Neutrino Production in AGN

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

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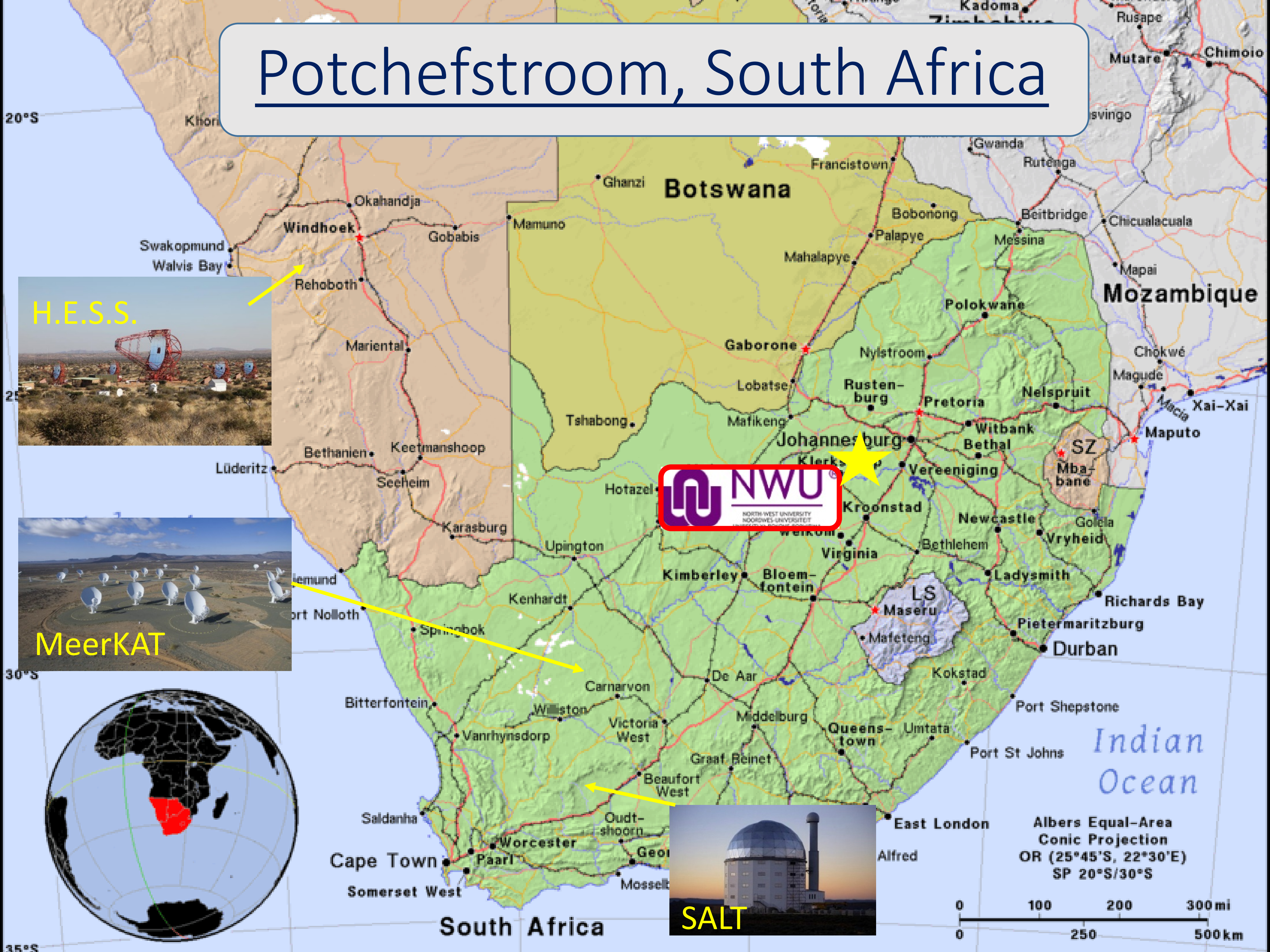
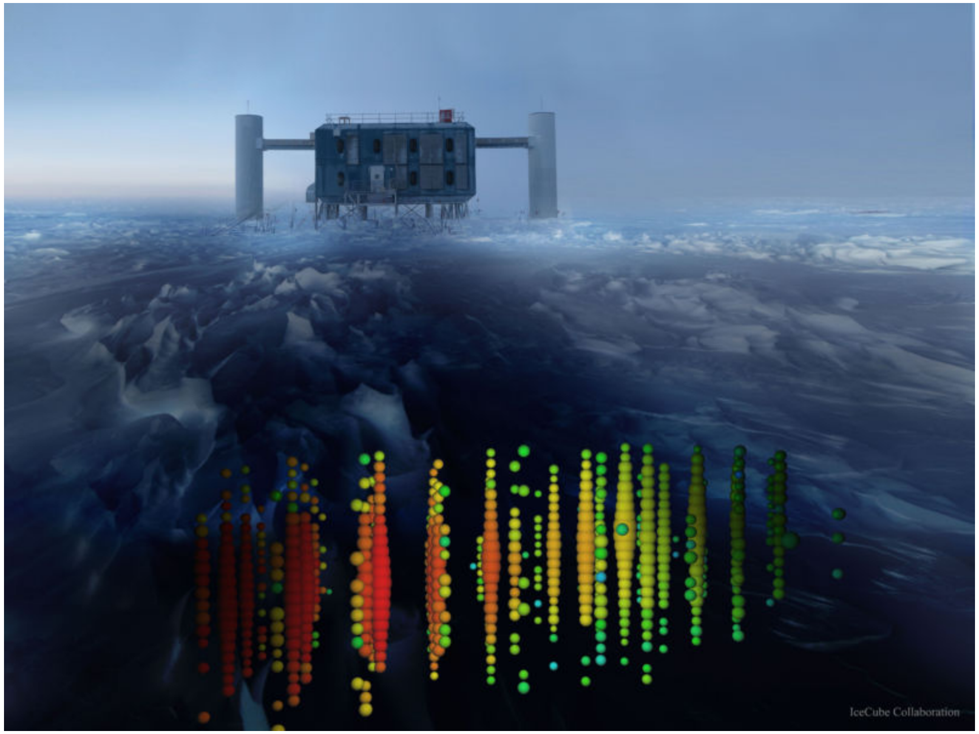
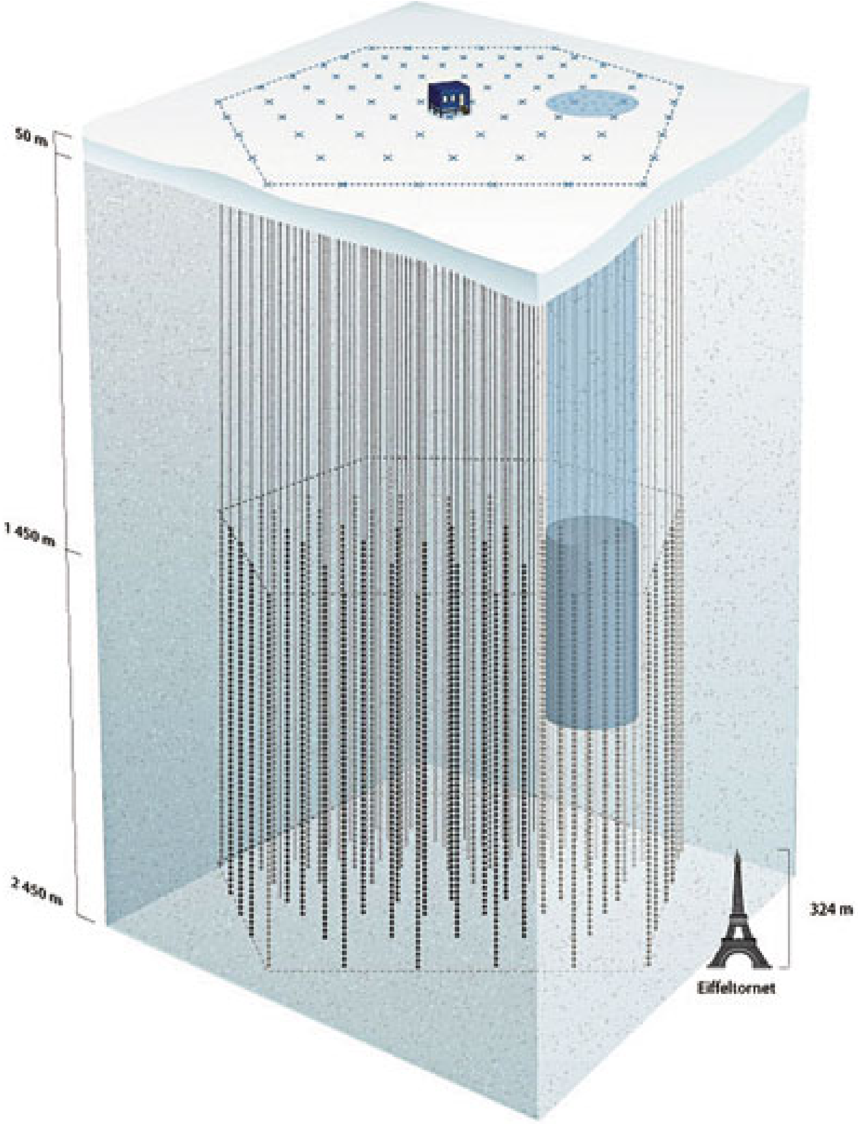
Potchefstroom, South Africa



The IceCube Detector at the South Pole



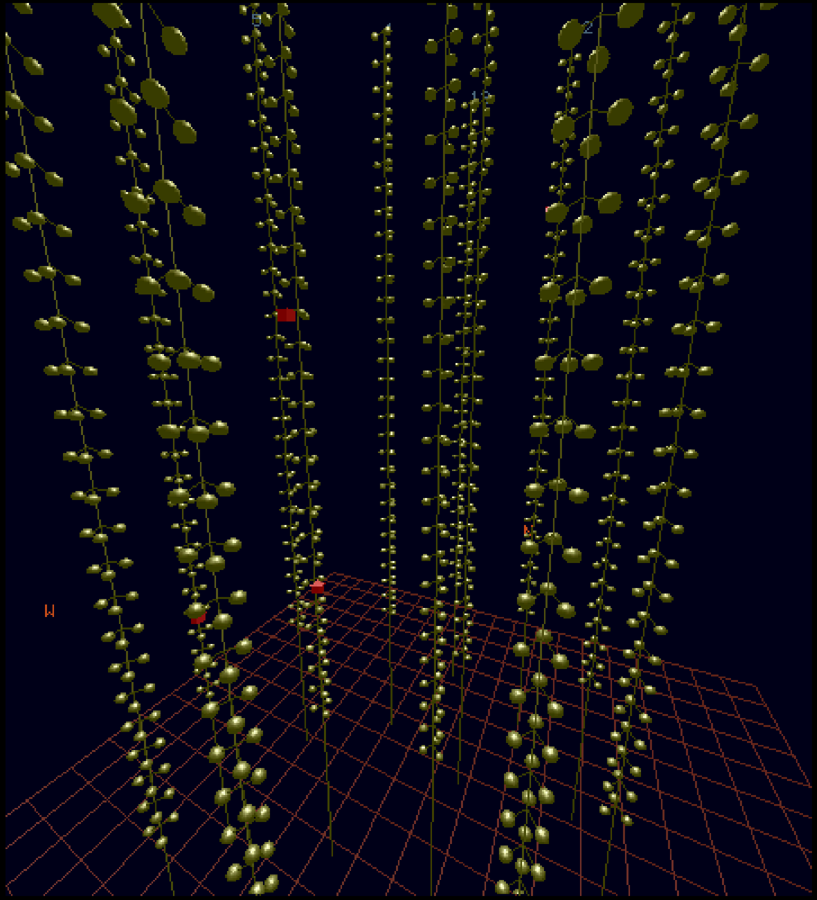
86 strings with 60 optical modules each, covering an effective detection volume of 1 km^3.
Fully operational since 2010.

