Photo-Hadronic Neutrino Production in Blazars

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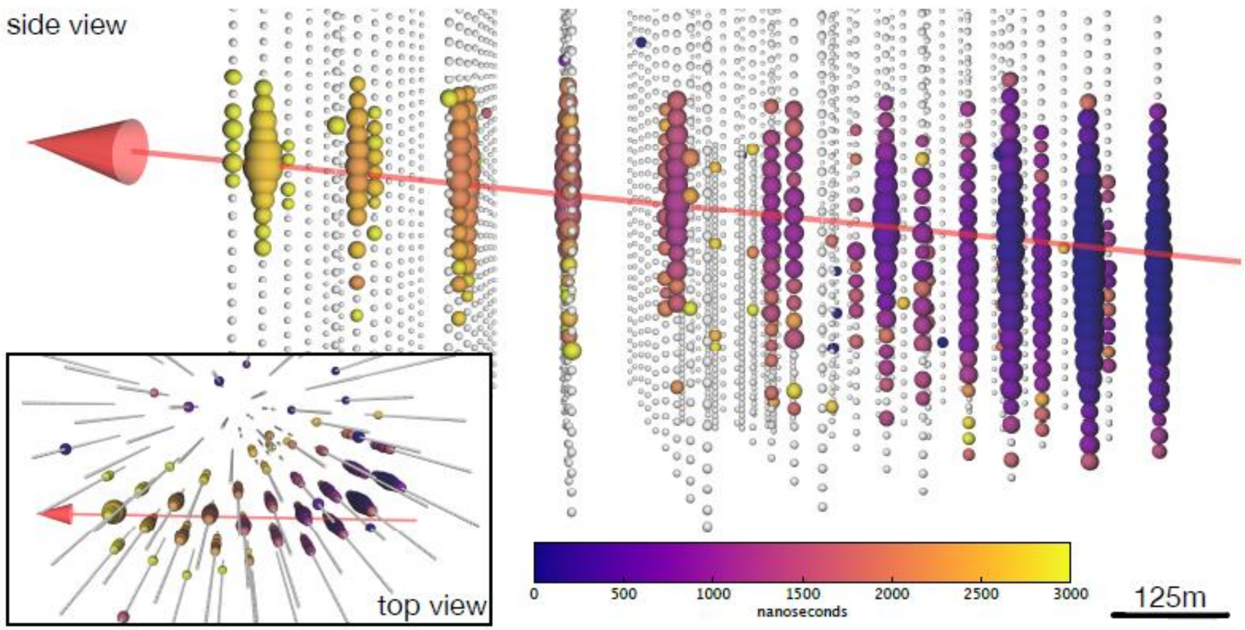
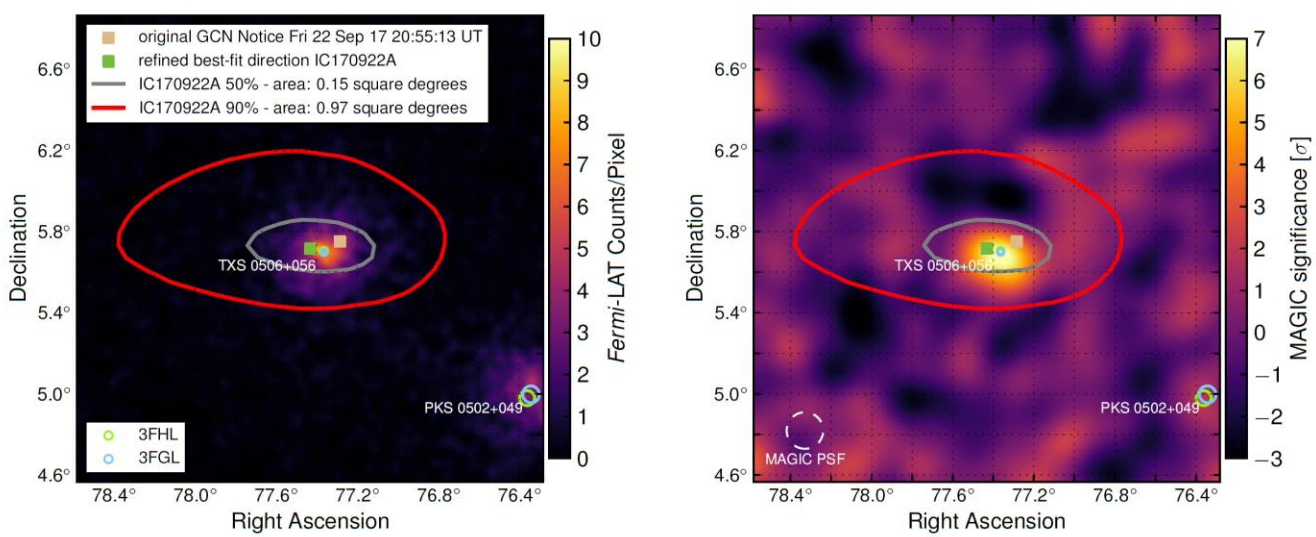
Neutrino Production in Blazars



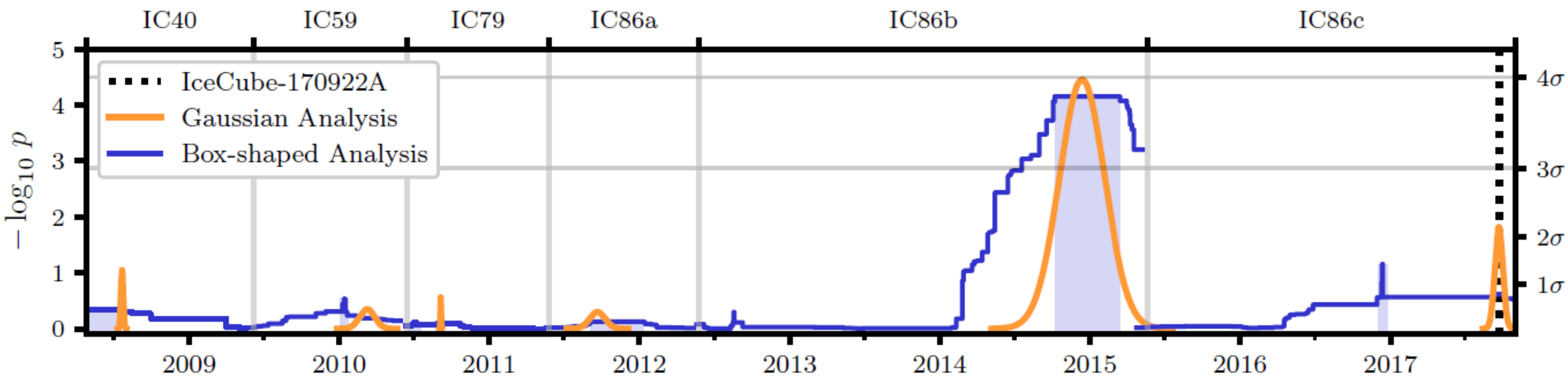
IceCube-170922A



TXS 0506+056

(IceCube et al. 2018)

