

Multi-wavelength Behaviour and Lepto-hadronic Modelling of PKS 0215+015

IceCube-220225A

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Blazars as Candidate PeV Neutrino Sources

IceCube's detection of high-energy astrophysical neutrinos opened a new window onto the most energetic particle accelerators in the Universe. The clearest evidence linking blazar jets to this flux came in 2017.

TXS 0506+056 (2017)

A 290 TeV neutrino coincided with a blazar flare, the first direct evidence that relativistic AGN jets can accelerate hadrons to photohadronic ($p\gamma$) threshold energies.

The open question

The blazar SED's high-energy hump can arise from leptonic (SSC/EC) or hadronic (p-synchrotron, $p\gamma$ cascades) processes. Only hadronic channels produce neutrinos, making candidate neutrino blazars a direct test.

IceCube-220225A and PKS 0215+015

IceCube-220225A

- Detected 25 Feb 2022, 14:12 UT (GCN 31650)
- Reconstructed energy ≈ 150 TeV
- Bronze-tier alert: $\sim 30\%$ astrophysical purity
- Best-fit position: RA $\approx 34.7^\circ$, Dec $\approx 0.0^\circ$

PKS 0215+015 ($z = 1.715$)

- Only γ -ray source in the 90% localisation region, ~ 1.75 deg from best-fit position
- Fermi-LAT: day-scale flux $> 7\times$, month-scale $> 3\times$ the 4FGL-DR3 average at the alert epoch

A changing-look blazar

PKS 0215+015 was originally classified as a featureless BL Lac (Gaskell 1982).

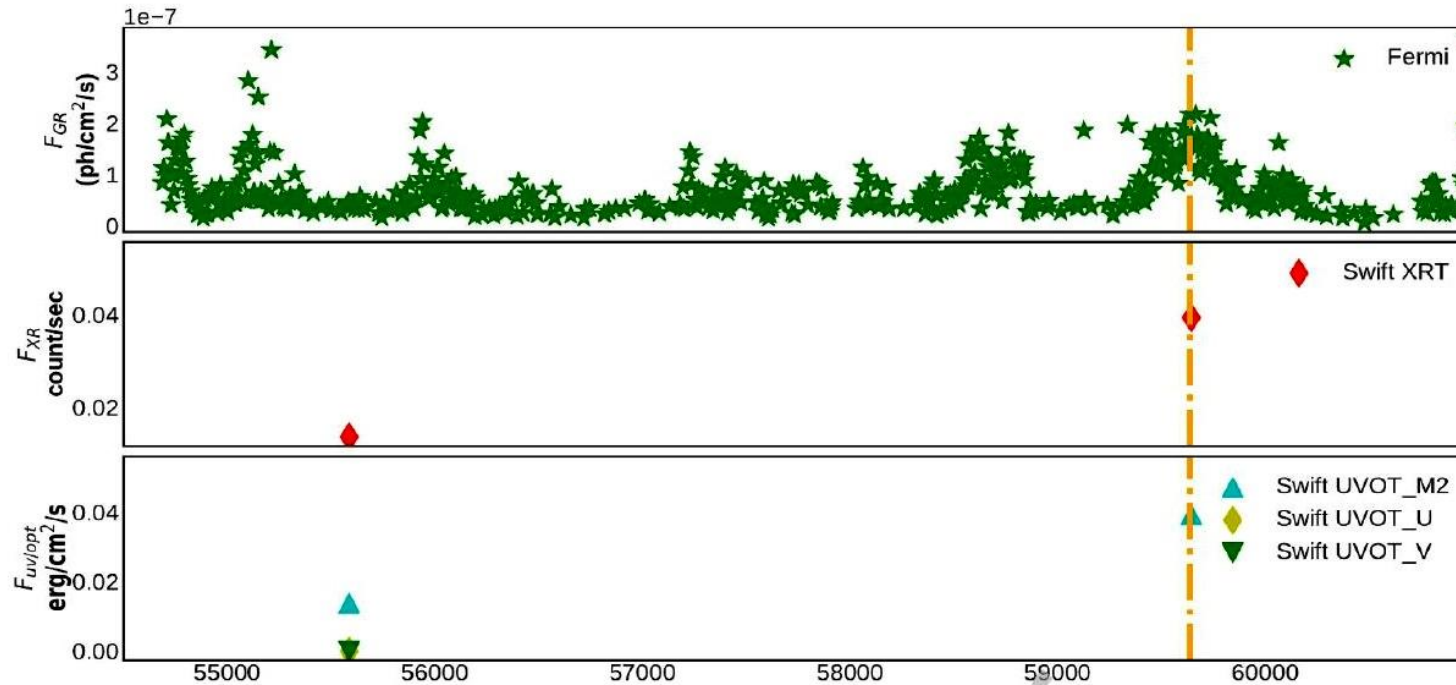
Later observations revealed prominent broad Ly α and C IV lines, leading to reclassification as an FSRQ (Blades et al. 1982; Foltz & Chaffee 1987).