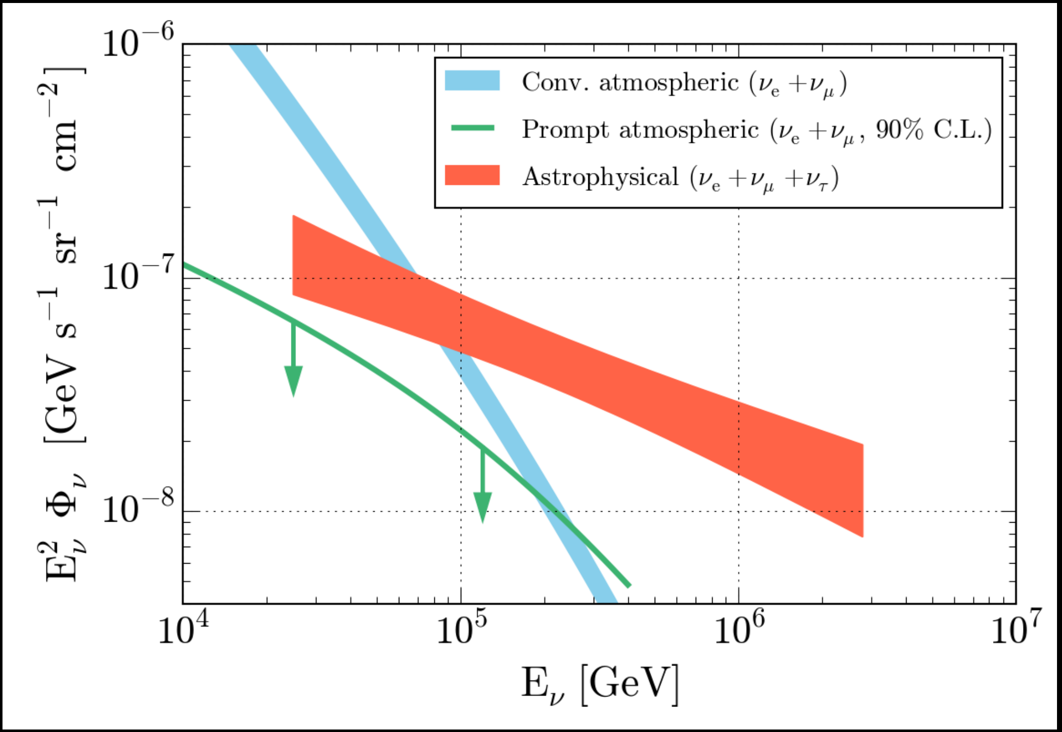


High-Energy Neutrino Detectors

ν interactions, followed by particle cascades in ice/water → Cherenkov light detection.

Neutrinos at > 1 PeV are almost certainly astrophysical.

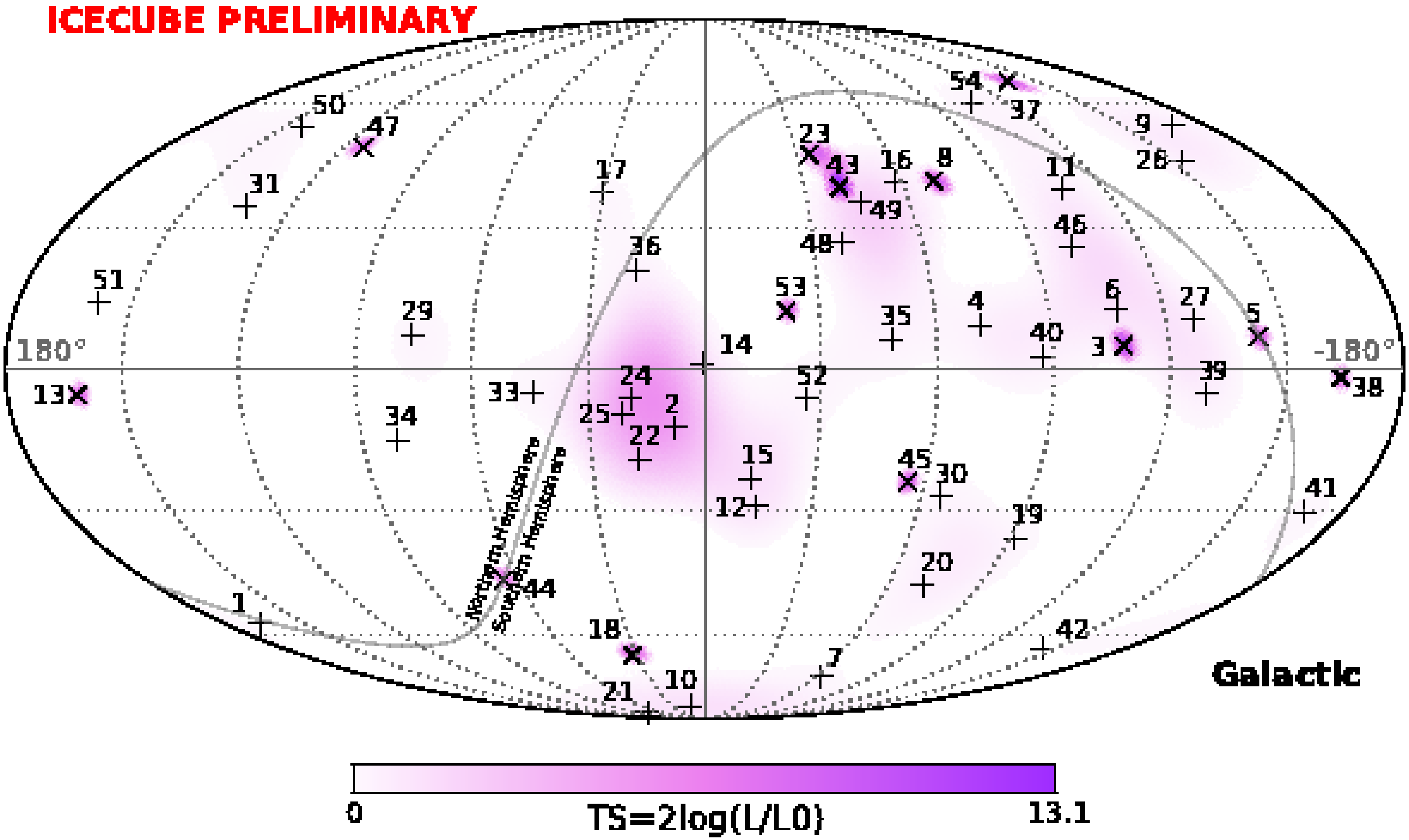




~ 100 astrophysical high-energy neutrinos detected!

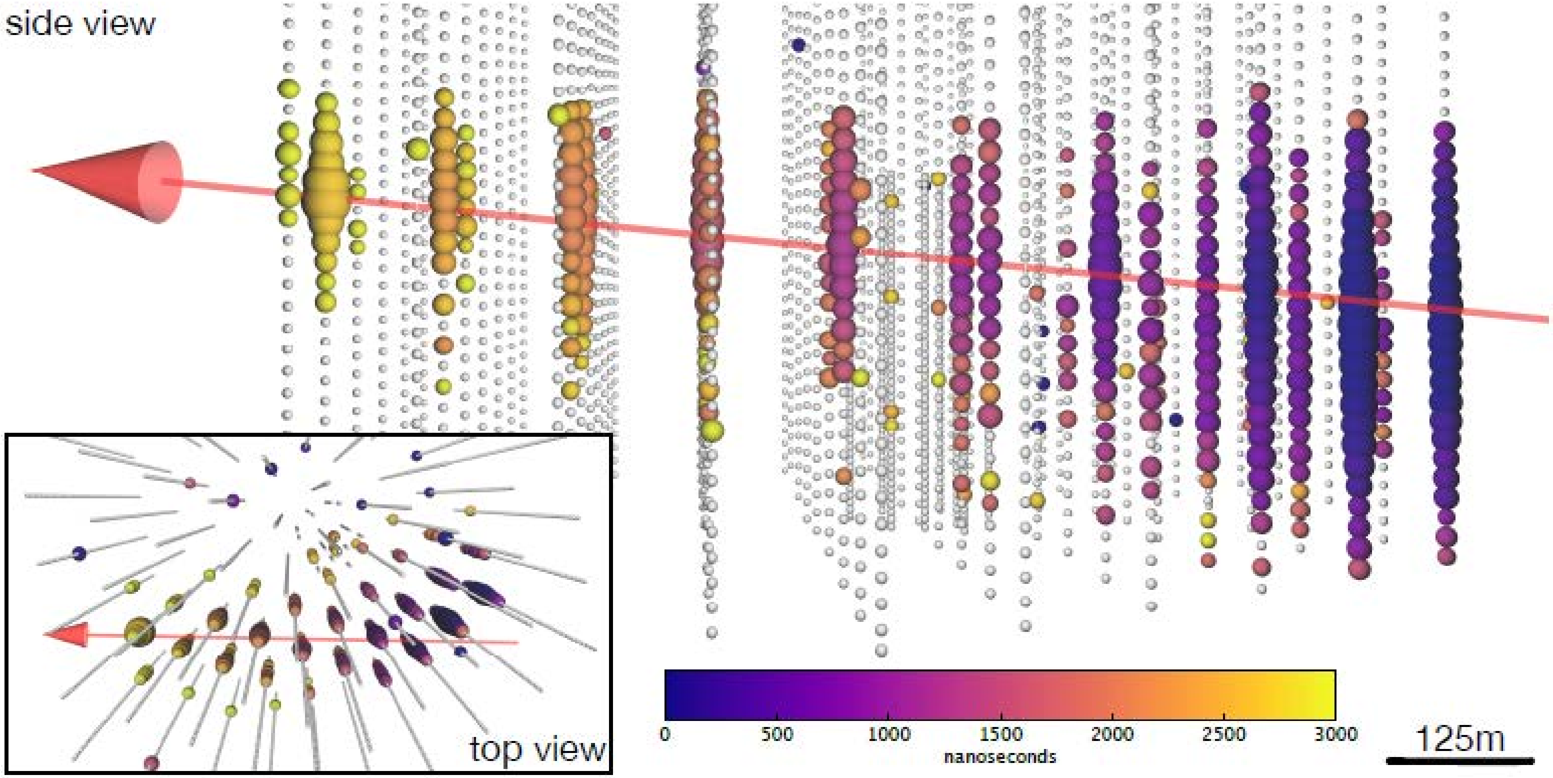
IceCube-Detected Neutrinos

Arrival Directions



No clear association with any known source class yet,
but some hints that AGN may make a significant contribution.

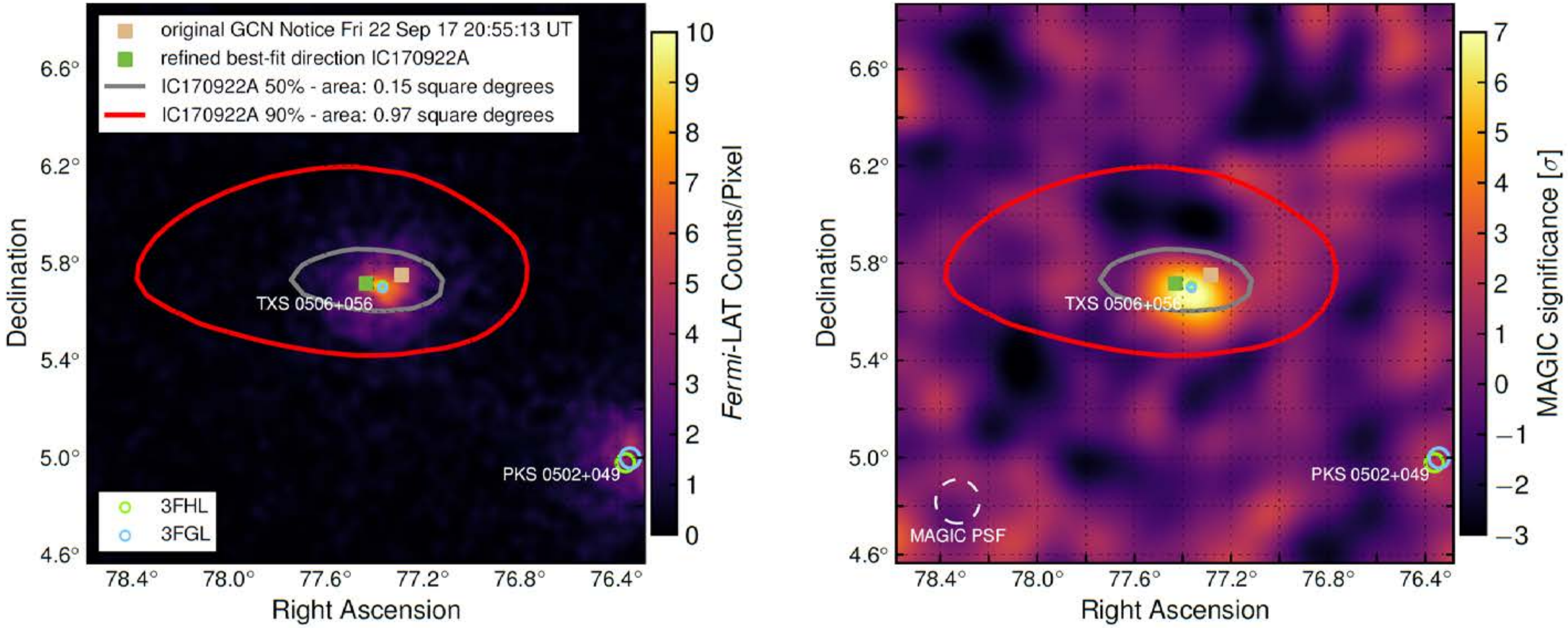
IceCube-170922A



(IceCube et al. 2018a)

Sept. 22, 2017: neutrino-induced muon track
with E_ν ~ 290 TeV
~ 50 % probability of being astrophysical

