Parameter spaces of one-zone models

in application to blazar multi-messenger modeling

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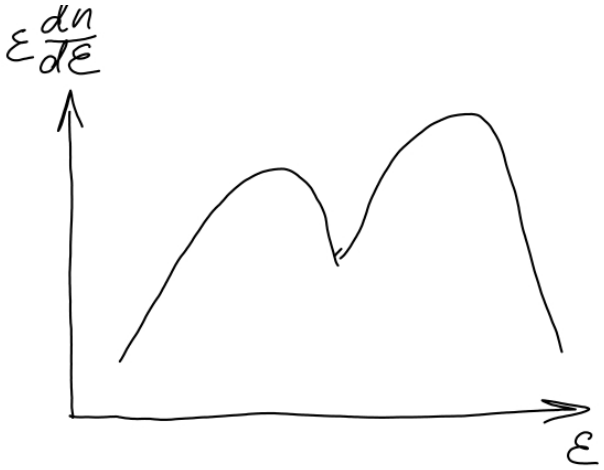
2nd workshop on numerical multi-messenger modeling
Paris, APC Laboratory

Blazar spectral energy distribution



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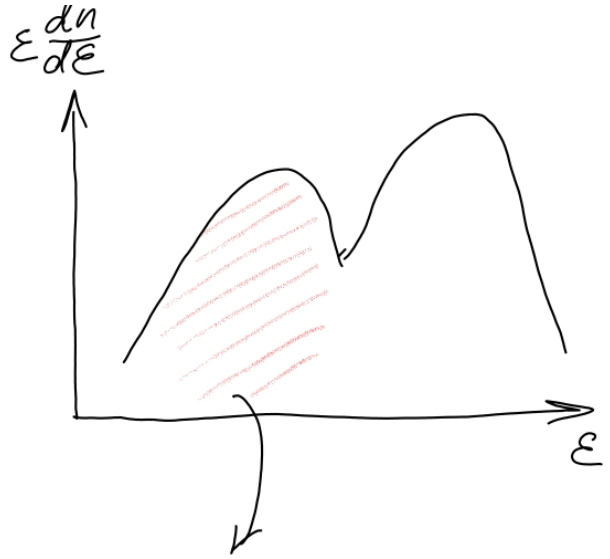
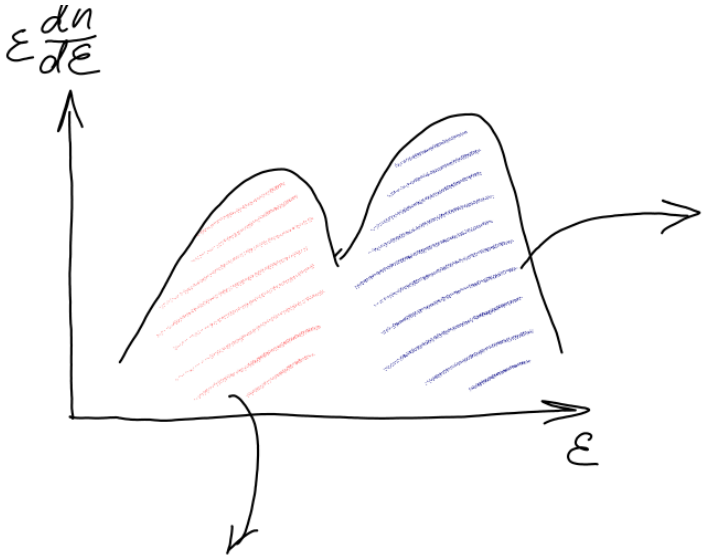


