

Tenth International Fermi Symposium

9th-15th October 2022



Physics of Neutrino Emission from Blazars

Markus Böttcher*



National
Research
Foundation



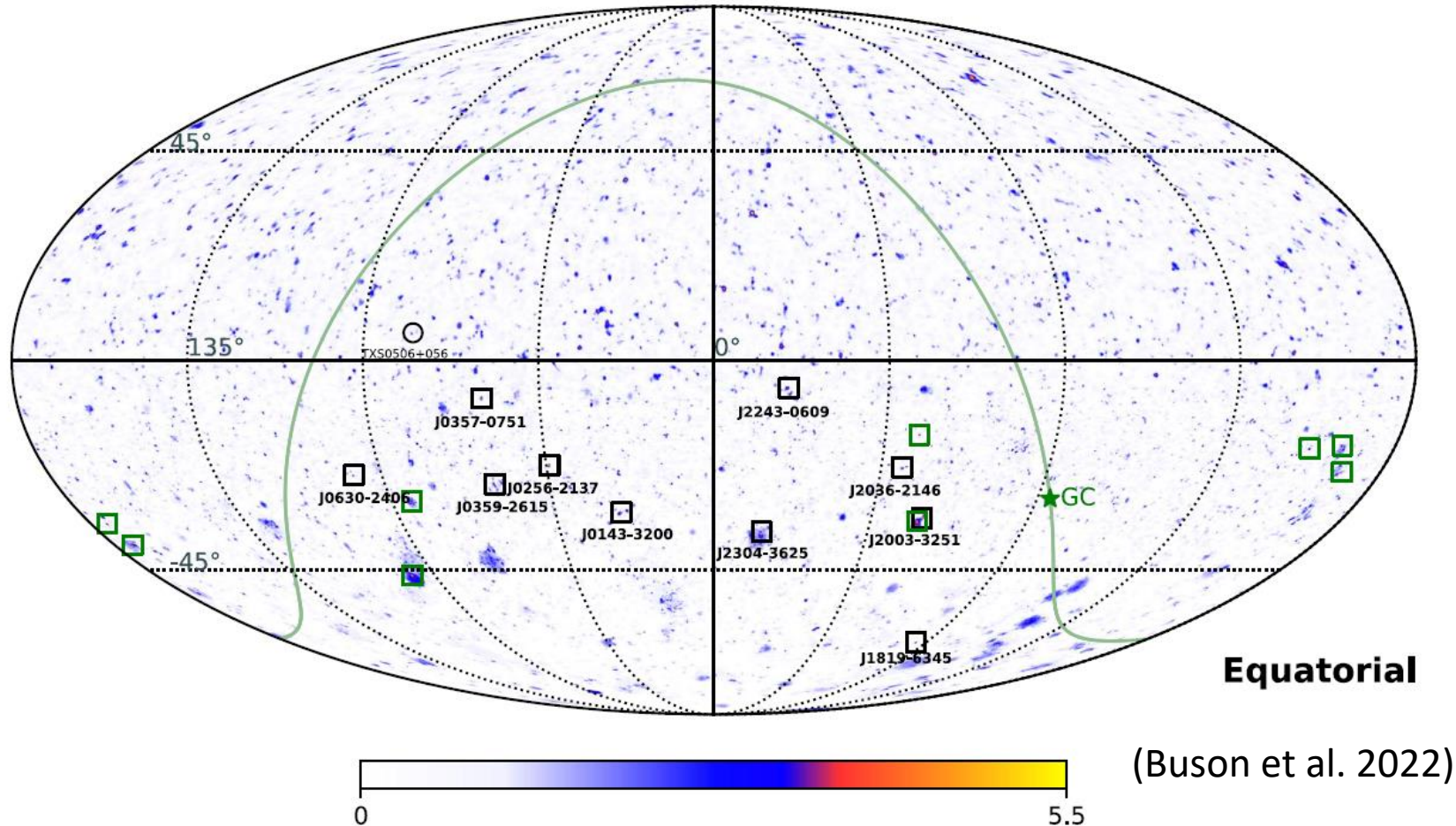
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*Markus.Bottcher@nwu.ac.za

Origin of IceCube-Detected Neutrinos



Significant correlation of IceCube neutrinos with **blazars**
(chance coincidence $p = 6 \cdot 10^{-7}$) – but can not be responsible
for all IceCube neutrinos (e.g., Murase et al. 2018)

Basics of Neutrino Production

- $p + p (N) \rightarrow p + p/n + n_0\pi^0 + n_+\pi^+ + n_-\pi^-$ ($\sigma_{pp} \sim 0.1 \text{ mb}$)
- $p + \gamma \rightarrow p + \pi^0$
or $n + \pi^+$ ($\sigma_{p\gamma} \sim 0.6 \text{ mb}$)

