 3\times10^{59}\, \Gamma_1\, R_{16}^{2}\ \mathrm{erg}$$

$$t_{p\gamma}^{obs} \sim 10^{6}\, R_{16}^{2}\, \delta_1^{3}\ \mathrm{yr}$$

$\Rightarrow$ Extremely radiatively inefficient!

$$L_{p,kin} \sim 6\times10^{51}\, R_{16}^{2}\, \Gamma_1\, \delta_1\, B_2^{2}\, \gamma_6\ \mathrm{erg/s}$$

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

Photo-pion production – Origin of Target Photons

b) Stationary target photon field

$$u'_t < 100\, \Gamma_1^{\,2}\, R_{t,17}^{\,-2} \text{ erg cm}^{-3}$$

$$E_{kin,\,p} > 3\times10^{54}\, \delta_1^{\,-4}\, \Gamma_1^{\,-1}\, R_{t,17}^{\,2} \text{ erg}$$

$$t_{p\gamma}^{\,obs} \sim 90\, \Gamma_1^{\,-2}\, R_{16}^{\,2} \text{ yr}$$

$\Rightarrow$ Radiatively inefficient, p-sy dominated!

$$L_{p,kin} \sim 6\times10^{46}\, \Gamma_1^{\,-1}\, \delta_1^{\,-3}\, B_2^{\,2}\, \gamma_6 \text{ erg/s}$$

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

$\Rightarrow$ Plausible!

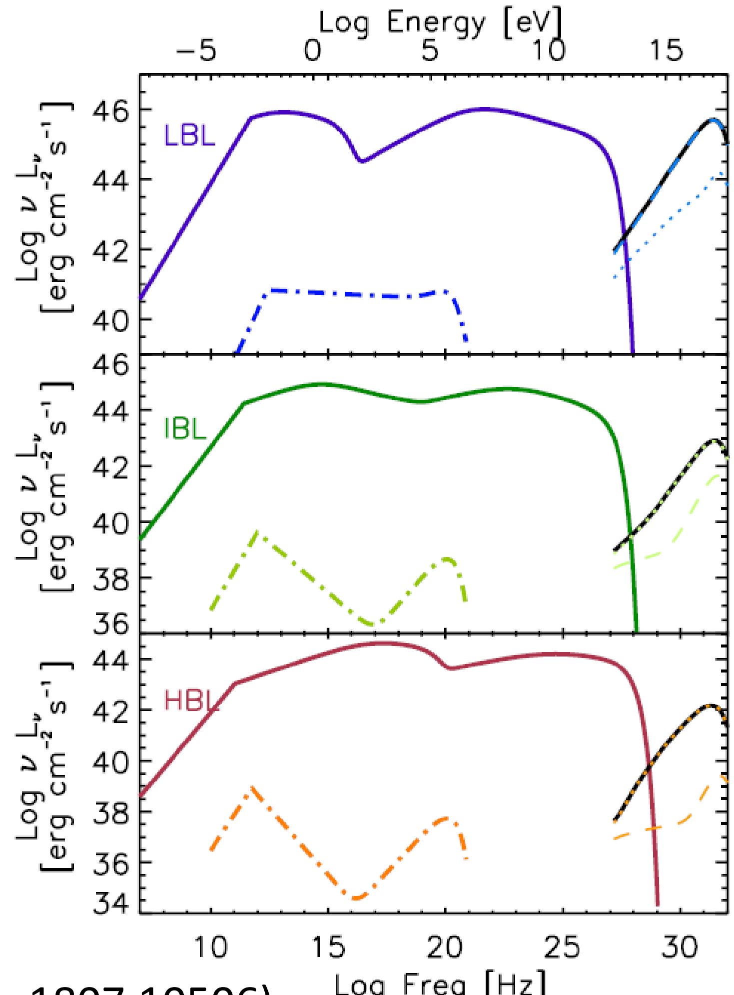
$\Rightarrow$ Might require stationary UV / soft X-ray target photon field external to the jet!

Photo-pion production – Origin of Target Photons

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

- BLR (?)
- Slow-moving sheath (Tavecchio & Ghisellini 2005)
- Accretion flow (RIAF) (Righi et al.: 1807.10506)

  -> Seems to favour LBLs as neutrino sources



(Righi et al.: 1807.10506)

Summary

- Production of IceCube neutrinos requires
  - Protons of ~ PeV energies (not UHECRs!)
  - Target photons of co-moving UV / X-ray energies

- No correlation between γ-ray and neutrino activity necessarily expected

- IceCube 170922A / TXS 0506+056 strongly favours
  - leptonically-dominated γ-ray emission
  - UV / soft X-ray target photon field external to the jet

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