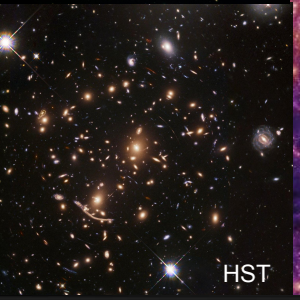
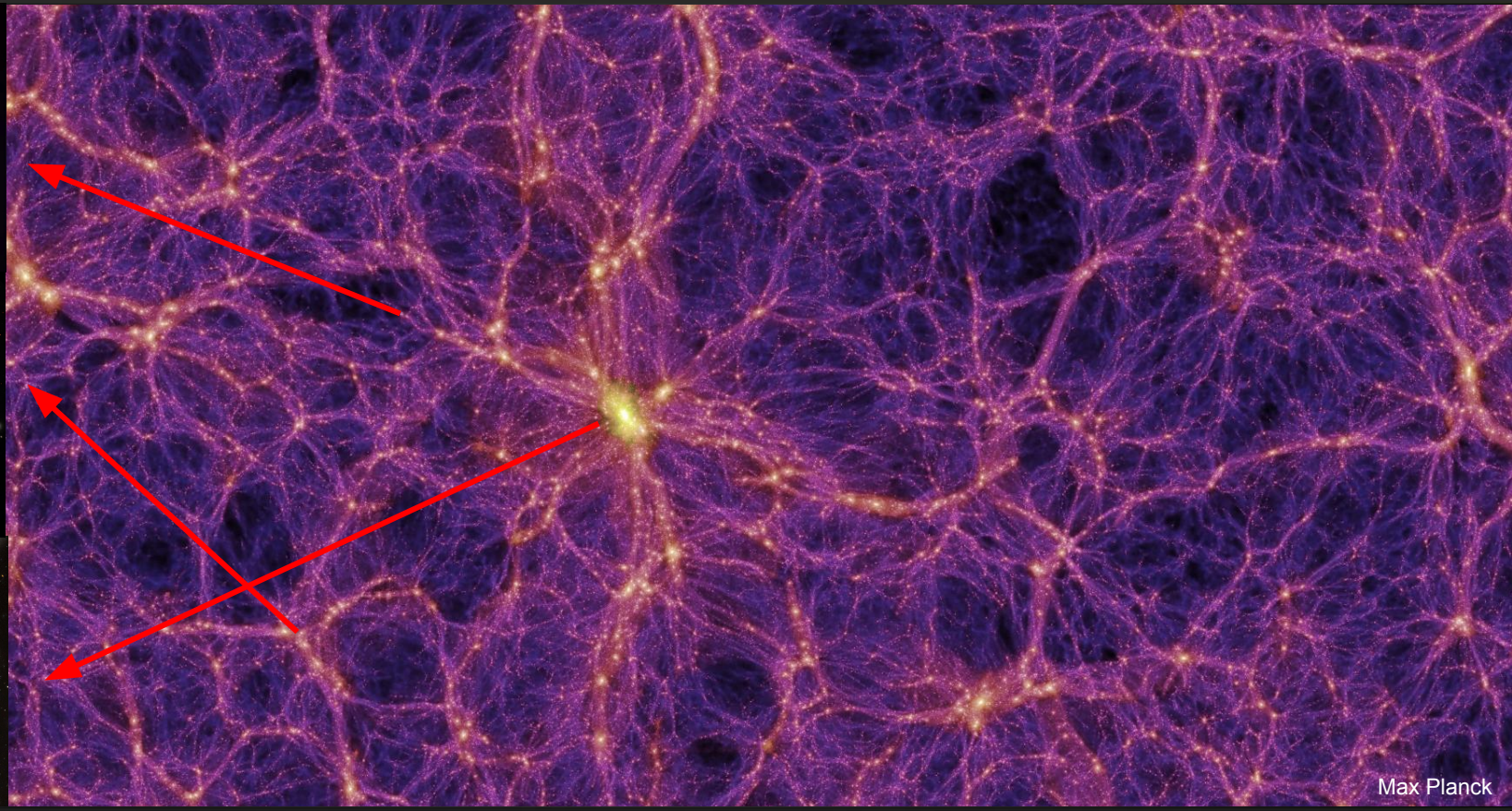
Investigating the gravitational lens of the **Helms18** system: two galaxy groups interacting in z=0.6?

Érick Cignachi

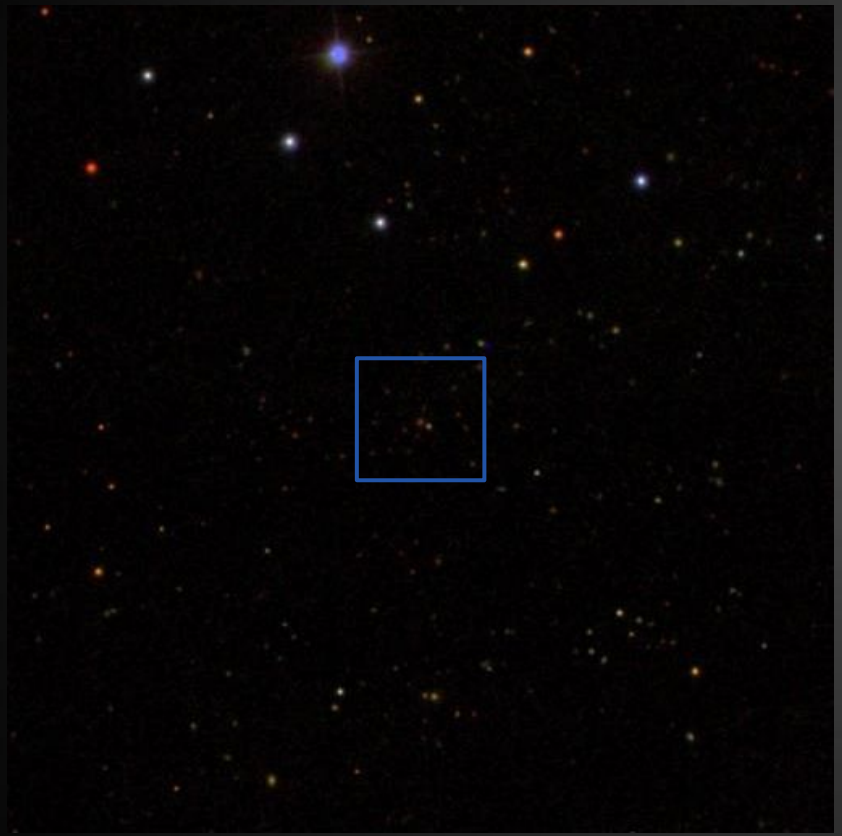
Cristina Furlanetto, Marina Trevisan and Vitor Bootz

