Modeling the mass distribution of a pair of galaxy groups

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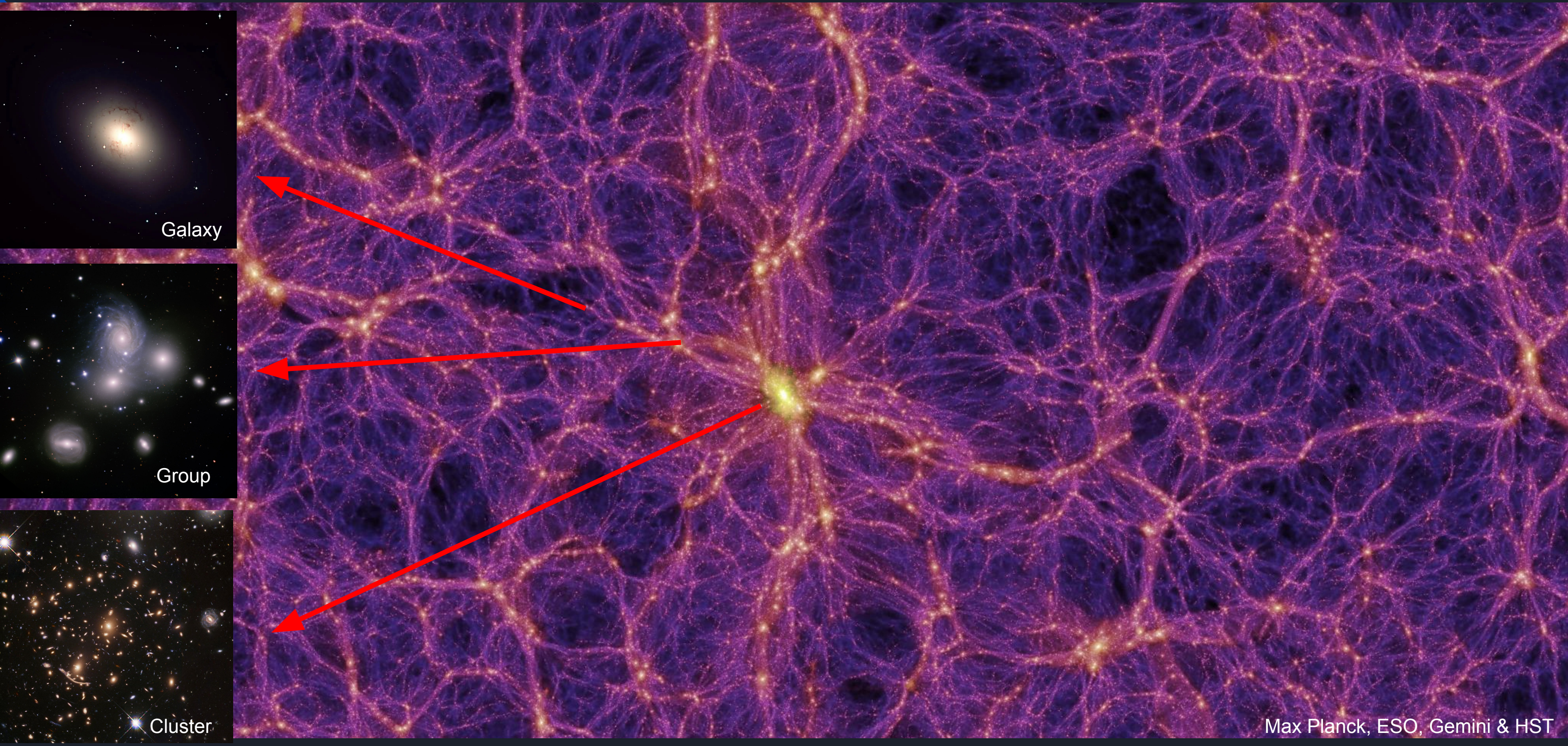
Structure formation in the Universe



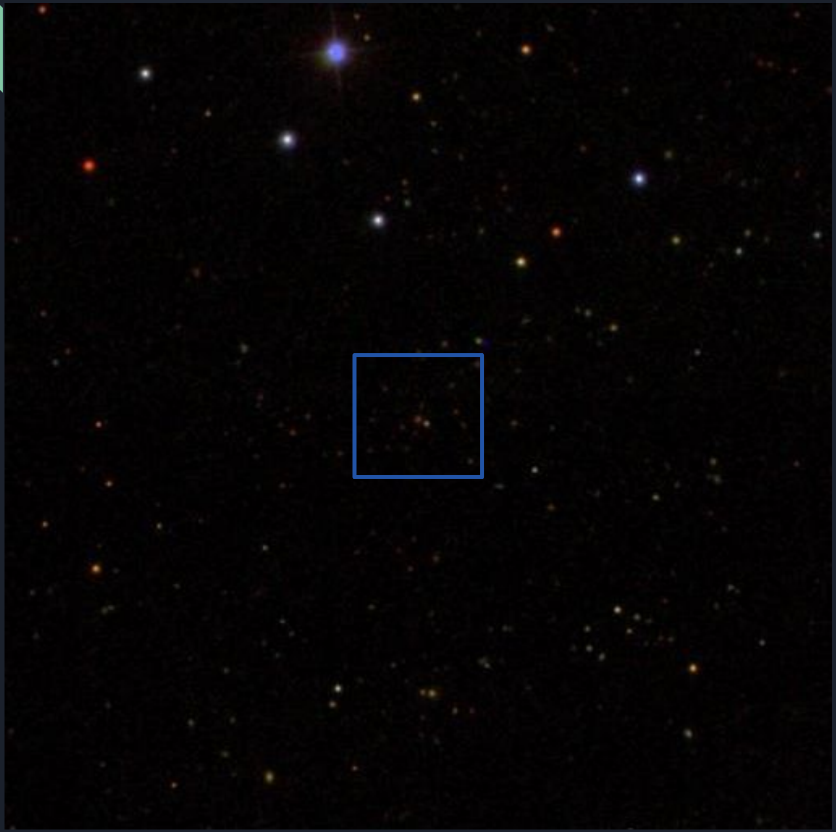
Importance of galaxy groups

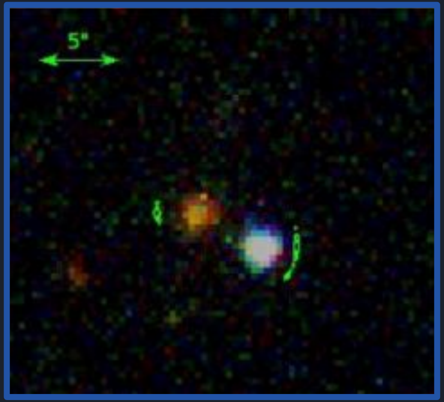
~55% of galaxies in the local universe are members of galaxy groups constituted of two or more galaxies (Eke et al. 2004).

According to Fukugita et al. (1998), galaxy groups host most of the mass in the universe.

The Helms 18 System

The HELMS18 system (SDSS)





HELMS18 lens object

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

Is the lens object a galaxy group?

Objectives

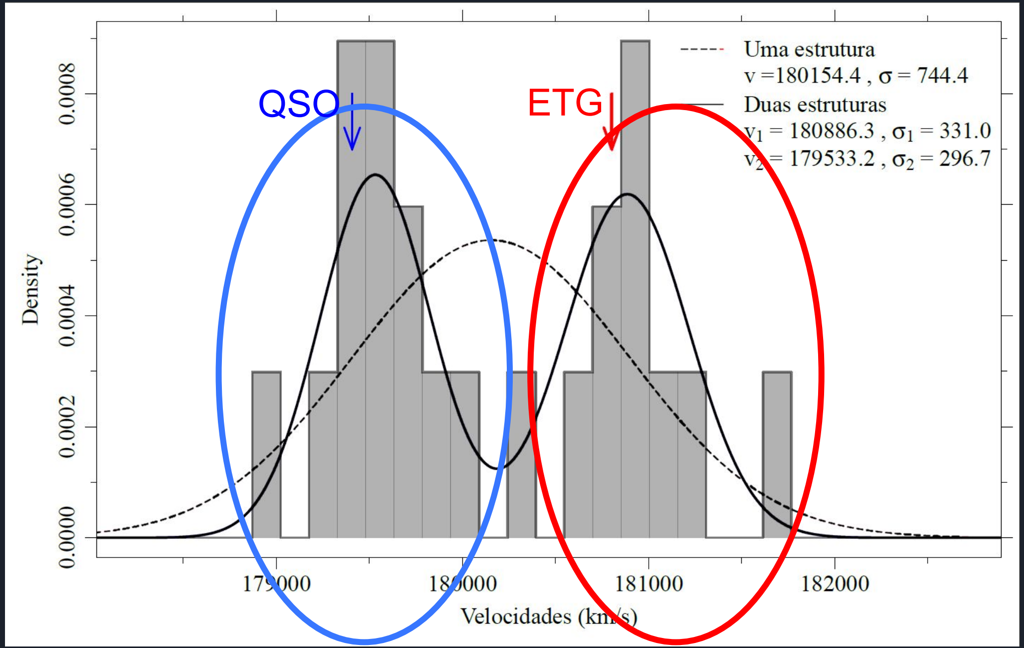
- Confirm if one of the central objects is a QSO;
- Determine which galaxies are part of the structure that acts as a lens;
- Determine the properties of the lens object:
  - Mass
  - Velocity dispersion
- Determine the probability of interaction if there is more than one group.
- Use the kinematic data to build a strong lens model.

