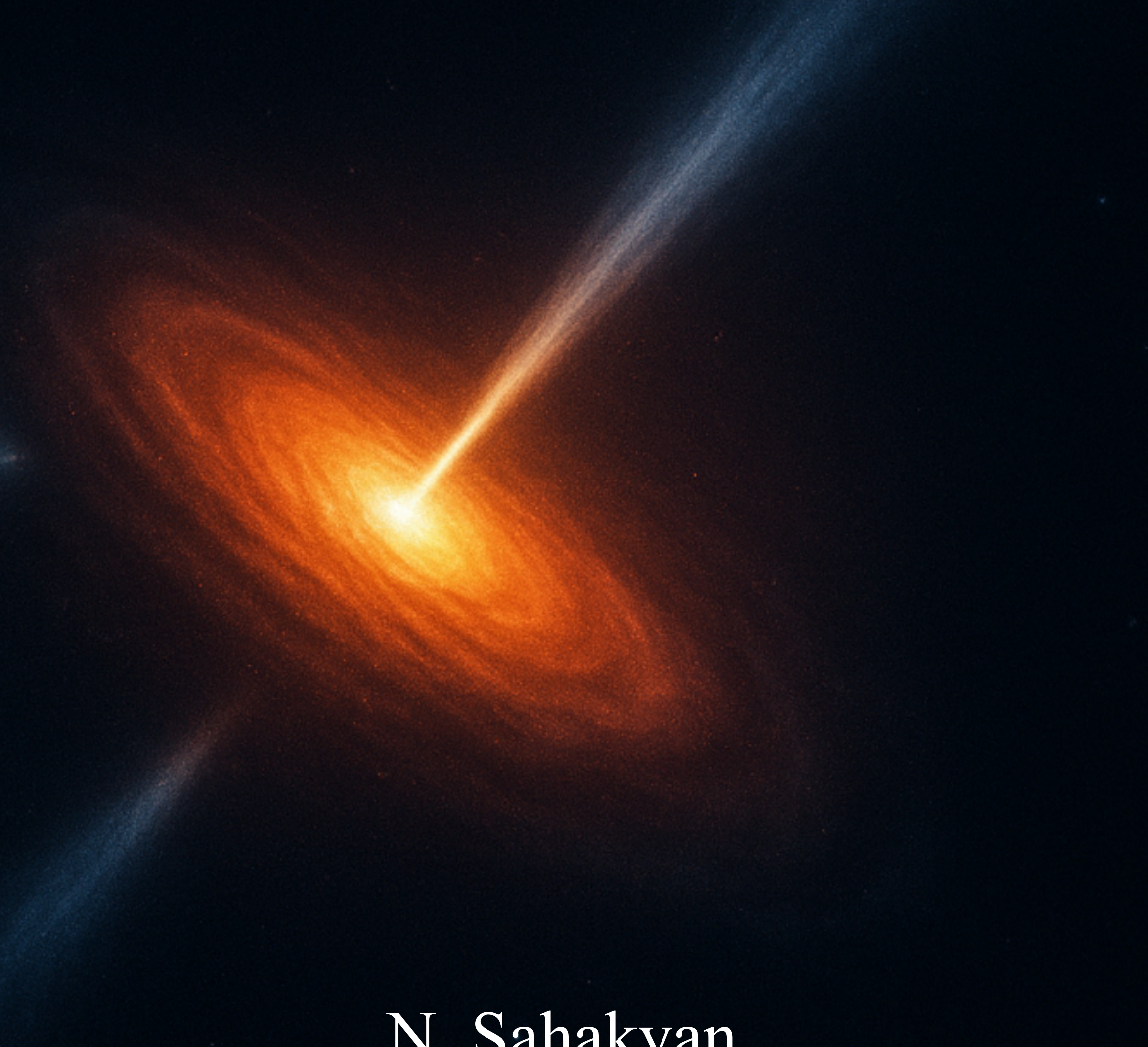


Modeling of Blazar Multimesessenger Emission with Convolutional Neural Network



N. Sahakyan

Recent Publications (2024–2025)

- ☑ Sahakyan, N., Bégué, D., Casotto, A., Dereli-Bégué, H., Vardanyan, V., Khachatryan, M., Giommi, P., Pe'er, A., **Modeling Blazar Broadband Emission with Convolutional Neural Networks. III. Proton Synchrotron and Hybrid Models**, The Astrophysical Journal, 990, 222 (2025), DOI: 10.3847/1538-4357/adf734S
- ☑ Harutyunyan, G., Sahakyan, N., Bégué, D., **Modelling of the Time-Resolved Spectral Energy Distribution of Blazar OJ 287 from 2008 to 2023: A Comprehensive Multi-Epoch Study**, Monthly Notices of the Royal Astronomical Society, 540, 582–593 (2025), DOI: 10.1093/mnras/staf713
- ☑ Sahakyan, N., Vardanyan, V., Giommi, P., Bégué, D., Israyelyan, D., Harutyunyan, G., Manvelyan, M., Khachatryan, M., Dereli-Bégué, H., Gasparyan, S., **Markarian Multiwavelength Data Center (MMDC): A Tool for Retrieving and Modeling Multitemporal, Multiwavelength, and Multimessenger Data from Blazar Observations**, The Astronomical Journal, 168, 289 (2024), DOI: 10.3847/1538-3881/ad8231.
- ☑ Sahakyan, N., **AI in the Cosmos**, arXiv e-prints, arXiv:2412.10093 (2024), IJMPD, in press, DOI: 10.48550/arXiv.2412.10093
- ☑ Mohana A, K., Gupta, A. C., Fan, J., Sahakyan, N., Raiteri, C. M., Cui, L., Lähteenmäki, A., Gurwell, M., Tornikoski, M., Villata, M., **Modeling the Multiwavelength Emission of 3C 279 during the 14 yr Fermi-LAT Era**, The Astrophysical Journal, 989, 125 (2025), DOI: 10.3847/1538-4357/ade77

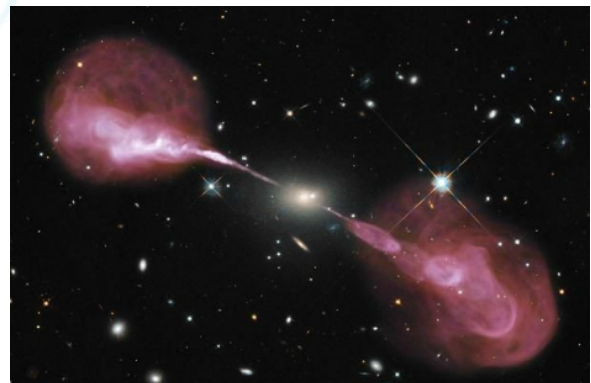
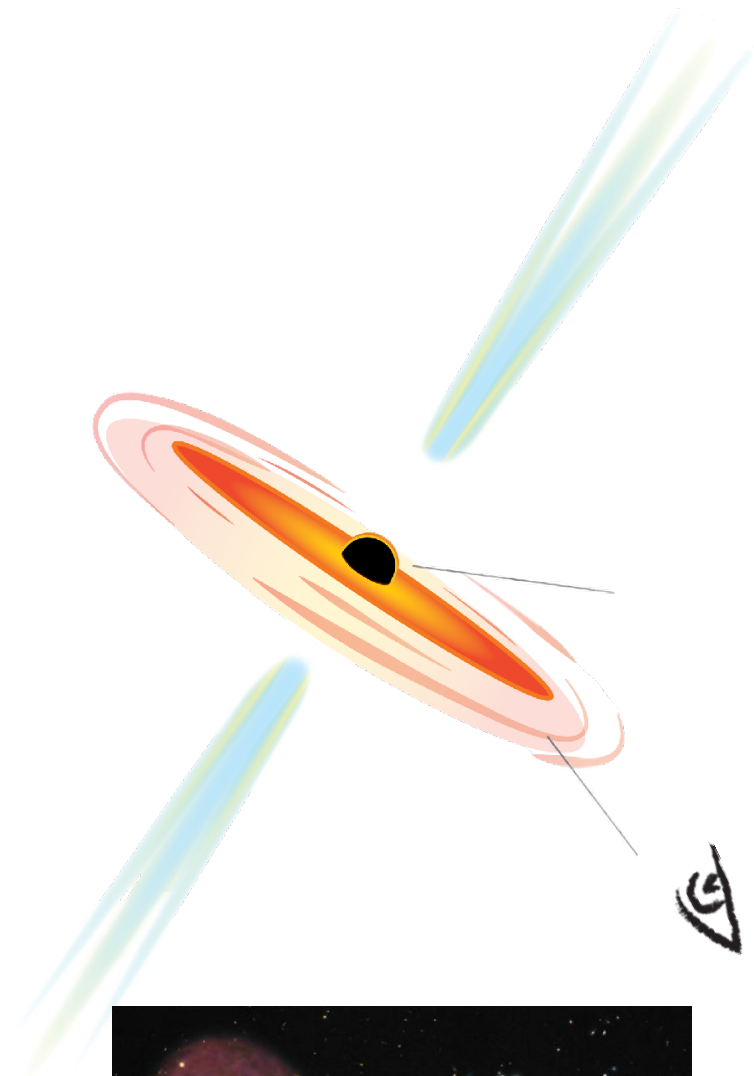
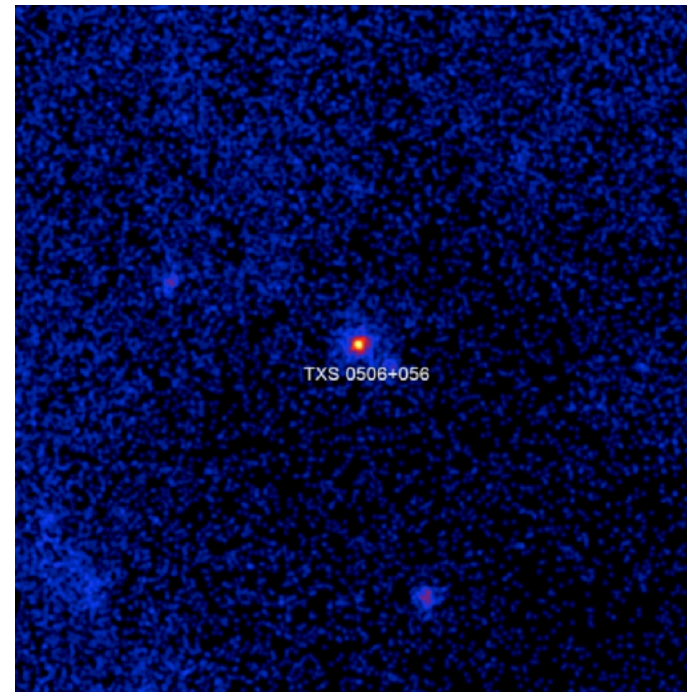


Blazars: Powerful and Rare Objects

The common model for blazar emission is that these sources are quasars in which a relativistic jet is pointing at the observer or very close to the observer's line of sight.

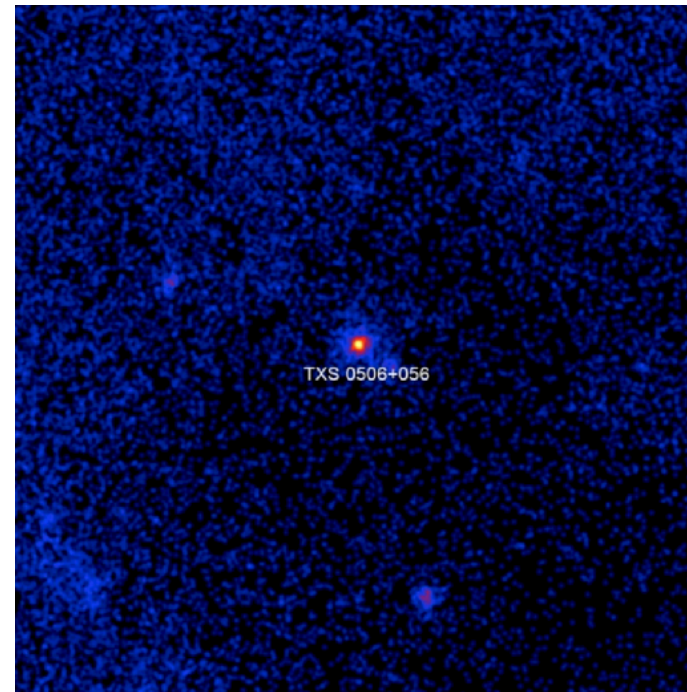
Blazars are rare objects. Even when combining data from multiple surveys, only about 6,000 sources exhibit blazar-like features among an estimated 100 to 200 billion galaxies.

Why blazars are interesting ?



Blazars: Powerful and Rare Objects

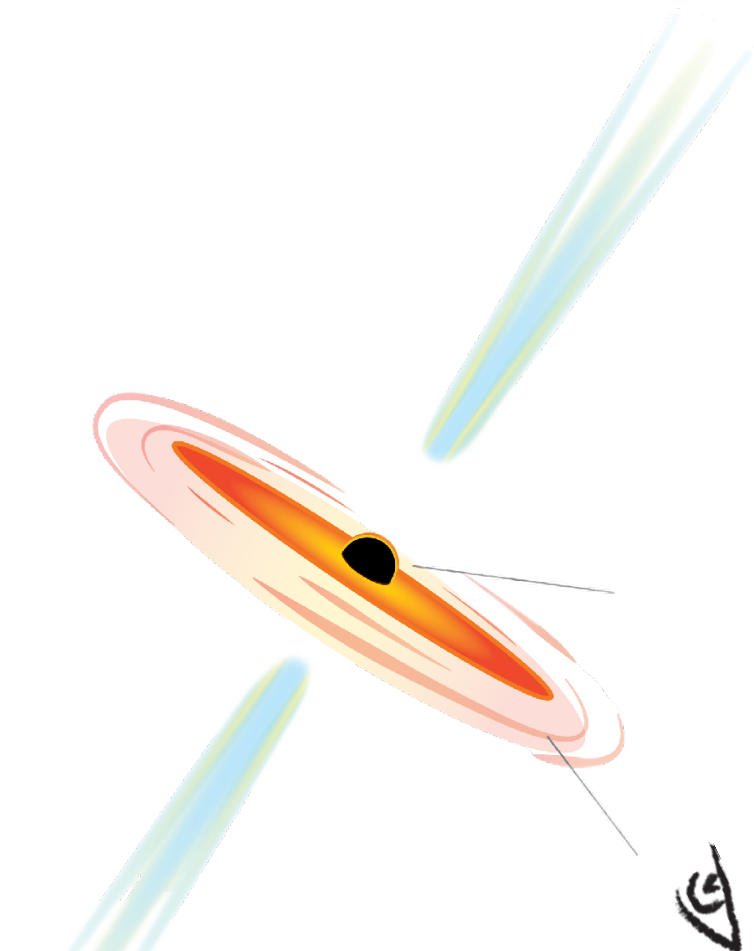
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Blazars are rare objects. Even when combining data from multiple surveys, only about 6,000 sources exhibit blazar-like features among an estimated 100 to 200 billion galaxies.

Why blazars are interesting ?

- High powers: most powerful “non-explosive” sources in the Universe ($\sim 10^{49}$ erg/s)
- Relativistic jets: emission is strongly Doppler amplified
- The powerful jets of blazars are powered by accretion onto supermassive black holes
- Fast variability/small emitting region; $R \leq c t_{\text{var}}/(1 + z)$
- Broadband emission: from radio to VHE γ -ray
- Blazar emission is often highly polarized, in the radio, optical, and X-ray bands
- Dominant sources in HE γ -ray sky: $\sim 55\%$ of 4FGL-DR3 sources are blazars.
- Blazars are important sources in MM astronomy, being linked to VHE neutrinos

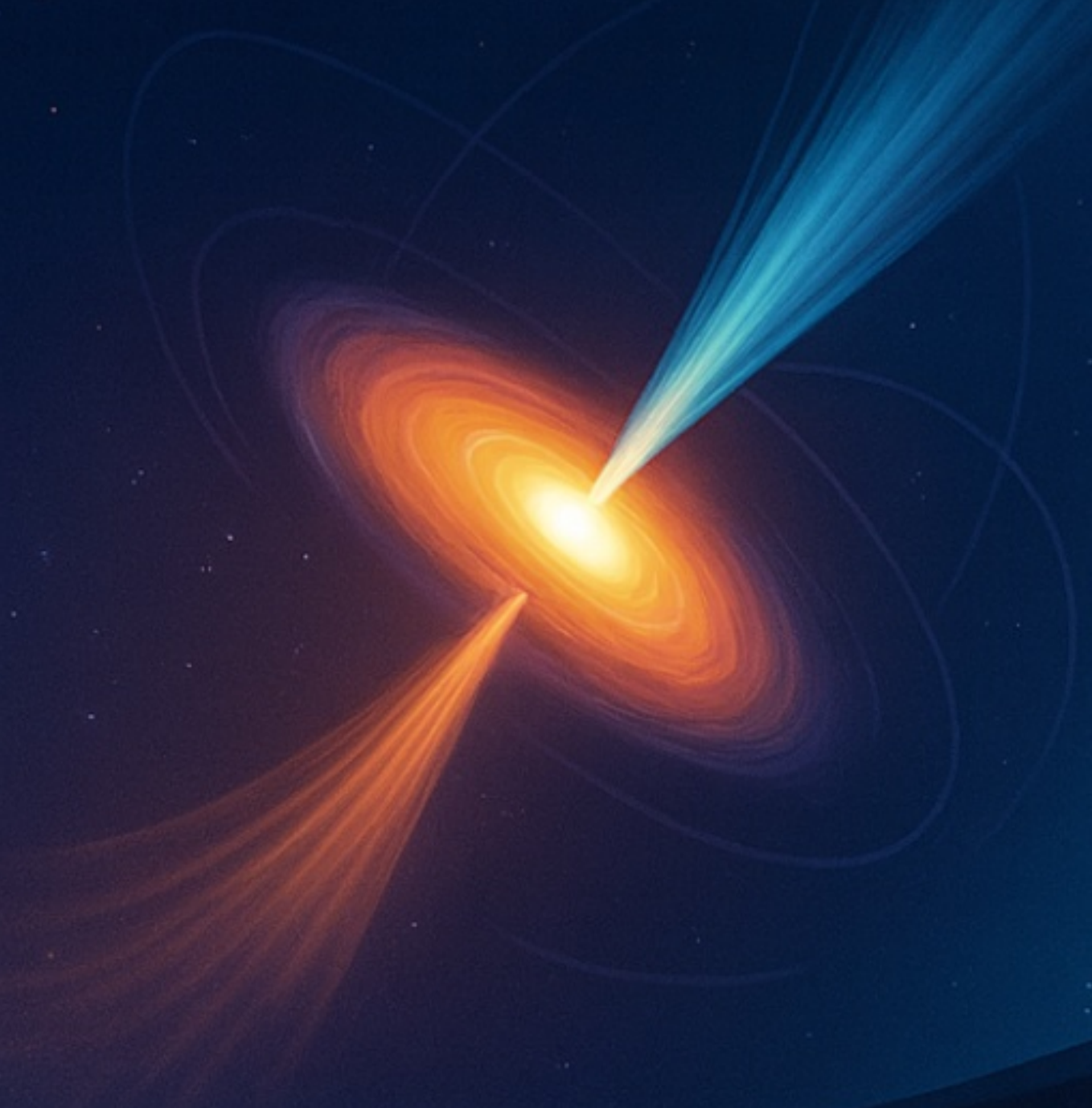


1963

First quasar
(3C 273)



Birth of blazar
observations
(1970s–1990s)



2025

Multimessenger
monitoring

γ X UV/Opt γ



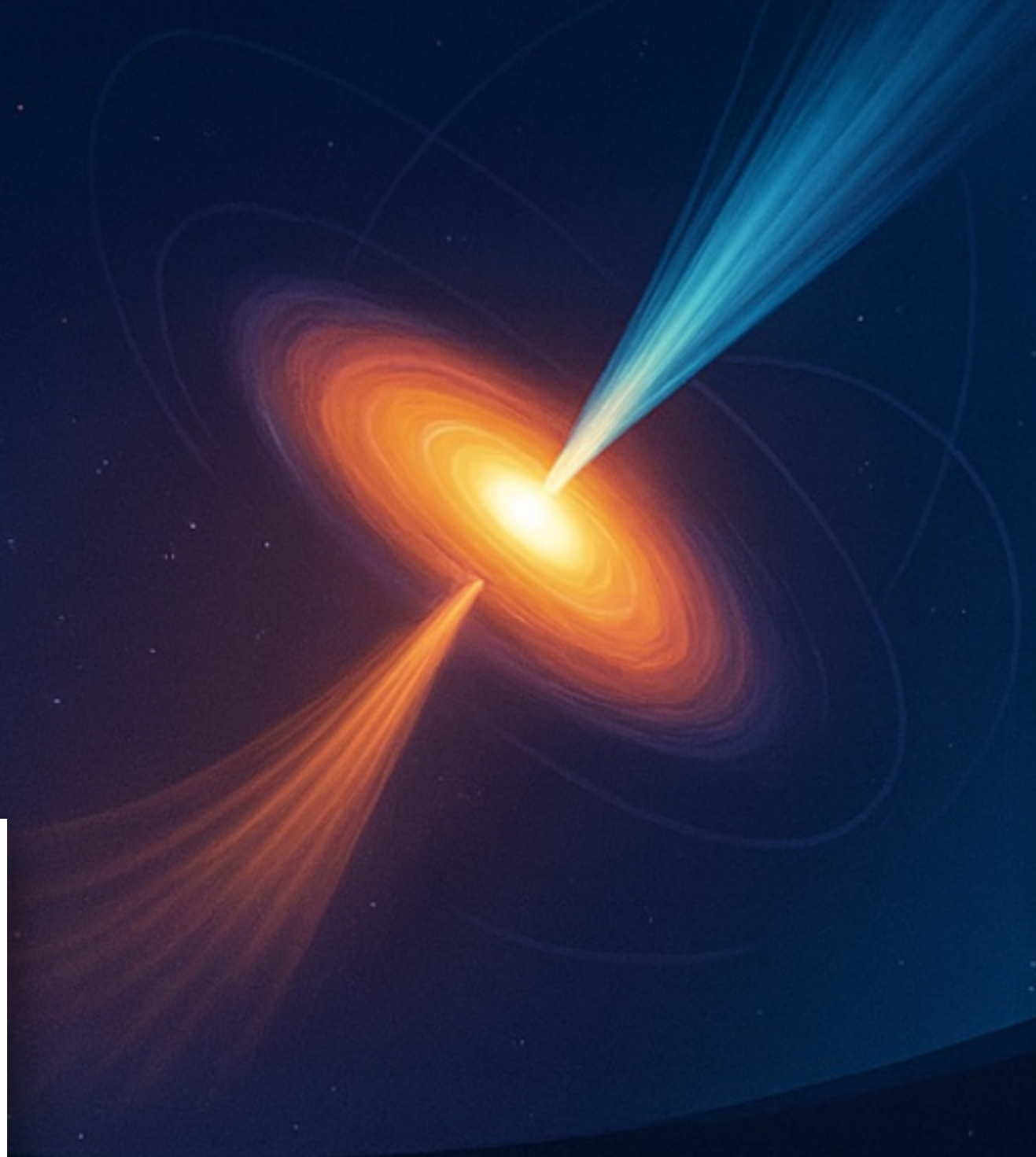
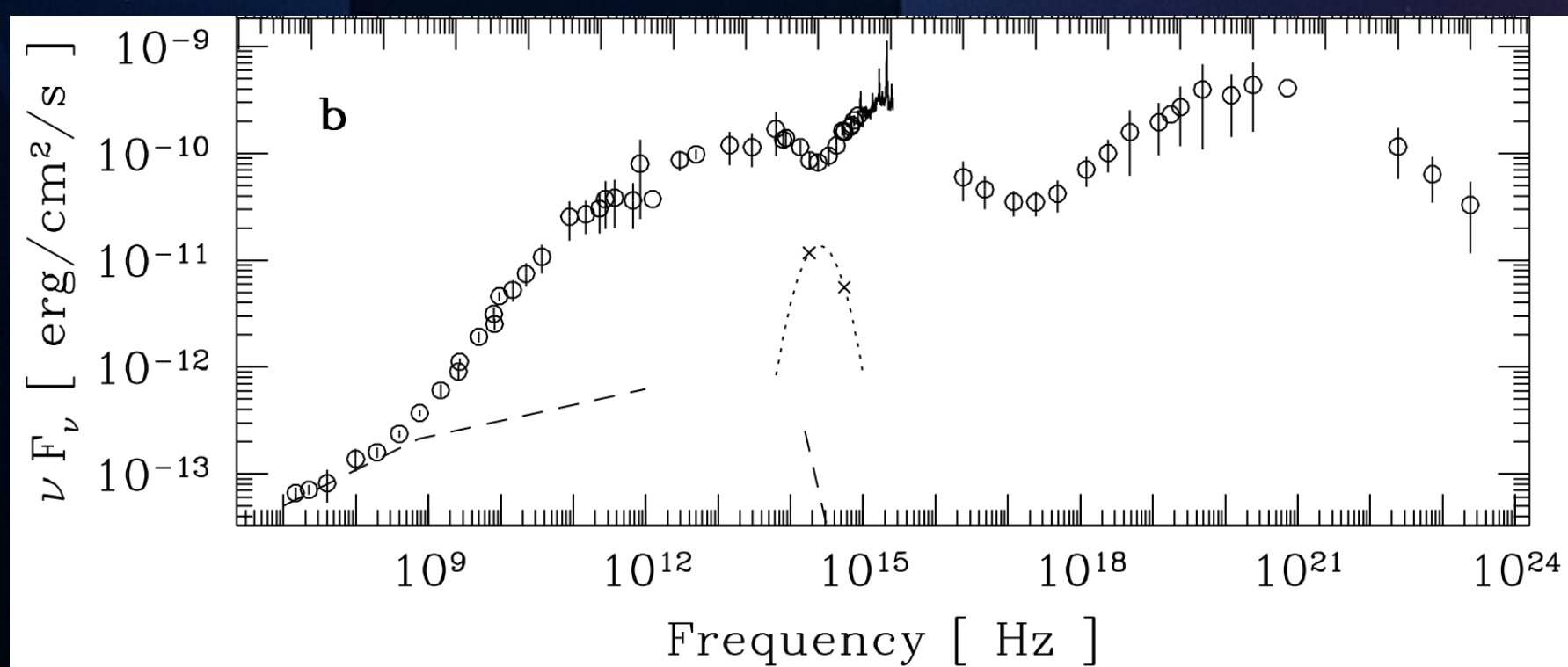
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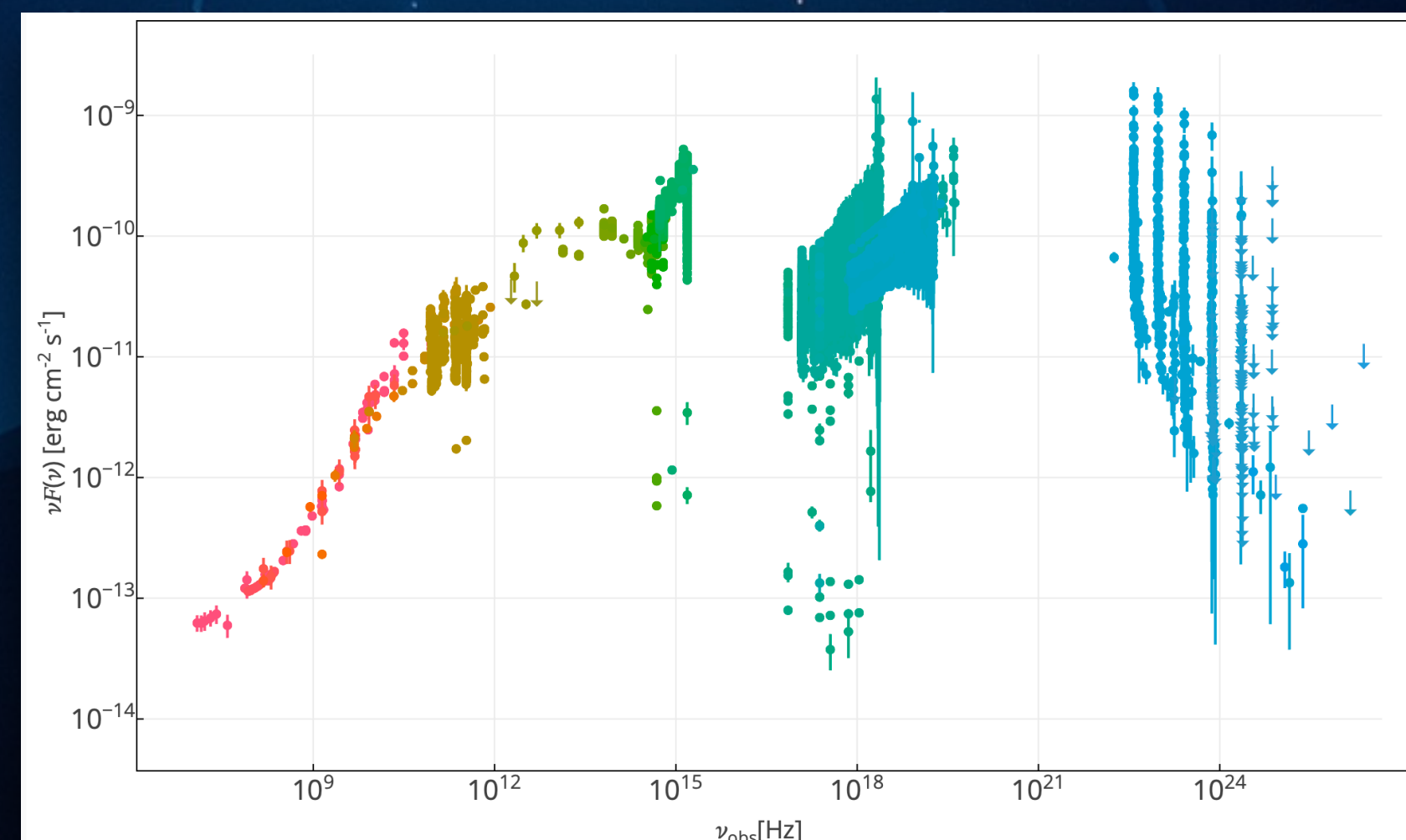


1999



γ X UV/Opt ν

2025

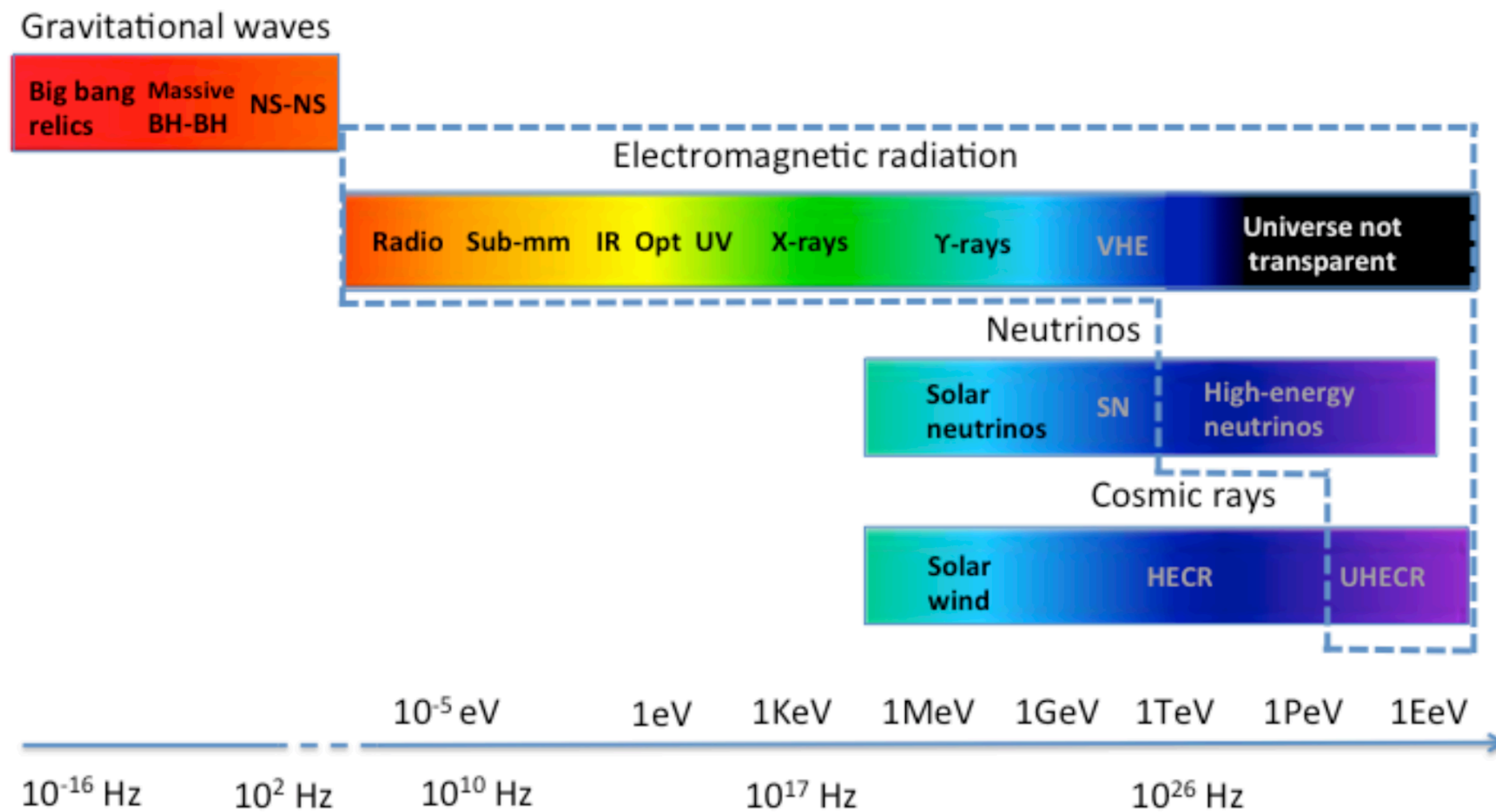


Astrophysical Messengers

Our knowledge of the Universe relies on four cosmic messengers:

- ☐ Gravitational waves
- ☐ Photons
- ☐ Cosmic rays
- ☐ Neutrinos

The information from these messengers spans a vast range of energies and frequencies, covering 50 orders of magnitude

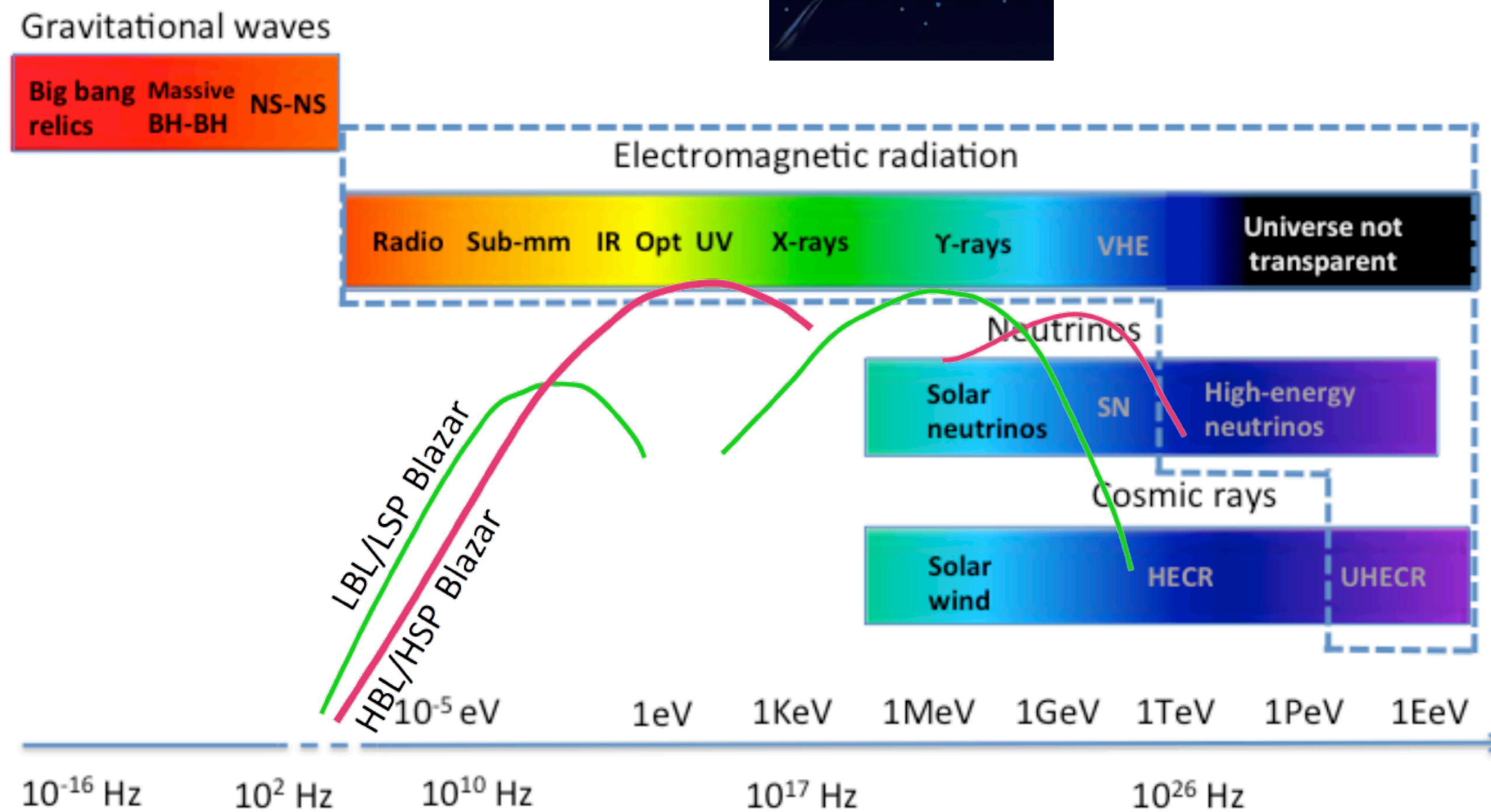
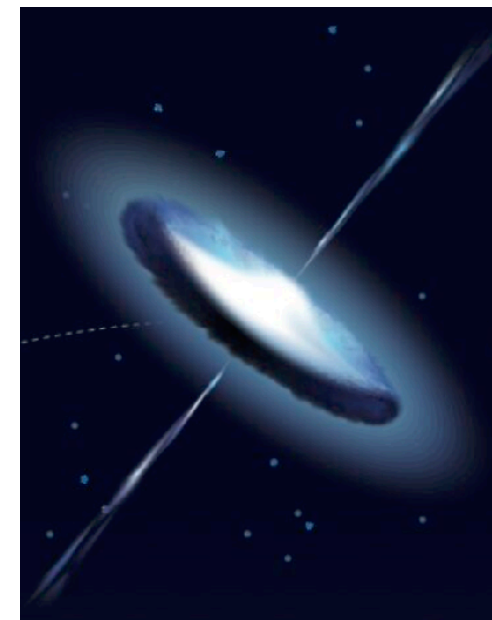


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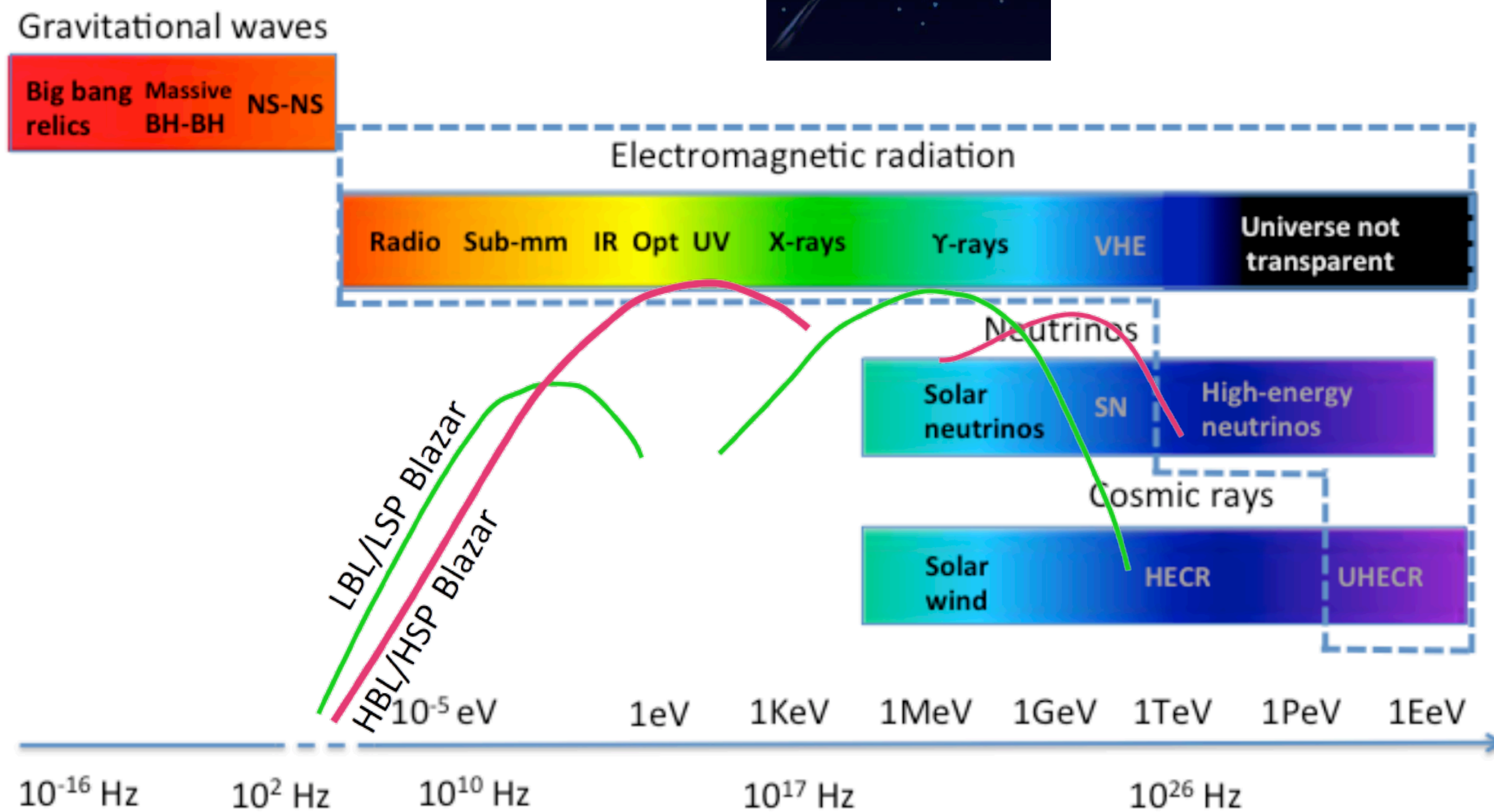
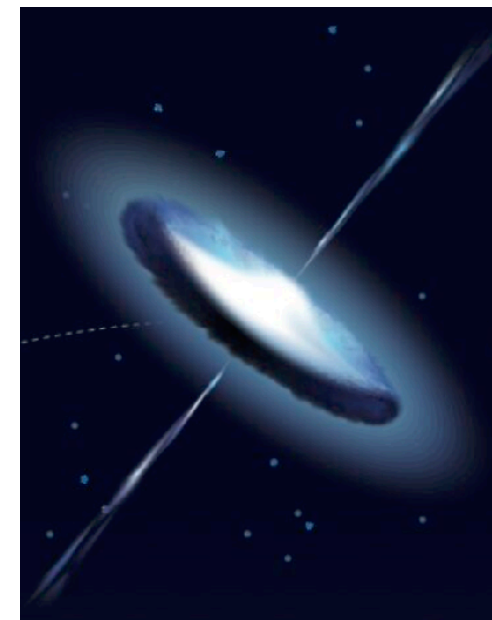


