Neutrino Production in AGN

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Based on:
Reimer, Böttcher & Buson, 2019, ApJ, in press (arXiv:1812:05654)

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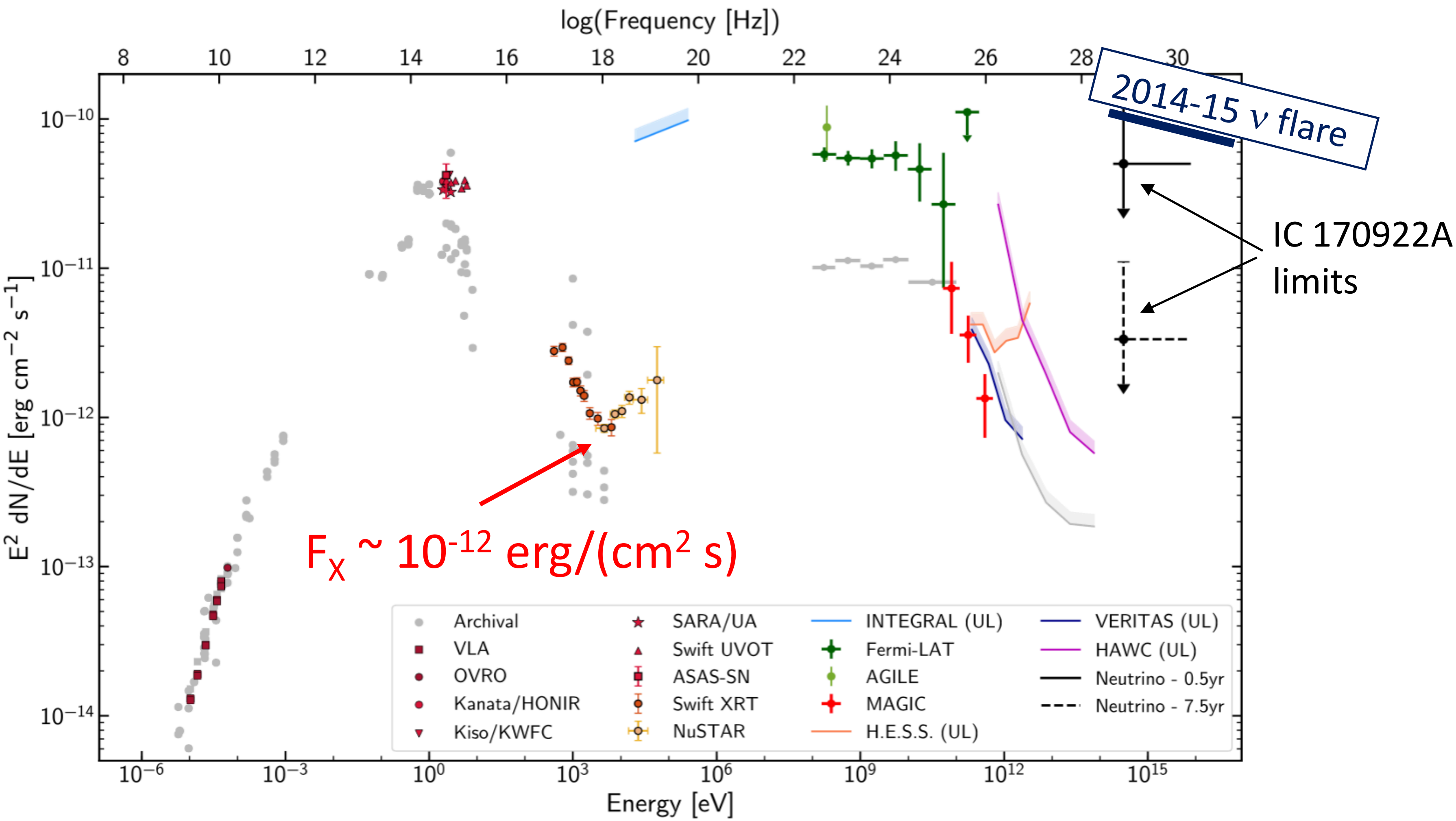
Spectral Energy Distribution of TXS 0506+056



