SOPRANO's Symphony: Decoding Blazar Emissions in the Multimessenger Era

S. Gasparyan, D. Bégué, N. Sahakyan

February, 2024

Content

- Intro to SOPRANO
- Lepto-Hadronic Processes: Kinetics
- Discretization in SOPRANO
- High Redshift Blazars and SOPRANO
- Future Directions with SOPRANO

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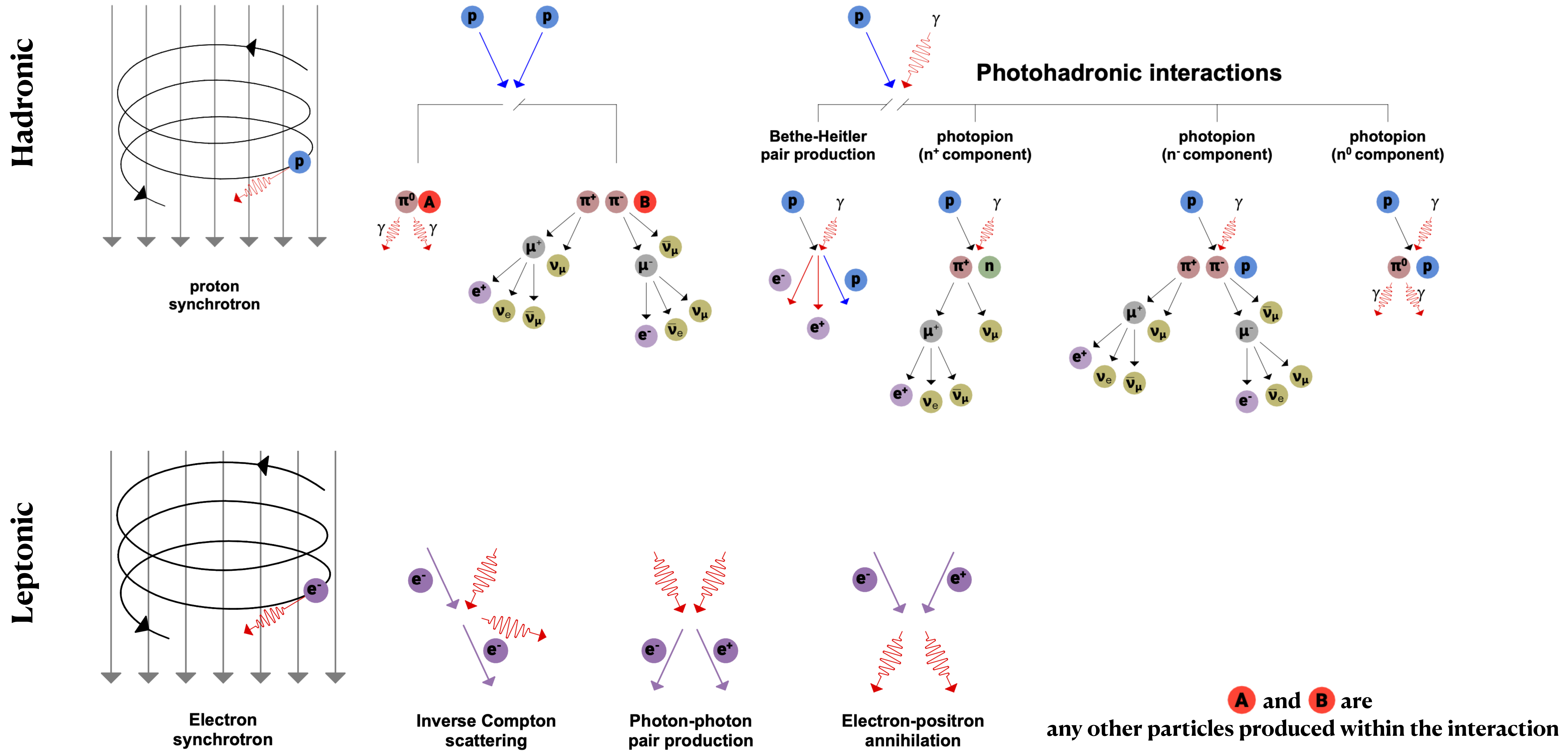
- Python interface (easy to use)
- Most of heavy iterations are executed through C
- Modular structure, i.e. new processes can be easily added (or removed)
- Preserves conservational properties (energy-always, particle number-when required)

Lepto-Hadronic Processes



Kinetic Equations

$$\frac{\partial N_p}{\partial t} = C_{p\gamma\to p\pi} + C_{p\gamma\to e^+e^-} + C_{\rm synch} - S_{\gamma p\to n\pi} + Q_{\gamma n\to p\pi}$$

$$\frac{\partial N_n}{\partial t} = - S_{n\gamma\to p\pi} + Q_{p\gamma\to n\pi} + C_{n\gamma\to n\pi}$$

$$\frac{\partial N_{\pi_\pm}}{\partial t} = Q_{p\gamma\to\pi} + Q_{n\gamma\to\pi} - S_\pi + C_{\rm synch}$$

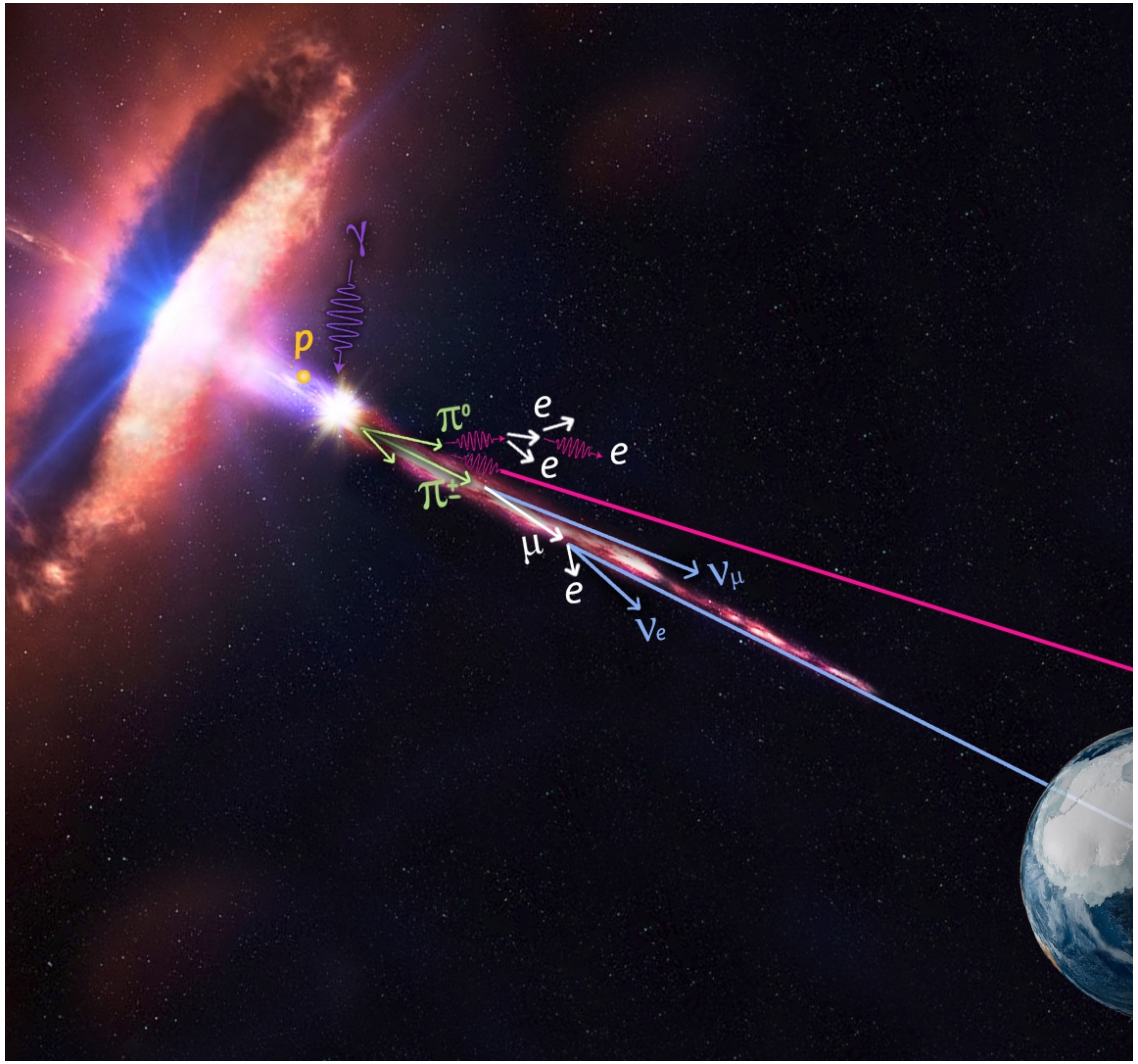
$$\frac{\partial N_\mu}{\partial t} = Q_{\pi_\pm} - S_\mu + C_{\rm synch}$$

$$\frac{\partial N_{\nu,\zeta}}{\partial t} = Q_{\pi_\pm} + Q_\mu$$

$$\frac{\partial N_{\rm e^\pm}}{\partial t} = Q_\mu + Q_{p\gamma\to e^+e^-} + Q_{\gamma\gamma\to e^+e^-} C_{\rm IC} + C_{\rm synch}$$

$$\frac{\partial n_{\rm ph}}{\partial t} = - S_{\gamma\gamma\to e^+e^-} + Q_{\pi_0} + R_{\rm IC} + \sum_i Q^i_{\rm synch}$$

Q: sink term
S: source term
C: cooling term



Extreme parameters are required: $E_p > 10^{19}$eV, $B > 30$ G etc.

Numerical Discretization

Core Principles

- Assumes homogeneous space
- Utilizes isotropic particle distributions

Energy discretization

- Implements Discontinuous Galerkin method (1st order)
- Guarantees particle number conservation

Temporal discretization

- Manages processes across diverse timescales
- Employs implicit time discretization for stability

Energy Discretization

Energy Discretization

Energy Grid Construction:

- Logarithmically spaced for precision across ranges.
- Specific cell allocations for photons, leptons, hadrons, and neutrinos.

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Particle	Number of cells	Minimum energy	Maximum energy
Photons :	150	$\nu = 10^{-2}$Hz	$\nu = 10^{30}$ Hz
Leptons :	130	$\gamma_{e^\pm} = 1.2$	$\gamma_{e^\pm} 5 \times 10^{13}$
Hadrons :	100	$\gamma_h = 1.2$	$\gamma_h = 10^{11}$
Neutrinos :	100	$E_\nu = 10^{-3}$ GeV	$E_\nu = 10^{11}$ Gev

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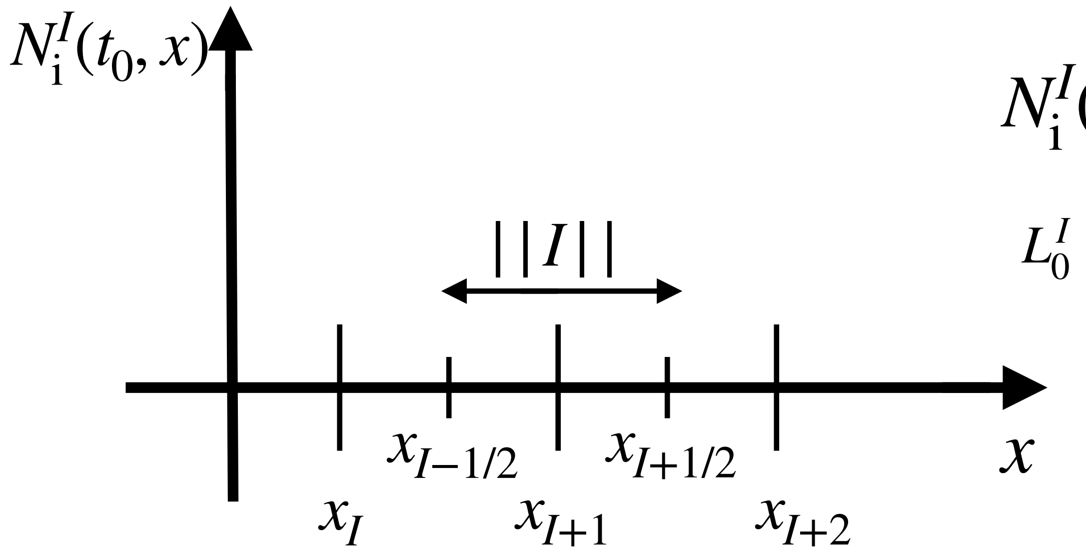
Distribution Functions:

- Each energy cell employs polynomial approximations.
- First-order Legendre polynomials are the basis function of choice.



$$N_i^I(t, x) = N_{i,0}^I(t) \times L_0^I(x)$$

$$L_0^I = \frac{1}{\sqrt{x_{I+\frac{1}{2}} - x_{I-\frac{1}{2}}}} \equiv \frac{1}{\sqrt{||I||}}$$

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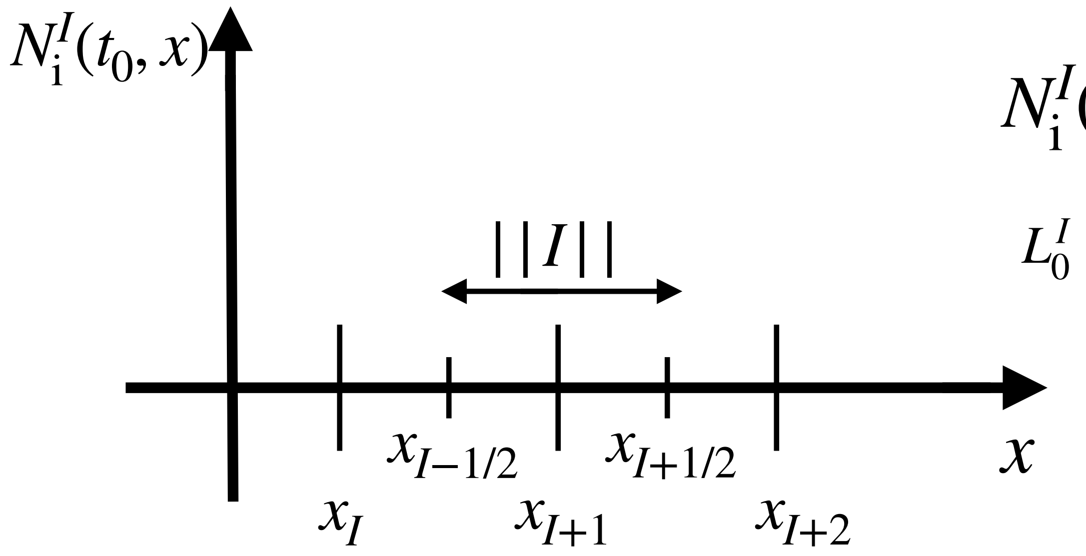

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Conservation and Integration:

- Finite volume method ensures accurate particle number conservation
- Integrates particle fluxes across energy cell boundaries
- Enforces energy conservation through strategic flux choices for diffusion-like terms and redistribution

Example of Discretization : Compton Scattering

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$$\frac{\partial n_{\mathrm{ph}}}{\partial t}(x_2) = \int_\gamma \int_{x_1} d\gamma dx_1 R(\gamma, x_1 \rightarrow x_2) N_{\mathrm{e}^\pm}(\gamma) n_{\mathrm{ph}}(x_1)$$

$$-n_{\mathrm{ph}}(x_2) \int_\gamma \int_{x_1} d\gamma dx_1 R(\gamma, x_2 \rightarrow x_1) N_{\mathrm{e}^\pm}(\gamma)$$

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$$\frac{\partial n^J_{\rm ph}}{\partial t} = \frac{1}{\sqrt{||J||}} \sum_k \sum_{I<J} \frac{N^k_{\rm e}}{\sqrt{||K||}} \frac{n^I_{\rm ph}}{\sqrt{||I||}} \sigma_{IKJ} - \frac{n^J_{\rm ph}}{||J||} \sum_k \frac{N^k_{\rm e}}{\sqrt{||K||}} \sum_{I>J} \sigma_{JKI}$$

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$$\downarrow$$

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- Adaptive Gauss-Kronrod Method
- More then 1M integrals
- Overall computation takes few months
- Computed once and got tabulated

