Investigating a pair of galaxy groups with strong lensing and dynamics

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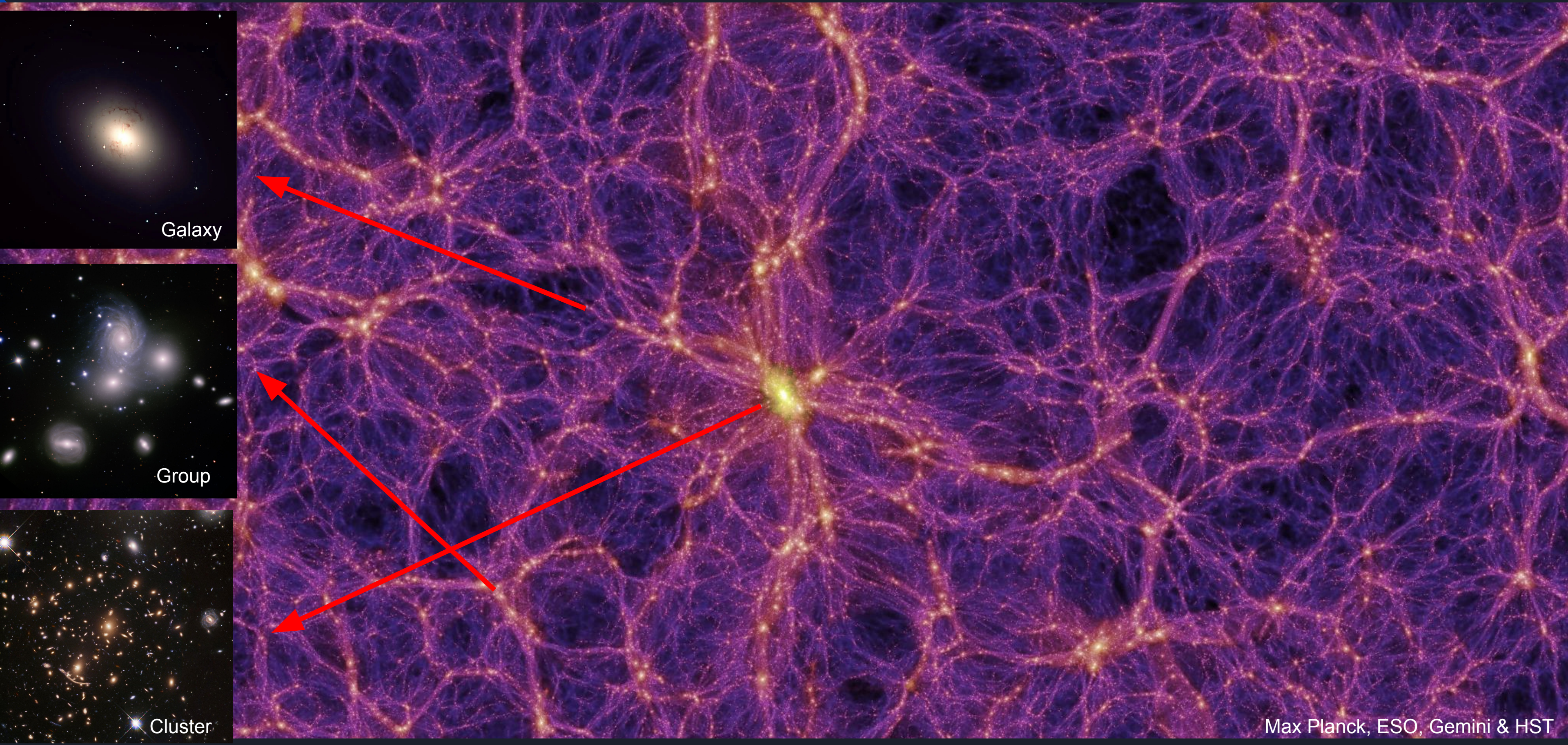
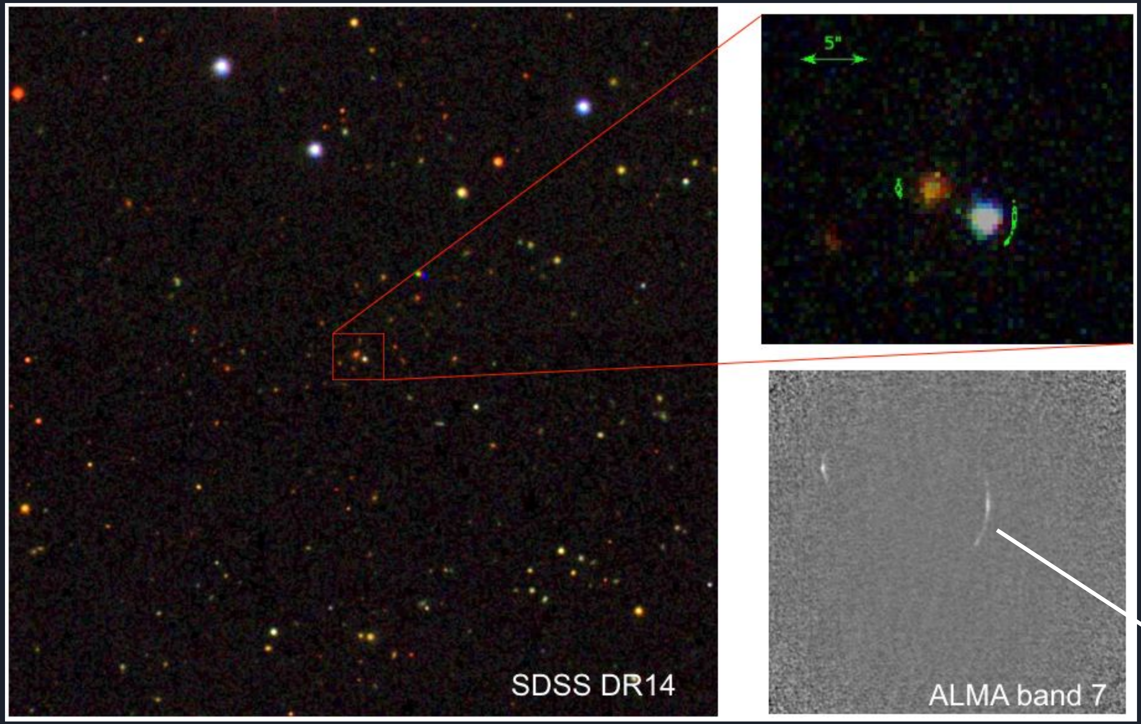
Structure formation in the Universe