The Neutrino Flare from TXS 0506+056

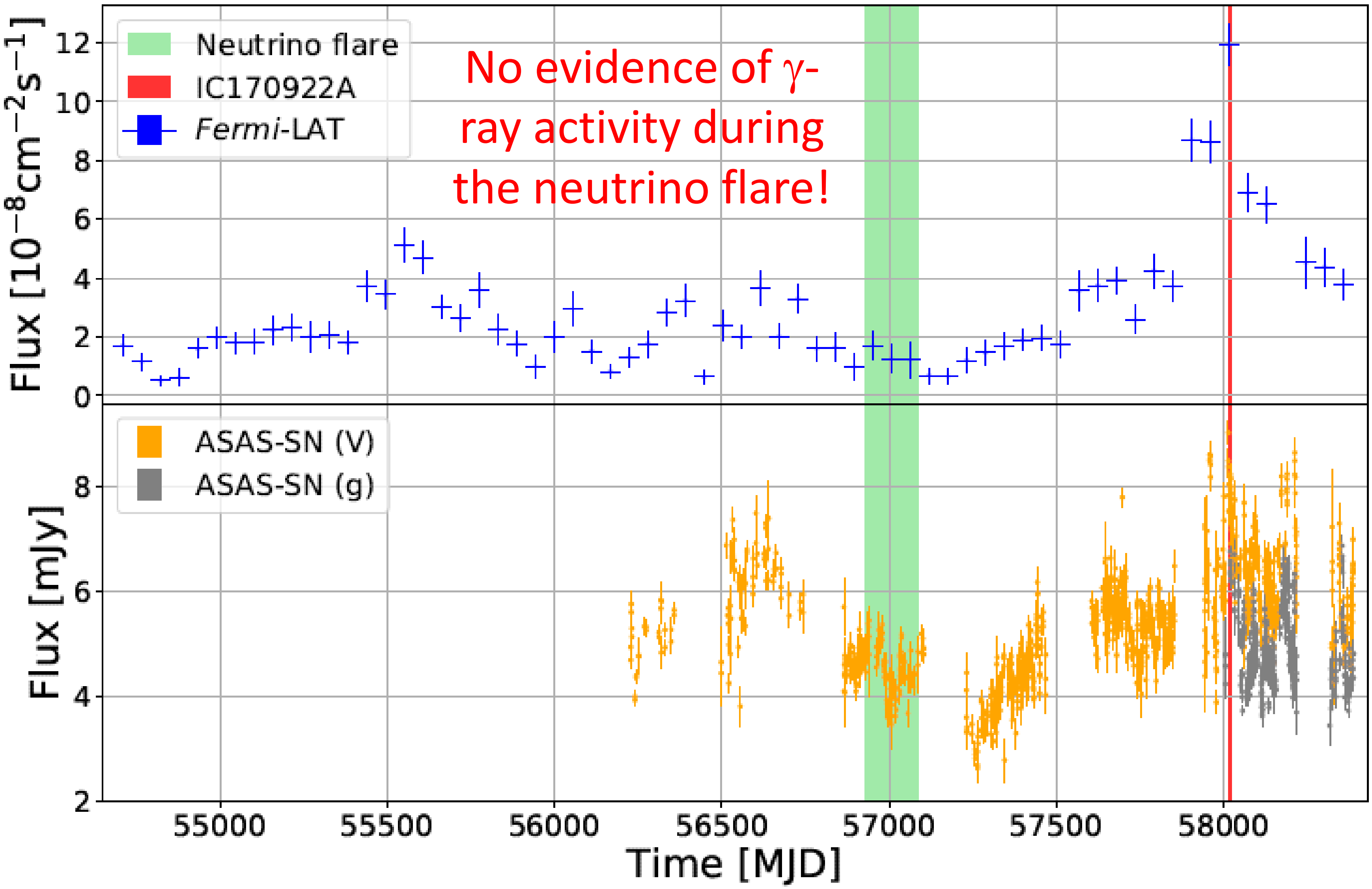


Photo-pion production - Energetics

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:

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

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

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

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

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

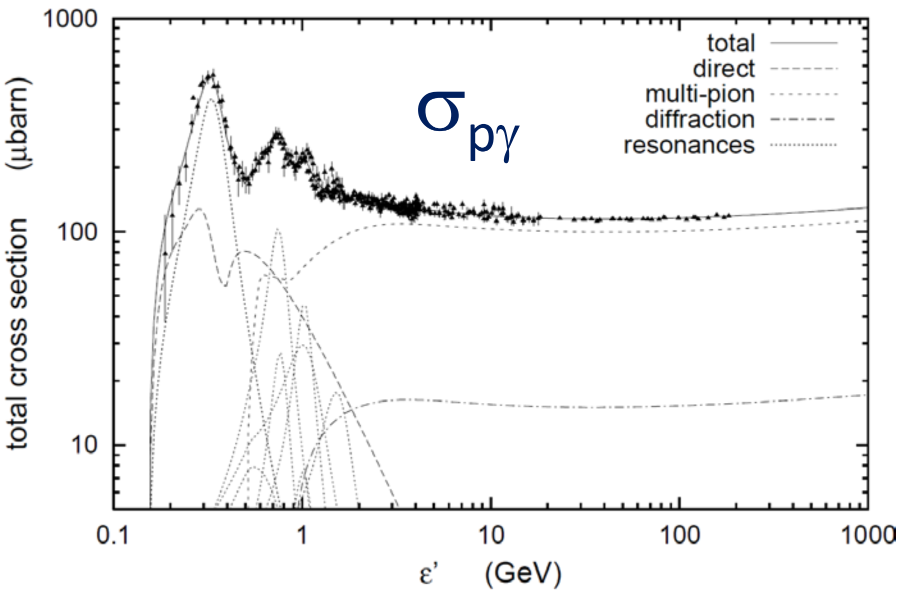
and target photons with $E'_t \sim 1.6\, E_{14}^{-1}\, \delta_1$ keV => X-rays