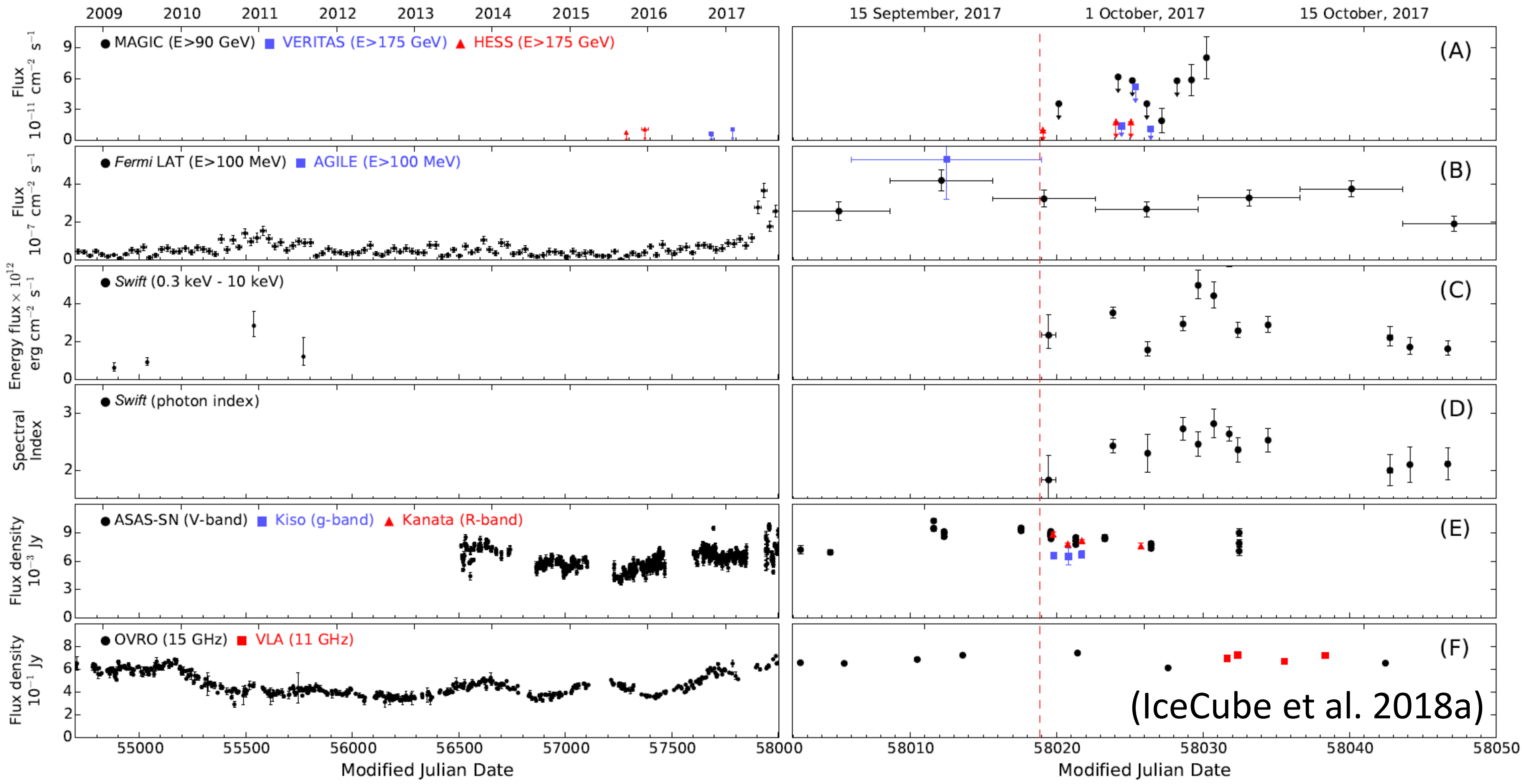
IceCube-170922A and TXS 0506+056



(IceCube et al. 2018a)

Position consistent with BL Lac object TXS 0506+056 ($z = 0.3365$)
during a ~ 4 weeks long γ-ray high state
(~ 3 σ probability of association)

IceCube-170922A and TXS 0506+056

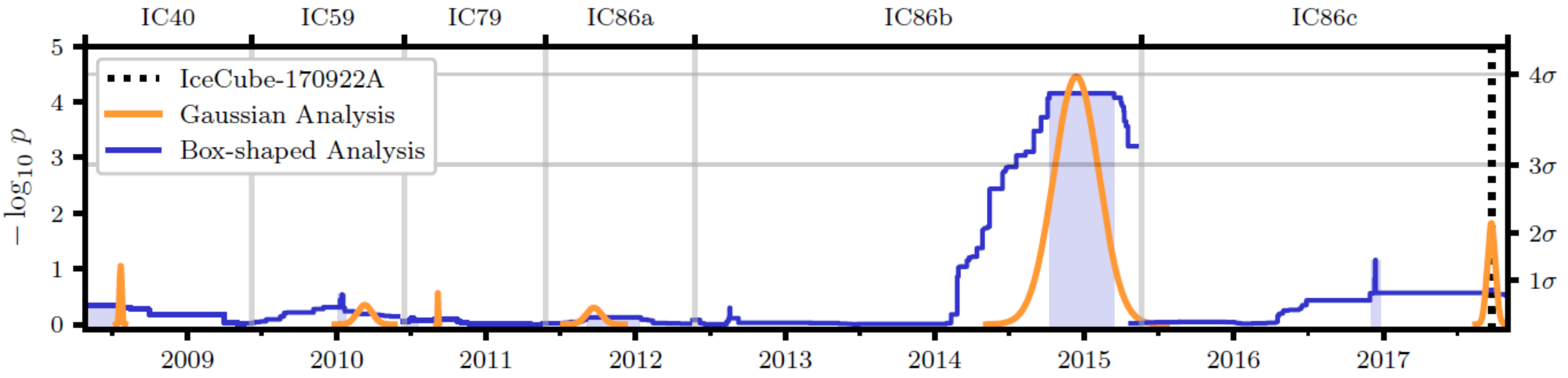


(IceCube et al. 2018a)

Position consistent with BL Lac object TXS 0506+056 ($z = 0.3365$) during a ~ 4 weeks long γ-ray high state.

Flare detection by MAGIC several days after neutrino

The Neutrino Flare from TXS 0506+056

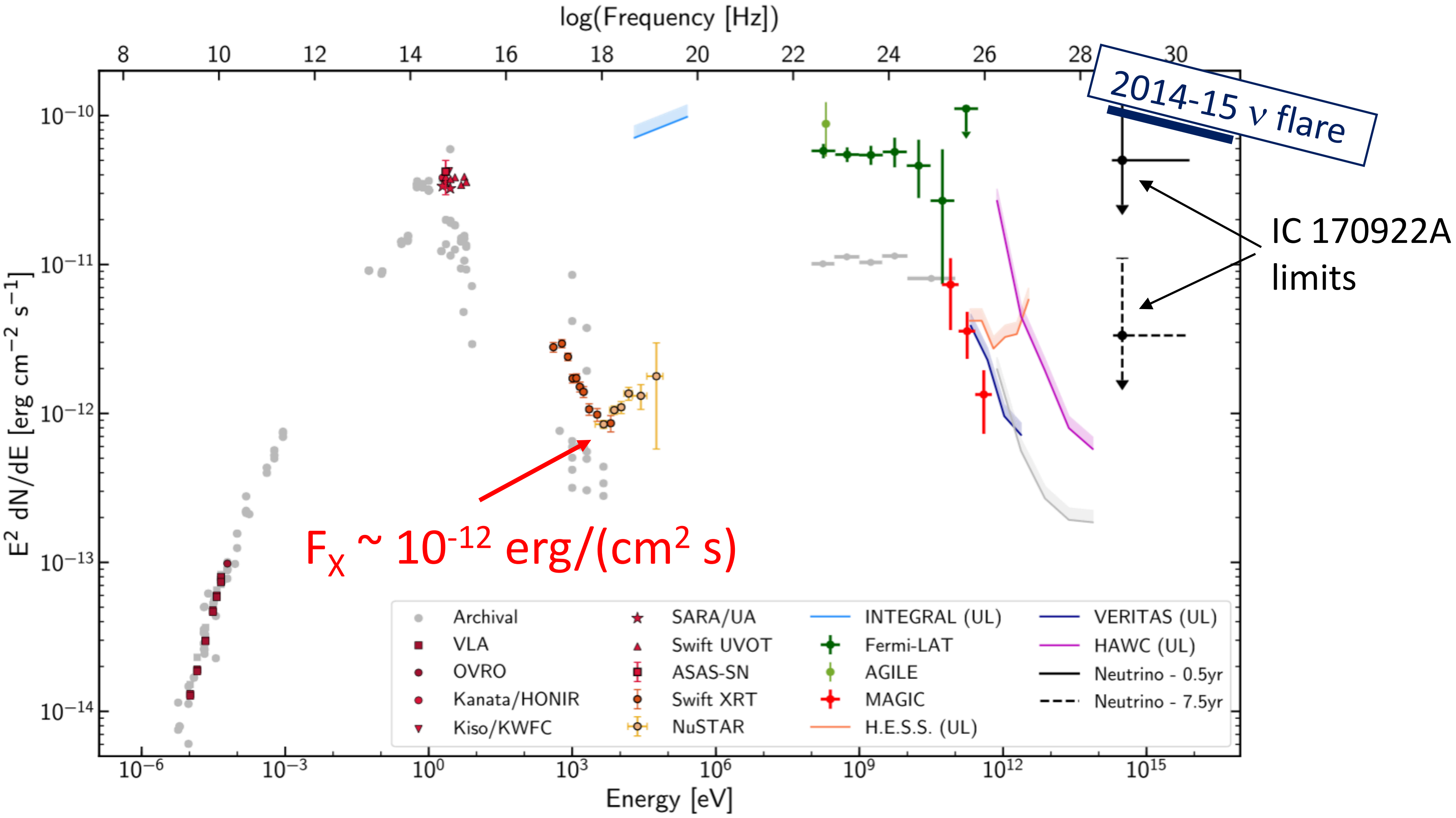


(IceCube et al. 2018b)

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!

Spectral Energy Distribution of TXS 0506+056

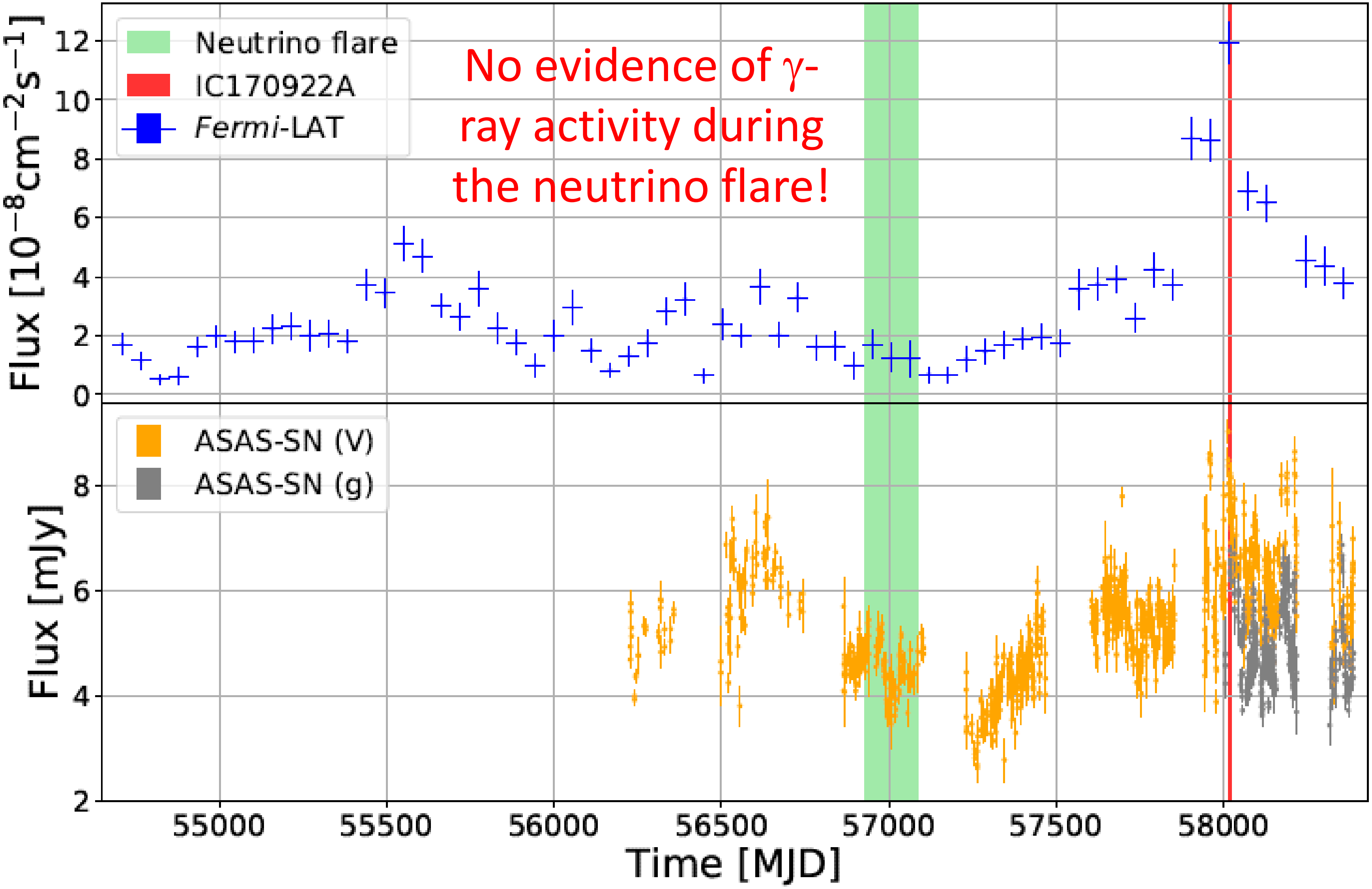


2014-15 ν flare

IC 170922A limits

$F_X \sim 10^{-12}$ erg/(cm^2 s)

The Neutrino Flare from TXS 0506+056



No evidence of γ-ray activity during the neutrino flare!

