Understanding blazar emission with the help of machine learning tools

Astroparticle School 2023

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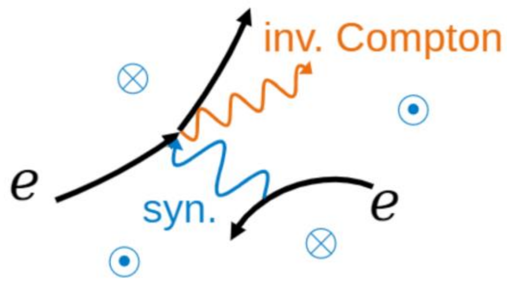
Spectral energy distribution (SED) of a blazar

SED shows a two bump structure:

- **Low-energy bump:** Synchrotron radiation from electrons
- **High-energy bump:** Synchrotron self compton; hadronic component



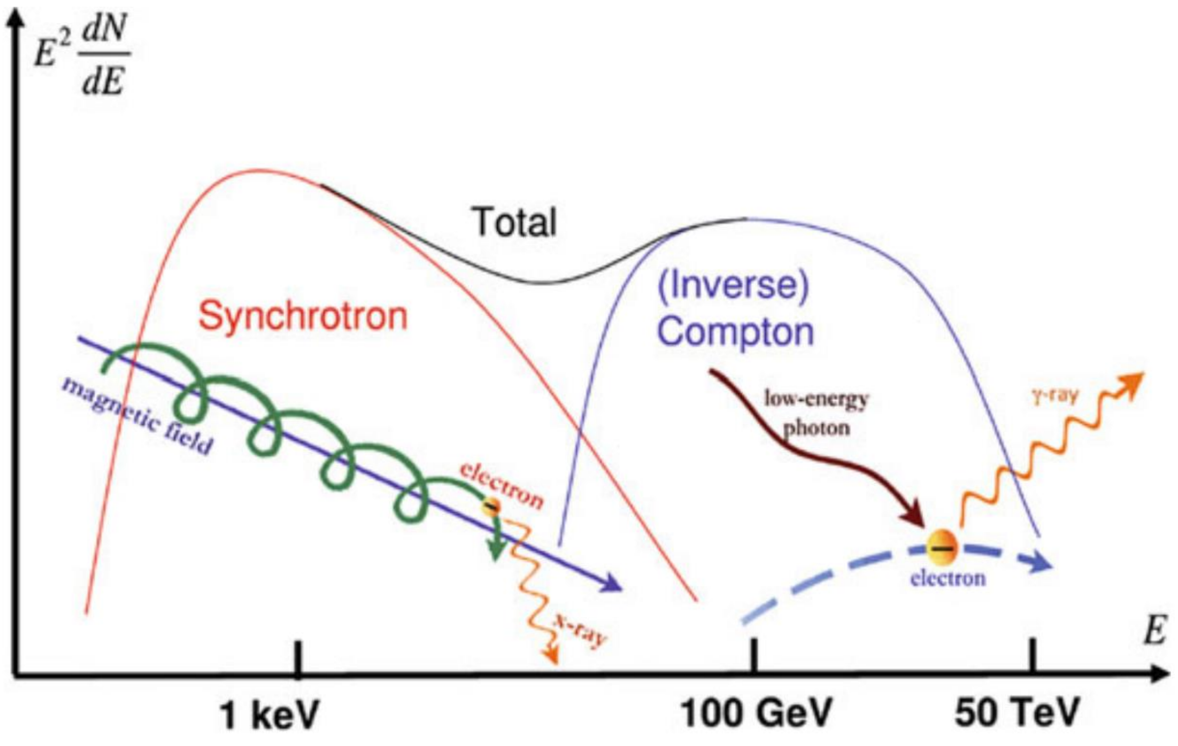


Figure taken from De Angelis and Pimenta (2018)

Leptonic, hadro-leptonic, hadronic models

The leptonic model

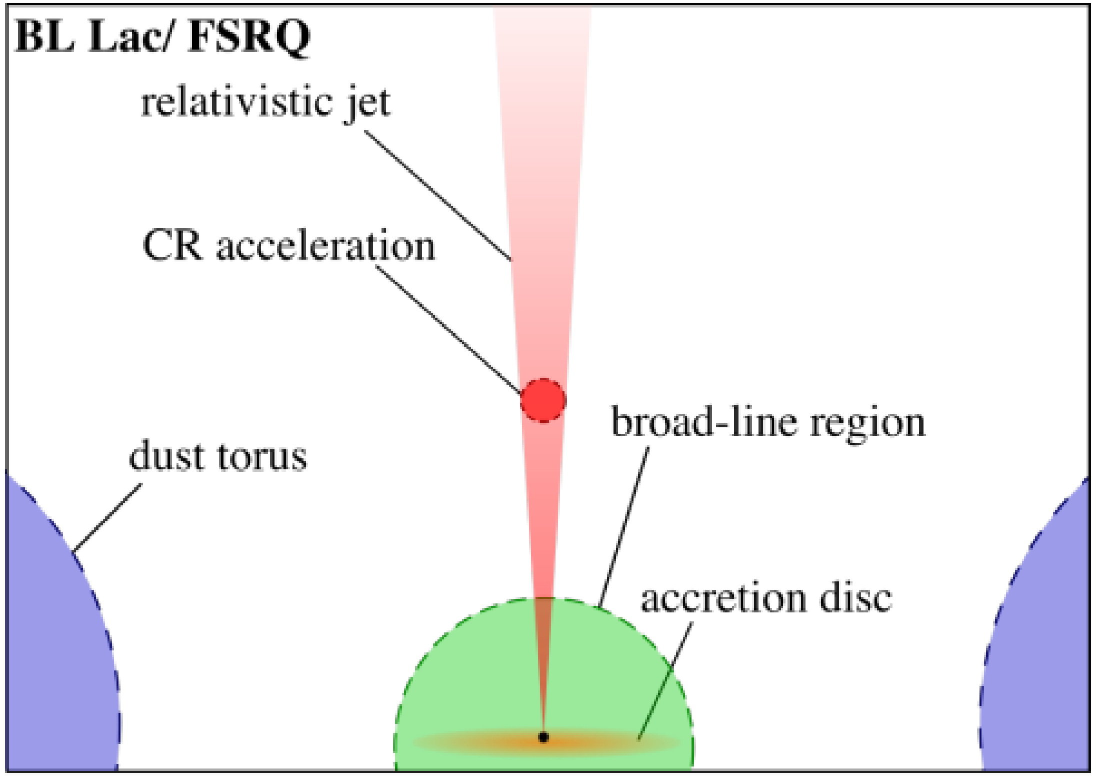


Figure taken from Rodrigues et al. (2018a)

Assuming a spherical zone with **radius R_{blob}** moving along a

Jet with a **Lorentz boost factor Γ_b**

Electrons get injected with **Luminosity L** and accelerated

in a **magnetic field with strength B**

with γ_{min} and γ_{max} describing the electrons **energies**

following a power law with **index α**

Modeling with numerical simulation code

- Using the time-dependent simulation code AM^3 which solves the particle transport equations numerically

- **Grid Scan**: define a range of values for each parameter and step size for variation
- Model curves resulting from each combination of the values
- χ^2 is a measure for the deviation between simulation and real data

$$\chi^2 = \frac{1}{K-1} \sum \frac{(y_{data} - y_{model})^2}{y_{error}^2}$$

with K as the number of degrees of freedom

Blazar PKS 0735+178

- Multiple possible solutions
- 10 million models from grid scan

How do the solutions change if we change the parameter space?

How can we visualize the parameter space?

