Galaxy Clusters: Laboratories of Galaxy Evolution and our Cosmic Probes

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Background: Pandora's Cluster with JWST
Credits: NASA/ESA/ CSA, I. Labbe, R. Bezanson, and, A. Pagan

Galaxy clusters are the most massive gravitationally bound structures in the Universe, consisting of hundreds to thousands of galaxies (~ 5%), intracluster medium (ICM, ~ 10%), and dark matter (~ 85%) held together by their gravity.

Most common ways of galaxy clusters identification:

- galaxy overdensity
- strong X-ray emission from ICM
- gravitational lensing
- SZ effect (distortion of CMB)

- ***Masses: ~ 10^{14}—10^{15} M⊙***
- ***R_{200} = 1-3 Mpc***
- ***R_{500} = 0.6-0.7R_{200}***

Abell S1063 galaxy cluster
Credits: ESA/Webb, NASA & CSA, H. Atek, M. Zamani

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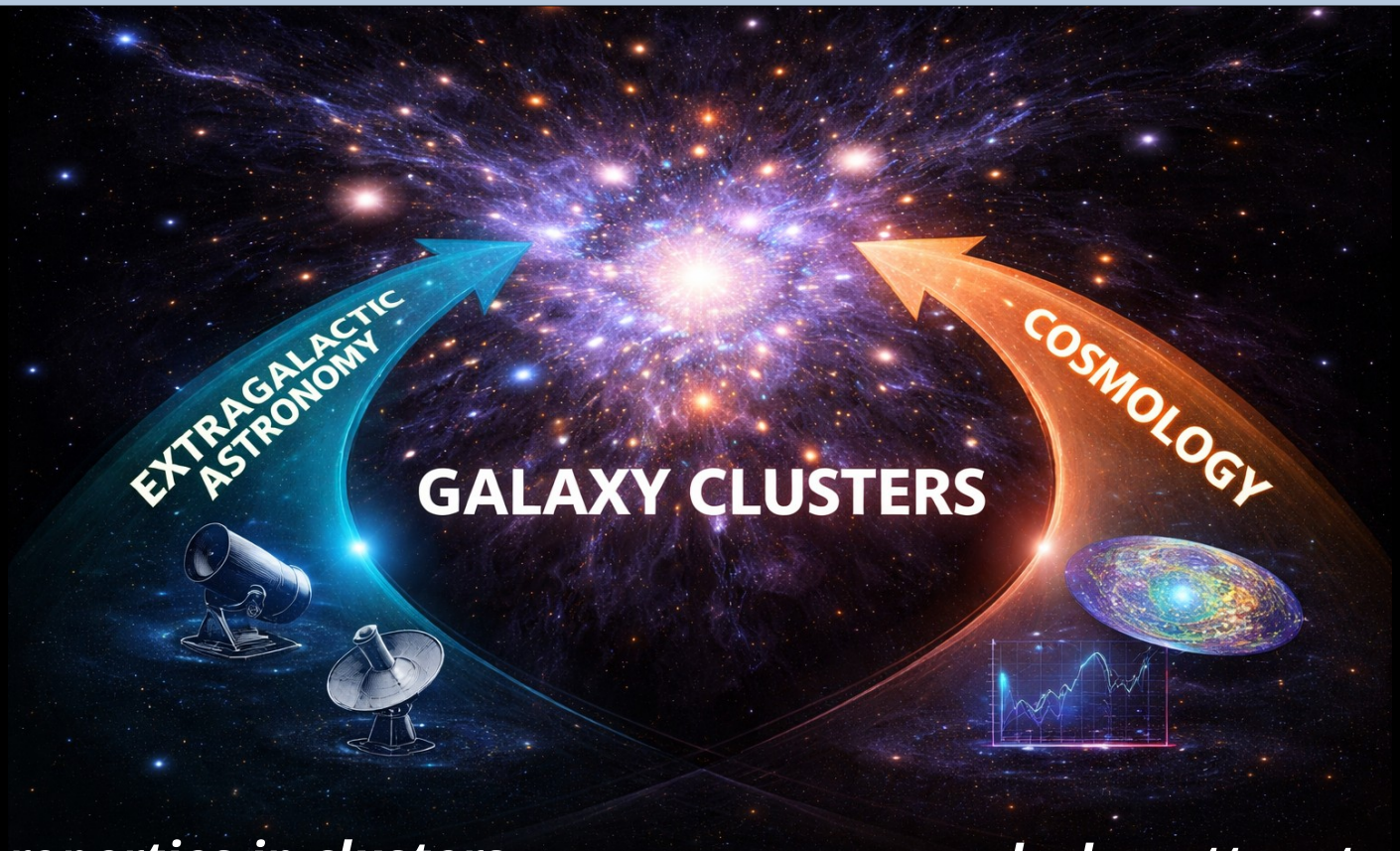
Most common ways of cluster members identification:

- spectroscopic redshifts selection
- photometric redshifts selection
- machine learning
(combination of parameters)

- red sequence selection
- position *(projected distance from cluster center)* ***+ velocity***
- lensing selection *(via mass peaks and galaxy association)*
- multiwavelength selection
(e.g., X-rays vs. optical)

Abell S1063 galaxy cluster
Credits: ESA/Webb, NASA & CSA, H. Atek, M. Zamani

Importance of galaxy clusters – our cosmic probes



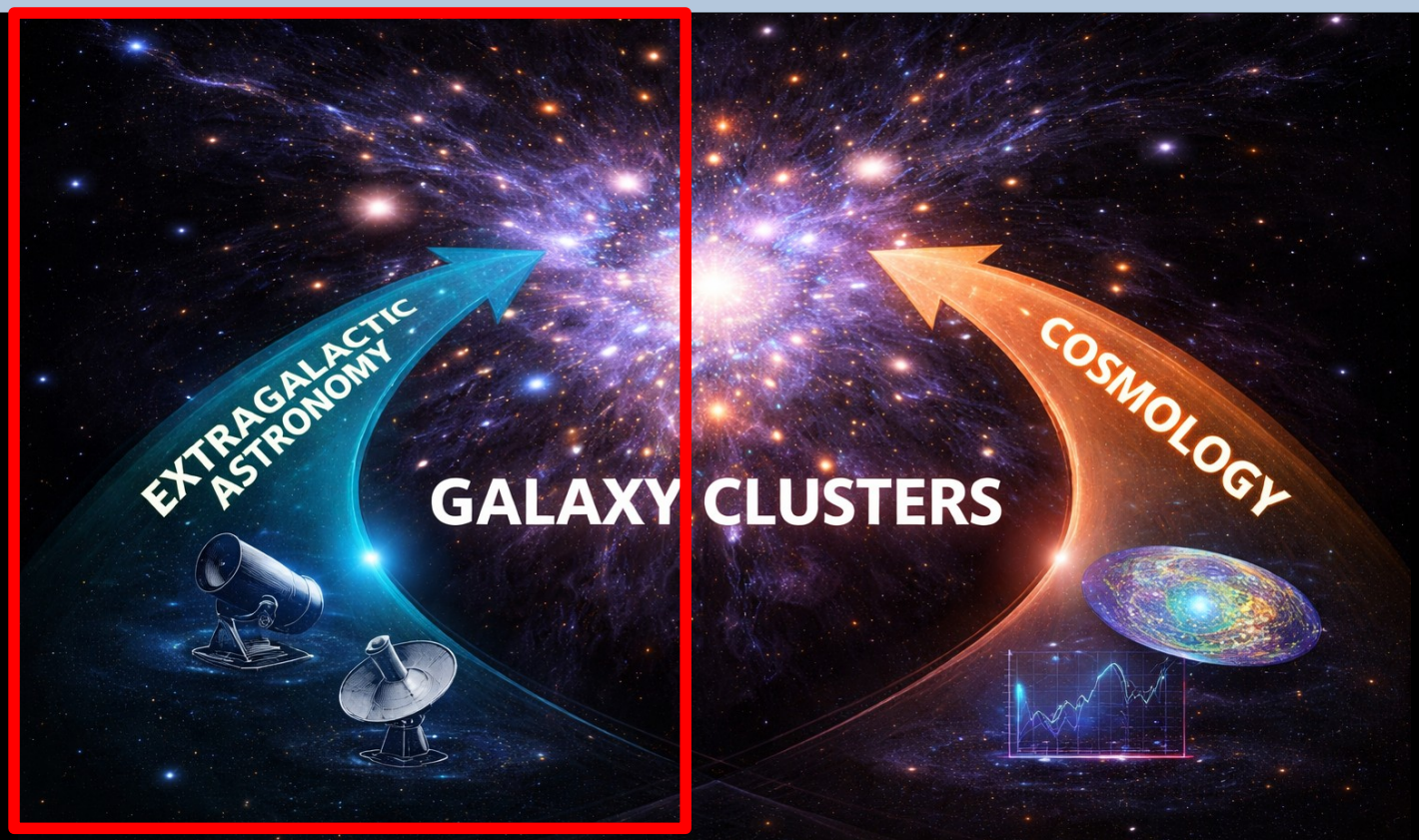
AI-generated using DALL·E (OpenAI)

→ *galaxy properties in clusters*
→ *SF and environment*
→ *AGN triggering*
→ *galaxy quenching, morphological transformation*
→ *galaxy evolution*

→ *dark matter studies*
→ *gravitational lensing*
→ *SZ effect and CMB studies*
→ *large scale structure*
→ *baryon fraction and cosmic composition*

→ *Galaxy formation and evolution models (testing of hierarchical model)*

Importance of galaxy clusters – our cosmic probes



AI-generated using DALL·E (OpenAI)

This talk:

- → *galaxy morphology in clusters*
- → *star formation (SF) and AGN activity in clusters*
- → *main dynamics*
- → *main relations*

- → *main open questions*
- → *role of next-generation telescopes*

Main challenges in galaxy cluster studies

→ selection effects and biases (selection of different clusters using different methods), incomplete samples

→ selection of cluster members
(e.g., spectroscopic and photometric redshift incompleteness and uncertainties)

→ projection effects
(foreground/background galaxies can appear as part of the cluster)

→ detection of high-redshift clusters (incomplete samples, faint signals),
with JWST the samples are still small

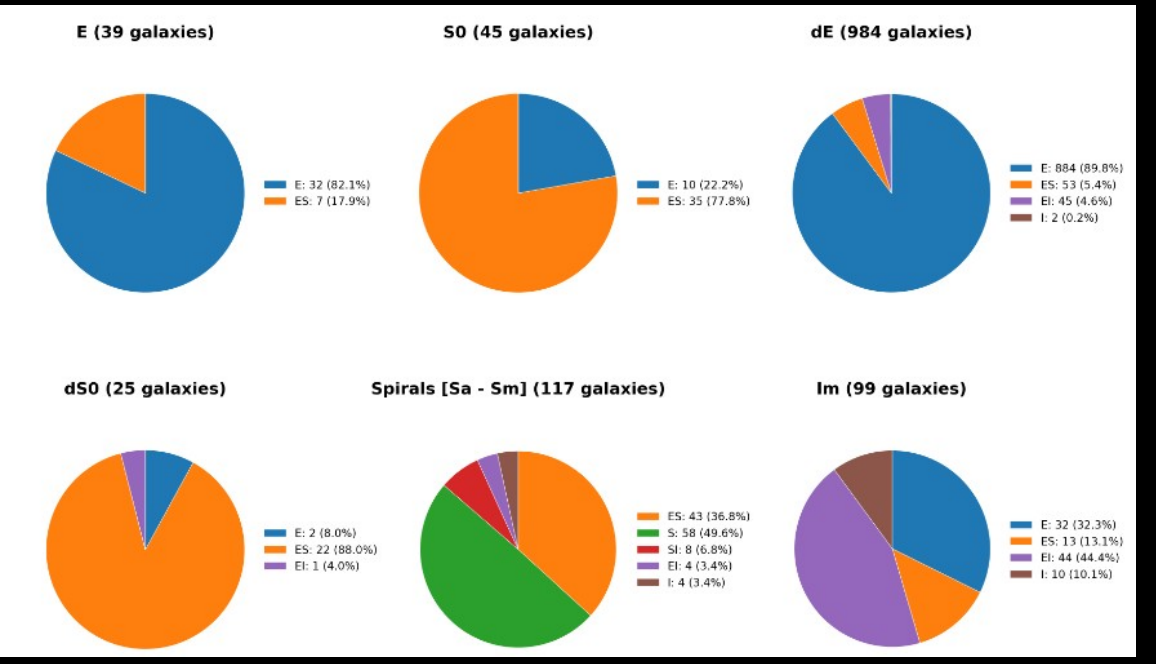
→ in galaxy evolution studies in clusters, it is difficult to separate mass-driven effects from environment-driven effects

Galaxy clusters host a full range of galaxies in terms of mass and morphology: from dwarfs to BCG/BCM, and from Ell/S0 to spiral (from early- to late-types)

