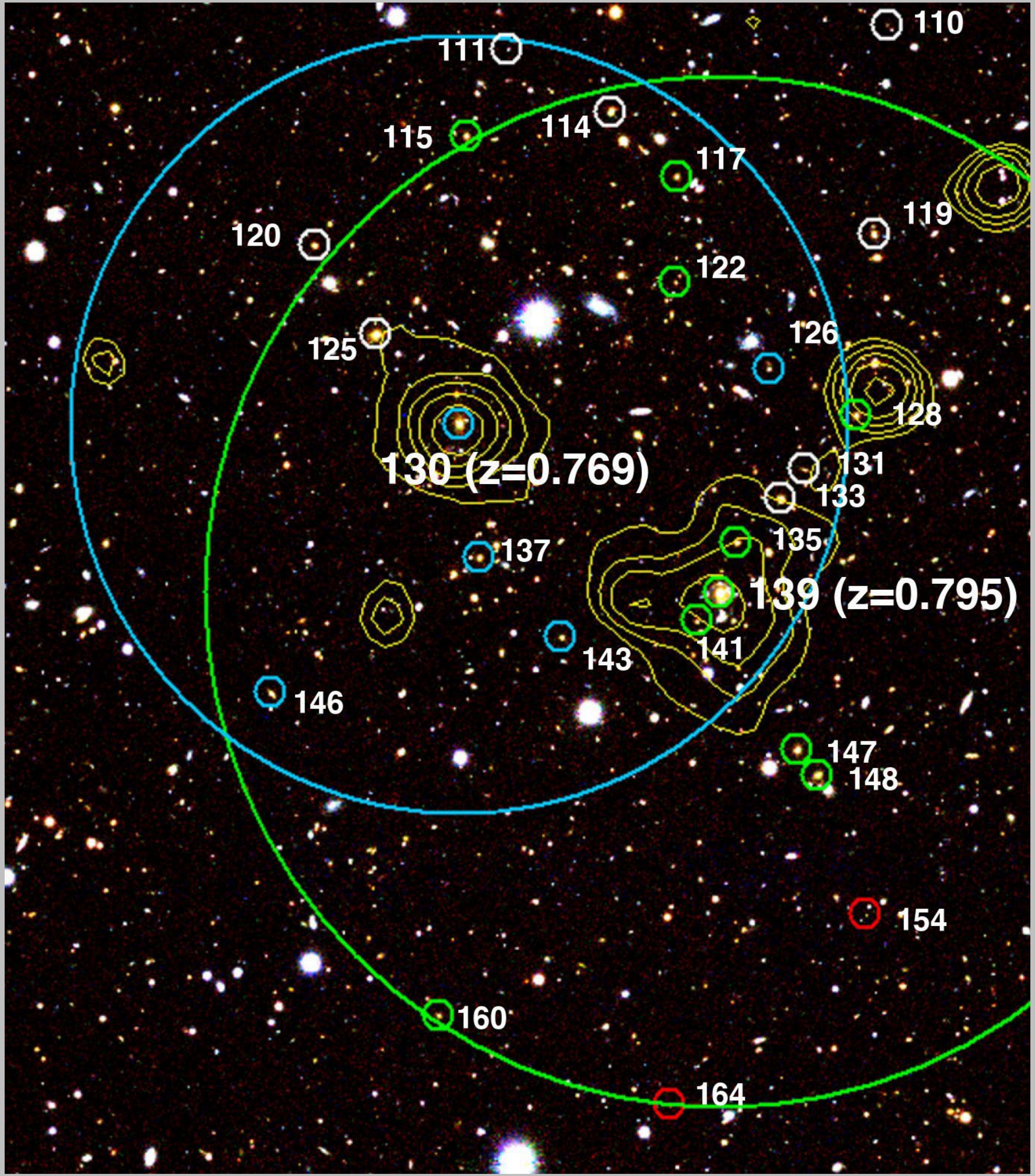


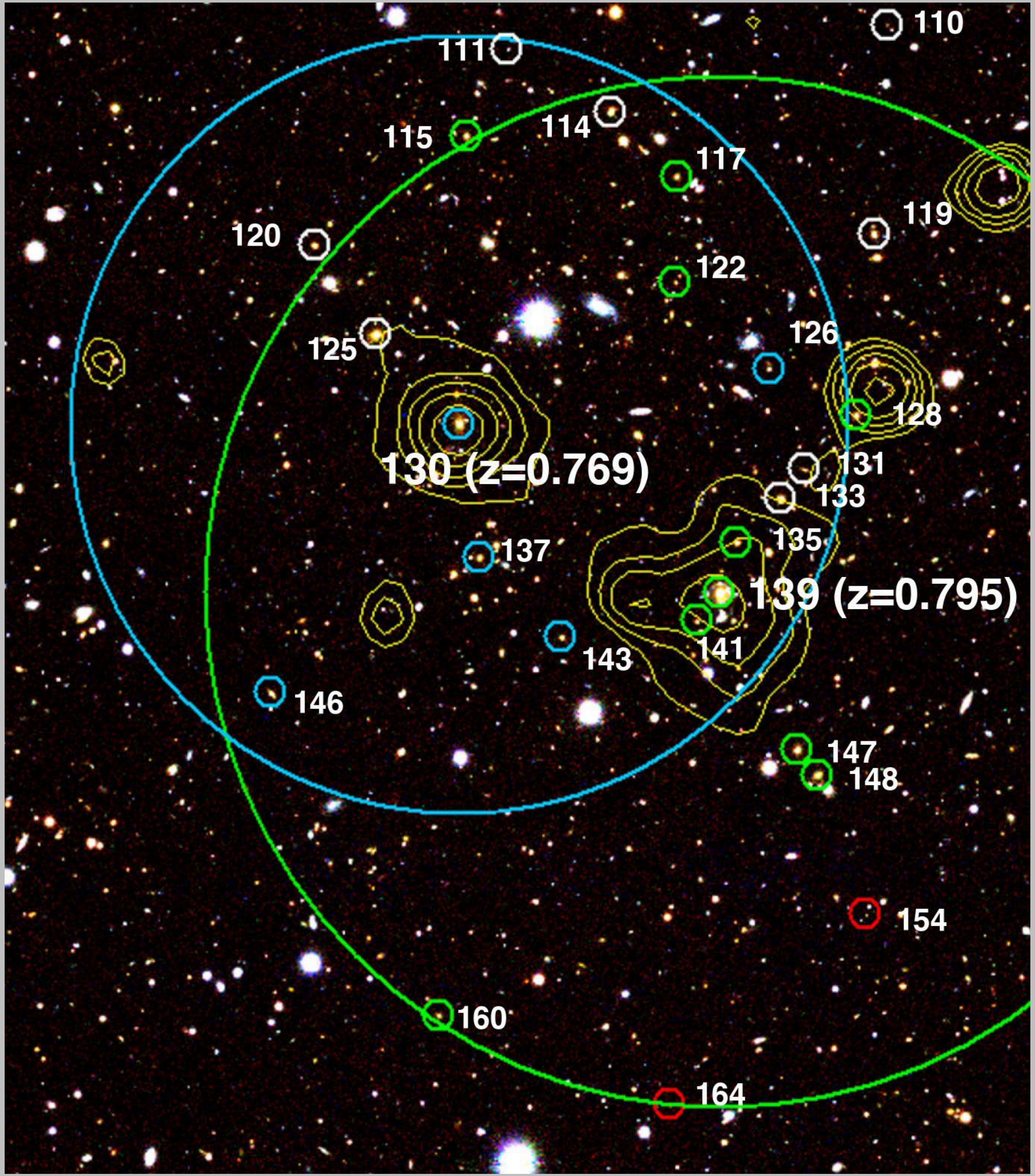
The Spectroscopic Survey of Galaxy Clusters at z~0.8 Using MMT/Binospec

Jiyun Di

1ST YEAR M.A. STUDENT

Steward Observatory, University of Arizona

Dept. of Physics and Astronomy, Stony Brook University



Research Category

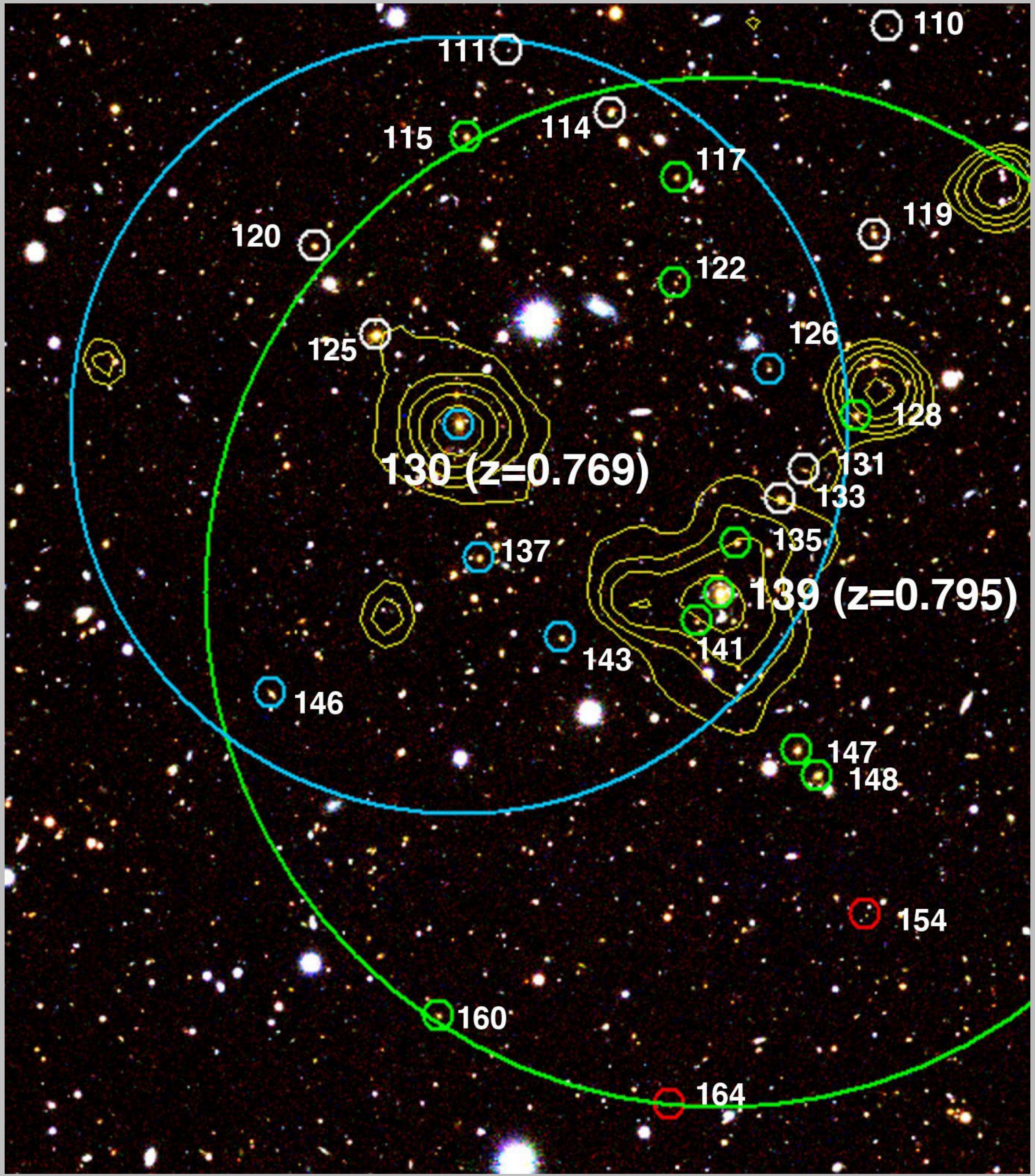
- Optical/IR Observation related
- Cosmology related
- Cluster of Galaxies

Group

Eiichi Egami	(Supervisor, Steward faculty)
Jiyun Di	(Me)
Kenneth Wong	(Coll., U of Tokyo, NAOJ)

...

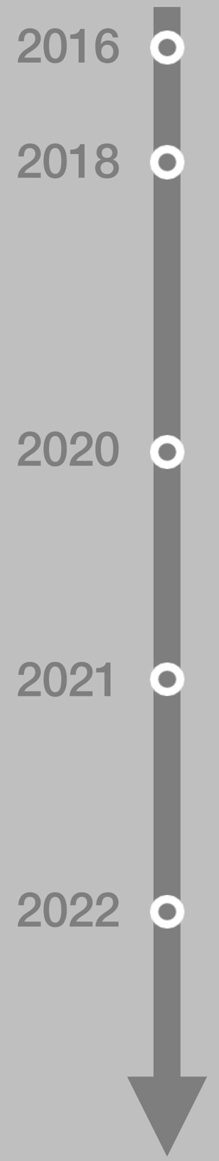
MMT/Binospec: z~0.8 Galaxy Cluster Spec Survey

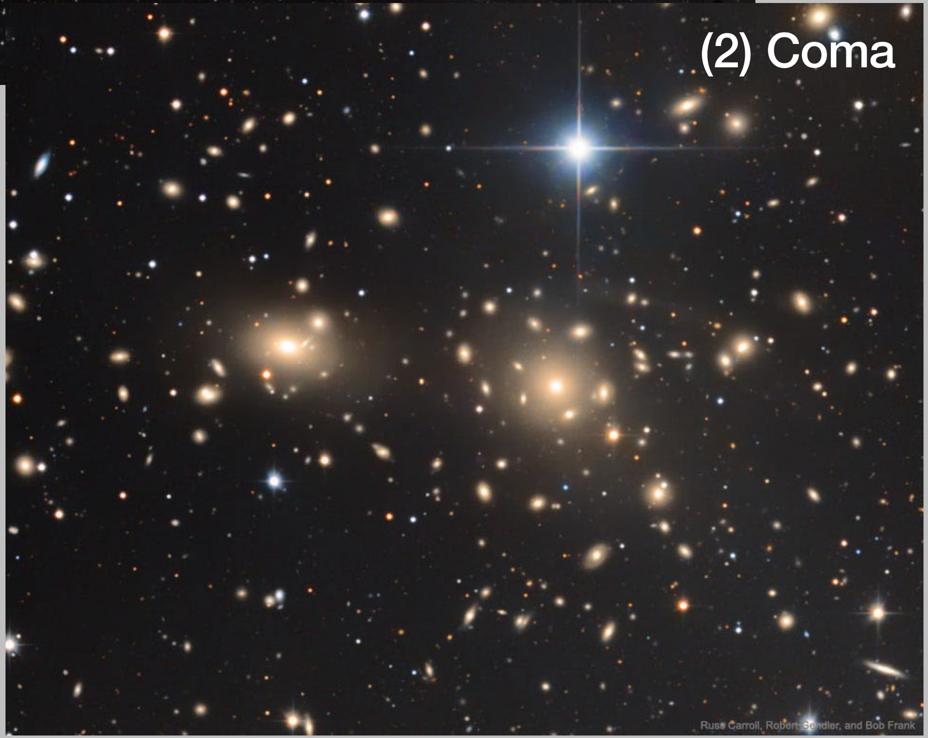


Outline

1. Background
2. Introduction
3. Observations
4. Play with spectra!
5. Results
6. Future goals

Timeline of this research





Background Knowledge

Cluster of Galaxies (CoG)