Synchrotron radiation

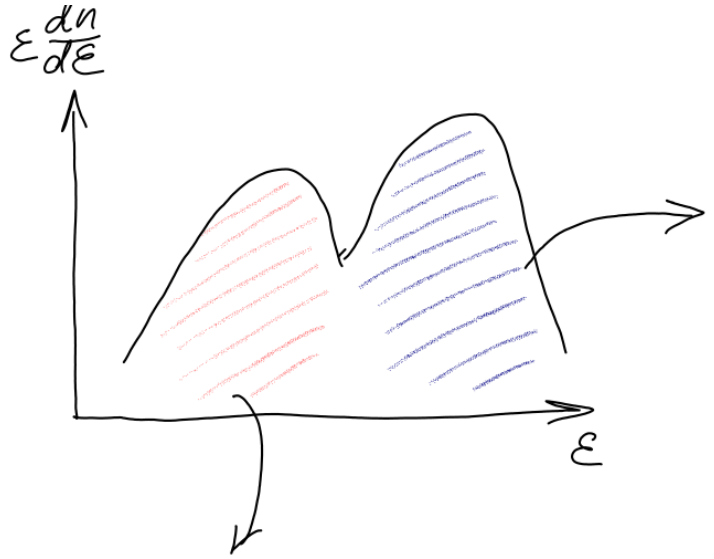
Blazar spectral energy distribution



- Leptonic origin
- Hadronic origin
- Leptohadronic origin

Synchrotron radiation

Blazar spectral energy distribution



Synchrotron radiation

- Leptonic origin
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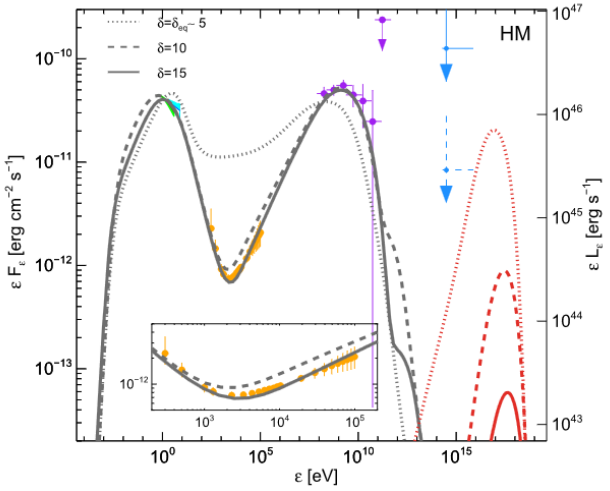
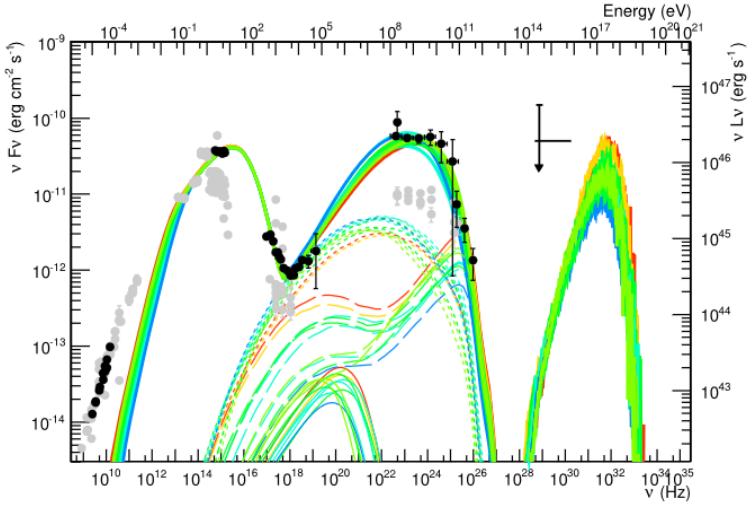
One-zone model as the simplest explanation of blazar SEDs

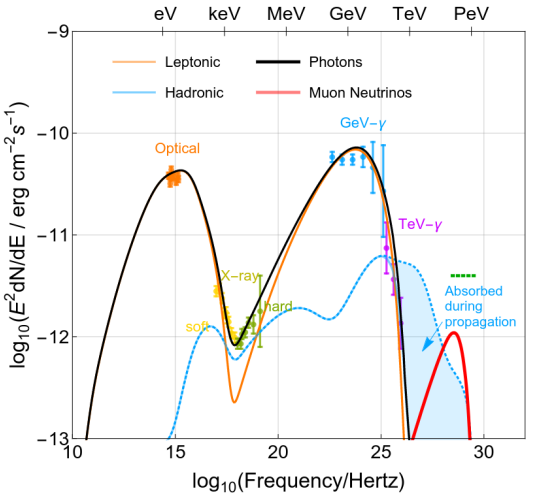
TXS 0506+056 – the first neutrino source



Keivani et al. 2018 (one-zone EIC)

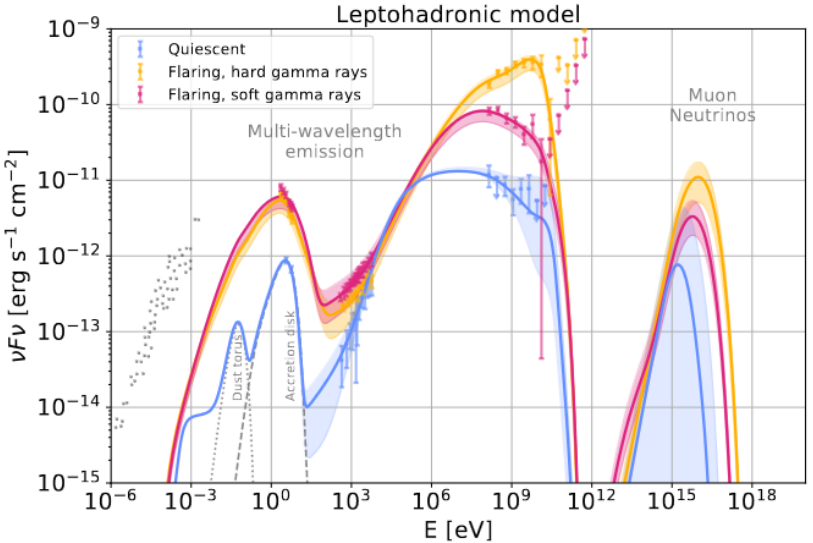


Cerruti et al. 2019 (one-zone SSC)