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

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

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

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

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

$$\tau = 2.55 \times 10^{-8} \text{ s}$$

$$\tau = 2.2 \times 10^{-6} \text{ s}$$

Neutrino Production in AGN Jets

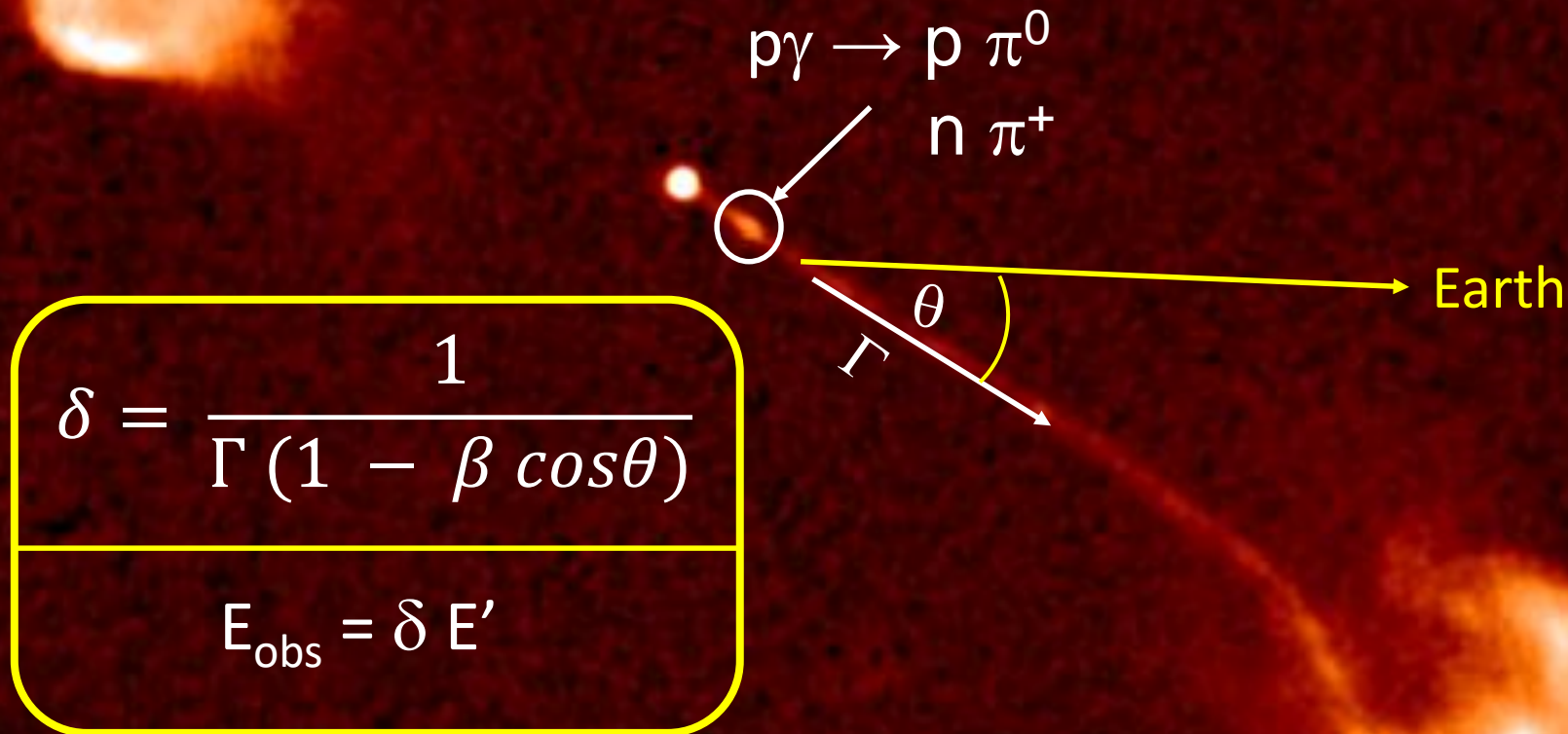
$$n_{ph} \sim \frac{L_{sy}}{\delta^4 \langle \varepsilon \rangle m_e c^2 4\pi R^2 c} \sim 3 \times 10^{18} \varepsilon_{-6}^{-1} R_{16}^{-2} L_{sy,44} \delta_1^{-4} \text{ cm}^{-3}$$

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

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

\Rightarrow In AGN jets, $p\gamma$ dominant over pp or pN .