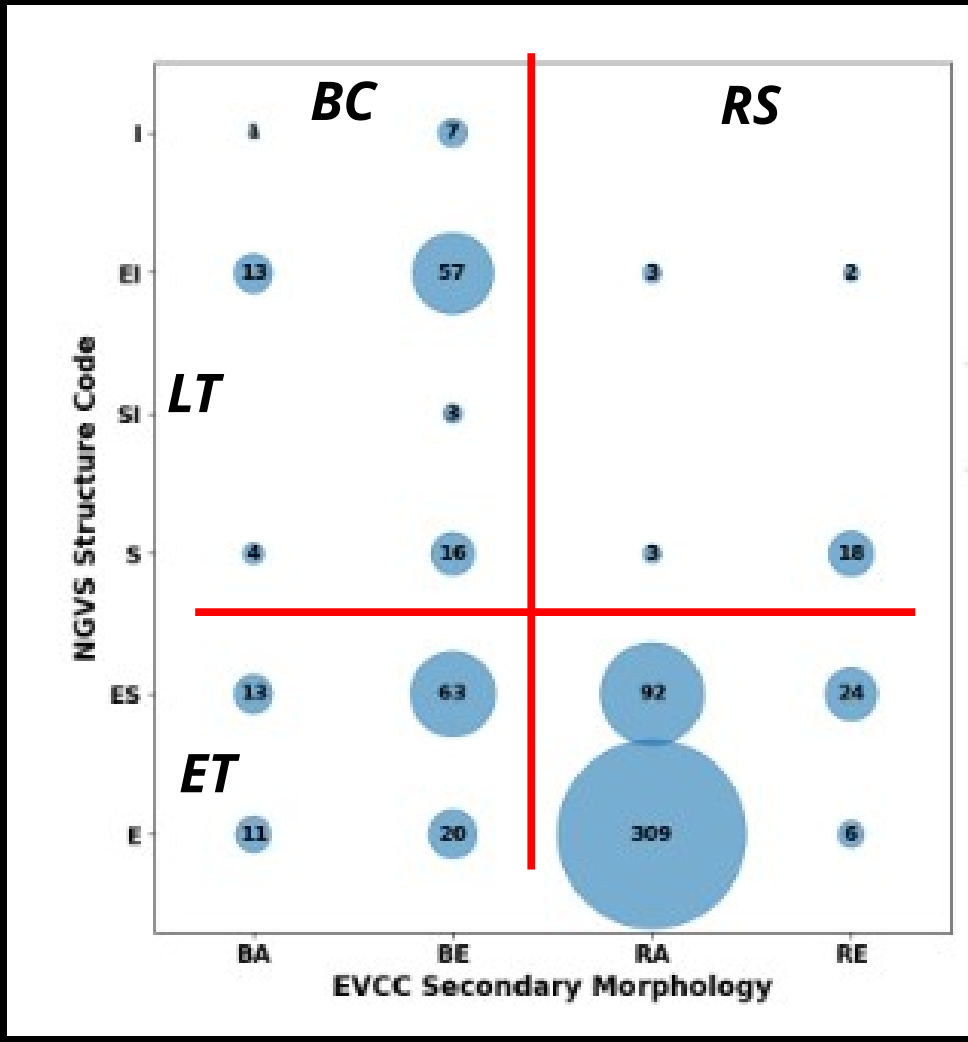
→ the excess of early-type and red sequence galaxies in the local universe

Virgo cluster at z ~ 0

(large fraction of dE galaxies)



Kurzner et al. 2025



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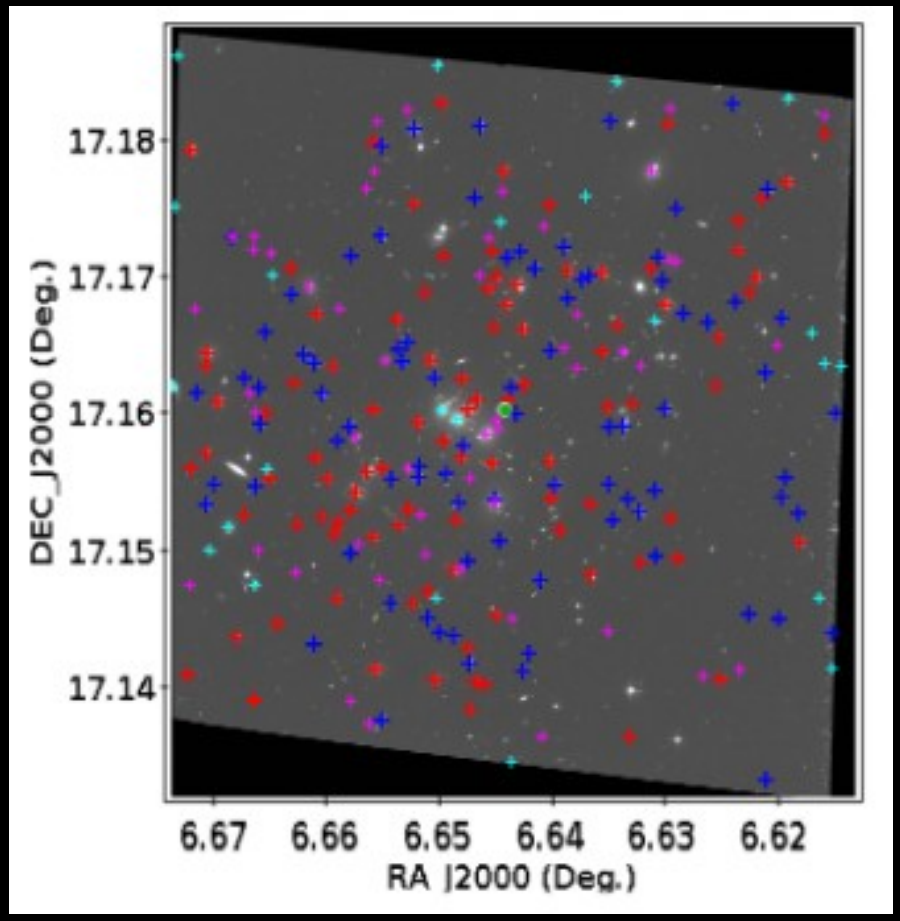
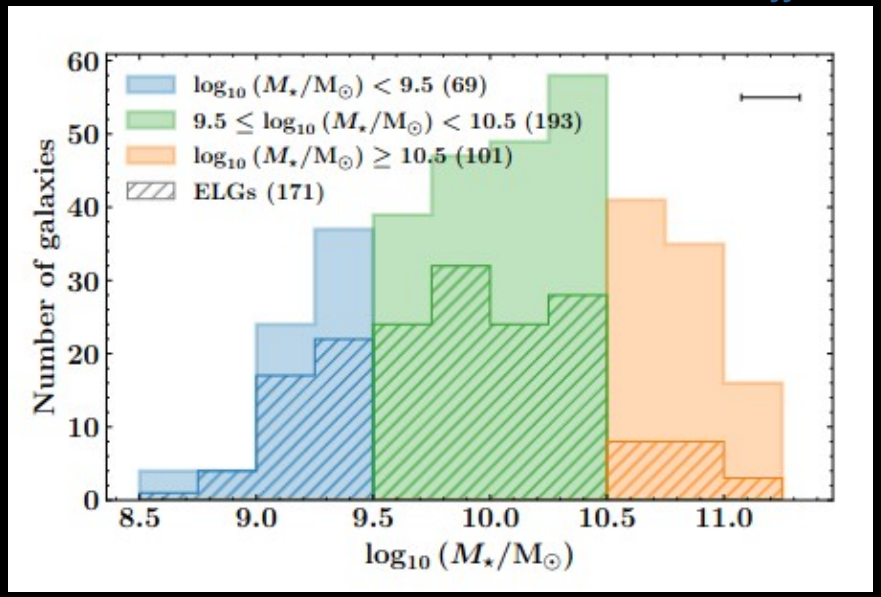
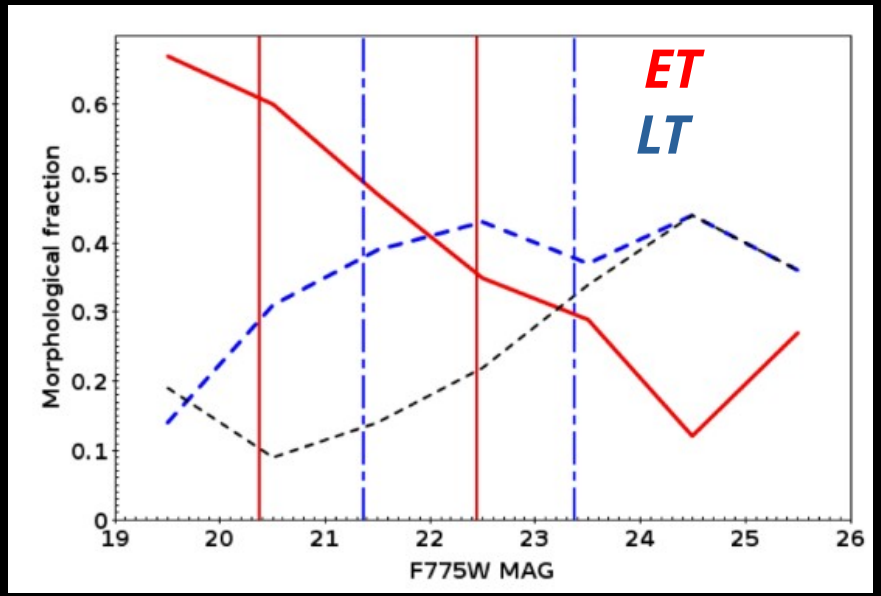
GLACE: ZwCl 0024.0+1652 cluster at z ~ 0.4
(42% ET, 36% LT, 22% unclassified)



Beyoro-Amado, Povic, Sanchez-Portal et al. 2019

De Daniloff et al. 2025





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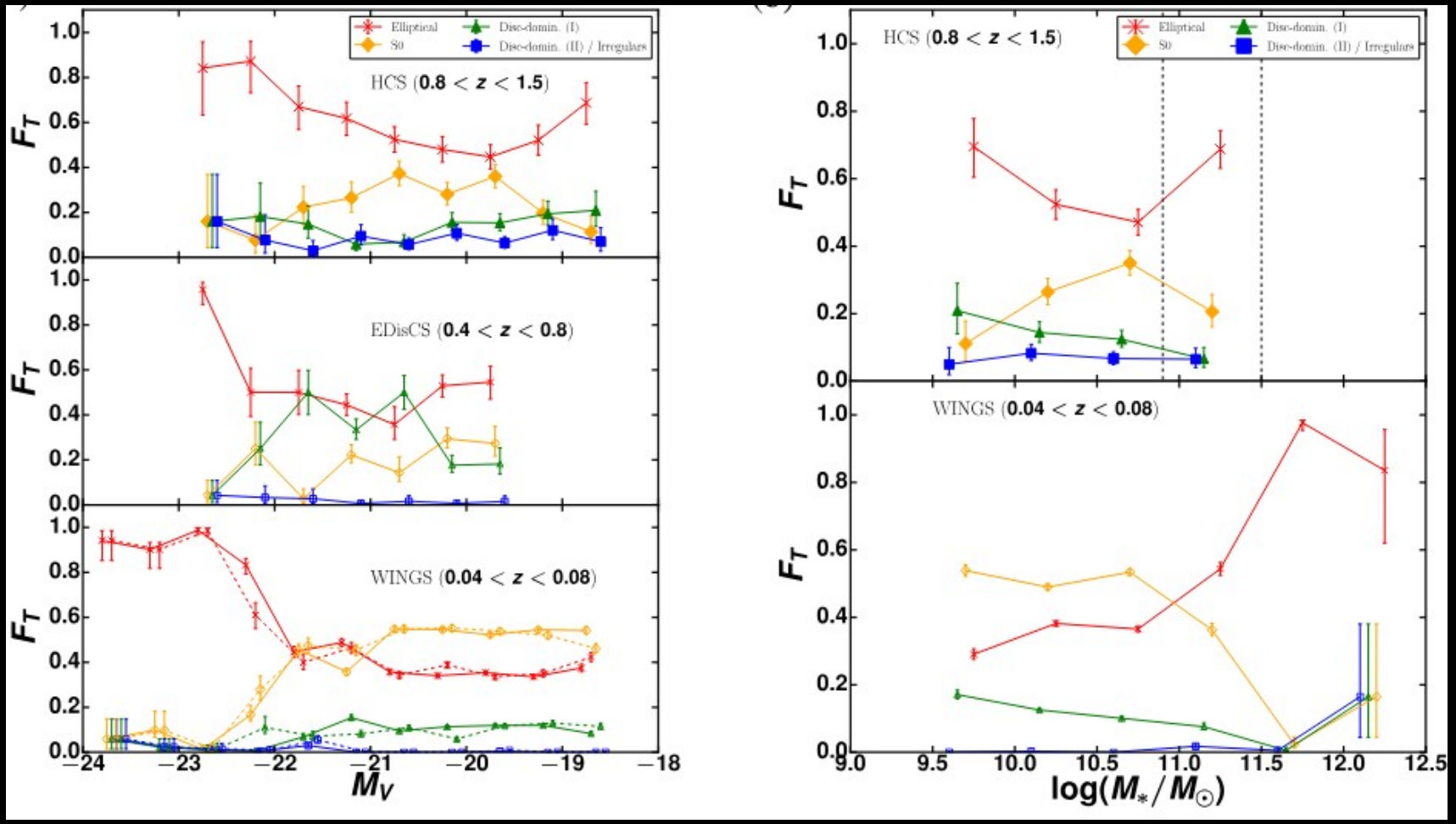
→ the excess of early-type and red sequence galaxies in the local universe

Example of red sequence dominating at all redshifts across all magnitudes and masses



Ell and S0 galaxies show different evolutionary trends in clusters

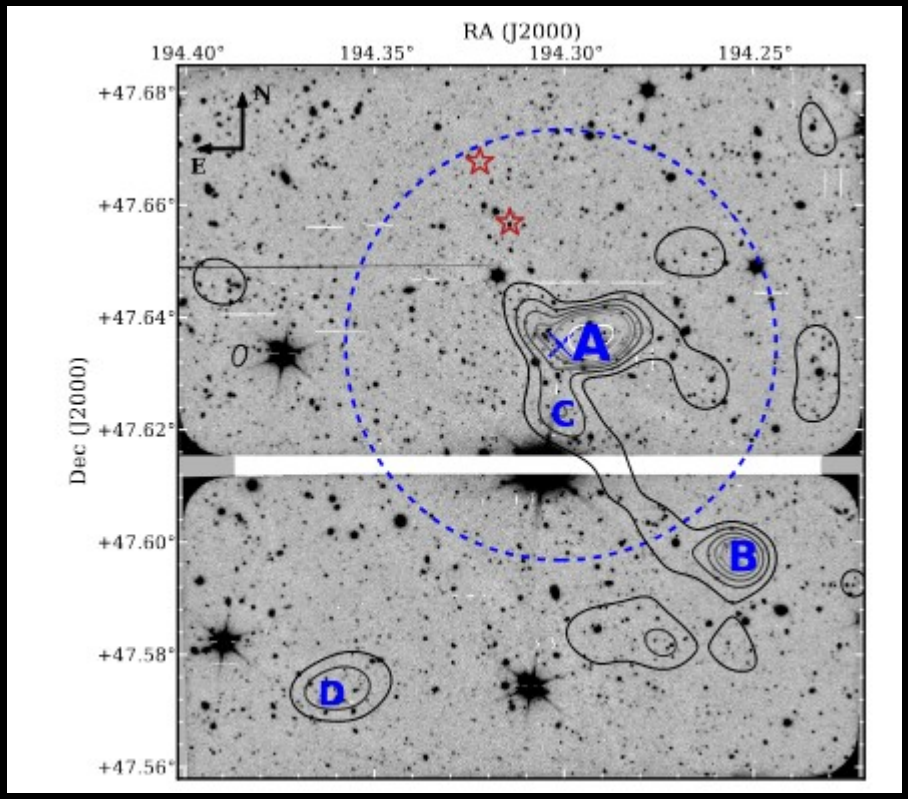
Cerulo et al. 2017

Galaxy clusters host a full range of galaxies in terms of mass and morphology: from dwarfs to BCG/BCM, and from Ell/S0 to spiral (from early- to late-types)

