# Photo-Hadronically Produced Neutrinos from TXS 0506+056?

**Markus Böttcher**

*North-West University*

*Potchefstroom, South Africa*

**Anita Reimer**

*University of Innsbruck, Austria*

**Sara Buson**

*University of Würzburg*

Based on:
Reimer, Böttcher & Buson, 2018, ApJ, submitted (arXiv:1812:05654)

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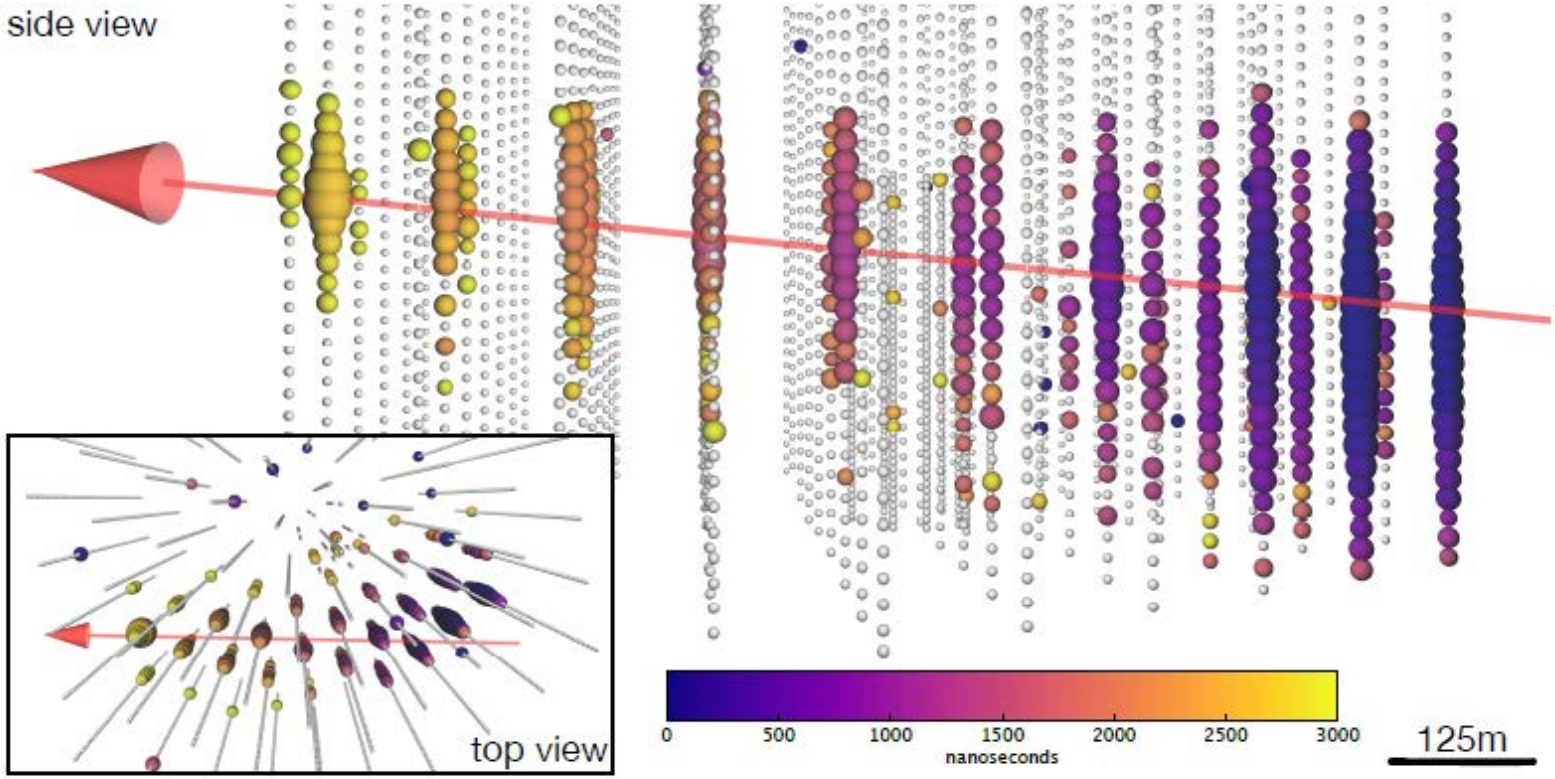
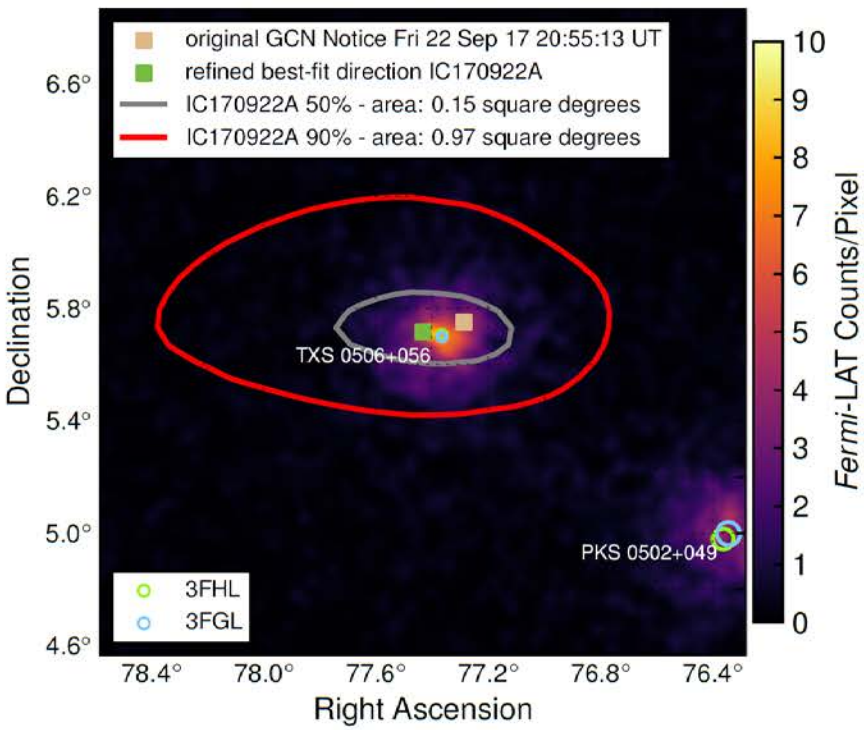
# IceCube-170922A

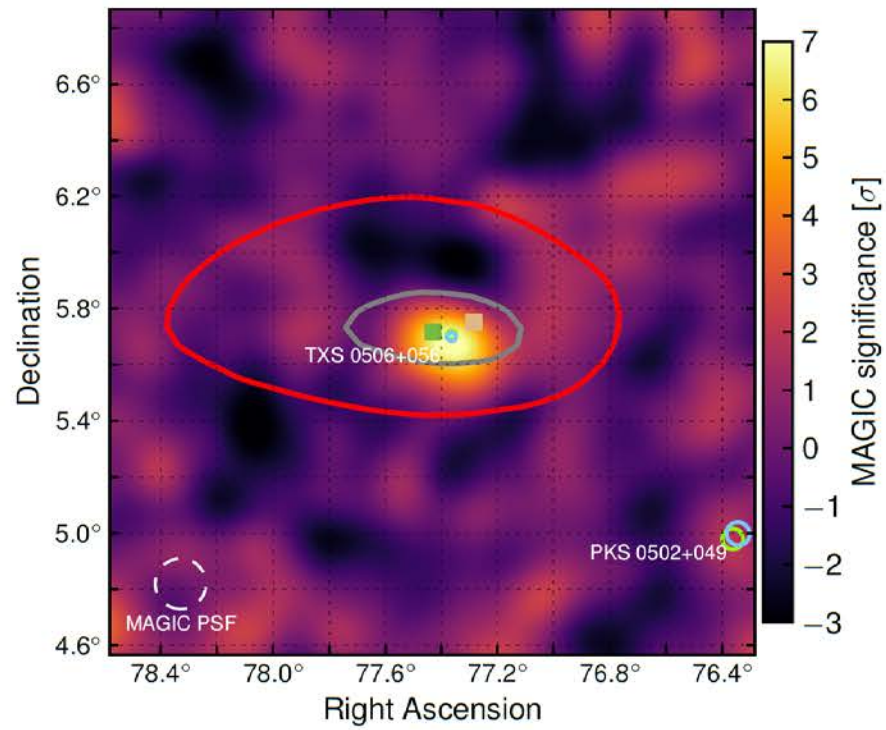



(IceCube et al. 2018a)

