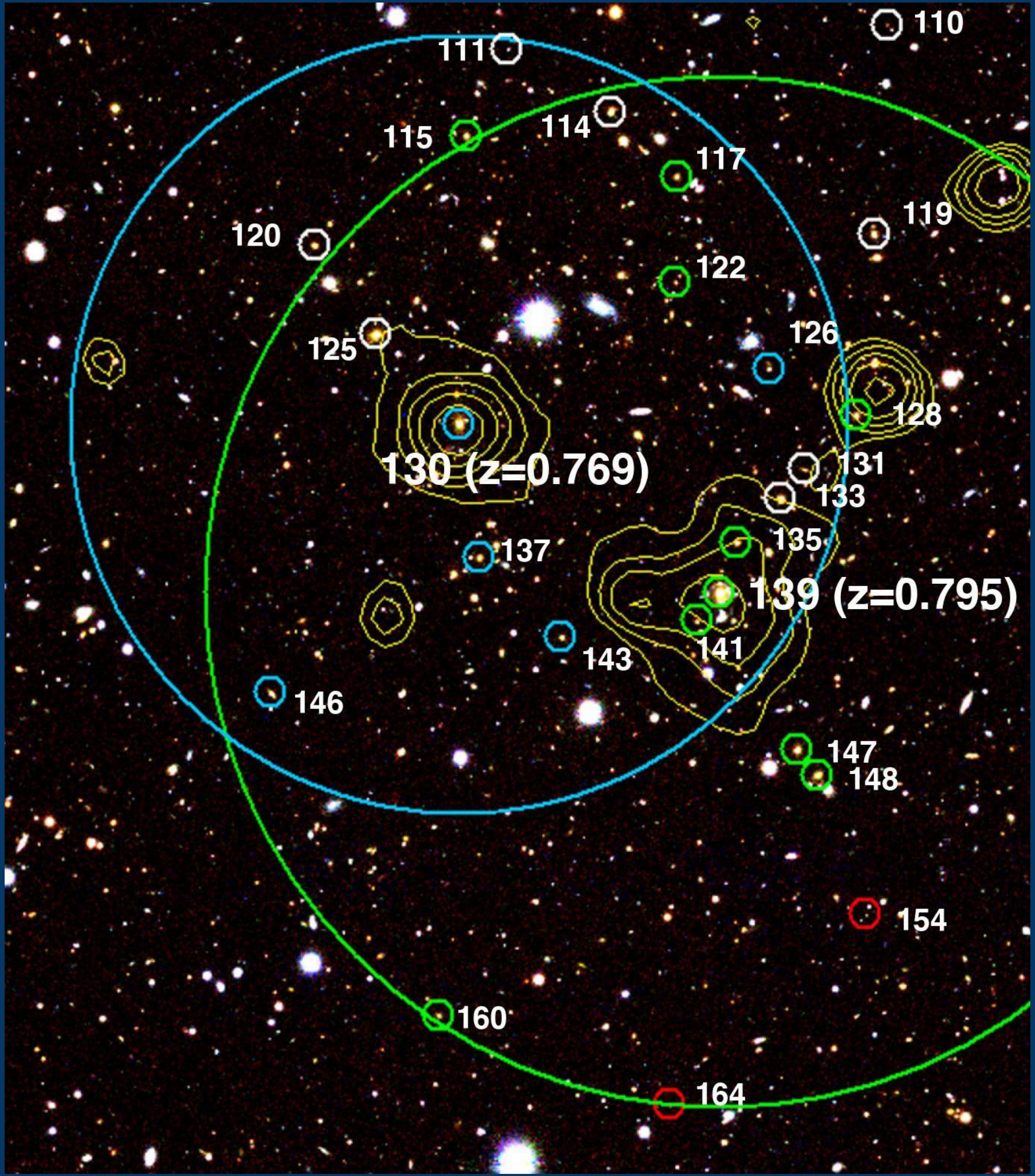

The Spectroscopic Survey of Galaxy Clusters at z~0.8 Using MMT/Binospec

Jiyun Di

Steward Observatory, University of Arizona

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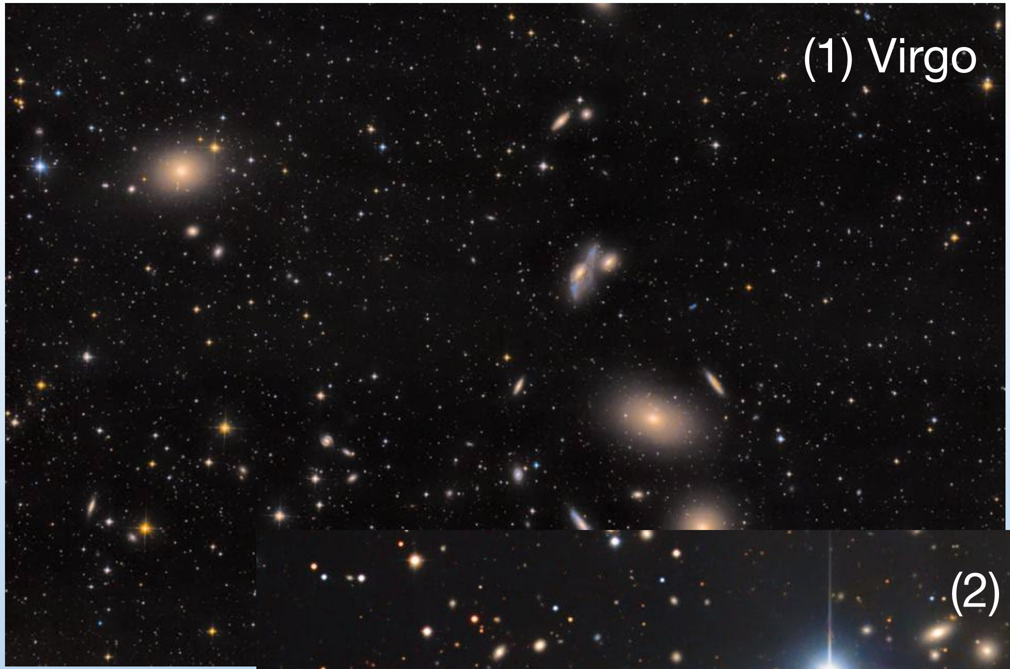
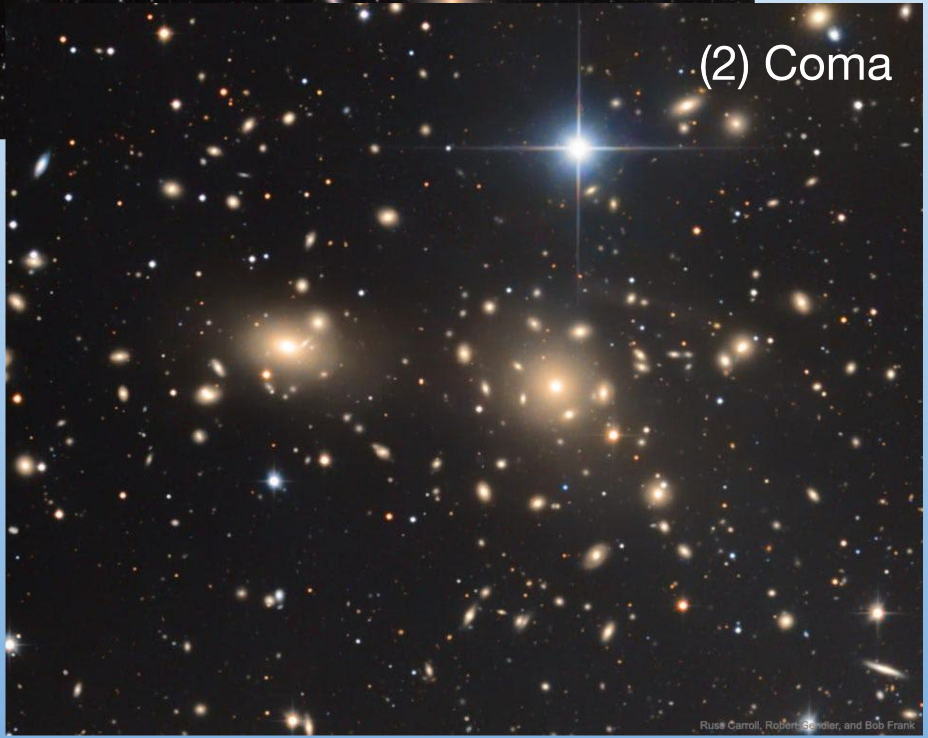




Introduction

Cluster of Galaxies

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

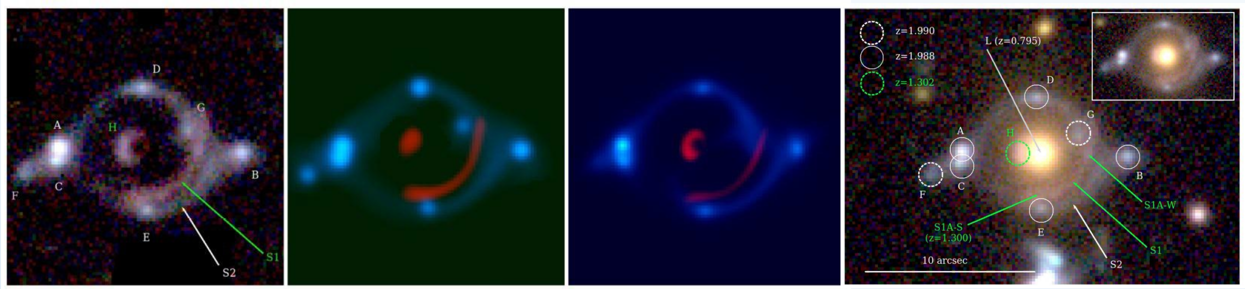
Strong Gravitational Lens (GL)

- Usually massive galaxies

"How the light from galaxies were bended?"
"Masses!"

--- Zwicky, 1937

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

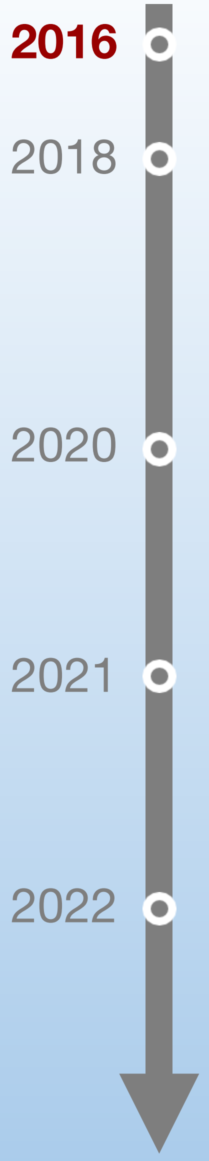


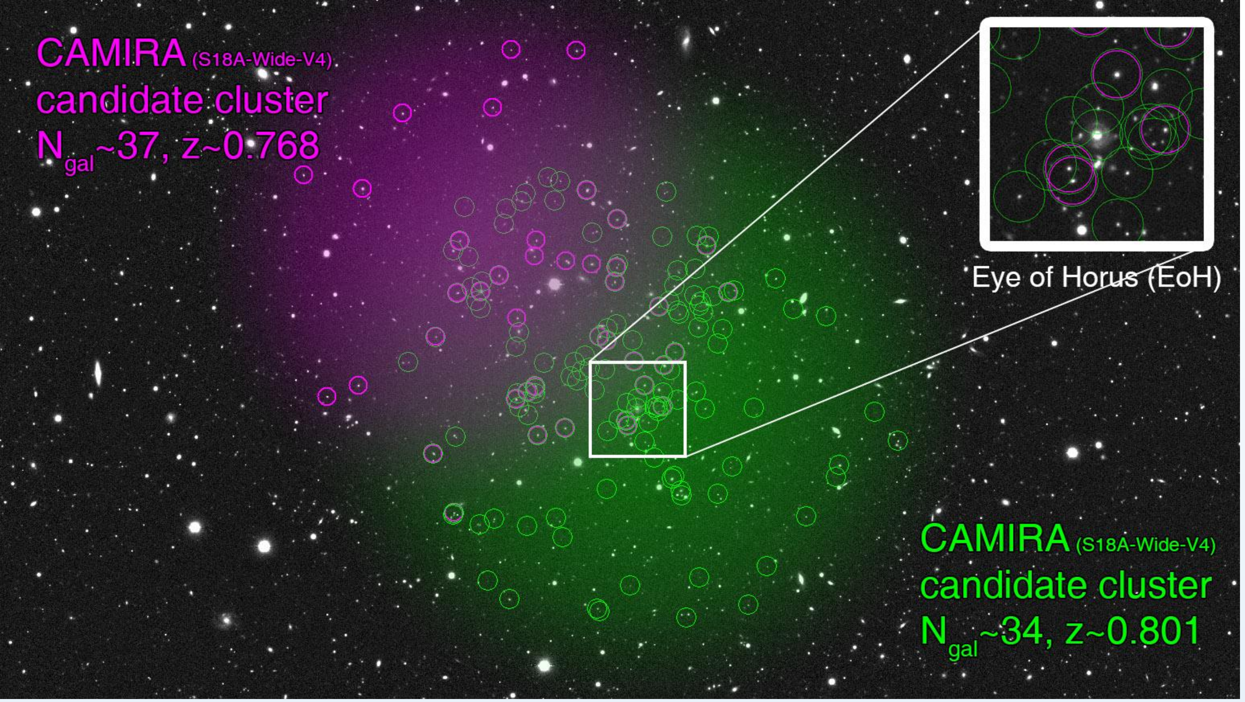
Tanaka et al. (2016)

Timeline of this research

Introduction

1. Discovery of “The Eye of Horus” GL
   - A double-source-plane (DSP) system (**rare**, <10 as of today),
   - Central galaxy acts as GL, with **strongly lensing two** background galaxies at z~1.3 and z~2.0.
   - Cluster redshift z_{cl}~0.8
   - Need a mass model accurate enough to describe this system





Oguri et al (2018)