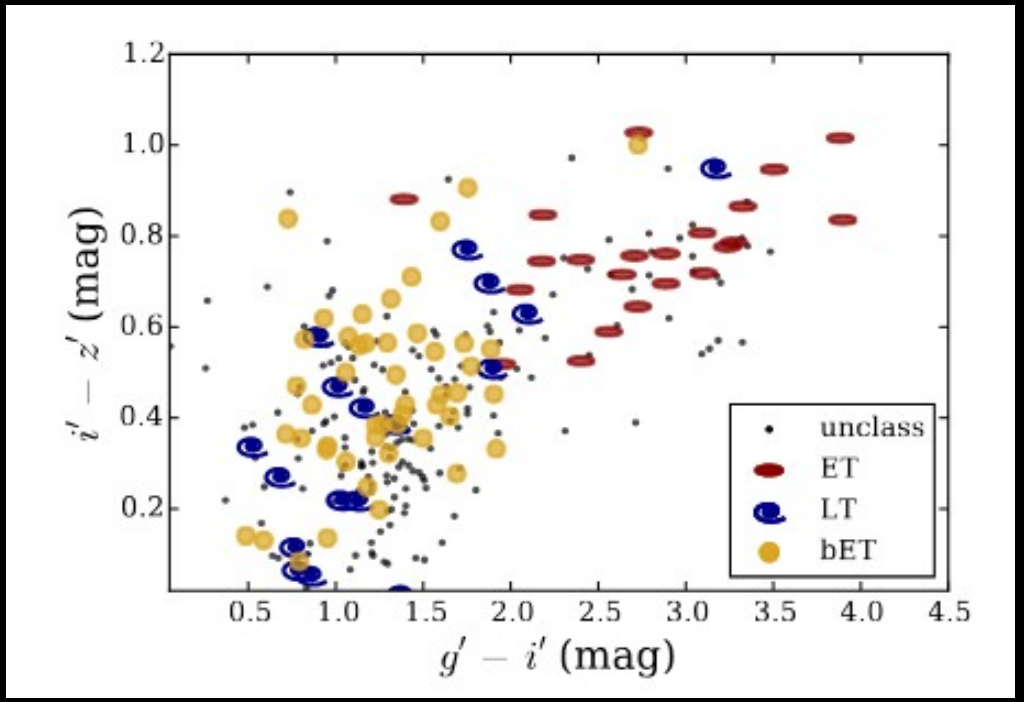
→ at higher refshifts, higher fraction of blue galaxies, Butcher–Oemler (BO) effect

(Butcher & Oemler 1978, 1984; Dressler et al. 1994; Metevier et al. 2000; Urquhart et al. 2010; Wang et al. 2020)

→ morphologies become more disky and disturbed, clusters become more clumpy



GLACE: RXJ1257 at z~0.9, excess of ET blue galaxies



Pintos-Castro, Povic, Sanchez-Portal et al. 2016

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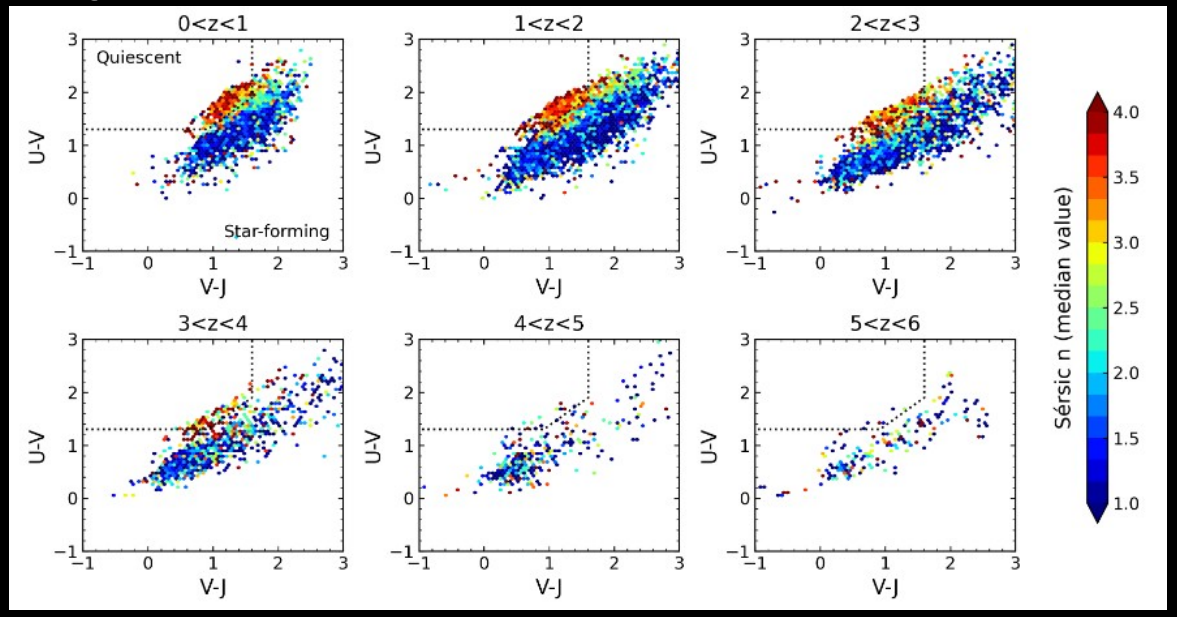
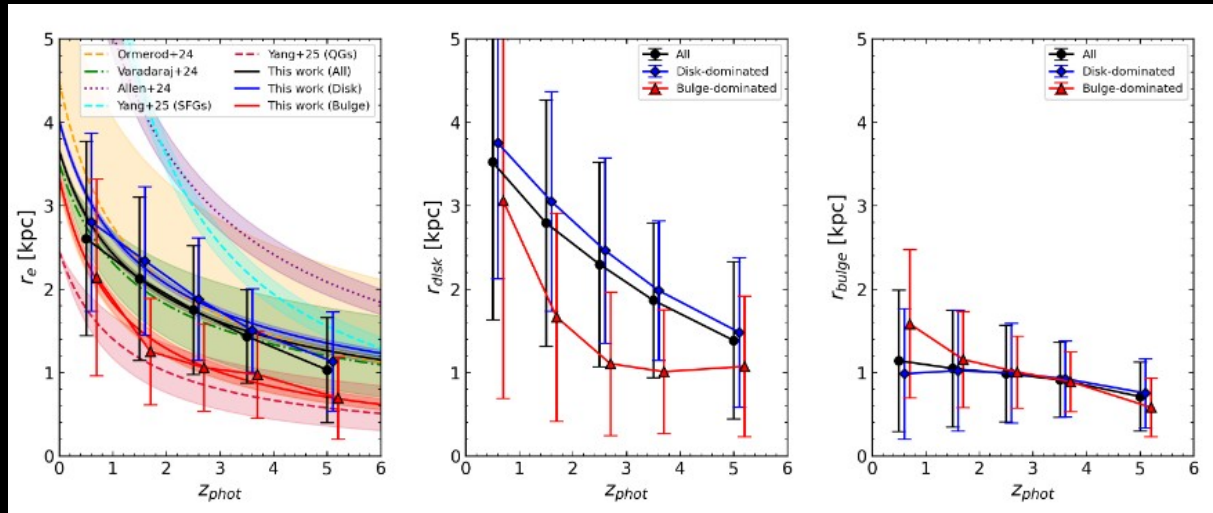


JWST galaxies in 4 fields (not only clusters): bi-modality and red sequence maintained up to the 'cosmic noon'

Size evolution, in particular disk-size evolution

→ still small samples for cluster galaxies



Genin et al. 2025

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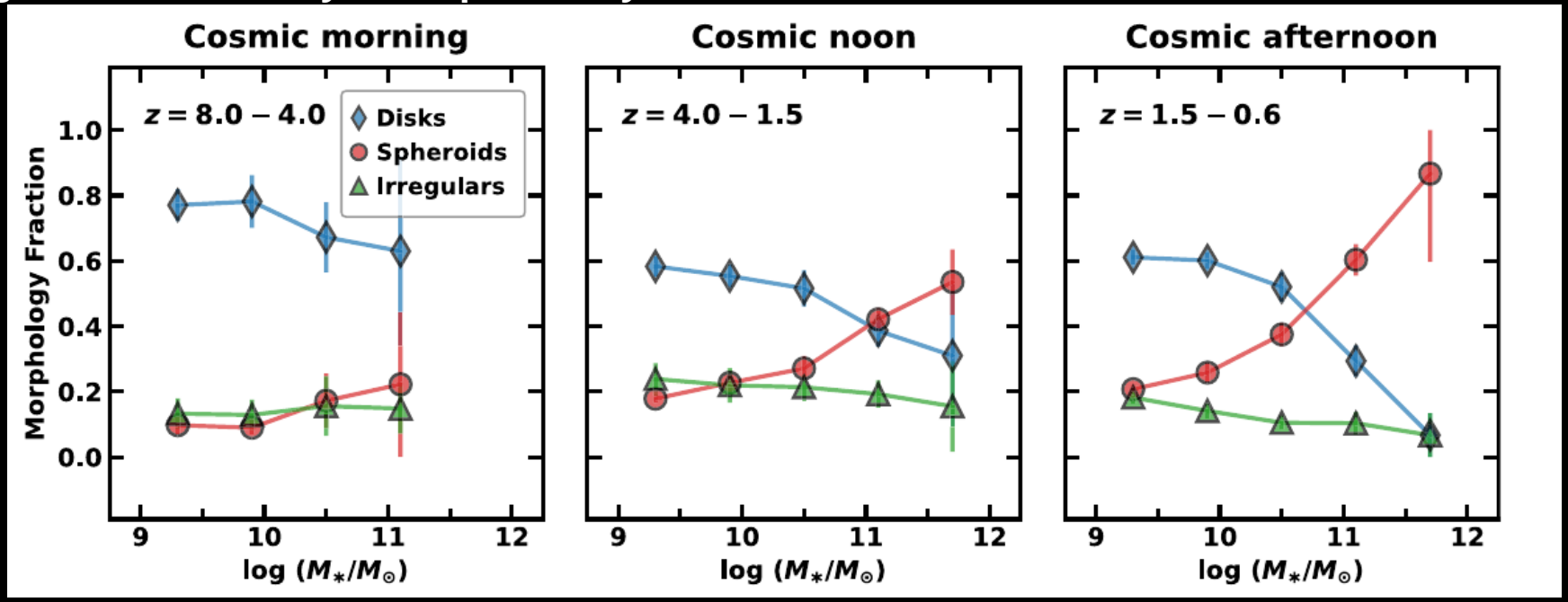
JWST galaxies in 6 surveys (independently on environment)



Lee et al. 2024

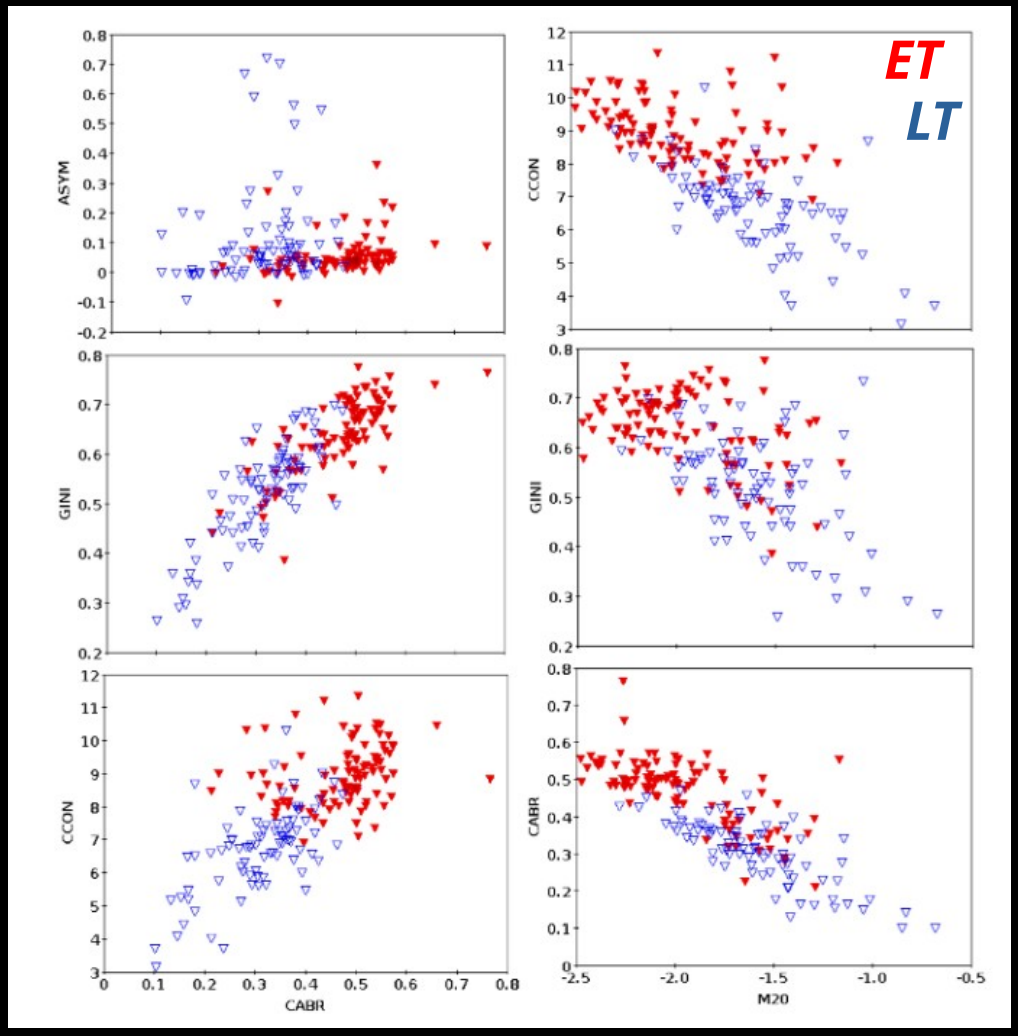
→ inconsistencies with previous studies at low-redshift