Time Discretization

Time Discretization

Temporal Challenges:

- Diverse timescales in blazar processes require sophisticated temporal management

Implicit Time Discretization:

- Ensures numerical stability across varying process timescales
- All leptonic processes are solved with implicit methods for enhanced stability
- Non-linearity from Compton scattering and pair production addressed with Newton-Raphson method

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Semi-Implicit Scheme for Hadrons:

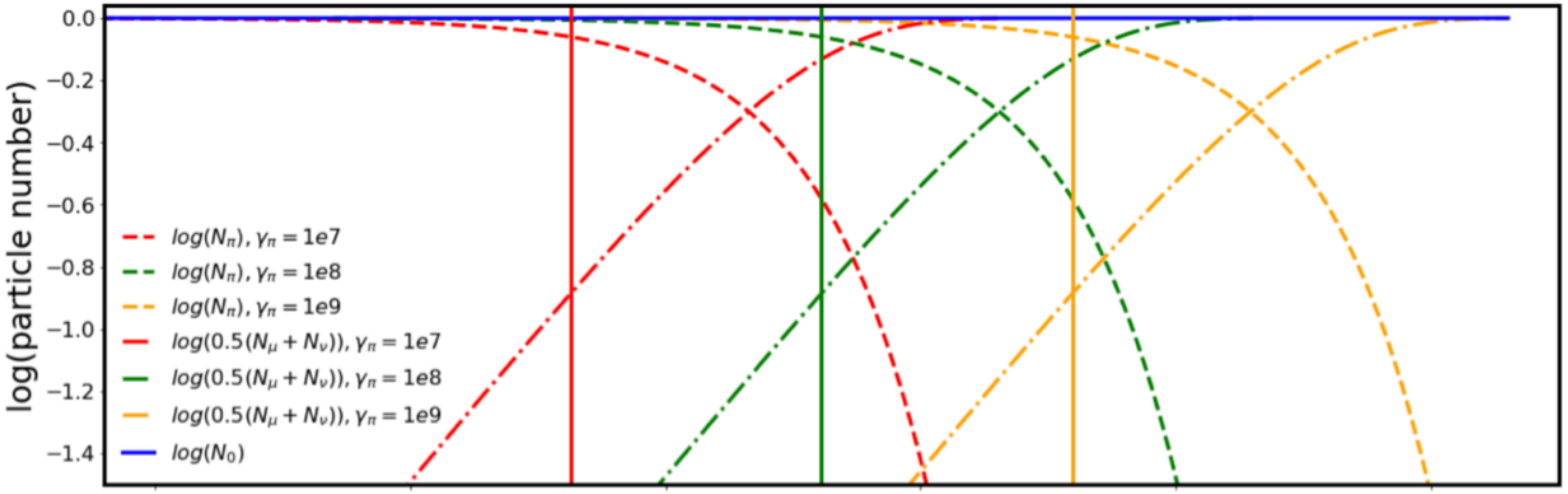
- The backward Euler method is adapted for photo-pion production
- Treats hadronic processes implicitly, photon spectrum explicitly
- Requires careful time step selection to accurately represent photo-pair and photo-pion interaction rates

Modeling Advantages:

- Linearizes hadron equations, isolating them from the rapid changes in the photon field
- Crucial for accurate simulations when photon-related timescales are significantly shorter

Energy and Number Conservation

Energy and Number Conservation



Evolution of the pion, neutrino and muon numbers as a function of time for the pion decay process

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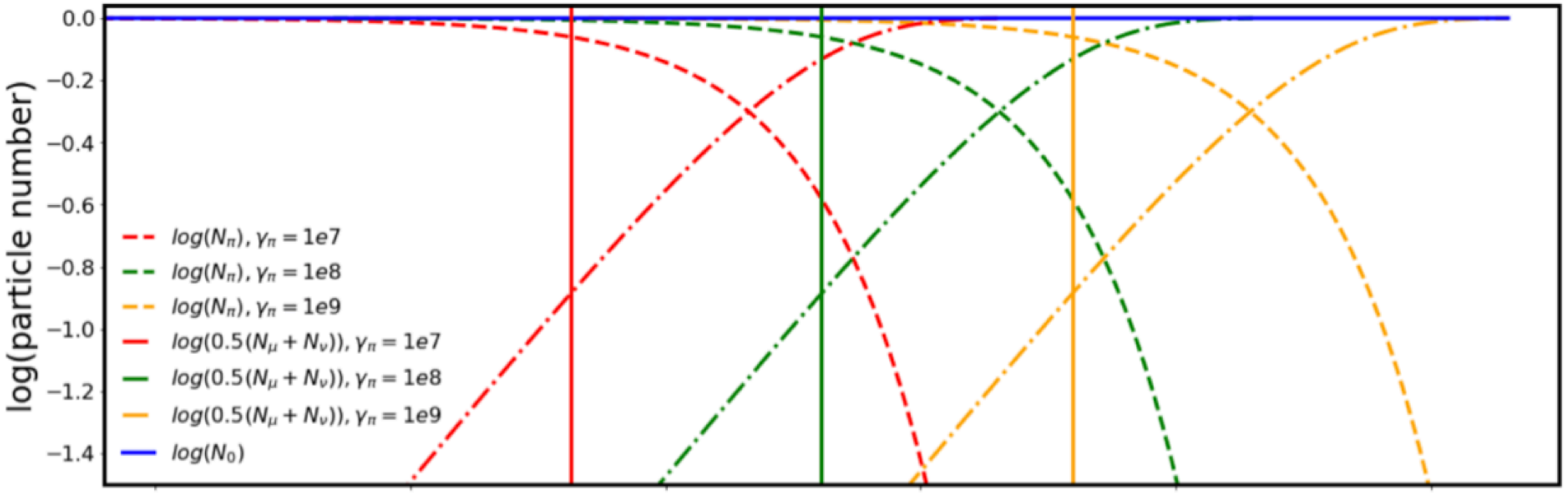

← **Evolution of the pion, neutrino and muon numbers as a function of time for the pion decay process**

✓ **The decay time is properly respected**

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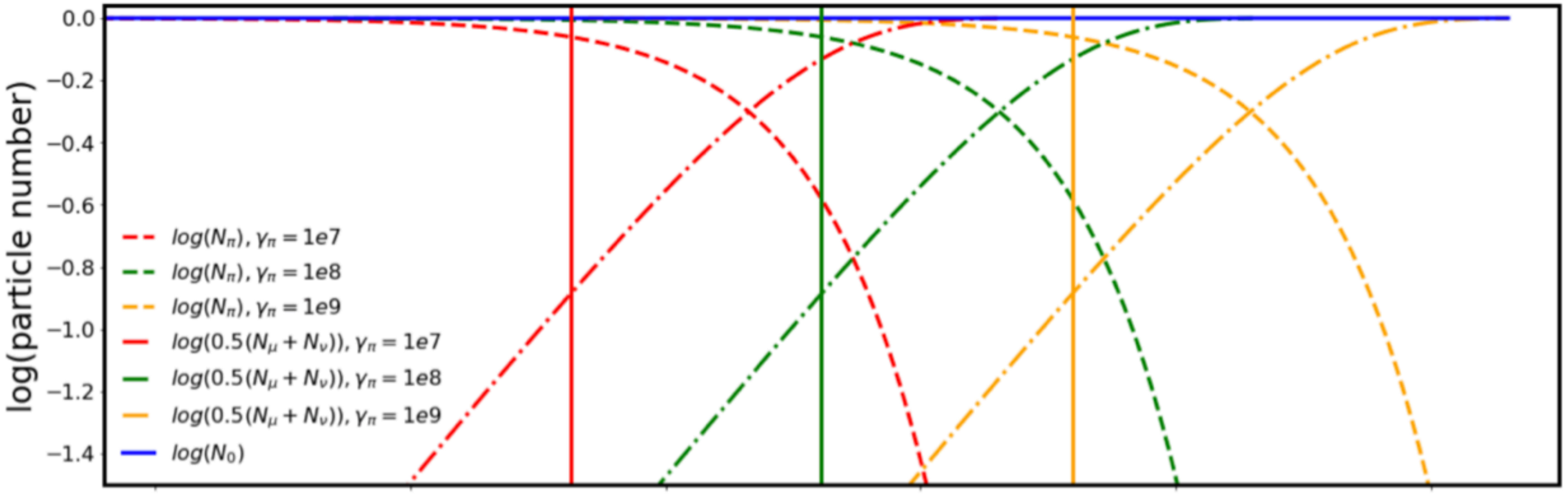

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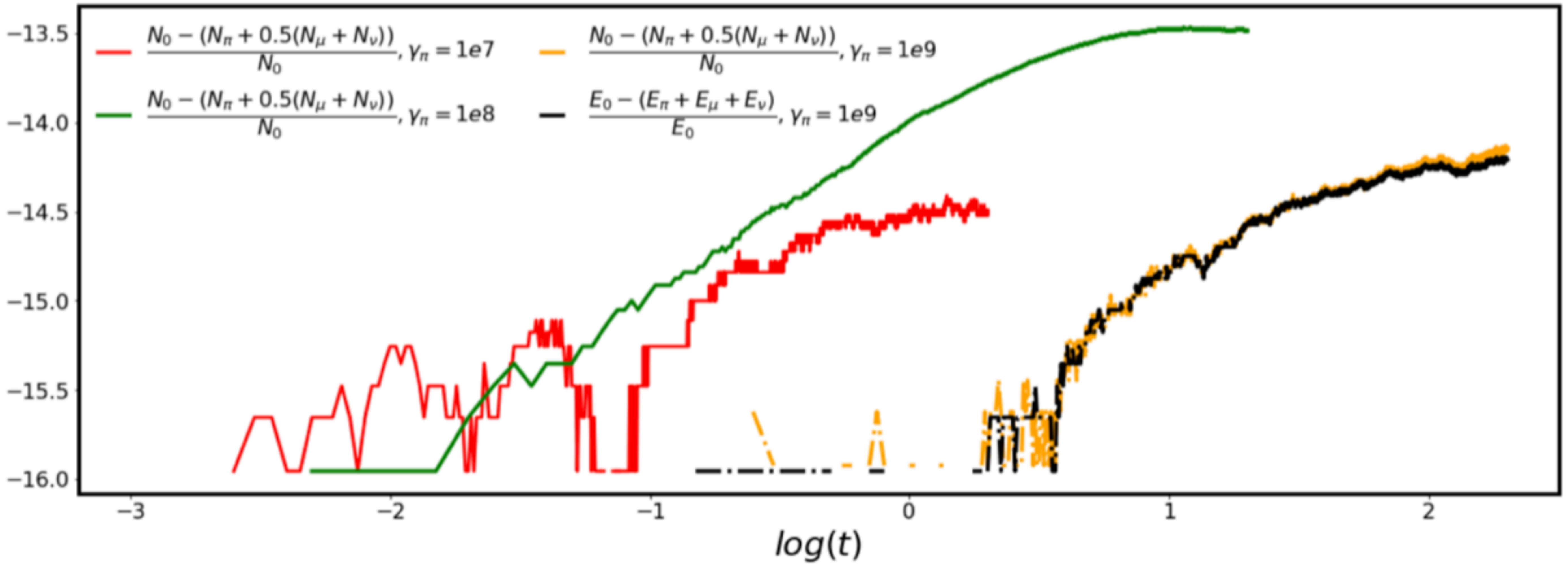

Temporal evolution of the particle number conservation and energy conservation.

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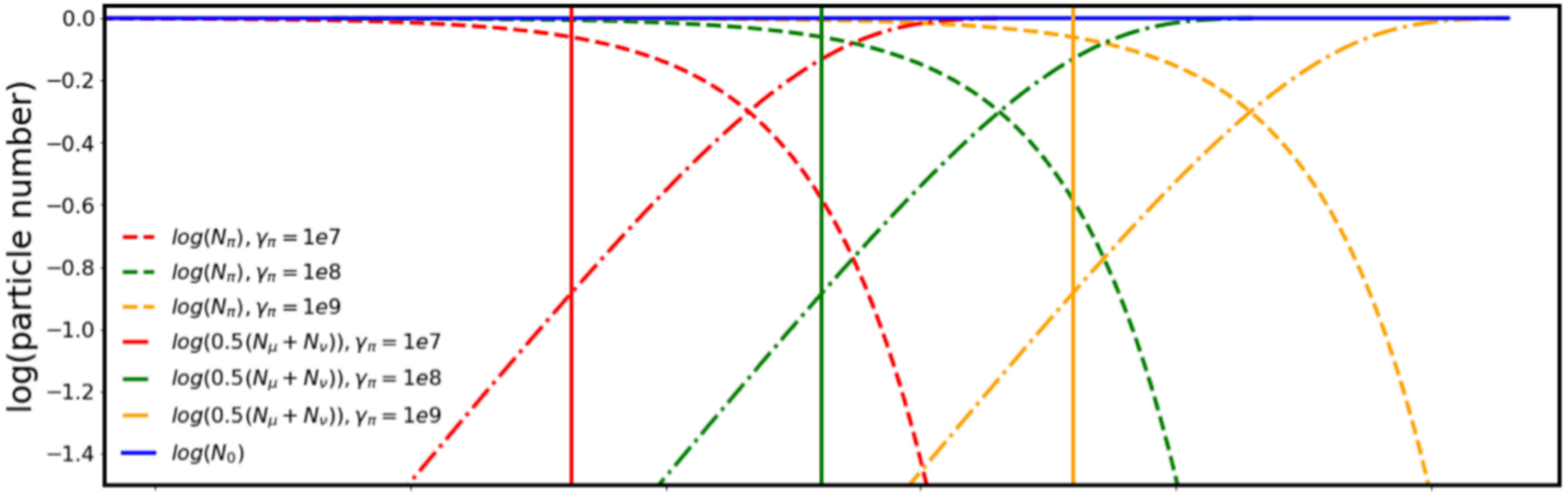

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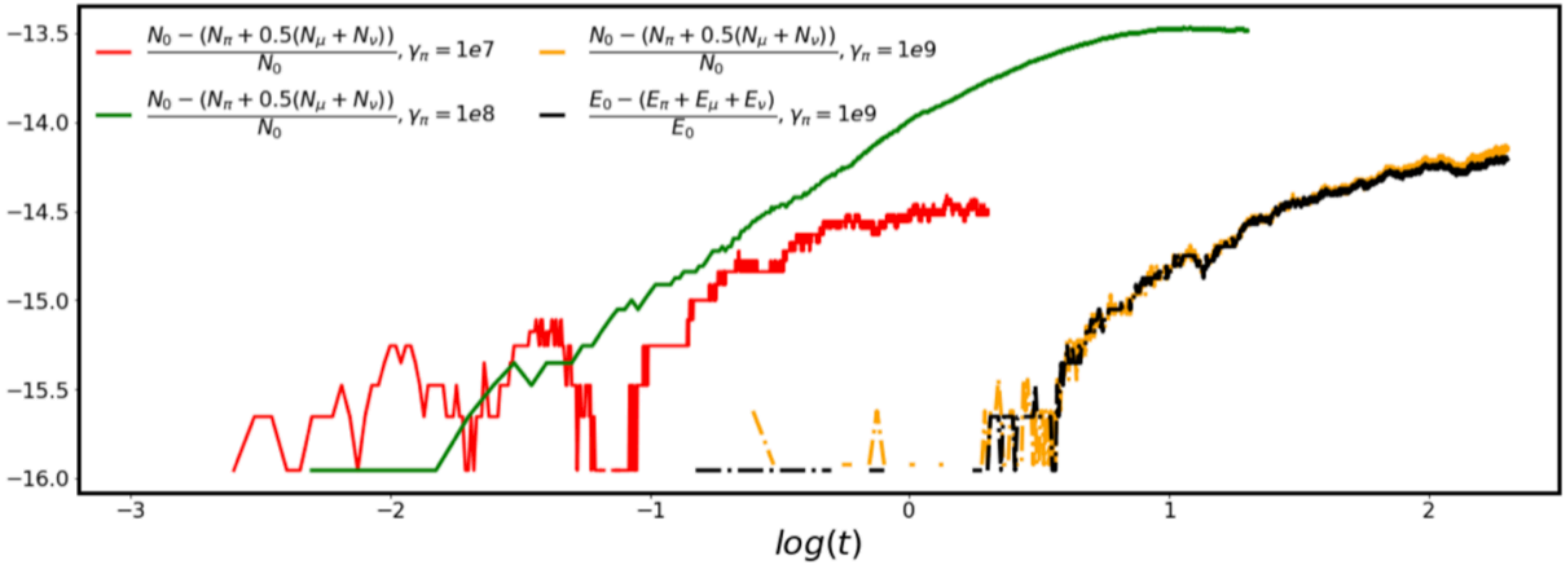

Temporal evolution of the particle number conservation and energy conservation.

