

First year Ph.D. progress report - Giulia Cuomo

1. Research topics and current results
2. Conferences, seminars, workshops and schools
3. Outreach activities

1.

Research topics and current results

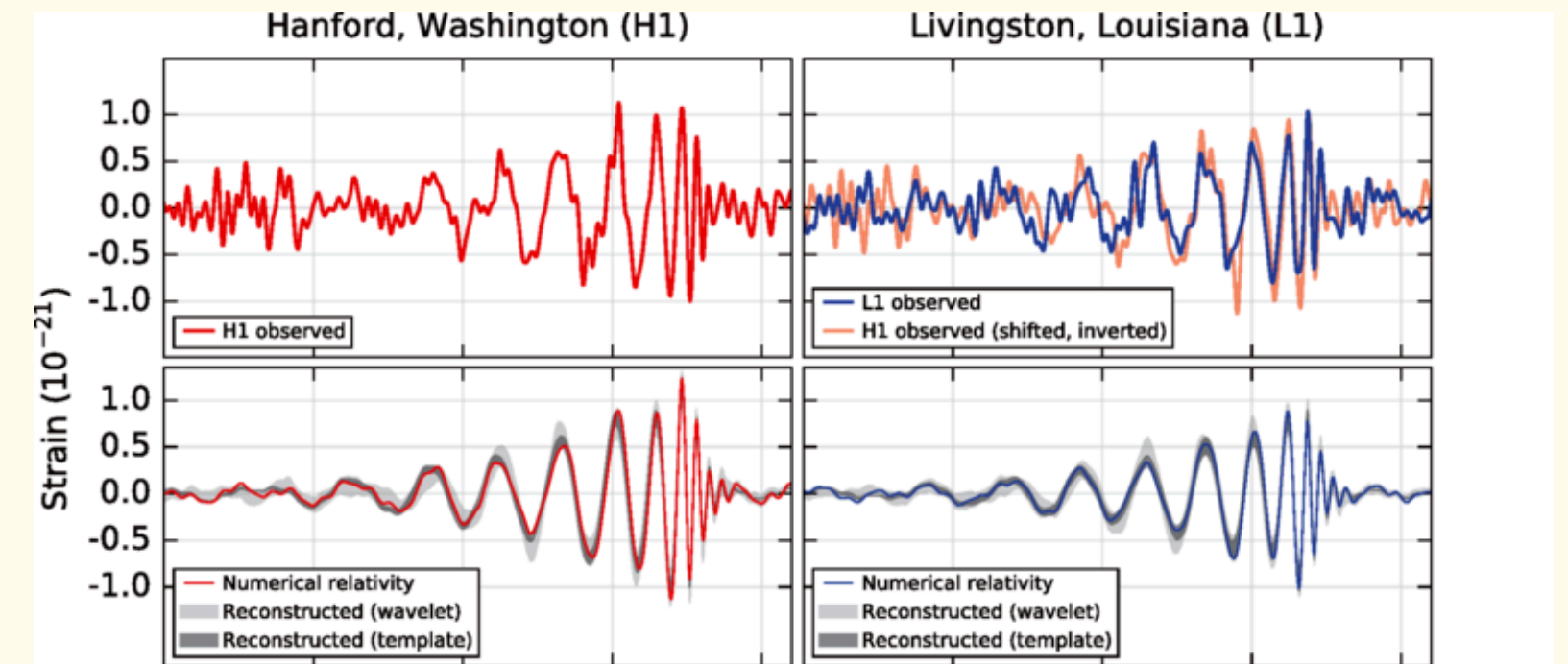
Current projects

- a) New method for object labelling in binary systems of compact objects that generate Gravitational Waves.
- b) Impact of the new method for object labelling on compact object population features, such as mass distributions.

Introduction

Gravitational wave signals from binary systems of compact objects can be used to infer source properties.

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration).
"Observation of Gravitational Waves from a Binary Black Hole Merger".
Phys. Rev. Lett. 116: 061102. DOI:10.1103/PhysRevLett.116.061102.



Introduction

Gravitational wave signals from binary systems of compact objects can be used to infer source properties. In particular, they provide information about the mass of the system.

$$\mathcal{M}_c, \eta \longrightarrow m_1, m_2$$

$m_1 [M_\odot]$	$m_2 [M_\odot]$
40.0	20.1
39.5	21.0
41.5	19.9
...	...
39.9	20.9

Introduction

The way we usually assign the *primary* and *secondary* labels to the objects is by determining which one is larger on a sample-by-sample basis.

This can become tricky when the mass ratio approaches unity.

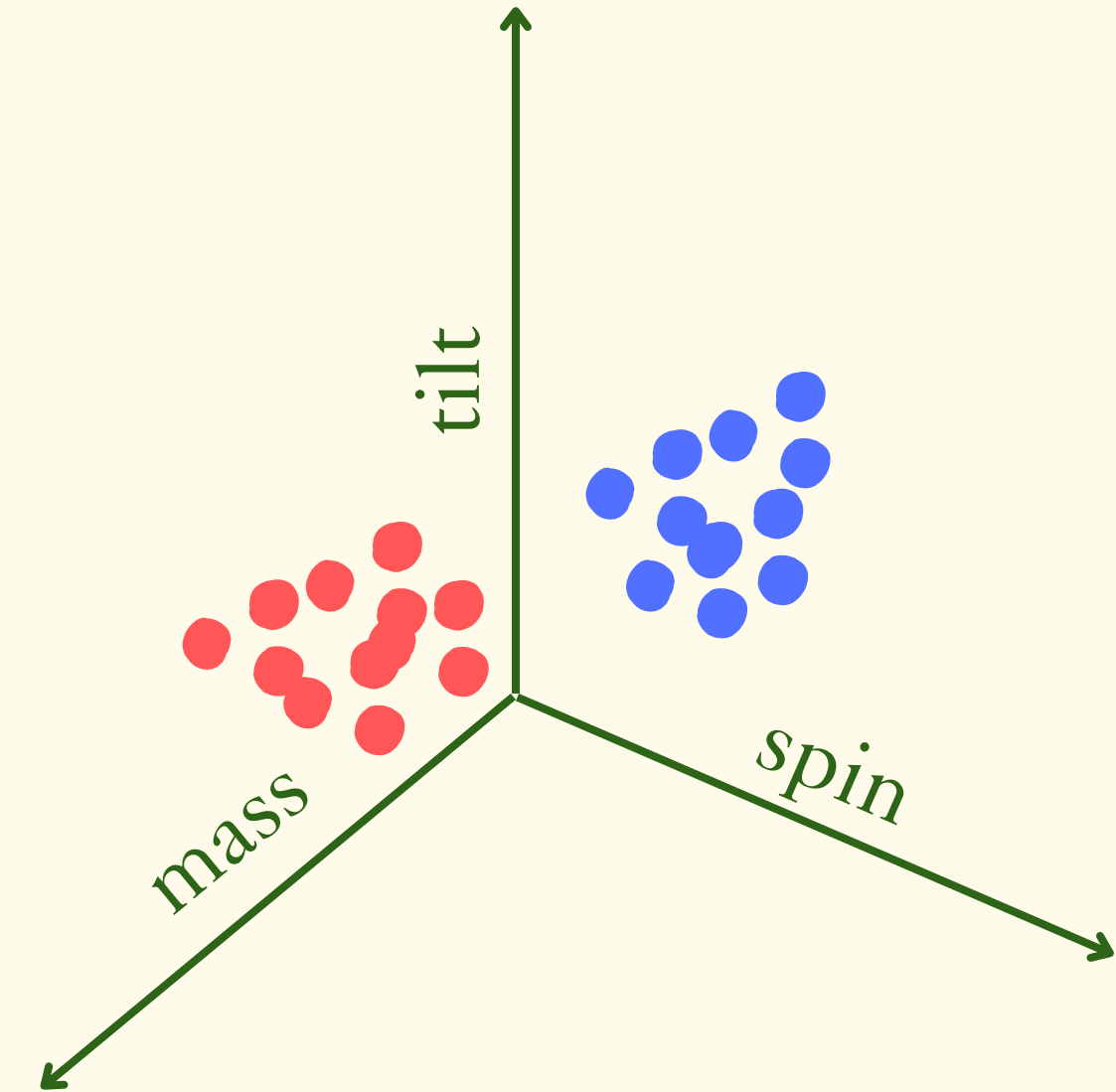
?