Basics of Neutrino Production

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

  or $\quad p + n\ (N') + \pi^+$

- $p + \gamma \rightarrow p + \pi^0$ $\quad$ ($\sigma_{p\gamma} \sim 0.6$ mb)

  or $\quad n + \pi^+$

$\pi^0 \rightarrow 2\gamma$

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

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

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

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

Basics of Neutrino Production

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

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

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

  or $n + \pi^+$ $\qquad (1/3)$

$$\boxed{\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 3 \times 10^{14}\ \frac{\Gamma_1^{\ 2}\ L_{sy,44}}{\varepsilon_{-6}\ \delta_1^{\ 4}\ L_{j,46}}}$$

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

$$n_p \leq \frac{L_j}{\Gamma^2\, m_p\, c^2\, \pi\, R^2\, c} \sim 10^4\, R_{16}^{\ -2}\, \Gamma_1^{\ -2}\, L_{j,46}\, cm^{-3}$$

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, e.g., Liu et al.: 1807.05113: UHECR interactions with BLR clouds

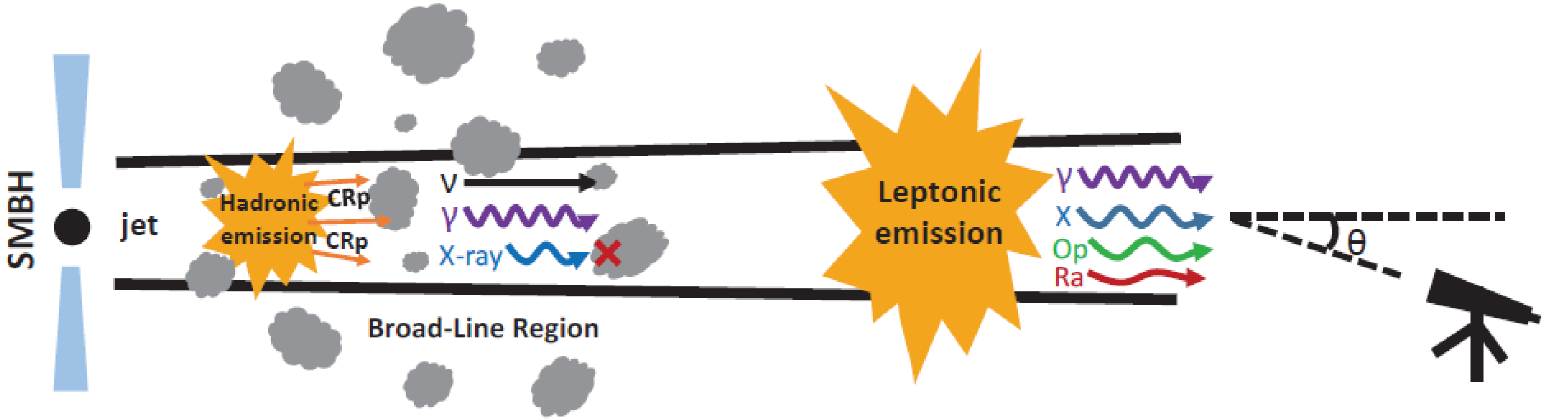
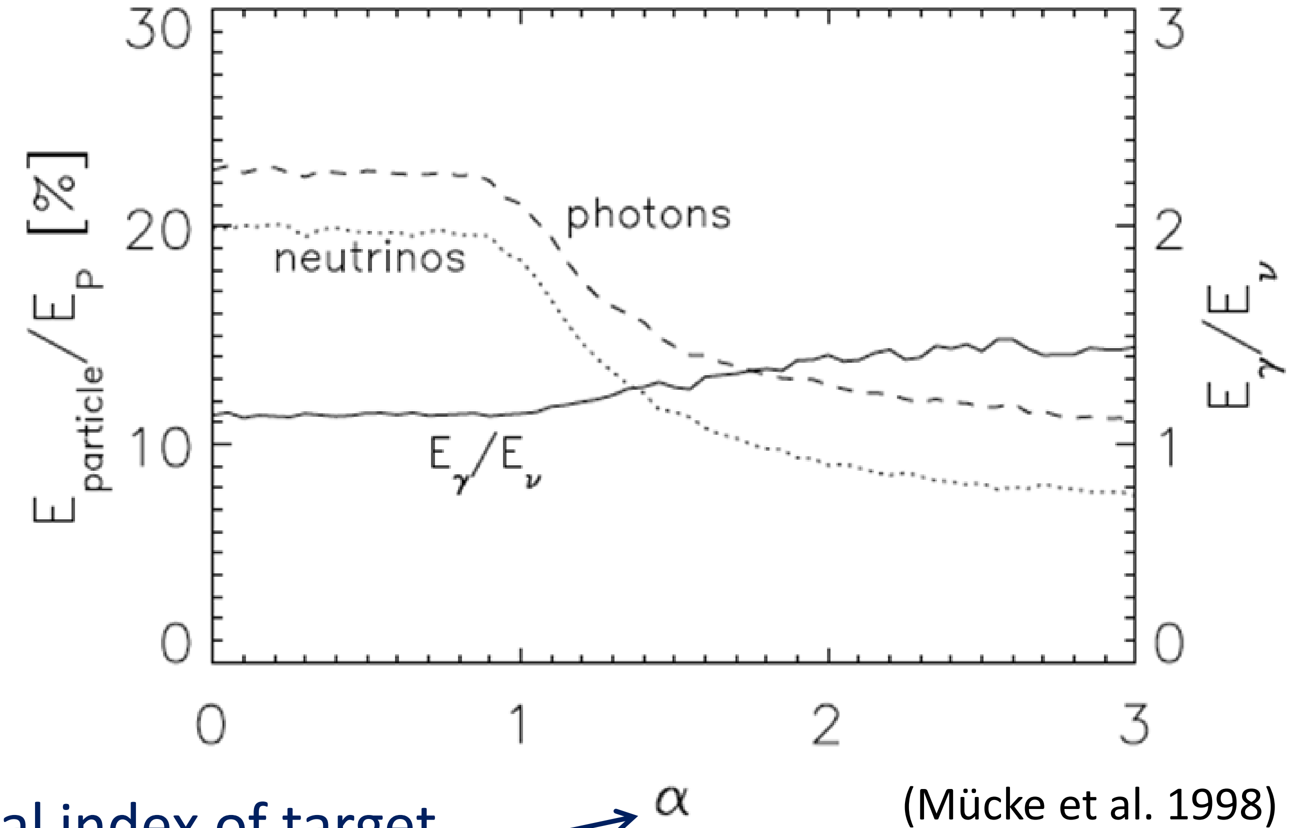