Formation of structures in the Universe





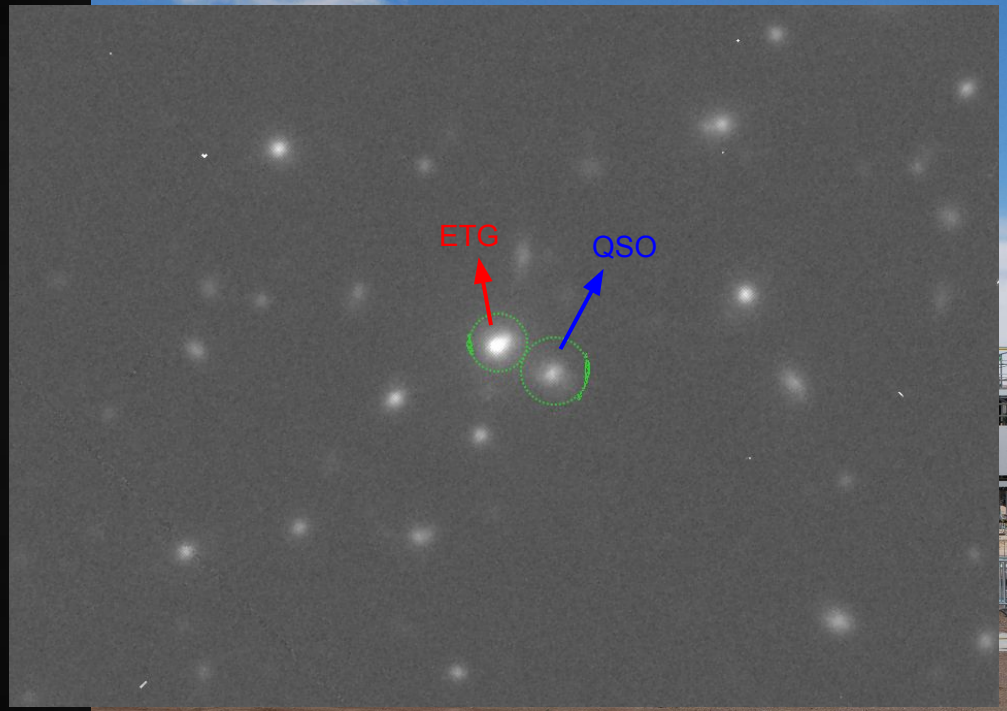
Lens object in the Sloan Digital Sky Survey (SDSS)



Lens Object HELMS18

- Quasar candidate (QSO) central galaxy
- Elliptical (ETG) central galaxy at $z_{spec} = 0.6$

ALMA observatory data



In **white**: i band from Gemini
In **green**: submm emission from ALMA

Separation between the arcs is typical of group-scale lenses.

Is the lens object a galaxy group?

Each of the arcs is centered on one of the central galaxies.

Alma Observatory

Objectives

- Confirm the redshifts of the central galaxies
- Determine the object members
- Determine the properties of the supposed group:
  - Mass
  - Radius
  - Velocity Dispersion

Target Selection for MOS observations

By using the SDSS photometric catalog, we selected the target galaxies in the field of HELMS18 system prioritizing:

1. Galaxies in the red sequence;

2. Galaxies whose photometric redshifts are around the redshift of the central ETG;

3. Other bright galaxies in the field, regardless of their color.

76 galaxies met these criteria

GMOS Instrument

GMOS

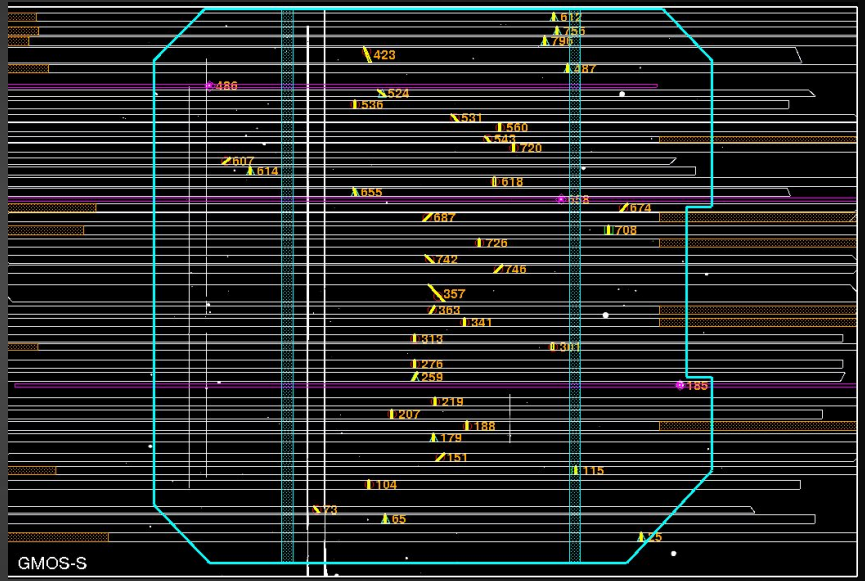
Gemini South

Observation Details

The selected objects were observed using **2 masks** and with the R400-G5325 grating, which covers the rest-frame spectral interval from **~3500A to ~6000A**.

