Modeling the Interactions of Particles: Very-high-energy neutrino production

Markus Böttcher

North-West University

Potchefstroom, South Africa

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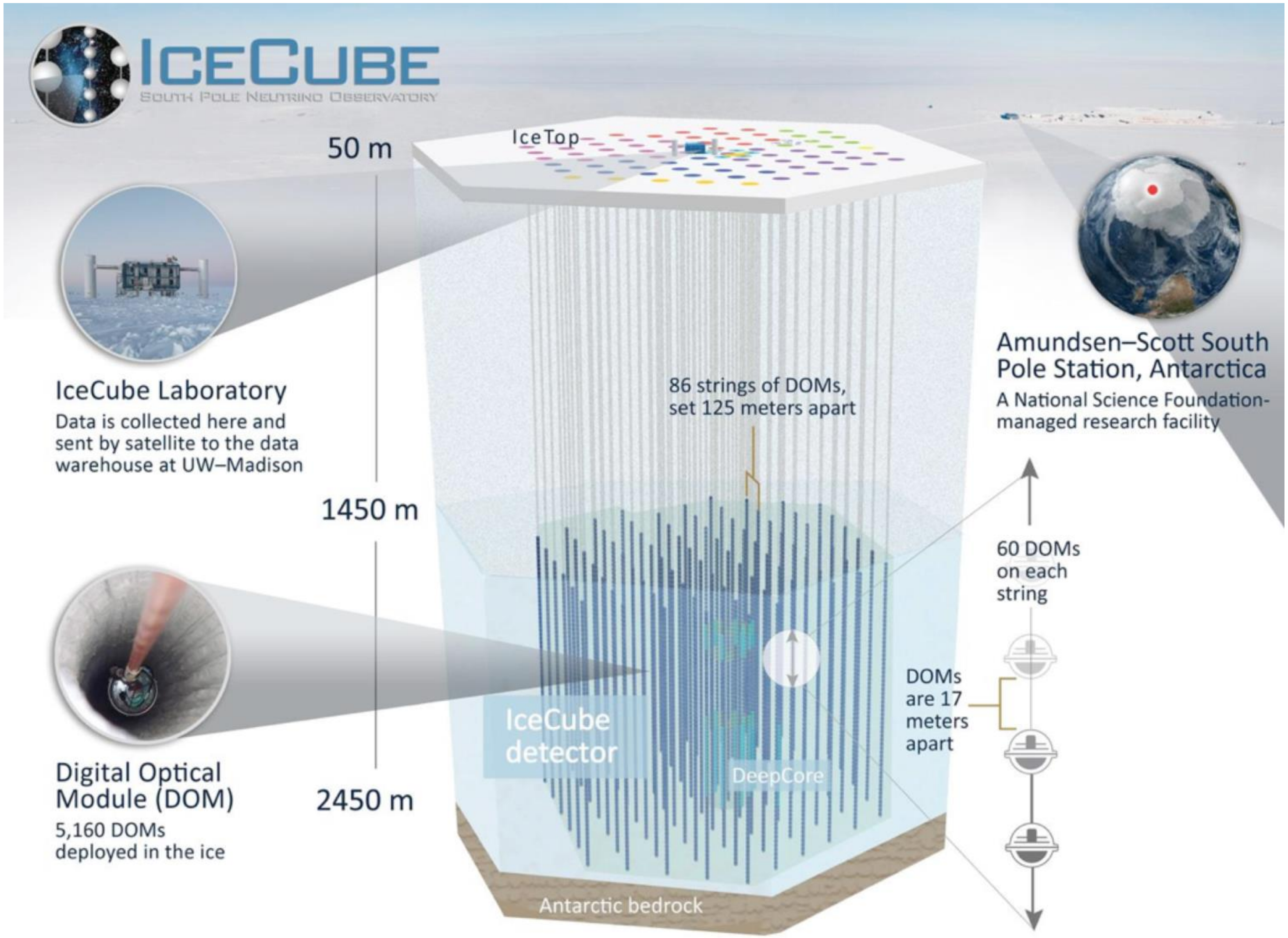
The IceCube Neutrino Detector at the South Pole



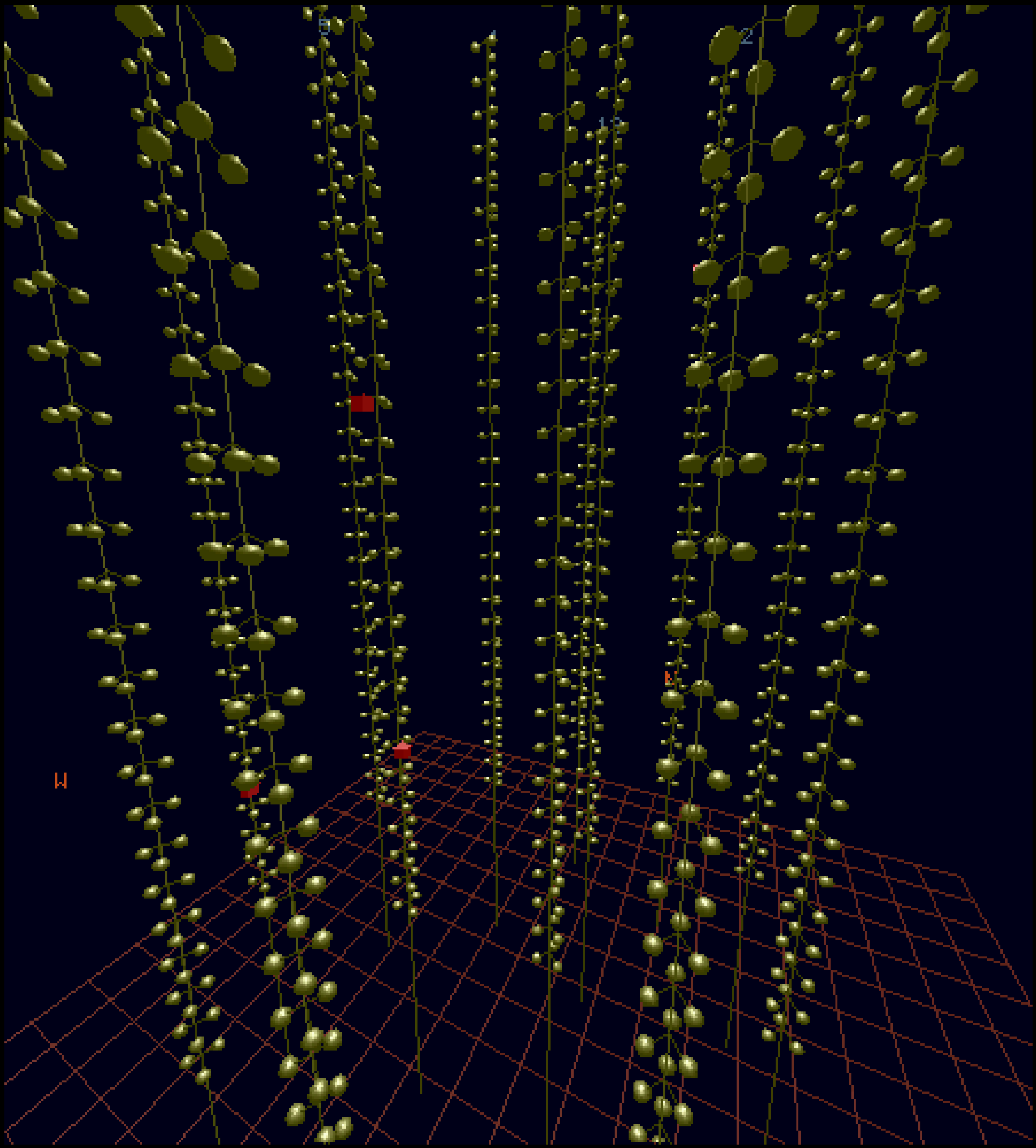
Fully operational since 2010.

High-Energy Neutrino Detectors

IceCube:

$E_\nu \sim$ 100 TeV – few PeV

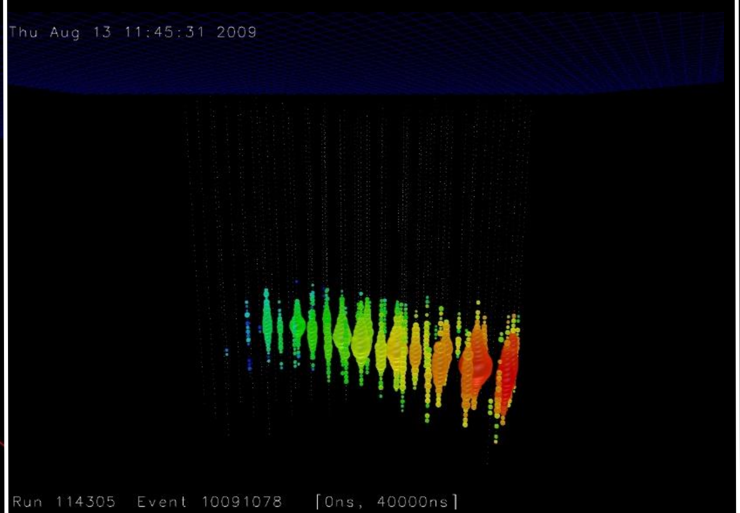
ν-matter scattering, followed by particle cascades in ice/water → Cherenkov light detection.



Neutrino Event Types

Tracks ← ν_μ

ν_μ interaction produces a muon
→ Long track
→ Localization down to ~ 0.4°.