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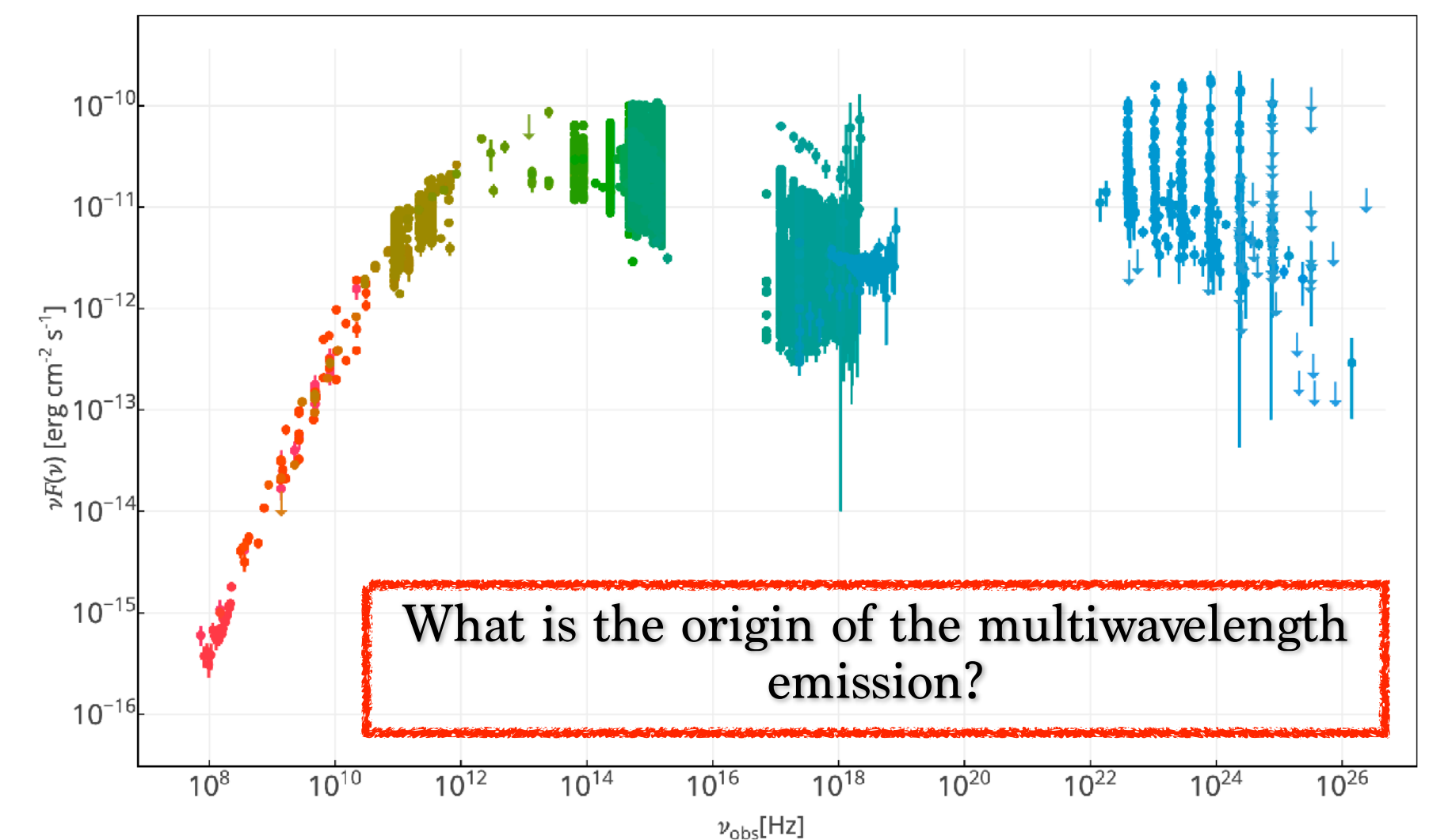
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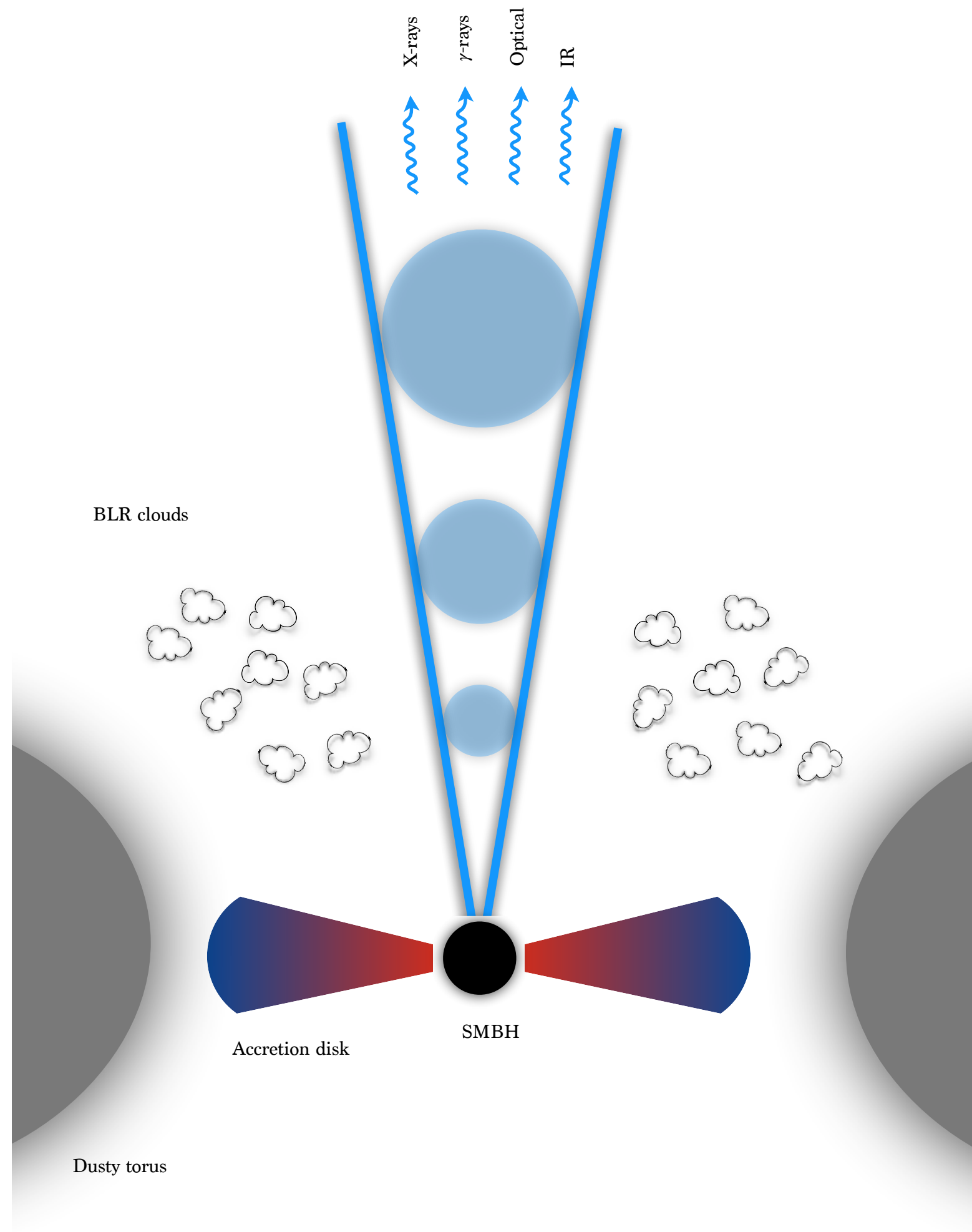


Blazar emissions can be investigated by detecting photons with energies ranging from radio to HE and VHE γ -rays.



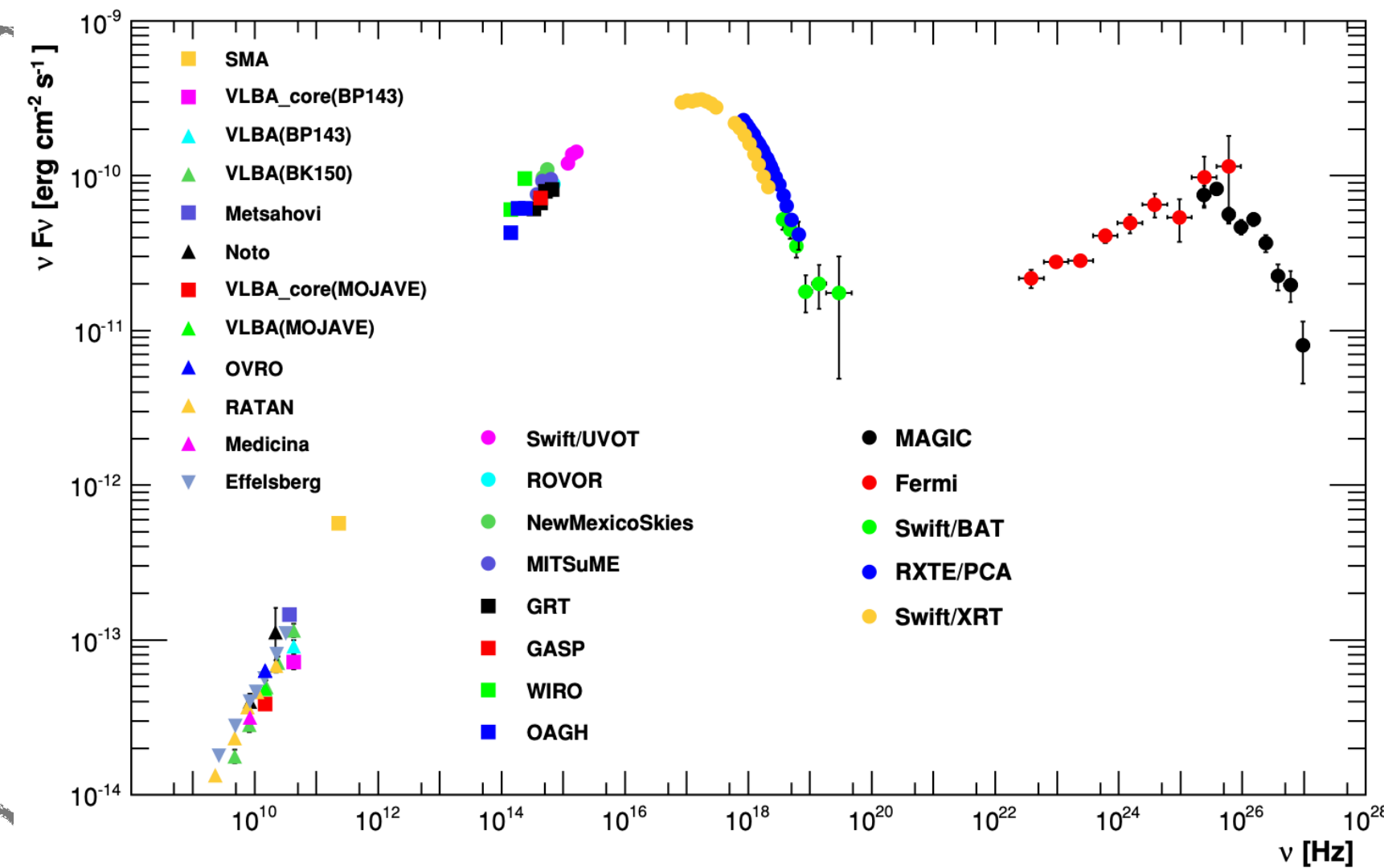
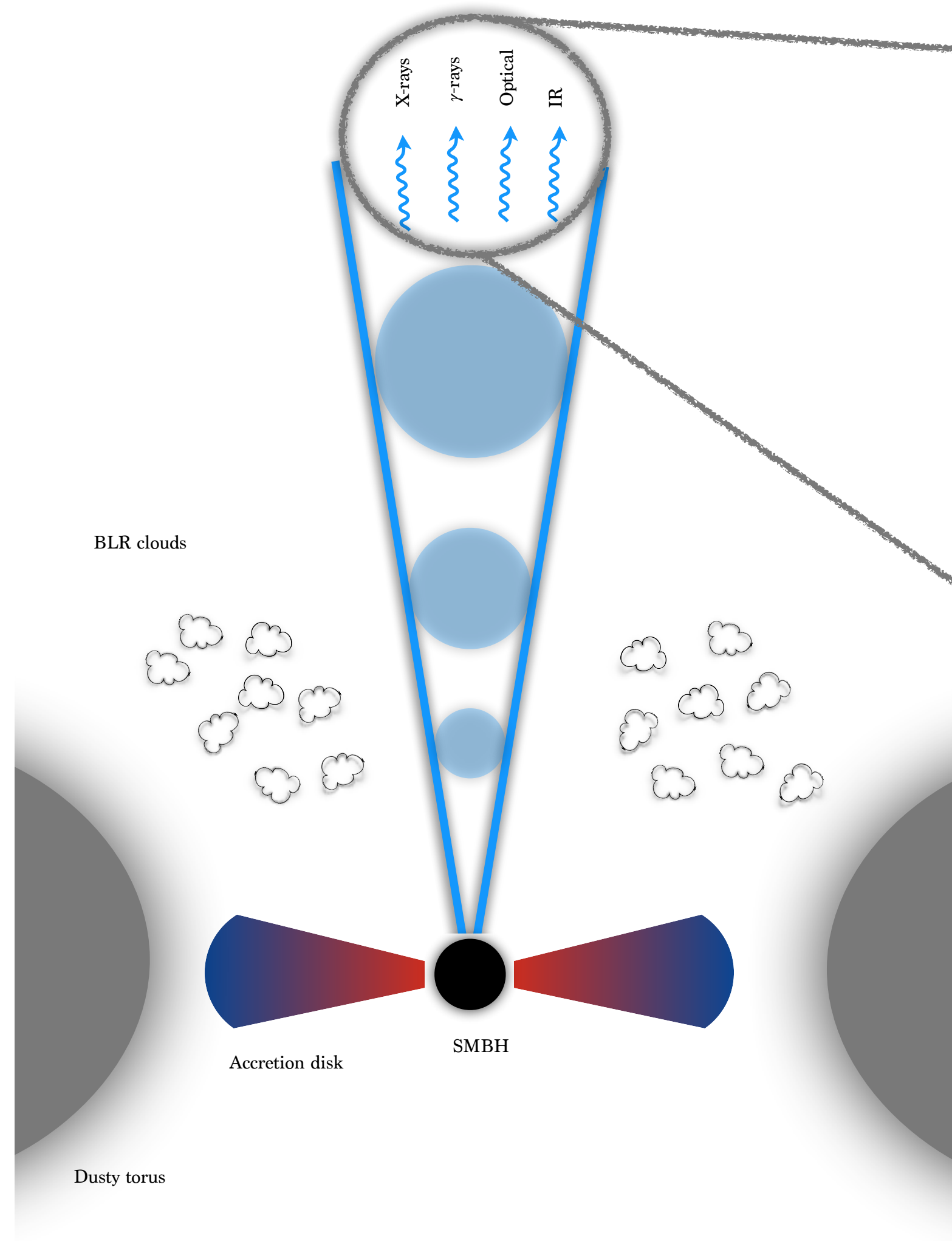
Origin of Multiwavelength Emission: Leptons

The double hump structure of the blazar broadband SED: the low-energy component usually peaks between far infrared and X-rays, while the high-energy (HE) component is observed between X-rays and very high-energy (VHE) γ -rays.



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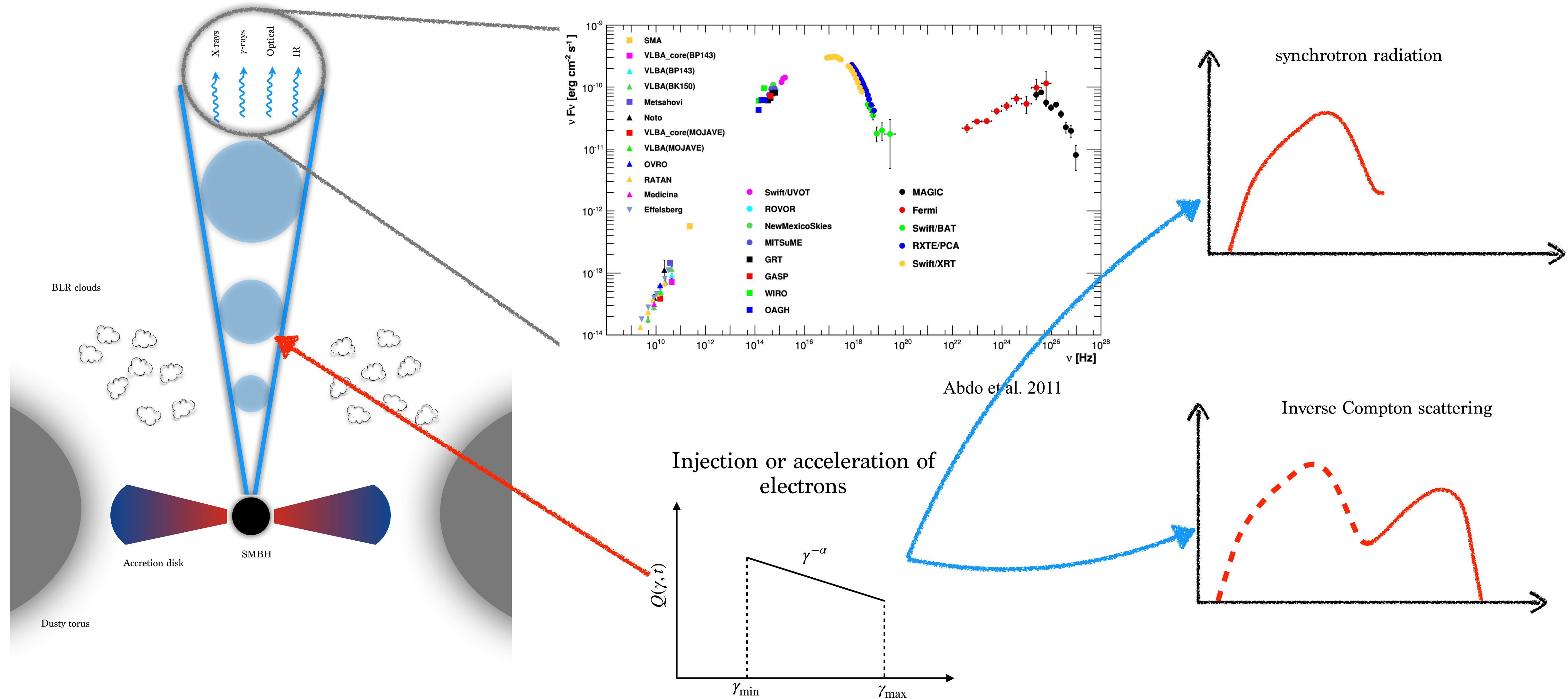
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Abdo et al. 2011

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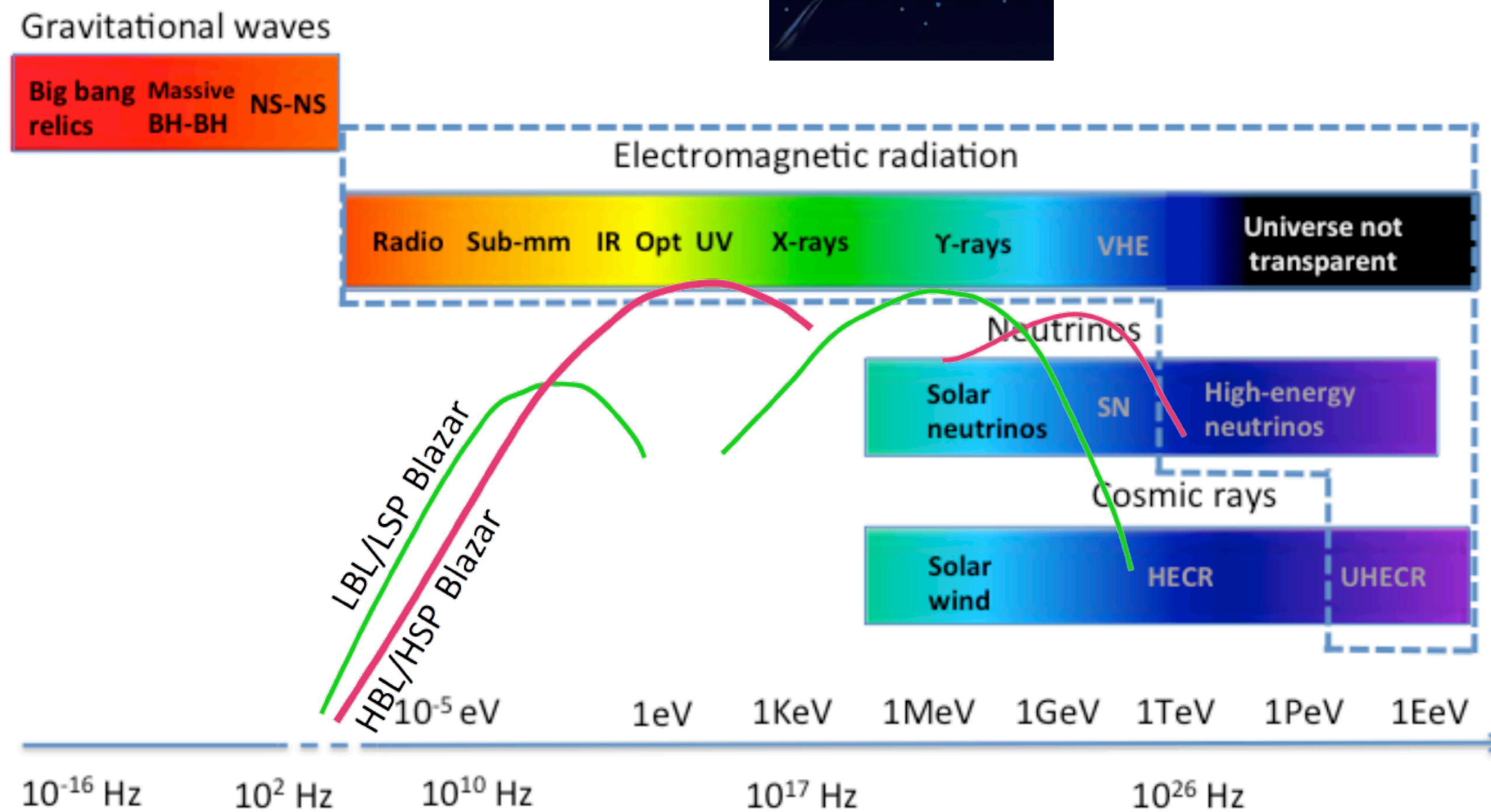
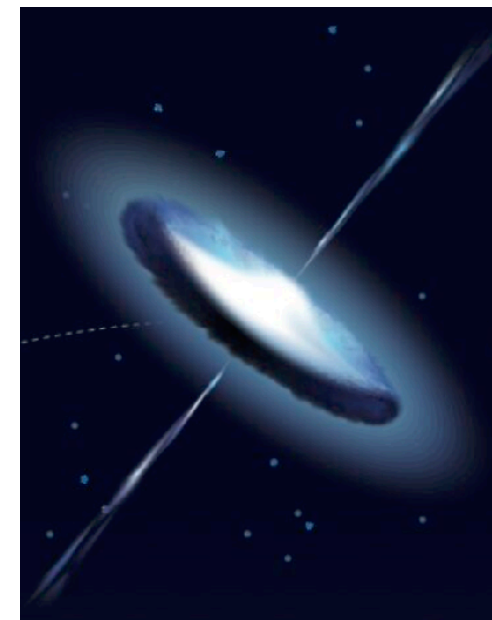


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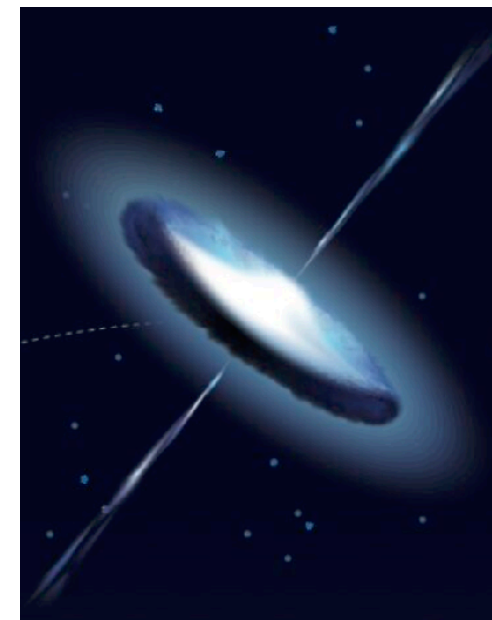


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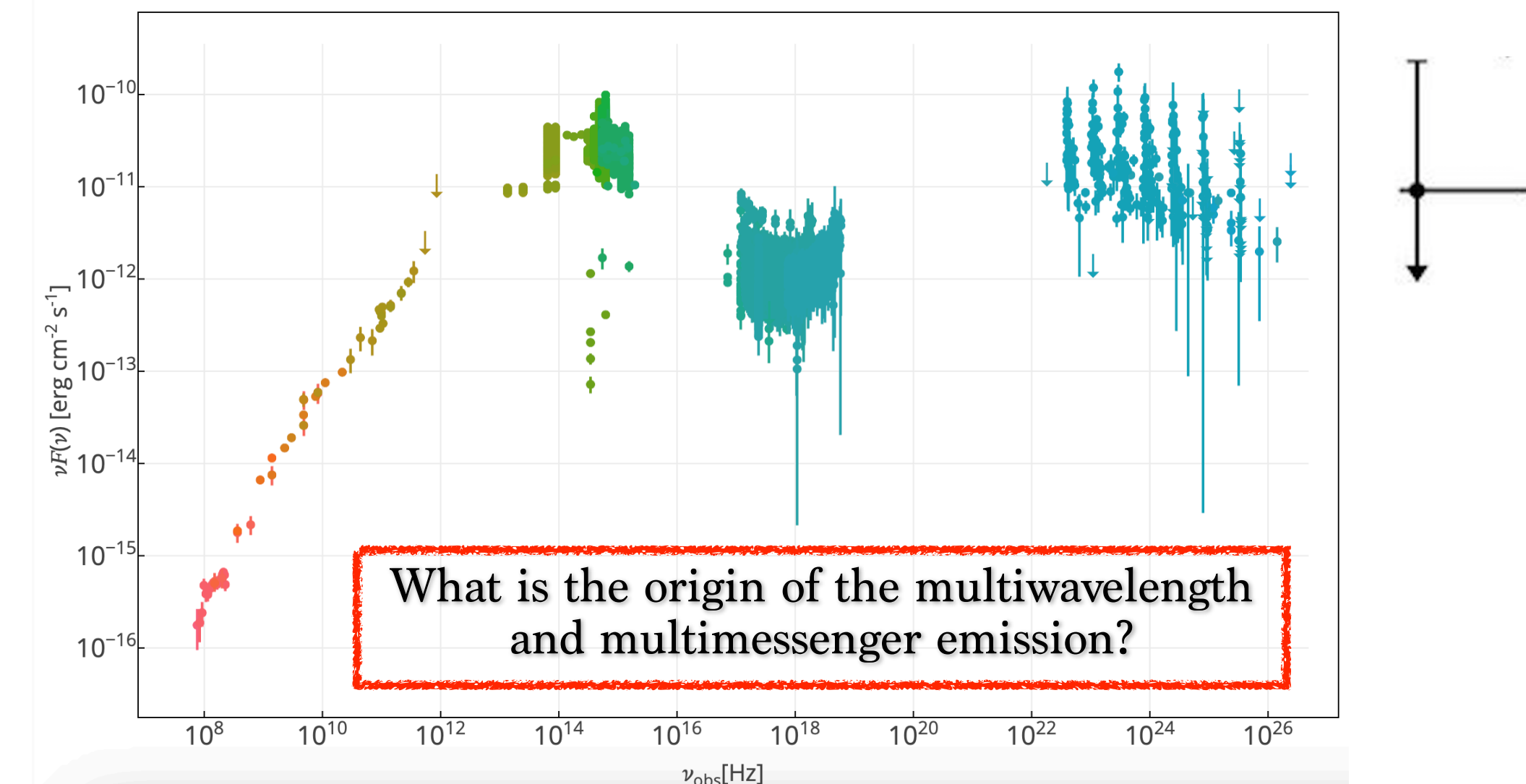
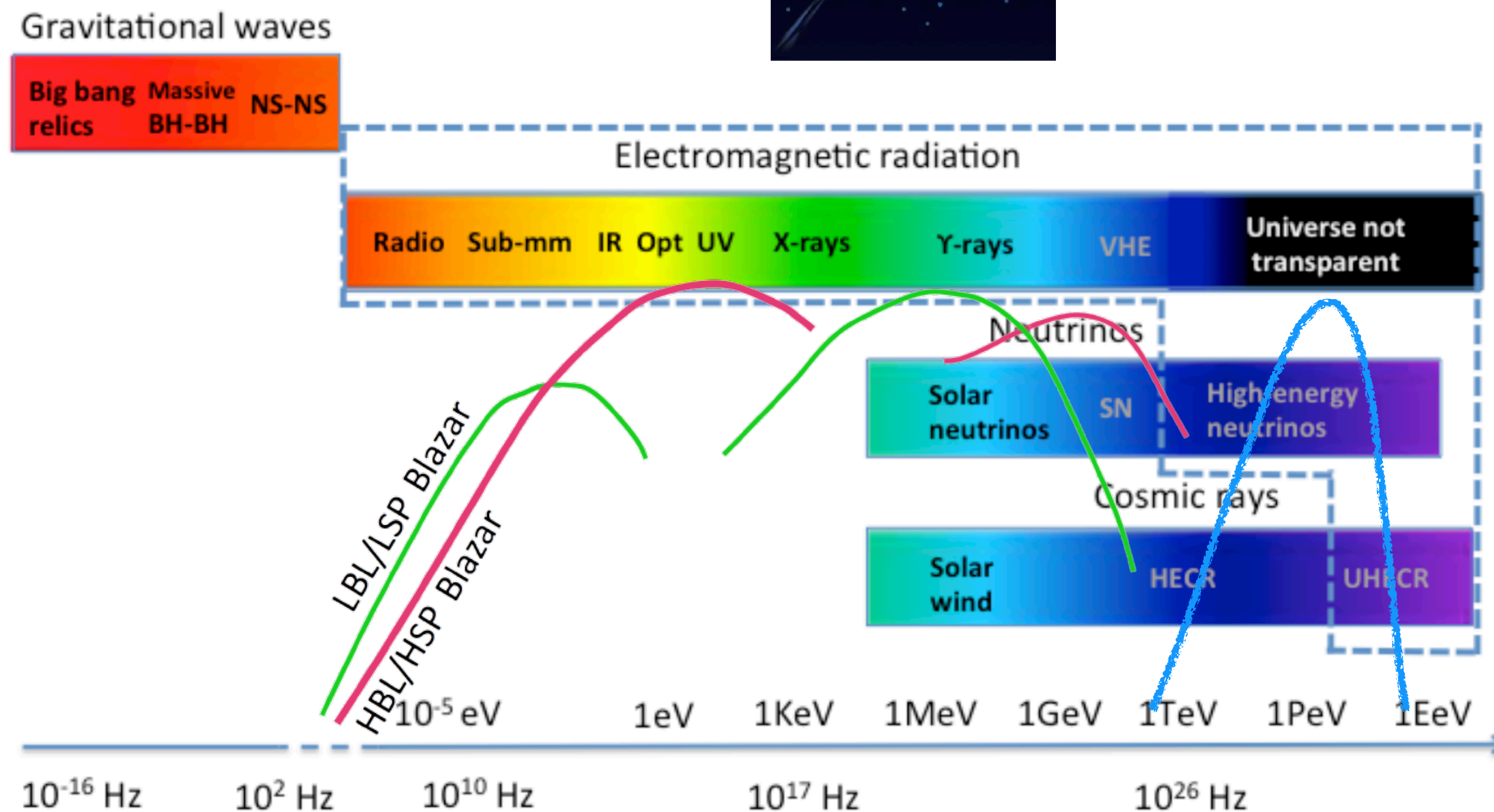
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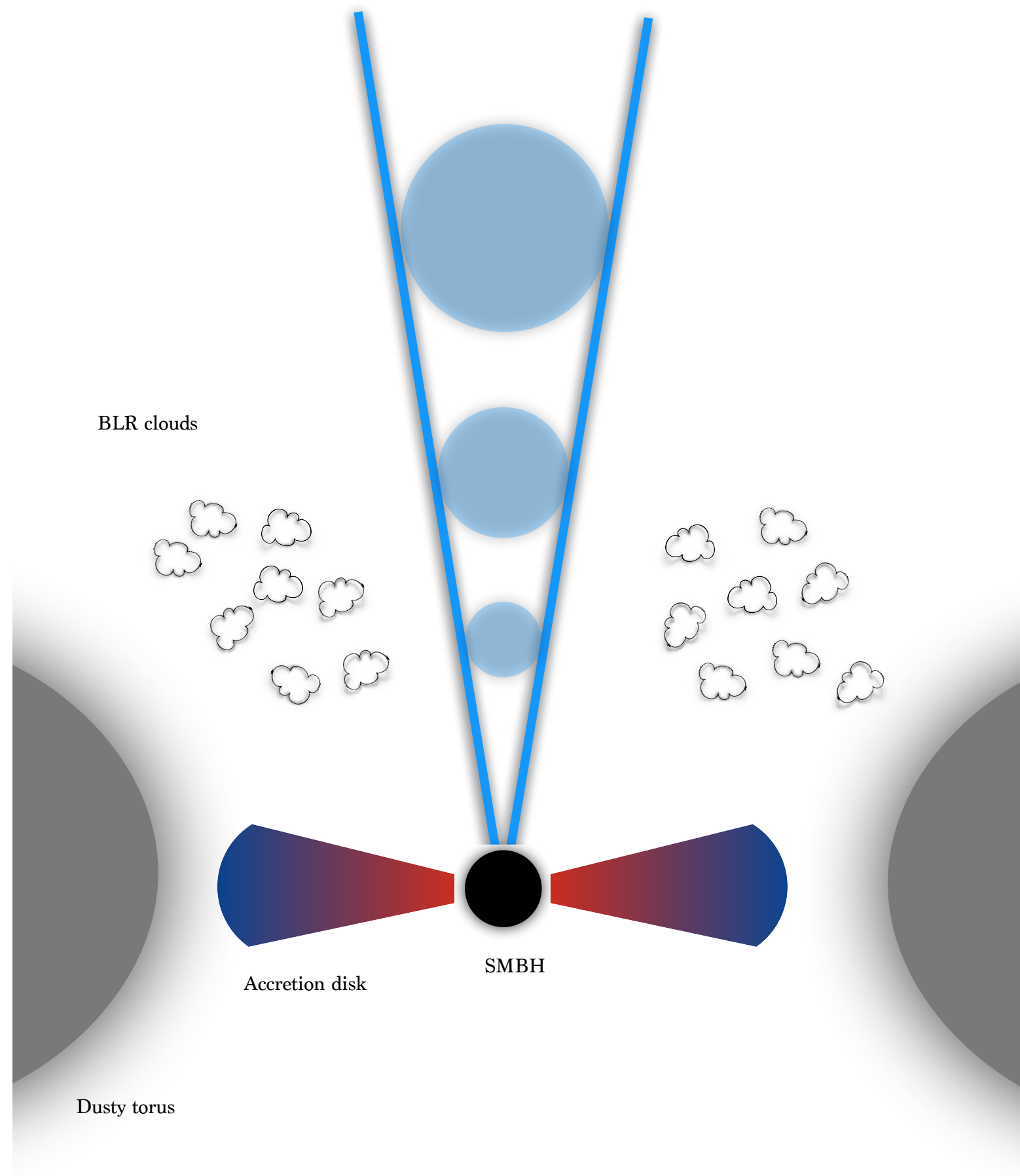
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Blazars are associated with VHE neutrinos.