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

# IceCube-170922A and TXS 0506+056

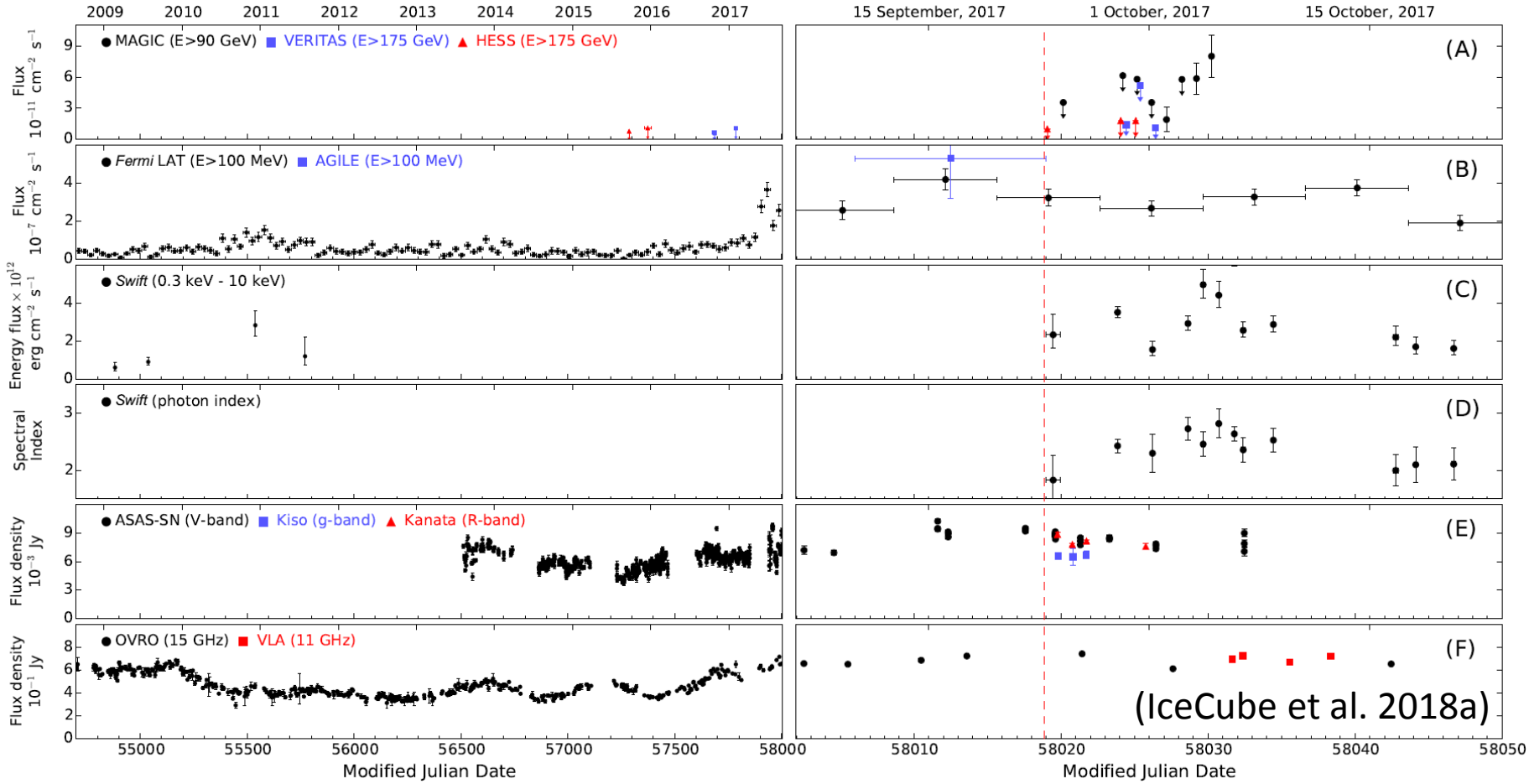



(IceCube et al. 2018a)

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)

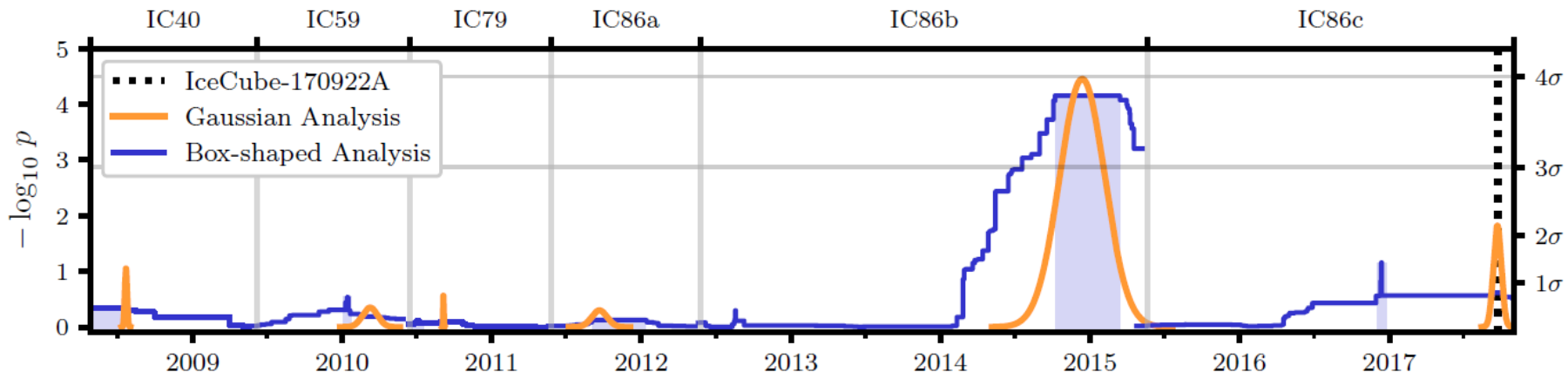
# IceCube-170922A and TXS 0506+056




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

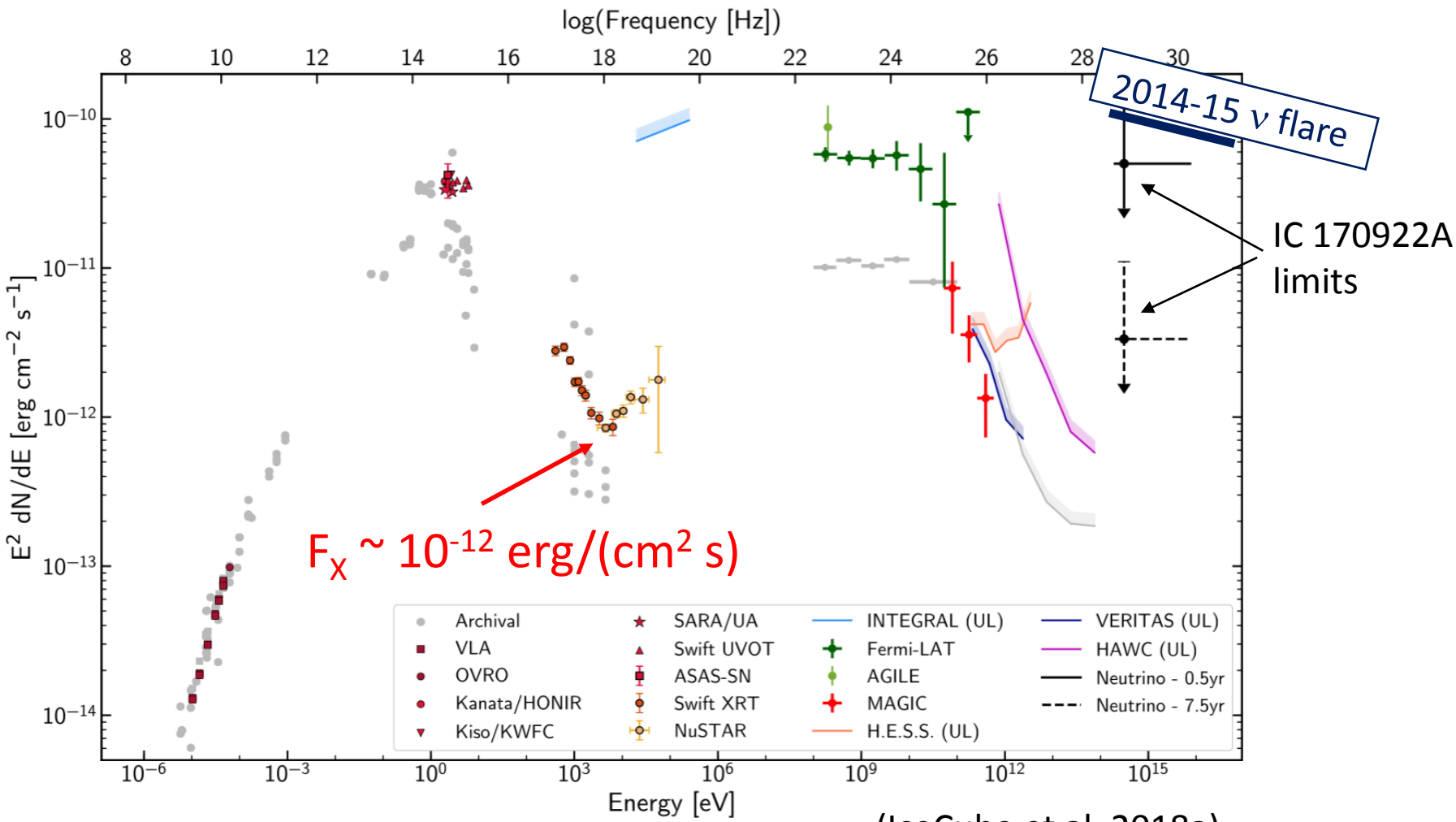



(IceCube et al. 2018b)

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

=> Well determined flux and spectrum!