✓ Particle and energy conserved up to machine precision

APPLICATIONS

SOPRANO's Insights on Neutrino-Candidate Blazars

- **SOPRANO Modeling:** Utilized for multi-messenger data analysis of neutrino-candidate blazars
- **Key Targets:** Focused on TXS 0506+056, 3HSP J095507.9+355101, 3C 279, and PKS 0735+178
- **Research Impact:** Resulted in several publications, contributing to the astrophysical community's understanding
- **Highlight on TXS 0506+056:** A recap of SOPRANO's findings on this particularly intriguing blazar

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- Hadronic scenario: Dominated by proton synchrotron radiation
- Lepto-hadronic scenario: Includes emissions from secondary pairs

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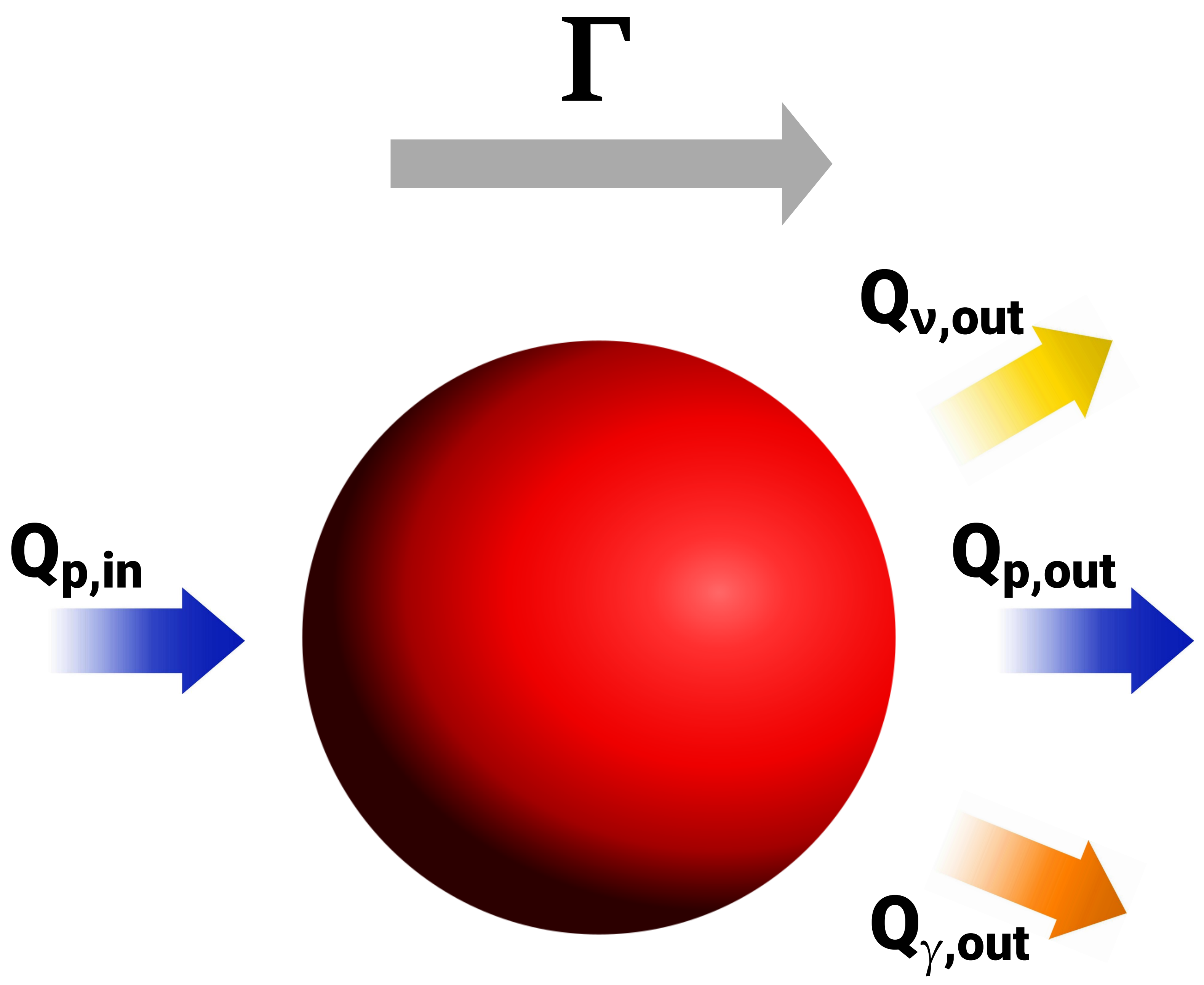
Simulation Environment:

- Single spherical emission zone with constant Lorentz factor
- Uniform magnetic field mirroring astrophysical jet conditions



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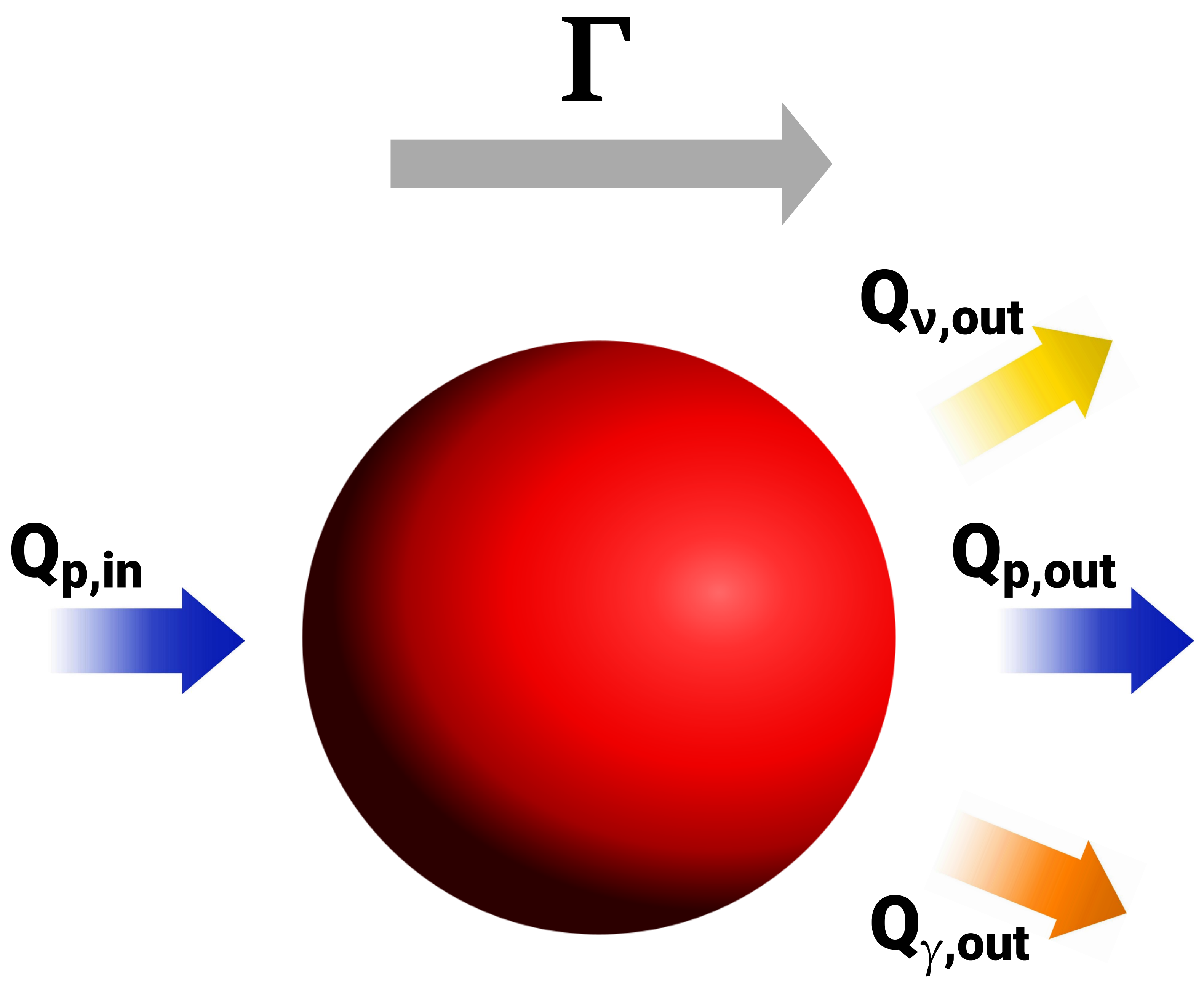
- Protons: Power-law distribution with exponential cutoff
- Electrons: Single power-law spectrum



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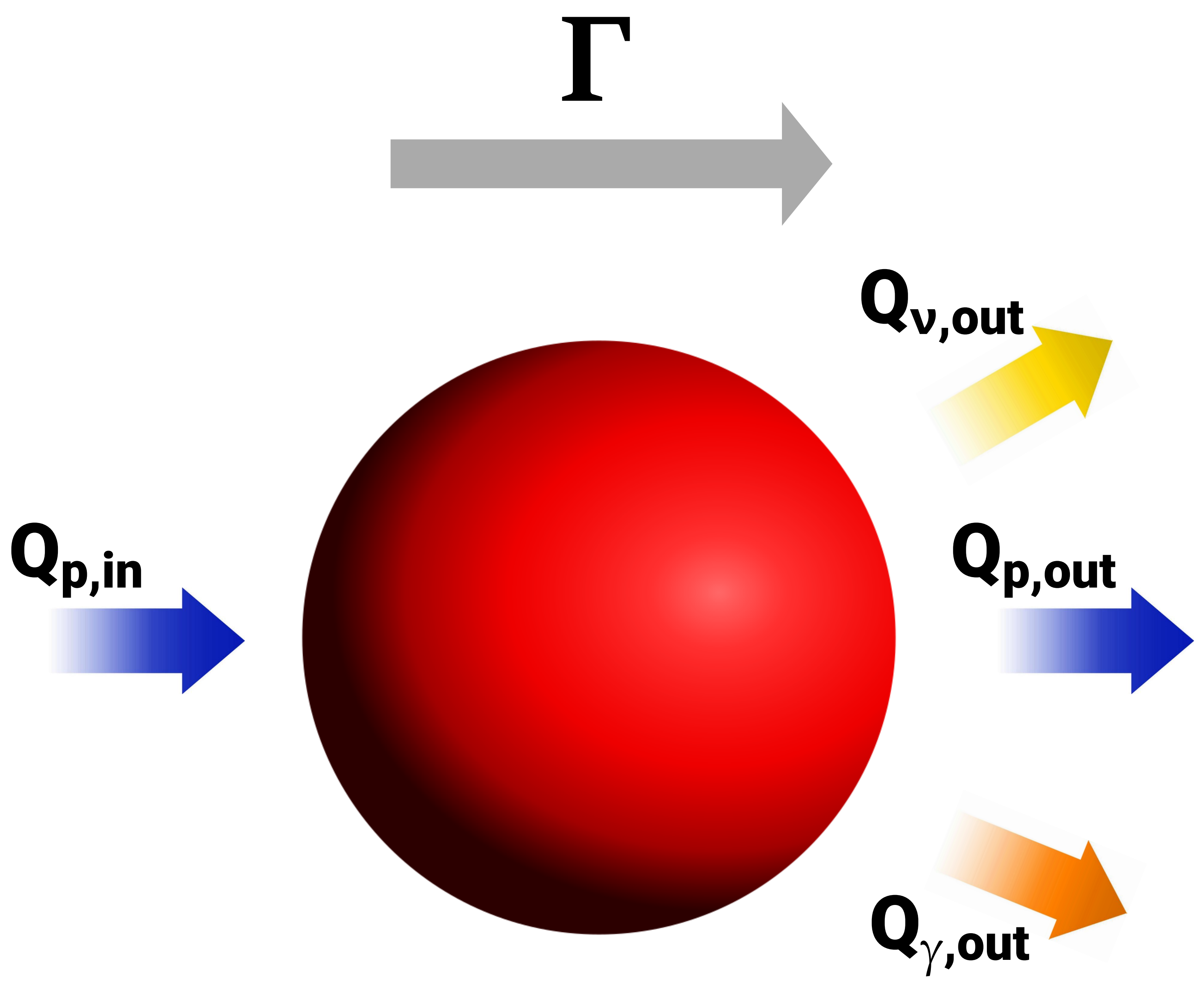
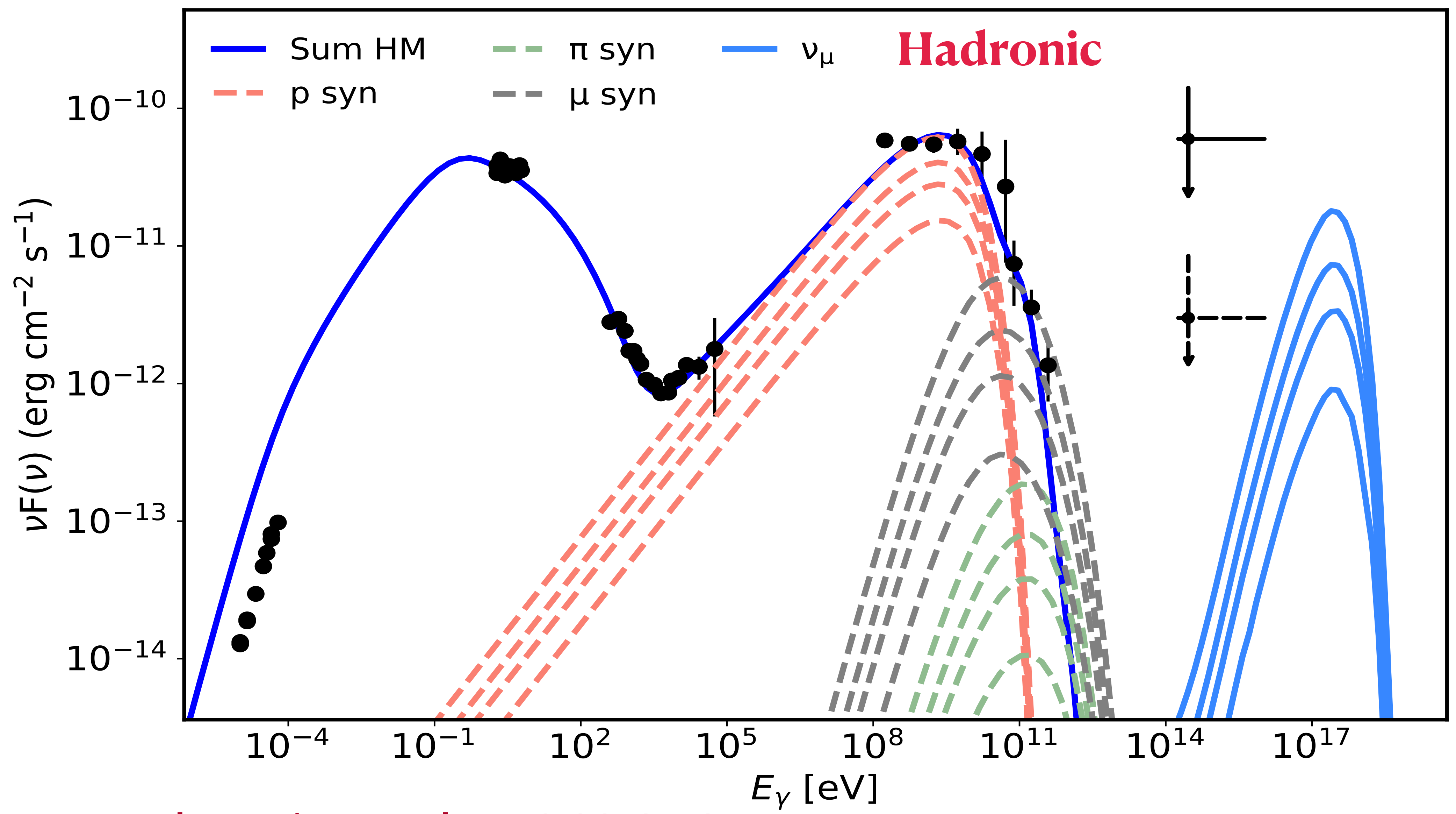
Tracking Particle Evolution:

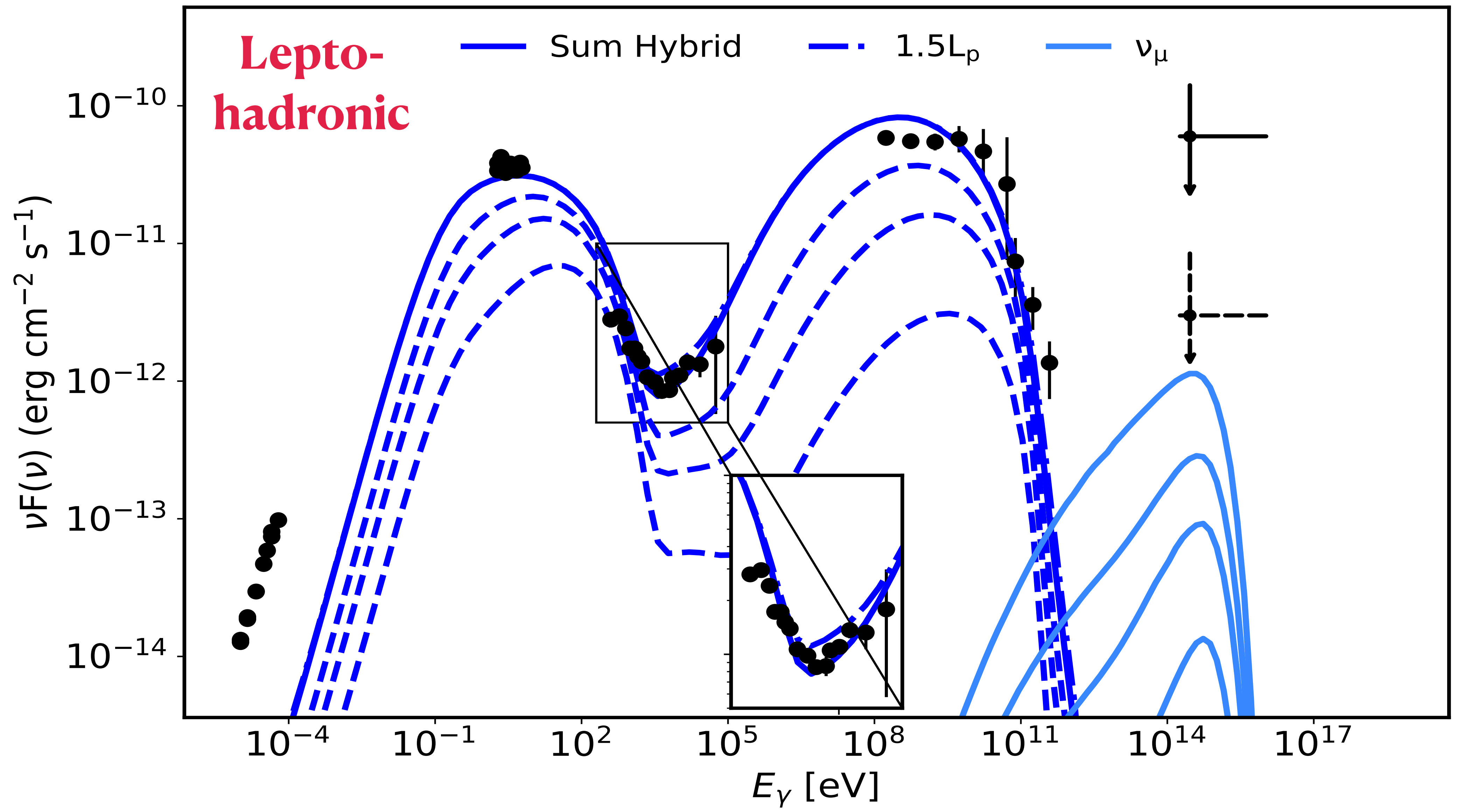
- Assumes escape time equals dynamical time scale for all particles
- Evolves kinetic equations across several time scales to reach a steady state



TXS 0506+056: 2017 event

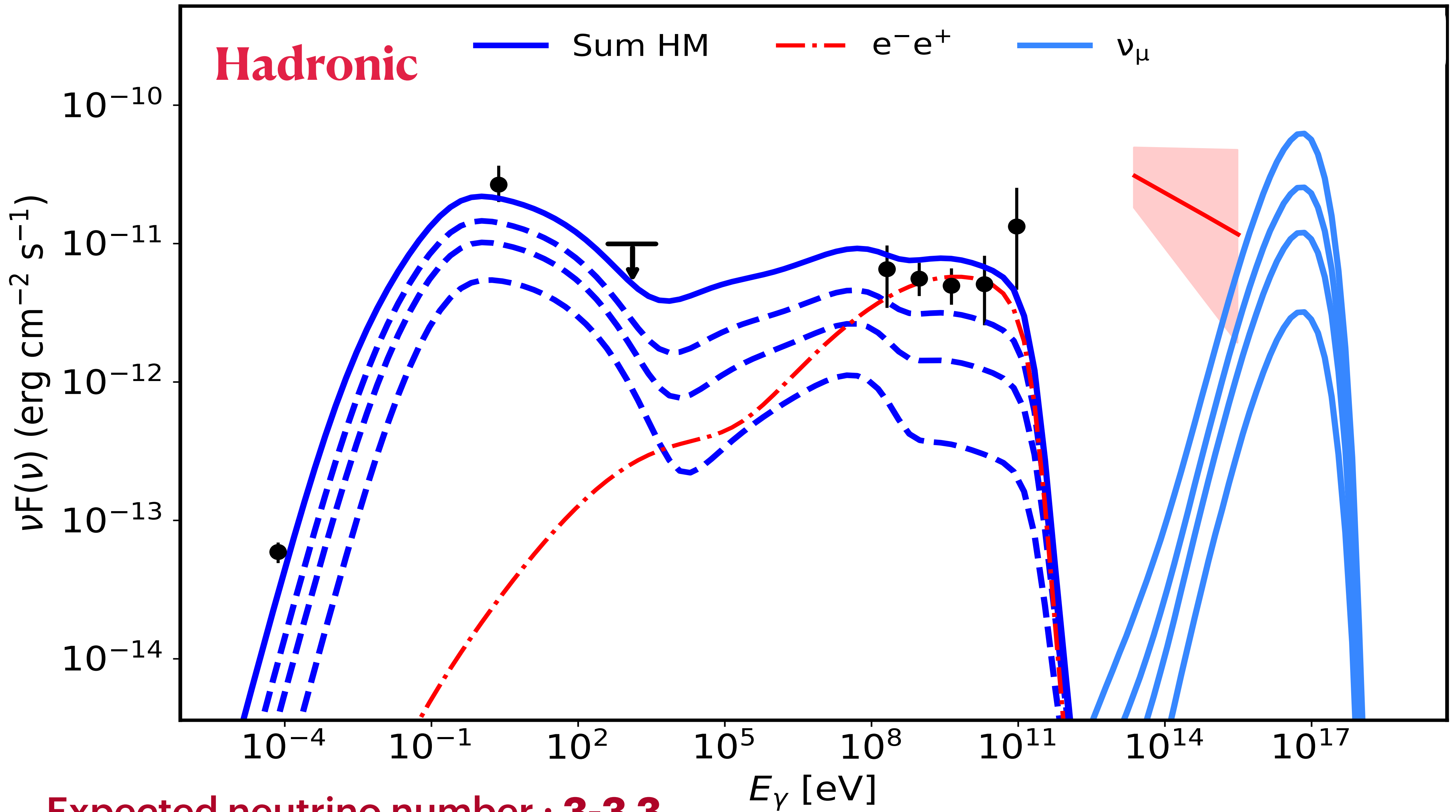


Expected neutrino number : **0,23-0,43**

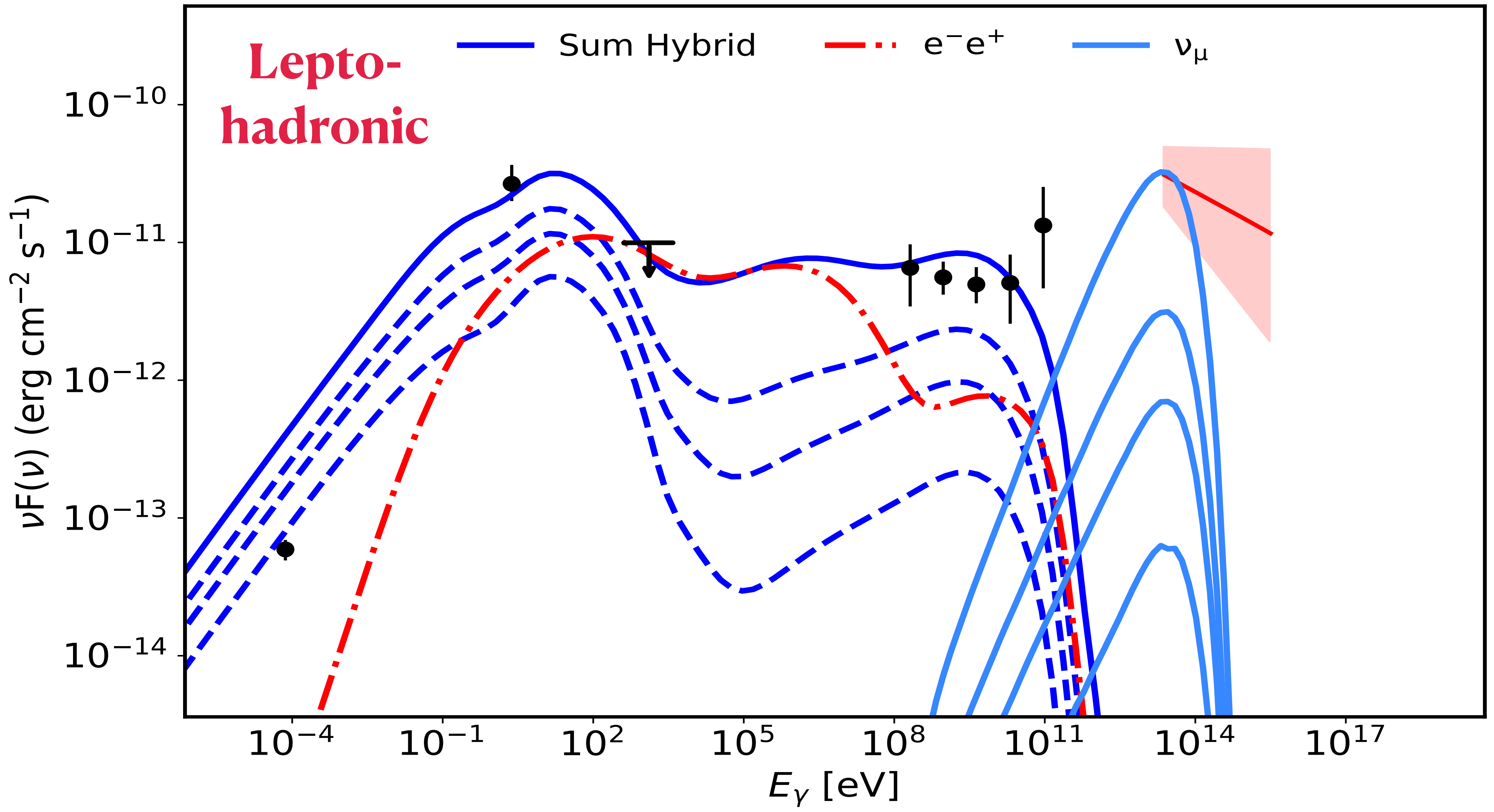


	Hadronic	Lepto-hadronic
δ	20	20
$R/10^{15}$ cm	2.5	10
B [G]	80	0.57
$\gamma_{e,min}$	100	1000
$\gamma_{e,cut}$	2.4×10^3	4.5×10^4
$\gamma_{e,max}$	3×10^4	6×10^4
α_e	2.1	2.0
$\alpha_p = \alpha_e$	2.1	2.0
$\gamma_{p,min}$	1	1
$\gamma_{p,max}$	10^9	10^6
L_e (erg s^{-1})	2.2×10^{44}	9.3×10^{44}
L_B (erg s^{-1})	6.0×10^{46}	4.9×10^{43}
L_p (erg s^{-1})	2.1×10^{47}	2.6×10^{50}

TXS 0506+056: 2014-15 flare



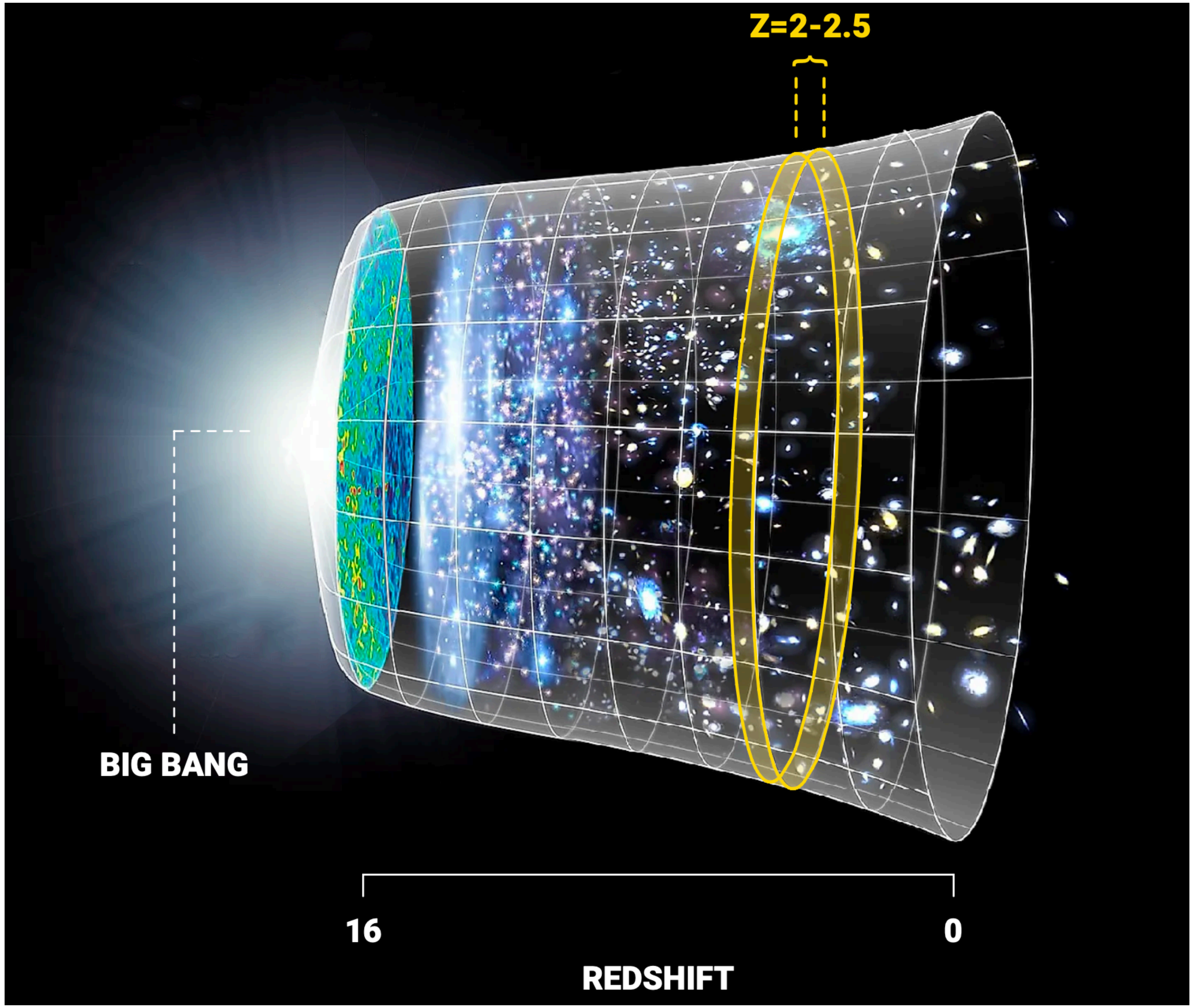
Expected neutrino number : **3-3,3**



	Hadronic	Lepto-hadronic
δ	15	10
$R/10^{15}$ cm	1	100
$B[G]$	35	0.65
$\gamma_{e,min}$	2×10^2	9×10^3
$\gamma_{e,cut}$	10^4	$=\gamma_{e,max}$
$\gamma_{e,max}$	8×10^4	8×10^4
α_e	2.0	2.0
$\alpha_p = \alpha_e$	2.0	2.0
$\gamma_{p,min}$	1	1
$\gamma_{p,max}$	2×10^8	1.2×10^5
L_e (erg s^{-1})	2.8×10^{44}	5.7×10^{43}
L_B (erg s^{-1})	10^{45}	1.6×10^{45}
L_p (erg s^{-1})	3.4×10^{47}	4.9×10^{52}