Introduction

2. Two galaxy clusters? (Oguri et al. 2018)
   a. Around redshifts z~0.8
   b. Photometric z w/ ~0.05 error

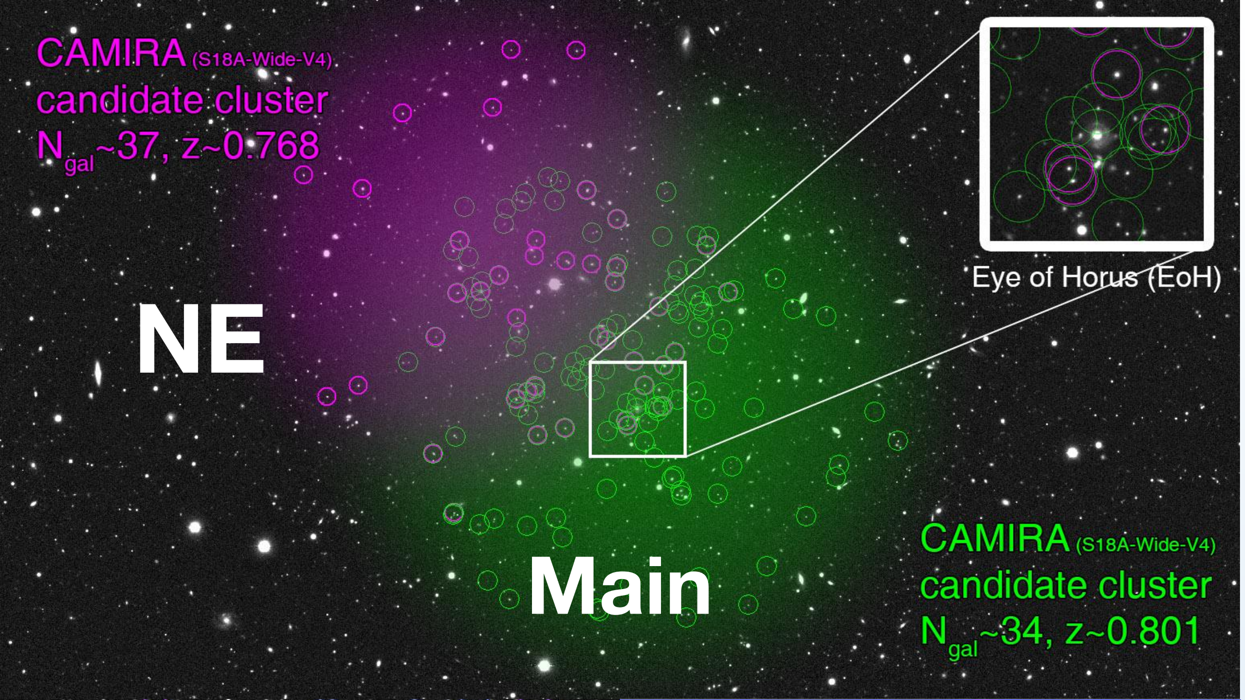
2016

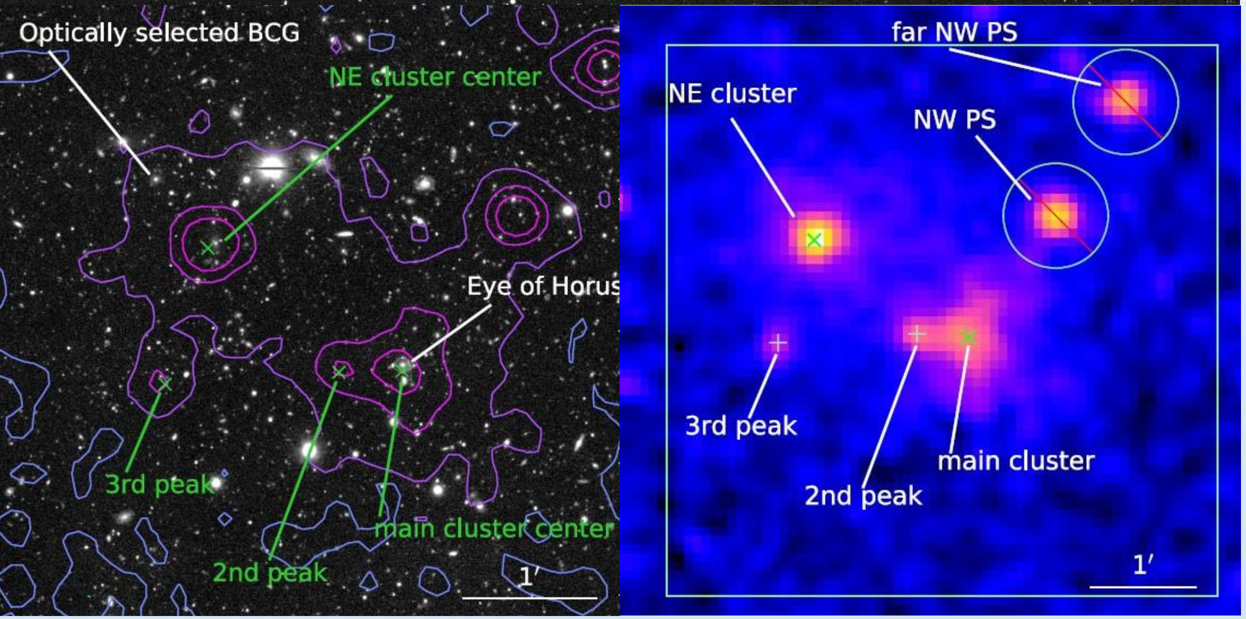
2018

2020

2021

2022



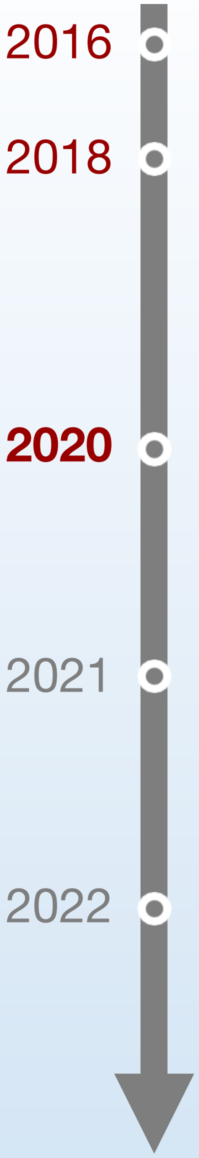


Oguri et al (2018), Tanaka et al. (2020)

Introduction

2. Two galaxy clusters? (Oguri et al. 2018)
    a. Around redshifts z~0.8
    b. Photometric z w/ ~0.05 error
3. X-ray Mapping (Tanaka et al. 2020)
    a. Signal of hot plasma in Intra-Cluster Medium (ICM) with Free-Free radiation
    b. Two bright X-ray peaks at z~0.795 and z~0.761
    c. 100’’ Separation

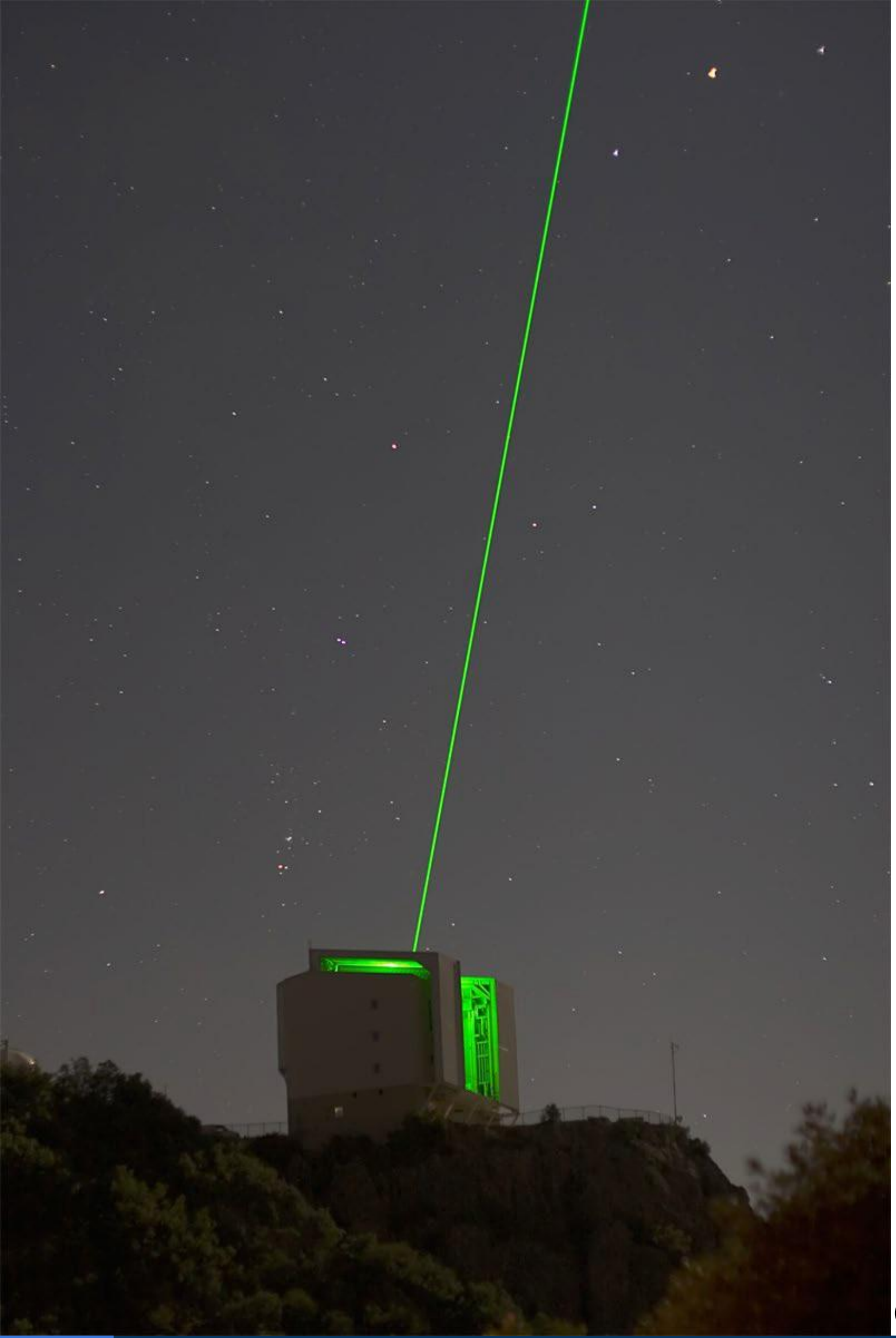
Still, no accurate info on spec-z



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



Observation

July 2019 Observation (Run #1)

- 190 targets

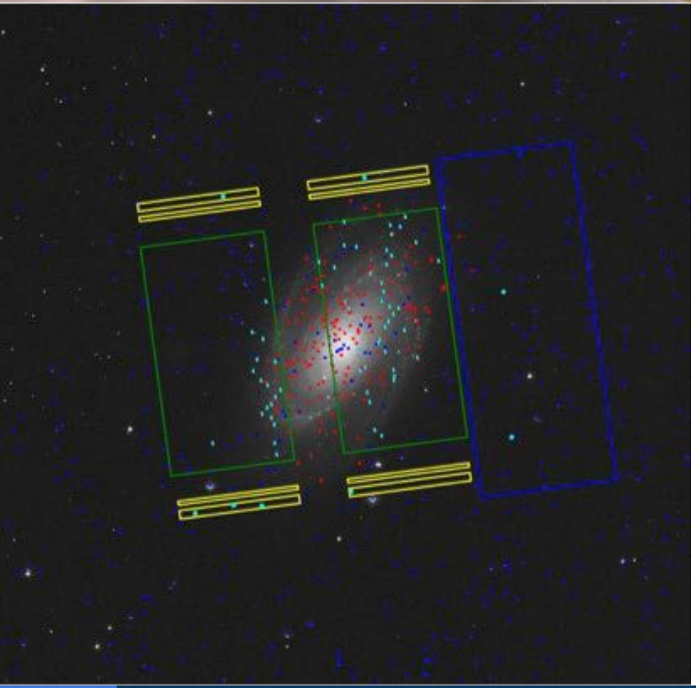
January 2022 Observation (Run #2)

- 181 targets

MMT

- Was Multiple Mirror Telescope (1979–1998)
- Mt. Hopkins, Tucson, AZ
- 6.5m in diameter
- The same size, mirror casting as Magellan I&II 6.5m

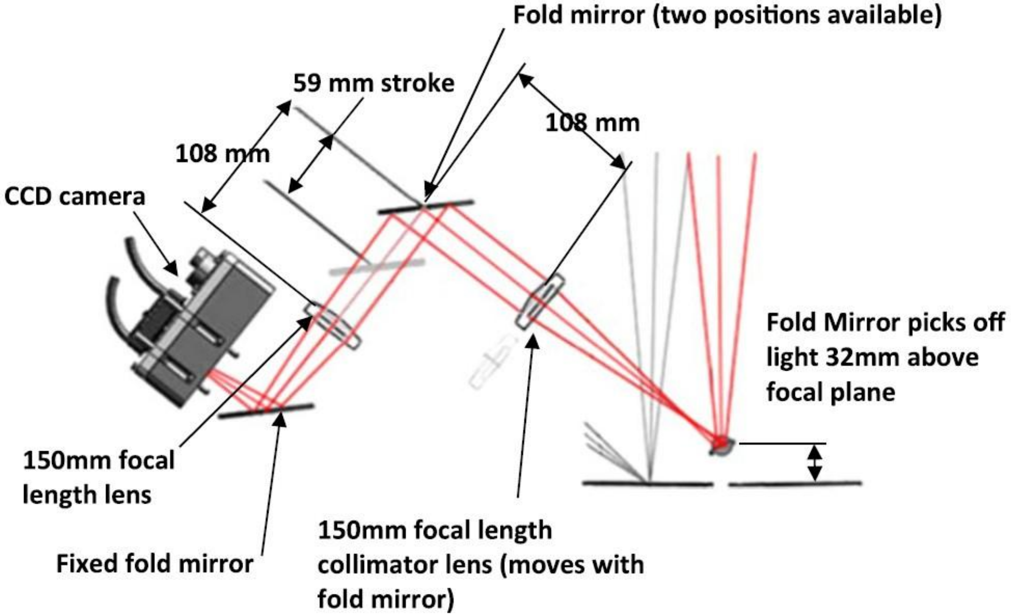
Credits: mmto.org



Observation

MMT/Binospec

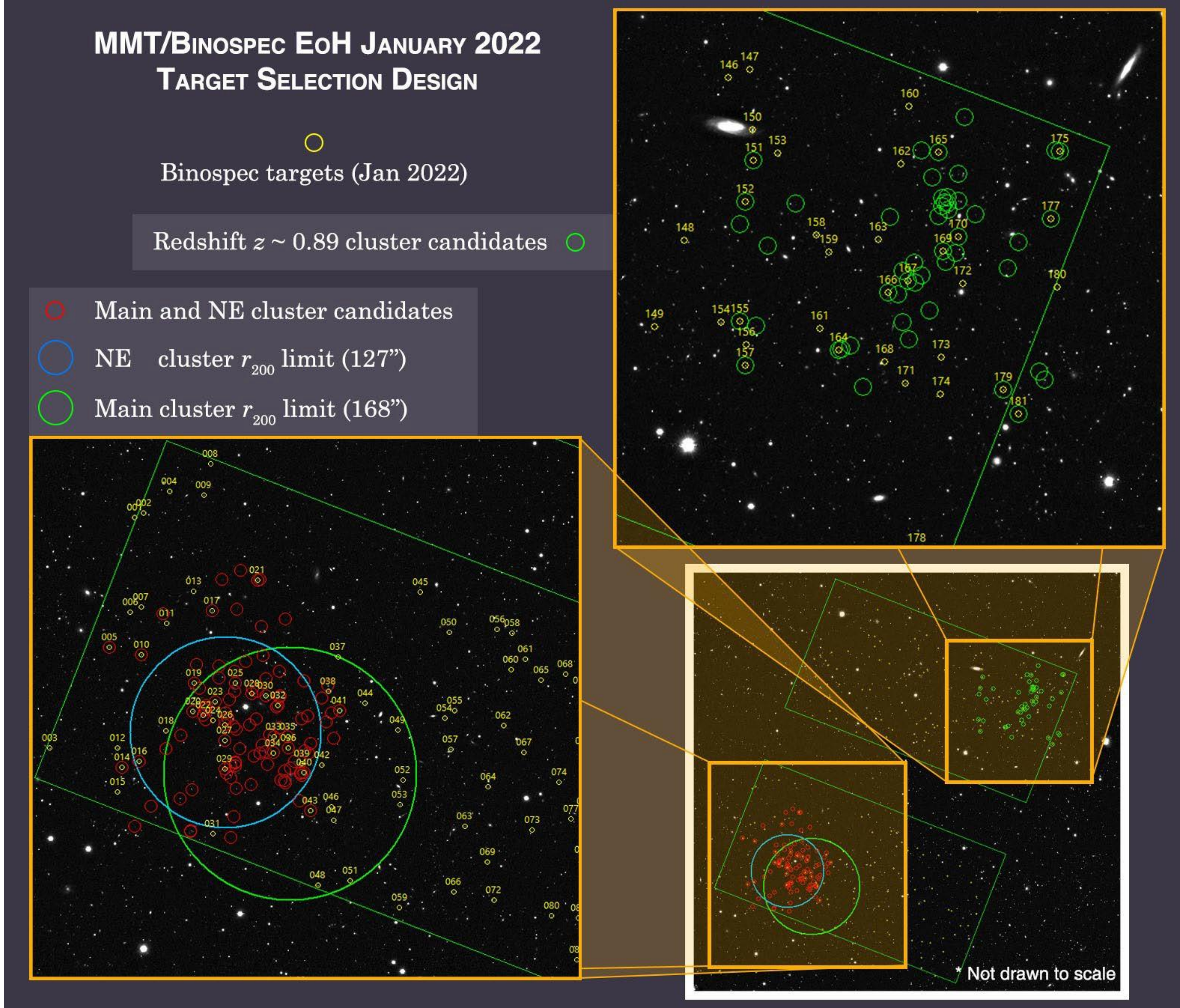
- Resolving power R~3500 (2Å at IR band)
- More spectral lines are legible (Ca H&K)
- Two field-of-views (8’ × 15’ each FoV)