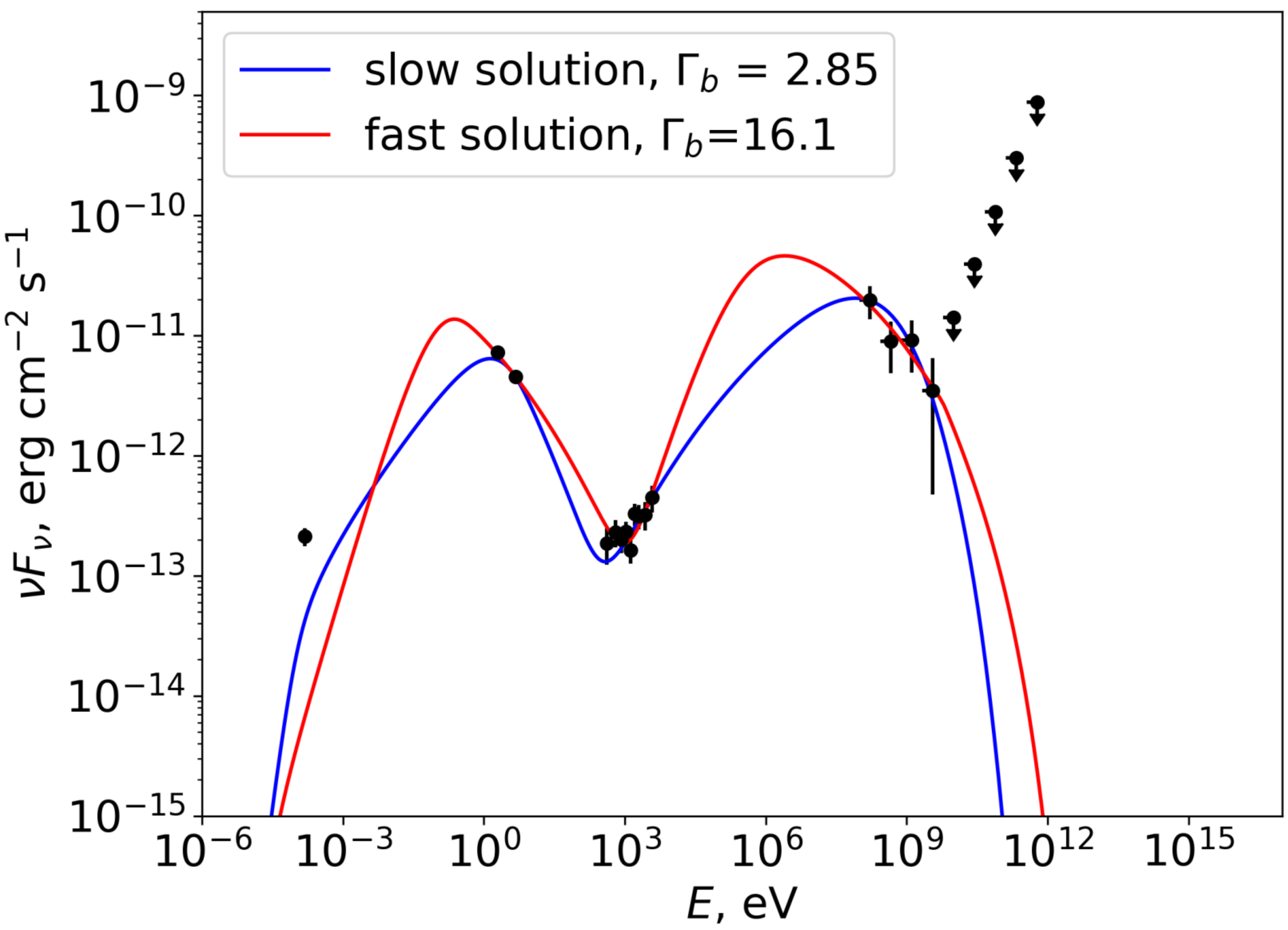


Figure taken from Omeliukh et al. (in prep)

t-distributed stochastic neighbor embedding (t-SNE)

- Machine learning tool for the visualization of high-dimensional data