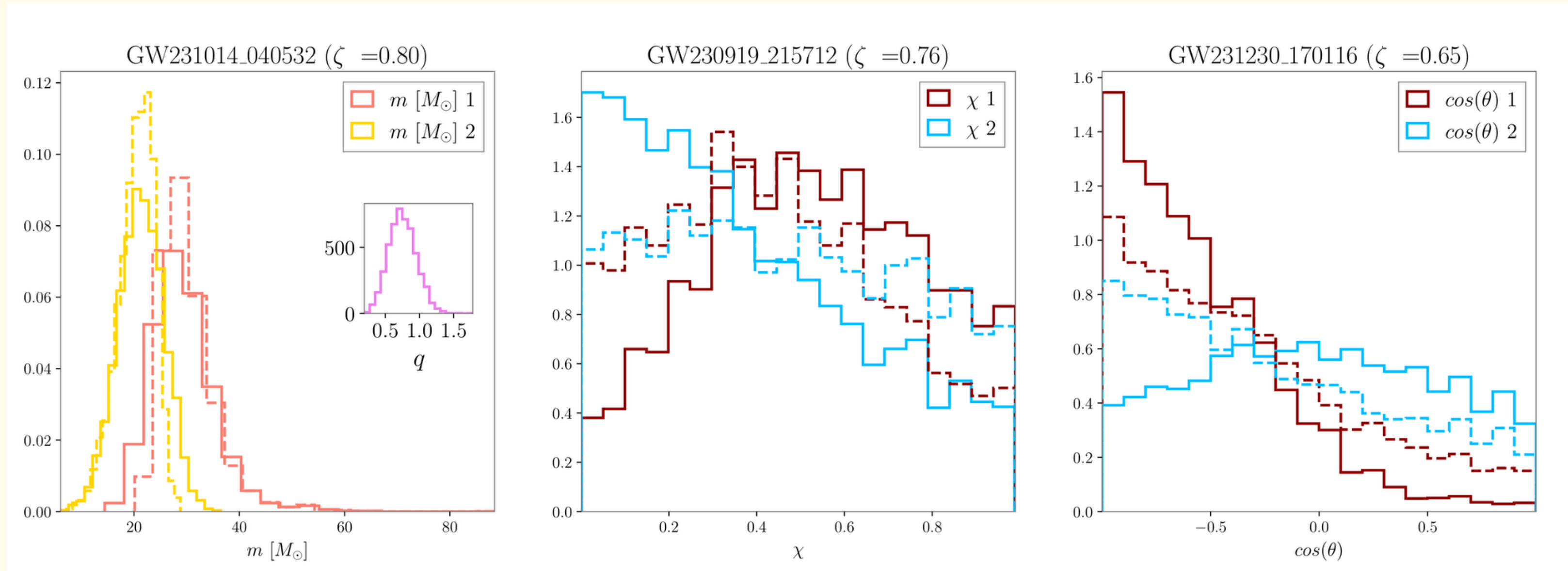
$m_1 [M_{\odot}]$	$m_2 [M_{\odot}]$
40.0	39.9
39.5	38.9
41.5	40.5
...	...
42.8	42.6

Introduction

A new approach (Gerosa et al. 2025) seeks to place all GW posterior samples in a feature space (e.g. mass, spin and tilt of the binary source) and allow a *semi-supervised clustering algorithm* to group the samples into two clusters, which ideally identify the two objects (**1** and **2**). This is an *a-posteriori approach* to labelling.



Introduction

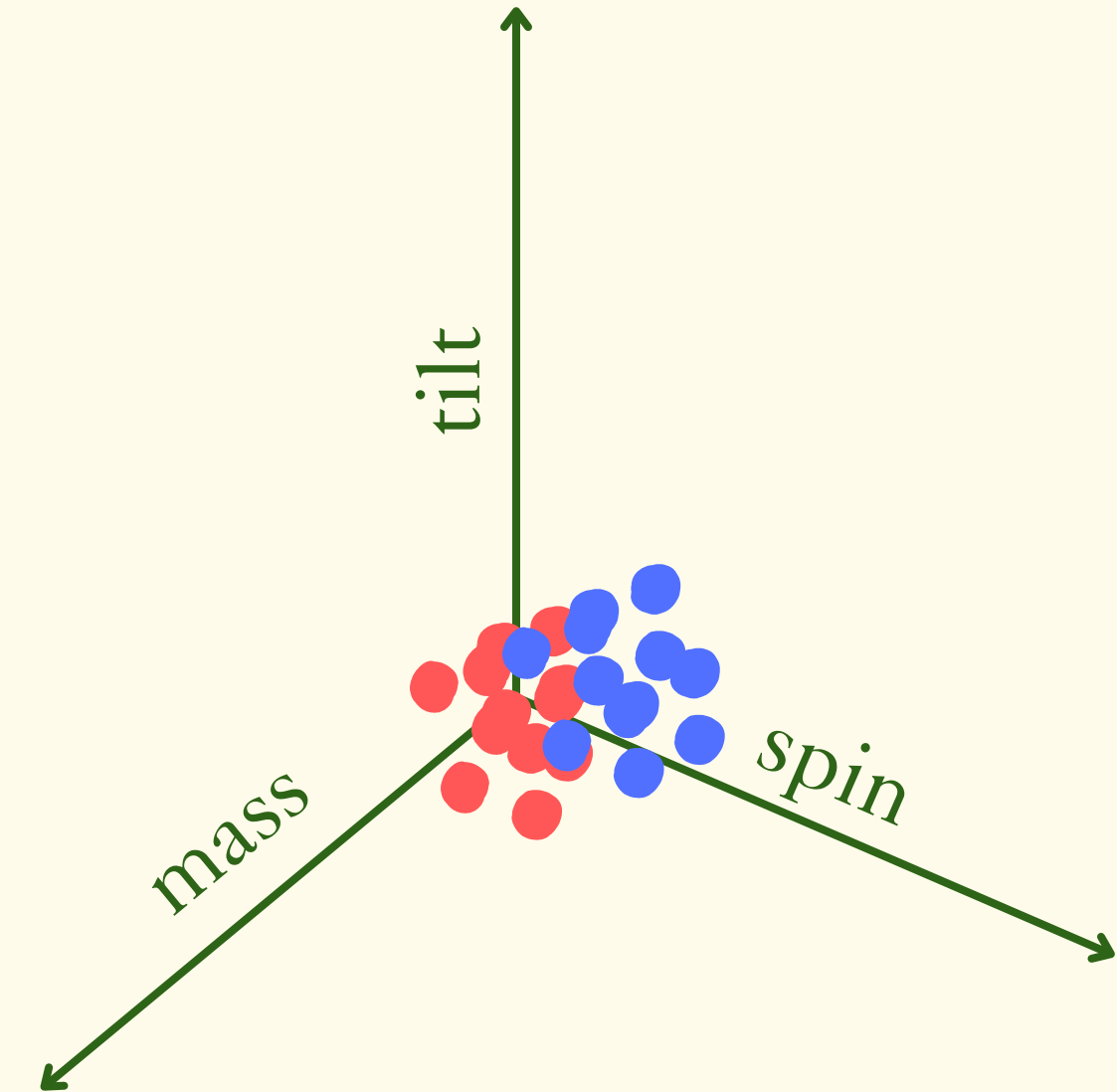


Relabelling of primary and secondary objects in real GW events (project b))

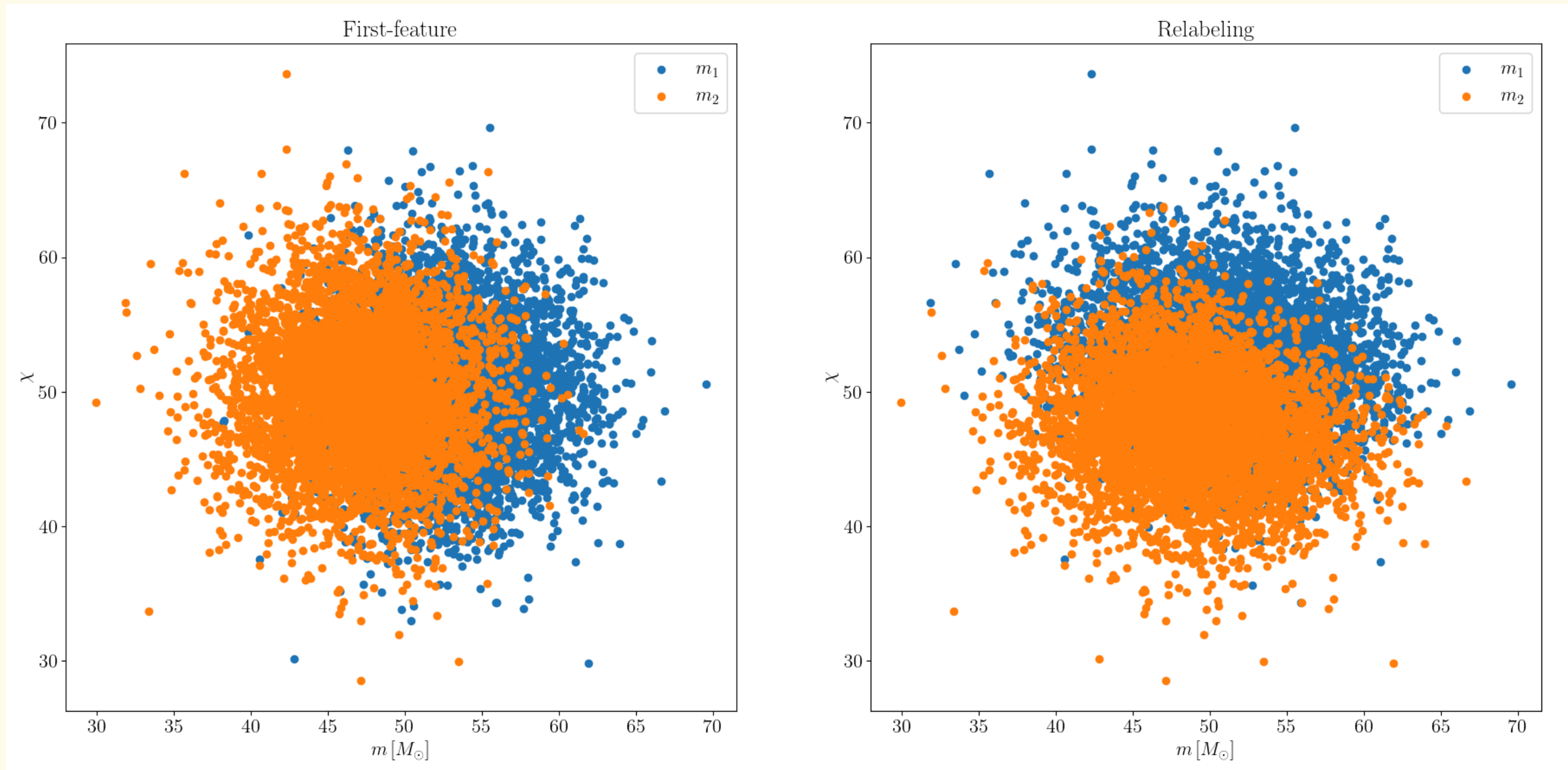
Introduction

The clustering algorithm has a tendency to identify two well-separated clusters of samples even when they are generated by the same analytical distribution.