The Neutrino Flare from TXS 0506+056

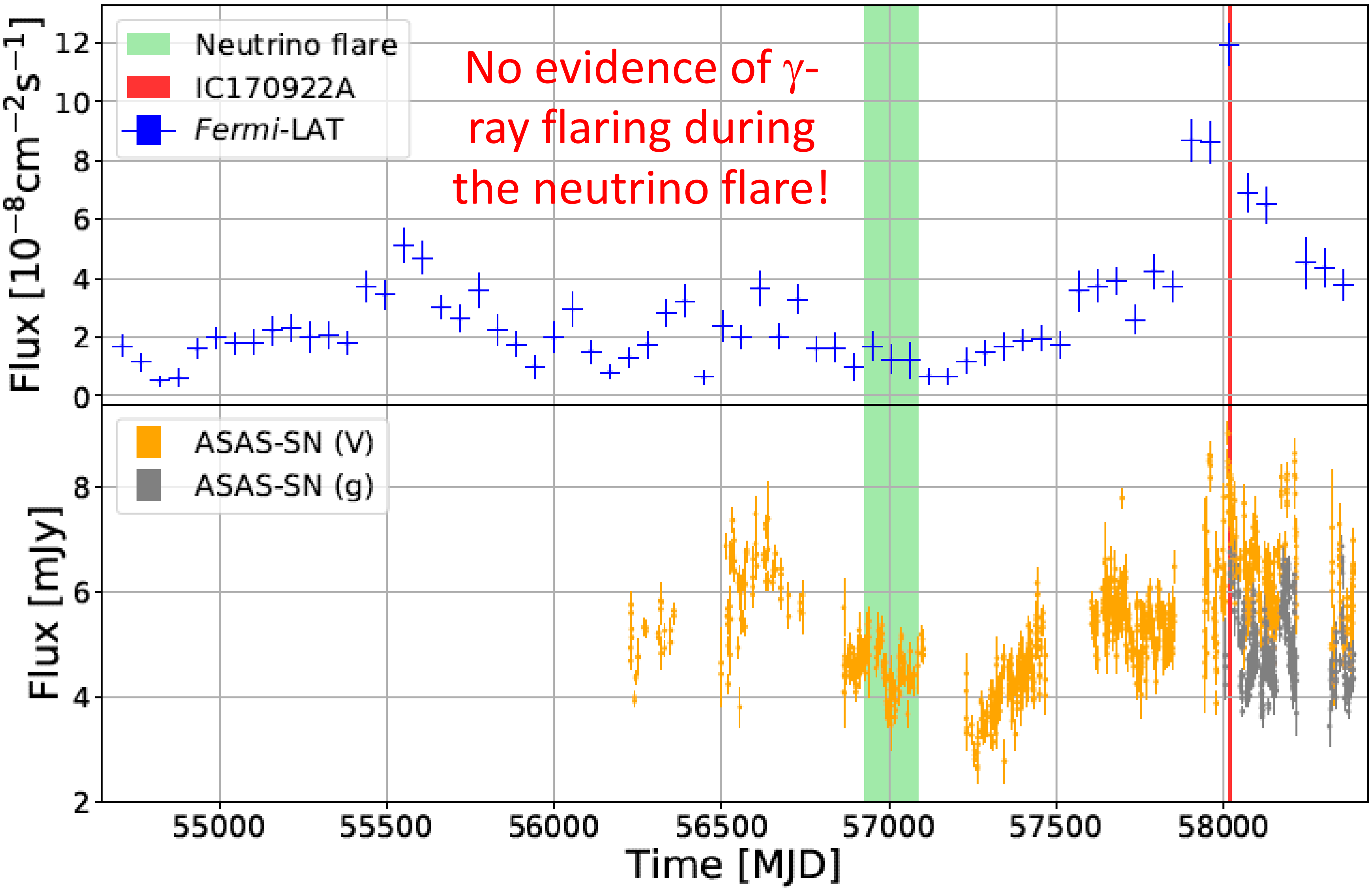


(IceCube et al. 2018b)

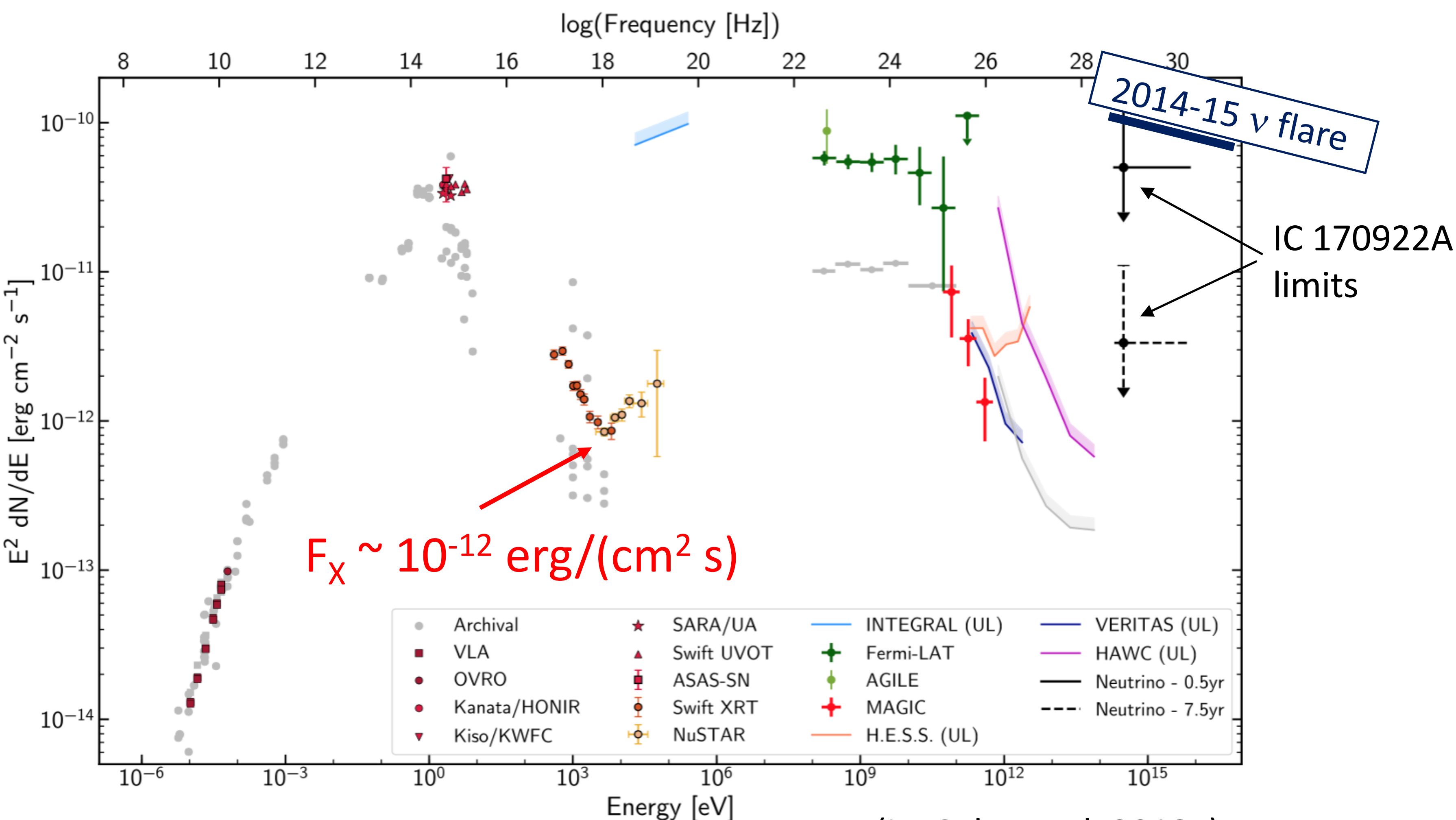
Search in archival data => Evidence for ~ 13 ± 5 excess neutrinos from the direction of TXS 0506+056 in 2014 – 2015 (~ 4 months around December 2014).