High Redshift Blazars and SOPRANO

- **Source Selection:** Analysis of 79 Fermi-detected blazars (64 FSRQs, 9 BL Lacs, 6 BCUs) with redshifts 2.0 to 2.5



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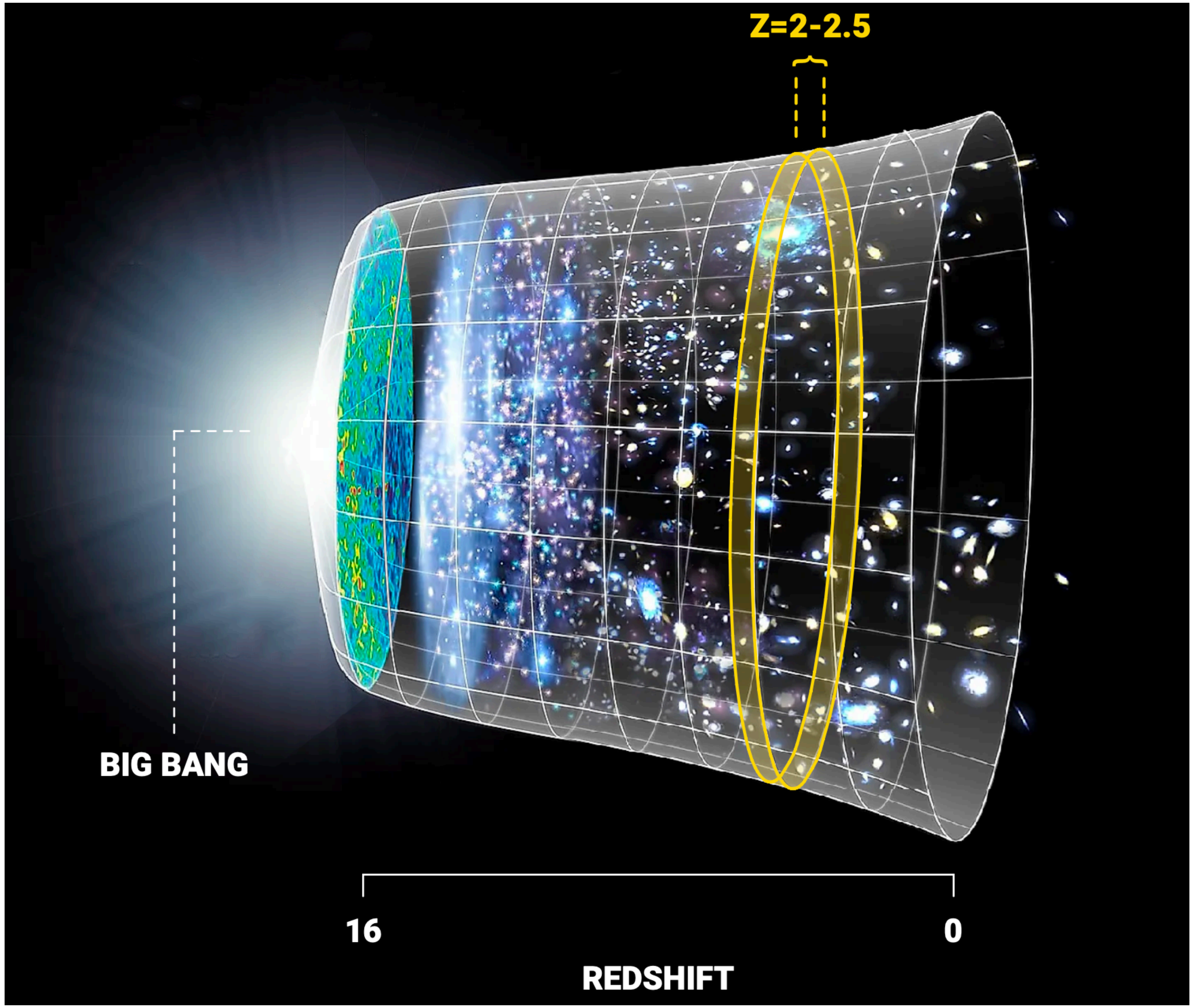

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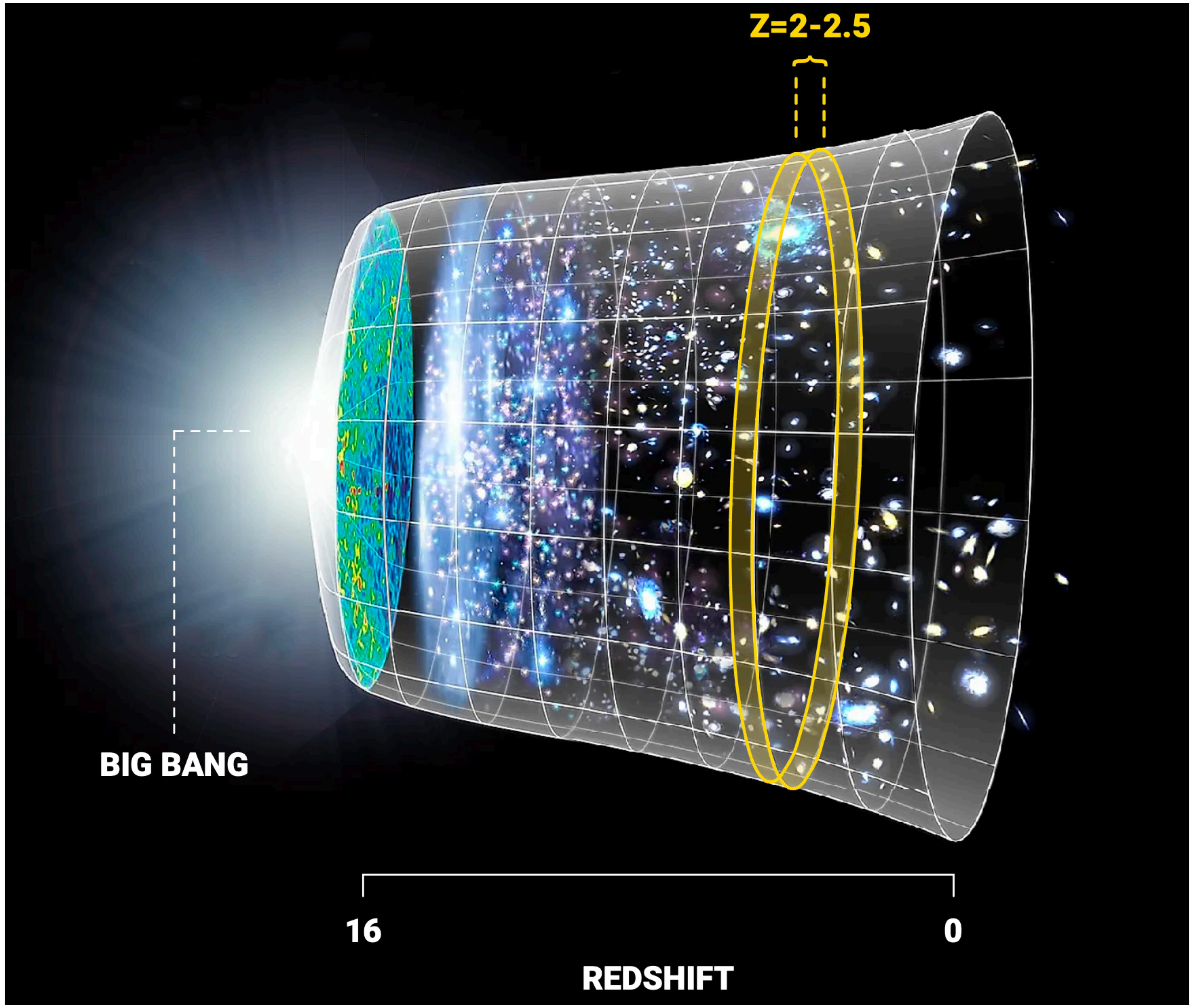
- **Modeling Scenarios:**
  Leptonic Model for average state analysis
  Lepto-Hadronic Model for flaring state insights



Leptonic Model

Sahakyan N., Harutyunyan G., Gasparyan S., and Israyelyan D., MNRAS, 2024, stae273

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Leptonic Model

Gamma-ray Band:

- Flux spans from 5.32×10^{-10} to 3.40×10^{-7} $photon\ cm^{-2}s^{-1}$
- Photon index between 1.66 and 3.15
- Illustrate diverse characteristics

Luminosity:

- Ranges from 3.67×10^{46} to 6.62×10^{48} $erg\ s^{-1}$
- Among the most brightest blazars detected in the γ-ray band

Flux Variability:

- Observed in 31 sources, most pronounced in 4C+01.02, 4C +71.07

Modeling with SSC/EIC scenario:

- Used to interpret multiwavelength SEDs
- Provides a view of emissions in average state

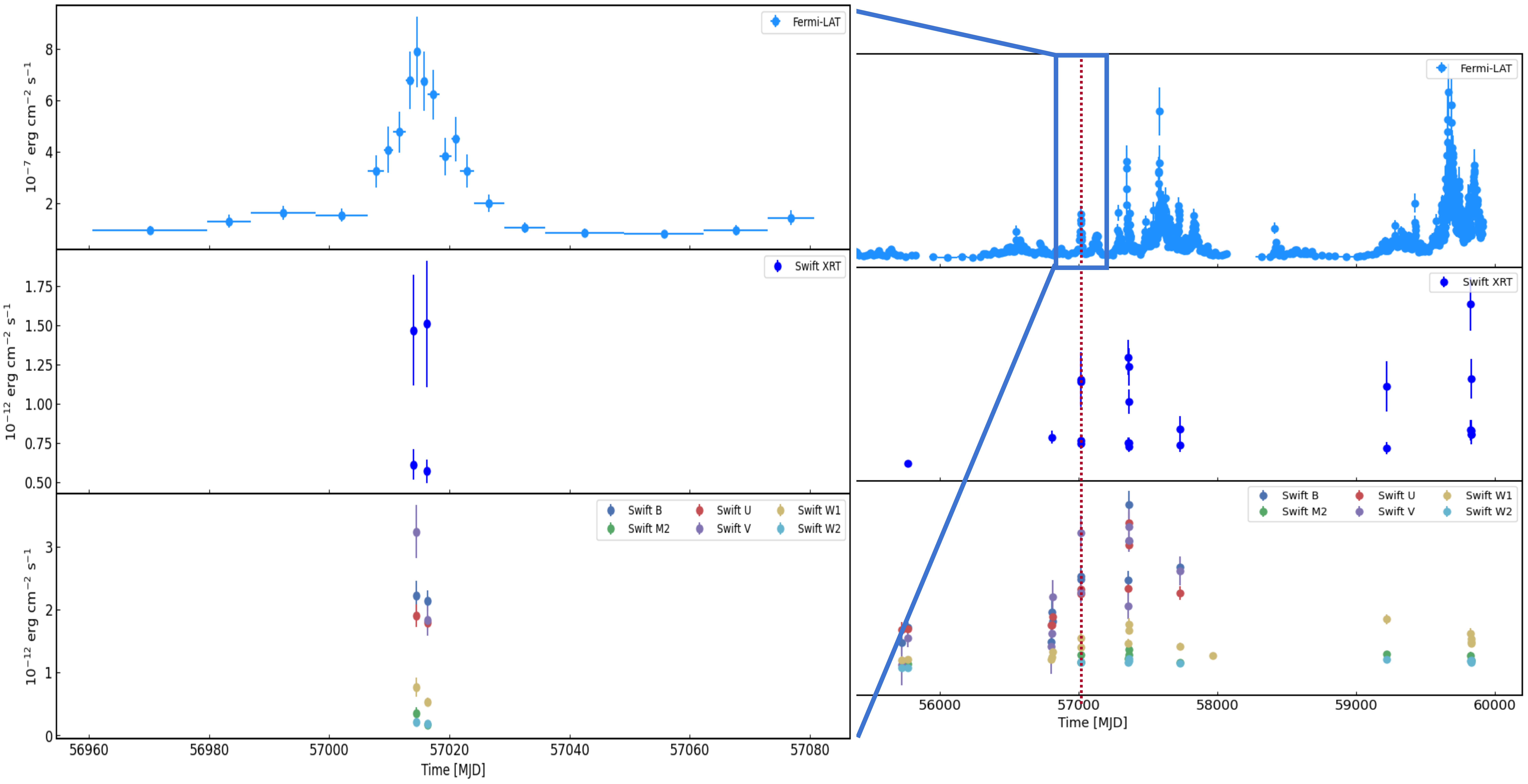
Jet and Disk Luminosity:

- Jet luminosity between 3.20×10^{44} and $6.51 \times 10^{45} erg\ s^{-1}$
- Disk luminosity from 4.15×10^{44} to 3.97×10^{47} $erg\ s^{-1}$