Photo-pion induced neutrino production in relativistic jets



Quasar 3C175

VLA 6cm image (c) NRAO 1996

Photo-Pion Production Cross Section

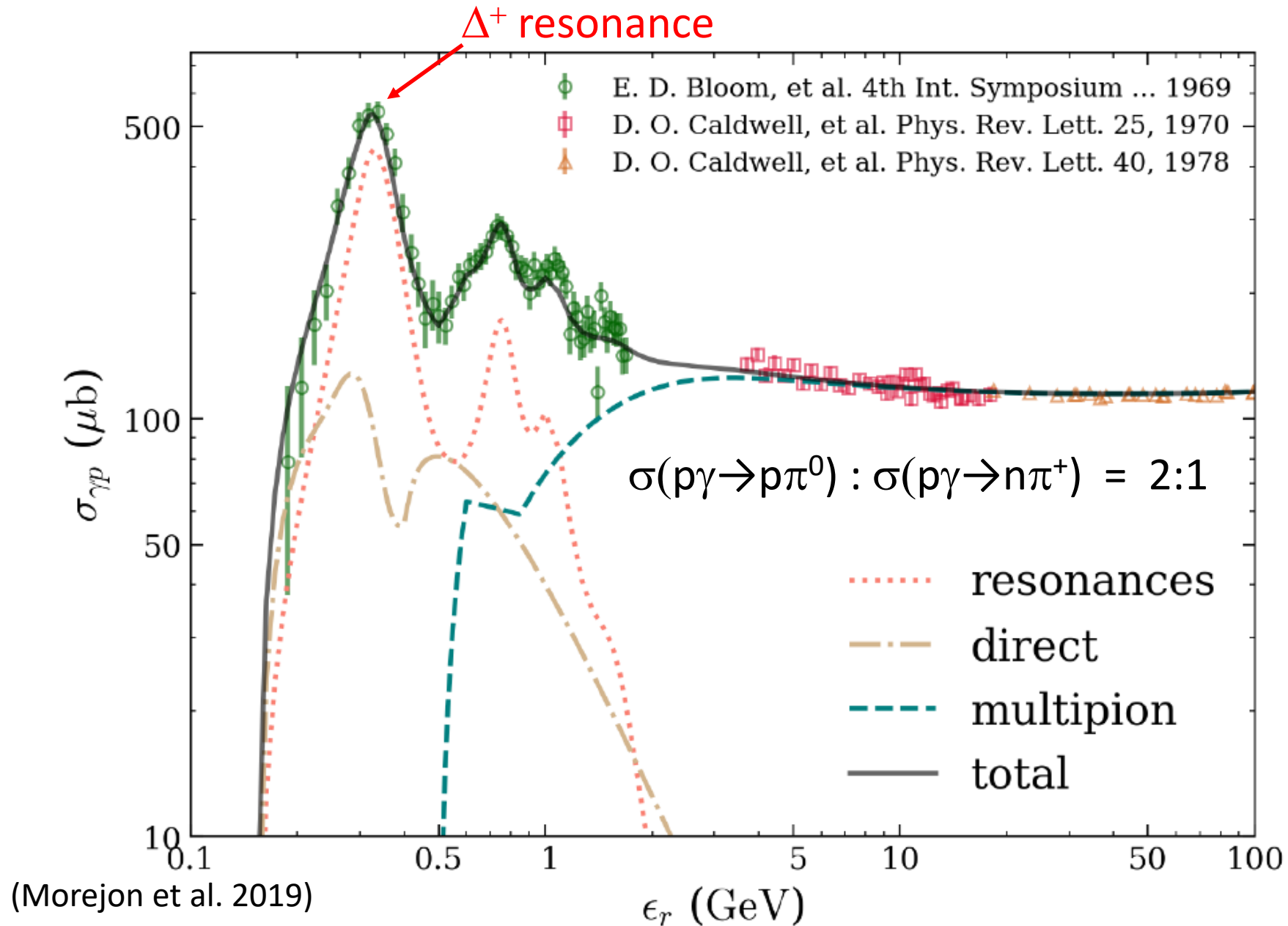
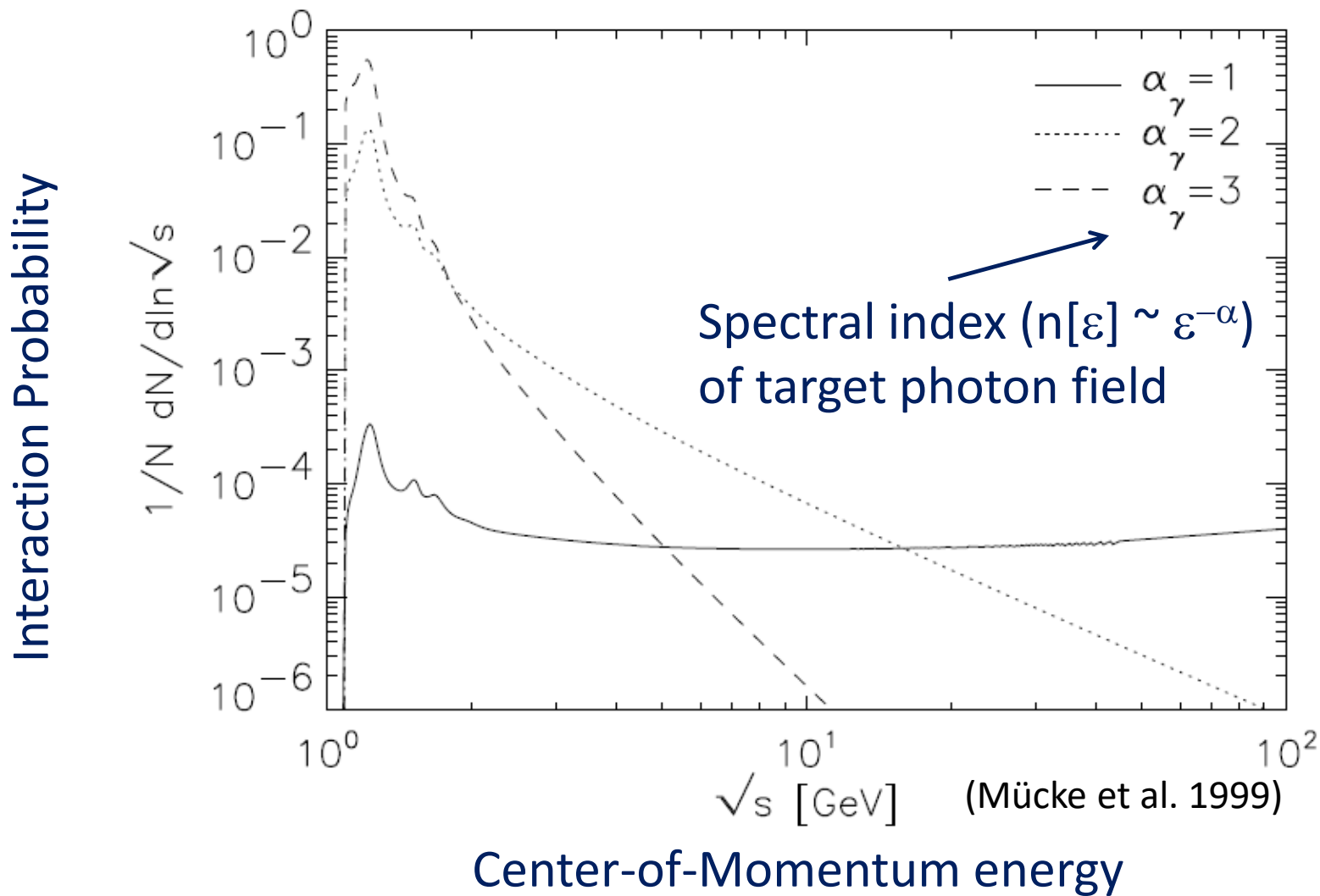