Credits: Fabricant et al. (2019), mmto.org

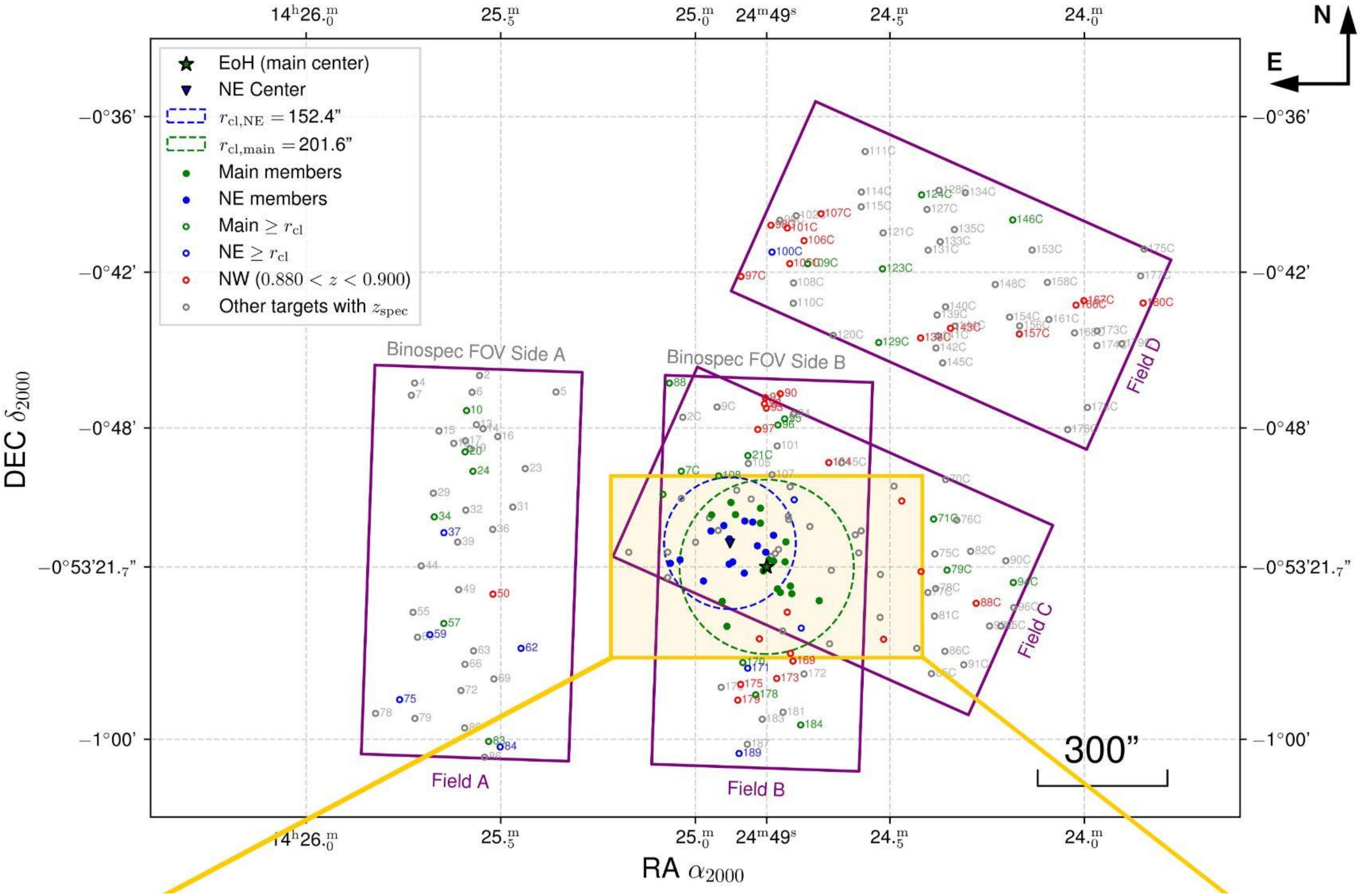
Target Selection

- CAMIRA candidates with near EoH and have photometric redshifts (photo-z's) at z~0.79, 0.759, and 0.896.
- Sufficient to select enough **red galaxies** due to CAMIRA algorithm.
- As the supplementary, add **blue galaxies** with similar magnitudes and photo-z's at z~0.8 in HSC catalogs.



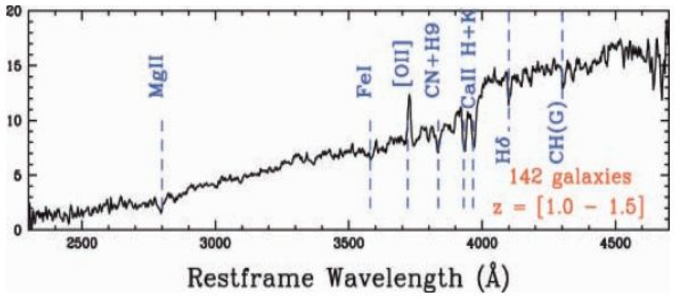
Target Selection - Mask Design

- CAMIRA candidates with near EoH and have photometric redshifts (photo-z's) at z~0.79, 0.759, and 0.896.
- Sufficient to select enough **red galaxies** due to CAMIRA algorithm.
- As the supplementary, add **blue galaxies** with similar magnitudes and photo-z's at z~0.8 in HSC catalogs.

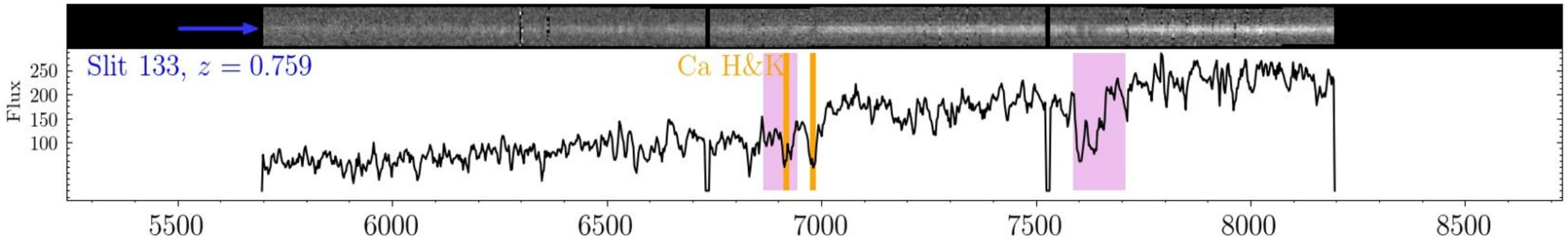


Measure the Redshift

- Many GUI tools available for **spectroscopic** redshift solutions:
  - **`EZ`**: **`Python`**-based, automatic (1005.2825, Garilli+2010, not maintained)
  - **`AUTOZ`**: **`IDL`**-based, automatic (1404.2626, Baldry+2014)
  - **`SpecPro`**: **`IDL`**-based, semi-auto (1103.3222, Masters+2011)
- They all need **typical spectrum templates** of galaxies at **rest-frame** wavelengths
- Aim at **absorption** and/or **emission lines**
- Find features appeared on **observed** spectrum of galaxy
- Takeaway: **shift the template** on wavelength space **to match observed spectrum**



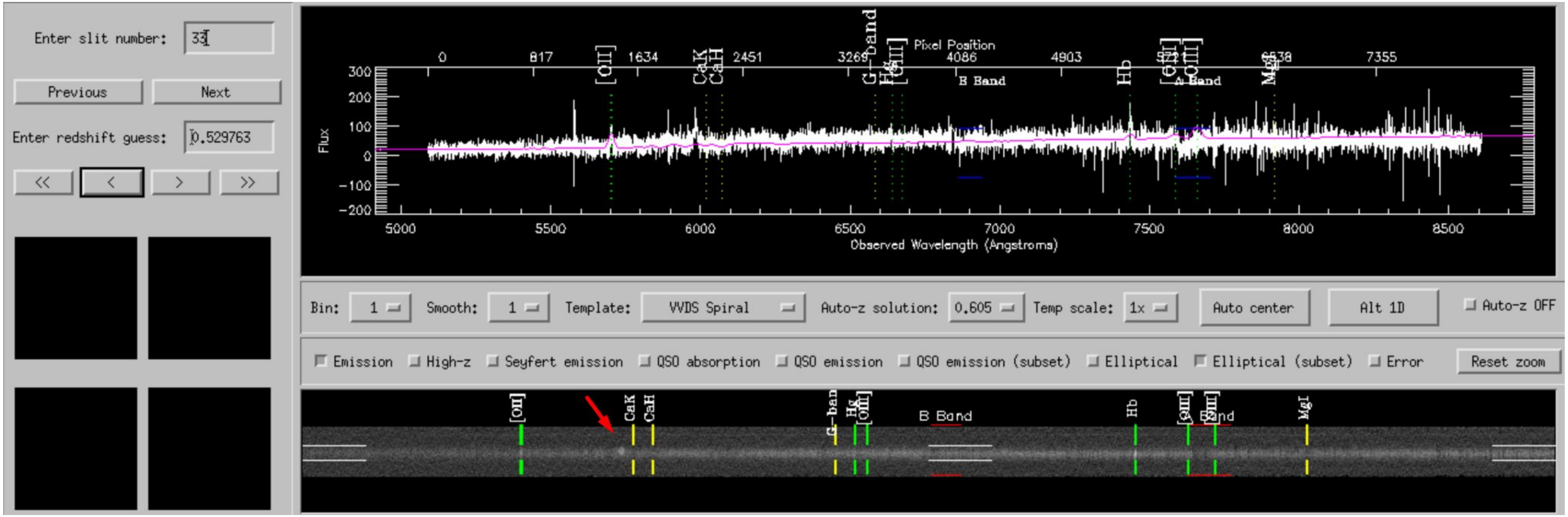
A galaxy template from VVDS early type galaxies



Sample spectrum from observation Run #1, this work

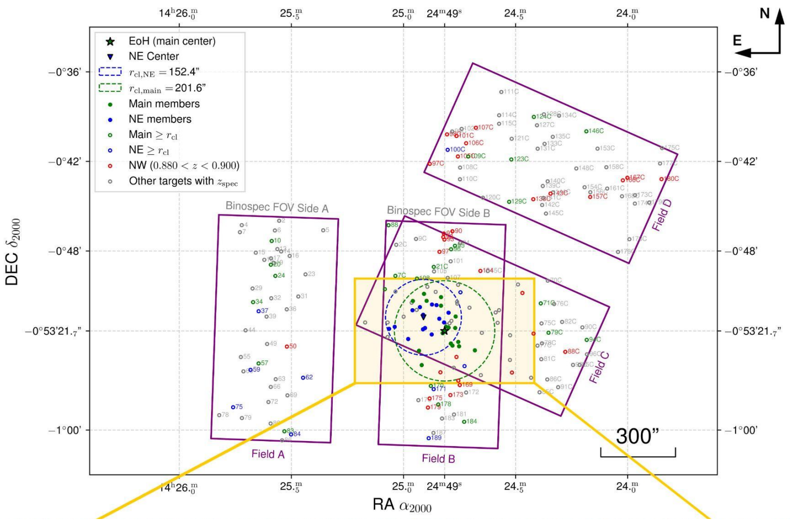
Measure the Redshift - `IDL/SpecPro` (Masters & Capak 2011)

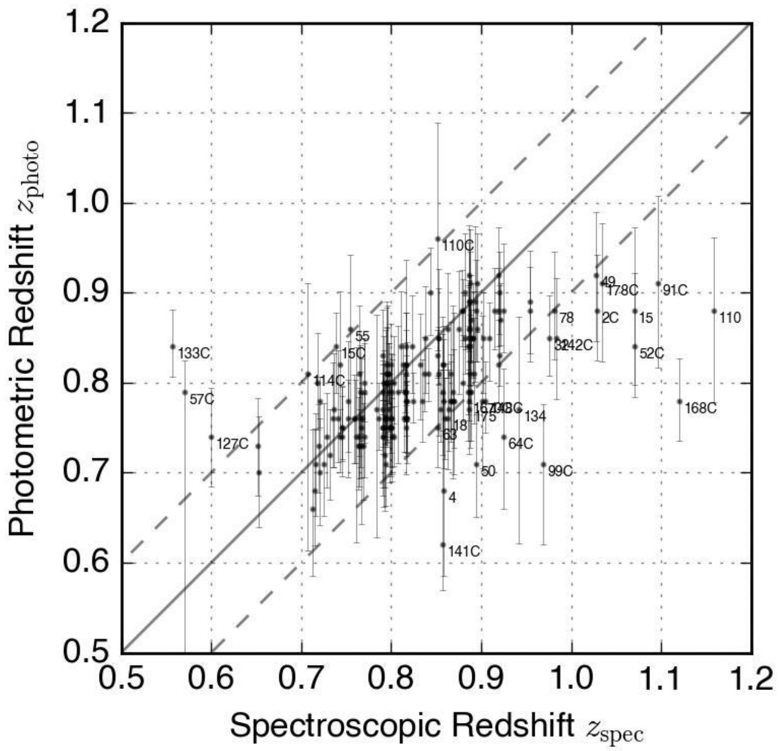
- Targeted ~400 galaxies (not huge amount ⇒ semi-auto)
- Used **`SpecPro`** for better goodness of measurements
- Choose template –> check auto-z solutions –> choose one that spectrum fits best

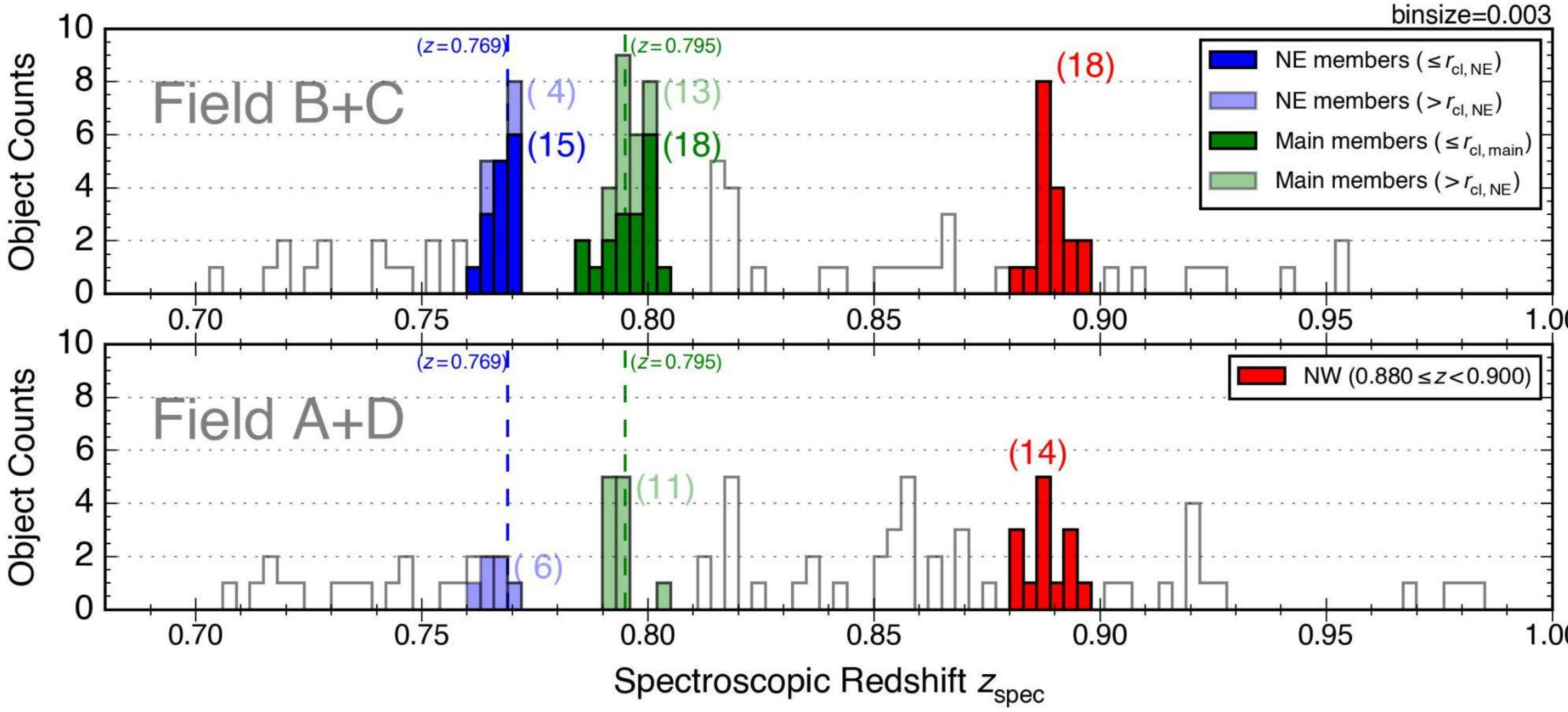


Results - (1) Spectroscopic Redshifts (spec-z's)