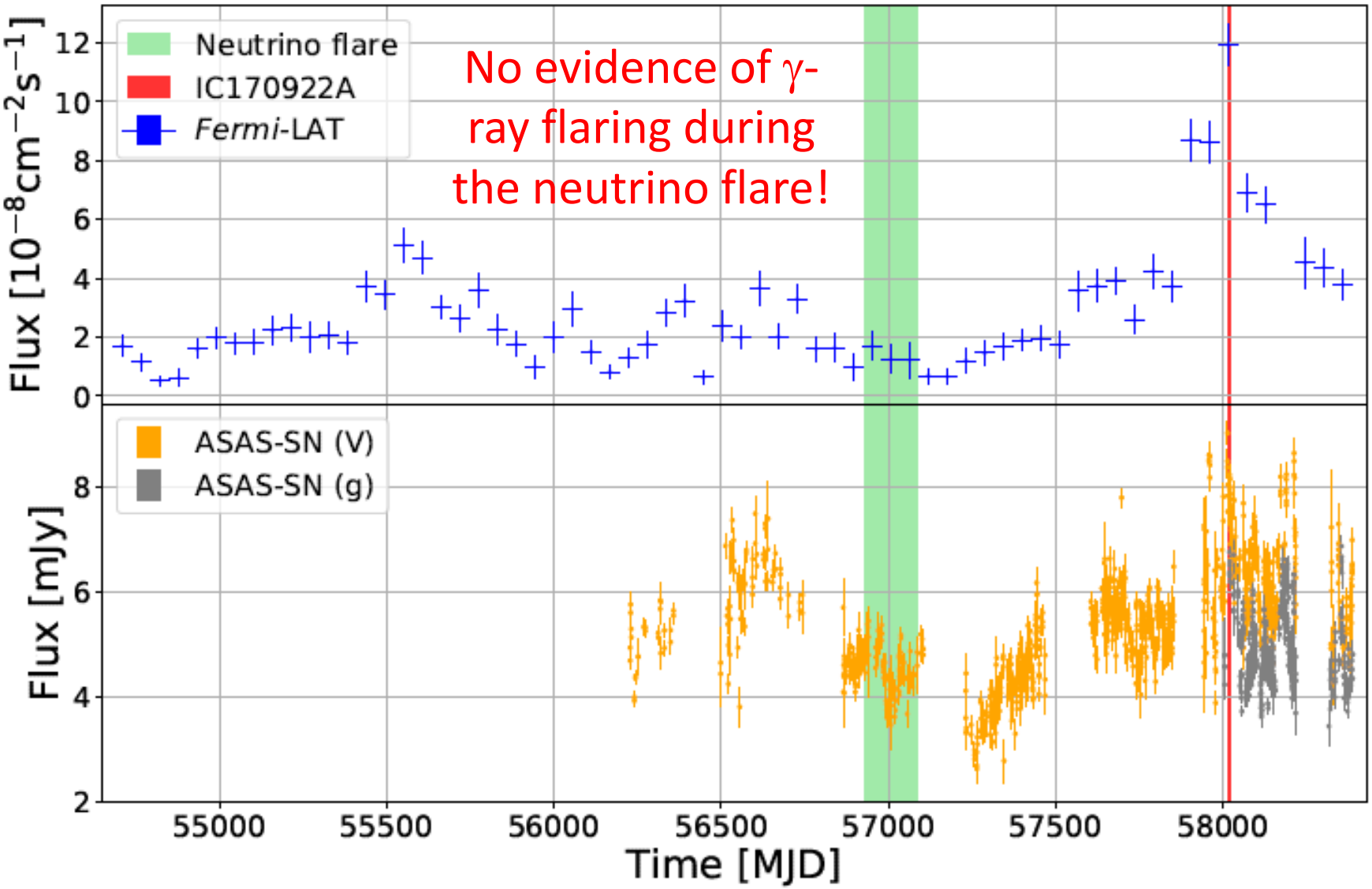
# Spectral Energy Distribution of TXS 0506+056



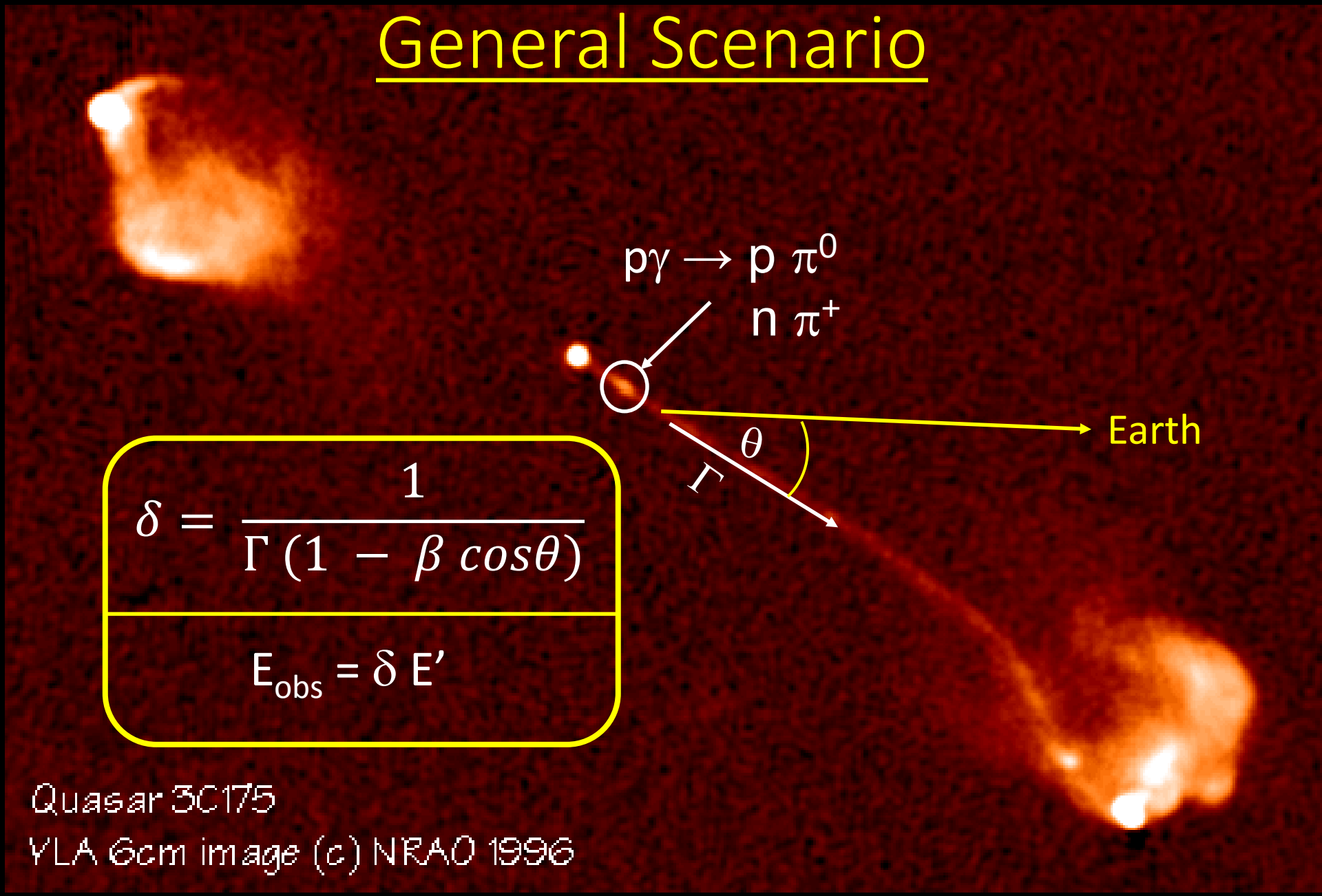

(IceCube et al. 2018a)