Data analysis: Distribution of velocities in the line of sight

We selected the possible members of the structure according to the criterion:

$0.596 < z < 0.608$ (3600 km s^{-1}).

We found 21 members.



Data analysis: Results

N_{ETG} = 9 members.

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

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

N_{QSO} = 13 members.

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

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

Data analysis: Interaction Model

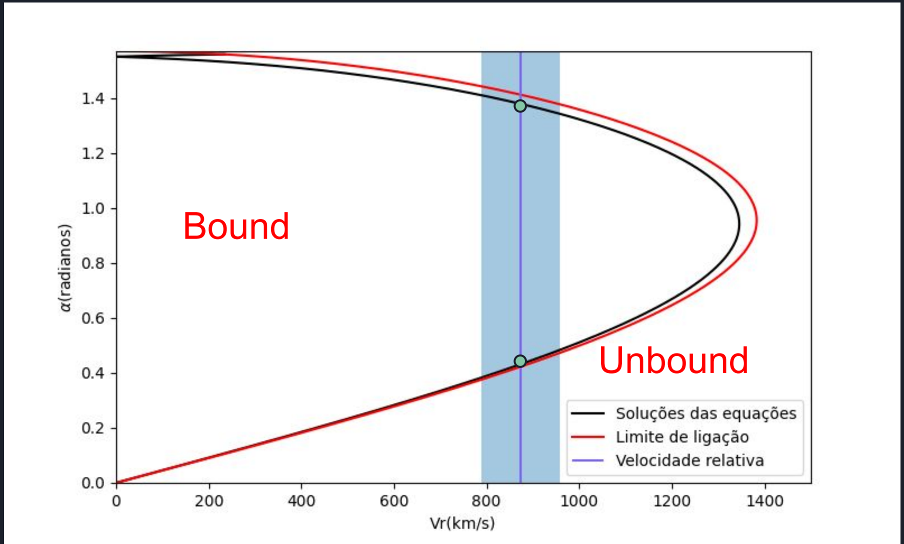
We calculate the probabilities of interaction:

Measured Relative velocity between the central objects

Newton's gravitational binding limit

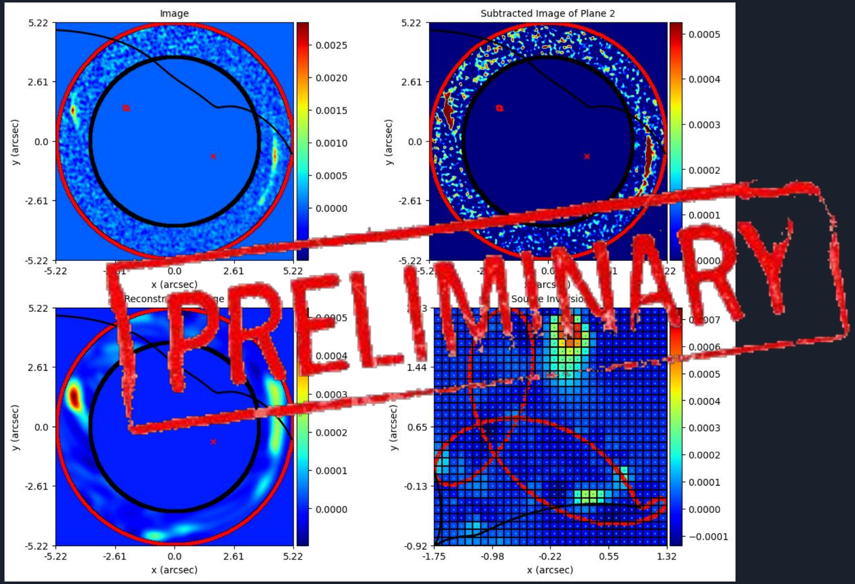
Solutions of the system of equations

Probability 58%



Ongoing work

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



Thank you!

Data analysis: Group Masses

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

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

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

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

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

Tracing mass profiles:

- Tracing mass profiles of different scale structures is very important to understand the formation of the Universe.

- Different techniques have to be used for different scales.

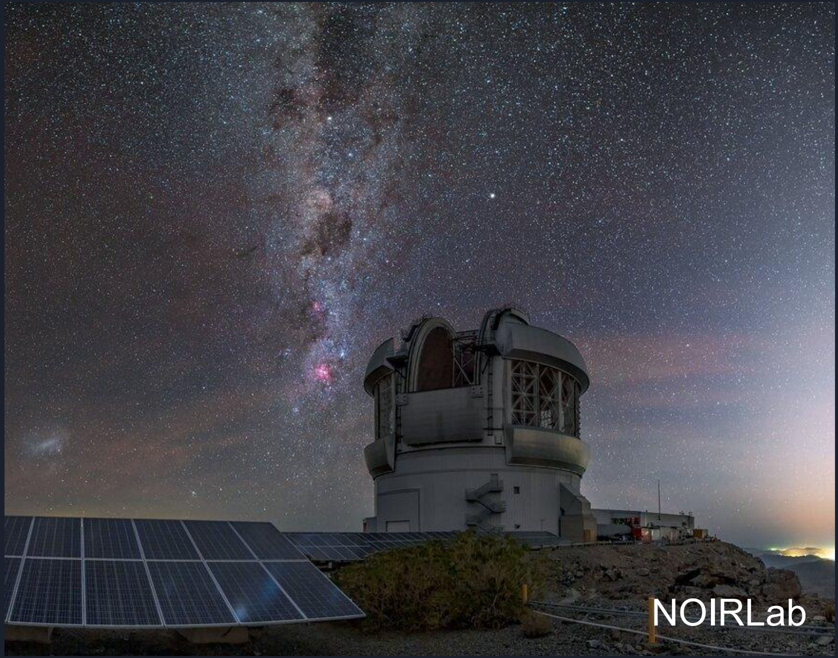
- Combine techniques is the best way to break degeneracies associated to each method.

The Helms 18 System

GMOS instrument

GMOS

Gemini South



Selecting Targets for MOS Observations

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

1. The galaxies in the red sequence: $0.9 \le (r_{\mathrm{petro}} - i_{\mathrm{petro}}) \le 1.5$
2. Galaxies in which the photometric redshifts are around the redshift of the central ETG ($z \sim 0.6$);
3. Other bright galaxies in the field, regardless of their color.

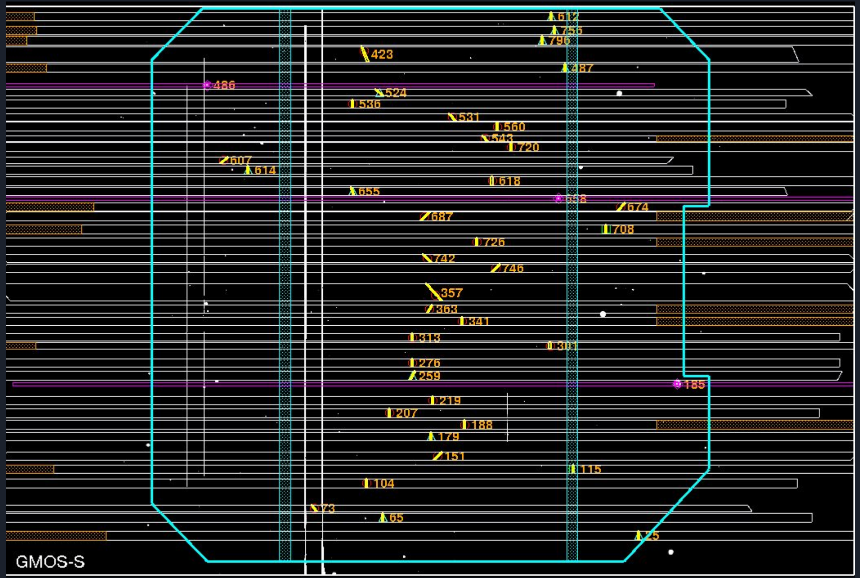
76 galaxies met the criteria

Observation details

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

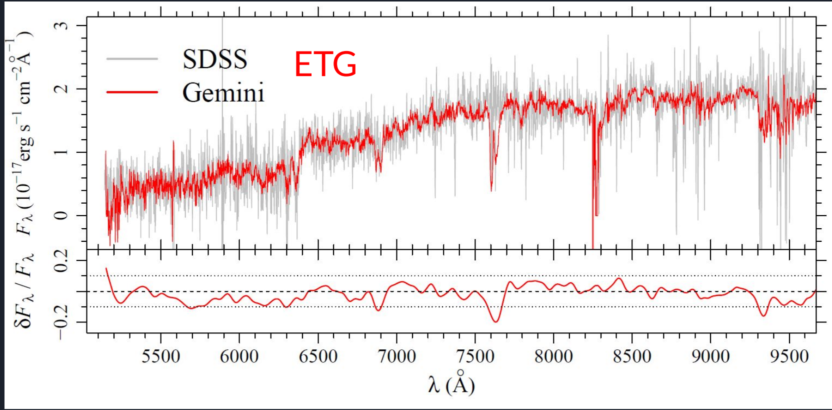
The total exposure time for each mask was **4 h**.

