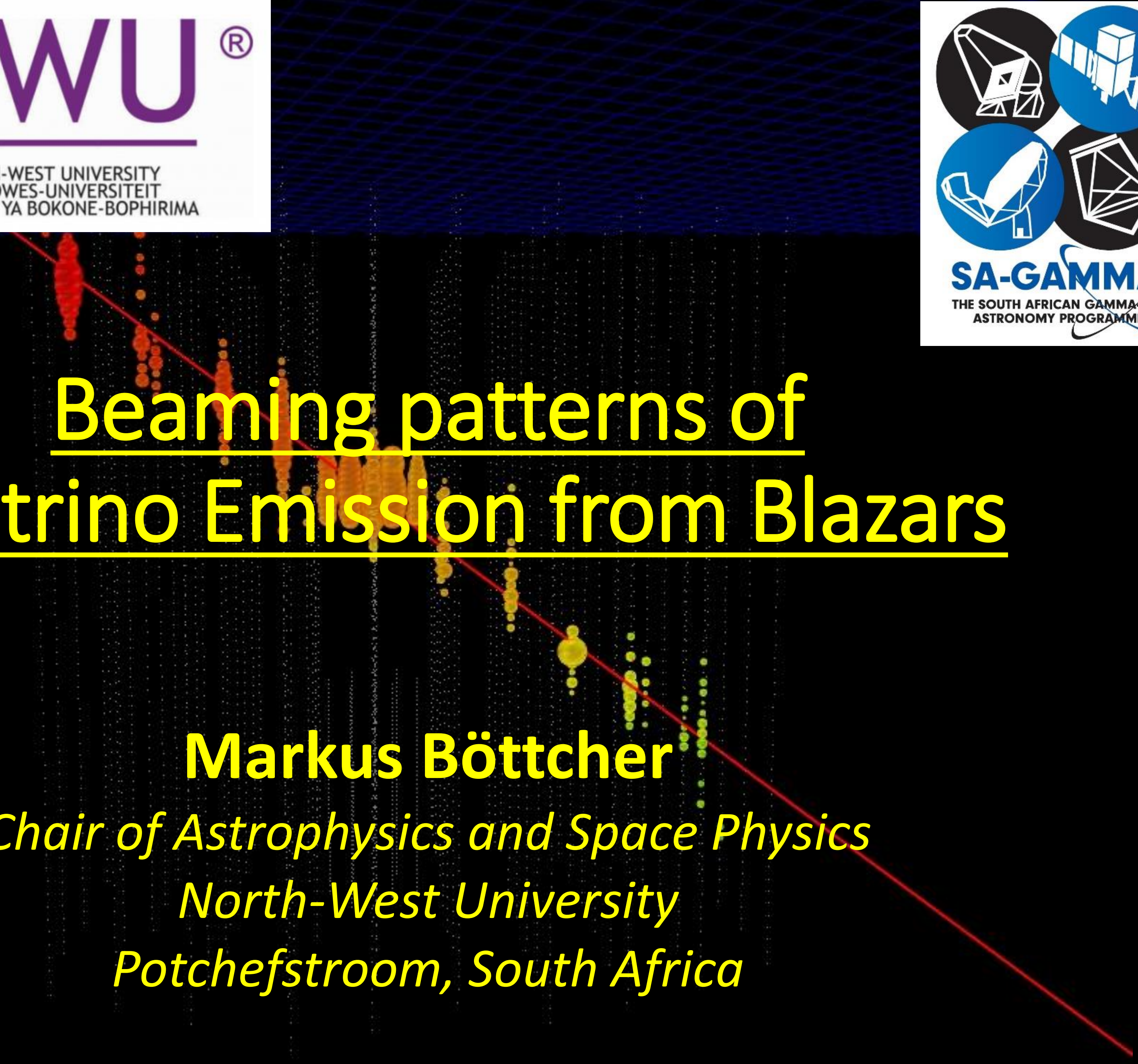

Beaming patterns of Neutrino Emission from Blazars