This BL Lac $\rightarrow$ FSRQ transition matters:

FSRQs are efficient neutrino producers precisely because the dense BLR and disc photon fields supply abundant target photons for $p\gamma$ interactions.

If PKS 0215+015 was in an FSRQ-like, BLR-dominated state near the neutrino epoch, that strengthens the case for a physical association.

An 18-Years Light Curve Around the Neutrino Epoch



- Fermi-LAT, Swift-XRT and Swift-UVOT (2008 Aug – 2026 May)
- Clear γ -ray and optical/UV enhancement coincident with the IceCube-220225A epoch (dashed line, MJD 59635)
- Radio: OVRO/VLBI show enhanced activity and changing polarization; a new superluminal jet component emerges close to the neutrino epoch (Eppel et al. 2026)
- Independent radio monitoring recorded an outburst exceeding 3 Jy, the highest radio state for this source in over two decades (Plavin et al. 2022)

An Independent, Model-Free Size Constraint

Flux-doubling/halving timescales in the Fermi-LAT light curve give a light-crossing limit on the emission-region size, independent of any SED fit.

Shortest doubling timescale

$$\tau \simeq 6.61 \text{ hr}$$

Flux-doubling law: $F(t) = F(t_0) \times 2^{-(t-t_0)/\tau}$, requiring the flux change to exceed 3σ (Foschini et al. 2011), during the flaring interval bracketing MJD 59635.

Emission-region size limit

$$R \lesssim 5.17 \times 10^{15} \text{ cm}$$

$$R \lesssim c\delta\tau/(1+z)$$

This variability-derived limit agrees closely with the value required independently by the broadband SED fit, $R = 5.0 \times 10^{15} \text{ cm}$, a model-independent cross-check on the adopted jet geometry.

One-Zone Leptonic and Lepto-hadronic Framework

We model the broadband SED for the flaring interval coincident with IceCube-220225A using the time-independent, one-zone framework of Böttcher et al. (2013).

Emission region

A spherical blob of radius R , tangled magnetic field B , moving with bulk Lorentz factor Γ and Doppler factor δ along the jet.

Leptonic channel

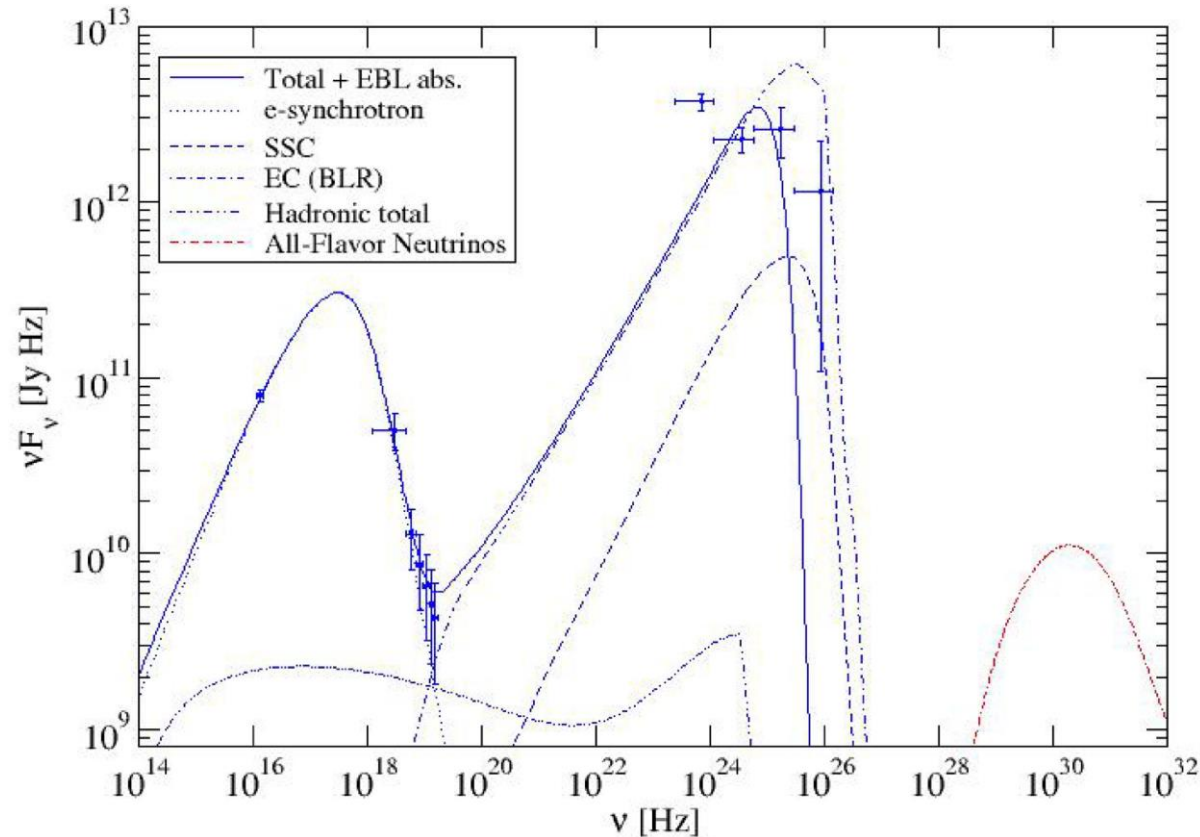
Power law + exponential-cutoff electrons; synchrotron, SSC, and two EC channels (accretion-disc and isotropic BLR/torus fields).

