Extragalactic (VHE) Gamma-Ray Sources and Hadronic Models

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Extragalactic VHE Gamma-Ray Sources

- Blazars
  - Most numerous source class, promising neutrino sources → Focus of this talk

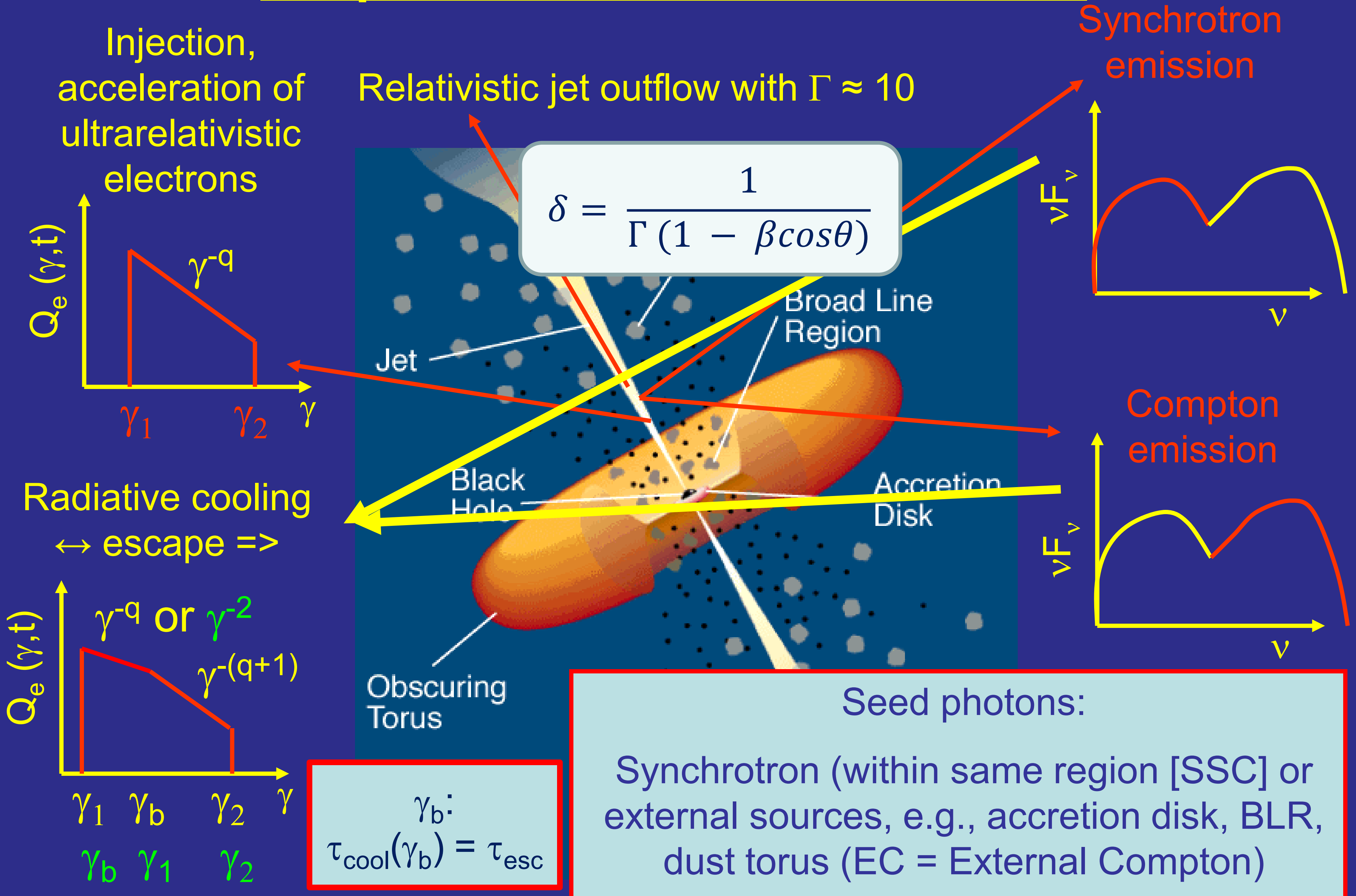
- Radio galaxies
  - 6 detected; probably same physics as blazars → Not covered separately.

- Gamma-ray bursts
  - 5 detected so far (incl. the BOAT, GRB 221009A); no coincidences with neutrino events so far → No compelling evidence of prominent hadronic interactions.

- Starburst galaxies
  - 2 detected (M82, NGC 253). Most likely hadronic cosmic-ray interactions. Not covered here due to lack of time.

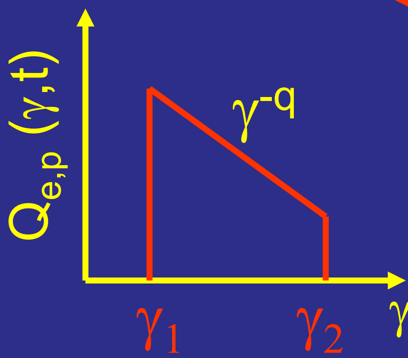
- Low-Luminosity AGN (LLAGN)
  - Only NGC 4278 → Giulia Migliori's talk Monday

Leptonic Blazar Model



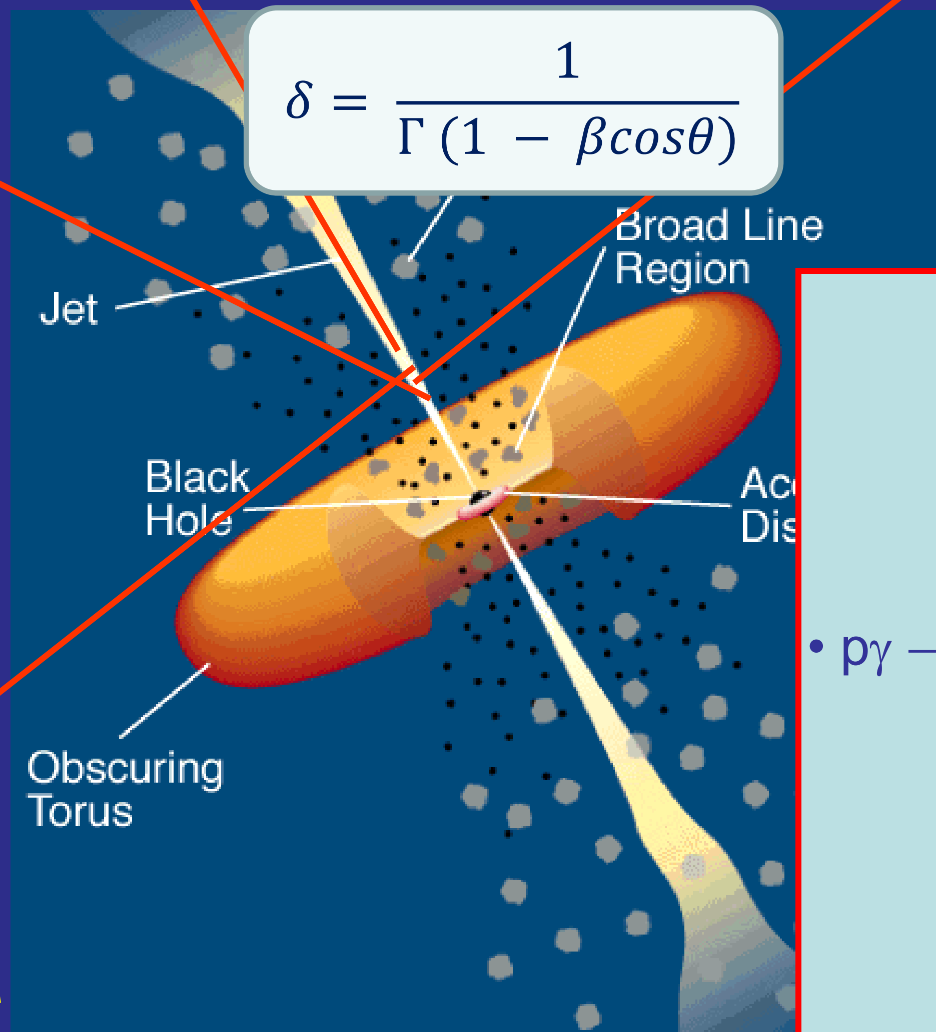
Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

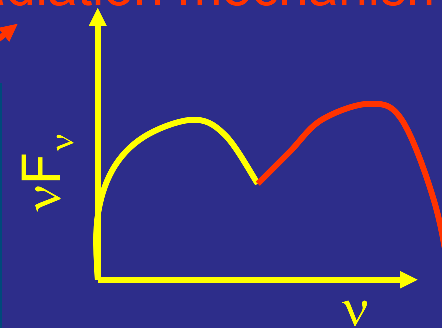


Relativistic jet outflow with $\Gamma \approx 10$

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

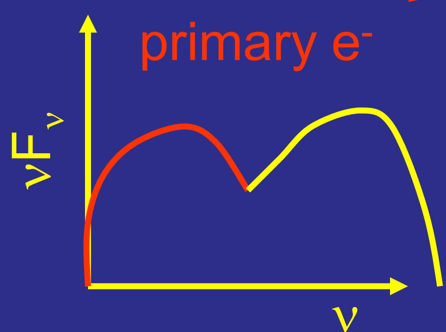


Proton-induced radiation mechanisms



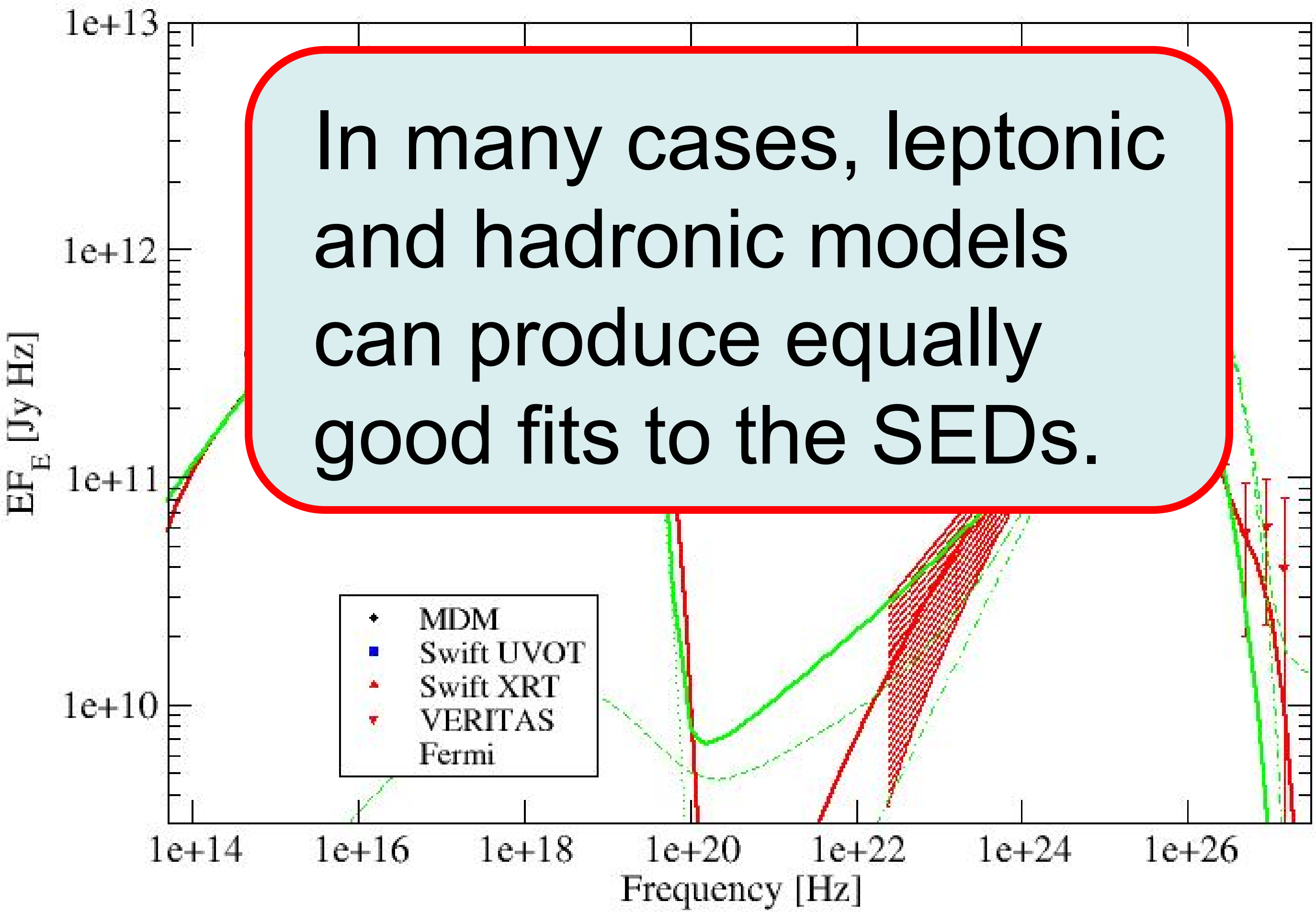
- Proton synchrotron
- $p\gamma \rightarrow p\pi^0$
  $\pi^0 \rightarrow 2\gamma$
- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$
  $\rightarrow$ secondary μ-, e-synchrotron
- Cascades …

Synchrotron emission of primary e^-



Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)