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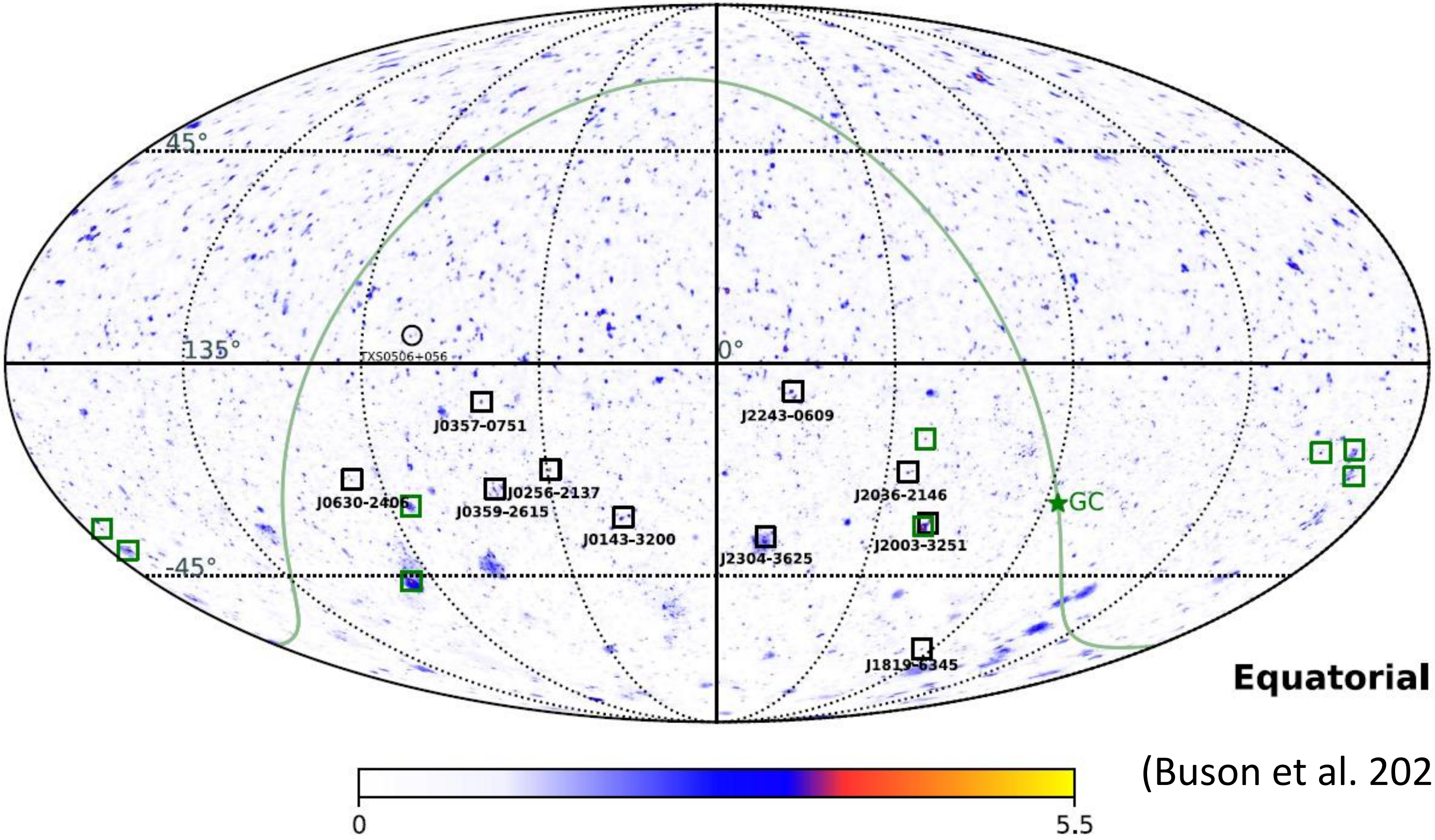
Based on: Böttcher 2023: ApJL, submitted