Hadronic channel

A co-accelerated proton population radiating via proton synchrotron and photohadronic ($p\gamma$) interactions with jet and external photons.

Data: Fermi-LAT (MJD 59625–59645, ± 10 days around the alert), Swift-XRT and Swift-UVOT.

A Leptonic Model Reproduces the SED, With a Caveat



We regard this as a plausible working model rather than a unique or completely satisfactory explanation

Key fit parameters

Γ	20
B	1.0 G
R	5×10^{15} cm
$\gamma_{e,\min} \rightarrow \gamma_{e,c}$	$1.2 \times 10^5 \rightarrow 1 \times 10^6$
Injection index q	5.5
LB / Le	≈ 0.65 (near equipartition)

Caveat

The fitted electron population spans less than one decade in Lorentz factor at an unusually high minimum energy, and $q = 5.5$ is steeper than the $q \approx 2-3$ expected from standard first-order Fermi acceleration. The fit also does not fully capture the Fermi-LAT spectral shape.

Maximum Hadronic Contribution: Severe Baryon Loading

A co-accelerated proton population is added to explore the maximum hadronic contribution allowed without violating the observed SED ($\alpha_p = 2.0$, 1 GeV to 10^{10} GeV).

Max. proton luminosity

$$L_p = 4 \times 10^{45} \text{ erg s}^{-1}$$

Proton-to-electron ratio

$$L_p / L_e \approx 69$$

protons carry $\sim 69\times$ more power

Proton-to-magnetic ratio

$$L_p / L_B \approx 107$$

far from equipartition

The model requires very strong baryon loading, far from equipartition

Predicted neutrino yield

$$N_\nu \approx 1.3 \times 10^{-5} \text{ (1 day)} \rightarrow 1.3 \times 10^{-4} \text{ (10-day SED window)} \rightarrow 7 \times 10^{-2} \text{ (full IceCube lifetime, } \sim 15 \text{ yr)}$$

All three estimates are far below unity, consistent with the single, moderate-significance Bronze-tier alert observed rather than a statistically significant excess.

Despite this large reservoir of proton kinetic energy, the intrinsic inefficiency of proton-synchrotron and $p\gamma$ channels keeps the hadronic emission subdominant to the leptonic component at every frequency.

Self-Consistency, and a Speculative Resolution

A model-independent cross-check

Emission-region size from short-term γ -ray variability: $R \lesssim 5.17 \times 10^{15}$ cm

Emission-region size from the broadband SED fit: $R = 5.0 \times 10^{15}$ cm

Two entirely independent methods, a light-crossing argument versus a multi-band radiative-transfer fit, converge on the same jet geometry.

The masquerading BL Lac scenario

PKS 0215+015's BL Lac $\rightarrow$ FSRQ transition may reflect a Doppler-boosted jet continuum episodically outshining a genuine, persistent BLR. If enhanced accretion activity around the flare boosted the BLR photon field beyond our time-averaged treatment, $p\gamma$ efficiency could rise without requiring the extreme proton luminosities implied here.

Presented as a plausible, physically motivated, but untested implication of the source's classification history, not a result demonstrated by this modelling.

Summary

- 1 PKS 0215+015 is the only γ -ray source in the 90% IceCube-220225A localisation region, in a substantially elevated γ -ray state, with a historic radio outburst and a new superluminal VLBI jet component near the alert epoch.
- 2 A leptonic model reproduces the flaring-epoch SED near equipartition ($LB/Le \approx 0.65$), but requires an unusually narrow, high-energy electron distribution, a plausible working fit, not a unique one.
- 3 The maximum allowed hadronic contribution implies severe baryon loading ($Lp/Le \approx 69$, $Lp/LB \approx 107$), yet predicts a neutrino event rate well below one detection over IceCube's lifetime, consistent with the single Bronze-tier alert.
- 4 Emission-region sizes from independent methods, short-term variability and SED fitting, agree closely ($\lesssim 5.17 \times 10^{15}$ cm vs. 5.0×10^{15} cm), supporting the physical self-consistency of the adopted jet model.

Thank you

Bharathan & Böttcher, 2026
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