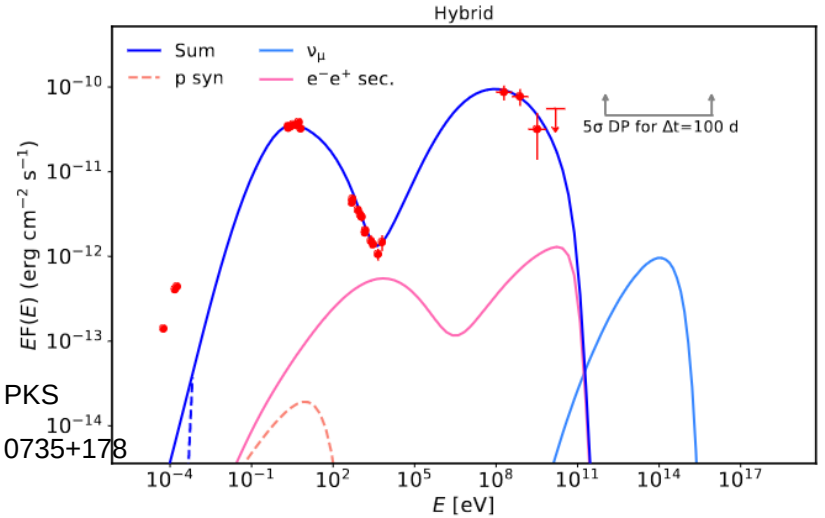


Gao et al. 2019 (one-zone SSC)

More potential neutrino sources

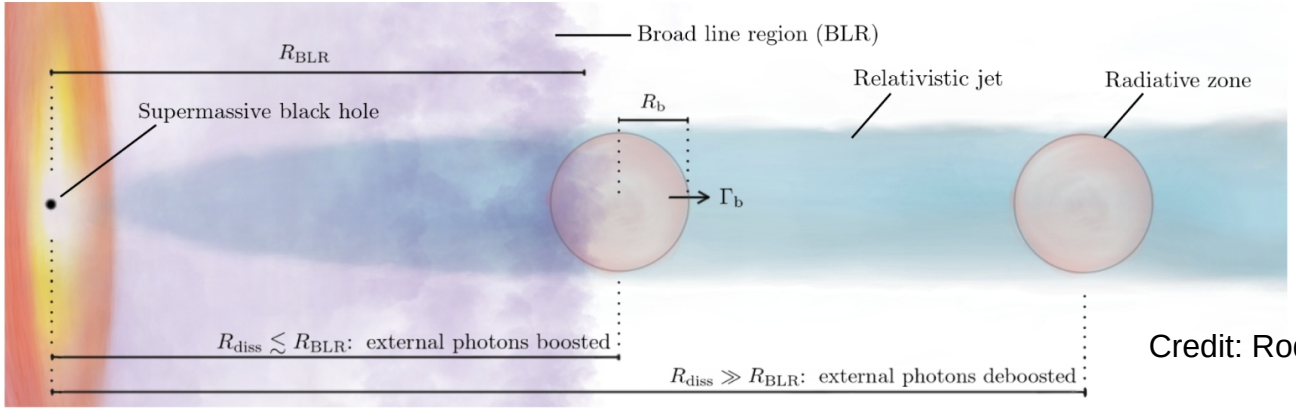


PKS 1502+106, Rodrigues et al. 2021



PKS 0735+178, Sahakyan et al. 2023

Parameters of one-zone models



Credit: Rodrigues et al. 2024

Purely leptonic models:

- Emission zone radius
- Magnetic field
- Blob Lorentz factor
- Minimal and maximal energies of accelerated electrons, power-law index
- Electron luminosity

7 parameters

Leptohadronic models:

+ Minimal and maximal energies of accelerated protons, power-law index

+ Proton luminosity

+ 4 parameters

Leptohadronic external photon field models:

+ accretion disk temperature

+ distance from emission zone to the black hole

+ 2 parameters

Approaches to parameter search

- Fitting “by hand” (+ semi-analytical constrains?)
- Genetic algorithm
- Markov Chain Monte Carlo

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- Genetic algorithm Xavier’s talk, 22/02

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- Markov Chain Monte Carlo

  + robust, provides good description of parameter space

  - computationally expensive, unreliable solutions in very heterogeneous parameter spaces

Grid scan based approach

Step 1. Discretize values of each parameter within a certain range. Run simulations with all possible combination of the parameters.

→ e.g. for leptonic model with 7 parameters and 10 values per parameter, we run 10^7 simulations

Step 2. Evaluate goodness-of-fit. Locally minimize the best solution(s) in the space between the grid points.