Photo-Pion Production



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

Photo-pion production - Energetics

At Δ^+ resonance:

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

and

$$E'_v \sim 0.05 E'_p$$

\Rightarrow To produce IceCube neutrinos ($\sim 100 \text{ TeV} \rightarrow E_v = 10^{14} E_{14} \text{ eV}$):

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

Need protons with

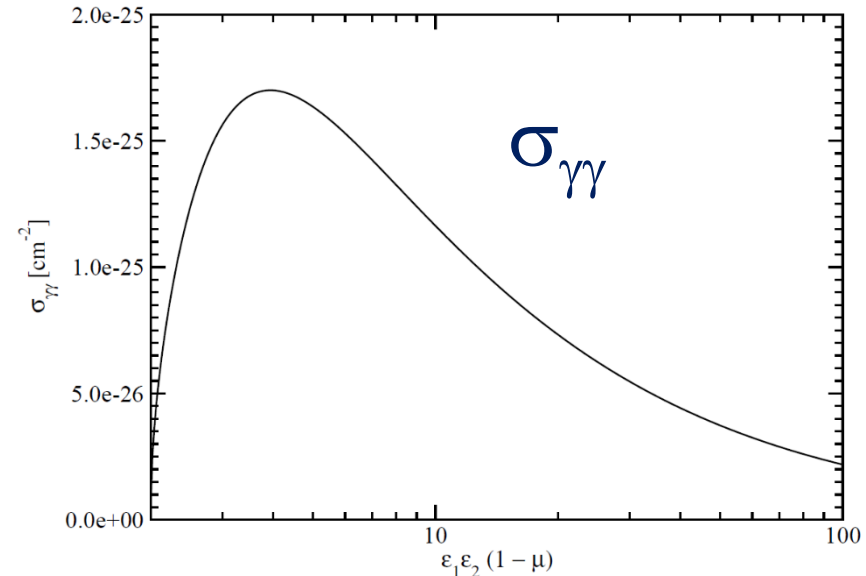
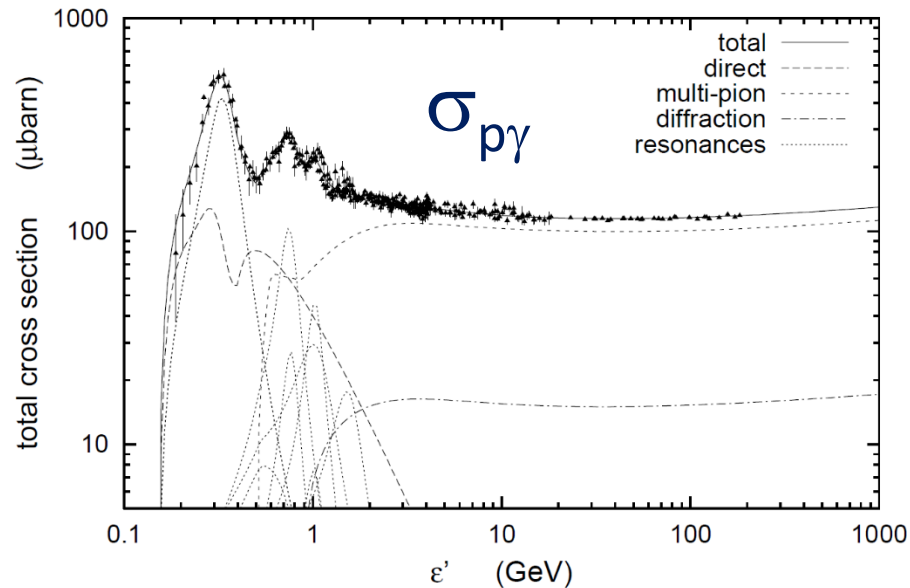
$$E'_p \sim 200 E_{14} \delta_1^{-1} \text{ TeV}$$

and target photons with

$$E'_t \sim 1.6 E_{14}^{-1} \delta_1 \text{ keV} \quad \Rightarrow \text{X-rays!}$$

The $p\gamma$ Efficiency Problem

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



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

\Rightarrow Photons at $E_{\gamma} \sim \text{GeV} - \text{TeV}$ are heavily absorbed.