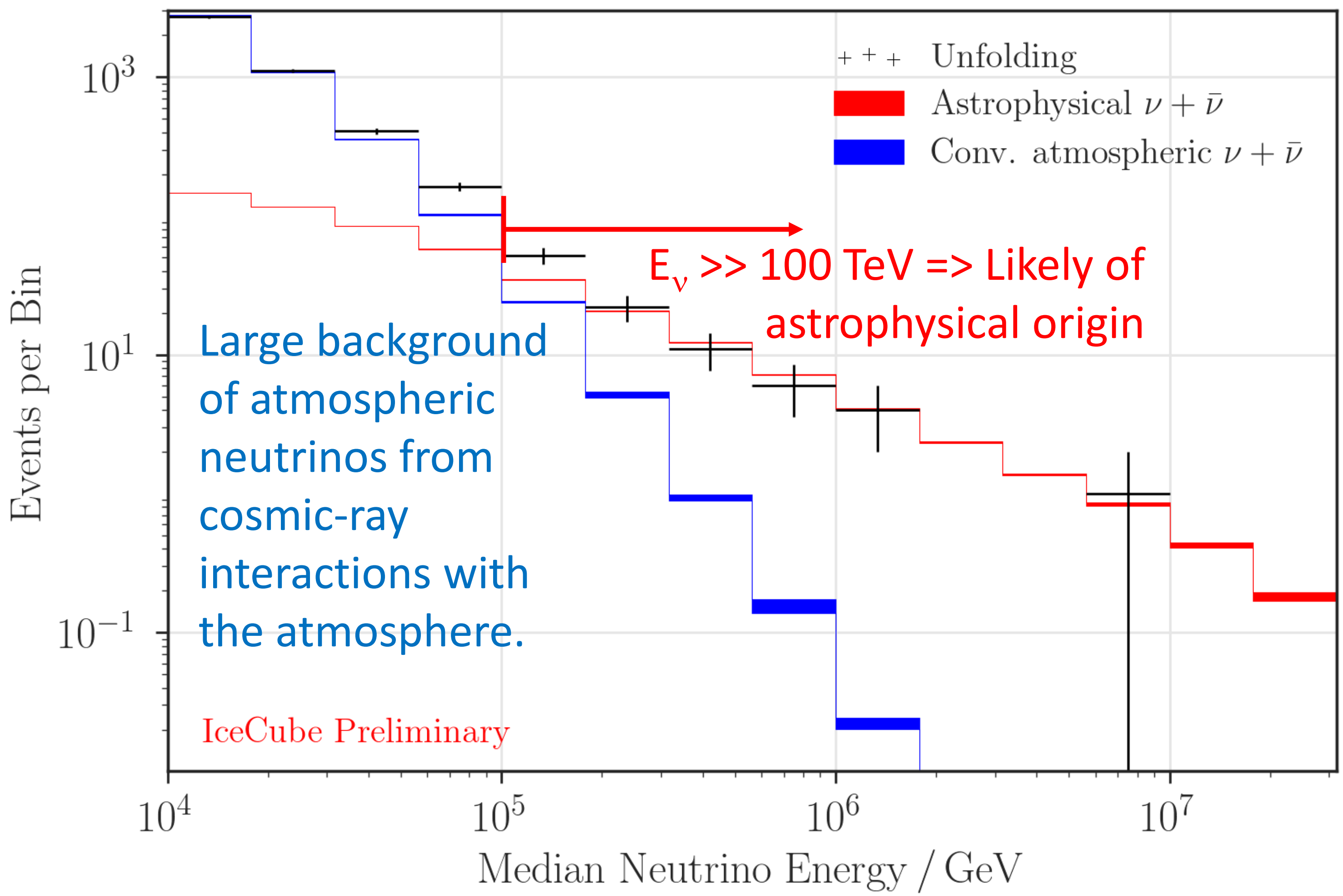
Cascades ← ν_e

ν_e interaction produces an electron
→ loses energy quickly in a blob-like cascade. Localization to ~ 8°.

Double Bang ← ν_τ

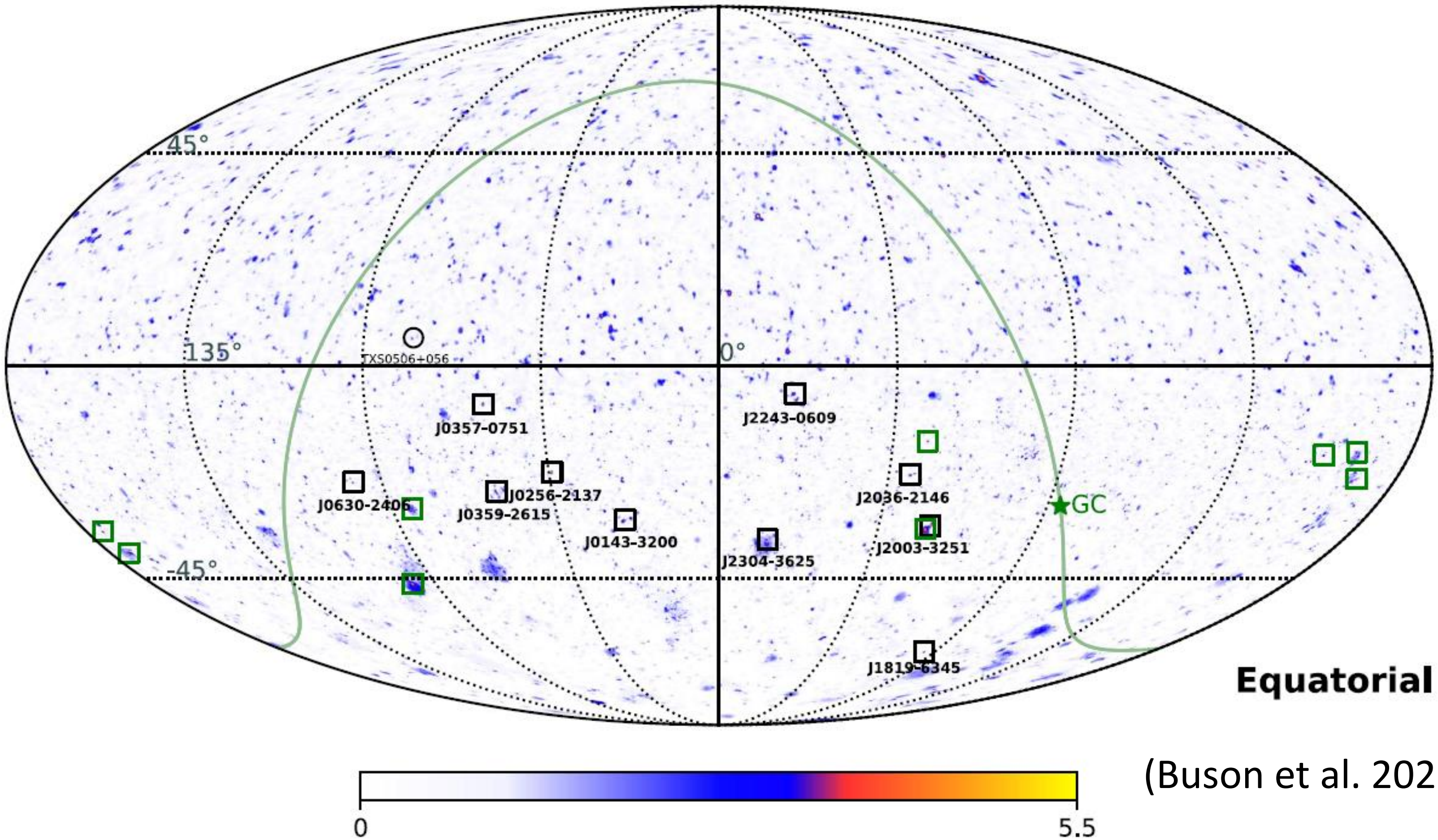
ν_τ interaction produces a tau lepton
→ 2 cascades: One at tau production, one at tau decay.

The IceCube Neutrino Spectrum



First evidence for astrophysical neutrinos published in 2013.

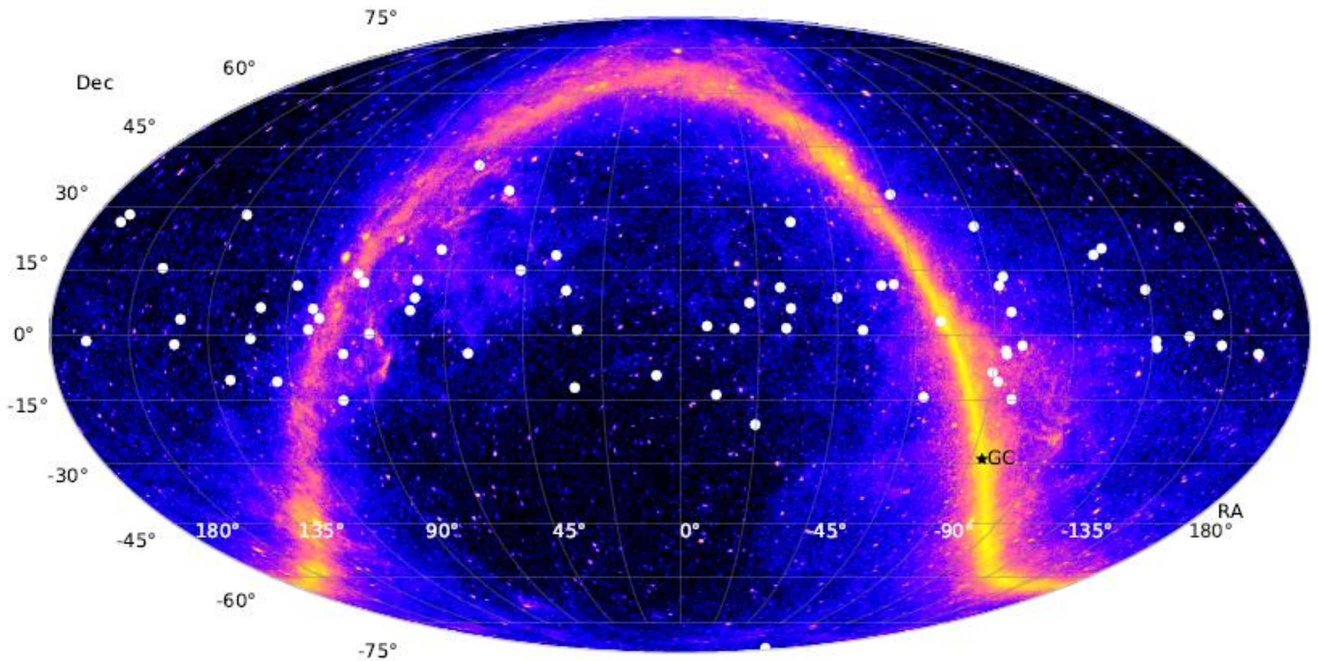
Origin of IceCube-Detected Neutrinos



(Buson et al. 2022)