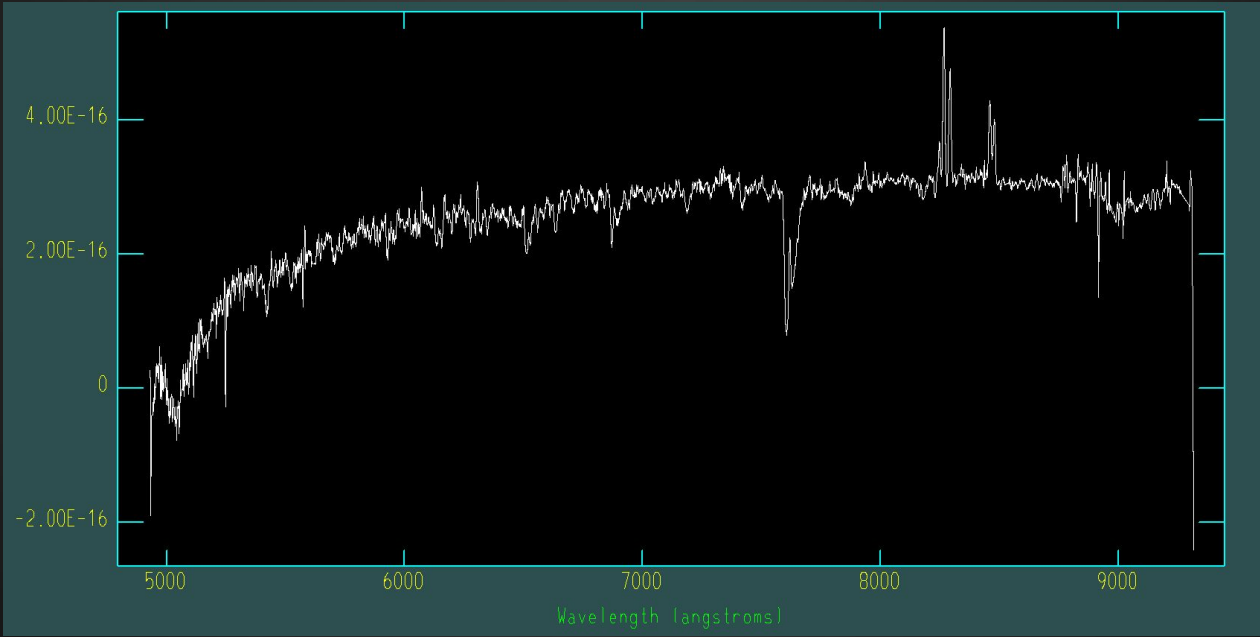
The total exposure time of each mask was **14400 s**.

The central galaxies were observed in both masks.