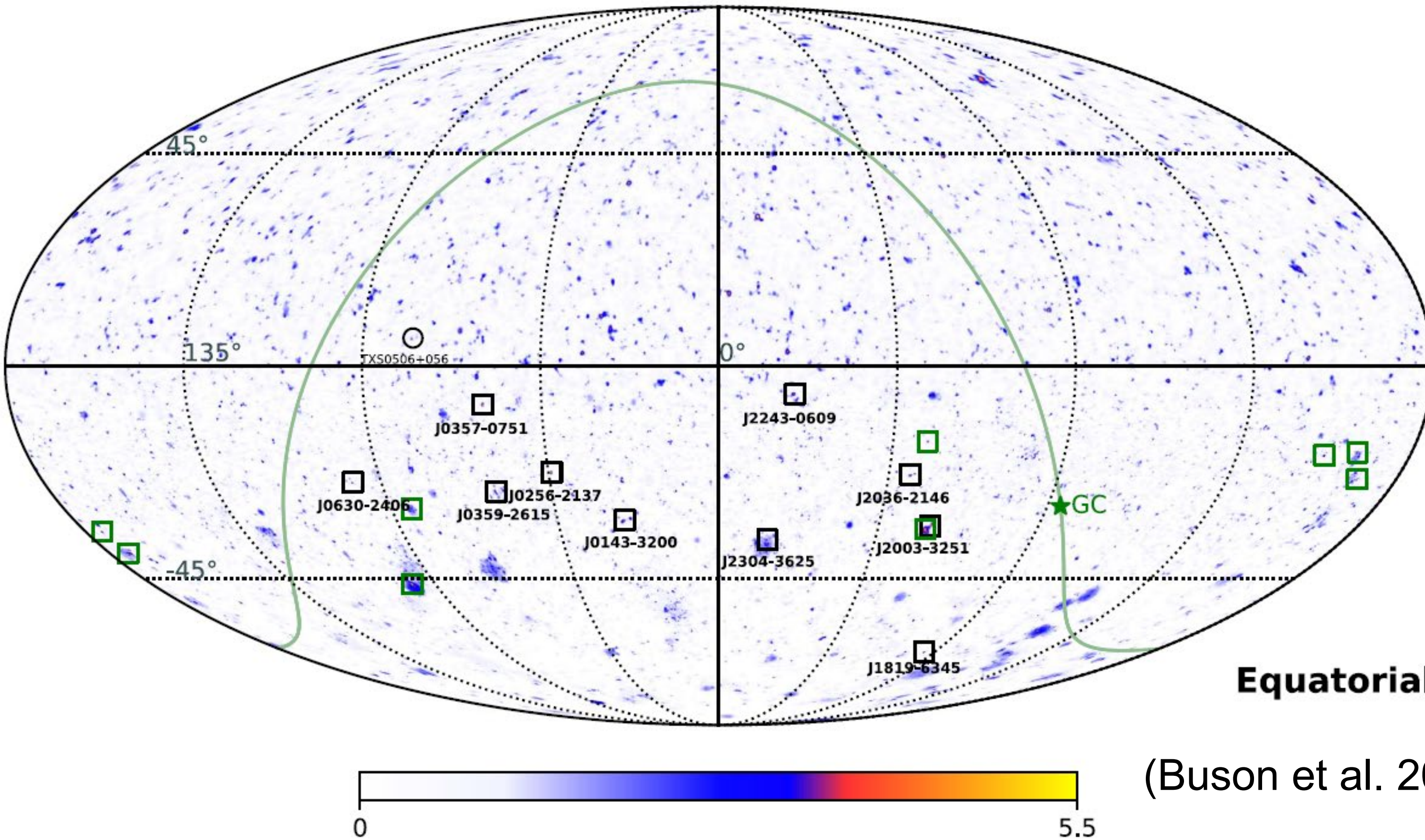


In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.

Possible Diagnostics to distinguish:

- Neutrinos
- Polarization
- Variability

Origin of IceCube-Detected Neutrinos

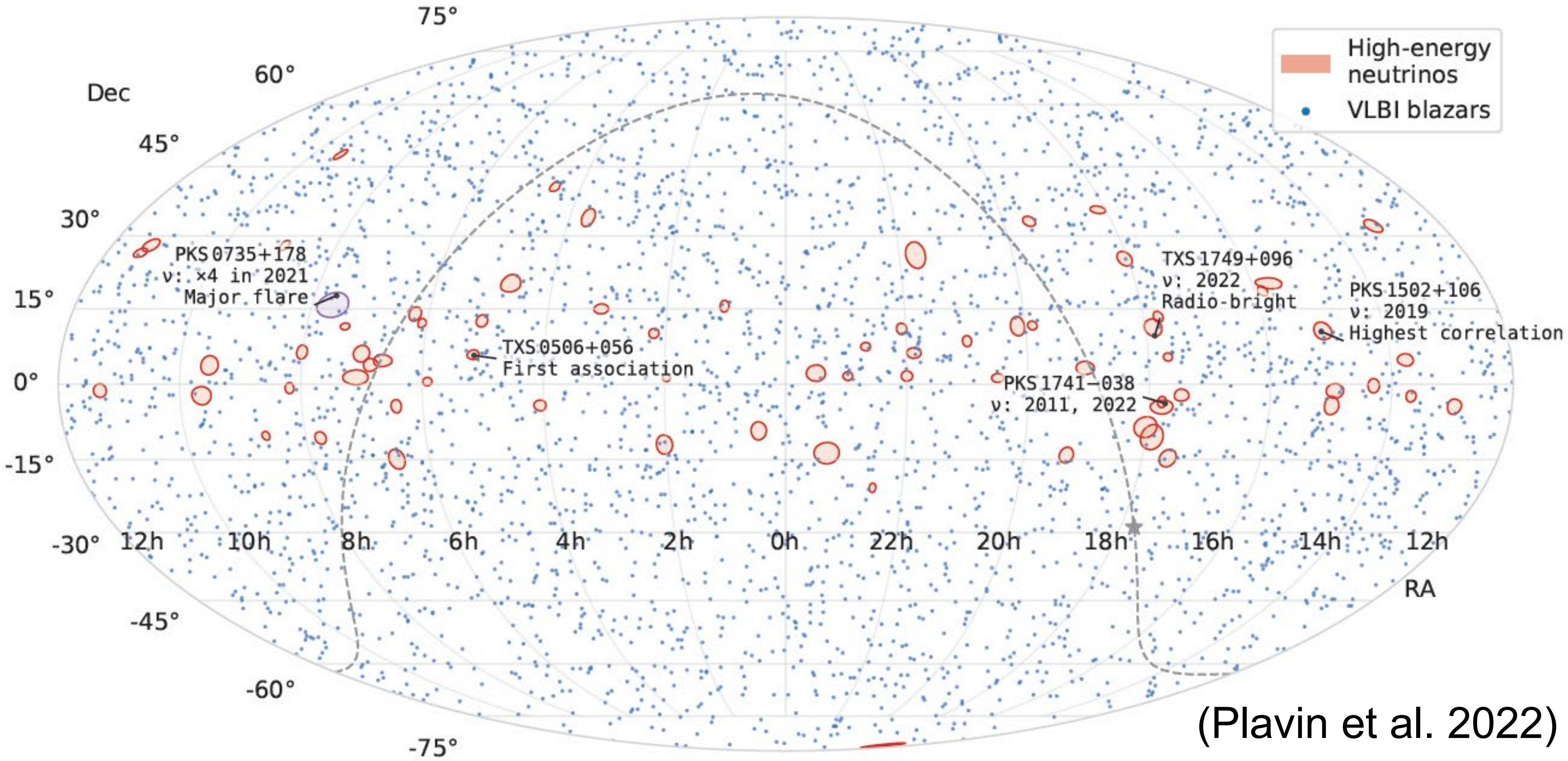


(Buson et al. 2022)

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)

Basic ingredients of hadronic jet multi-messenger emission models

- Particle acceleration/injection (usually modelled as instantaneous injection; 2nd-order [stochastic] acceleration included in some models/codes)
- Particle interaction / radiation modules (synchrotron, SSC, EC standard, but differences in pγ interactions and cascades)
- Secondary particle (pions, muons, neutronos, electron-positron pair) production (MC vs. semi-analytical templates)
- Radiative transport (emission / absorption / scattering) (geometry-dependent in multi-zone / extended jet models; polarization?)
- Evolution of particle distributions (re-acceleration / cooling / escape) (usually through solutions to Fokker-Planck equations)

Basics of Neutrino Production

- $p + p\ (N) \rightarrow p + p/n + n_0\pi^0 + n_+\pi^+ + n_-\pi^-$ ($\sigma_{pp} \sim 0.1$ mb)
- $p + \gamma \rightarrow p + \pi^0$ (2/3) ($\sigma_{p\gamma} \sim 0.6$ mb)
  or $n + \pi^+$ (1/3)

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

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

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

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

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

Neutrino Production in AGN Jets

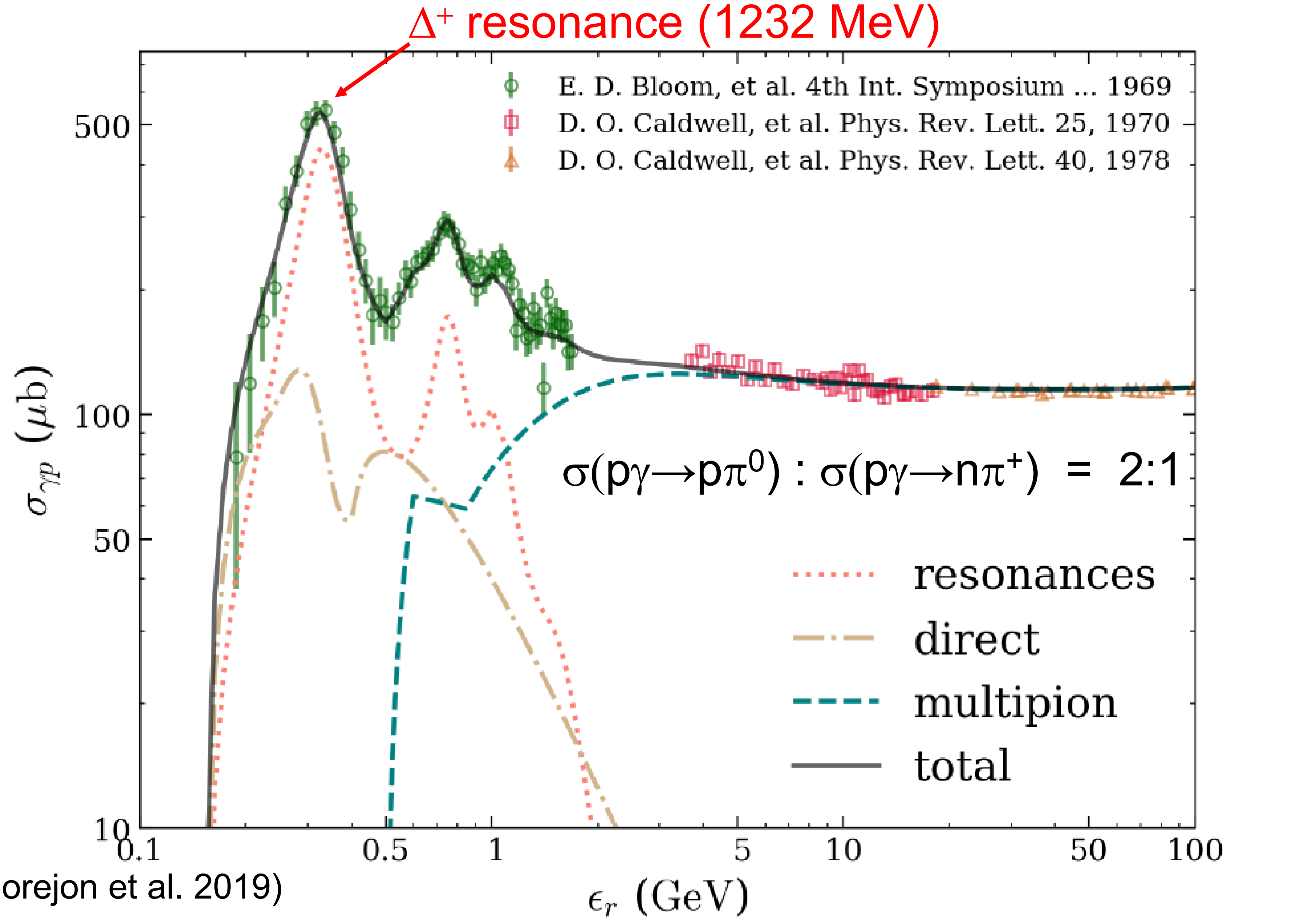
$$n_{ph} \sim \frac{L_{sy}}{\delta^4 < \varepsilon > m_e c^2 4\pi R^2 c} \sim 3 \times 10^{18} \varepsilon_{-6}^{-1} R_{16}^{-2} L_{sy,44} \delta_1^{-4} cm^{-3}$$

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

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

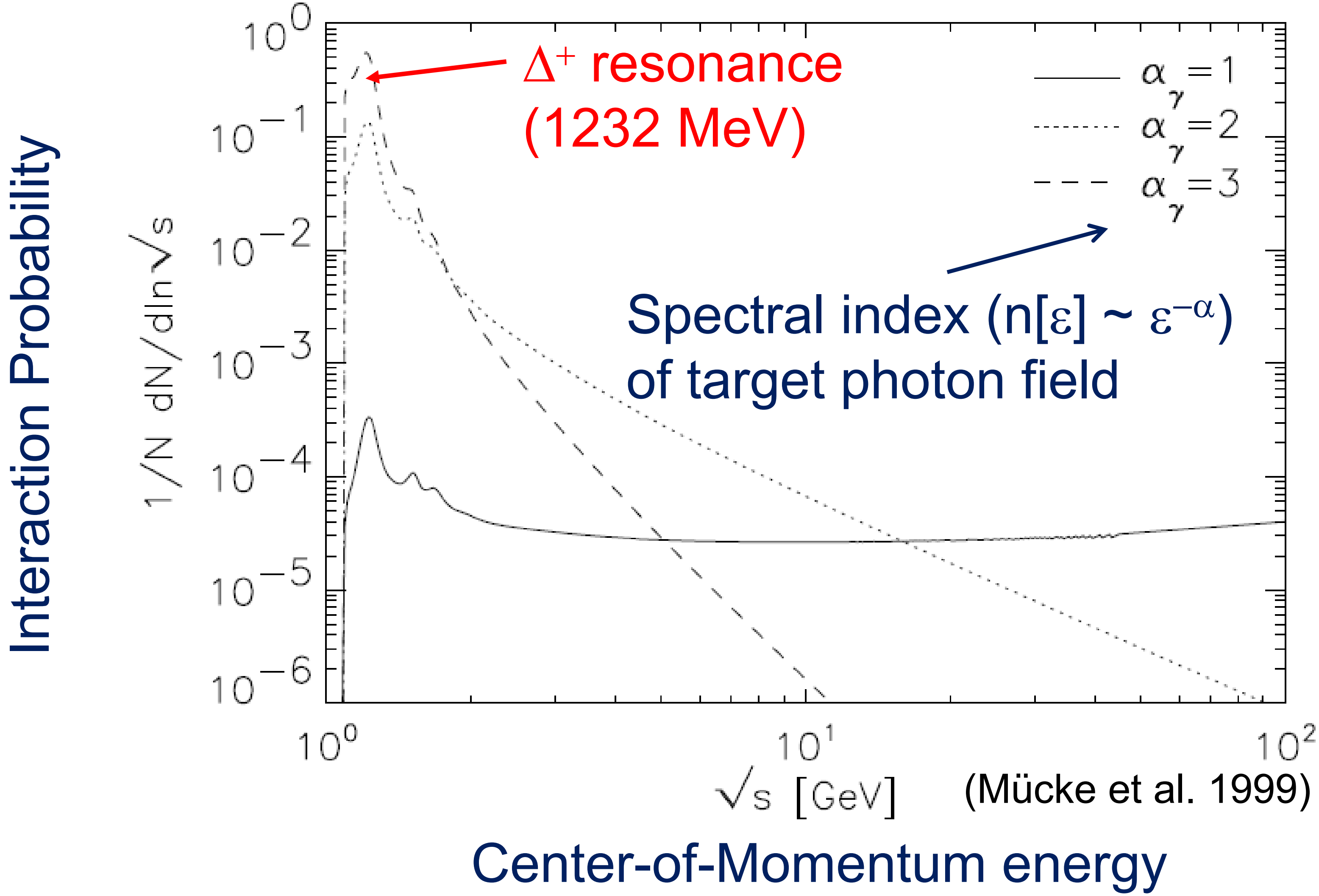
$$\frac{t_{pp}}{t_{p\gamma}} \sim \frac{n_{ph}}{n_p} \sim 3 \times 10^{14} \frac{\Gamma_1^2 L_{sy,44}}{\varepsilon_{-6} \delta_1^4 L_{j,46}}$$