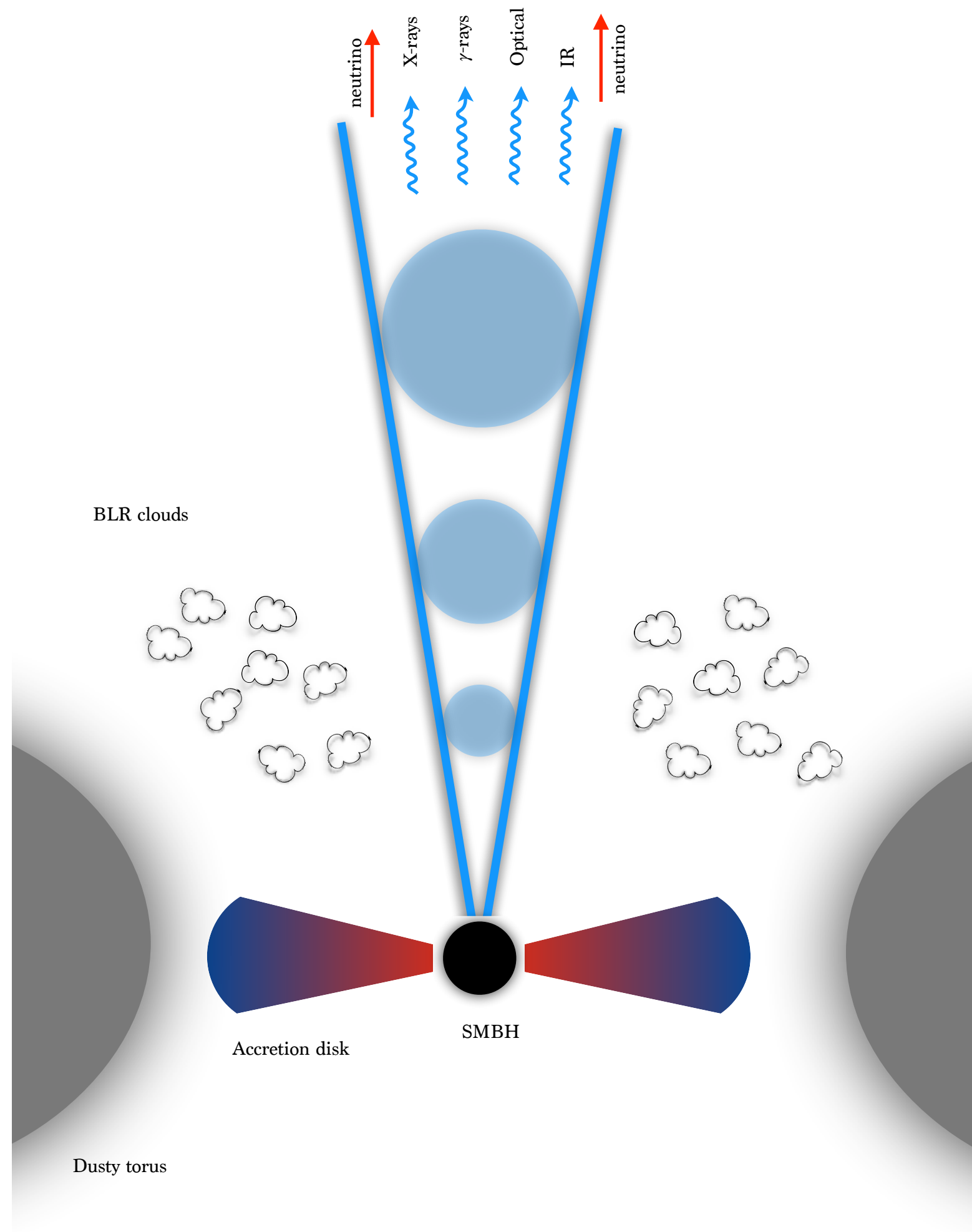
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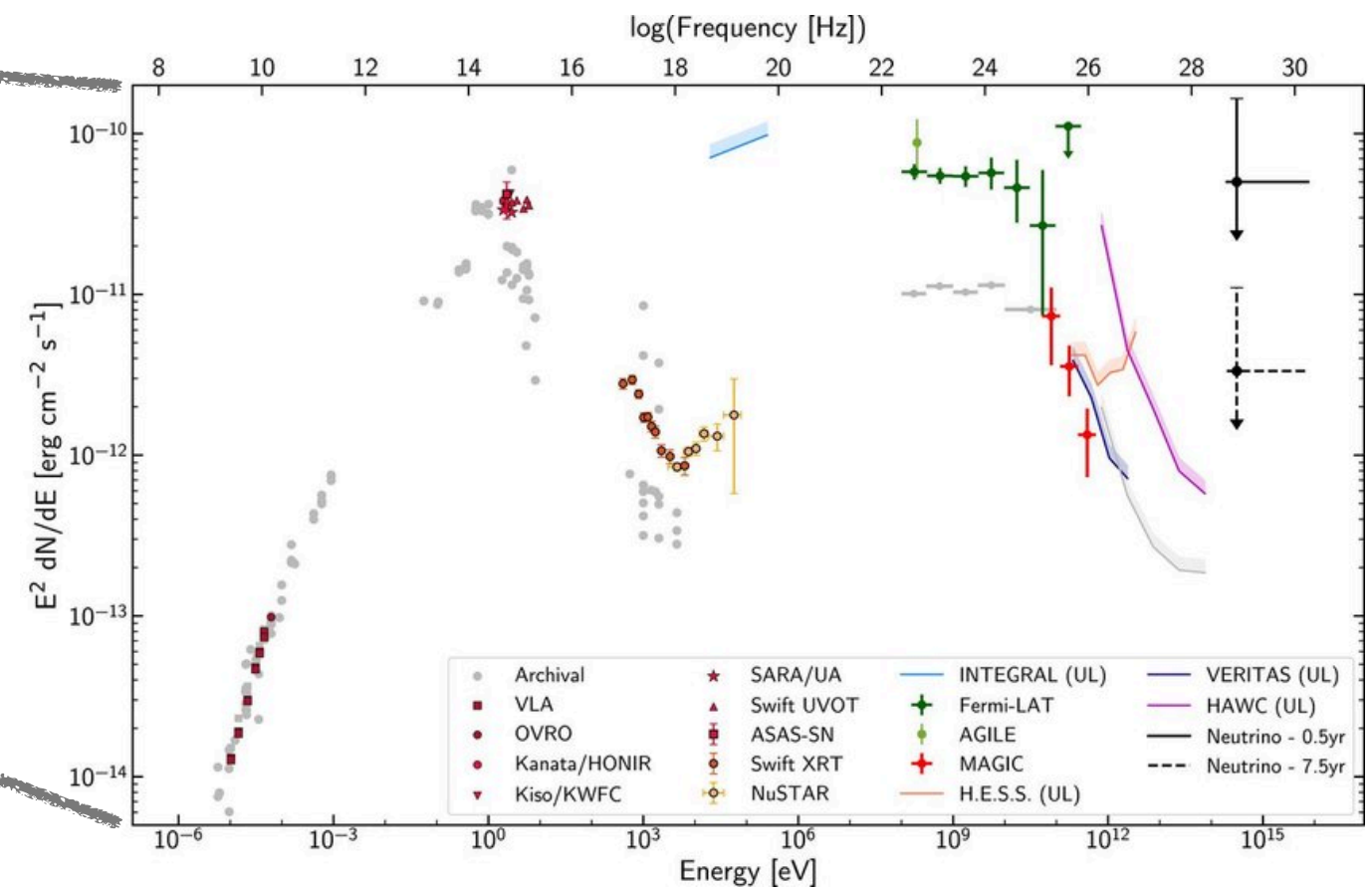
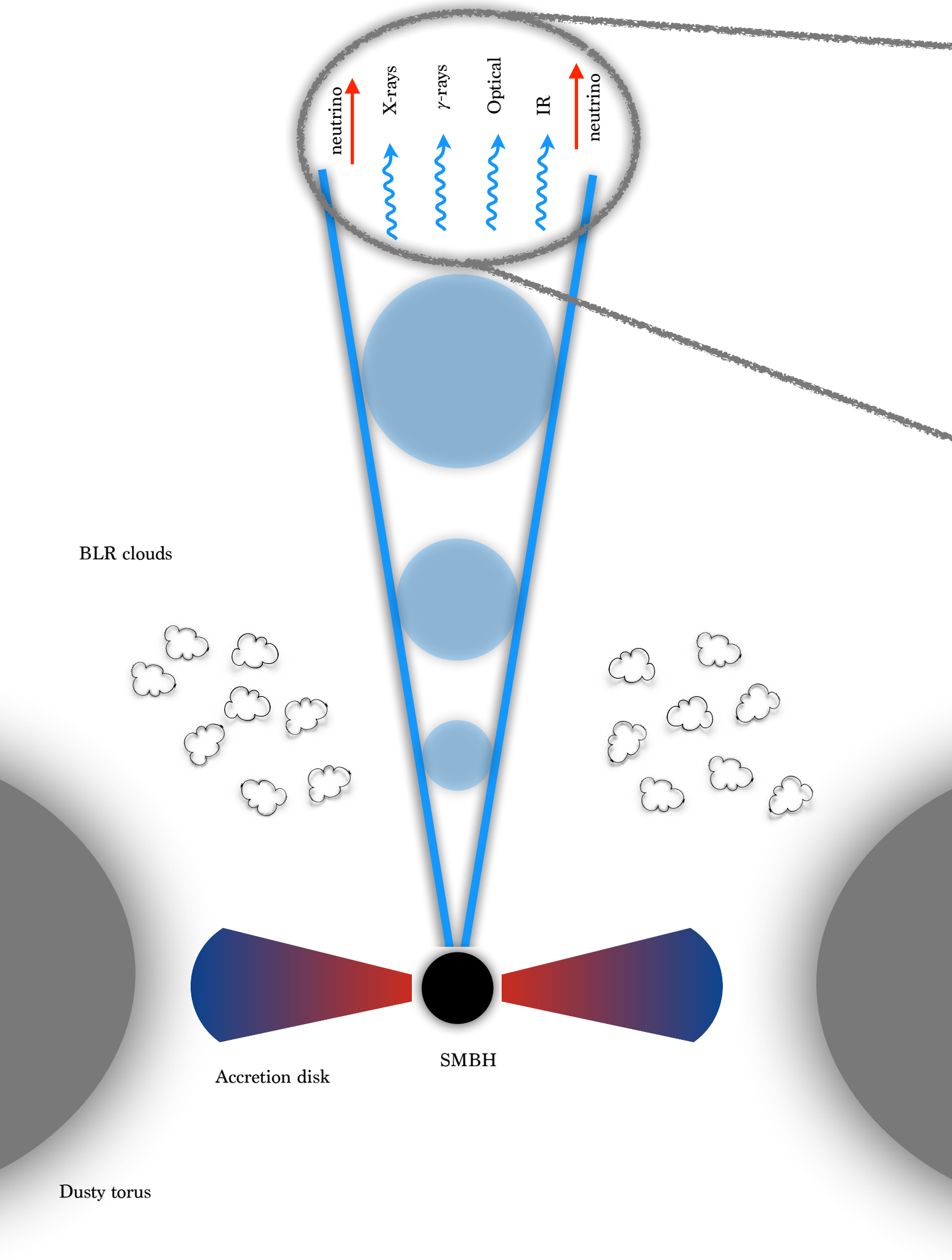
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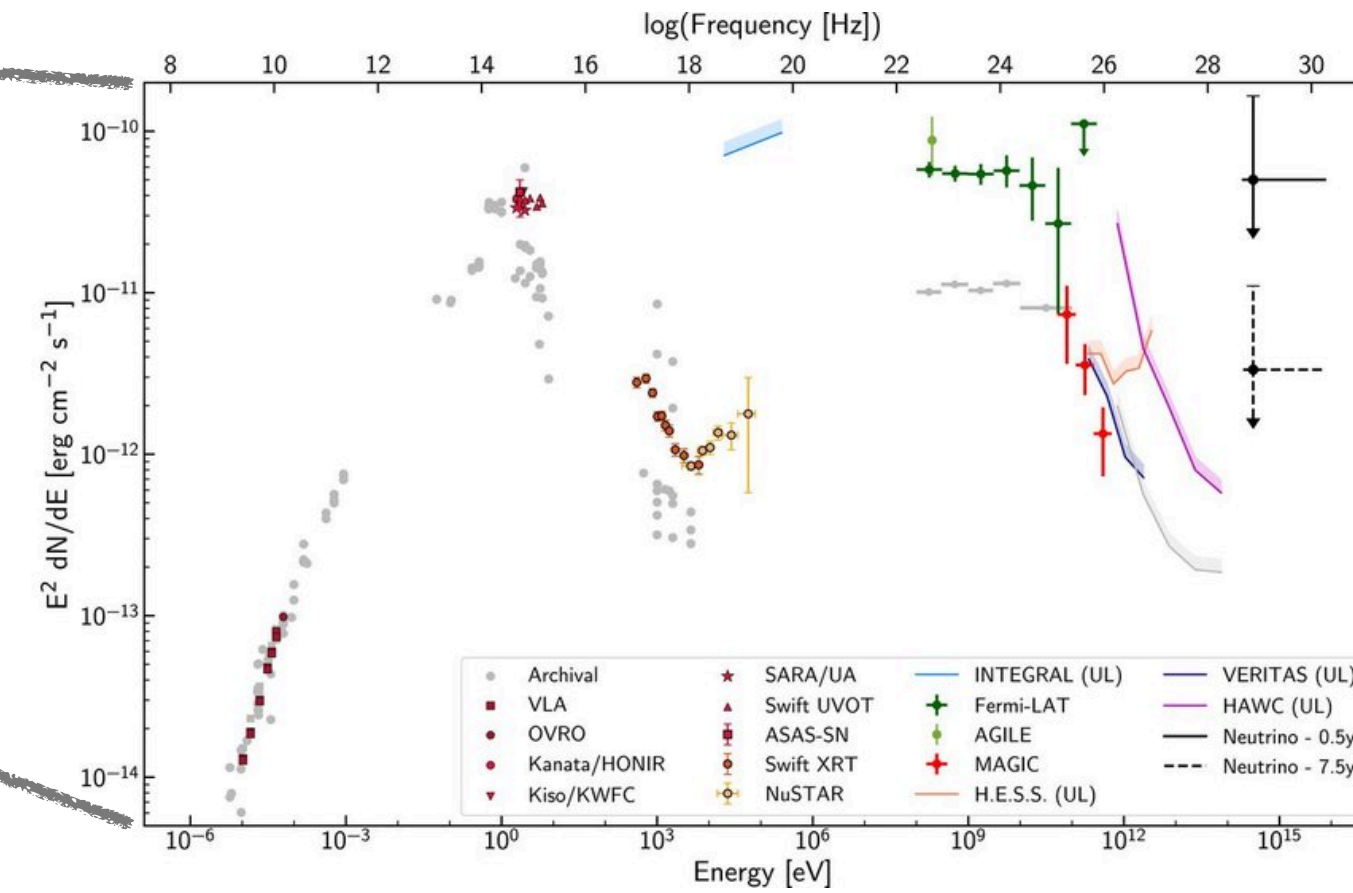
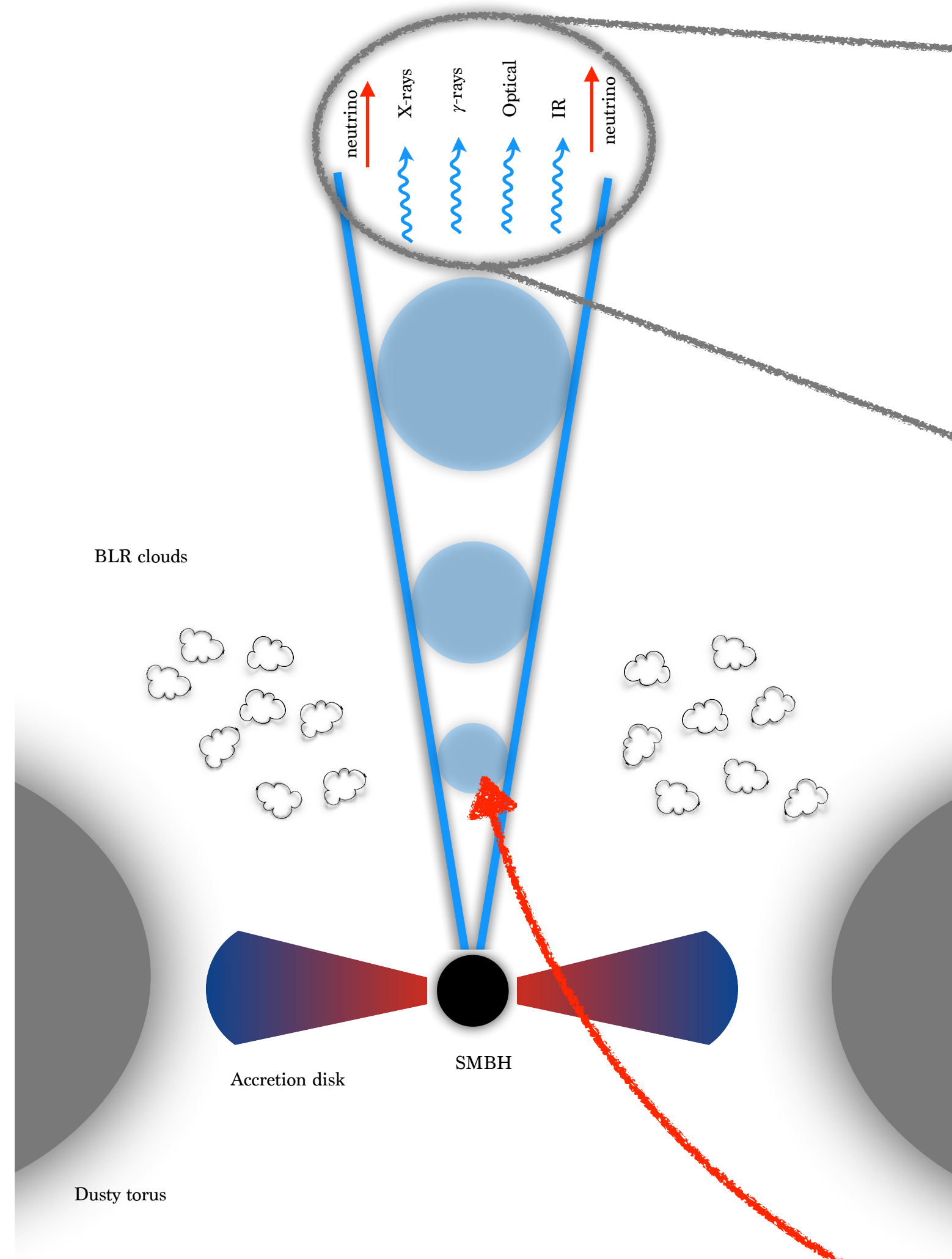
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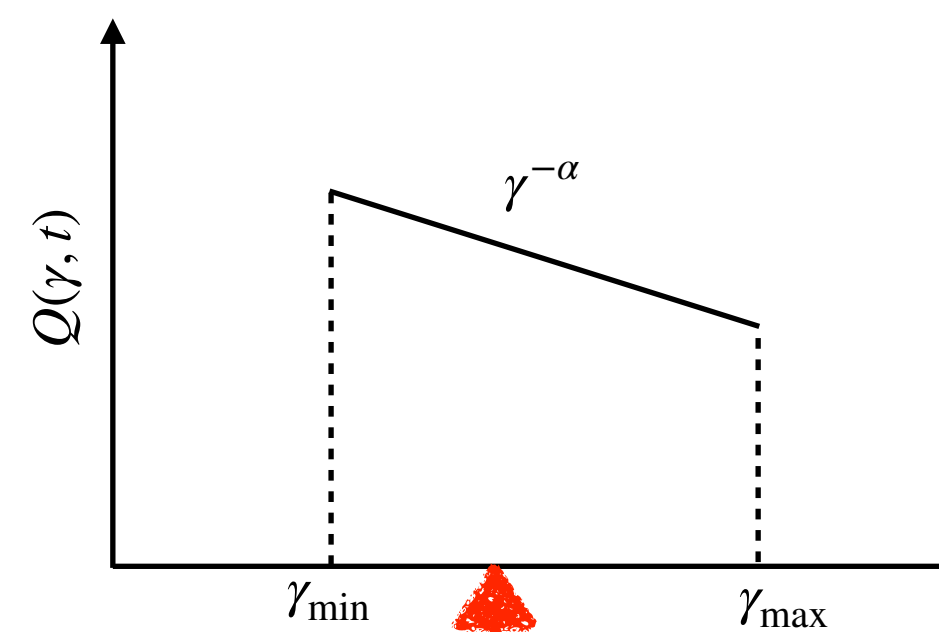


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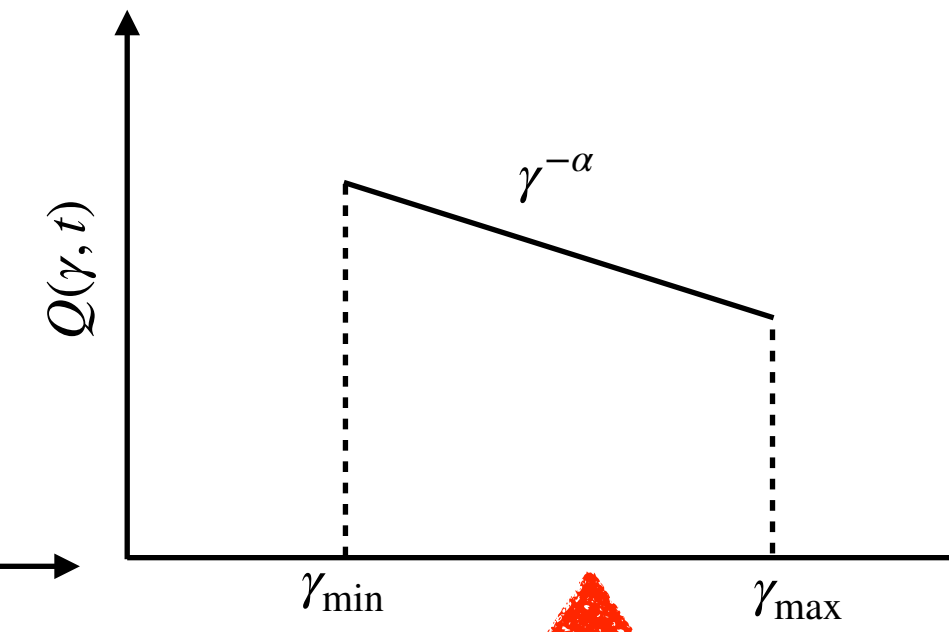
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Injection or acceleration of electrons

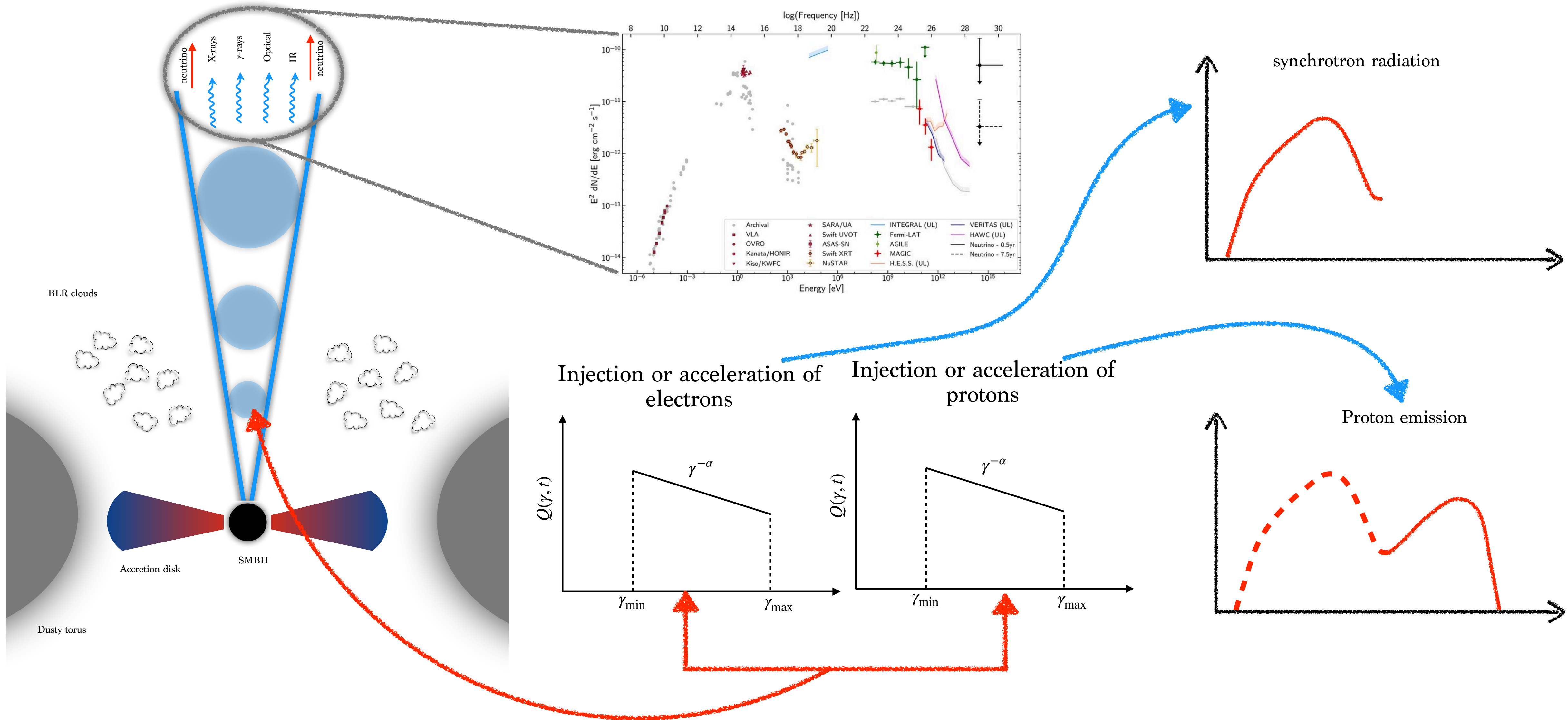


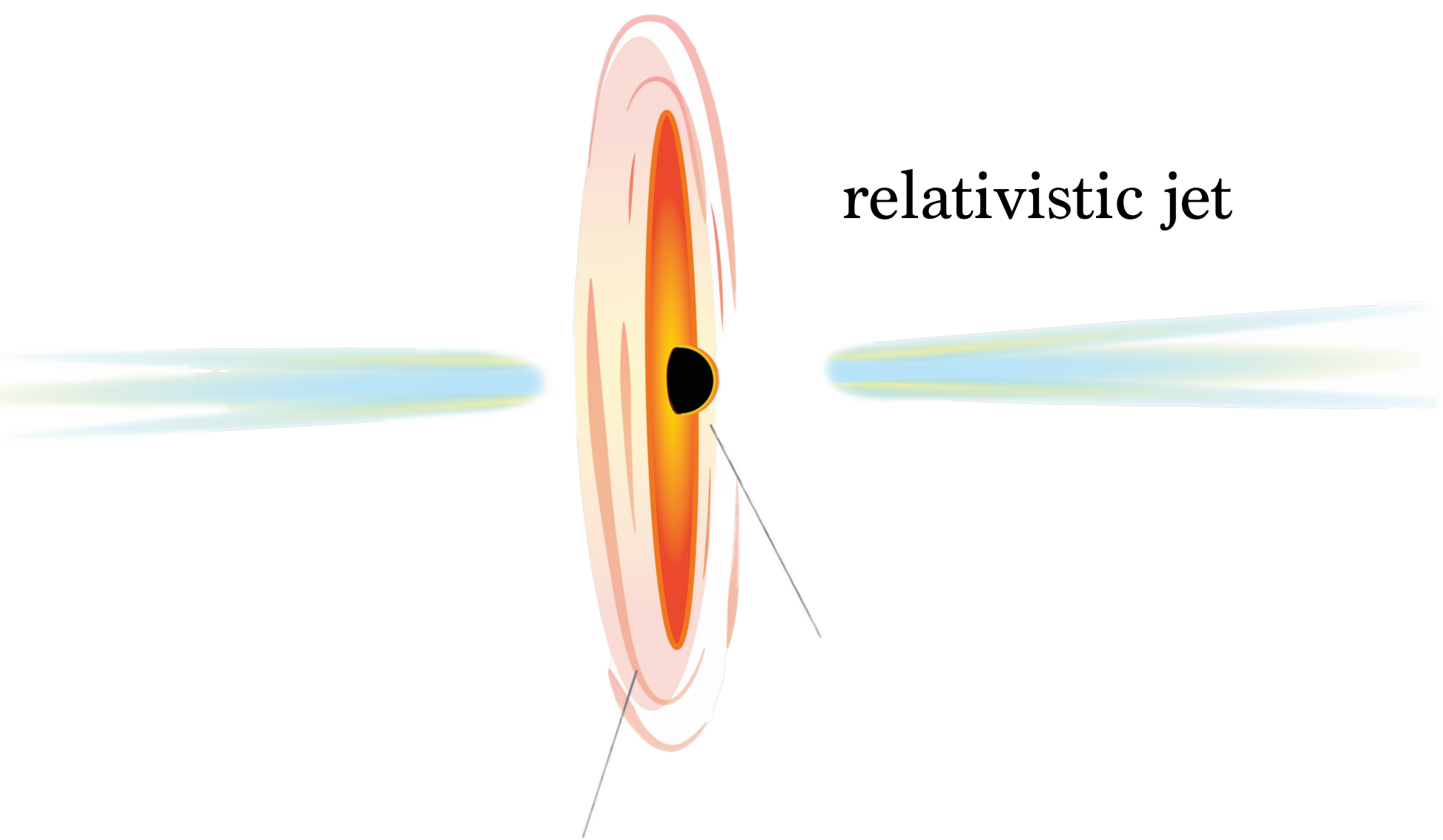
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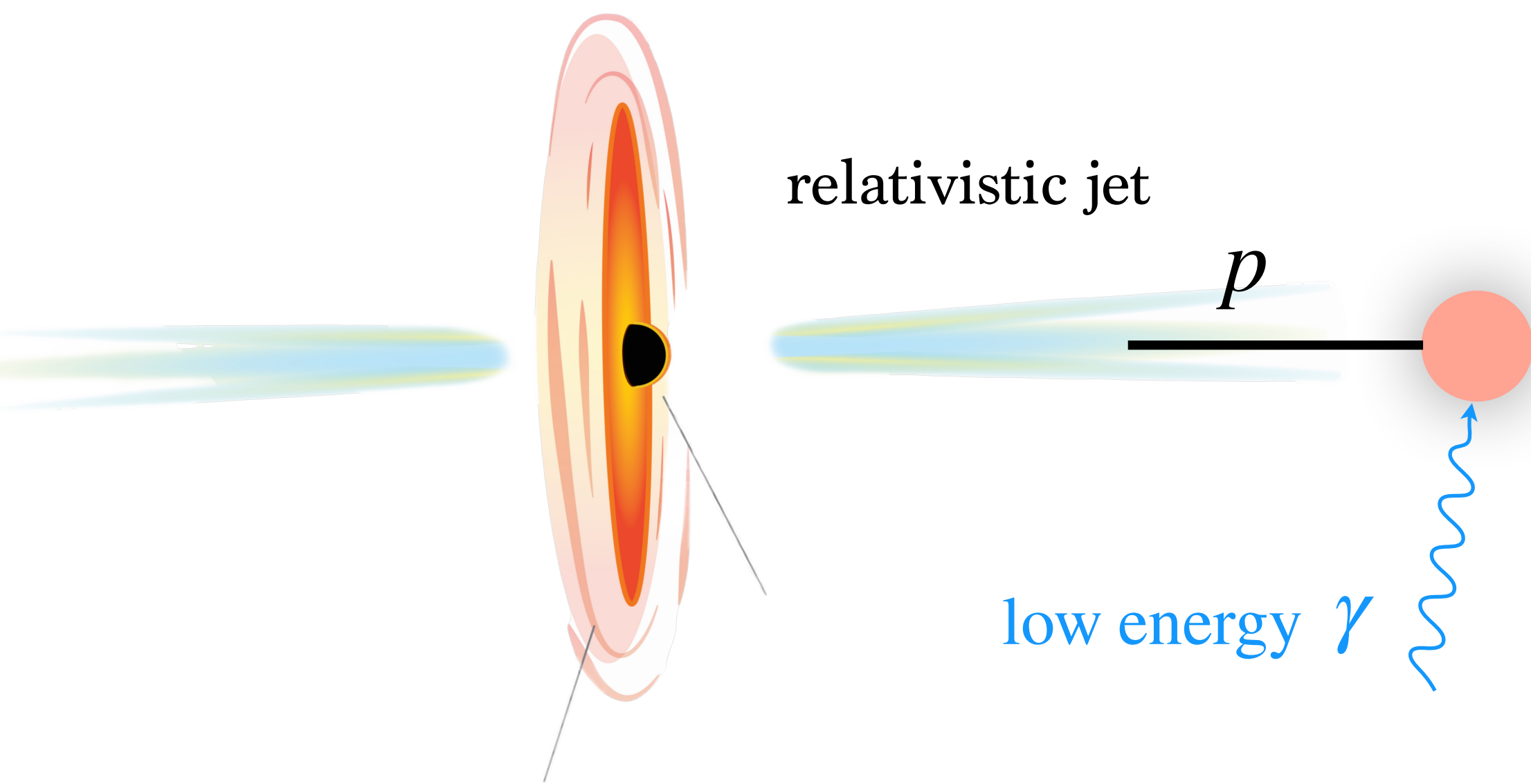
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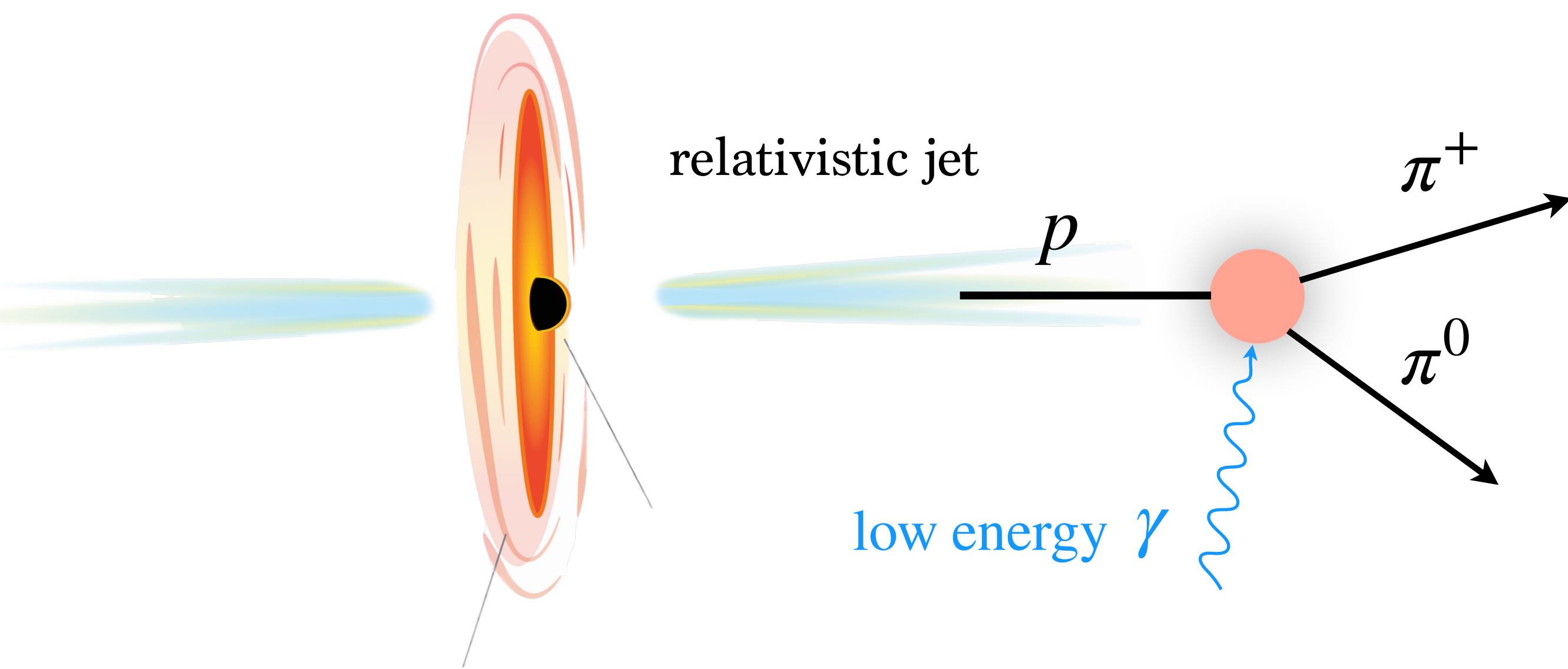
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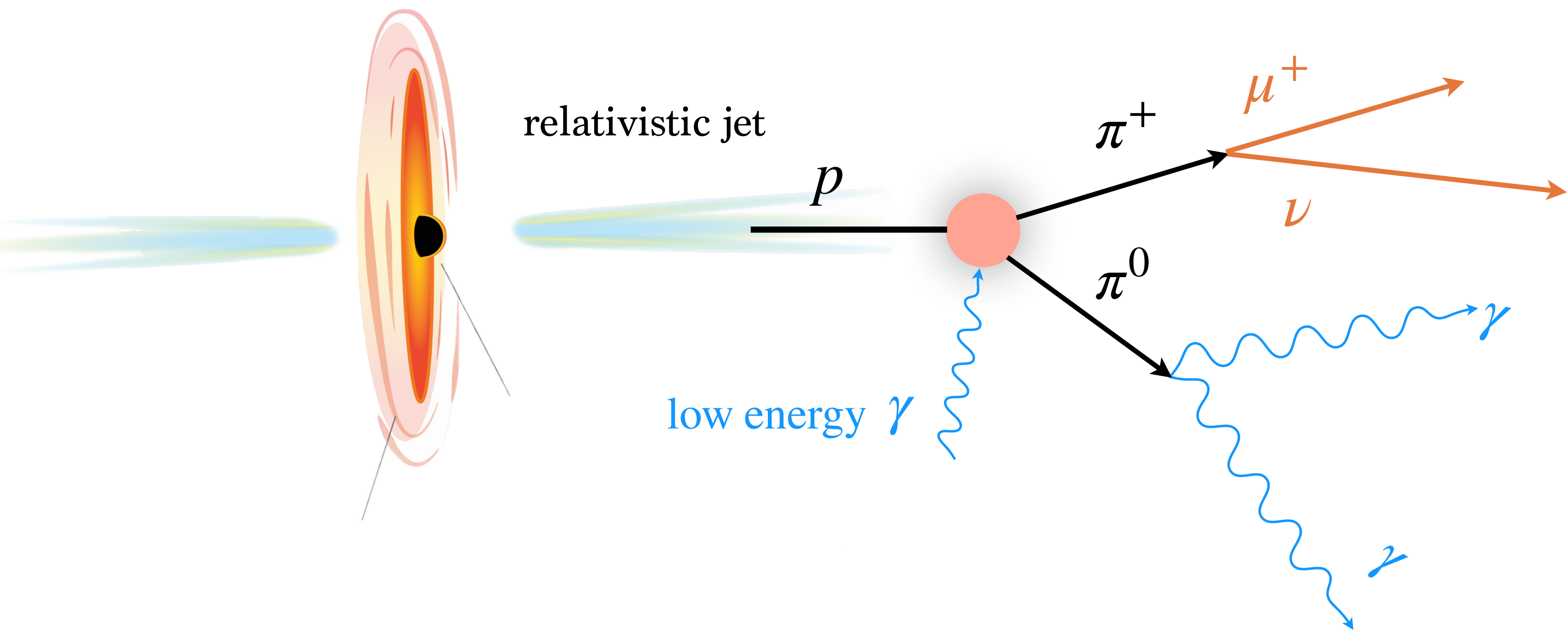


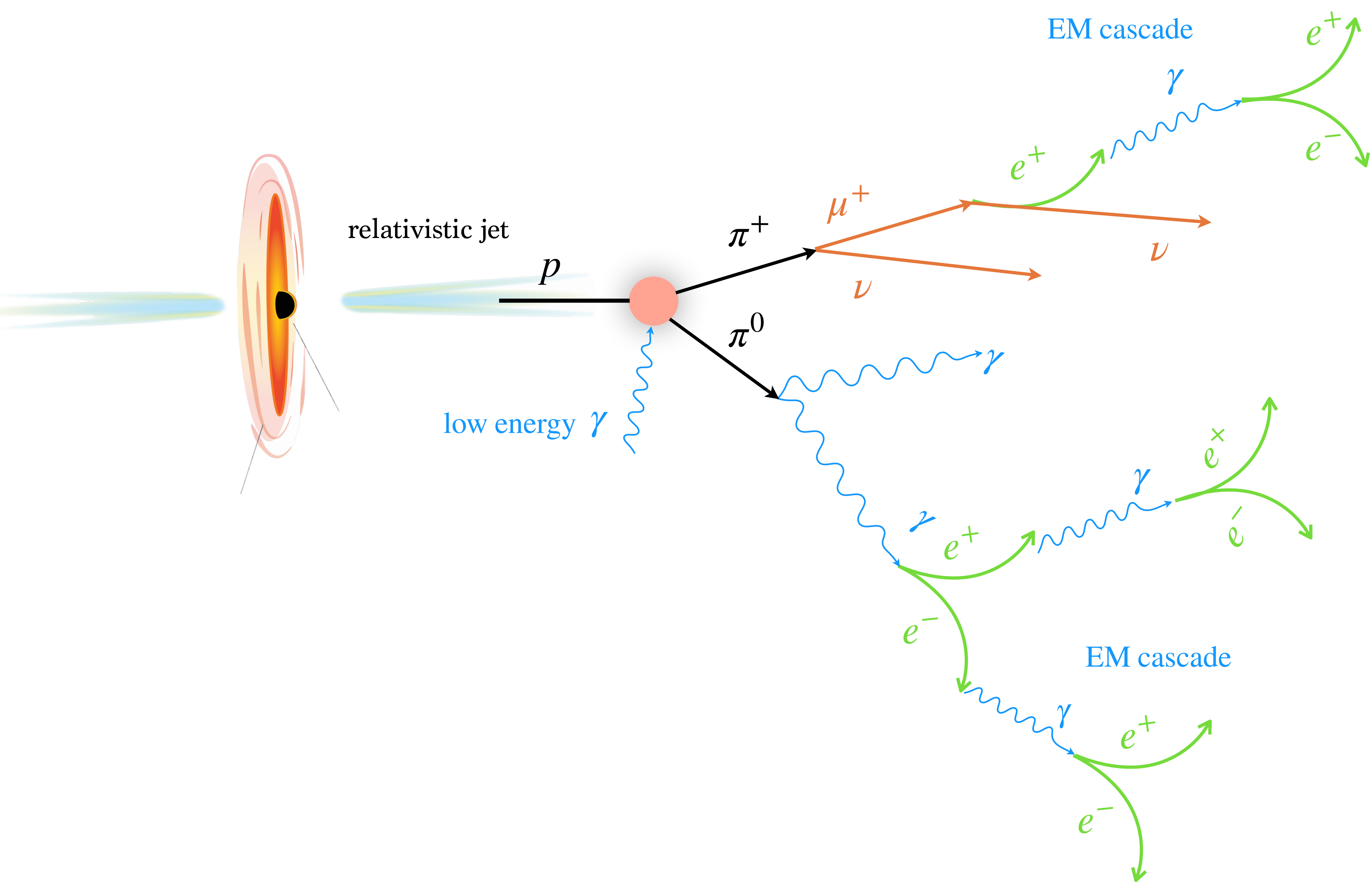


relativistic jet





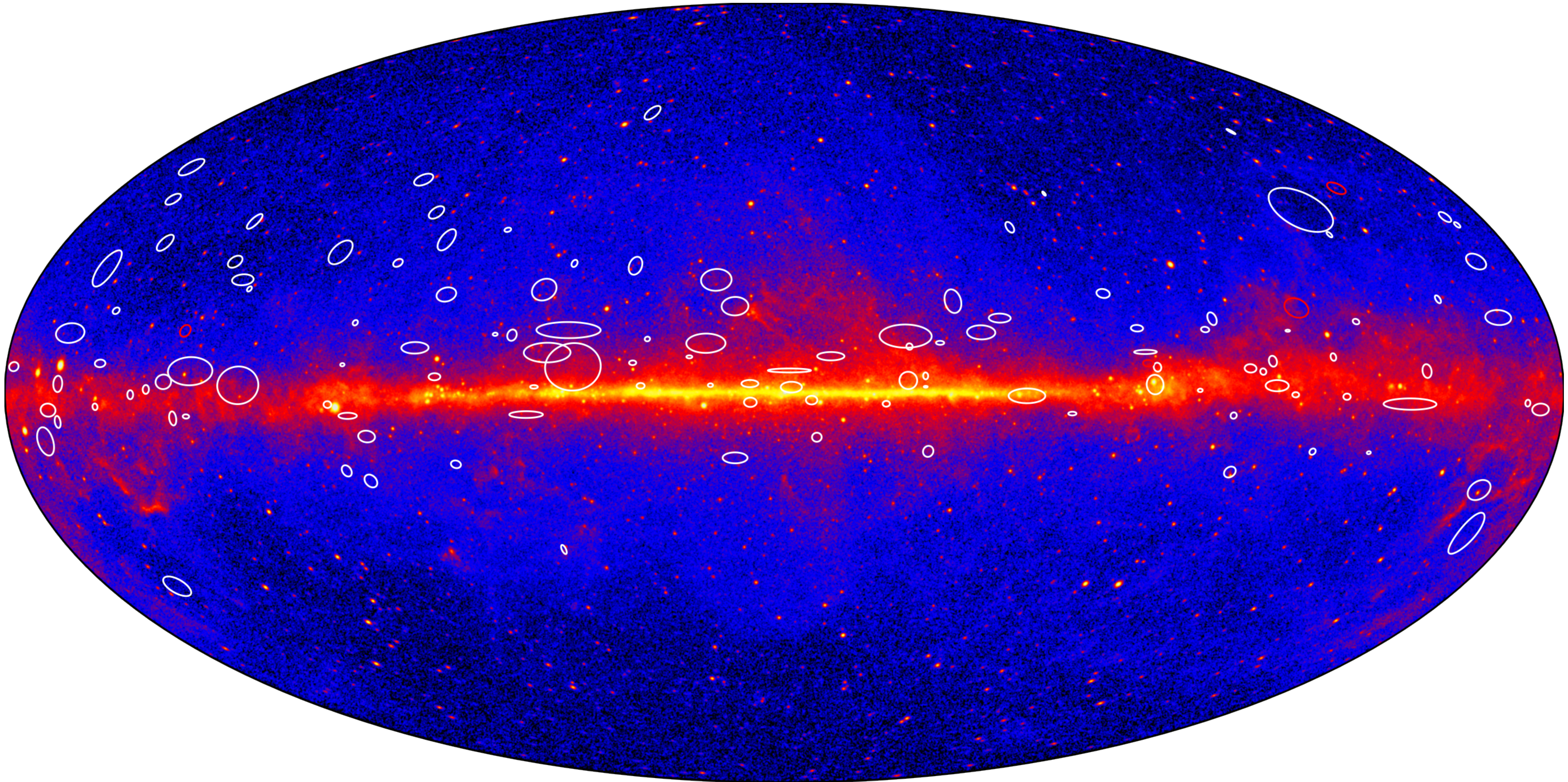




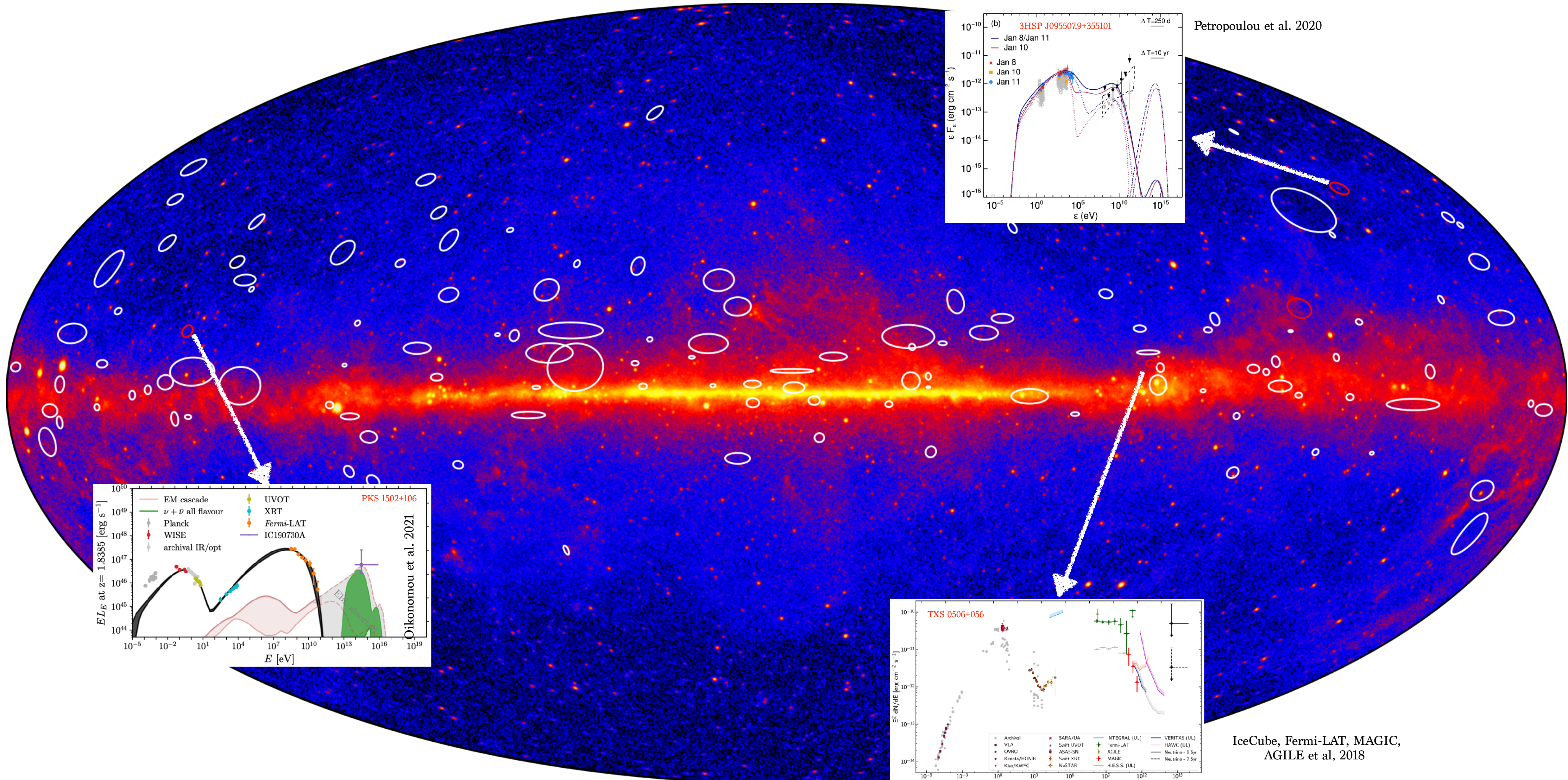
In recent years, a large network of observatories has been deployed on remote places in the land, in the sea, underground and in space, to detect the signals coming from the "visible" Universe and even earlier, in the first moments beyond the "recombination wall" when nuclei and electrons formed neutral atoms and the Universe became transparent.