Source	δ	p	γ_{min}	γ_{cut}	B	L_D	L_e	L_B	L_p
S5 1053+70	18.42 ± 1.42	2.08 ± 0.21	69.49 ± 7.30	12.50 ± 1.22	3.96 ± 0.42	1.44	4.40	0.76	0.39
PMN J1344-1723	47.18 ± 1.66	2.10 ± 0.06	18.56 ± 1.83	35.32 ± 3.13	4.21 ± 0.27	0.84	2.93	0.08	0.70
PKS 1915-458	24.53 ± 1.14	2.29 ± 0.22	65.94 ± 6.50	4.09 ± 0.69	7.62 ± 0.80	4.14	4.55	0.24	0.62
PKS 0226-559	33.13 ± 2.03	1.56 ± 0.06	17.32 ± 2.23	27.07 ± 2.54	4.25 ± 0.33	7.68	4.37	0.12	0.45
PKS 0601-70	24.91 ± 1.20	1.92 ± 0.17	71.10 ± 6.49	6.39 ± 0.59	5.81 ± 0.62	3.23	3.28	2.43	0.34
B2 1436+37B	21.06 ± 0.96	2.00 ± 0.21	95.07 ± 10.48	4.69 ± 0.42	5.07 ± 0.57	0.75	2.64	1.71	0.25
2MASS J16561677-3302127	17.15 ± 0.22	1.93 ± 0.02	97.22 ± 1.59	14.50 ± 0.29	9.91 ± 0.24	33.50	6.39	2.56	0.42
TXS 1645+635	24.58 ± 0.94	1.92 ± 0.18	67.97 ± 8.10	3.87 ± 0.37	7.46 ± 0.70	1.28	1.70	2.40	0.21
PKS B1149-084	25.62 ± 0.93	1.92 ± 0.19	64.32 ± 6.41	4.86 ± 0.59	5.98 ± 0.39	1.98	1.64	4.50	0.19
S5 0212+73	23.24 ± 0.65	2.66 ± 0.14	207.00 ± 9.11	7.63 ± 0.73	8.48 ± 0.38	9.96	7.23	0.13	0.39
B2 0552+39A	13.93 ± 0.82	2.12 ± 0.07	105.80 ± 7.80	27.18 ± 2.45	6.91 ± 0.77	39.70	5.60	0.43	0.34
PKS 2149-306	25.83 ± 0.83	1.82 ± 0.04	83.20 ± 1.31	3.02 ± 0.12	5.14 ± 0.06	12.50	29.40	0.04	3.16
PKS 1430-178	26.31 ± 1.22	2.25 ± 0.17	43.81 ± 5.82	4.17 ± 0.62	9.80 ± 0.83	6.21	5.32	0.20	1.00
S3 0458-02	33.82 ± 1.37	2.21 ± 0.11	55.51 ± 7.02	7.16 ± 0.75	7.21 ± 0.59	6.08	6.60	1.09	0.93
PMN J0157-4614	22.59 ± 1.43	1.94 ± 0.21	133.10 ± 21.74	4.26 ± 0.68	6.59 ± 0.63	0.69	0.72	2.63	0.05
PKS 0420+022	26.55 ± 1.18	2.78 ± 0.14	48.92 ± 4.10	8.32 ± 0.95	8.01 ± 0.55	3.55	2.31	1.54	0.45
PKS 2245-328	24.98 ± 1.46	1.94 ± 0.23	47.52 ± 6.02	4.15 ± 0.51	8.18 ± 0.74	3.06	2.47	1.86	0.40
PKS B2224+006	21.38 ± 1.01	1.79 ± 0.20	29.27 ± 4.49	3.13 ± 0.38	8.02 ± 0.87	0.25	2.78	1.33	0.59
PKS 2244-37	26.04 ± 1.94	1.99 ± 0.25	63.82 ± 7.72	5.28 ± 0.96	10.89 ± 1.30	4.46	1.59	0.03	0.19
B2 0242+23	26.05 ± 1.26	2.10 ± 0.18	34.78 ± 4.12	4.95 ± 0.69	6.21 ± 0.48	1.93	3.08	0.69	0.62
4C +71.07	32.34 ± 1.30	2.24 ± 0.16	43.72 ± 3.72	4.38 ± 0.40	9.94 ± 0.52	23.20	22.70	0.14	4.23
PKS 2022+031	24.37 ± 1.31	2.18 ± 0.17	32.99 ± 3.38	11.10 ± 1.17	7.10 ± 0.84	0.12	2.32	0.96	0.45
MG2 J153938+2744	19.46 ± 0.80	2.12 ± 0.13	51.00 ± 3.55	8.96 ± 0.96	8.28 ± 0.52	0.30	1.50	8.67	0.20
S4 0917+44	27.14 ± 0.81	2.42 ± 0.11	69.94 ± 6.35	8.84 ± 0.67	5.32 ± 0.26	3.83	7.48	1.27	0.91
PMN J2135-5006	5.45 ± 0.21	2.85 ± 0.06	158.70 ± 14.13	355.10 ± 48.94	1.30 ± 0.10	0.66	3.23	2.85	0.18
OX 131	21.83 ± 0.77	1.60 ± 0.12	109.00 ± 10.71	13.76 ± 0.93	1.76 ± 0.10	0.41	4.30	0.04	0.21
PMN J1959-4246	20.98 ± 0.84	2.02 ± 0.17	57.41 ± 4.50	5.07 ± 0.63	7.88 ± 0.71	0.17	2.54	1.13	0.34
PKS 0446+11	23.19 ± 1.12	1.98 ± 0.17	16.67 ± 2.26	5.53 ± 0.73	5.34 ± 0.46	0.16	4.36	8.05	1.42
PKS 1329-049	22.29 ± 0.87	2.30 ± 0.16	69.16 ± 8.12	12.00 ± 1.99	3.62 ± 0.34	6.52	8.00	0.43	0.87
PMN J0134-3843	24.71 ± 0.98	2.54 ± 0.19	86.57 ± 8.43	4.61 ± 0.61	15.17 ± 0.90	9.01	1.59	1.40	0.19
87GB 080551.6+535010	26.16 ± 1.11	1.90 ± 0.20	59.01 ± 5.16	3.34 ± 0.34	4.58 ± 0.40	3.78	3.21	0.46	0.46
PKS B1043-291	26.98 ± 1.61	2.50 ± 0.20	56.45 ± 4.78	10.30 ± 1.28	9.58 ± 1.15	1.89	1.80	0.88	0.25
OM 127	22.03 ± 1.16	2.59 ± 0.14	49.91 ± 5.54	18.73 ± 3.19	7.31 ± 0.66	2.48	2.56	1.90	0.42
PKS 0227-369	20.02 ± 0.68	2.83 ± 0.09	81.14 ± 8.13	25.89 ± 2.97	5.32 ± 0.50	2.52	3.59	1.22	0.41
OF 200	15.55 ± 0.59	2.13 ± 0.11	38.66 ± 1.92	11.03 ± 0.68	5.45 ± 0.24	1.22	2.14	0.88	0.35
B3 0803+452	19.64 ± 0.94	2.28 ± 0.25	44.72 ± 5.38	3.17 ± 0.43	8.56 ± 0.77	1.35	2.11	3.03	0.42
4C +01.02	26.29 ± 0.98	1.88 ± 0.13	28.05 ± 2.99	5.55 ± 0.52	3.04 ± 0.19	2.08	9.23	5.25	1.88
PKS 1348+007	24.93 ± 1.94	1.70 ± 0.21	59.32 ± 8.57	7.87 ± 0.81	2.50 ± 0.29	0.04	2.95	2.19	0.27
SDSS J100326.63+020455.6	26.93 ± 0.76	2.03 ± 0.08	40.09 ± 1.28	7.69 ± 0.39	12.03 ± 0.28	1.12	1.75	0.13	0.27
PKS 0528+134	15.71 ± 0.87	2.15 ± 0.10	46.04 ± 5.30	20.93 ± 2.60	3.67 ± 0.25	0.80	7.91	0.90	1.01
TXS 0322+222	31.80 ± 0.99	2.12 ± 0.25	122.40 ± 11.04	2.38 ± 0.22	7.92 ± 0.58	4.45	3.51	0.51	0.32
4C +13.14	20.30 ± 1.03	1.72 ± 0.14	44.37 ± 5.16	4.10 ± 0.43	8.13 ± 0.62	11.00	3.38	1.21	0.49
PMN J0625-5438	12.52 ± 0.70	2.61 ± 0.23	200.50 ± 27.17	13.10 ± 2.07	5.12 ± 0.55	3.38	2.38	0.95	0.12
OX 110	24.62 ± 0.87	2.08 ± 0.08	29.37 ± 2.40	18.94 ± 1.26	4.89 ± 0.23	0.86	1.06	0.29	0.19
PKS 0549-575	27.49 ± 2.14	1.86 ± 0.21	37.63 ± 4.32	4.47 ± 0.43	6.42 ± 0.69	0.06	3.22	1.29	0.52
PKS B1412-096	5.24 ± 0.17	2.32 ± 0.14	199.30 ± 17.68	13.22 ± 1.08	3.17 ± 0.26	2.17	2.20	40.60	0.10

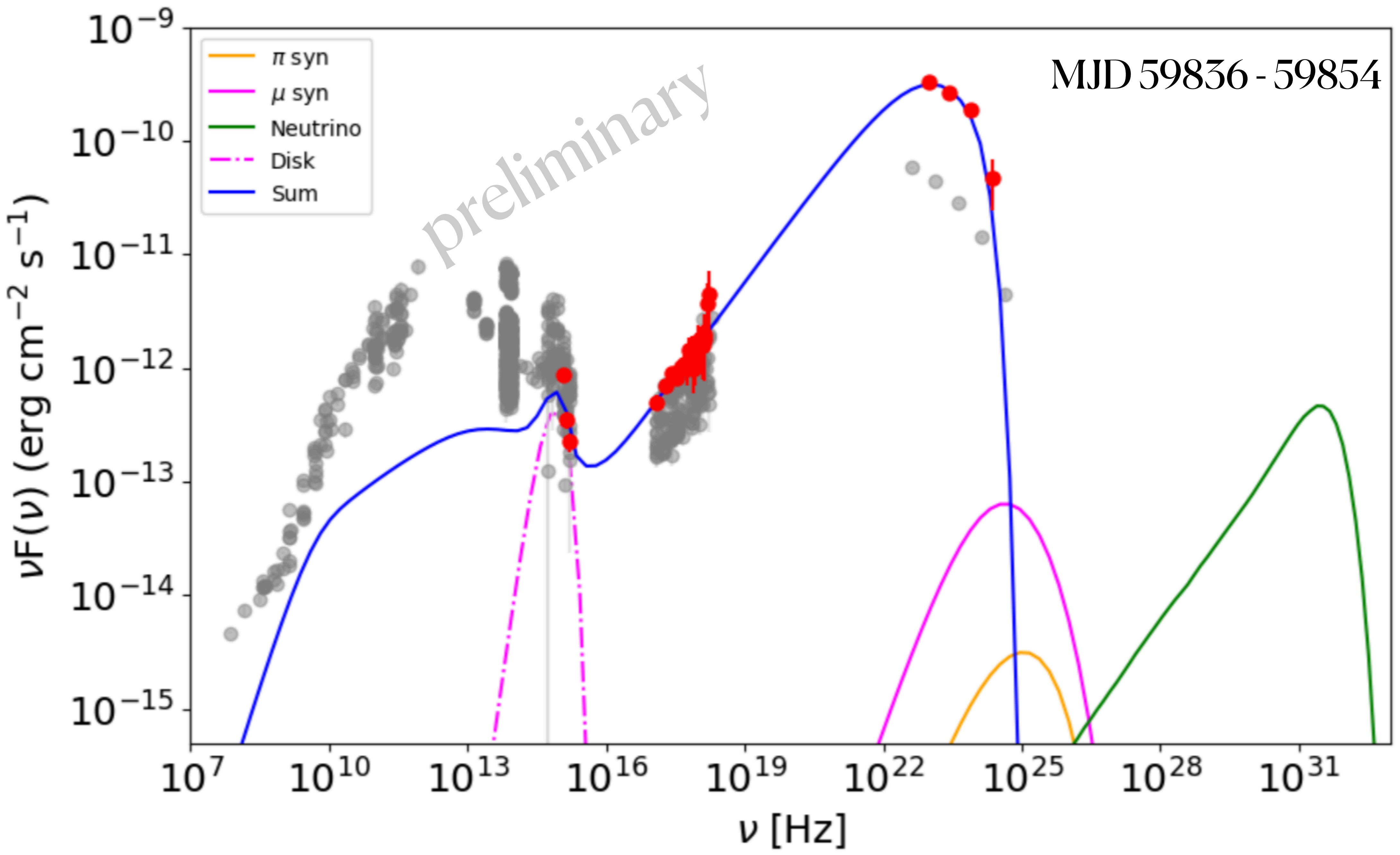
Sahakyan N., Harutyunyan G., Gasparyan S., and Israyelyan D., MNRAS, 2024, stae273

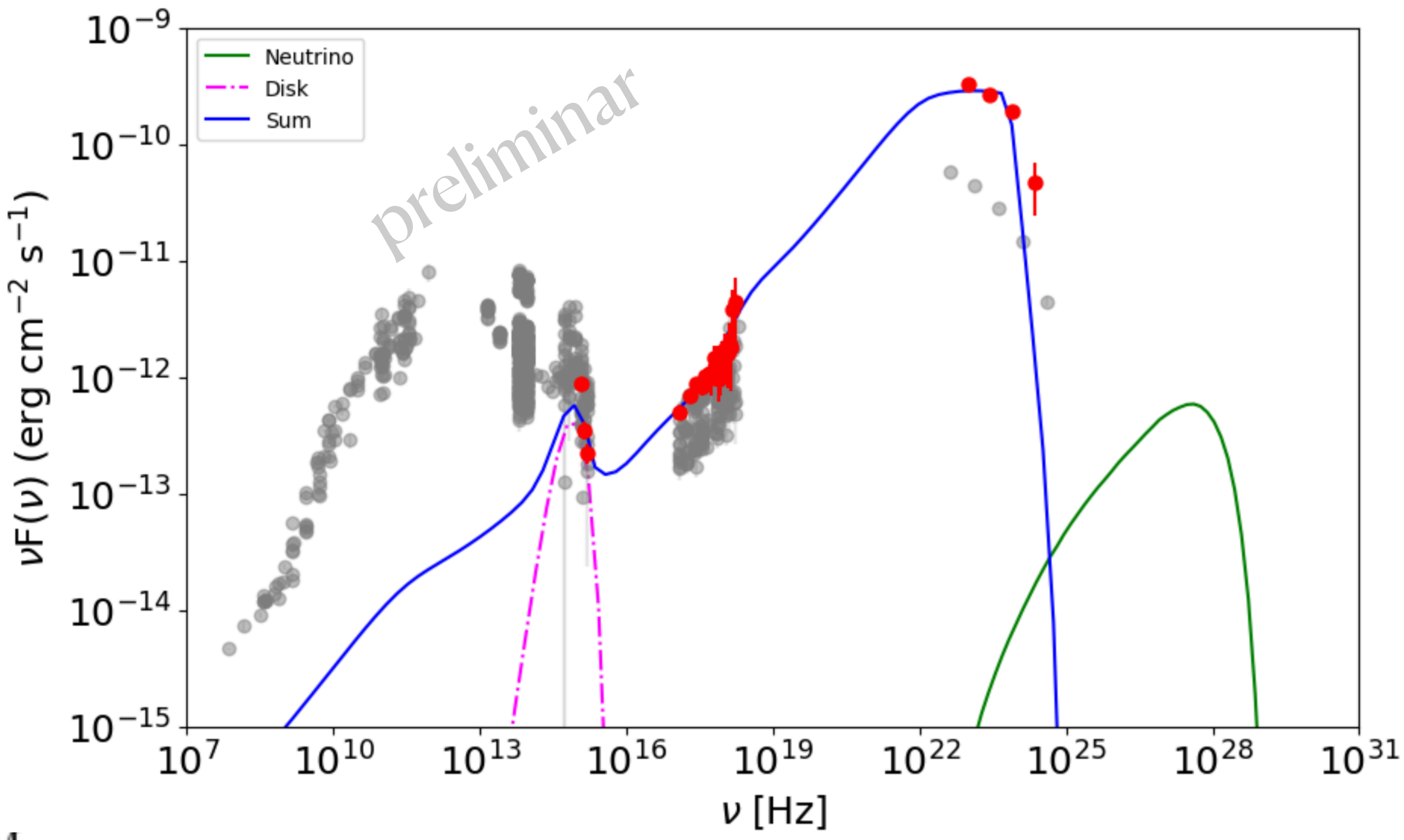
4C+01.02



Fermi-LAT
Swift XRT
Swift B
Swift U
Swift W1
Swift M2
Swift V
Swift W2
10^{-7} erg cm^{-2} s^{-1}
10^{-12} erg cm^{-2} s^{-1}
10^{-12} erg cm^{-2} s^{-1}
Time [MJD]
Time [MJD]