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)

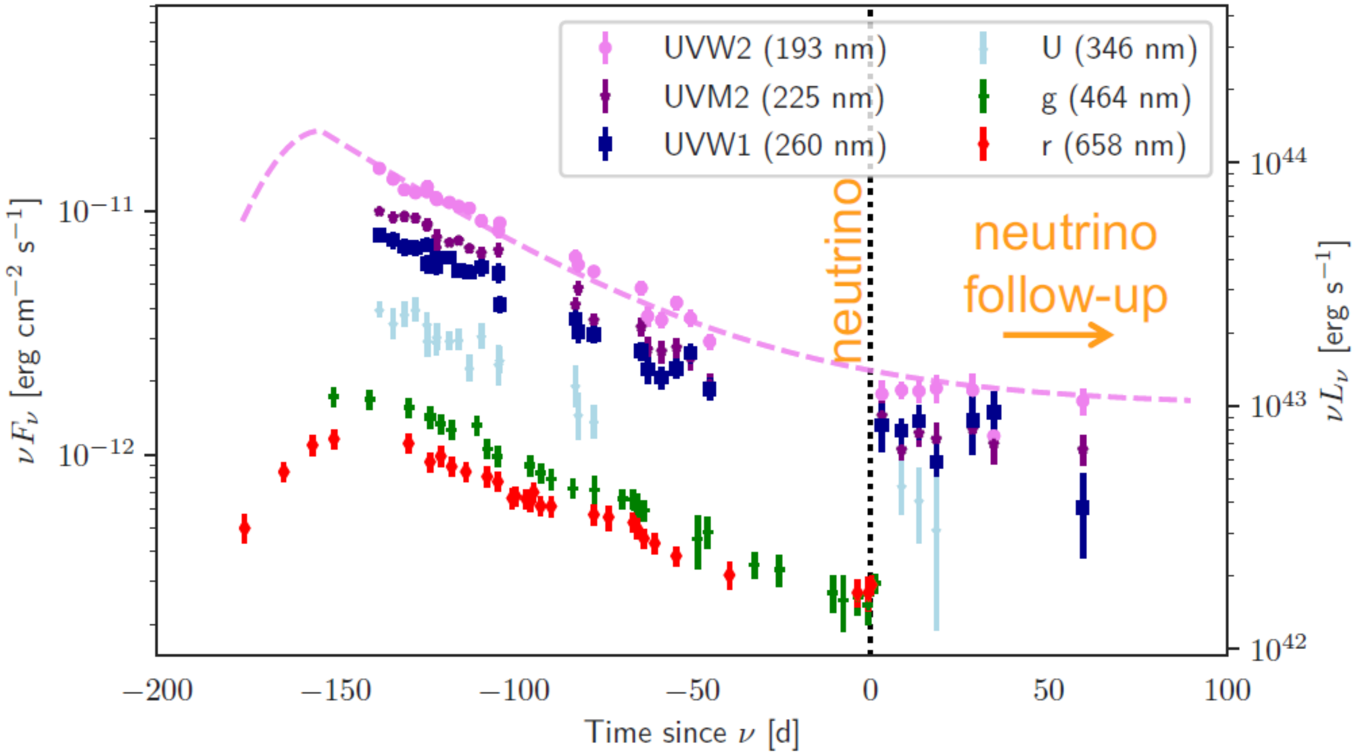
Origin of IceCube-Detected Neutrinos



(Kovalev et al. 2022)

Also: 4.1 σ evidence for IceCube neutrinos preferentially originating at **low Galactic latitude** (chance coincidence $p = 4 \cdot 10^{-5}$).

Origin of IceCube-Detected Neutrinos



(Stein et al. 2021)

Alternative potential source class: (non-jetted) **Tidal Disruption Events** (e.g., IC-191001A – AT2019dsg)

Basics of Neutrino Production

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

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

  or $n + \pi^+$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \tau = 2.55\times10^{-8}\ \text{s}$$

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

$$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e \qquad \tau = 2.2\times10^{-6}\ \text{s}$$

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

Neutrino Production in AGN Jets

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

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

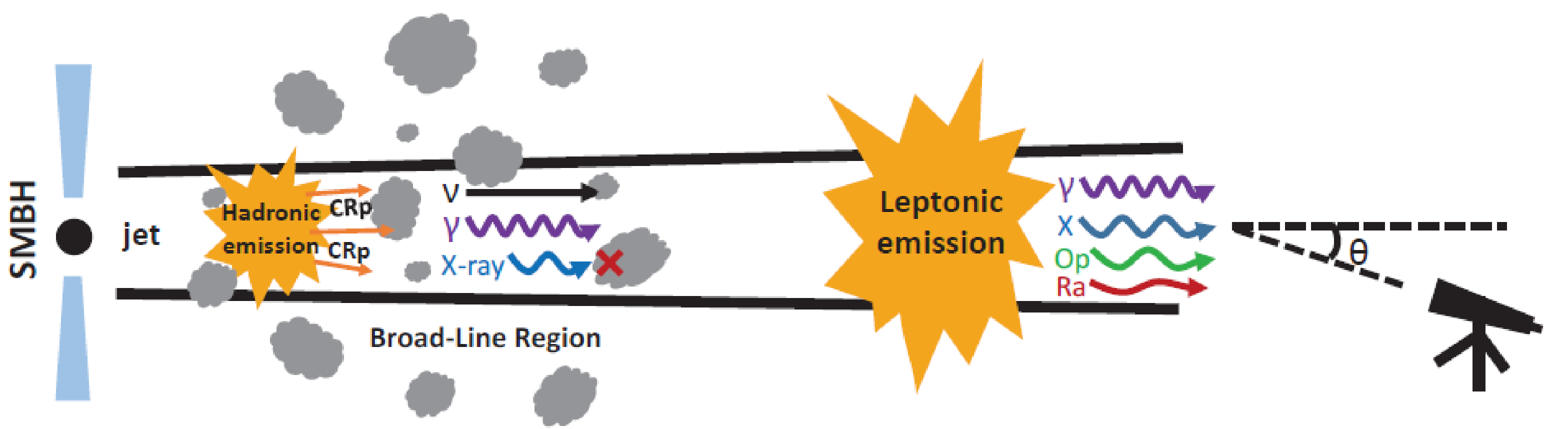
$$\varepsilon = \frac{E_{ph}}{m_e c^2}$$

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

Neutrino Production in AGN Jets

⇒ 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. (2019): UHECR interactions with BLR clouds



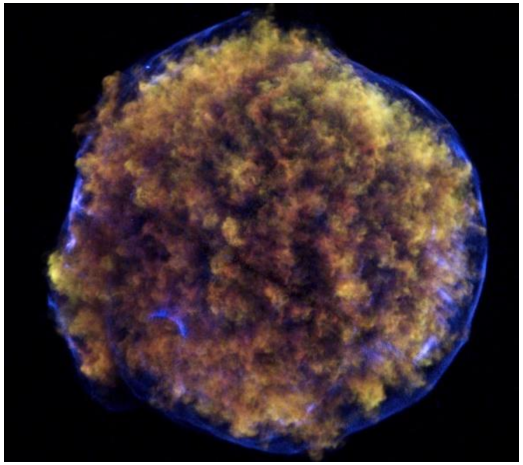
Neutrino Production in SNRs

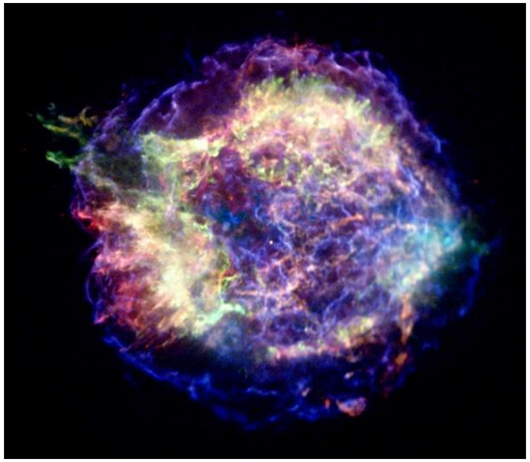
$$n_{ph} \sim \frac{L_o}{< \varepsilon > m_e\, c^2\, 4\pi\, R^2\, c} \sim 2 \times 10^{-3}\, R_{pc}^{-2}\, L_{o,34}\, cm^{-3}$$

$$n_p \sim 1\, n_0\, cm^{-3}$$

$$\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 2 \times 10^{-3}\, L_{o,34}\, R_{pc}^{-2}\, n_0^{-1}$$

$\Rightarrow$ In SNRs, pp likely dominant over pγ.