\Rightarrow Cascade emission at lower energies.

\Rightarrow Expect correlation with X-rays / soft γ -rays.

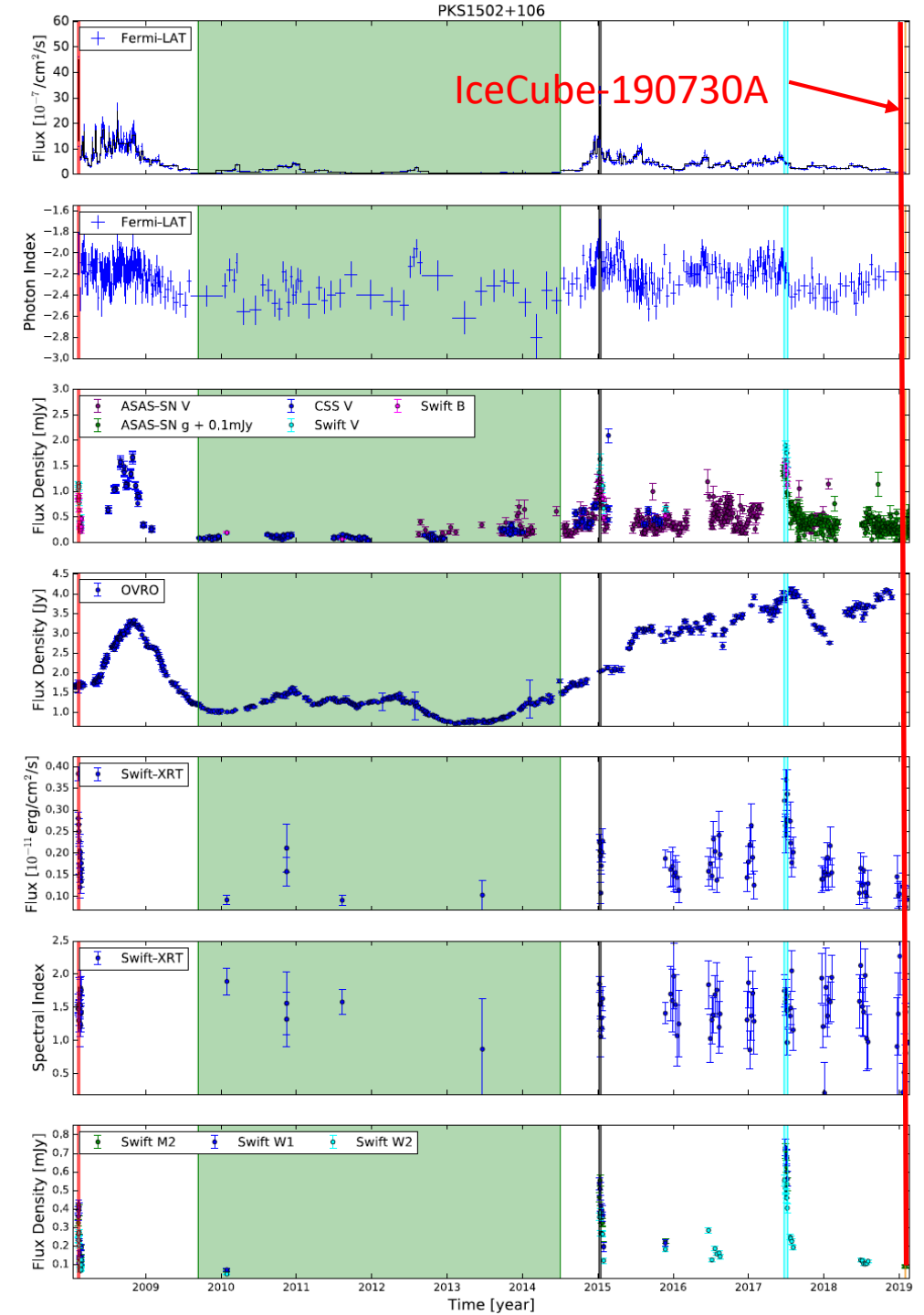
Examples of neutrino – X-ray correlation without γ -ray activity

IceCube-190730A – PKS 1502+106

(IceCube Collaboration et al. 2019; Franckowiak et al. 2020; Rodrigues et al. 2021)

- Neutrino event during a long-term radio outburst (started 2014).
- Low γ -ray flux, but moderate X-ray activity.