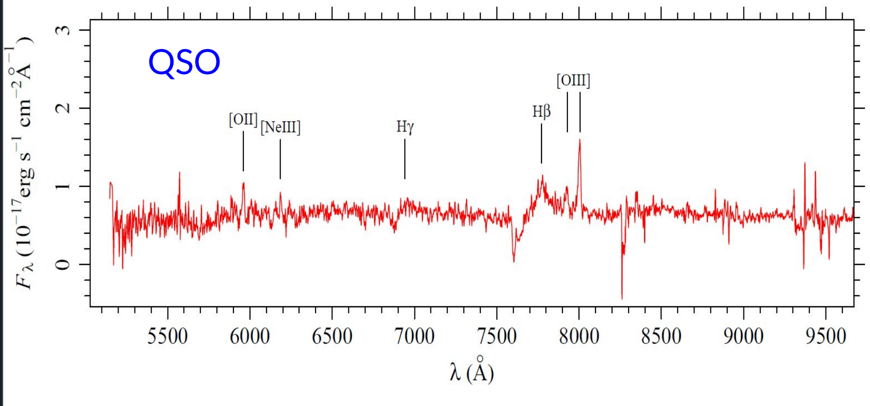
The central galaxies were observed in both masks.



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.



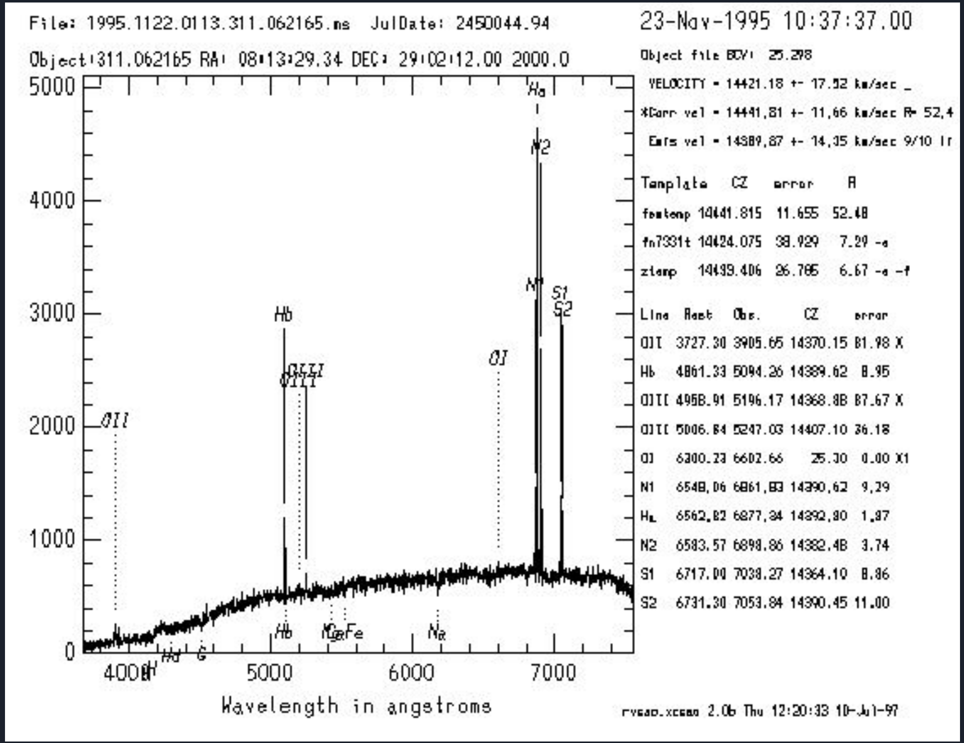


We obtained 70 spectra

Data analysis: Redshift Estimation

We used the XCSAO and EMSAO tasks of the RVSAO package in IRAF to determine the redshifts of the observed galaxies.

The EMSAO task is mainly used when the analyzed galaxy has emission lines while the XCSAO task is used in all other cases.



Data analysis: Distribution of velocities in the line of sight

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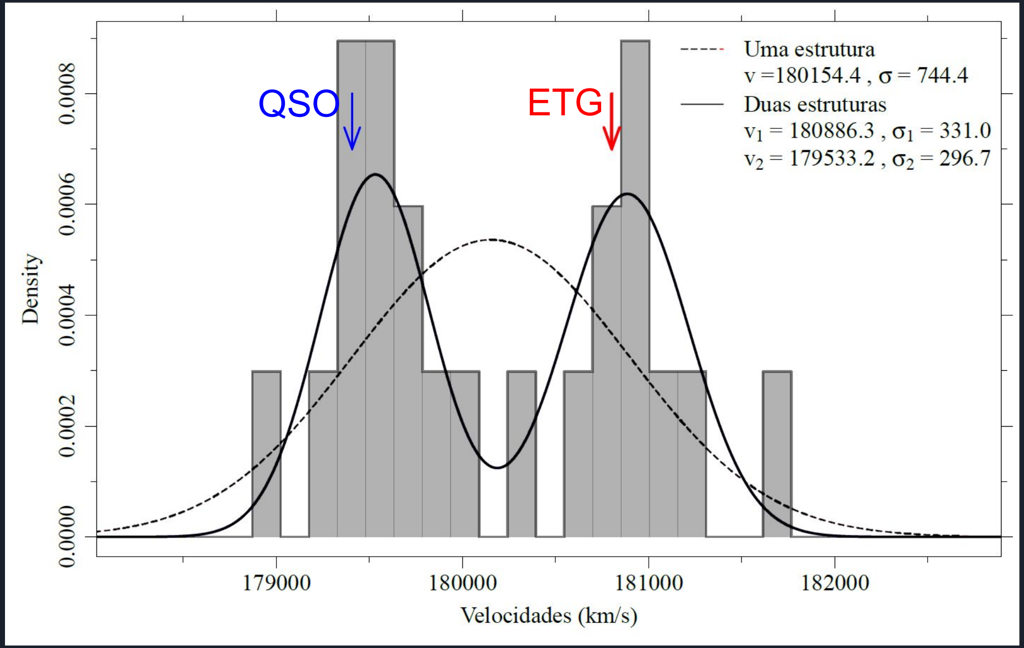
0.596 < z < 0.608 (3600 km s^{-1}).

We found 21 members.

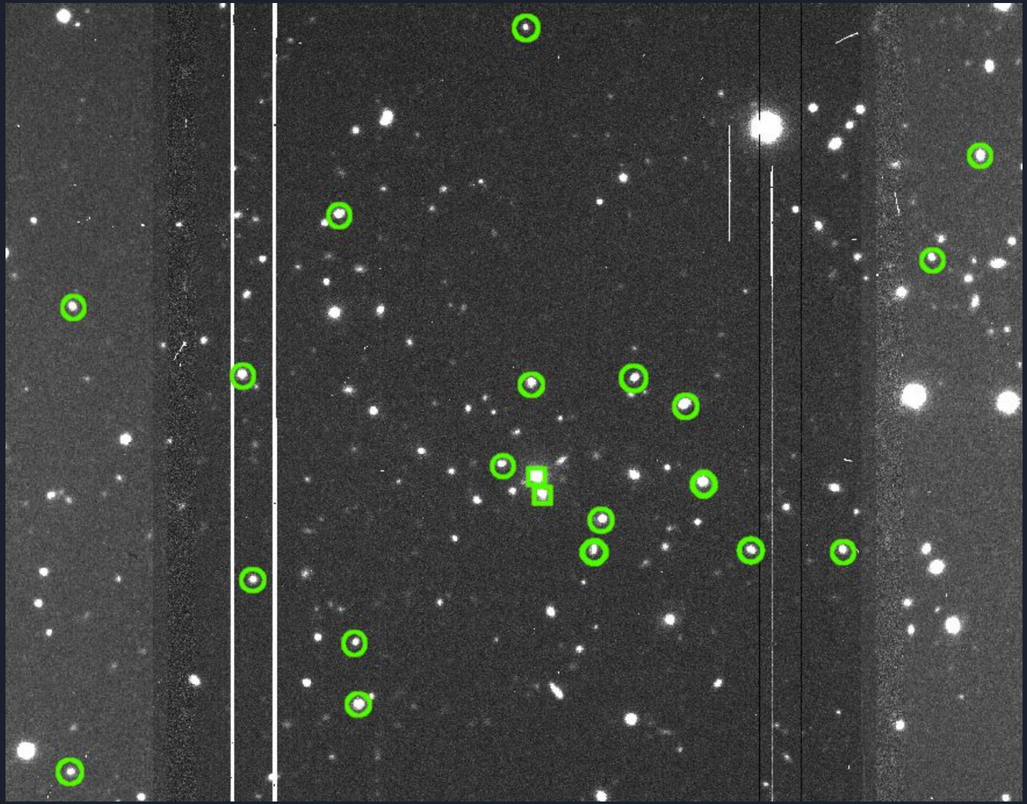


Data analysis: Clustering

(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 $\sigma(v)$.