LISTENING TO NEW COSMIC MESSENGERS

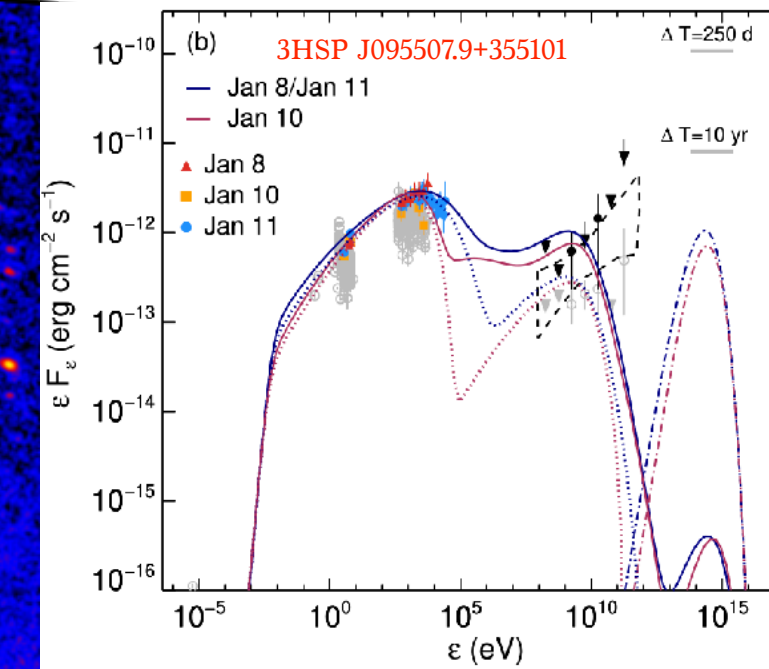
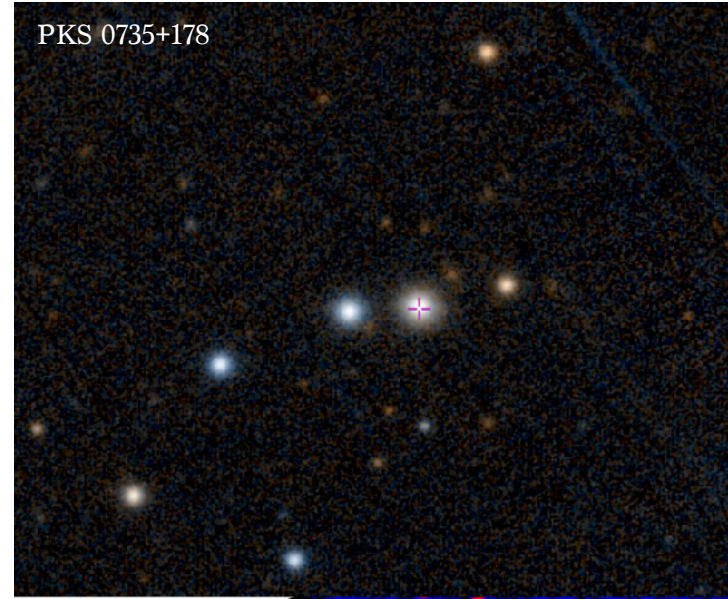
Multiwavelength + Multimessenger data



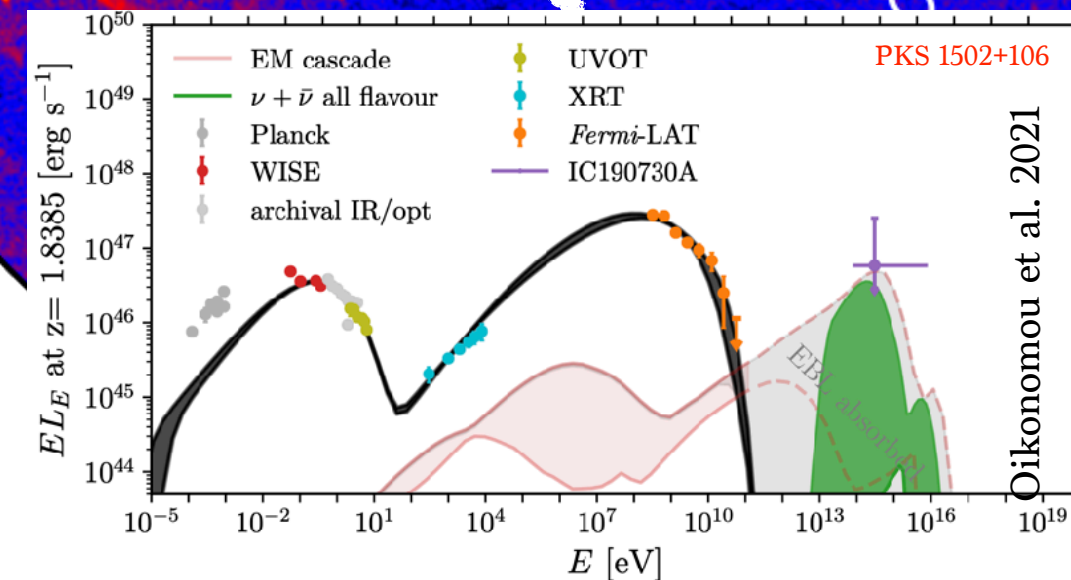
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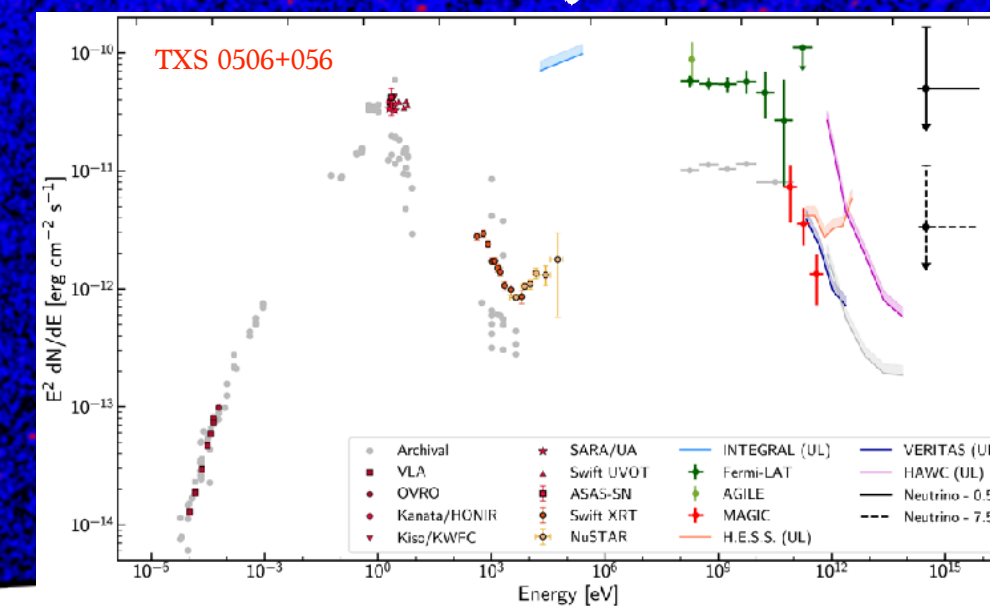
Multiwavelength + Multimessenger data



Petropoulou et al. 2020



Olkonomou et al. 2021



IceCube, Fermi-LAT, MAGIC, AGILE et al, 2018

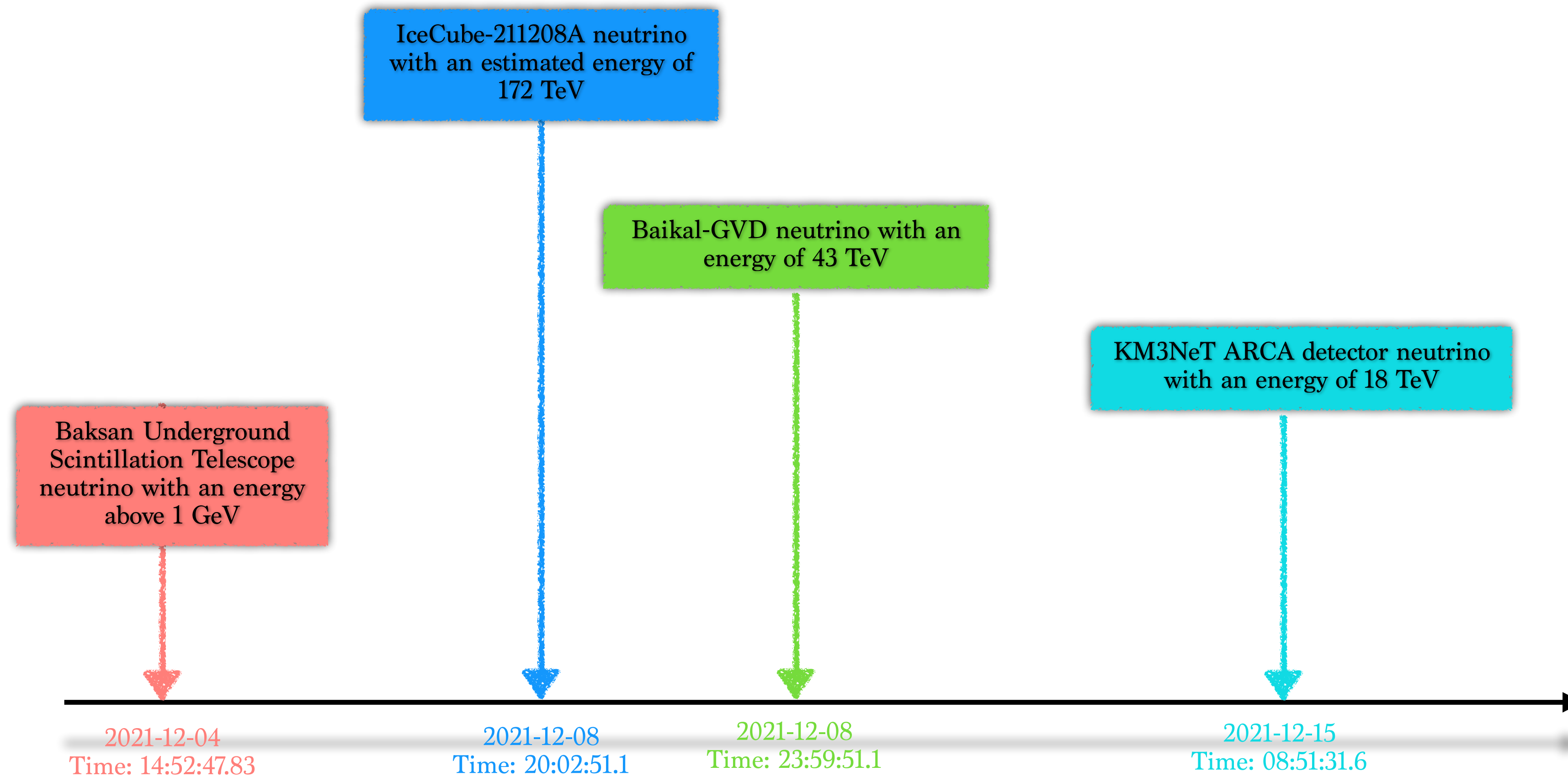
Neutrinos from PKS 0735+178

IceCube-211208A neutrino
with an estimated energy of
172 TeV

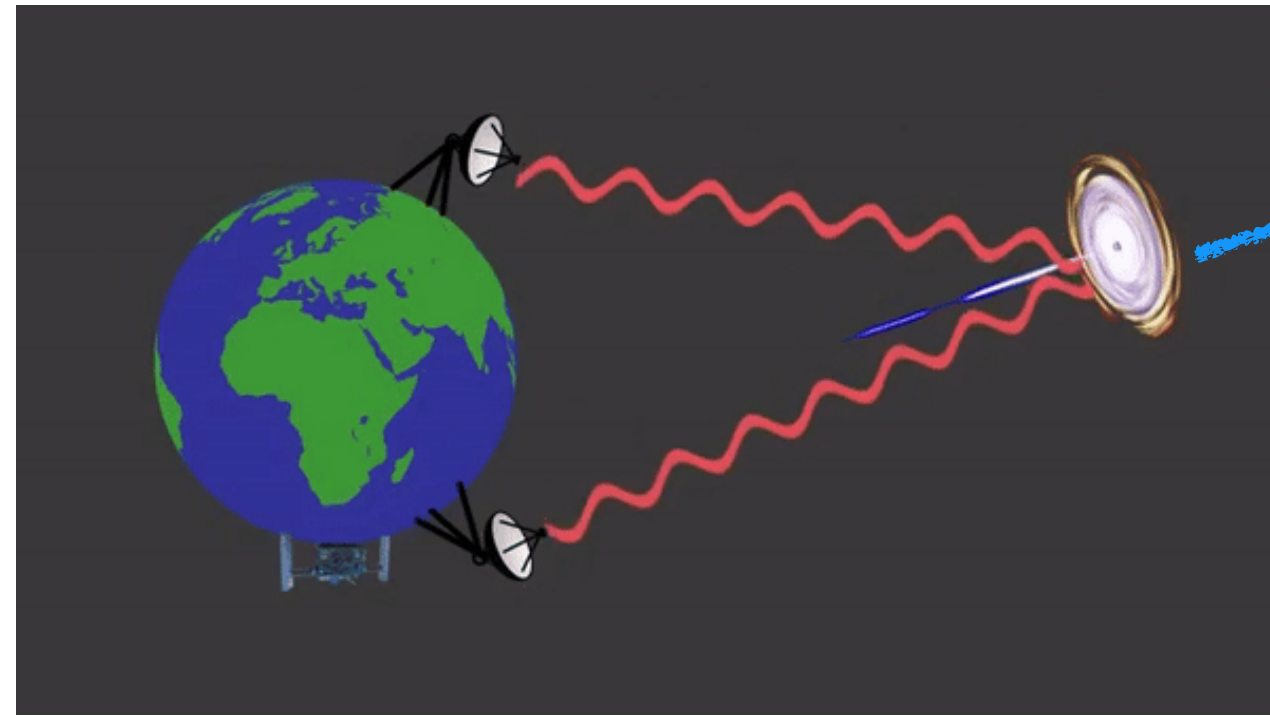


2021-12-08
Time: 20:02:51.1

Neutrinos from PKS 0735+178



Neutrinos from PKS 0735+178



IceCube-211208A neutrino
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172 TeV

Baikal-GVD neutrino with an
energy of 43 TeV

Baksan Underground
Scintillation Telescope
neutrino with an energy
above 1 GeV

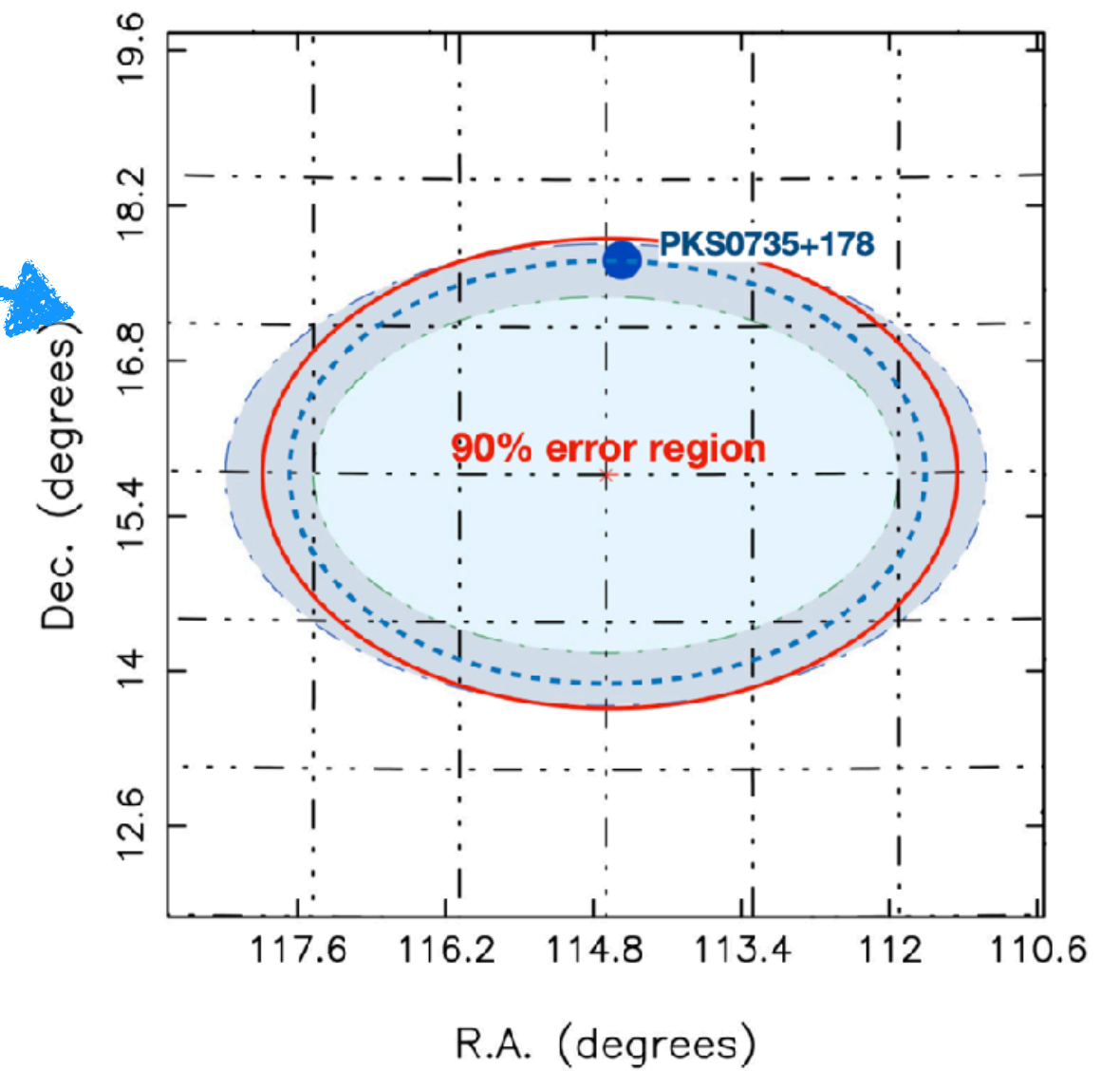
KM3NeT ARCA detector neutrino
with an energy of 18 TeV

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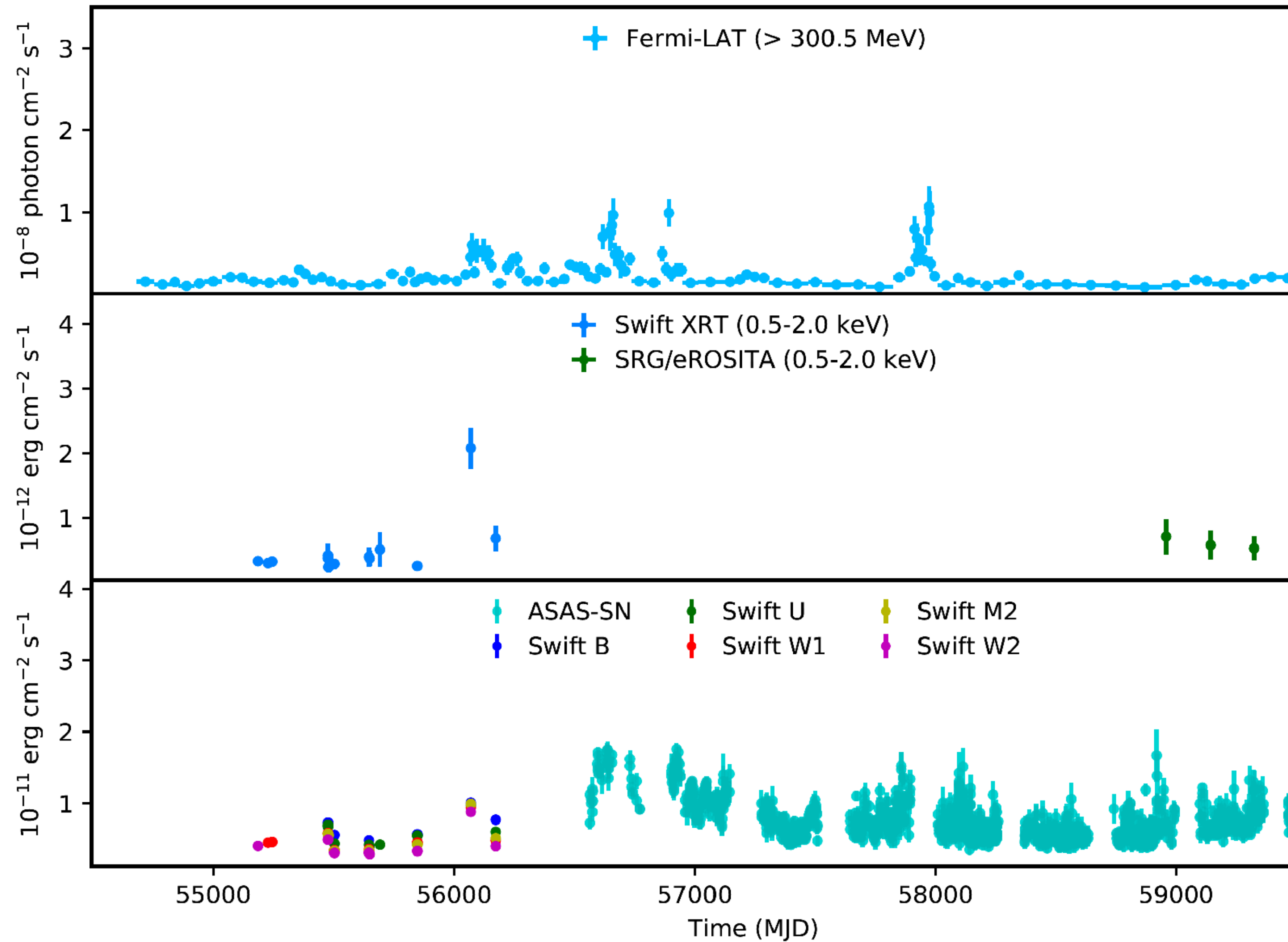
2021-12-08
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2021-12-08
Time: 23:59:51.1

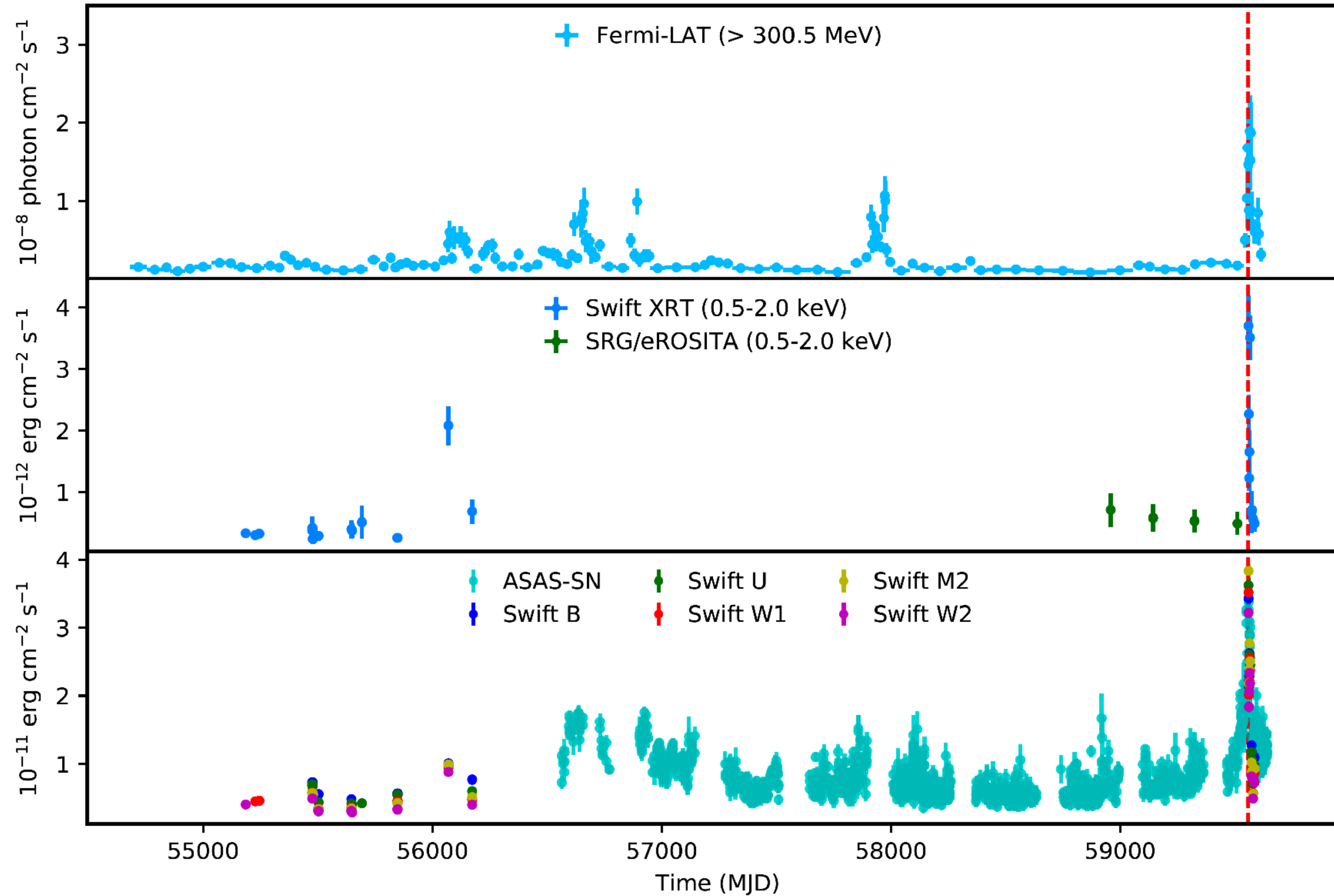
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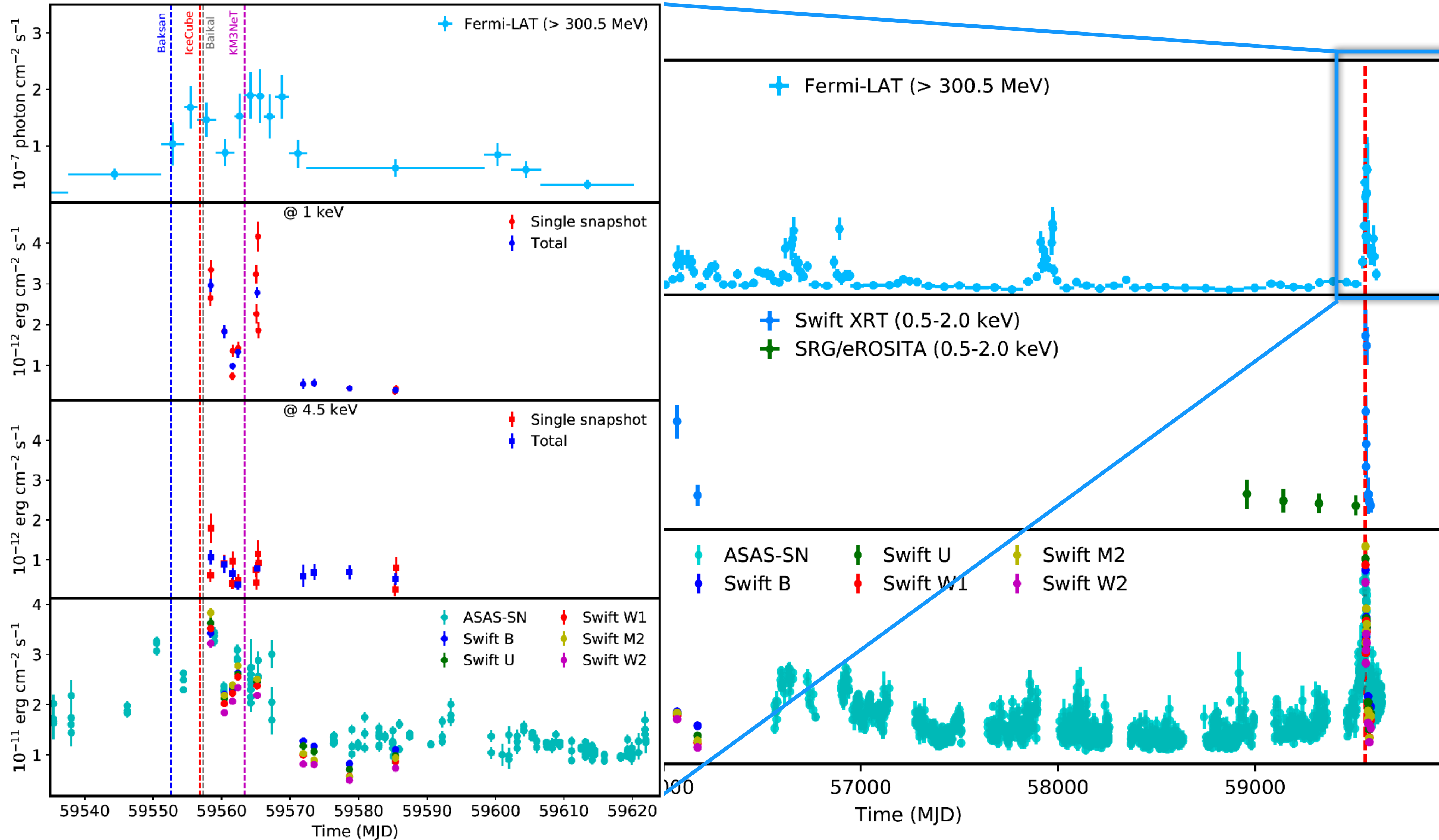
MW lightcurve of PKS 0735+178



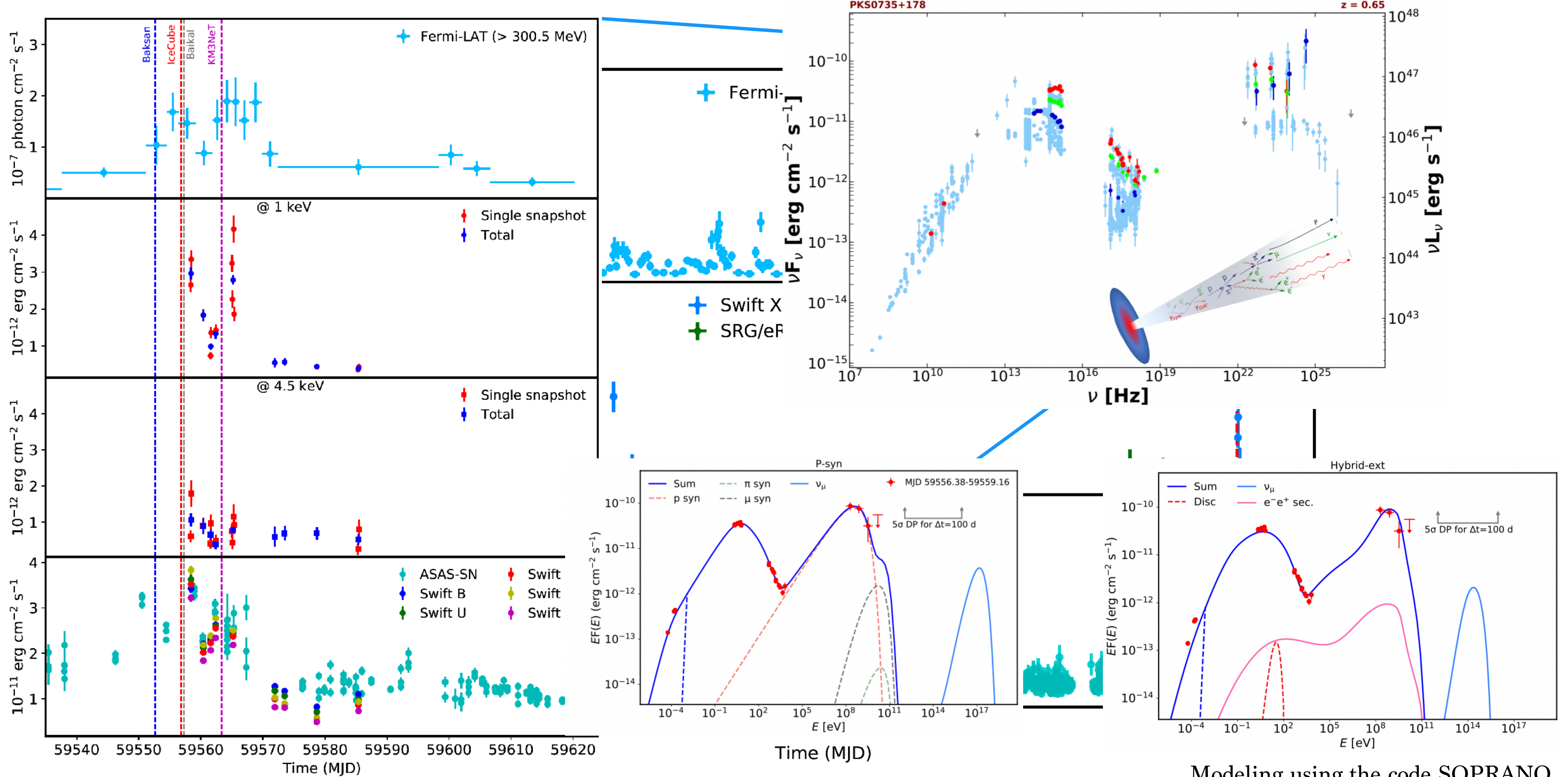
MW lightcurve of PKS 0735+178



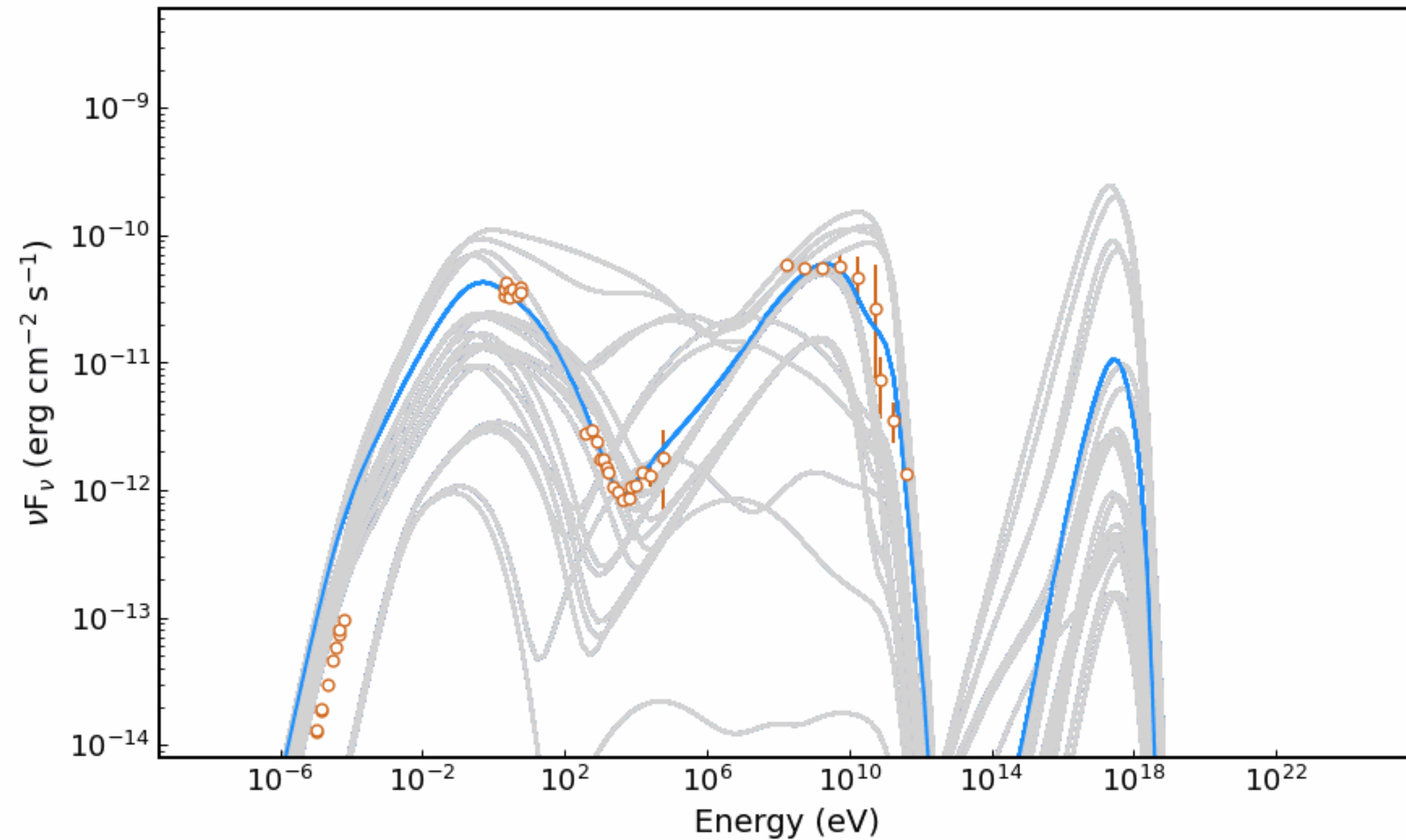
MW lightcurve of PKS 0735+178 and origin of the emission



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Computational Challenges and ML-based Solutions



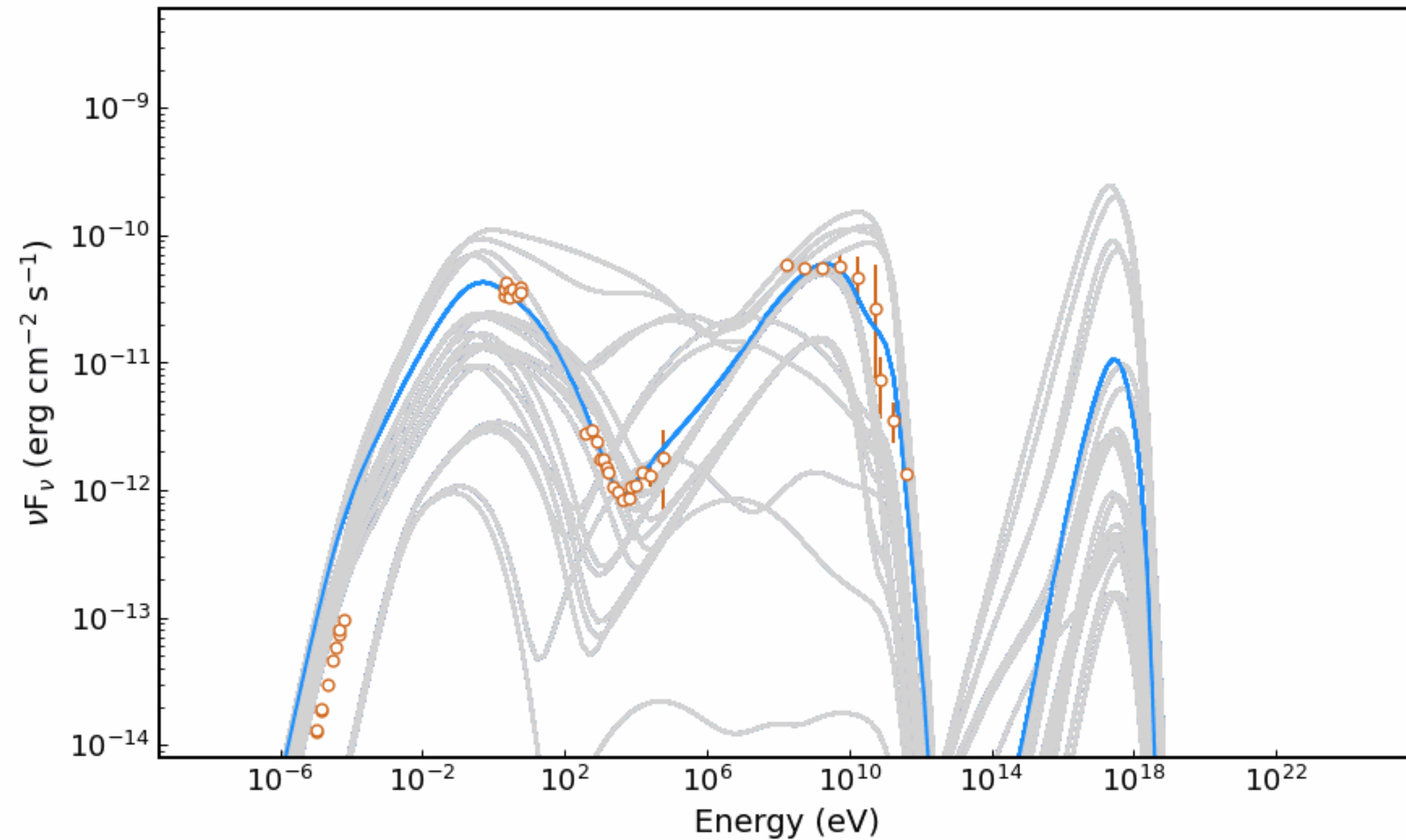
Traditional Modeling :

- Frequent likelihood evaluations, making computations time-consuming.
- Models computed for each dataset, resulting in redundant and costly computations.
- For Bayesian fitting, models must be evaluated 10^4 - 10^5 times.