Photo-Pion Production Cross Section



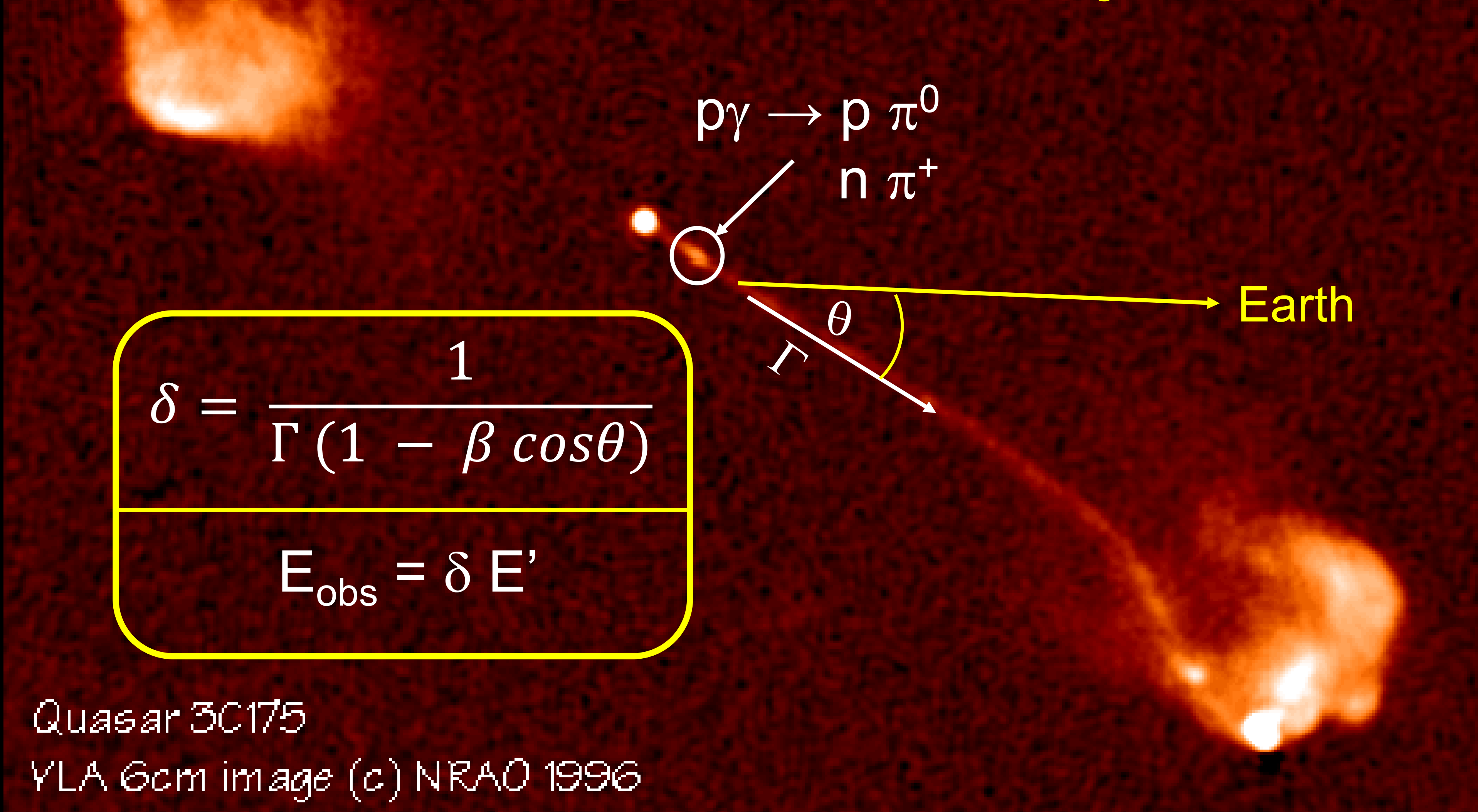
(Morejon et al. 2019)

Photo-Pion Production



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

Phohto-pion induced neutrino production in relativistic jets



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

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

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:

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

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

⇒ 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

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

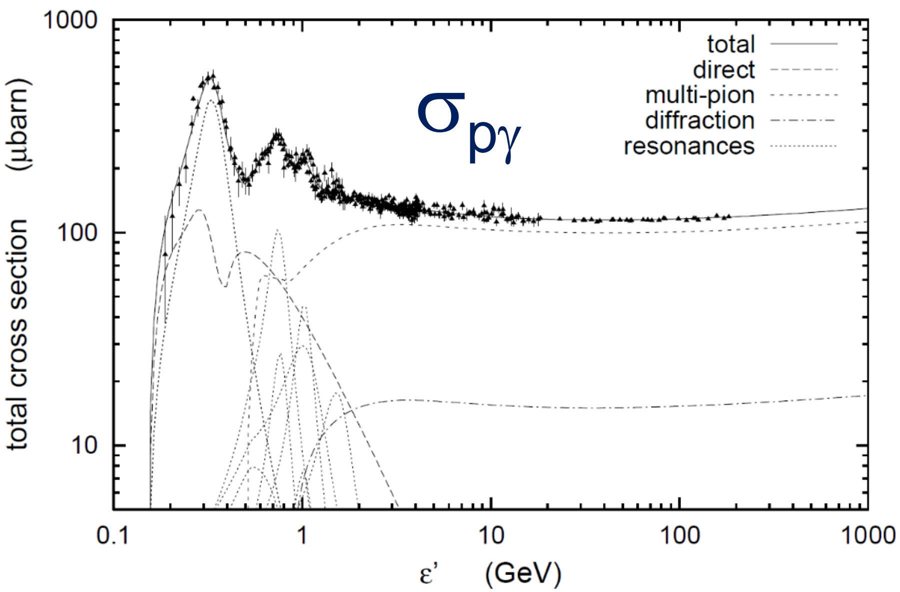
⇒ $E_t^{obs} \sim 160\,E_{14}^{-1}/(1+z)$ eV

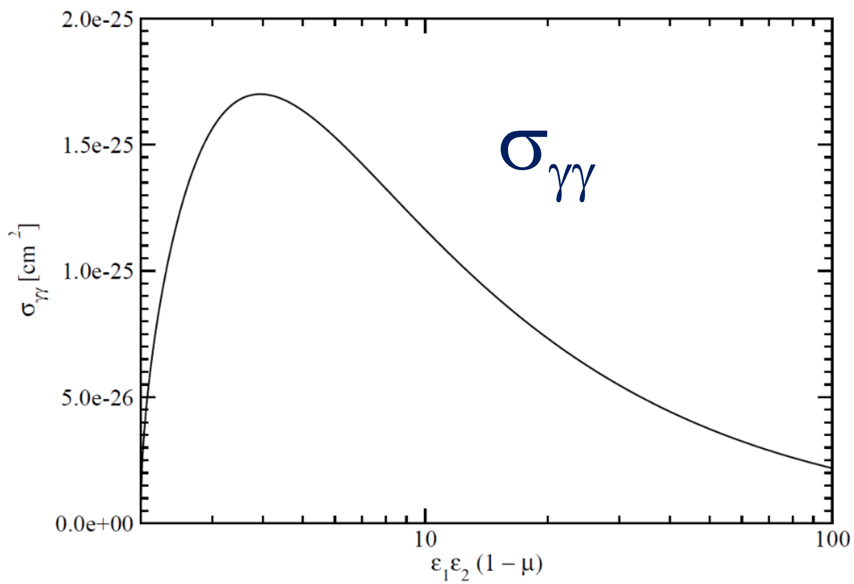
⇒ Observed as UV / soft X-rays, Doppler boosted into the emission-region frame

Much more relaxed energetics constraints.

The pγ Efficiency Problem

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





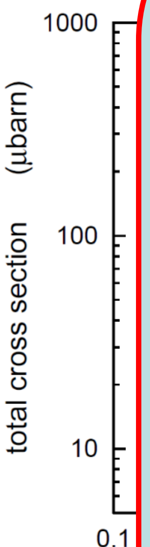
$$\frac{\tau_{p\gamma}}{\tau_{\gamma\gamma}} = \frac{\sigma_{p\gamma}\,\ell_{esc}}{\sigma_{\gamma\gamma}\,R} \approx \frac{1}{300}\,\frac{\ell_{esc}}{R}$$

ℓ_{esc} = average length travelled by protons until escape

at $E_\gamma \sim \frac{m_e^2 c^4}{E_t} \sim 3.3 \times 10^{-5} E_\nu$ ← ~ few to tens of GeV γ-rays

The pγ Efficiency Problem

- Efficiency for protons to undergo pγ interaction ~ $\tau_{p\gamma} = \ell_{esc}\, \sigma_{p\gamma}\, n_{ph}$
- Likel



⇒ Efficient neutrino production sites are likely to be optically thick to gamma-rays

⇒ Expect no correlation between GeV – TeV gamma-ray and neutrino activity!

⇒ Cascades! → Expect correlation with X-ray / soft (MeV) γ-ray and possibly multi-TeV gamma-ray activity!

⇒ Promising targets for ASTRI / SSTs

gth

ons

until escape

at $E_\gamma \sim \frac{m_e^2 c^4}{E_t} \sim 3.3 \times 10^{-5} E_\nu$ ⟵ ~ few to tens of GeV γ-rays

Modeling Multi-messenger Emissions from photo-pion production

- Most accurate method: Monte-Carlo simulations of individual reactions (e.g., SOPHIA: Mücke et al. 2000: Comp. Phys. Comm., 124, 290)

- 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: $\pi^+ \rightarrow Q_\mu(E_\mu)$
$\pi^0 \rightarrow Q_\gamma(E_\gamma)$

(e.g., Diltz et al. 2016, Zacharias et al. 2019, 2021)

(Lepto-)Hadronic codes "on the market"

- AM^3 (Gao et al. 2017; Klinger et al. 2024)
- Atheνa (Mastichiadis & Kirk 1995; Mastichiadis et al. 2005; Dimitrakoudis et al. 2012; Petropoulou et al. 2014)
- B13 (Böttcher et al. 2013)
- LeHa-Paris (Cerruti et al. 2015)
- LeHaMoC (Stathopoulos et al. 2024)
- OneHaLe (Zacharias et al. 2019, 2021)

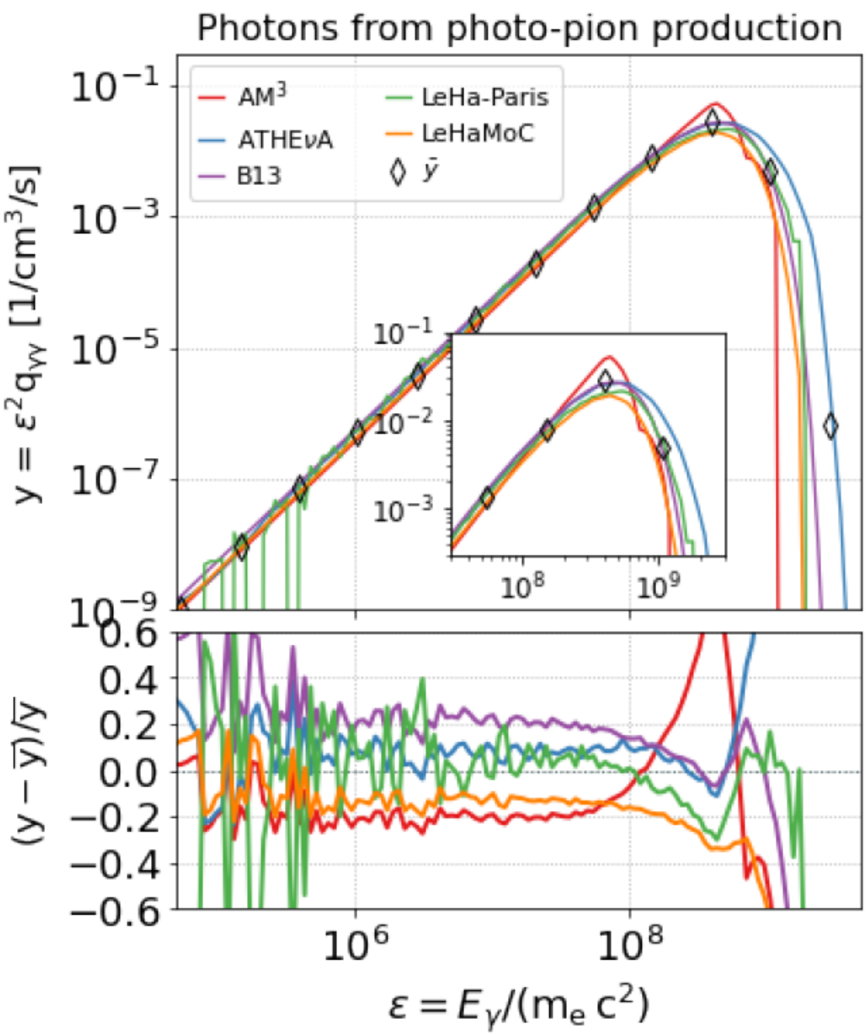
Table 1
Physical Processes Included in the Numerical Codes