(Photon SED from the time of IC 170922A)

# The Neutrino Flare from TXS 0506+056



# General Scenario




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

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

# Photo-pion production - Energetics

p-$\gamma$ 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 $\Delta^+$ resonance:

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

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

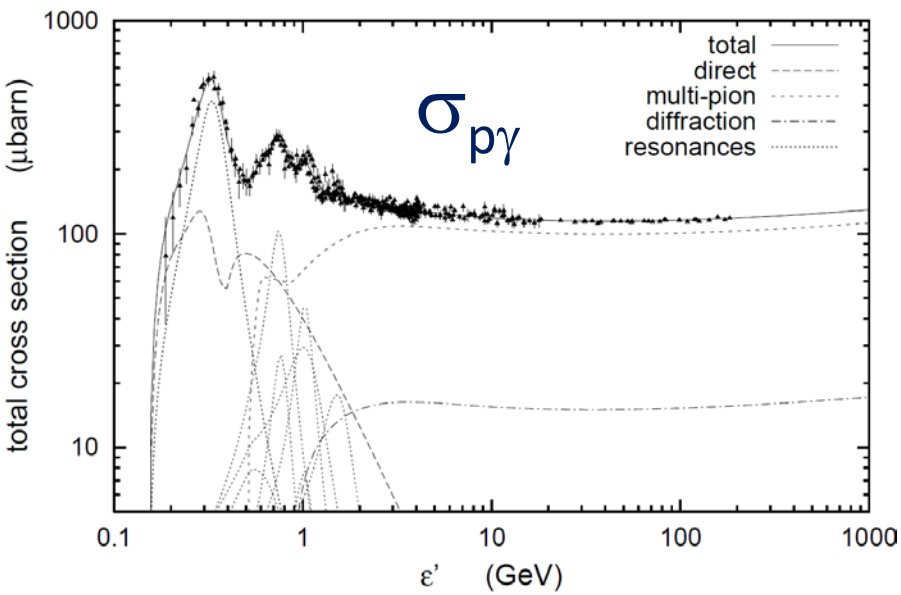
$\Rightarrow$ To produce IceCube neutrinos (~ 100 TeV $\rightarrow$ $E_\nu = 10^{14}\, E_{14}$ eV):

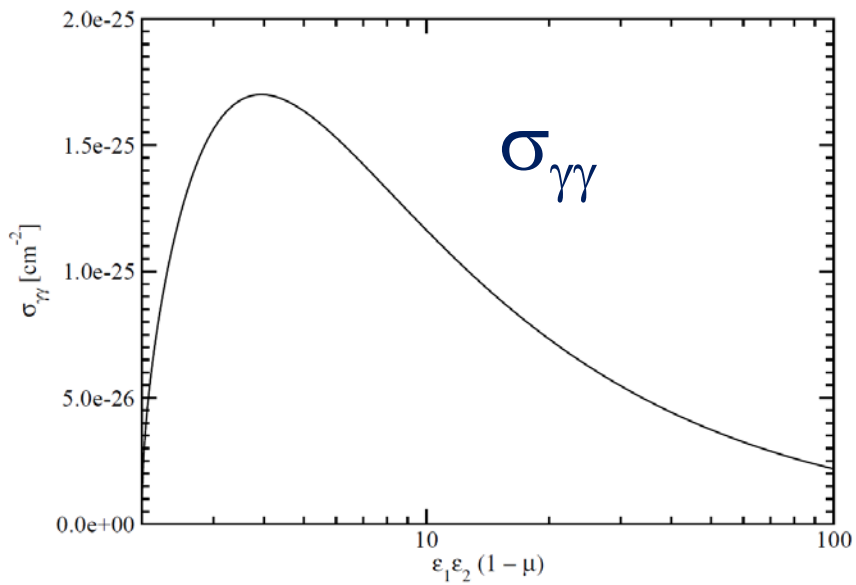
(i.e., $E'_\nu = 10\, E_{14}\, \delta_1^{-1}$ TeV)

| | | |
|---|---|---|
| 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! |

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



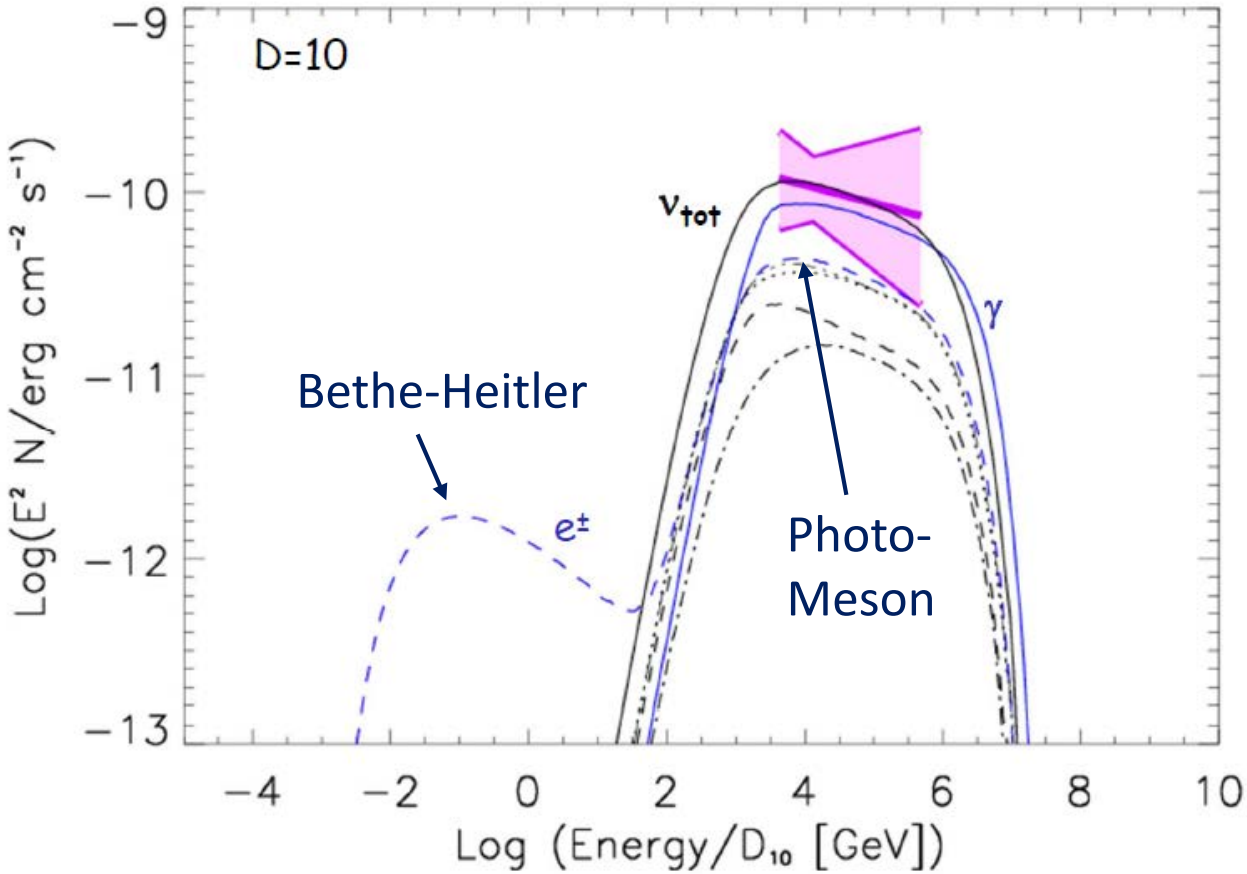

$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx \frac{1}{300} \quad \text{at} \quad E_\gamma \sim \frac{m_e^{\,2}\,c^4}{E_t} \sim 3.3 \times 10^{-5}\,E_\nu$$

⇒ Photons at $E_\gamma$ ~ 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: $n'_{ph}(\varepsilon') \sim \varepsilon'^{-\alpha}$, $\varepsilon'_{min} = 10$ keV, $\varepsilon'_{max} = 60$ keV, $\alpha = 1$
- Proton spectrum: $n'_p(E'_p) \sim E'^{-\alpha_p}_p$, $E'_{p,max} = 30$ PeV, $\alpha_p = 2.0$