Photo-Pion Production

Fractional energy output

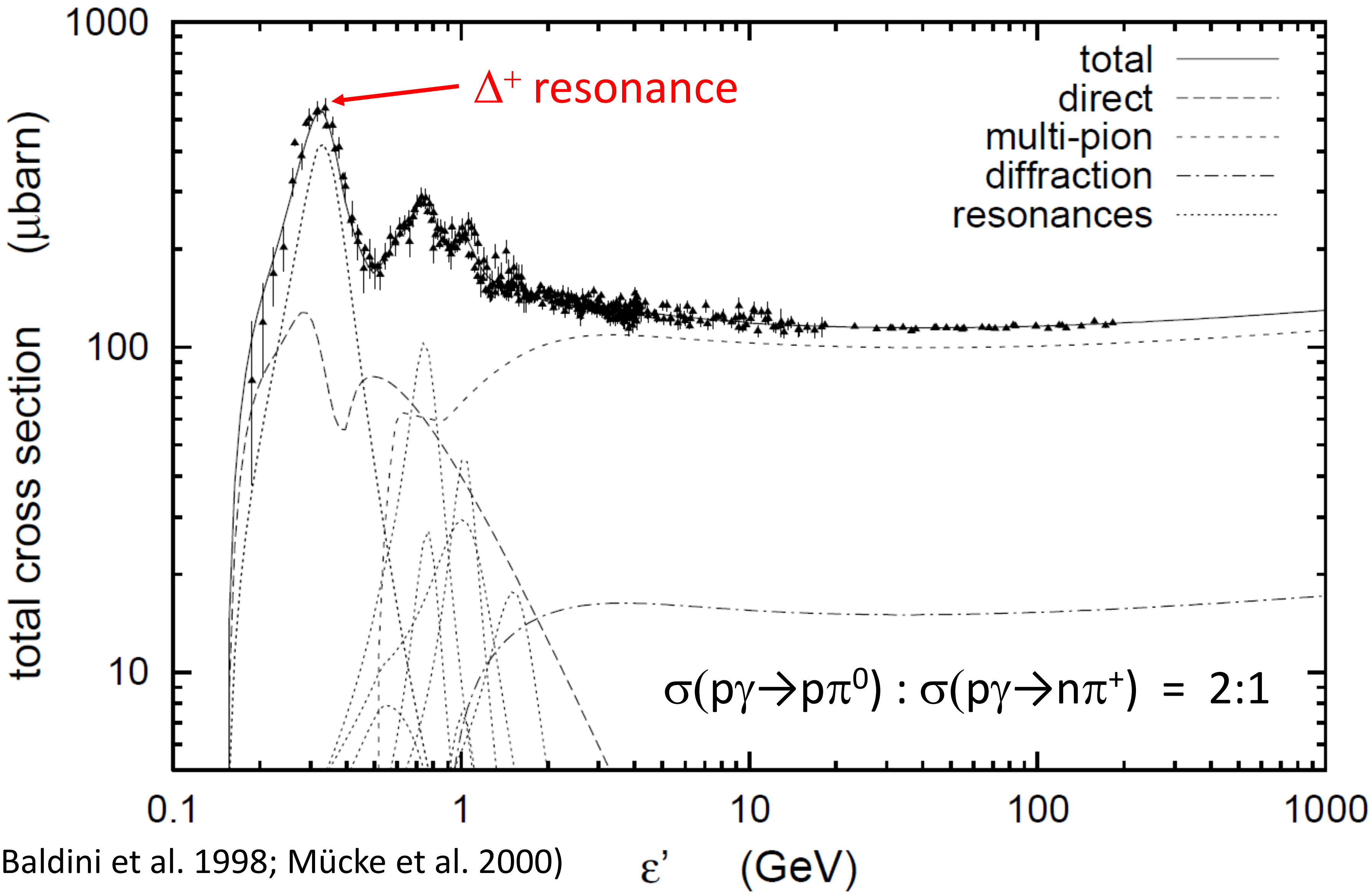


Spectral index of target photon field

(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



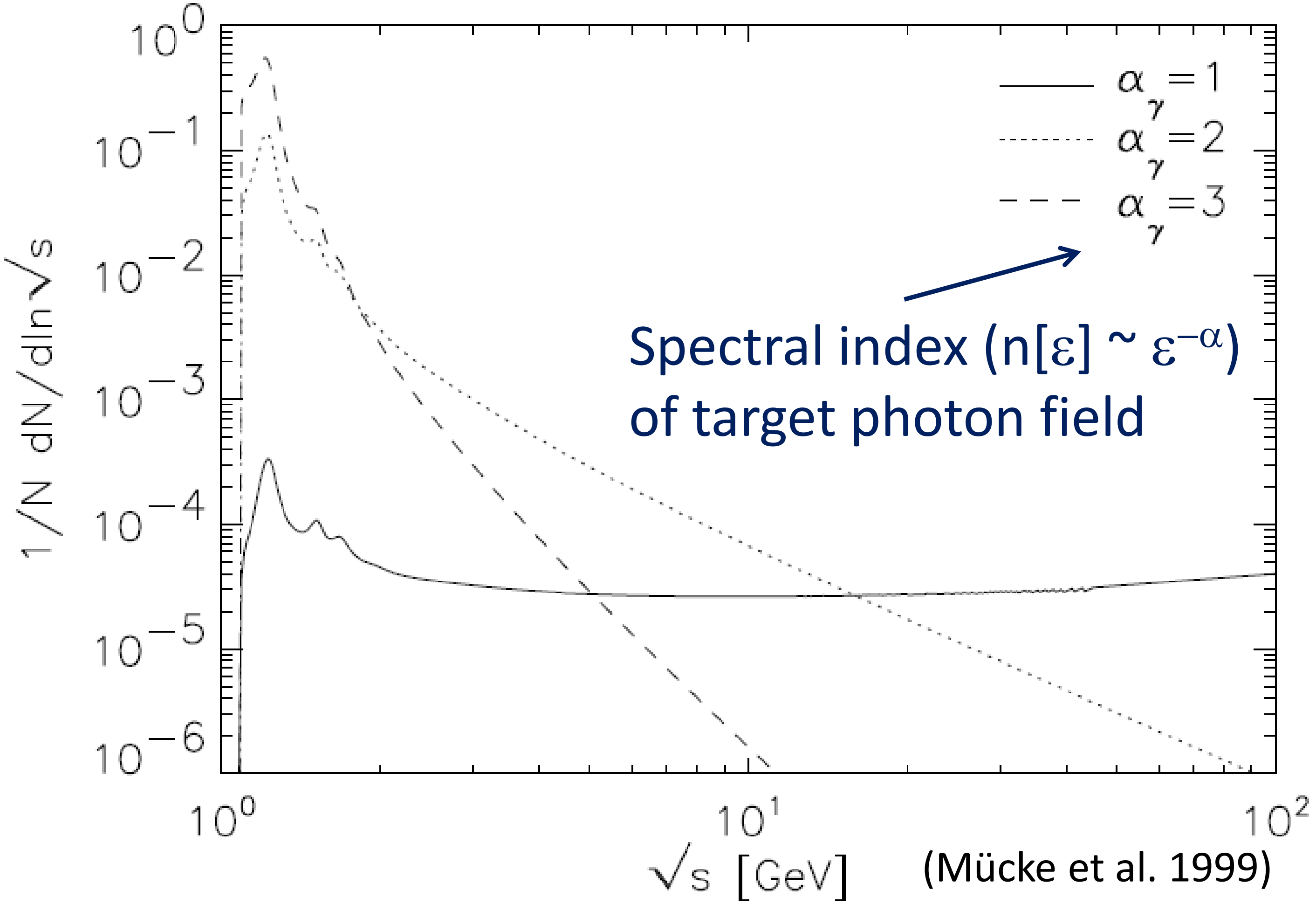
Δ^+ resonance

$\sigma(p\gamma \rightarrow p\pi^0) : \sigma(p\gamma \rightarrow n\pi^+) = 2:1$

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

Photo-Pion Production

Interaction Probability



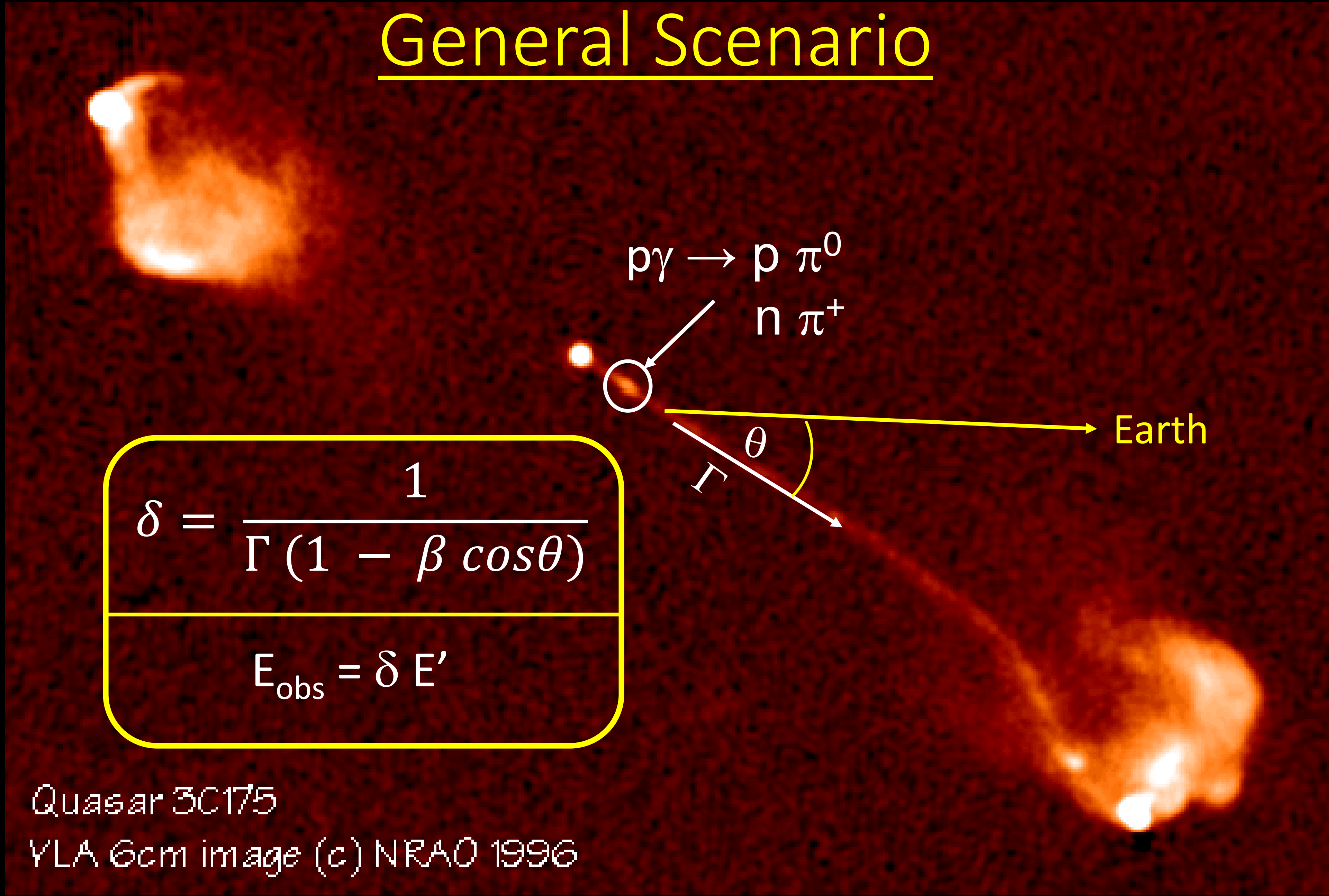
Spectral index ($n[\varepsilon] \sim \varepsilon^{-\alpha}$) of target photon field

(Mücke et al. 1999)

Center-of-Momentum energy

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

General Scenario



$$p\gamma \longrightarrow p\,\pi^0$$
$$n\,\pi^+$$

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

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

Quasar 3C175

VLA 6cm image (c) NRAO 1996

Photo-pion production - Energetics

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

At Δ^+ resonance:

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

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 => Not UHECRs!

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

Photo-pion production - Energetics

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

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

γ-ray production through:

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)

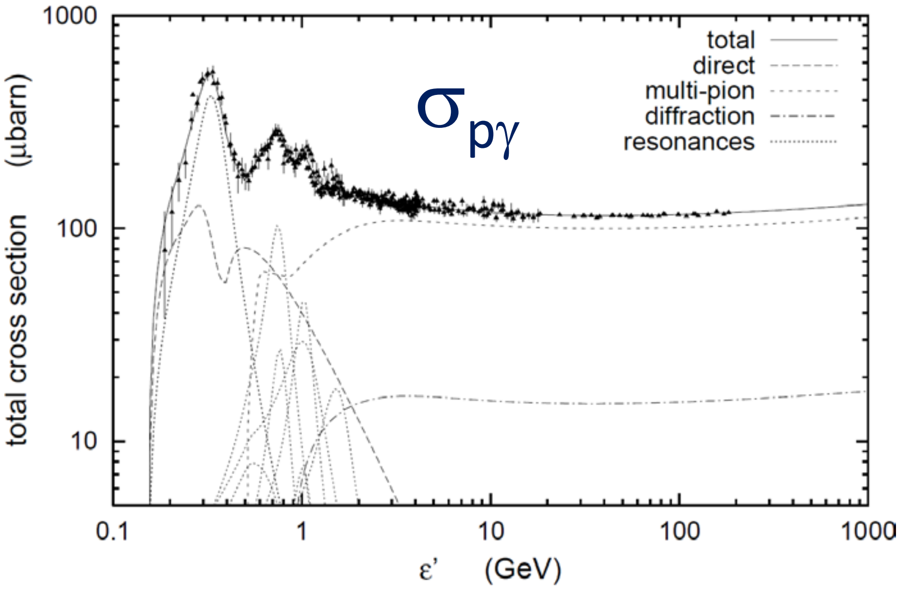
c) Secondary electron synchrotron at

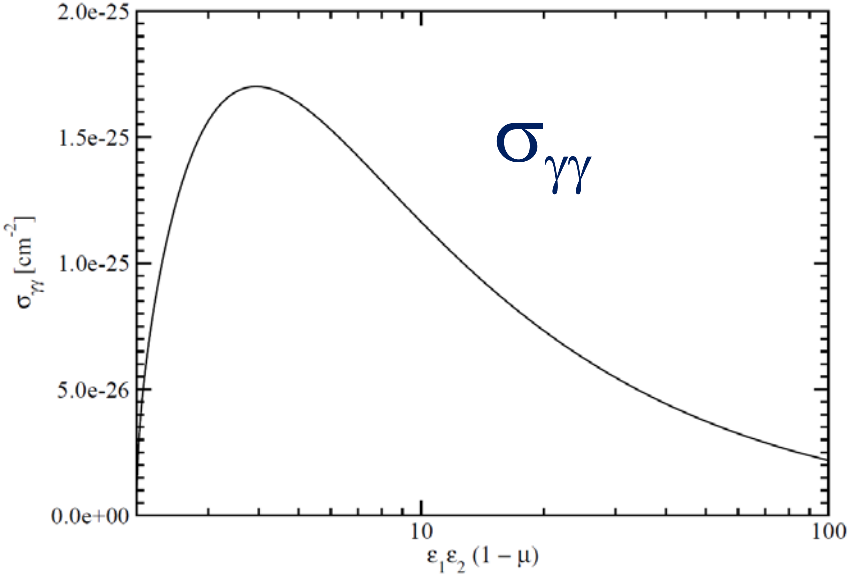
$\nu_{esy} \sim 4\times10^{21}\ \gamma_6^2\ B_2\ \delta_1$ Hz (~ 20 MeV)

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

The pγ Efficiency Problem

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





$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{1}{300}$$

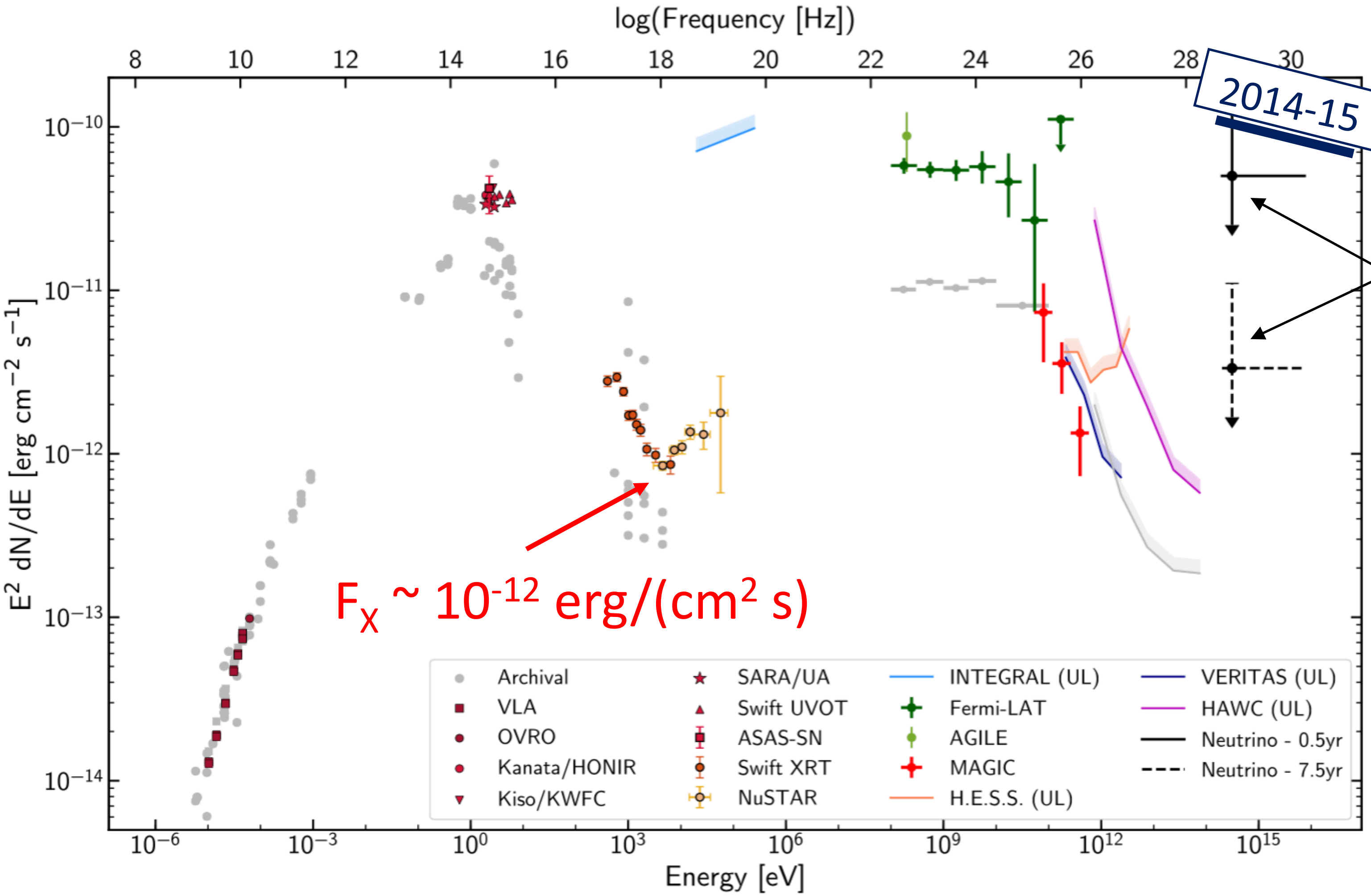
at

$$E_\gamma \sim \frac{m_e^{2}\,c^{4}}{E_t} \sim 3.3\times 10^{-5}\,E_\nu$$

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

⇒ Cascade emission at lower energies.