- Step 1: Measuring similarities between points in the high-dimensional space to get a 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

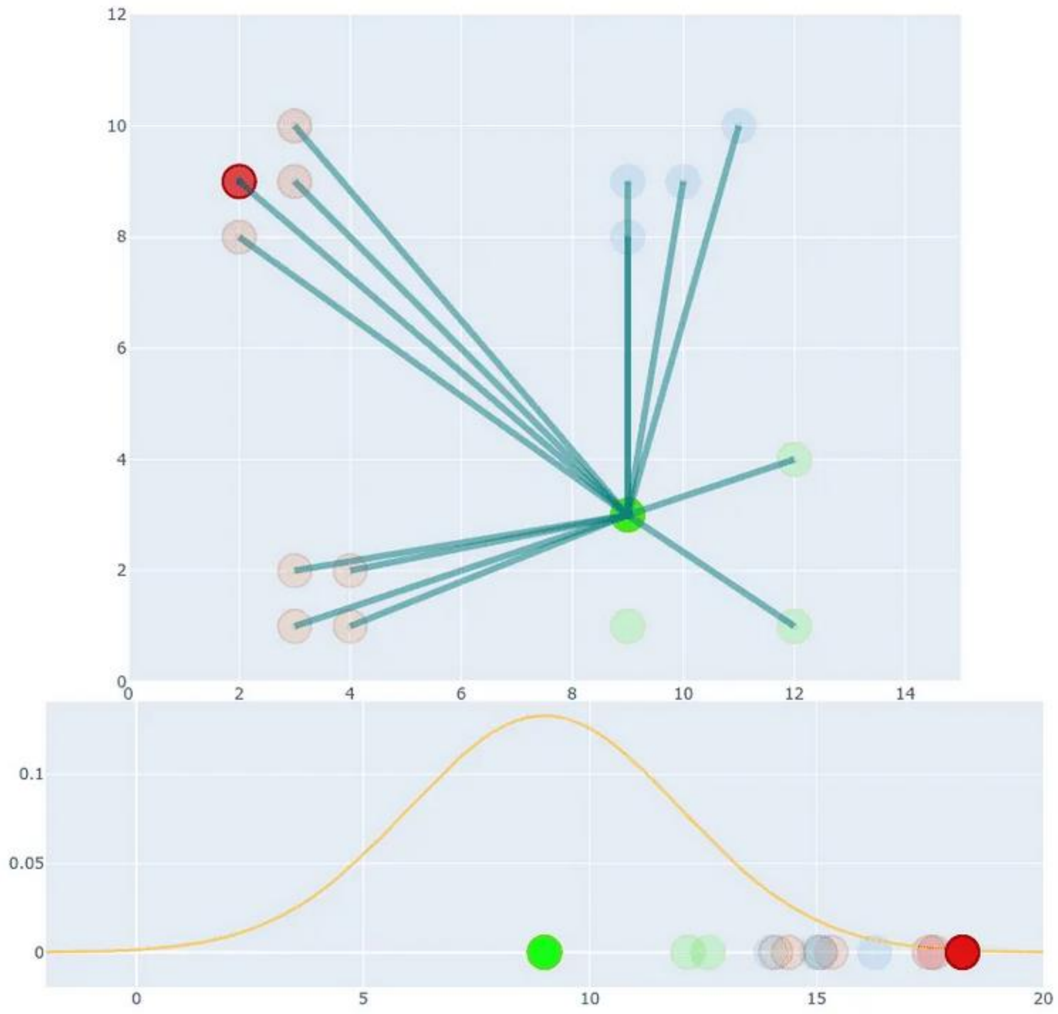
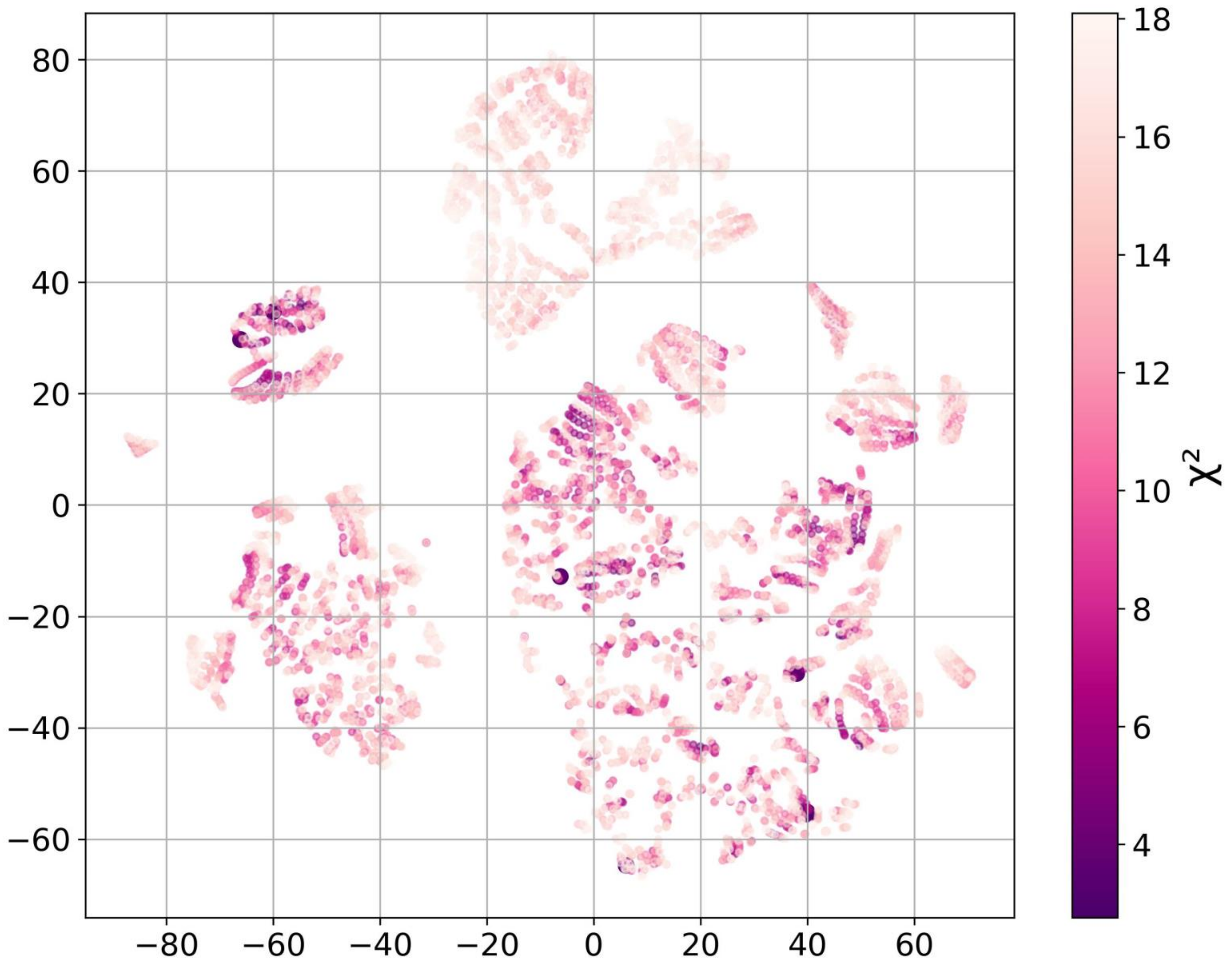
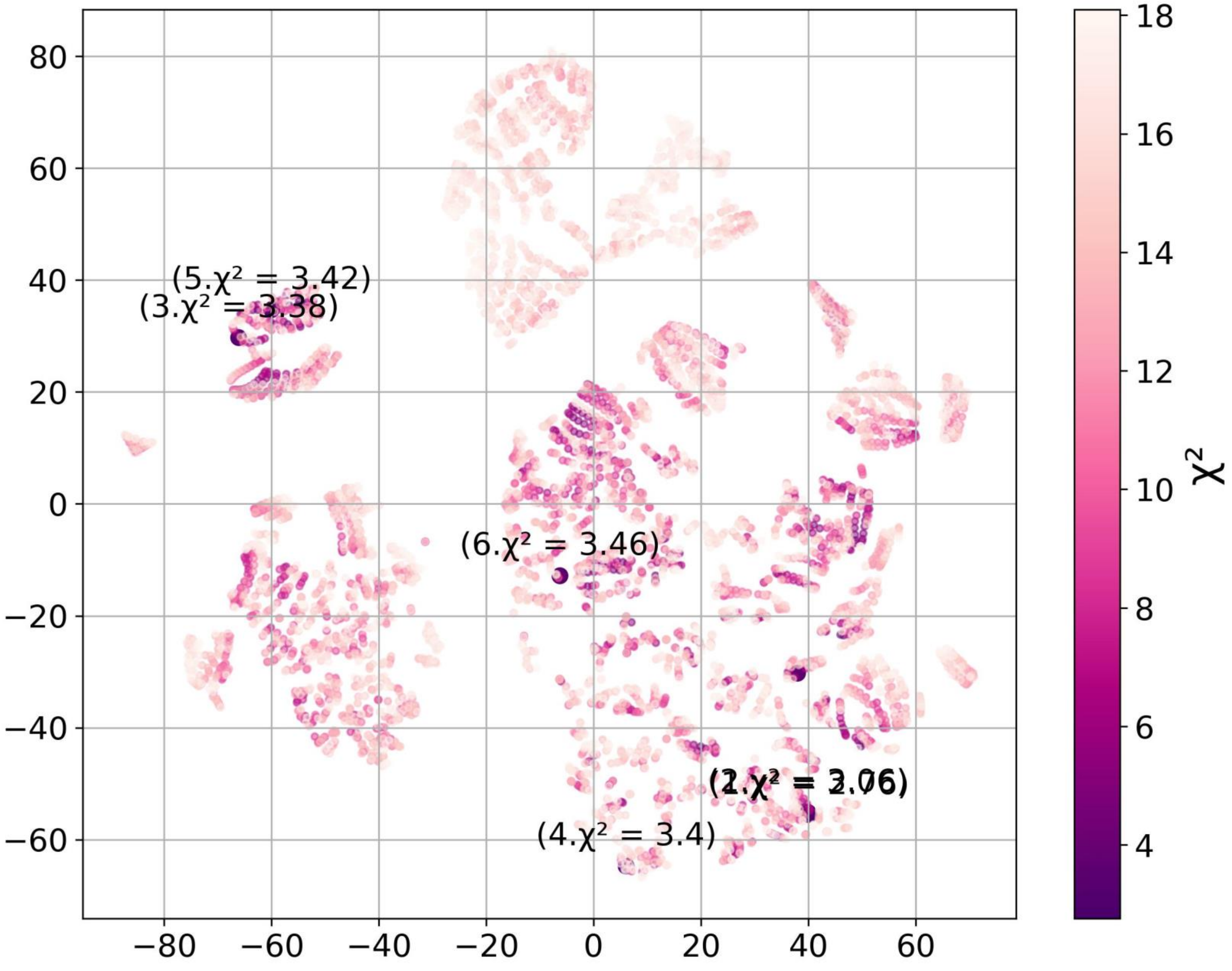