For this reason, a refined version of this approach is proposed.



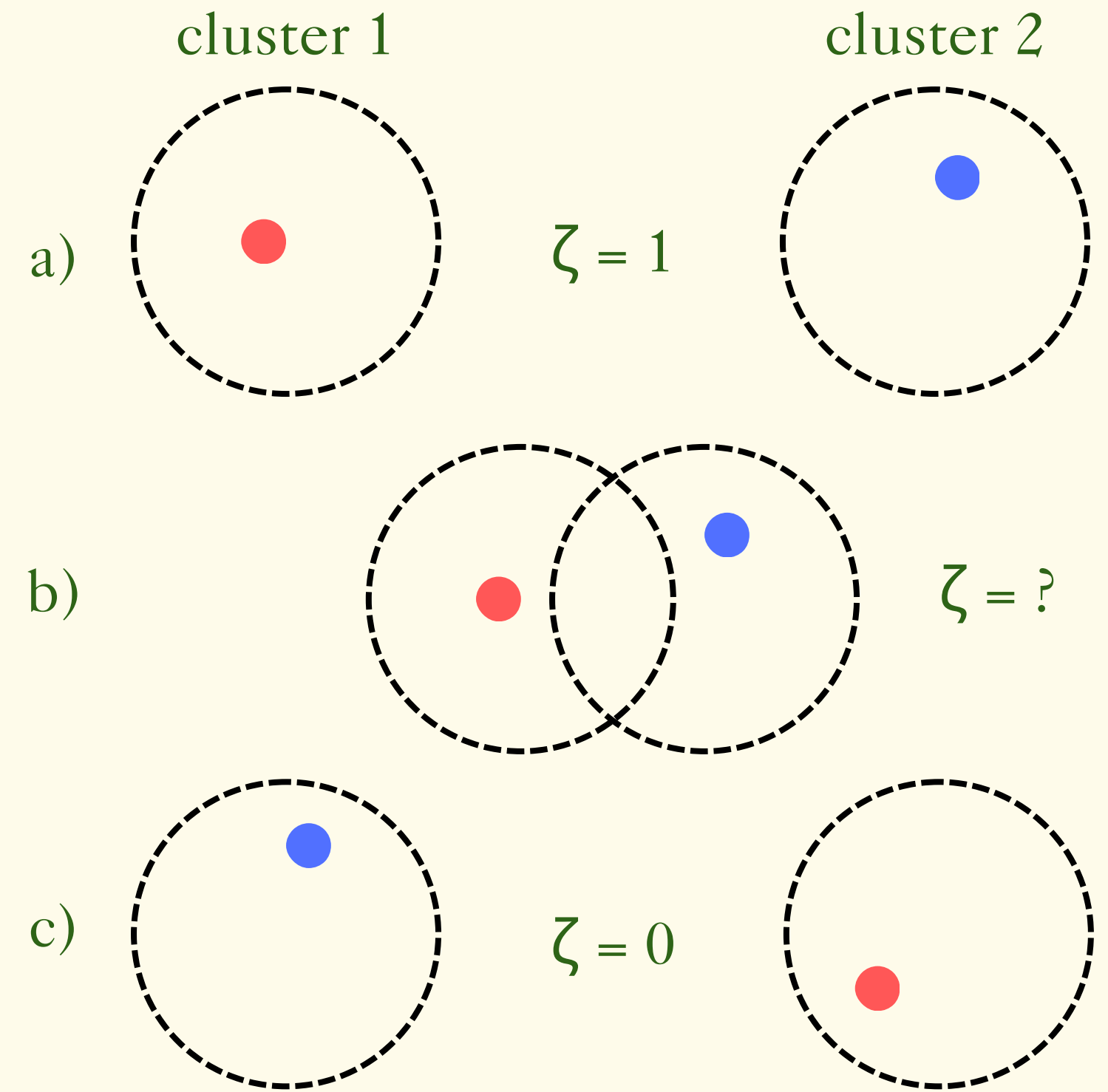
Introduction



Mass-driven vs clustering-driven labelling

Method

Instead of assigning a discrete identifier to each sample to tell whether it belongs to one cluster or the other, we choose to assign a *belonging probability* ζ distributed in the range $[0,1]$: if the **first item** of a given couple of points is more likely to belong to the *first cluster* (arbitrary) and the **second item** to the *second cluster*, then ζ will be closer to 1.



1. Research topics and current results

Method

Log-likelihood (Gaussian Mixture Model)

$$\log p(\{x_i\}_{i=1}^{2N} \mid \mu_1, \mu_2, \Sigma_1, \Sigma_2) = -\frac{N}{2} \left[D \log(2\pi) \right. \\ \left. + \log |\Sigma_1| + \log |\Sigma_2| \right] + \sum_{i=1}^N \text{LSE}(K_i, S_i).$$

$$K_i = -\frac{1}{2}(x_i - \mu_1)^T \Sigma_1^{-1}(x_i - \mu_1) \\ -\frac{1}{2}(x_{i+N} - \mu_2)^T \Sigma_2^{-1}(x_{i+N} - \mu_2)$$

Keep the original
assignment

$$S_i = -\frac{1}{2}(x_i - \mu_2)^T \Sigma_2^{-1}(x_i - \mu_2) \\ -\frac{1}{2}(x_{i+N} - \mu_1)^T \Sigma_1^{-1}(x_{i+N} - \mu_1)$$

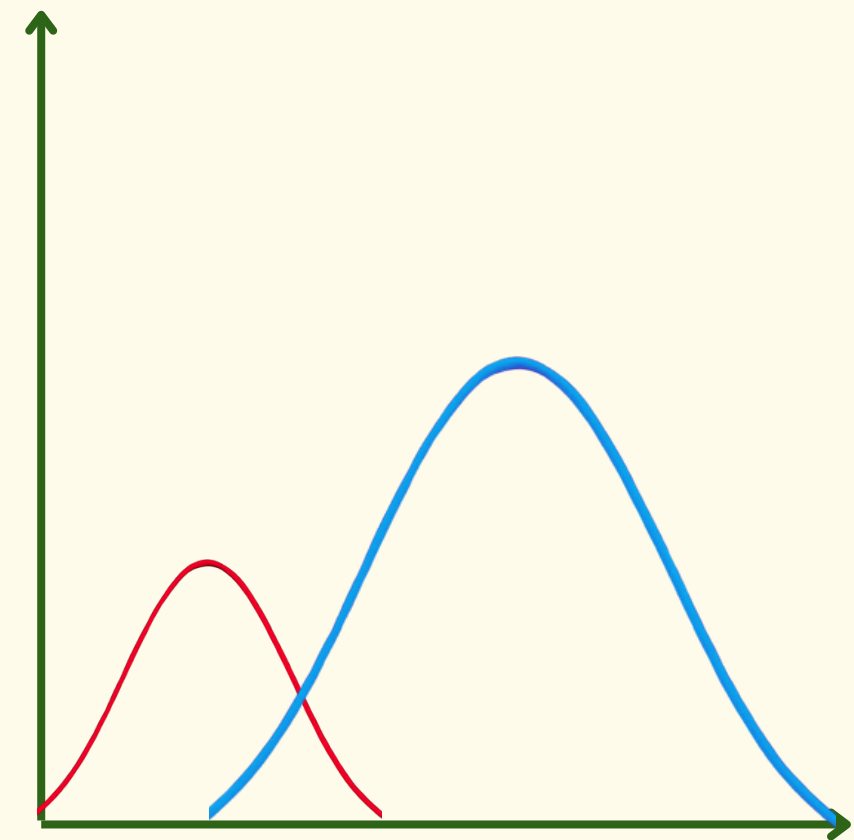
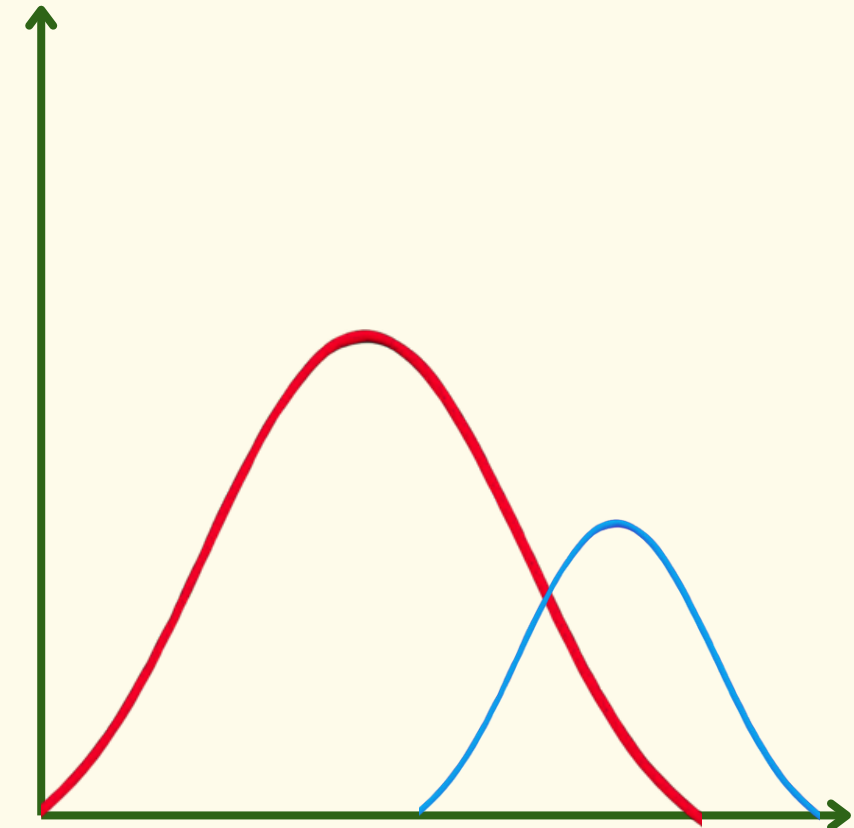
Switch assignments
1. Research topics and current results