=> Well determined flux and spectrum!

The Neutrino Flare from TXS 0506+056



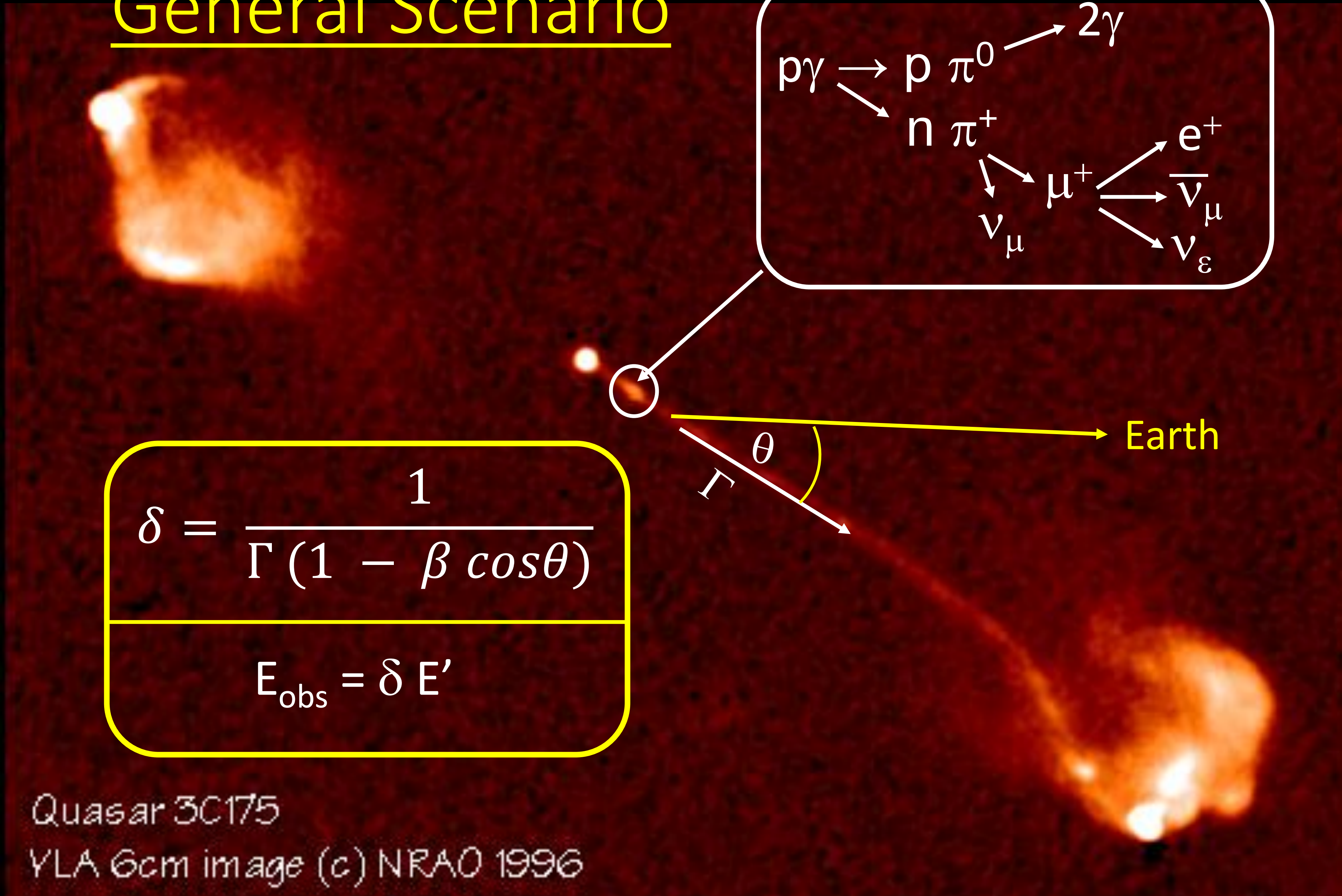
Spectral Energy Distribution of TXS 0506+056



(IceCube et al. 2018a)

(Photon SED from the time of IC 170922A)