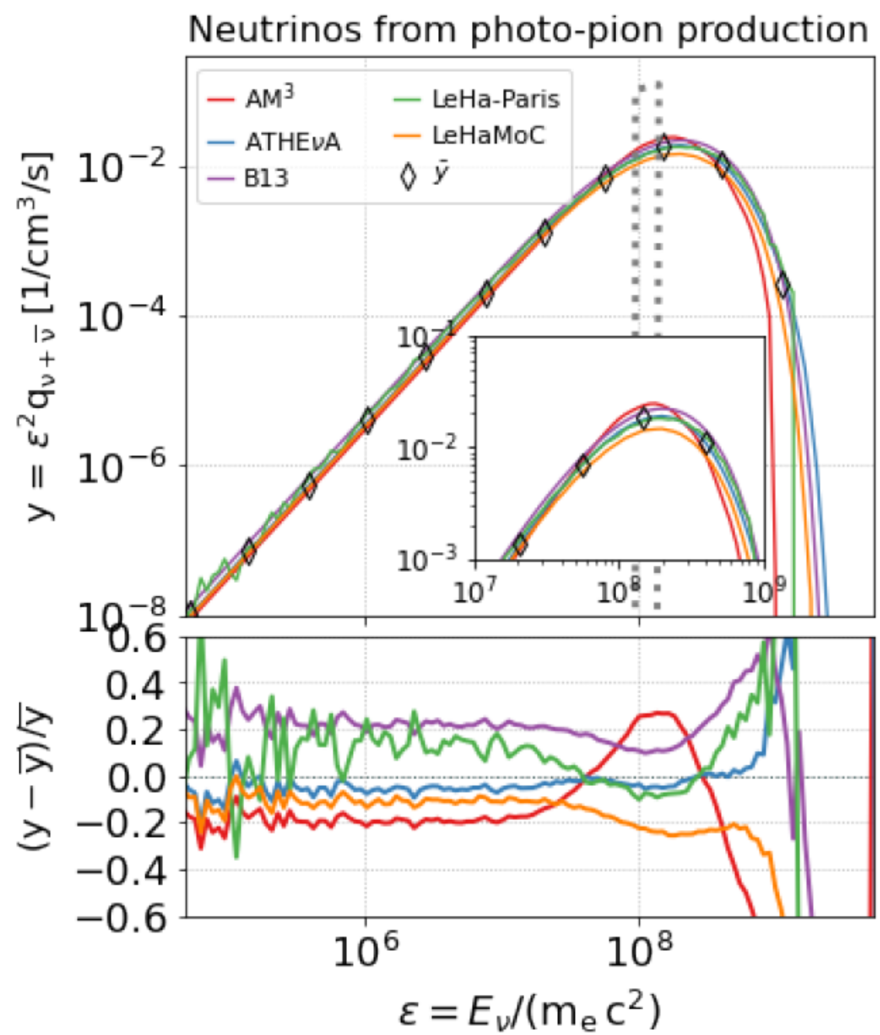
Physical Processes	Codes				
	AM^3	ATHEνA	B13	LeHa-Paris	LeHaMoC
Electron synchrotron radiation	✓	✓	✓	✓	✓
Synchrotron self-absorption	✓	✓	✓	✓	✓
Electron inverse Compton scattering	✓	✓	✓	✓	✓
Electron–positron annihilation	✗	✓	✓	✗	✗
Photon–photon pair production	✓	✓	✓	✓	✓
Triplet pair production	✗	✓	✗	✗	✗
Proton synchrotron radiation	✓	✓	✓	✓	✓
Proton inverse Compton scattering	✓	✗	✗	✗	✗
Proton–photon pair production	✓	✓	✗	✓	✓
Proton–photon pion production	✓	✓	✓	✓	✓
Proton–proton pion production	✗	✗	✗	✓	✓
Neutron–photon pion production	✓	✓	✗	✗	✗
Neutron decay	✗	✓	✗	✗	✗
Kaon synchrotron radiation	✗	✓	✗	✗	✗
Pion synchrotron radiation	✓	✓	✗	✗	✗
Muon synchrotron radiation	✓	✓	✗	✓	✗

(Cerruti et al. 2026: Hadronic code comparison project)

(Lepto-)Hadronic codes “on the market”

Various codes agree with each other to within a few %.

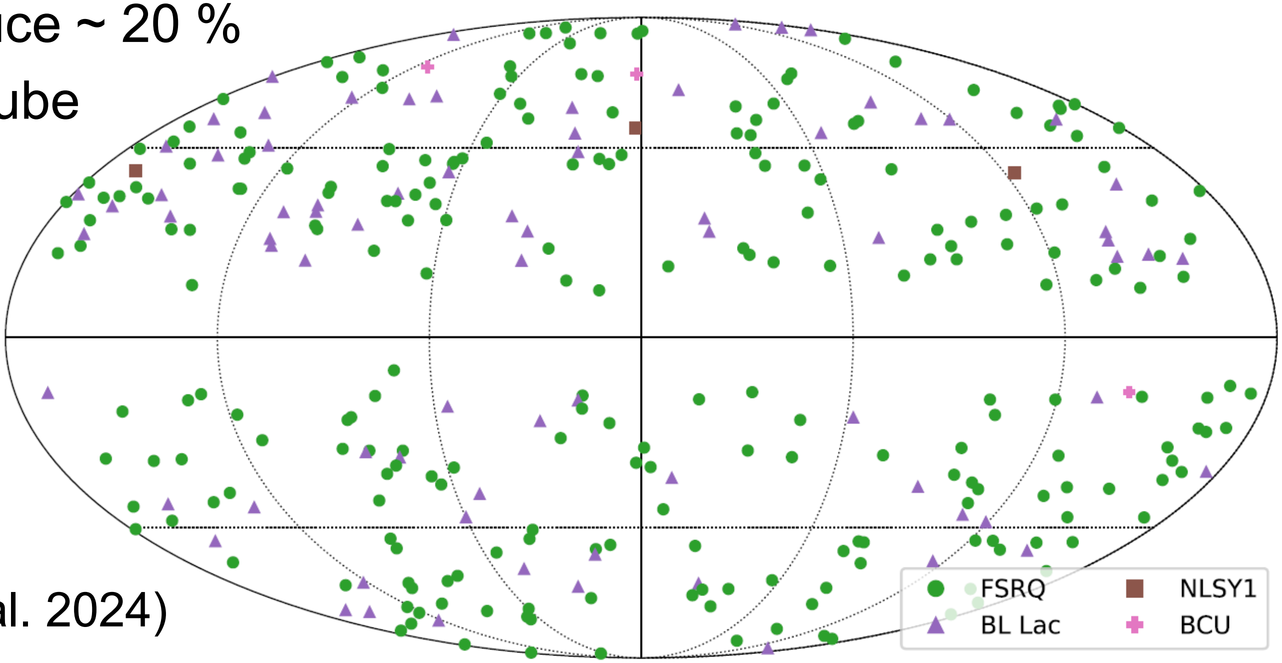




(Cerruti et al. 2026: Hadronic code comparison project)

Recent candidate neutrino blazar modelling results

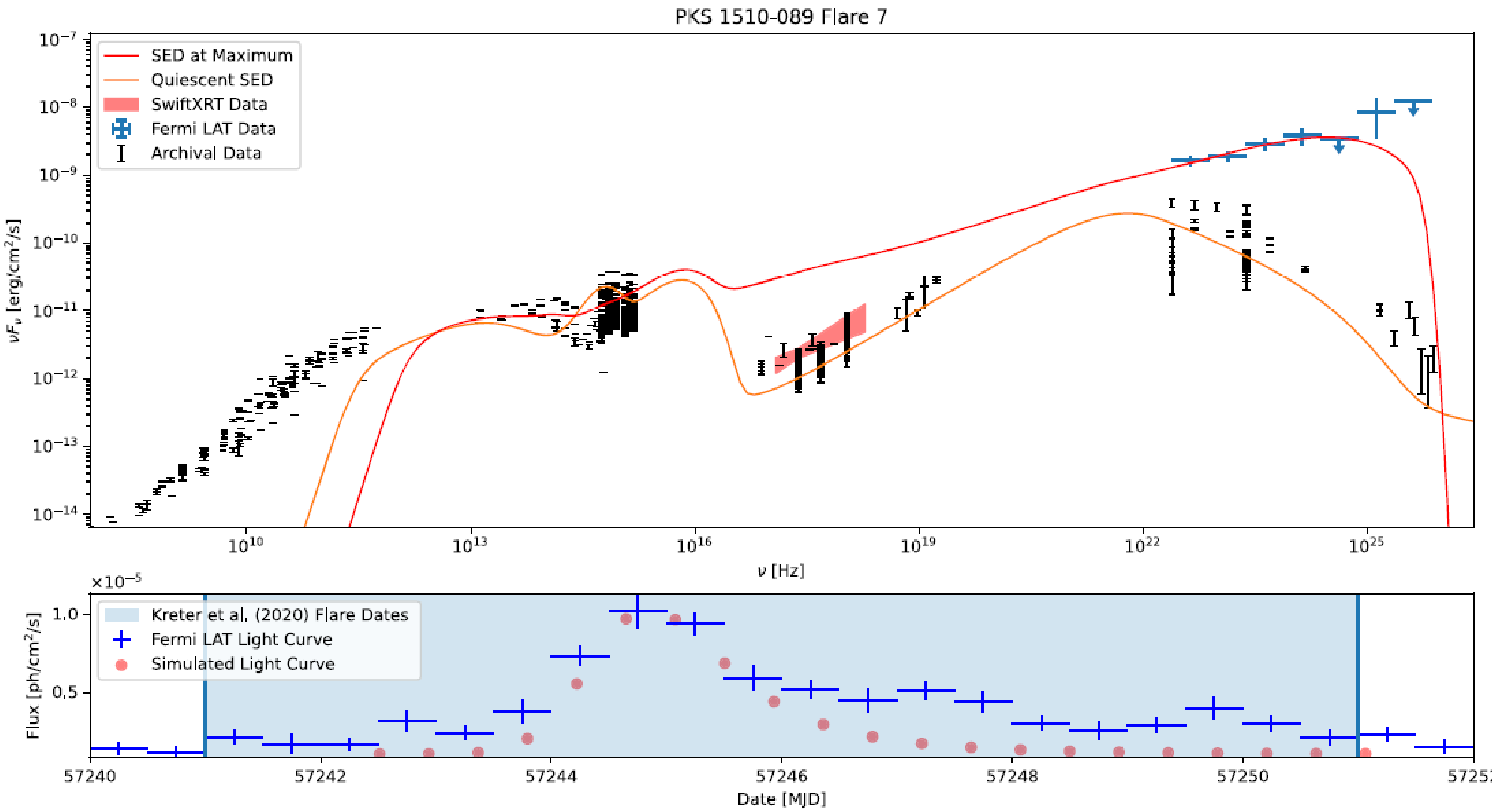
- Large body of publications on candidate neutrino blazar modelling using various codes.
- Arguably most comprehensive: Rodrigues et al. (2024): Systematic modelling (AM^3) of the SEDs of 324 bright blazars :
  - In most cases, leptonic-dominated models suffice;
  - only ~ 33 % benefit from an additional hadronic component.
- Blazars may produce ~ 20 % of the diffuse IceCube neutrino flux, in agreement with stacking limits.



(Rodrigues et al. 2024)

Neutrino detection potential from bright blazar flares

- Using OneHaLe for hadronically-dominated modelling of SEDs and light curves of the 20 brightest Fermi-LAT blazar flares studied by Kreter et al. (2020) with a simple calorimetric method (neutrino output proportional to bolometric high-energy flux).