# Constraints from Cascades

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

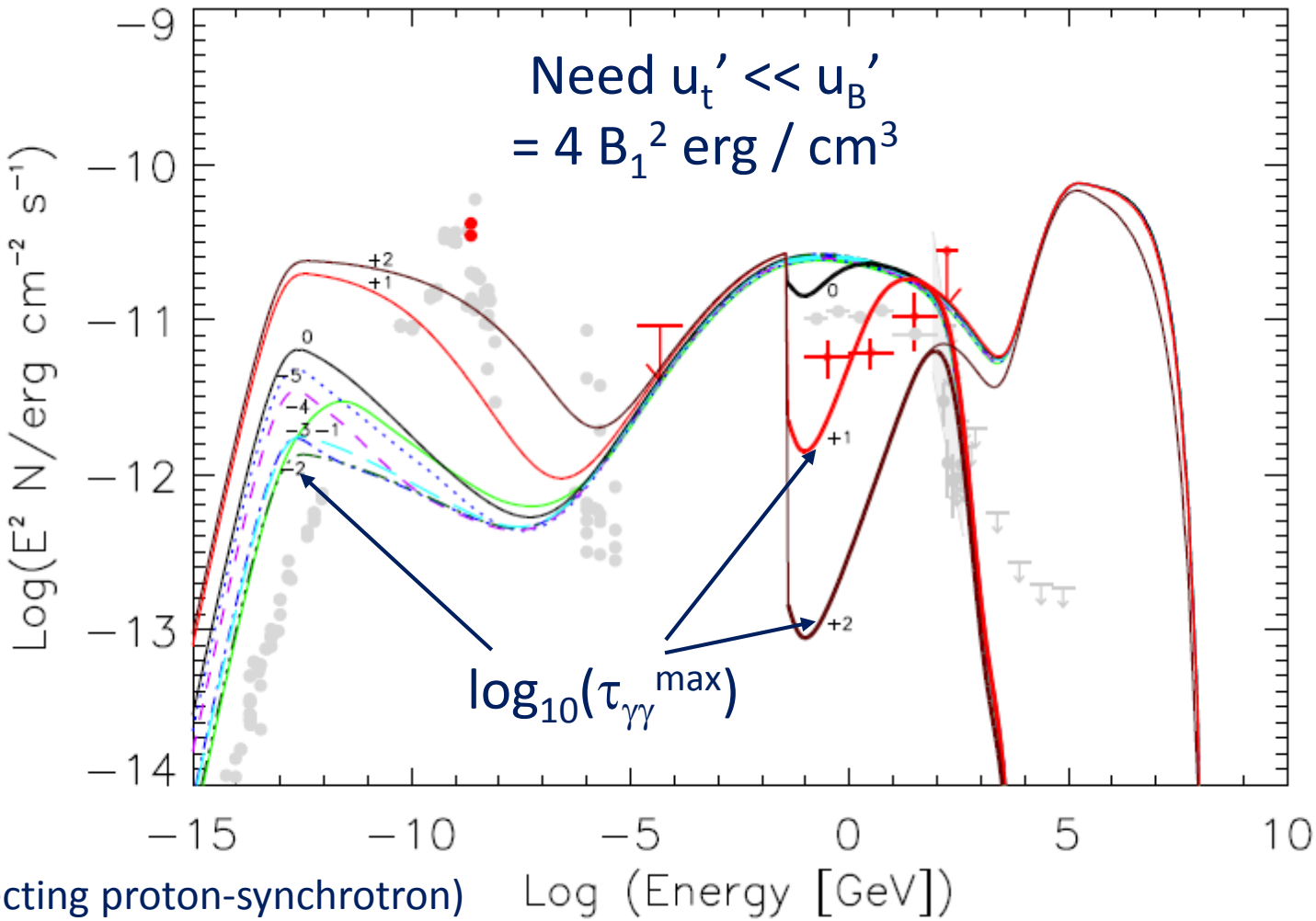
3) Simulate pair cascades initiated by secondary $\gamma$-rays and electrons/positrons

- 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

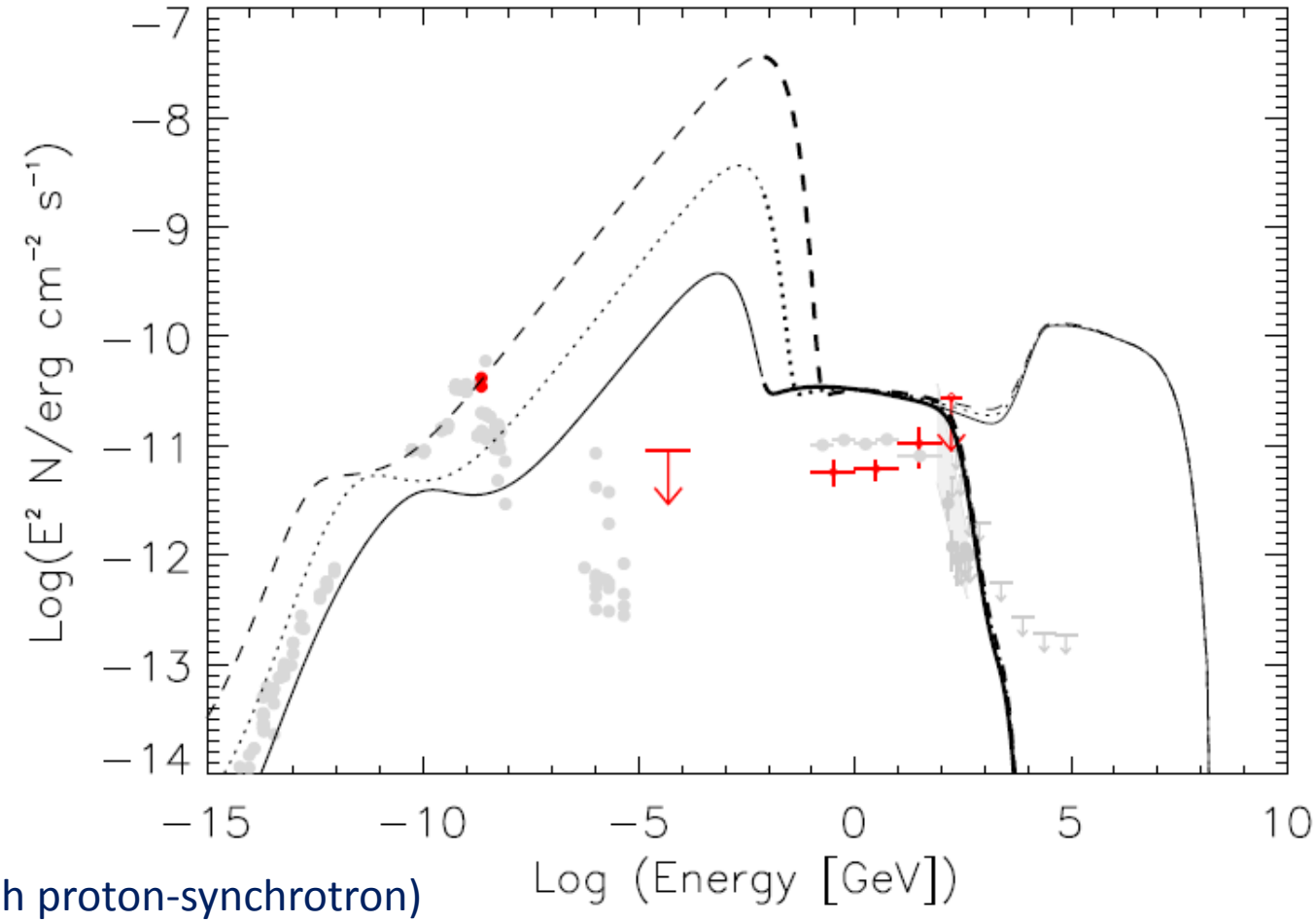



(neglecting proton-synchrotron)