→ still small samples for cluster galaxies

Galaxy clusters host a full range of galaxies in terms of mass and morphology: from dwarfs to BCG/BCM, and from Ell/S0 to spiral (from early- to late-types)

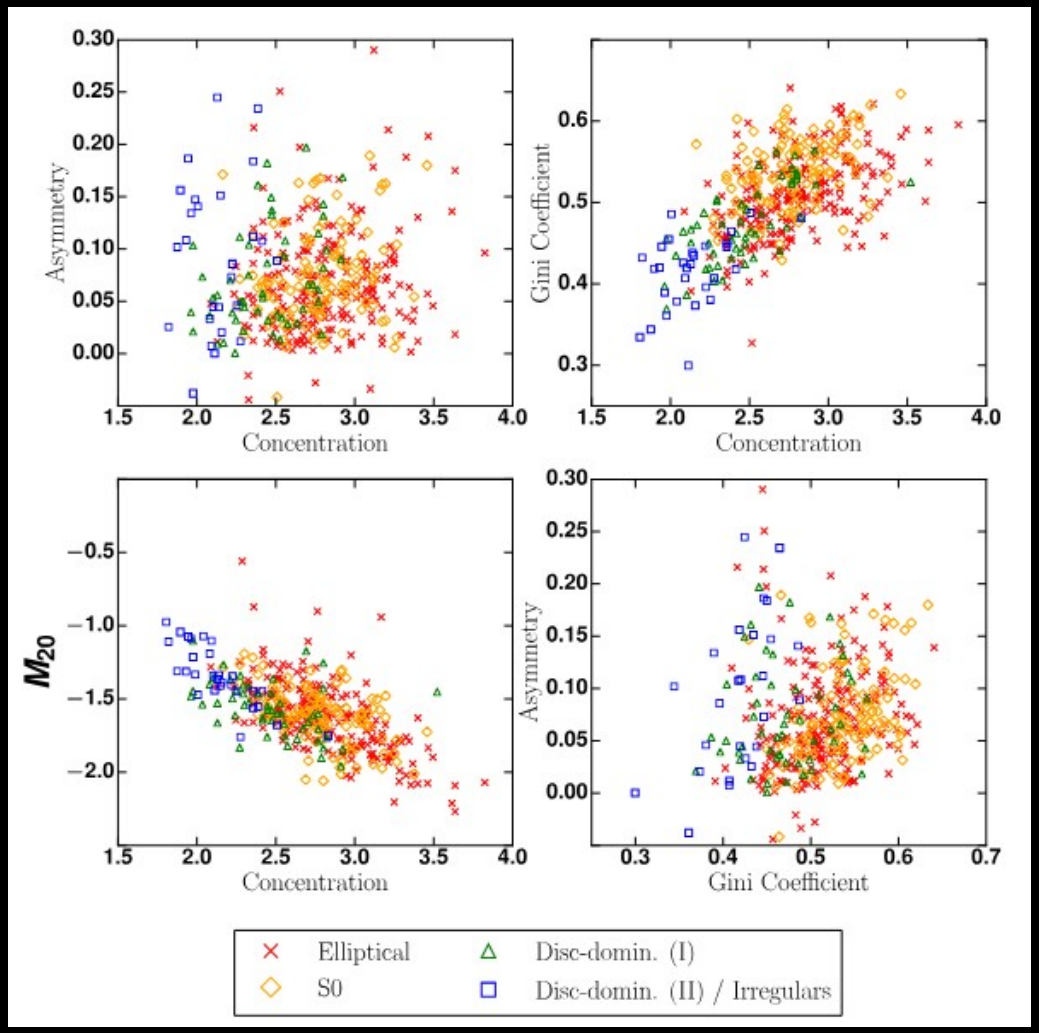
→ relations of structural parameters are maintained for galaxies in clusters

GLACE: ZwCl 0024 at z ~ 0.4



Beyoro-Amado et al. 2019

HCS: 9 clusters at 0.8 < z < 1.5

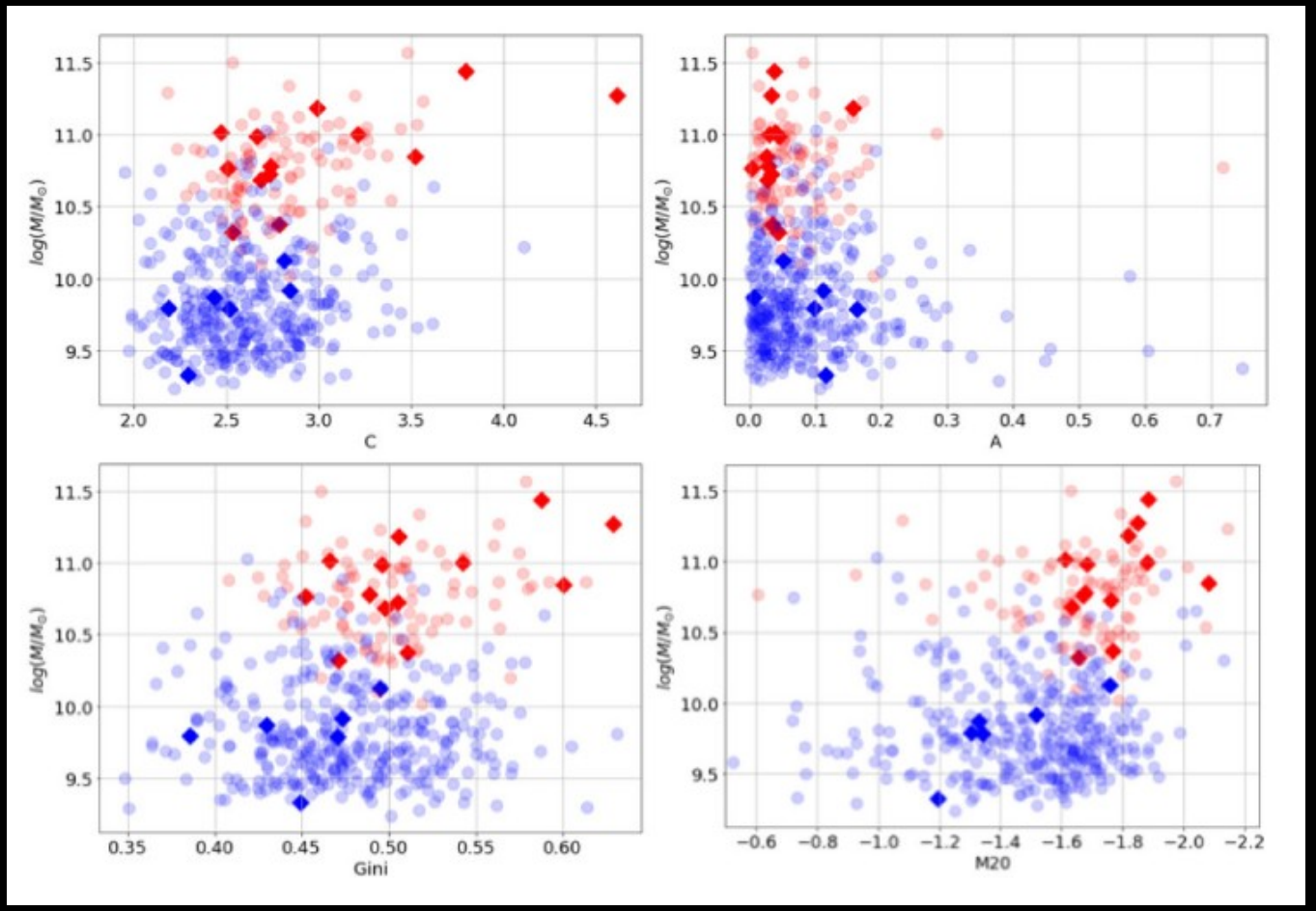


Cerulo et al. 2017

Galaxy clusters host a full range of galaxies in terms of mass and morphology: from dwarfs to BCG/BCM, and from Ell/S0 to spiral (from early- to late-types)

→ similar trends of structural parameters to those observed in field galaxies

XLSSC 122 cluster at z ~ 2 vs. field galaxies



Leste et al. 2024

Galaxy clusters also host a full range of galaxies in terms of their star formation (from star-forming to quiescent) and nuclear activity

→ suppressed star formation (more quenched galaxies than in the field)
→ but also the opposite: enhanced star formation
→ depends on the distance from the cluster center (more SFGs in cluster outskirts than in the core) and on the local density

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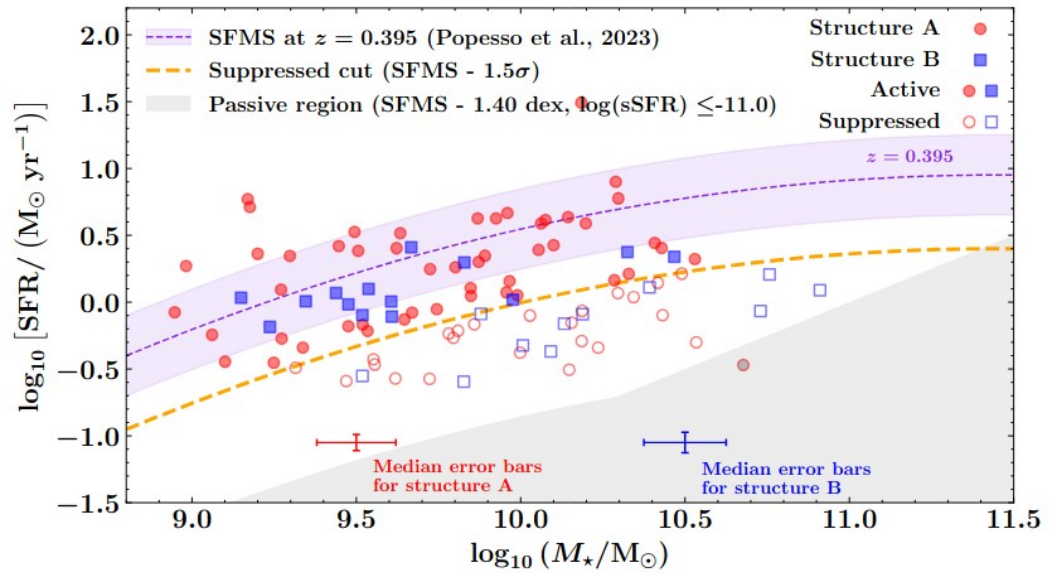

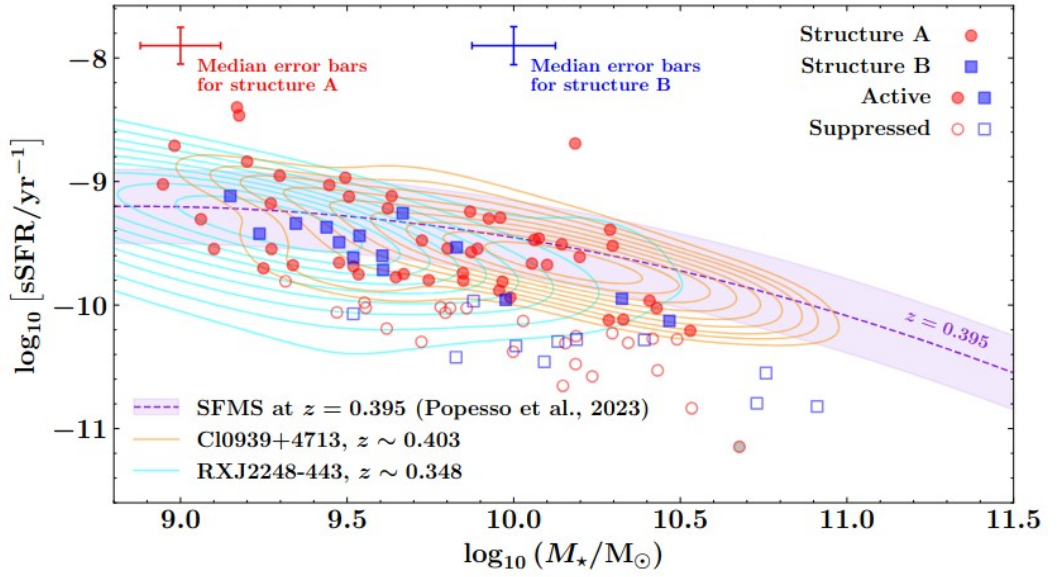

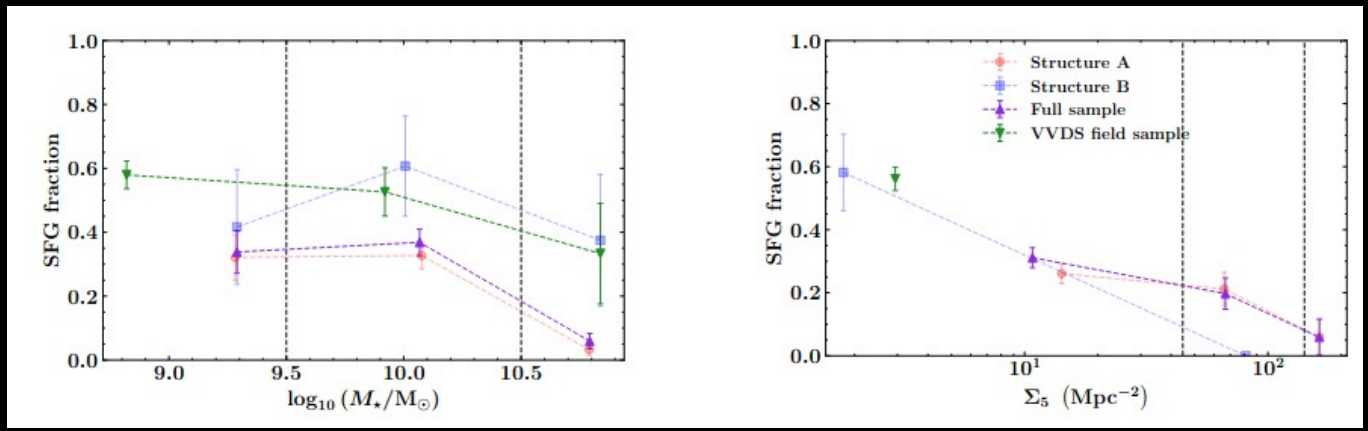

SF in clusters at z ~ 0.4, comparison with field galaxies (VVDS)