Helms18 System

ETG at z_{spec} 0.6

QSO car



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

The separation between the arcs is typical of group-scale lenses.

Is the lens object a group of galaxies?

Lensed submm galaxy

$z_{spec} = 2.4$

Objectives

- Confirm the nature of the QSO;
- Determine which galaxies are part of the structure that acts as a lens;
- Determine the properties of the lens object:
    - Mass
    - Velocity dispersion
- Determine the properties of central galaxies;
- Determine the probability of interaction if there is more than one group.

GMOS instrument

GMOS

Gemini Sul

Selecting Targets for MOS Observations

LeGaC

Using the SDSS photometric catalog, we selected the target galaxies in the HELMS18 field by prioritizing:

1. The galaxies in the red sequence: $0.9 \leq (r_{\mathrm{petro}} - i_{\mathrm{petro}}) \leq 1.5$

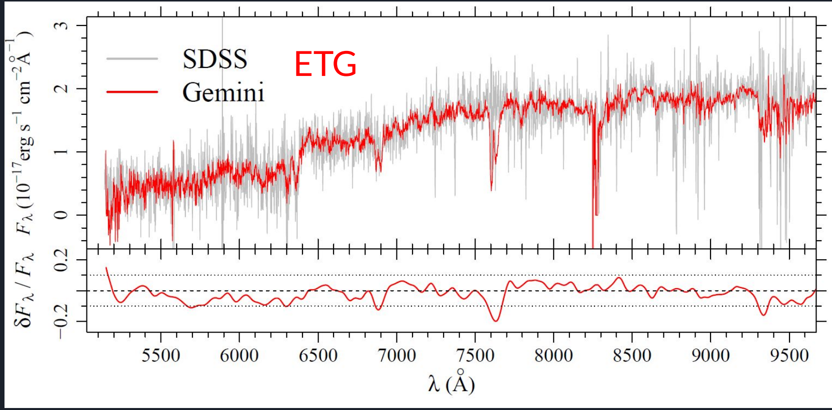
2. Galaxies in which the photometric redshifts are around the redshift of the central ETG (z ~ 0.6);

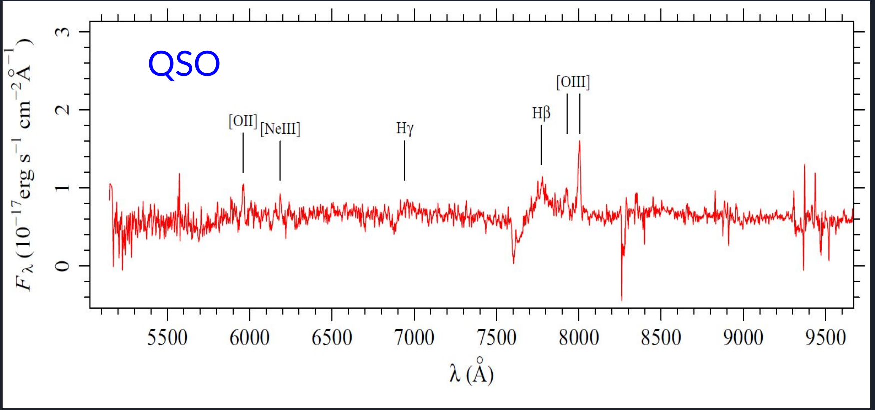
3. Other bright galaxies in the field, regardless of their color.