- Largest gravitational field labs
- Dark matter halo wrapped
- E.g., Virgo (~$10^{15}M_\odot$), Coma (~$10^{14}M_\odot$)

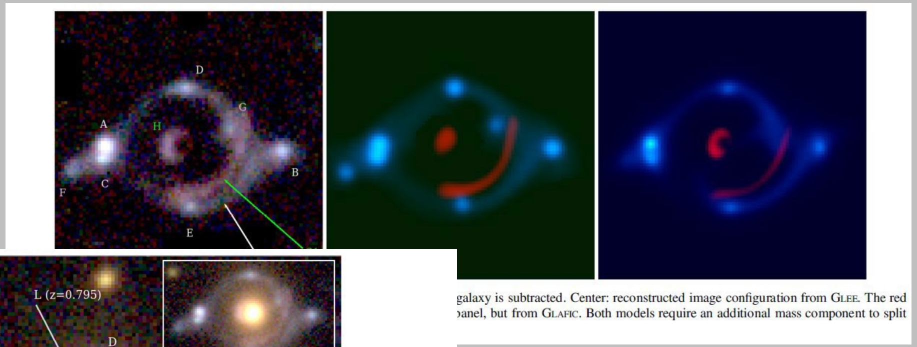
Strong Gravitational Lens (GL)

- Usually found in CoGs, massive galaxies, …

“How the light from galaxies were bended?”
“Masses!”

--- Zwicky, 1937

Credits: (1) Fernando Pena (2) NASA/Carroll et al



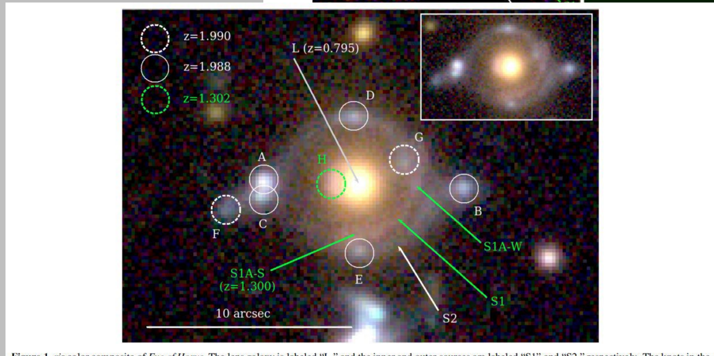
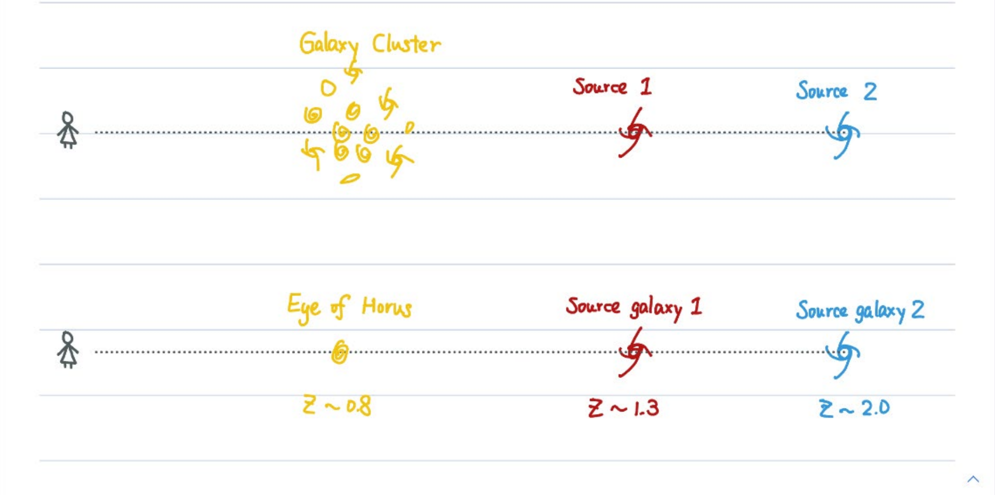


Figure 1. riz color composite of Eye of Horus. The lens galaxy is labeled "L," and the inner and outer sources are labeled "S1" and "S2," respectively. The knots in the sources are labeled alphabetically in approximate order of brightness. Note that the two rings clearly have different colors. The spectroscopic redshifts of the various features are indicated by the colored circles in the upper left. The angular scale is shown by the bar at the bottom left. The inset shows the lens system with no labels overlaid.



Credits: Tanaka et al. (2016)

Project Introduction

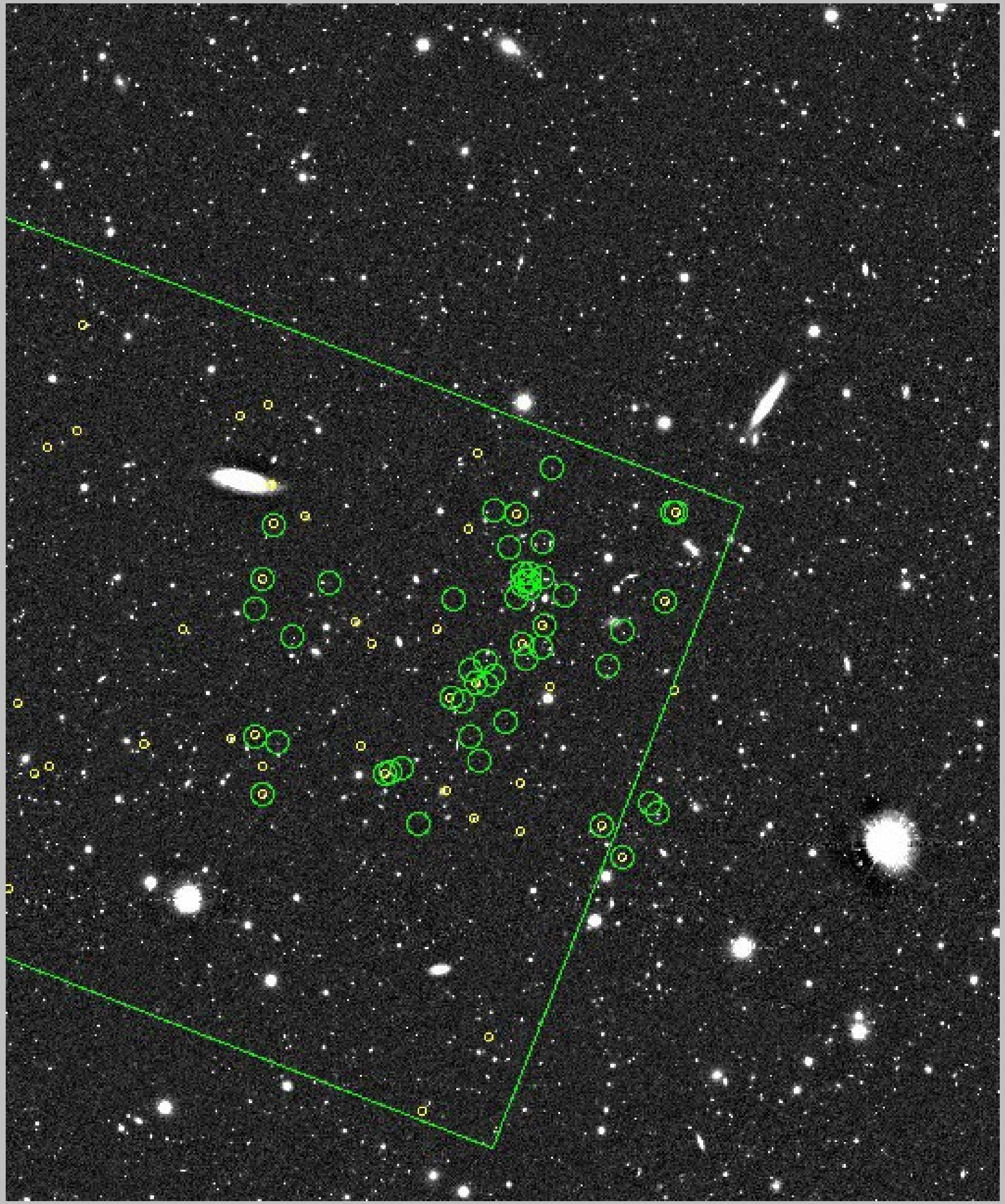
1. Discovery of "The Eye of Horus" GL
   - A rare (<10), Double Source Plane system
   - Central galaxy acts as GL, not cluster around it.
   - That is why DSP systems are rare.
   - Redshift~0.8
   - Need a mass model accurate enough to describe this system

2016

2018

2021

2022



Project Introduction

2. Two background sources and
   Two galaxy clusters? (Oguri et al.)
   - Around redshifts z~0.8
   - Photometric methods

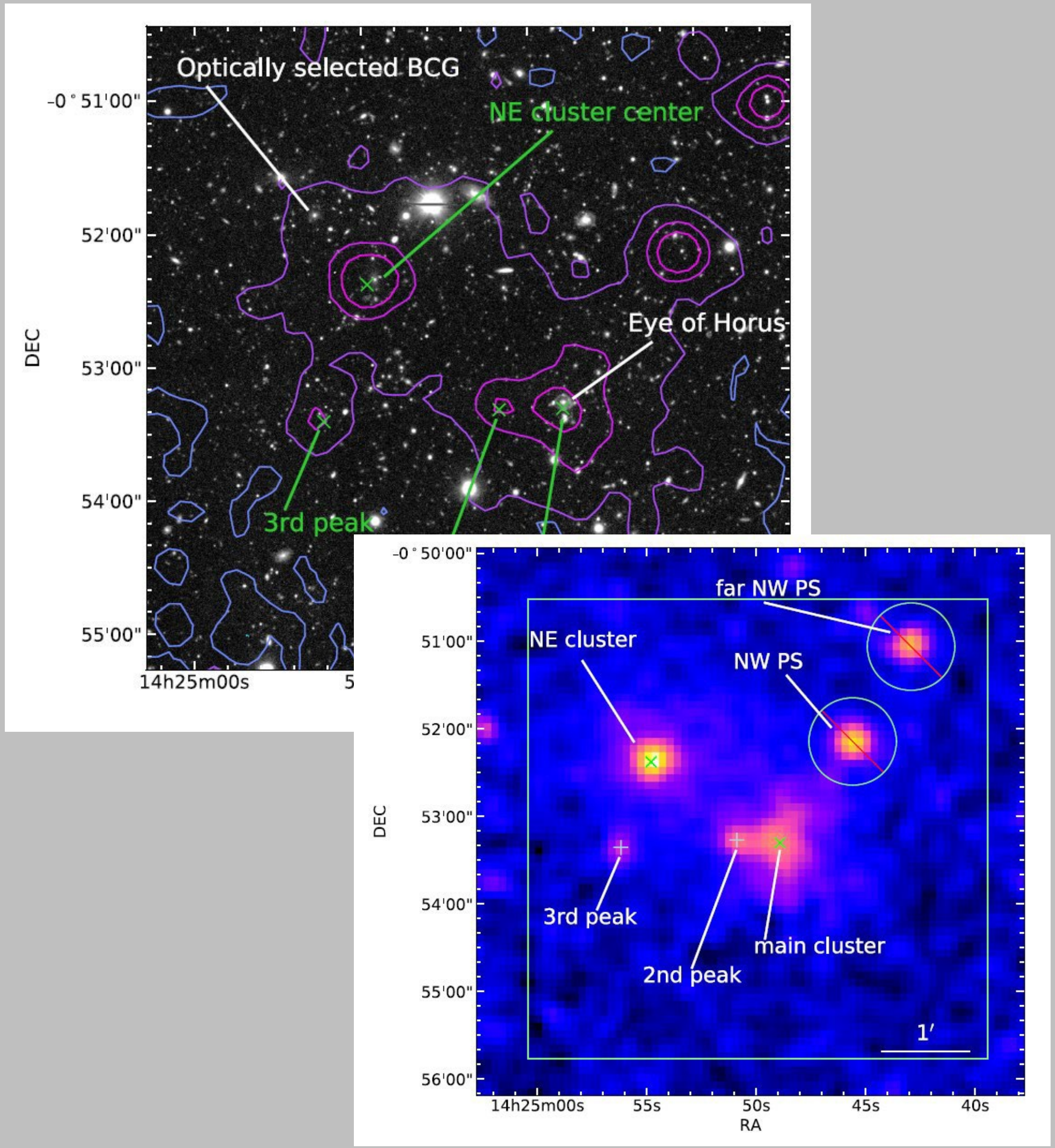
2016

2018

2020

2021

2022

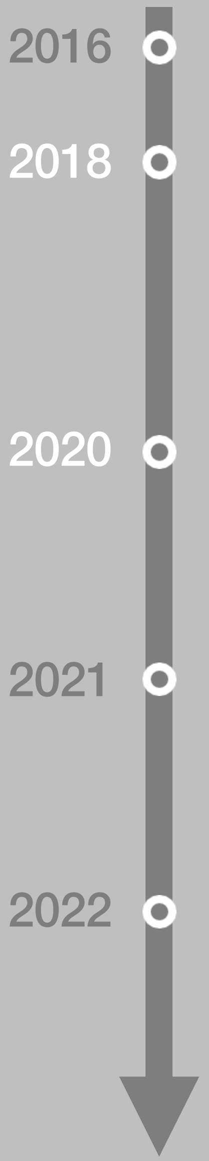


Credits: Tanaka et al. (2020)