Figure taken from https://towardsdatascience.com/t-sne-clearly-explained-d84c537f53a

Visualization of the parameter space

- This is the **2D projection of the 7D space** (7 different parameters)
- Every point contains as good as possible all information about each parameter set
- It is recommended **not** to draw any conclusions only from the distances between the clusters
- With this visualization tool we want to show **how solutions with different χ^2 are distributed with regard to their similarities**

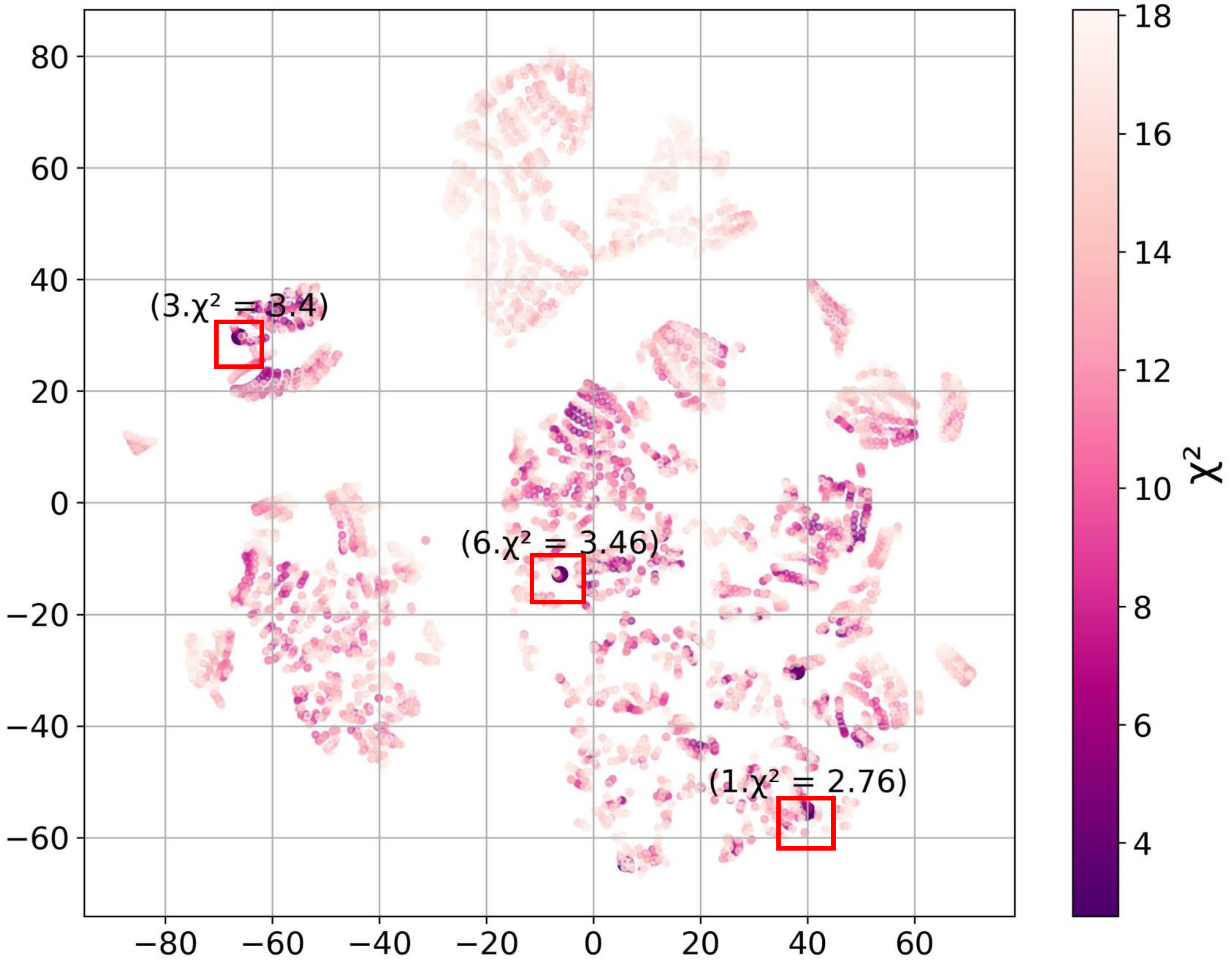


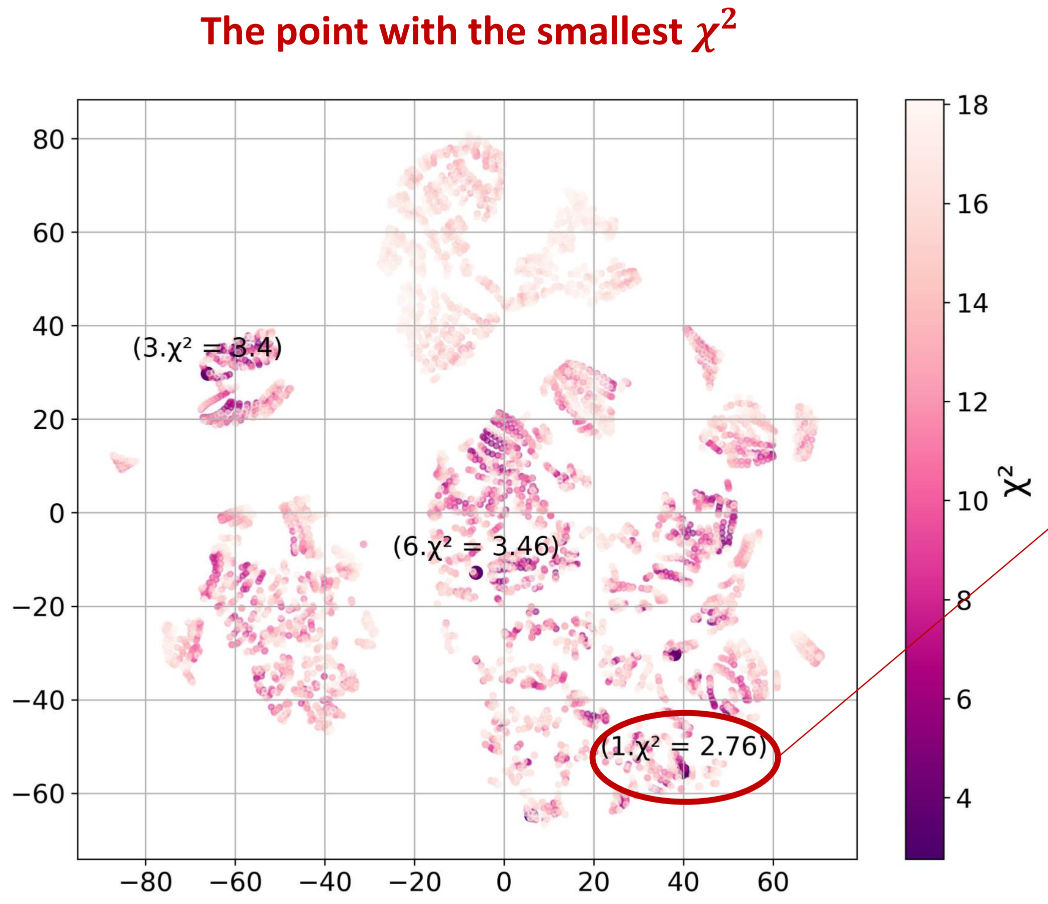


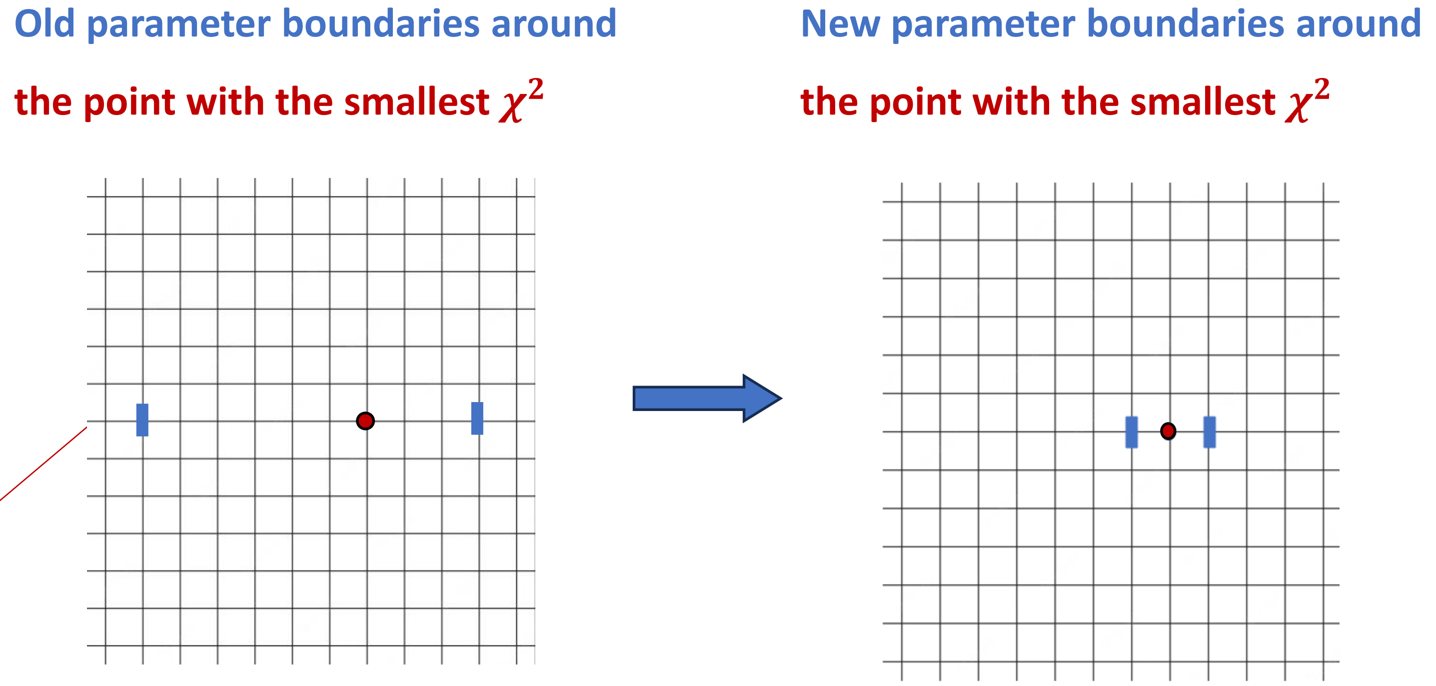
We decided to take 3 of the best fits from the old table from 3 different regions

With these three models we wanted to look at a finer parameter grid.

