Revealing the production mechanism of high-energy neutrinos from NGC1068

TeVPA 2024

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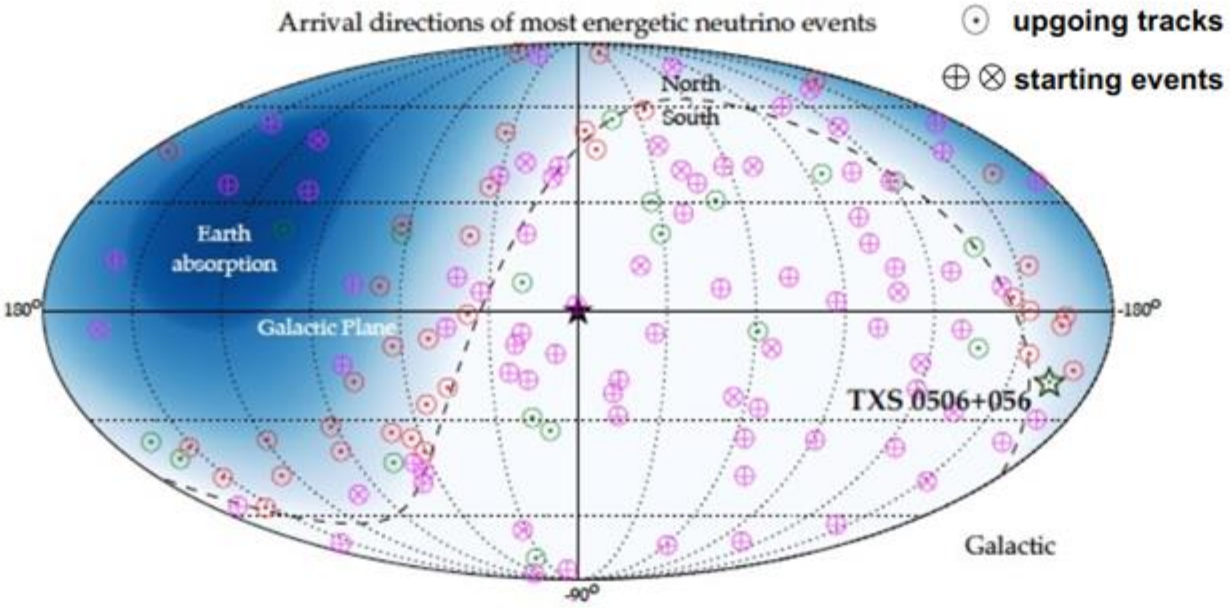
PennState

Chicago 2024

High-energy neutrino sky

Slide courtesy: Kohta Murase



consistent w. isotropic distribution/extragalactic origins

#Galactic contribution: ~10% (IceCube 23 Science)

Slide courtesy: Kohta Murase

Sources of extragalactic neutrinos

Cosmic-ray Accelerators

Cosmic-ray Reservoirs

Type equation here.

$$p + \gamma \rightarrow N\pi + X$$

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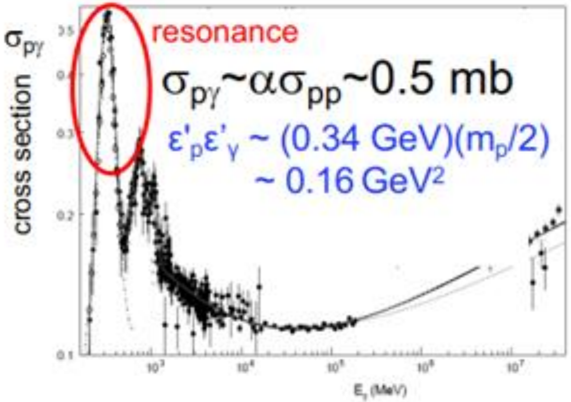
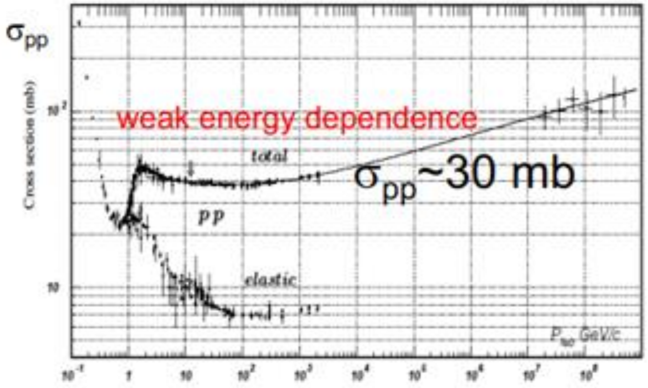


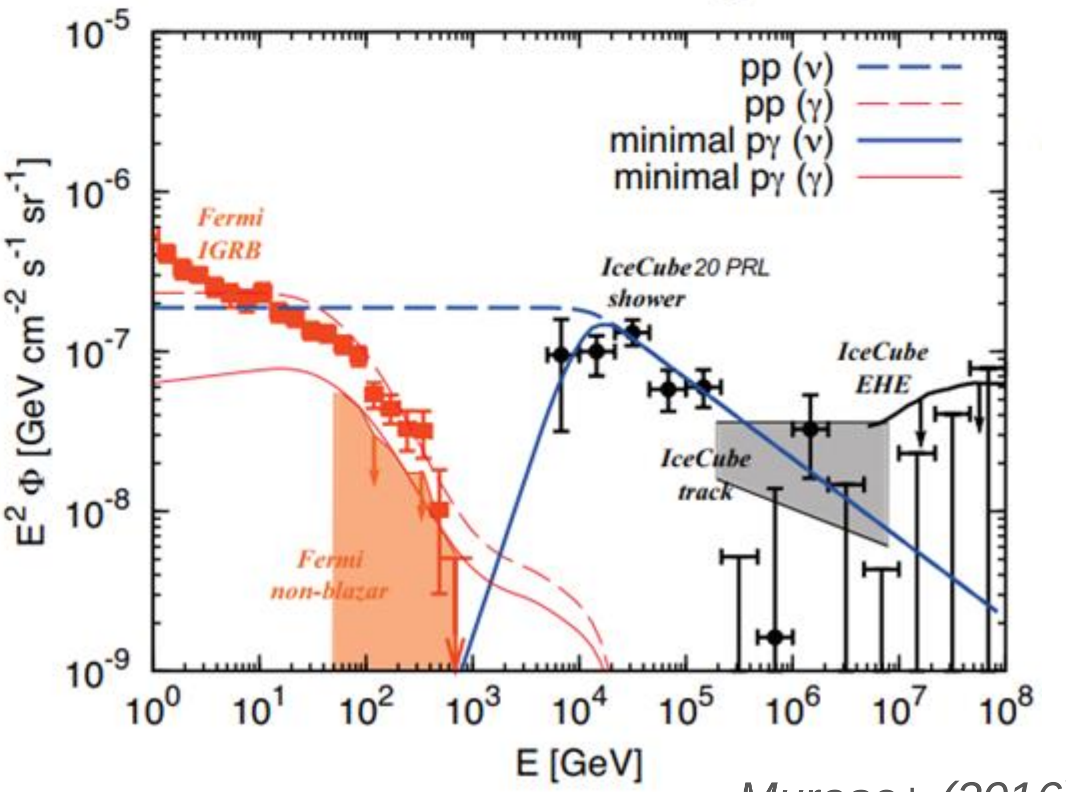


$$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e \ (\text{or } \bar{\nu}_e) + e^\pm \qquad \pi^0 \rightarrow 2\gamma$$