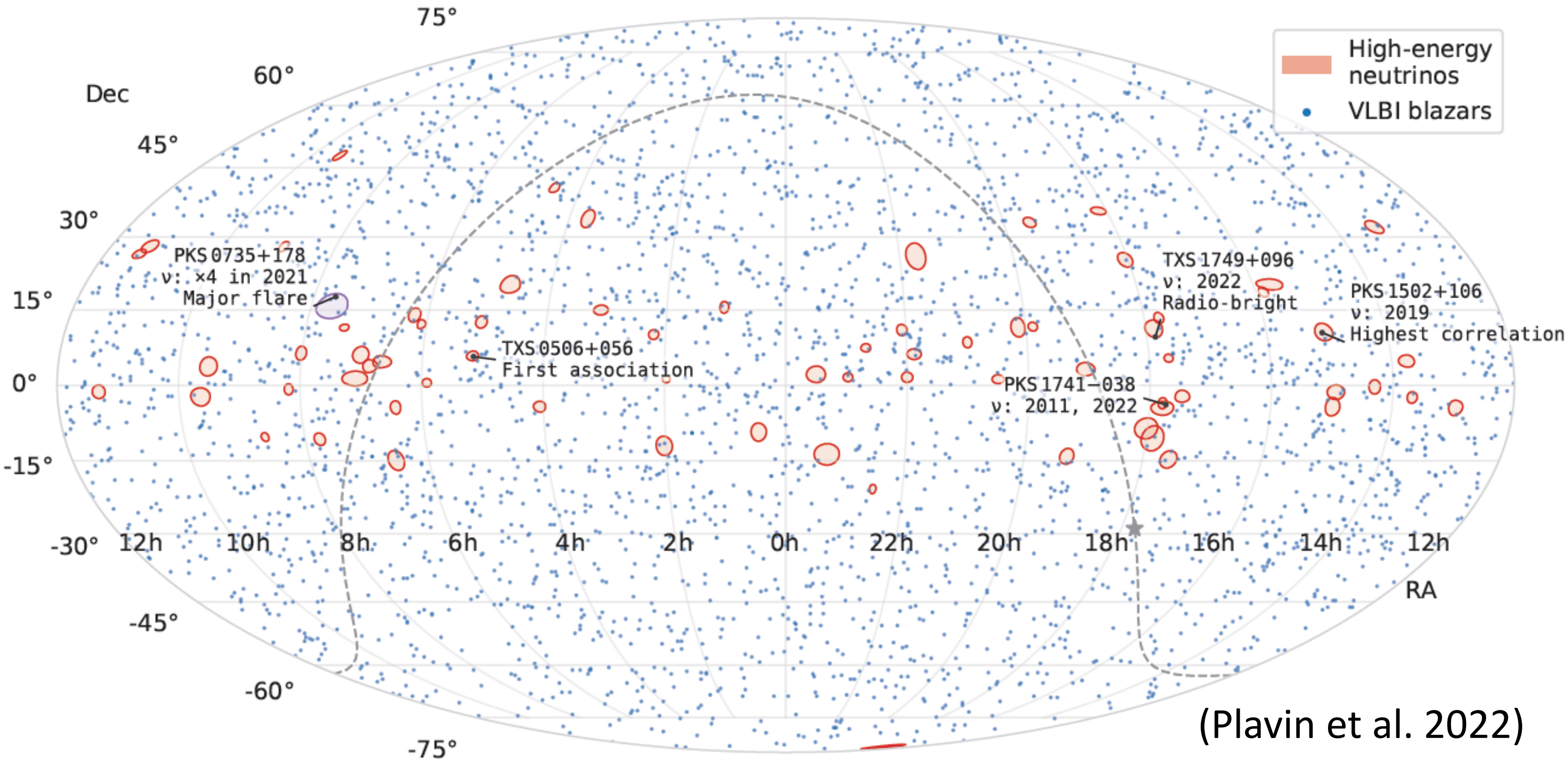
Origin of IceCube-Detected Neutrinos



(Buson et al. 2022)