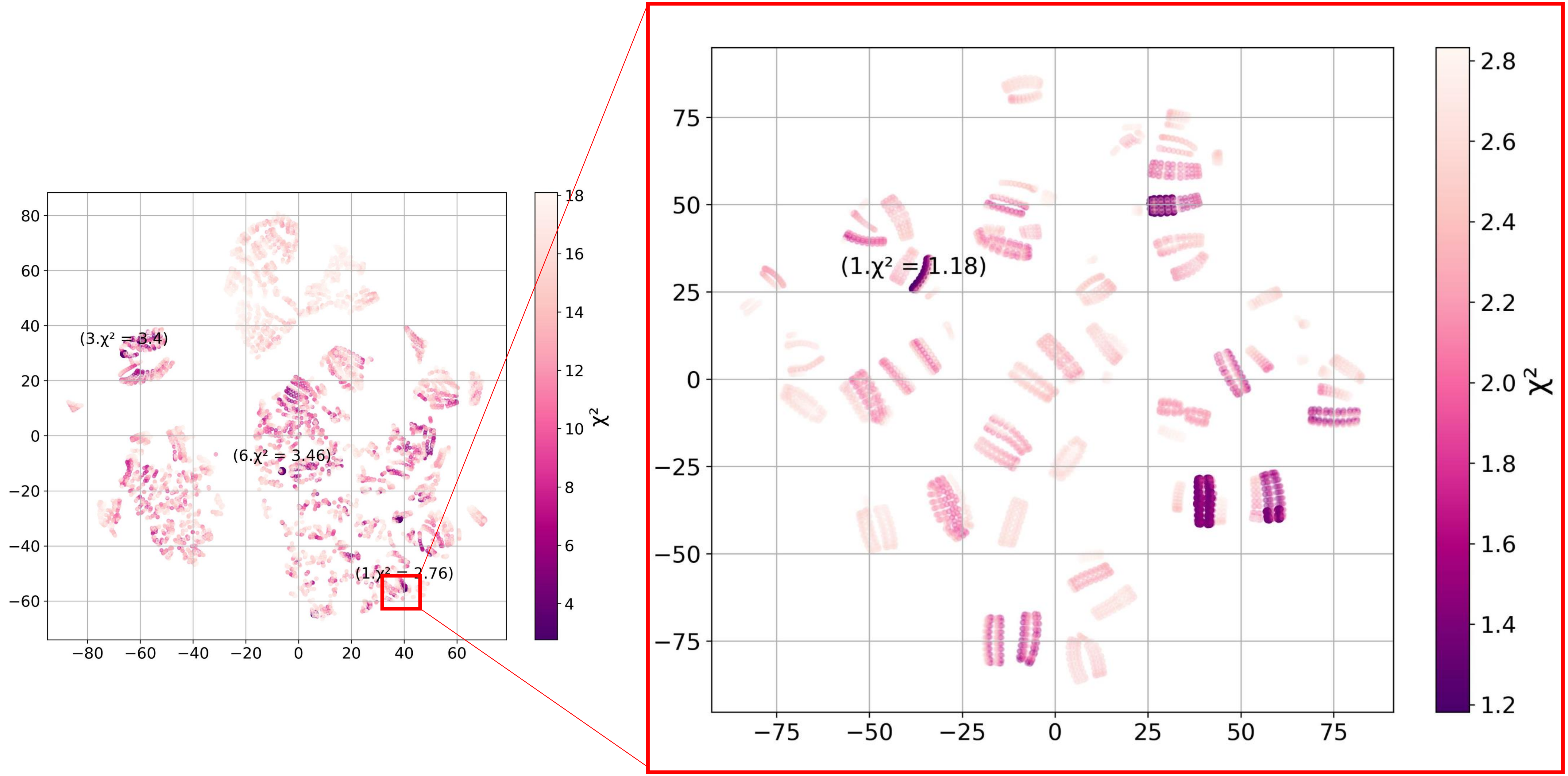
We modeled the SED three times with a parameter space very narrow around the parameters of each of the three models.

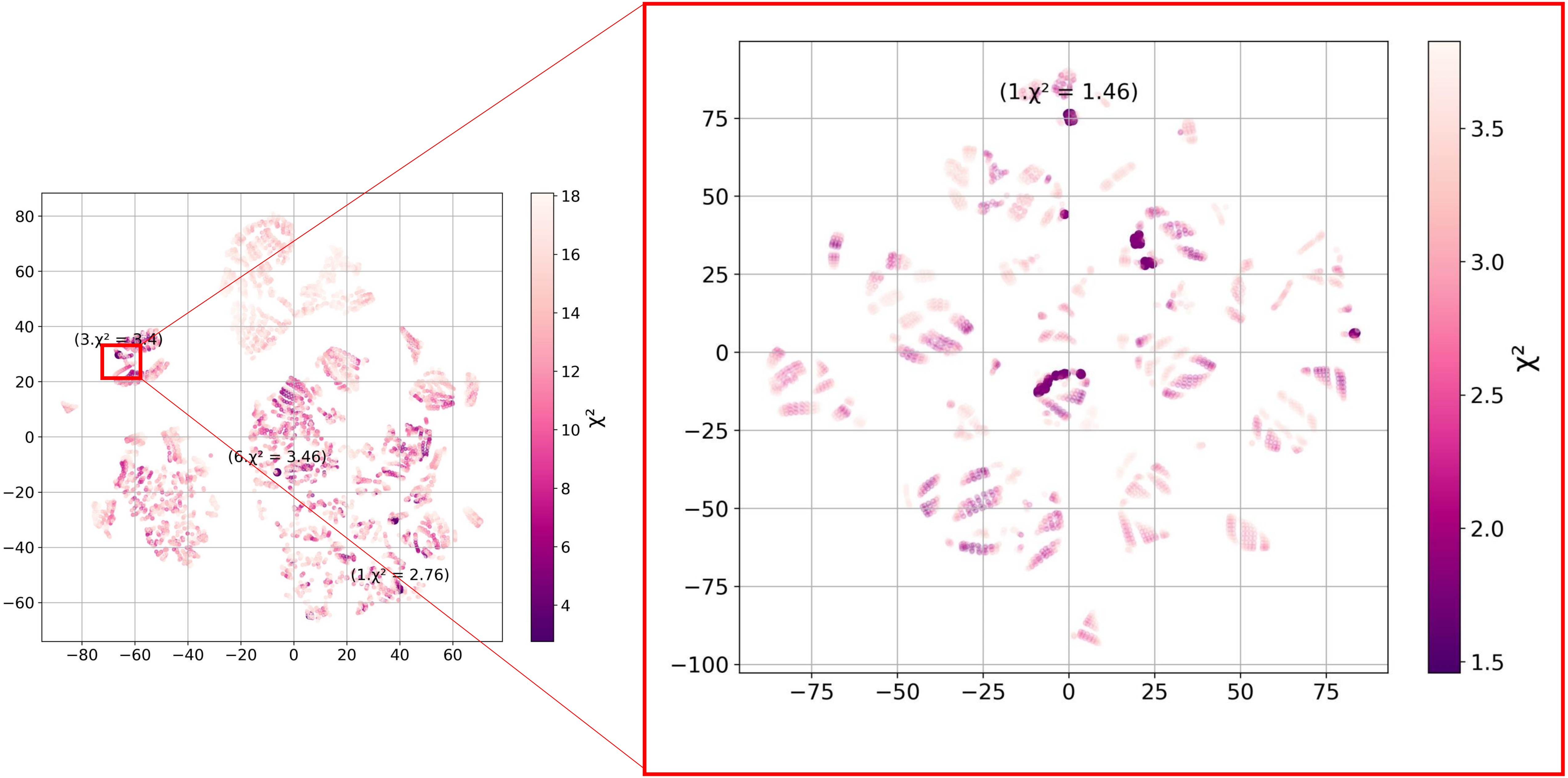






	$\log(R_{blob})$ [cm]	B [G]	$\log(\gamma_{min})$	$\log(\gamma_{max})$	$\log(L_e\ [erg\ s^{-1}])$	Γ_b	index α
Old grid	15 - 17.5	0.1 - 5	3 - 3.95	4 - 5	42 - 47	3 - 30	0.5 - 3.5
New grid	15 - 15.56	0.6 - 1.7	3.2 - 3.29	4.9 - 5	42 - 43.11	12 - 18	3.4 - 3.6