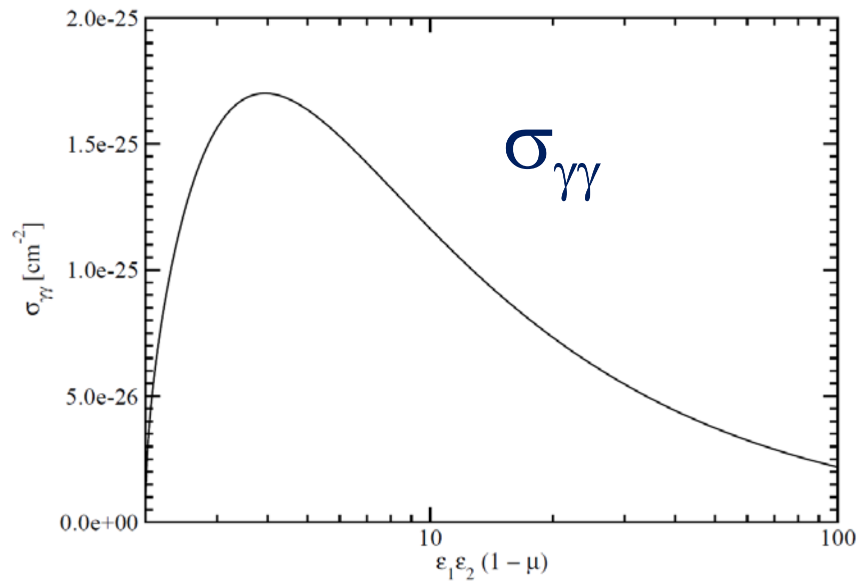
The pγ Efficiency Problem

- Efficiency for protons to undergo pγ interaction ~ $\tau_{p\gamma} = \eta R \sigma_{p\gamma} n_{ph}$

  ($t_{esc,p} = \eta R/c$; $\eta \geq 1$)

- Likelihood of γ-ray photons to be absorbed ~ $\tau_{\gamma\gamma} = R \sigma_{\gamma\gamma} n_{ph}$





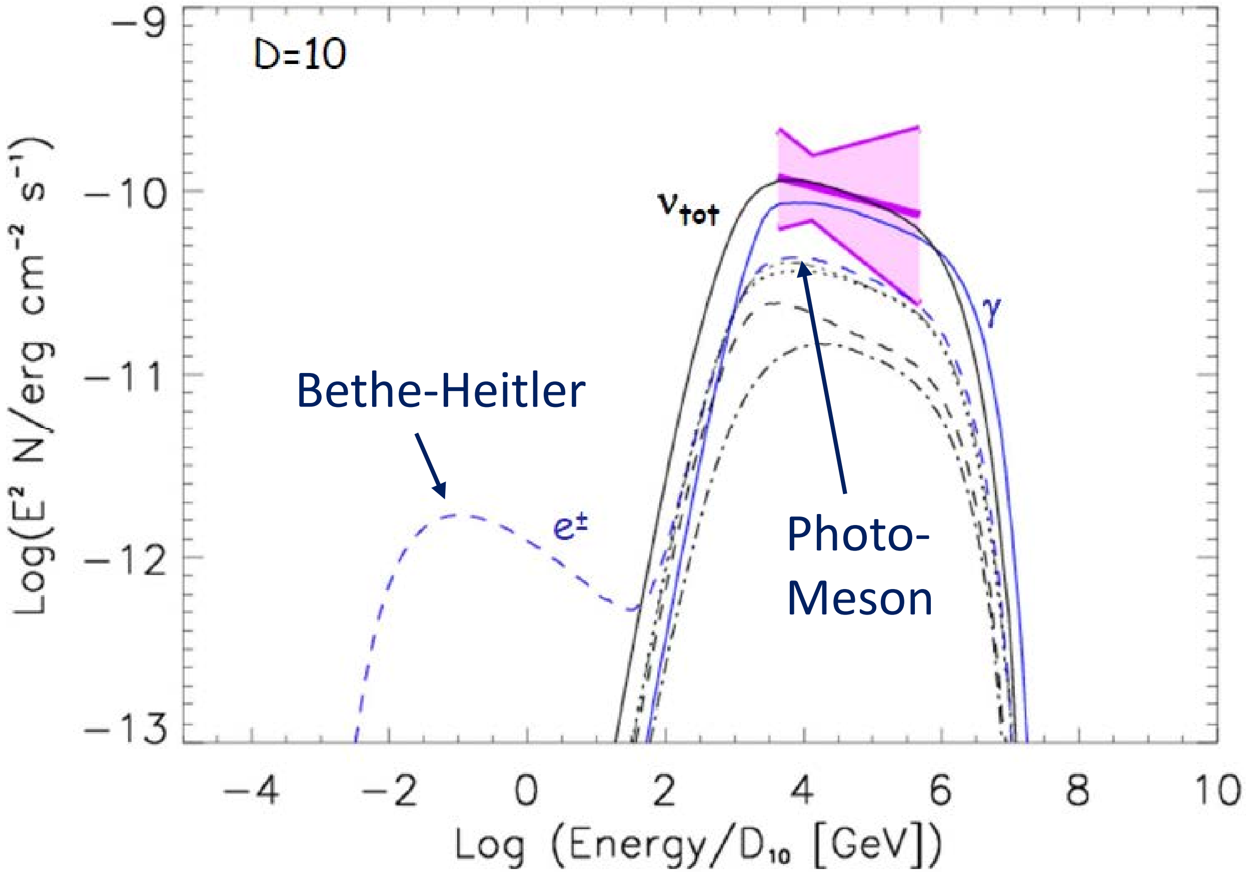
$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{\eta}{300} \quad \text{at} \quad E_\gamma \sim \frac{m_e^2 c^4}{E_t} \sim 3.3 \times 10^{-5} E_\nu$$