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

Origin of IceCube-Detected Neutrinos

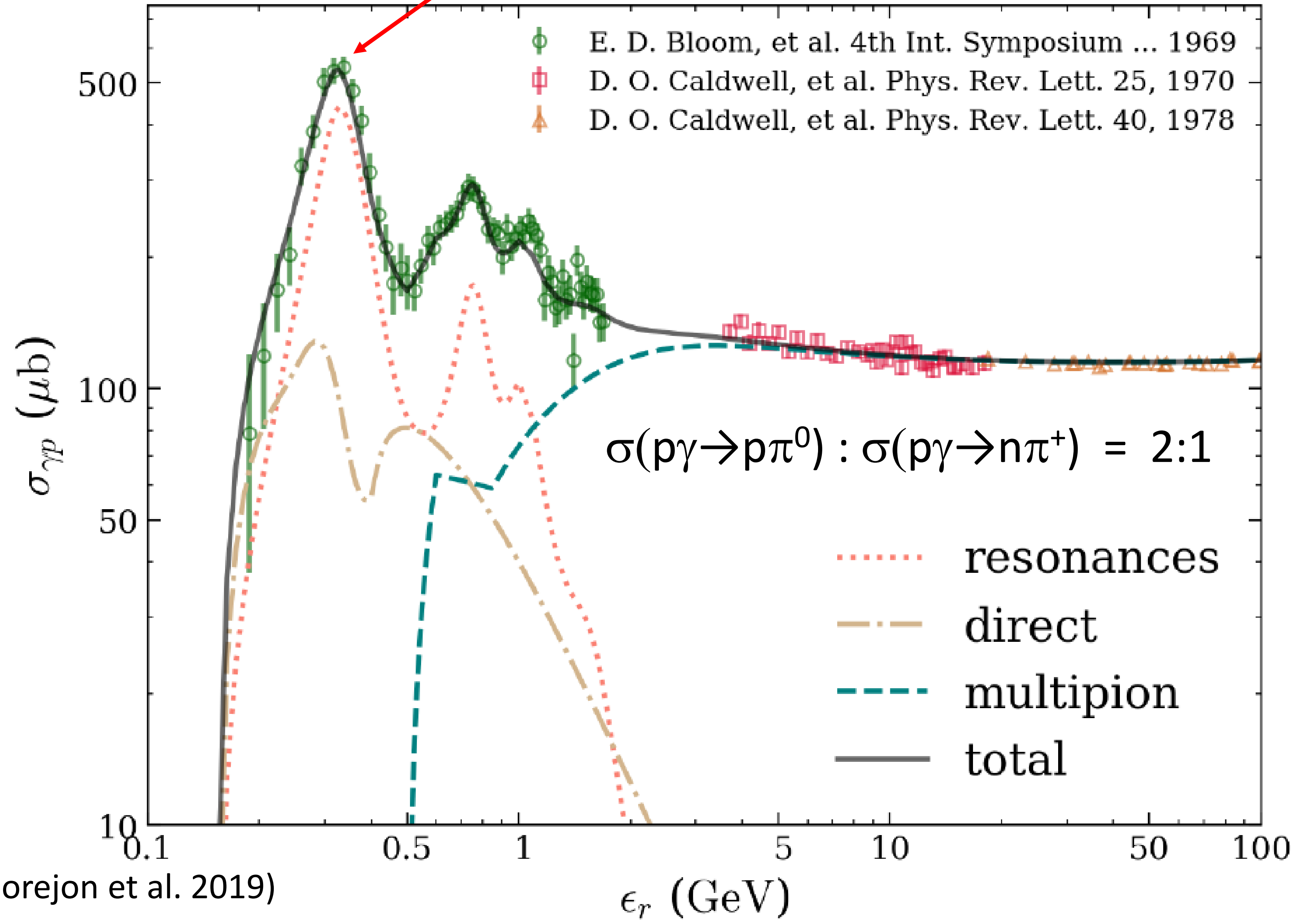


(Plavin et al. 2022)

Also: Correlation with radio-loud blazars
(chance-coincidence probability of $p = 3 \cdot 10^{-4}$)
(Plavin et al. 2020, 2021, 2022)

Photo-Pion Production Cross Section

Δ^+ resonance (1232 MeV)