Project Introduction

2. Two galaxy clusters? (Oguri et al.)
   - Around redshifts z~0.8
   - Photometric methods

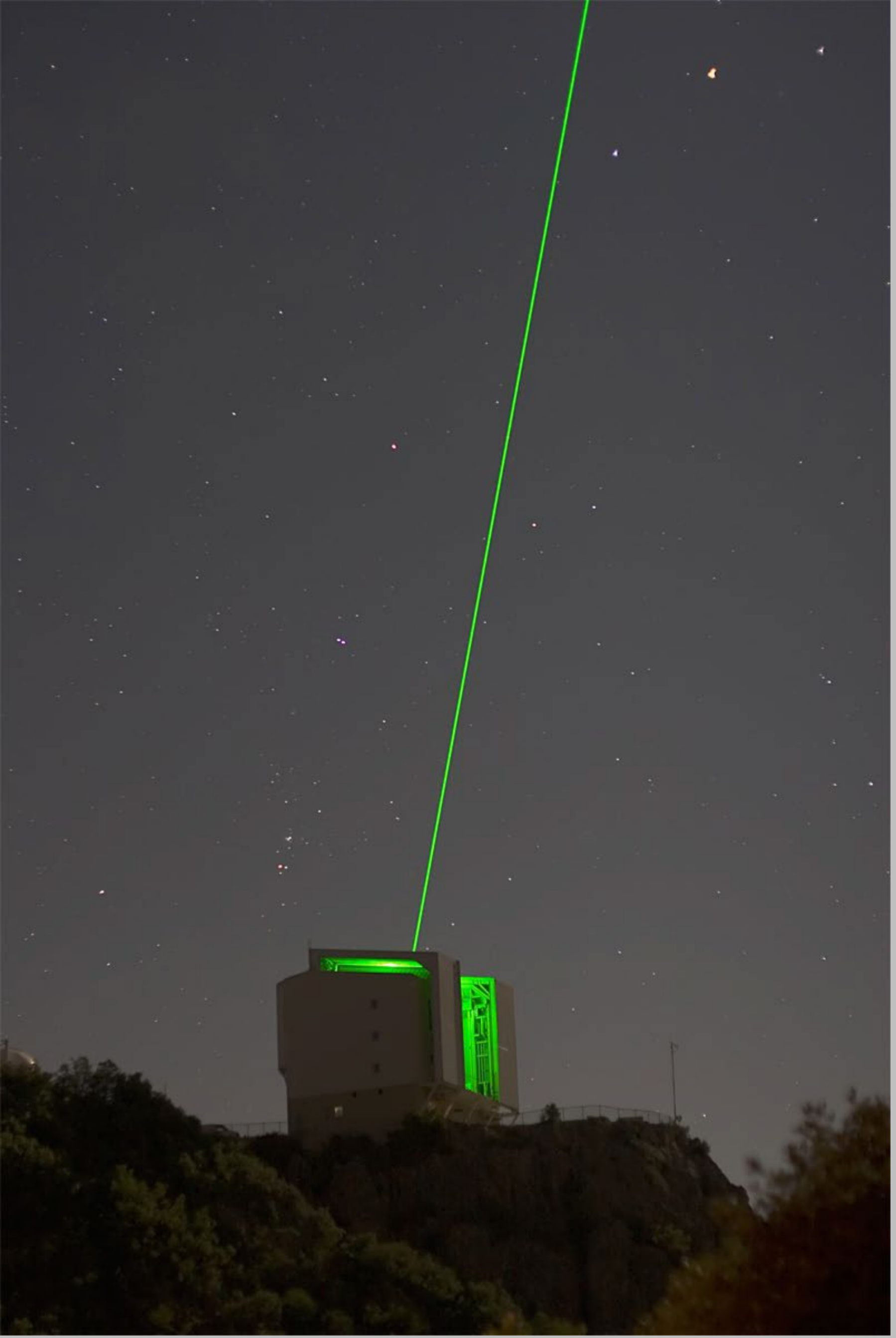
3. X-ray Mapping (Tanaka et al.)
   - Signal of hot plasma in Intra-Cluster Medium (ICM) with Free-Free radiation
   - Two brightest center galaxies (BCGs) at z~0.795 and z~0.761
   - 100'' Separation
   - Still, no accurate info on spec-z



The Spectroscopic Survey of Galaxy Clusters at z~0.8 Using MMT/Binospec

Big Questions

1. How many cluster(s) of galaxies are located near EoH GL system?
2. Is this combination a cluster merger or a superposition along the light of sight?
3. Masses derived from spectroscopic observations



Credits: mmto.org

Observation

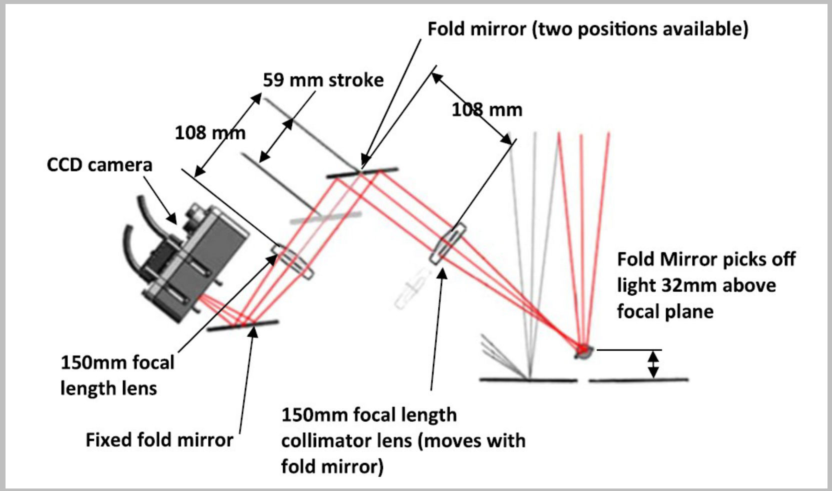
MMT

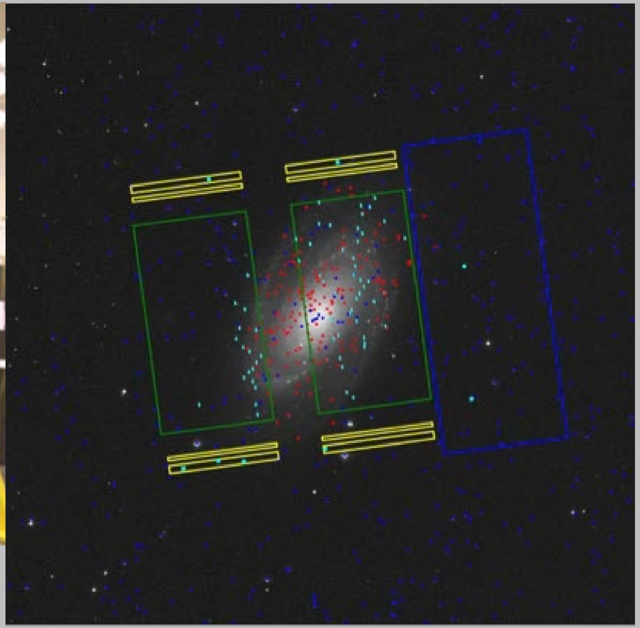
- Was Multiple Mirror Telescope
- Mt. Hopkins, Tucson, AZ
- 6.5m in diameter
- The same size, mirror casting as Magellan I&II 6.5m

Binospec

- Resolving power R~3500 (2Å at IR band)
- More spectral lines are legible (Ca H&K)
- Two field-of-views (8’ × 15’ each FoV)

2016
2018
2020
2021
2022





Observation

2016

2018

2020

2021

2022

MMT

- Was Multiple Mirror Telescope
- Mt. Hopkins, Tucson, AZ
- 6.5m in diameter
- The same size, mirror casting as Magellan I&II 6.5m

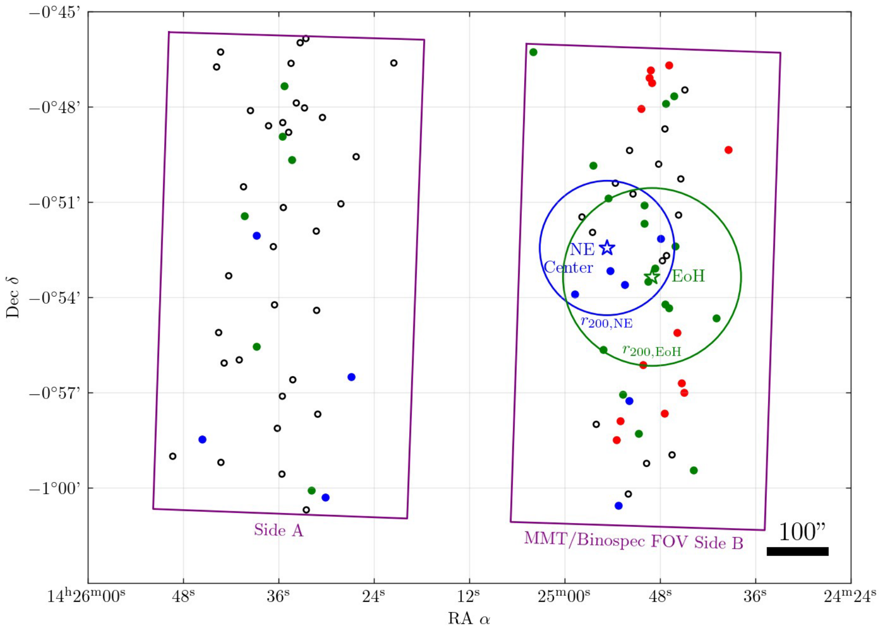
Binospec

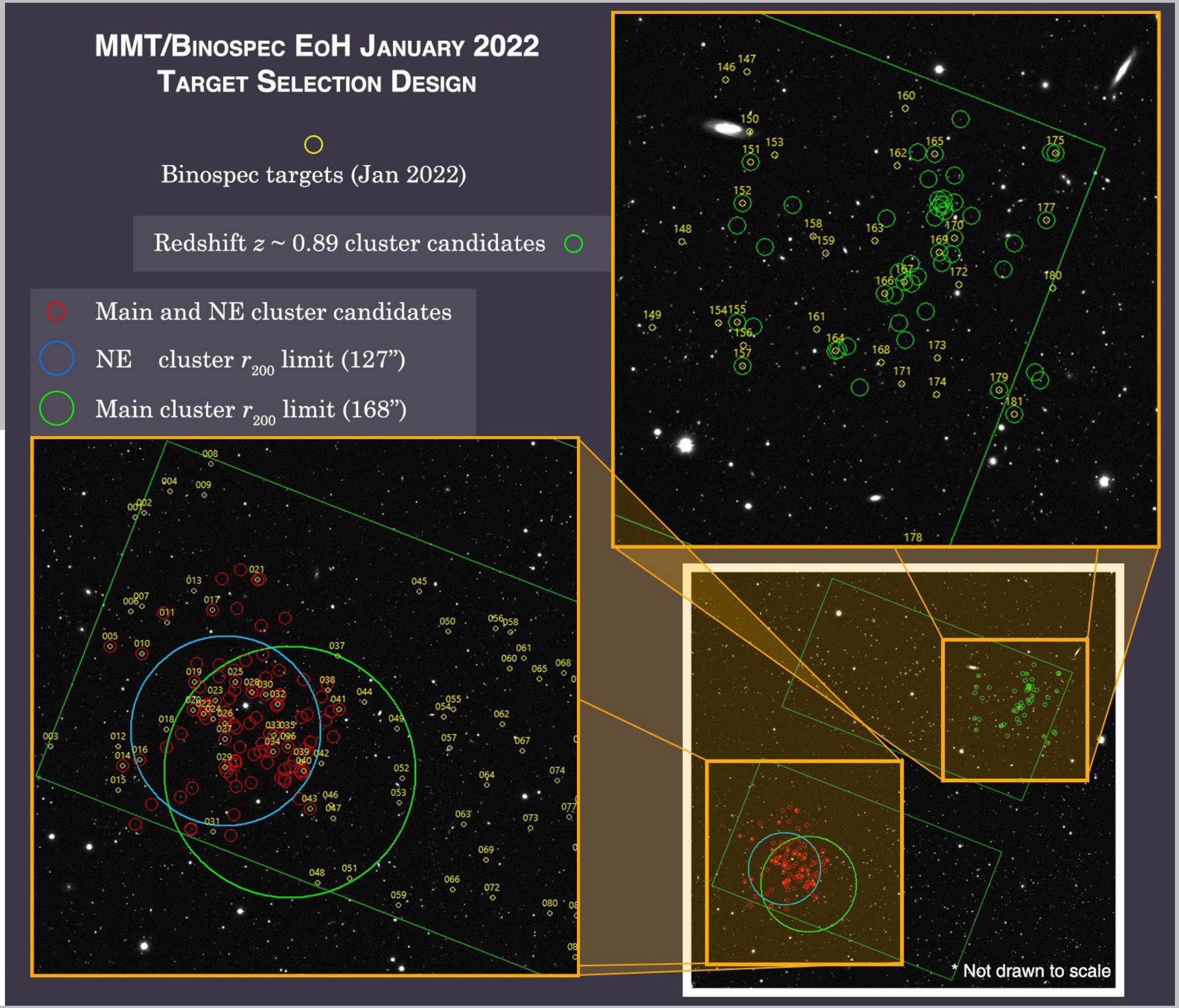
- Resolving power R~3500 (2Å at IR band)
- More spectral lines are legible (Ca H&K)
- Two field-of-views (8’ × 15’ each FoV)

Credits: Fabricant et al. 2019, mmto.org

Target Selection

- CAMIRA survey: candidates with close angular separations and similar photometric redshifts in the FoV
- Similar magnitudes