De Daniloff et al. 2025

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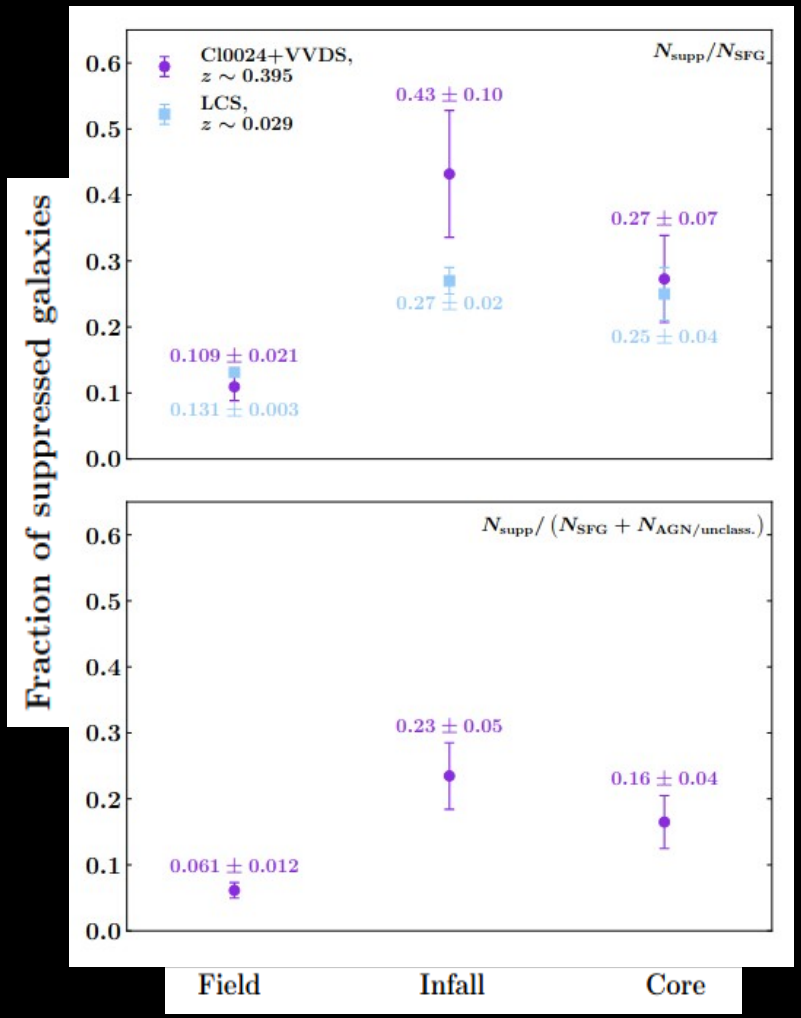
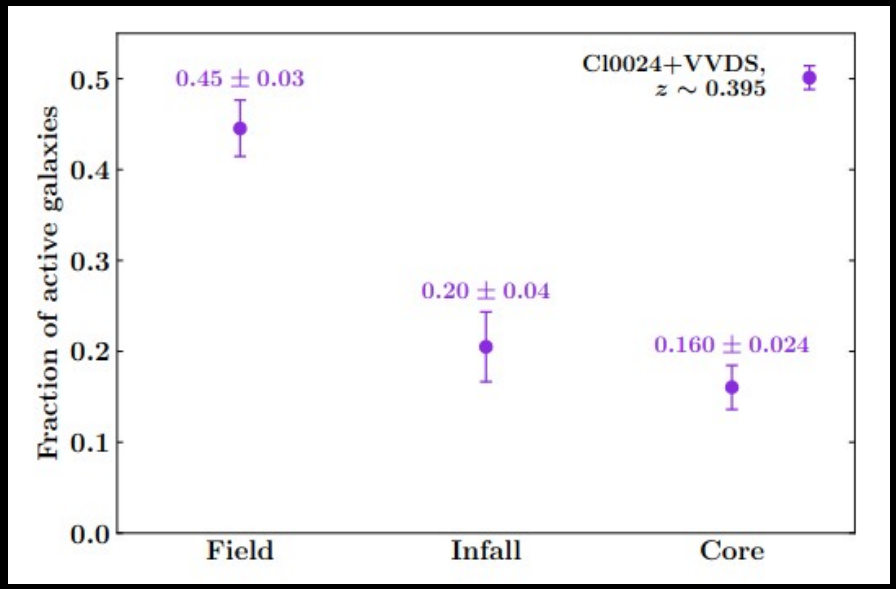
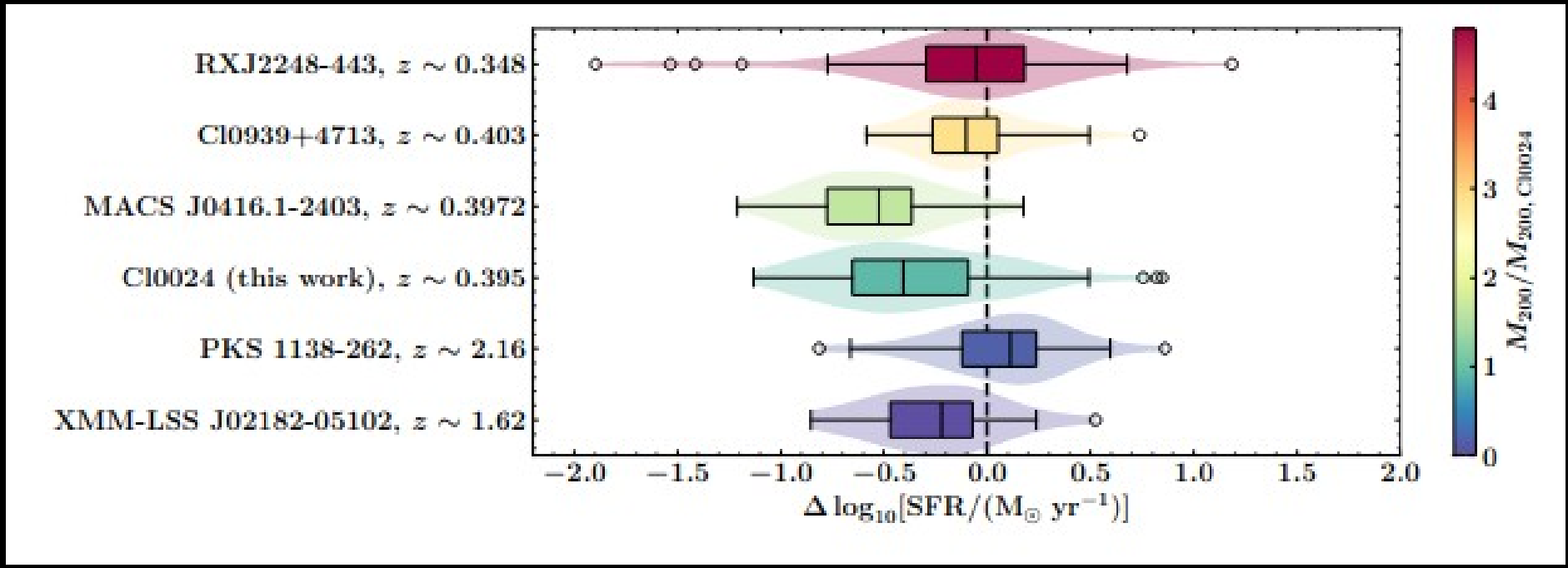


→ AGN activity is normally lower than in the field
→ depends on the distance from cluster center (higher fraction in cluster outskirts than in the core) and on the local density



De Daniloff et al. 2025

Galaxy clusters also host a full range of galaxies in terms of their star formation (from star-forming to quiescent) and nuclear activity



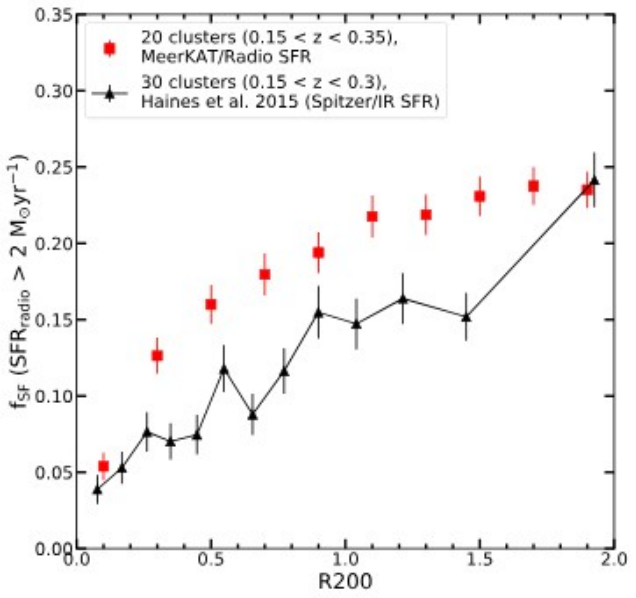
The virial mass of the cluster appears to have no direct effect on the quenching of the cluster galaxies.

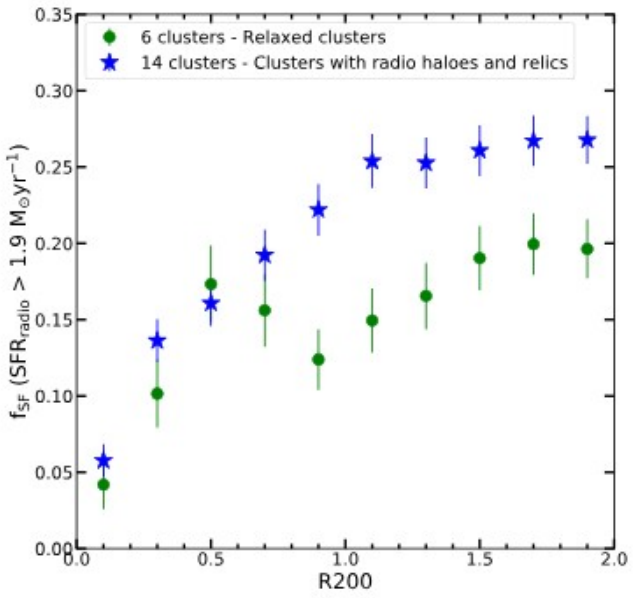
De Daniloff et al. 2025

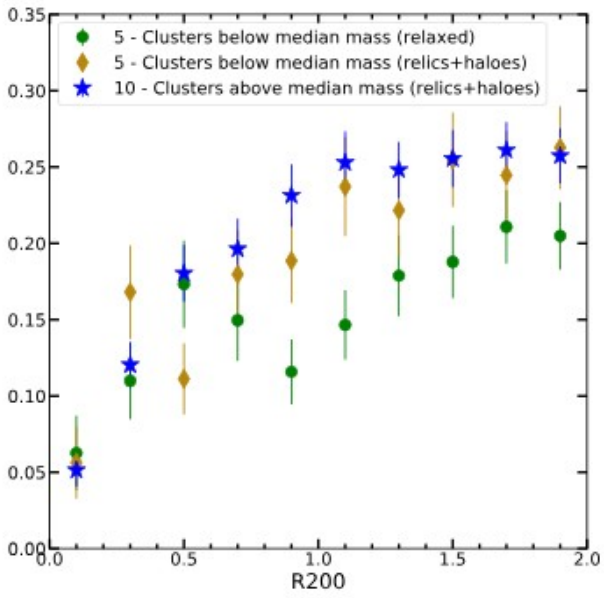
Galaxy clusters also host a full range of galaxies in terms of their star formation (from star-forming to quiescent) and nuclear activity

→ measured SFRs in clusters depend on SF indicators
(e.g., if measured through Hα, UV, IR, etc.)
→ SF in clusters can also depend on their dynamical state (if relaxed or disturbed)

MeerKAT Galaxy Cluster Legacy Survey (MGCLS)