Extragalactic multimessenger connection

-Fermi diffuse gamma-ray background is violated (>3σ) if sources are transparent.

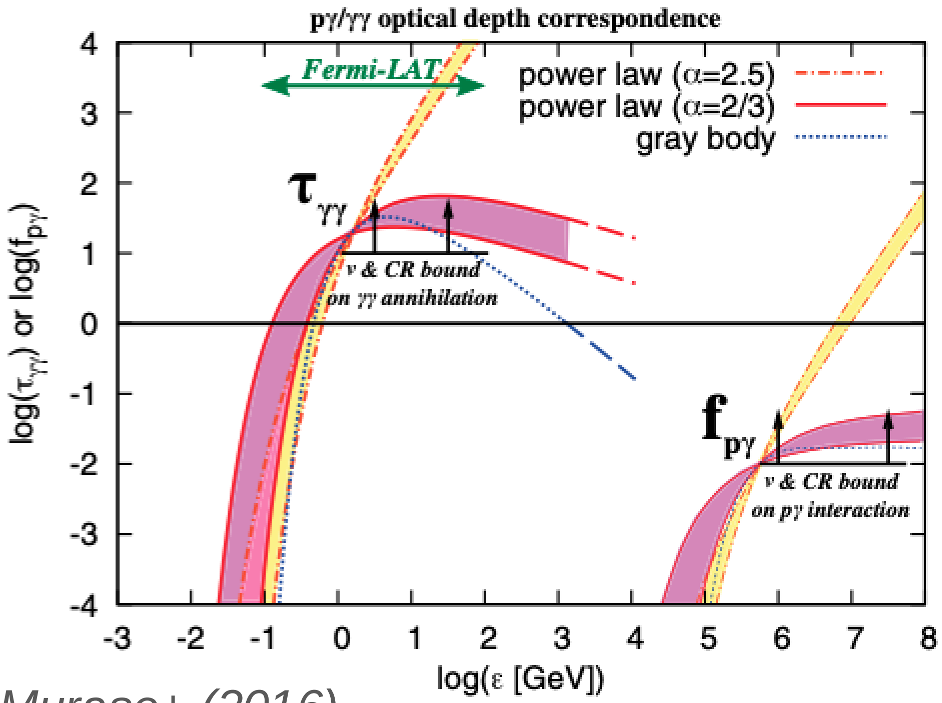
Solution:
Hidden (gamma-ray opaque) cosmic-ray accelerators

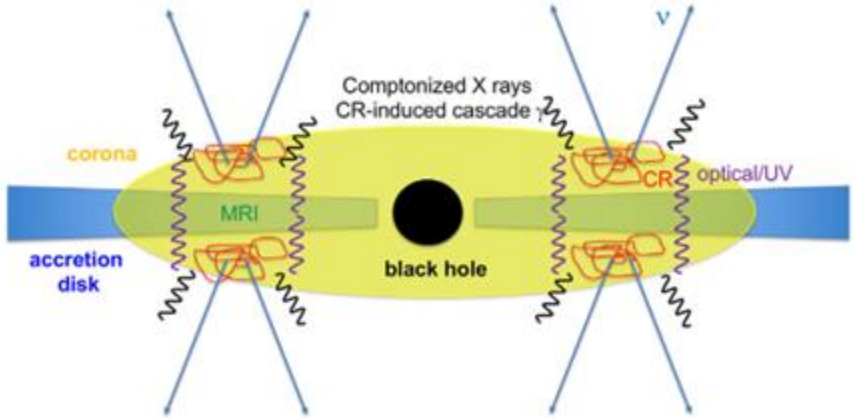


Murase+ (2016)

Opacity argument and prediction

$\gamma\gamma \rightarrow e^+e^-$ optical depth $\tau_{\gamma\gamma} \approx \frac{\sigma_{\gamma\gamma}^{\rm eff}}{\sigma_{p\gamma}^{\rm eff}} f_{p\gamma} \sim 1000 f_{p\gamma} \gtrsim 10$