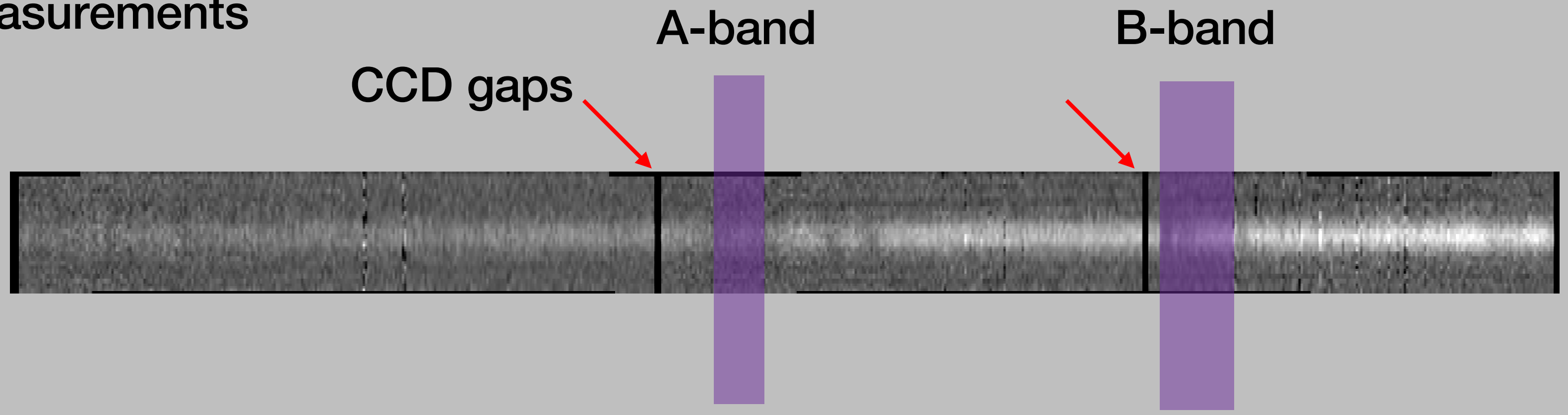




2016
2018
2020
2021
2022

Spectra

Redshift measurements



2016
2018
2020
2021
2022

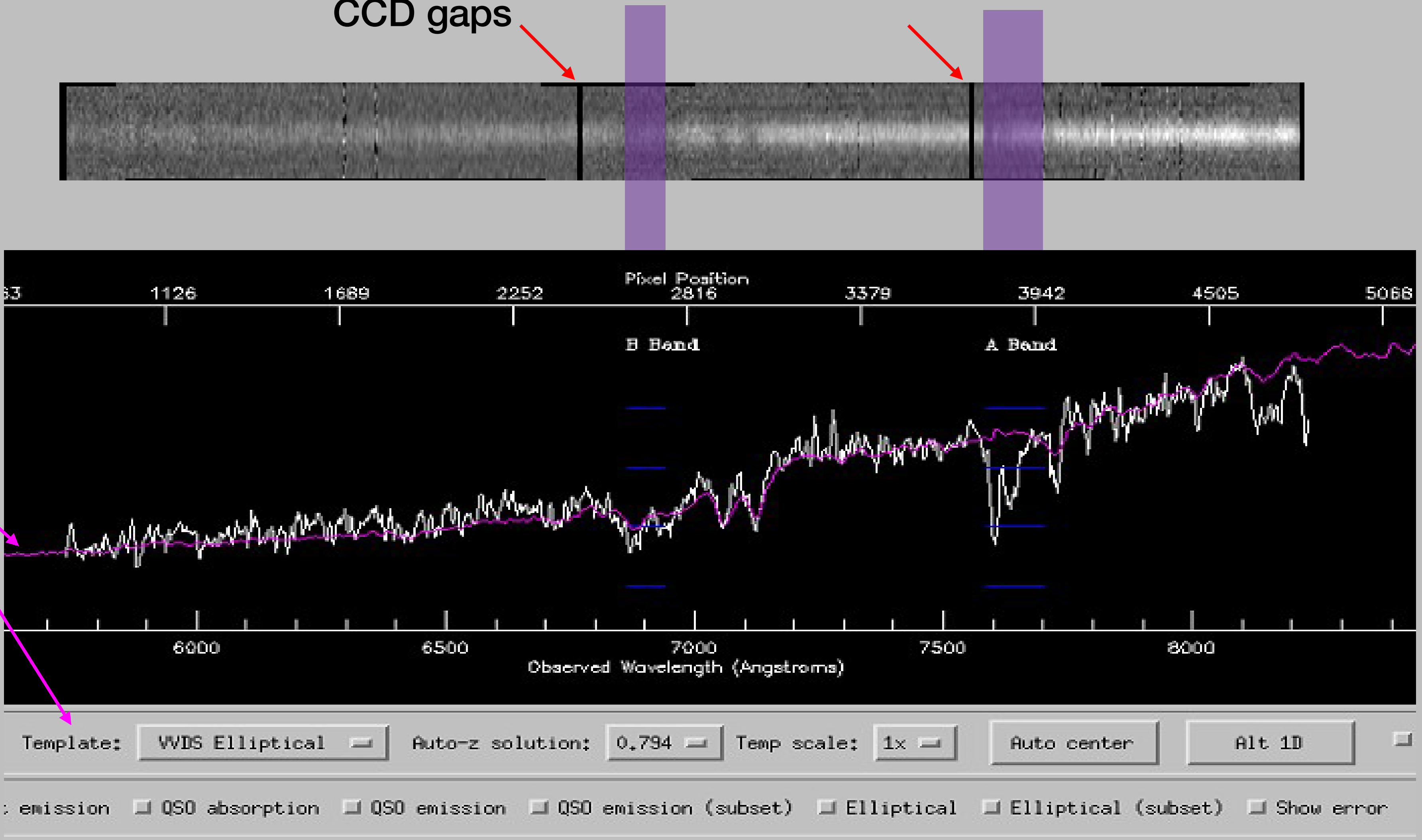
Spectra

Redshift measurements

CCD gaps

A-band

B-band



Spectrum Templates

2016

2018

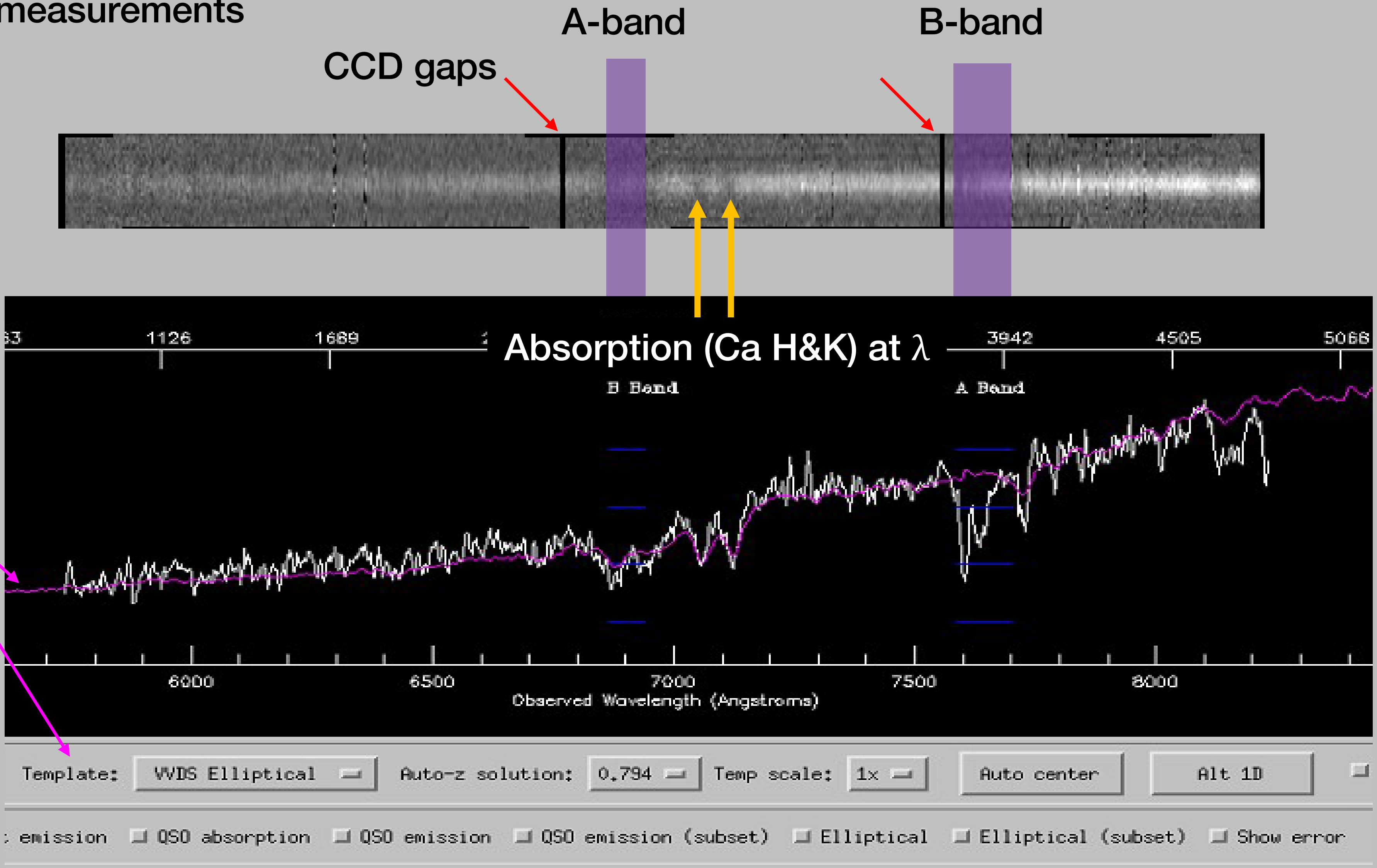
2020

2021

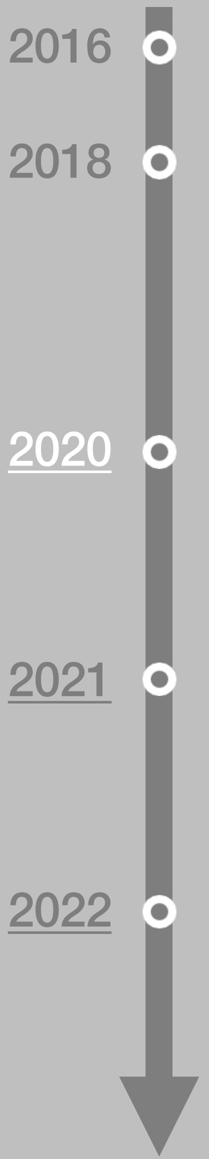
2022

Spectra

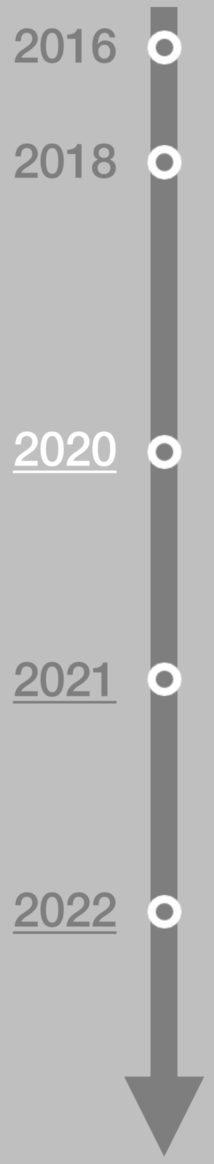
Redshift measurements



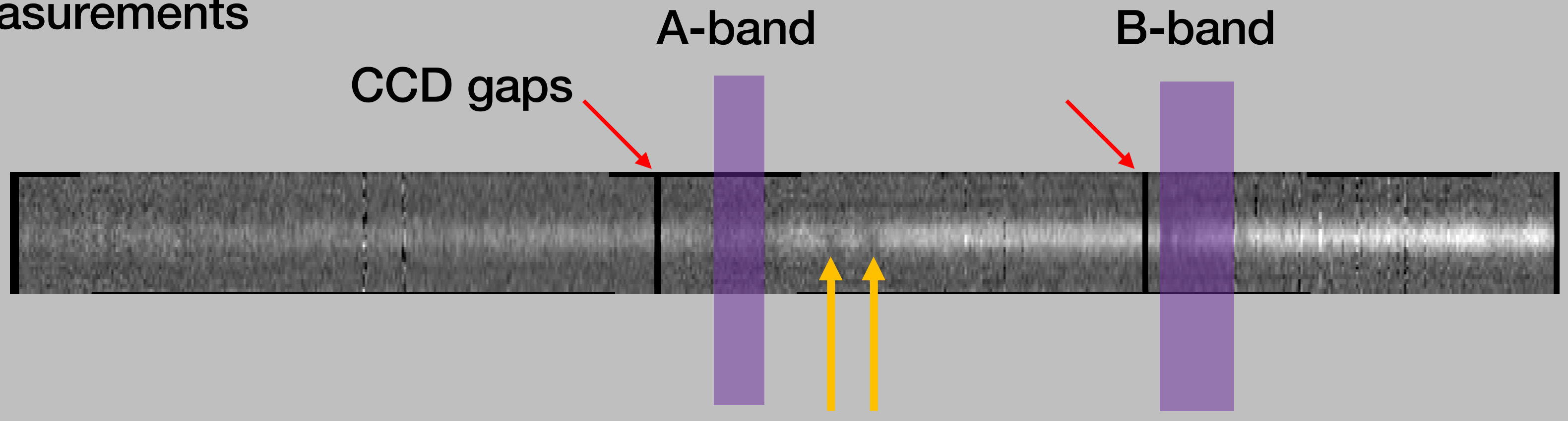
Spectrum
Templates



Spectra

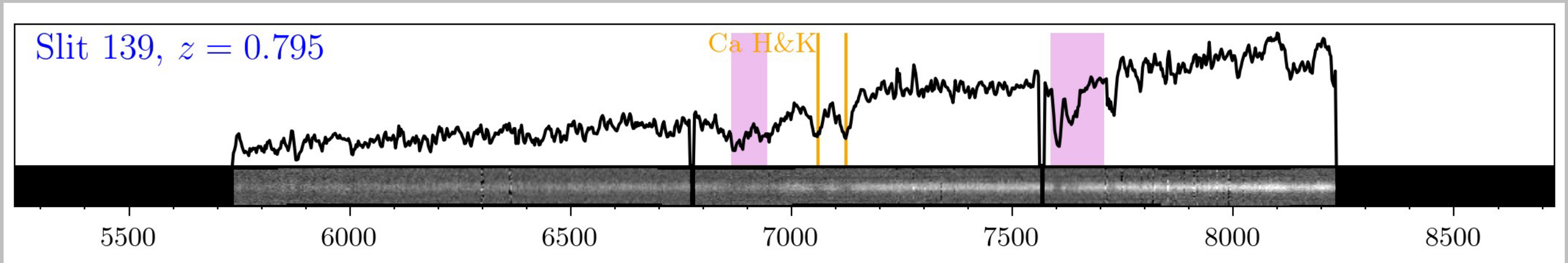


Redshift measurements



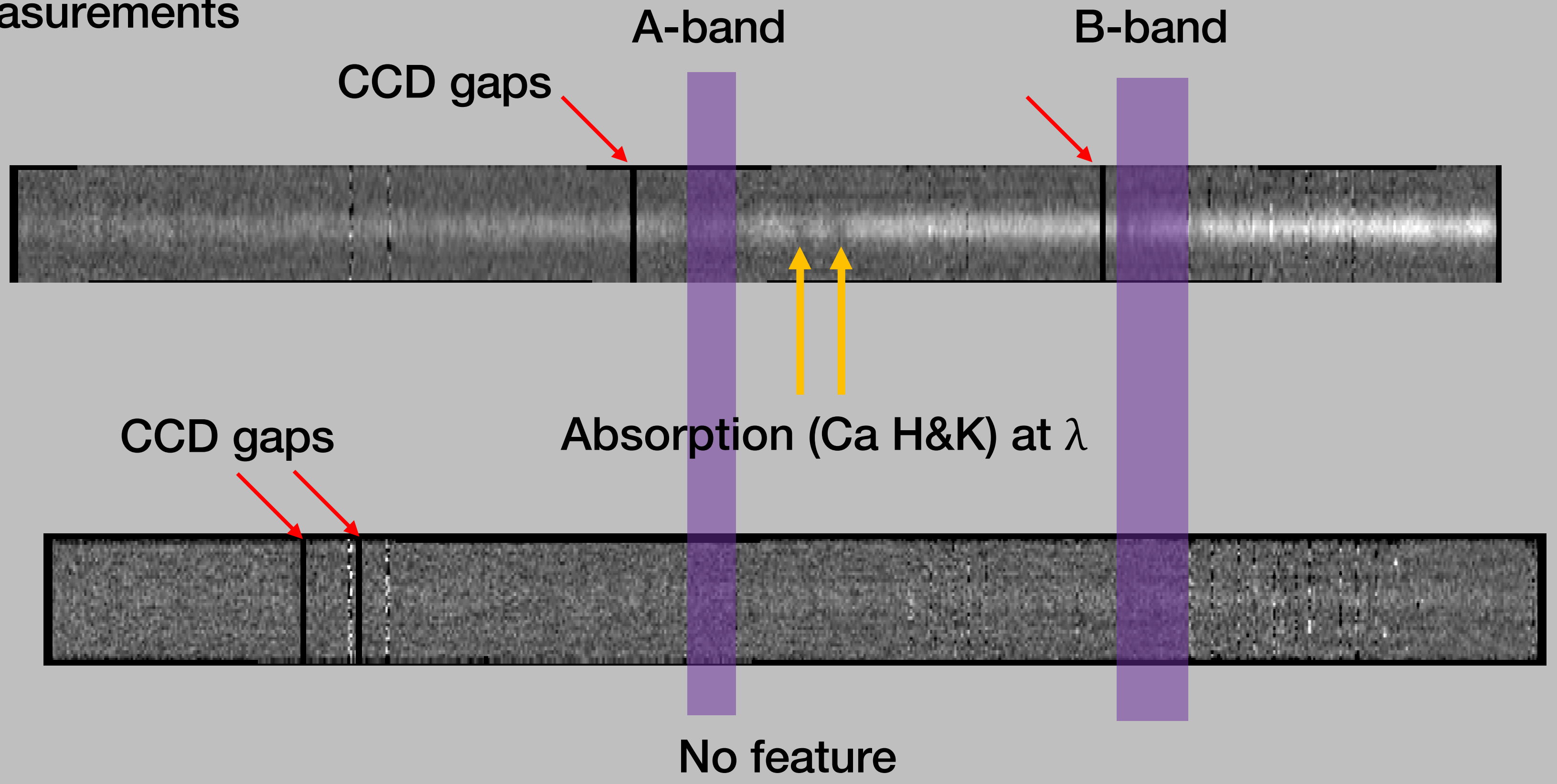
Absorption (Ca H&K) at λ

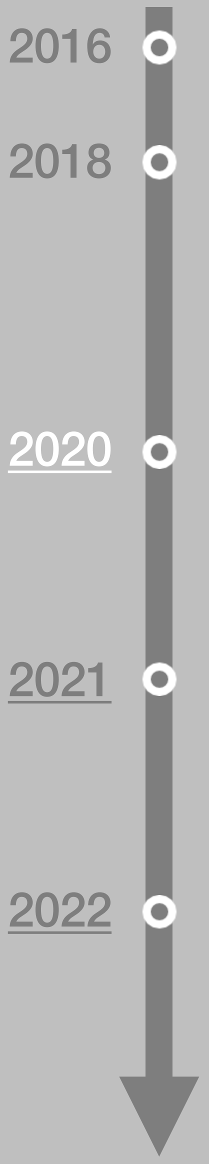
Redshift $z = \dfrac{\lambda - \lambda_0}{\lambda_0}$ λ_0 = 3933Å at z=0