(Franckowiak et al. 2020)



Examples of neutrino – X-ray correlation without γ -ray activity

IceCube-200107 – 3HSP J095507.9+35510

(Giommi et al. 2020; Paliya et al. 2020; Krauss et al. 2020; Petropoulou et al. 2020)

- HBL at $z = 0.5573$ (Paiano et al. 2020; Paliya et al. 2020)

- HESE with uncertain energy ($E_\nu \sim 330^{+2230}_{-270}$ TeV)

- Bright X-ray flare on the day after the neutrino event (Swift ToO), but no γ -ray flare.

(Paliya et al. 2020)

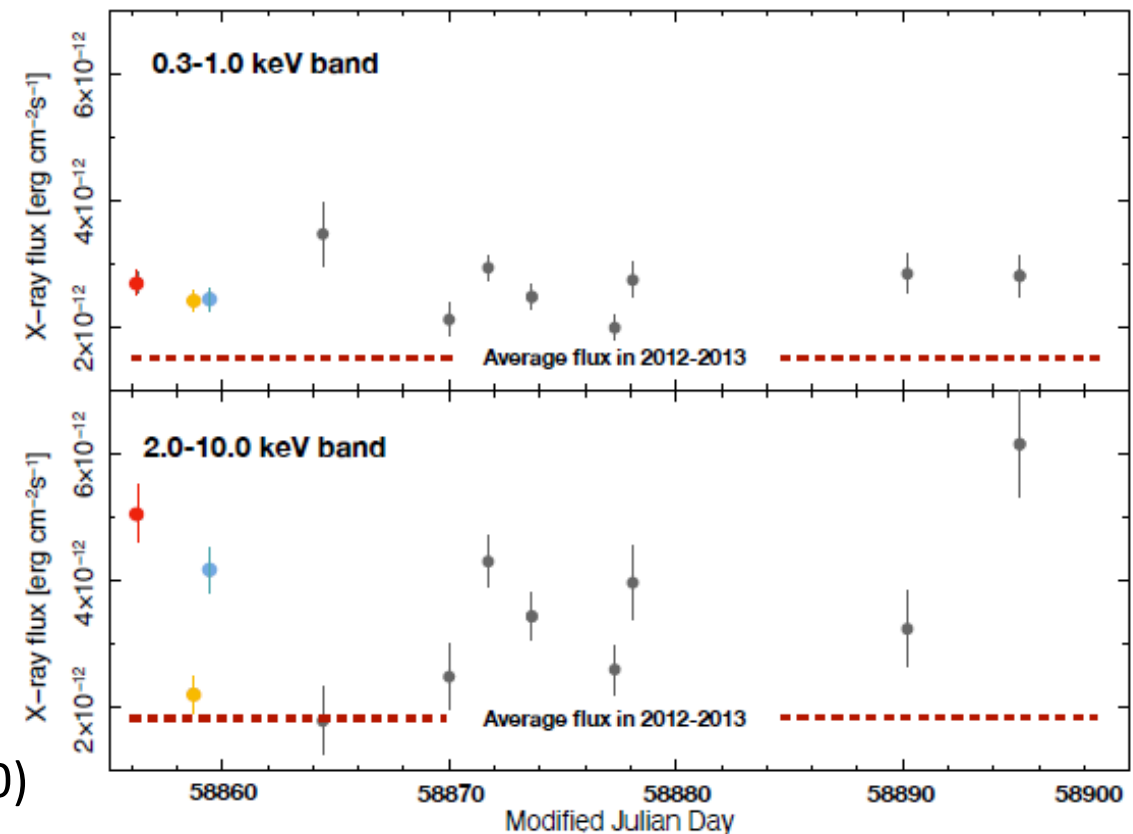


Photo-pion production – Origin of Target Photons

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

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

and target photons with $E'_t \sim 1.6 E_{14}^{-1} \delta_1 \text{ keV}$

(At least) two possible scenarios for target photons:

a) Co-moving with the emission region

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

\Rightarrow Observed as hard X-rays

\Rightarrow Doppler boosted into observer's frame

\Rightarrow Stringent constraints on co-moving energy density

\Rightarrow Typically large proton power requirements!