(3.χ² = 3.4)
(6.χ² = 3.46)
(1.χ² = 2.76)
χ²
(1.χ² = 1.18)
χ²



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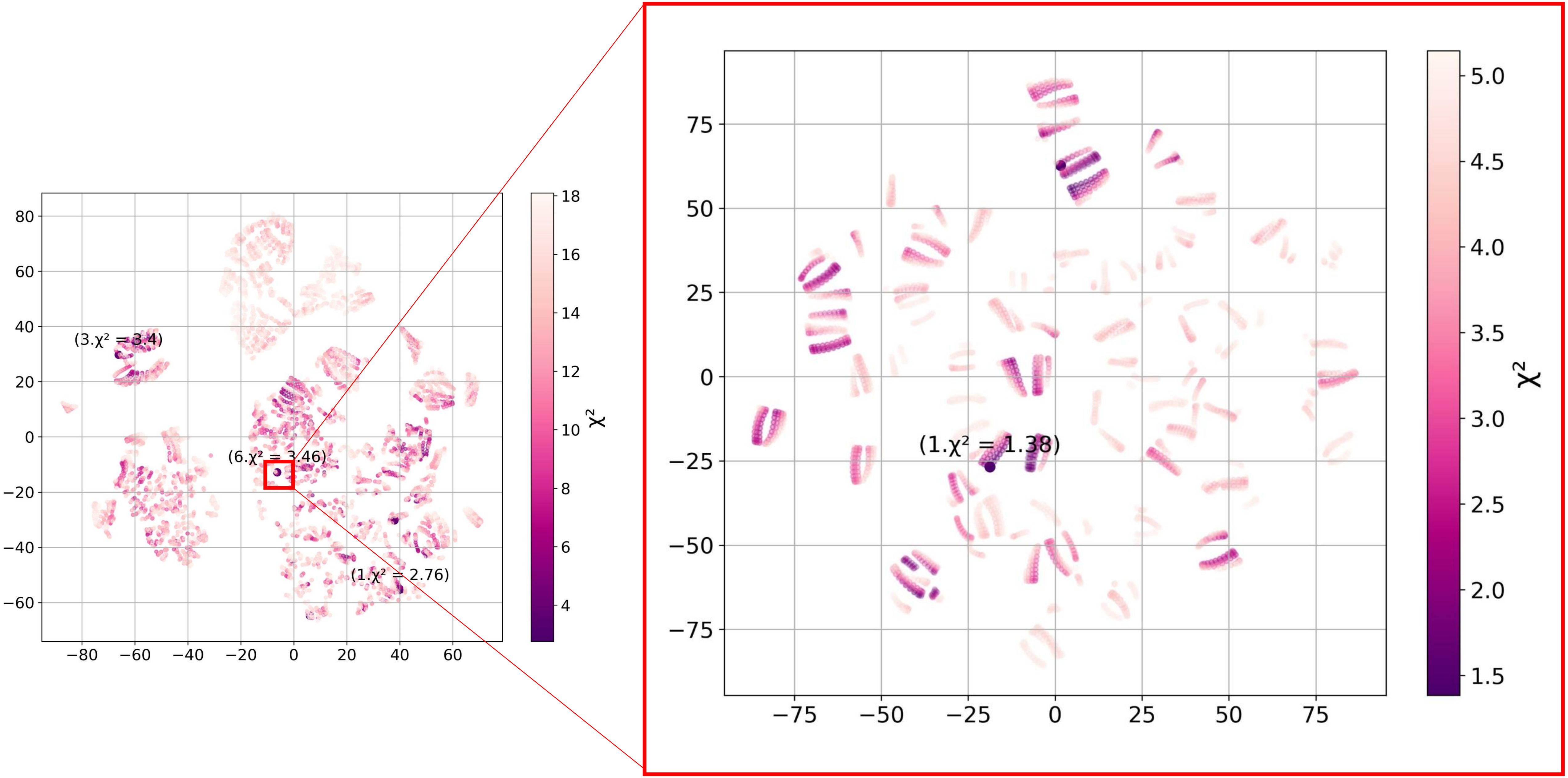
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(1.χ² = 2.76)
χ²
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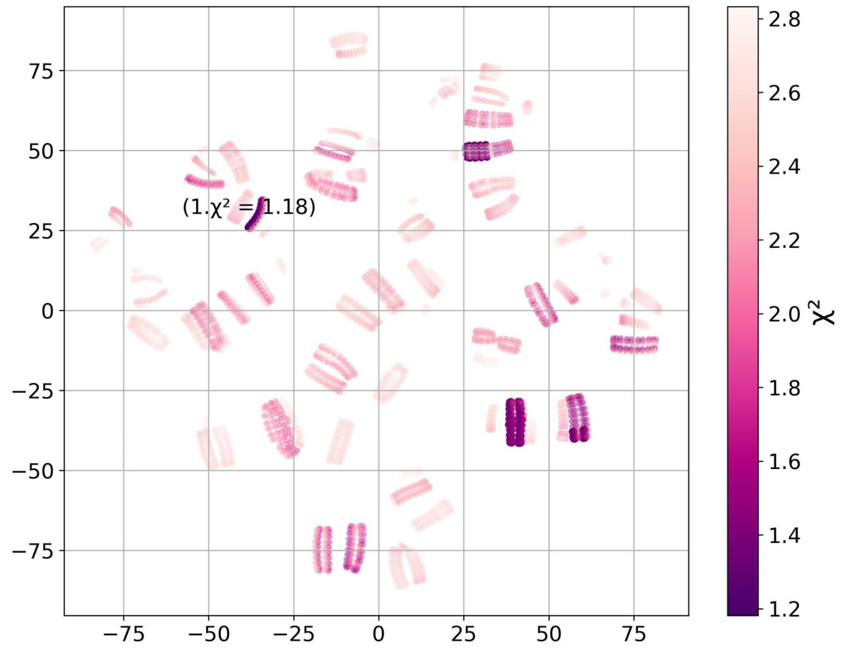
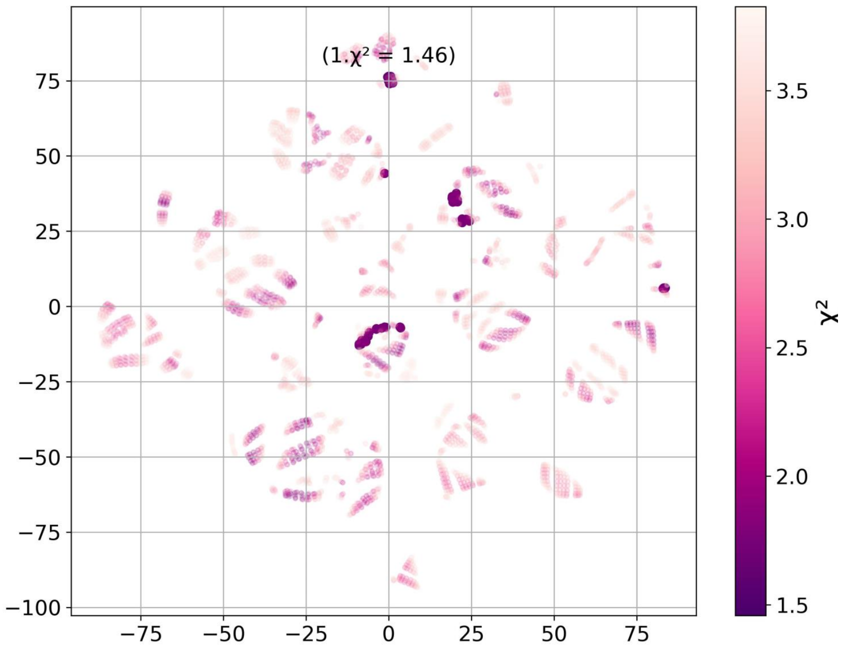
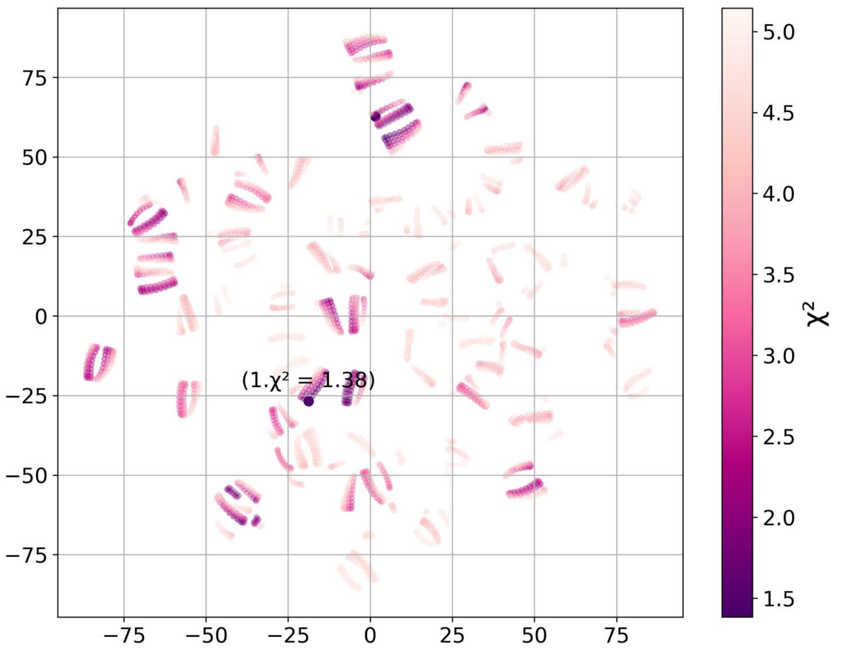
χ²







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old table	15 - 17.5	0.1 - 5	3 - 3.95	4 - 5	42 - 47	3 - 30	0.5 - 3.5
Result 1	15 - 15.56	0.6 - 1.7	3.2 - 3.29	4.9 - 5	42 - 43.11	12 - 18	3.4 - 3.6
Result 2	16.6 - 17.2	0.1 - 1.19	3.8 - 3.95	4.4 - 4.7	44.2 - 45.3	2 - 6	3.4 - 3.6
Result 3	16.4 - 16.9	0.1 - 1.19	3.42 - 3.63	4.8 - 5	43.11 - 44.2	3 - 9	3.4 - 3.6

Summary and Outlook

We visualized the parameter space of the leptonic models for the emission of blazar PKS 0735+178 for the first time. We found that the parameter space is **not smooth and highly heterogeneous**. The grid scans with a finer parameter mesh lead to better solutions.

Outlook:

- Investigate how the parameter degeneracy changes when there is more data available
- Focus on the analysis of the single parameters
- How can we expand these findings for the modeling of other sources?

Thank you!