General Scenario



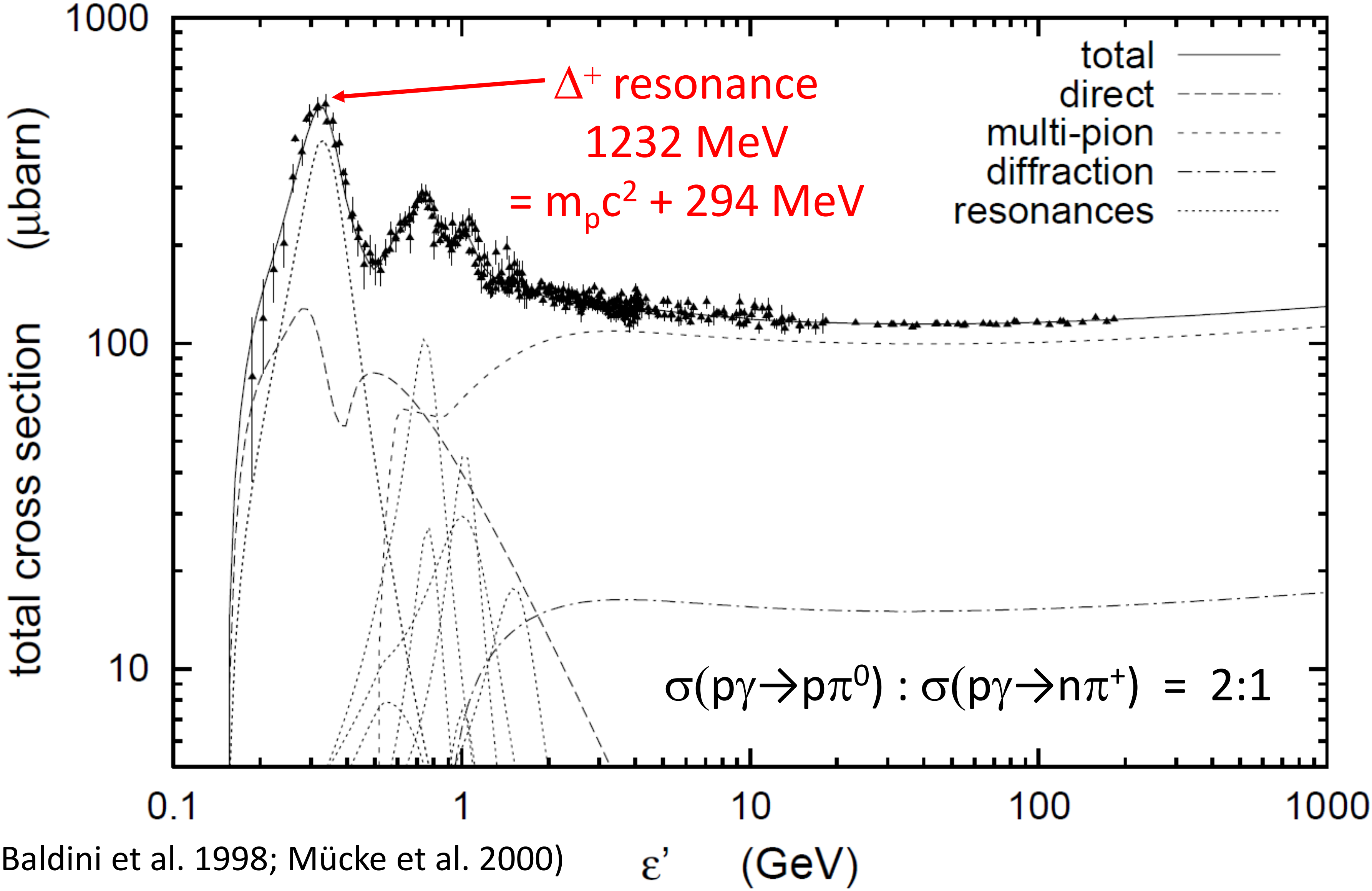
$$p\gamma \rightarrow p\,\pi^0 \rightarrow 2\gamma$$

$$p\gamma \rightarrow n\,\pi^+,\quad \pi^+ \rightarrow \mu^+ + \nu_\mu,\quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_\varepsilon$$

$$\delta = \frac{1}{\Gamma\,(1 - \beta\,cos\theta)}$$

$$E_{obs} = \delta\, E'$$

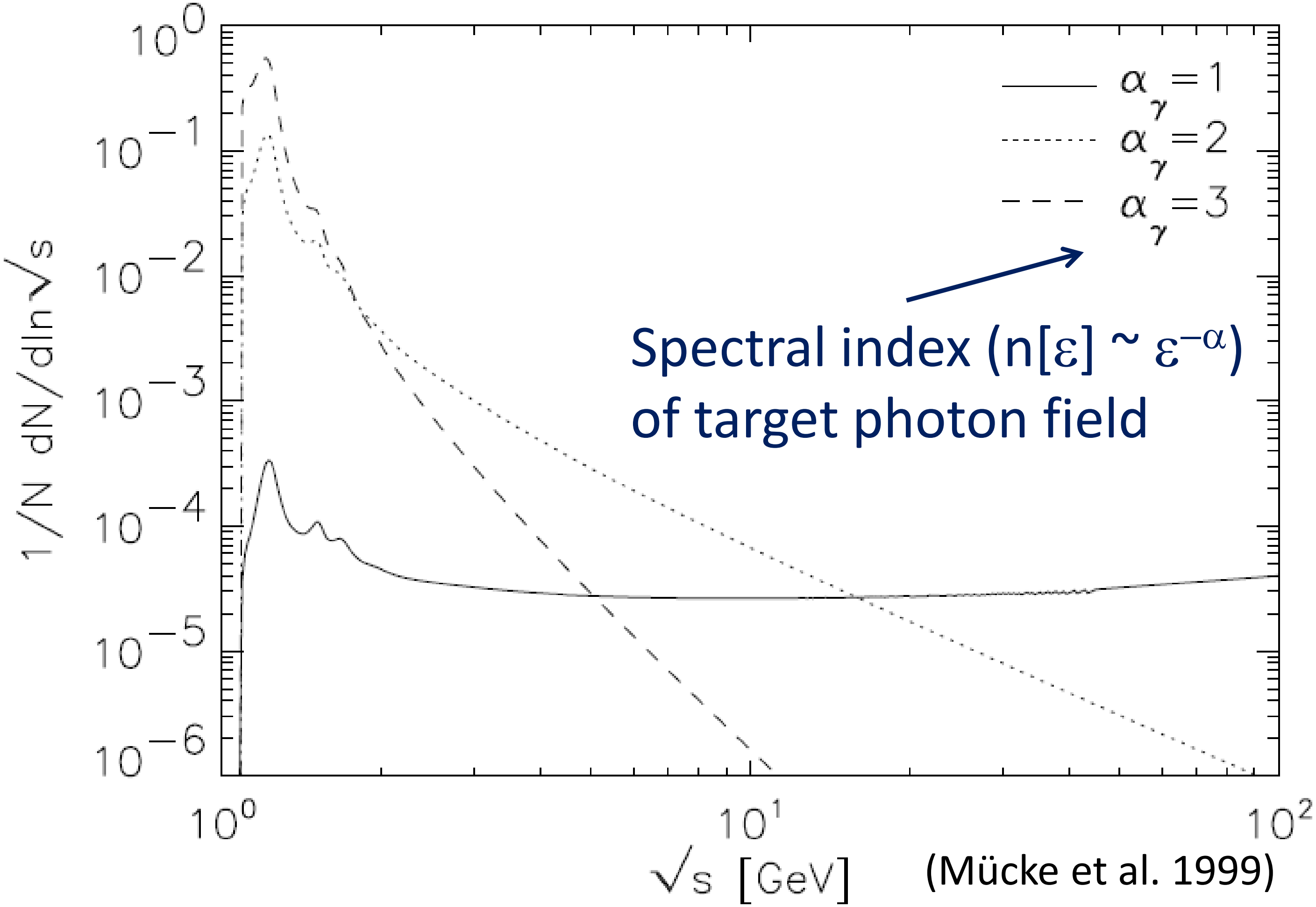
Photo-Pion Production



(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 Δ^+ resonance.

Photo-pion production - Energetics

At Δ^+ resonance:

$$s = E'_p\, E'_t\, (1 - \beta_p'\, \mu) \sim E'_p\, E'_t \sim E_{\Delta^+}{}^2 = (1232\ \mathrm{MeV})^2$$

and $$E'_\nu \sim 0.05\, E'_p$$

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

$$(\text{i.e., } E'_\nu = 10\, E_{14}\, \delta_1^{-1}\ \mathrm{TeV})$$

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

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

Cosmic-Ray Acceleration in Blazars

- No conclusive correlation between AGN and UHECR arrival directions observed.