Method

The two terms we identify in the LSE term (*log-sum of exponentials*) represent the contributions of the **keep** and **switch** terms to the likelihood.

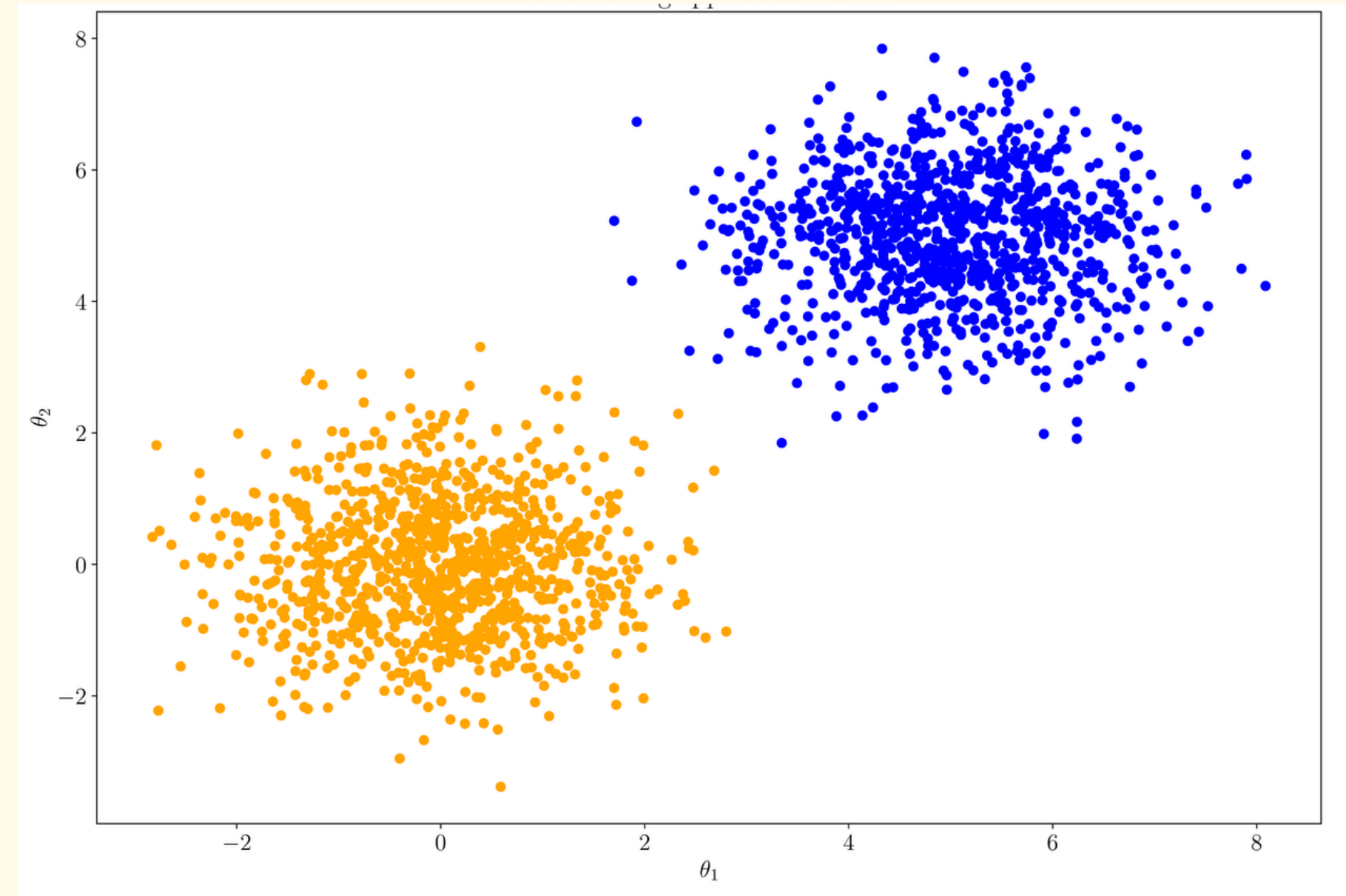
We therefore define ζ as the *responsibility* of the keep term, i.e.

$$\zeta_i = P(i \in 1; i + N \in 2) = \frac{e^{K_i}}{e^{K_i} + e^{S_i}}$$



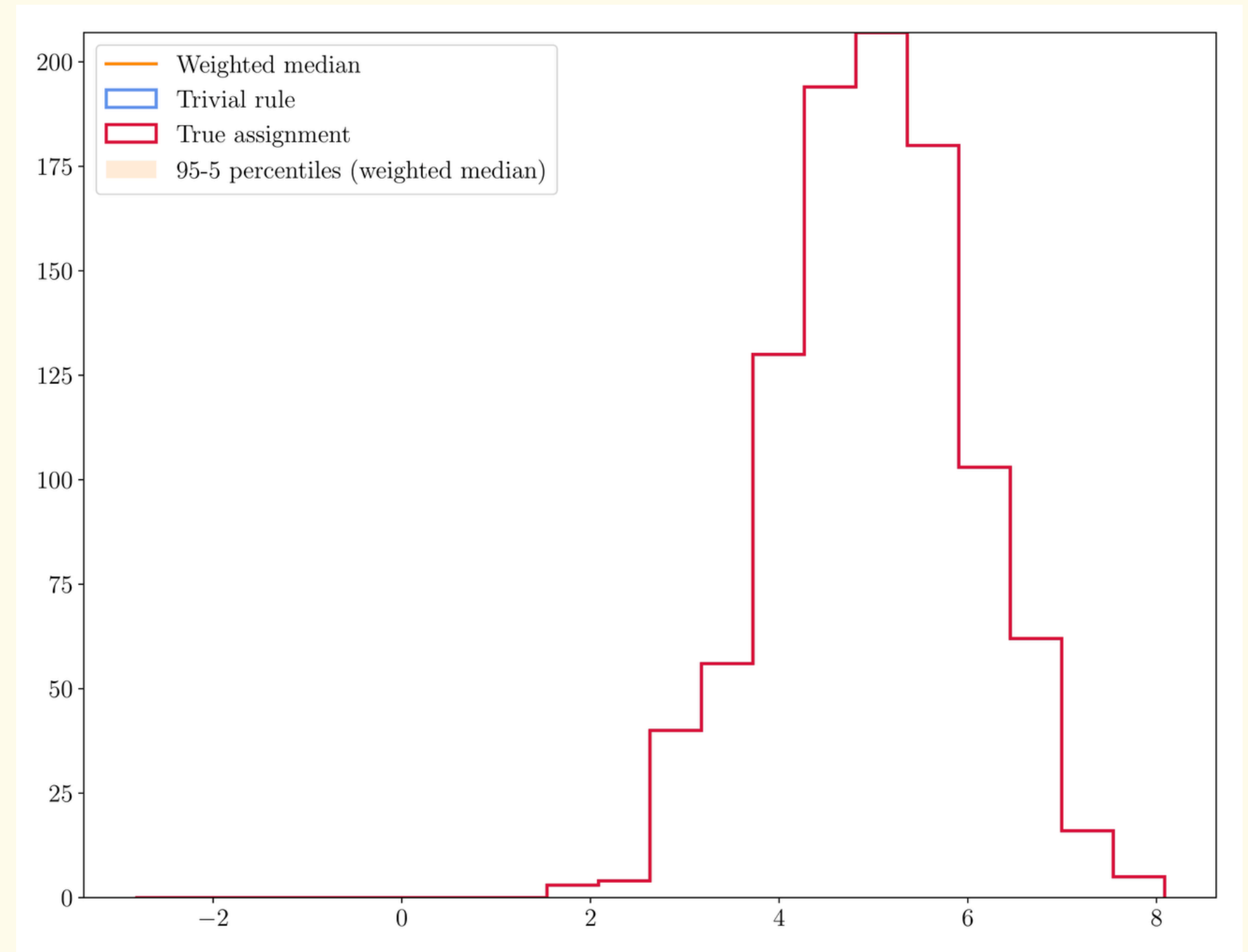
Results

What does the distribution of samples that belong to the *primary object* look like for this specific configuration of samples? 1000 couples of gaussianly-distributed sample pairs, well-separated in a 3D feature space. We call *primary object* the one whose first-feature median after relabelling is larger.