- 221 secure redshifts (Run #1+2)
- ~70% of CAMIRA candidate galaxies
- Scatter = 0.07 for spec-photo consistency

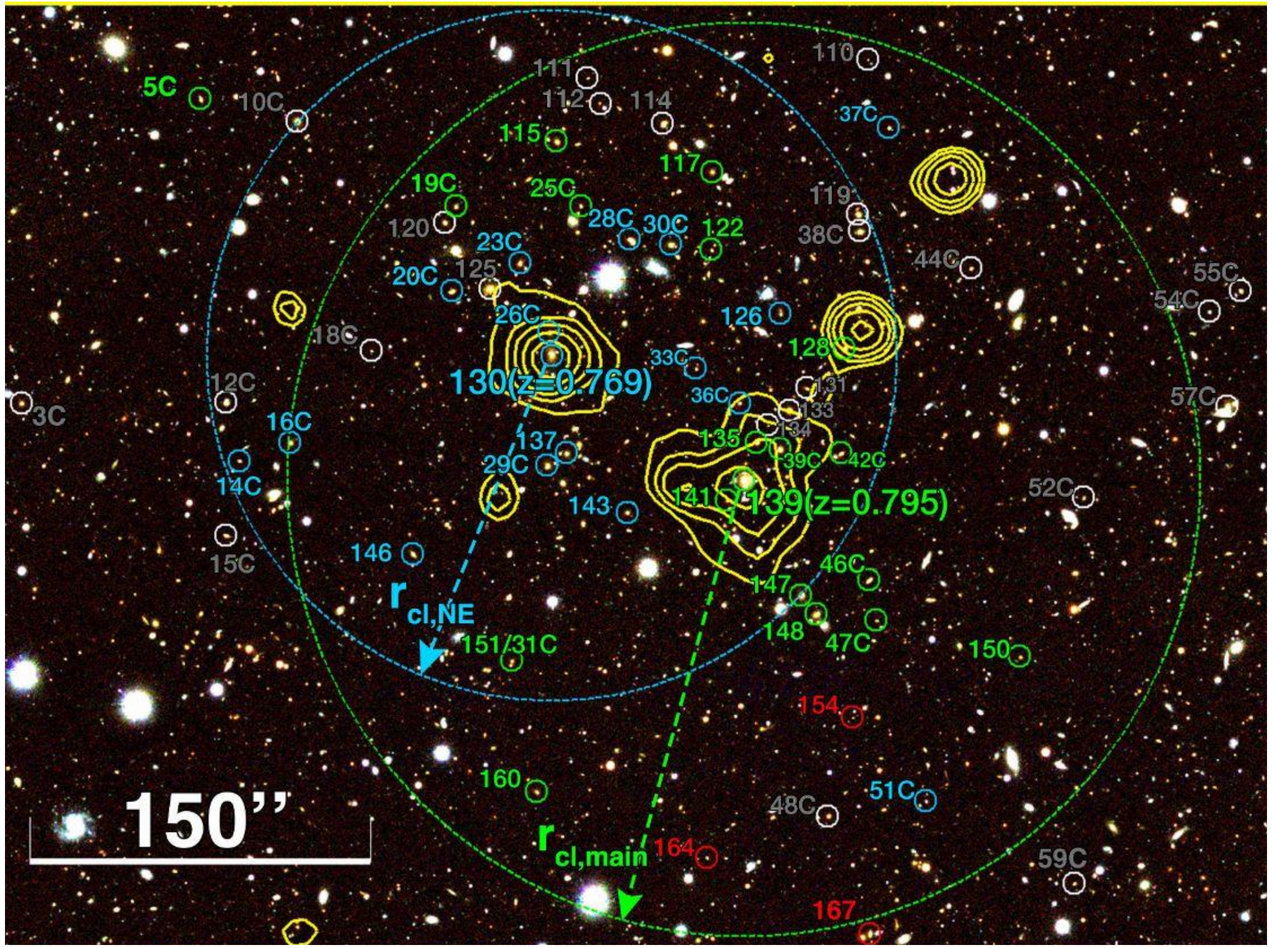






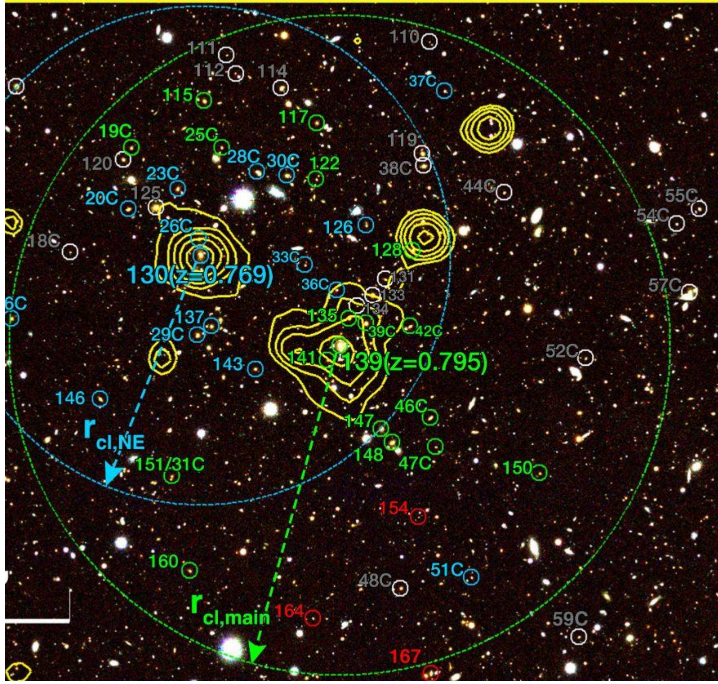
Results - (2) Cluster Identification

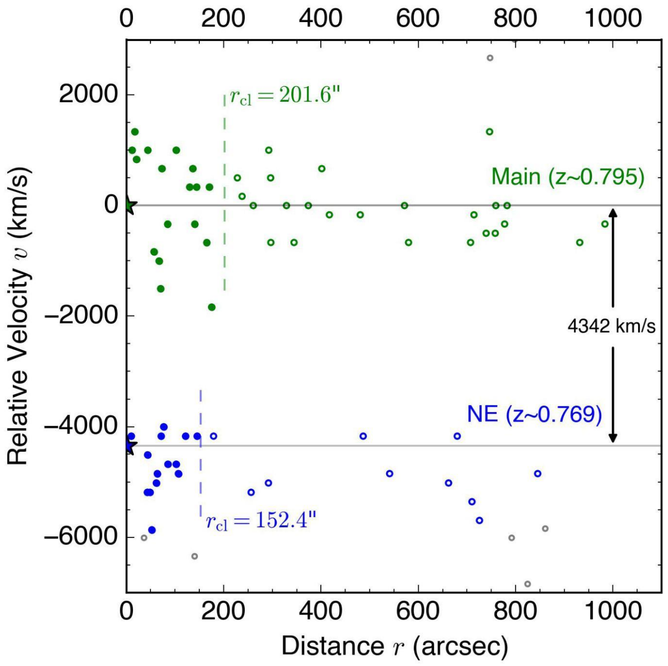
- Define a cluster
  - A virialized core + in-fall component
  - Boundary of cluster = ∞
  - **Boundary of core** $r_{cl} = n \times r_{200}$
  - r_{200} = *where enclosed average mass density is equal to 200 times the critical mass density of the universe at those redshifts/ages*
  - $$M_{200} \equiv M(r_{200}) = 200 \cdot \frac{3H^2}{8\pi G} \cdot \frac{4\pi}{3} \cdot r_{200}^3$$
  - n=1.2 for adding on-boundary ones
  - r_{cl} = 201.6″ = 1.510 Mpc (main) and r_{cl} = 152.4″ = 1.129 Mpc (NE)

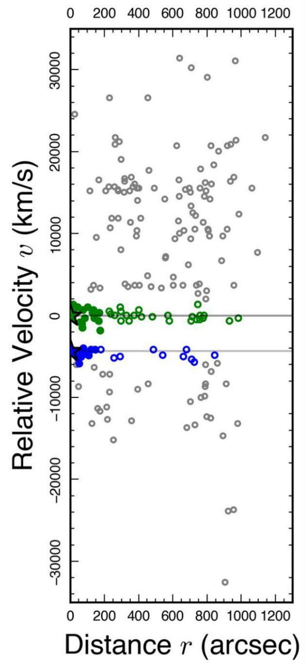


Results - (2) Cluster Identification

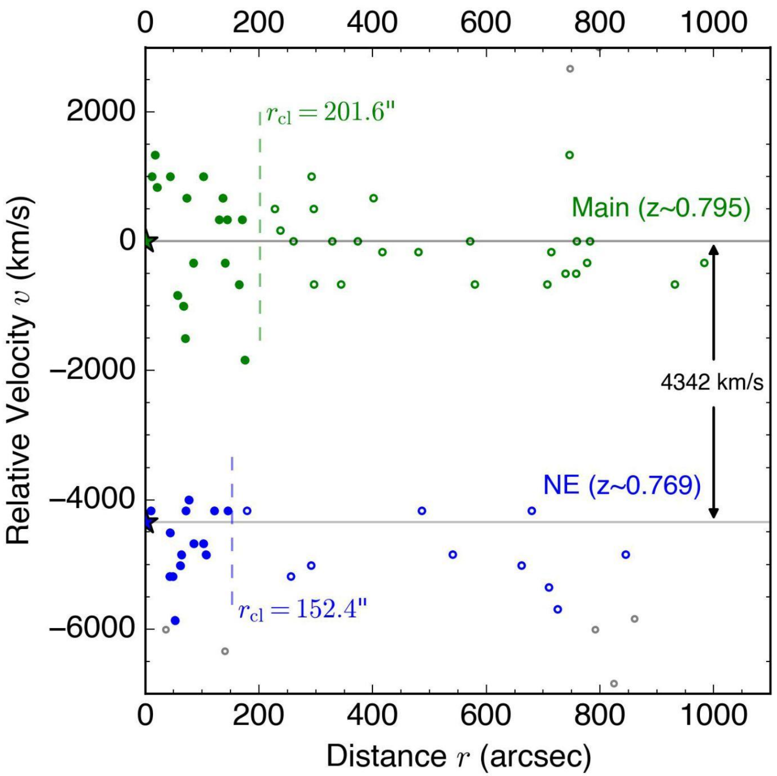
- Define member galaxies of a cluster
  - BCG as center (EoH for main)
  - Galaxies with…
    - Similar z as BCG redshifts (z=0.795 and 0.769)
    - Small radii to center
- **Shifting-gapper method** (Fadda+1996, Sifón+2013, Sifón+2016)
  - Galaxies → bins of >250-kpc radii
  - → sort by light-of-sight velocities (*v*)
  - Cut 1: < 4000 km/s
  - (“shifting”) (“gap”)
    Cut 2: Examine in galaxy pairs, *v* offset of pair < 500 km/s
  - Make-up: add < 1000 km/s, from Cut 2
  - After a few iterations above, remained are member galaxies of a cluster

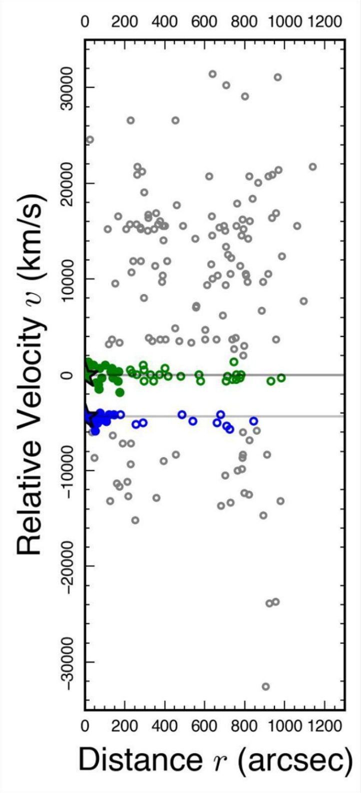




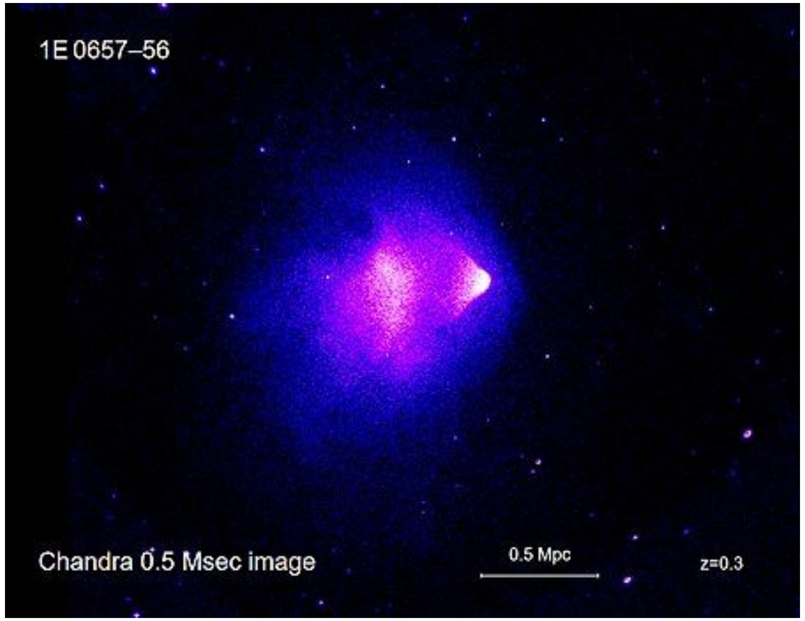


Results - (2) Cluster Identification

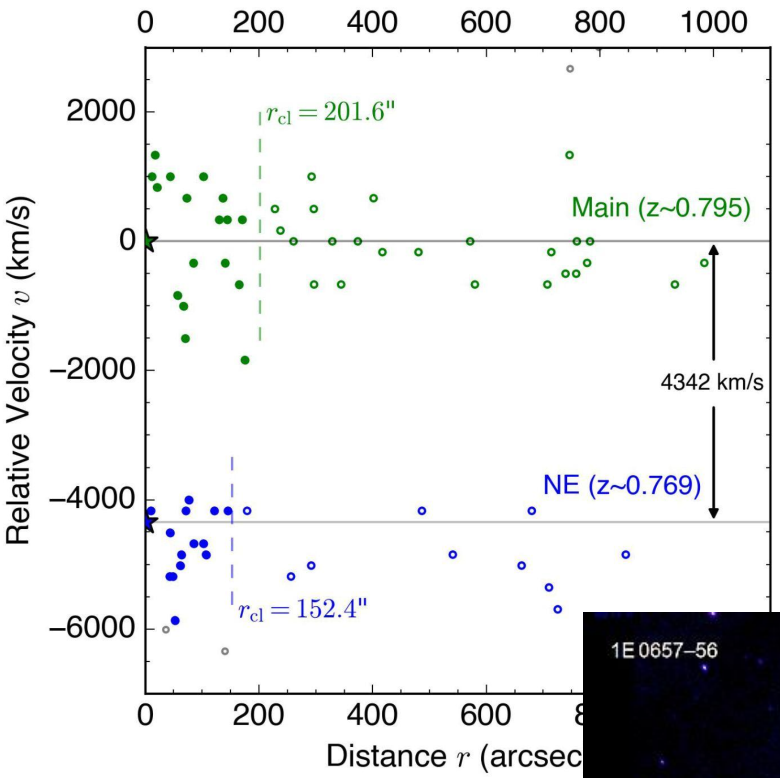


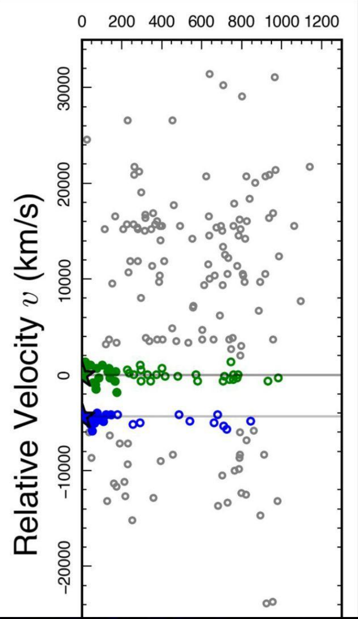


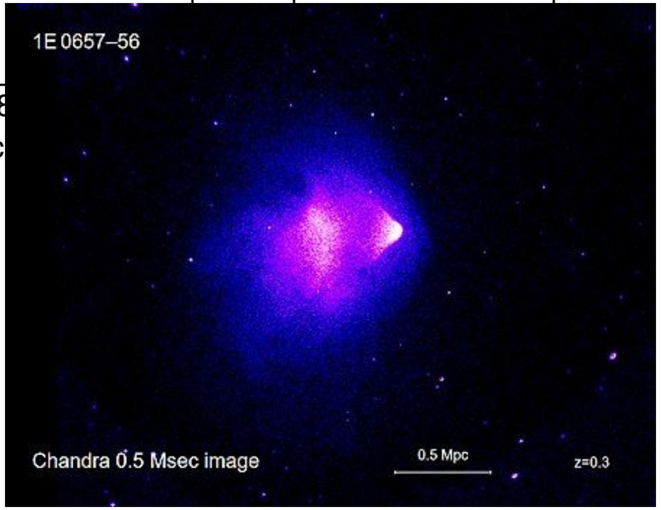
- Velocity offset between two clusters
  - ~4300 km/s
  - No overlaps between
- Cluster Merger Case
  - Two clusters sit very close (spatially)
  - But they ***still*** should have a large velocity offset (in velocity space)