- To produce > 100 TeV neutrinos $\rightarrow$ Need PeV protons

- Simplest constraint: Confinement (Hillas Criterion):

$$E'_n < Z\,e\,B\,R = 3 \times 10^{18}\,B_2\,R_{16}\text{ eV}$$

(Z = 1 for protons)

for hadronic blazar models with $B = 100\,B_2$ G

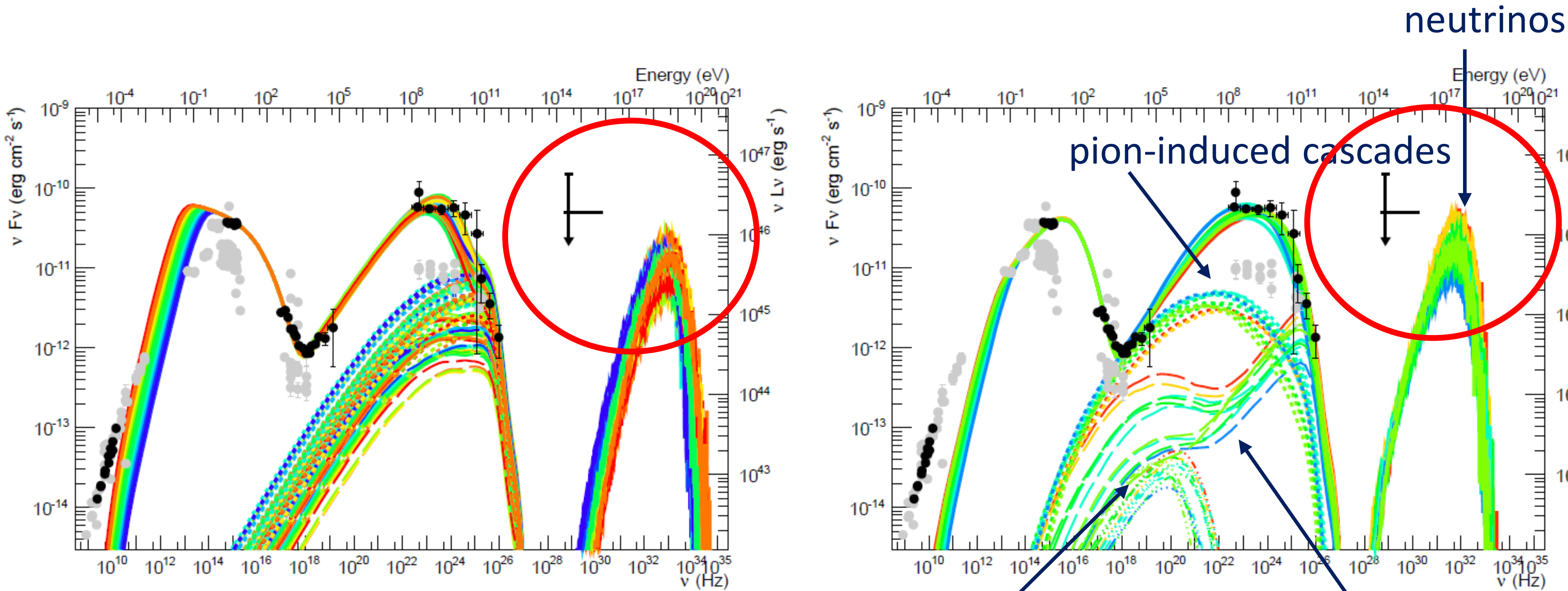
$R = 10^{16}\,R_{16}$ cm

$\Rightarrow$ PeV Protons for IceCube neutrino production: 

$\Rightarrow$ UHECRs ($E = \delta\,E' > 10^{19}$ eV): Plausible for heavy elements (Z >> 1)

(e.g., Rodrigues et al., 2018: ApJ, 854, 54)

Photo-Pion Models for TXS 0506+056



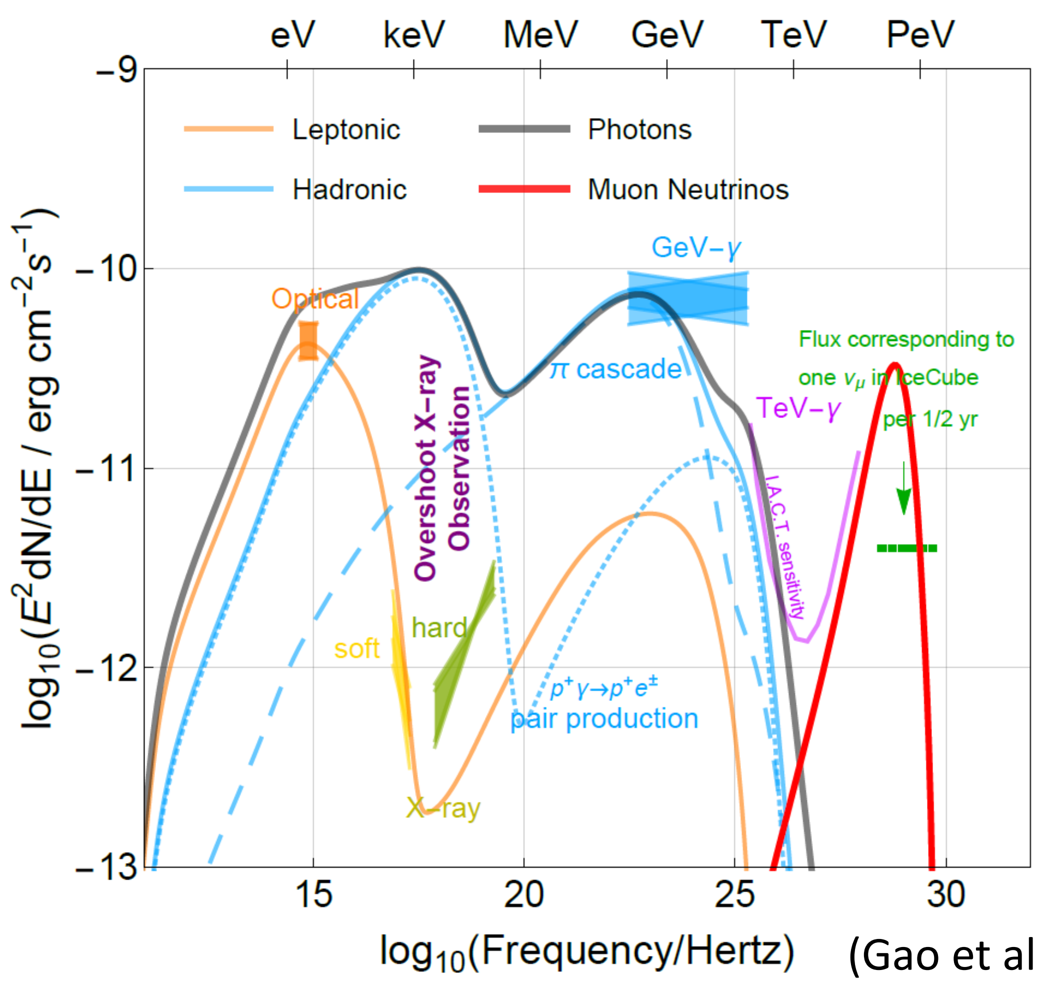
(a) Proton synchrotron modeling of TXS 0506+056