76 galaxies met the criteria

Data reduction

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



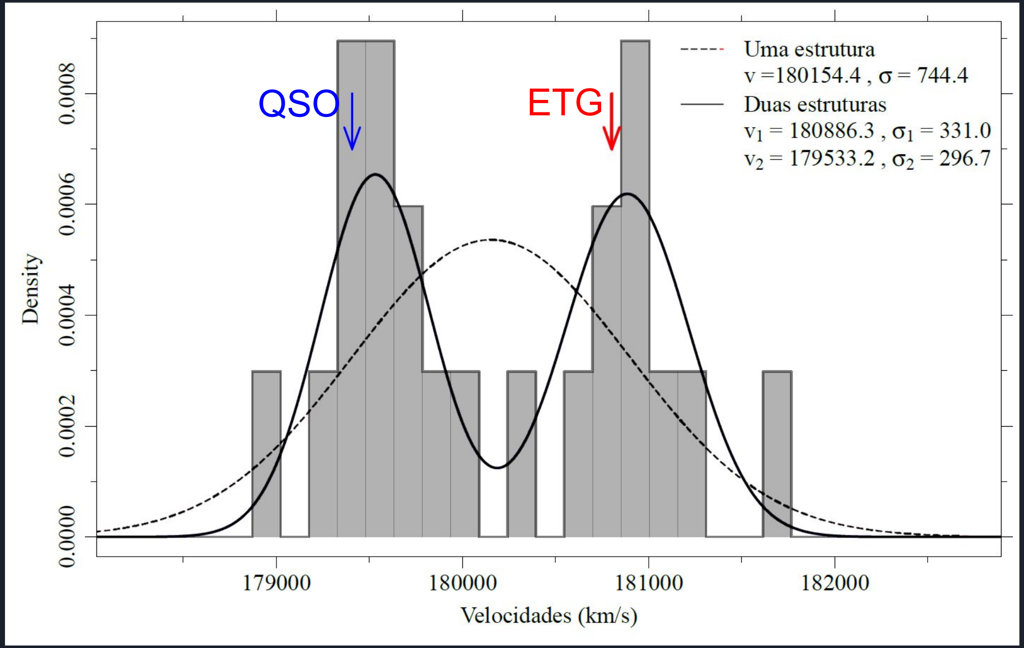


We obtained 70 spectra

Data analysis: Distribution of velocities in the line of sight

We selected the members of the structure according to the criterion: $0.596 < z < 0.608$ (3600 km s-1).

We found 21 members.

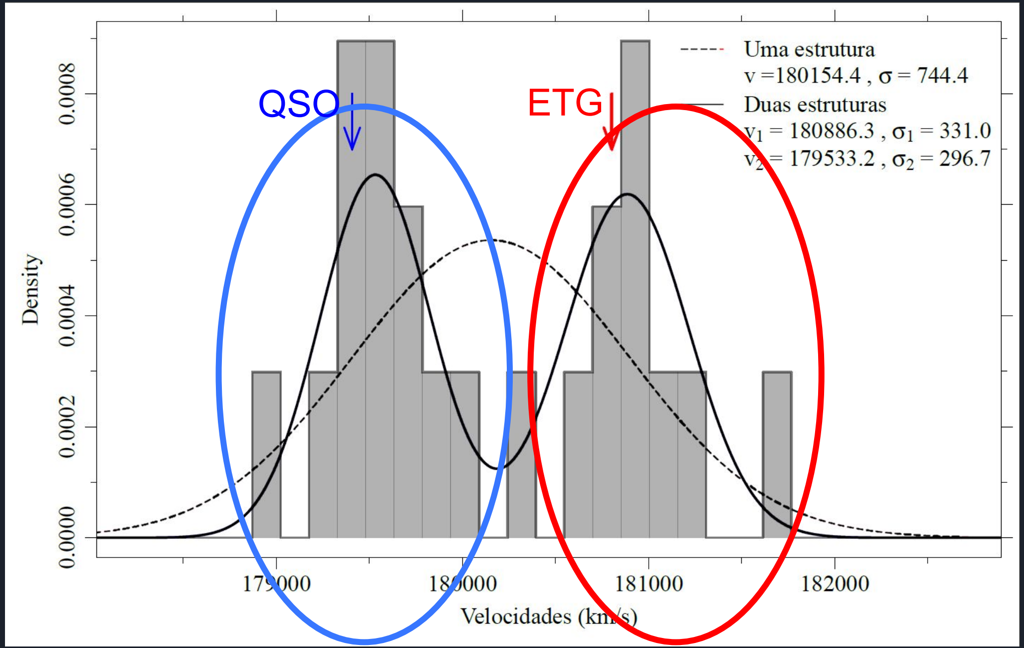


Data analysis: Distribution of velocities in the line of sight

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

Holzmann Vollmer's bimodality indicator (2008).

$d \approx$ **2.1**



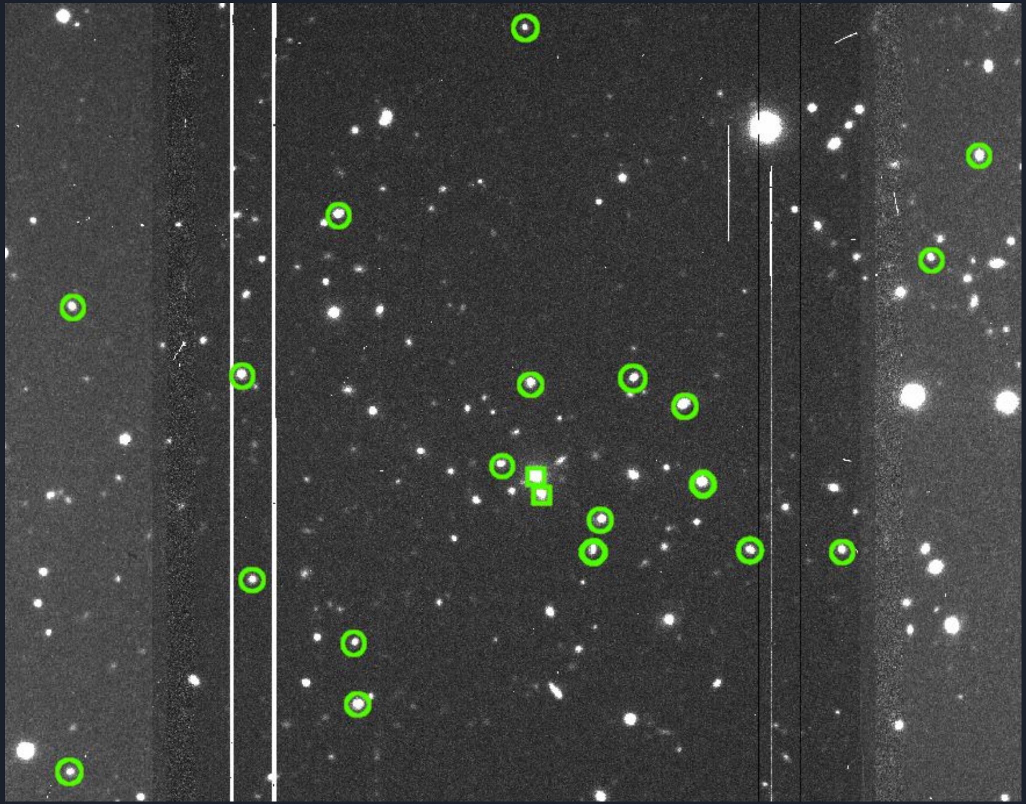
There are two groups of galaxies!