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+ re-usable for different sources, robust, no prior assumptions, highlights multiple zones of possible solutions
- computationally expensive

Exploring the method with pseudo-data

- generate leptonic SED with certain parameters and produce pseudo-data

- run 10^7 simulations with AM³ Marc's talk, 21/02

- calculate reduced χ^2

- plot the parameter space and look for 'families' of the solutions

Parameter	Value range
$R'_{\rm blob}$, cm	$[10^{15}, 10^{17.5}]$
B', gauss	[0.1, 5]
$\Gamma_{\rm b}$	[3.0, 30.0]
$\gamma_{\rm e}'^{\rm min}$	$[10^{3.0}, 10^{3.95}]$
$\gamma_{\rm e}'^{\rm max}$	$[10^{4}, 10^{5}]$
$\alpha_{\rm e}$	[0.5, 3.5]
$L'_{\rm e}$ / erg s^{-1}	$[10^{42},10^{47}]$

Visualization of high dimensional data

Frederike Apel, Master thesis

t-distributed stochastic neighbor embedding (t-SNE) `scikit-learn`

- Machine learning tool for the visualization of high-dimensional data
- Step 1: Set of probabilities which are proportional to the similarities
- Step 2: Get a second set of probabilities in the low dimensional space (Student t-distribution)
- Step 3: Measuring the difference between the probability distributions by using the Kullback-Leibler divergence and minimize it

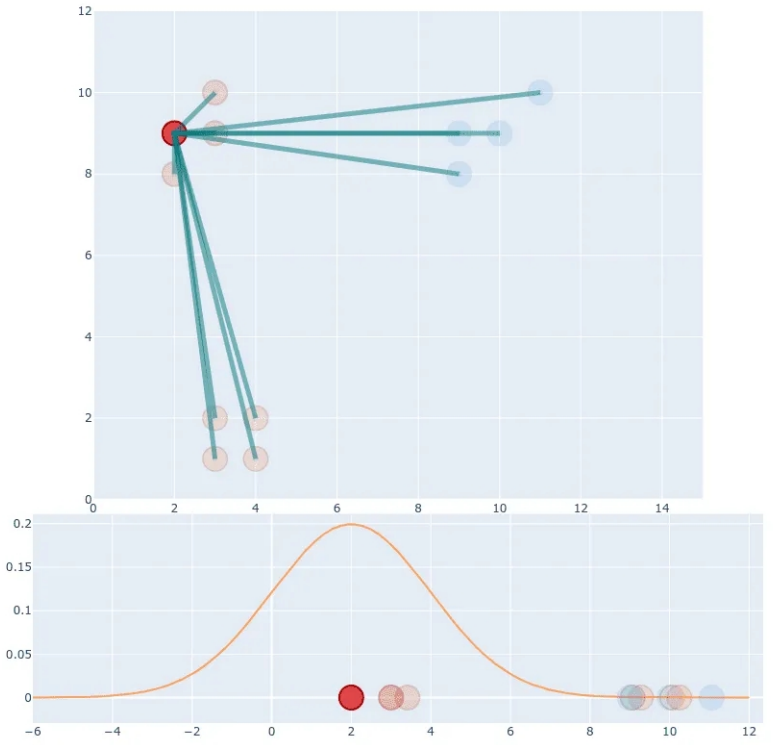
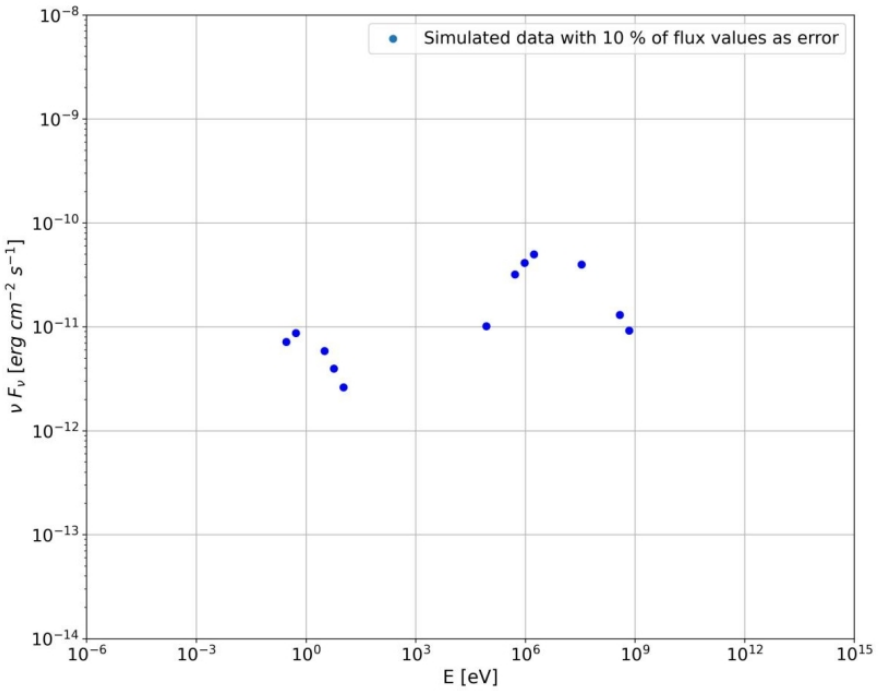
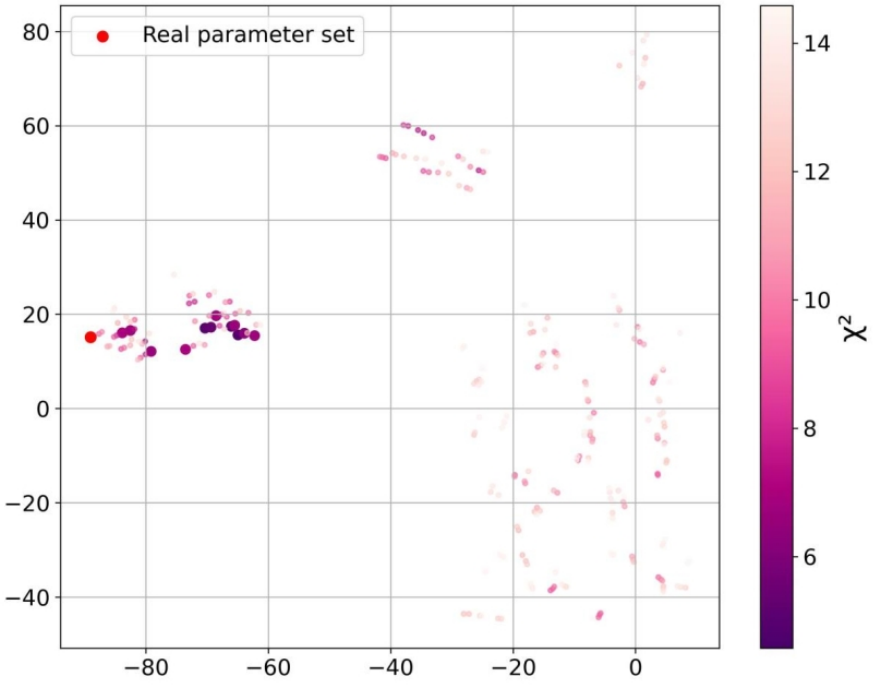