Computation Time Estimates (8 cores) :

- SSC / EIC model: ~ 30 sec $\rightarrow$ 3.5 – 35 days
- Hadronic model: ~ 90 sec $\rightarrow$ 10 – 100 days

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Machine Learning for Accelerated Model computations:

- ☑ Efficient: avoids exhaustive parameter space exploration.
- ☑ Reusable across different datasets after training.
- ☑ Several orders-of-magnitude faster evaluations.

References :

- ☑ Bégué, Sahakyan et al., ApJ, 963, 71 (2024)
- ☑ Sahakyan, Bégué et al., ApJ, 971, 70 (2024)
- ☑ Sahakyan, Bégué et al., ApJ, 990, 222 (2025)

Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	δ	3.5	100	Linear
Blob radius	cm	R	$10^{14.5}$	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{\text{e,min}}$	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{\text{e,max}}$	10^2	10^8	Logarithmic
Maximum proton injection Lorentz factor	-	$\gamma_{\text{p,max}}$	10^3	10^{11}	Logarithmic
Injection index electrons	-	p_e	1.7	5	Linear
Injection index protons	-	p_p	1.6	3.5	Linear
Electron luminosity	erg.s^{-1}	L_e	10^{42}	10^{49}	Logarithmic
Proton luminosity	erg.s^{-1}	L_p	10^{42}	10^{52}	Logarithmic
Magnetic field	G	B	10^{-3}	$10^{3.5}$	Logarithmic

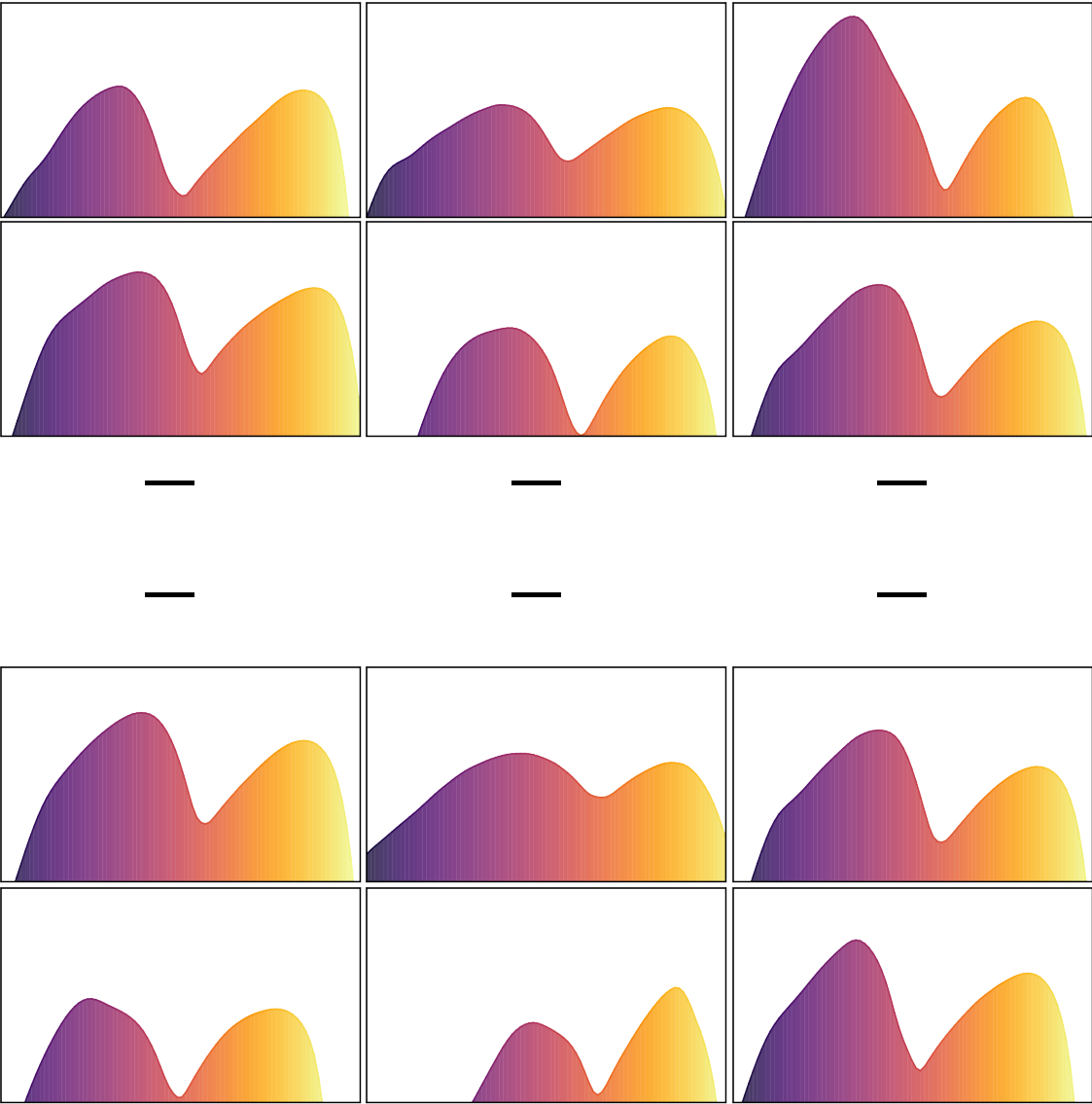
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Blob radius	cm	R	$10^{14.5}$	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{e,\text{min}}$	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{e,\text{max}}$	10^2	10^8	Logarithmic
Maximum proton injection Lorentz factor	-	$\gamma_{p,\text{max}}$	10^3	10^{11}	Logarithmic
Injection index electrons	-	p_e	1.7	5	Linear
Injection index protons	-	p_p	1.6	3.5	Linear
Electron luminosity	erg.s^{-1}	L_e	10^{42}	10^{49}	Logarithmic
Proton luminosity	erg.s^{-1}	L_p	10^{42}	10^{52}	Logarithmic
Magnetic field	G	B	10^{-3}	$10^{3.5}$	Logarithmic

Gasparyan, Bégué, Sahakyan 2022



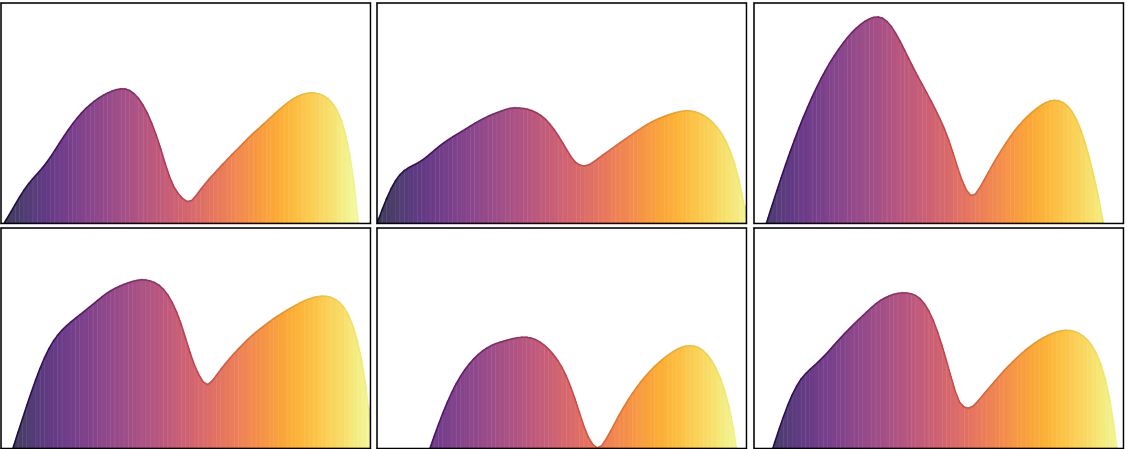
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Blob radius	cm	R	$10^{14.5}$	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{e,\text{min}}$	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{e,\text{max}}$	10^2	10^8	Logarithmic
Maximum proton injection Lorentz factor	-	$\gamma_{p,\text{max}}$	10^3	10^{11}	Logarithmic
Injection index electrons	-	p_e	1.7	5	Linear
Injection index protons	-	p_p	1.6	3.5	Linear
Electron luminosity	erg.s^{-1}	L_e	10^{42}	10^{49}	Logarithmic
Proton luminosity	erg.s^{-1}	L_p	10^{42}	10^{52}	Logarithmic
Magnetic field	G	B	10^{-3}	$10^{3.5}$	Logarithmic

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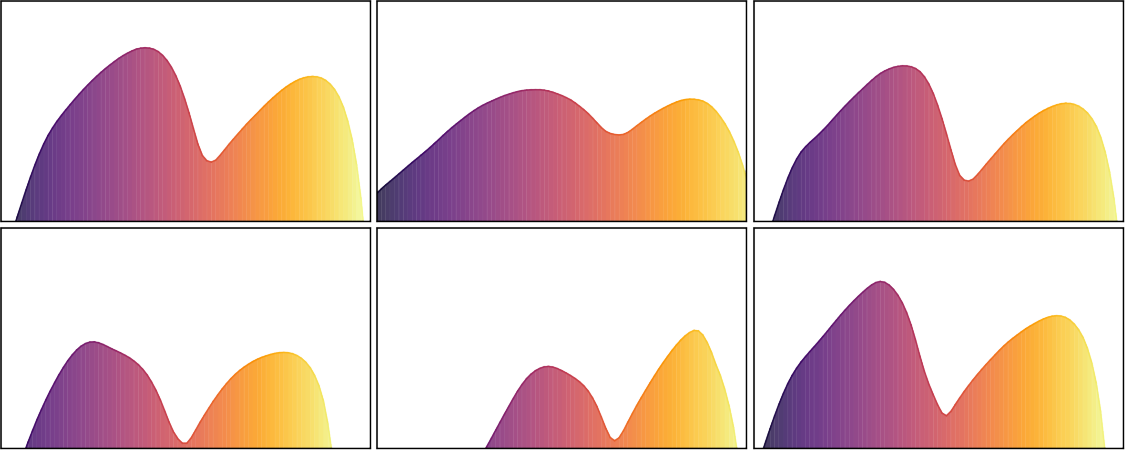


Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	δ	3.5	100	Linear
Blob radius	cm	R	$10^{14.5}$	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{e,\min}$	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{e,\max}$	10^2	10^8	Logarithmic
Maximum proton injection Lorentz factor	-	$\gamma_{p,\max}$	10^3	10^{11}	Logarithmic
Injection index electrons	-	p_e	1.7	5	Linear
Injection index protons	-	p_p	1.6	3.5	Linear
Electron luminosity	erg.s^{-1}	L_e	10^{42}	10^{49}	Logarithmic
Proton luminosity	erg.s^{-1}	L_p	10^{42}	10^{52}	Logarithmic
Magnetic field	G	B	10^{-3}	$10^{3.5}$	Logarithmic

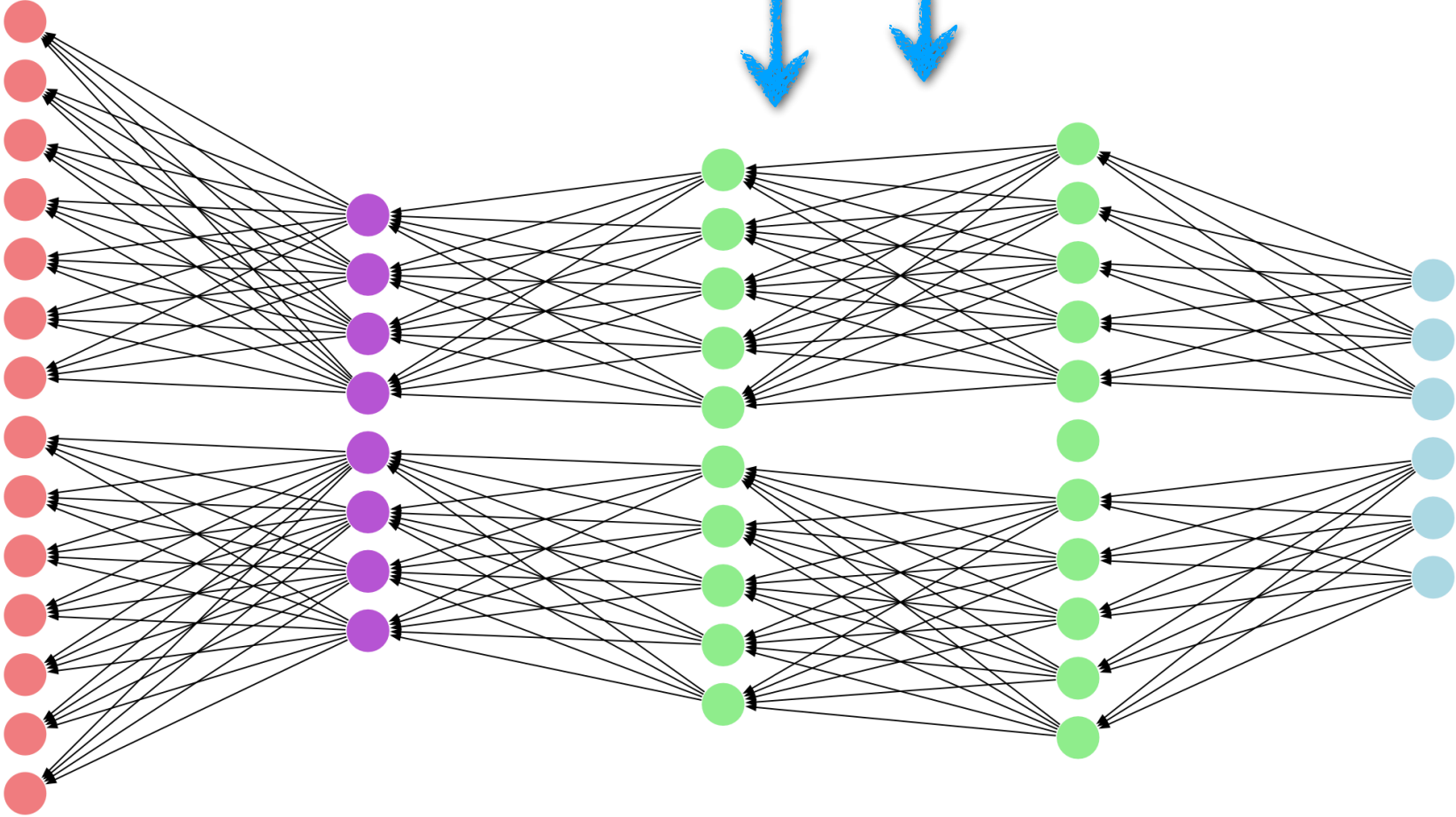
Gasparyan, Bégué, Sahakyan 2022



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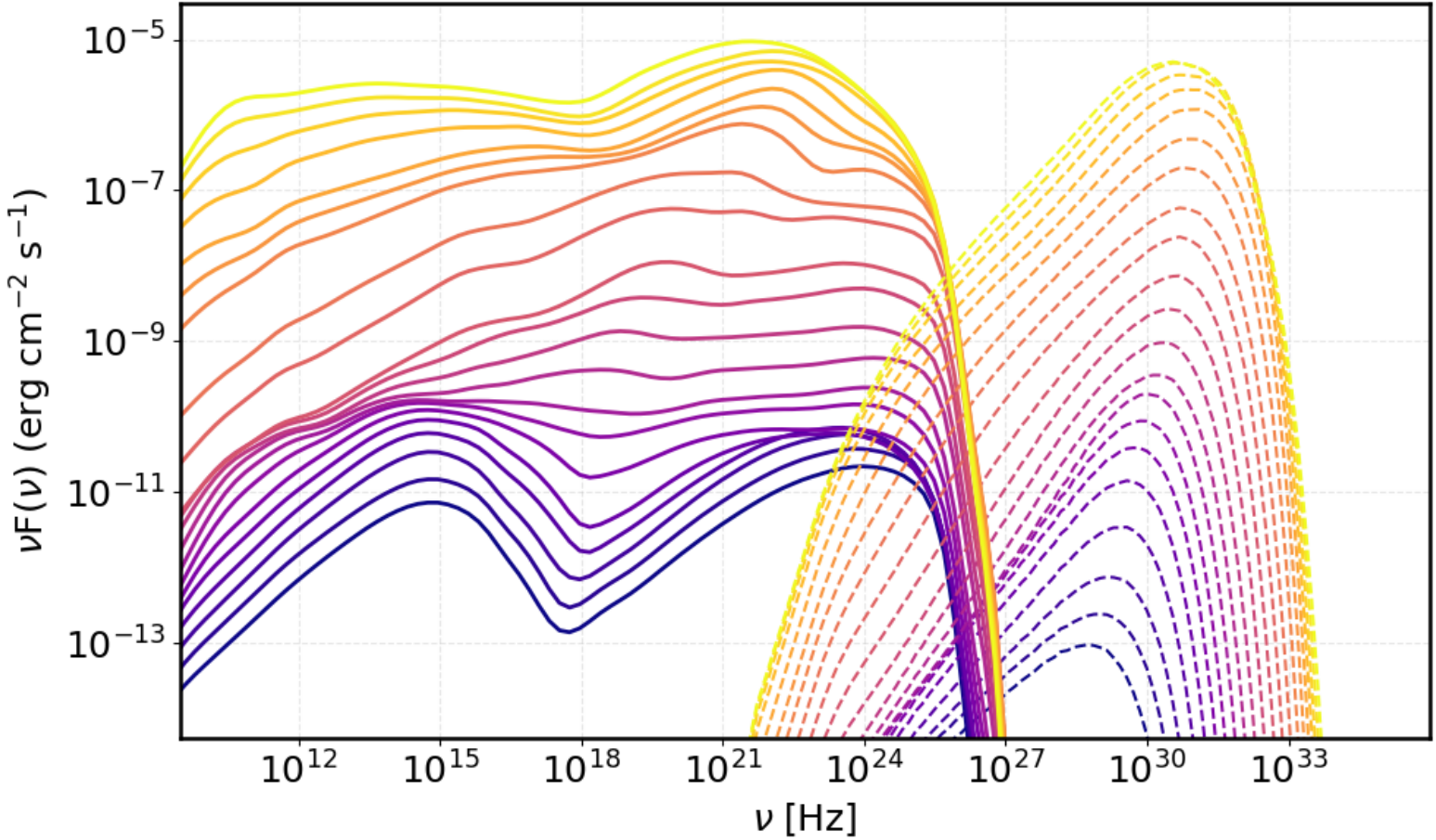
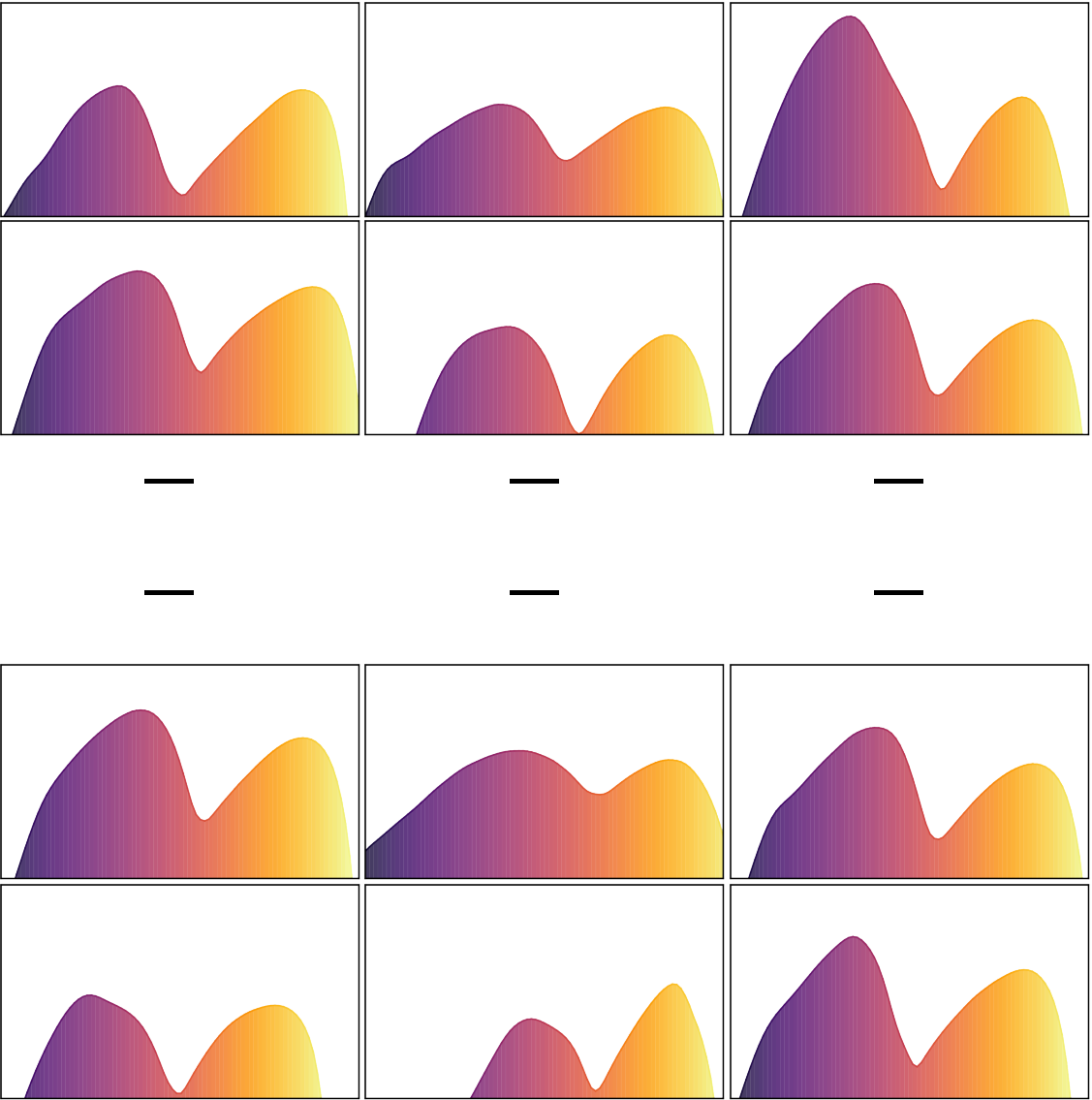
output



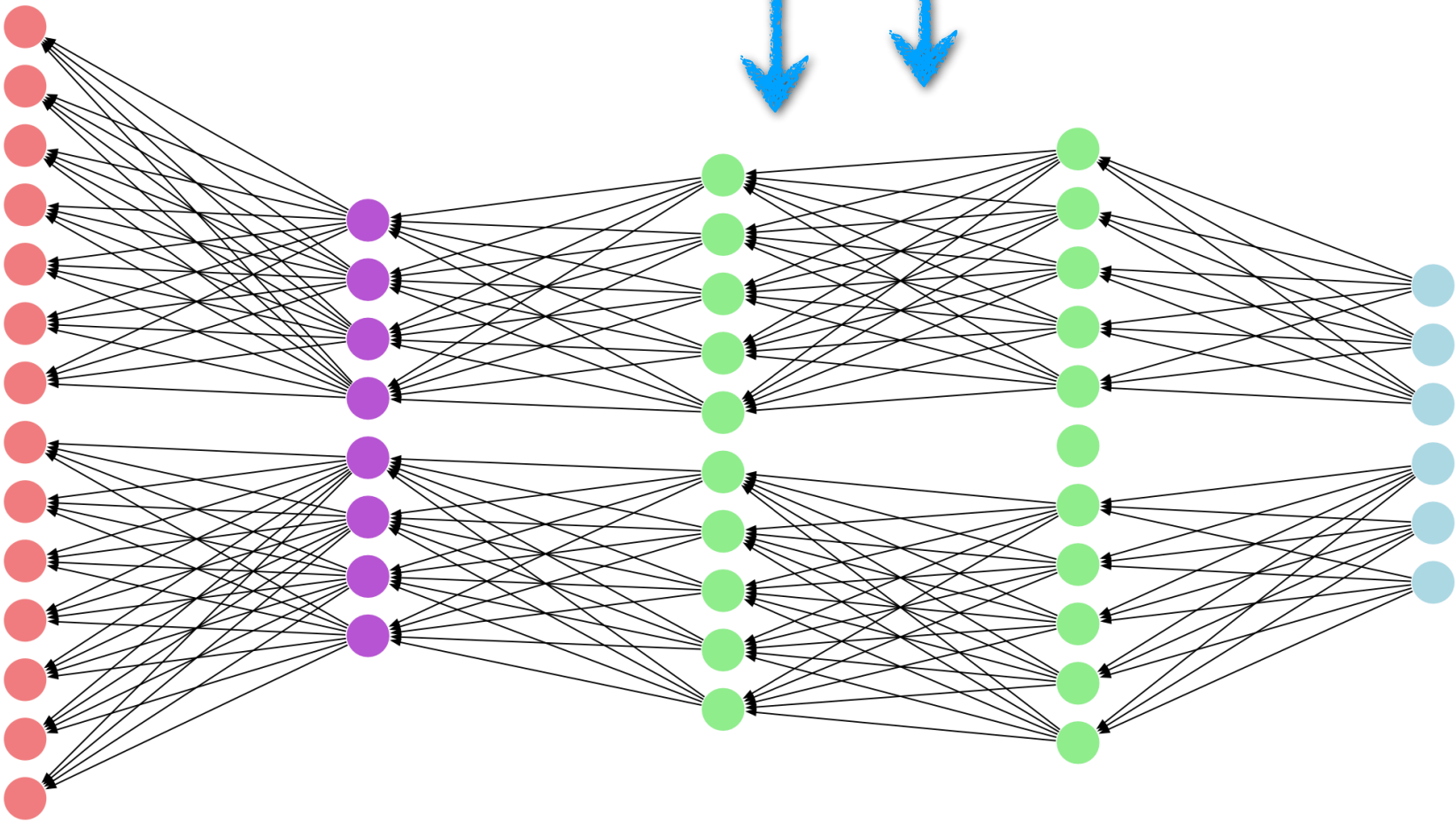
input

Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	δ	3.5	100	Linear
Blob radius	cm	R	$10^{14.5}$	10^{18}	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{e,\min}$	$10^{1.5}$	10^5	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{e,\max}$	10^2	10^8	Logarithmic
Maximum proton injection Lorentz factor	-	$\gamma_{p,\max}$	10^3	10^{11}	Logarithmic
Injection index electrons	-	p_e	1.7	5	Linear
Injection index protons	-	p_p	1.6	3.5	Linear
Electron luminosity	erg.s^{-1}	L_e	10^{42}	10^{49}	Logarithmic
Proton luminosity	erg.s^{-1}	L_p	10^{42}	10^{52}	Logarithmic
Magnetic field	G	B	10^{-3}	$10^{3.5}$	Logarithmic

Gasparyan, Bégué, Sahakyan 2022



output



input

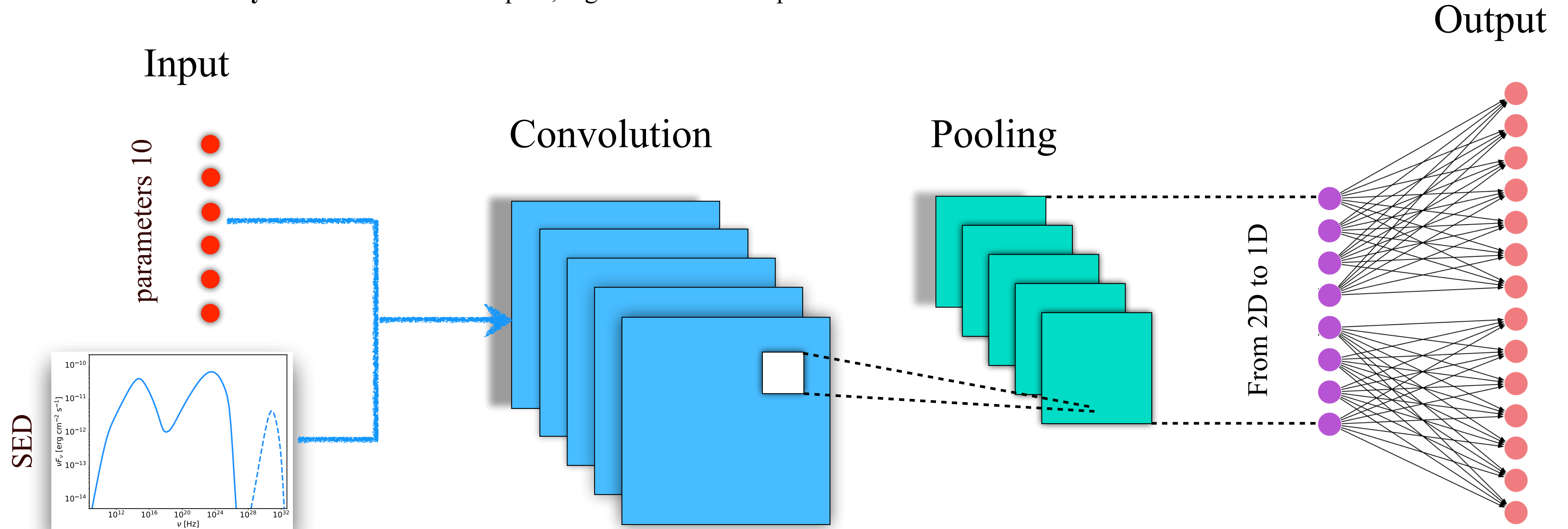
Convolutional Neural Network

Why CNN?

- **Structured Data Handling:** Ideal for 1D structured inputs like spectra and time-series.
- **Pattern Recognition:** Detects local emission features
- **Parameter Scalability:** Scales well with complex, high-dimensional inputs.

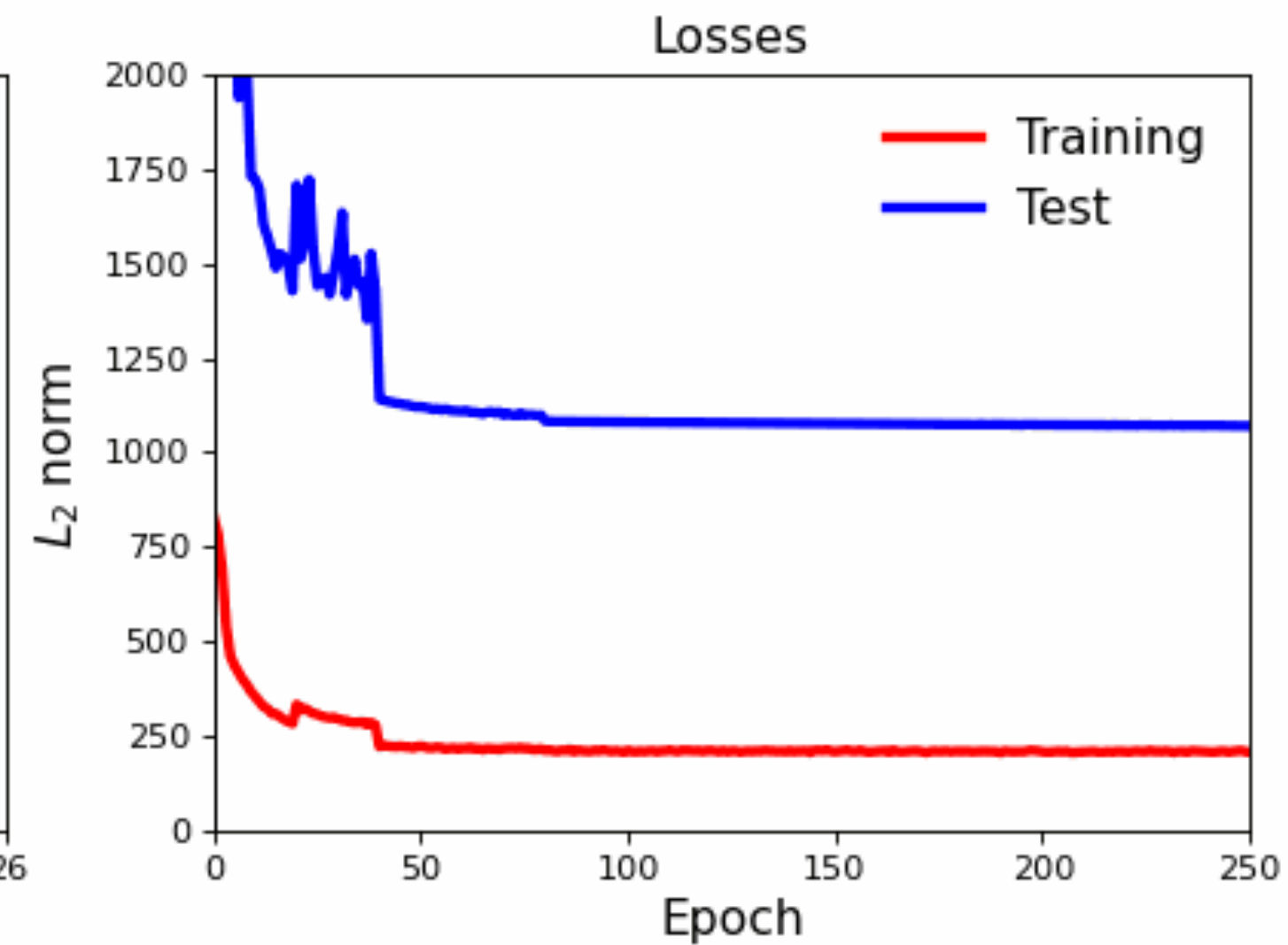
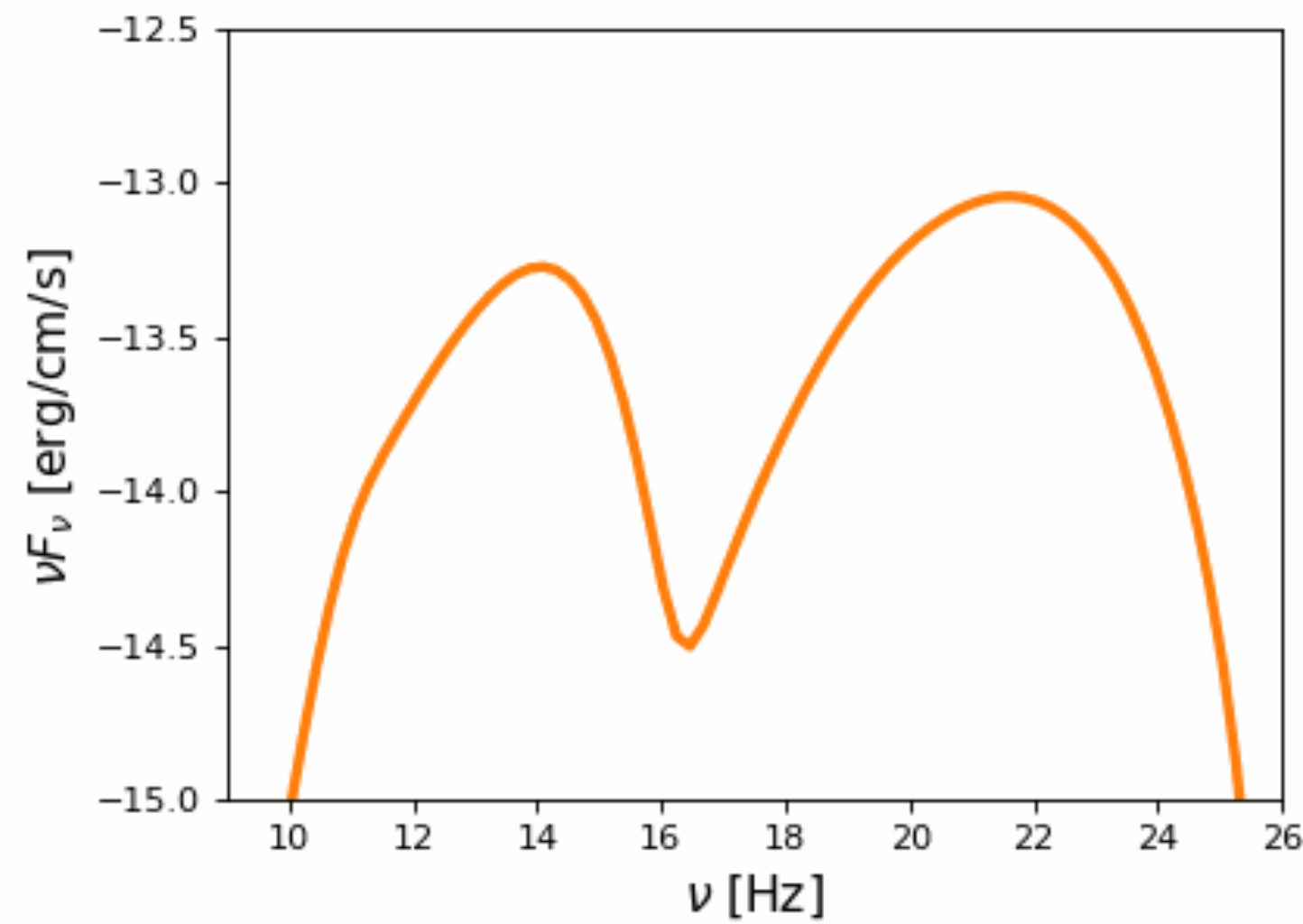
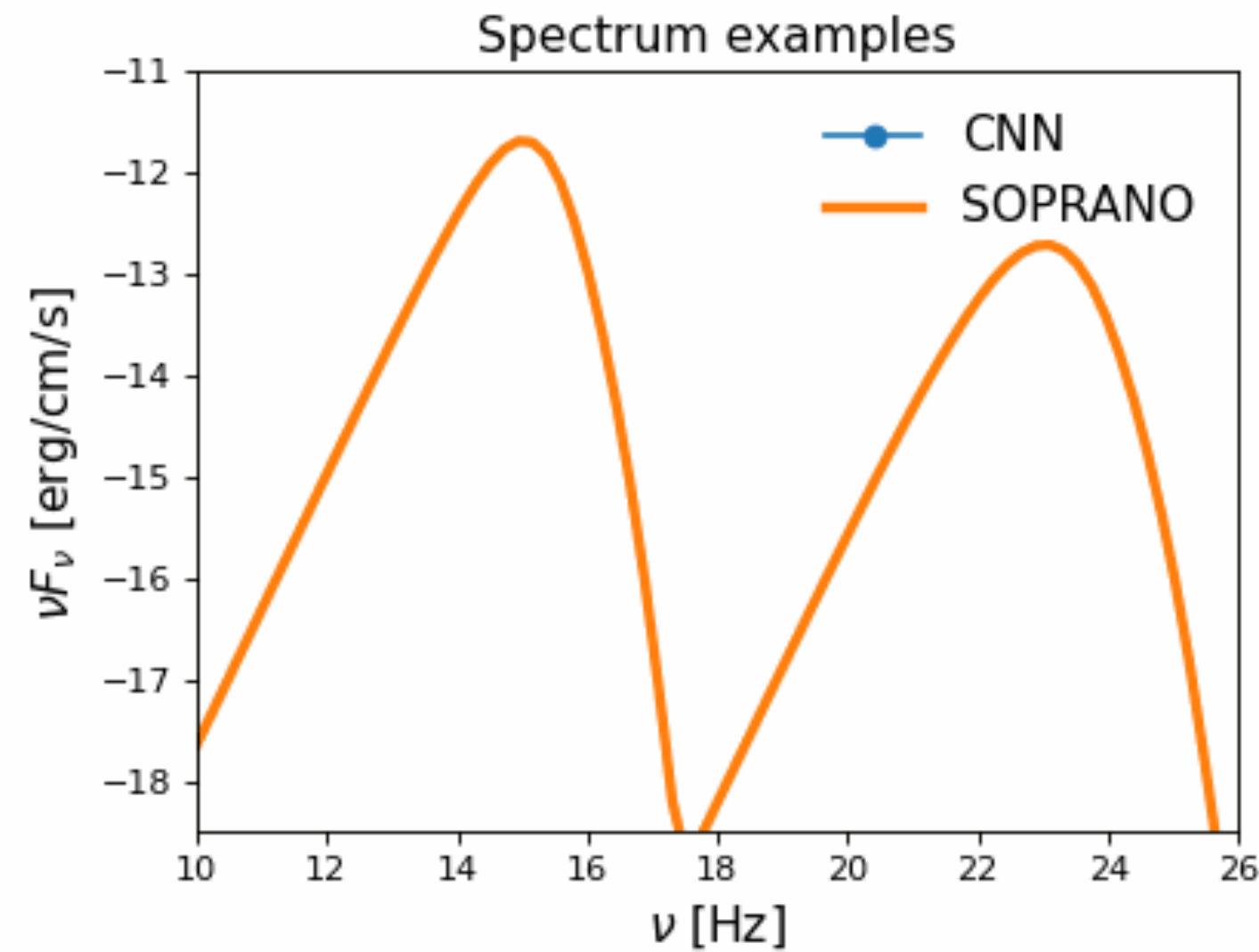
Architecture Overview

- ☑ Input: 10 physical parameters
- ☑ Dense $\rightarrow$ 5 $\times$ Conv1D $\rightarrow$ MaxPool $\rightarrow$ Flatten $\rightarrow$ Dense
- ☑ Output: 150 independent observables