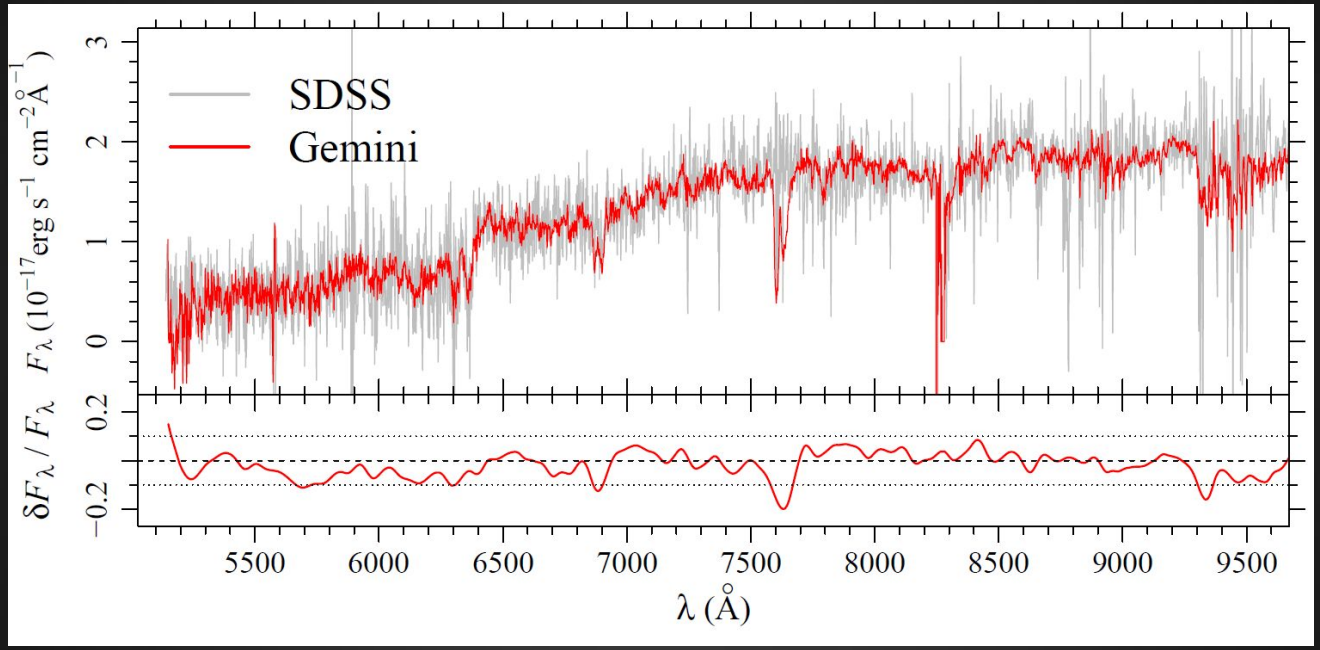


Data Reduction

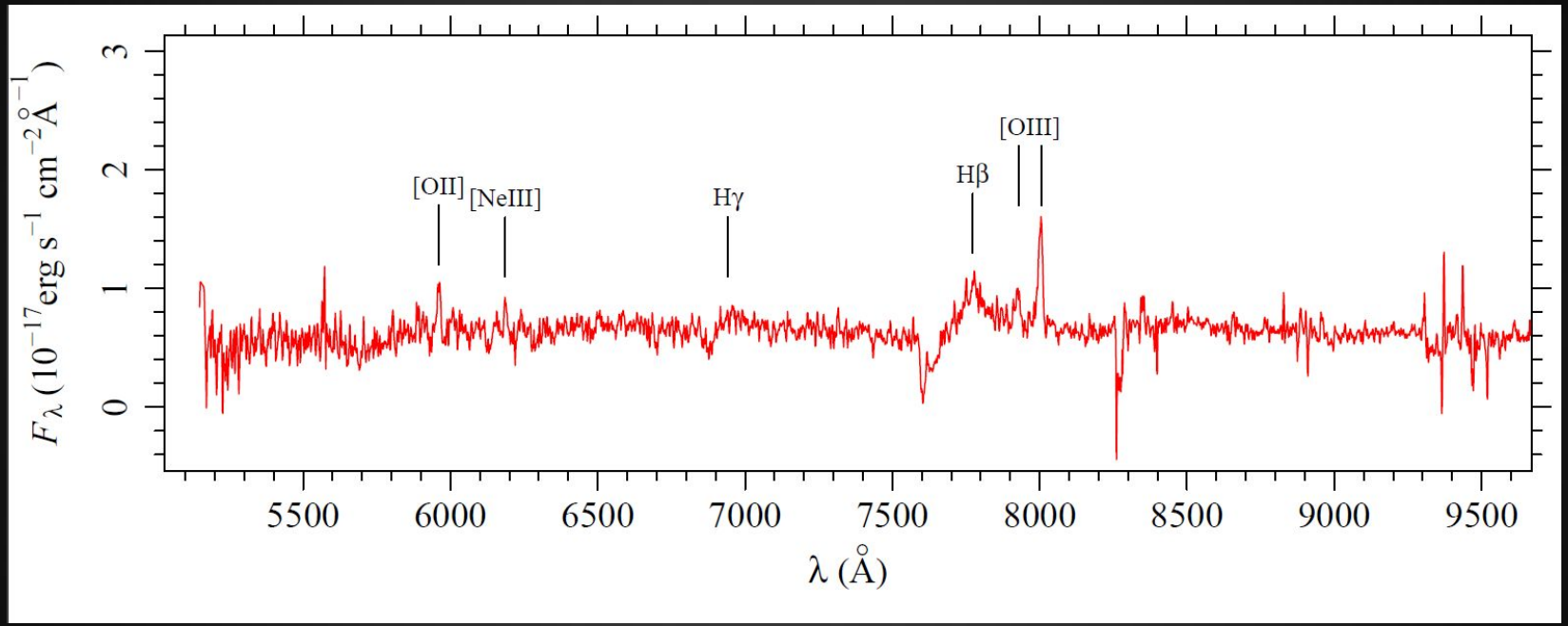
The data was reduced using the standard GMOS data reduction pipeline, taking into account the bias subtraction, flat field correction, quantum efficiency correction, wavelength and flux calibration.



Data Reduction - ETG spectrum



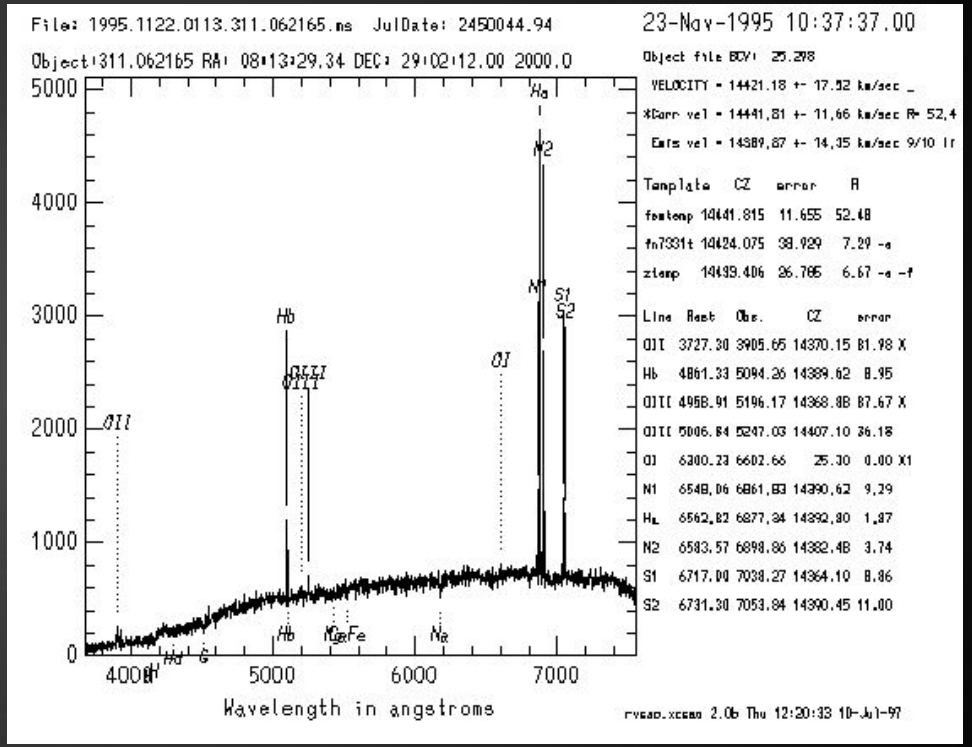
Data Reduction - QSO spectrum



Data Analysis: Redshift Estimation

We use the tasks **XCSAO** and **EMSAO** of the RVSAO package in IRAF to determine the redshifts of the target galaxies.

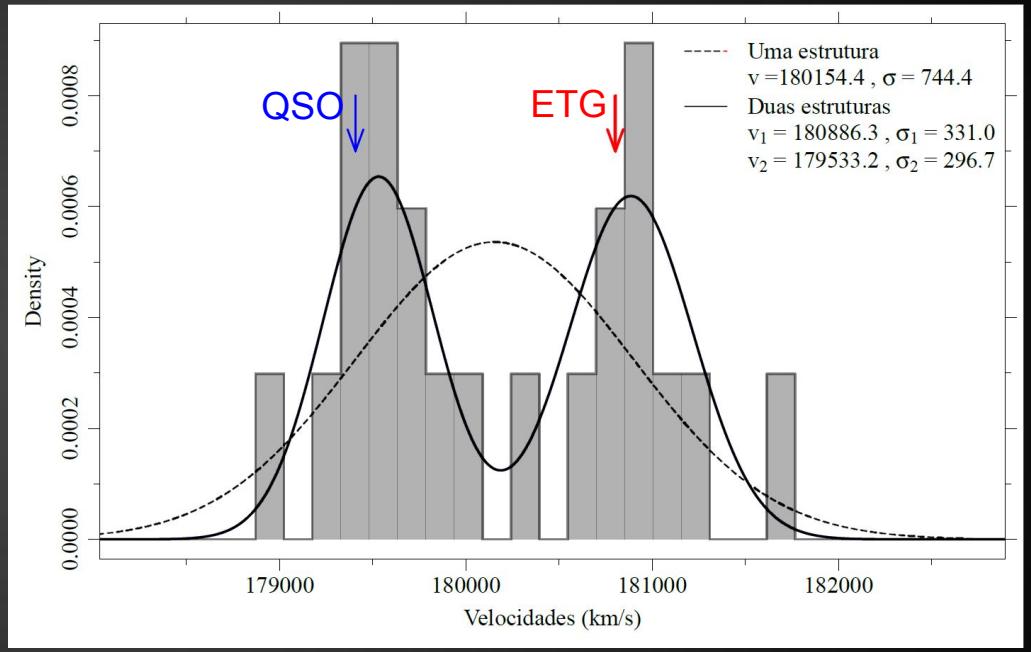
The EMSAO task is mainly used when the analysed galaxy has emission lines, while the XCSAO task is used for every other case.