Data analysis: Clustering

(i) The **Mclust** clustering algorithm.

(ii) The formalism described in Wilman et al. (2005), implemented in a similar way to Muñoz et al. (2013).

GBE (Gapper and Biweight Estimator) for the $\sigma(v)$.



Data analysis: Clustering

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Formalism of Wilman et al.

N_{QSO} = 13 members.

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

N_{ETG} = 8 members.

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

MClust Method

N_{QSO} = 13 members.

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

N_{ETG} = 9 members.

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

Data analysis: Group Masses

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We estimate the virial mass of both structures using the following equation (Beers+82):

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

Formalism of Wilman et al.

$$M_{v_{QSO}} = (9.6 \pm 0.1) \times 10^{12} M_\odot$$

$$M_{v_{ETG}} = (3.4 \pm 0.1) \times 10^{12} M_\odot$$

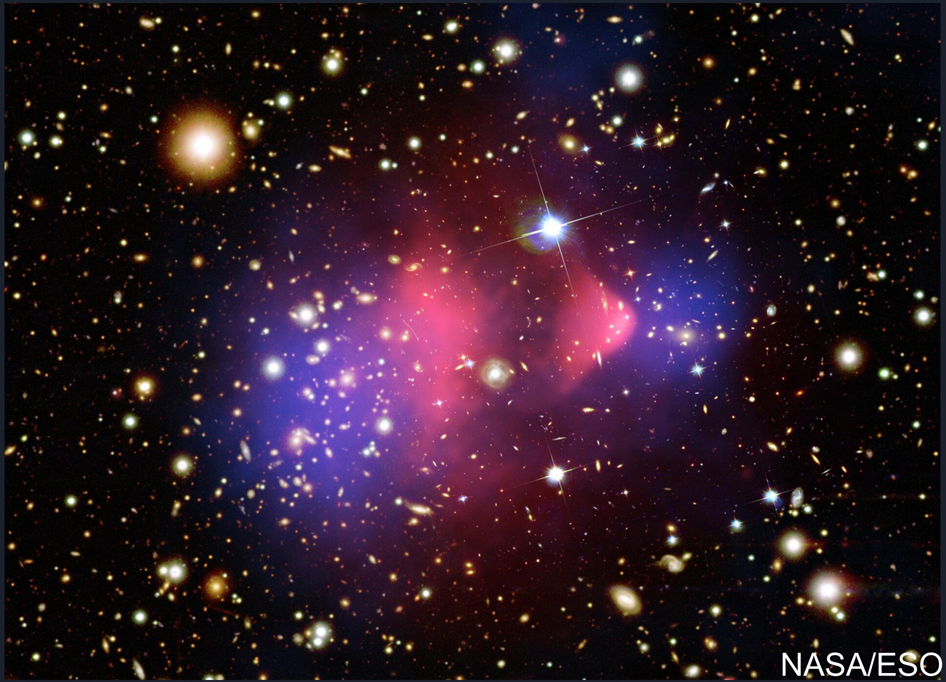
MClust Method

$$M_{v_{QSO}} = (9.6 \pm 0.1) \times 10^{12} M_\odot$$

$$M_{v_{ETG}} = (8.6 \pm 0.2) \times 10^{12} M_\odot$$

Data analysis: Interaction Model

Treating the system as a two-body problem, we apply the method described in Beers et al. (1982), assuming that the groups start with zero separation at $t = 0$ and that they are approaching or moving away for the first time in the history of the Universe.