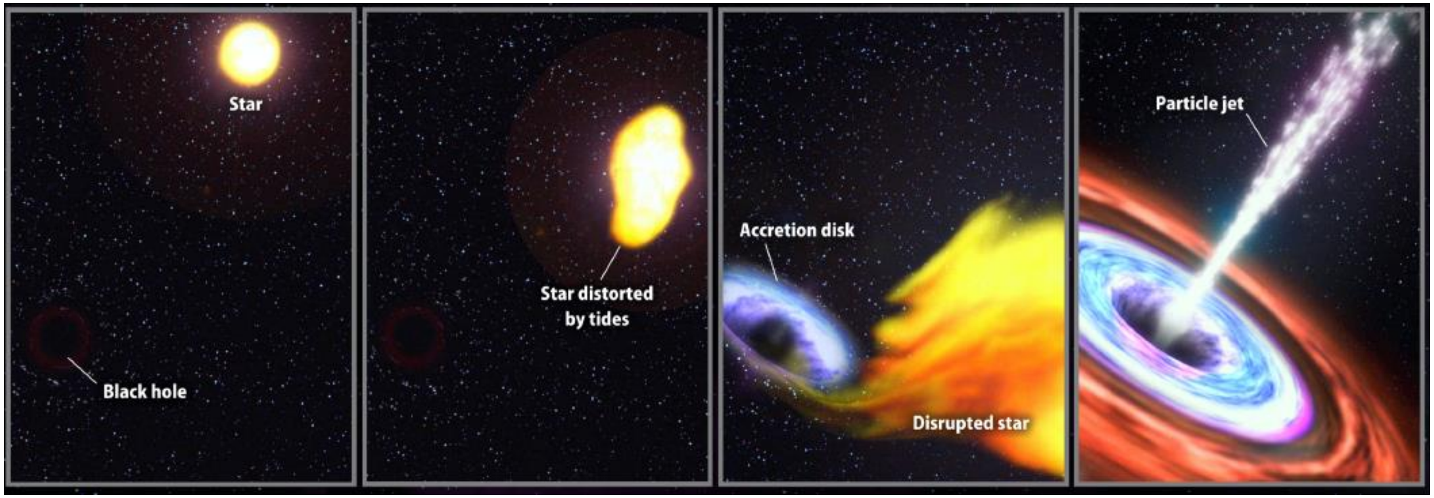
Neutrino Production in Non-Jetted TDEs

$$n_{ph} \sim \frac{L_X}{< \varepsilon > m_e c^2 4\pi R^2 c} \sim 2 \times 10^{15} R_{13}^{-2} L_{X,44} \, cm^{-3}$$

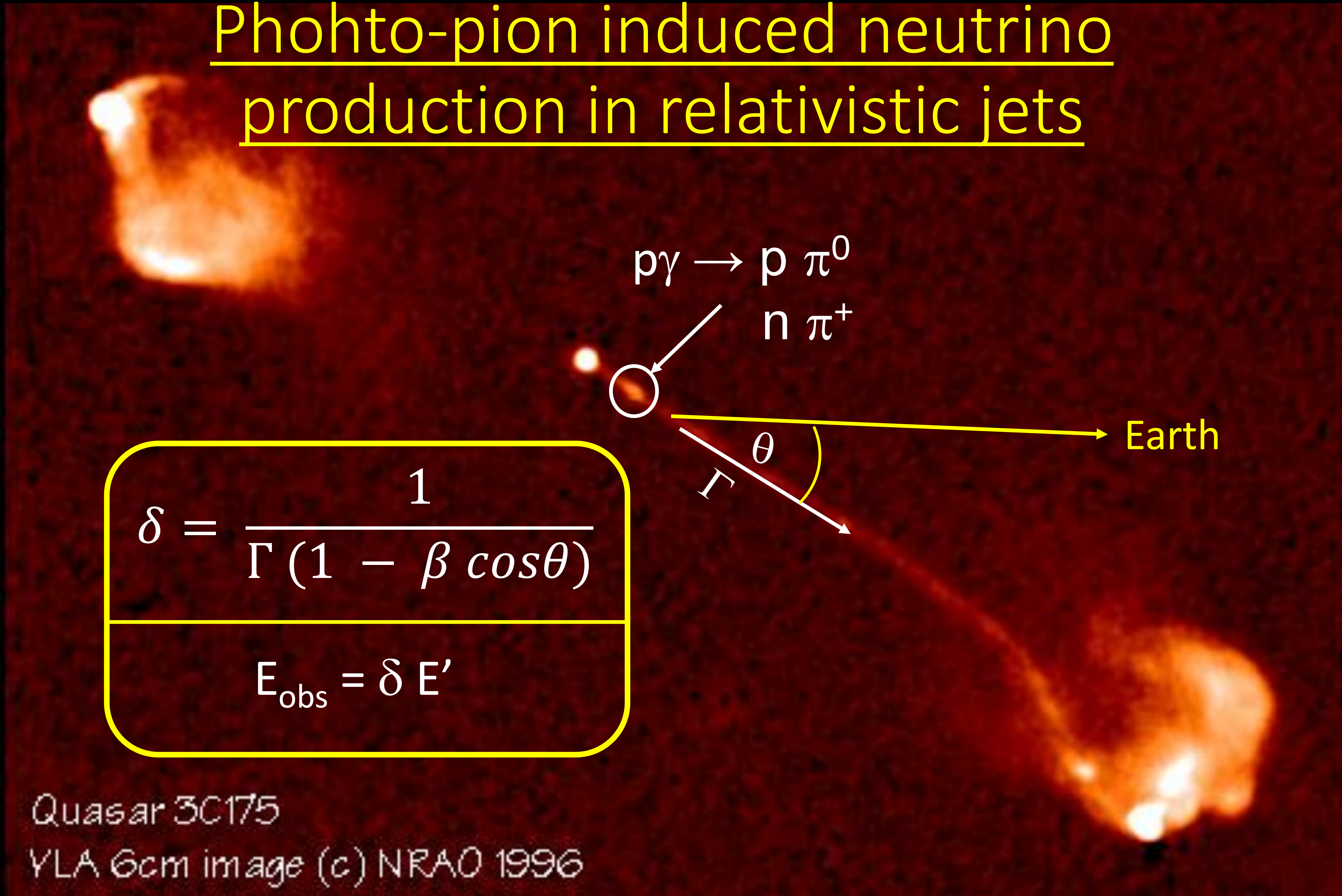
$$n_p \sim \frac{M}{\frac{4}{3} \pi R^3 m_p} \sim 3 \times 10^{17} \left(\frac{M}{M_0}\right) R_{13}^{-3} \, cm^{-3}$$

$$\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 7 \times 10^{-3} L_{X,44} R_{13} \left(\frac{M}{M_0}\right)$$

$\Rightarrow$ In non-jetted TDEs, both pp and pγ can be relevant.



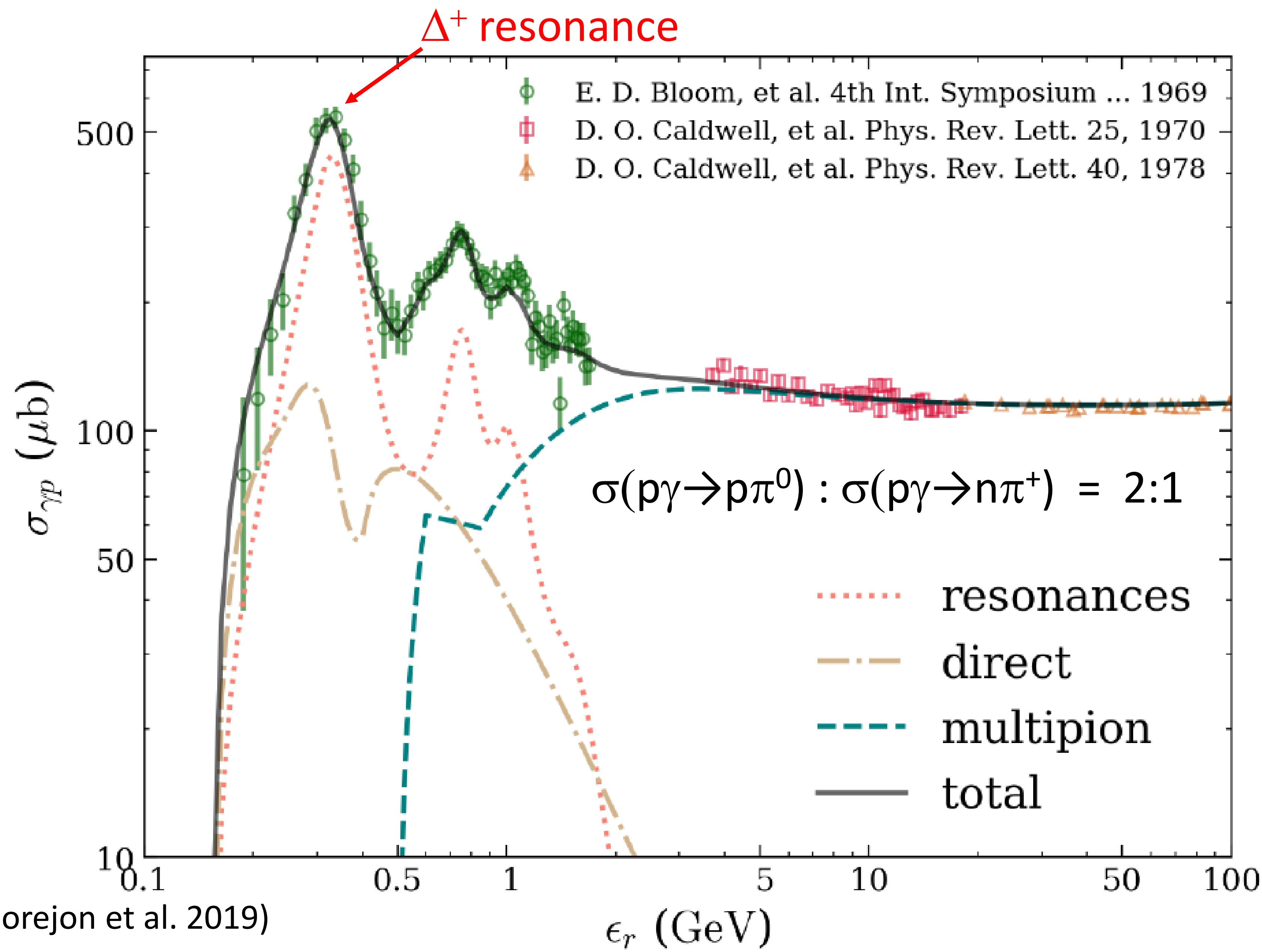
Phohto-pion induced neutrino production in relativistic jets