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

(Cerruti et al. 2019: MNRAS, 483, L12)

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

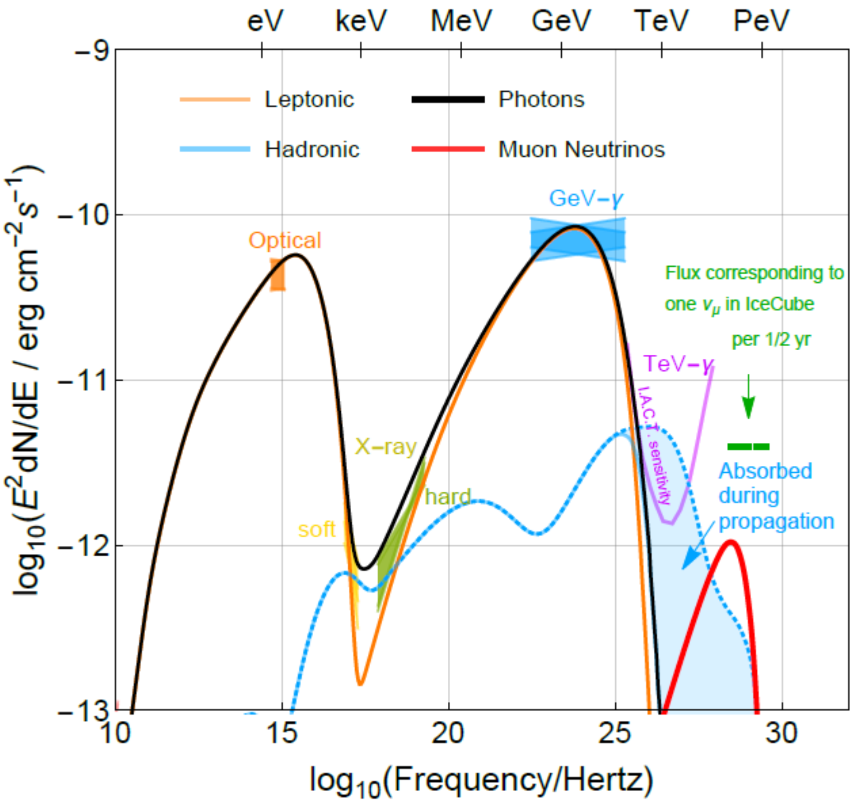
Photo-Pion Models for TXS 0506+056



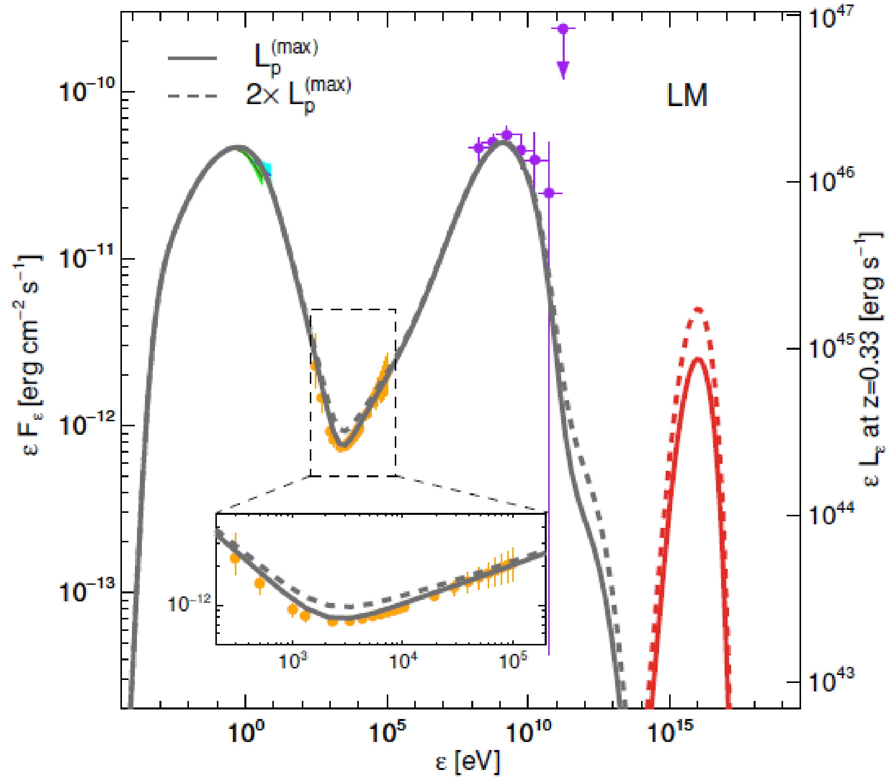
(Gao et al. 2018, Nature Astron., 3, 88)

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. 2018, Nature Astron., 3, 88)