Spectra

Redshift measurements





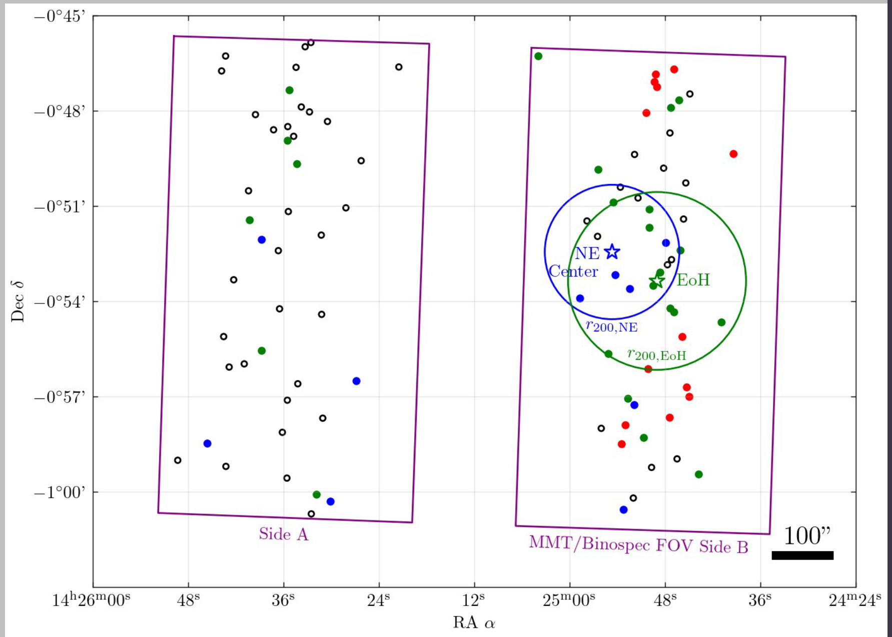
Spectra

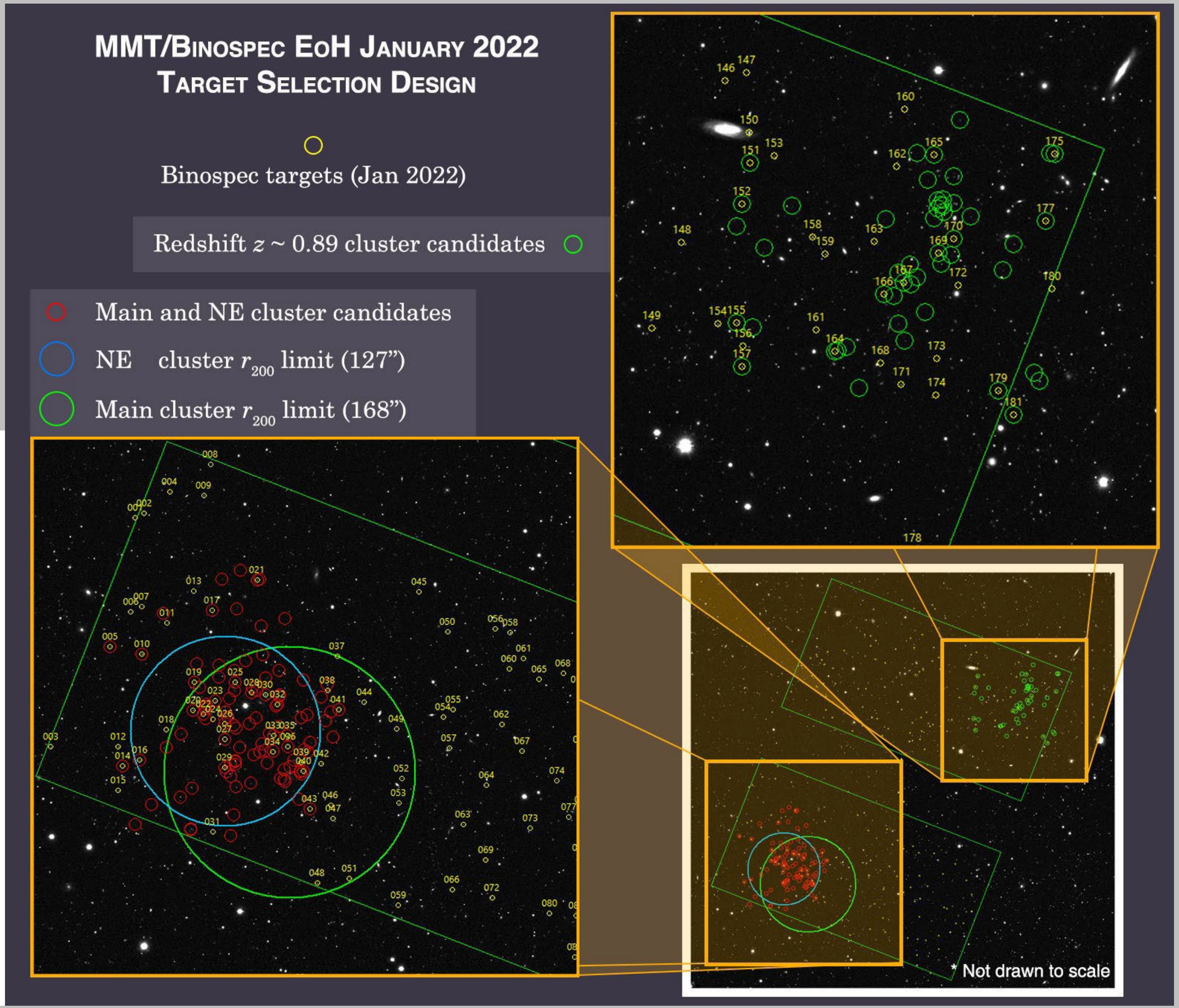
July 2019 Observation

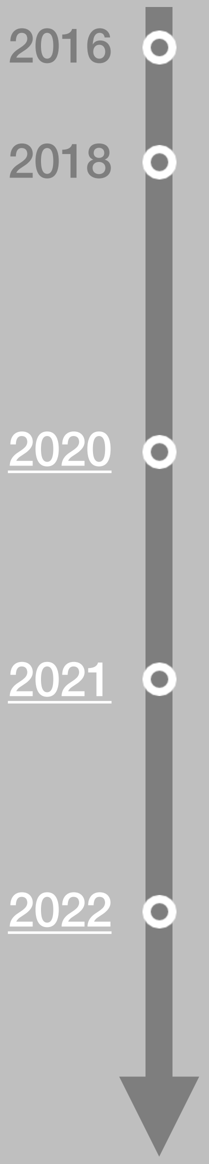
- 190 slits, 97 redshifts obtained

January 2022 Observation

- 181 slits, 117 redshifts obtained



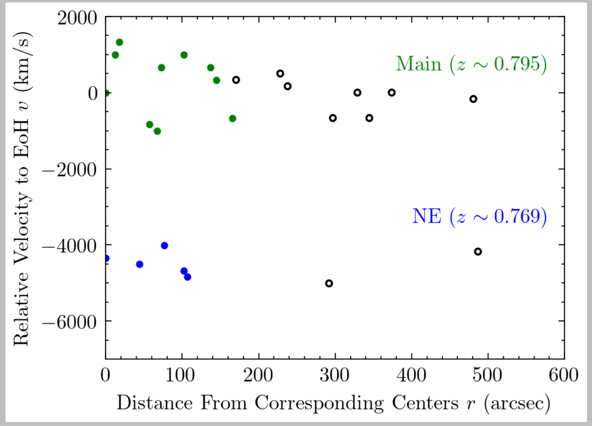


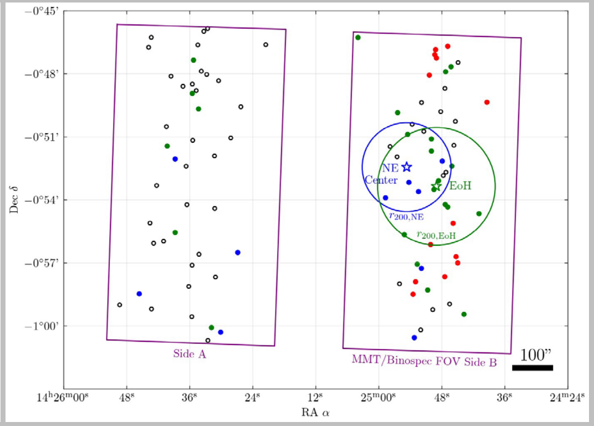


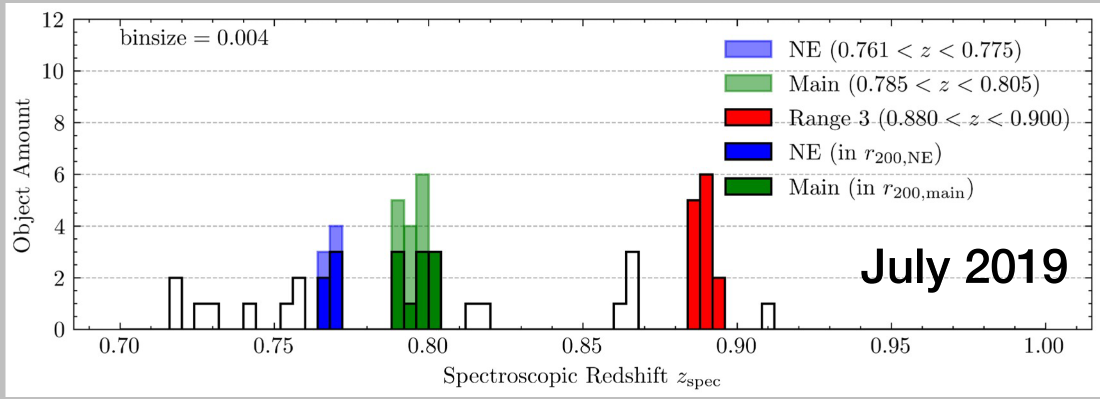
Results

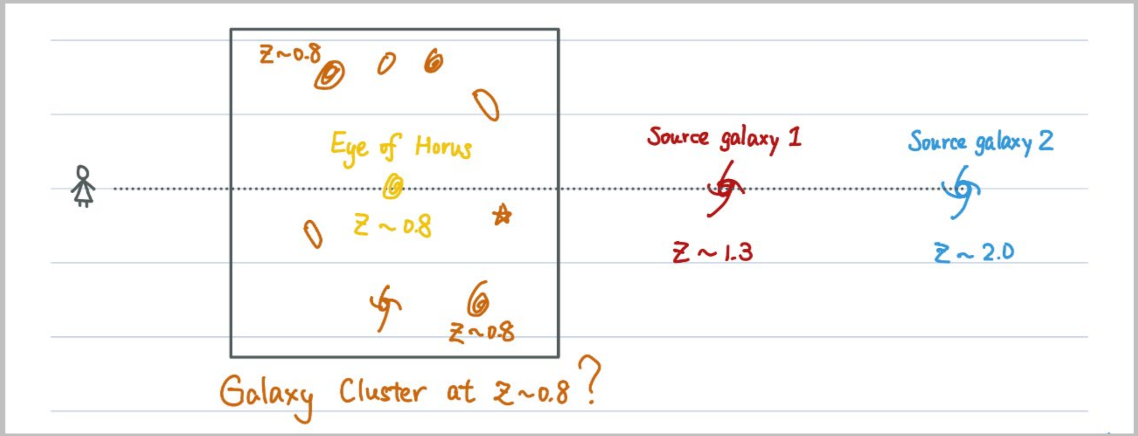
1. Cluster Identification

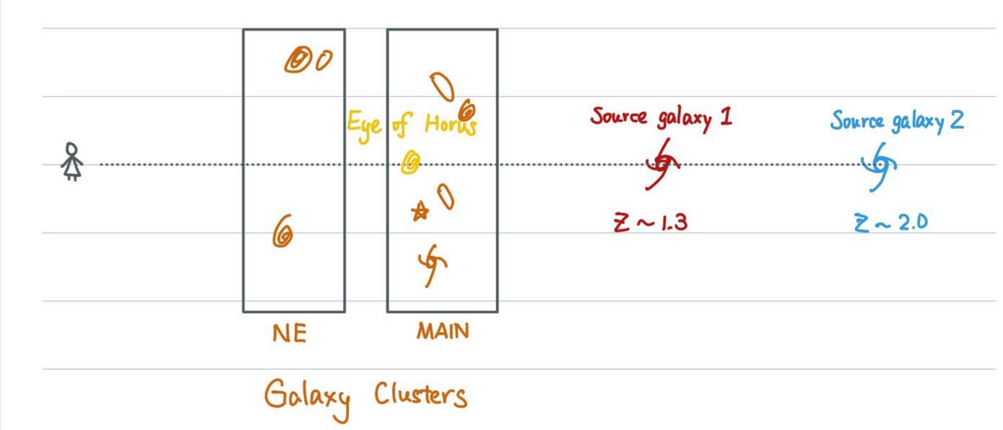
- Redshift distribution
- Criteria: Δ>500km/s or 0.003 clear b/w peaks
- Main 0.785-0.805
- NE 0.761-0.775