b) Stationary in the AGN frame

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

\Rightarrow Observed as UV / soft X-rays

\Rightarrow Doppler boosted into co-moving frame

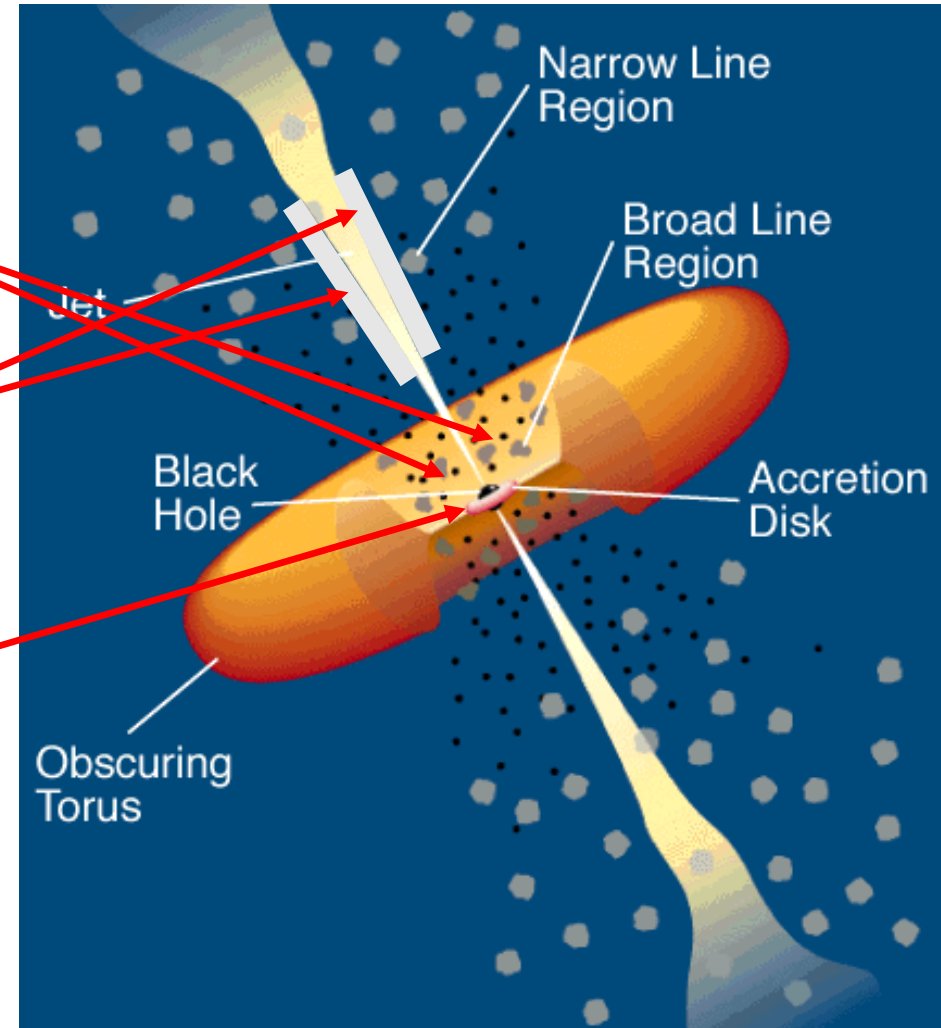
\Rightarrow Strongly relaxed constraints on energy density

\Rightarrow Much lower proton power requirements!

Photo-pion production – Origin of Target Photons

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

- Broad Line Region?
(Padovani et al. 2019)
- Slow-moving sheath
(Tavecchio & Ghisellini 2005)
- Accretion flow (RIAF)
(Righi et al. 2019)



Summary

- Production of IceCube neutrinos requires
 - Protons of \sim PeV energies
 - Target photons of co-moving UV / X-ray energies
 - For IceCube neutrino production in AGN jets, external target photon fields strongly preferred over co-moving (electron-synchrotron) photon field.
 - $\gamma\gamma$ opacity for co-spatially produced GeV – TeV γ -rays is \sim 300 times larger than $p\gamma$ efficiency
- => Expect neutrino correlation with X-ray / soft γ -ray activity more naturally than with GeV – TeV γ -rays!



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Senior Postdoc Opening at NWU

- Senior Postdoc in observational or theoretical extragalactic high-energy / multi-messenger astrophysics.
- Initially for one year, **renewable up to 5 years**, depending on satisfactory performance.
- The salary will be **ZAR 438 000** per year (~ US \$ 24 200 ~ € 24 900 – income-tax free and significantly higher than a usual postdoc salary in South Africa).
- Prior postdoctoral experience highly desirable, but **Ph.D. not more than 5 years ago**.
- Institutional expectations:
 - publication of at least 4 refereed journal papers per year;
 - co-supervision of at least 1 M.Sc. or Ph.D. student per year;
 - participation in grant proposal writing - at least one submission per year;
 - a moderate amount of participation in administration.
- Send CV, publication list, statement of research experience and interests, contact information of 3 references
- Application deadline: **20 October 2022**
- Contact: Markus.Bottcher@nwu.ac.za

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Thank you for your attention!