⇒ Photons at E_γ ~ GeV – TeV are heavily absorbed!

⇒ Cascade emission at lower energies.

Constraints from Cascades

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



- 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

Constraints from Cascades

2) Target photon field => $\gamma\gamma$ absorption optical depth $\tau_{\gamma\gamma}$

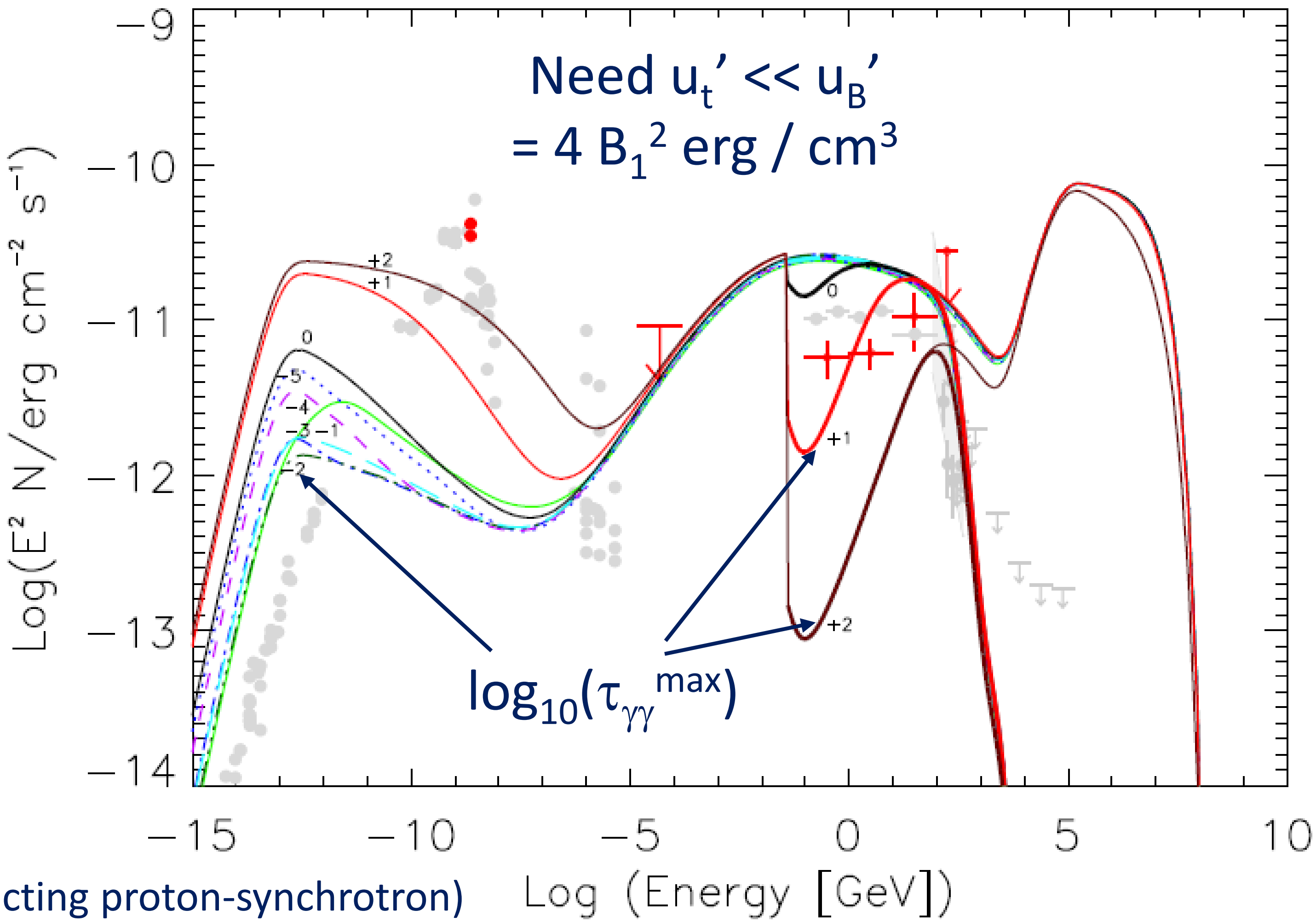
3) Simulate pair cascades initiated by secondary γ-rays and electrons/positrons