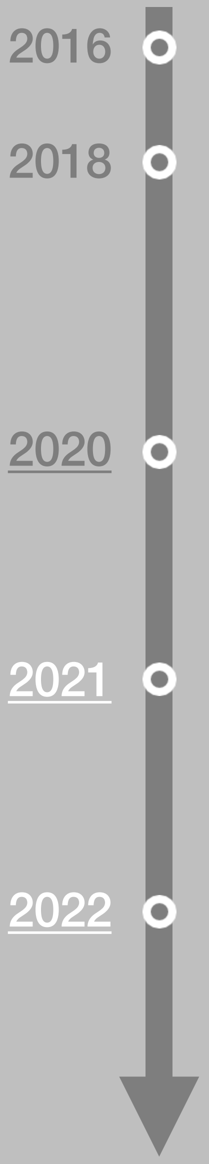












Results

1. Cluster Identification

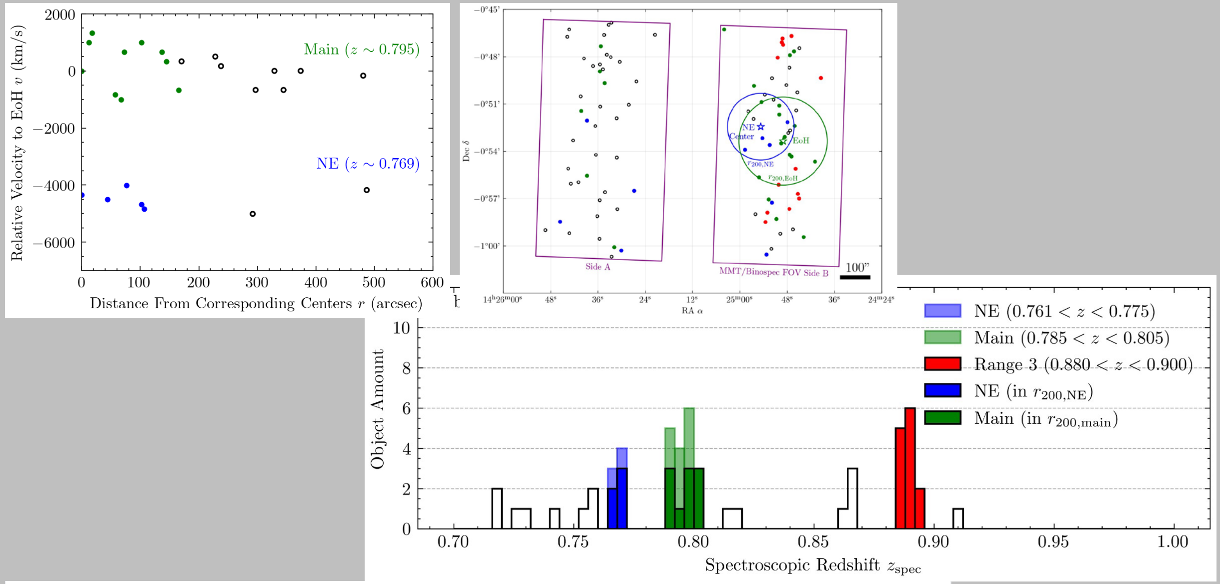
- Redshift distribution
- Criteria: Δ>500km/s or 0.003
  clear b/w peaks
- Main 0.785-0.805
- NE 0.761-0.775

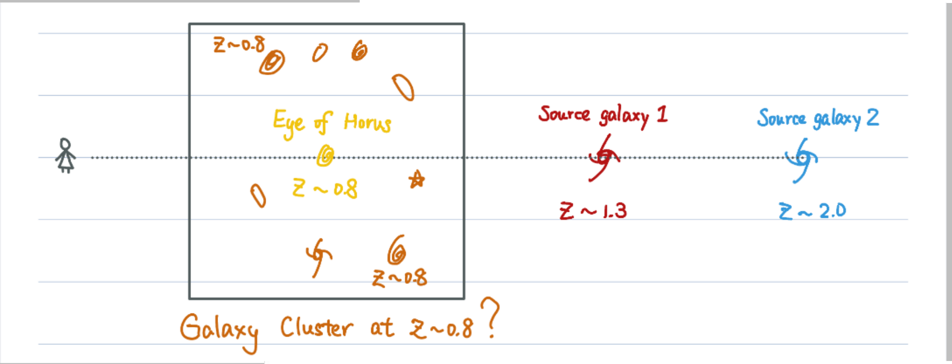
<u>Big Question 2</u>

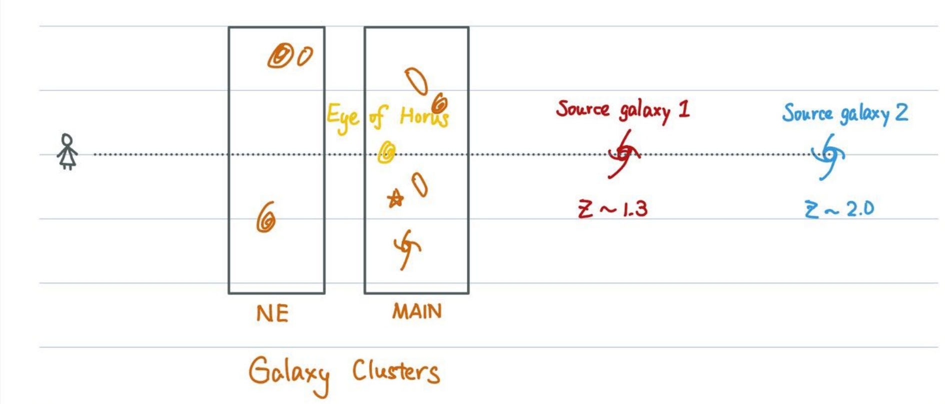
Is this combination a cluster merger or a superposition along the light of sight?

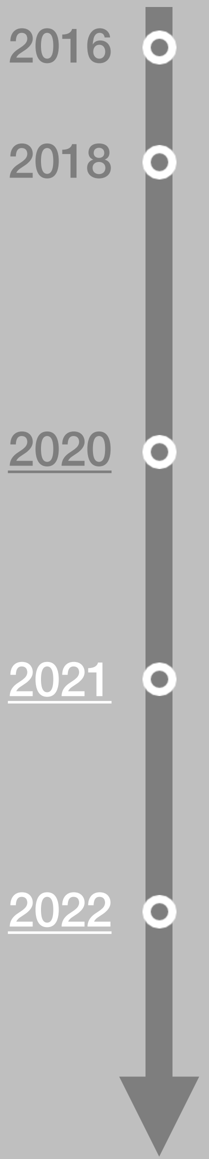
<u>Answer</u>

NOT a merger





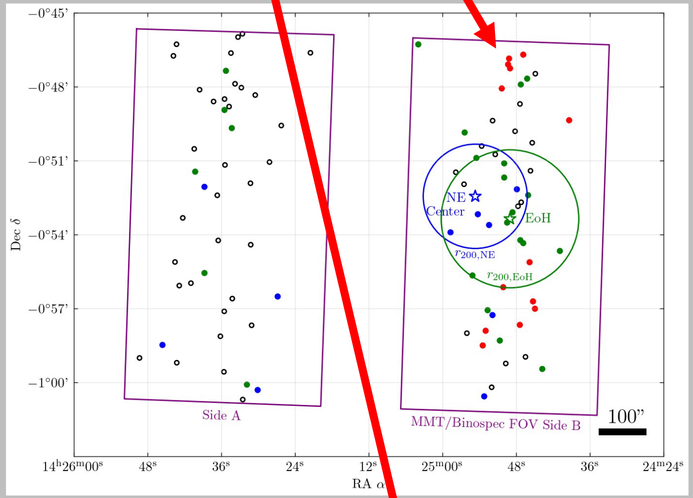


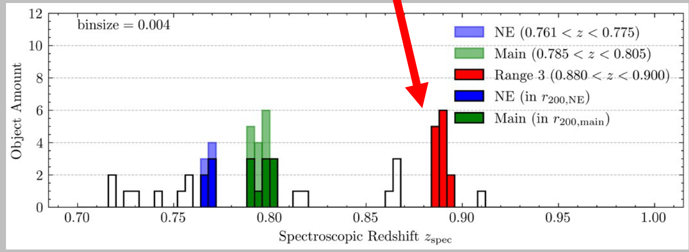


Results

2. The third cluster?

(Range 3)