Data Analysis: Line of Sight (LOS) Velocity Distribution

We select the members of the structure according to the following criteria: **0.583 < z < 0.607**.

We found 21 members.

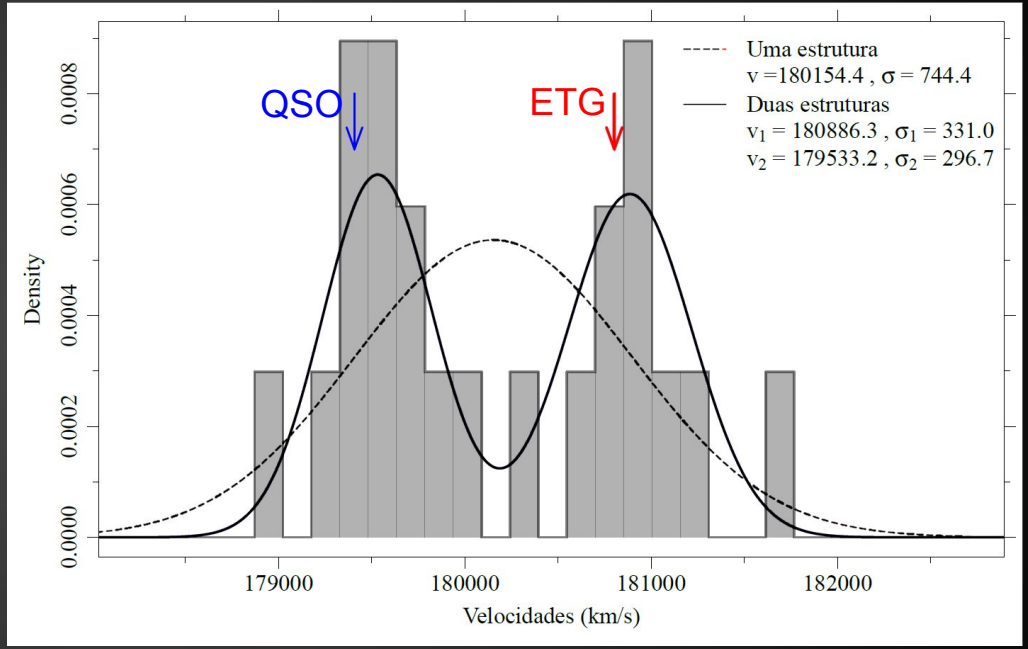


Data Analysis: Line of Sight(LOS) Velocity Distribution

$$d = \frac{|\mu_1 - \mu_2|}{2\sqrt{\sigma_1 \sigma_2}}$$

Holzmann Vollmer (2008) bimodality indicator.

$d \approx 2.1$



Data Analysis: Completeness

We followed a Monte Carlo approach for determining the completeness of the data similar to that described at Verdugo et al. (2016).

$$C(r_i) \equiv \frac{N_{spec}(r_i)}{N_t(r_i) - N_{field,r}(r_i)}$$

N_{spec}: number of confirmed group members in the i-th bin

N_t: number of galaxies catalogued in i-th bin

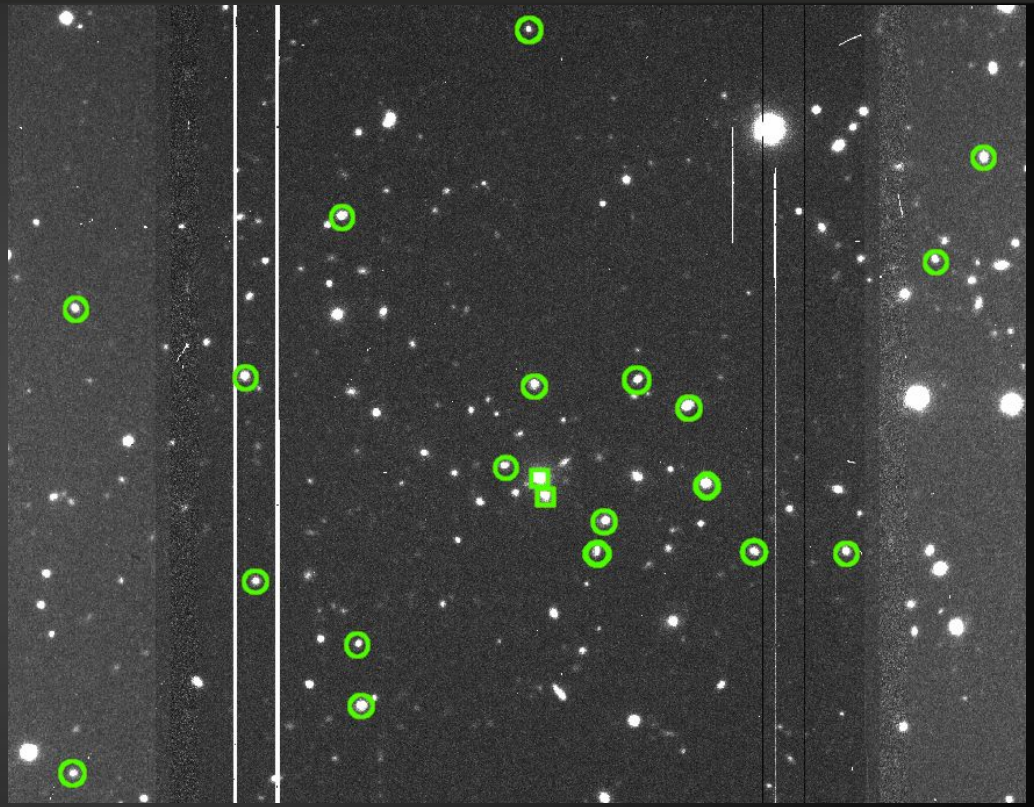
N_{field}: number of field galaxies in the ith bin

Completeness of ~ 90%

Data Analysis: Membership

(i) The **Mclust** clustering algorithm for separation and classification, and the **Shifting Gapper and Biweight Estimator (SGBE)** algorithm for the $\sigma(v)$

(ii) A **spatial and redshift shell** approach described in Muñoz et al. (2013) for separation and classification, followed by the **SGBE** method for the $\sigma(v)$.