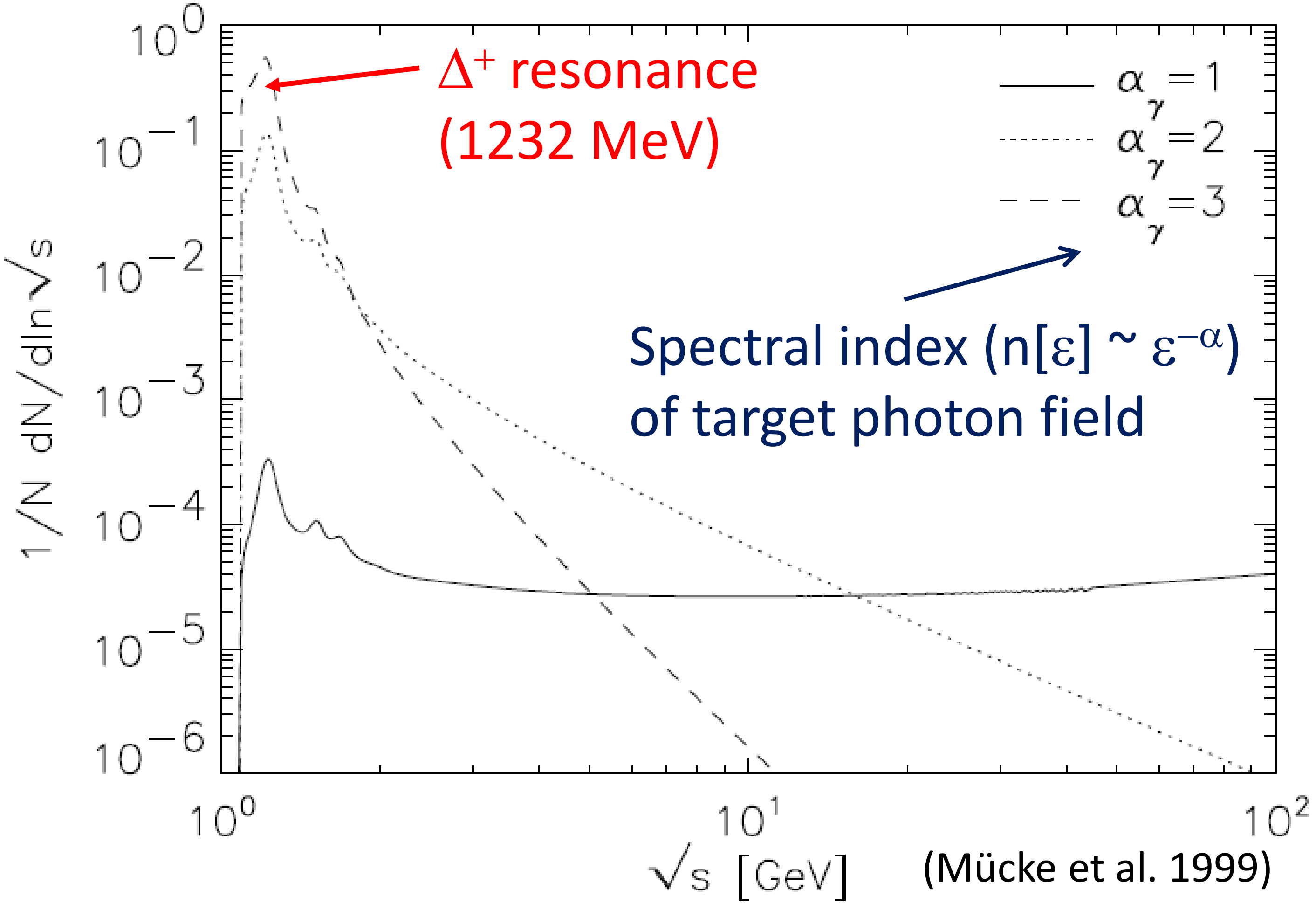


$\sigma(p\gamma \rightarrow p\pi^0) : \sigma(p\gamma \rightarrow n\pi^+) = 2:1$

(Morejon et al. 2019)

Photo-Pion Production

Interaction Probability



Δ^+ resonance
(1232 MeV)

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).

Photo-pion production - Energetics

At Δ^+ resonance:

$$s = E_p' E_t' (1 - \beta_p' \chi) = E_{\Delta^+}^2 = (1232\ \mathrm{MeV})^2$$

Each neutrino takes about ~ 5 % of the proton's energy

$\Rightarrow$ 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

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

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 => 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 Doppler-boosted hard X-rays

Tightly constrained by observed hard X-ray flux -> Energetics constraints.

b) Target photons stationary in the AGN frame

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

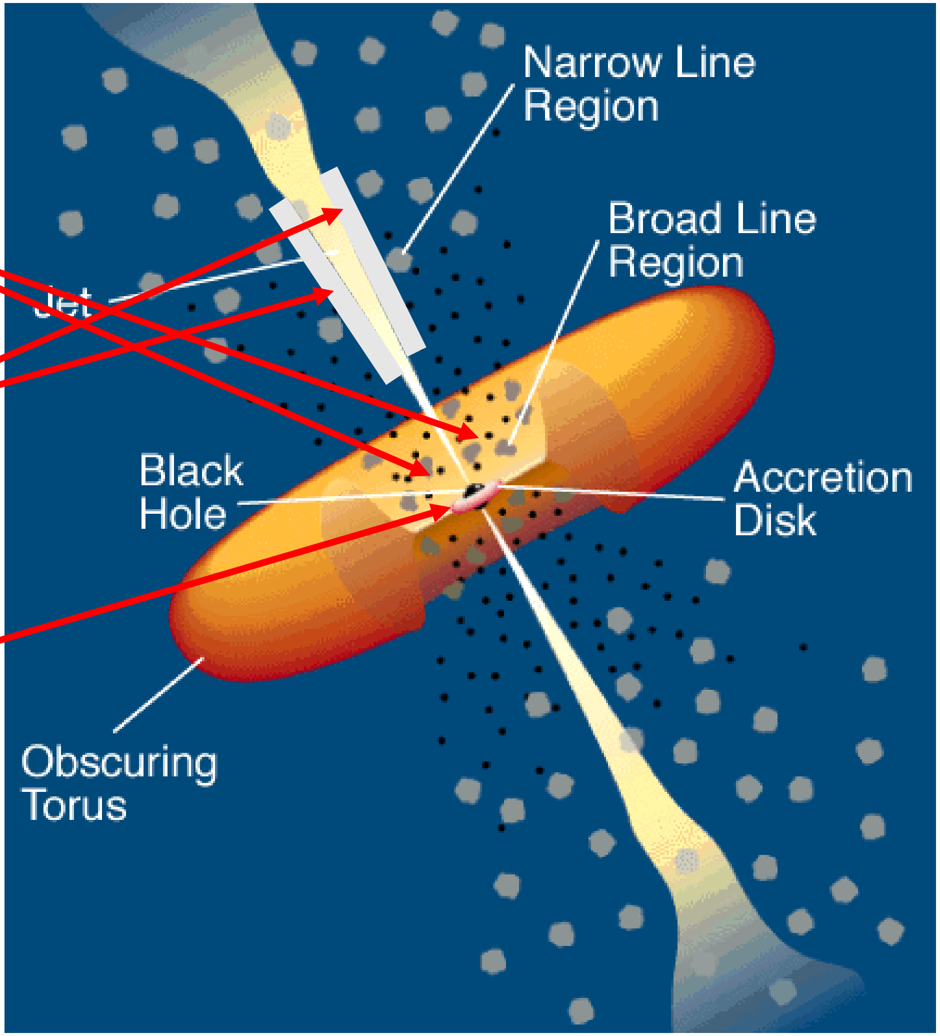
⇒ Observed as UV / soft X-rays, Doppler boosted into the emission-region frame