2016

2018

2020

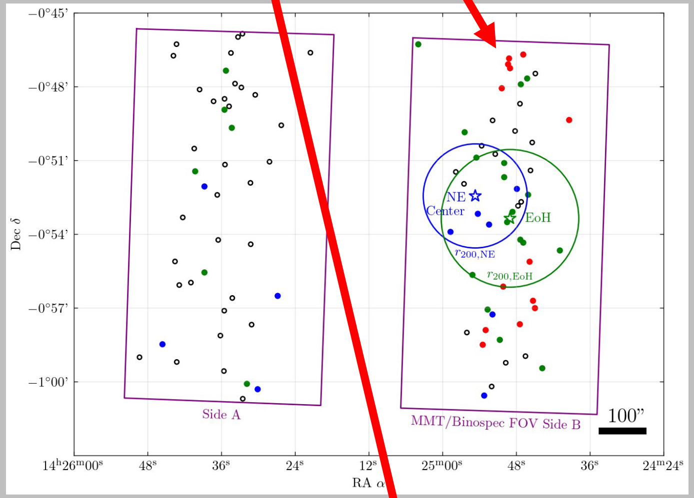
2021

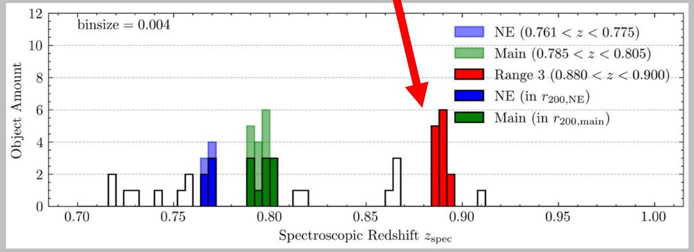
2022

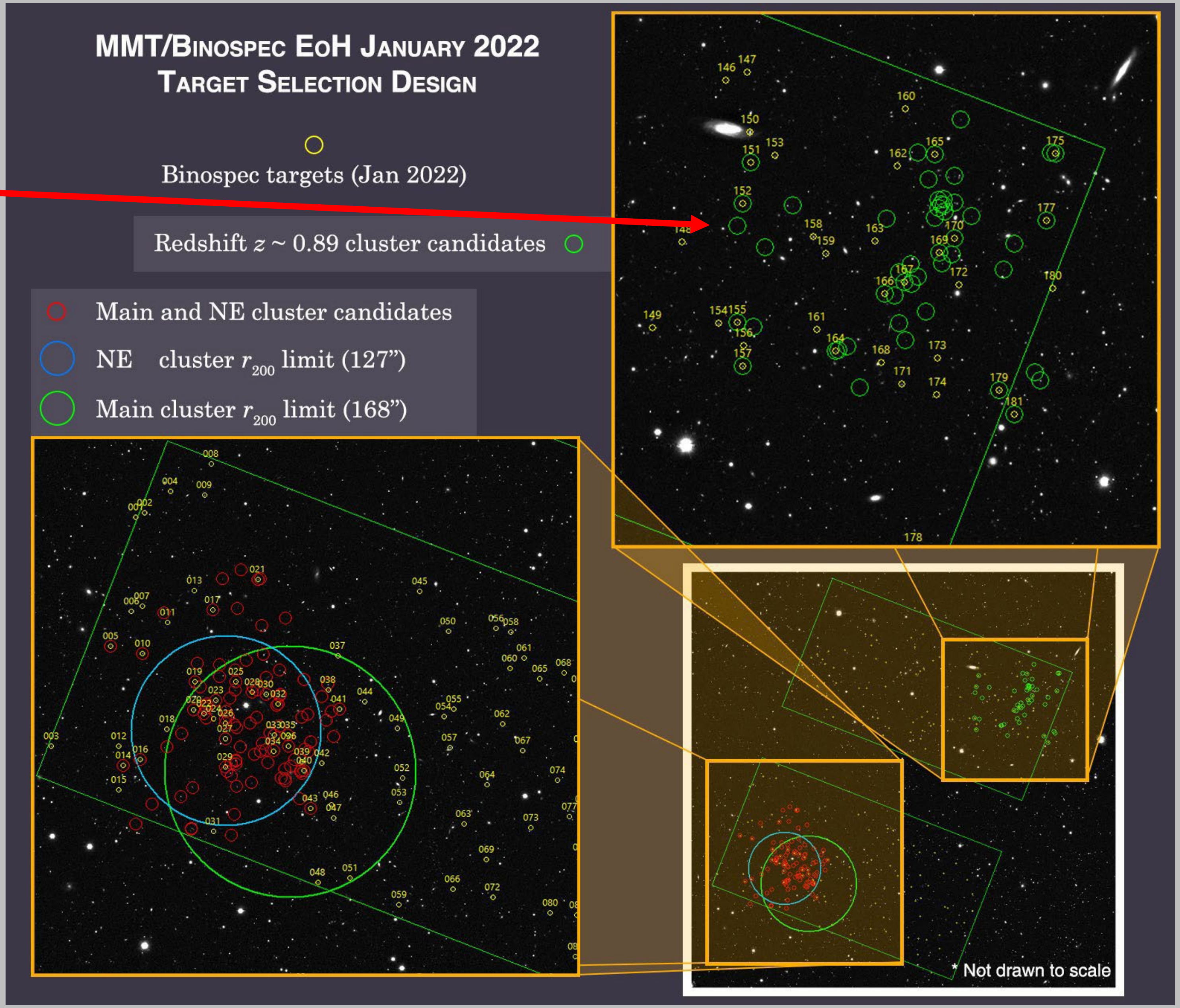
Results

2. The third cluster?

(Range 3)





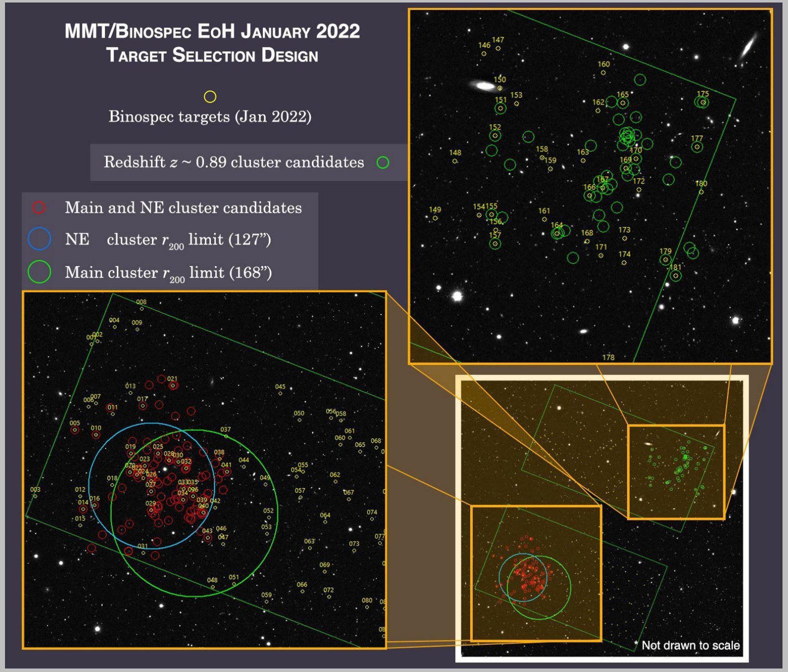


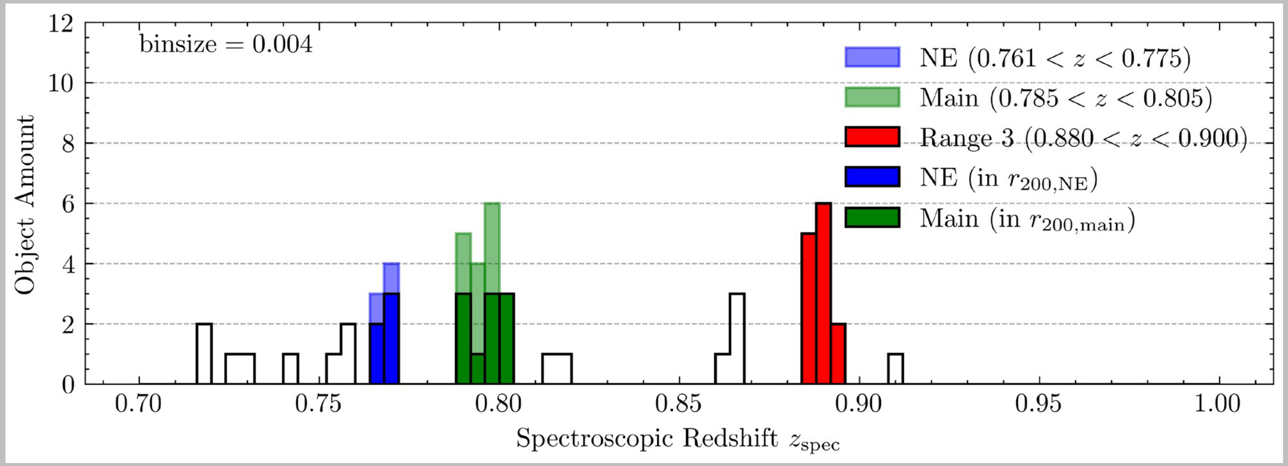
2016
2018
2020
2021
2022

Results

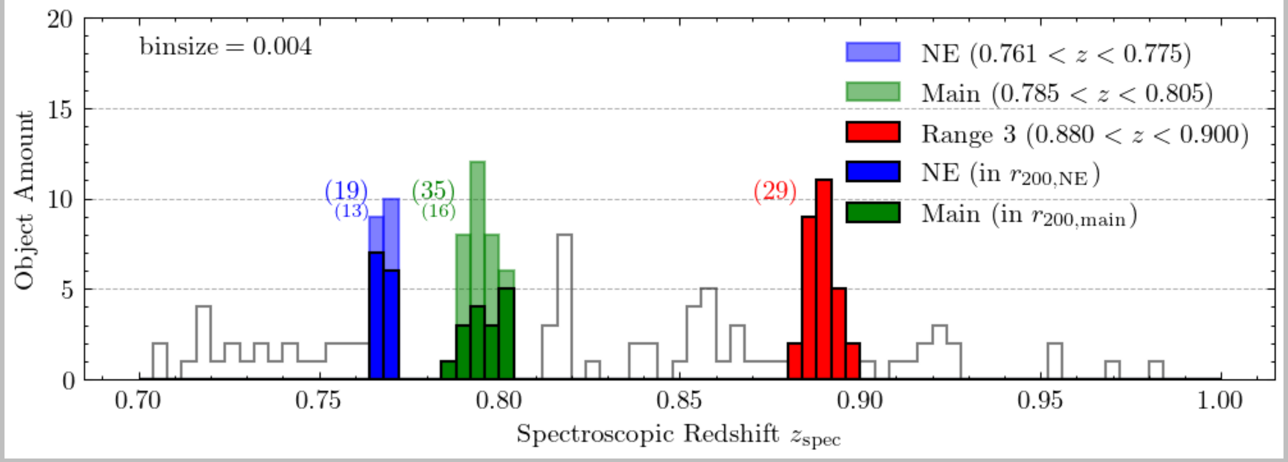
2. The third cluster? (Range 3)

- Possible
- Center location

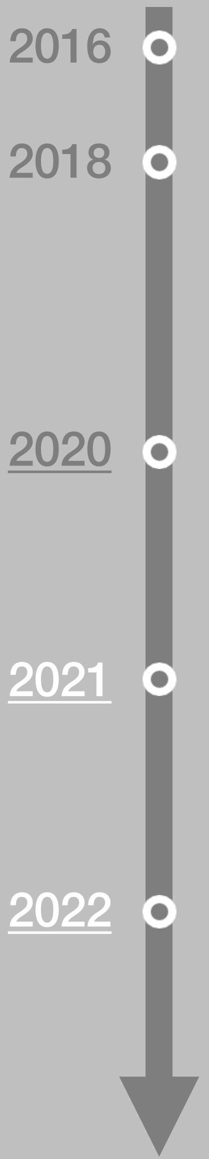




July 2019



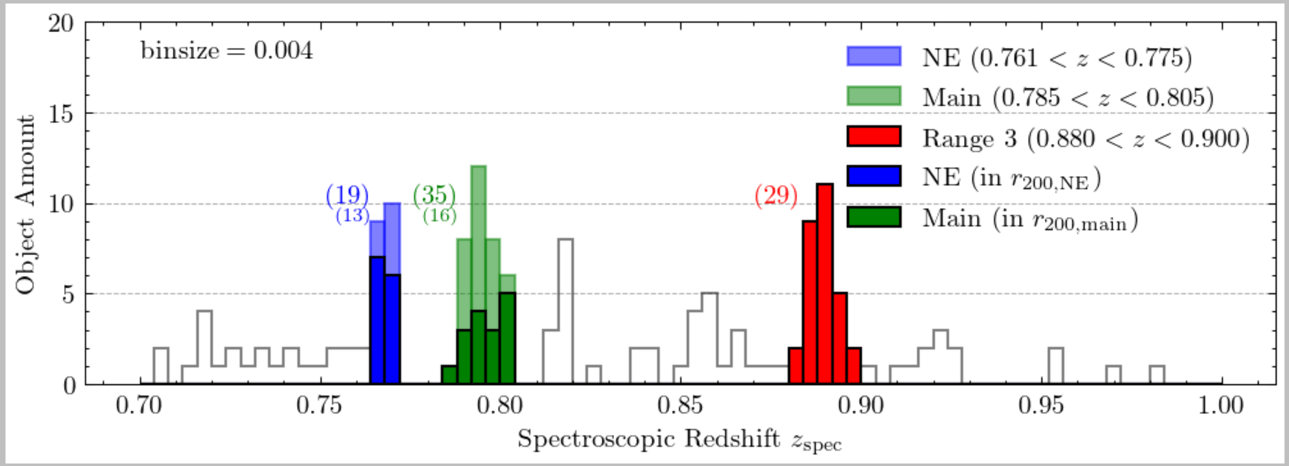
January 2022 + July 2019



Results

2. The third cluster? (Range 3)

- Possible
- Center location?



January 2022 + July 2019

2016

2018

2020

2021

2022

<u>Big Question 1</u>

How many cluster(s) of galaxies are located near EoH GL system?

<u>Answer</u>

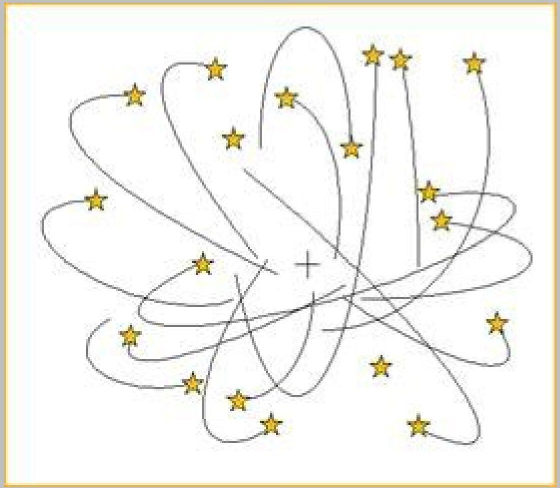
2 clusters: NE and main.