Credit: NASA/JPL-Caltech

Appendix

Result 1

Parameter Space

$$R_{blob} = 10^{15} - 3.6 \cdot 10^{15} cm$$

$$B = 0.6 - 1.7\ G$$

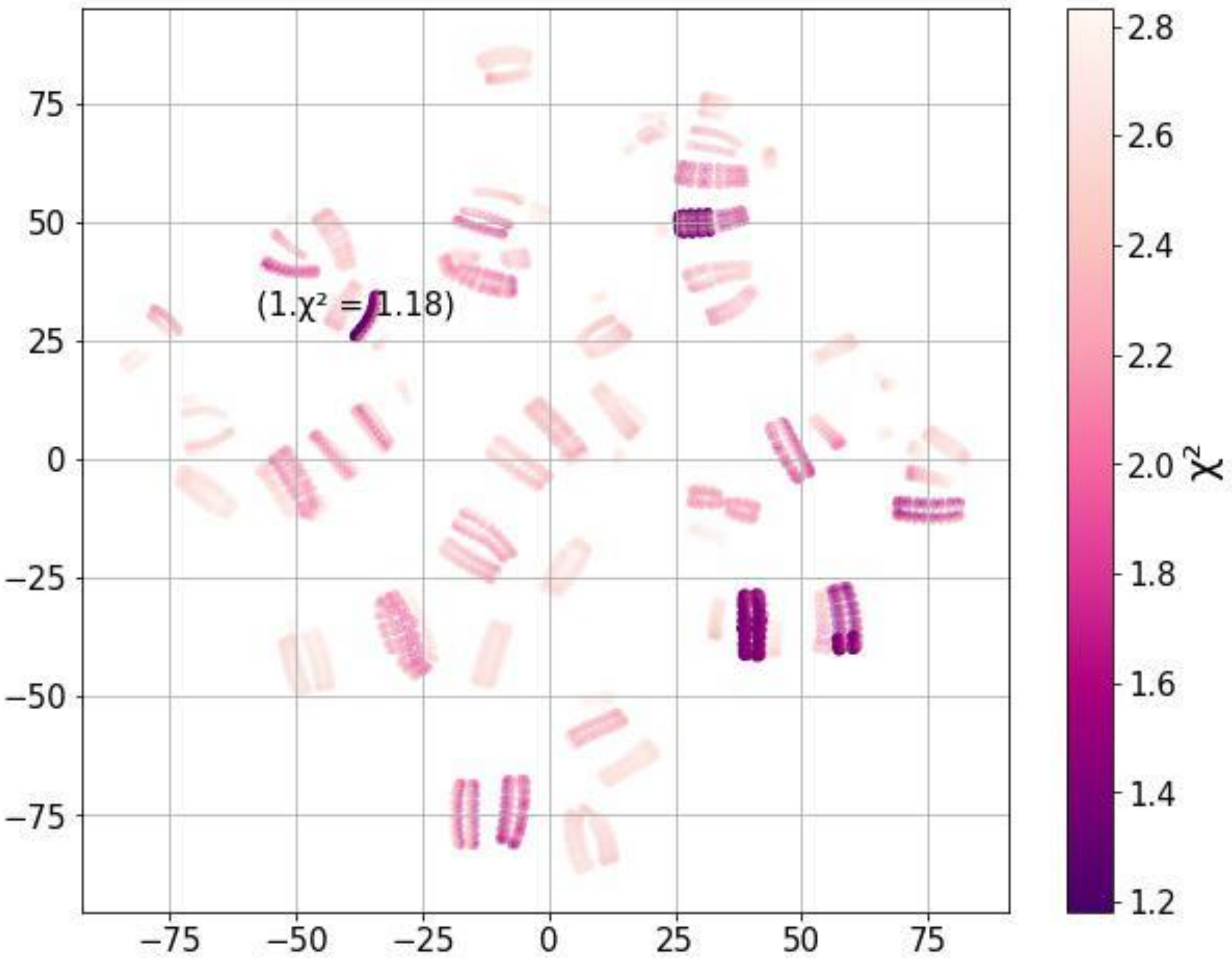
$$\gamma_{min} = 10^{3.8} - 10^{3.29}$$

$$\gamma_{max} = 10^{4.4} - 10^{4.7}$$

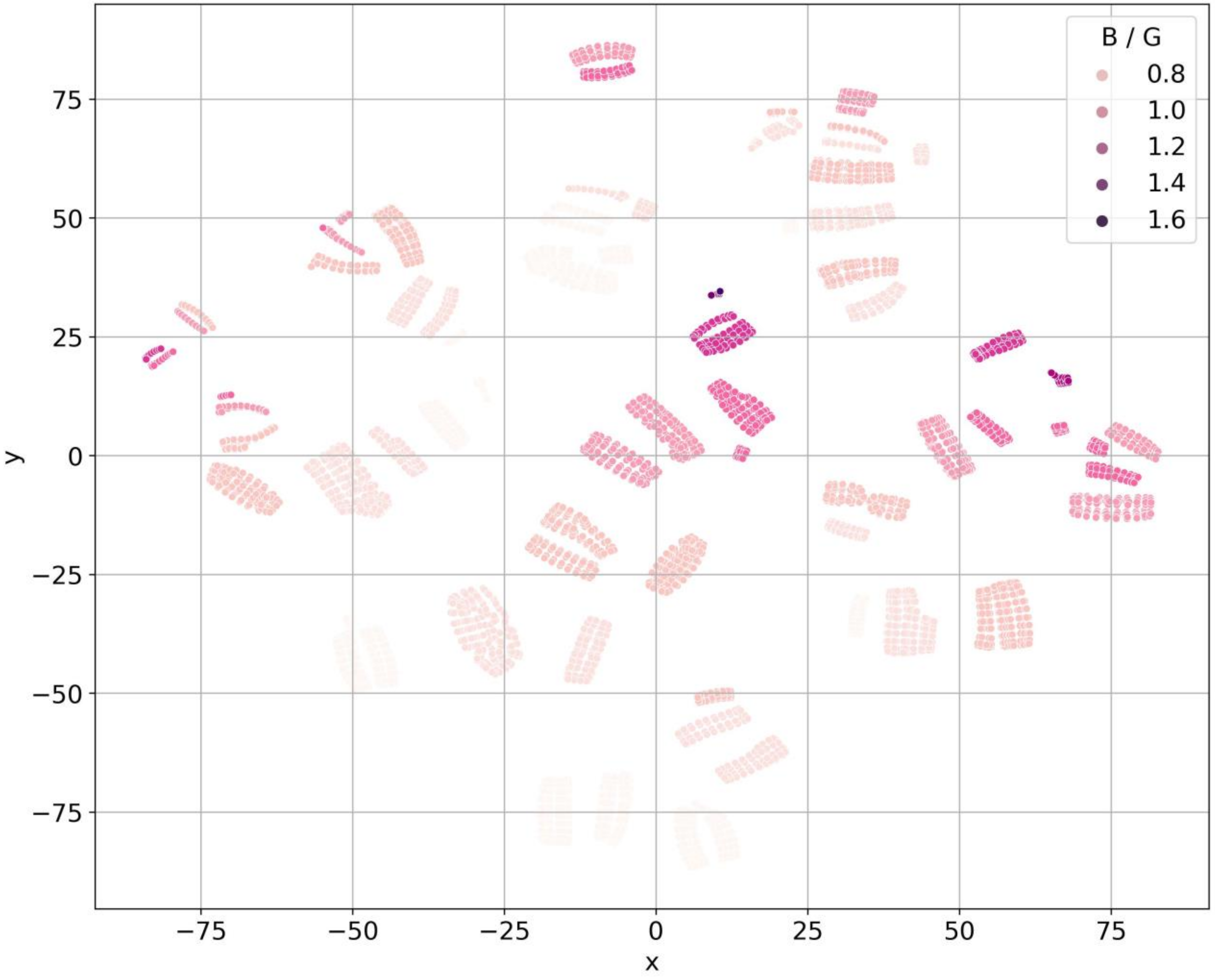
$$L_e = 10^{42} - 10^{43.11}\ erg\ s^{-1}$$