Results - (2) Cluster Identification







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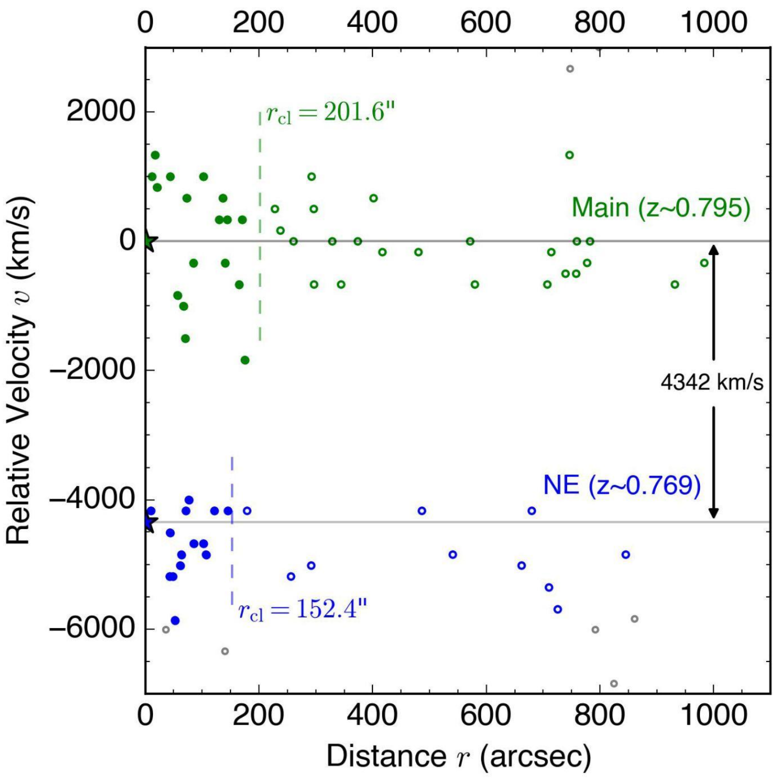
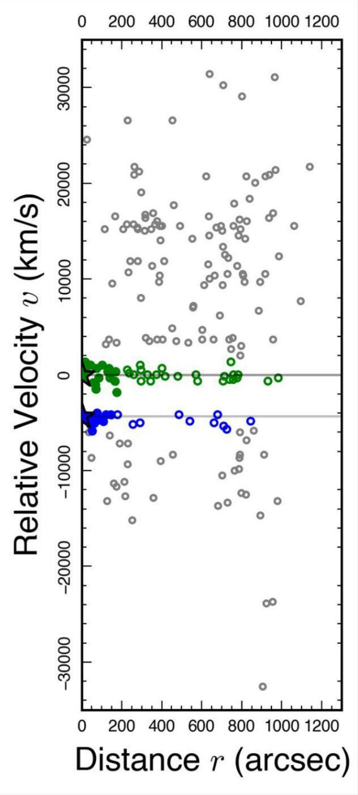
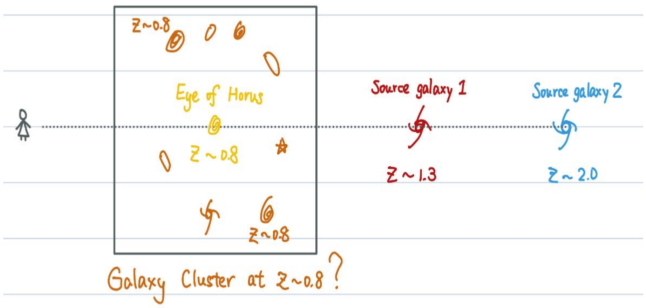
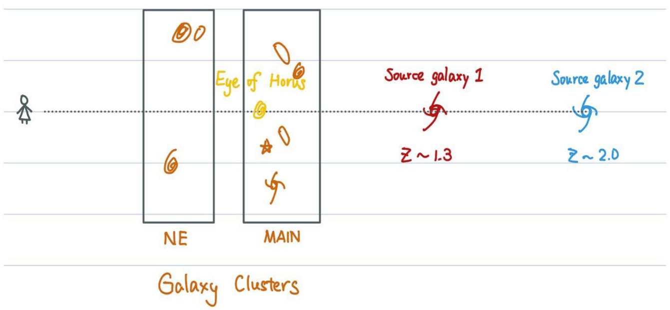
  - Lee & Komatsu (2010): **Probability of a merger with**
    - *P*(>2000 km/s) = 0.002
    - *P*(>3000 km/s) = 0.000 000 0036

Results - (2) Cluster Identification









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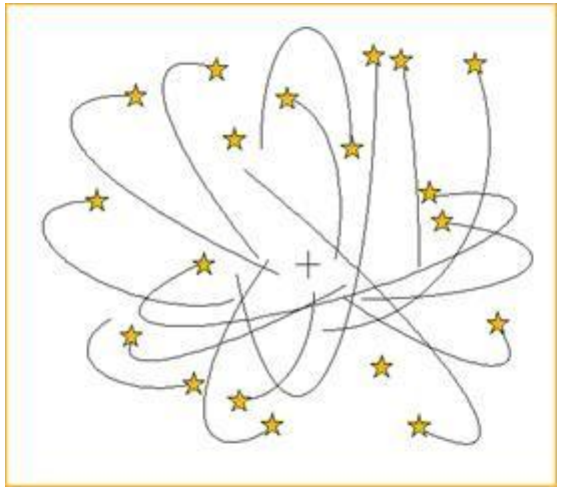
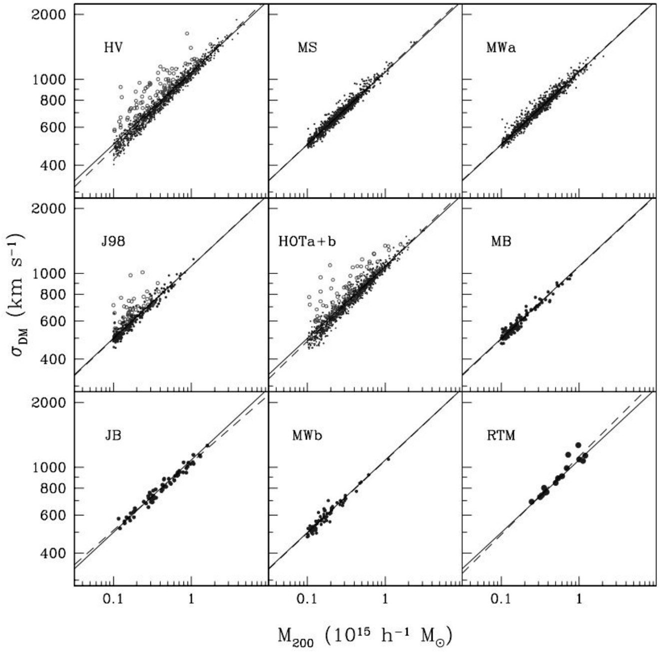
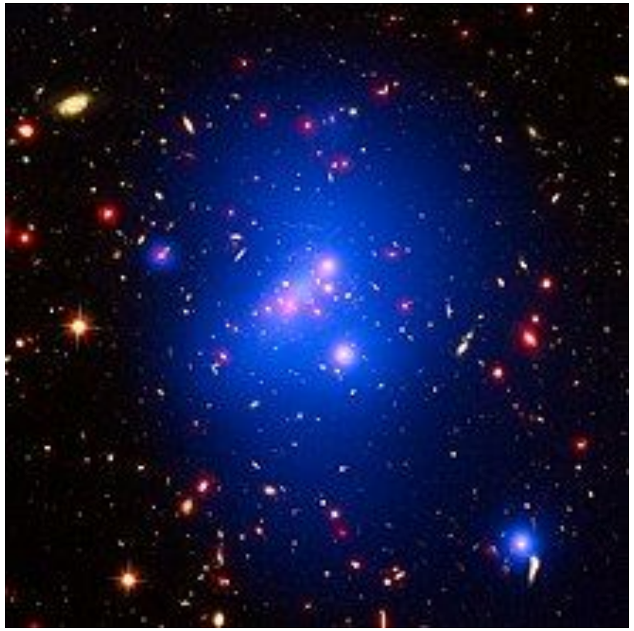
  - Two clusters sit very close (spatially)
  - But they ***still*** should have a large velocity offset (in velocity space)
  - Lee & Komatsu (2010): **Probability of a merger with**
    - *P*(>2000 km/s) = 0.002
    - *P*(>3000 km/s) = 0.000 000 0036
  - *So*, *P*(~4300 km/s) → 0
- **NE and main clusters are not merging**

Results - (3) Cluster Masses

Virial Theorem	Scaling Relations	Hydrostatic Density
Random motion of galaxies in cluster	Relationship between the **redshifts** and **masses** of galaxy clusters at similar redshifts	**High energy hot plasma** (at temperature T and mass density) in ICM
		

Selected in this research

Results - (3) Cluster Masses

Virial Theorem	Scaling Relations	Hydrostatic Density
Random motion of galaxies in cluster	Relationship between the **redshifts** and **masses** of galaxy clusters at similar redshifts	**High energy hot plasma** (at temperature T and mass density) in ICM
N, $\sigma_P(z)$, R_{ij}	$\sigma_{200}(z)$ within R_{200}	$T(r)$
$\sigma_P = \sqrt{\frac{\sum_i V_i^2}{N-1}}, \; R_{PV} = \frac{N(N-1)}{\sum_{i>j} R_{ij}^{-1}},$ $\boxed{M_V = \frac{3\pi}{2} \frac{\sigma_P^2 R_{PV}}{G}}$	$\alpha = 0.364 \pm 0.002$ $A_{1D} = 1177 \pm 4.2\,\mathrm{km\,s^{-1}}$ $E(z) = \left(\Omega_\Lambda + (1+z)^3 \Omega_m\right)^{1/2}$ $\boxed{\sigma_{200} = A_{1D} \left(\frac{hE(z)M_{200}}{10^{15}\,M_\odot}\right)^\alpha}$	$\rho(r) = \frac{1}{4\pi r^2} \cdot \frac{3k_B T\beta}{G\overline{m}_{ion}} \left\{ \frac{3r^2}{r^2 + r_c^2} - \frac{2r^4}{(r^2 + r_c^2)^2} \right\}$ $\boxed{M(r) = \frac{3k_B T\beta r}{G\overline{m}} \cdot \frac{r^2}{r^2 + r_c^2}}$

$\underbrace{\hspace{10em}}_{\text{Selected in this research}}$

Tanaka et al. (2020)

Selected in this research

Results - (3) Cluster Masses - a systematic offset

Virial Theorem	**Scaling Relations**	**Hydrostatic Density**
Random motion of galaxies in cluster	Relationship between the **redshifts** and **masses** of galaxy clusters at similar redshifts	**High energy hot plasma** (at temperature T and mass density) in ICM
N, $\sigma_P(z)$, R_{ij}	$\sigma_{200}(z)$ within R_{200}	$T(r)$
$\boxed{M_V = \frac{3\pi}{2}\frac{\sigma_P^2 R_{PV}}{G}}$ *(Overestimated 30% - assumptions of velocity anisotropy)*	$\boxed{\sigma_{200} = A_{1D}\left(\frac{hE(z)M_{200}}{10^{15}\,M_\odot}\right)^\alpha}$	$\boxed{M(r) = \frac{3k_B T\beta r}{G\bar{m}} \cdot \frac{r^2}{r^2 + r_c^2}}$
R_{PV} = 1.036 Mpc, σ_P = 516 km/s	R_{200} = 0.940 Mpc, σ_{200} = 517 km/s	$M_{200,\,NE}$ = **2.2** x 10^{14} M_{sun}
$M_{V,\,NE}$ = **3.26** x 10^{14} M_{sun}	$M_{200,\,NE}$ = **0.97** x 10^{14} M_{sun}	
		$M_{200,main}$ = 5.6 x 10^{14} M_{sun}

Selected in this research

Tanaka et al. (2020)

Results - (3) Cluster Masses - a systematic offset: $M_V \approx 2M_{200}$

Virial Theorem	Scaling Relations	-
Random motion of galaxies in cluster	Relationship between the **redshifts** and **masses** of galaxy clusters at similar redshifts	-
N, $\sigma_P(z)$, R_{ij}	$\sigma_{200}(z)$ within R_{200}	-
$\boxed{M_V = \frac{3\pi}{2}\frac{\sigma_P^2 R_{PV}}{G}}$ *(Overestimated 30% - assumptions of velocity anisotropy)*	$\boxed{\sigma_{200} = A_{1D}\left(\frac{hE(z)M_{200}}{10^{15}\,M_\odot}\right)^\alpha}$	-
R_{PV} **= 1 Mpc,** σ_P **= 1000 km/s**	R_{200} **= 1 Mpc,** σ_{200} **= 1000 km/s**	-
M_V = 8 x 10^{14} M_{sun}	M_{200} = 4 x 10^{14} M_{sun}	
		-

Selected in this research

Results - (3) NE and Main Cluster Masses

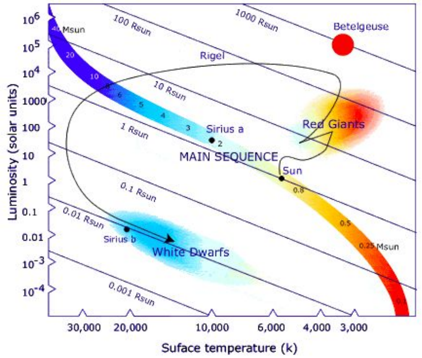
Virial Theorem	Scaling Relations	Hydrostatic Density
Systematic offset: $M_V \approx 2M_{200}$		**High energy hot plasma** (at temperature T and mass density) in ICM
		$T(r)$
		$\boxed{M(r) = \frac{3k_B T \beta r}{G\overline{m}} \cdot \frac{r^2}{r^2 + r_c^2}}$
R_{PV} = 1.036 Mpc, σ_P = 516 km/s	R_{200} = 0.940 Mpc, σ_{200} = 517 km/s	$M_{200,\ NE}$ = **2.2** x 10^{14} M_{sun}
$M_{V,\ NE}$ = **3.26** x 10^{14} M_{sun}	$M_{200,\ NE}$ = **0.97** x 10^{14} M_{sun}	
R_{PV} = 1.181 Mpc, σ_P = 929 km/s	R_{200} = 1.259 Mpc, σ_{200} = 850 km/s	$M_{200,main}$ = **5.6** x 10^{14} M_{sun}
$M_{V,\ main}$ = **8.62** x 10^{14} M_{sun}	$M_{200,\ main}$ = **3.75** x 10^{14} M_{sun}	

Dynamical masses (M_V & M_{200}): good within a factor of a few, but not conclude which is more accurate.