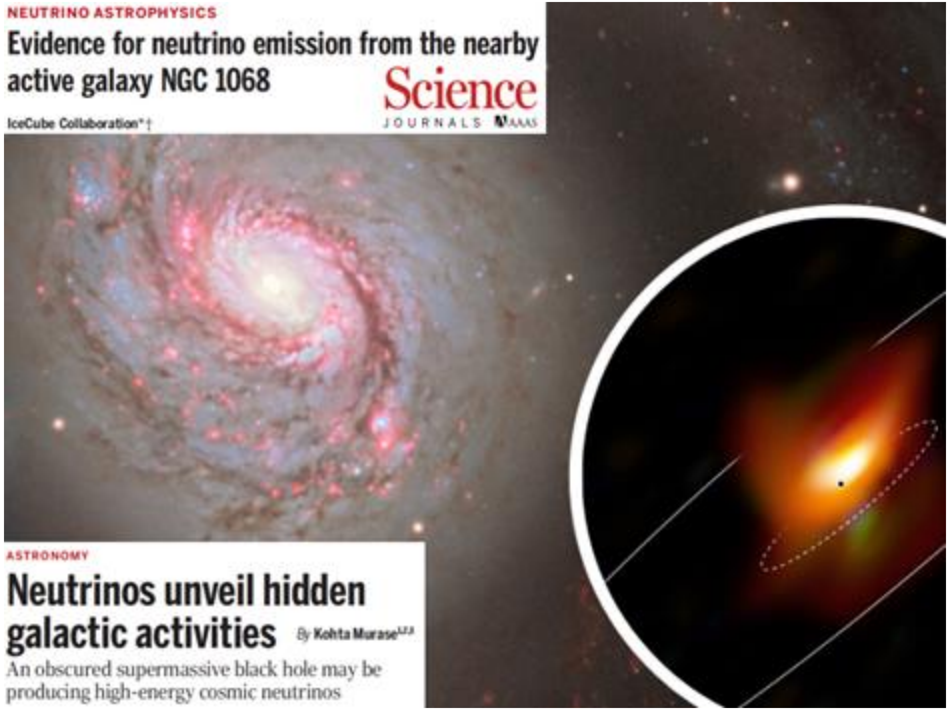


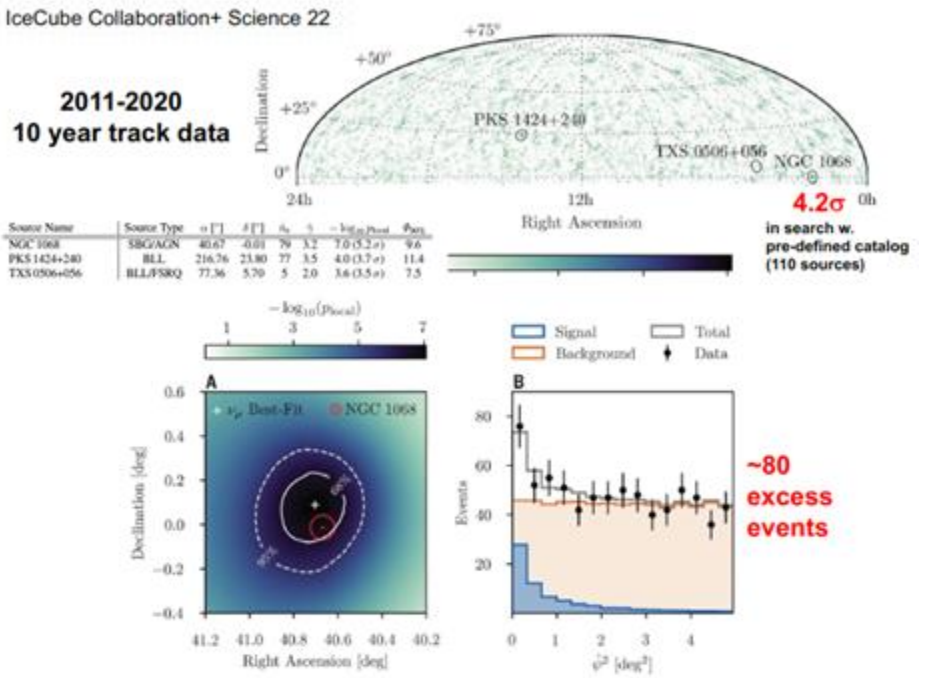
Murase+ (2016)