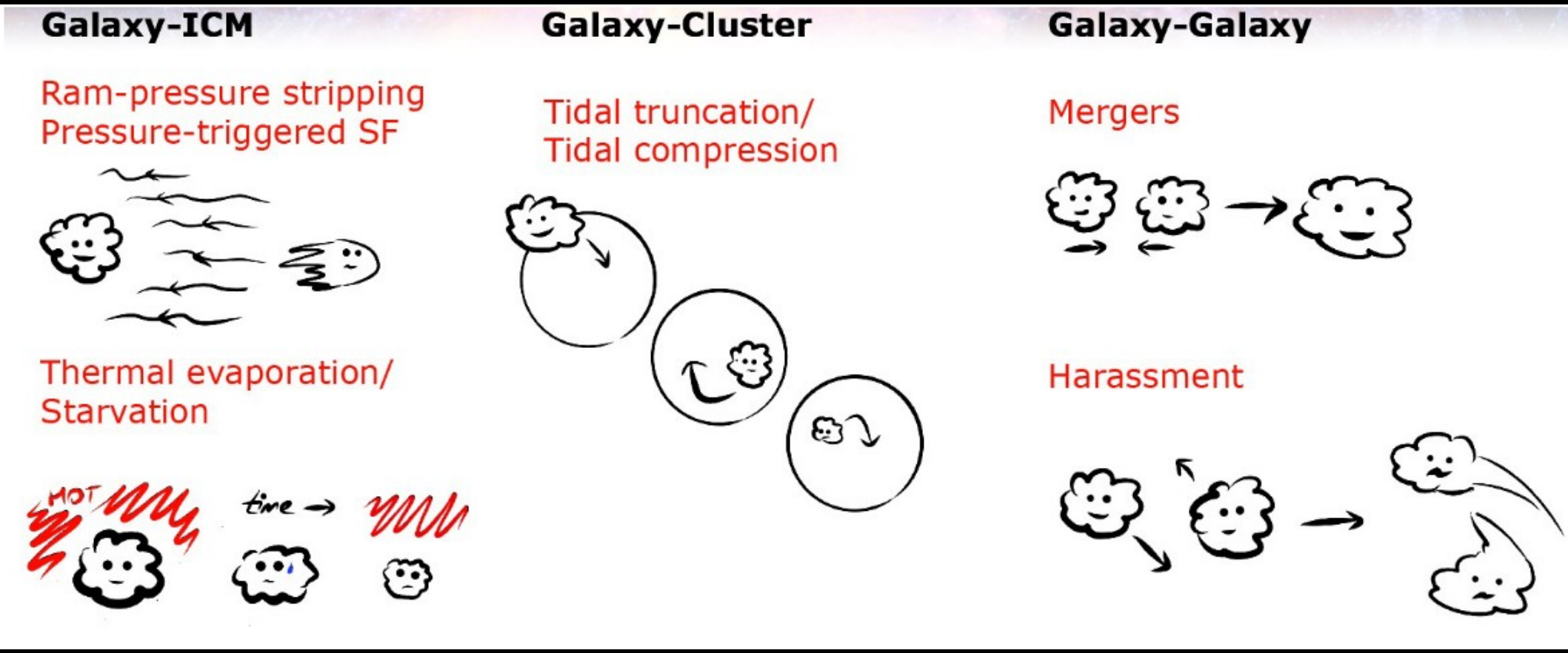






Kesebonye et al. 2023

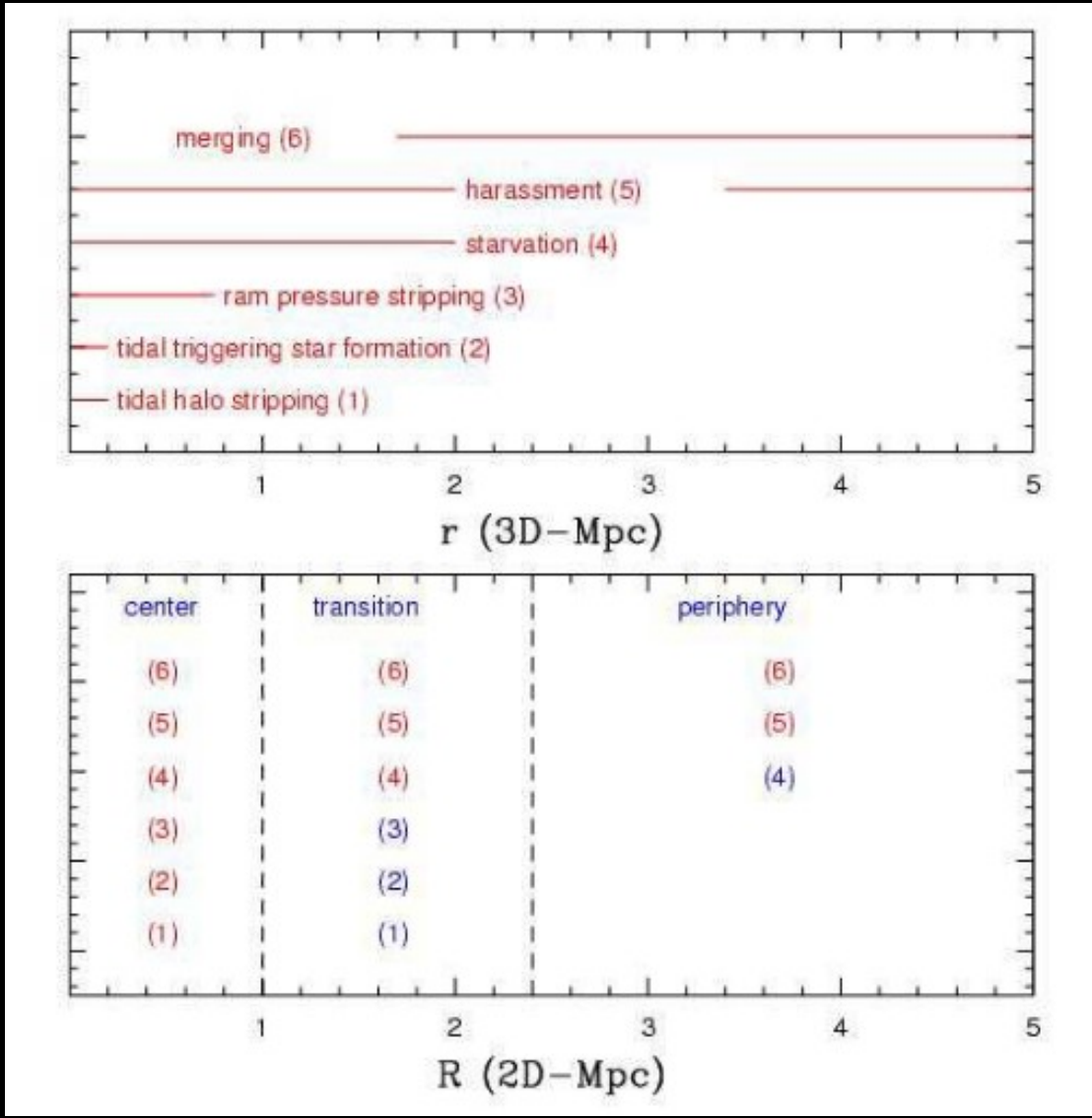
Galaxy clusters are extreme environments, with many processes affecting cluster members, their star formation and nuclear activity



Credits image: Steven Ehlert

→ these processes can either quench and enhance star formation and AGN activity in galaxies, and can change other properties such as their structure, size, mass, etc.

Galaxy clusters are extreme environments, with many processes affecting cluster members, their star formation and nuclear activity



Treu et al. 2003

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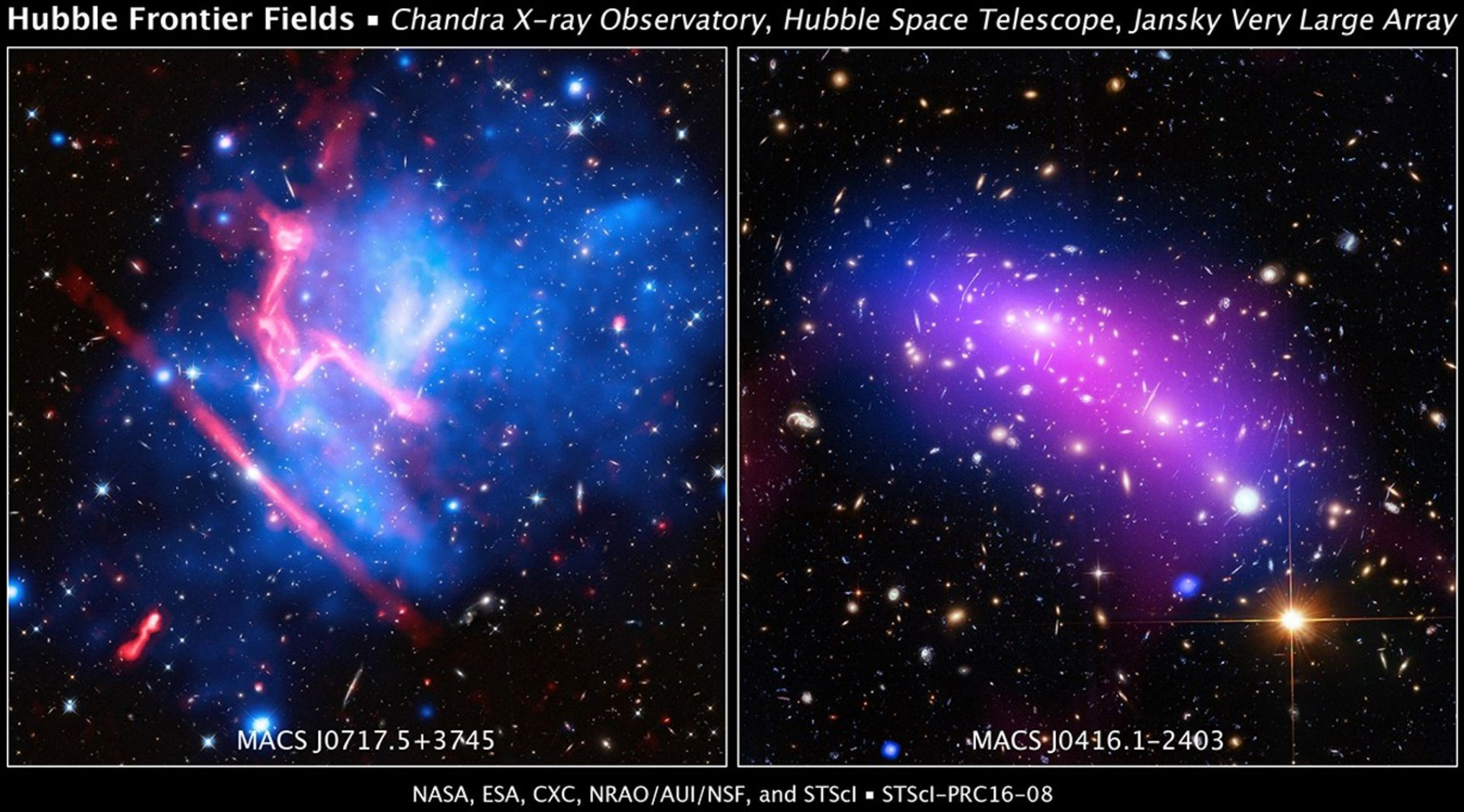
Extreme examples of colliding clusters

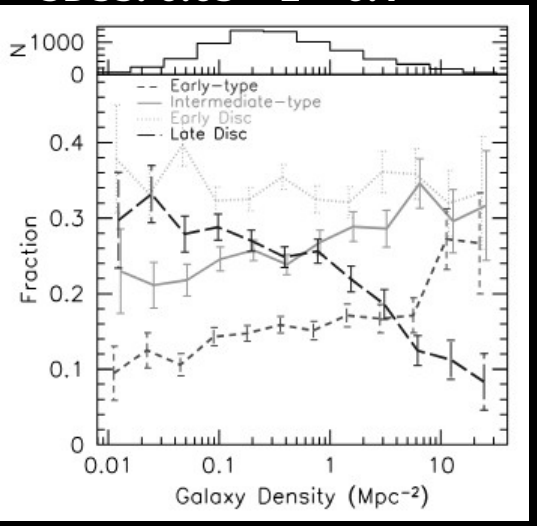


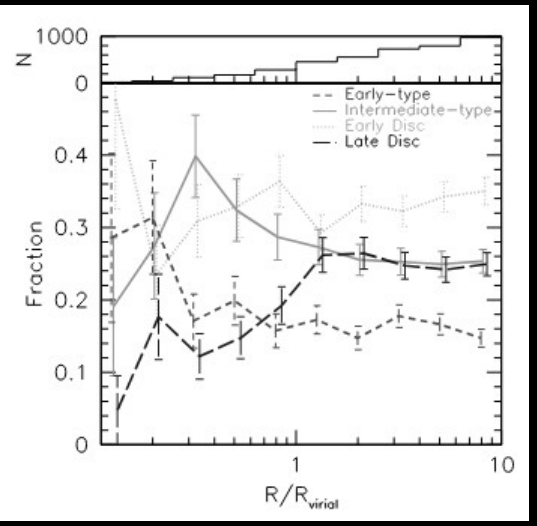
Tuesday's talk of Mpati Ramatsoku for MeerKAT studies using MeerKAT

Main relations in galaxy clusters

Morphology-density relation and morphology-clustercentric distance relation

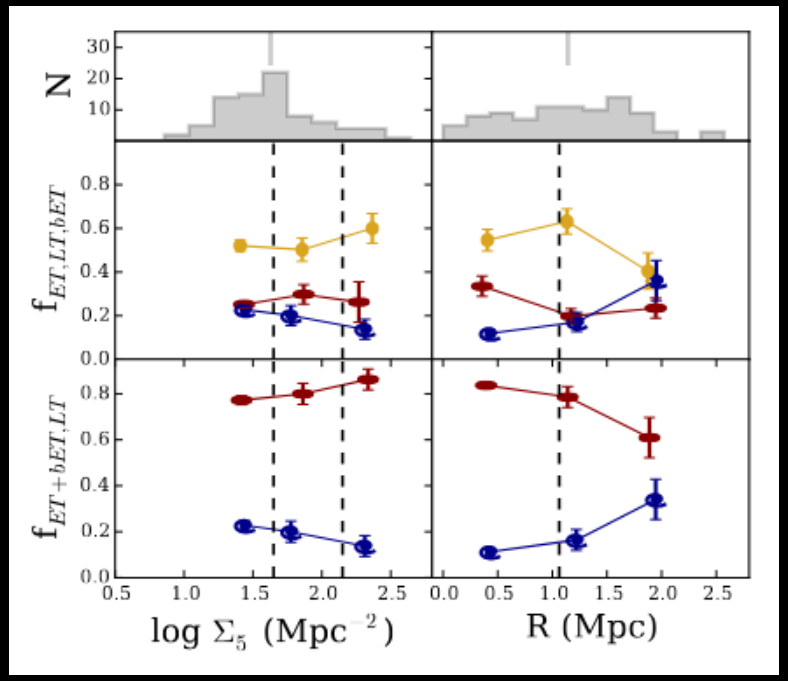
SDSS: 0.05 < z < 0.1





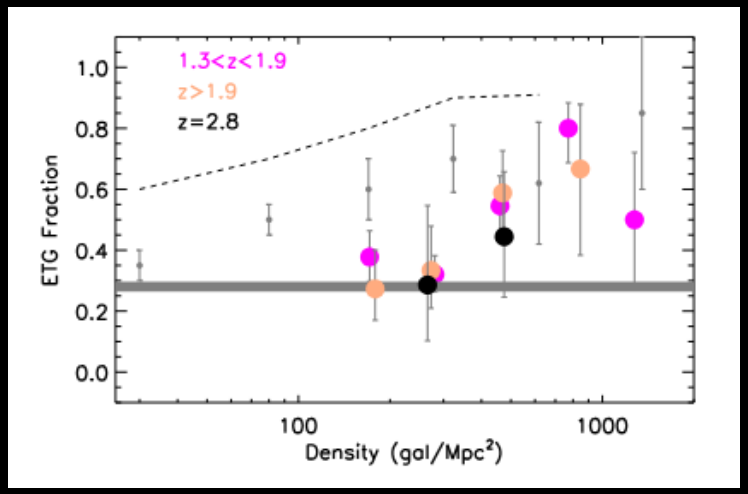
Goto et al. 2003

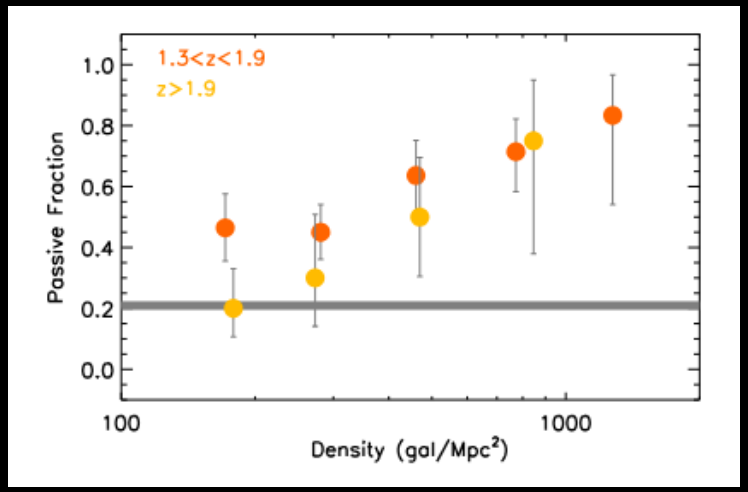
GLACE: RXJ1257 at z~0.9 in clumpy clusters