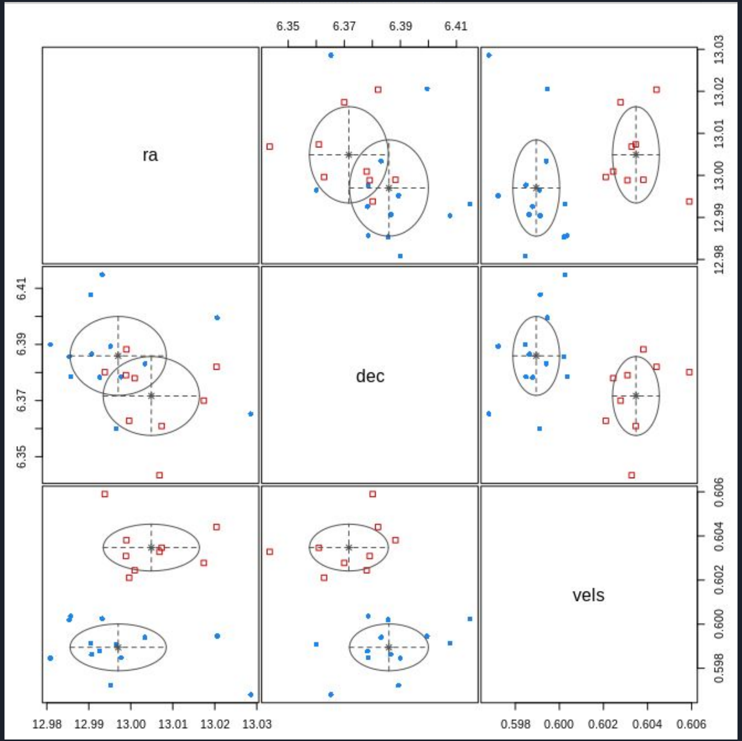
Data analysis: Clustering - Mclust

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.

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

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



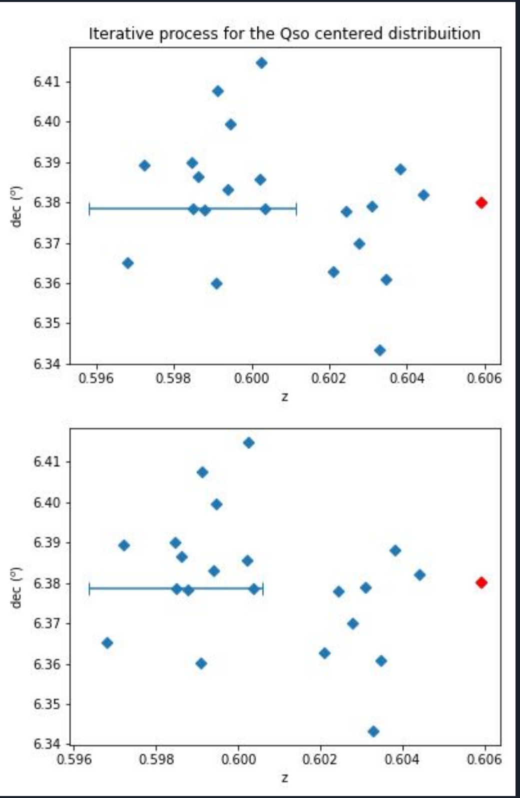
Data analysis: Clustering - Formalism of Wilman et al.

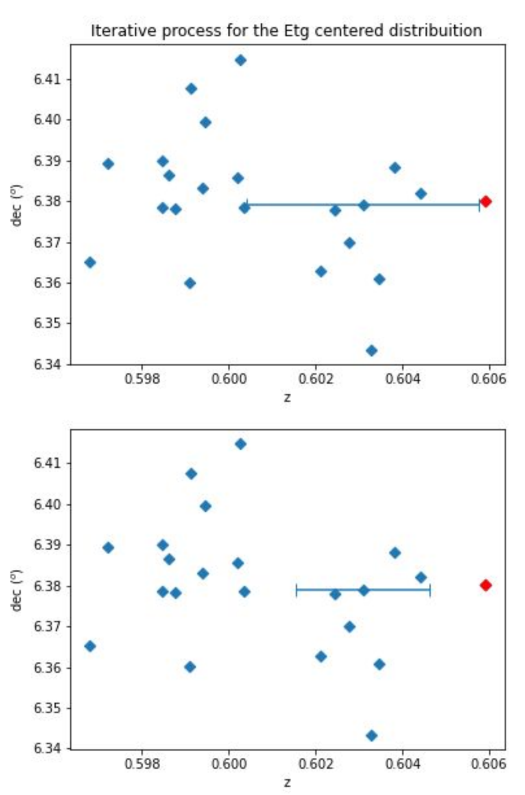
$$\sigma(v)_{obs} = 250(1 + z_{cen})\, km\, s^{-1}$$

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

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

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.

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

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

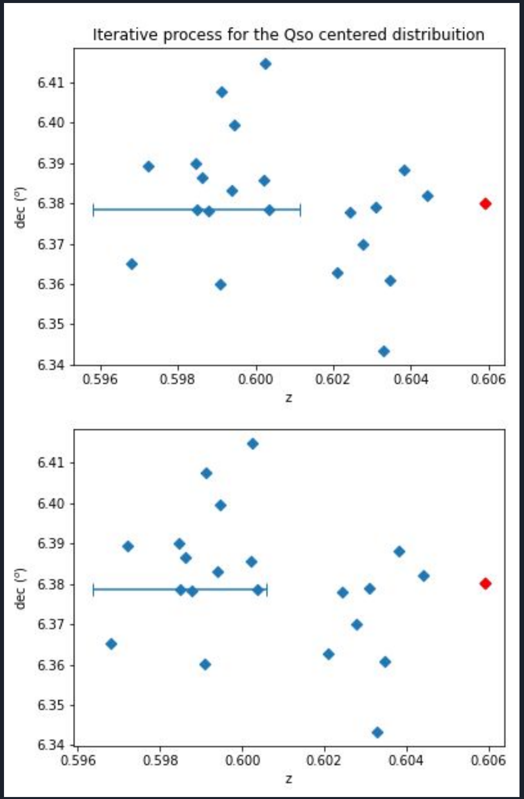
$\sigma(v)_{QSO} =$ 197.5 ± 65.8 $km\ s^{-1}$

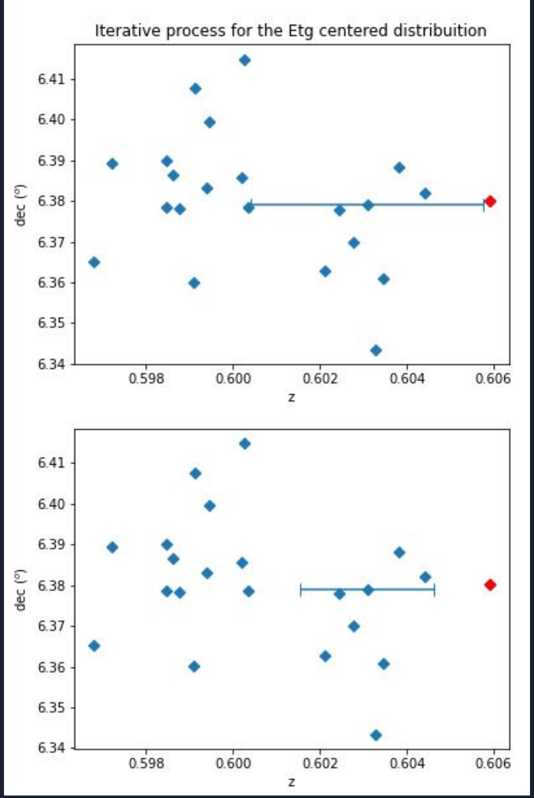
With the red galaxy:

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

without

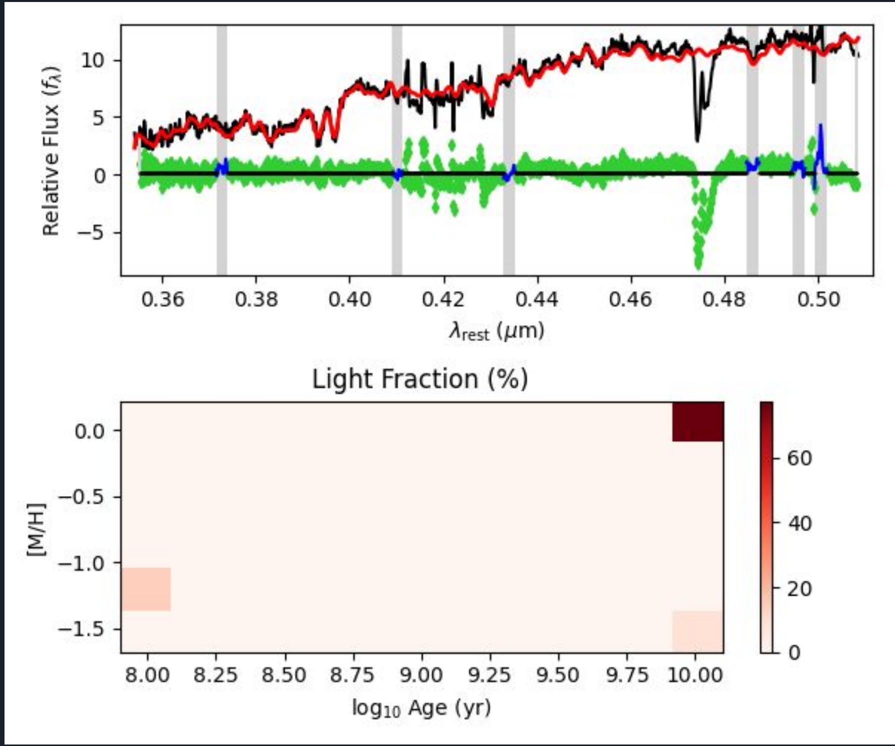
$\sigma(v)_{ETG} =$ 143.7 ± 52.2 $km\ s^{-1}$





Data analysis: Stellar synthesis of central galaxies (pPXF)

Using the pPXF algorithm (Cappellari, 2023), we determined the following parameters for the central galaxies:



ETG

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

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

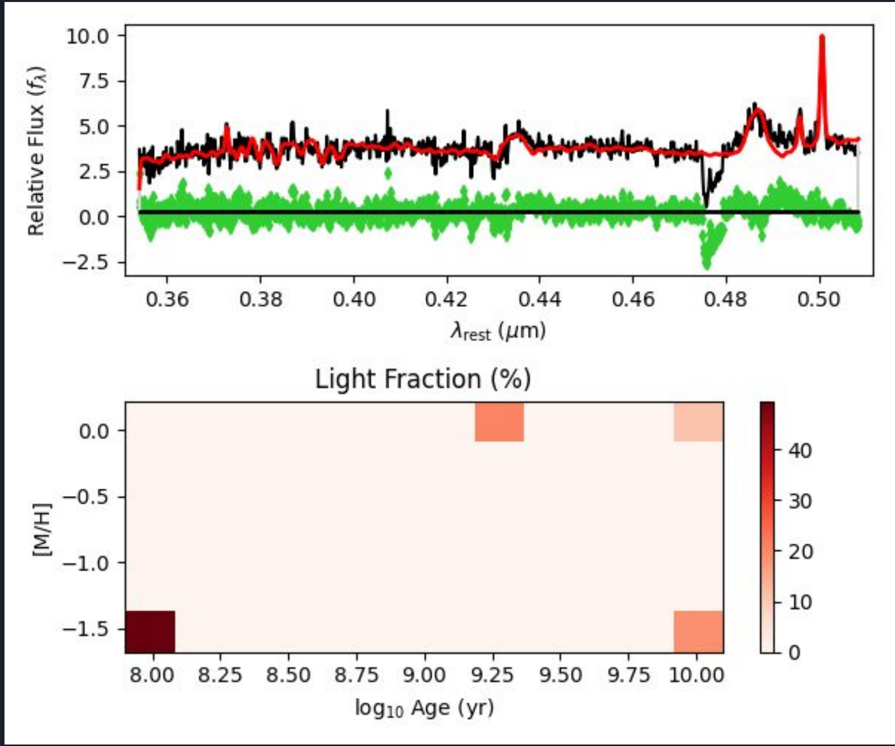
Data analysis: Stellar synthesis of central galaxies (pPXF)

Using the pPXF algorithm (Cappellari, 2023), we determined the following parameters for the central galaxies:

QSO

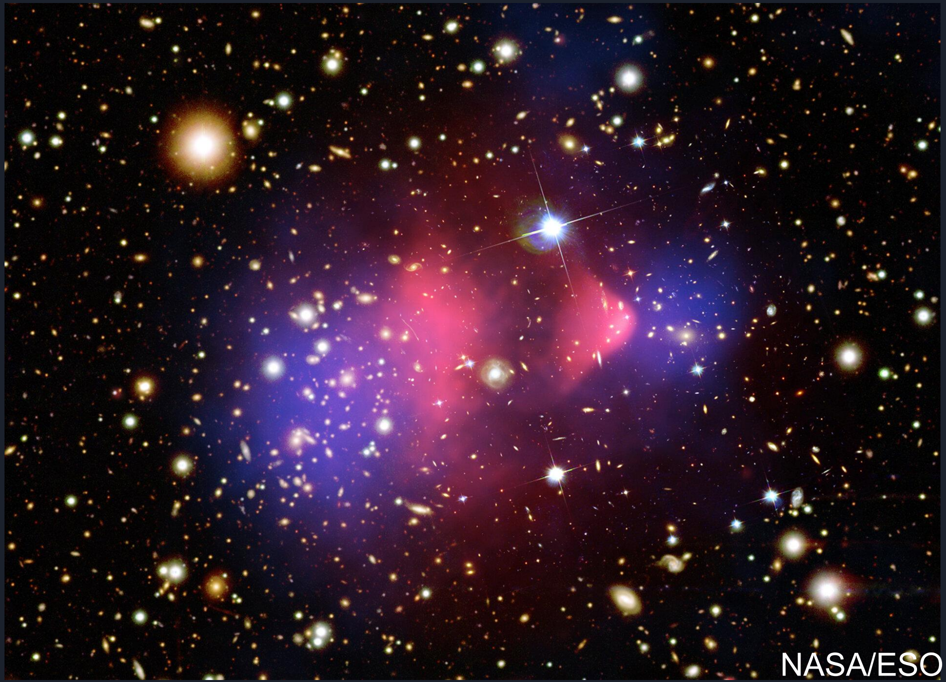
Stellar velocity dispersion:
$\sigma(v)_{\star QSO}$ = 162 km s^{-1}

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



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:

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

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

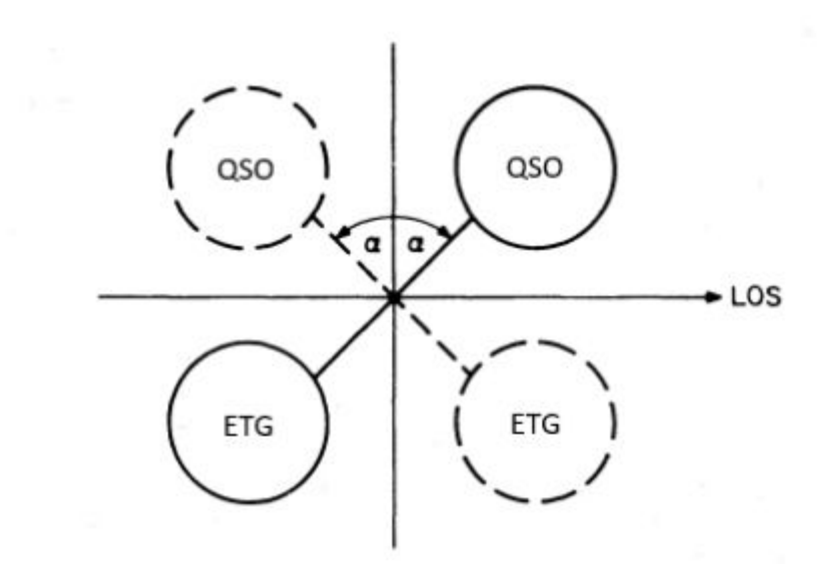
$$V = \left(\frac{2GM}{R_m}\right)^{\frac{1}{2}} \frac{\sin\chi}{(1 - \cos\chi)}$$