Spectral Energy Distribution of TXS 0506+056

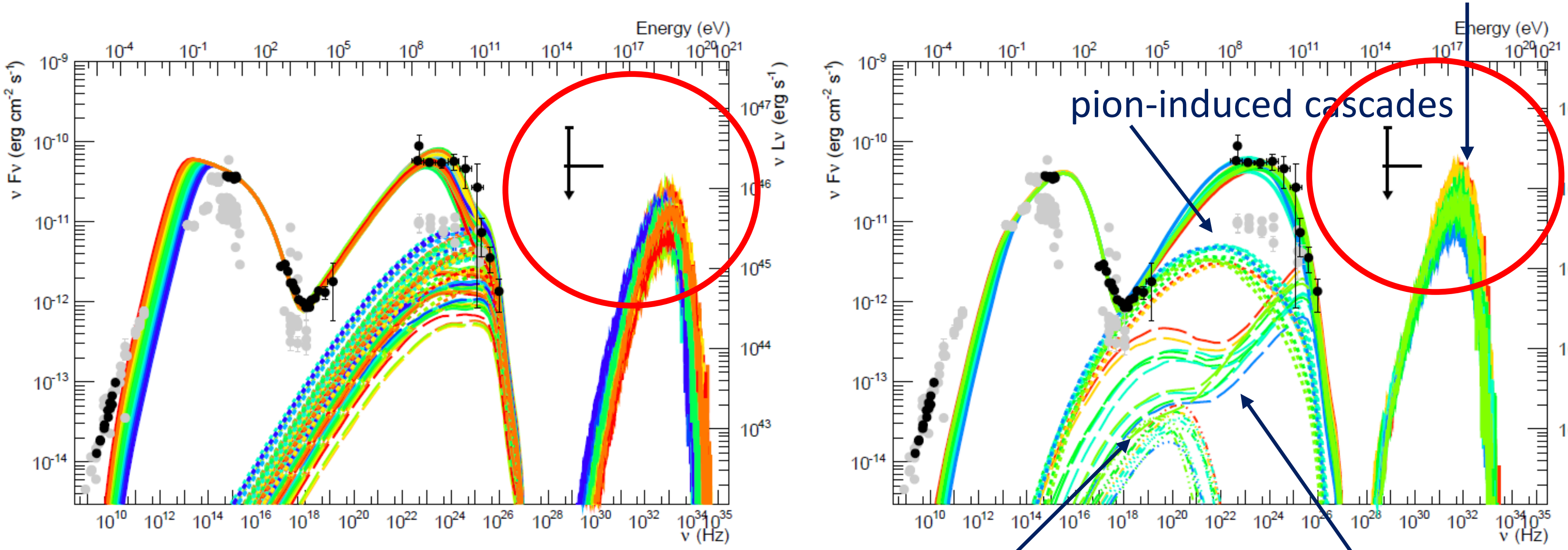


2014-15 ν flare

IC 170922A limits

$F_X \sim 10^{-12}$ erg/(cm^2 s)

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)

neutrinos

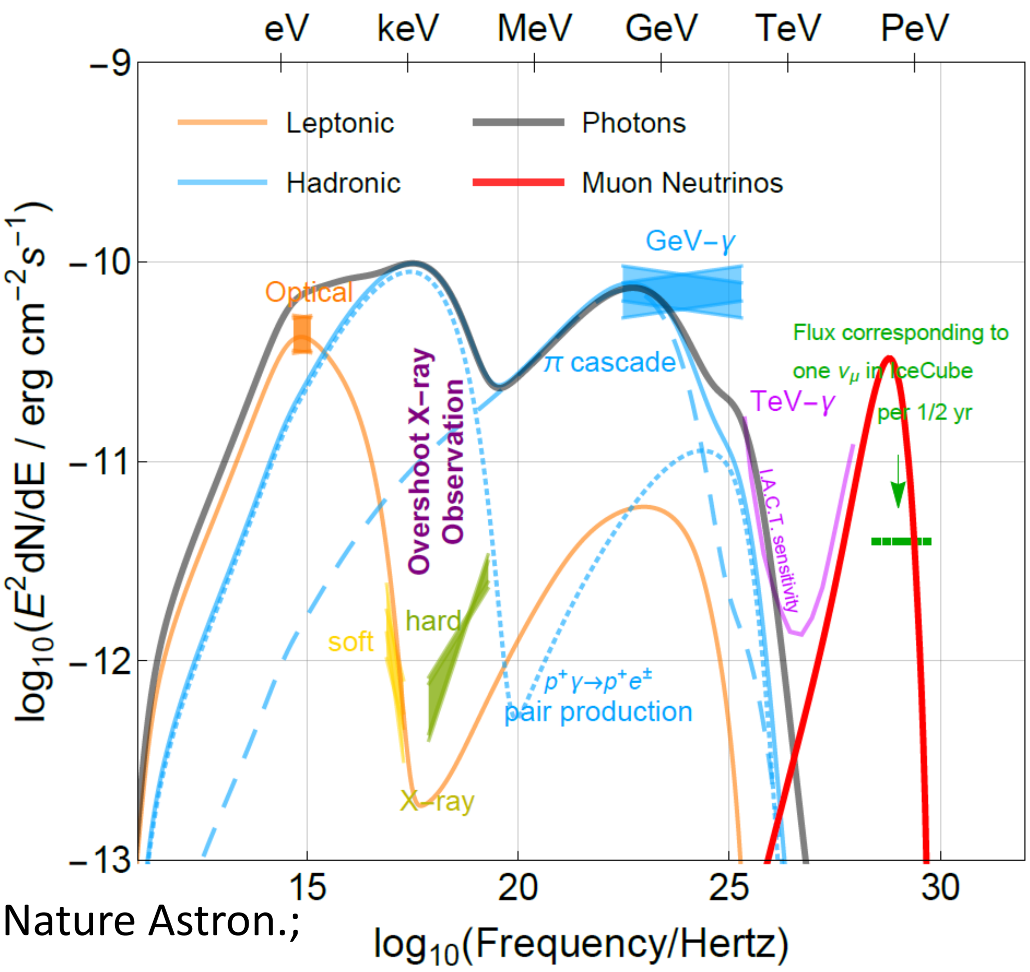
pion-induced cascades

Proton-synchrotron

Bethe-Heitler-induced cascades

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

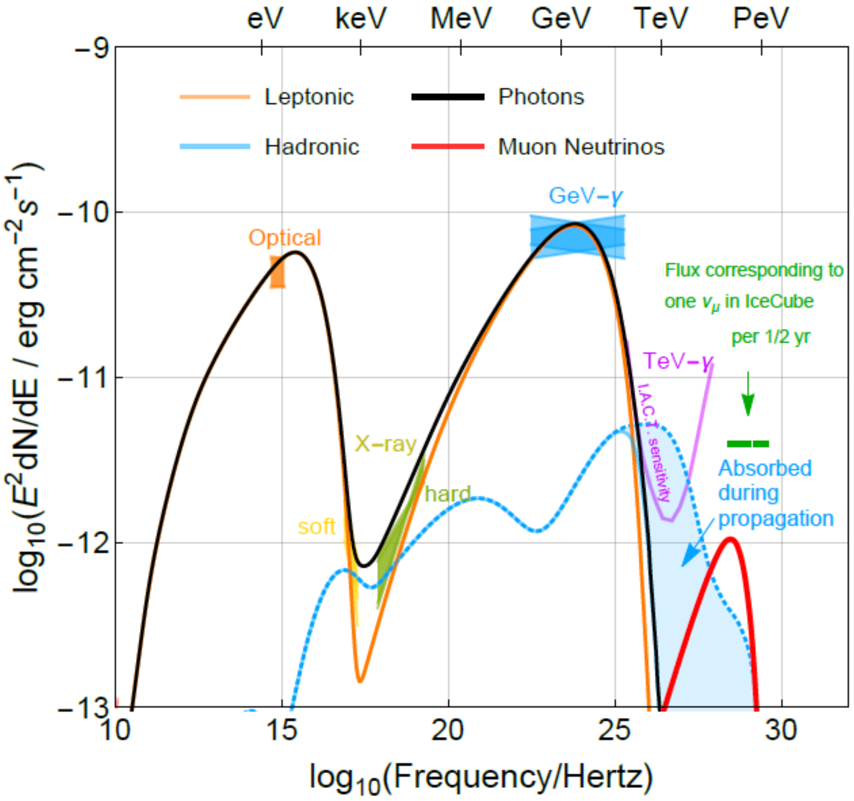
Photo-Pion Models for TXS 0506+056



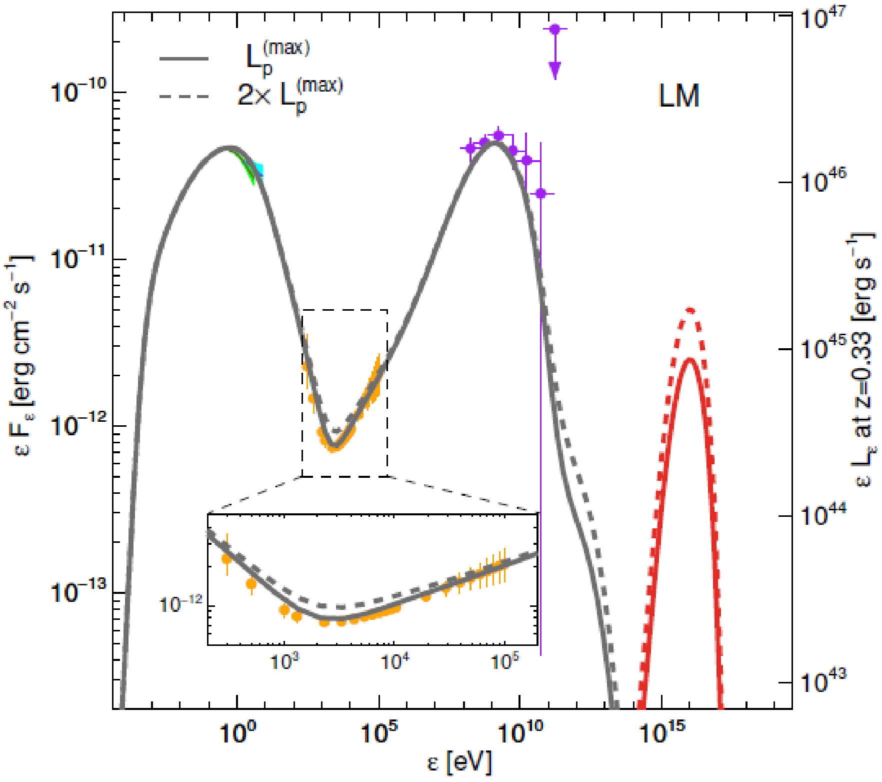
(Gao et al., 2018, Nature Astron.; 1807.04275)

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., arXiv: 1807.04275)