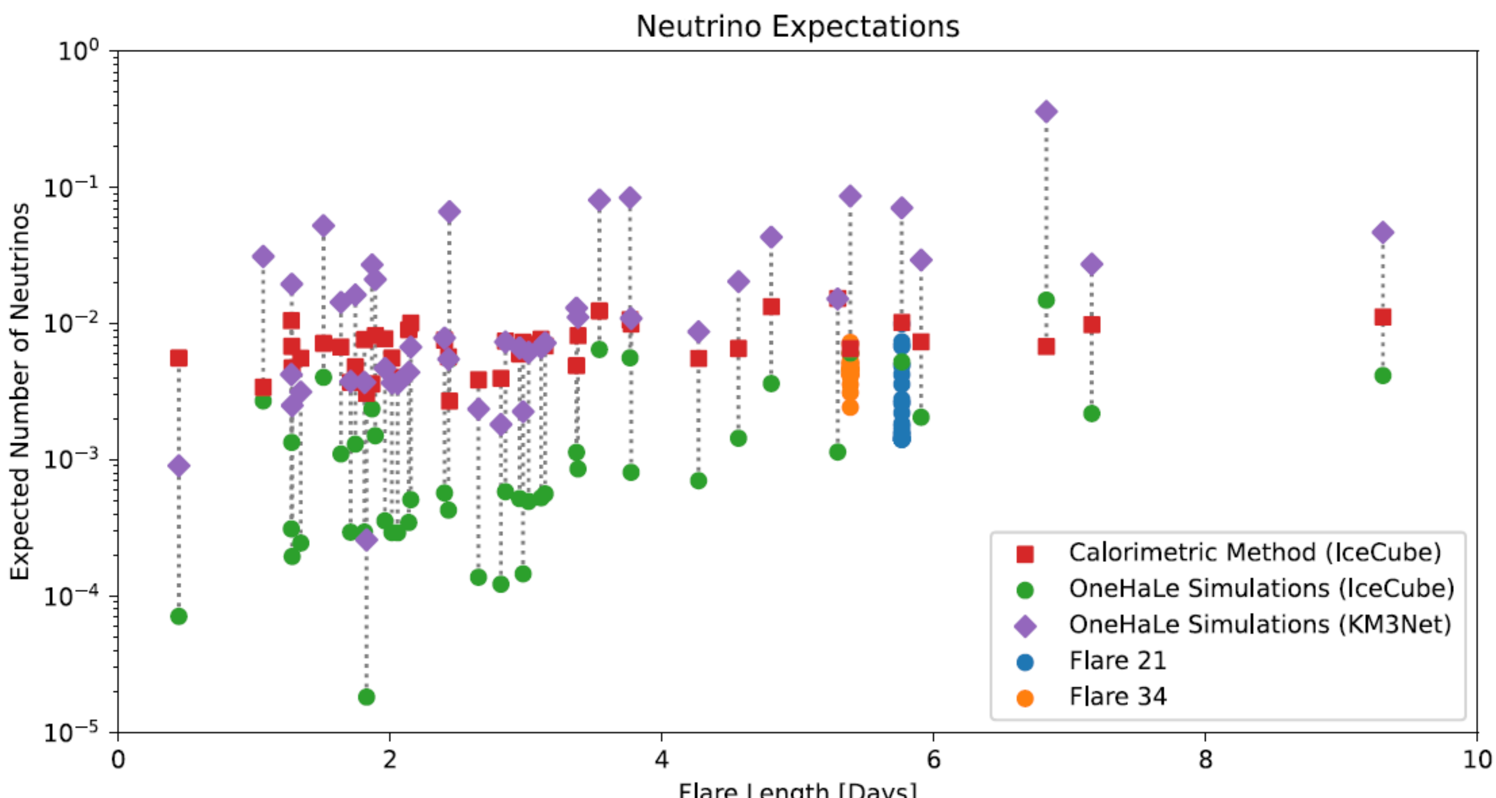


(Robinson & Böttcher 2024)

Neutrino detection potential from bright blazar flares

- Even the brightest blazar flares expected to yield < 0.1 neutrinos even for KM3NeT design configuration.

- Calorimetric approximation tends to over-estimate neutrino expectations by about an order of magnitude.



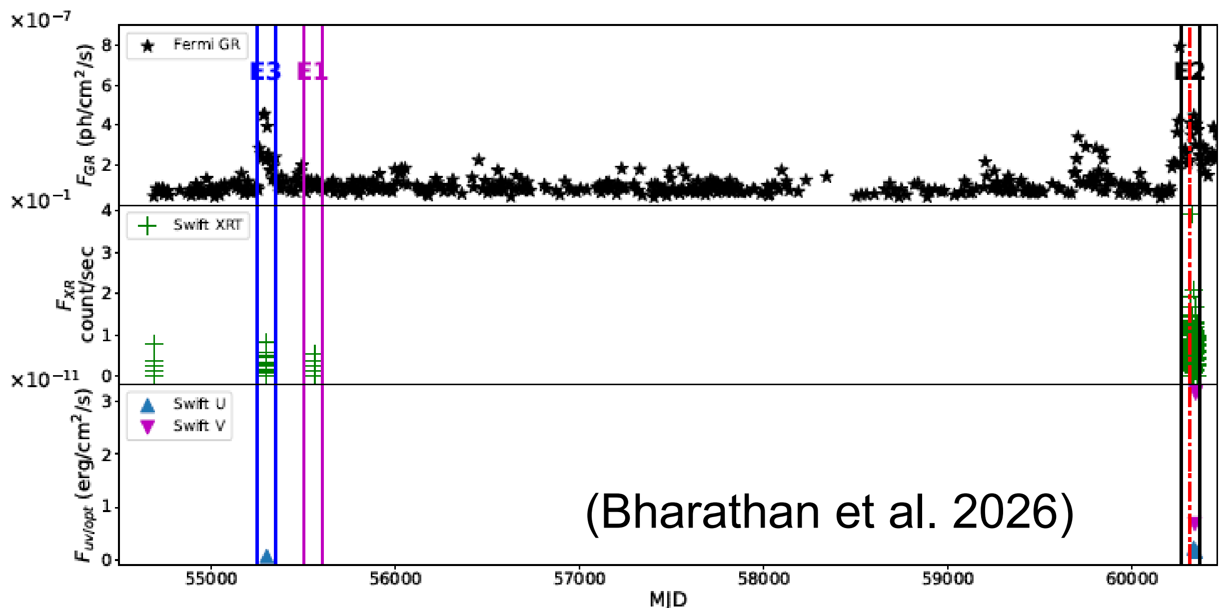
(Robinson & Böttcher 2024)

Dedicated SED modelling of 4 neutrino blazas

- Bharathan et al. (2026): Selected 4 recent blazar-neutrino coincidences with good broadband coverage:
  - PKS 0446+112 (z = 2.153; IC 240105)
  - TXS 0506+056 (z = 0.3365; IC170922A)
  - PKS 1424-418 (z = 1.522; IC 121204)
  - PKS 1502+106 (z = 1.8378; IC 190730A)

- Selected 3 different states for each source:
  - E1: quiescent
  - E2: around neutrino alert
  - E3: bright γ-ray flare

- Lepto-hadronic modelling with Böttcher et al. (2013) code.



(Bharathan et al. 2026)

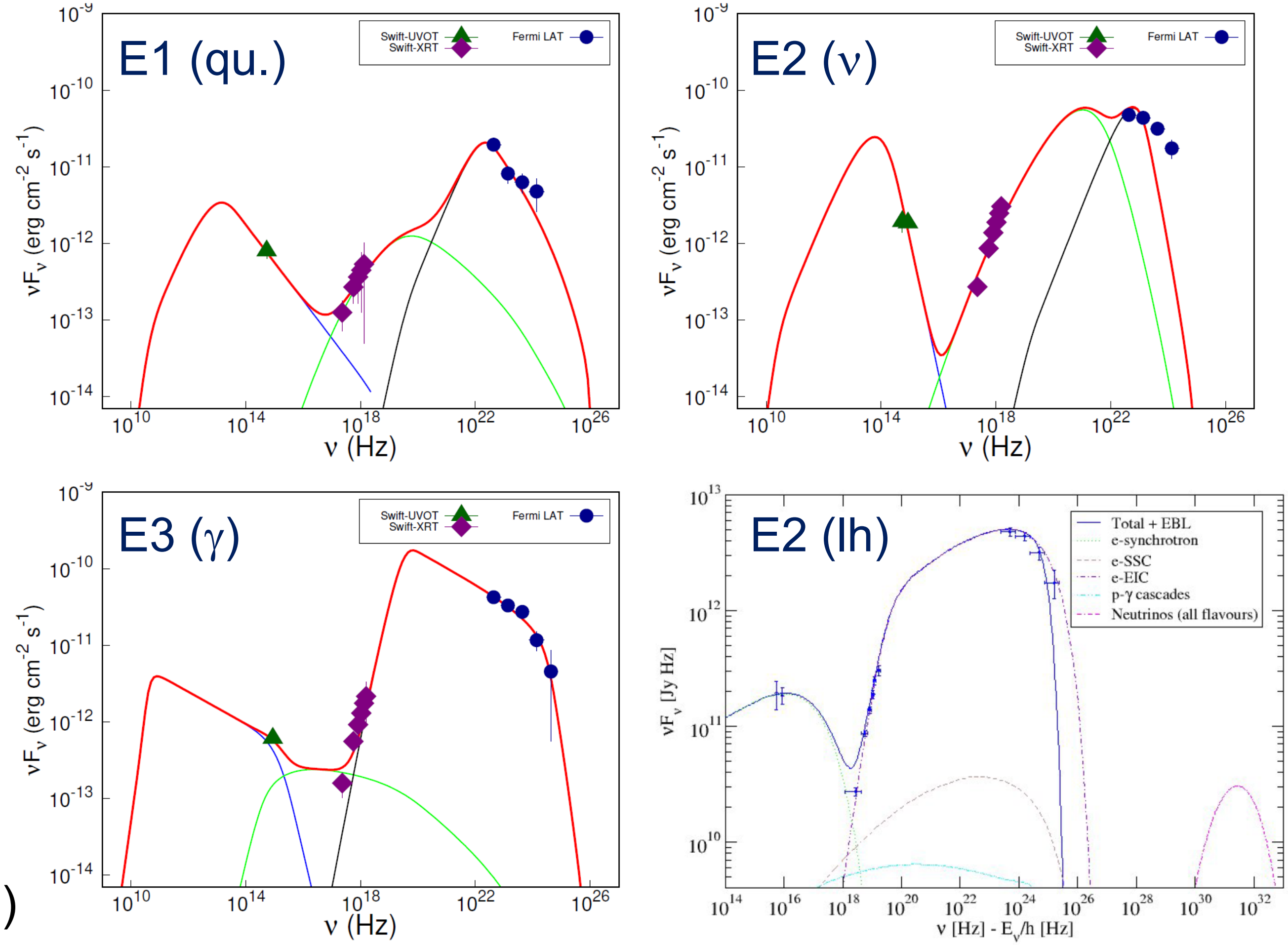
Dedicated SED modelling of 4 neutrino blazars

- Most SEDs well fitted with purely leptonic models; hadronically (pγ) dominated models excluded by hard X-ray spectra.

- 2 exceptions where leptonic models fail:
  - PKS 0446+112 during neutrino detection, but pγ cascade component still sub-dominant (see also Khatoon et al. 2026)
  - PKS 1502+106 during neutrino detection.

(Bharathan et al. 2026)

PKS 0446+112



Summary

1. Association of IceCube neutrinos with γ-ray and radio bright blazars becomes more and more significant.
2. Energetics constraints prefer external target radiation fields for $p\gamma$ interactions.
3. SED modeling of blazars generally prefers leptonically dominated broadband emission with at most a sub-dominant contribution of hadronic processes to X-ray – γ-ray emission.
4. Even the brightest γ-ray flares of blazars are unlikely to yield a neutrino detection probability of > 10 % even for KM3NeT design sensitivity.

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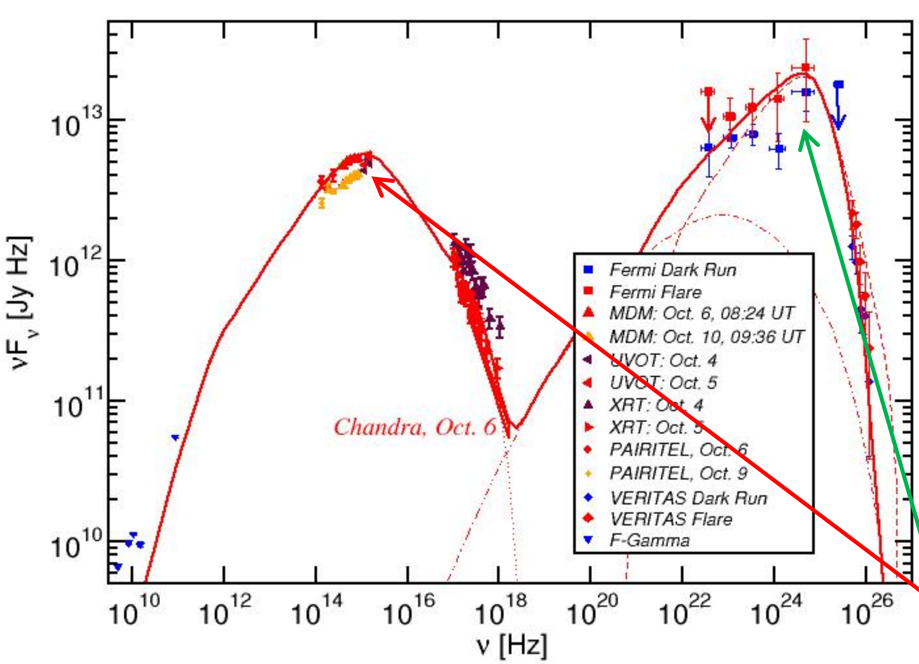
Thank you!