Much more relaxed energetics constraints.

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)



Neutrino production on external target photon fields

- Assume target photon field isotropic in the AGN rest frame.
- Highly anisotropic in the co-moving (blob) frame.
- Assume pγ interactions only at the Δ^+ resonance:

$E_t E_p (1 - \beta_p \chi) = E_\Delta^2$ with χ = cosine of interaction angle

=> In blob frame:

$E_p \approx 20\, E_\nu$; $E_t \approx E_\Delta^2 / (20\, E_\nu [1 - \beta_p \chi])$

- Hugely dominant proton momentum => $\widehat{\Omega}_{proton} = \widehat{\Omega}_{neutrino}$
- Efficient head-on collisions for neutrino production along the jet axis.
- Expect significantly stronger Doppler boosting and beaming than for co-moving target photon field (see Dermer 1995 for similar effect on external-Compton scattering)

Evaluation of neutrino beaming patterns (I)

- Relevant quantity: Neutrino number flux:

$$\Phi_\nu\left(\Omega_{obs}\right) = \int_{E_{\nu,1obs}}^{E_{\nu,2obs}} \Phi_{\nu,E^{obs}}\, dE_\nu^{obs} = \frac{\delta^3\,(1+z)}{4\pi\, d_L^{\,2}}\, V_b \int_{E_{\nu,1}}^{E_{\nu,2}} \dot{n}_{E_\nu}\,(\Omega) dE_\nu$$

with $\mu = \frac{\mu_{obs} - \beta_\Gamma}{1 - \mu_{obs}\beta_\Gamma}$ and $E_\nu^{obs} = \delta\, E_\nu$.

$$\dot{n}_{E_\nu}\,(\Omega) \;\propto\; \int_{-1}^{1} d\mu_t \int_0^{2\pi} d\varphi_t\, n_t(E_t, \Omega_t)\, n_p(E_p)(1 - \beta_p\chi)$$

with $\chi = \widehat{\Omega}_t \cdot \widehat{\Omega}_p = \widehat{\Omega}_t \cdot \widehat{\Omega}_\nu$

Evaluation of neutrino beaming patterns (II)

Assume simple power-law proton and photon spectra:

$n_p(E_p) \propto E_p{}^{-p}$ and $n_t(E_t) \propto E_t{}^{-\alpha}$

Photon field isotropic in co-moving frame (internal)

$$n_t(E_t, \Omega_t) = \frac{n_t(E_t)}{4\pi}$$

Photon field isotropic in AGN frame (external)

$$n_t(E_t, \Omega_t) = \frac{n_t{}^*(E_t{}^*)}{4\pi\, \delta_*{}^2}$$

with $\delta_* = \Gamma\,(1 + \beta_\Gamma \mu_t)$

Results shown for full numerical angle integration.