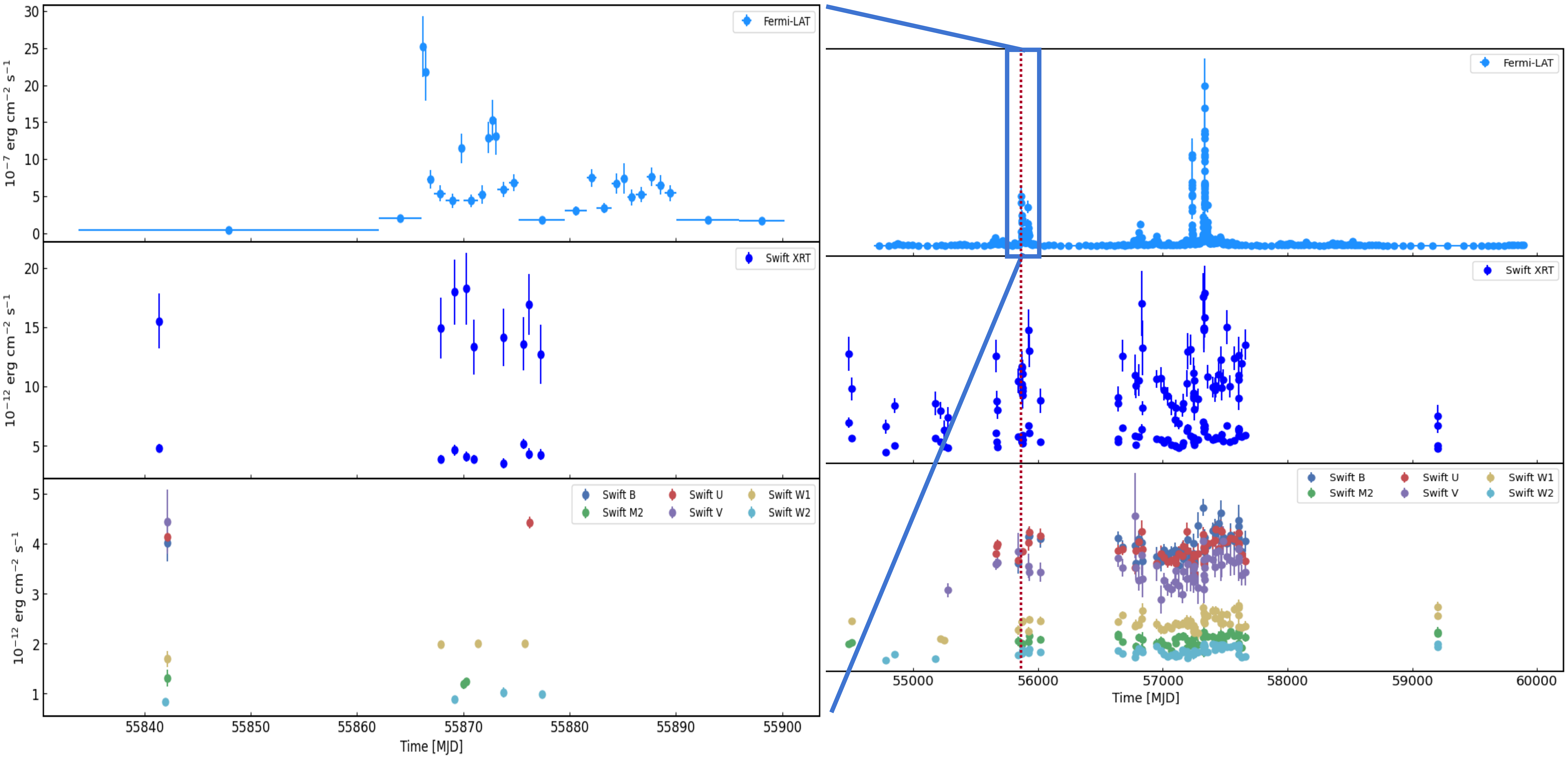
Lepto-Hadronic: 4C+01.02





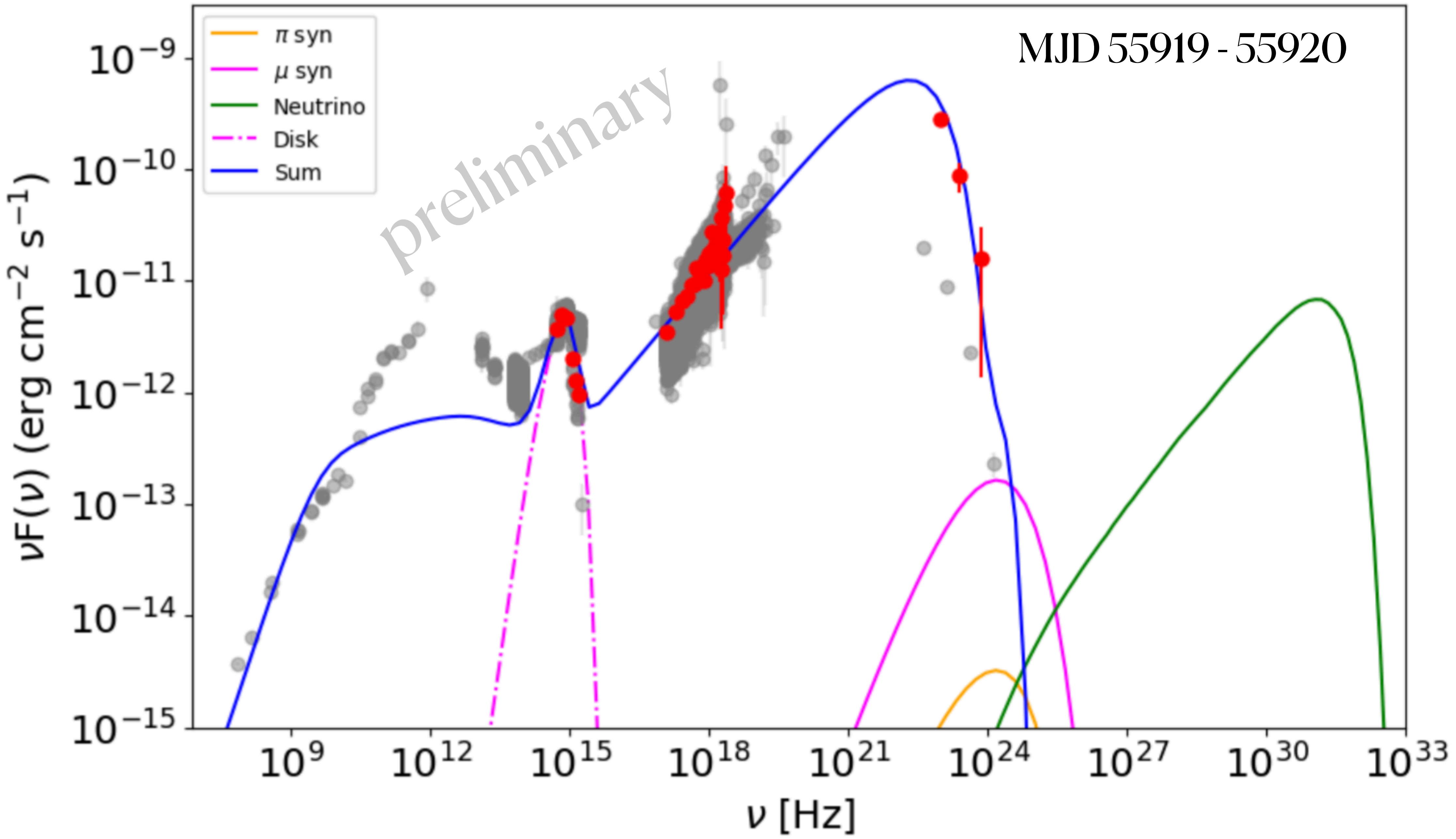
	HM	LHM
R_b	5e16 cm	8e15 cm
B	60 G	0.75 G
δ	26.29	26.29
$\alpha_p = \alpha_e$	1.9	2
$\gamma_{p,min}$	1	1
$\gamma_{p,max}$	1e9	1e5
$\gamma_{e,min}$	55	200
$\gamma_{e,max}$	1000	1e4
L_e	2.6e43 erg/s	7.4e46 erg/s
L_p	1.2e48 erg/s	2.2e49 erg/s
L_B	2.3e49 erg/s	9.4e43 erg/s

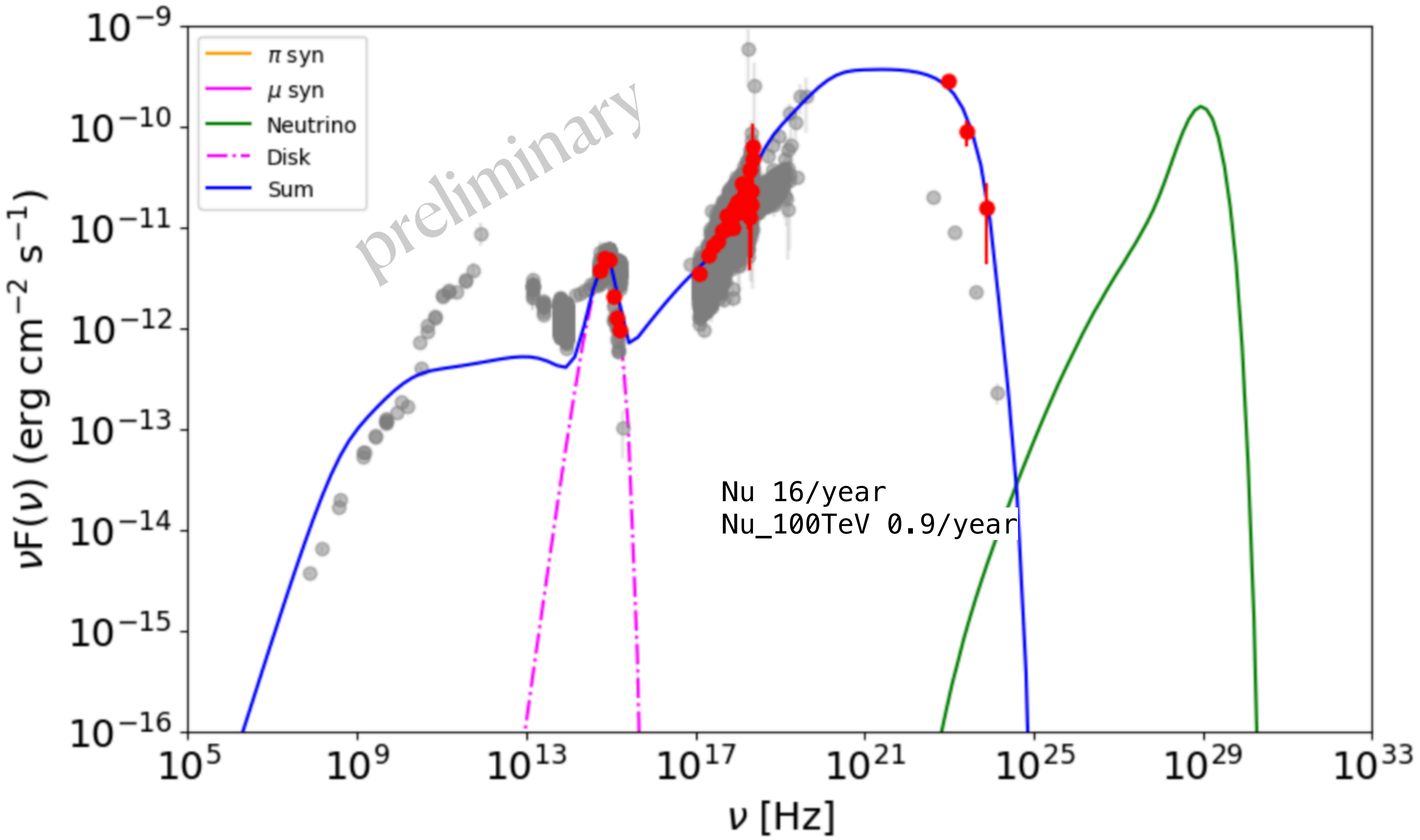
4C+71.07



Fermi-LAT
Swift XRT
Swift B
Swift U
Swift W1
Swift M2
Swift V
Swift W2
10^{-7} erg cm^{-2} s^{-1}
10^{-12} erg cm^{-2} s^{-1}
10^{-12} erg cm^{-2} s^{-1}
Time [MJD]
Time [MJD]