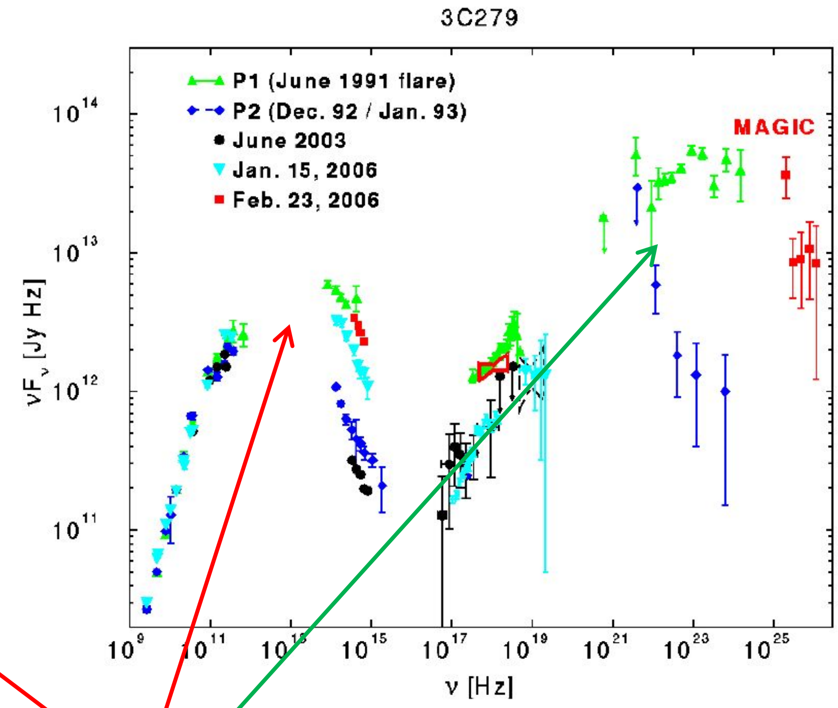
Backup

Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars with relativistic jets pointing close to our line of sight
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio knots often with superluminal motion
- Radio and optical (and X-ray) polarization

Blazar Spectral Energy Distributions (SEDs)

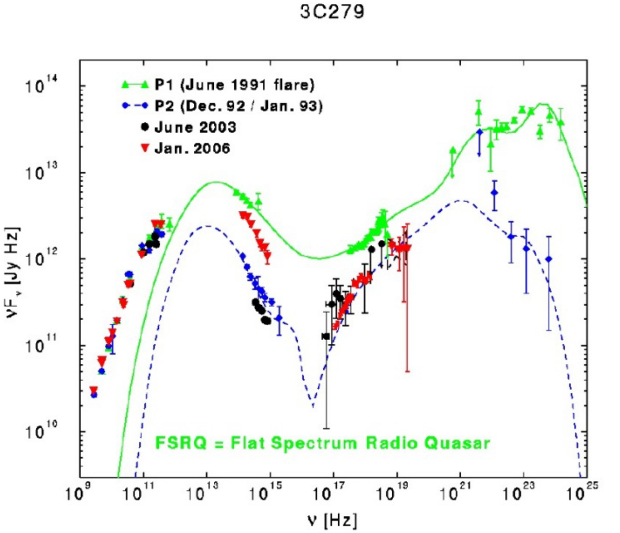




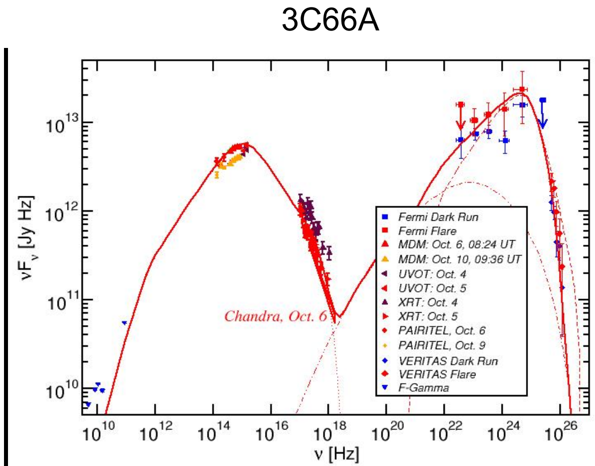
Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – γ-rays)

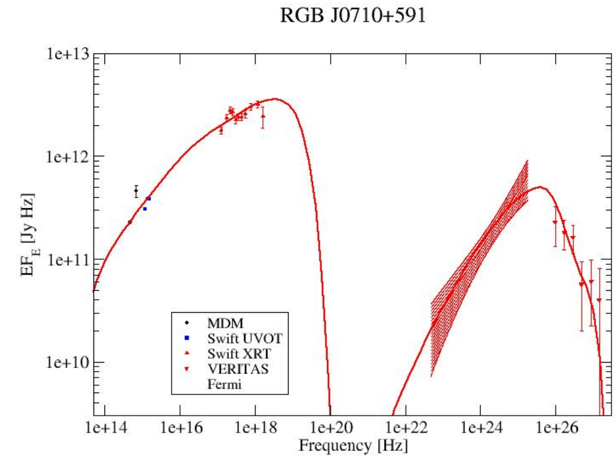
Blazar Classification



(Hartman et al. 2000)



(Abdo et al. 2011)



(Acciari et al. 2009)

<u>Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/ Low-frequency peaked BL Lac Objects (LBLs)</u>

Low-frequency component from radio to optical/UV,

$\nu_{sy} \leq 10^{14}$ Hz

High-frequency component from X-rays to γ-rays, often dominating total power

<u>Intermediate-Synchrotron Peaked (ISP): Intermediate BL Lacs (IBLs):</u>

Peak frequencies at IR/Optical and GeV gamma-rays,

10^{14} Hz $< \nu_{sy} \leq 10^{15}$ Hz

Intermediate overall luminosity

Sometimes γ-ray dominated

<u>High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):</u>

Low-frequency component from radio to UV/X-rays,

$\nu_{sy} > 10^{15}$ Hz

often dominating the total power

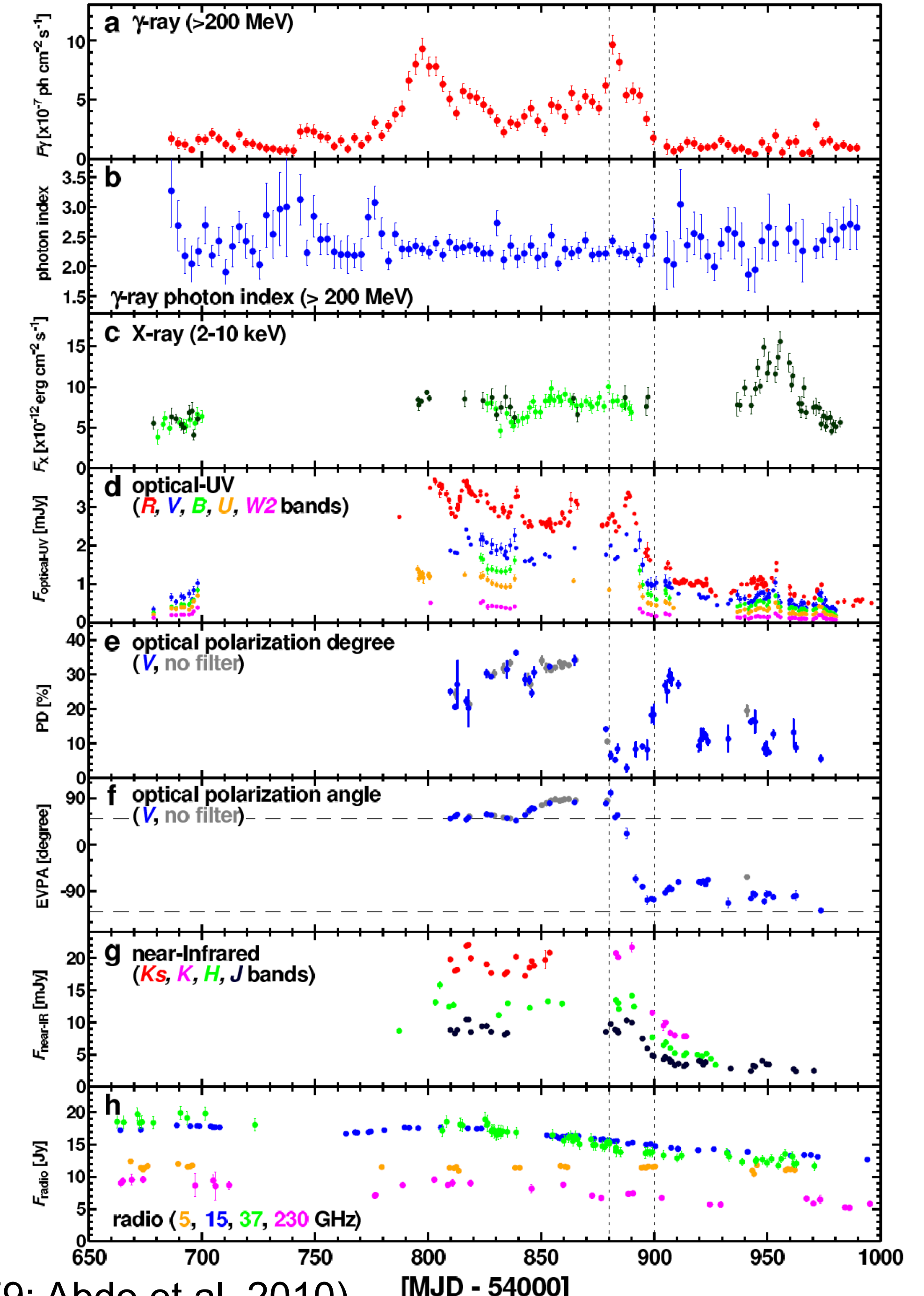
High-frequency component from hard X-rays to high-energy gamma-rays

Flux and Polarization Variability

Multi-wavelength variability on various time scales (months – minutes)
Sometimes correlated, sometimes not

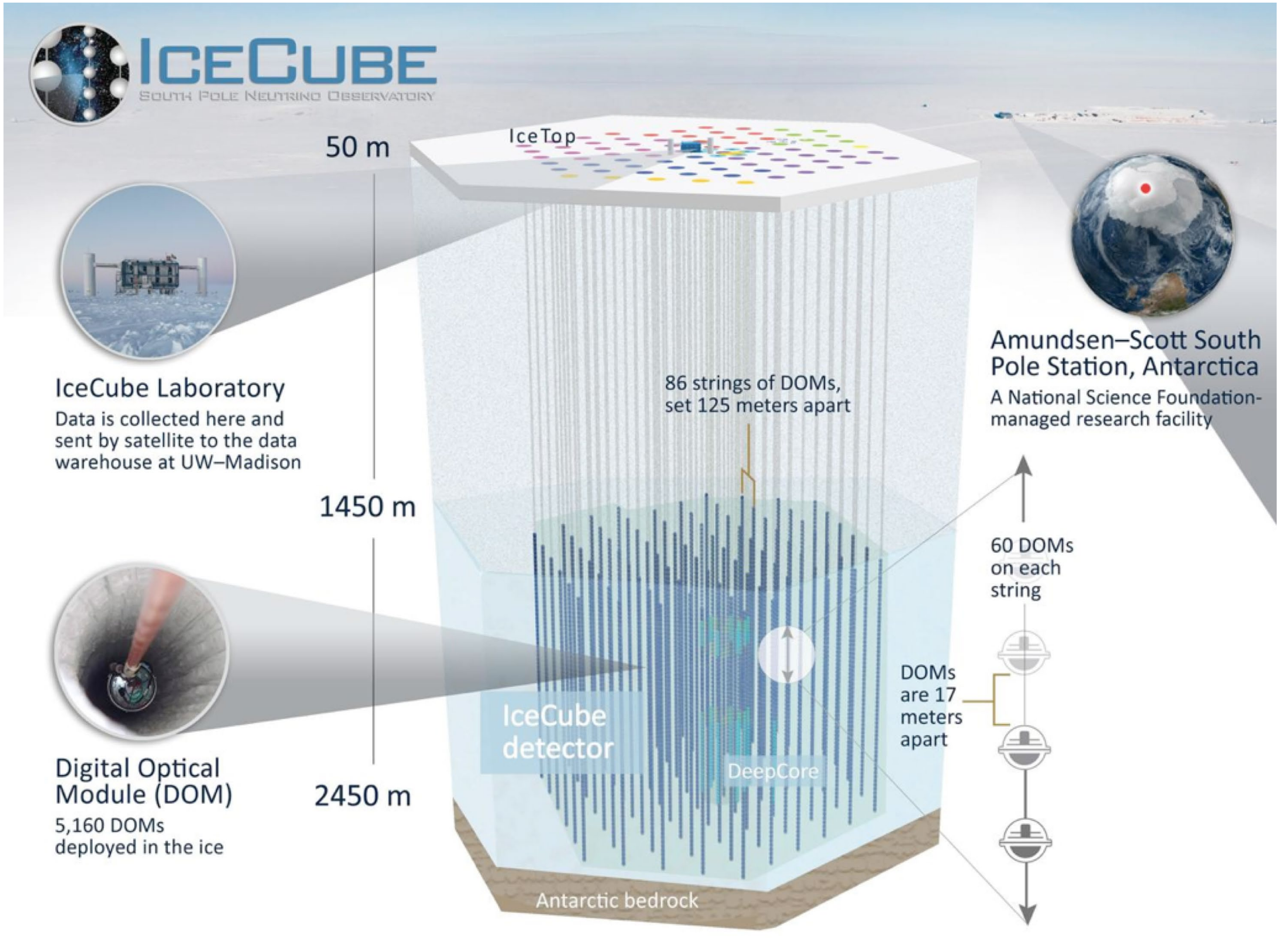
Observed optical polarization degrees
Π_{opt} <~ 30 %

Both degree of polarization and polarization angles vary.



(3C279: Abdo et al. 2010)

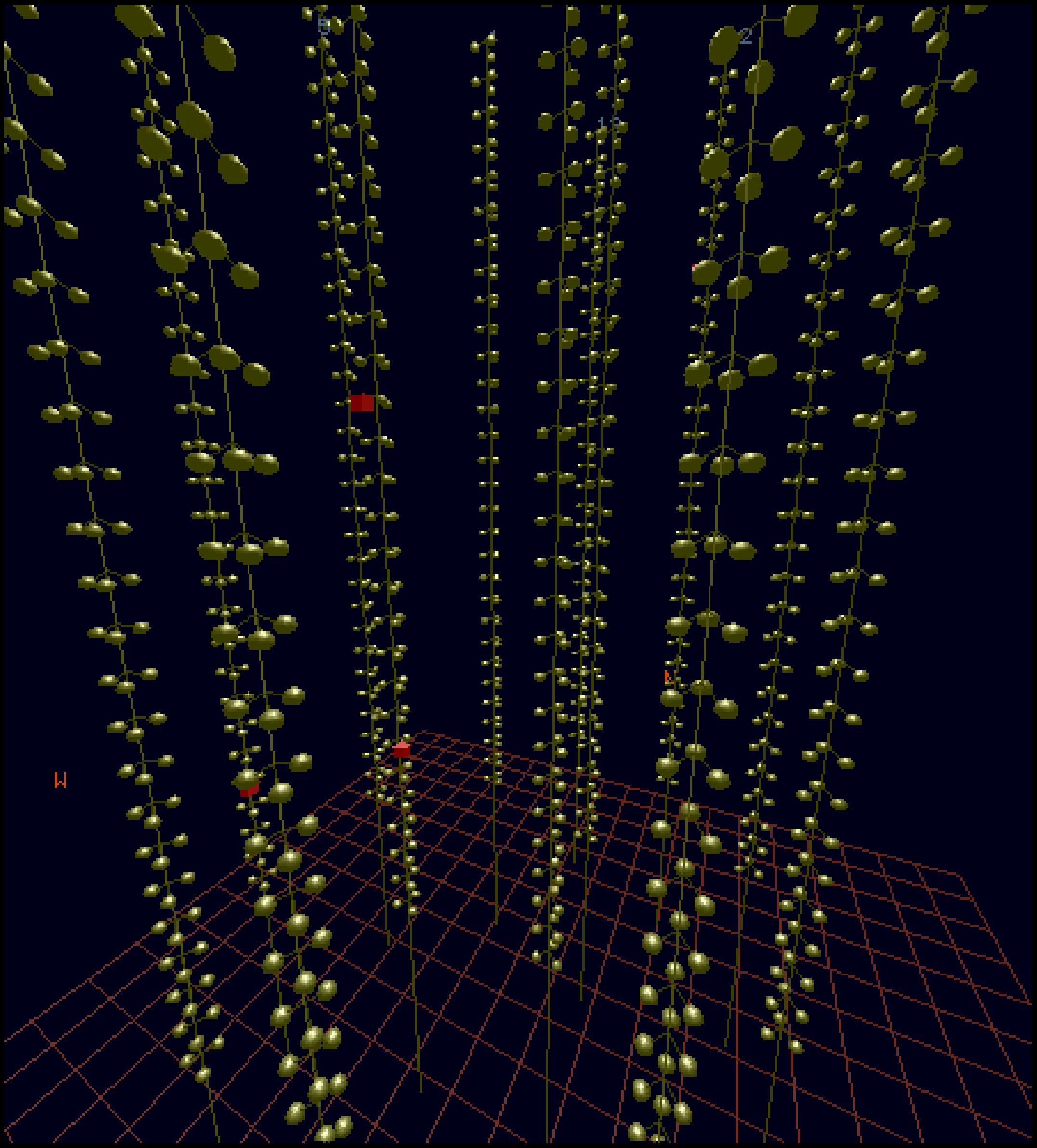
The IceCube Neutrino Detector at the South Pole



Fully operational since 2010.