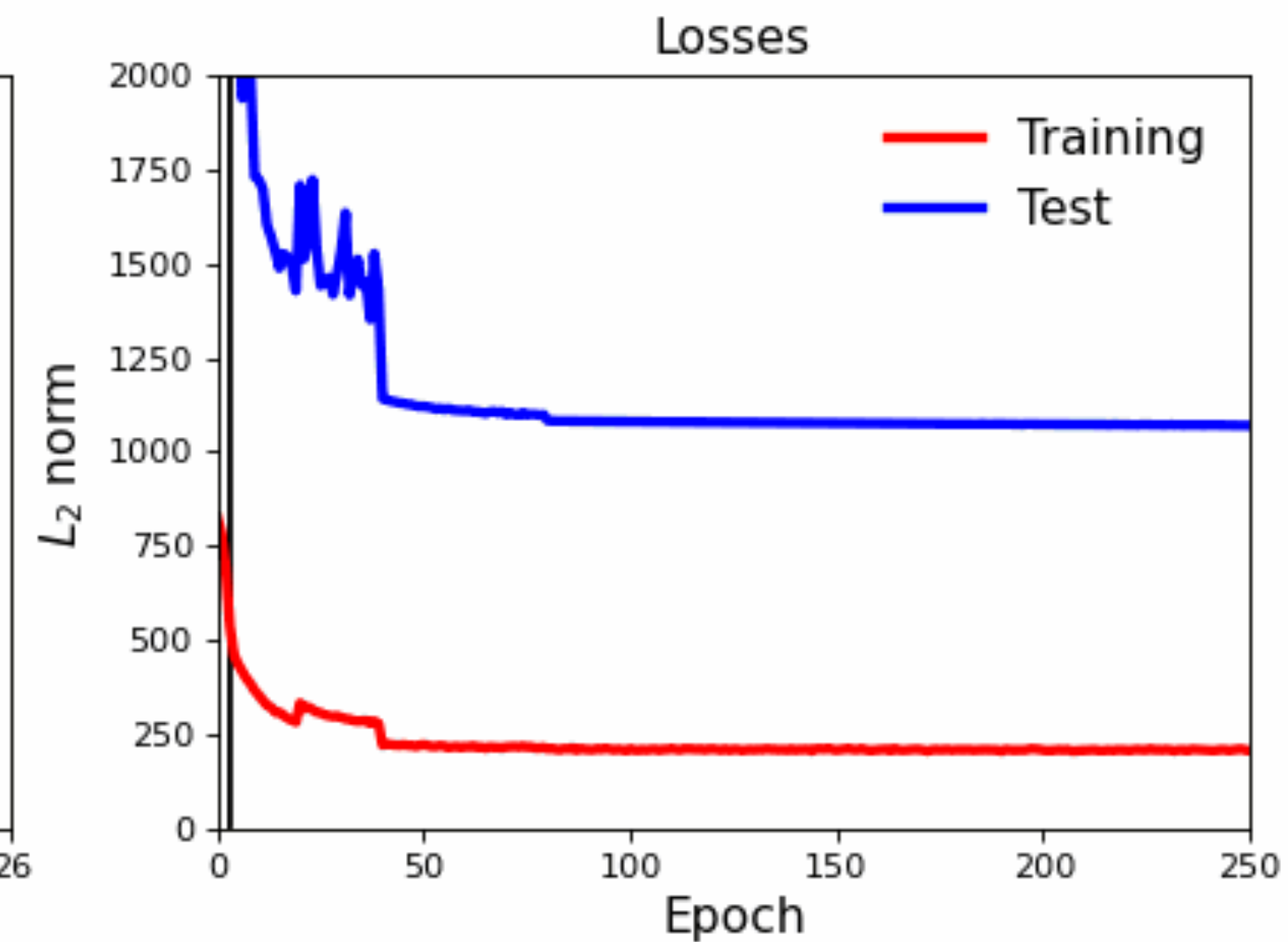
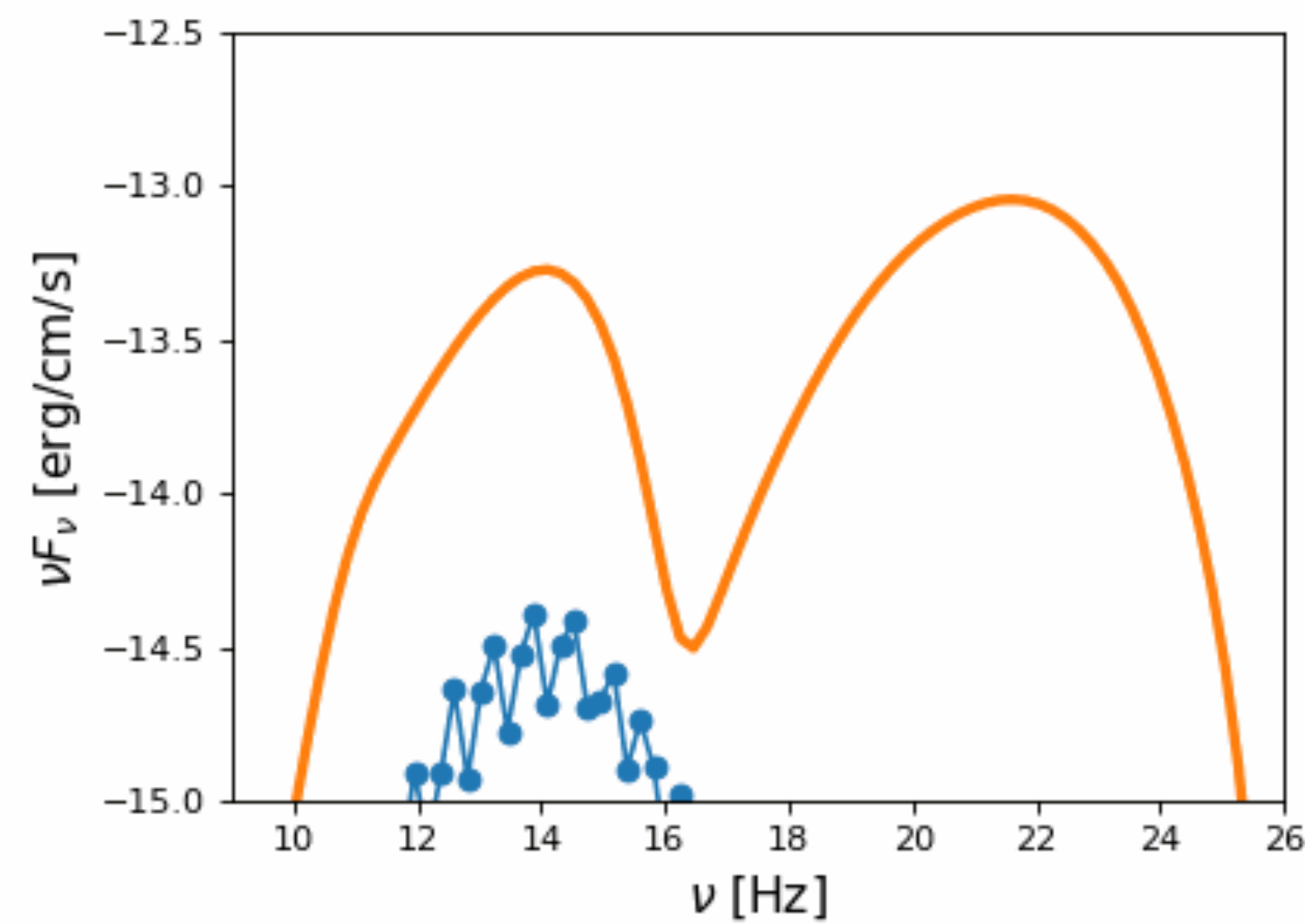
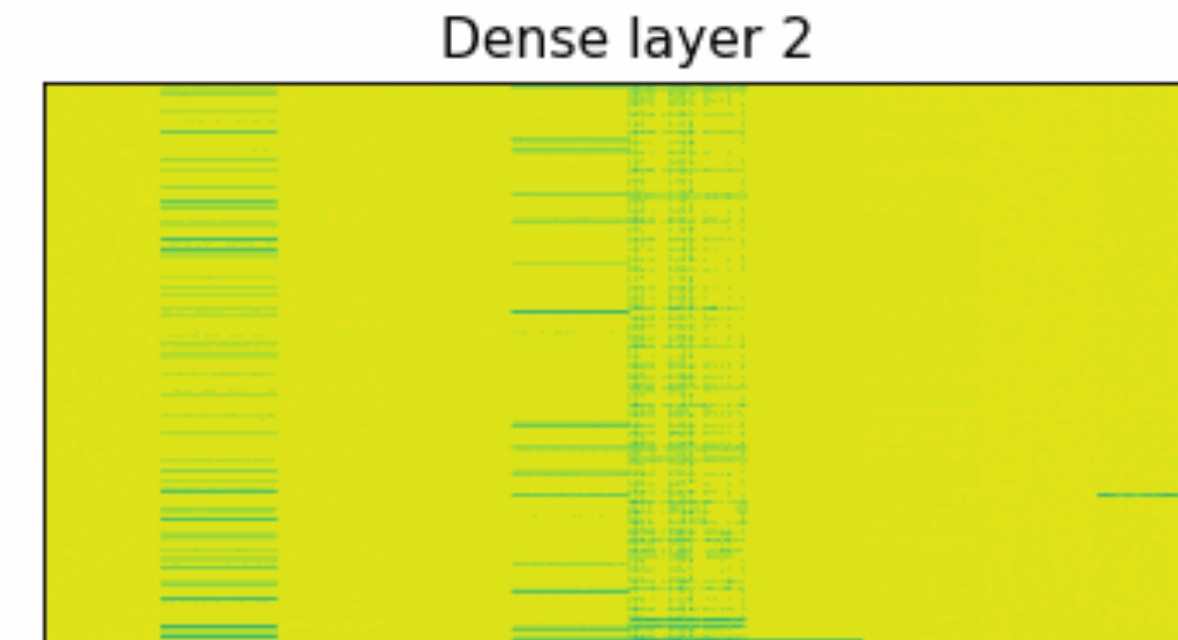
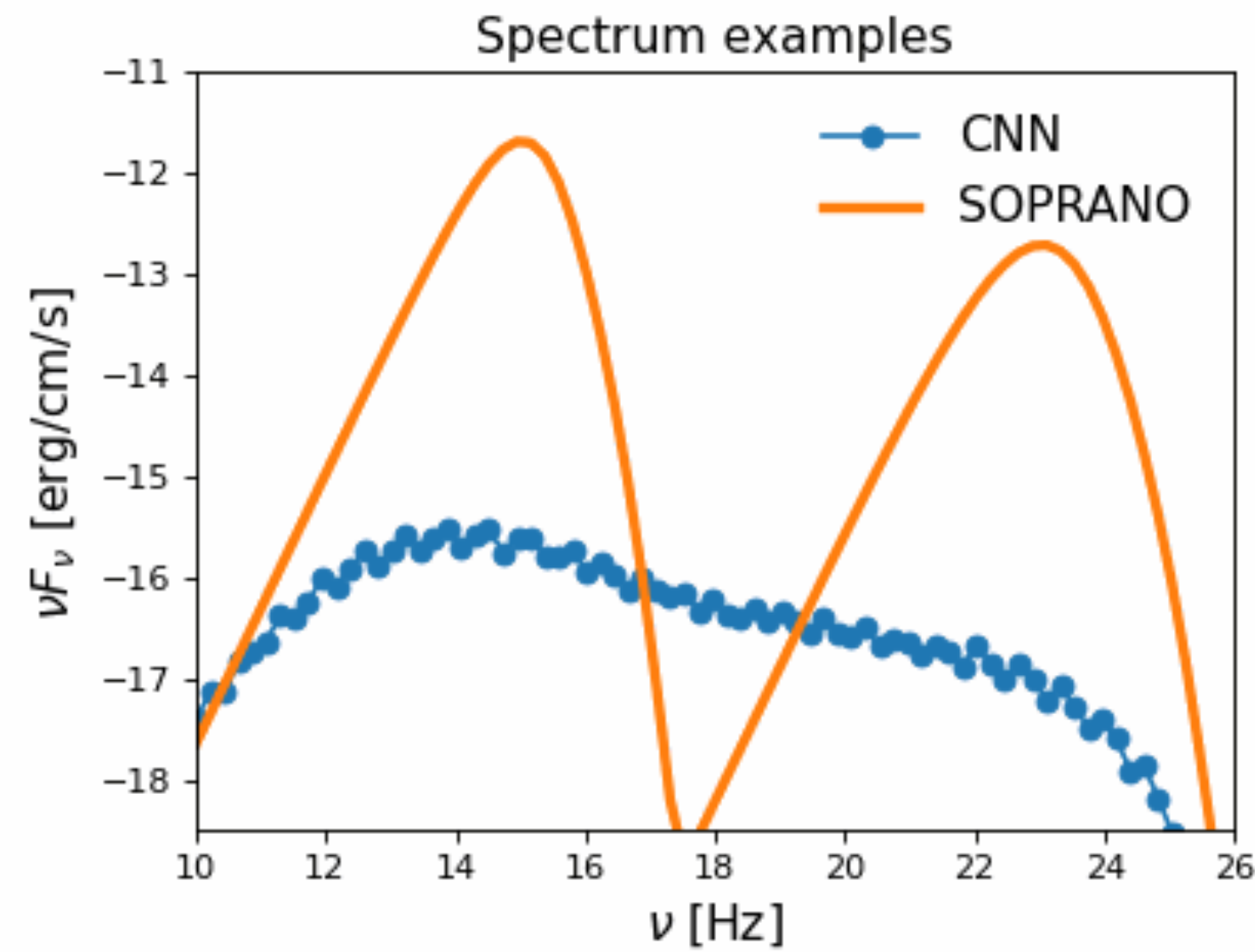
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 0



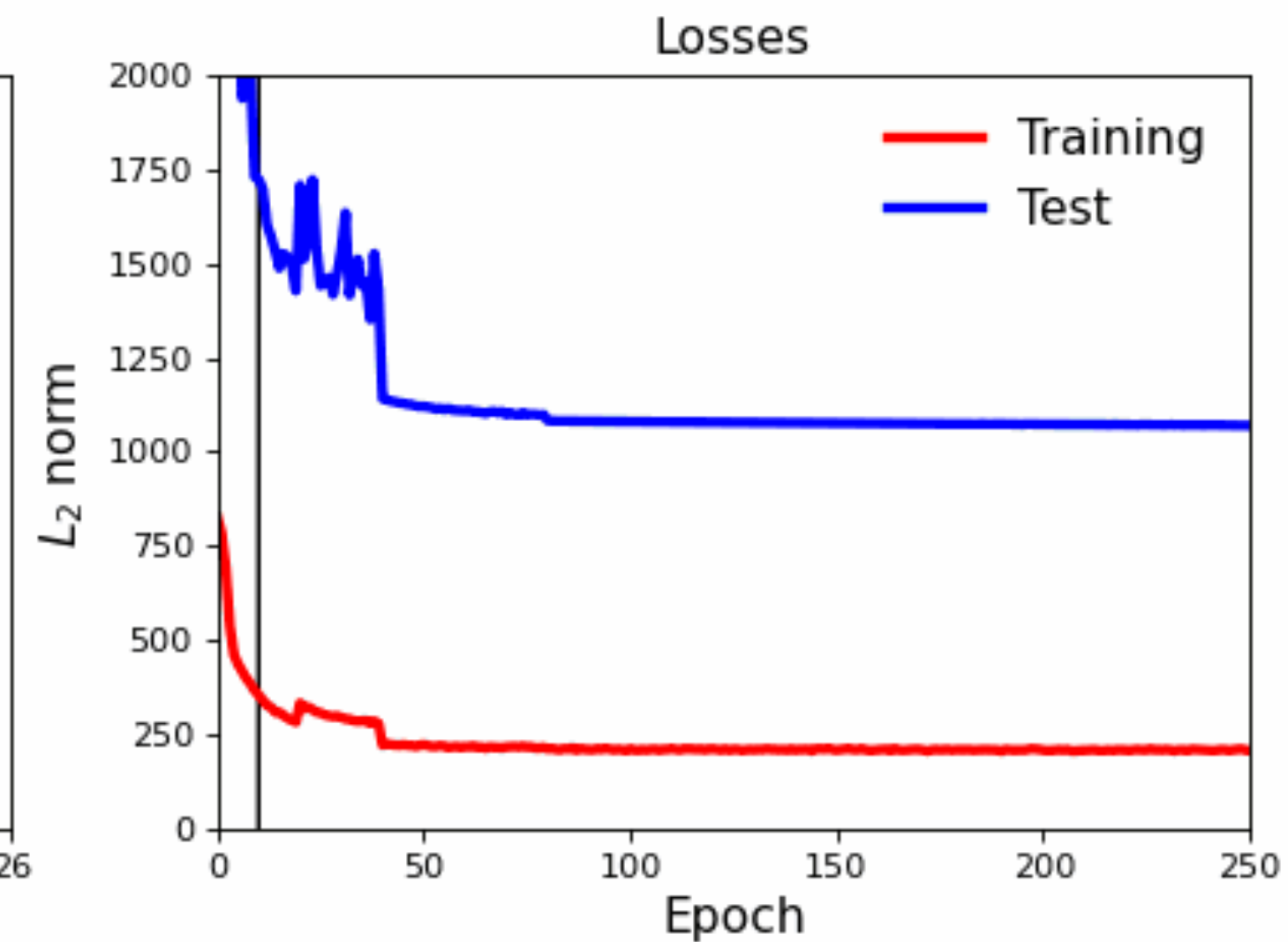
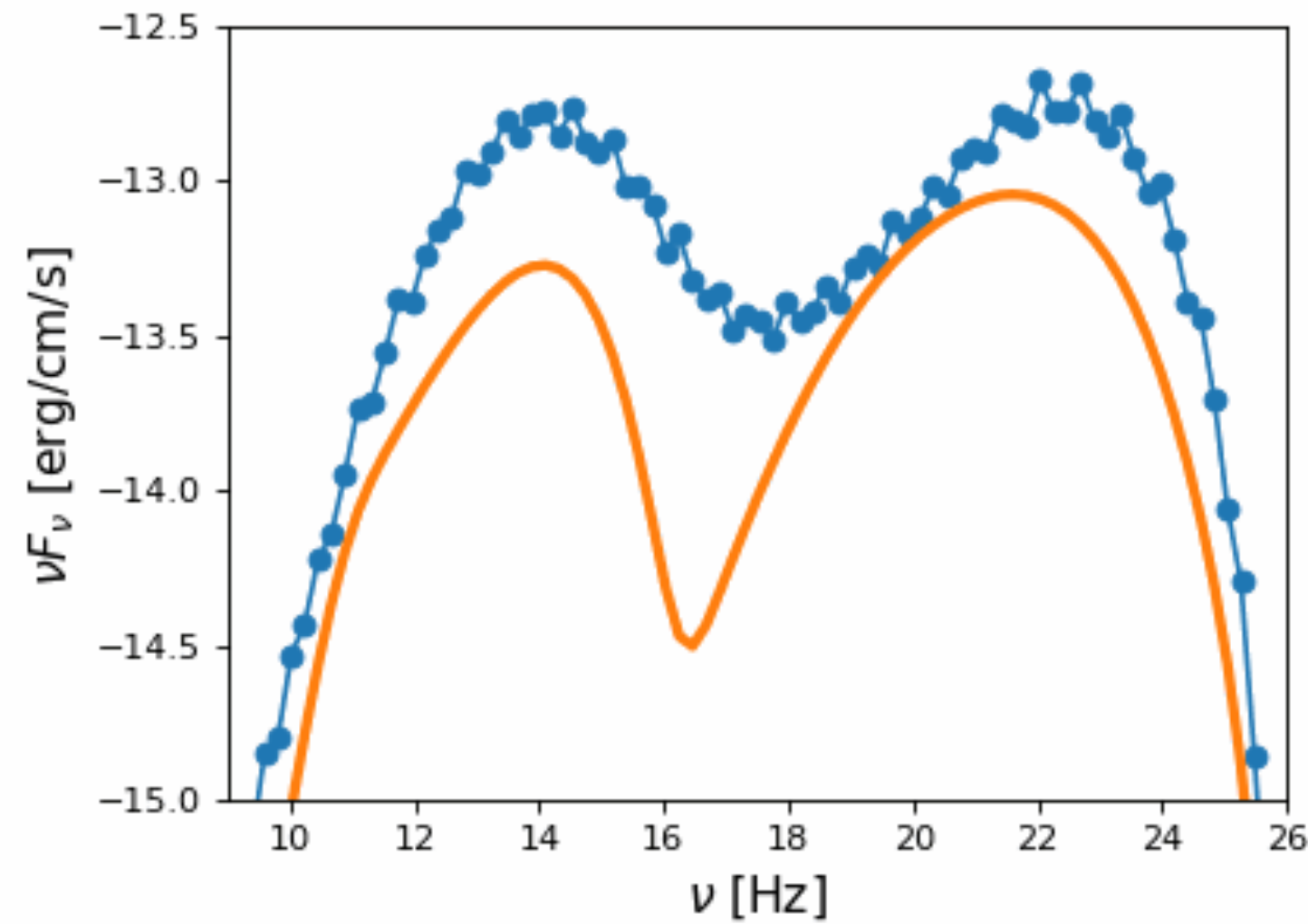
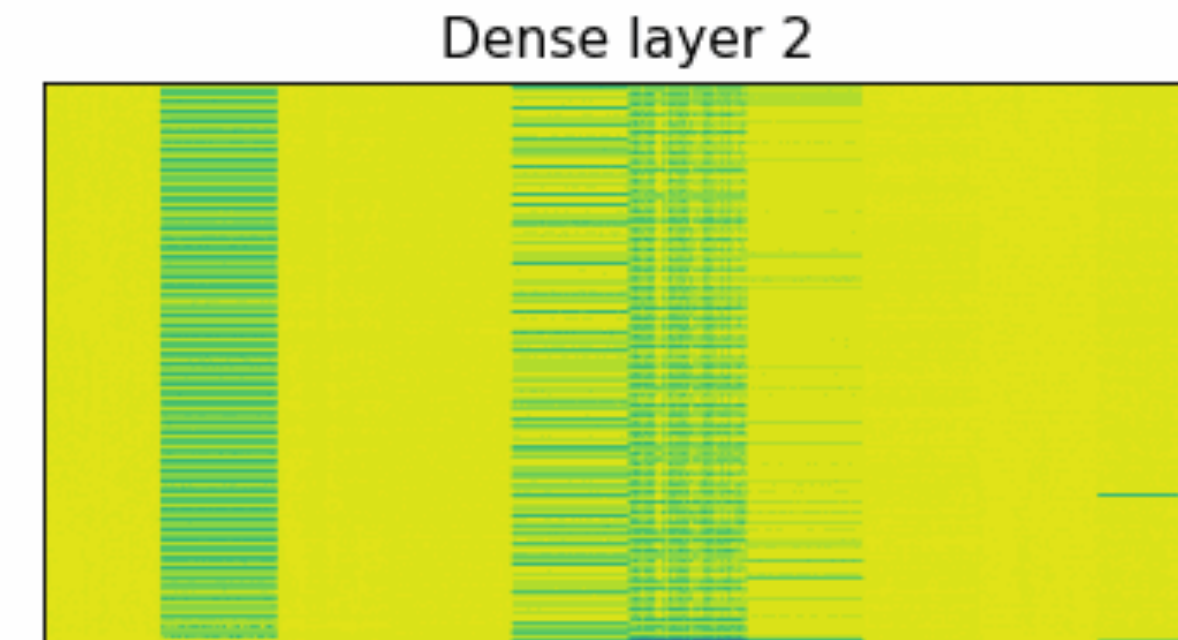
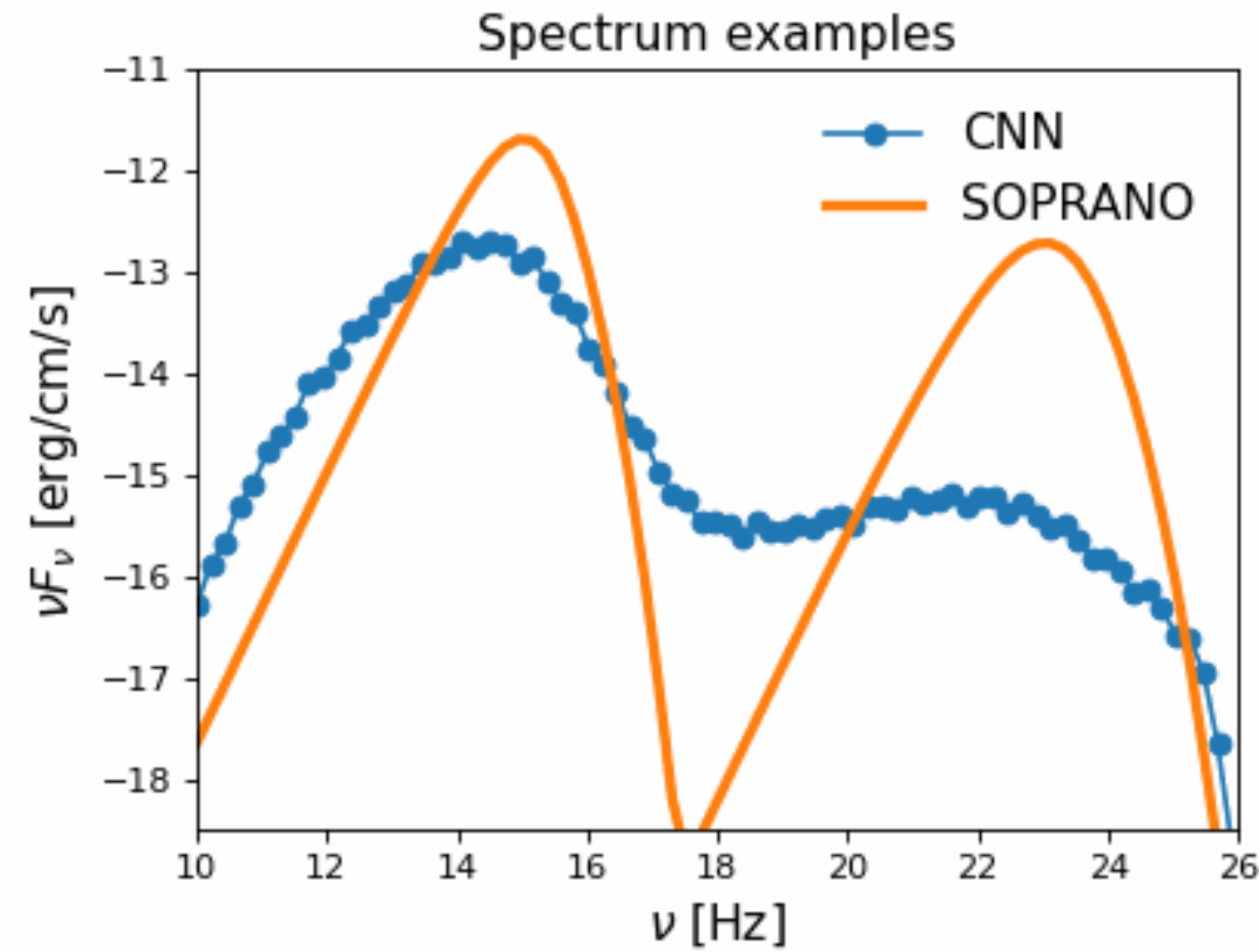
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 3



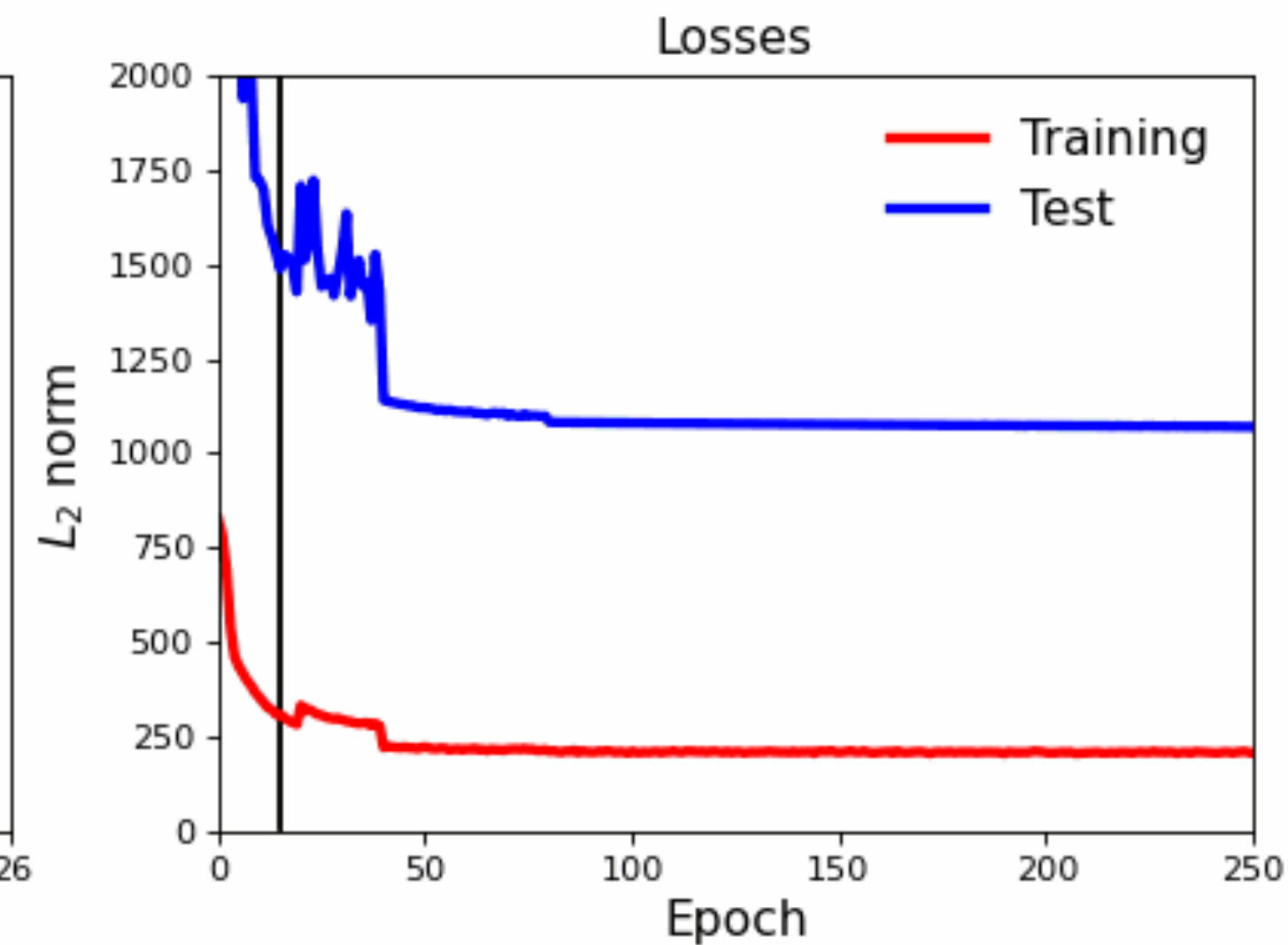
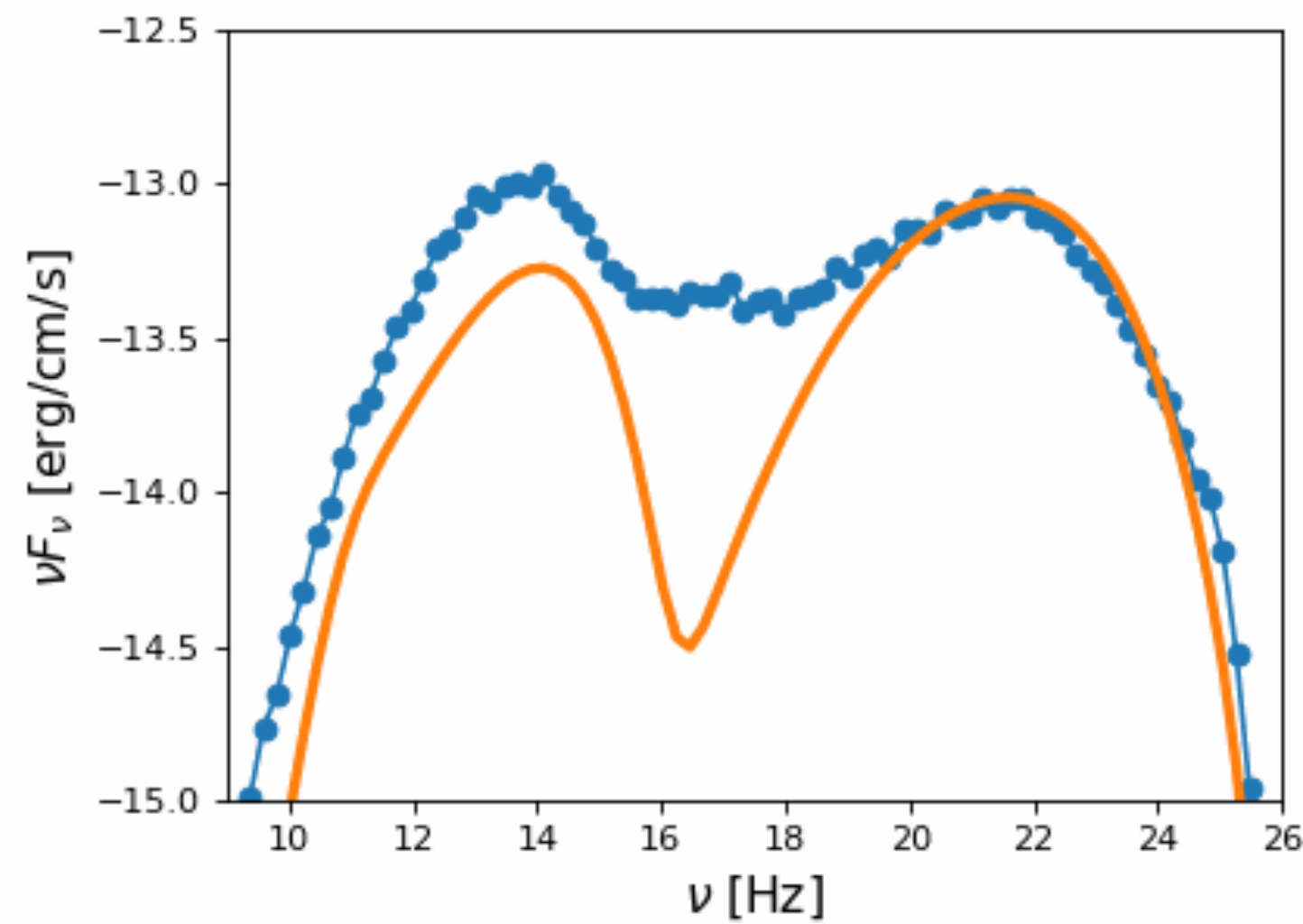
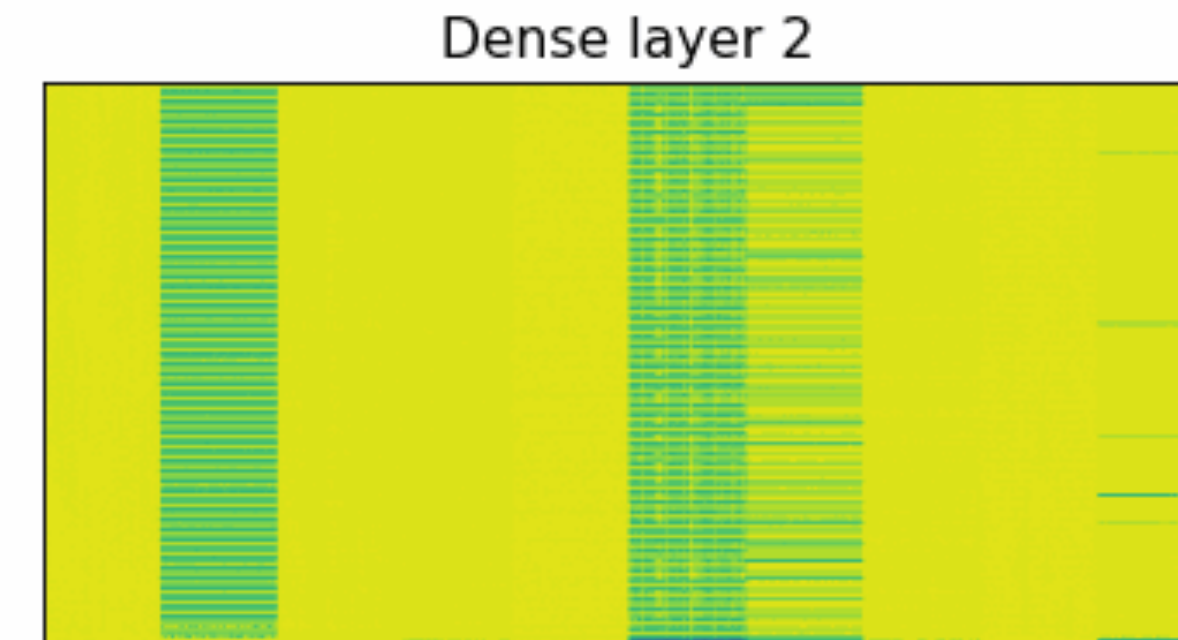
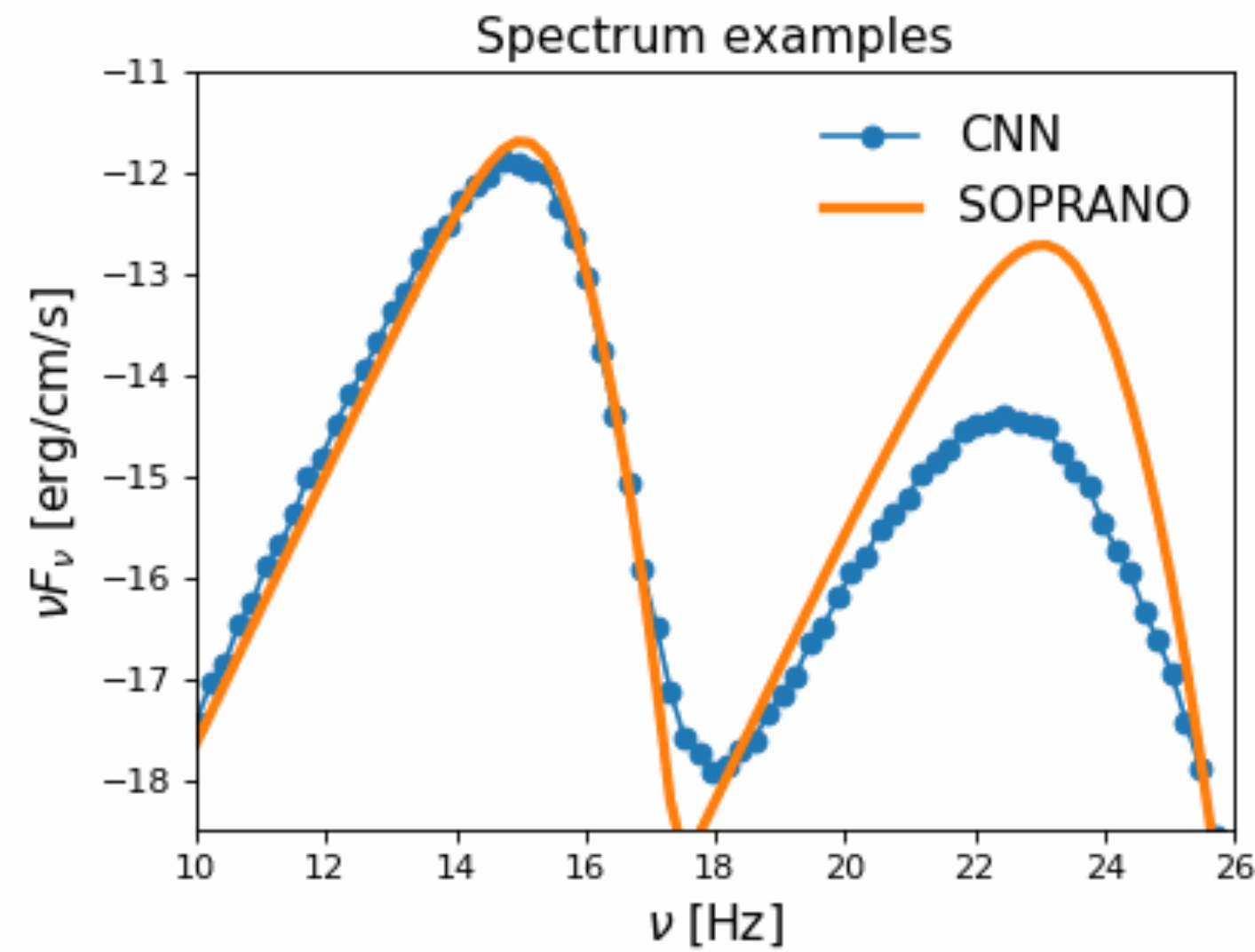
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 10