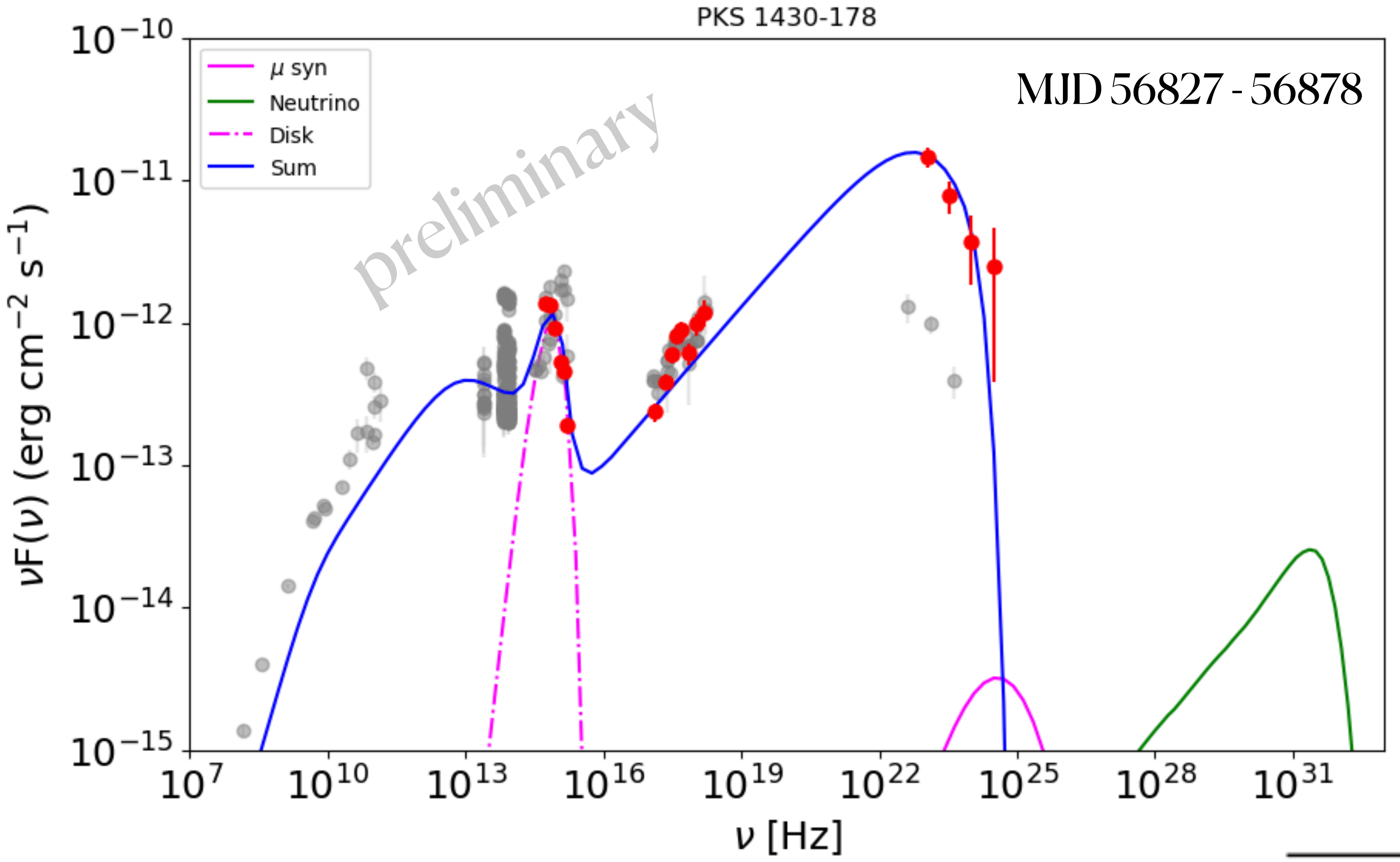
Lepto-Hadronic: 4C+71.07

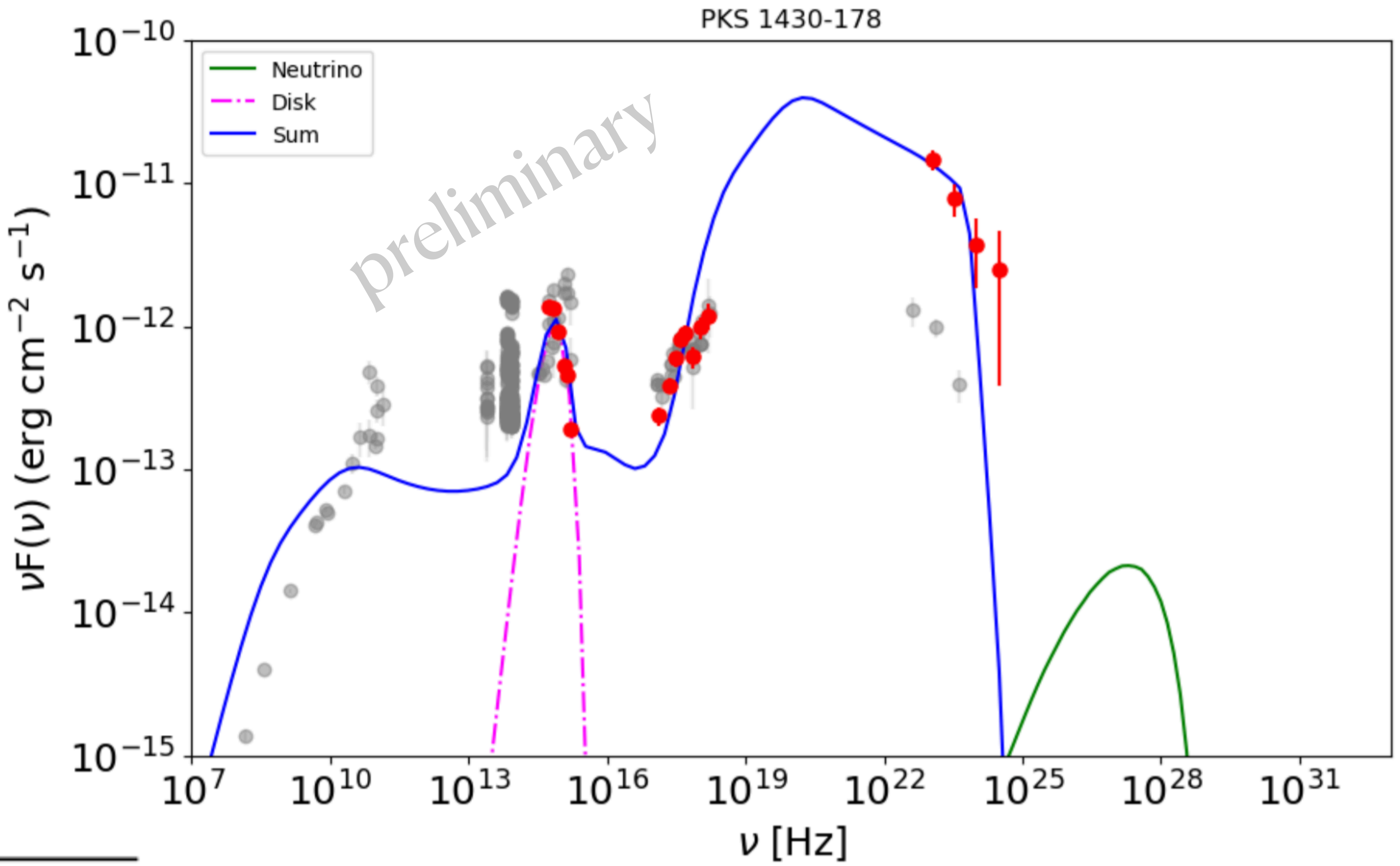




	HM	LHM
R_b	5e16 cm	4e15 cm
B	40 G	4 G
δ	32.34	32.34
$\alpha_p = \alpha_e$	2	2
$\gamma_{p,\min}$	1	1
$\gamma_{p,\max}$	3.5e8	1e6
$\gamma_{e,\min}$	55	10
$\gamma_{e,\max}$	1000	800
L_e	6.8e43 erg/s	8.5e46 erg/s
L_p	1.6e49 erg/s	1.0e45 erg/s
L_B	1.6e49 erg/s	1.4e49 erg/s

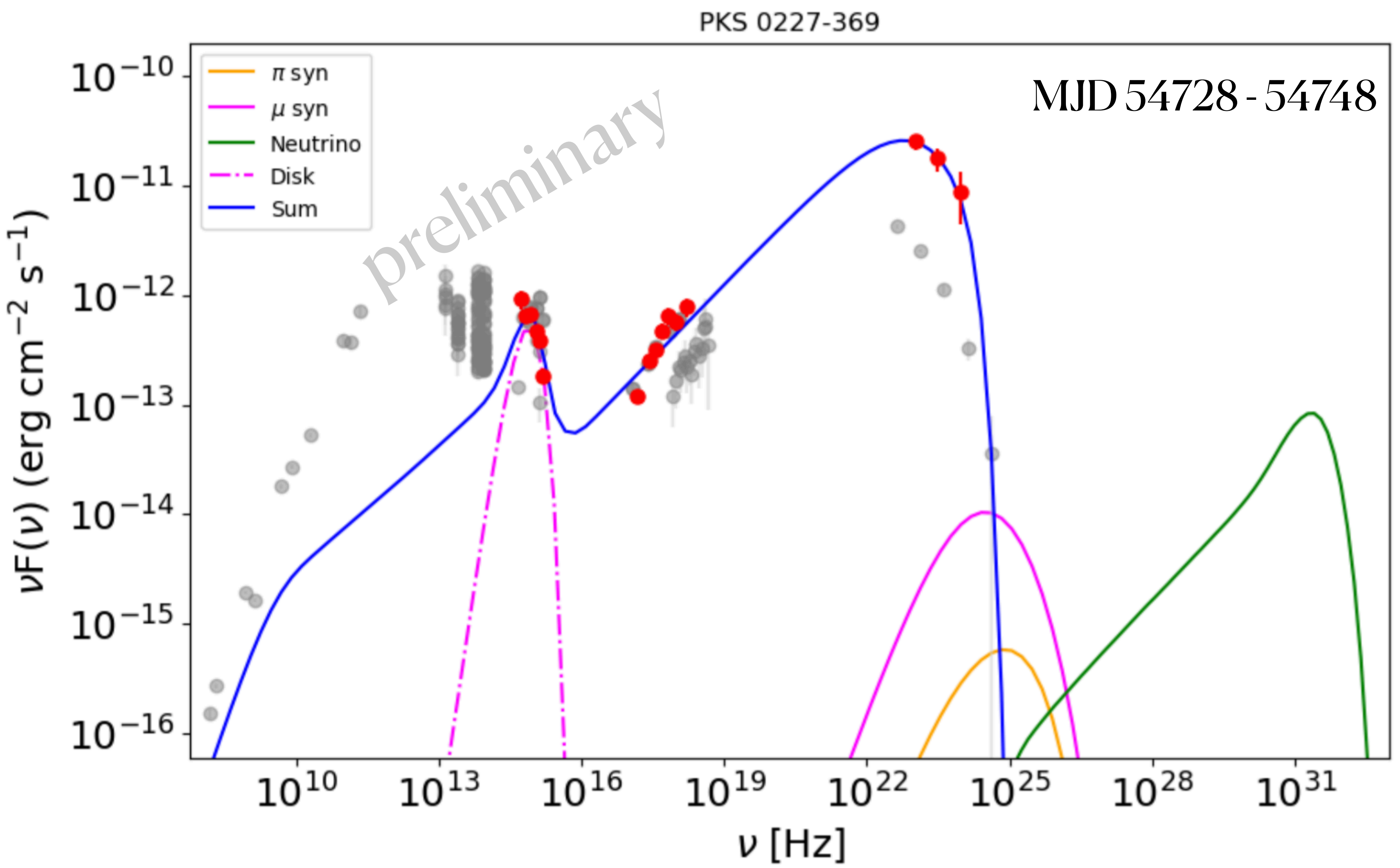
Lepto-Hadronic: PKS 1430-178

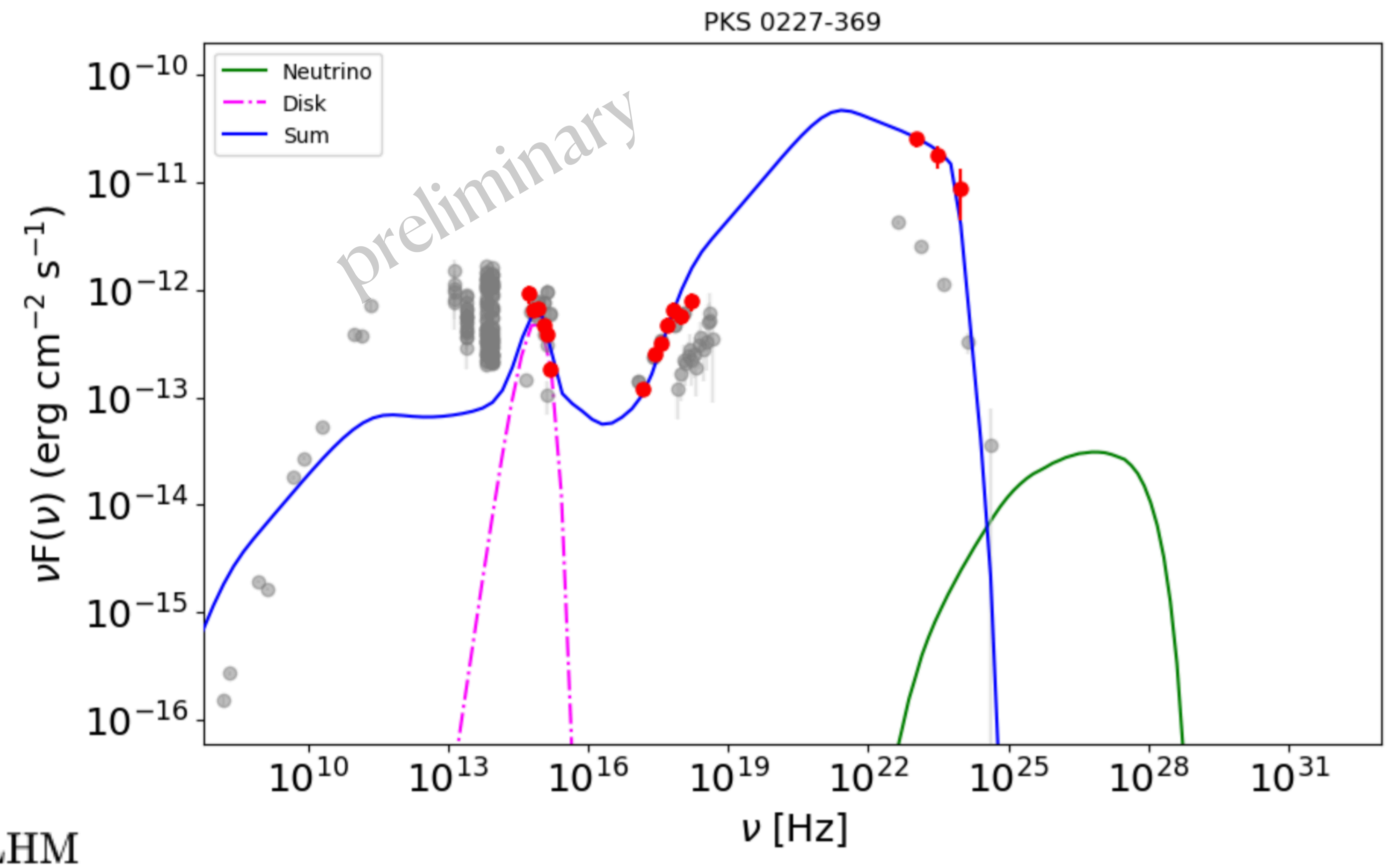




	HM	LHM
R_b	5e16 cm	8e15 cm
B	60 G	5.2 G
δ	26.31	26.31
$\alpha_p = \alpha_e$	2.4	2.4
$\gamma_{p,\min}$	1	1
$\gamma_{p,\max}$	1e9	1e5
$\gamma_{e,\min}$	50	10
$\gamma_{e,\max}$	1e3	1e4
L_e	1.2e44 erg/s	1.5e46 erg/s
L_p	4.6e48 erg/s	4.5e45 erg/s
L_B	2.3e49 erg/s	7.1e48 erg/s

Lepto-Hadronic: PKS 0227-369



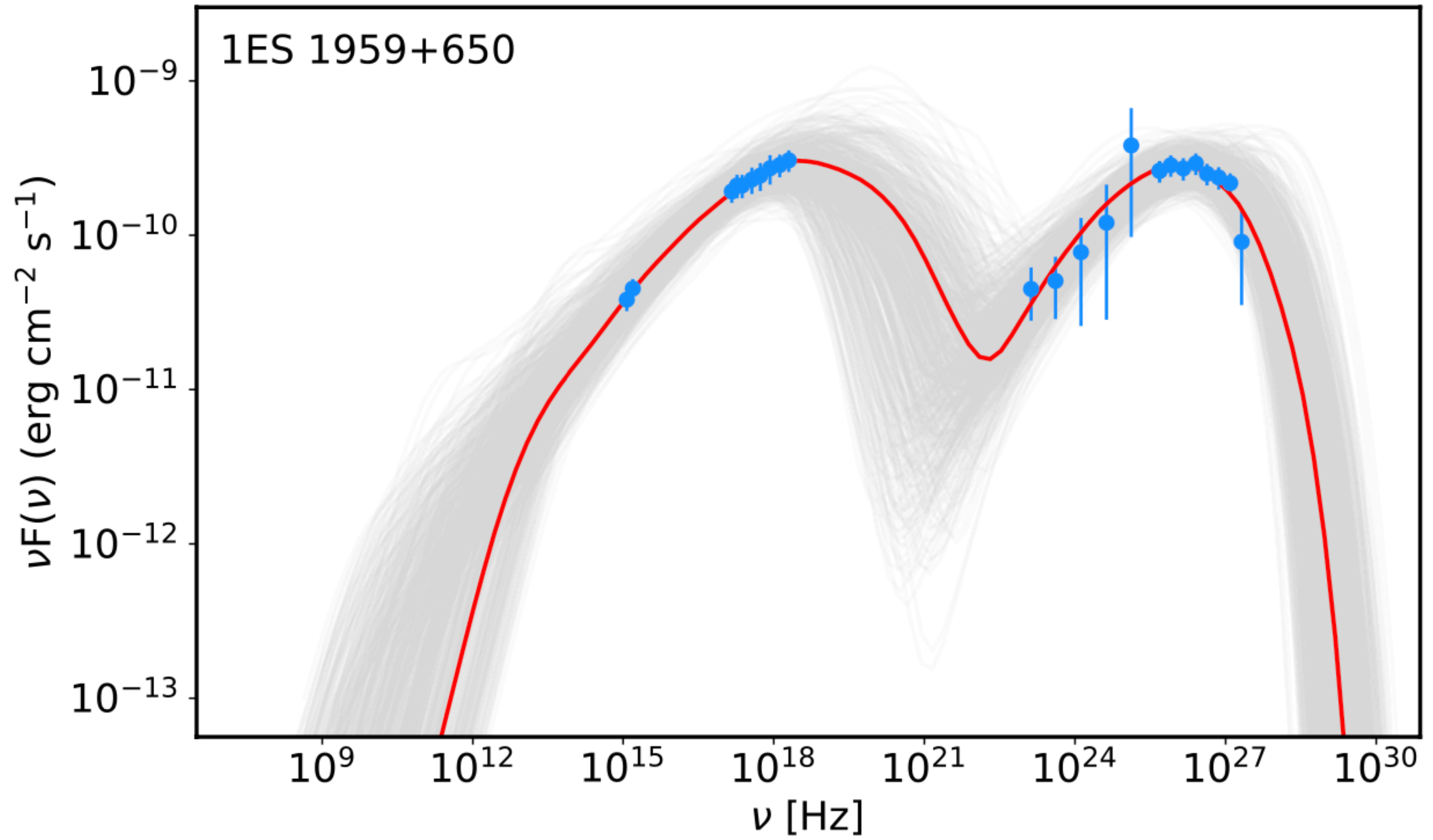


	HM	LHM
R_b	5e16 cm	8e15 cm
B	60 G	2.78 G
δ	20.02	20.02
$\alpha_p = \alpha_e$	2.1	2.4
$\gamma_{p,\min}$	100	1
$\gamma_{p,\max}$	1e9	1e5
$\gamma_{e,\min}$	600	50
$\gamma_{e,\max}$	1000	1e4
L_e	3.5e43 erg/s	2.1e46 erg/s
L_p	1.3e49 erg/s	7.5e44 erg/s
L_B	7.0e47 erg/s	1.6e49 erg/s

Future Directions with SOPRANO

- **SOPRANO's New Frontier:** Introduction of a Convolutional Neural Network (CNN) trained on SOPRANO outputs for real-time SED fitting, significantly enhancing speed
- **Leptonic Model Validation:** Validated approach includes particle cooling considerations within the leptonic model framework
- **Accessibility:** Available for public use via the Markarian Multiwavelength Datacenter (MMDC). For access, visit www.mmdc.am

Bégué D., et al, 2023, arxiv:2311.02979



- **Future Directions:** Plans to extend capabilities by incorporating hadronic processes for broader analysis
- **Special Highlight:** For an in-depth exploration of these advancements, Damien will detail this innovative approach in his talk.

THANK YOU
FOR YOUR ATTENTION