Prediction: Cosmic-ray acceleration site must be much closer to SMBH

Slide courtesy: Kohta Murase

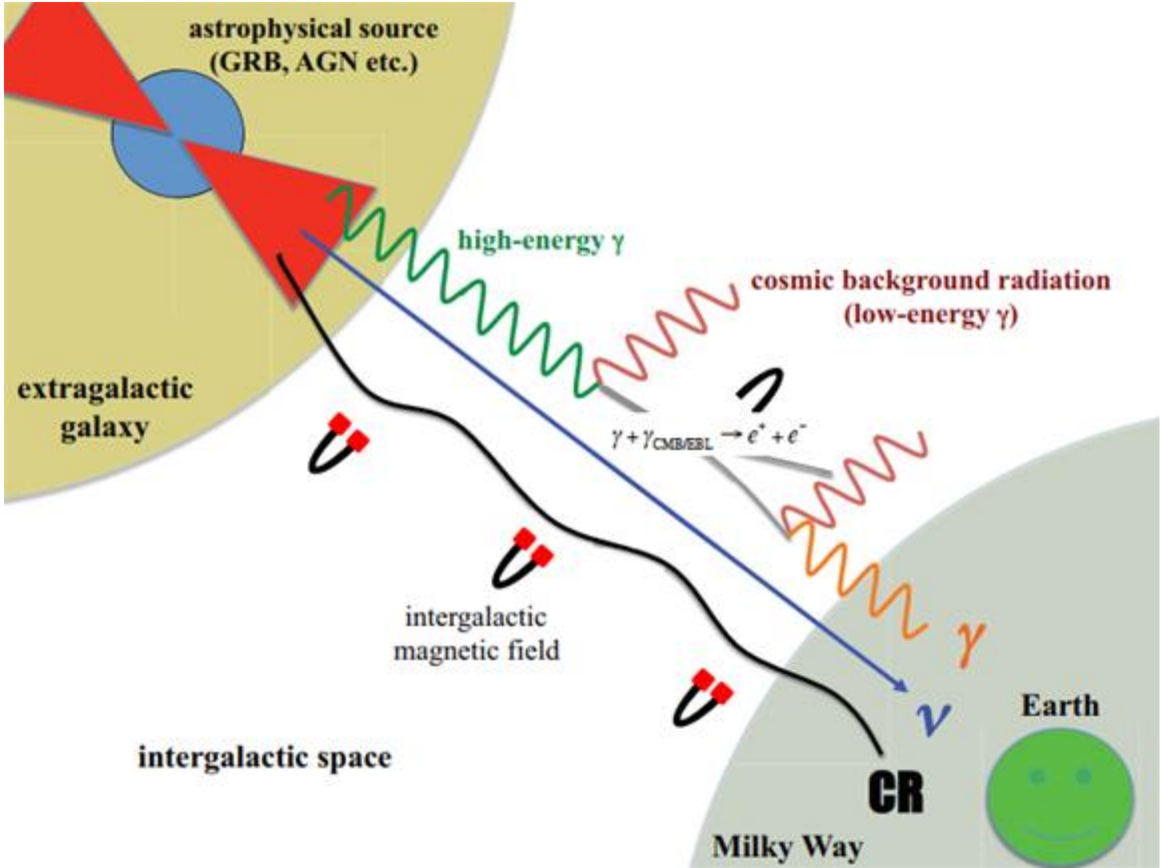
IceCube detects Neutrinos from NGC 1068





Slide courtesy: Kohta Murase

Neutrino advantage



NGC 1068 as a Hidden source

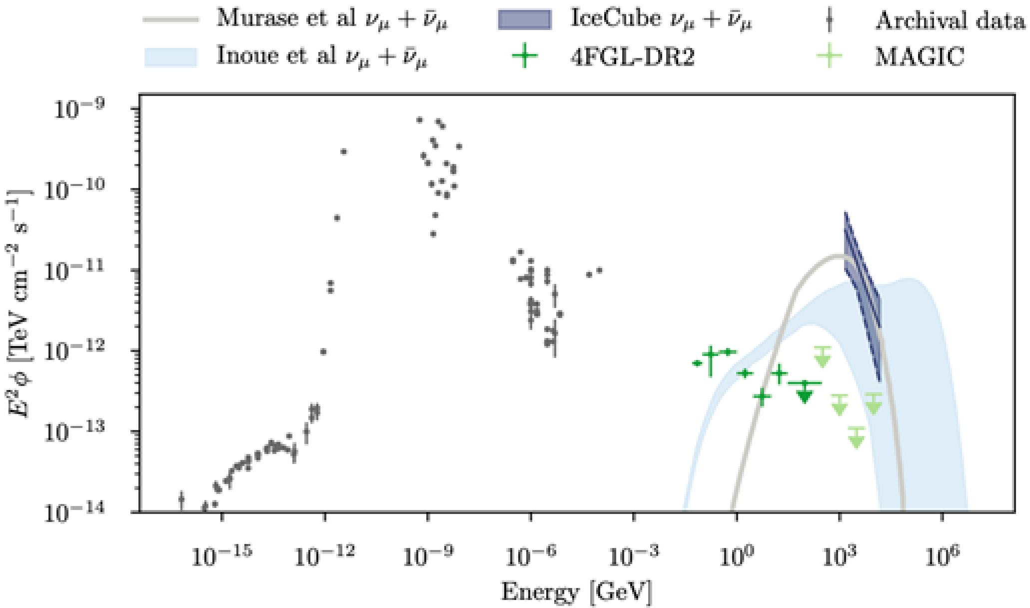
- Between 1.5 TeV and 15 TeV,

$$L_\nu = (2.9 \pm 1.1) \times 10^{42} \mathrm{erg/s}$$

- Between 100 MeV and 200 GeV, *Fermi*-LAT reports

$$L_\gamma = 1.6 \times 10^{41} \mathrm{erg/s}$$

Conclusion:
Emission region must be optically thick to gamma rays.



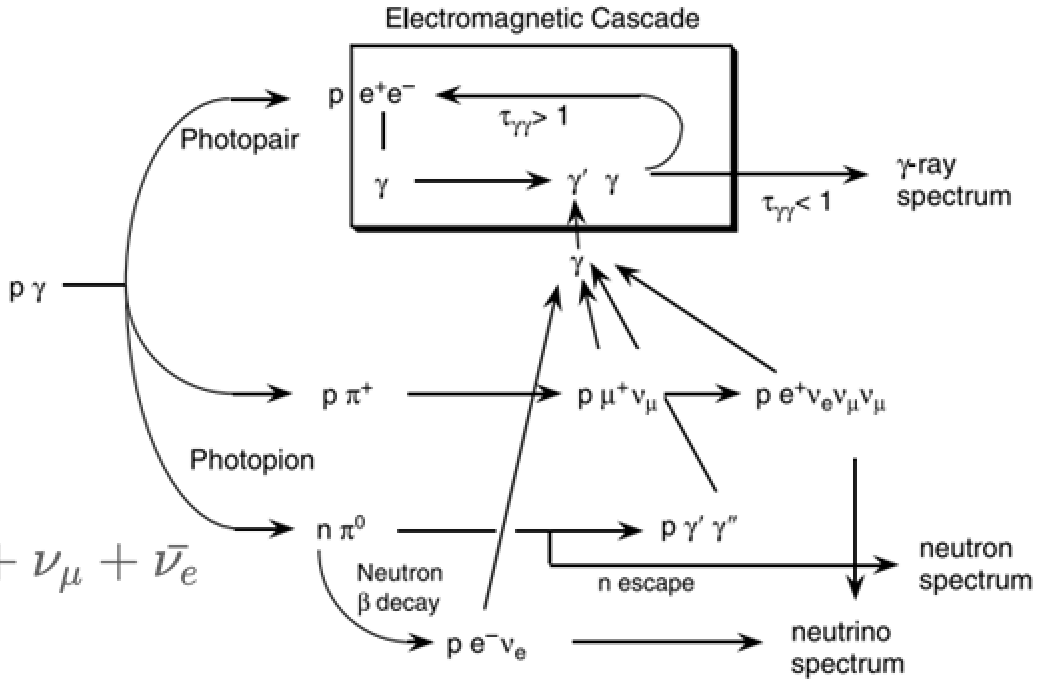
Abbasi+ (2022)

Cascade formation and observed spectra

- Ultrarelativistic CR protons interact with target photons forming electromagnetic cascades.

- Leptonic mechanism

$$\gamma\gamma \rightarrow \mu^+\mu^-$$
$$\rightarrow e^+ + \bar{\nu_\mu} + \nu_e + e^- + \nu_\mu + \bar{\nu_e}$$



Dermer, Menon (2009)

Revealing the Production Mechanism of High-energy Neutrinos from NGC 1068

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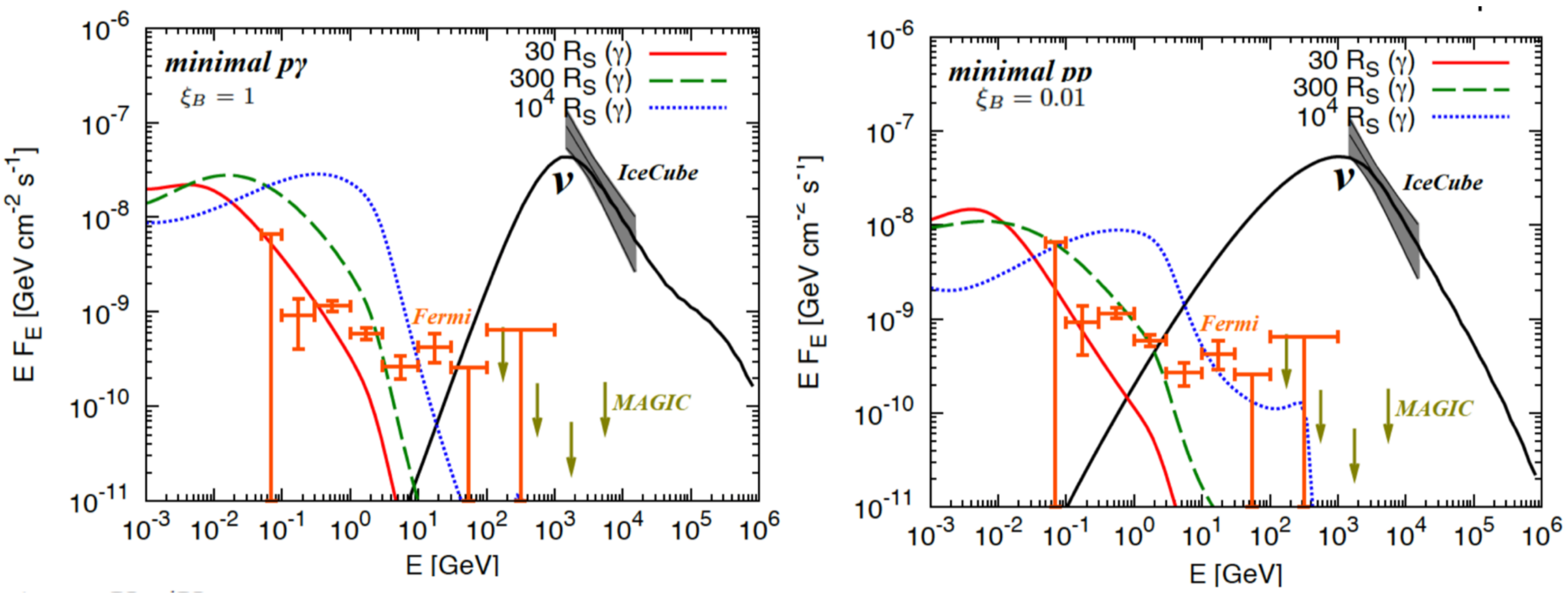
Abstract