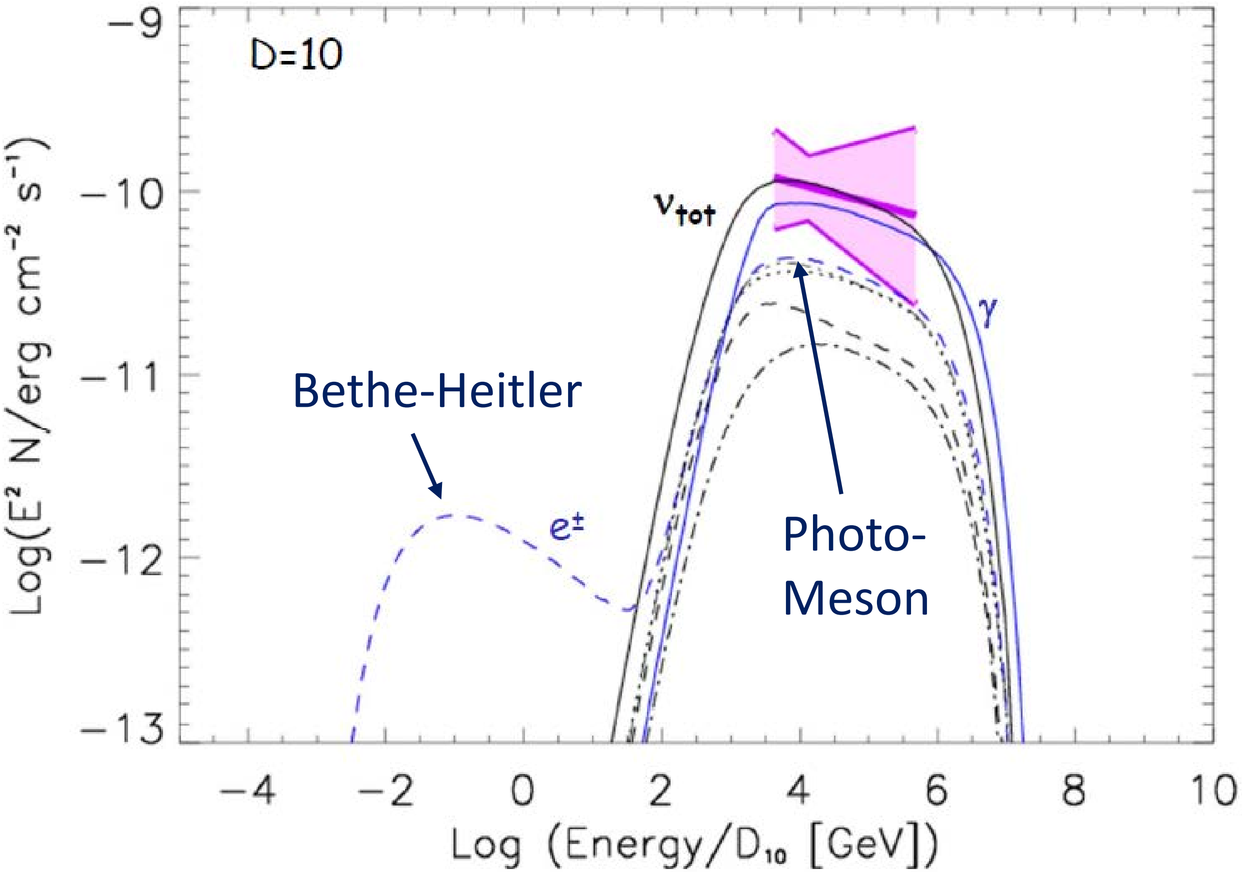


(Keivani et al.:, 2018, ApJ, 864, 84; arXiv: 1807.04537)

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

Constraints from Cascades

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



Bethe-Heitler

Photo-Meson

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

Constraints from Cascades

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

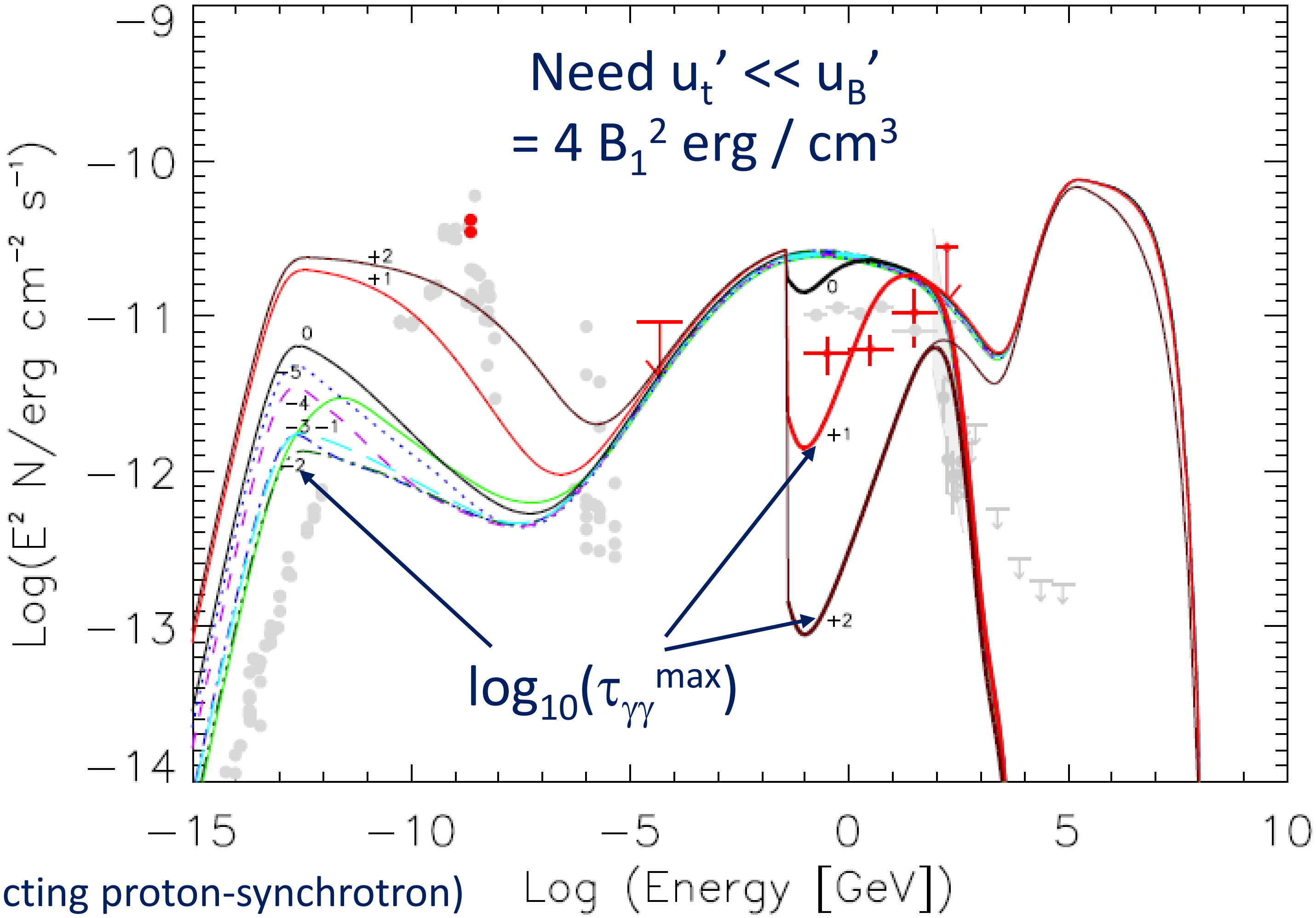
3) Simulate pair cascades initiated by secondary γ-rays and electrons/positrons

- 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



Need $u_t' \ll u_B'$

$= 4\, B_1^2$ erg / cm^3

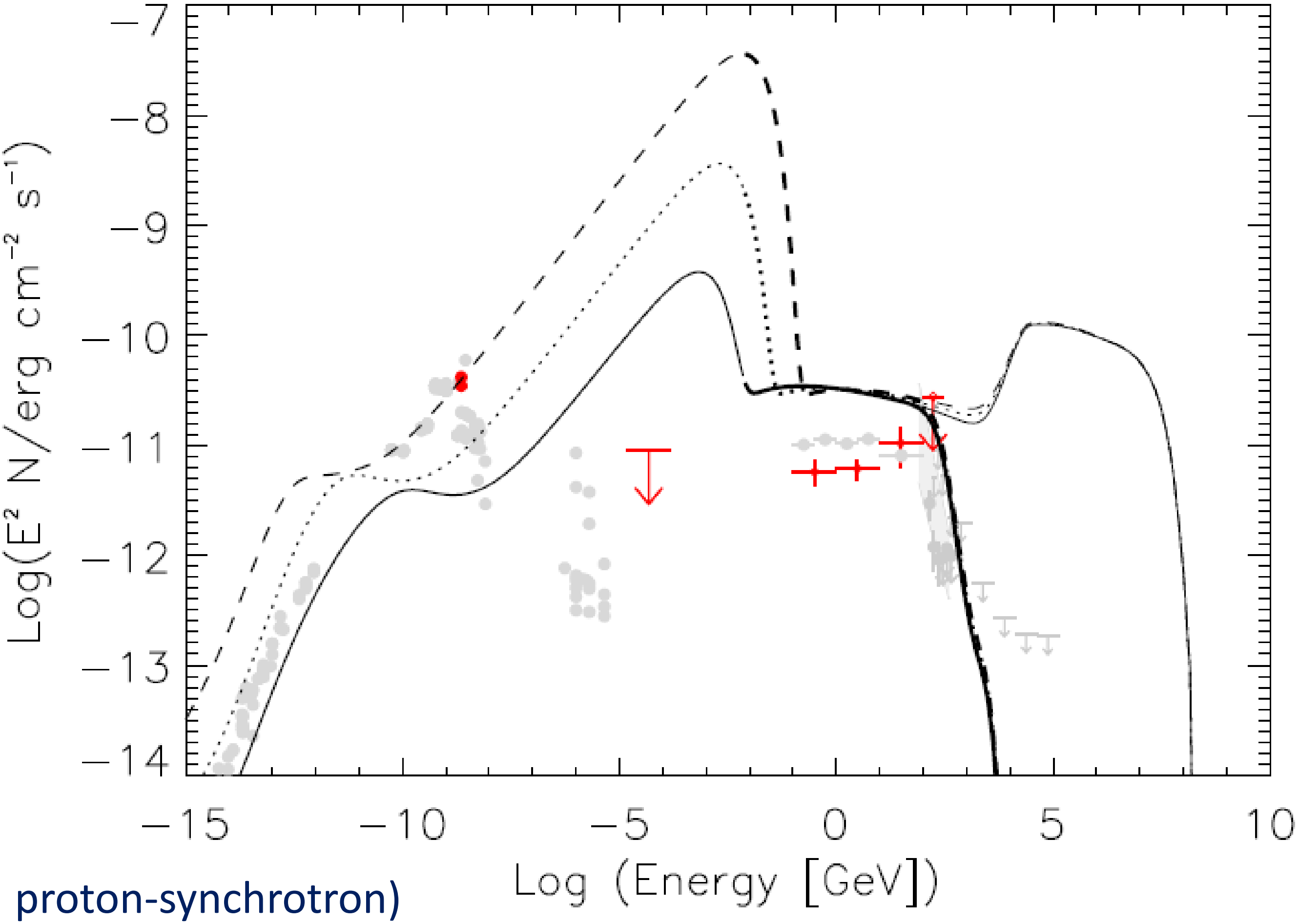
$\log_{10}(\tau_{\gamma\gamma}^{\max})$

(neglecting proton-synchrotron)

Ruled out by MWL spectra

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

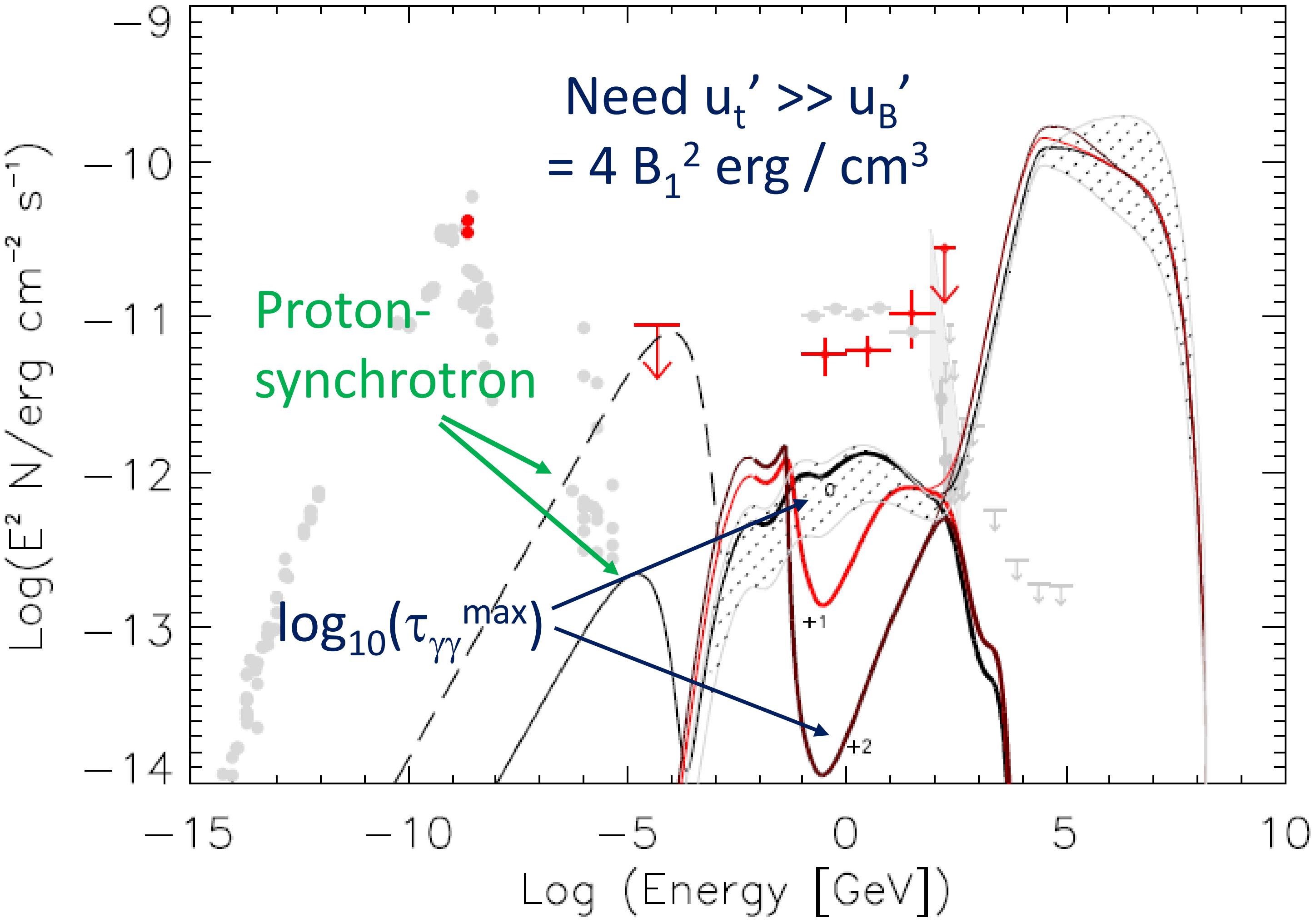
Synchrotron Supported Cascades



(with proton-synchrotron)