Data analysis: Interaction Model

We connect the equations of motion with the observables $\mathbf{R_p}$ e $\mathbf{V_r}$ with:

$$R_p = R\cos\alpha$$

$$V_r = V\sin\alpha$$



Data analysis: Interaction Model

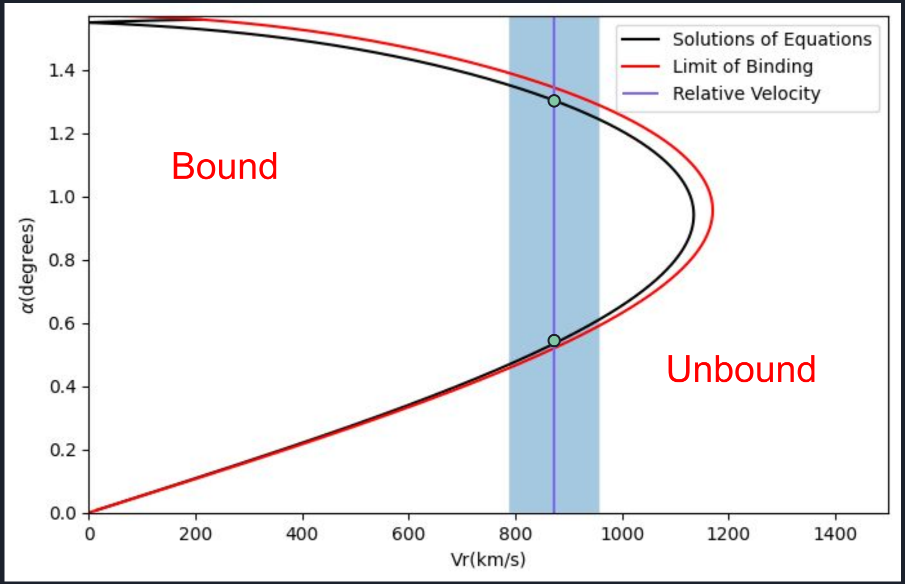
We connect the equations of motion with the observables **R_p** e **V_r** with:

$$R_p = R\cos\alpha$$

$$V_r = V\sin\alpha$$

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

Model: Mclust



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

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.

Conclusion

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)

Conclusion

In this work, we obtained the following results:

- Viral mass of the groups;

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

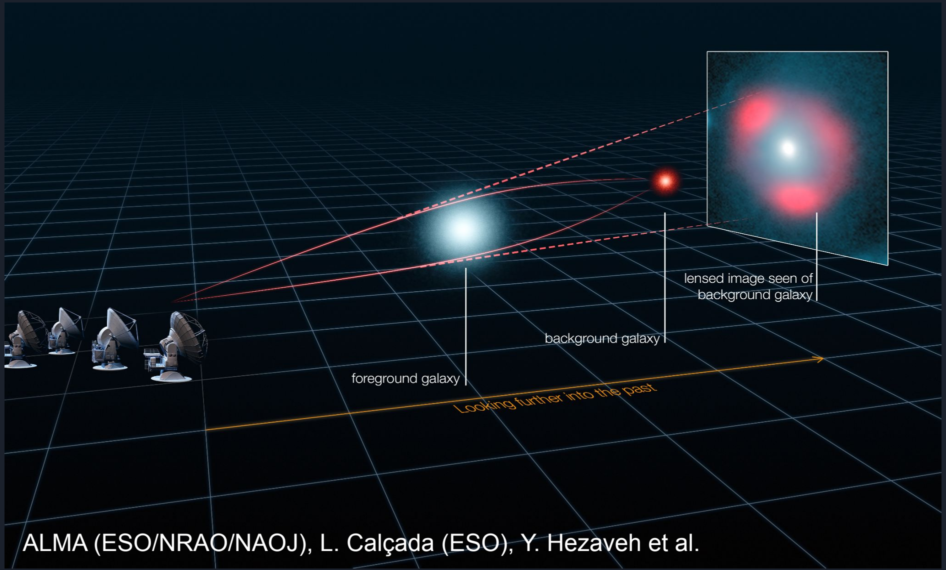
$$M_{v_{ETG}} = (3.4 \pm 0.1) \times 10^{12} M_{\odot} \quad \text{ou} \quad M_{v_{ETG}} = (8.6 \pm 0.2) \times 10^{12} M_{\odot}$$

- 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).

Tracing mass profiles: The Galactic Scale

Strong Gravitational Lensing

Joachim Dietrich

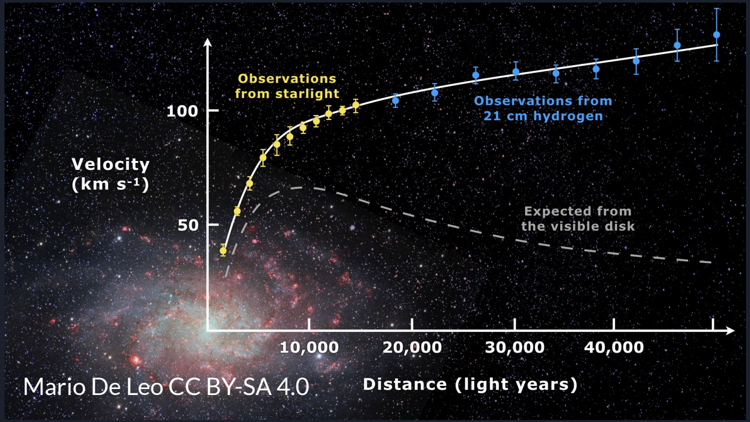


ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Tracing mass profiles: The Galactic Scale

Strong Gravitational Lensing

Stellar and gas kinematics



Tracing mass profiles: The Galactic Scale

Strong Gravitational Lensing

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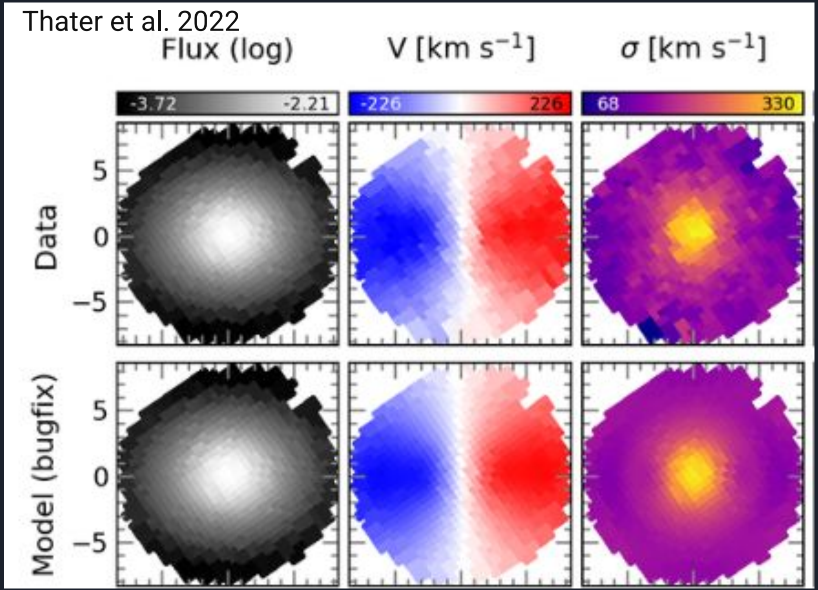
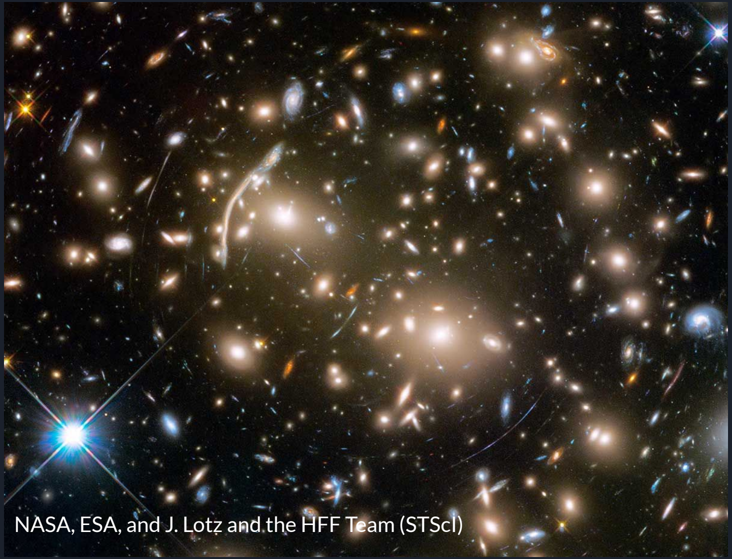


Tracing mass profiles: The Cluster Scale

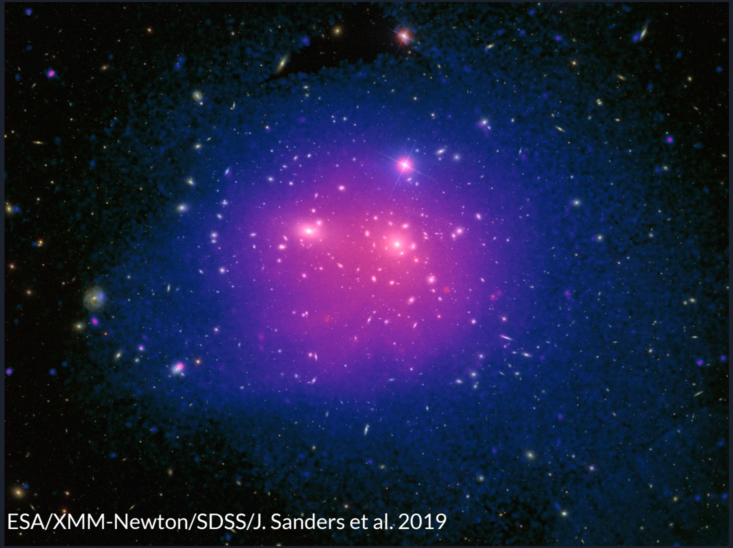
We consider clusters bound structures with hundreds of members.