The detection of high-energy neutrino signals from the nearby Seyfert galaxy NGC 1068 provides us with an opportunity to study nonthermal processes near the center of supermassive black holes. Using the IceCube and latest Fermi-LAT data, we present general multimessenger constraints on the energetics of cosmic rays and the size of neutrino emission regions. In the photohadronic scenario, the required cosmic-ray luminosity should be larger than ~1%–10% of the Eddington luminosity and the emission radius should be $\lesssim 15 R_S$ in low-β plasma and $\lesssim 3 R_S$ in high-β plasma. The leptonic scenario overshoots the NuSTAR or Fermi-LAT data for any emission radii we consider, and the required gamma-ray luminosity is much larger than the Eddington luminosity. The beta-decay scenario also violates not only the energetics requirement but also gamma-ray constraints, especially when the Bethe–Heitler and photomeson production processes are consistently considered. Our results rule out the leptonic and beta-decay scenarios in a nearly model-independent manner and support hadronic mechanisms in magnetically powered coronae if NGC 1068 is a source of high-energy neutrinos.

Hadronic scenario



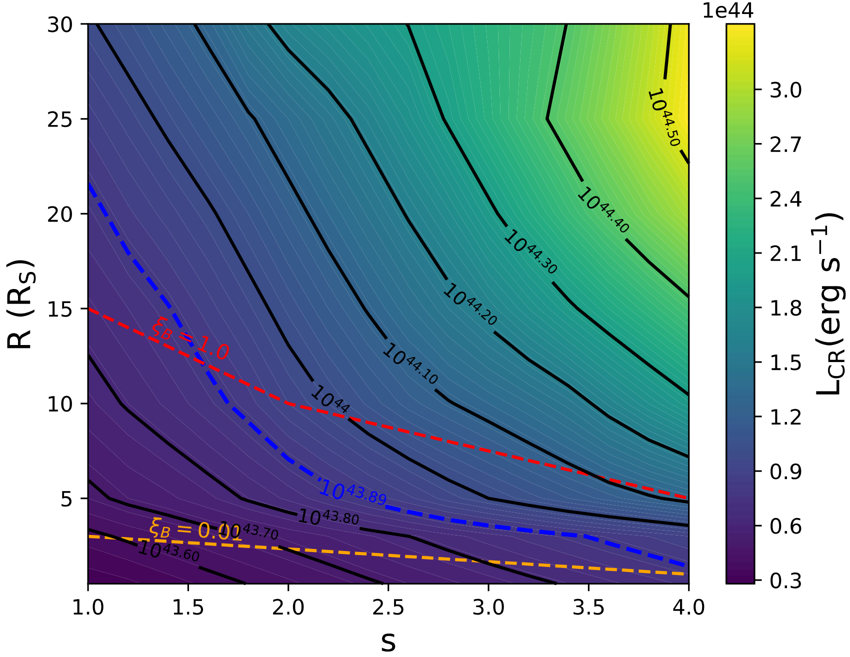
Constraint on emission radius: R < (30 – 100) R_S

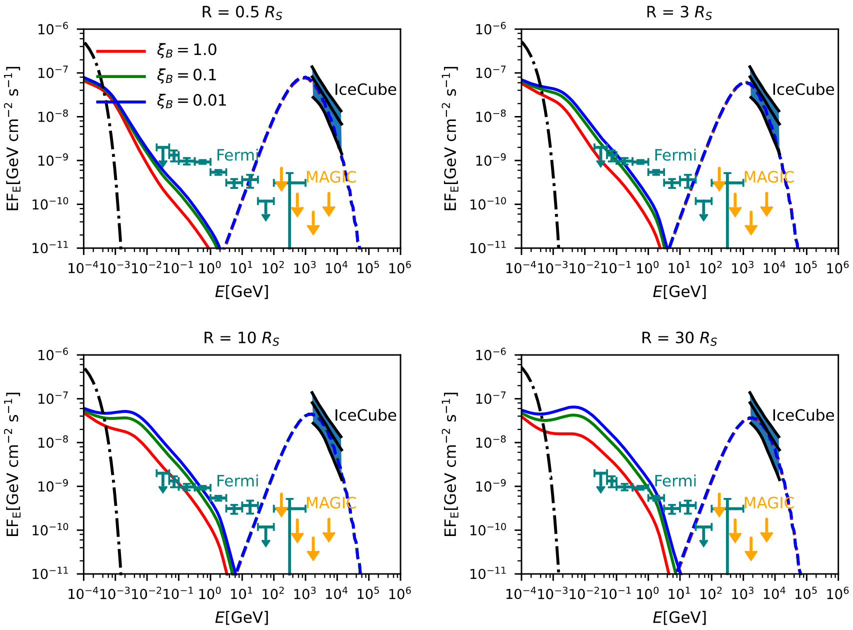
Murase 2022

Hadronic scenario results

$$\beta = \frac{8\pi n_p k_B T_p}{B^2} \approx \frac{\tau_T G M_{\rm BH} m_p}{\sqrt{3}\zeta_e \sigma_T R^2 U_\gamma} \xi_B^{-1} \approx \left(\frac{\tau_T}{\sqrt{3}\zeta_e \lambda_{\rm Edd}}\right) \xi_B^{-1}$$