- MC codes including Photo-Meson + Bethe-Heitler pair production (SOPHIA – Mücke et al. 2000)

- Pair cascades with Matrix Multiplication Method (Protheroe & Johnson 1996)

- Steady-state, linear cascades

Synchrotron Supported Cascades

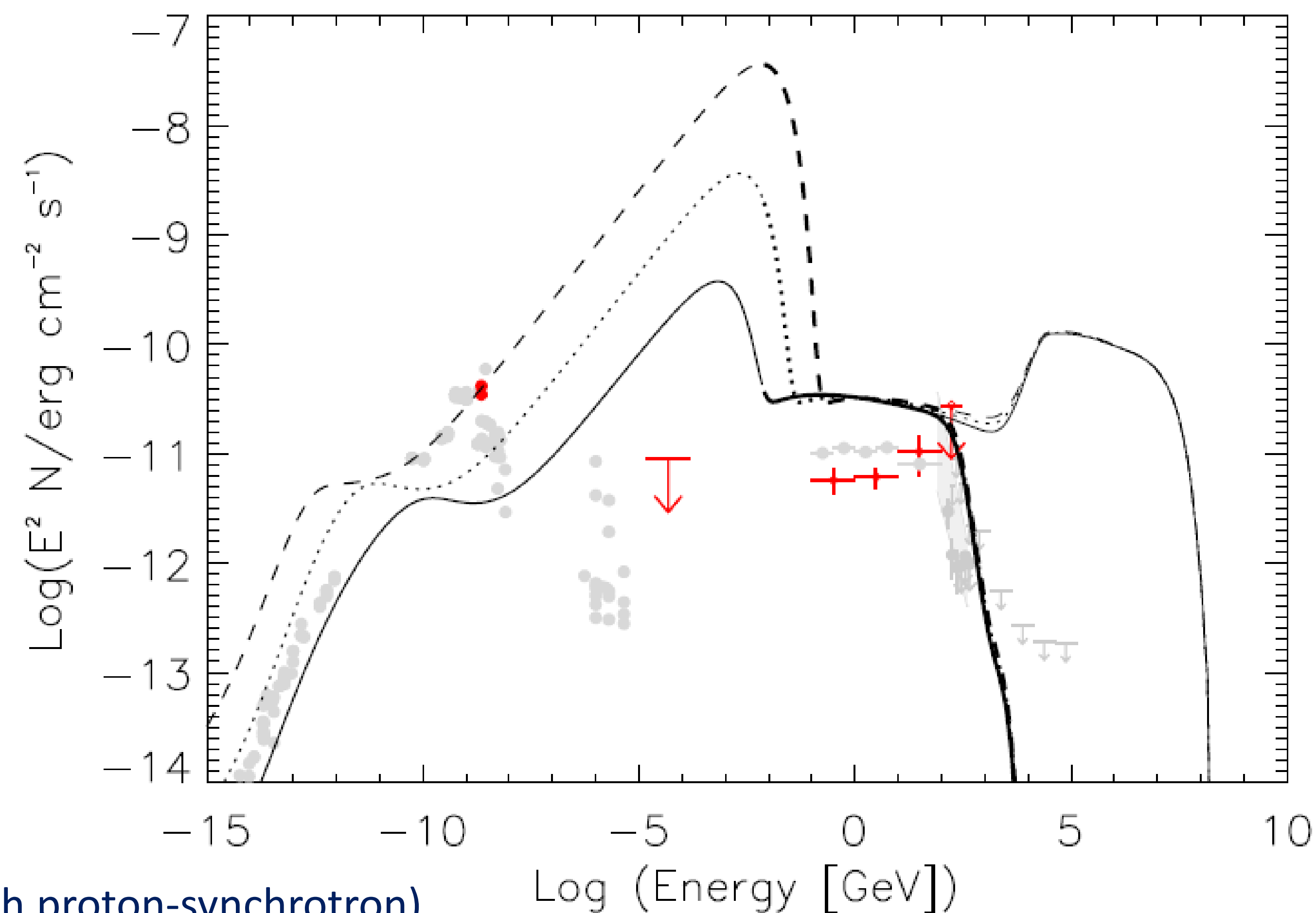


(neglecting proton-synchrotron)