Bullet Cluster

Data analysis: Interaction Model

For the bound case, we have these equations of motion:

$$R = \frac{R_m}{2}(1 - \cos\chi)$$

$$t = \left(\frac{R_m^3}{8GM}\right)^{\frac{1}{2}}(\chi - \sin\chi)$$

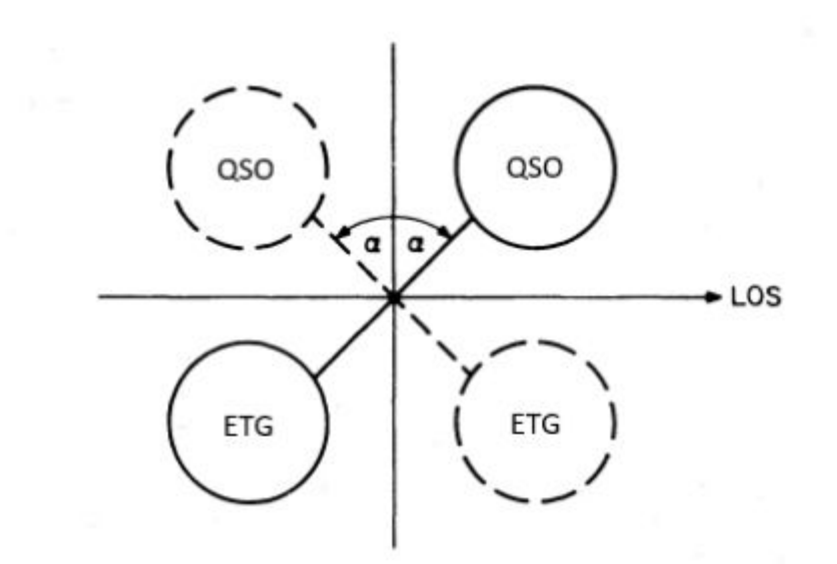
$$V = \left(\frac{2GM}{R_m}\right)^{\frac{1}{2}}\frac{\sin\chi}{(1 - \cos\chi)}$$

Data analysis: Interaction Model

We connect the equations of motion with the observables **R_p** e **V_r** with:

$$R_p = R\cos\alpha$$

$$V_r = V\sin\alpha$$



Data analysis: Interaction Model

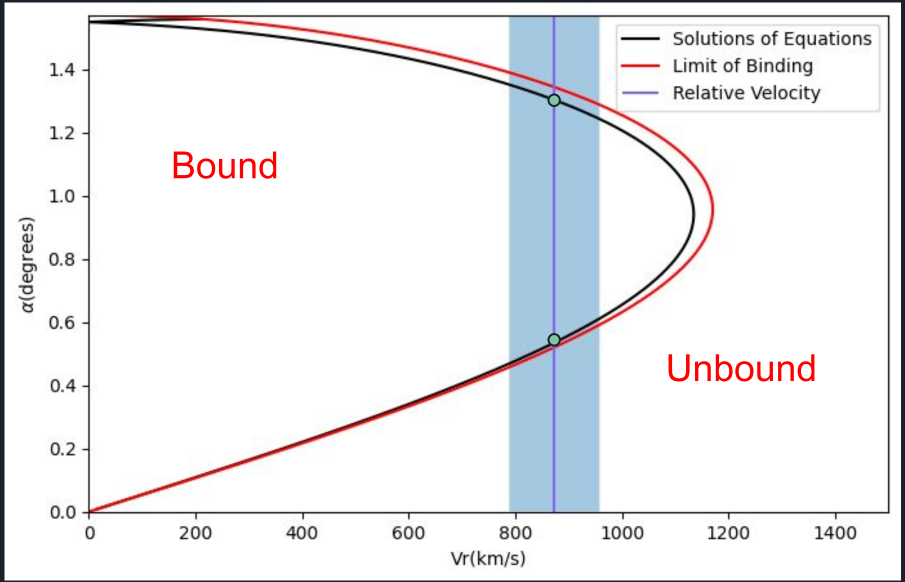
We connect the equations of motion with the observables **R_p** e **V_r** with:

$$R_p = R\cos\alpha$$

$$V_r = V\sin\alpha$$

$$V_r^2 R_p \leq 2GM\sin^2\alpha\cos\alpha$$

Model: Mclust



$$V_r = (873 \pm 85)\,km\,s^{-1}$$

Data analysis: Interaction Model

We calculate the probabilities of interaction:

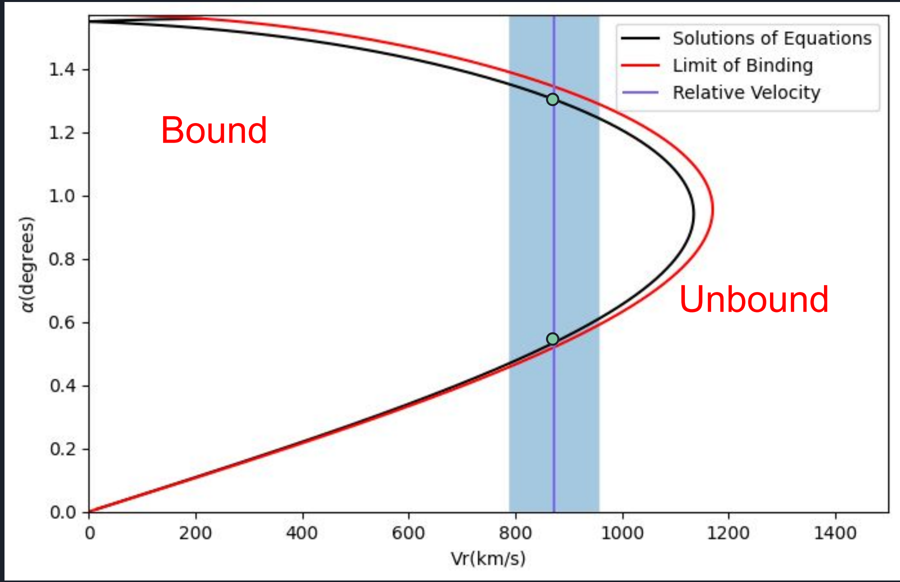
MClust Method

Probabilidade de 58%

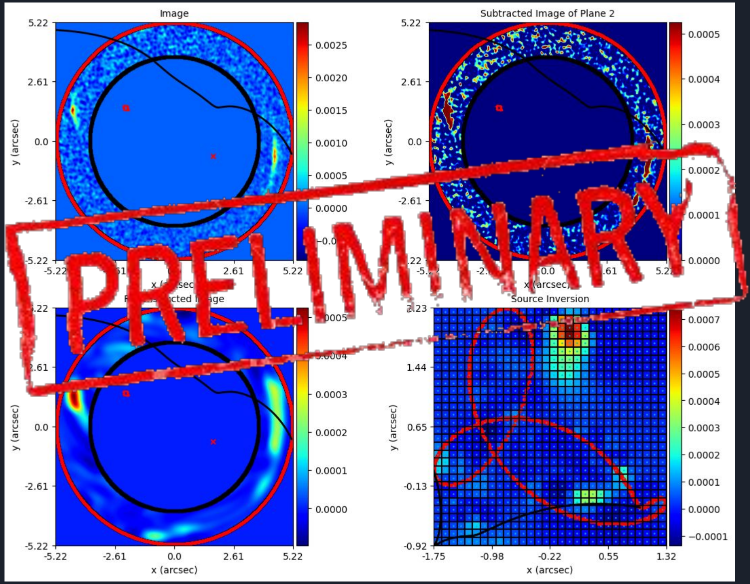
Formalism of Wilman et al.

Probabilidade de 47%

Model: Mclust



We are using the kinematic information as new constraints for a strong lens model.



Ongoing work

At this stage, we have as objectives:

- Model the gravitational lens without the kinematic parameters;
- Model the gravitational lens with the kinematic parameters and compare with the previous model;
- Estimate the dark matter and baryonic mass fractions of the lens object.

Conclusions

In this work, we obtained the following results:

- 70 galaxy spectra in the HELMS18 region
- Two groups of galaxies lensing the same object!
- Number of members: N_{ETG}= 8 ou 9, N_{QSO}= 13 (Low number of members)

Conclusions

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In this work, we obtained the following results:

- Viral mass of the groups;

$$M_{v_{QSO}} = (9.6 \pm 0.1) \times 10^{12} M_{\odot}$$

$$M_{v_{ETG}} = (3.4 \pm 0.1) \times 10^{12} M_{\odot} \text{ ou } M_{v_{ETG}} = (8.6 \pm 0.2) \times 10^{12} M_{\odot}$$

- Interaction model between the groups, probability of 47% or 58% depending on the clustering (the possibility of interaction may affect the measurement of viral mass).

Thank you!

Data analysis: Clustering - Mclust

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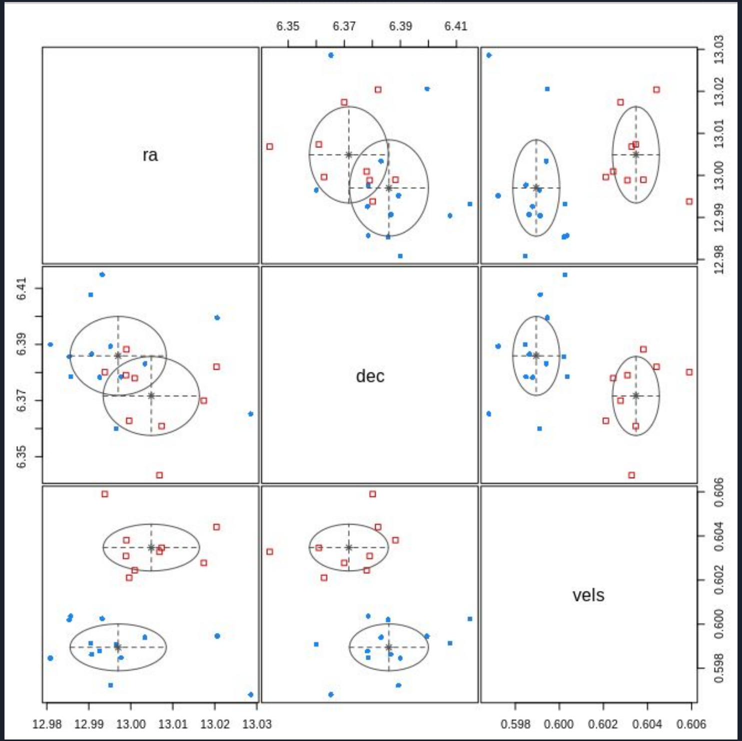
Mclust is an R language package used for normal mixture modeling and model-based clustering.

Using the EM (Expectation Maximization) algorithm, we tested different models to find the one that best aggregates the objects in three-dimensional space, i.e. the model with the highest BIC (Bayesian information criterion) value.