Results

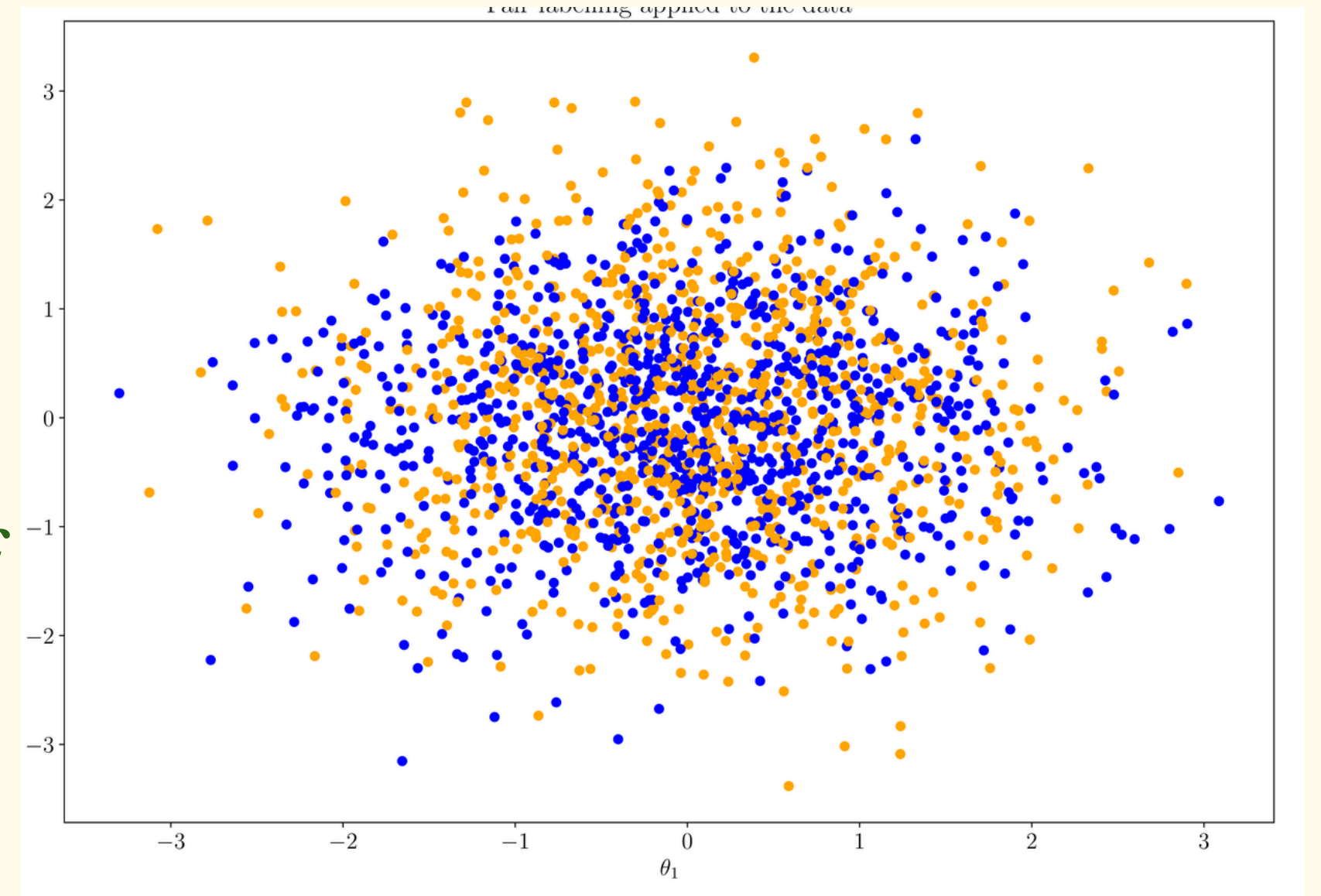
The first-feature distribution we get after relabelling for the *primary object* is identical to the one we derive from the true assignment labels and the application of the sample-by-sample *trivial rule* (the usual approach to labelling). This is to be expected.



Results

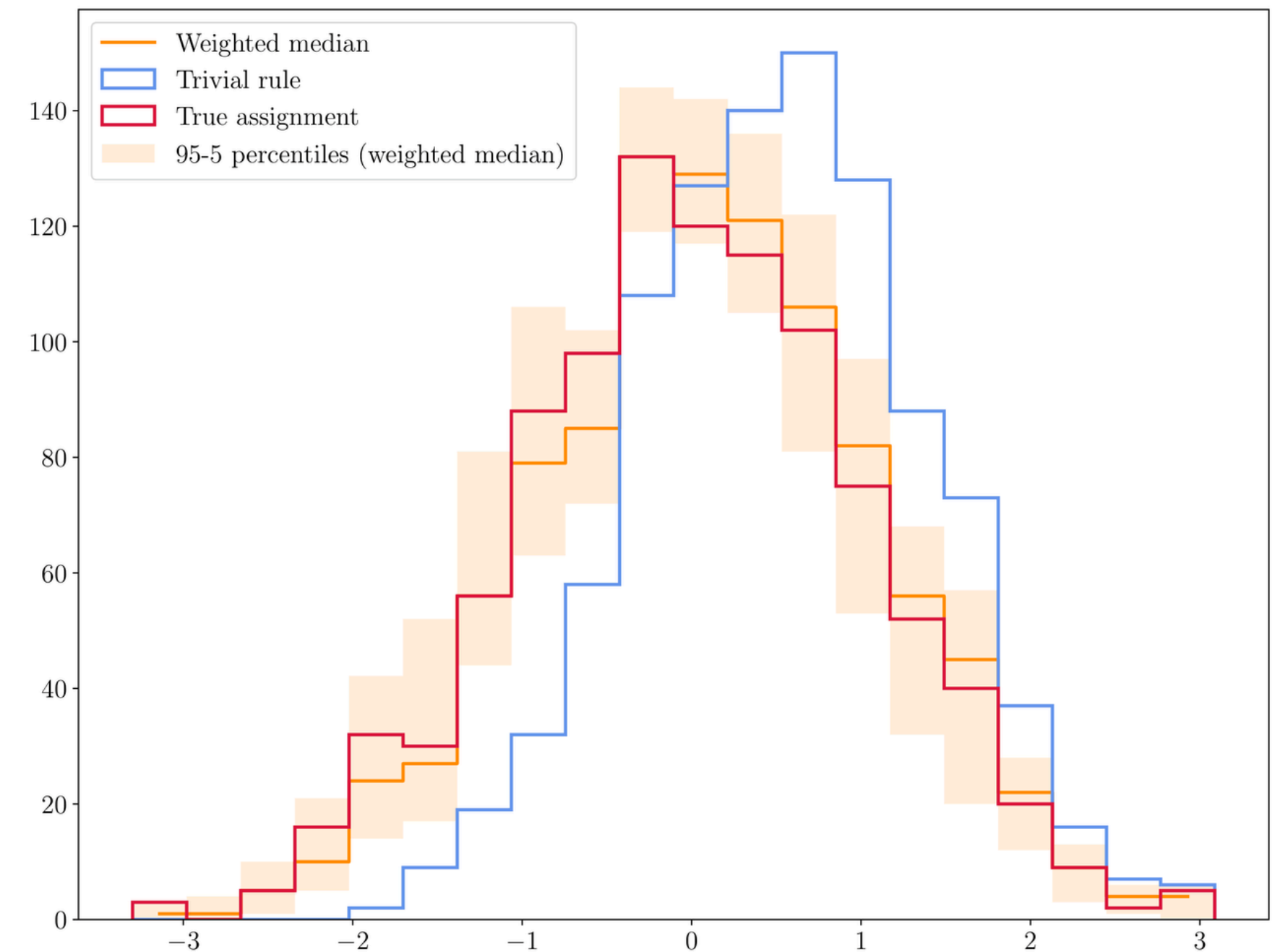
What happens when the distributions overlap in all features (which would correspond to the case of identical objects in a binary system)?

And how do we quantify the results of our relabelling procedure?