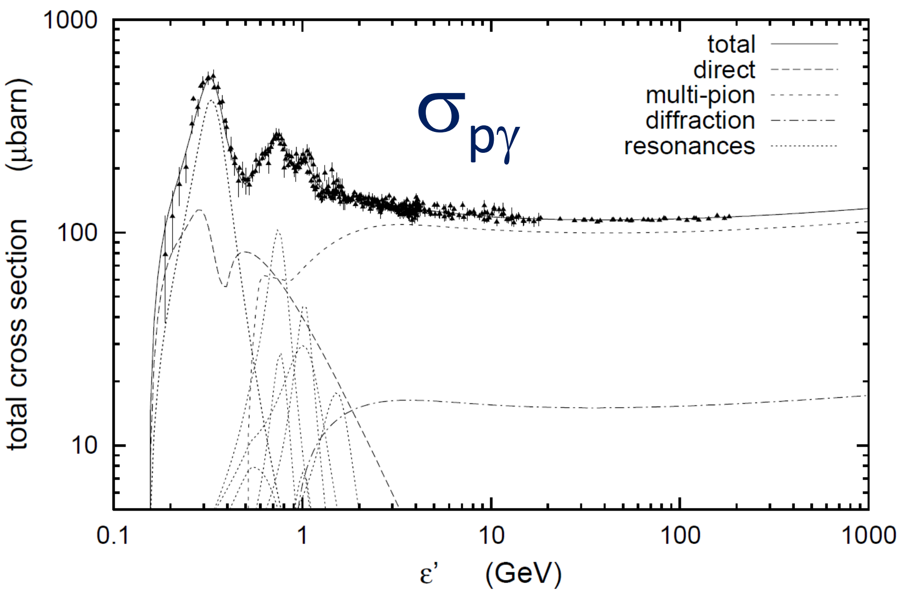


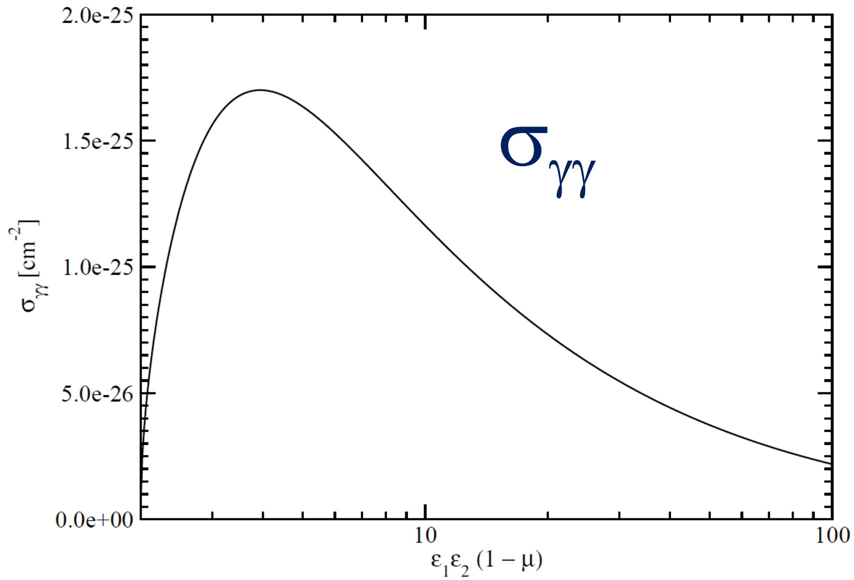
(Keivani et al. 2018, ApJ, 864, 84)

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

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 ~ $\tau_{\gamma\gamma} = R\, \sigma_{\gamma\gamma}\, n_{ph}$





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

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

The pγ Efficiency Problem

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

$\ell_{\rm esc}$ = average length travelled by protons until escape

$\ell_{\rm esc}$ from random walk:

mean free path $\lambda = \eta(\gamma)\, r_g(\gamma)$

Number of scatterings to escape, N_s: $R = \sqrt{N_s}\,\lambda$

$$\ell_{\rm esc} = N_s\,\lambda = \frac{R^2}{\lambda} \approx 3.3 \times 10^{21}\,\eta(\gamma)^{-1}\,R_{16}^{2}\,B_2\,E_{15}^{-1}\ \text{cm}$$

$$\Rightarrow \quad \frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\,\ell_{\rm esc}}{\sigma_{\gamma\gamma}\,R} \approx 1.1 \times 10^{3}\,\eta(\gamma)^{-1}\,R_{16}\,B_2\,E_{15}^{-1}$$

$\Rightarrow$ Proton pγ efficiency can be >> $\tau_{\gamma\gamma}$, but misleading, as $t_{{\rm cool},p\gamma}$ and $t_{{\rm esc},p}$ >> R/c

The pγ Efficiency Problem

Relevant constraint for proton bulk kinetic luminosity:

$$L'_\nu \approx \frac{1}{2}\, m_p c^2 \int d\gamma_p\, N_p(\gamma_p) |\dot{\gamma}_{p,\,p\gamma}| = L'_\nu\ (\text{obs})$$

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

2014-15 neutrino flare of TXS 0506+056

$$\Rightarrow \quad L_p\, u'_{ph} \approx 1.4\times10^{52}\, \delta_1^{-4}\, \Gamma_1^{\,2}\, R_{16}^{\,-1} \left(\frac{erg}{s}\right) \left(\frac{erg}{cm^3}\right)$$

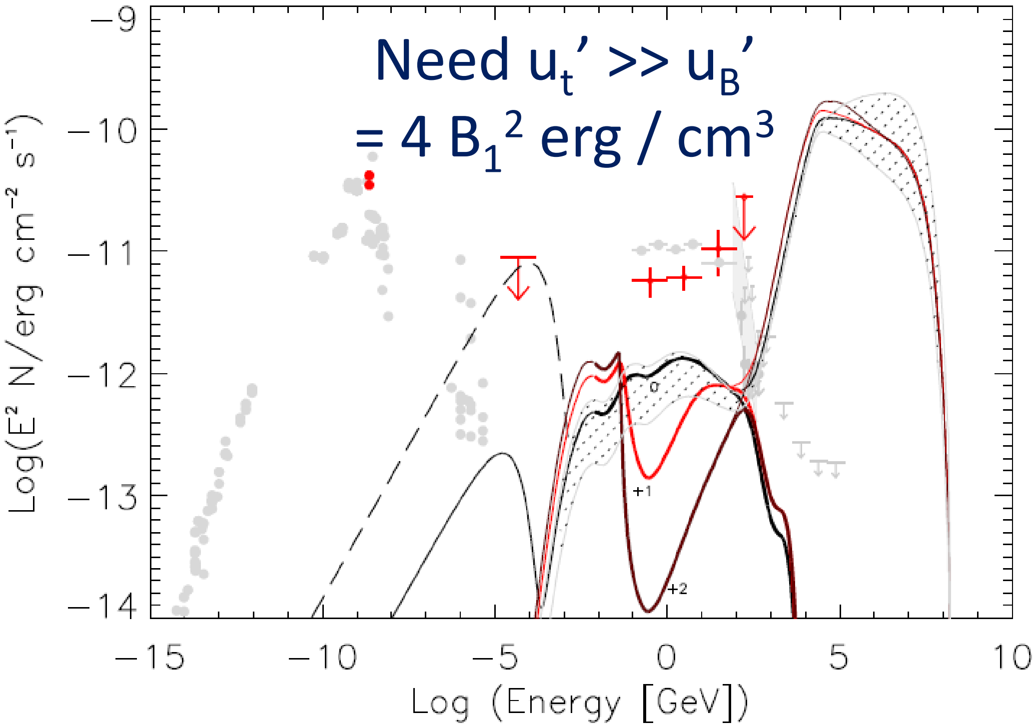
Constrained from observed X-ray flux

(Reimer et al. 2019: ApJ, 881, 46)

Cascading Constraints for TXS 0506+056

pγ neutrino production in TXS 0506+056 possible with strong **external UV/X-ray radiation field**, but under-predicts Fermi γ-rays.

=> No neutrino – γ-ray correlation expected!