τ_T~0.1-1 for X-ray corona, λ_{Edd}~0.5
ξ_B >~ 0.1 leads to **β <~ 1**





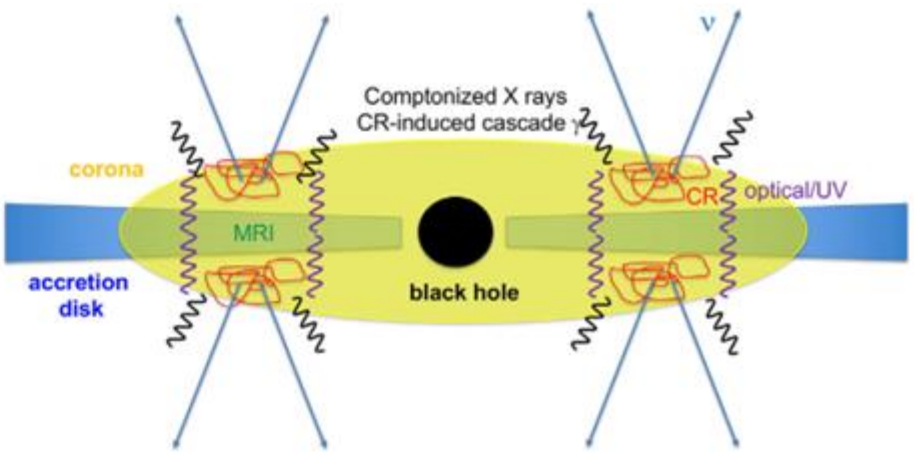
$R \leq 15\ R_S$ for low-β plasma (synchrotron dominated)

$R \leq 3\ R_S$ for high-β plasma (IC dominated, smaller than ISCO for non-rotating BH)

Emission region and acceleration mechanism

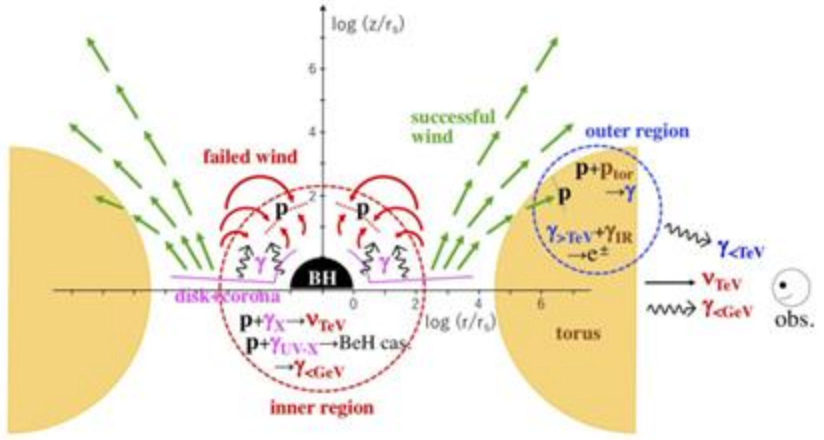
Magnetic corona model favored by low-β plasma

disk-corona



Murase+ (2020)

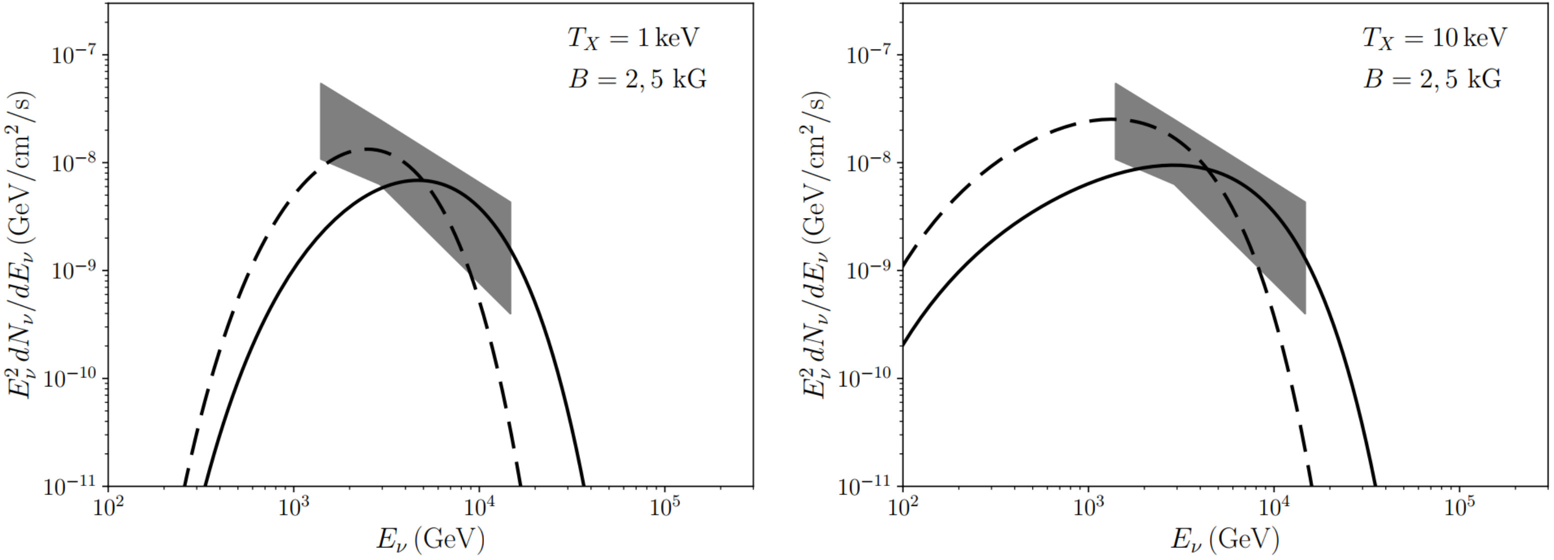
failed winds/ accretion shock



S. Inoue+ (2022)

Leptonic scenario

In principle, neutrinos can be produced by two-photon annihilation and muon-antimuon pair production. (Li & Waxman 2007 for neutrino production in intergalactic space)