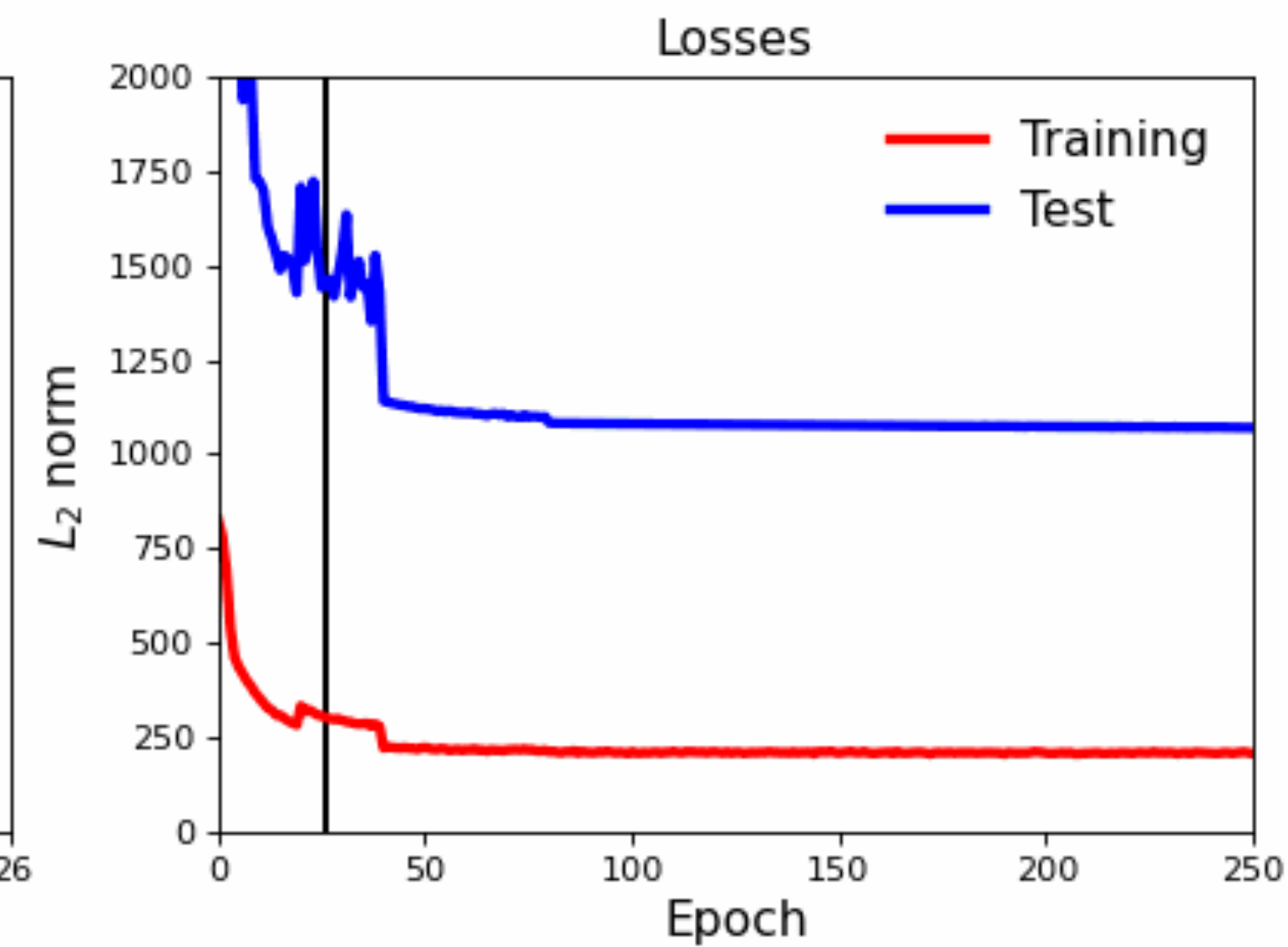
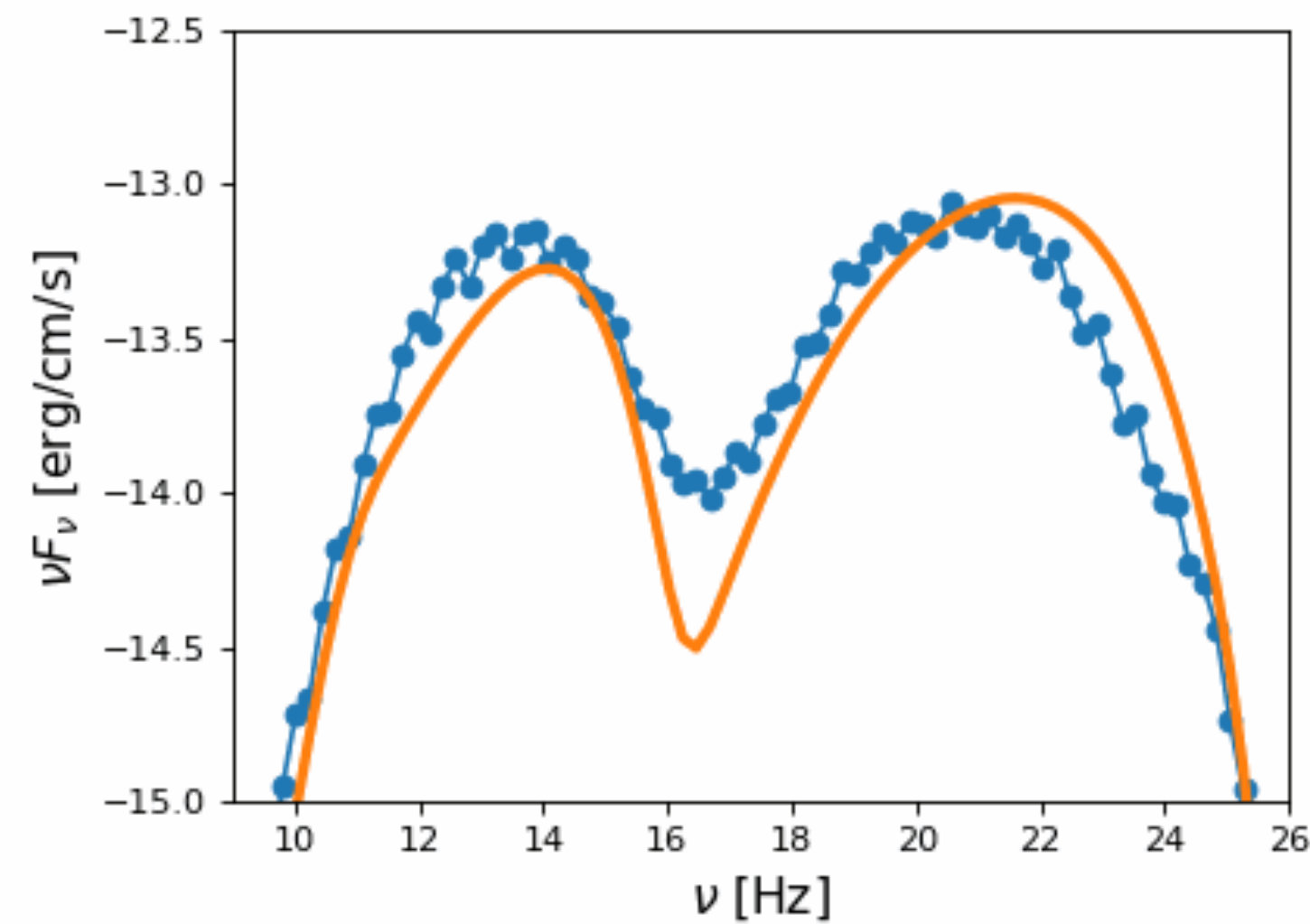
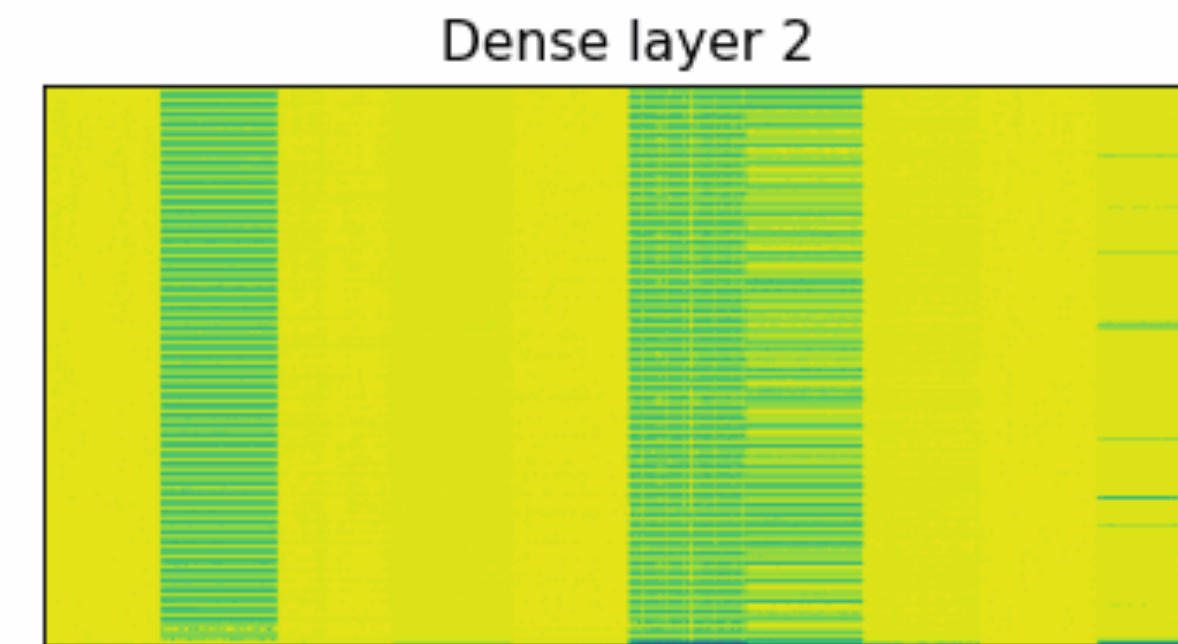
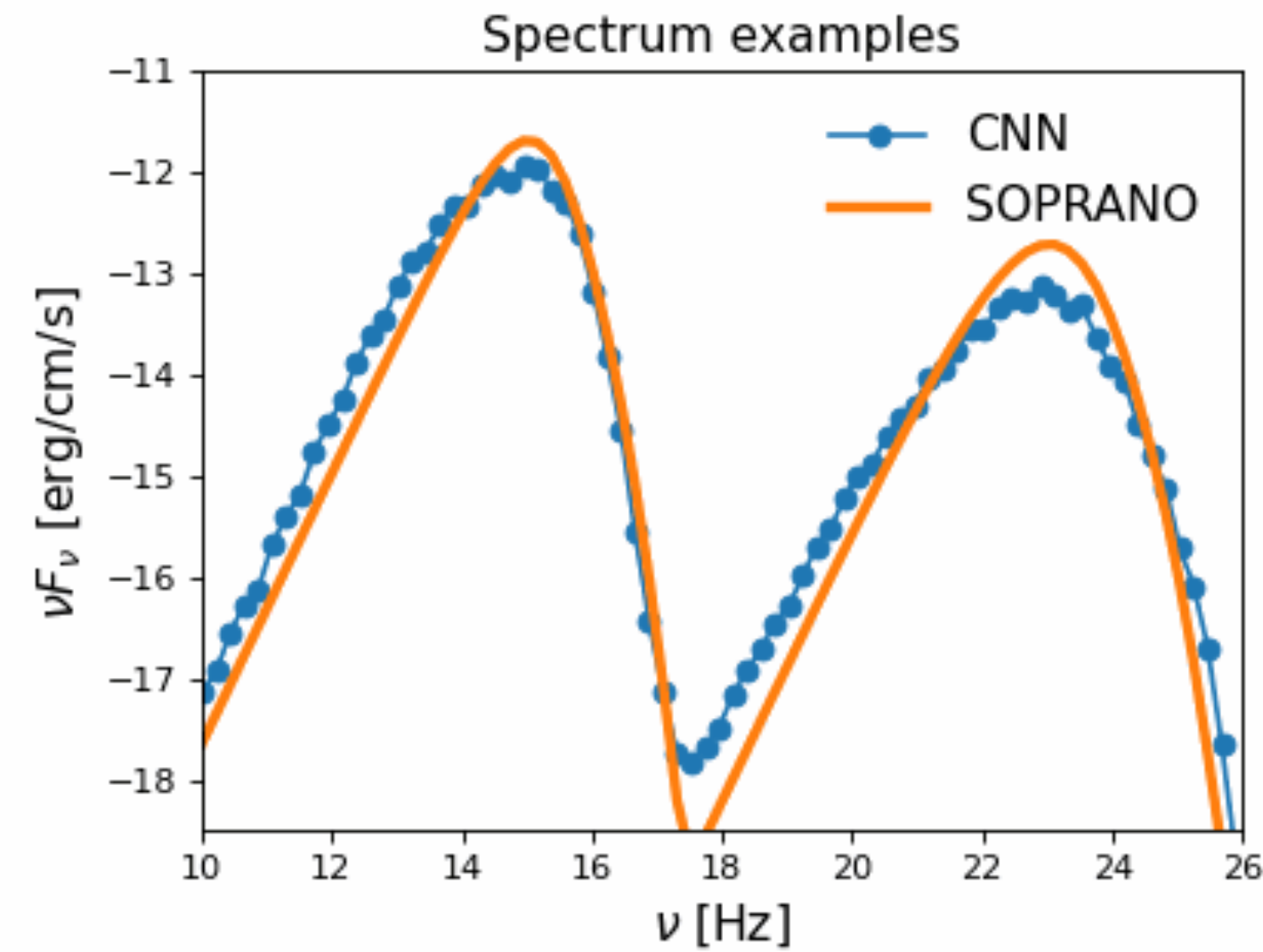
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 15



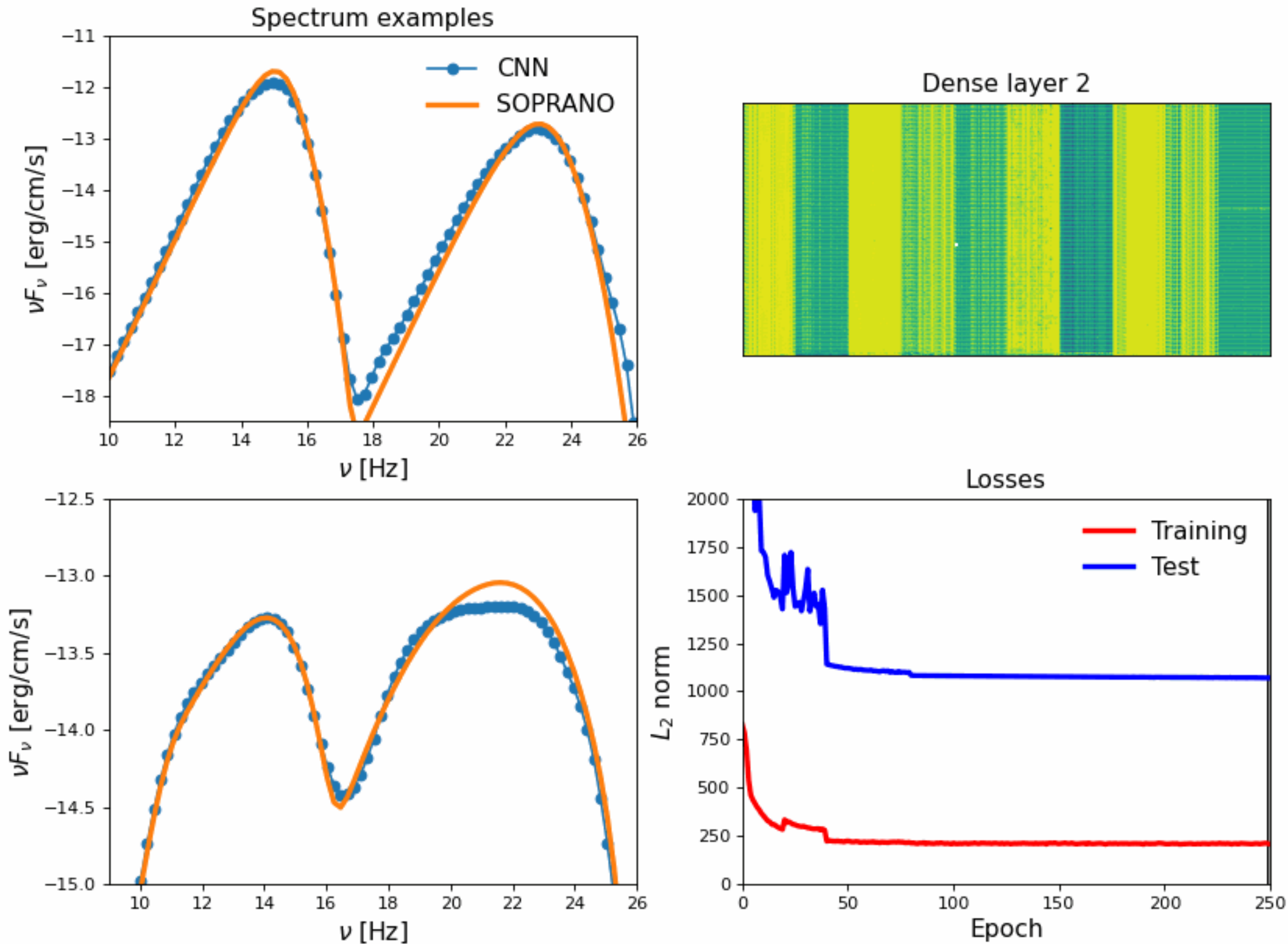
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 26



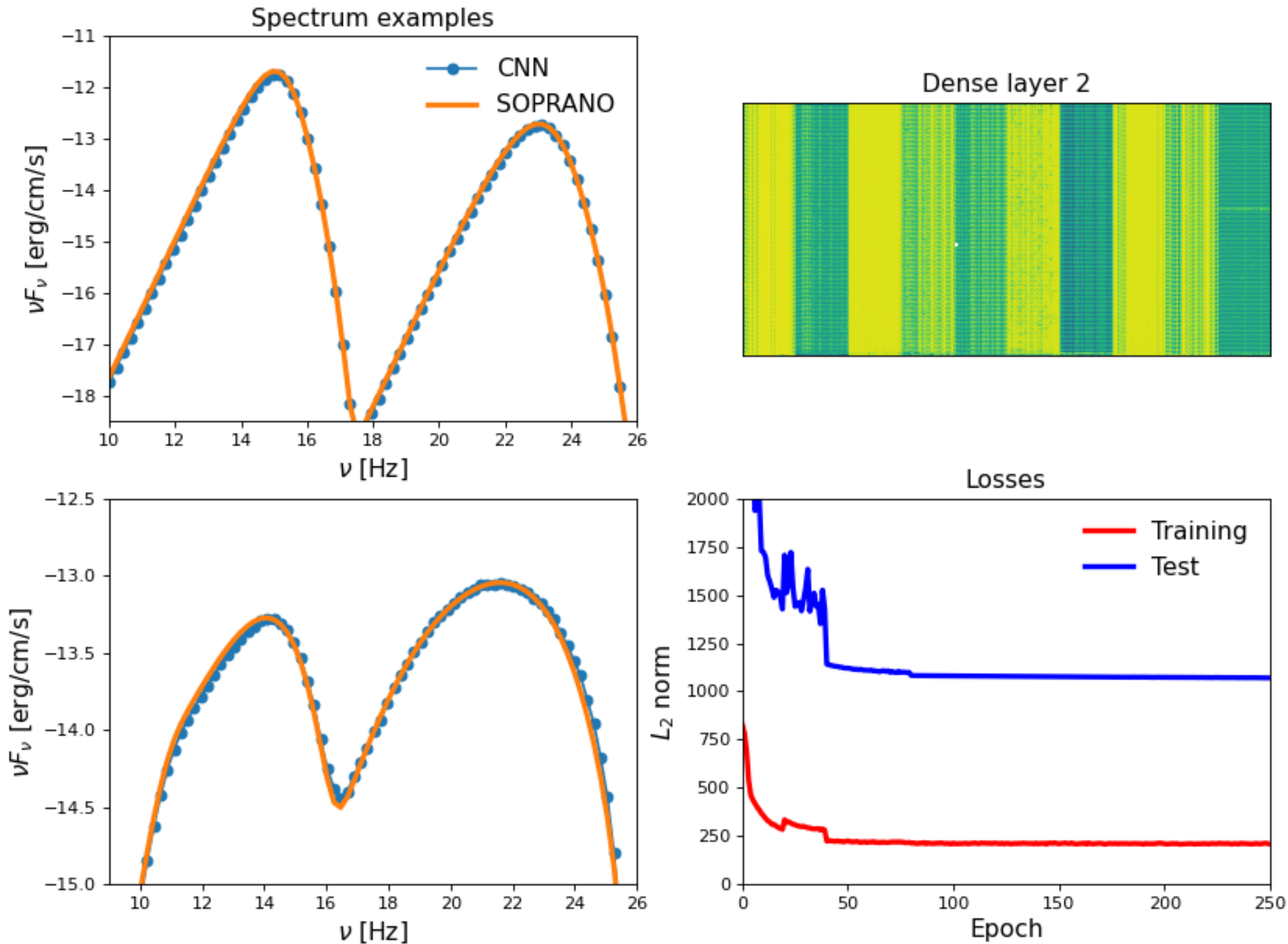
What is CNN doing ?

Training of the SSC model on 1% of the database: Epoch 249



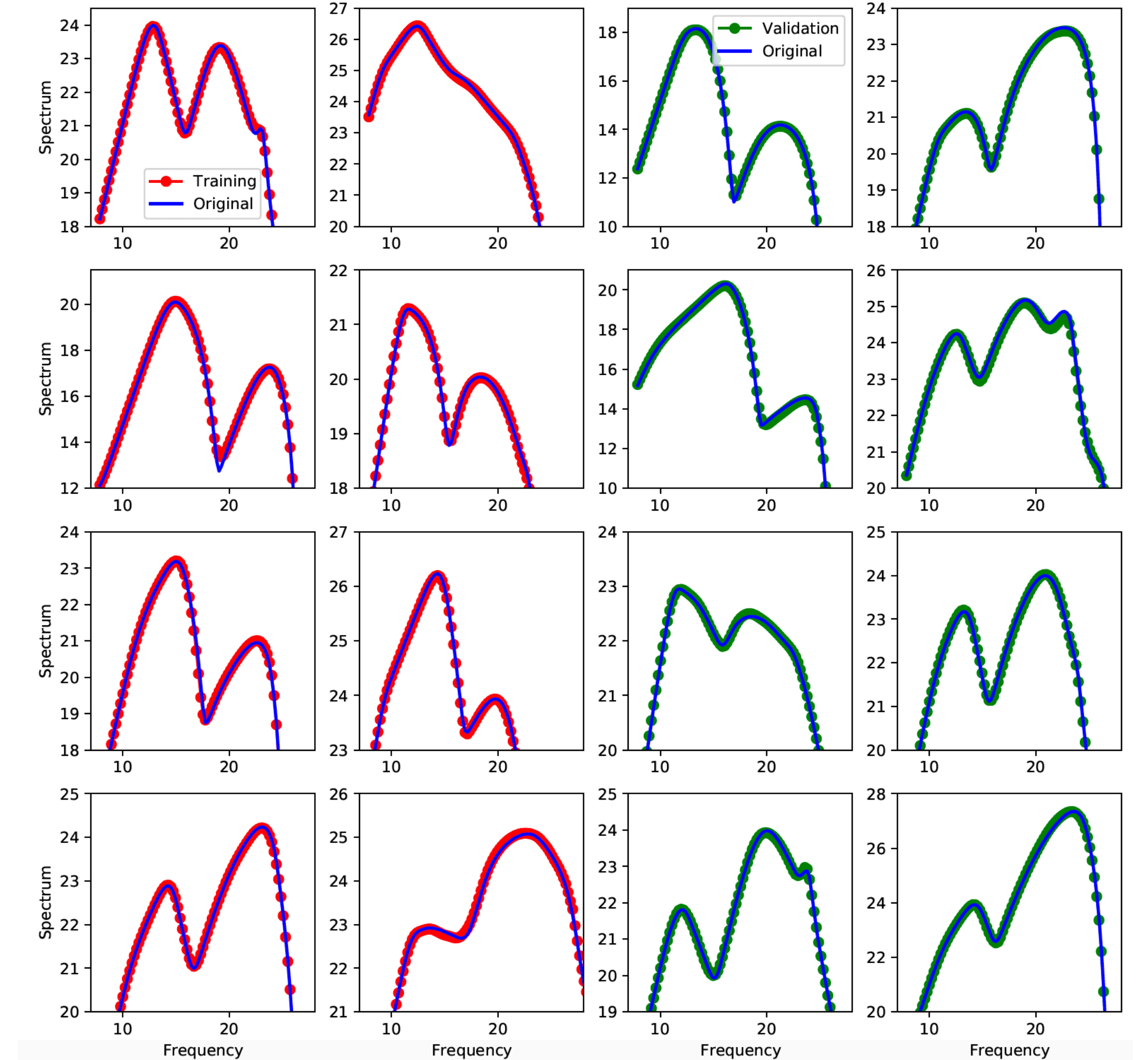
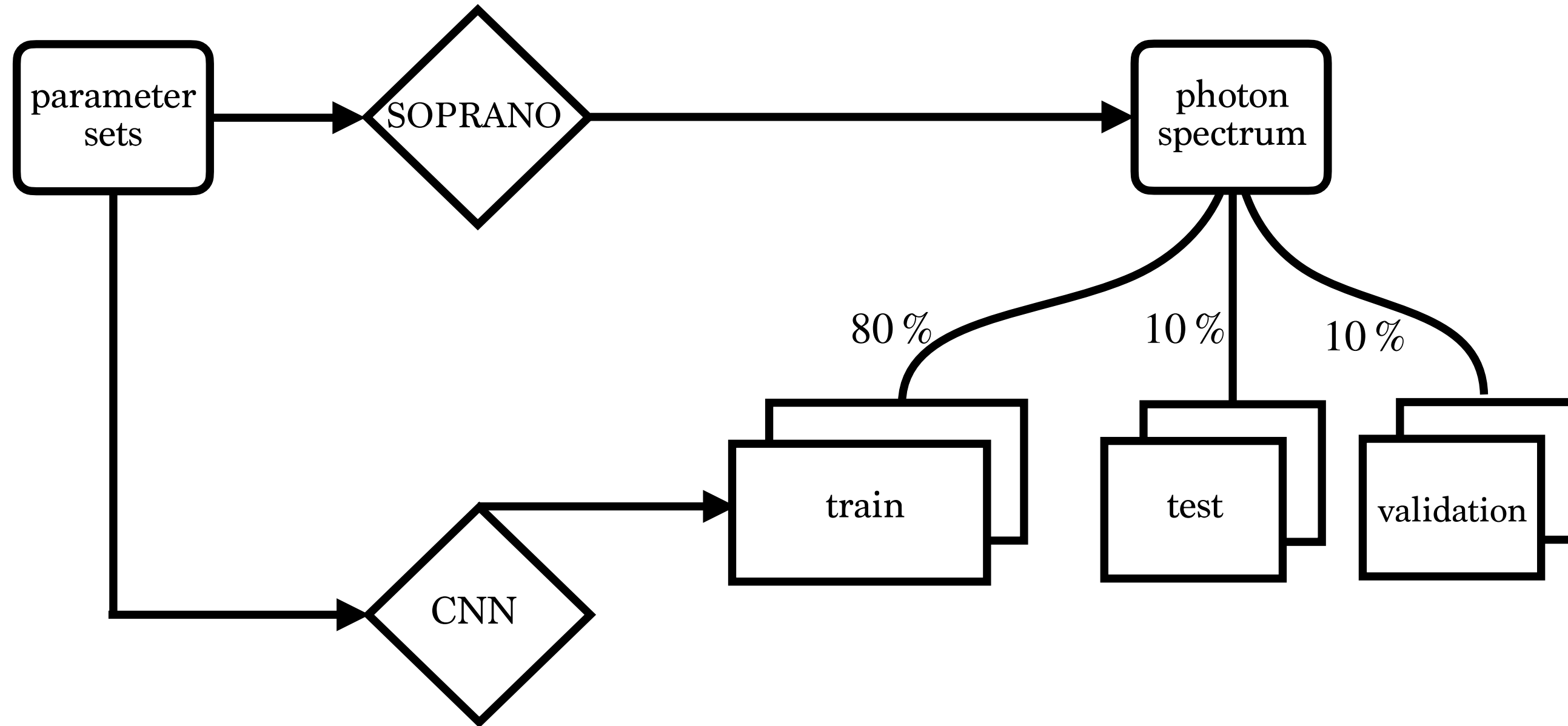
What is CNN doing ?

Training of the SSC model. Full database



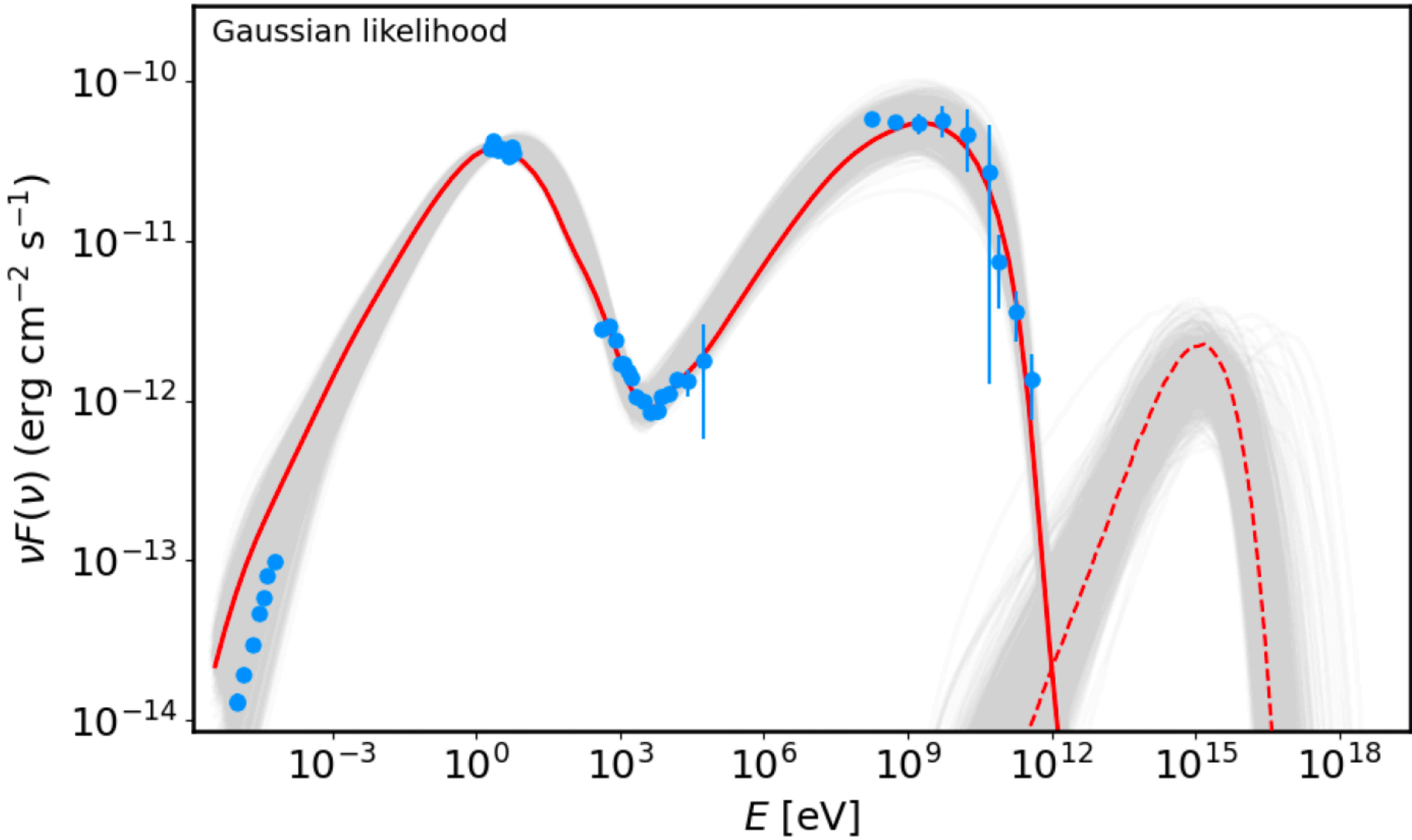
Training CNN Surrogates for Hadronic Blazar Models

- CNN trained on 7 million spectra generated using the SOPRANO code.
- Training spans 10-dimensional parameter space with broad, physically motivated ranges.



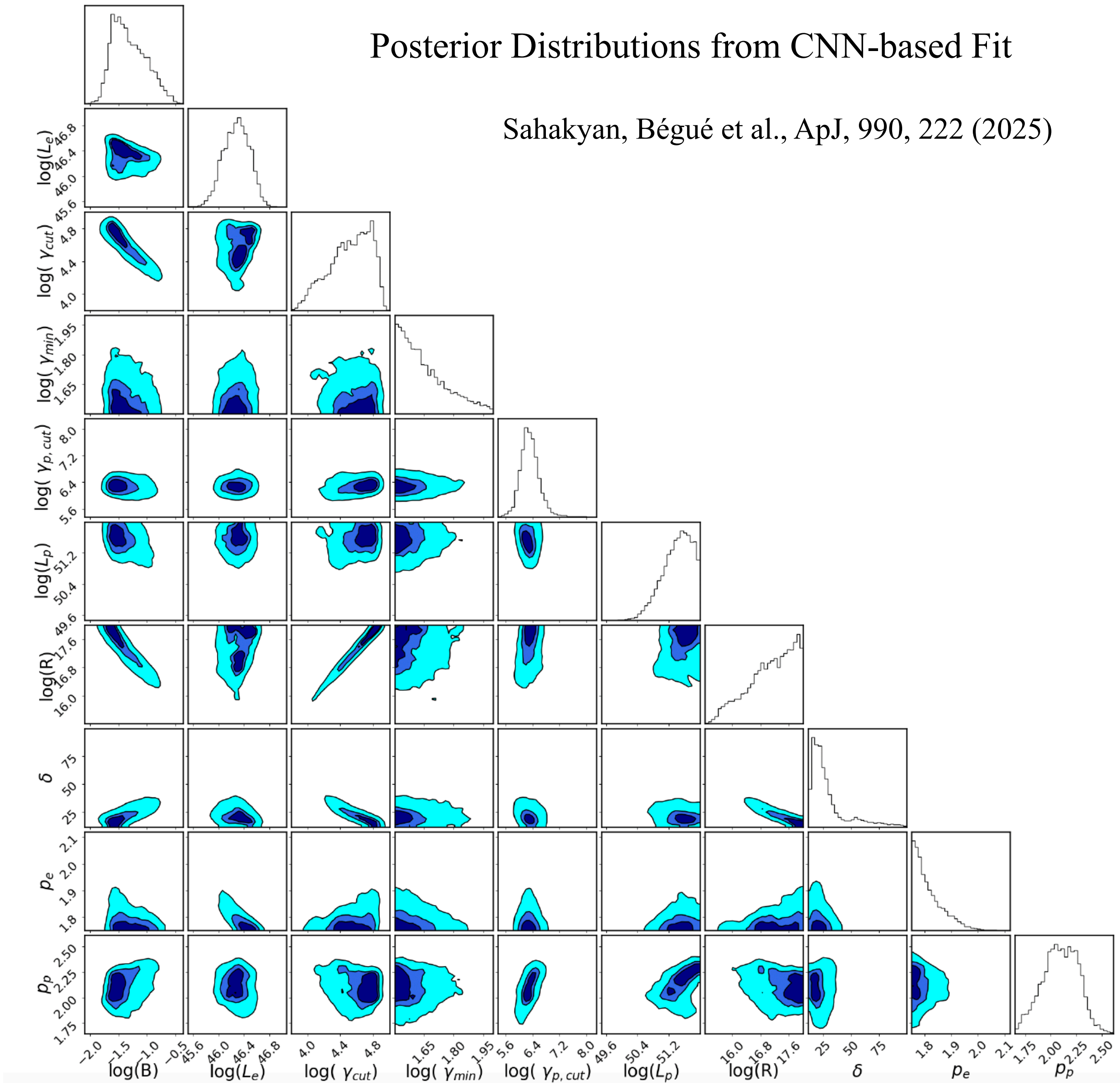
Parameter Estimation in hadronic Modeling

Modeling the SED of TXS 0506+056 during the IceCube-170922A neutrino event using a convolutional neural network trained on hadronic models.



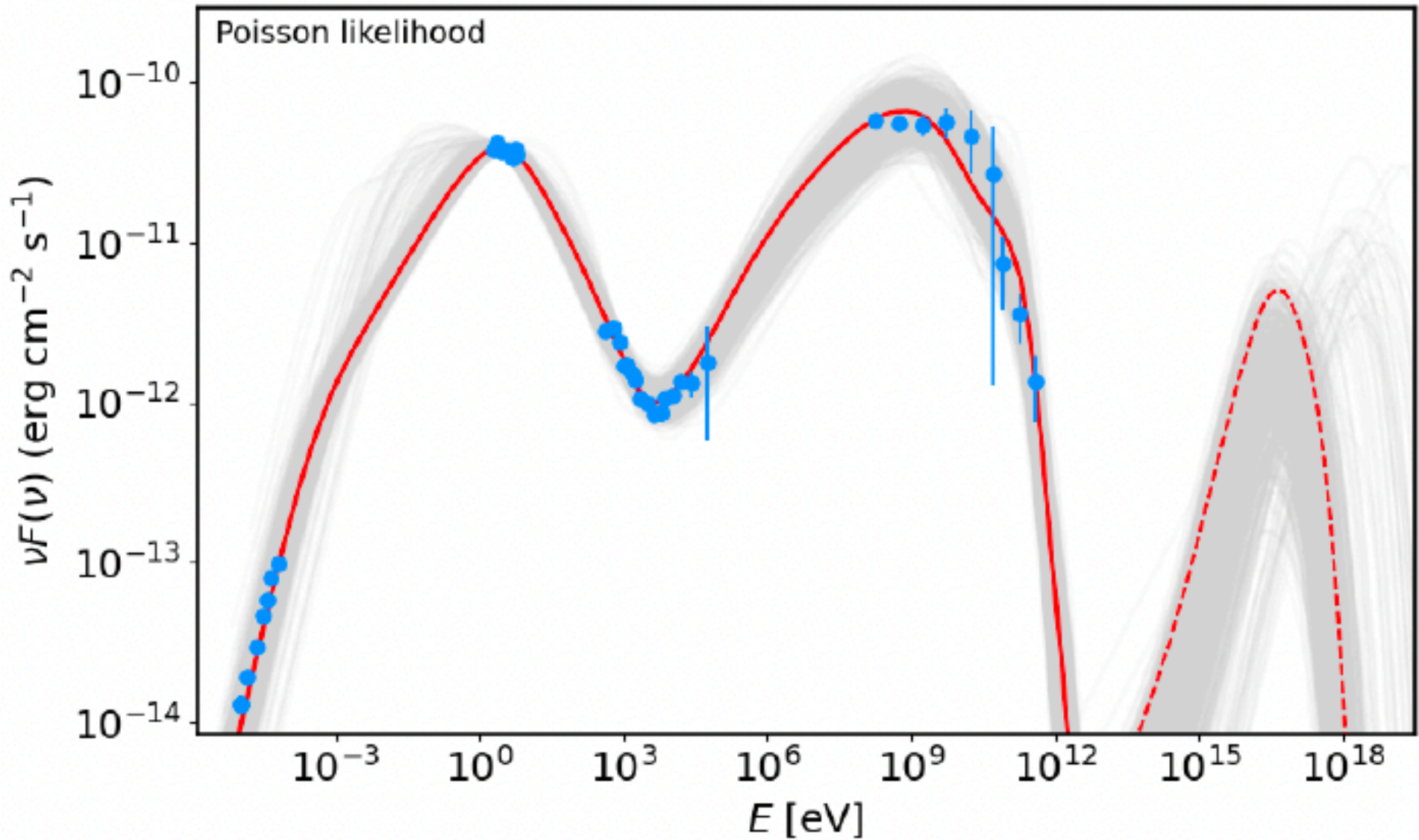
Model parameters for TXS 0506+059

Parameter	Value	Parameter	Value
p_e	1.77	p_p	2.03
$\log_{10}(\gamma_{e,max})$	4.76	$\log_{10}(\gamma_{e,min})$	1.52
$\log_{10}(\gamma_{p,max})$	6.37	δ	15.49
$\log_{10}(B \text{ [G]})$	-1.52	$\log_{10}(R \text{ [cm]})$	17.76
$\log_{10}(L_e \text{ [erg/s]})$	46.50	$\log_{10}(L_p \text{ [erg/s]})$	51.18



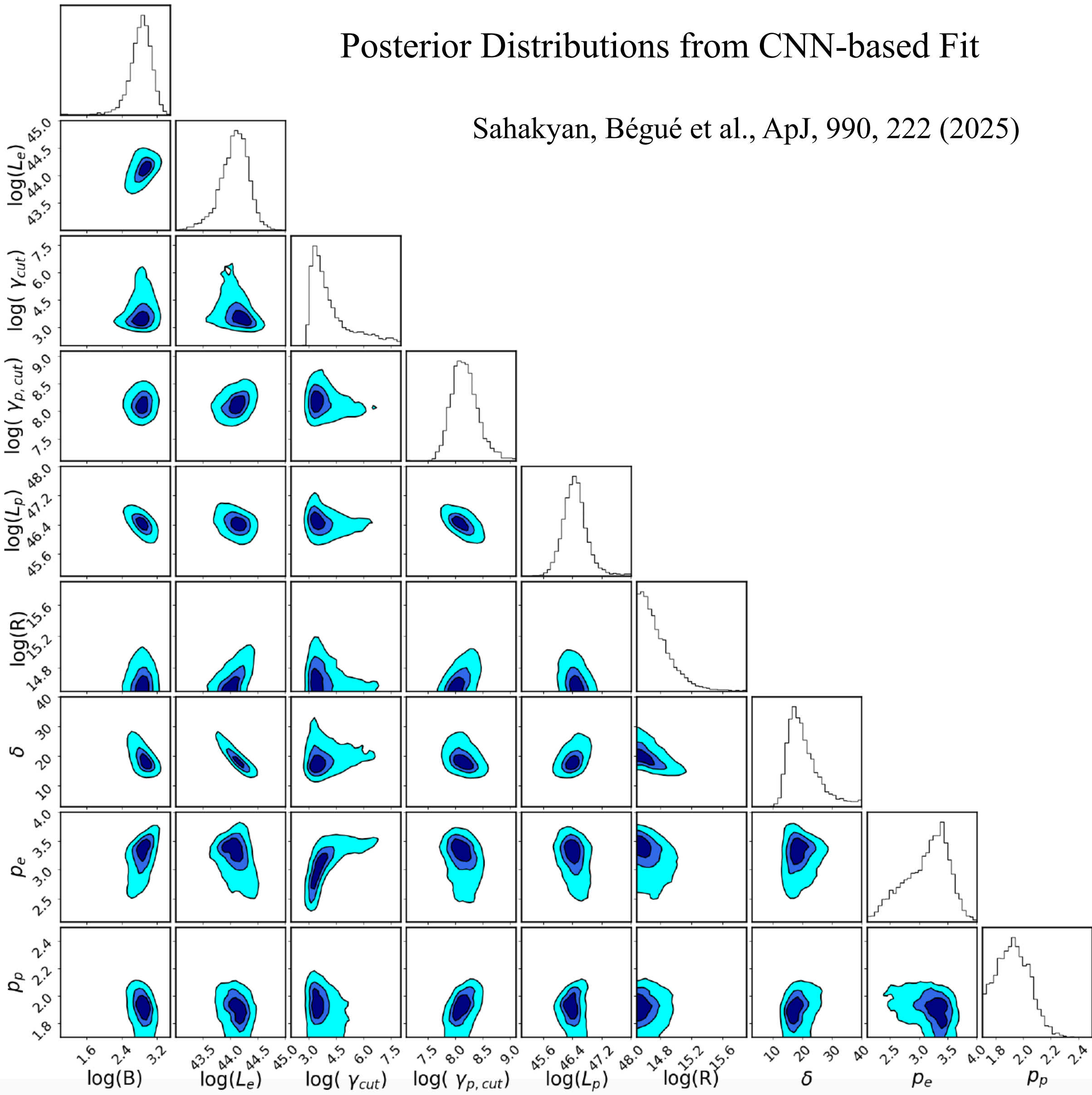
Parameter Estimation in hadronic Modeling

Modeling the SED of TXS 0506+056 during the IceCube-170922A neutrino event using a convolutional neural network trained on hadronic models.