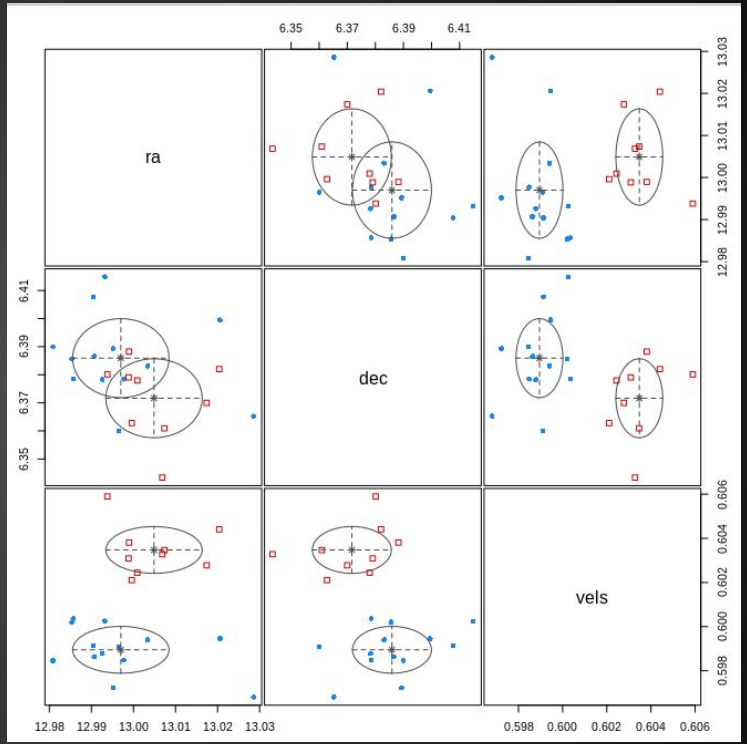
Data Analysis: Membership - Mclust

The **Mclust** is an R package used for normal mixture modeling and model-based clustering.

By making use of the **Expectation Maximization (EM) algorithm**, we test a variety of different models, to find the one that best aggregates the objects in the tridimensional space i.e. the model with the **highest BIC value**.

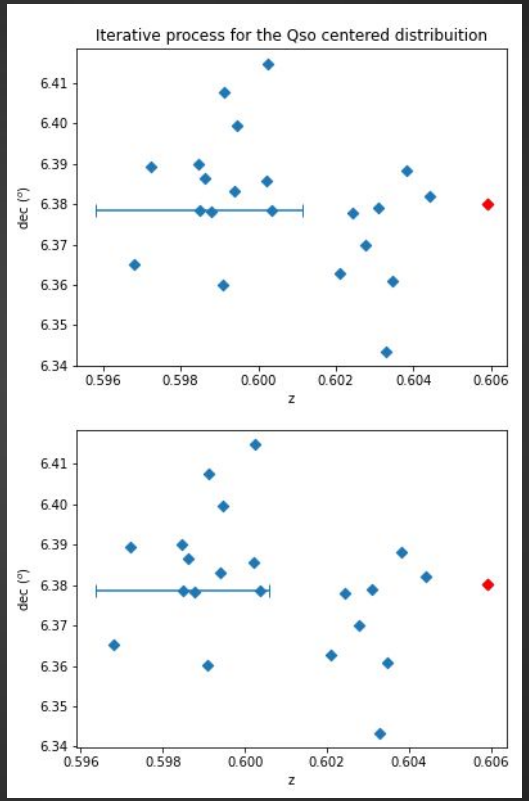
$$\sigma(v)_{ETG} = 242.9 \pm 51.6\ km\ s^{-1}$$

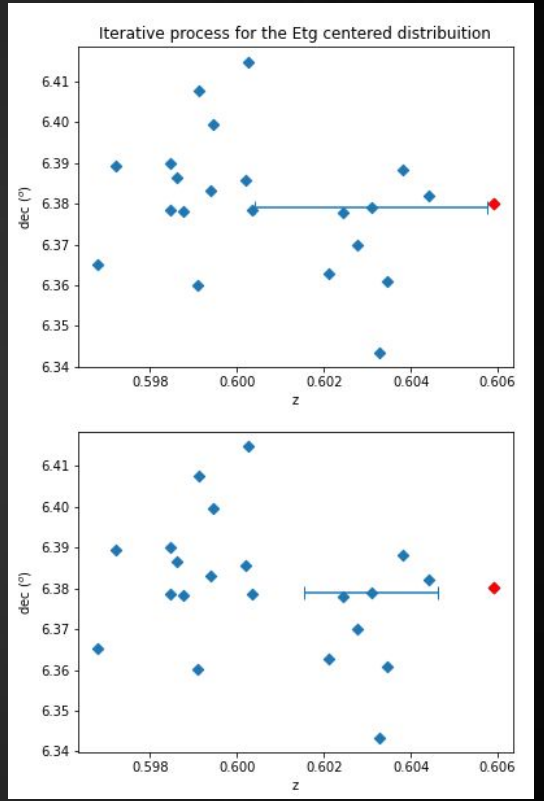
$$\sigma(v)_{QSO} = 197.5 \pm 65.9\ km\ s^{-1}$$



Data Analysis: Membership - Shells

We implement the Shifting Gapper and Biweight estimator algorithm in similar way as in Muñoz et al., (2013).