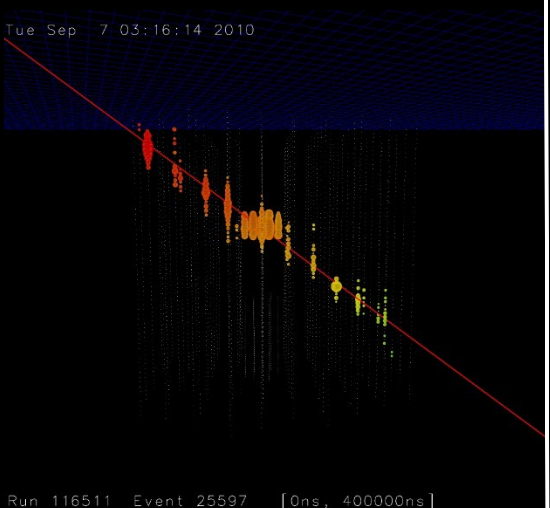
High-Energy Neutrino Detectors

IceCube:
E_ν ~ 100 TeV – few PeV



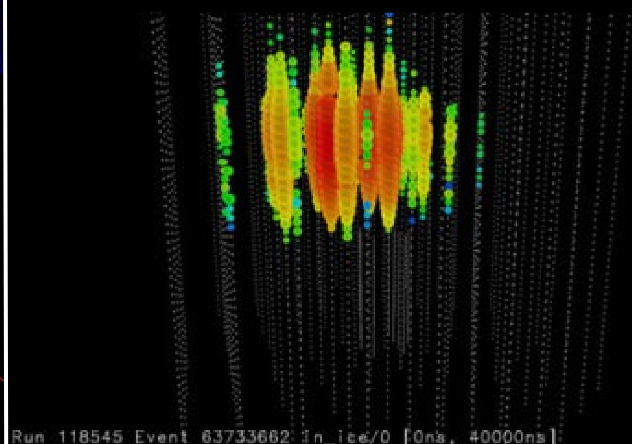
ν-matter scattering, followed by particle cascades in ice/water → Cherenkov light detection.

Neutrino Event Types



Tracks ← ν_μ

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



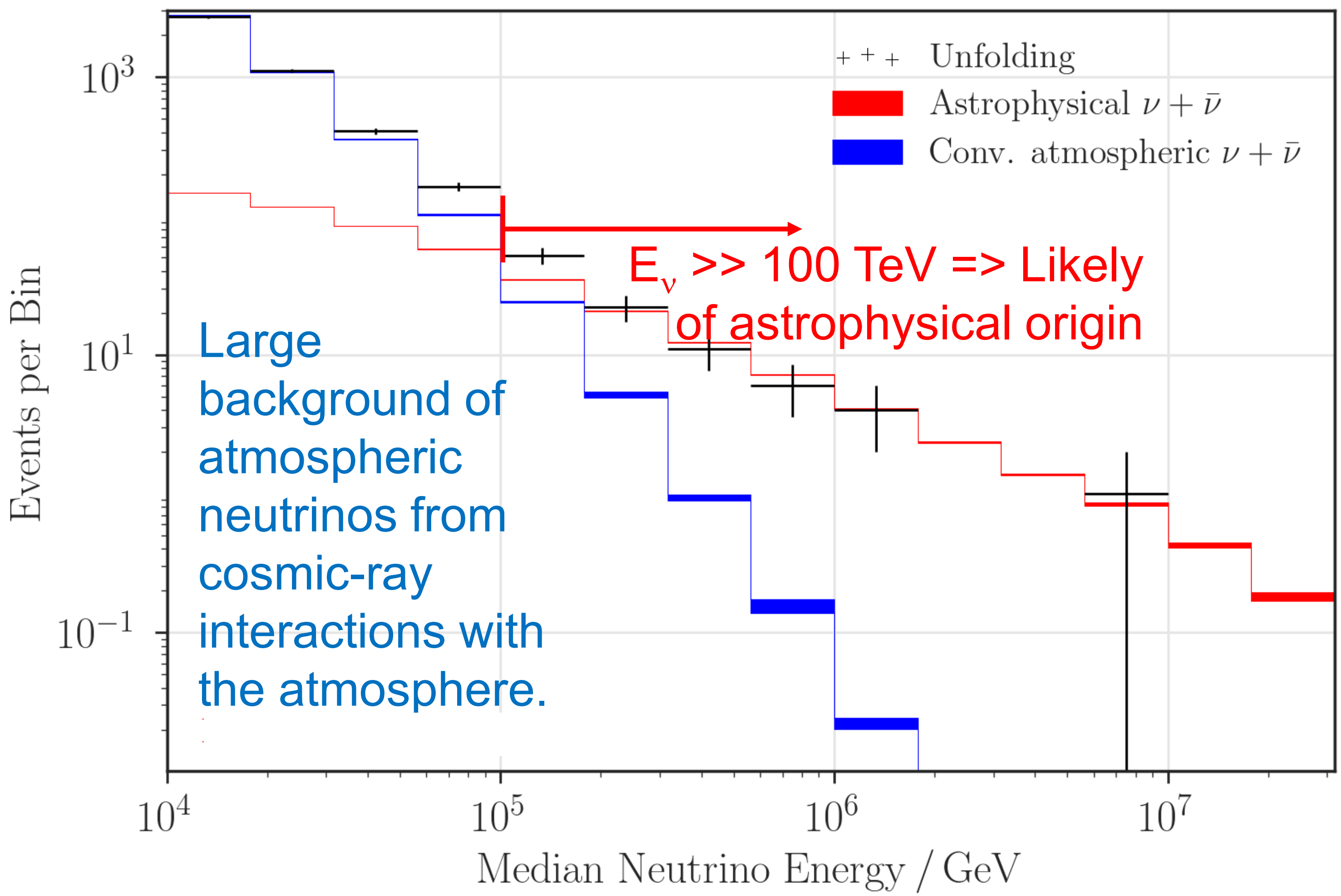
Cascades ← ν_e

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

Double Bang ← ν_τ

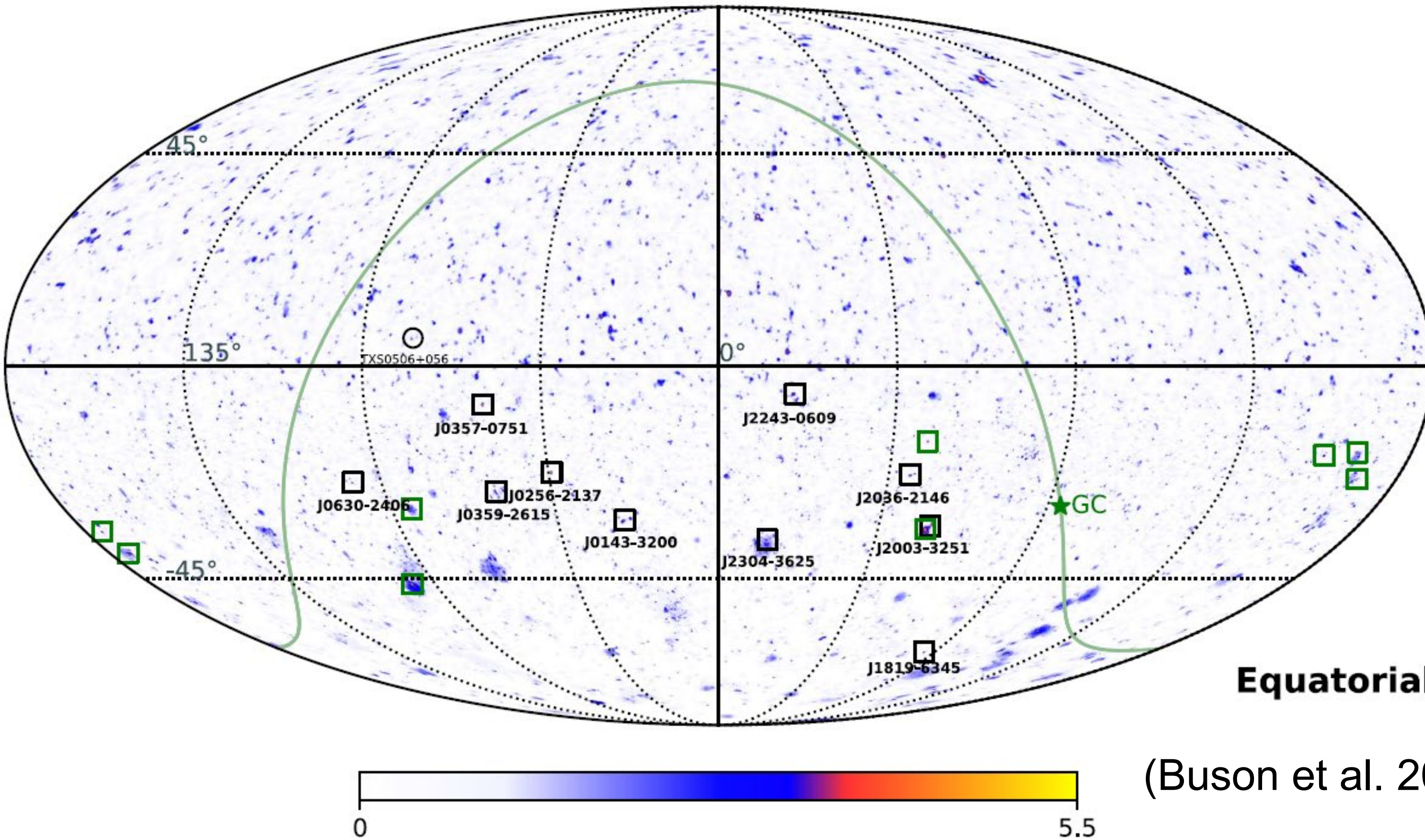
ν_τ interaction produces a tau lepton
→ 2 cascades: One at tau production, one at tau decay.

The IceCube Neutrino Spectrum



First evidence for astrophysical neutrinos published in 2013.

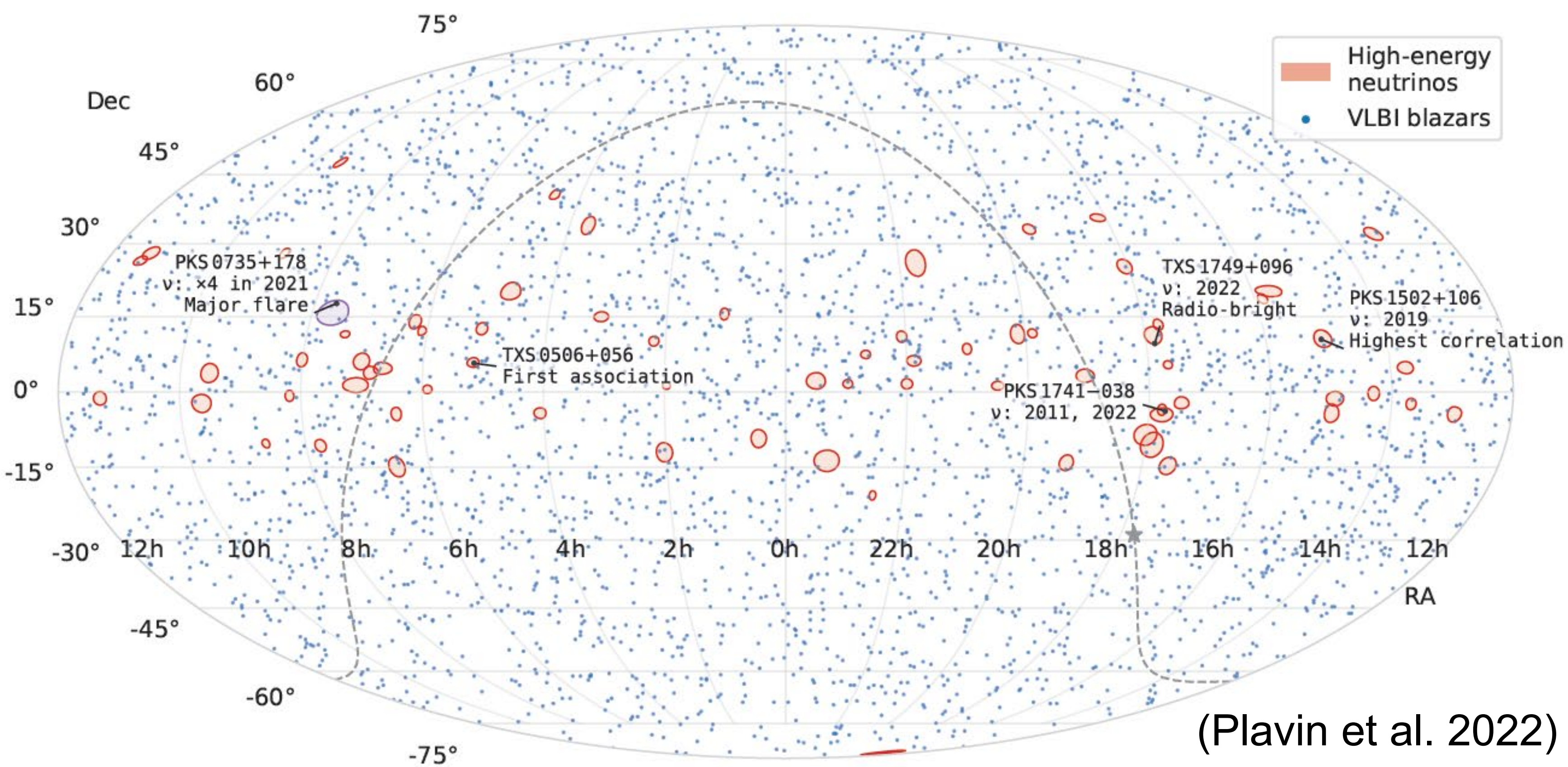
Origin of IceCube-Detected Neutrinos



(Buson et al. 2022)