Strong and Weak Lensing



NASA, ESA, and J. Lotz and the HFF Team (STScI)

X-ray Emission



ESA/XMM-Newton/SDSS/J. Sanders et al. 2019

+ member kinematics, number density, Sunyaev-Zeldovich effect.

Tracing mass profiles: Gravitational interactions

Interactions and mergers

- Through gravitational interaction smaller objects assimilate into bigger objects.

Galaxy

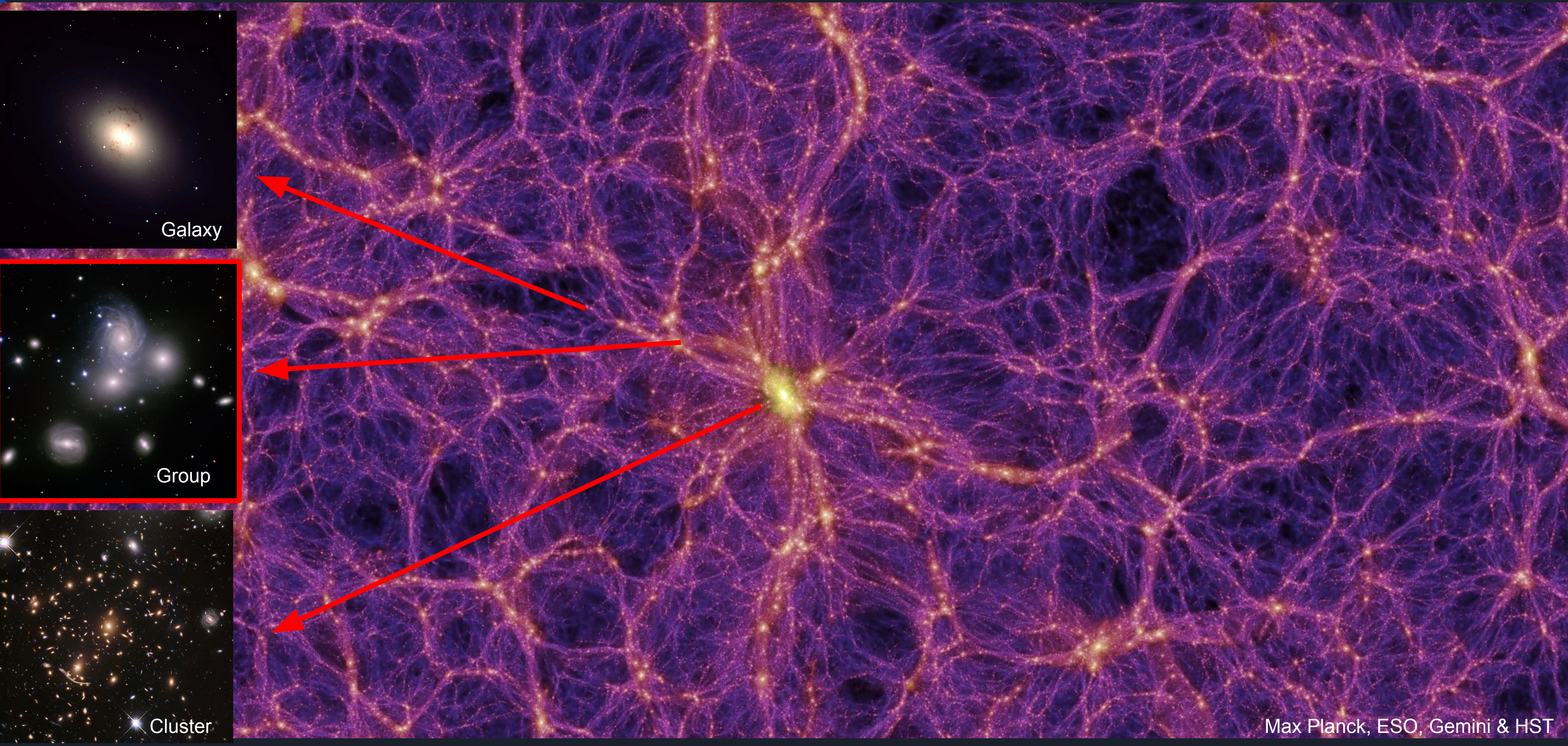
Disturbances and asymmetries in the luminous component of the galaxy.

Clusters

Disturbances and asymmetries in the X-ray emissions.

Bullet Cluster

Structure formation in the Universe



What is a galaxy group

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

Interaction of large scale structures

- Interactions
  - Has a fundamental role in the hierarchical structure formation.
  - Studied by X-ray emission and galaxy distribution and kinematics.
  - Group interactions are less studied.

Raio-X: NASA/CXC/CfA/M.Markevitch, optic and lens map: NASA/STScI, Magellan/U.Arizona/D.Clowe, lens map: ESO WFI

Bullet Cluster

Dark matter haloes

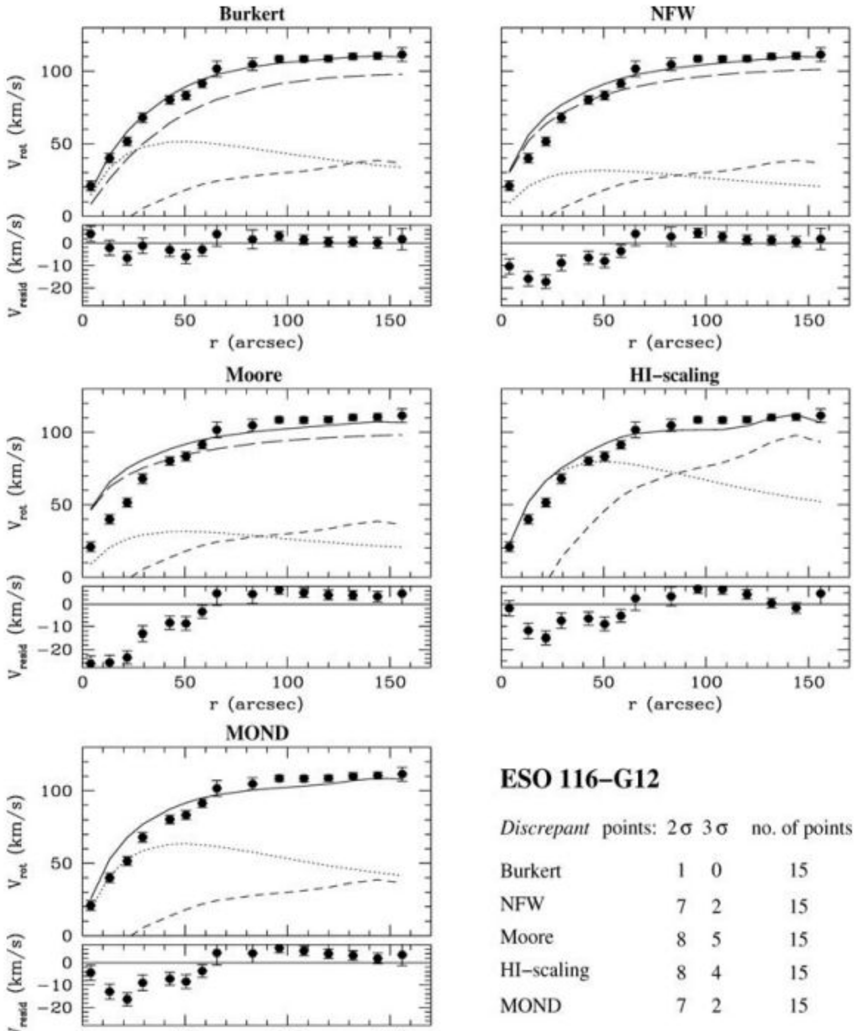
- Cuspy vs. Core

NFW profile

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Burkert profile

$$\rho(r) = \frac{\rho_0 r_{core}^3}{(r + r_{core})(r^2 + r_{core}^2)}$$



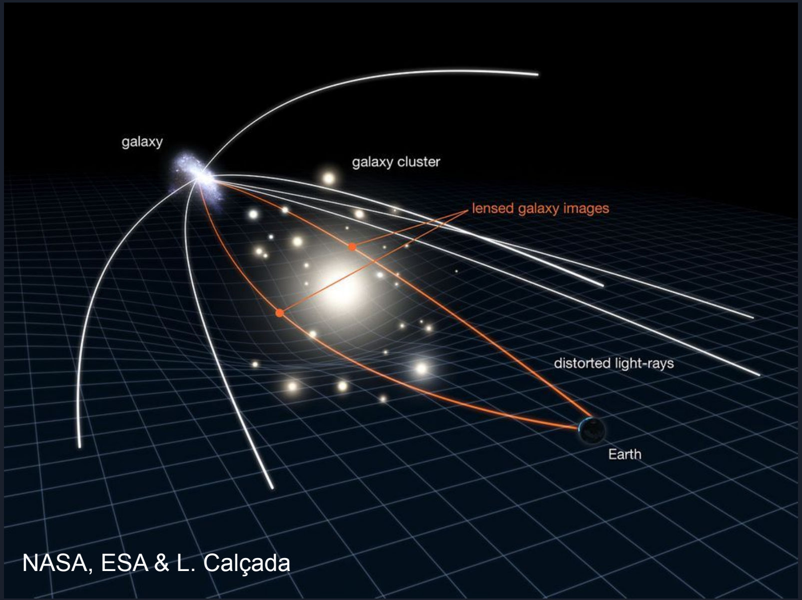
(G. Gentile et al. 2004)