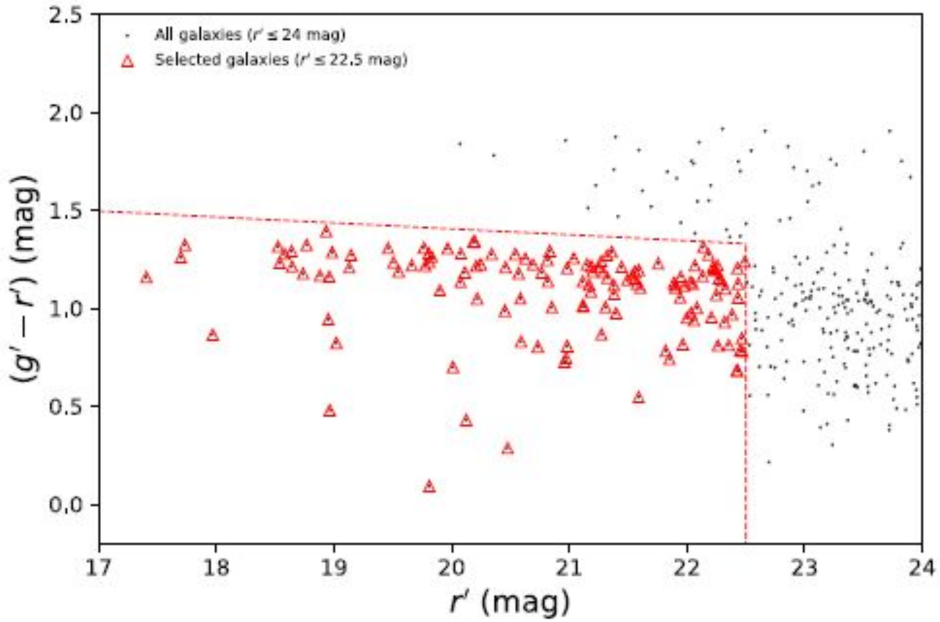
Results - (4) Color vs. Magnitude

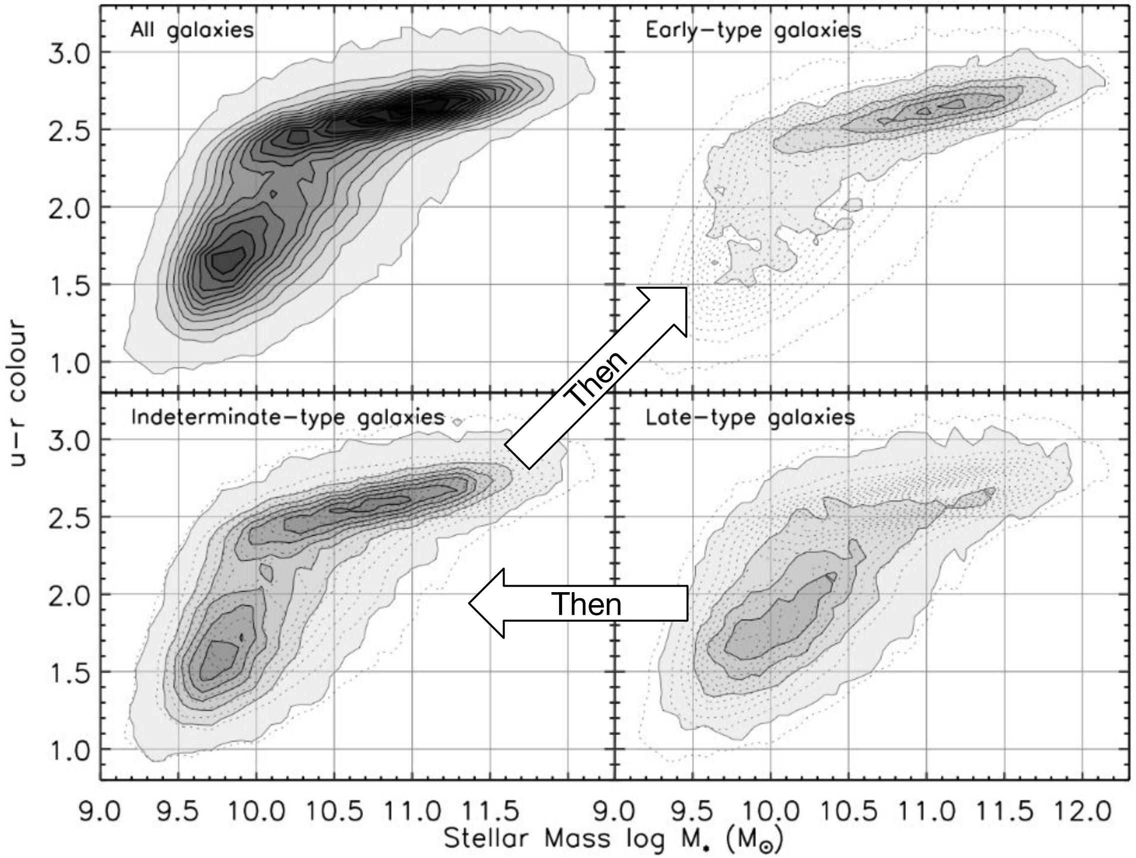
- *Similar to H-R Diagram*
- Color-Magnitude Diagram (CMD)
    - Evolution of cluster members
    - Cluster membership

H-R Diagram
Web pictures



CMD for Cluster MS0440.5+0204 (z=0.2)
Carrasco et al. (2021) ApJ, 918, 61

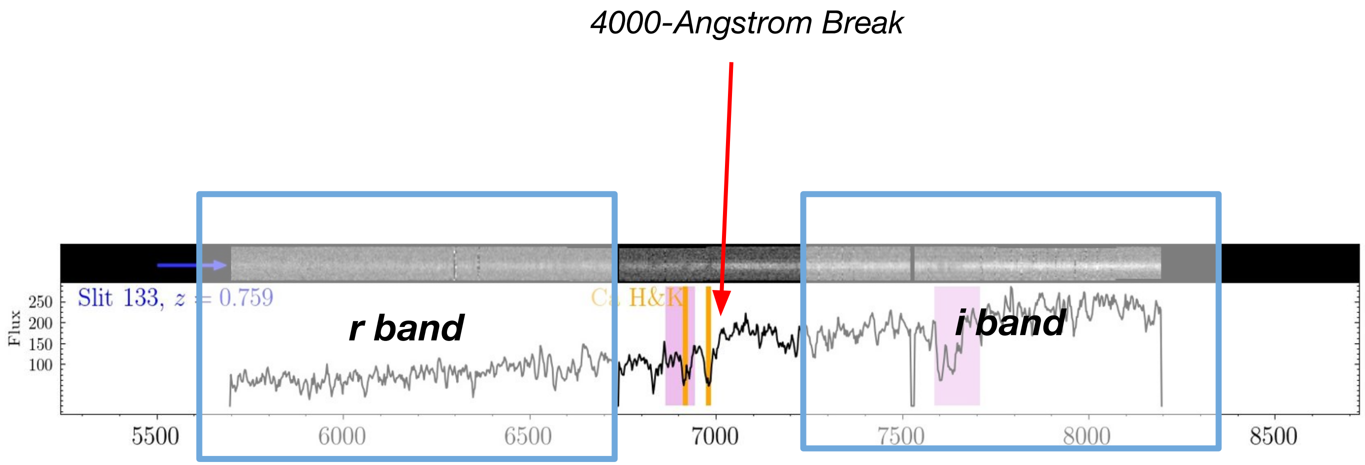




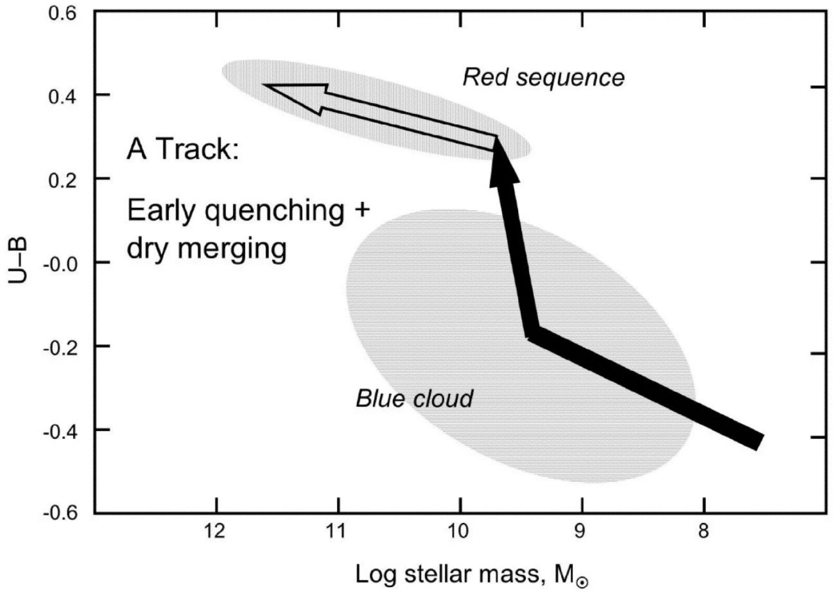
Color-Magnitude Diagram for "Galaxy Zoo" 47k+ Galaxies
Schawinski et al (2010) ApJ, 711, 284

Results - (4) Color vs. Magnitude

- X-axis – Mass or **Magnitude** *in any of the bands that clamped the wavelength of 4000A break at mean observed redshift*
- Y-axis – **Color:** *the magnitude difference*
- Central galaxies: upper-left on CMD



Schematic arrows showing galaxies migrating to the red sequence
Faber et al. (2007) ApJ, 665, 265



Results - (4) Color vs. Magnitude

- Elliptical/early-type by spectral features

  ⇒ define **red-sequence (RS) galaxies**

  - Linear-fit slope = -0.04 mag/mag (fixed)
  - +/- 0.2 color mag constraint (while fitting)
  - Expect to see more galaxies to RS as CoG evolving
  - Scatter of RS correlates with cluster redshift?

Schematic arrows showing galaxies migrating to the red sequence

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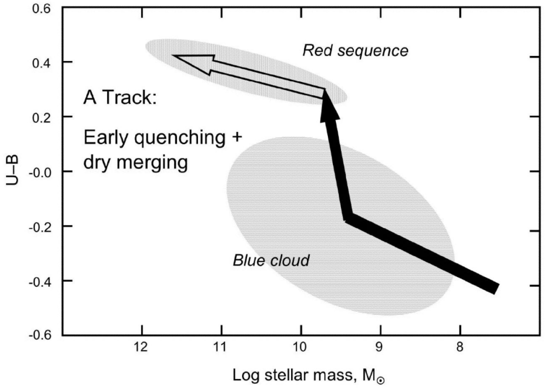
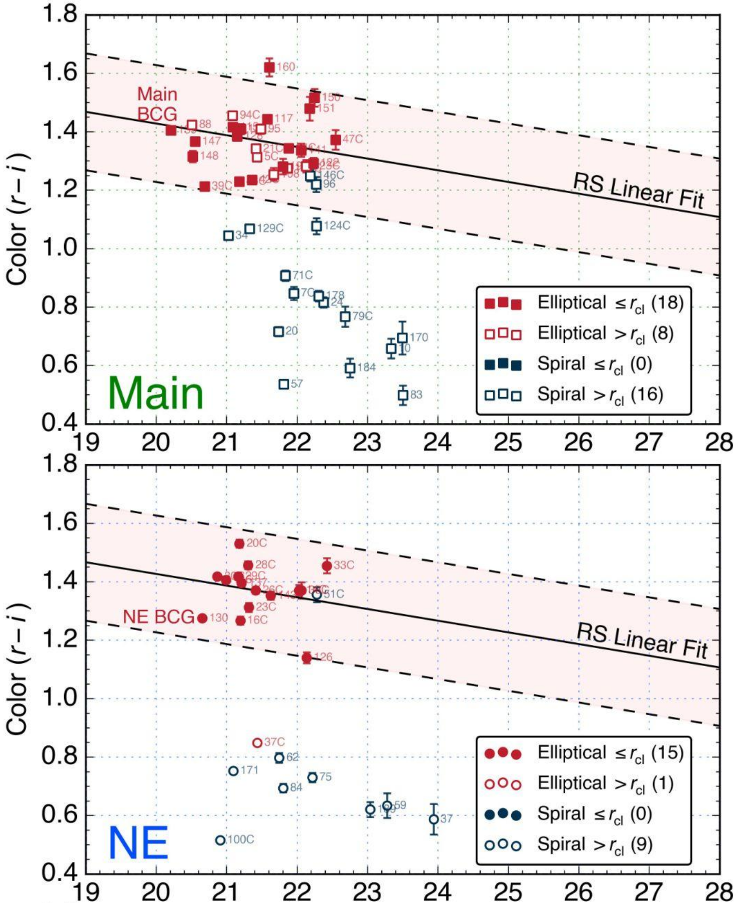
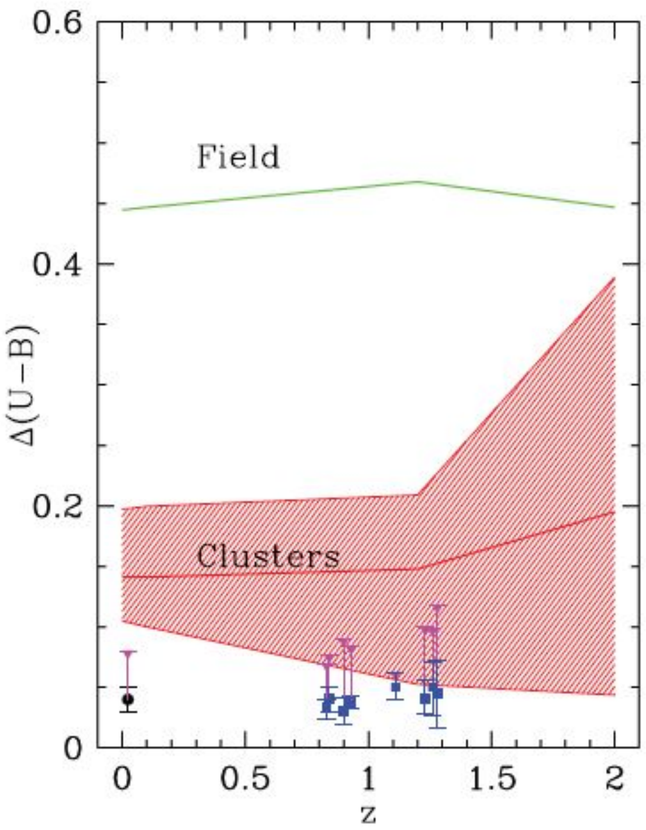




Red-Sequence scatter correlates with cluster redshift?

1. High-redshift galaxies in clusters just started evolved towards the RS (Menci+2008)



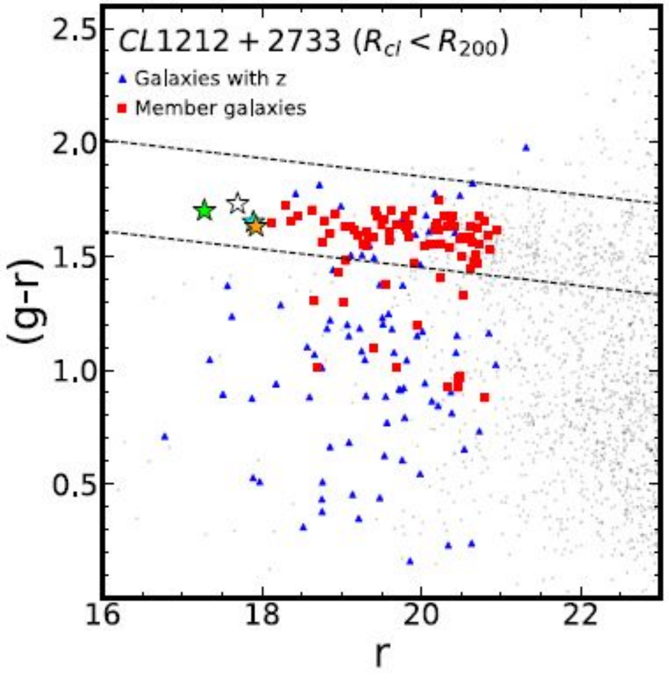
1. RS linear fit would be biased by Z-mag degeneracy (Connor+2019)
2. CAMIRA-selected galaxy clusters at $0.1 < z < 1.1$ with HSC photometry — RS scatter is small in colour-magnitude relation (Nishizawa+2018)

Larger scatters at higher cluster redshifts?