Figure: https://towardsdatascience.com/t-sne-clearly-explained-d84c537f53a

Frederike Apel, Master thesis





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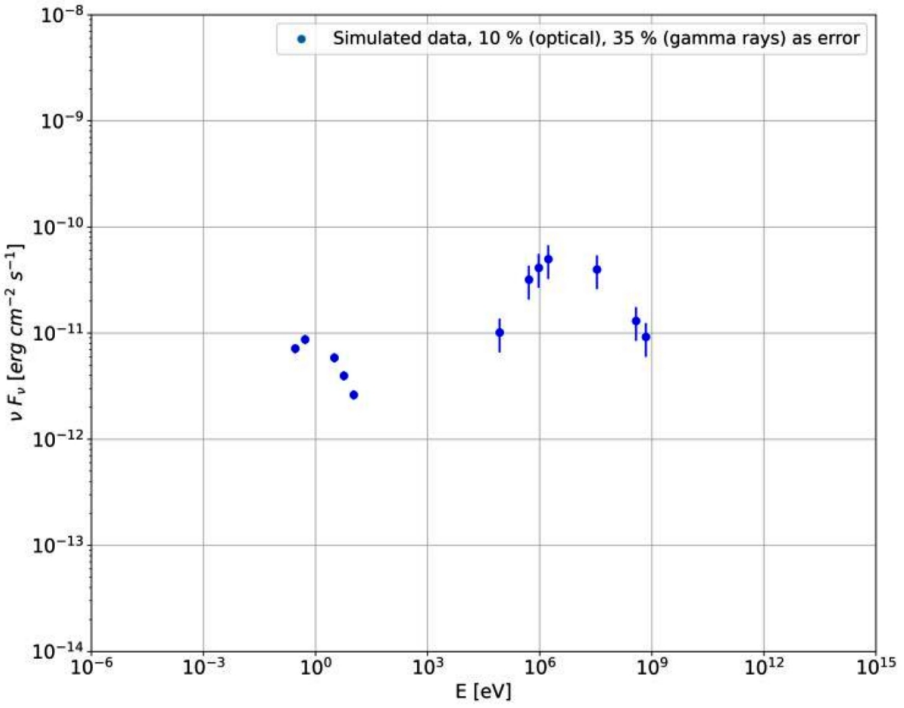
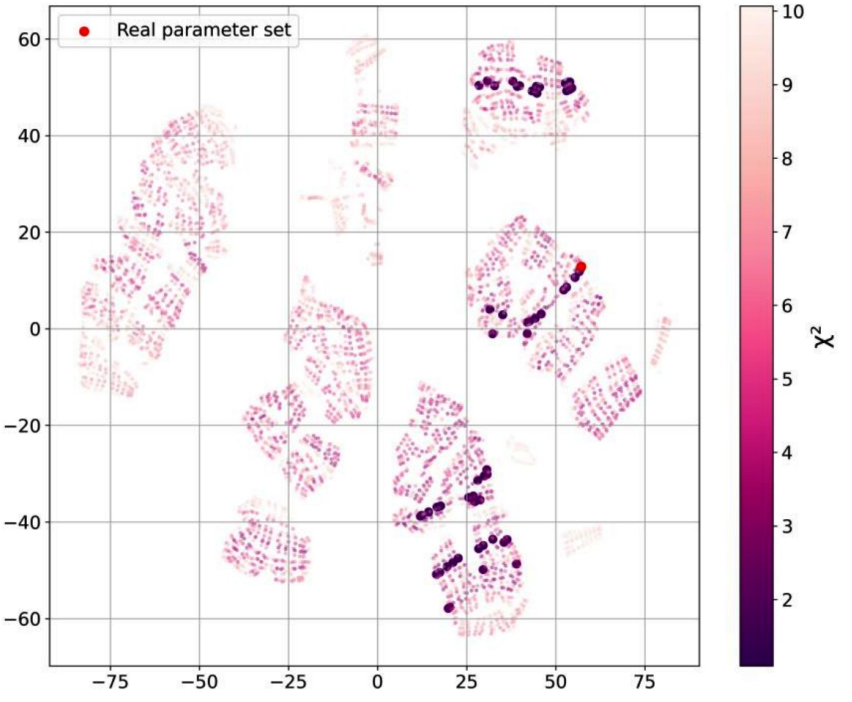
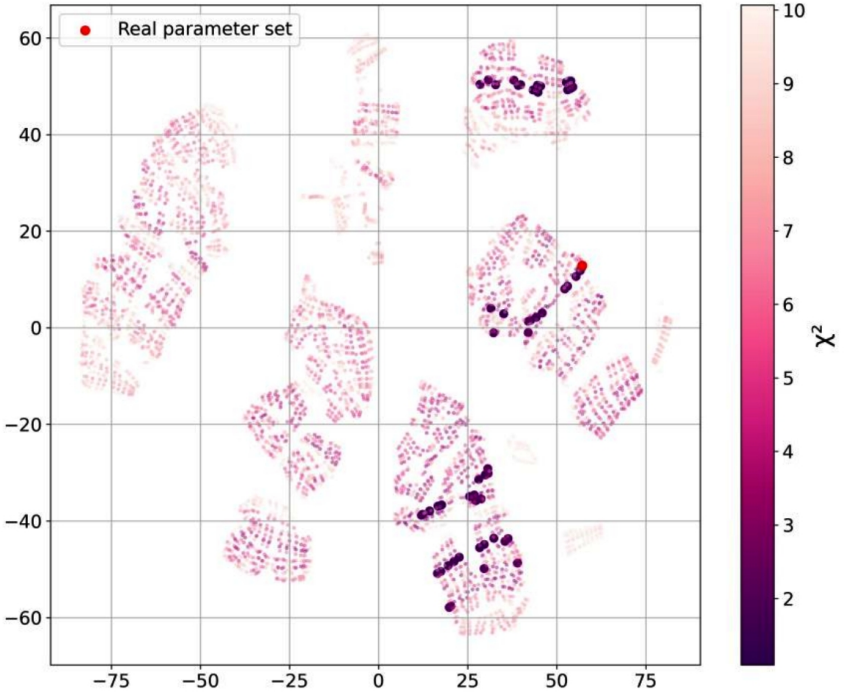
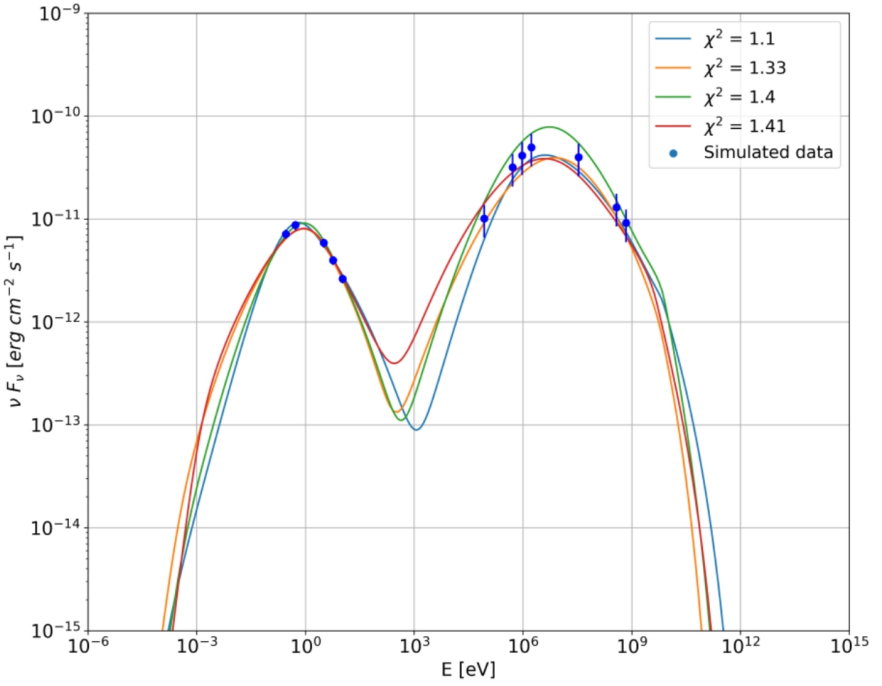