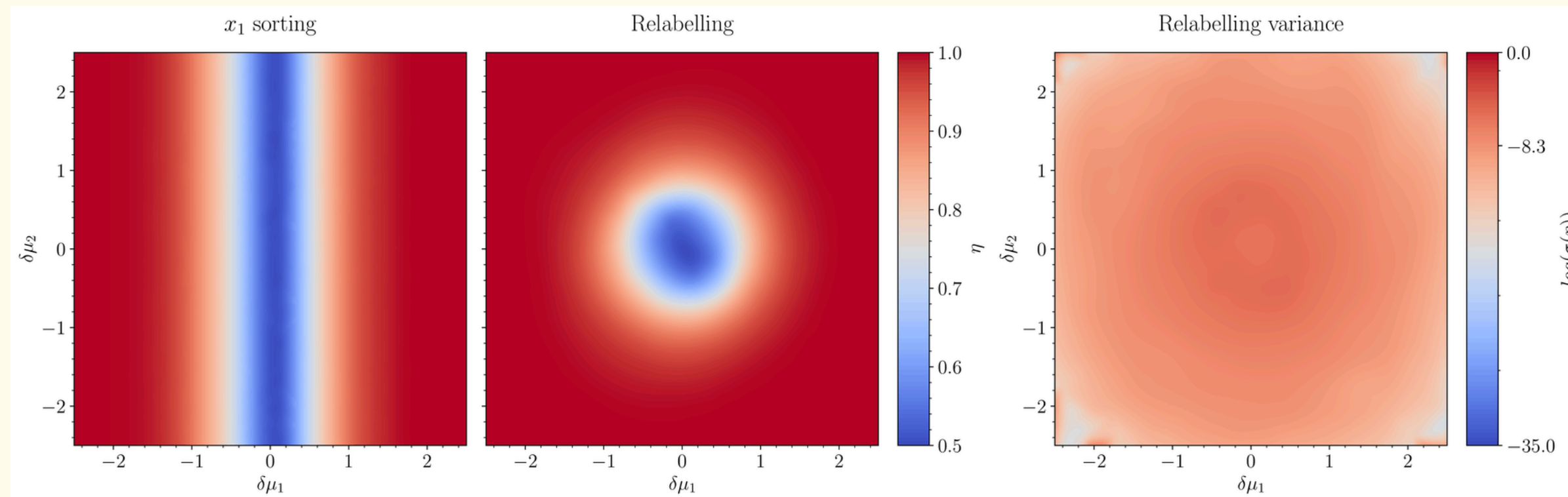
Results

The first-feature distribution we get after relabelling for the *primary object* is slightly closer to the true one with respect to the trivial one. A visual inspection alone is not enough to deem our method as more valid, and we would also like to compare it to clustering.



Results

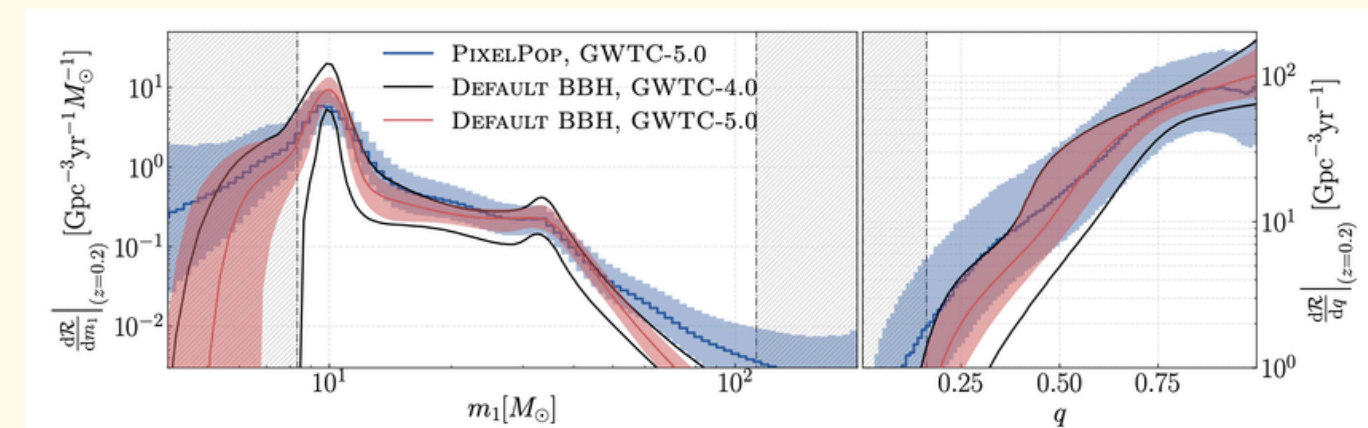
Our method can provide a distribution of possible relabellings, not just the maximum likelihood configuration. On the bottom, three gradient plots which represent the ratio of agreement between input (true values) and output (relabelling); on the right, the variance of said ratio.



What's next

- Interpretation of the results and development of a method to exploit them for labelling.
- Analysis of real Gravitational Wave events (large and small mass ratios).
- Study of the population distributions in mass, spin and cosine of the tilt (*what changes when we label compact objects in a binary this way?*)

The LIGO Scientific Collaboration and the Virgo Collaboration and the KAGRA Collaboration, *GWTC-5.0: Population Properties of Merging Compact Binaries* (2026)



2.

Conferences, seminars, workshops
and schools

Workshops

- *2026 TEONGRAV Workshop* (University of Pisa, 14th - 16th of January, 2026);
- *2026 GW Open Data Workshop* (online, 20th - 23rd of April, 2026);
- *2026 gweccentricity Workshop* (Corfù, 1st - 6th of September, 2026).

Schools

- *School on Gravity* (Niels Bohr Institute, Copenhagen (Denmark), 22nd - 26th of June, 2026).

Conferences

- *1st BiCoQ Conference - from gravity to particles* (University of Milano-Bicocca, 15th - 19th of June, 2026; delivered a talk titled *Tackling labelling-related uncertainties in the mass and spin distributions of compact objects in binary systems observed via Gravitational Waves*).

Courses

- *Scientific Computing with Python* (Prof. Davide Gerosa).
- *Galaxy Evolution in Cosmic Structures B* (Dr. Alejandro Benitez-Llambay).
- *Current and Future Challenges in Gravitational-Wave Astronomy* (Dr. Caroline Bright Owen).
- *Introduction to Grant Writing* (Prof. Gianfranco Pacchioni, Dr. Fiorenza de Micheli and Dr. Balthasar Kenda).
- *Realising the Green Transition* (Prof. Heiko Lange and Prof. Elena Collina).
- *Surfing the Academic Job Market: how to publish in high impact international journals* (Prof. Marco Brambilla).
- three *RRI (Responsible Research and Innovation)* courses held within the University of Milano-Bicocca.

3.

Outreach activities

Outreach activity @ primary school (Lesmo, MB)

The activity was organised under the supervision of my tutor (Michele Fumagalli) and it consisted in:

- interactive experiments on the topic of gravity and Gravitational Waves;
- traditional frontal lectures tailored to the young audience;
- pauses in the lectures to allow for naturally-arising questions about science, astrophysics and gravity.

Thank you for your attention!