Linear fit slope = -0.04, +/- 0.2 color constraint
Add accurate galaxy morphologies to identify red/ellipticals

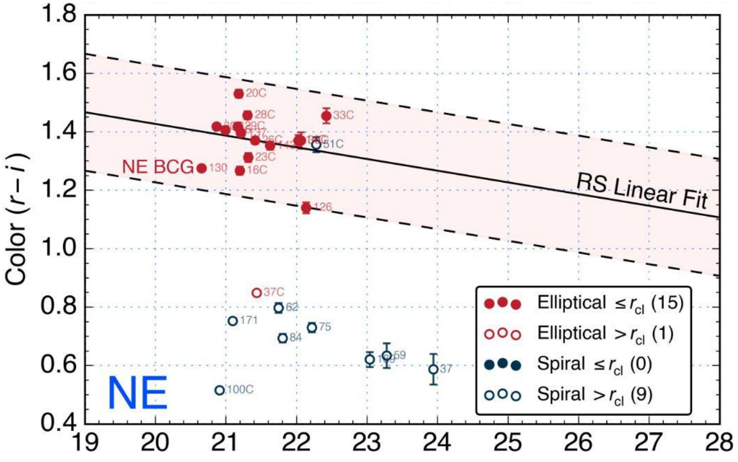
Rines+2022: Abell 1489 (z=0.351)

$\Delta_{(g-r)}$ = 0.**062**±0.005



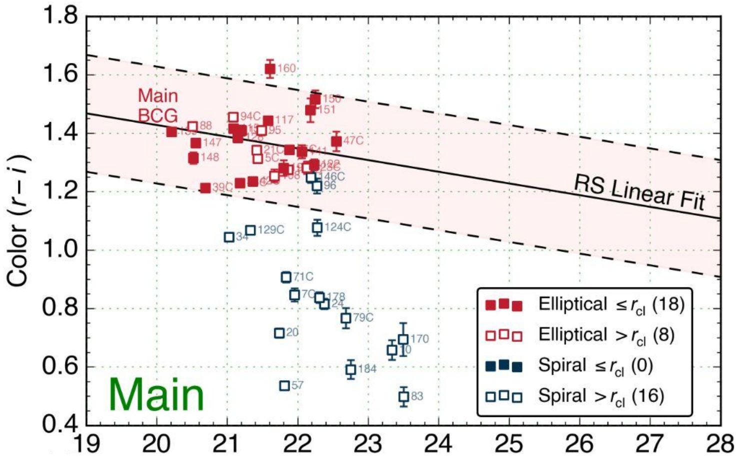
This work: NE cluster (z=0.769)

$\Delta_{(r-i)}$ = 0.**09**±0.02



This work: Main cluster (z=0.795)

$\Delta_{(r-i)}$ = 0.**11**±0.02



BCG Analysis (from spectroscopy)

- Galaxy evolution, age, formation time
- **Flux scale**
  - This work: ~ 10^{-17} erg/s/cm^2/A
  - depends on **stellar population mass (*M**)**
- **Shape** (or slope)
  - late-type / young
  - early-type / old
- **Lines**
  - (CaH+**Hε**)/CaK ⇒ young A- and B-type stars
  - Width ⇒ **stellar doppler velocity (σ_*)**
- Star formation models

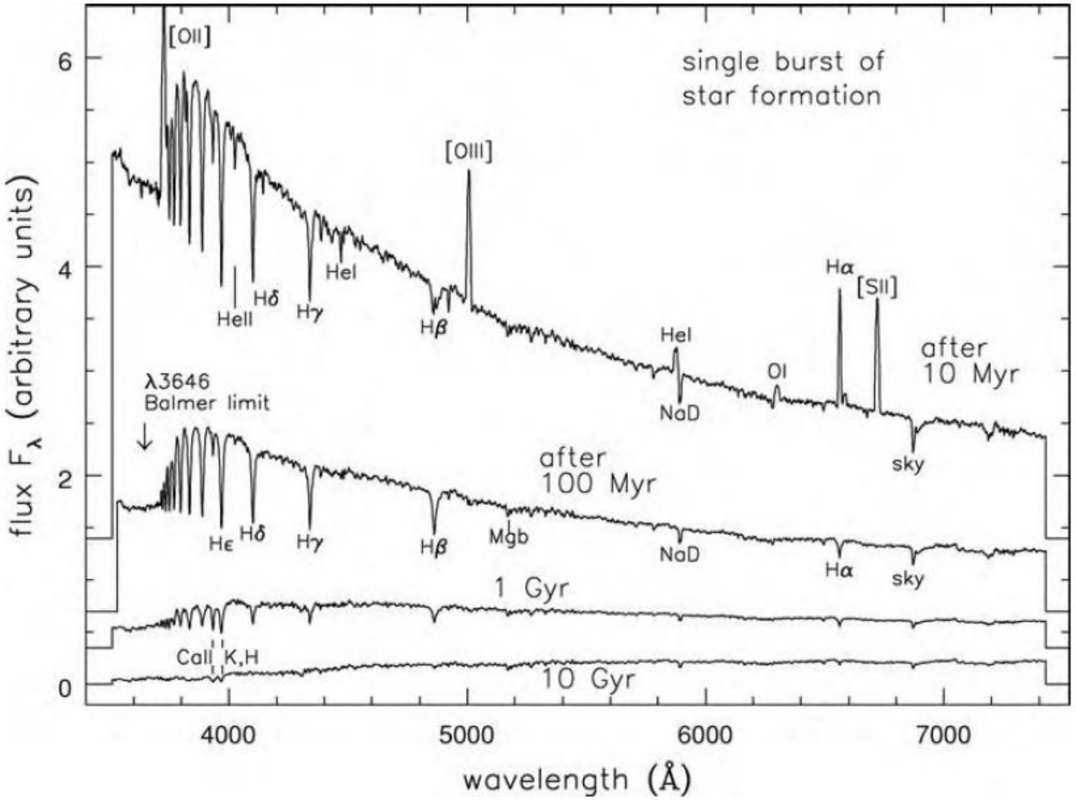


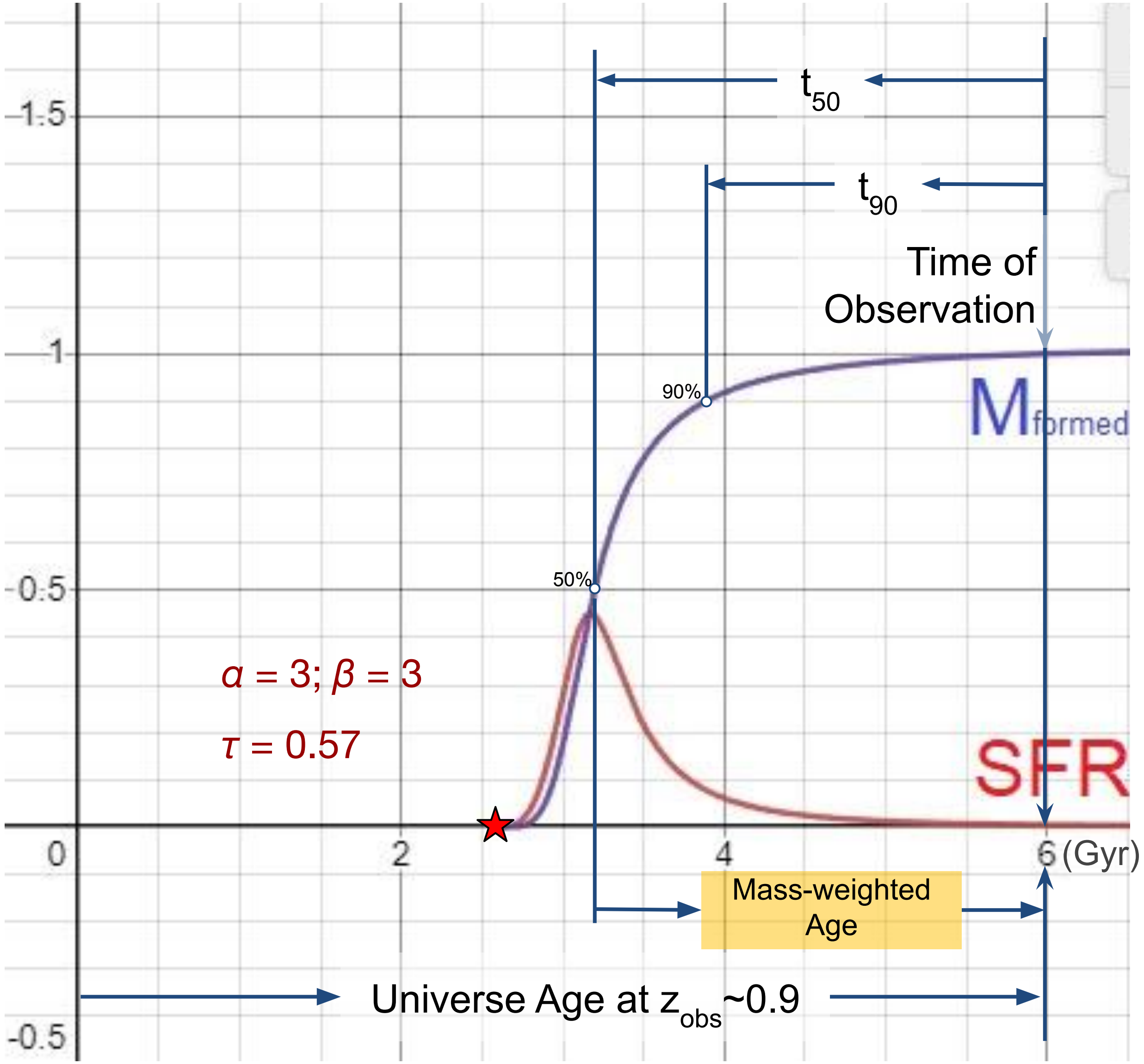
Fig. 6.18. Spectra for a 'galaxy' that makes its stars in a 10^8 yr burst, all plotted to the same vertical scale. Emission lines of ionized gas are strong 10 Myr after the burst ends; after 100 Myr, the galaxy has faded and reddened, and deep hydrogen lines of A stars are prominent. Beyond 1 Gyr, the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

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

BCG Analysis - Star formation history

- Double power law (Behroozi+2013, Diemer+2017)
  - $$\mathrm{SFH(t)} \propto \left[\left(\frac{t}{\tau}\right)^{\alpha} + \left(\frac{t}{\tau}\right)^{-\beta}\right]^{-1}$$
  - *α – raising slope; β – falling slope*
  - *τ – peak*
- Integrated stellar mass ($M_{\mathrm{formed}} := \int^{t_{\mathrm{obs}}} \mathrm{SFH}(t)\, \mathrm{d}t$)
  - current stellar + died and turned into medium
- Mass-weighted Age **(*a*)**
  - $:= \int^{t_{\mathrm{obs}}} \boldsymbol{t}\, \mathrm{SFH}(t)\, \mathrm{d}t \;/\; \int^{t_{\mathrm{obs}}} \mathrm{SFH}(t)\, \mathrm{d}t$
  - = **from** *when 50% of* $M_{\mathrm{formed}}(t_{\mathrm{obs}})$ **to** t_{obs}
- Other (t_{50}, t_{90}, …)

t_{50} definition: Khullar+2022, Man+2021



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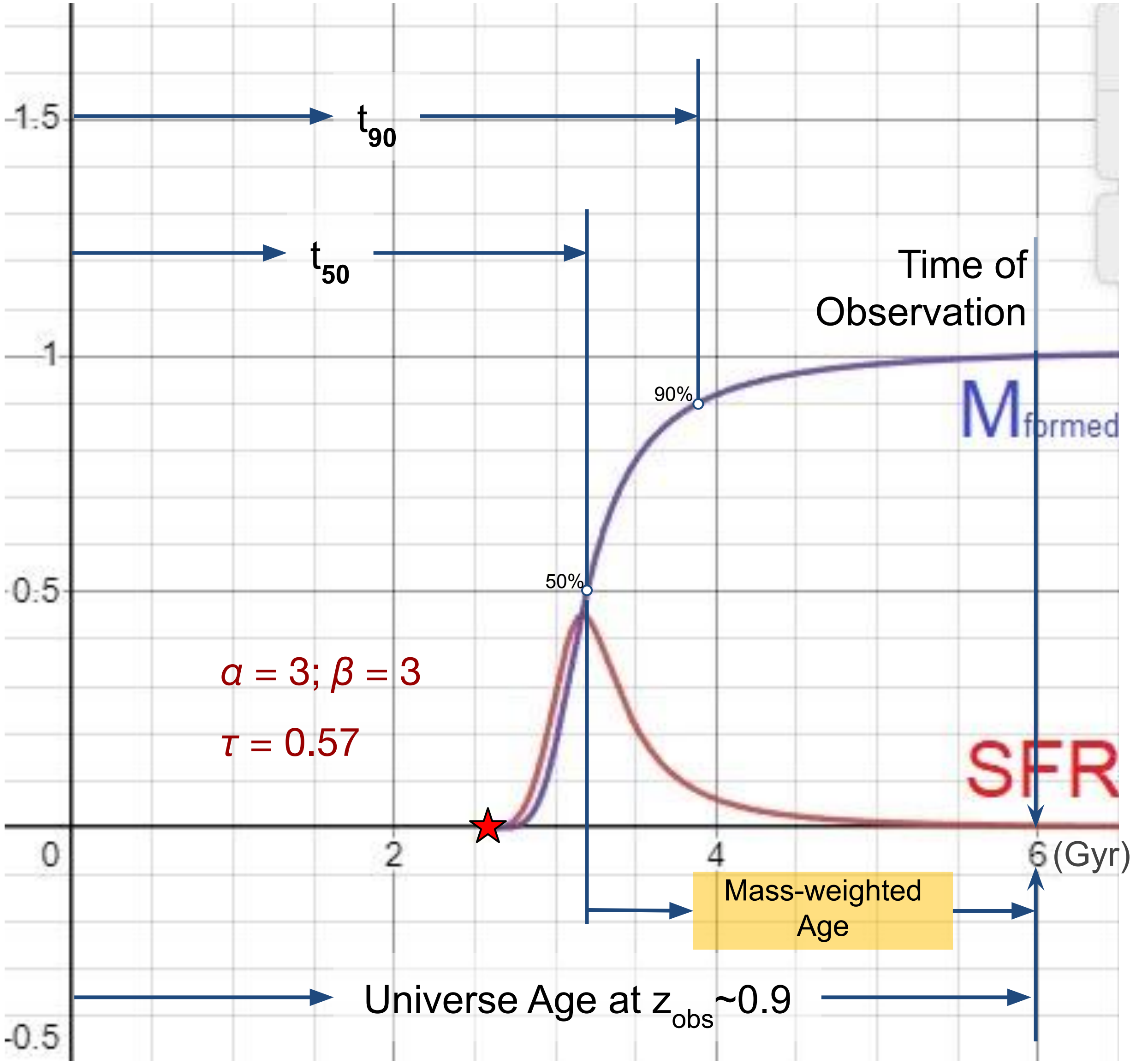
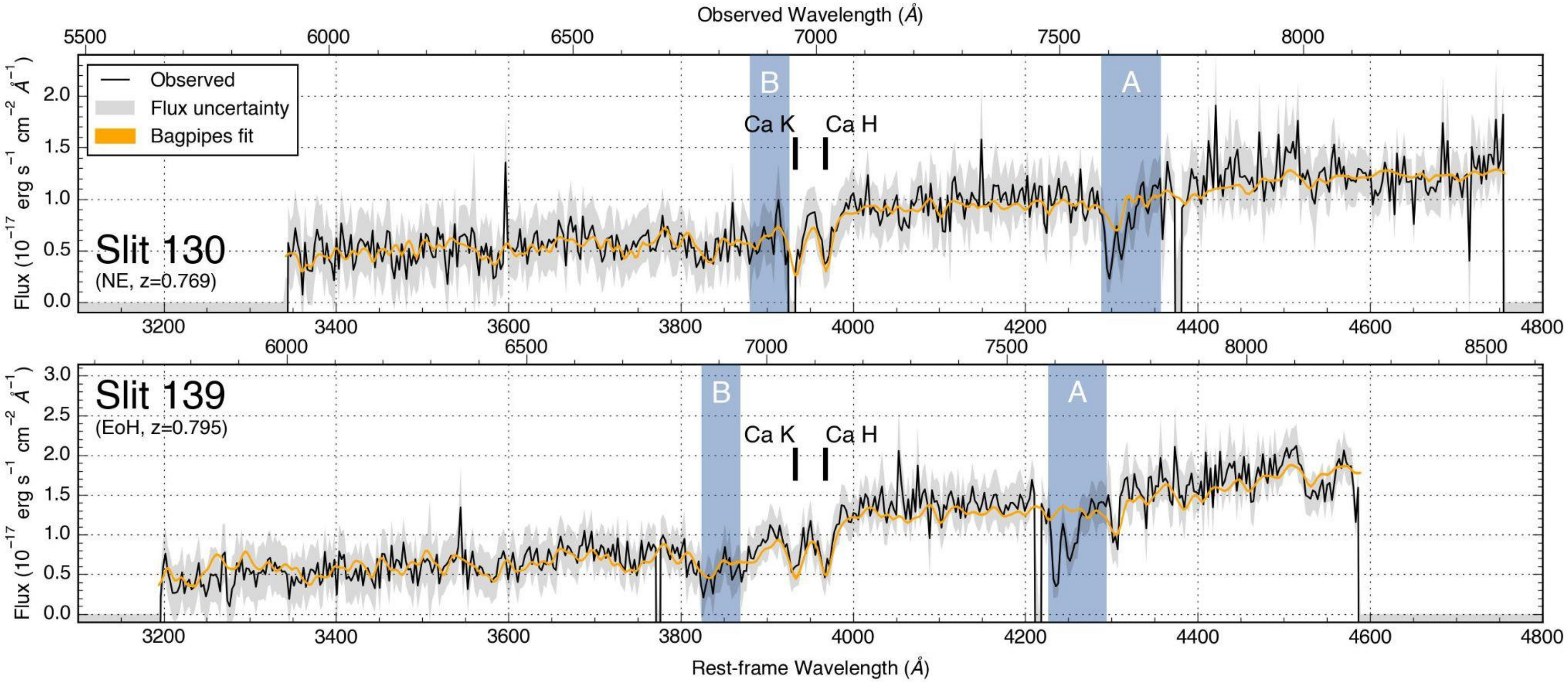
- Other (t_{50}, t_{90}, …)
  - *definitions may vary*