Analytical approximations to beaming patterns

Internal target photon field

Set $\beta_p = 1, \chi = -1$

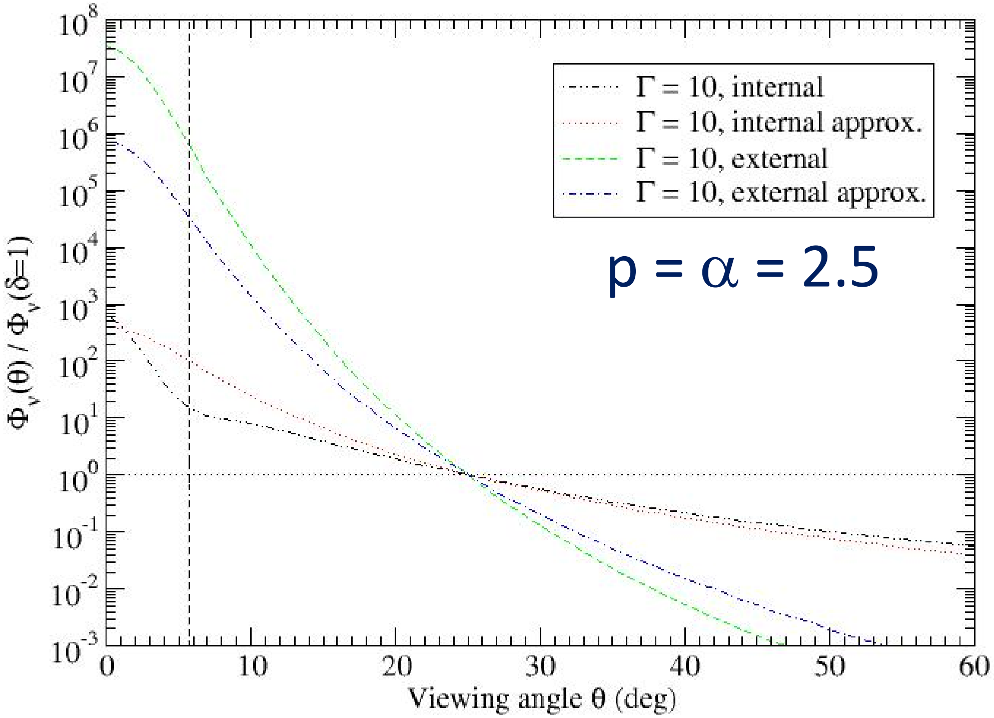
=> $\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p-\alpha}$

External target photon field

Set $\beta_p = 1, \mu_t = -1$

=> $\chi = -\mu$

=> $\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p}\,(1+\mu_{obs})^\alpha$



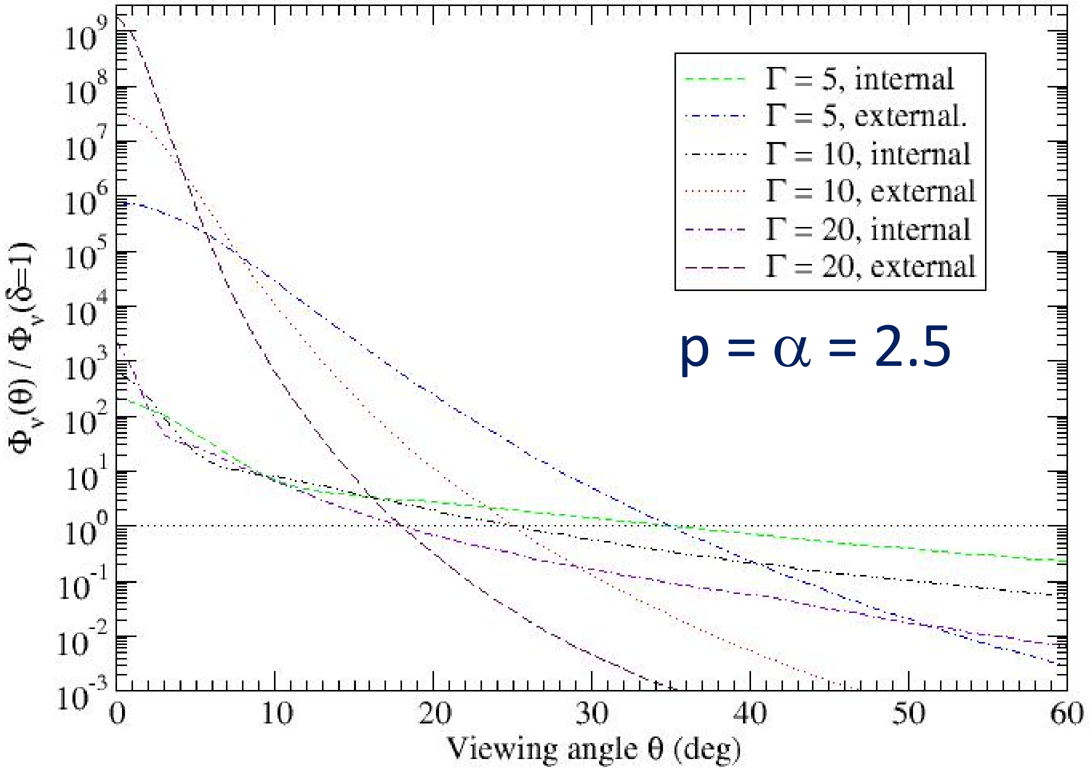
Dependence of beaming patterns on Lorentz factor