Ruled out by MWL spectra

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

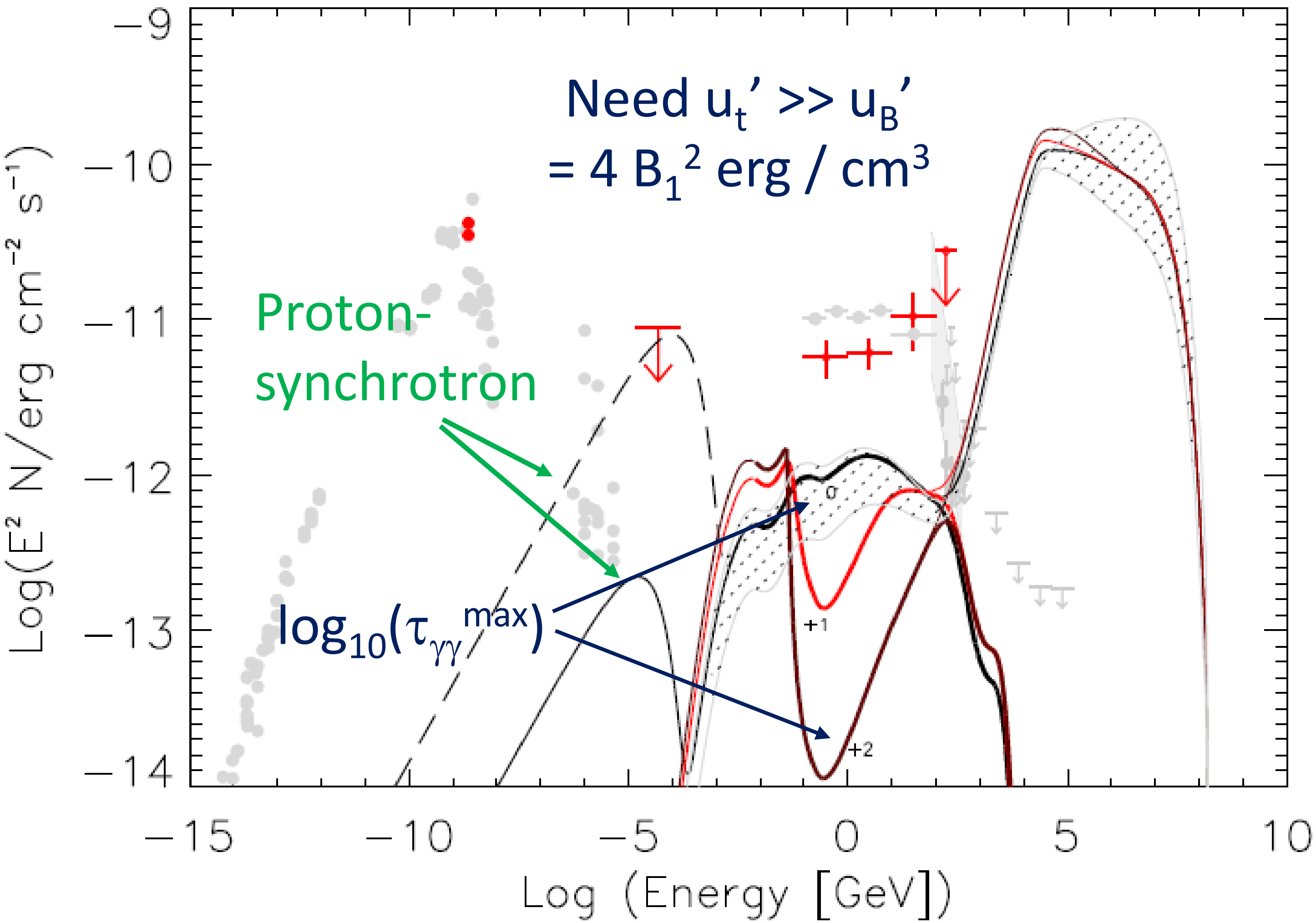
Synchrotron Supported Cascades



(with proton-synchrotron)

Expected proton-synchrotron grossly over-predicts X-ray flux!

Compton Supported Cascades



In principle, allowed by MWL spectra:

Significantly below observed fluxes

=> No neutrino – γ-ray correlation expected!

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	=> Not UHECRs!
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 hard X-rays