First day →

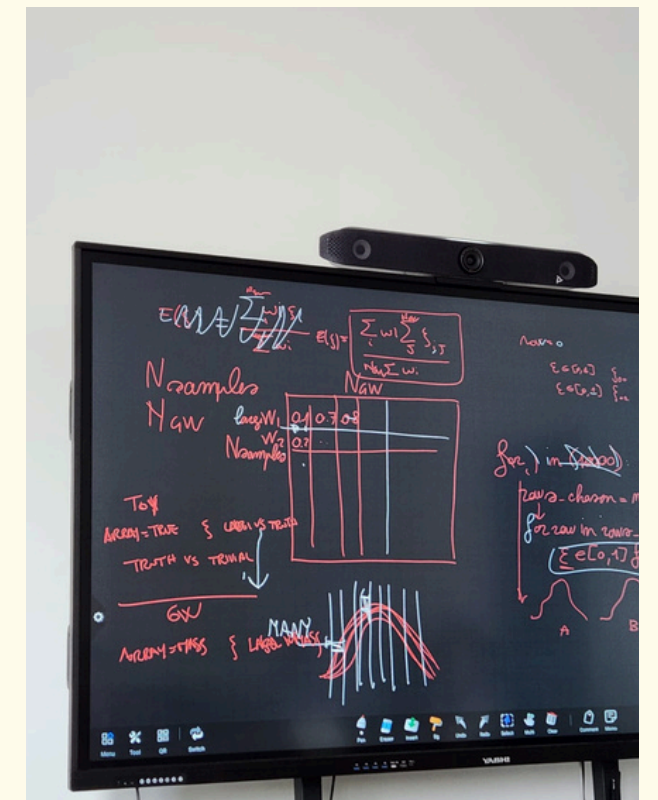


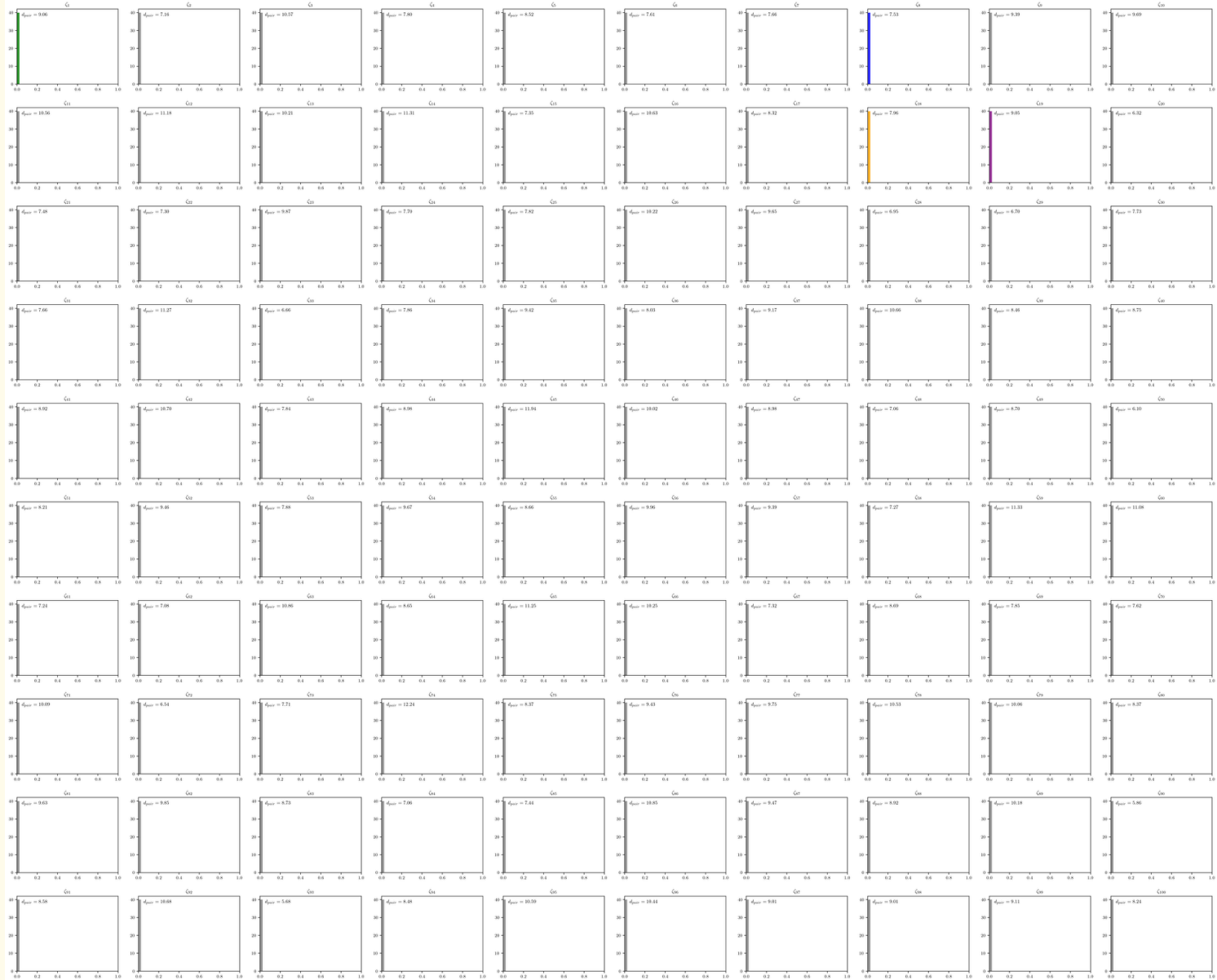
TEONGRAV
Workshop in
Pisa
←

School on
Gravity @ Niels
Bohr Institute →



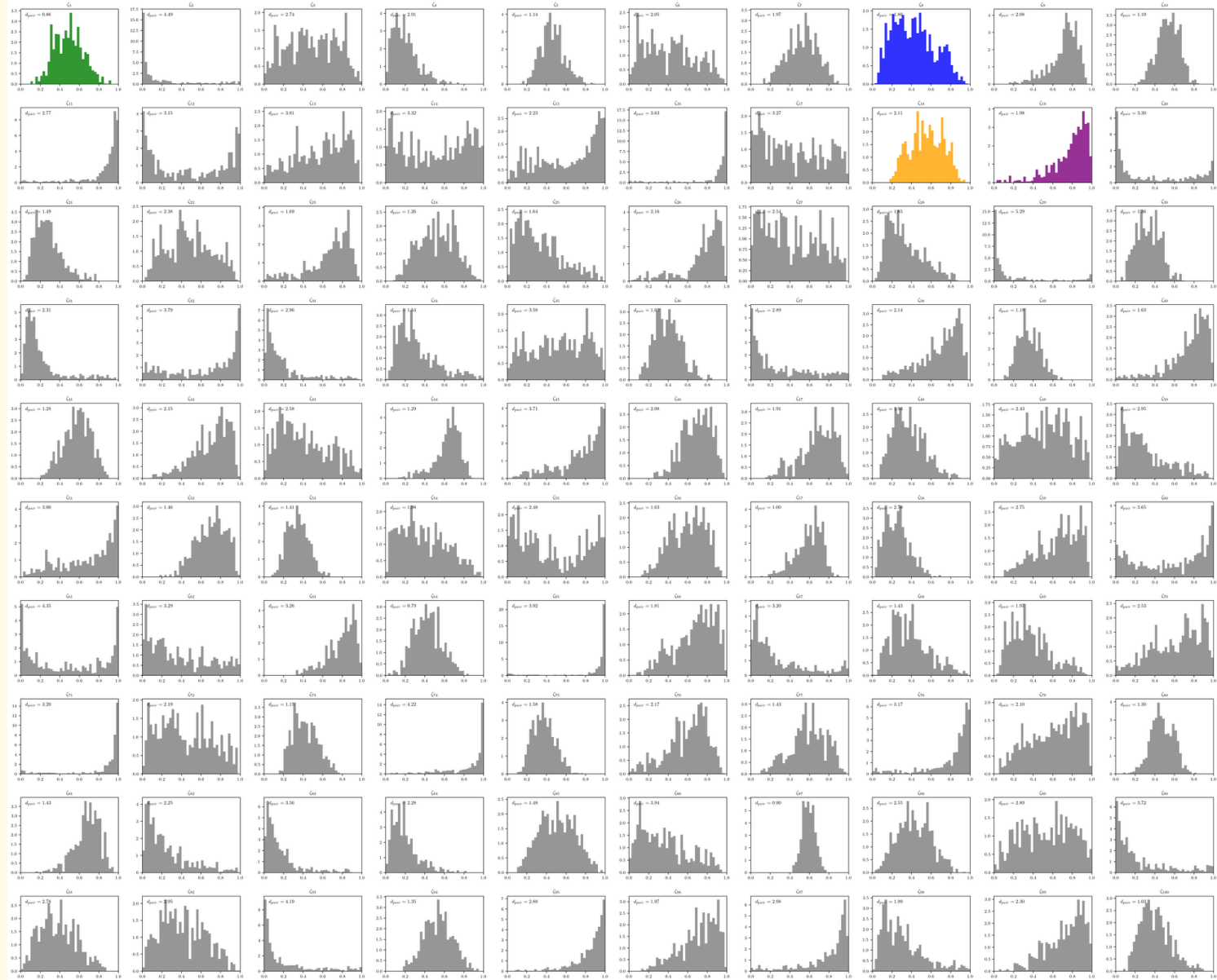
Relabelling blackboard →