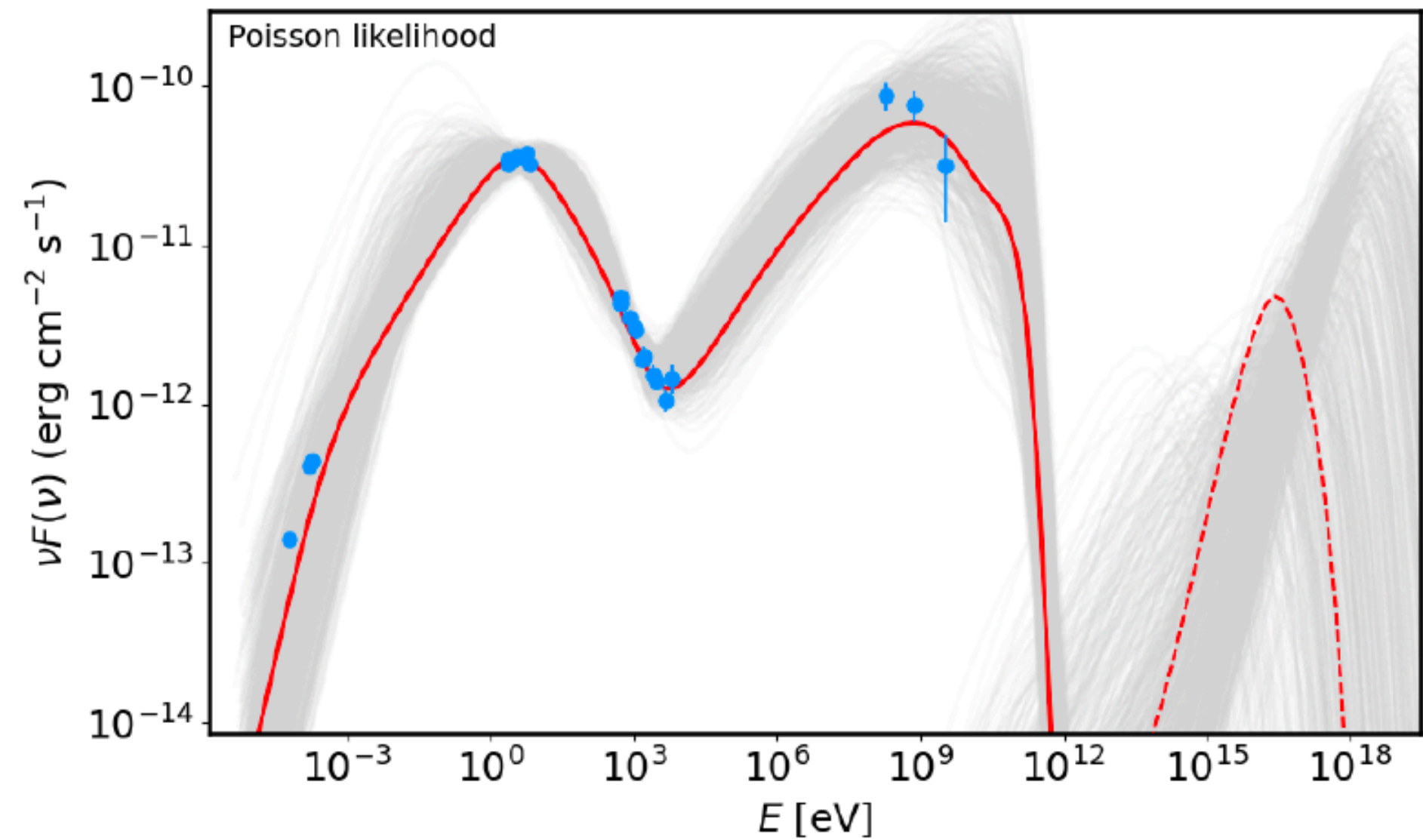
Model parameters for TXS 0506+059

Parameter	Value	Parameter	Value
p_e	2.87	p_p	2.00
$\log_{10}(\gamma_{e,\text{max}})$	3.25	$\log_{10}(\gamma_{e,\text{min}})$	2.00
$\log_{10}(\gamma_{p,\text{max}})$	8.00	δ	23.18
$\log_{10}(B \text{ [G]})$	2.73	$\log_{10}(R \text{ [cm]})$	14.53
$\log_{10}(L_e \text{ [erg/s]})$	43.99	$\log_{10}(L_p \text{ [erg/s]})$	46.69



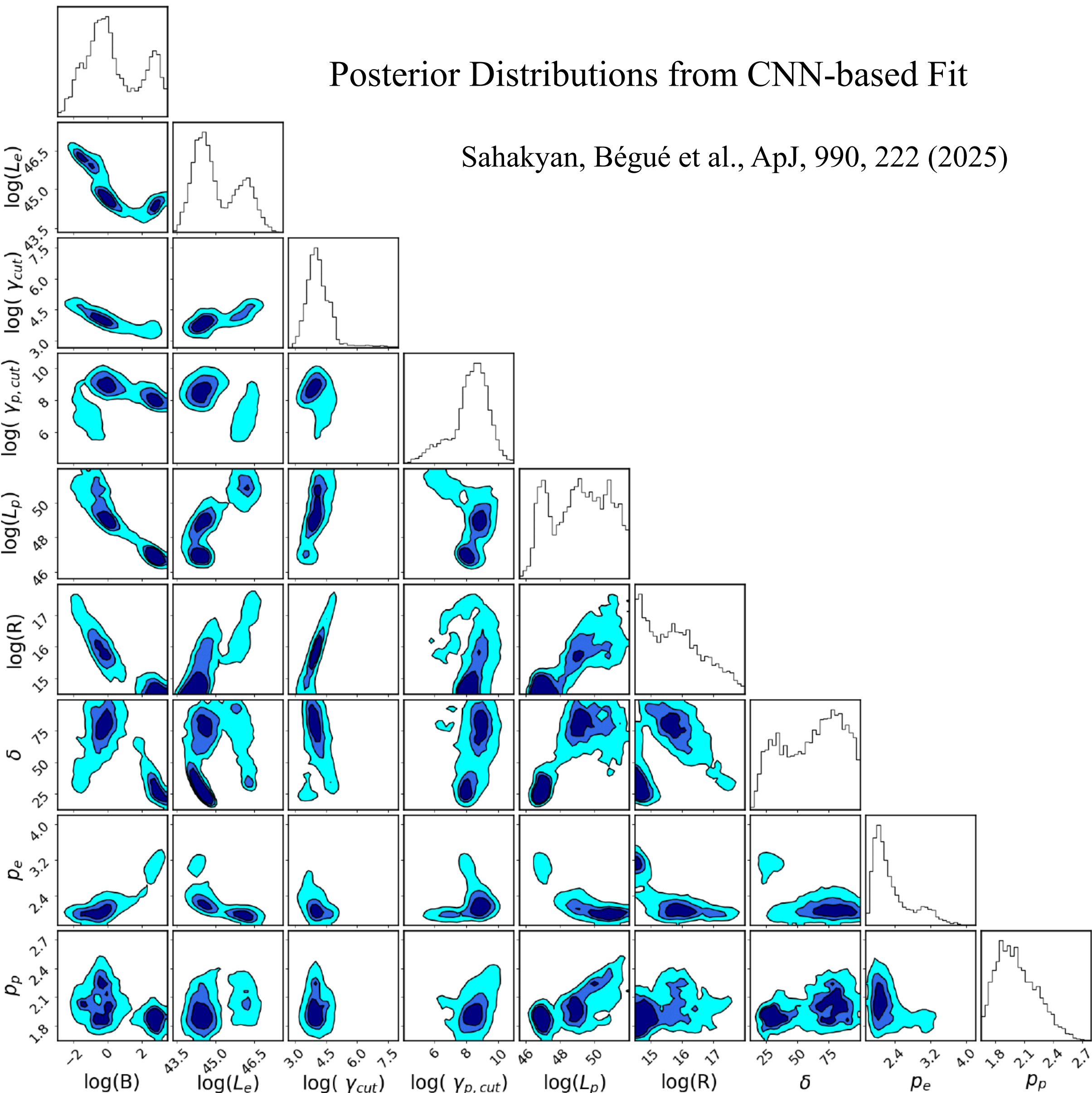
Parameter Estimation in hadronic Modeling

Modeling the SED of PKS 0735+178 during the IceCube-211208A neutrino event using a convolutional neural network trained on hadronic models.



Model parameters for PKS 0735+178

Parameter	Value	Parameter	Value
p_e	2.62	p_p	1.87
$\log_{10}(\gamma_{e,max})$	3.10	$\log_{10}(\gamma_{e,min})$	2.00
$\log_{10}(\gamma_{p,max})$	7.95	δ	26.00
$\log_{10}(B \text{ [G]})$	2.88	$\log_{10}(R \text{ [cm]})$	14.55
$\log_{10}(L_e \text{ [erg/s]})$	44.61	$\log_{10}(L_p \text{ [erg/s]})$	46.91



www.mmdc.am

WELCOME TO MMDC

Markarian Multiwavelength Data Center (MMDC): a platform for building and analyzing multiwavelength SEDs.

GET STARTED

Markarian Multiwavelength Data Center

THE ASTRONOMICAL JOURNAL

OPEN ACCESS

Markarian Multiwavelength Data Center (MMDC): A Tool for Retrieving and Modeling Multitemporal, Multiwavelength, and Multimessenger Data from Blazar Observations

N. Sahakyan, V. Vardanyan, P. Giommi, D. Bégué, D. Israyelyan, G. Harutyunyan, M. M. Khachatryan, H. Dereli-Bégué, and S. Gasparyan

Published 2024 November 28 • © 2024. The Author(s). Published by the American Astronomical Society

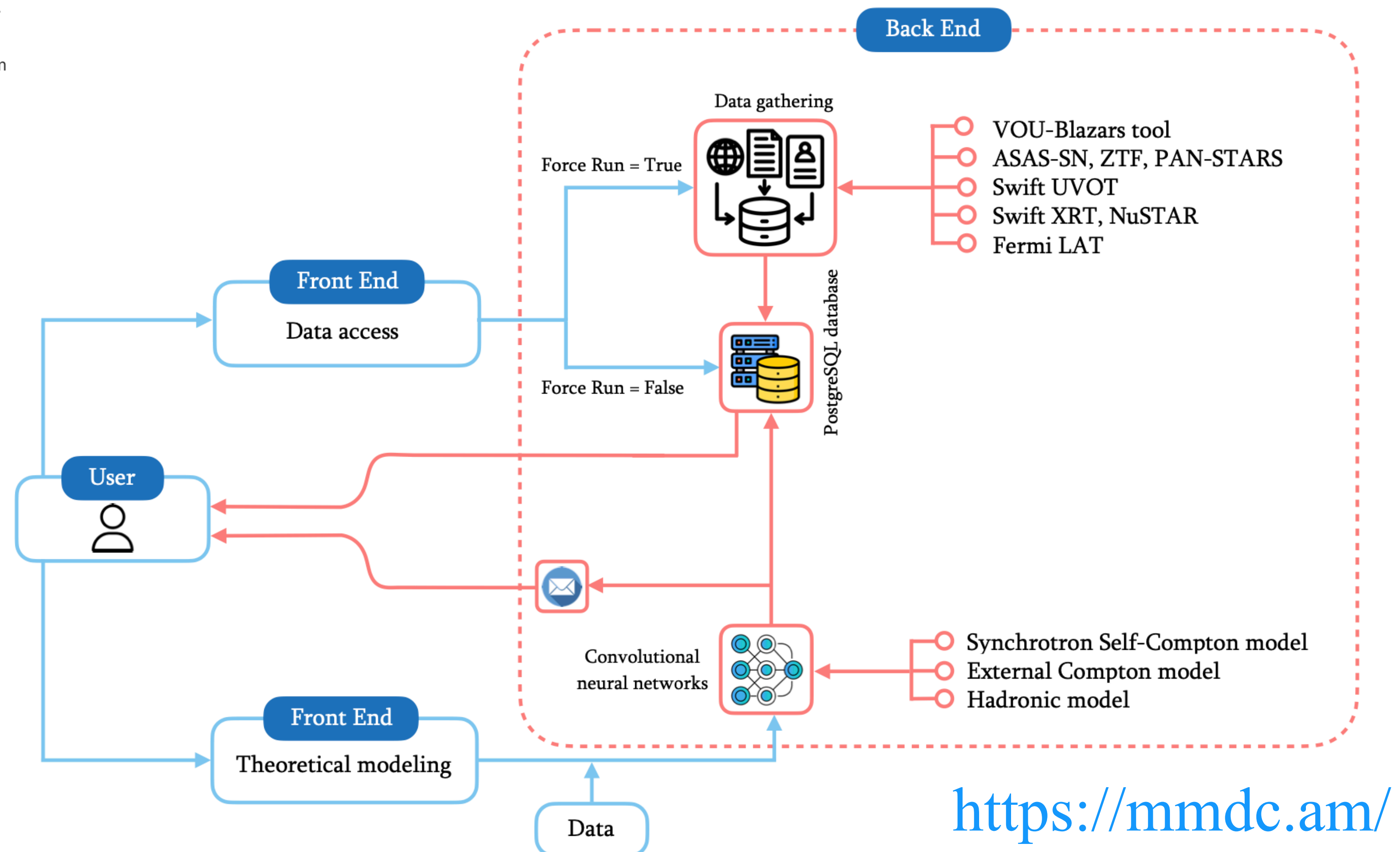
[The Astronomical Journal](#), Volume 168, Number 6

Citation N. Sahakyan et al 2024 AJ 168 289

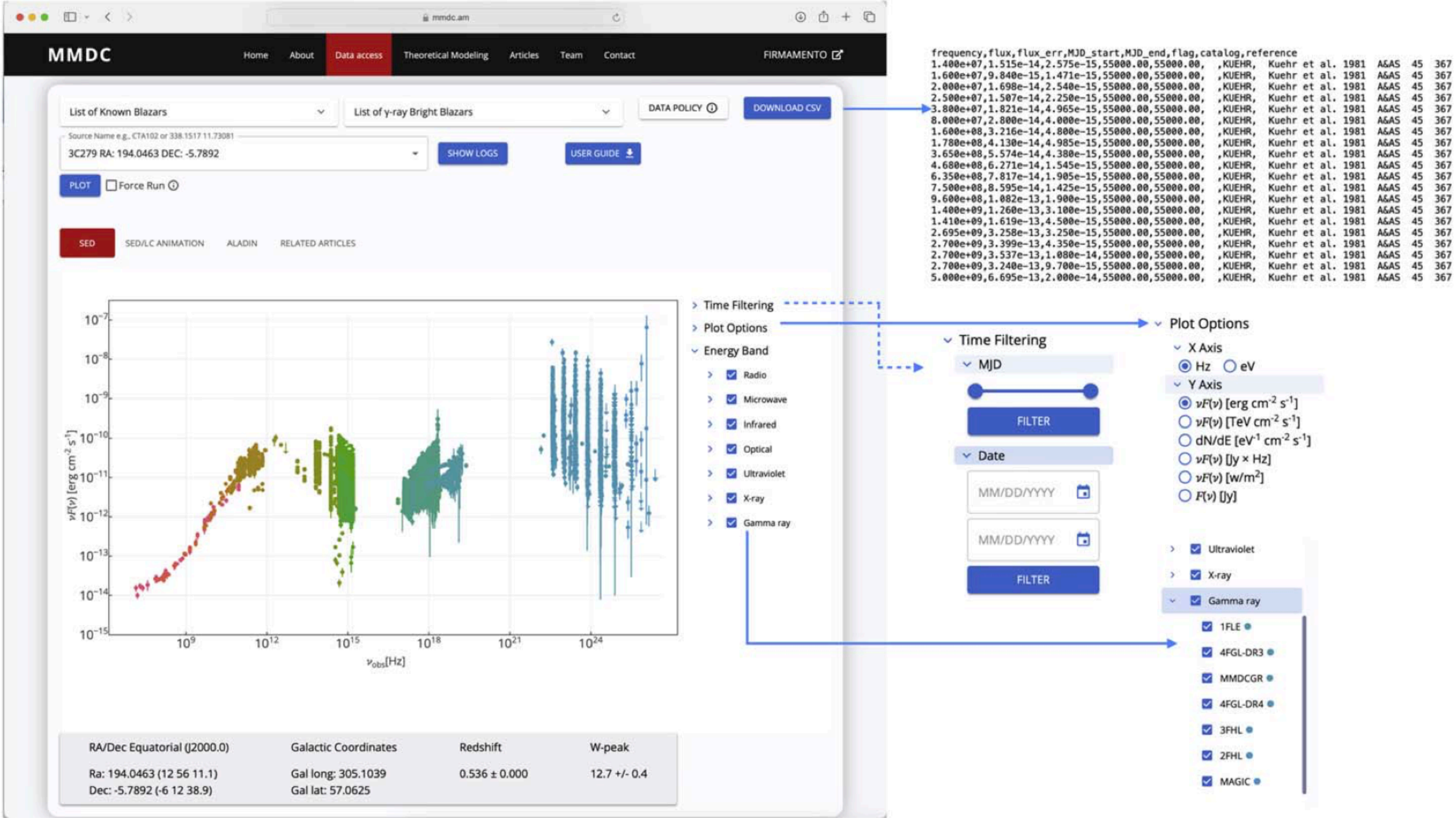
DOI 10.3847/1538-3881/ad8231

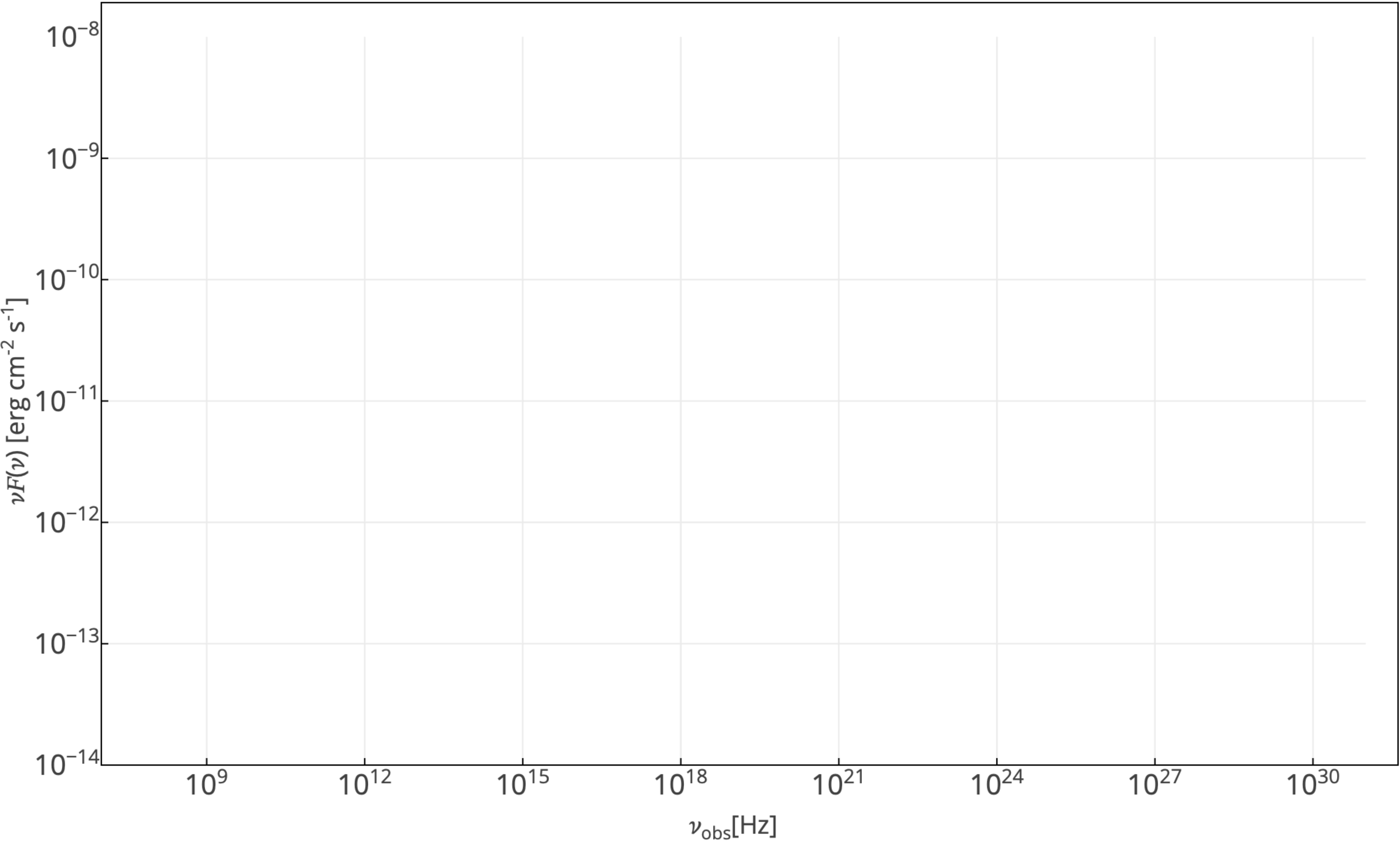


Sahakyan et al., 2024, ApJ, 168, 289, 2024



Data access





SSC	EIC
Hadronic	

pe

δ

pp

log10(γ_{min}) ☐

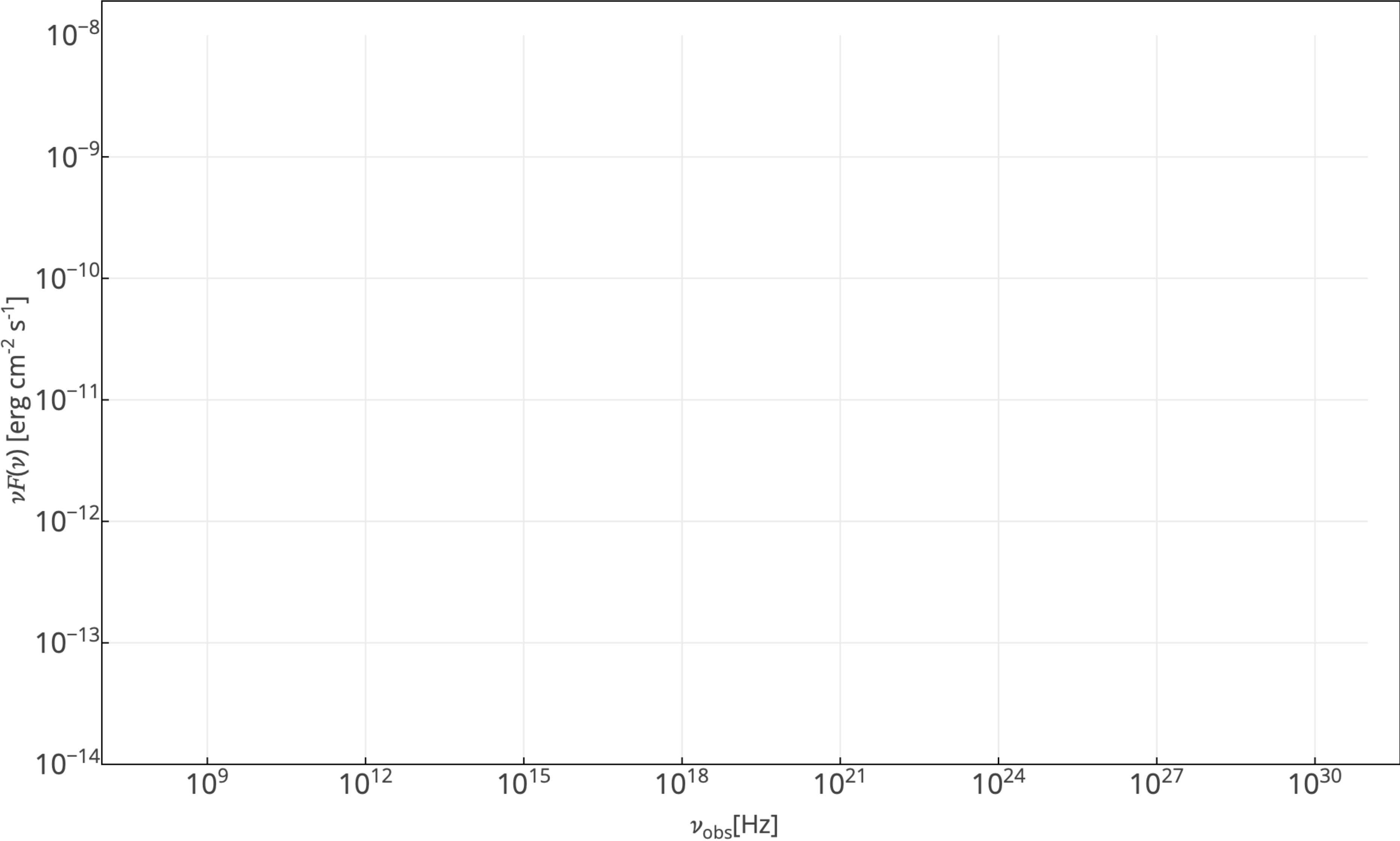
log10($\gamma_{\text{e,max}}$)

log10($\gamma_{\text{p,max}}$)

log10(B /[G])

log10(R /[cm])

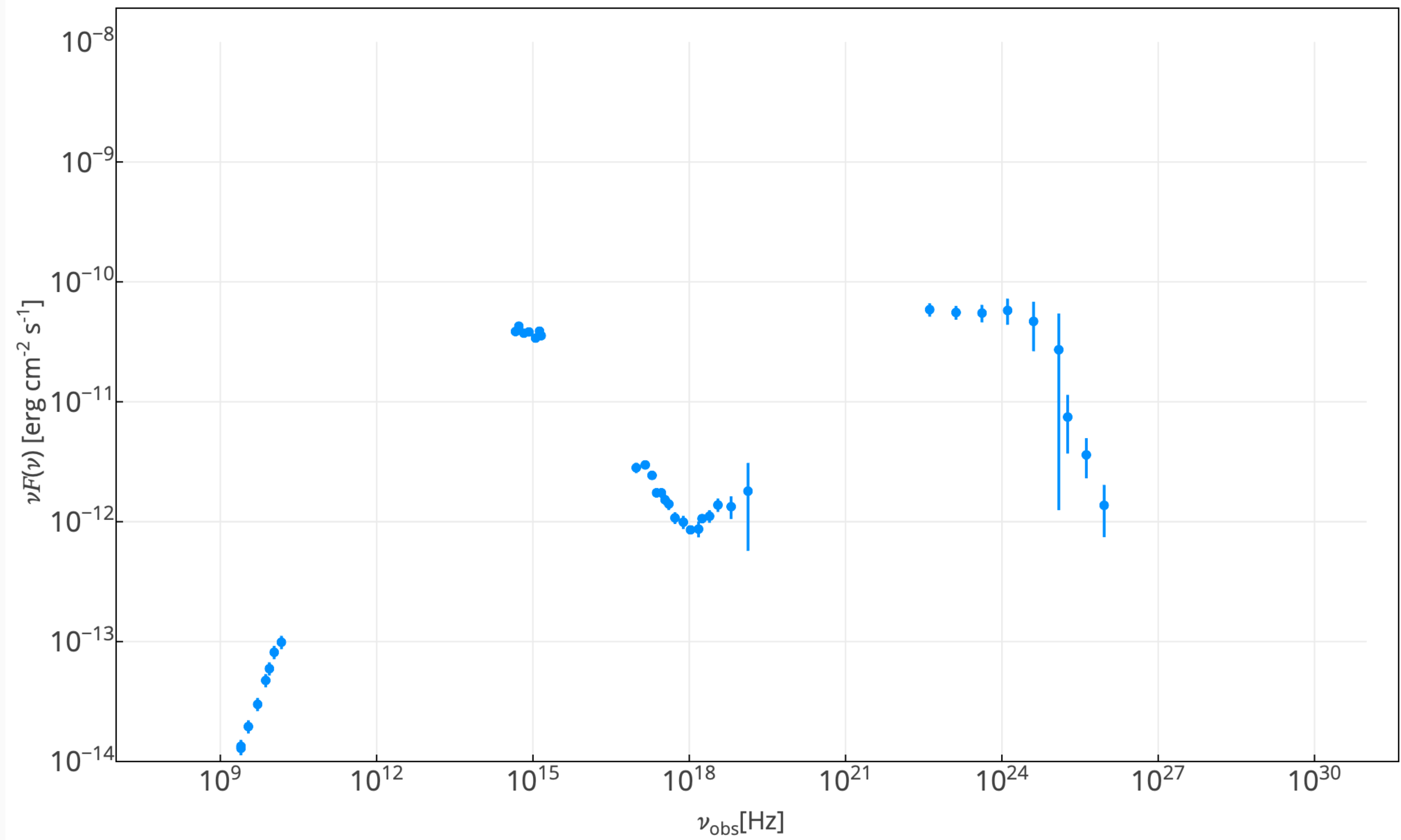
log10(L_{e} /[erg s⁻¹])



☐ EBL

> Spectral information

> Number of neutrinos



log10(R/[cm])

log10(Le/[erg s⁻¹])

log10(Lp/[erg s⁻¹])

^z
0.033

☐ EBL

> Spectral information

> Number of neutrinos

RUN MODEL

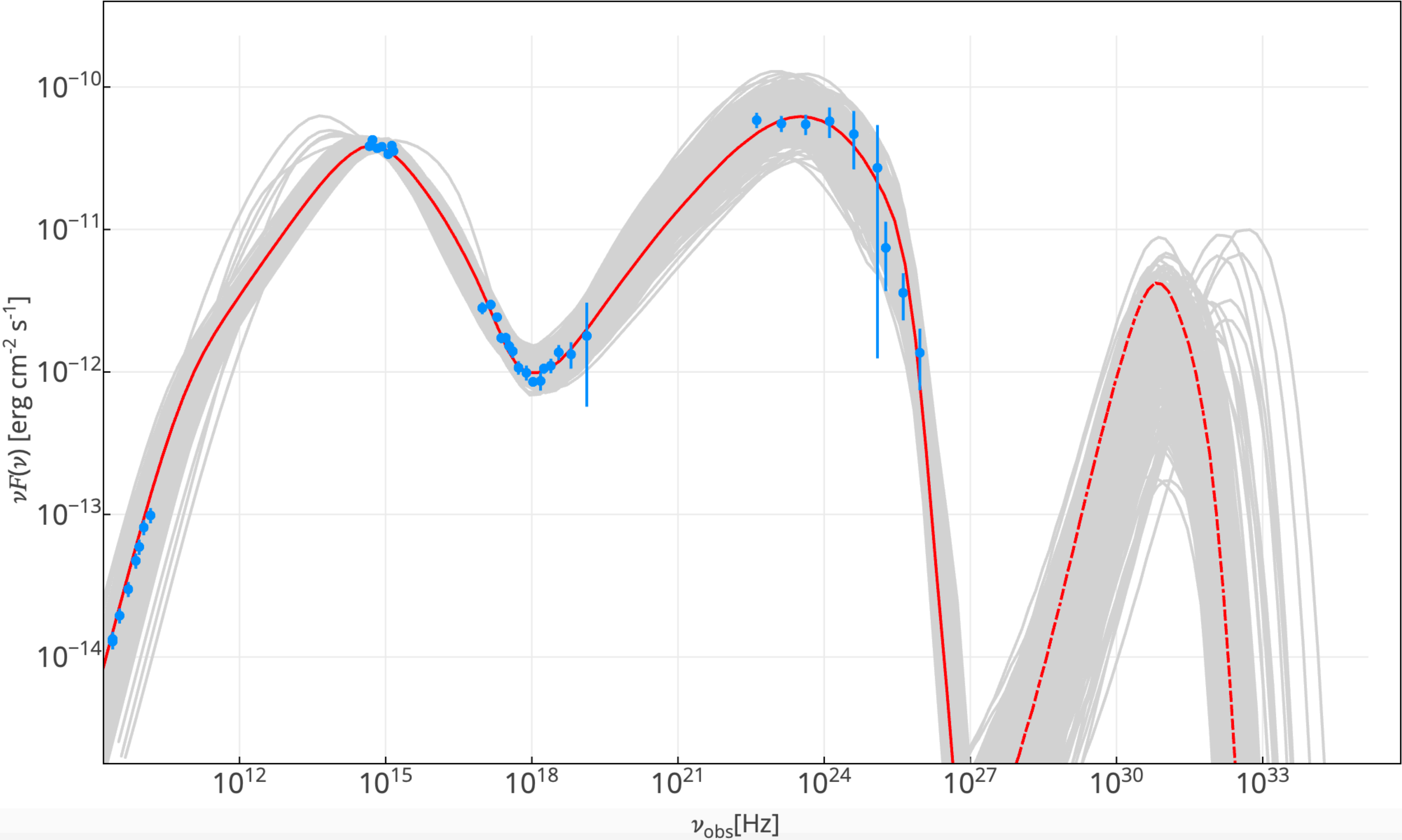
UPLOAD FILE

email

FIT

CORNER PLOT

BEST PARAMETERS



SSC	EIC
Hadronic	

pe 2.344	δ 14.527
-------------	--------------------

pp 1.853

log10(ymin) 2	☒
------------------	-------------------------------------

log10(ye,max) 3.030

log10(yp,max) 8.287

log10(B/[G]) 2.770

log10(R/[cm]) 14.977

log10(Le/[erg s ⁻¹]) 44.660
--

Rapid Multimessenger data Fitting

Key Result

- ✓ CNN-based training for hadronic & lepto-hadronic models
- ✓ Achieves full multimessenger data fit in ≈ 3 minutes
- ✓ No one else can currently fit, let alone this fast

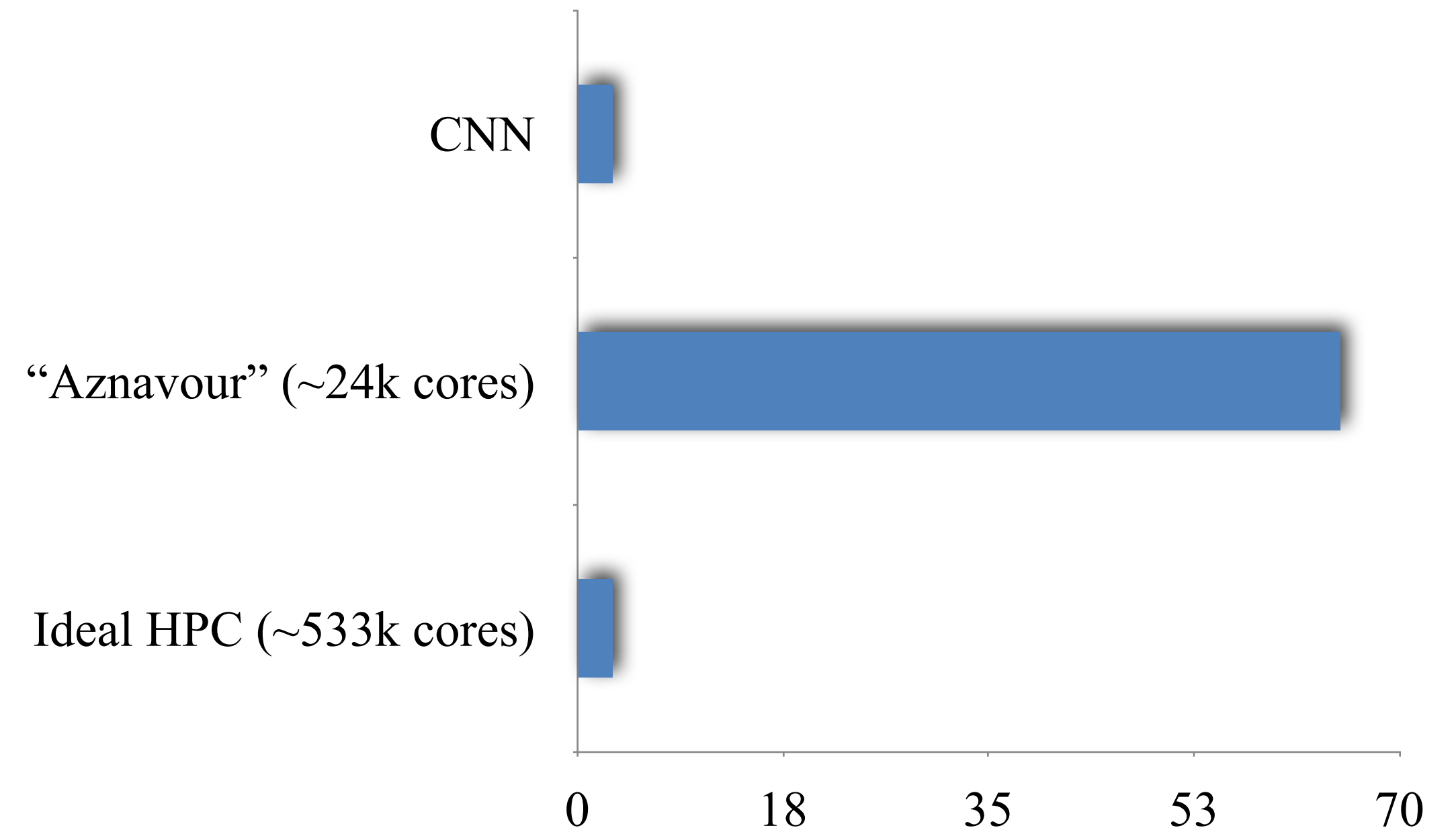
Traditional HPC Requirement for a single fit

- One job: $8 \text{ cores} \times 2 \text{ min} = 16 \text{ core-minutes}$
- 100,000 jobs = 1.6 million core-minutes
- To finish in 3 min: $\geq 533,000$ cores
- “Aznavour” Supercomputer resources (24,480 cores):
Runtime ≈ 65 min

CNN Approach

Train once $\rightarrow$ inference is instantaneous

Runtime (minutes) for 100,000 jobs

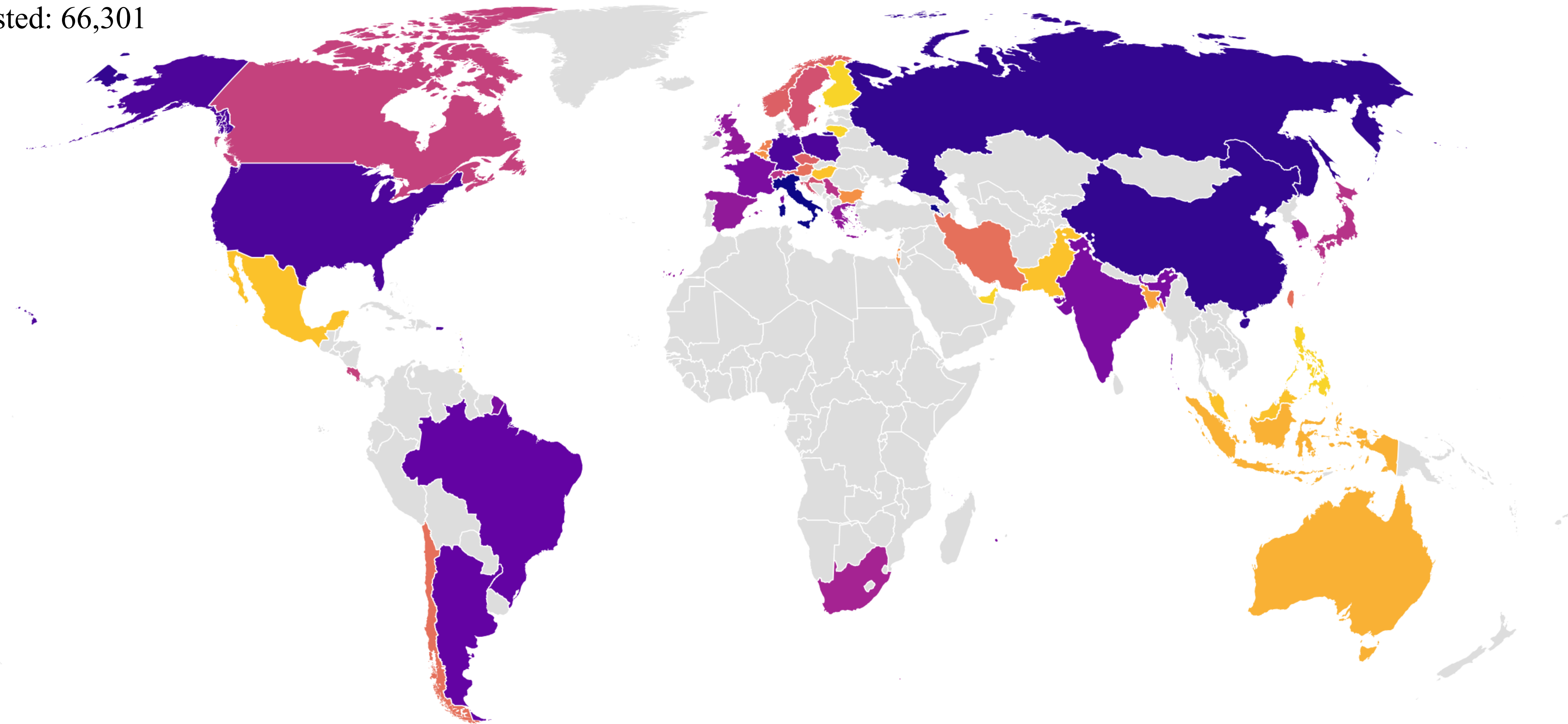


Markarian Multiwavelength Data Center (MMDC): a platform for building and analyzing multiwavelength SEDs.

Users of MMDC

- Accessed from 50 countries worldwide
- Total number of jobs requested: 66,301
- Selected countries include:

1. 🇦🇲 Armenia
2. 🇺🇸 United States
3. 🇨🇳 China
4. 🇷🇺 Russia
5. 🇮🇳 India
6. 🇩🇪 Germany
7. 🇫🇷 France
8. 🇮🇹 Italy
9. 🇬🇧 United Kingdom
10. 🇪🇸 Spain
11. 🇵🇱 Poland
12. 🇬🇷 Greece
13. 🇧🇷 Brazil
14. 🇦🇷 Argentina
15. 🇯🇵 Japan
16.
17.



Next step

$$\sum_i |p_i(x)| = 1$$

$$E^2 = p^2 c^2 + m^2 c^4$$



Next step



AI-powered domain-specific multi-agent research assistant for advancing Astrophysical Discovery

AstroGenesis will make the simple simpler and complex possible