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

Spectral Energy Distribution of TXS 0506+056

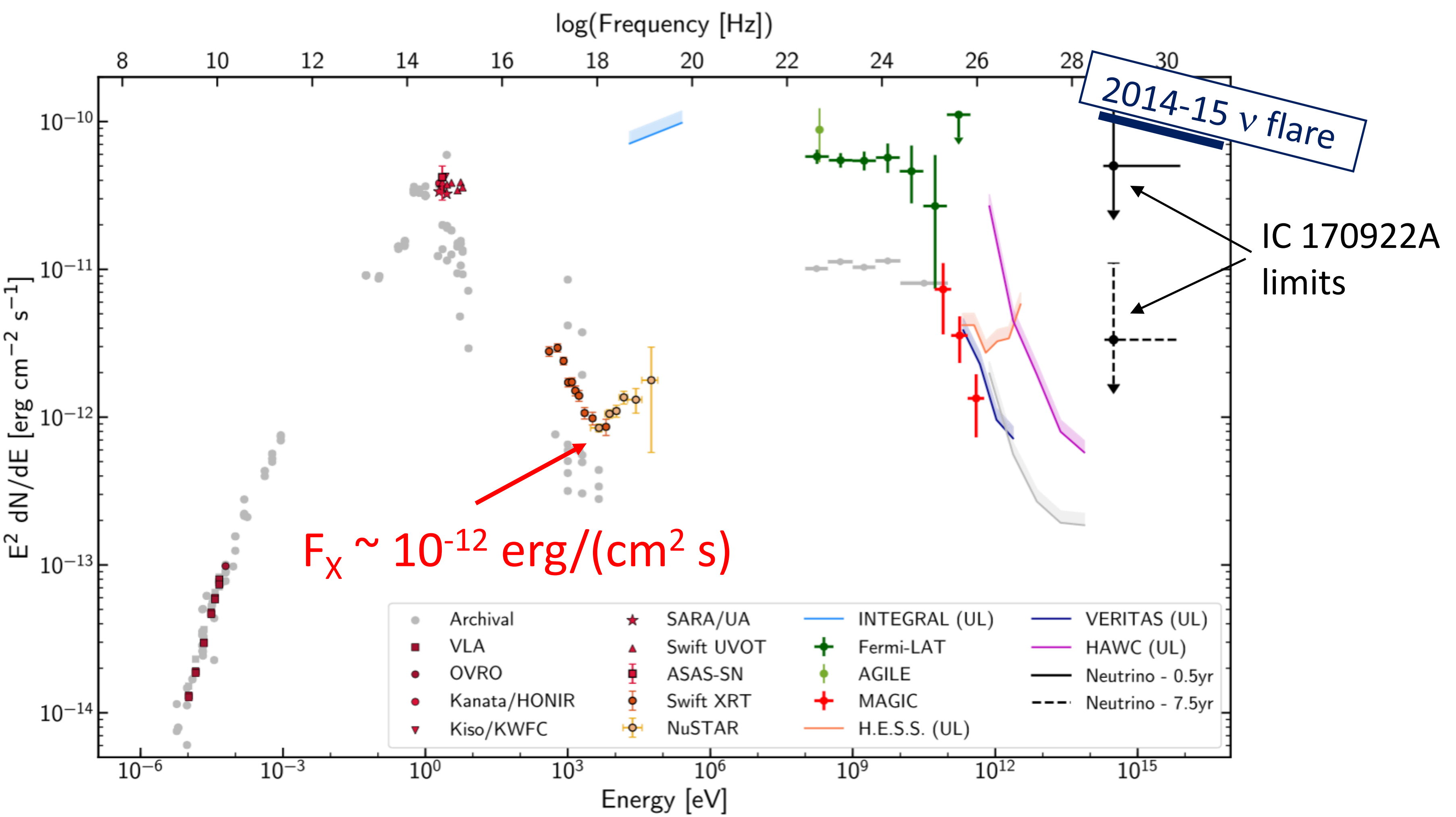


Photo-pion production – Origin of Target Photons

Constrain target photon luminosity and required proton power from

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

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

$L_{kin,p}$

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

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

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

Plausibly below Eddington limit.

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

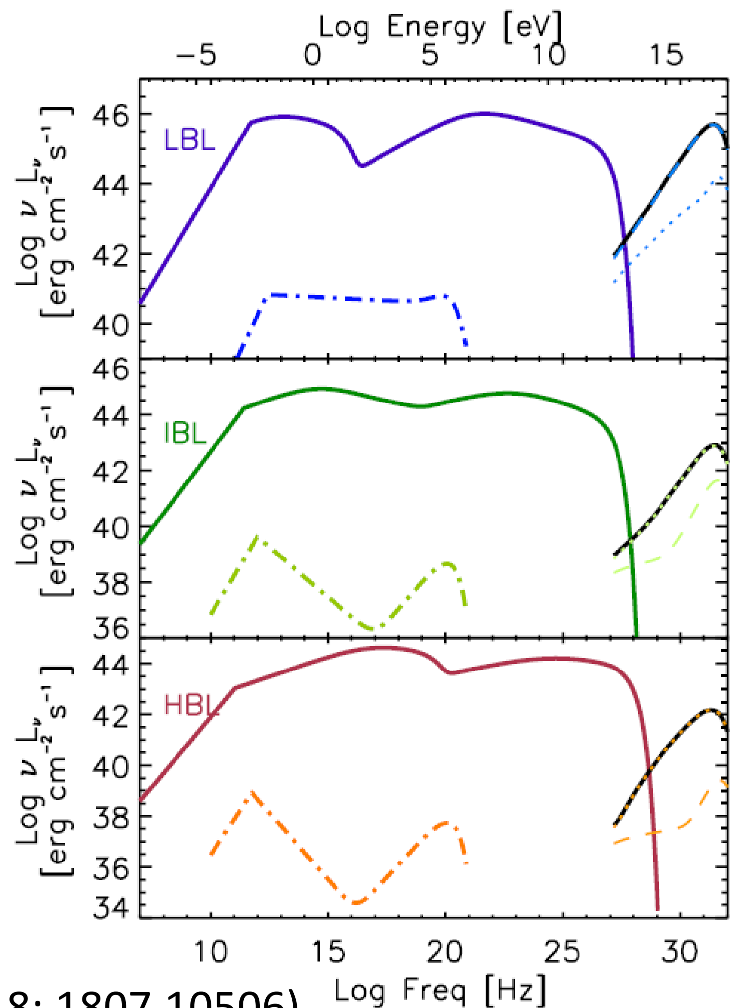
$\Rightarrow$ Plausible!