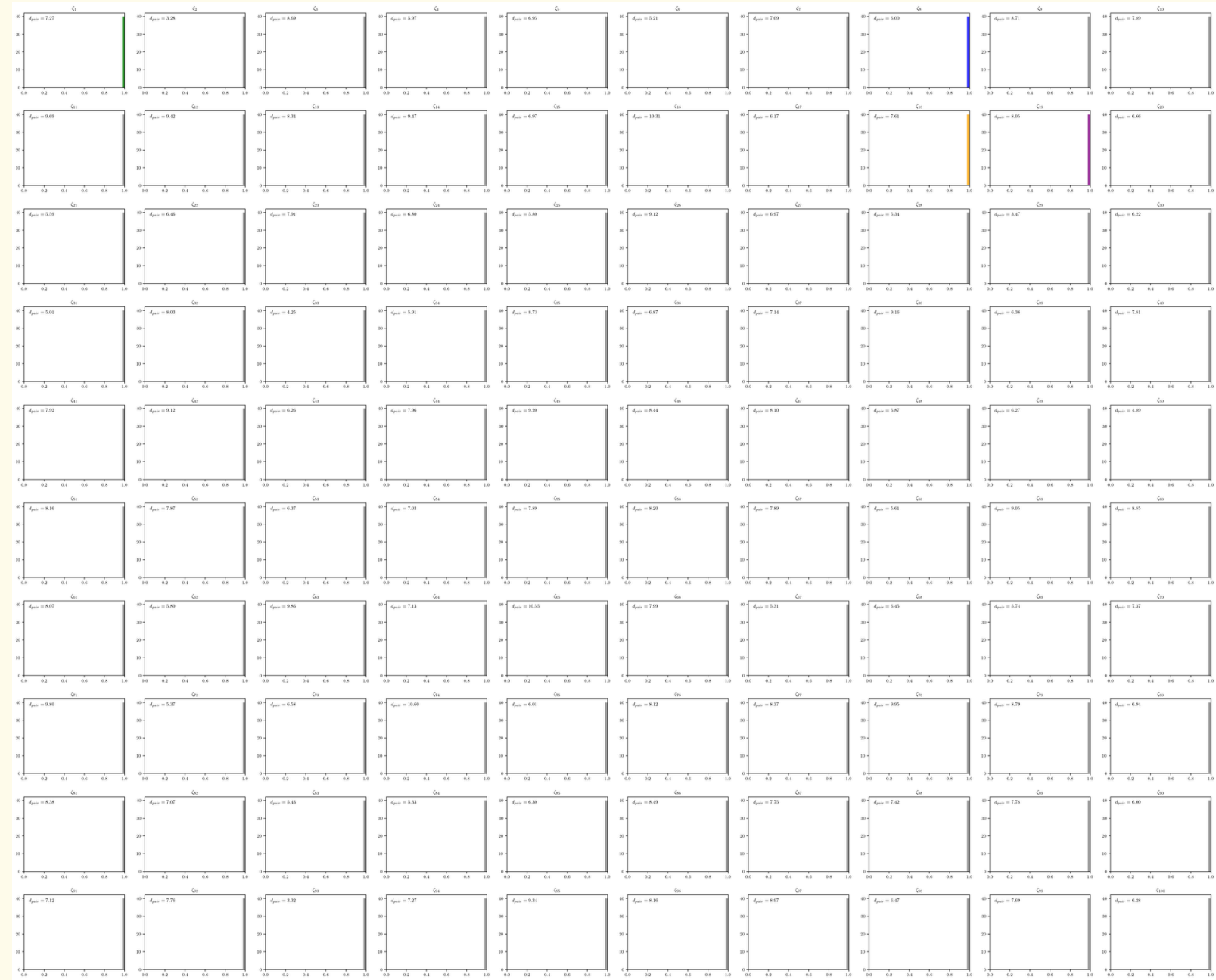
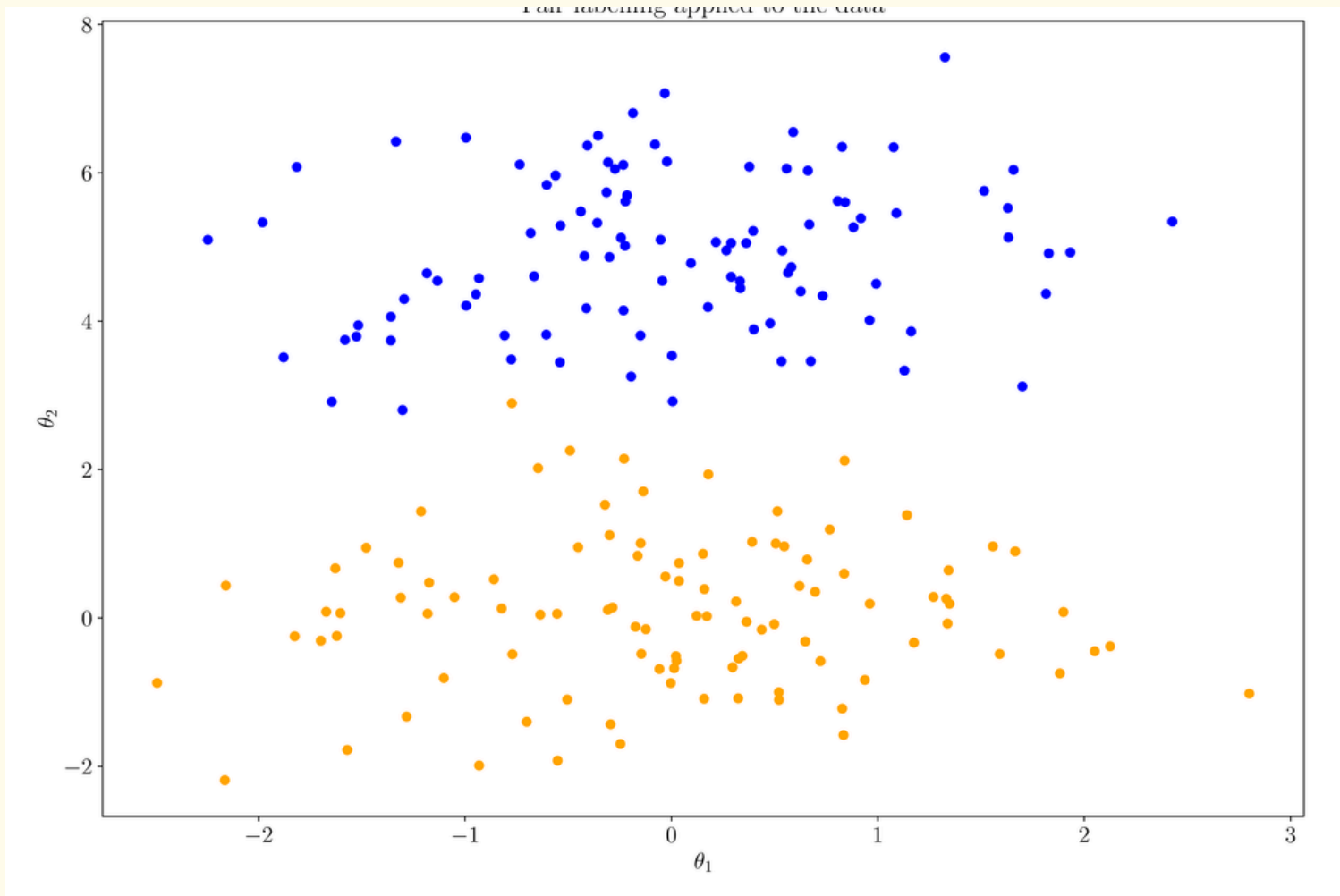


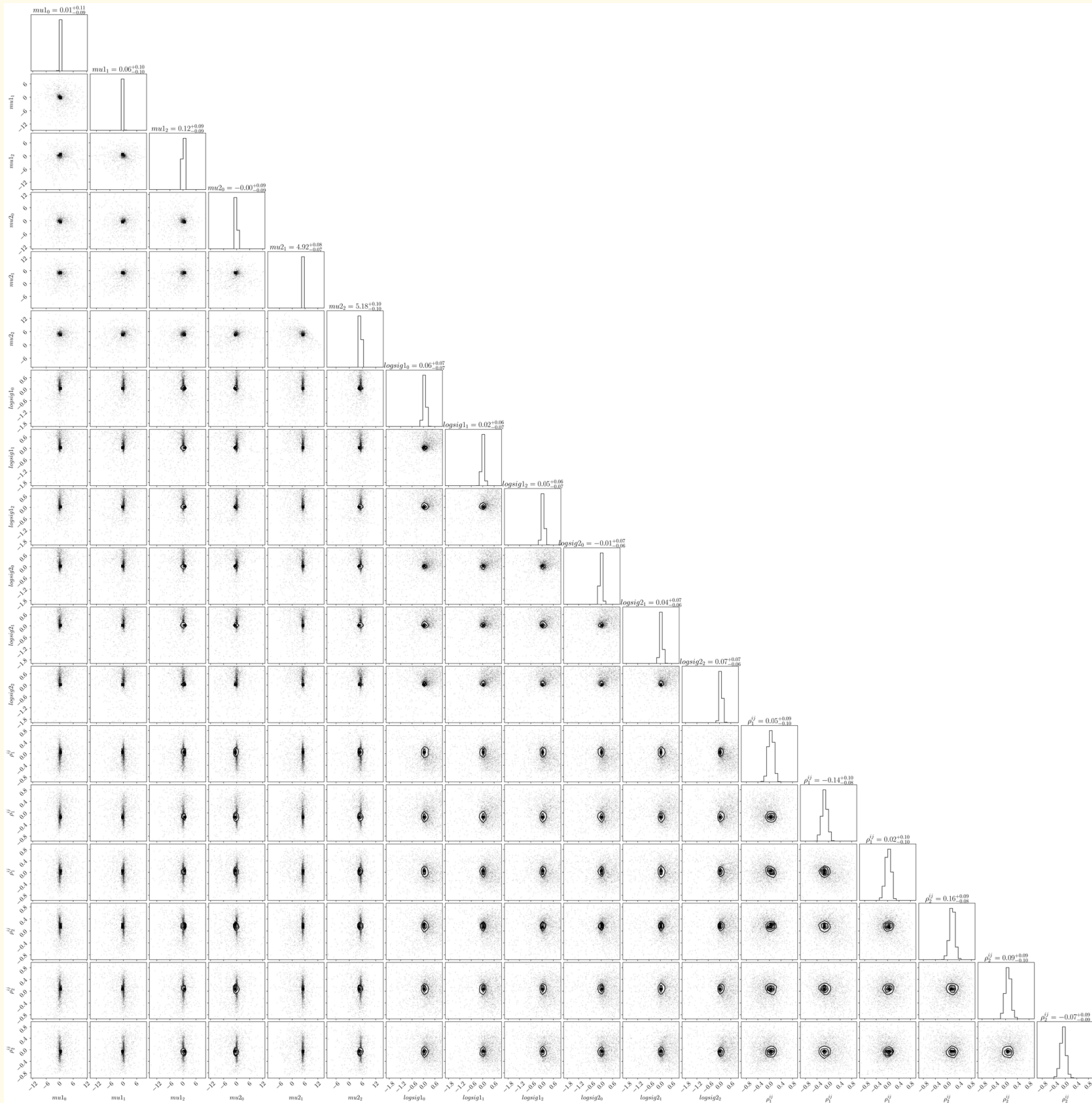
Distinguishable objects

VS



Undistinguishable objects





Parameters of the GMM
posterior in 3 dimensions