Internal target photon field

$$\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p-\alpha}$$

External target photon field

$$\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p}\,(1+\mu_{obs})^{\alpha}$$



p = α = 2.5

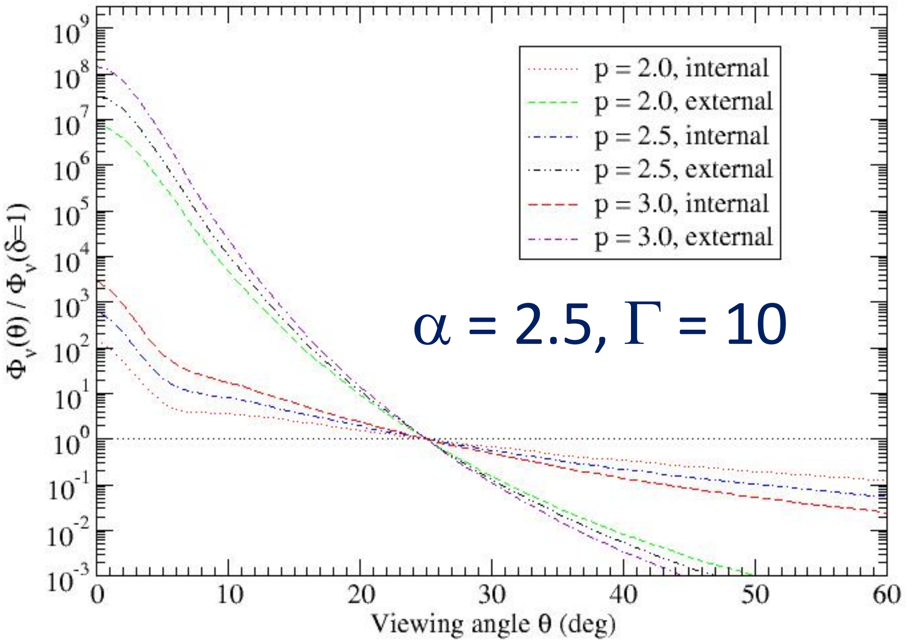
Dependence of beaming patterns on spectral indices

Internal target photon field

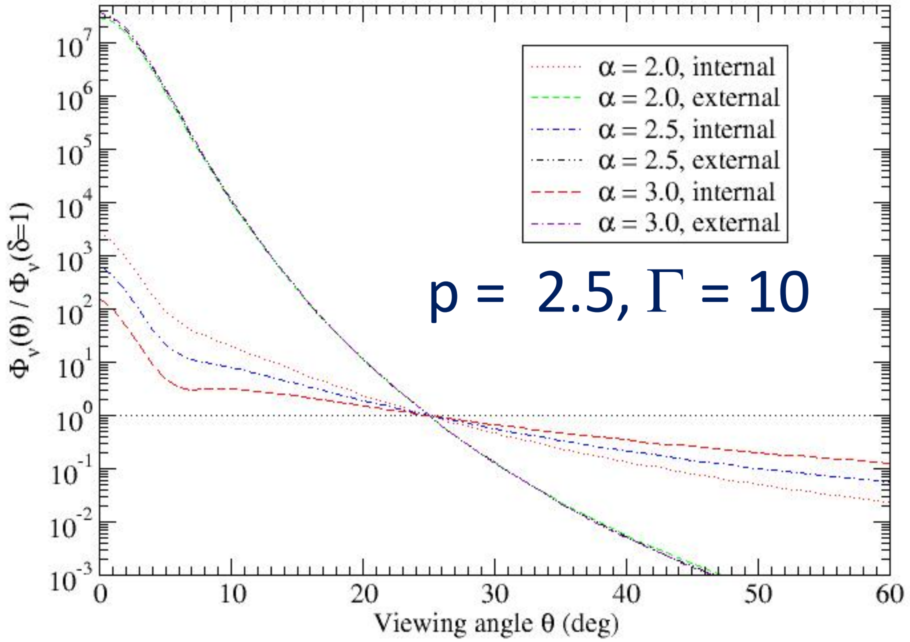
$$\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p-\alpha}$$

External target photon field

$$\Phi_\nu\,(\Omega_{obs}) \propto \delta^{\,2+p}\,(1+\mu_{obs})^{\alpha}$$



α = 2.5, Γ = 10



p = 2.5, Γ = 10

Summary

- Production of IceCube neutrinos in blazar jets requires target photons of co-moving UV / X-ray energies, most plausibly from outside the jet
- Doppler boosting and beaming of neutrino production on external target photon fields are much narrower and stronger than for co-moving isotropic target fields.
- Look for the most closely aligned blazars as most promising neutrino blazars.
- Neglecting detailed beaming patterns might under-estimate the neutrino flux by huge factors (~ 10^6 for $\Gamma = 20$) and, conversely, over-estimate power requirements.

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Thank you!