Pintos-Castro, Povic, Sanchez-Portal et al. 2016

→ relation in place at z ~ 2 - 3





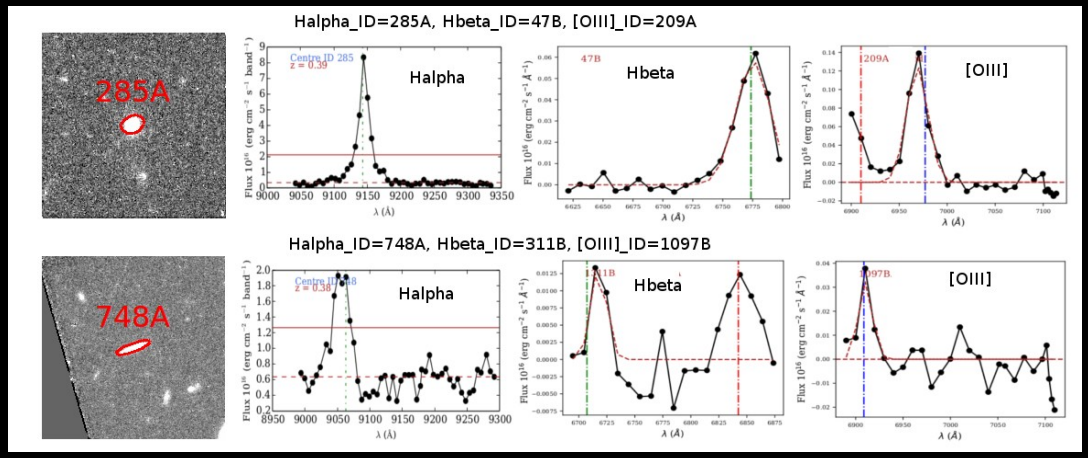
Mei et al. 2023

→ Local density and clustercentric distance play different roles for elliptical and S0 and spiral galaxies → Ell (except low-mass ell) related to primordial densities, and S0/spiral to cluster dynamics (within Rvir)

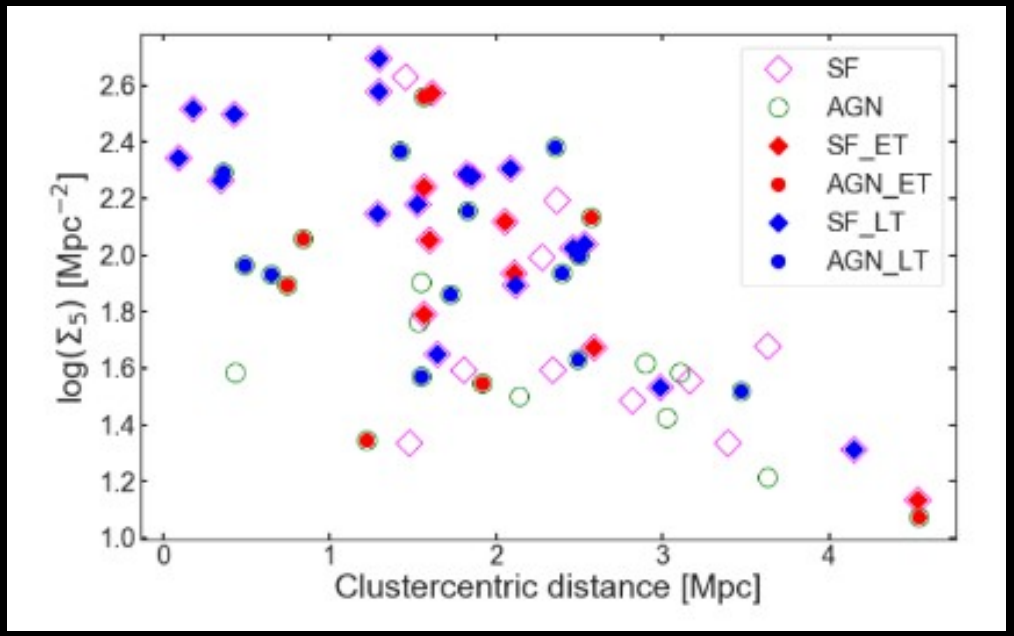
(see Vulcani et al. 2023)

Main relations in galaxy clusters

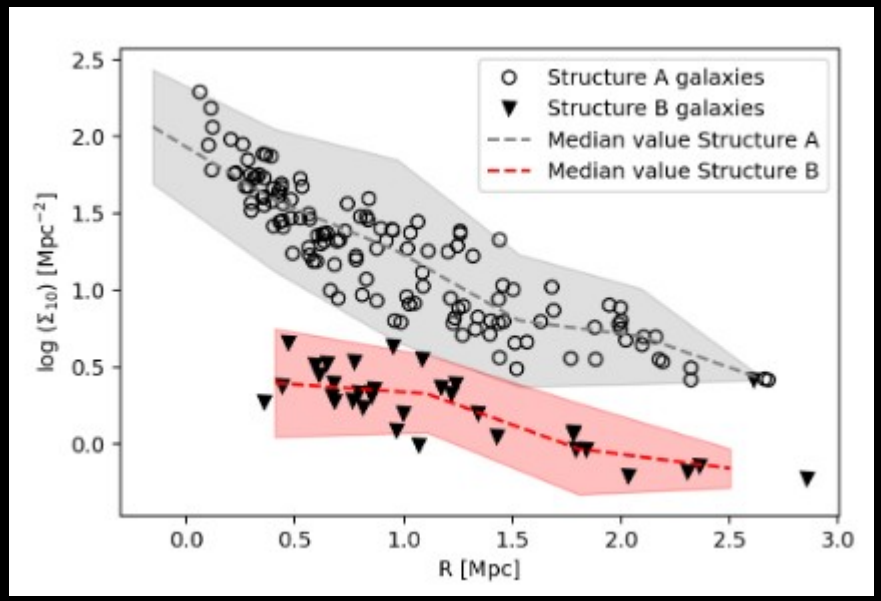
Density-clustercentric distance relation



Cl 0024 cluster



Beyoro-Amado et al. 2021



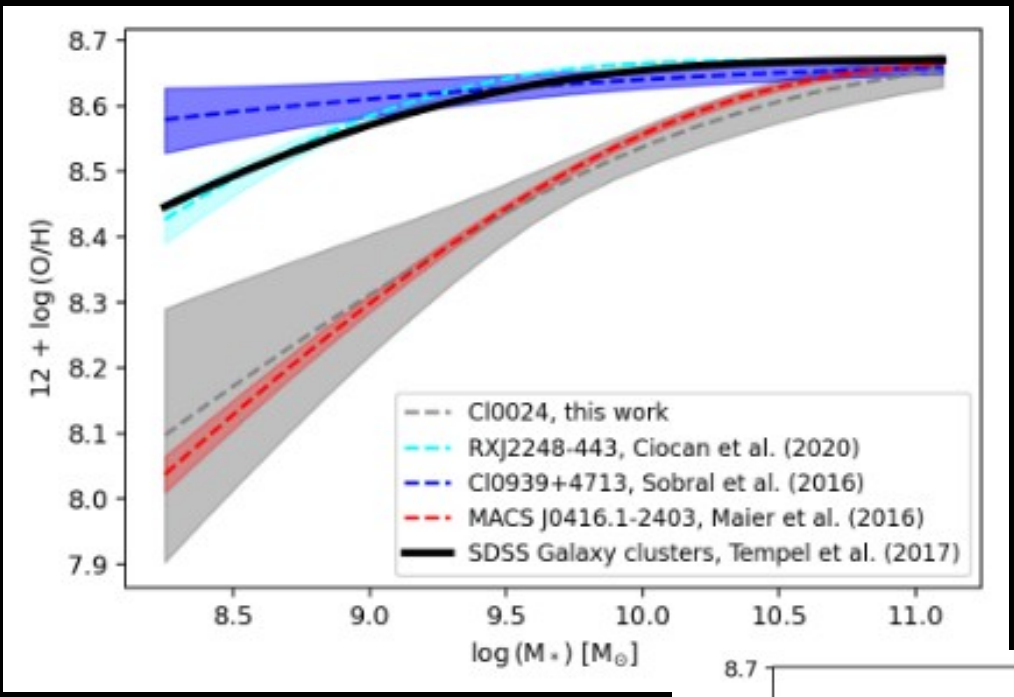
Cedres et al. 2024

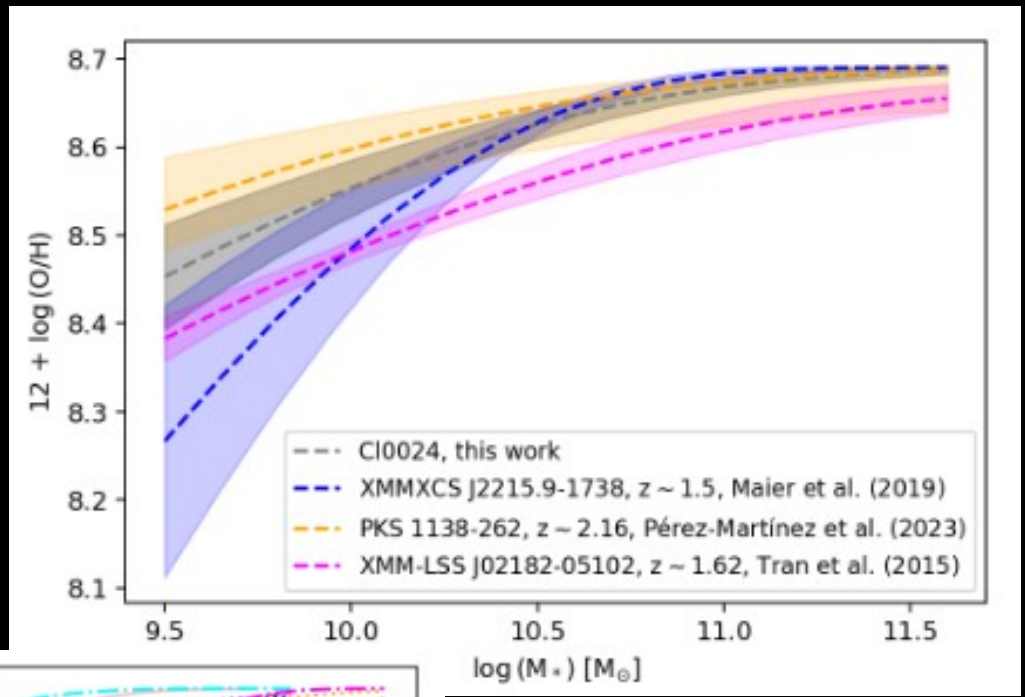
→ seen at higher redshifts
→ need for detailed studies at z > 3

Main relations in galaxy clusters

Mass-metallicity relation (MZR) for SFG

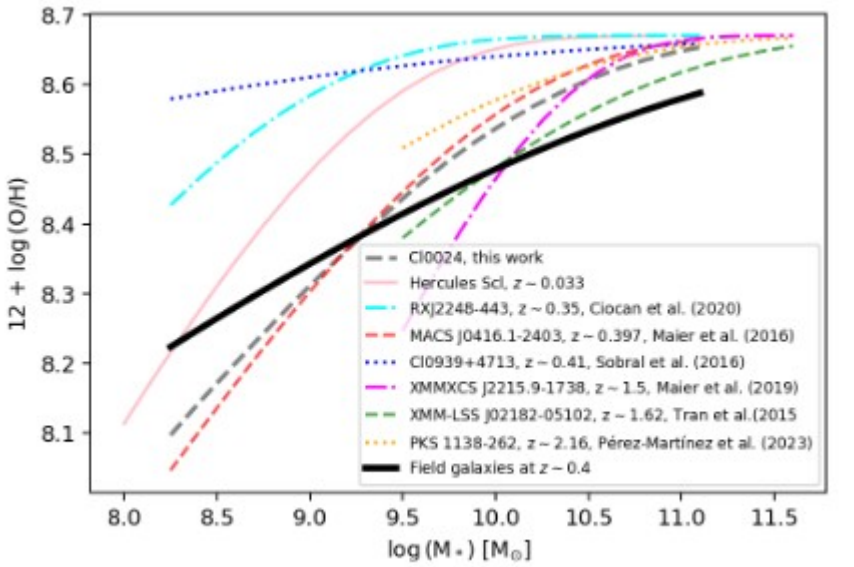
MZR at z ~ 0.4 and comparison with low-z galaxies (left), and MZR for the same M200 at different redshifts (right)