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

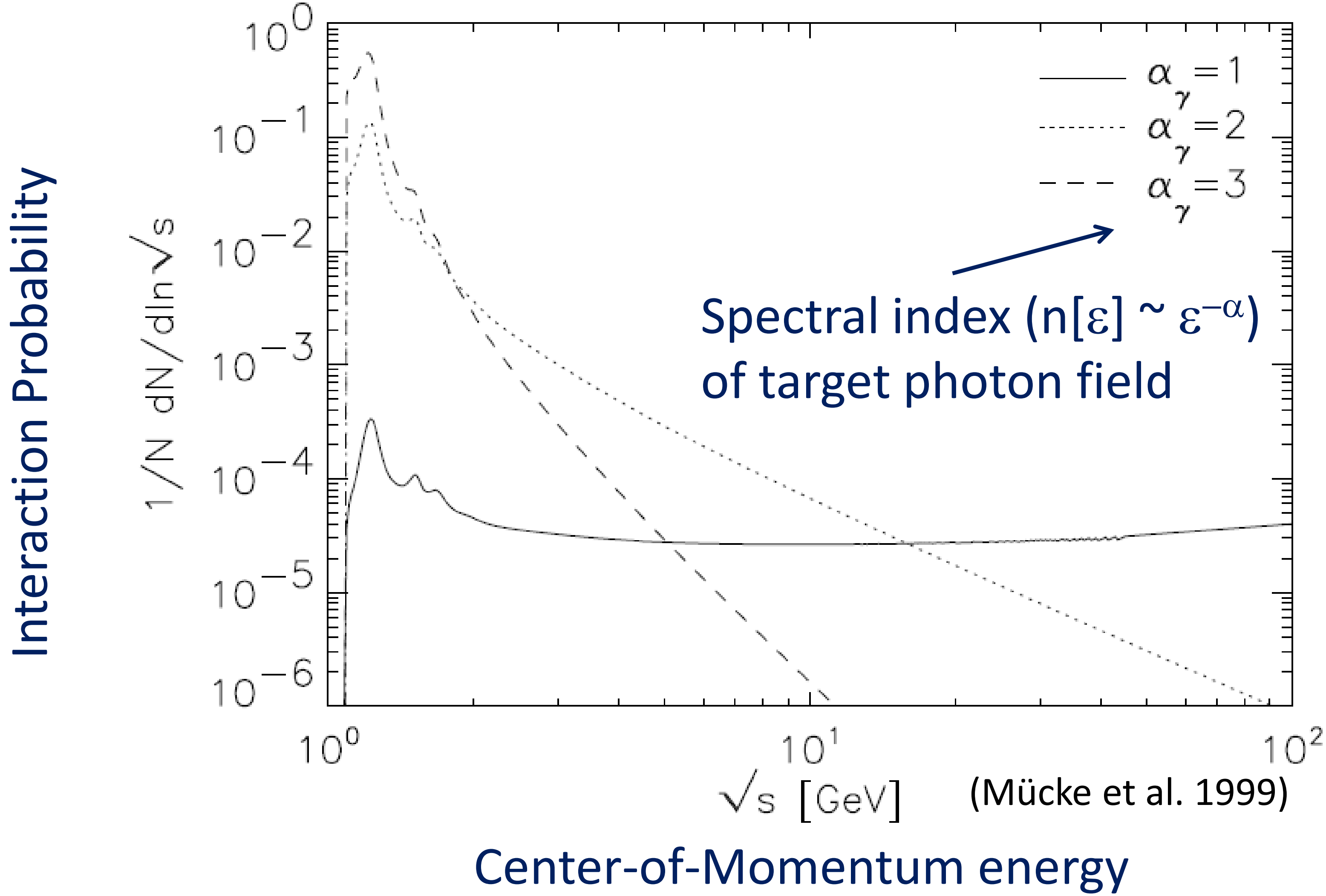
$$E_{obs} = \delta\, E'$$

Photo-Pion Production Cross Section



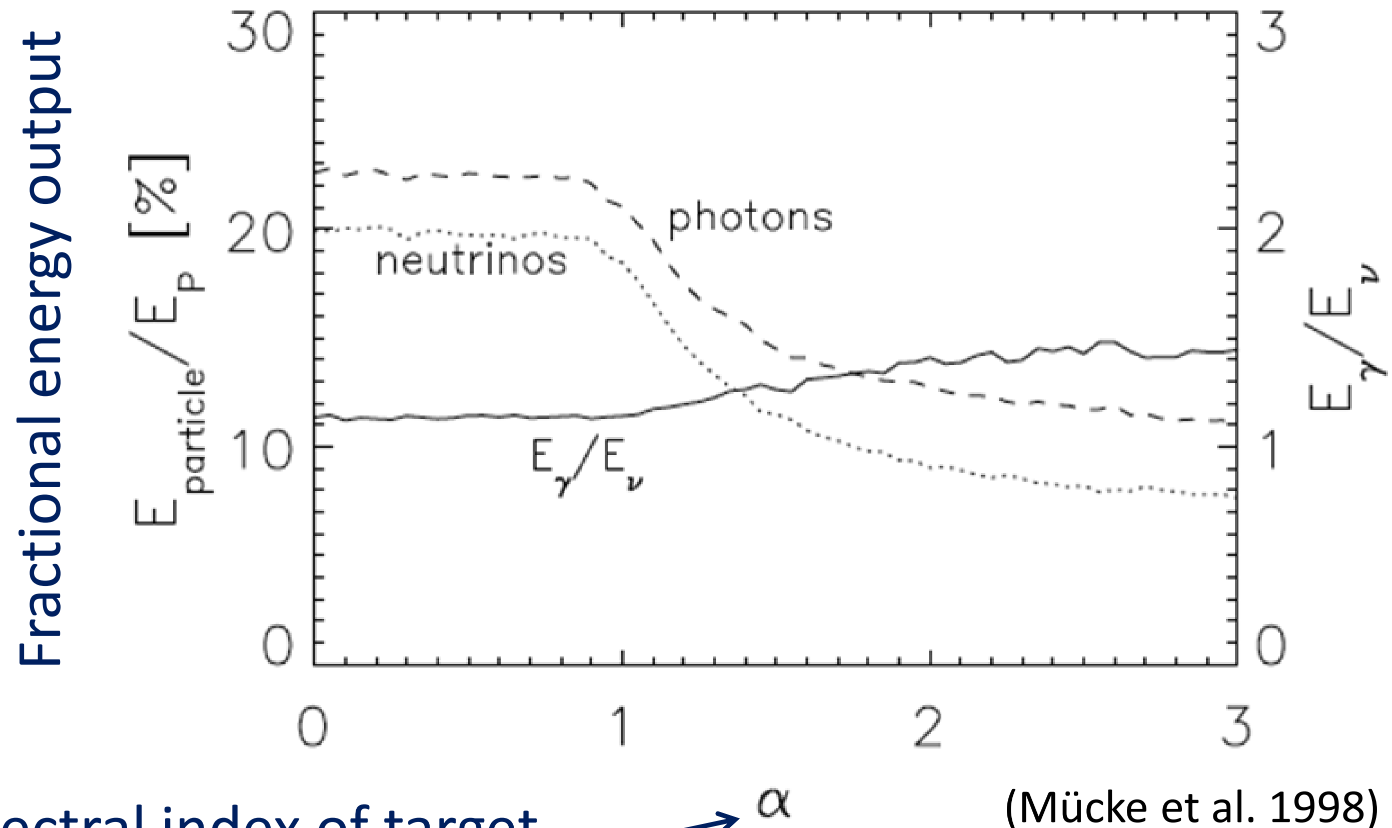
(Morejon et al. 2019)

Photo-Pion Production



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

Photo-Pion Production



(Mücke et al. 1998)

Spectral index of target photon field

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 - 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:

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

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

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

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

<u>γ-ray production through:</u>

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

b) Proton synchrotron at

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

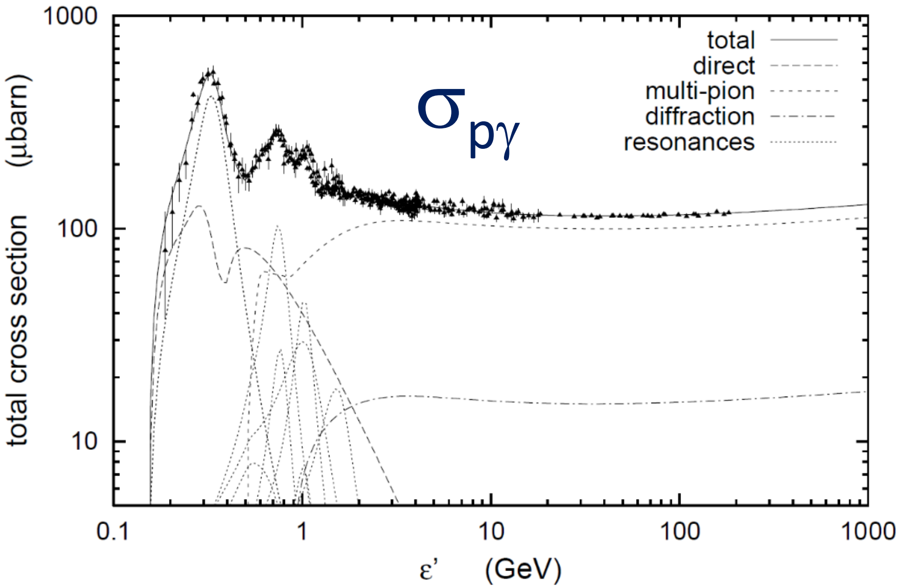
c) Secondary electron synchrotron at

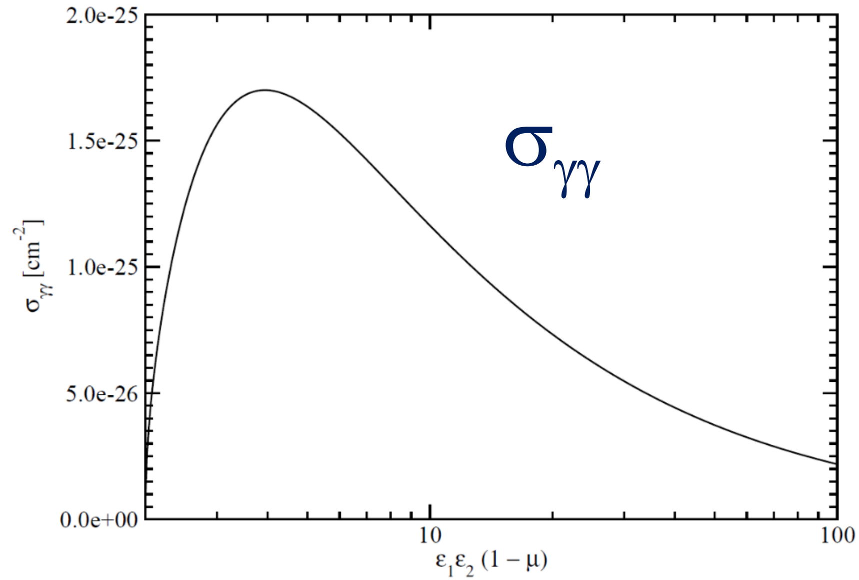
$\nu_{esy} \sim 4\times10^{21}\ \gamma_6^2\ B_2\ \delta_1$ Hz (~ 20 MeV)

⇒ Protons producing IceCube neutrinos will not produce GeV 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 ~ $\tau_{\gamma\gamma} = R\, \sigma_{\gamma\gamma}\, n_{ph}$





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

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

⇒ Cascade emission at lower energies.

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

(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

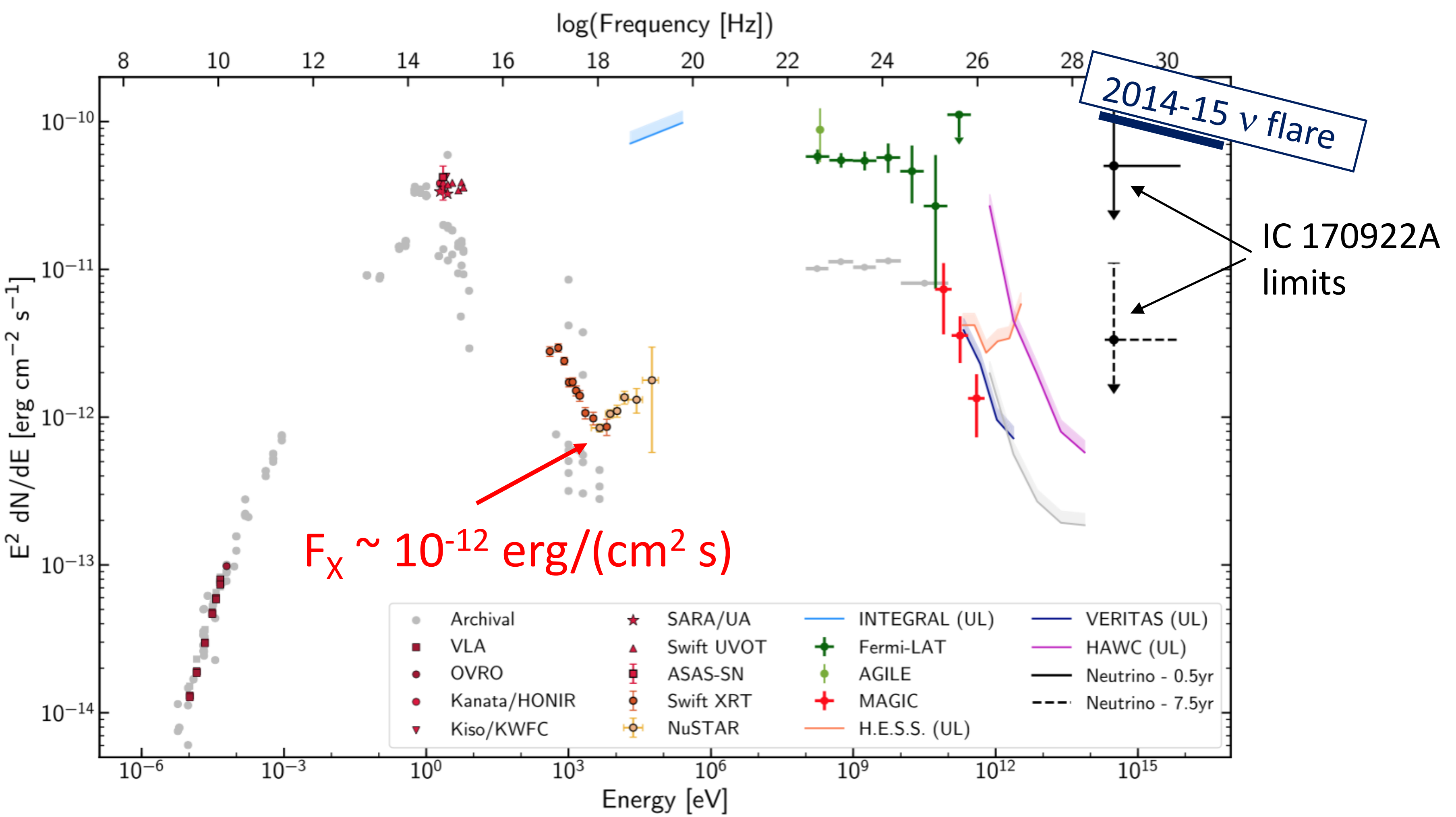


Photo-pion production – Origin of Target Photons

Constrain target photon luminosity and required proton power from

- observed neutrino luminosity
  ($L'_\nu \sim 1.7\times10^{42}\,\delta_1^{-4}$ 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)

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

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

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

Photo-pion production – Origin of Target Photons

a) Co-moving target photon field

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

=> $L_{p,kin} \gtrsim 4.9 \times 10^{52}\, R_{16}\, \Gamma_1^{2}$ 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}

$\Rightarrow L_{p,kin} \gtrsim 4.7\times10^{47}\, \delta_1^{-4}\, R_{t,17}^{2}\, R_{16}^{-1}$ erg/s

Below Eddington limit for $M_{BH} \gtrsim 10^9\, M_0$ => plausible.

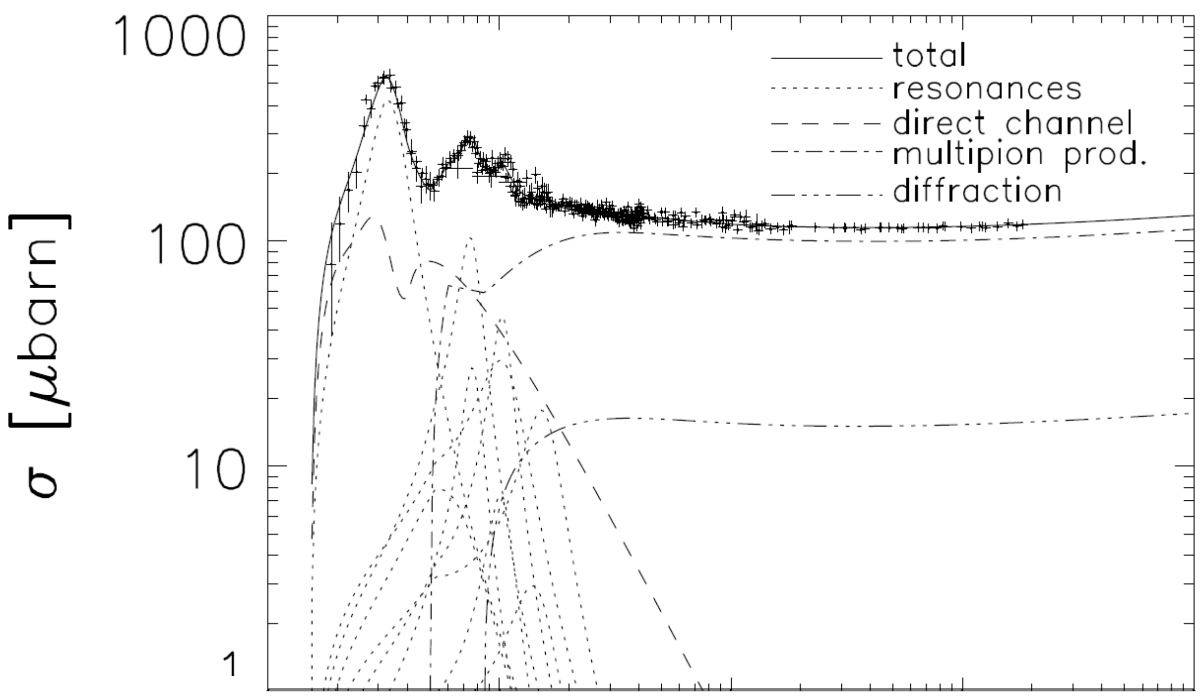
Can suppress p-sy below UV/X-ray limit for B ~ 10 G.

$\Rightarrow$ Plausible!