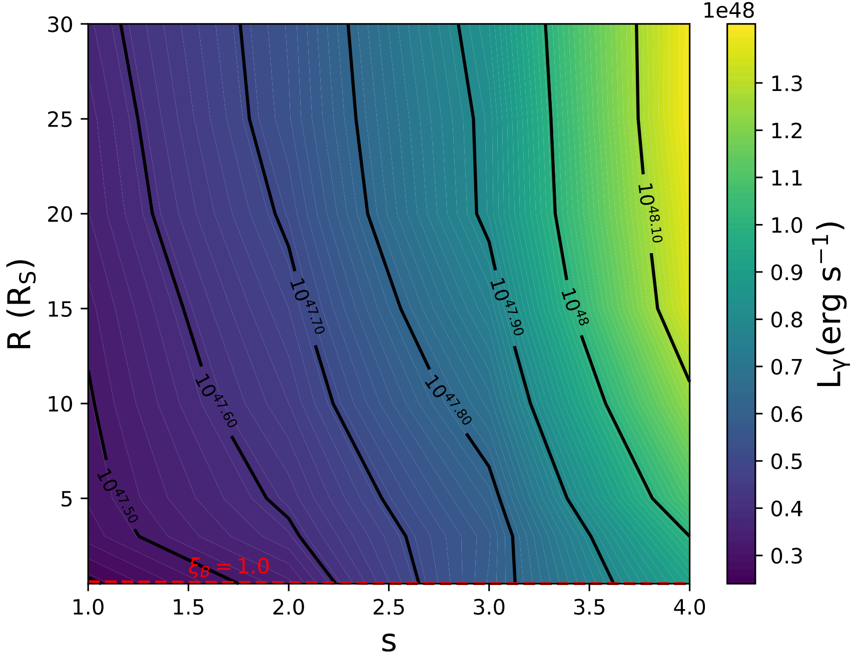


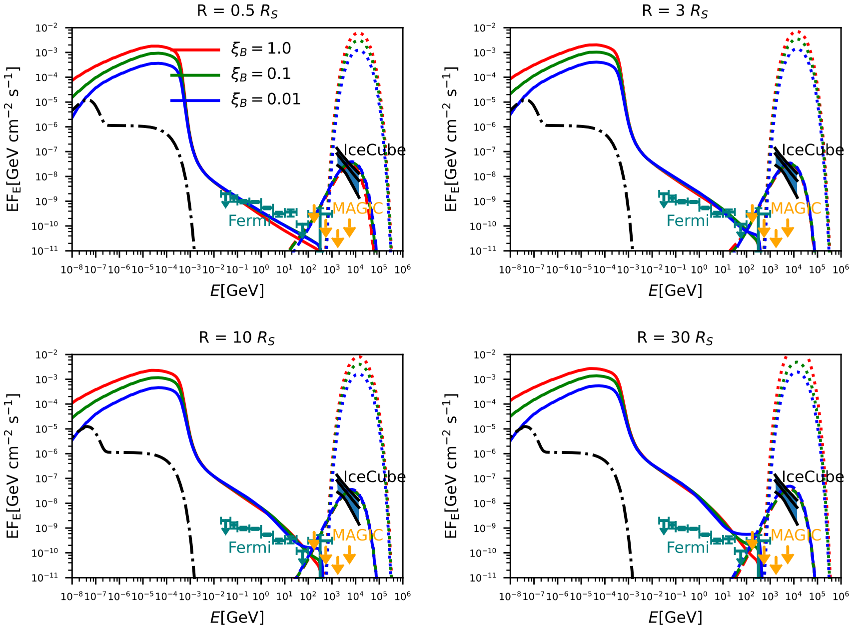
$$\gamma\gamma \rightarrow \mu^+\mu^-$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e + e^- + \nu_\mu + \bar{\nu}_e$$

Hooper & Plant (2023)

Leptonic scenario results

$$\frac{\tau_{\gamma\gamma\to e^+e^-}}{\tau_{\gamma\gamma\to\mu^+\mu^-}} \sim 2\times10^6\left(\frac{\tilde{L}_{\rm disk,\,44.7}}{\tilde{L}_{\rm cor,\,43.3}}\right)\Lambda_1, \quad \varepsilon_\nu \frac{dL_{\varepsilon_\nu}}{d\varepsilon_\nu}\approx \frac{2}{3}\frac{\tau_{\gamma\gamma\to\mu^+\mu^-}}{\tau_{\gamma\gamma\to e^+e^-}}\varepsilon_\gamma\frac{dL_{\varepsilon_\gamma}}{d\varepsilon_\gamma}$$



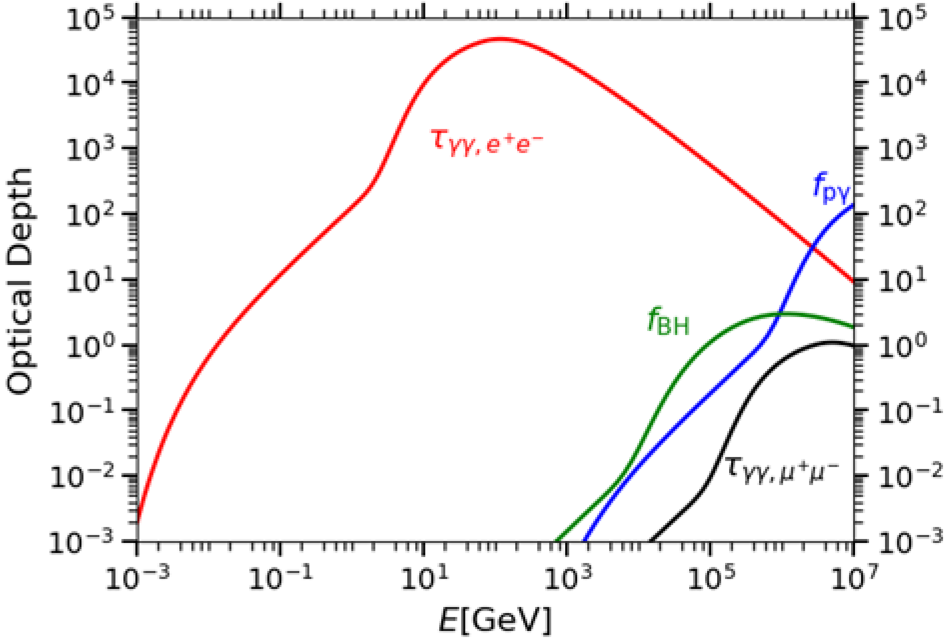


No viable parameter space found for physically motivated SED and magnetic field strengths.