Results

3. Masses

Virial

Use Virial Theorem to describe the random motion of galaxies in cluster



Statistical

The relationship between the redshifts and masses of galaxy clusters at similar redshifts

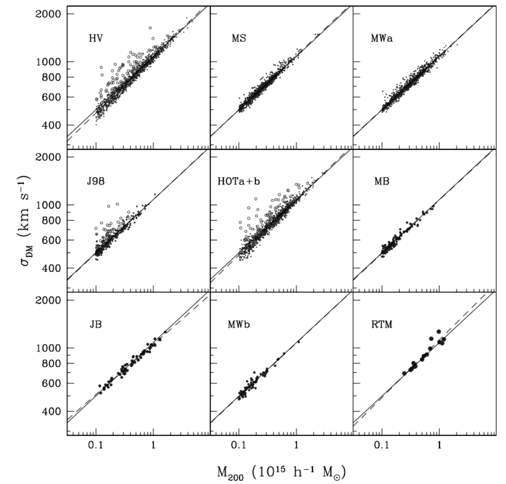


TABLE 1
ΛCDM Simulations

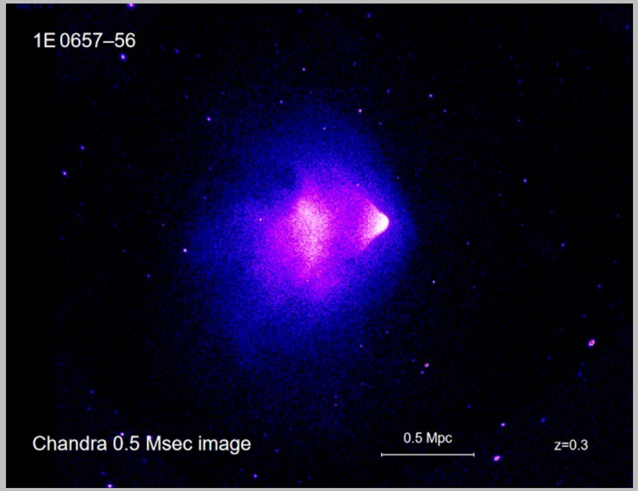
Sample	N_p	L (h^{-1} Mpc)	ε (h^{-1} kpc)	Gas?	Code	Ref.	Remarks
HV	1000^3	3000	100	No	HYDRA	1	$z = 0$ and four sky survey outputs
MS	2160^3	500	5	No	GADGET	2	...
MWa	1024^3	500	18	No	TreePM	3	...
J98	256^3	239.5	36	No	HYDRA	4	...
HOTa	256^3	768	100	No	HOT	5	New
HOTb	256^3	384	50	No	HOT	5	New
MB	256^3	200	30	No	GADGET	6	Evolved to $a = 100$
CP	$0.3–1 \times 10^8$	32.5–479	0.06–5	No	GADGET/PKDGRAV	7	23 resimulations
JD	$10^5–10^8$	213	1.3–355	No	PKDGRAV	8	Resolution series, partly new
JB	2×192^3[a]	80–140	20–40	10%	P3MSPH	9	68 resimulations
MWb	2×192^3	150	20	13%	TreePM	10	...
RTM	2×256^3[a]	479	5	10%	GADGET	11	16 resimulated clusters

[a] Effective particle number in high-resolution zone.

References.—(1) Evrard et al. 2002; (2) Springel et al. 2005; (3) White 2002; (4) Jenkins et al. 1998; (5) this work; (6) Busha et al. 2007; (7) Navarro et al. 2004; (8) Diemand et al. 2004b; (9) O'Hara et al. 2006; (10) White et al. 2002; (11) Rasia et al. 2004.

Hydrostatic

Derived from high energy hot plasma (at energy kT and resulting mass density) in ICM



Results

2016
2018
2020
2021
2022

3. Masses

Virial

Use Virial Theorem to describe the random motion of galaxies in cluster

Statistical

The relationship between the redshifts and masses of galaxy clusters at similar redshifts

Hydrostatic

Derived from high energy hot plasma (at energy kT and resulting mass density) in ICM

Input variables: (observables)

Virial

- Velocity dispersion (N, z)
- Virial/avg. radius
  (ang. radius, z, scaling)

Statistical

- Velocity dispersion (N, z)

Hydrostatic

- Temperature
- Hubble param. (z)
- Angular radii of gal.
  (z, scaling)
- Spherical symmetry

Results

Results from this research

3. Masses

Virial

Statistical

Hydrostatic

Results

	σ (km/s)	Girardi (10^{14} $M_\odot$)	Tran (10^{14} $M_\odot$)	Within r_{200}	r_{200} ($''$)	σ_{200} (km/s)	Sifon (10^{14} $M_\odot$)	X-ray (10^{14} $M_\odot$)
July 2019								
NE (7)	366.1	**3.49** (918%)	**6.02** (1584%)	NE (5)	127	326.0	**0.38** (100%)	2.2 (319%)
Main (18)	687.4	**10.98** (218%)	**23.53** (468%)	Main (10)	168	837.9	**5.03** (100%)	5.6 (106%)
January 2022 + July 2019								
NE (19)	422.9	**4.03** (584%)	**6.71** (972%)	NE (13)	127	407.1	**0.69** (100%)	2.2 (319%)
Main (35)	683.6	**14.71** (279%)	**32.39** (613%)	Main (16)	168	852.7	**5.28** (100%)	5.6 (106%)

2016

2018

2020

2021

2022

Results

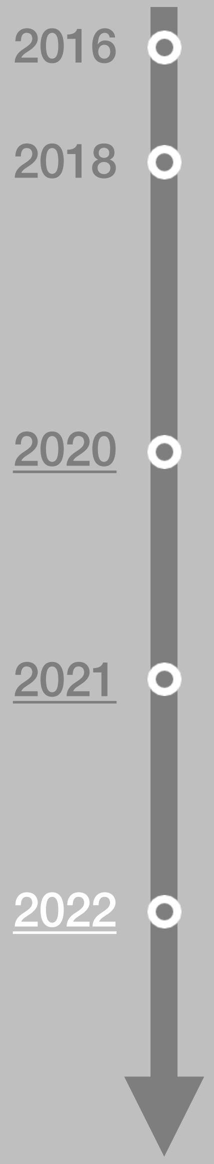
Results from this research

3. Masses

Virial — Statistical — Hydrostatic

Results

	σ (km/s)	Girardi (10^{14} M$_\odot$)	Tran (10^{14} M$_\odot$)	Within r_{200}	r_{200} ($''$)	σ_{200} (km/s)	Sifon (10^{14} M$_\odot$)	X-ray (10^{14} M$_\odot$)
July 2019								
NE (7)	366.1	**3.49** (918%)	**6.02** (1584%)	NE (5)	127	326.0	**0.38** (100%)	2.2 (319%)
Main (18)	687.4	**10.98** (218%)	**23.53** (468%)	Main (10)	168	837.9	**5.03** (100%)	5.6 (106%)
January 2022 + July 2019								
NE (19)	422.9	**4.03** (584%)	**6.71** (972%)	NE (13)	127	407.1	**0.69** (100%)	2.2 (319%)
Main (35)	683.6	**14.71** (279%)	**32.39** (613%)	Main (16)	168	852.7	**5.28** (100%)	5.6 (106%)



Results

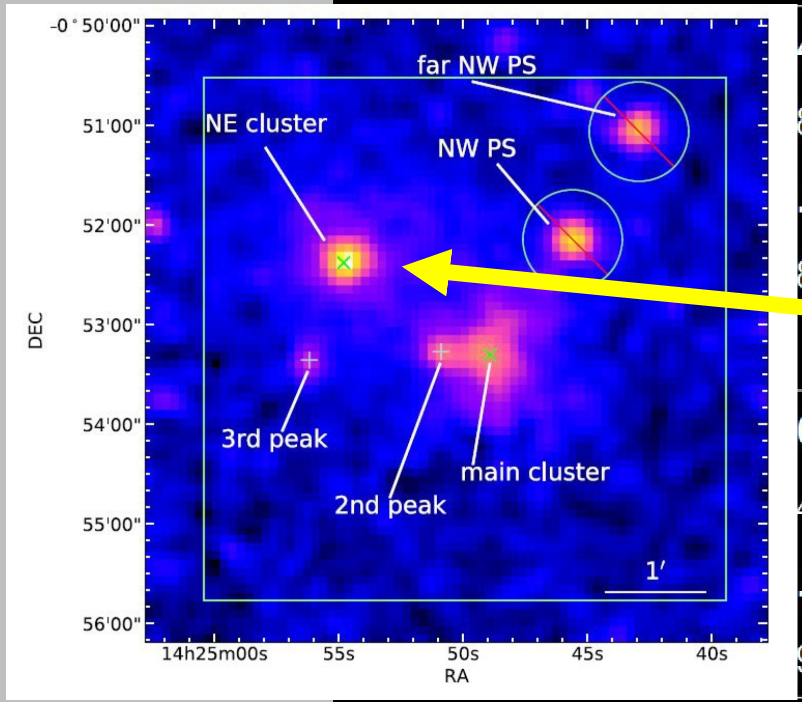
Results from this research

3. Masses

Virial | Statistical | Hydrostatic

Results

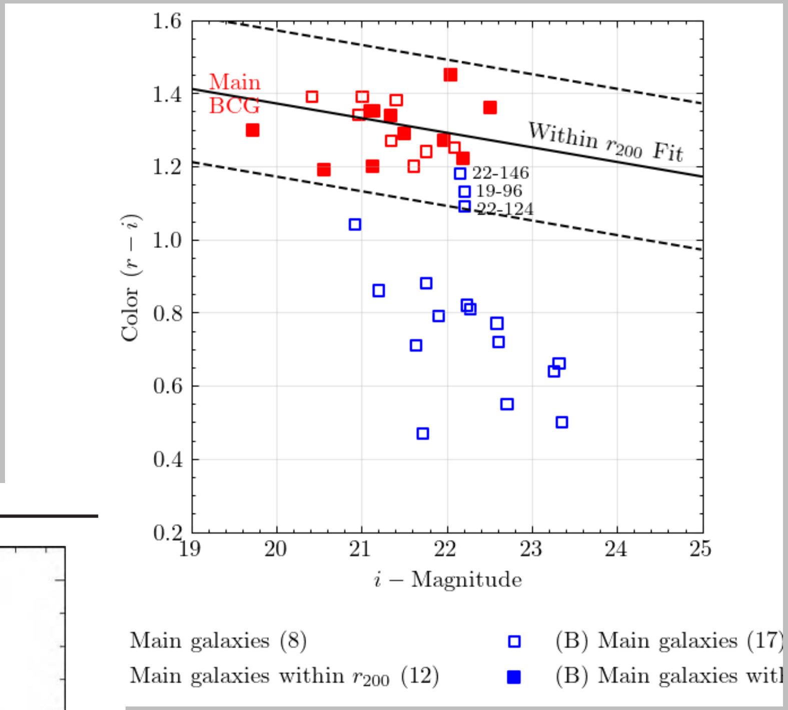
	σ (km/s)	Girardi ($10^{14}\,M_{\odot}$)	Tran ($10^{14}\,M_{\odot}$)	Within r_{200}	r_{200} ($''$)	σ_{200} (km/s)	Sifon ($10^{14}\,M_{\odot}$)	X-ray ($10^{14}\,M_{\odot}$)
July 2019								
		49	**6.02**	NE	127	326.0	**0.38**	2.2
		8%)	(1584%)	(5)			(100%)	(319%)
		.98	**23.53**	Main	168	837.9	**5.03**	5.6
		8%)	(468%)	(10)			(100%)	(106%)
January 2022 – July 2019								
		03	**6.71**	NE	127	407.1	**0.69**	2.2
		4%)	(972%)	(13)			(100%)	(319%)
		.71	**32.39**	Main	168	852.7	**5.28**	5.6
		9%)	(613%)	(16)			(100%)	(106%)

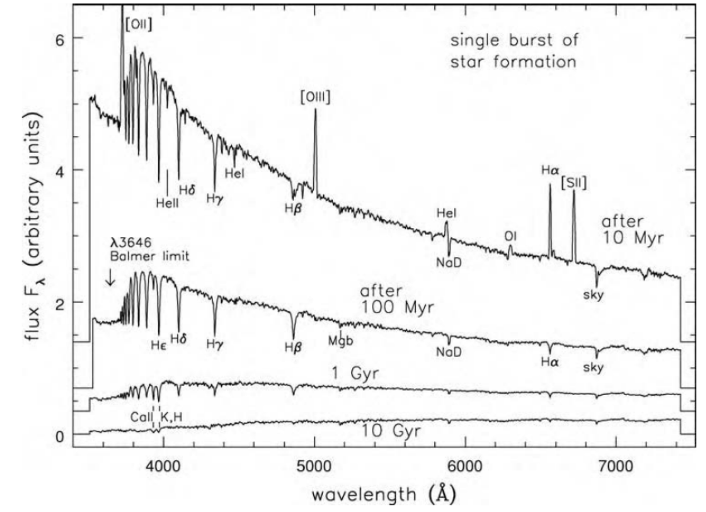


2016
2018
2020
2021
2022

Future goals

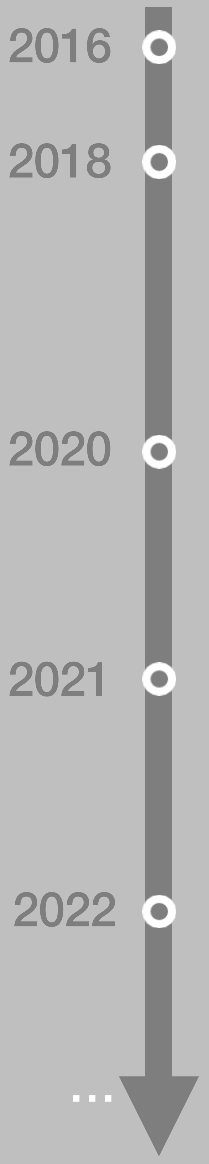
- Color-Magnitude (like H-R)
- Galaxy spectrum aging
- More?





268 Elliptical galaxies

Fig. 6.18. Spectra for a 'galaxy' that makes its stars in a 10^8 yr burst, all plotted to the same vertical scale. Emission lines of ionized gas are strong 10 Myr after the burst ends; after 100 Myr, the galaxy has faded and reddened, and deep hydrogen lines of A stars are prominent. Beyond 1 Gyr, the light dims and becomes slightly redder, but changes are much slower – B. Poggianti.



Credits:
(Textbook) *Galaxies in the Universe* by Linda S. Sparke (2007)

End