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

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



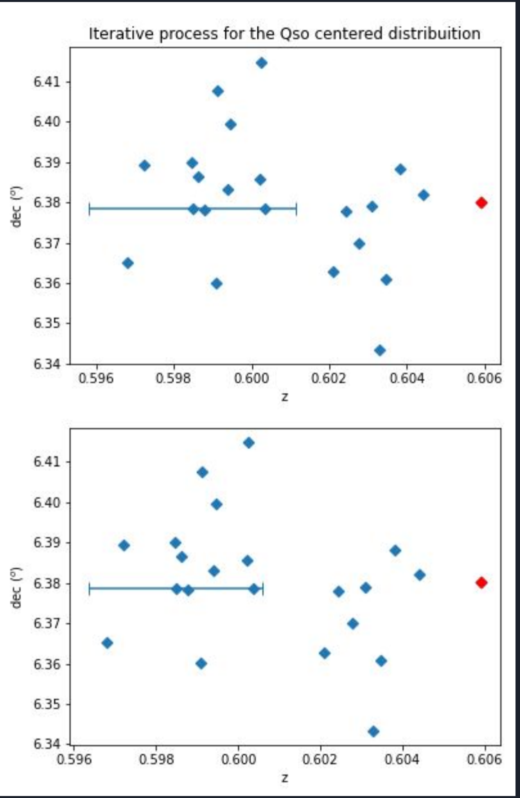
Data analysis: Clustering - Formalism of Wilman et al.

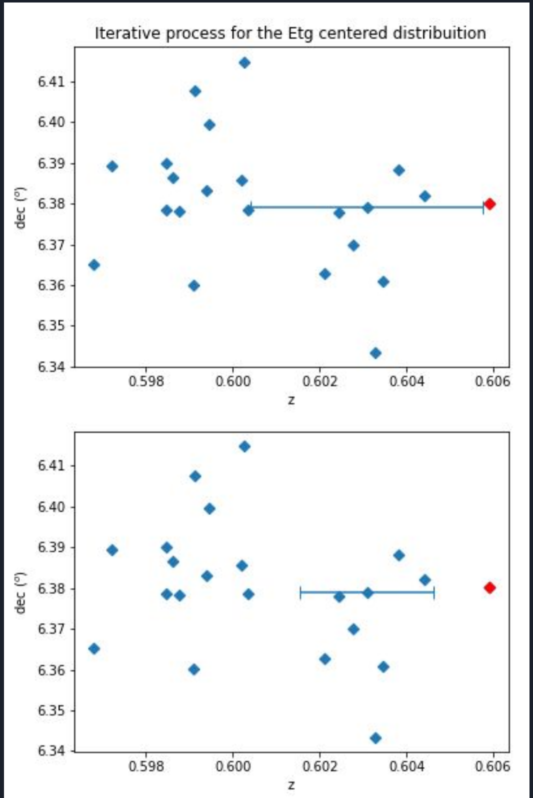
$$\sigma(v)_{obs} = 250(1 + z_{cen})\, km\, s^{-1}$$

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

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

Where c is the speed of light, $H(z)$ is the Hubble constant in z, $D\theta$ (z) is the angular diameter distance in z and b is the axis ratio of the cylindrical linking volume.





Data analysis: Clustering - Formalism of Wilman et al.

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

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

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

With the red galaxy:

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

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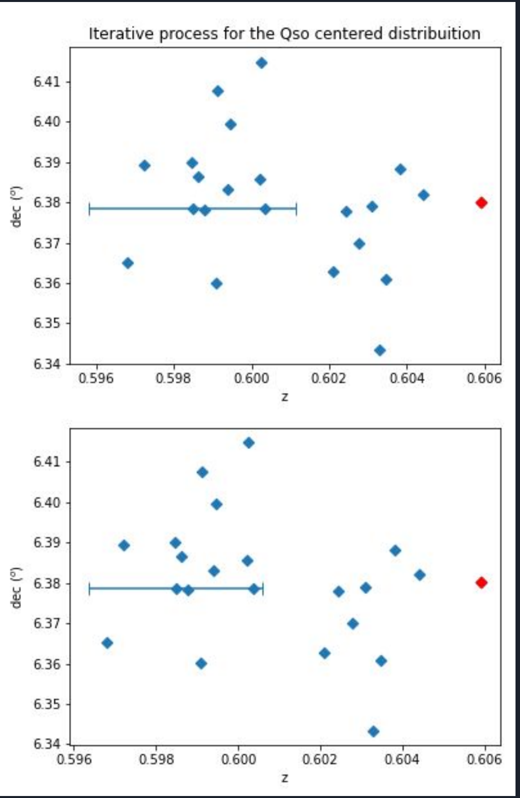
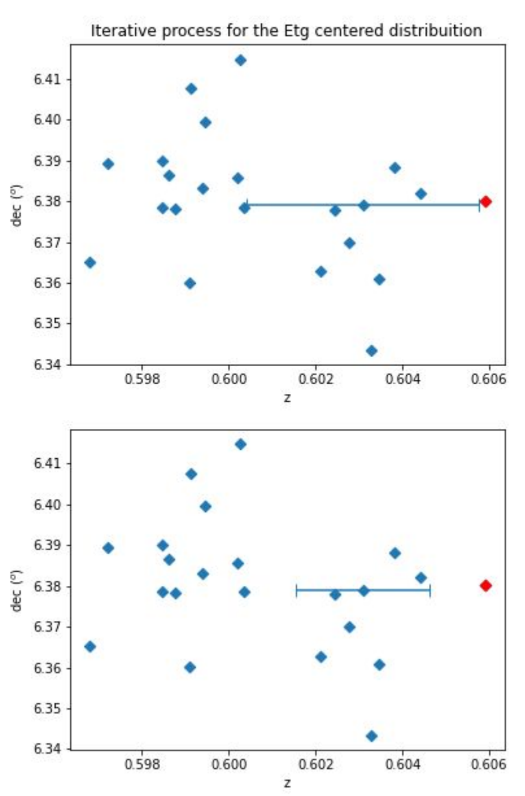
$\sigma(v)_{ETG} =$ 143.7 ± 52.2 $km\ s^{-1}$