Ruled out by MWL spectra

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

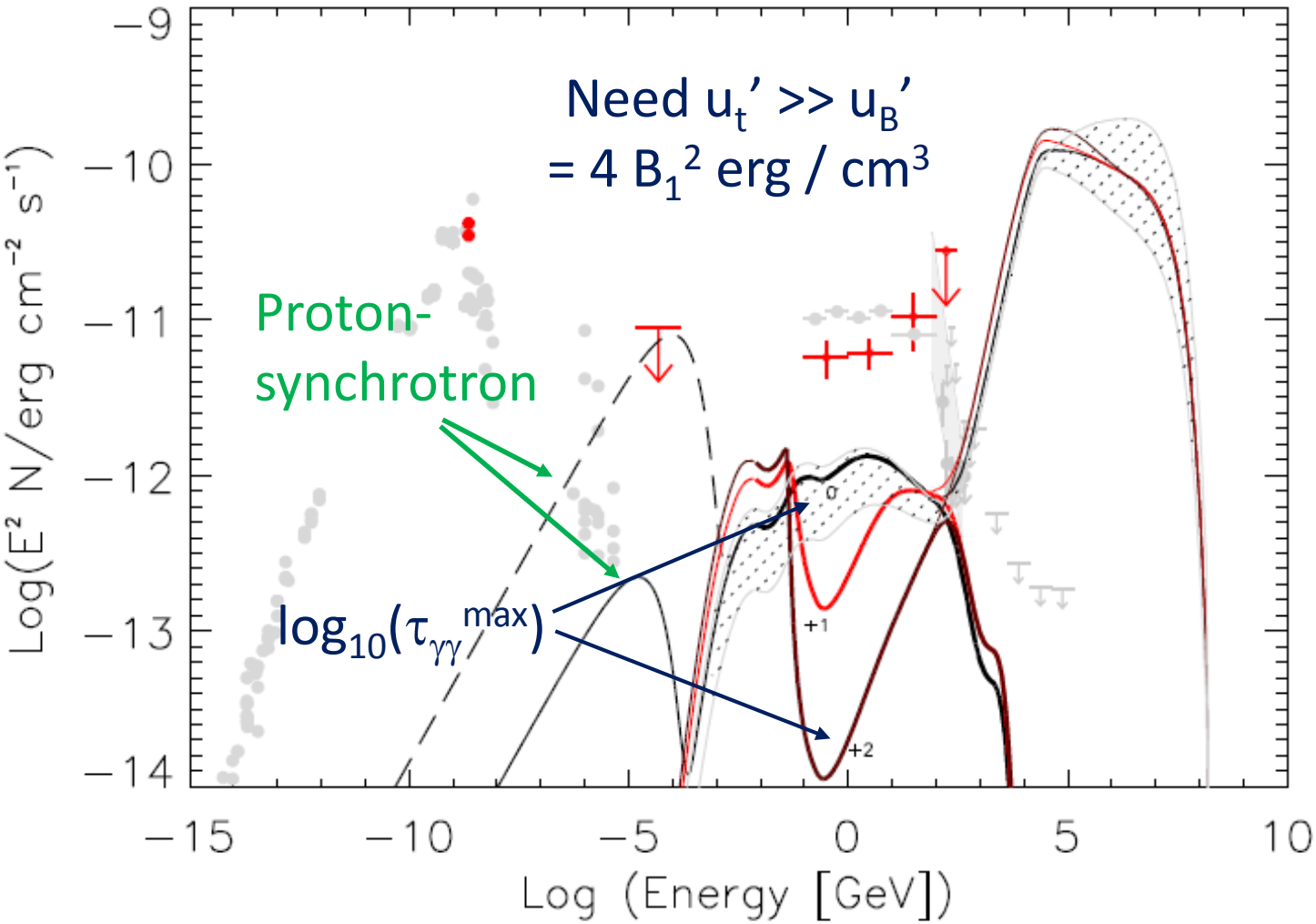
# Synchrotron Supported Cascades




(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 $\rightarrow E_\nu = 10^{14}\ E_{14}$ 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

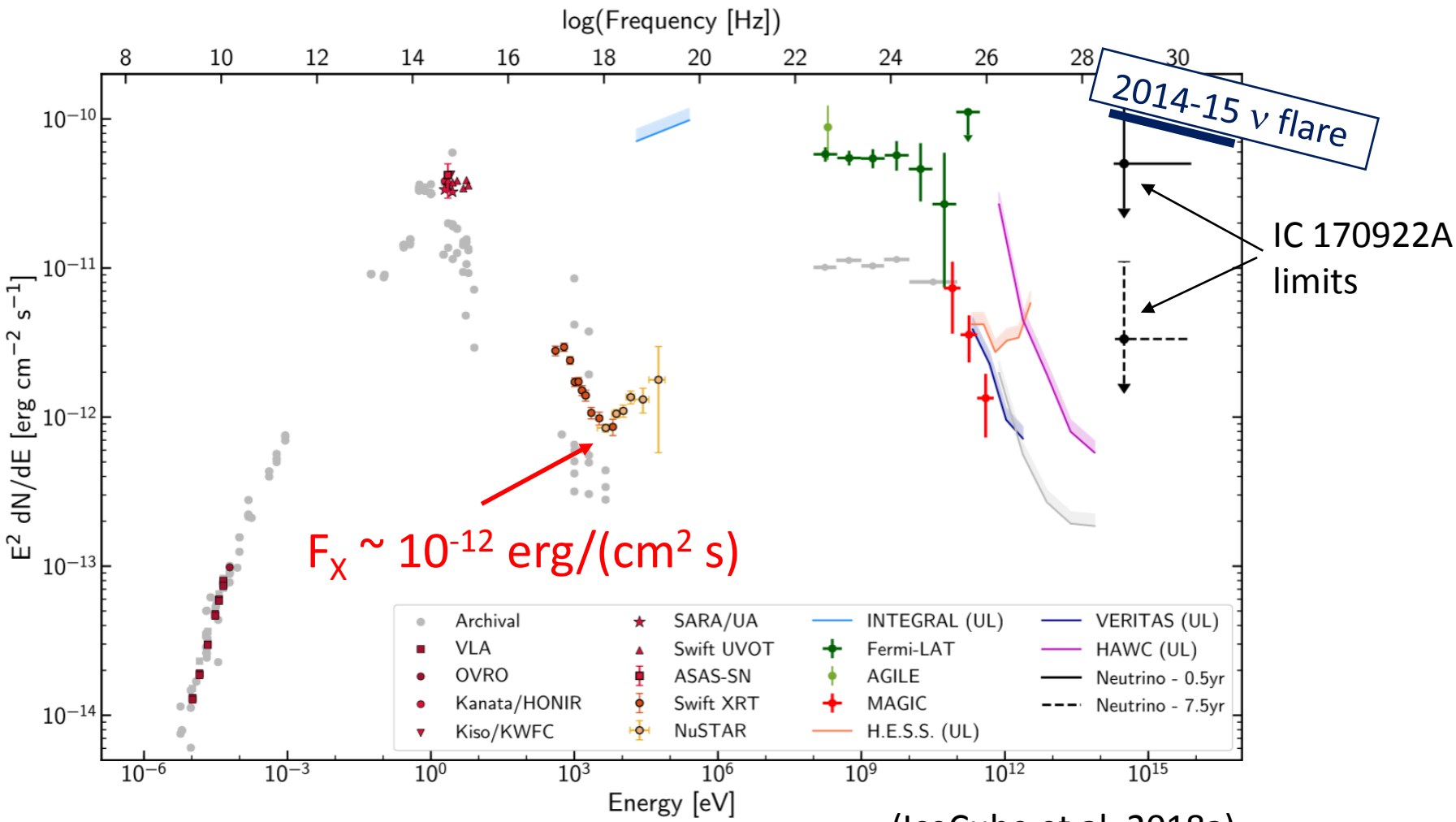
$\Rightarrow$ Observed as hard X-rays

b) Target photons stationary in the AGN frame

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

$\Rightarrow$ Observed as UV / soft X-rays

# Spectral Energy Distribution of TXS 0506+056




(IceCube et al. 2018a)

# 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)

$L_{kin,p}$

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

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

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

# 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!

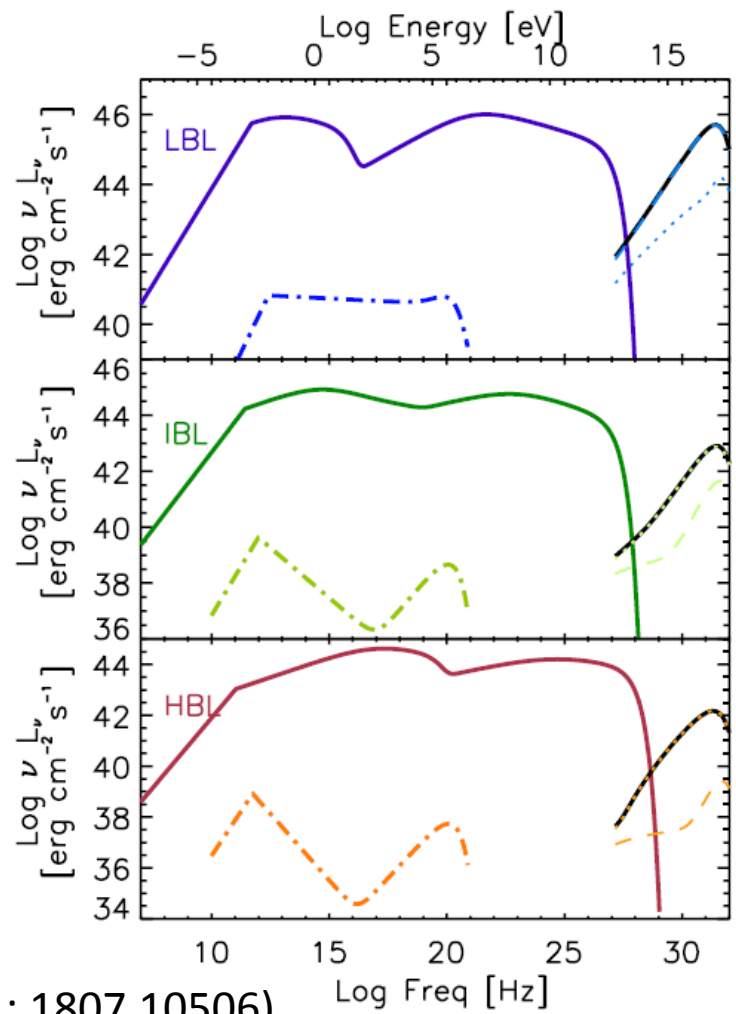
$\Rightarrow$ Stationary UV / soft X-ray target photon field external to the jet is plausible!