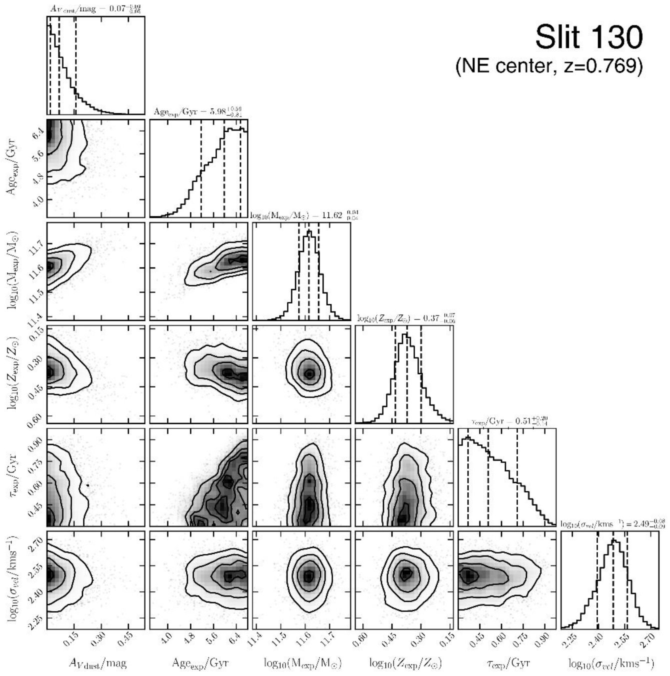
t_{50} definition: Kaushal+2023

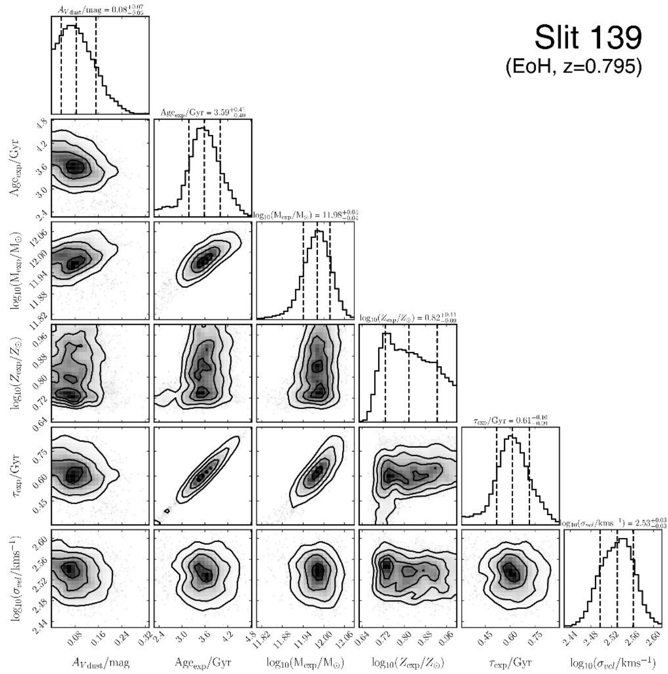


BCG Analysis - `Bagpipes` (Carnall et al. 2018)

Perform fitting and use stellar population synthesis modeling: Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation







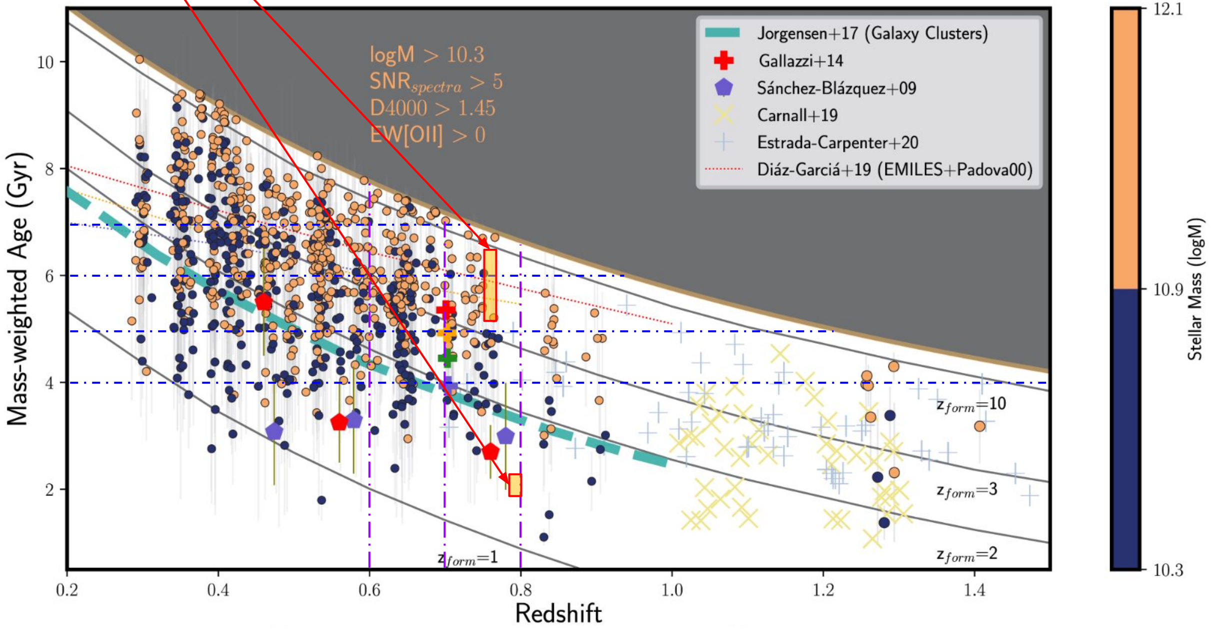
	Age (Gyr)	σ_* (km/s)	$\log(M^*/M_{sun})$
NE Center (#130)	$6.0^{+0.6}_{-0.8}$	309^{+63}_{-58}	$11.30^{+0.01}_{-0.02}$
EoH (#139)	$3.6^{+0.4}_{-0.4}$	339^{+24}_{-24}	$11.61^{+0.04}_{-0.05}$

BCG Analysis - Bagpipes (Carnall et al. 2018)

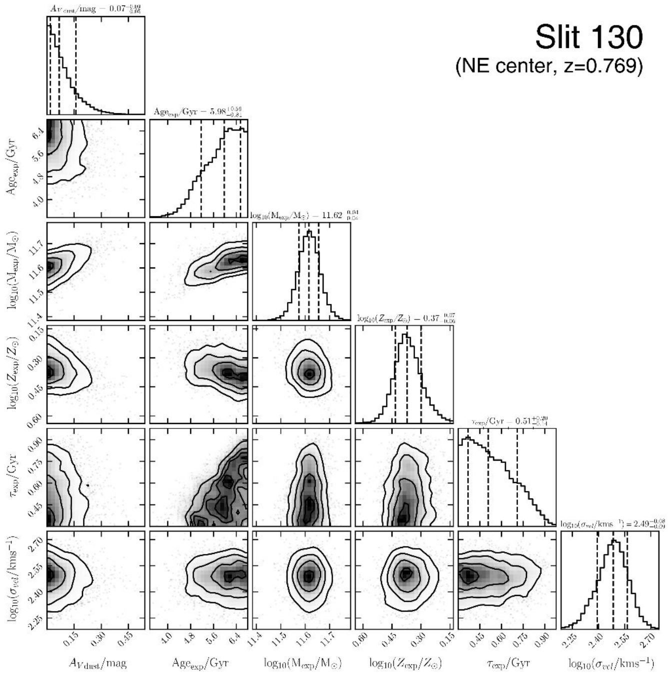
Perform fitting and use stellar population synthesis modeling: Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation

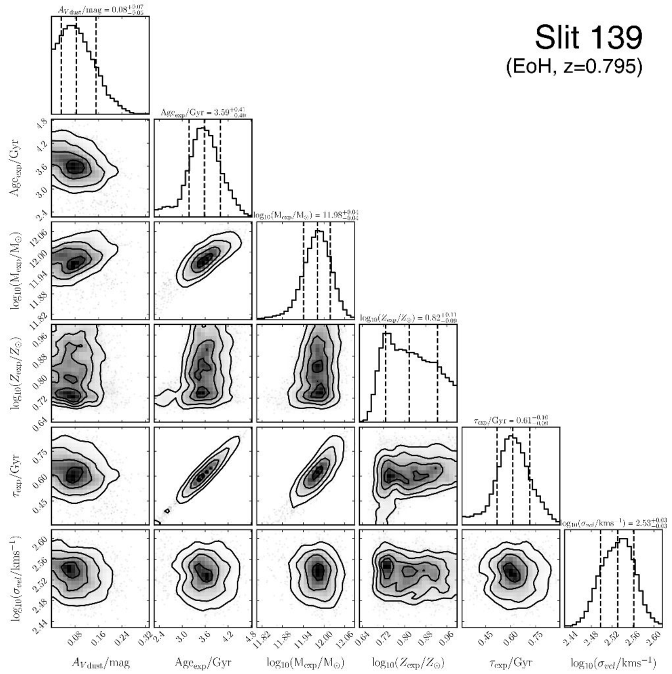
	Age (Gyr)	z_f	σ_* (km/s)	$\log(M^*/M_{sun})$
NE Center (#130)	$6.0^{+0.6}_{-0.8}$	4 – 15	309^{+63}_{-58}	$11.30^{+0.01}_{-0.02}$
EoH (#139)	$3.6^{+0.4}_{-0.4}$	1.9 – 2.3	339^{+24}_{-24}	$11.61^{+0.04}_{-0.05}$

- NE cluster BCG gives a very rough estimate on its age but formation z may be OK
- EoH has a better fitting result



Khullar et al. (2022)





BCG Analysis - `Bagpipes` (Carnall et al. 2018)

Perform fitting and use stellar population synthesis modeling: Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation

	Age (Gyr)	z_f	σ_* (km/s)	$\log(M^*/M_{sun})$	HSC	CAMIRA
NE Center (#130)	$6.0^{+0.6}_{-0.8}$	4 – 15	309^{+63}_{-58}	$11.30^{+0.01}_{-0.02}$	11.16	-
EoH (#139)	$3.6^{+0.4}_{-0.4}$	1.9 – 2.3	339^{+24}_{-24}	$11.61^{+0.04}_{-0.05}$	11.80	11.942

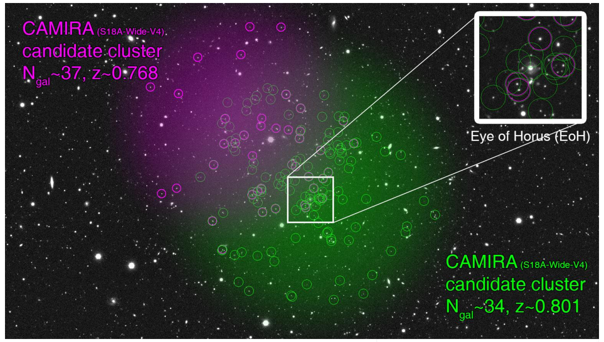
- NE cluster BCG gives a very rough estimate on its age but formation z may be OK
- EoH has a better fitting result
- HSC & CAMIRA photometric M^* are close to results from this work

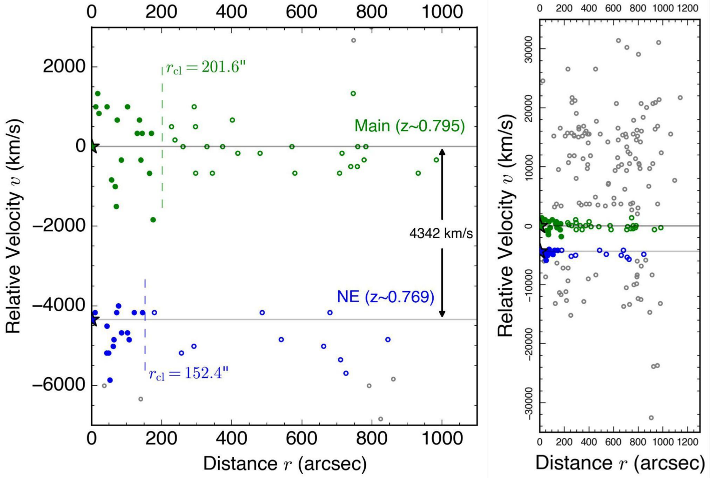
Summary

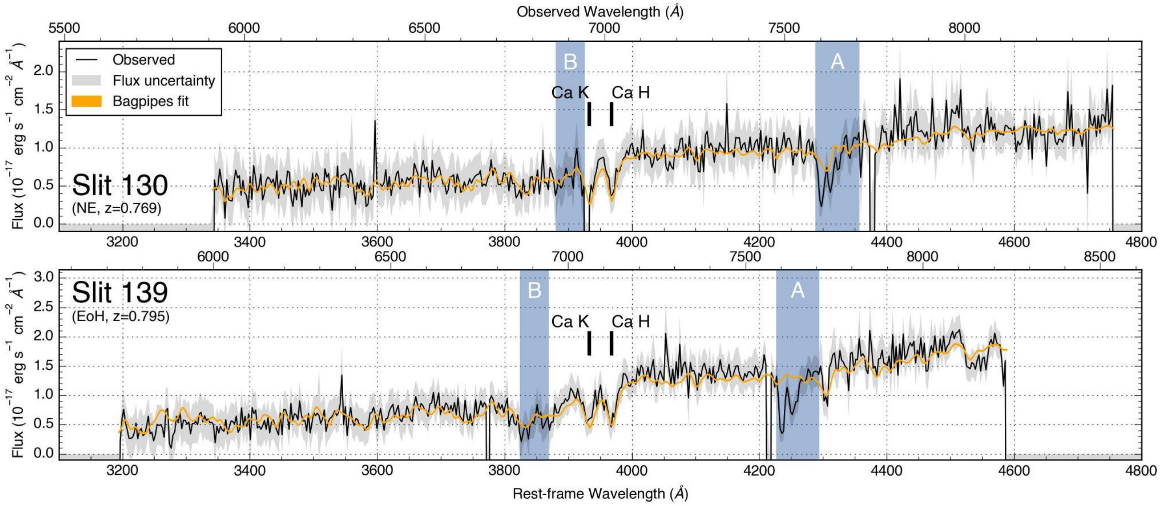
1. This work showed how to judge a light-of-sight galaxy concentration as multi-cluster merger, given **velocity offsets obtained from spectroscopy**

2. **Dynamical** masses are as good as **hydrostatic** masses within a factor of a few

3. Spectral analysis for two BCGs with **stellar properties** will improve the value of **future studies on gravitational lens**







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