Significant correlation of IceCube neutrinos with 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)

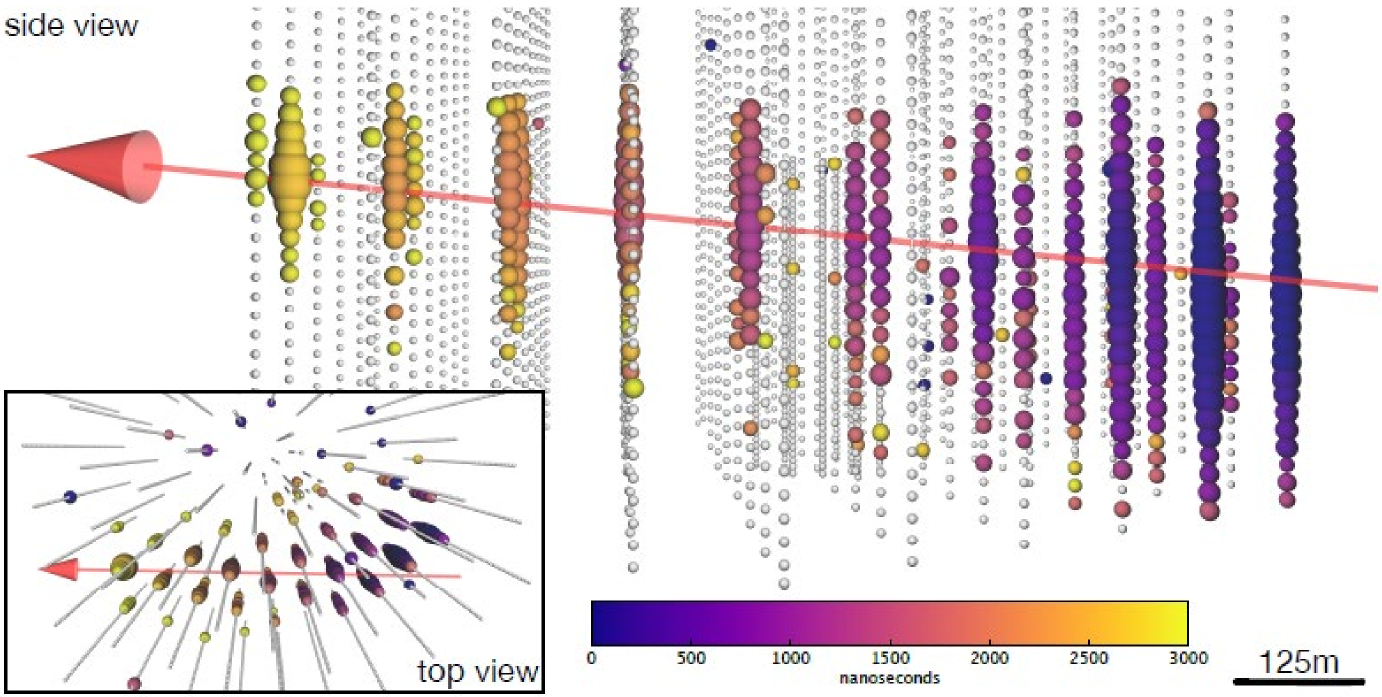
Also: Correlation with radio-loud blazars
(chance-coincidence probability of $p = 3 \cdot 10^{-4}$)
(Plavin et al. 2020, 2021, 2022)

The Eddington Bias

- Most modelled blazar – neutrino coincidences based on 1 single neutrino.
- ~ 100 other blazar sources with similar properties (same neutrino flux?)
- Models only need to produce ~ 0.01 neutrinos from any individual source! (Strotjohann et al. 2019)

Tentative Associations of IceCube Neutrinos with Blazars

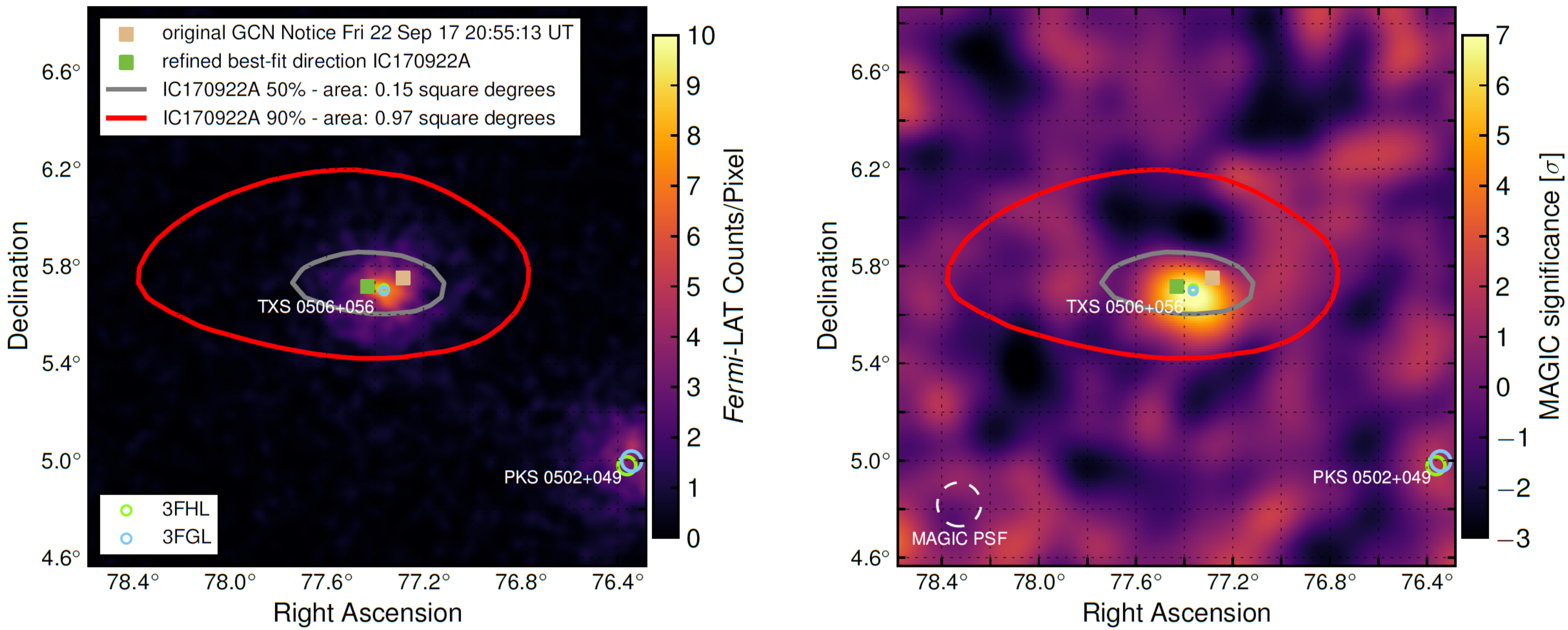
IceCube-170922A



(IceCube et al. 2018a)

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

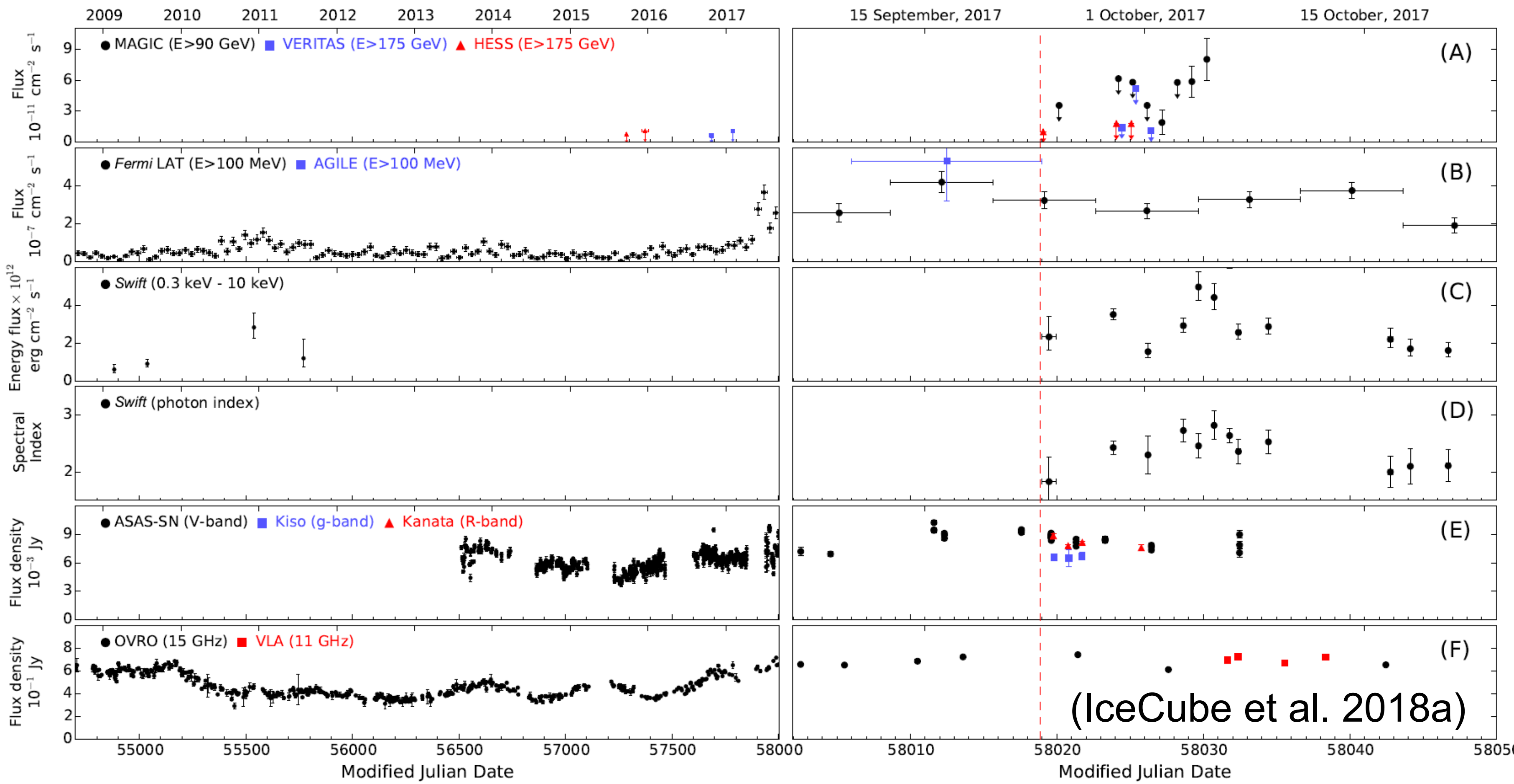
IceCube-170922A and TXS 0506+056



(IceCube et al. 2018a)

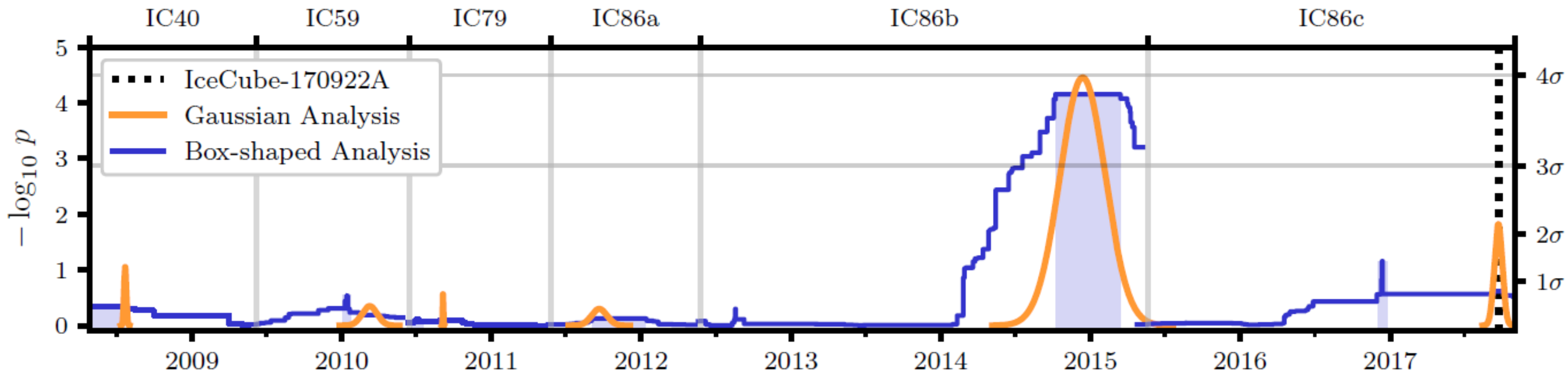
Position consistent with BL Lac object TXS 0506+056 ($z = 0.3365$) during a ~ 4 weeks long γ-ray high state (~ 3 σ probability of association)

IceCube-170922A and TXS 0506+056



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 lower-energy (< 100 TeV) neutrinos from the direction of TXS 0506+056 in 2014 – 2015 (~ 4 months around December 2014)

=> Possible to estimate flux and spectrum!