But neutrino production efficiency very low ($\tau_{p\gamma} \sim 10^{-3}$)

# Photo-pion production – Origin of Target Photons

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

- BLR (?) – Foteini's talk;
  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

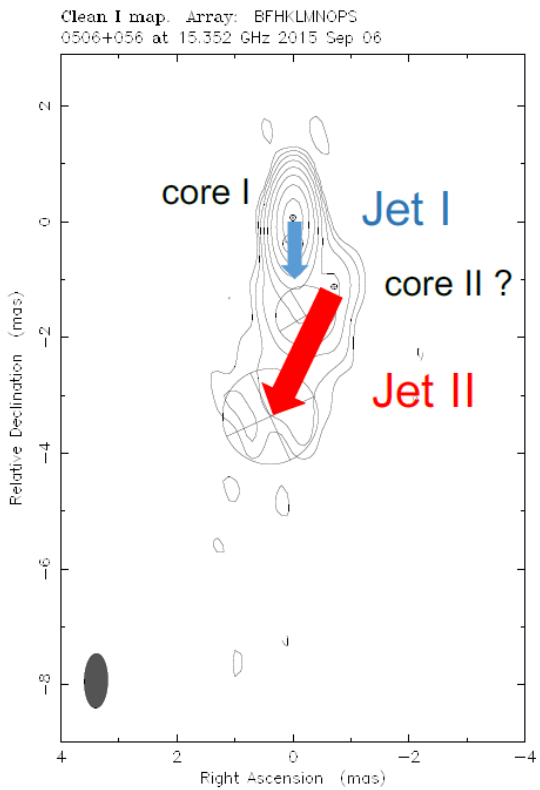


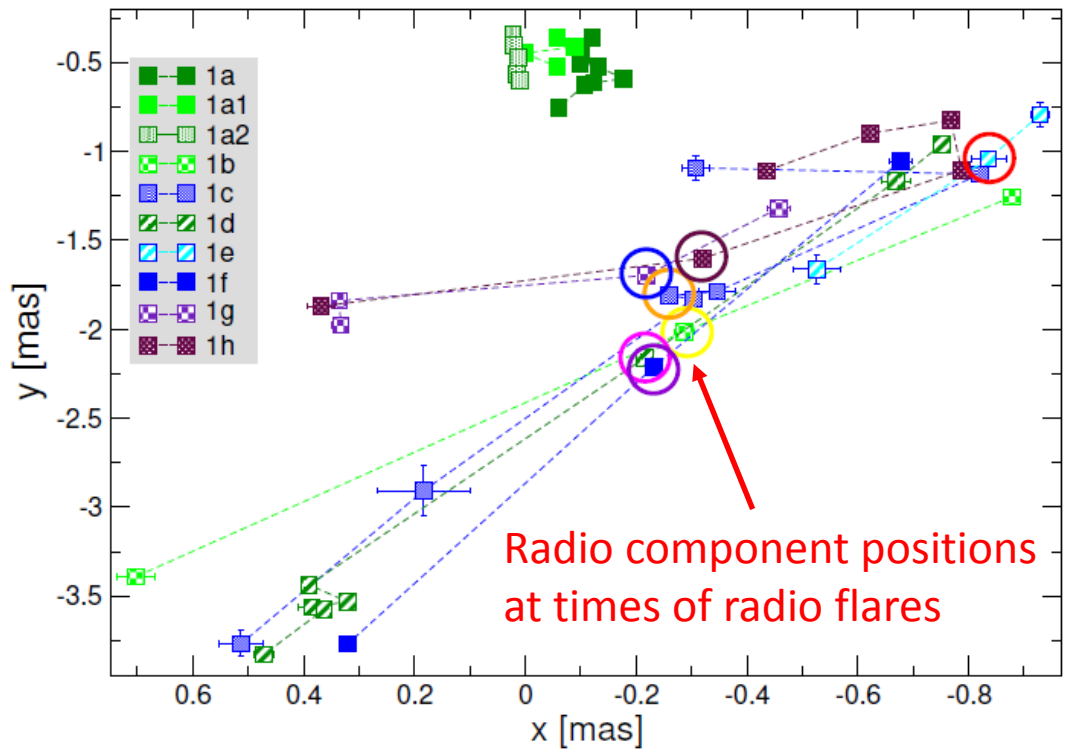

(Righi et al.: 1807.10506)

# 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)

# Summary

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

- No correlation between $\gamma$-ray and neutrino activity necessarily expected

- IceCube 170922A / TXS 0506+056 strongly favours
  - leptonically-dominated $\gamma$-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, submitted; arXiv:1812.05654

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# Backup Slides

# 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>$\gamma$-ray production through:</u>

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

b) Proton synchrotron at

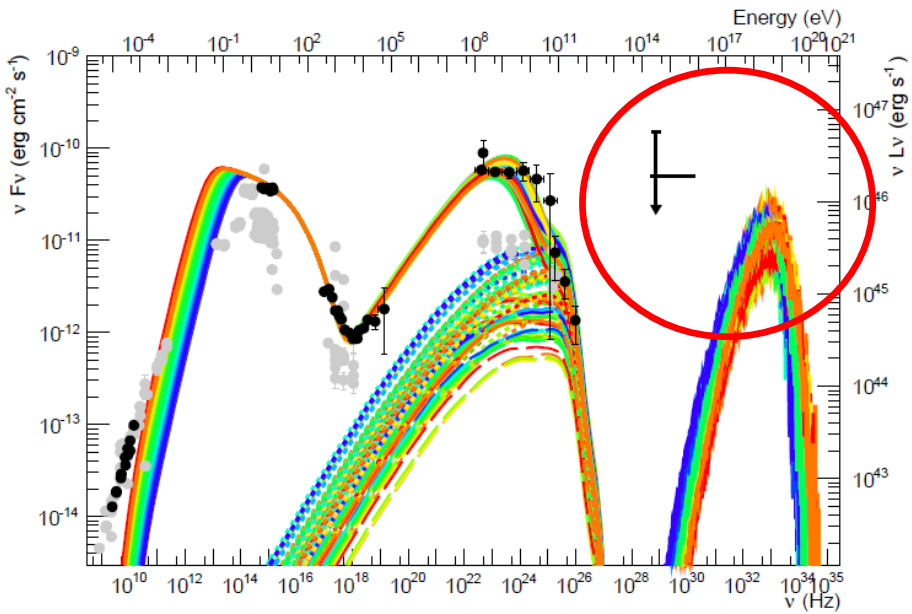
$\nu_{psy} \sim 2\times10^{18}\, \gamma_6^2\, B_2\, \delta_1$ Hz (~ 10 keV)

c) Secondary electron synchrotron at

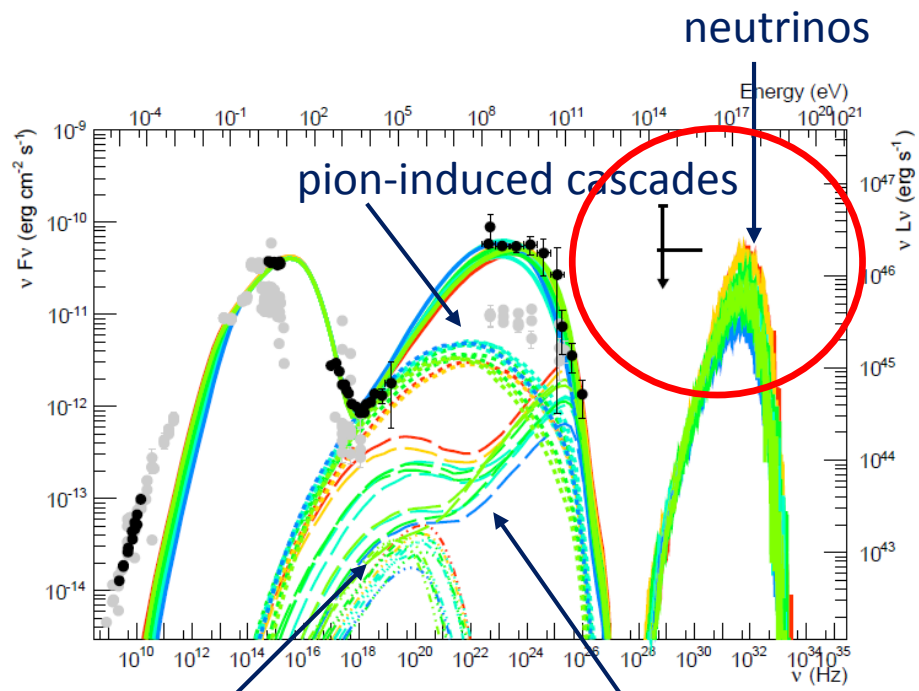
$\nu_{esy} \sim 4\times10^{21}\, \gamma_6^2\, B_2\, \delta_1$ Hz (~ 20 MeV)