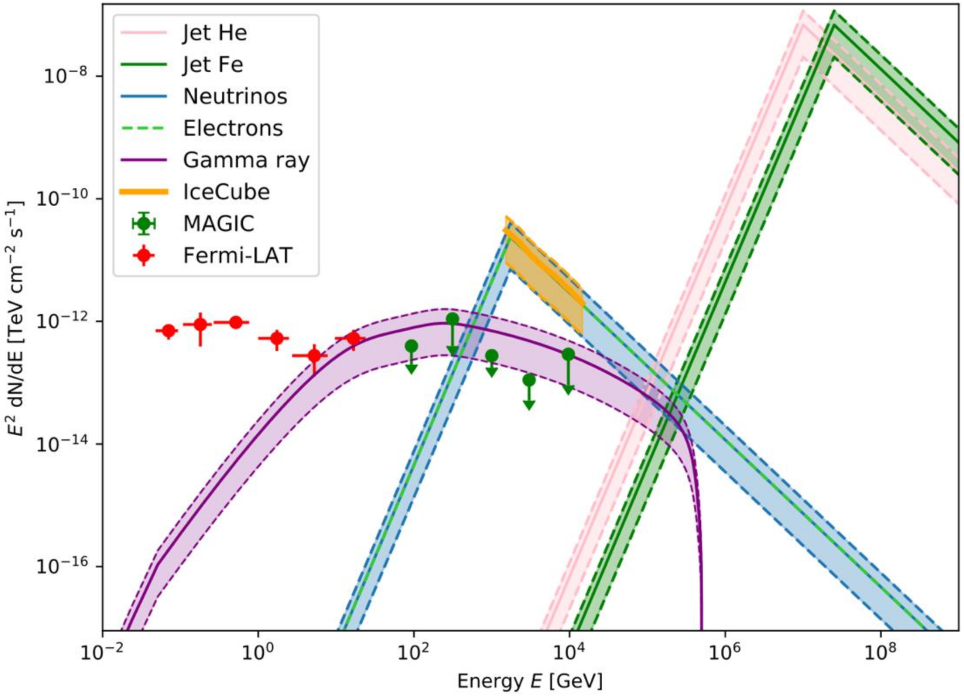
Optical Depth calculations

$$\varepsilon_{\gamma\gamma,\hat{e}^+e^-} = m_e^2c^4/\varepsilon_0$$
$$\simeq 0.13\mathrm{GeV}(\varepsilon_0/2\mathrm{keV})^{-1}$$

$$\varepsilon_{\gamma\gamma,\hat{\mu}^+\mu^-} = m_\mu^2c^4/\varepsilon_0$$
$$\simeq 5.6\times10^3\mathrm{GeV}(\varepsilon_0/2\mathrm{keV})^{-1}$$



Beta Decay scenario



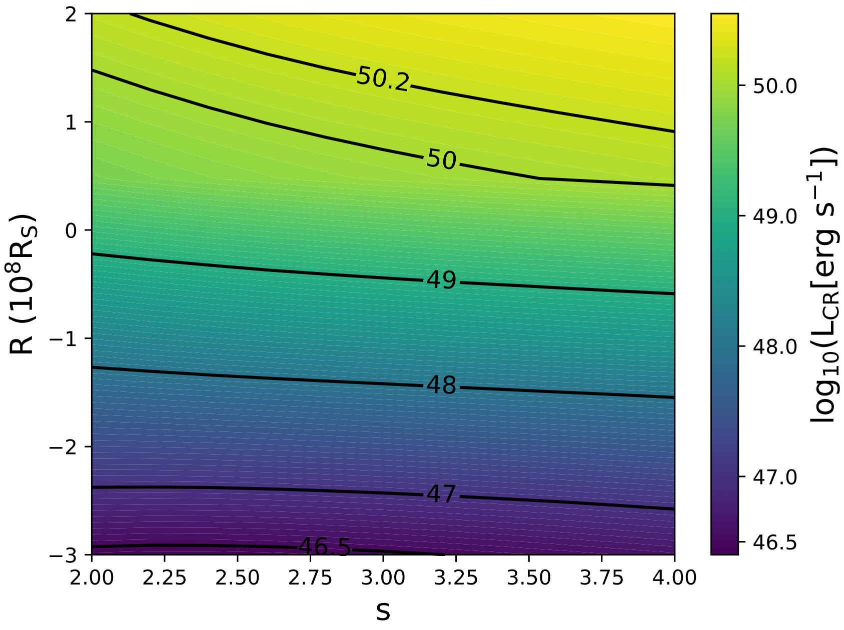
Yasuda et al. (2024)

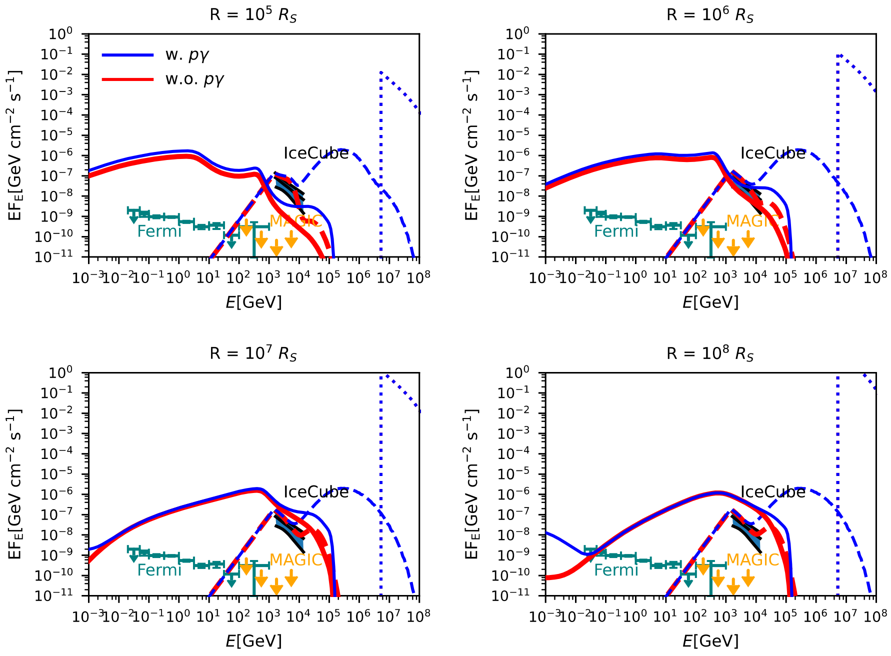
Photodisintegration of heavy nuclei accelerated by the jets produces neutrons, which undergo beta decay to form neutrinos.

Electrons from beta decay undergo IC scattering with CMB and EBL photons to produce gamma rays.

Emission region is located outside the dust torus if nuclei are accelerated in jets (Pe’er et al. 2009).

Beta Decay scenario results





No viable parameter space found upon considering Bethe-Heitler pair production (threshold for electron-positron production is lower than that for nuclear decay).

Summary & Conclusions

- Neutrino production from AGN strongly implies the acceleration of cosmic ray protons. Exotic models of neutrino production do not work if other relevant processes are included (violates limits set by EM observations).
- X-ray and gamma-ray observations set strong limits on the emission region. R $\leq 15\ R_S$ for low-β plasma and R $\leq 3\ R_S$ for high-β plasma (smaller than ISCO for non-spinning black hole).
- Emission region must be very close to the SMBH (magnetized corona). Disk-corona model (stochastic acceleration) is favored while failed line-driven wind model (shock acceleration) is ruled out by energetics.

Thank you!