Galaxy groups and dark matter haloes

Some dark matter profiles results found in the literature:

- Simon et. al. (2004) / Galaxies/ Found core and cuspy
- Genina et. al. (2017)/ Galaxies/ Found core and cuspy
- Chan, Man Ho (2018)/ Clusters/ Highly cuspy with variation by baryonic processes.
- K., Gopika and Desai, Shantanu (2006) / Clusters / Cuspy
- K., Gopika and Desai, Shantanu (2021) / Groups / Cuspy with high variation.

Gravitational Lensing

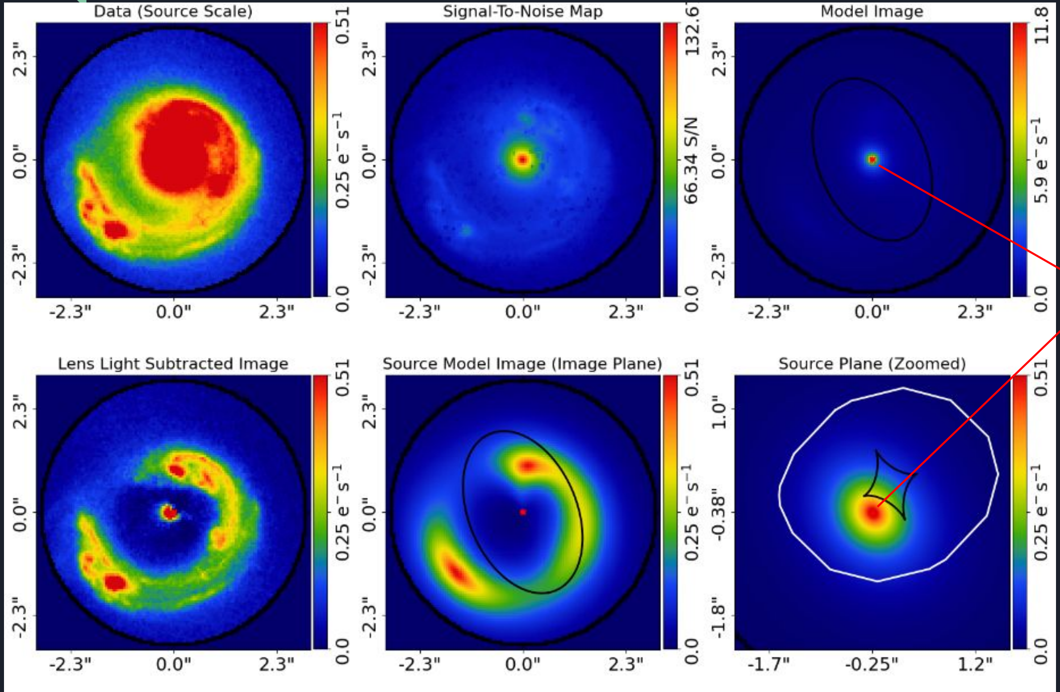


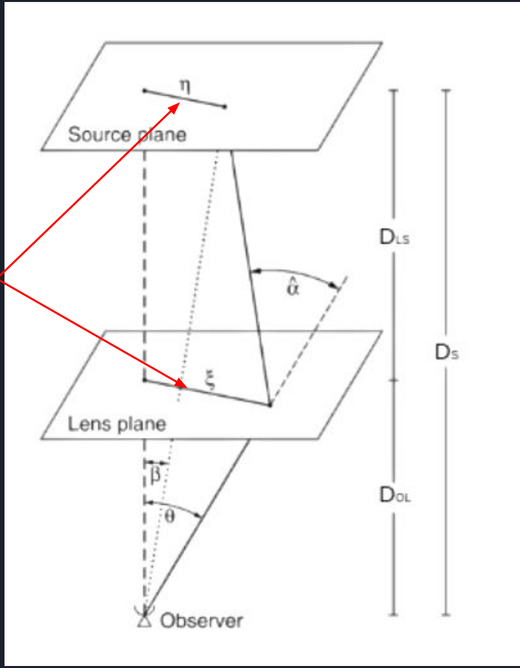
NASA, ESA & L. Calçada

ESA/Hubble & NASA

Calculating baryonic and dark matter mass

Estimating mass via gravitational lensing modeling:





extra: source of second claim

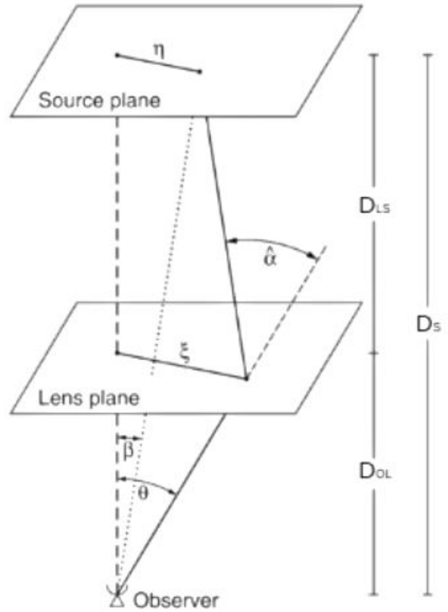
Table 3. The Baryon Budget

	Component	Central	Maximum	Minimum	Grade[a]
	Observed at $z \approx 0$:				
1	stars in spheroids	$0.0026h_{70}^{-1}$	$0.0043h_{70}^{-1}$	$0.0014h_{70}^{-1}$	A
2	stars in disks	$0.00086h_{70}^{-1}$	$0.00129h_{70}^{-1}$	$0.00051h_{70}^{-1}$	A–
3	stars in irregulars	$0.000069h_{70}^{-1}$	$0.000116h_{70}^{-1}$	$0.000033h_{70}^{-1}$	B
4	neutral atomic gas	$0.00033h_{70}^{-1}$	$0.00041h_{70}^{-1}$	$0.00025h_{70}^{-1}$	A
5	molecular gas	$0.00030h_{70}^{-1}$	$0.00037h_{70}^{-1}$	$0.00023h_{70}^{-1}$	A–
6	plasma in clusters	$0.0026h_{70}^{-1.5}$	$0.0044h_{70}^{-1.5}$	$0.0014h_{70}^{-1.5}$	A
7a	warm plasma in groups	$0.0056h_{70}^{-1.5}$	$0.0115h_{70}^{-1.5}$	$0.0029h_{70}^{-1.5}$	B
7b	cool plasma	$0.002h_{70}^{-1}$	$0.003h_{70}^{-1}$	$0.0007h_{70}^{-1}$	C
7′	plasma in groups	$0.014h_{70}^{-1}$	$0.030h_{70}^{-1}$	$0.0072h_{70}^{-1}$	B
8	sum (at $h = 70$ and $z \simeq 0$)	0.021	0.041	0.007	...
	Gas components at $z \approx 3$:				
9	damped absorbers	$0.0015h_{70}^{-1}$	$0.0027h_{70}^{-1}$	$0.0007h_{70}^{-1}$	A–
10	Lyman-α forest clouds	$0.04h_{70}^{-1.5}$	$0.05h_{70}^{-1.5}$	$0.01h_{70}^{-1.5}$	B
11	intercloud gas (HeII)	...	$0.01h_{70}^{-1.5}$	$0.0001h_{70}^{-1}$	B
	Abundances of:				
12	deuterium	$0.04h_{70}^{-2}$	$0.054h_{70}^{-2}$	$0.013h_{70}^{-2}$	A
13	helium	$0.010h_{70}^{-2}$	$0.027h_{70}^{-2}$		A
14	Nucleosynthesis	$0.020h_{70}^{-2}$	$0.027h_{70}^{-2}$	$0.013h_{70}^{-2}$	...

[a]Confidence of evaluation, from A (robust) to C (highly uncertain)

Fukugita et al. (1998)

Gravitational Lensing



Bartelmann & Schneider (2001).

$$\beta = \theta - \frac{D_{LS}}{D_S}\hat{\alpha}$$

no cluster eu falei de strong lensing mas n falei de weak lensing

na parte de mergers eu como via em cluster, mas eu esqueci de falar que n era o unico método

slide 11 o texto estava muito próximo