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

Photo-pion production – Origin of Target Photons

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

- BLR (?) – Padovani et al. (2019)
  (arXiv:1901.06998)
- Slow-moving sheath
  (Tavecchio & Ghisellini 2005)
- Accretion flow (RIAF)
  (Righi et al.: 1807.10506)
  -> Seems to favour LBLs as
  neutrino sources

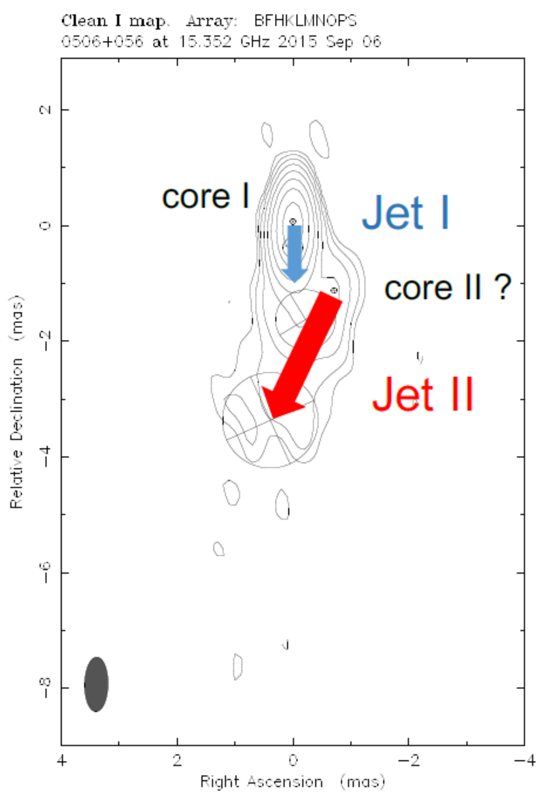


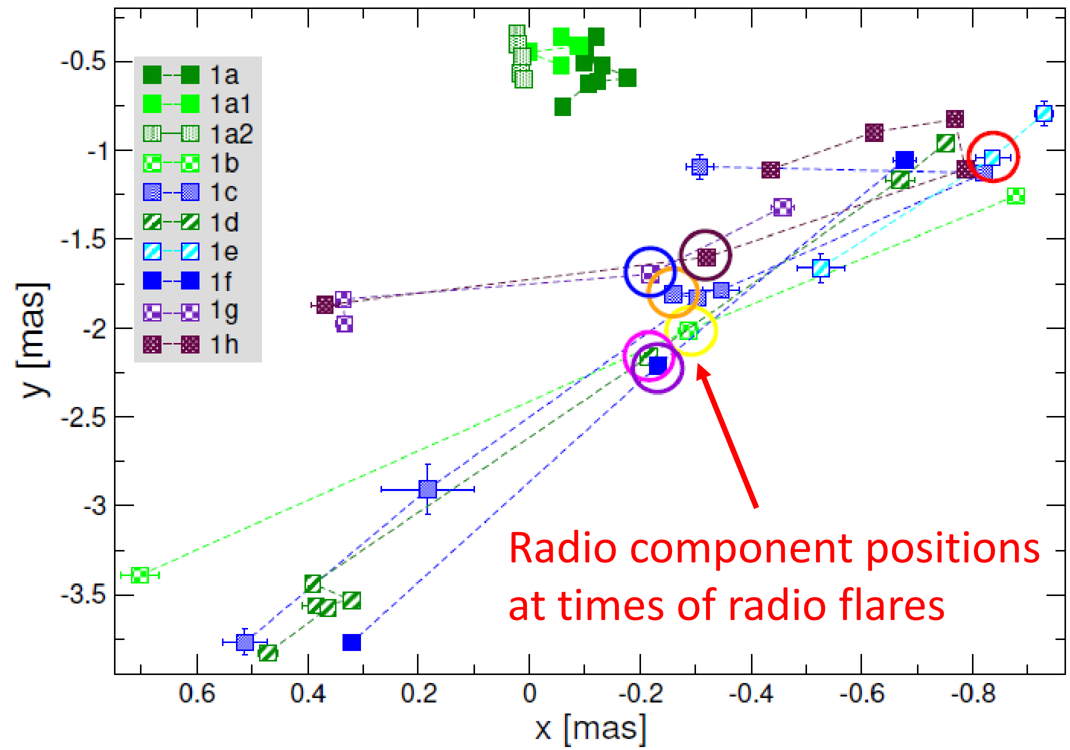
(Righi et al. 2018: 1807.10506)

Photo-pion production – Origin of Target Photons

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

- Jet-Jet interaction / Self-interaction of strongly bent jet? Synchrotron photon field of jet I = pγ target for neutrino production in jet II?





(Britzen et al., 2018, MNRAS, submitted) – see next talk.

Summary

- Production of IceCube neutrinos requires
  - Protons of ~ PeV energies
  - 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 (possibly due to jet-jet / jet self-interaction)

Reimer, Böttcher & Buson, 2018, ApJ, in press (arXiv:1812.05654)

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