R_{blob} [cm]	B [G]	γ_{min}	γ_{max}	Γ_b	L [erg/s]	index α
10^{15}	1.19	1000	35900	21	10^{42}	3.17
$3.59 \cdot 10^{15}$	1.73	2070	12900	9	$1.29 \cdot 10^{43}$	2.83
10^{15}	1.73	1630	16700	15	$3.59 \cdot 10^{42}$	3.17
$1.9 \cdot 10^{15}$	3.37	1630	27800	9	$1.29 \cdot 10^{43}$	3.17

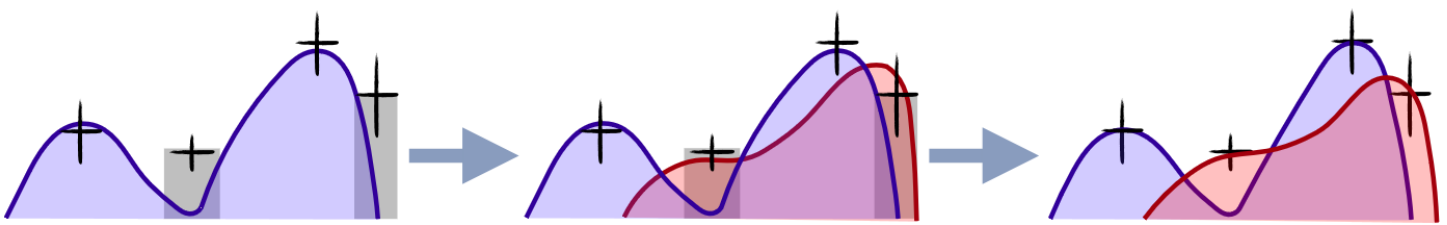
A case of PKS 0735+178

1. Leptonic grid scan (same boundaries) + local optimization for IR, optical, UV and gamma-rays

2. Hadronic grid scan with fixed leptonic parameters, full dataset

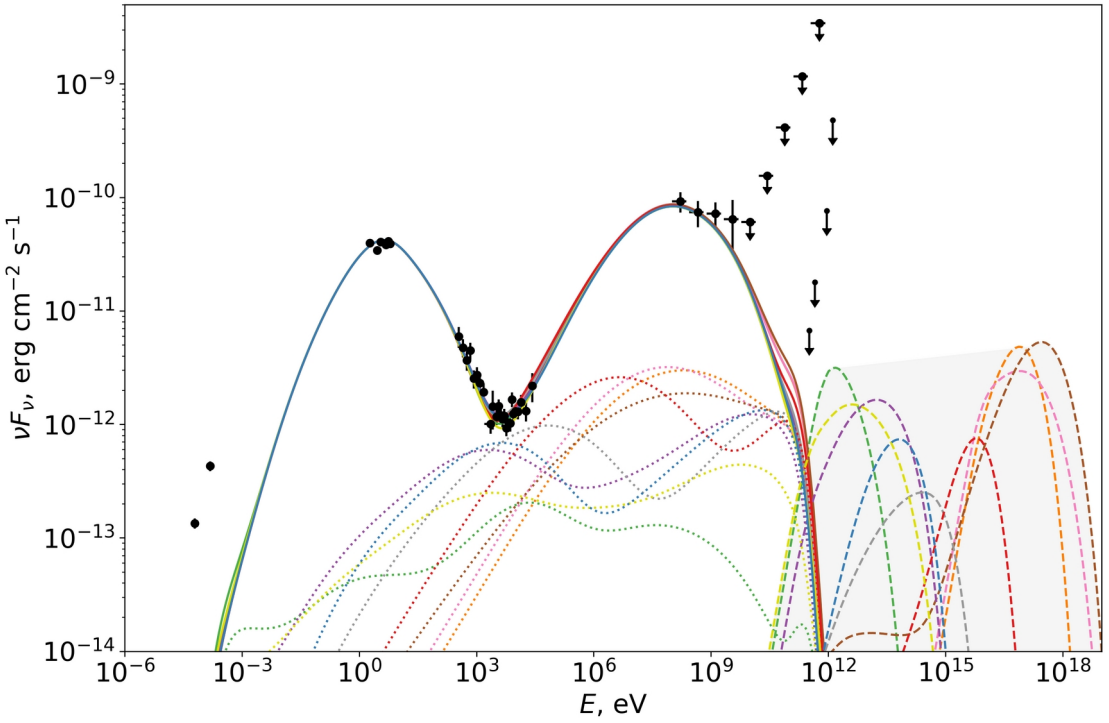
3. Local optimization for the full dataset