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

Modeling Multi-messenger Emissions from photo-pion production

- Previous slides: only order-of-magnitude estimates of energetics, based on reactions at Δ^+ resonance only. – Not good enough for detailed modelling.
- Most accurate method: Monte-Carlo simulations of individual reactions (e.g., SOPHIA: Mücke et al. 2000: Comp. Phys. Comm., 124, 290)



Modeling Multi-messenger Emissions from photo-pion production

- Most often used method: Semi-analytical approximations of spectra of final decay products, e.g.,

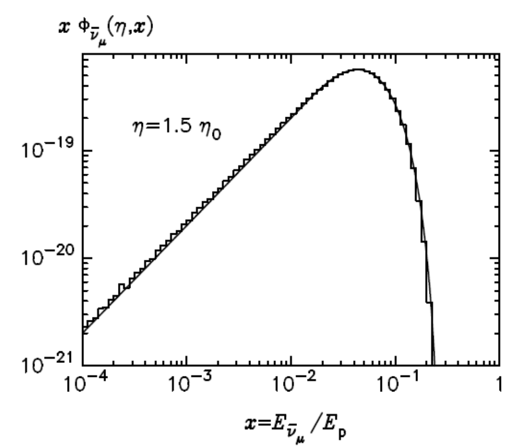
$$\frac{dN_l(E_l)}{dE_l} = \int \frac{dE_p}{E_p} f_p(E_p) \int d\varepsilon\, f_{ph}(\varepsilon)\, \Phi_l(\eta, x)$$

With $\eta = \frac{4\,\varepsilon\, Ep}{(m_p\, c^2)^2}$, $x = E_l/E_p$, and $\Phi_l(\eta, x)$ tabulated in Kelner & Aharonian (2008: Phys. Rev. D., 78, 034013)

- Integrates out over intermediate (π, μ) particles, i.e., neglects π, μ synchrotron emission (and losses).

=> Only applicable if $\tau_{sy}(\pi,\mu) >> \gamma_p\, \tau'_{decay}$

=> Requires $\gamma_{p,\,max}$ B << 5.6 x 10^{10} G



Modeling Multi-messenger Emissions from photo-pion production

- More generally applicable method: Production (injection) rates of pions $Q_\pi(E_\pi)$ based on semi-analytical templates from Hümmer et al. (2010: ApJ, 721, 630)
- Solve coupled Fokker-Planck equations for the evolution of all particle species, e.g.,

$$\frac{\partial n_\pi(\gamma,t)}{\partial t} = \frac{\partial}{\partial\gamma}\left[\frac{\gamma^2}{(a+2)t_{\rm acc}}\frac{\partial n_\pi(\gamma,t)}{\partial\gamma}\right] - \frac{\partial}{\partial\gamma}(\dot{\gamma}_{rad} n_\pi(\gamma,t)) + Q_\pi(\gamma,t) - \frac{n_\pi(\gamma,t)}{t_{\rm esc}} - \frac{n_\pi(\gamma,t)}{\gamma t'_{\rm decay}}$$

Stochastic acceleration

Radiative (synchrotron) losses

Pion production

Escape

Pion decay: $\pi^+ \longrightarrow Q_\mu(E_\mu)$
$\pi^0 \longrightarrow Q_\gamma(E_\gamma)$

(e.g., Diltz et al. 2016)

Neutrino Production through proton-proton interactions

(e.g., SNRs, CRs on ISM, …)

Interactions of CR protons with cold target protons:

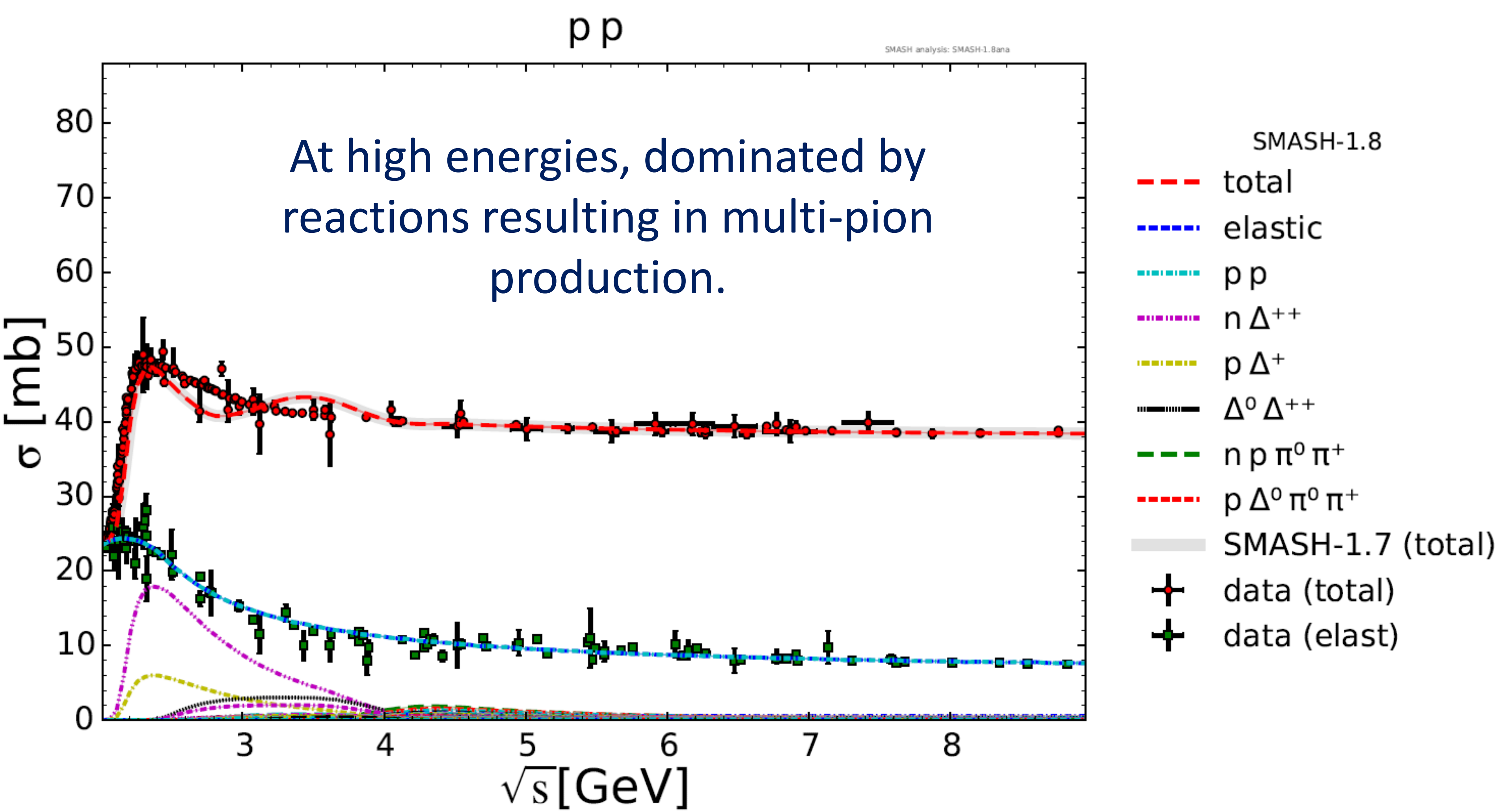
Threshold for pion production:

$$E_{CR,\,thr} = \frac{2\,m_p{}^2 + 4\,m_p m_\pi + m_\pi{}^2}{2\,m_p}\,c^2 = 1.23\;GeV$$

(i.e., $\gamma_p = 1.3$) – produces only $E_{\nu_\mu} \approx 32$ MeV.

$\Rightarrow$ Need (again) ultra-relativistic protons, large $s = E_{cm}{}^2$, to produce VHE neutrinos.

Neutrino Production through proton-proton interactions



Neutrino Production through proton-proton interactions

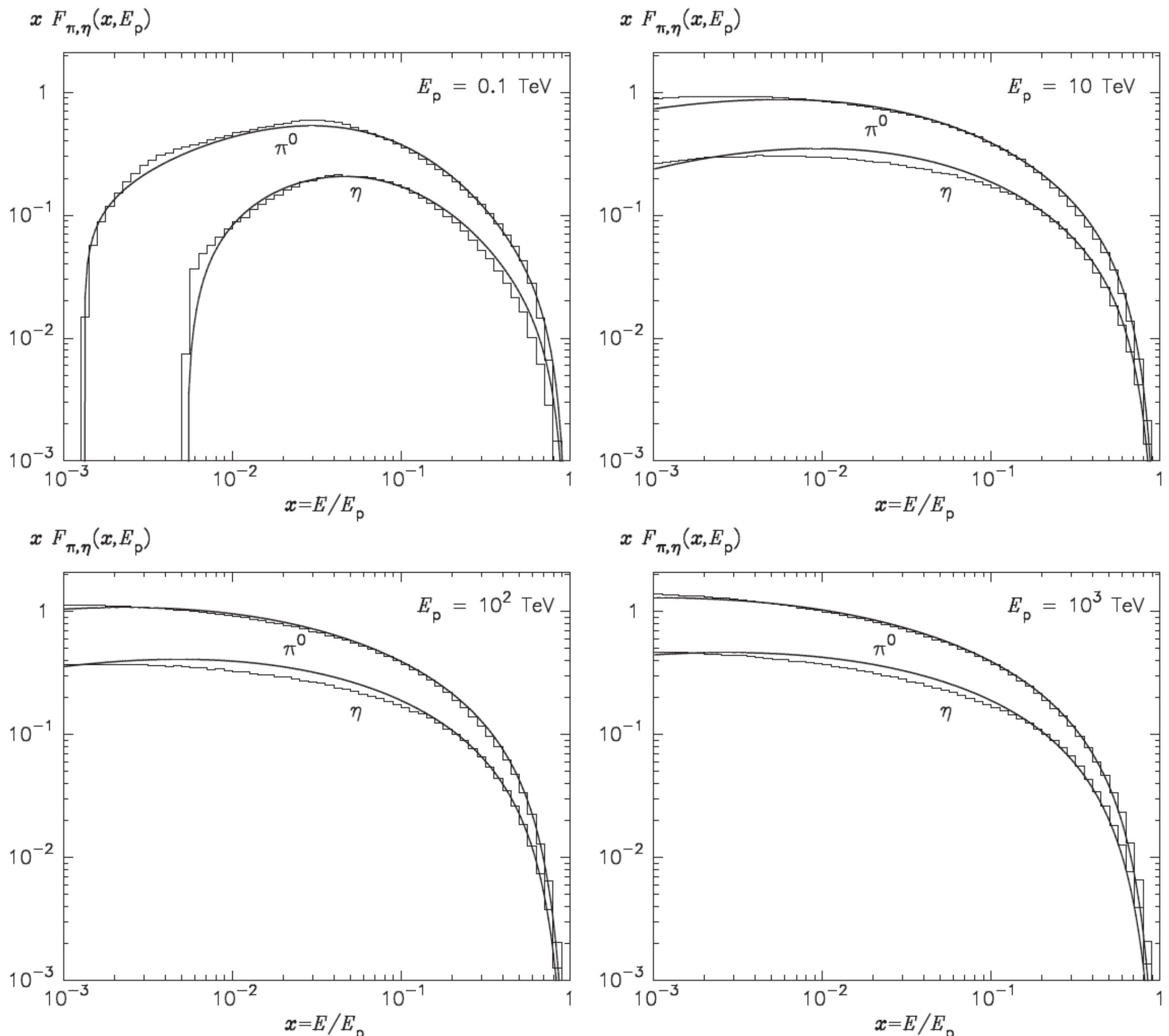
Most accurate way of evaluating electromagnetic and neutrino output: Monte-Carlo simulations:

- Pythia (Sjöstrand, Lonnblad & Mrenna 2001)
- SIBYLL (Fletcher, Gaisser, Lipari & Stanev, 1994)
- QGSJET (Kalmykov, Ostapchenko & Pavlov, 1997)
- CORSICA (Heck & Knapp, 2003, KZK Report)

Neutrino Production through proton-proton interactions

Fraction of CR proton energy transferred to individual pions decreases with increasing proton energy → Multiplicity increases.

For 1 PeV protons, very few pions with E > 100 TeV produced.

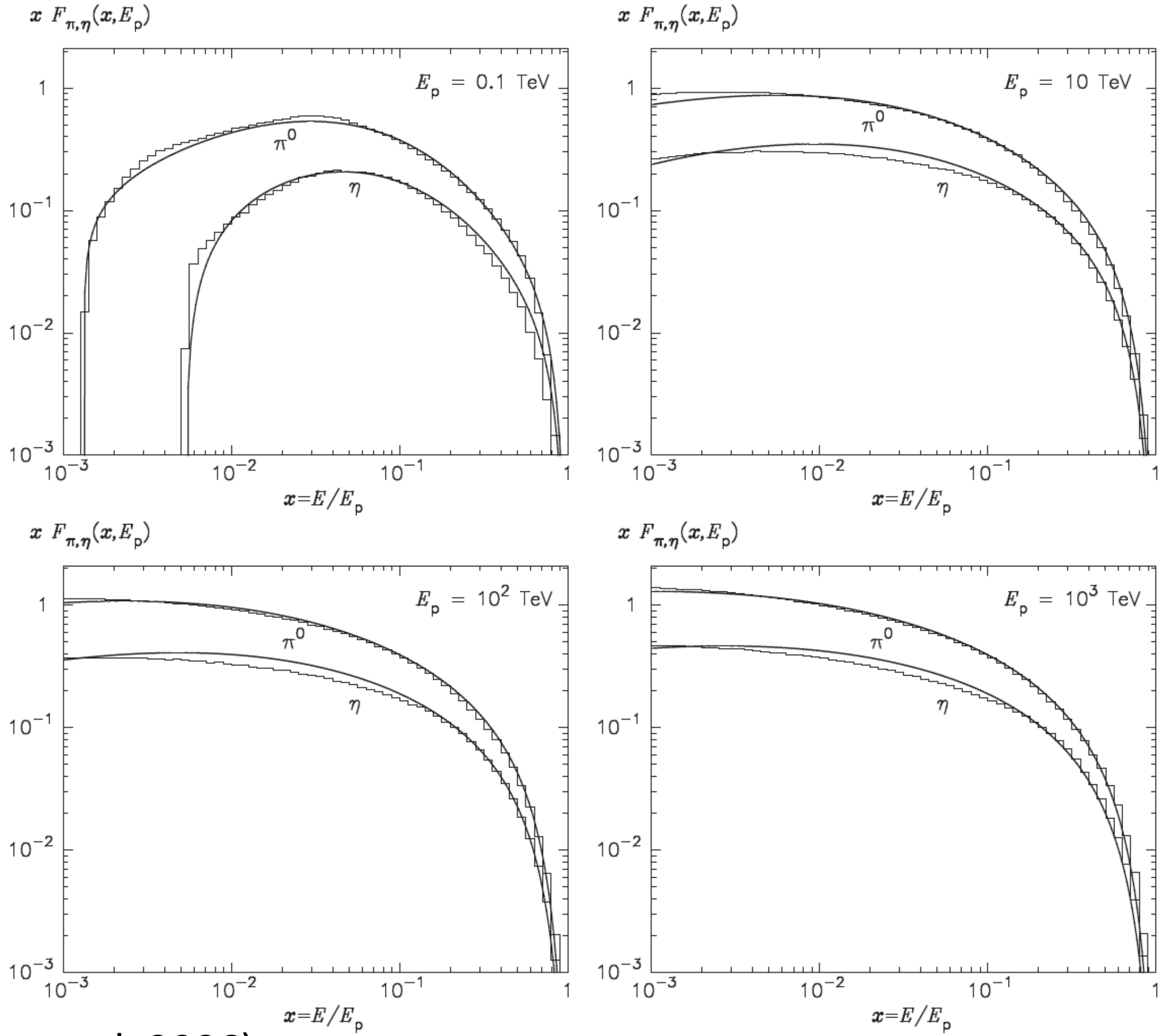


(Kelner et al. 2006)

Neutrino Production through proton-proton interactions

ν_μ energy in π rest frame:
$E_\nu \sim 30$ MeV $\sim 0.2\ E_\pi$

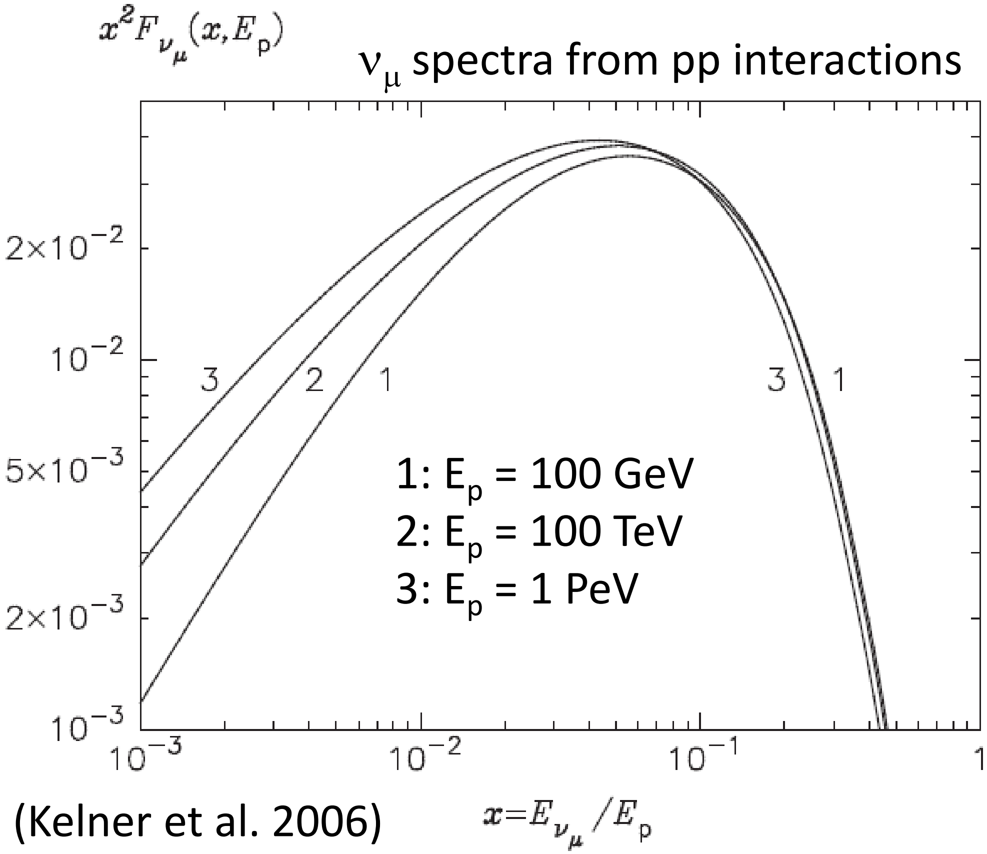
=> Need protons with $E_p >> 1$ PeV to produce > 100 TeV neutrinos.



(Kelner et al. 2006)

Neutrino Production through proton-proton interactions

Most commonly used semi-analytical representations of γ-ray, electron, and neutrino spectra: Kelner, Aharonian & Bugayov, 2006, Phys. Rev. D., 74, 034018



(Kelner et al. 2006)

Summary

- Production of IceCube neutrinos requires
  - Protons of ~ PeV energies
  - Target photons of co-moving UV / X-ray energies

- For IceCube neutrino production in AGN jets, external target photon fields strongly preferred

- pp interactions very inefficient in producing > 100 TeV neutrinos (need protons of >> 1 PeV energies)

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Thank you!