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

Compton Supported Cascades



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

Proton-synchrotron

$\log_{10}(\tau_{\gamma\gamma}^{max})$

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

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

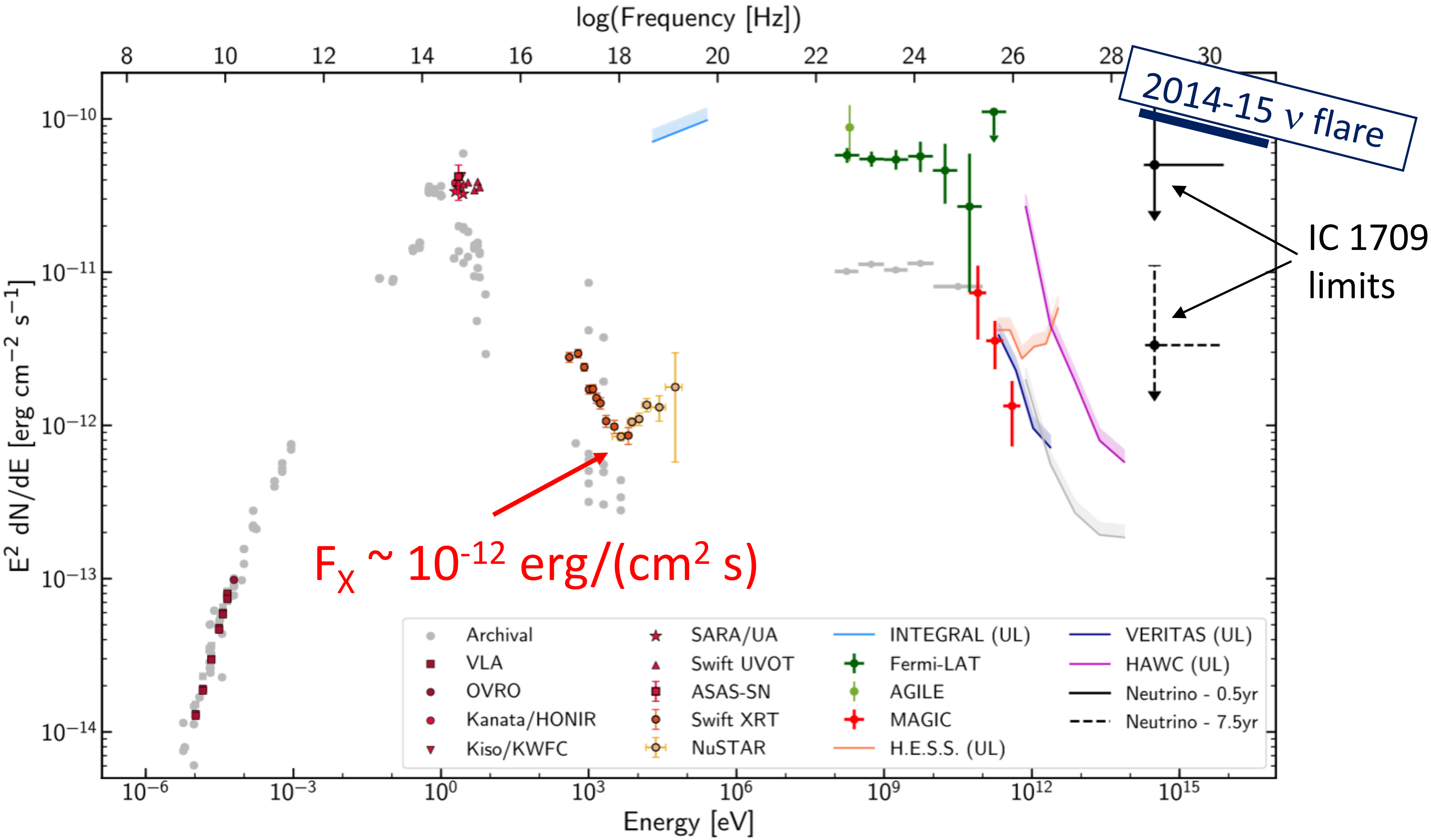
⇒ Observed as hard X-rays

b) Target photons stationary in the AGN frame

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

⇒ Observed as UV / soft X-rays

Spectral Energy Distribution of TXS 0506+056



2014-15 ν flare

IC 170922A limits

$F_X \sim 10^{-12}$ erg/(cm^2 s)

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)

$L_{\mathrm{kin,p}}$

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

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

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

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.

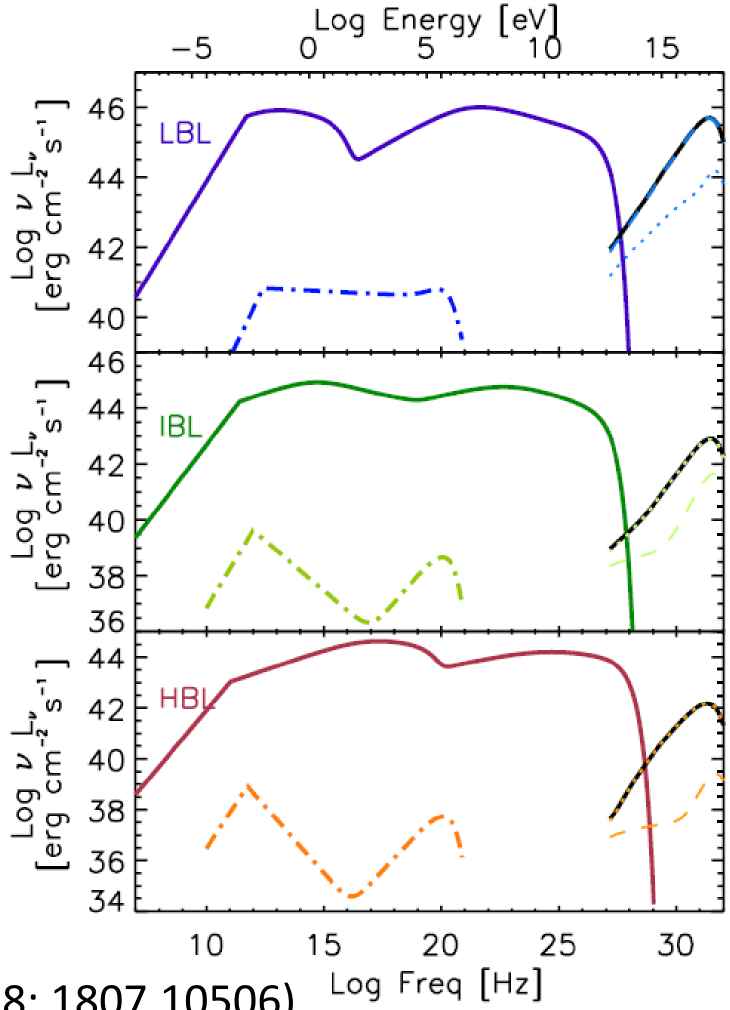
$\Rightarrow$ Plausible!

$\Rightarrow$ 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

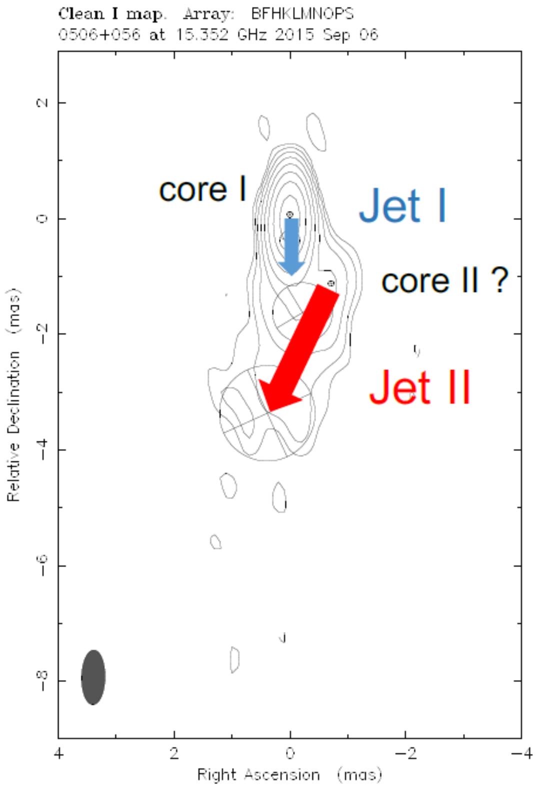


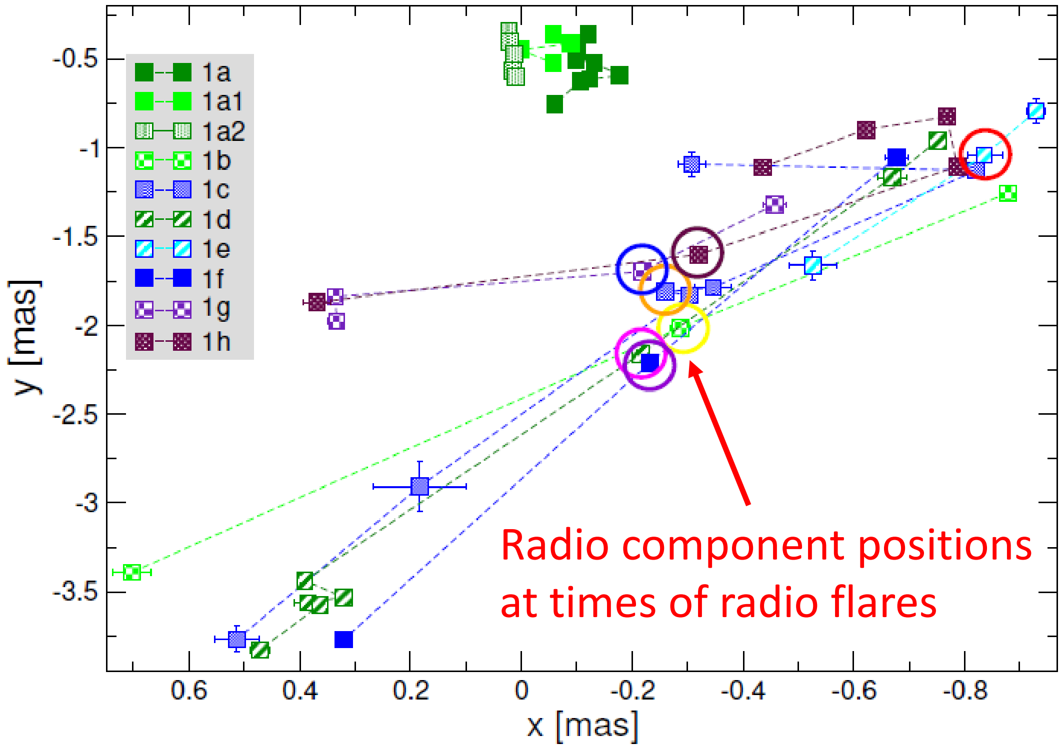
(Righi et al. 2018: 1807.10506)

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?





Radio component positions at times of radio flares

(Britzen et al., 2018, MNRAS, submitted)

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 (possibly due to jet-jet / jet self-interaction)

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

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Thank you!