Markus Böttcher*

Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

*Markus.Bottcher@nwu.ac.za

Backup

Spectral Energy Distribution of TXS 0506+056

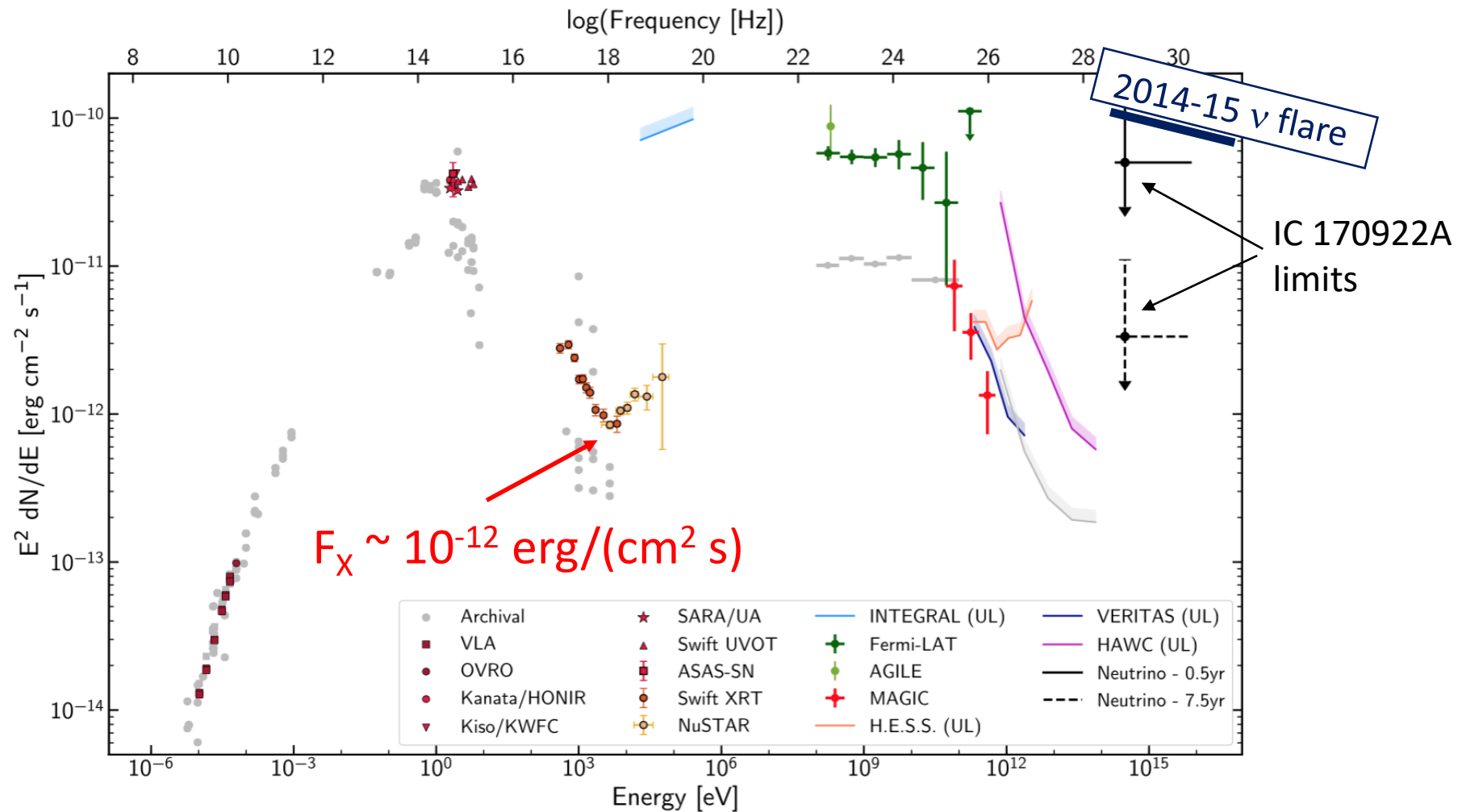
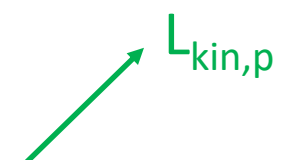


Photo-pion production – Origin of Target Photons

Constrain target photon luminosity and required proton power from

- observed neutrino luminosity
($L'_\nu \sim 1.7 \times 10^{42} \delta_1^{-4}$ 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)

$$L'_\nu \approx \frac{1}{2} N_0 m_p c^2 \int_{\gamma_1}^{\gamma_2} \gamma_p^{-\alpha_p} |\dot{\gamma}_{p,p\gamma}| d\gamma_p \approx 1.3 \times 10^{-14} N_0 u'_t \epsilon'^{-1}_t \text{ cm}^3 \text{ s}^{-1}$$



$$\dot{\gamma}_{p,p\gamma} \approx -c \underbrace{\langle \sigma_{p\gamma} f \rangle}_{\approx 10^{-28} \text{ cm}^2} \frac{u'_t}{\epsilon'_t m_e c^2} \gamma_p \rightarrow F_{X/UV} = \frac{u'_t R^2 \delta^4 c}{d_L^2}$$


Photo-pion production – Origin of Target Photons

a) Co-moving target photon field

$$\text{X-ray flux limit} \Rightarrow u'_t < 9 \times 10^{-4} R_{16}^{-2} \delta_1^{-4} \text{ erg cm}^{-3}$$

$$\Rightarrow L_{p,\text{kin}} \gtrsim 4.9 \times 10^{52} R_{16} \Gamma_1^2 \text{ erg/s}$$

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

\Rightarrow Ruled out!

Photo-pion production – Origin of Target Photons

b) Stationary target photon field

From UV / X-ray flux: $u'_t < 100 \Gamma_1^2 R_{t,17}^{-2} \text{ erg cm}^{-3}$

$$\Rightarrow L_{p,\text{kin}} \gtrsim 4.7 \times 10^{47} \delta_1^{-4} R_{t,17}^2 R_{16}^{-1} \text{ erg/s}$$

Below Eddington limit for $M_{\text{BH}} \gtrsim 10^9 M_0 \Rightarrow$ plausible.

Can suppress p-sy below UV/X-ray limit for $B \sim 10 \text{ G}$.
 \Rightarrow Plausible!

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