Parameter	Value range
$\gamma_p'^{min}$	$[10^{1.0}, 10^6]$
$\gamma_p'^{max}$	$[10^1, 10^9]$
α_p	1.0, 2.0, 3.0
L_p' / erg s^{-1}	$[10^{40},10^{48}] \cup \{0\}$



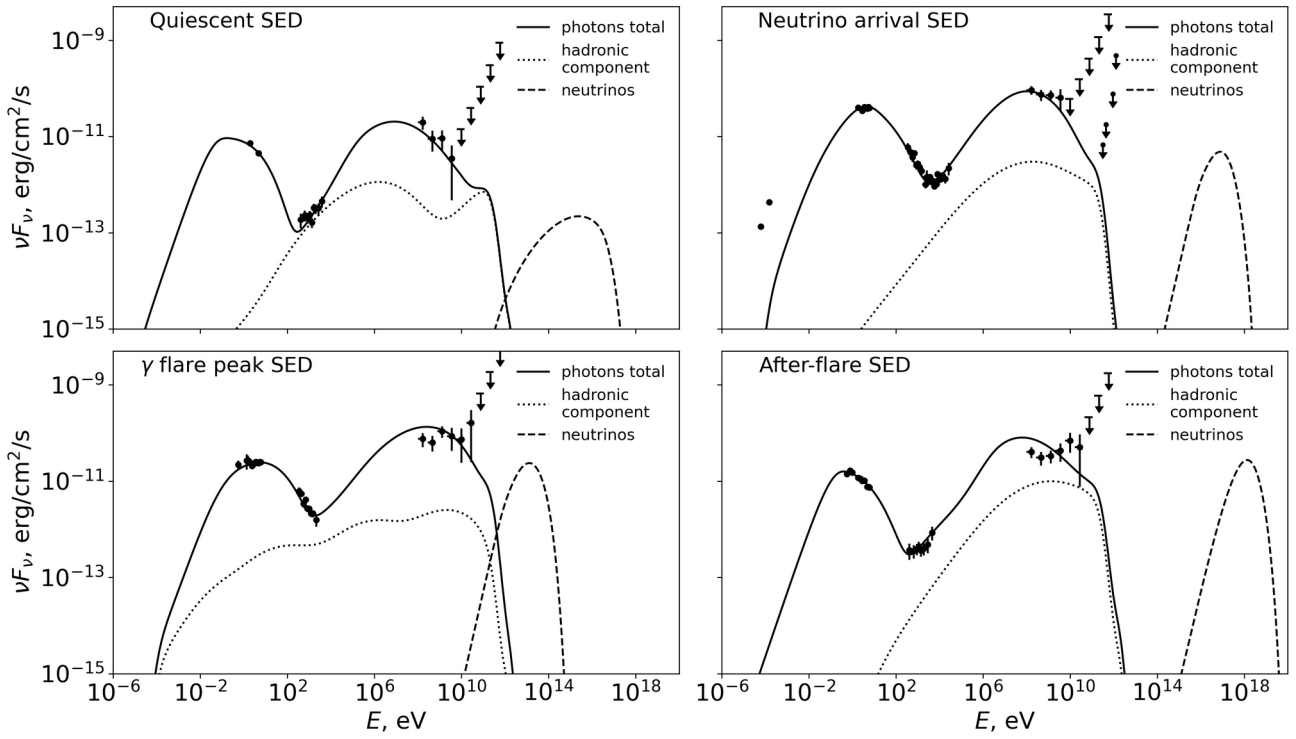
Rodrigues et al. 2024

Neutrino spectrum prediction



$\log_{10}\gamma'^{p}_{min}$	$\log_{10}\gamma'^{p}_{max}$	α_p	$\log_{10} L'_p$, erg/s
7.0	9.0	3.2	44.55
1.0	9.0	2.5	47.17
1.0	4.9	2.0	48.3
1.5	5.7	1.8	46.85
2.5	6.7	1.5	45.5
1.0	4.9	2.8	50.1

Maximization of neutrino events in IceCube



Quiescent state: at most 0.04 neutrinos/year

Flare (50 days): at most 0.2 neutrinos

Summary and outlook

- State-of-the-art radiation models depend on many free parameters
- Grid scan + local minimization allows to locate multiple regions of possible parameters in the parameter space
- Neutrino spectrum cannot be unambiguously predicted based on the available photon fluxes data
- New data or polarization measurements are required to investigate potential neutrino sources

We want to continue with:

- better investigation of multi-dimensional parameter spaces
- proper comparison with other algorithms for parameter search
- simulated a lot of leptonic SEDs → re-usable for other sources, NN training
- leptohadronic grid scan