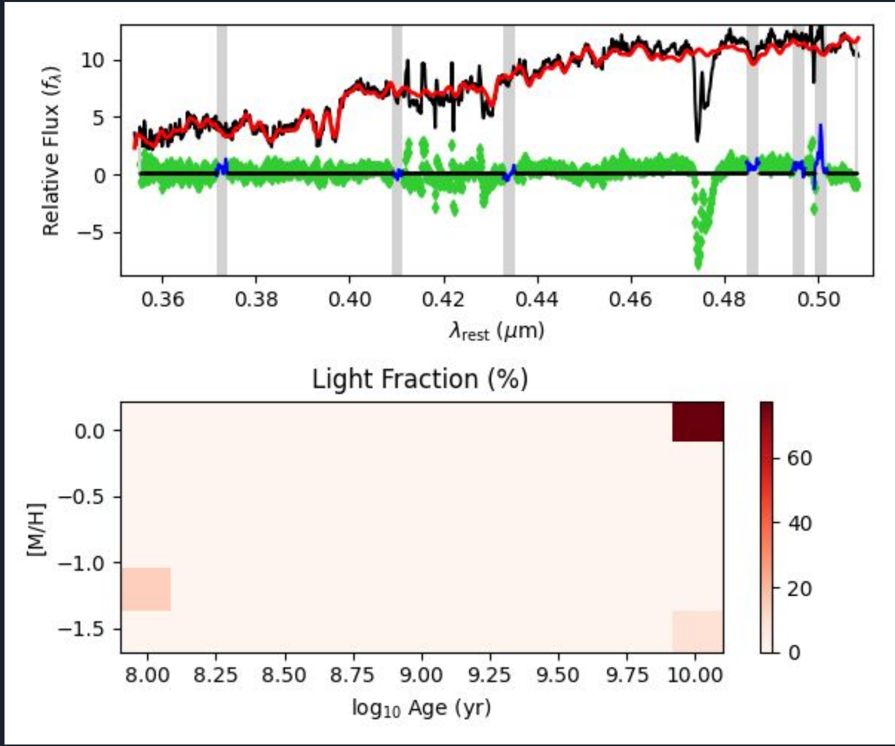
Data analysis: Stellar synthesis of central galaxies (pPXF)

Using the pPXF algorithm, we determined the following parameters for the central galaxies:

ETG

Stellar velocity dispersion:
$\sigma(v)_{\star ETG} = 314 \text{ km s}^{-1}$

Stellar mass:
$M_{\star ETG} = 4.92 \times 10^{11} M_{\odot}$



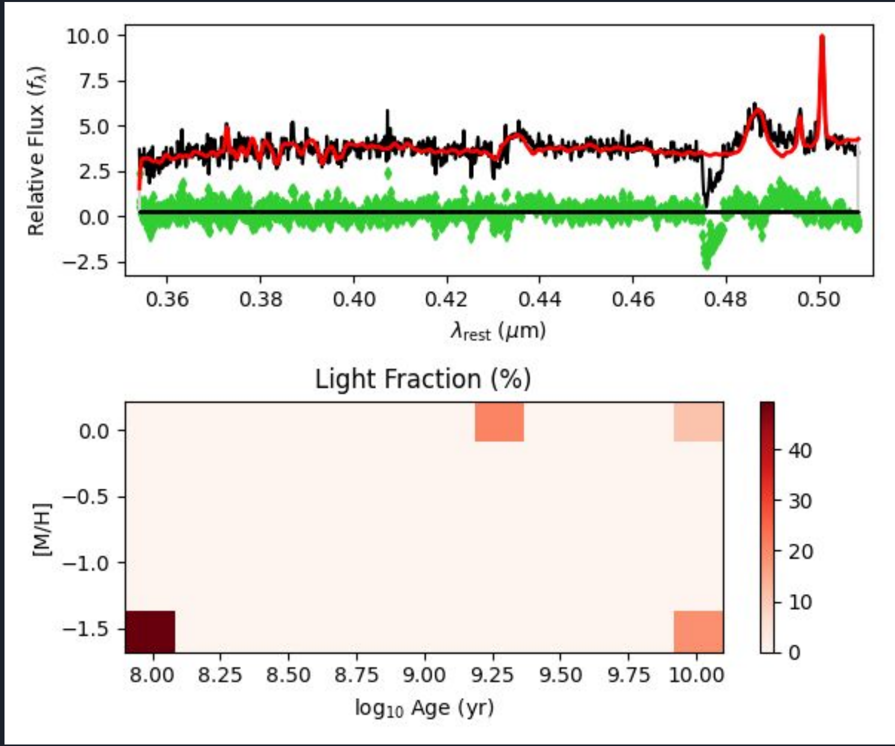
Data analysis: Stellar synthesis of central galaxies (pPXF)

Using the pPXF algorithm, we determined the following parameters for the central galaxies:

QSO

Stellar velocity dispersion: $\sigma(v)_{\star QSO}$ = 162 km s^{-1}

Stellar mass:
$M_{\star QSO} = 1.14 \times 10^{11}\ M_\odot$



Extra: Raio

We estimate the Inertial Radius and the Gravitational Radius of bot 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