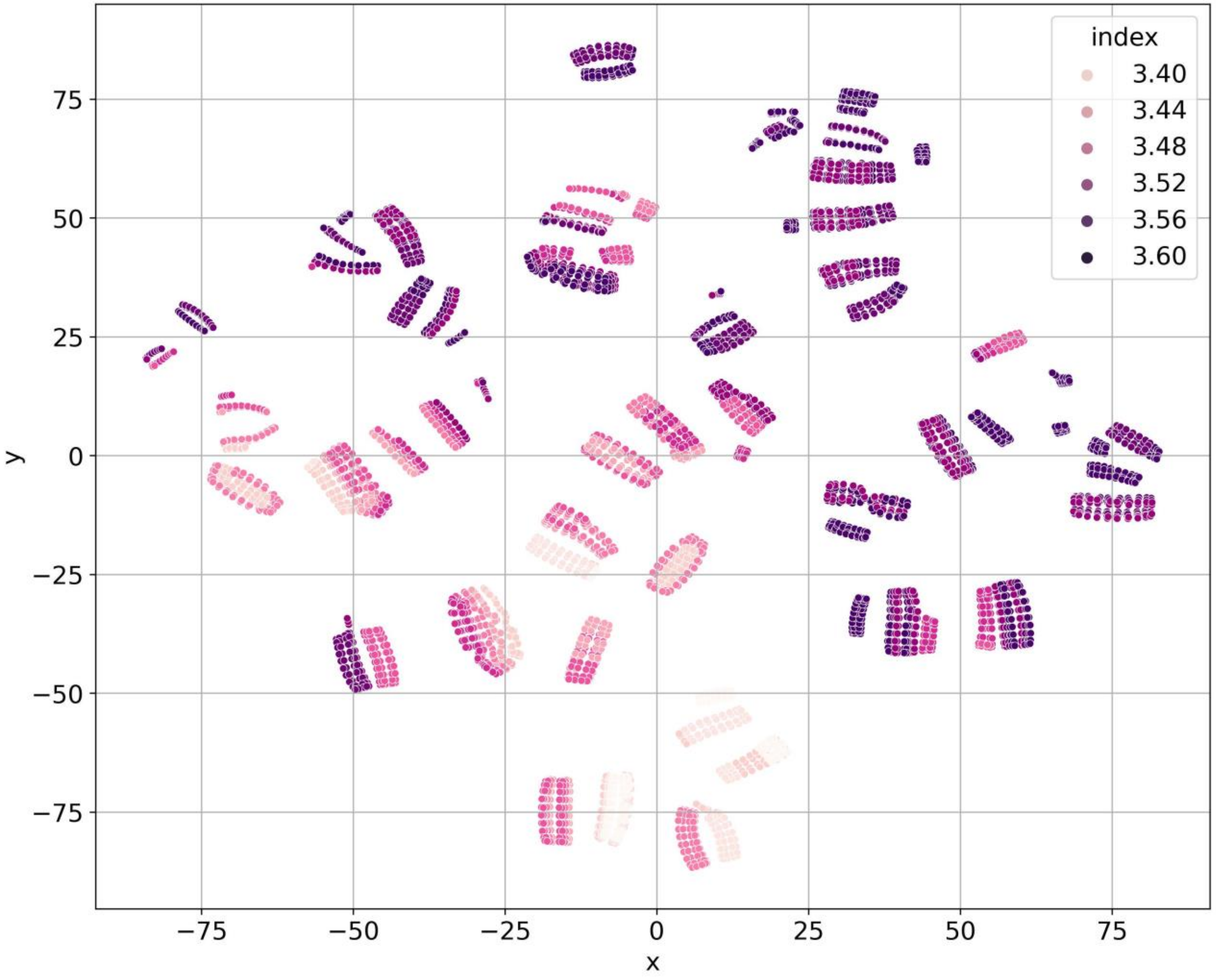
$$\Gamma_b = 12 - 18$$

$$index\ \alpha = 3.4 - 3.6$$



Result 1 – The parameters





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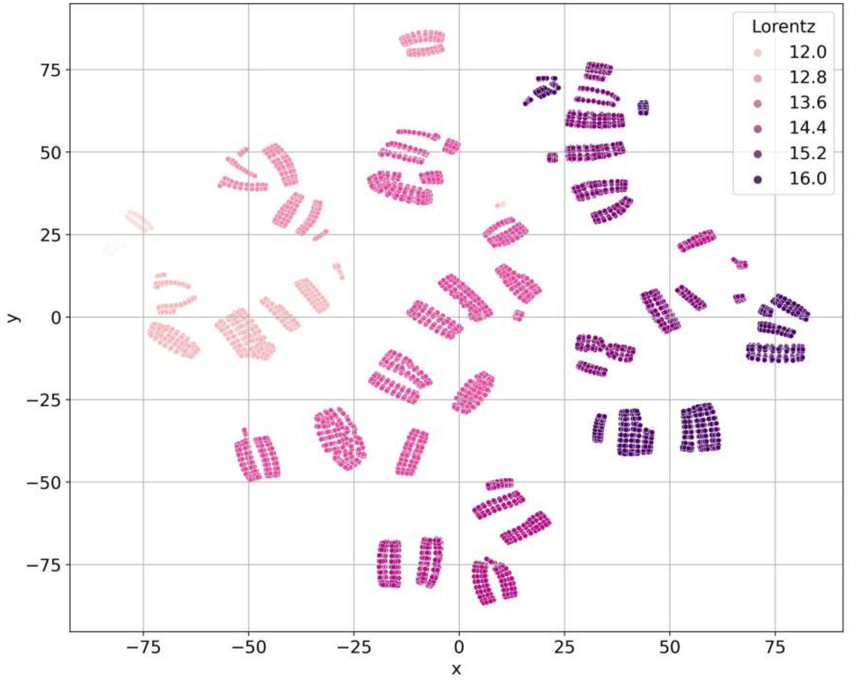

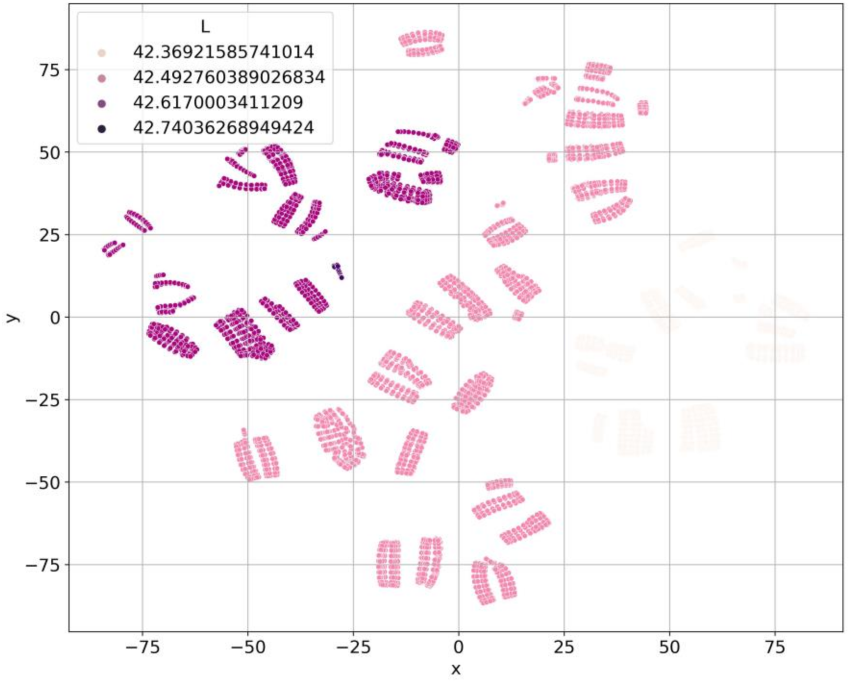

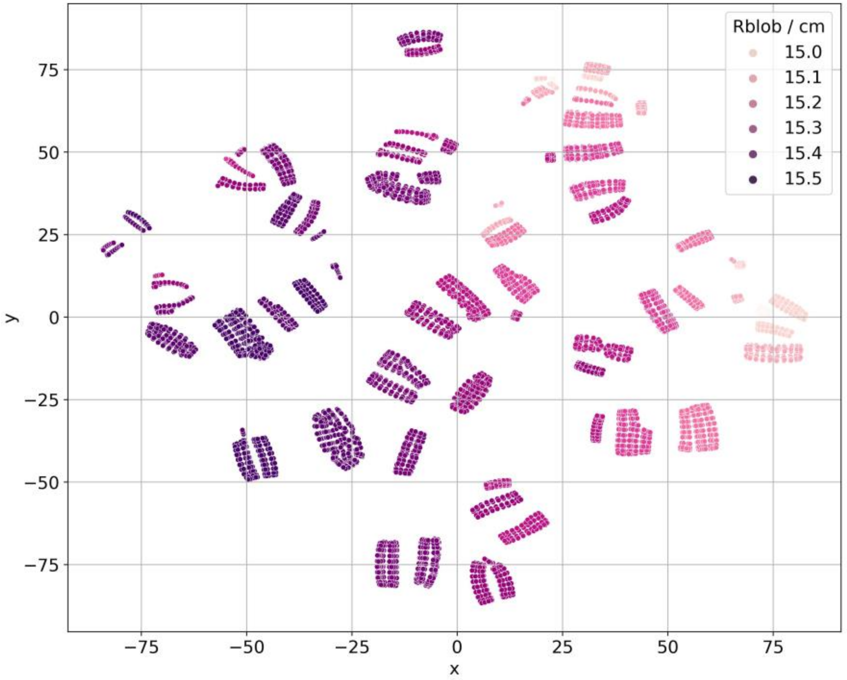

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