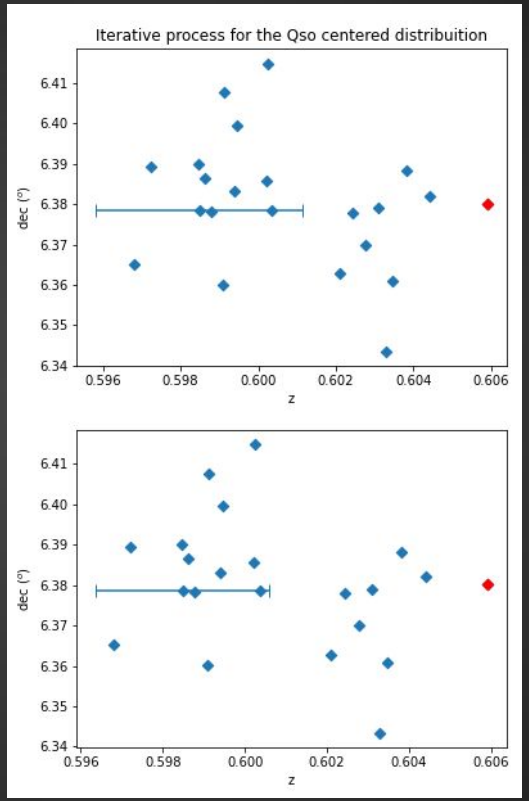
Data Analysis: Membership - Shells

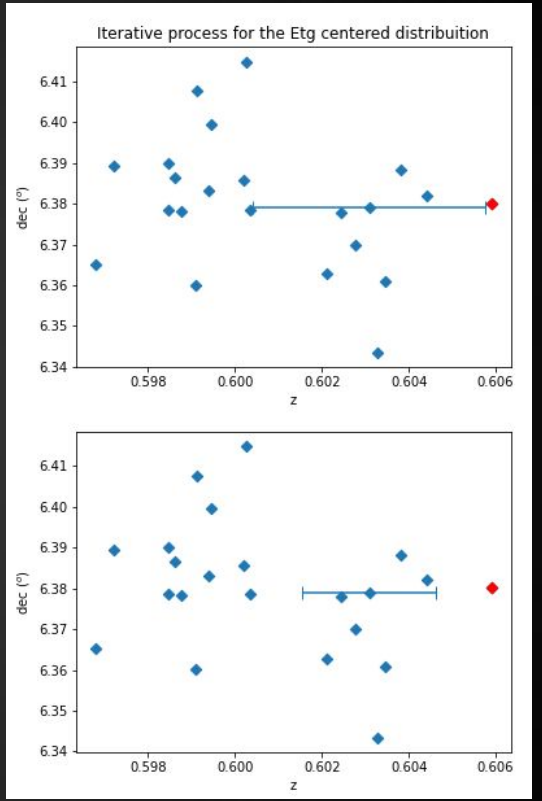
$$\delta z_{max} = \frac{2\sigma(v)_{obs}}{c}$$

$$\delta\theta_{max} = 206,265'' \frac{c\delta z_{max}}{b(1+z_{cen})H(z)D_{\theta}(z)}$$

$$\sigma(v)_{obs} = 250(1+z_{cen})\, km\, s^{-1}$$

Where c is the speed of light, H (z) is the Hubble constant at z, D_θ (z) is the angular diameter distance at z, and b is the is the axis ratio of the cylindrical linking volume.





Data Analysis: Membership - Shells

$$\delta z_{max} = \frac{2\sigma(v)_{obs}}{c}$$

$$\delta\theta_{max} = 206,265'' \frac{c\delta z_{max}}{b(1+z_{cen})H(z)D_\theta(z)}$$

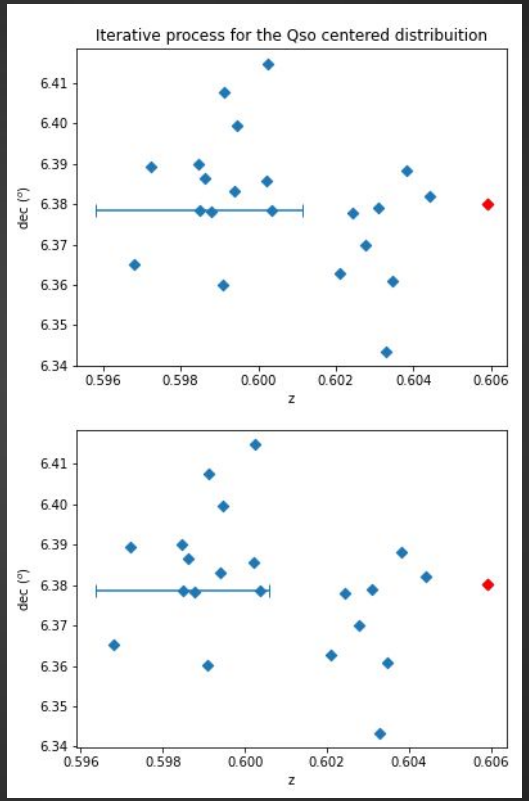
$$\sigma(v)_{QSO} = 197.5 \pm 65.8\ km\ s^{-1}$$

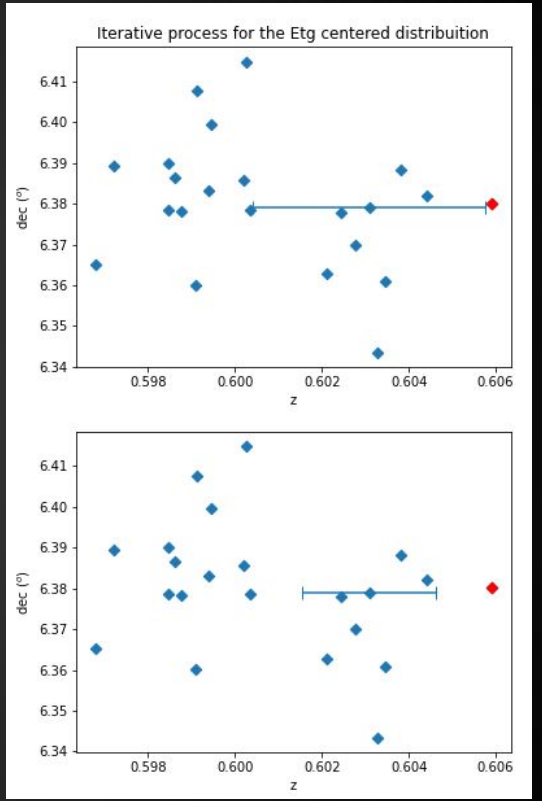
With red galaxy:

$$\sigma(v)_{ETG} = 242.9 \pm 51.8\ km\ s^{-1}$$

Without

$$\sigma(v)_{ETG} = 143.7 \pm 52.2\ km\ s^{-1}$$





Data Analysis: Membership

Shell Method	MClust Method
N_{QSO} = 13 members.	N_{QSO} = 13 members.
N_{ETG} = 8 members.	N_{ETG} = 9 members.