$\Rightarrow$ Protons producing IceCube neutrinos will not produce HE 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

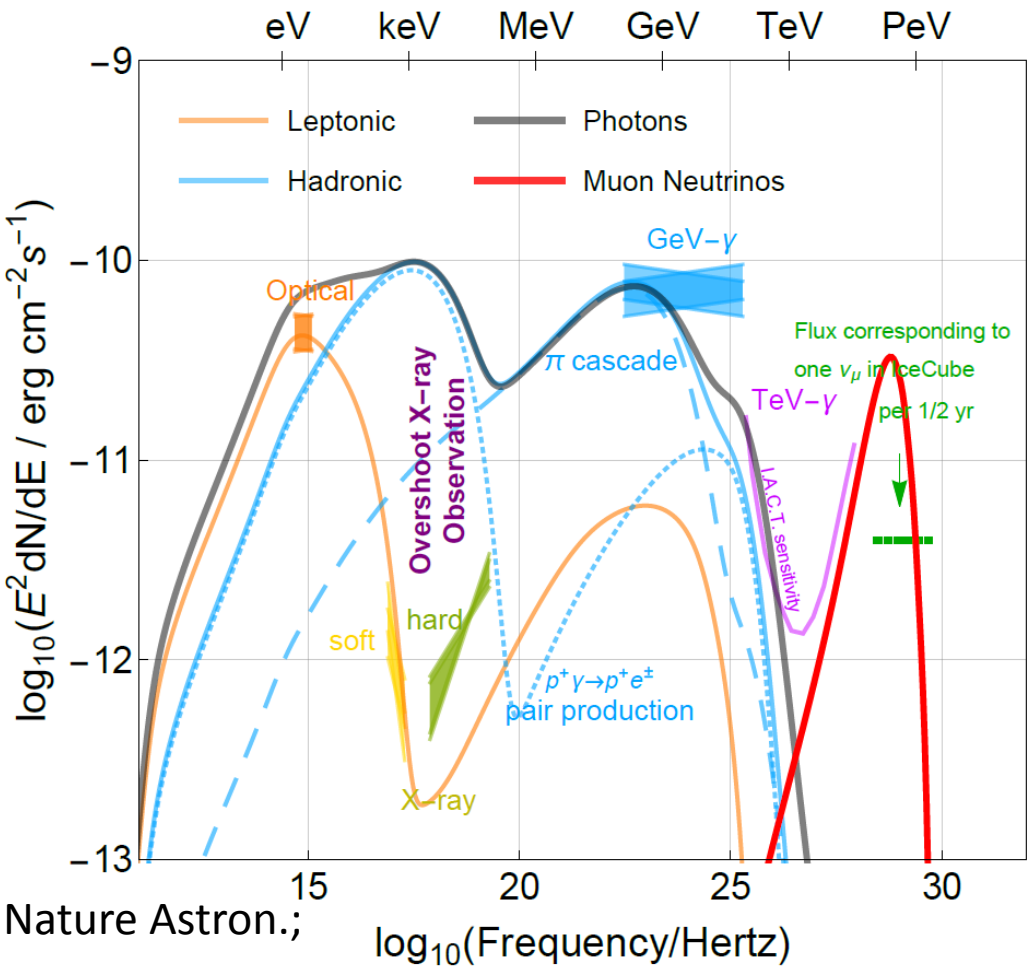
(Cerruti et al.: 1807.04335)

Proton-synchrotron

Bethe-Heitler-induced cascades

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

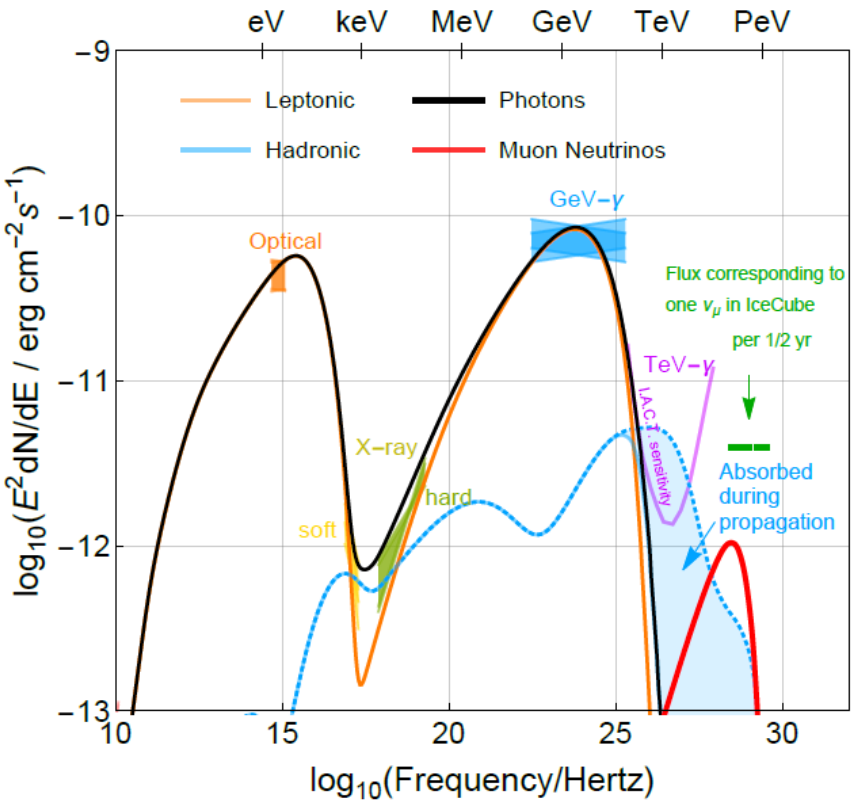
# Photo-Pion Models for TXS 0506+056



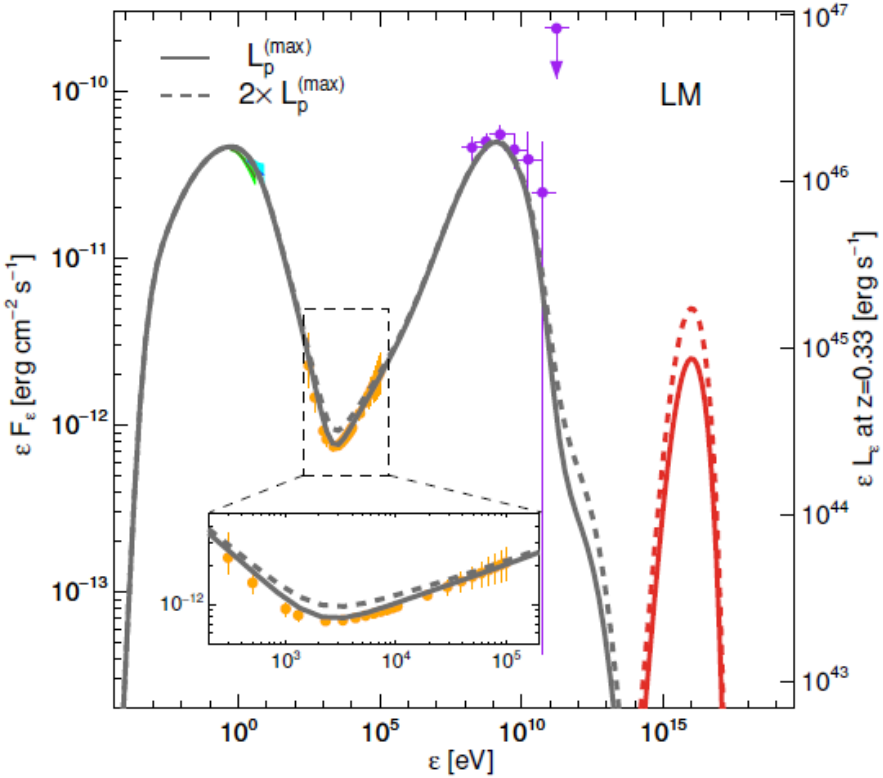

(Gao et al., 2018, Nature Astron.; 1807.04275)

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!