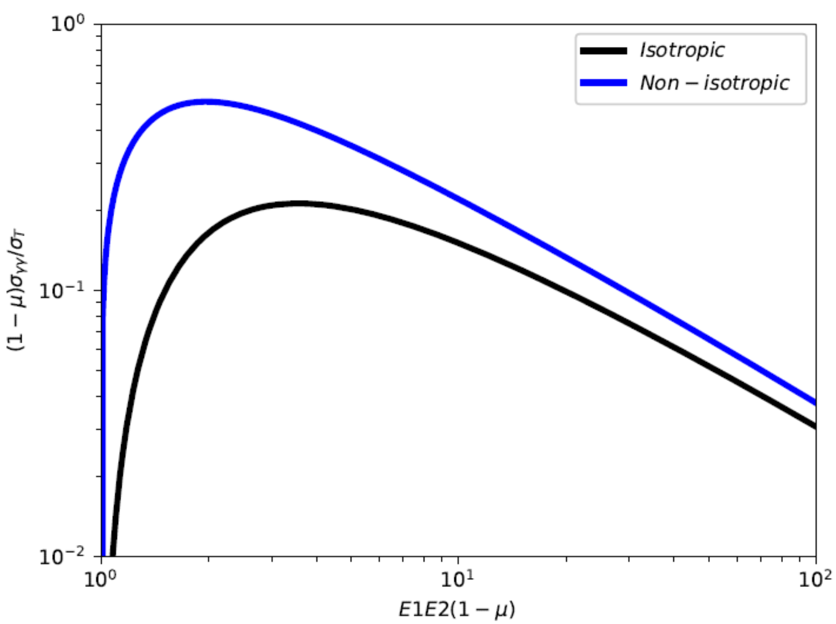
Requires $L_{p,kin} \sim$
$1.5{\times}10^{49}\ \delta_1^{-4}\ R_{t,17}^{2}\ R_{16}^{-1}$ erg/s

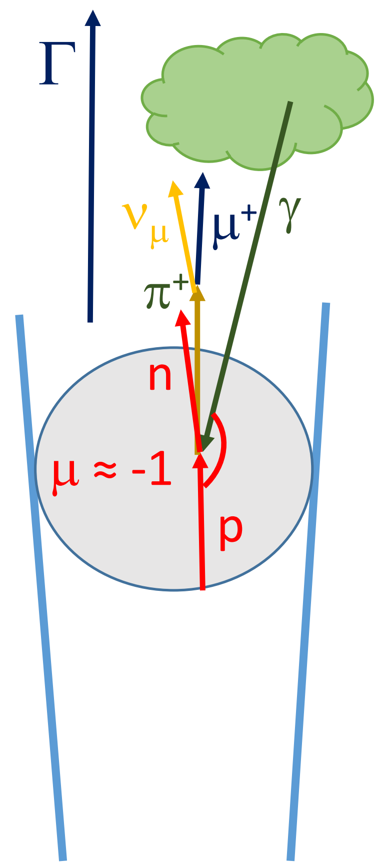
(Reimer et al. 2019: ApJ, 881, 46;
See also last year's TeVPA talk)

=> External Radiation field Doppler boosted and strongly anisotropic in co-moving frame

Effects of the Anisotropic Radiation Field

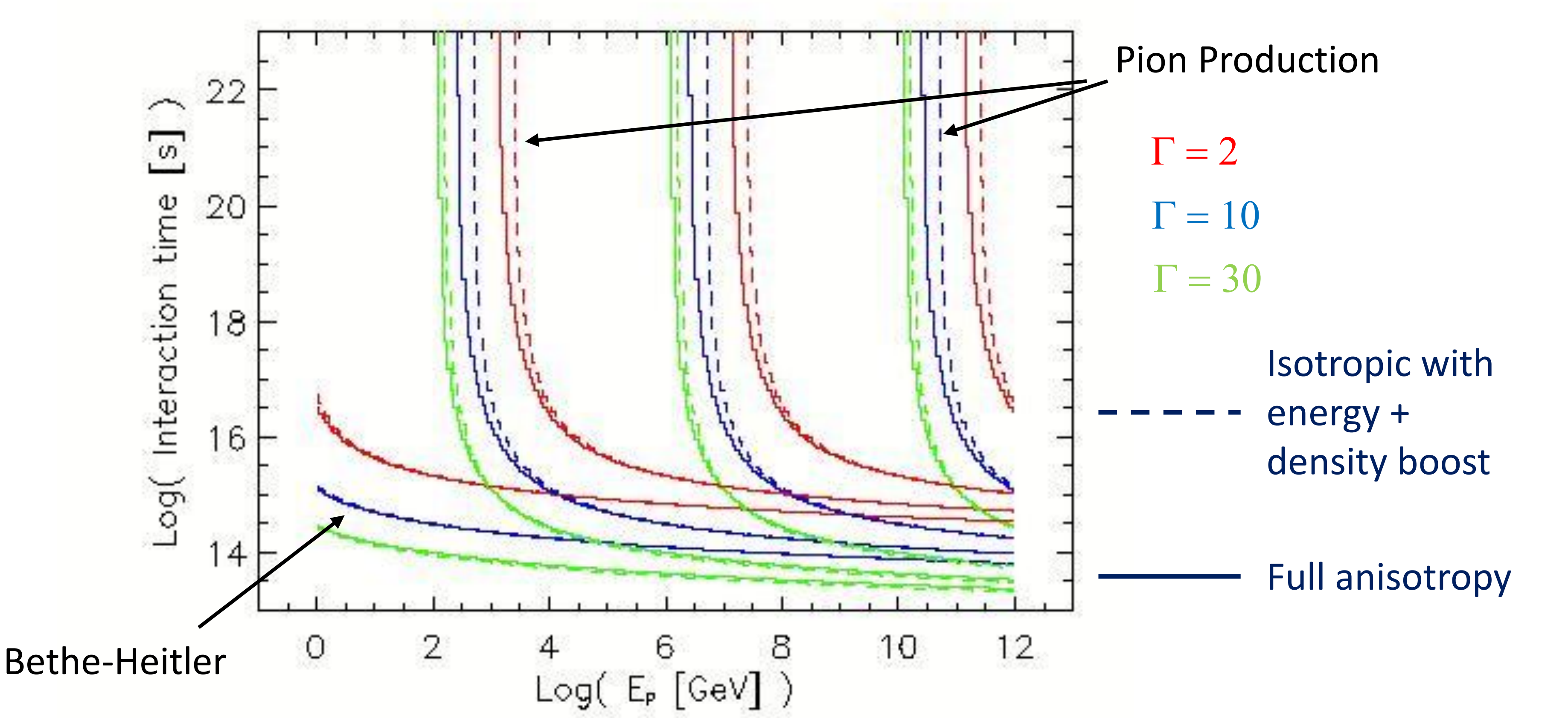
Primary effect: $(1 - \mu) \rightarrow 2$
~ Factor 2 reduction of interaction threshold





Effects of the Anisotropic Radiation Field

Reduction of interaction time scales primarily for pion production near threshold;
Negligible effect at Δ^+ resonance and above.



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
- TXS 0506+056 neutrino flare of 2014-15 strongly favours UV / soft X-ray target photon field external to the jet
- Effects of the anisotropic radiation field properly captured by simply accounting for Doppler boosting.

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Thank you!

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