Data Analysis: Groups Mass

We estimate the Virial Mass of both structures by the following equation (Beers+82):

$$M_{vt} = \frac{N_c}{G} \sum_i v_i^2 \left(\sum_i \sum_{j<i} \frac{1}{r_{ij}} \right)^{-1}$$

Shell Method	MClust Method
$M_{v_{QSO}} = (9.6 \pm 0.1) \times 10^{12} M_\odot$	$M_{v_{QSO}} = (9.6 \pm 0.1) \times 10^{12} M_\odot$
$M_{v_{ETG}} = (3.4 \pm 0.1) \times 10^{12} M_\odot$	$M_{v_{ETG}} = (8.6 \pm 0.2) \times 10^{12} M_\odot$

Data Analysis: Radius

We estimate the Inertial Radius and the Gravitational Radius of both structures by the following equations Yaryura et al. (2022):

$$R_I = \left(\sum_i^N r_i^2 / N \right)^{1/2}$$

$$R_G = \frac{N^2}{\sum_i \sum_{j<i} \frac{1}{r_{ij}}}$$

Shell Method

	Rg(Mpc)	Ri(Mpc)
ETG	0.85 ± 0.13	0.48 ± 0.06
QSO	0.92 ± 0.06	0.52 ± 0.03

MClust Method

	Rg(Mpc)	Ri(Mpc)
ETG	0.80 ± 0.11	0.45 ± 0.05
QSO	0.92 ± 0.06	0.52 ± 0.03

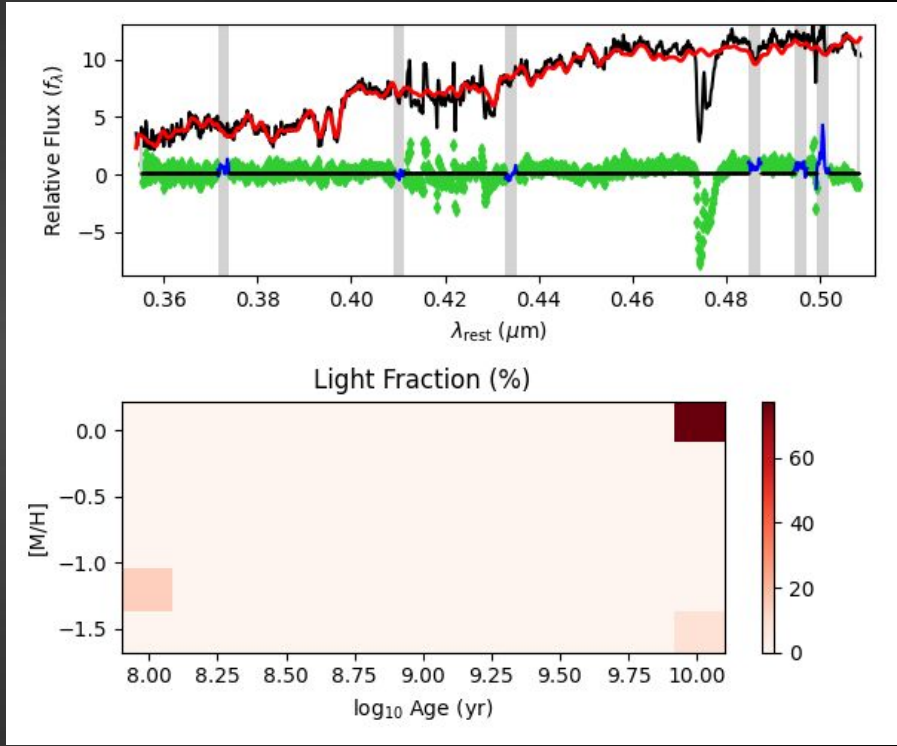
Data Analysis: Central Galaxies Stellar Synthesis (pPXF)

Using the pPXF algorithm, we are able to determine the following parameters for the central galaxies:

ETG

Stellar Velocity Dispersion: 314 km s^{-1}

Stellar Mass: 4.92 x 10^{11} $M_{\odot}$



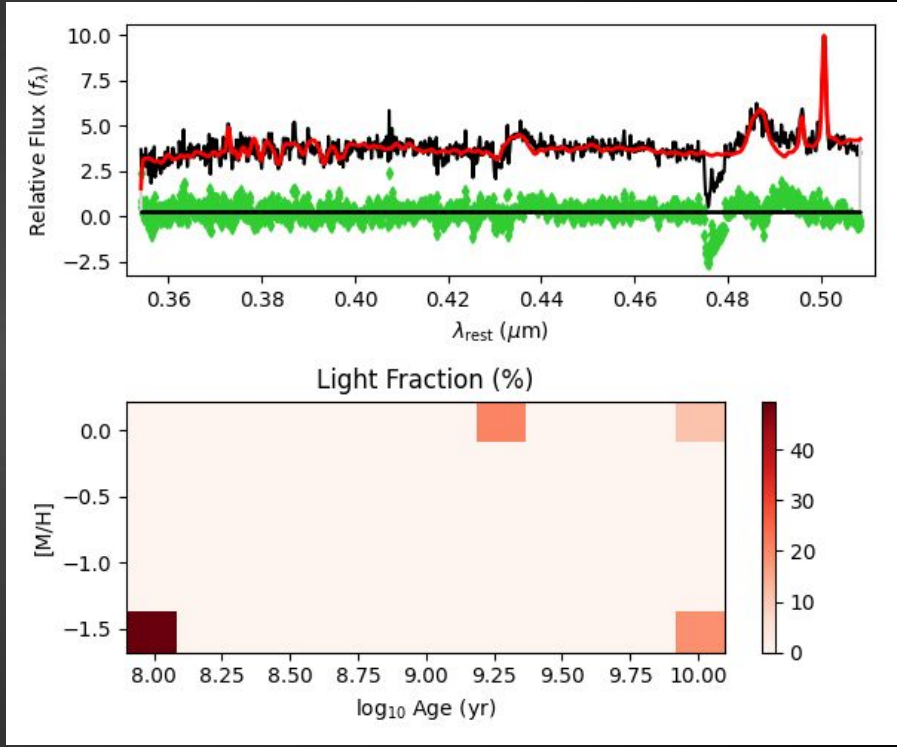
Data Analysis: Central Galaxies Stellar Synthesis (pPXF)

Using the pPXF algorithm, we are able to determine the following parameters for the central galaxies:

QSO

Stellar Velocity Dispersion: 209 km s^{-1}

Stellar Mass: 1.14 x 10^{11} $M_{\odot}$



Future Works

- Determine the level of interaction between the groups;

- Use the kinematic information as new constraints for a strong lens model.

Thank you!