→ effect of cluster mass
→ larger effect of mass than redshift
→ no strong effect of environment on MZR in the same cluster

Cedres et al. 2024 based on Nadolny et al. 2020

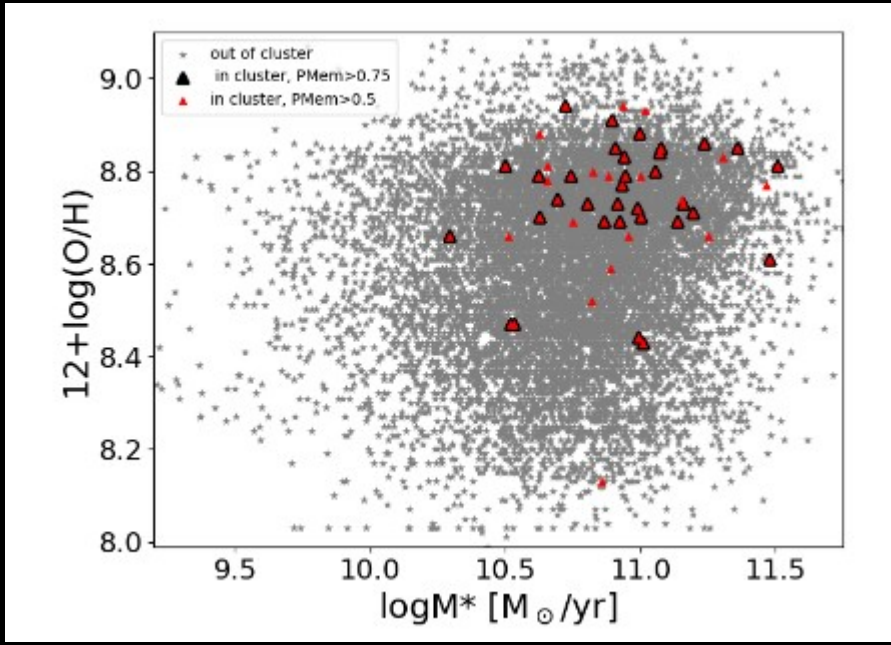


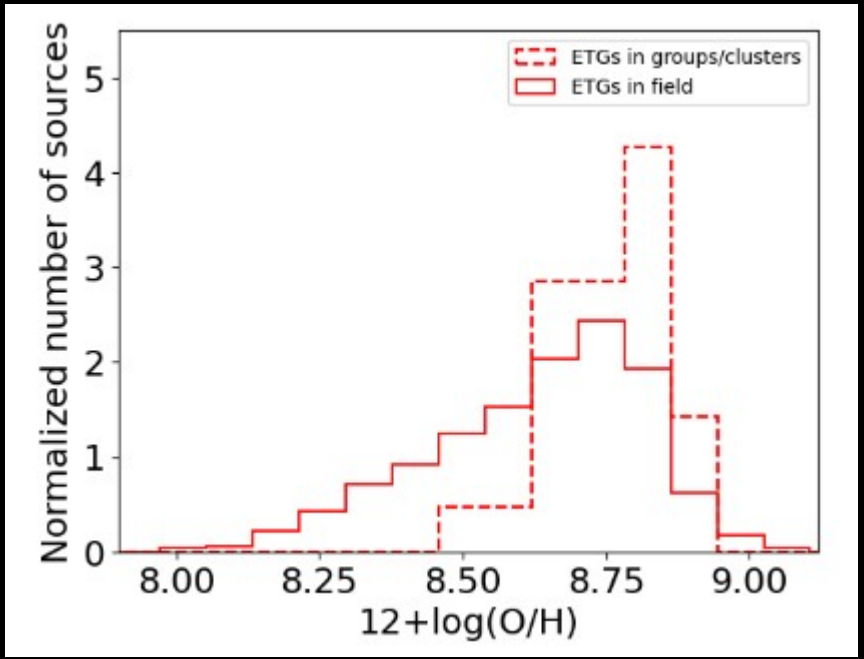
MZR up to z ~ 2 and comparison with field galaxies

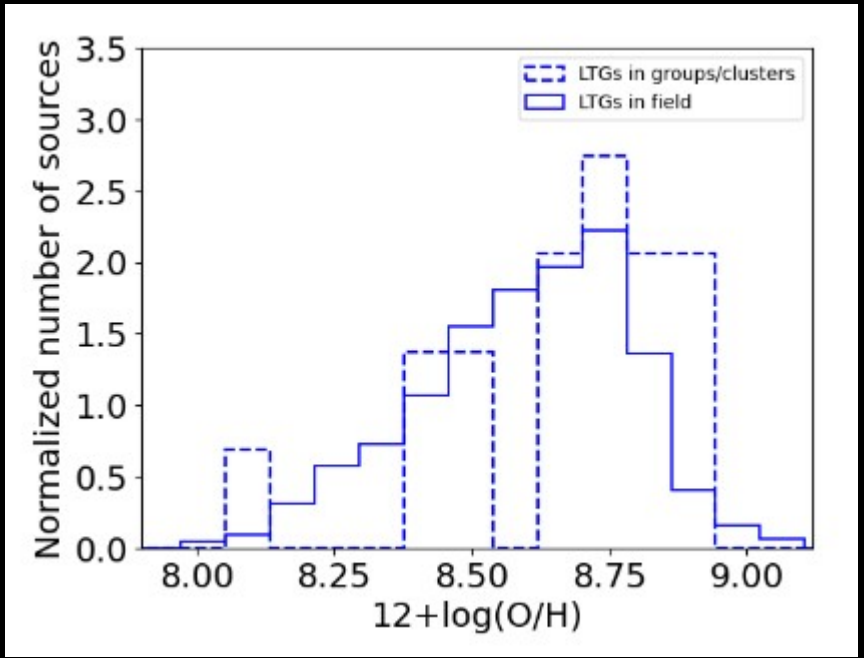
Main relations in galaxy clusters

Mass-metallicity relation (MZR) for AGN

The most detailed study of Sy 2 metallicities







→ AGN in groups and clusters more metal rich (?)
→ need for more studies and larger samples of Agn in clusters

Ahmed and Povic, in prep.

Still as open questions:

- what are the properties of different types of galaxies (massive vs. dwarf, SFG vs. AGN, ET vs. LT, etc.) in galaxy clusters and the role of environment on galaxy properties?

- what are the typical metallicities and their variability within clusters?

- what is the impact of SF/AGN feedback vs. the environment on galaxy properties and evolution?

- mass-driven vs. environment-driven galaxy evolution?

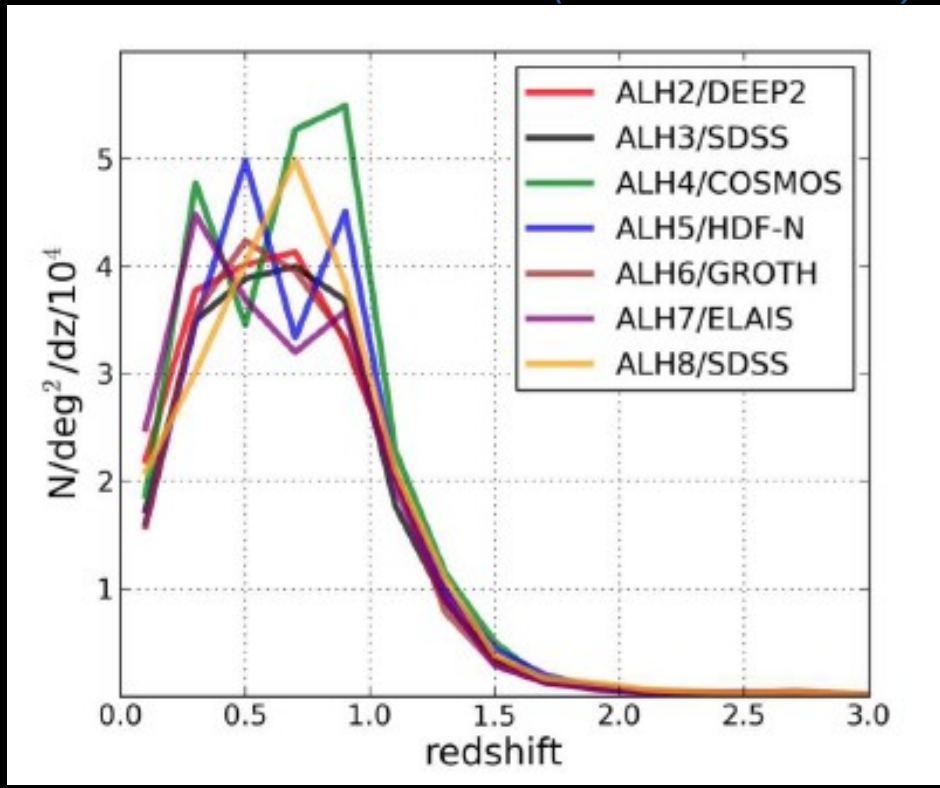
- what are the properties of the ICM and its impact on SF/AGN activity in galaxies?

- initial conditions vs. environmental processes in galaxy evolution?

- evolution of galaxy clusters (from proto-clusters to virialised clusters)?

- impact of cosmic variance on clusters?

Cosmic variance in ALHAMBRA fields
(Molino et al. 2014)



Need for:

- larger and complete high-z samples, in particular at z > 2
  → JWST, E-ELT

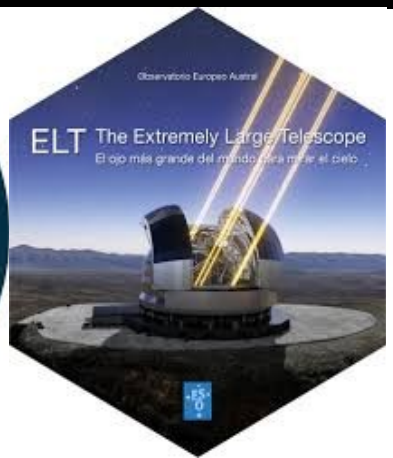
- extension of studies to low-mass galaxies → Roman, E-ELT

- we need more spectroscopy, including IFS!! → JWST, E-ELT

- better characterisation of AGN → Athena, LSST, JWST, E-ELT, SKA

- larger FoV!!! → Roman, SKA

- more multiwavelength studies!!



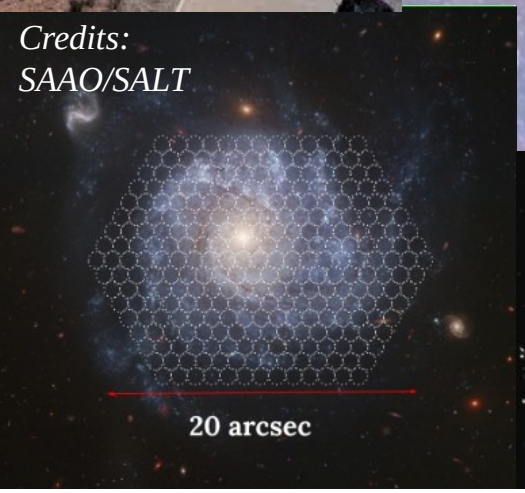
AGN IFU survey in the southern hemisphere

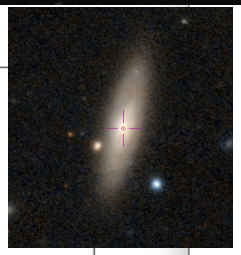
(PIs. M. Povic & A. Mahoro)

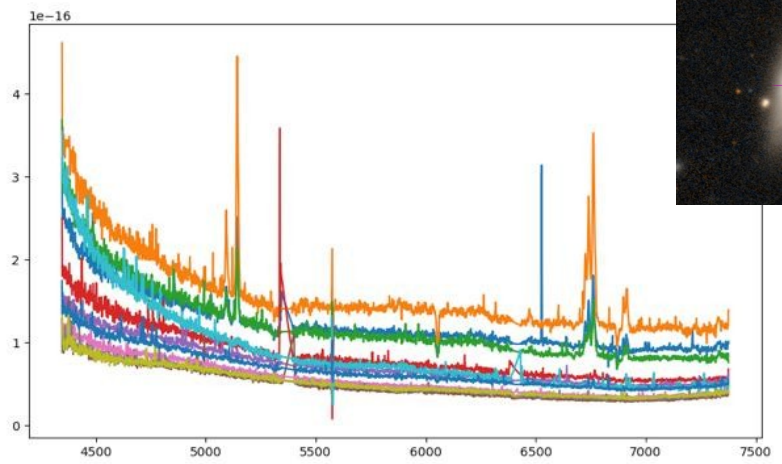
PanAfroAGN-SI
Pan-African AGN survey using SALT-IFS

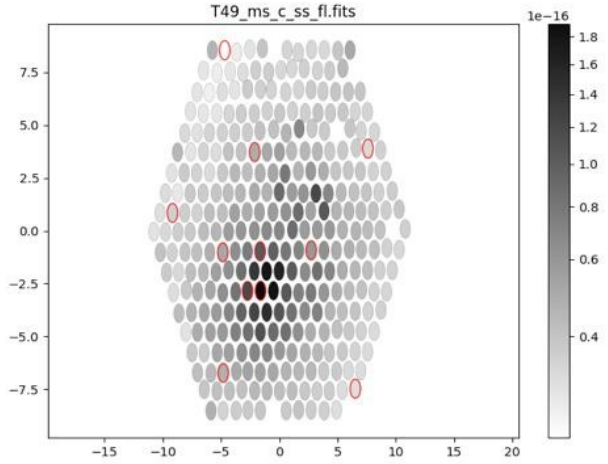
Pan-African AGN survey using SALT-Integral Field Spectroscopy (PanAfroAGN-SI)

→ NEW LARGE PROGRAM AT 11m SALT









> 80 members, 14 African & 5 EU countries

Watoto Wa Africa Children's Home, Tanzania, 2007