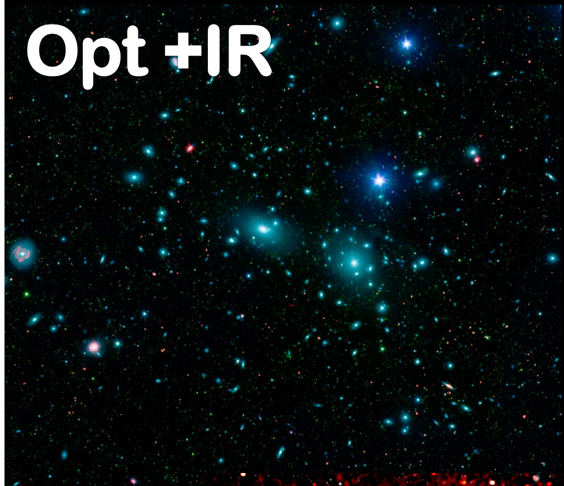
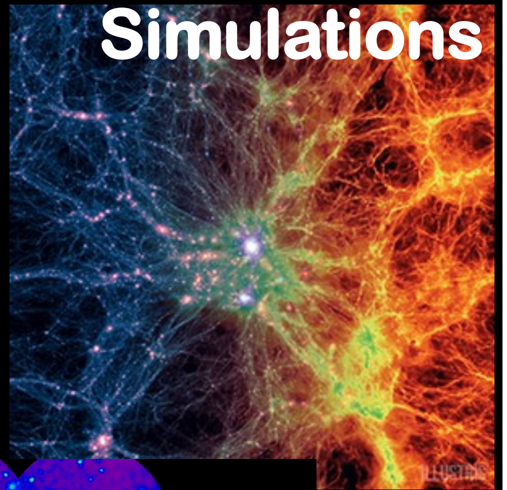
Large scale structure and physics of matter:

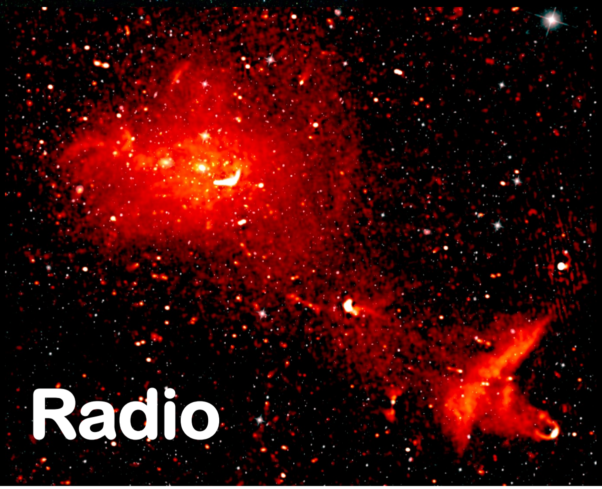
overdense regions

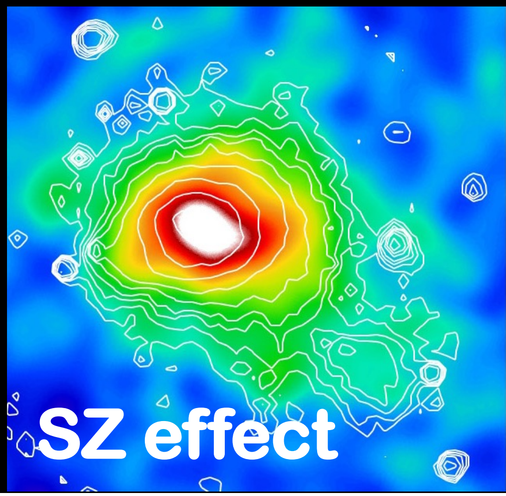
(galaxy groups & clusters)

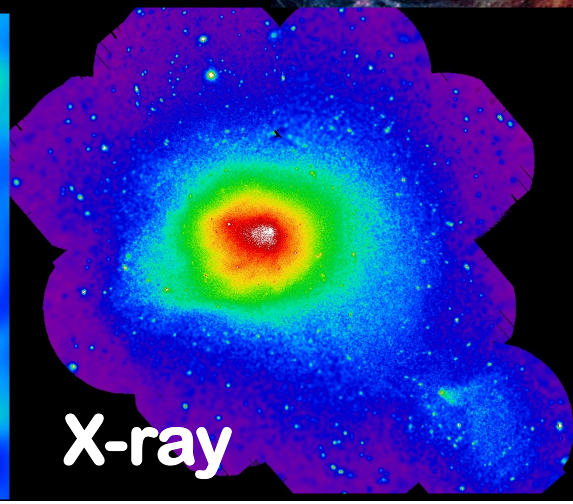


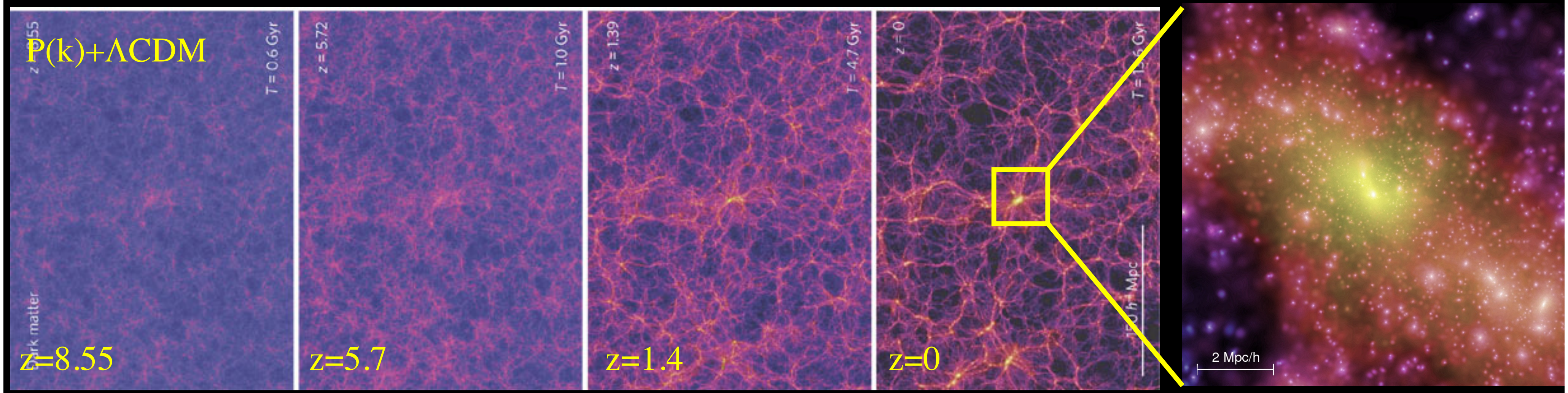
Stefano Ettori
INAF-OAS Bologna

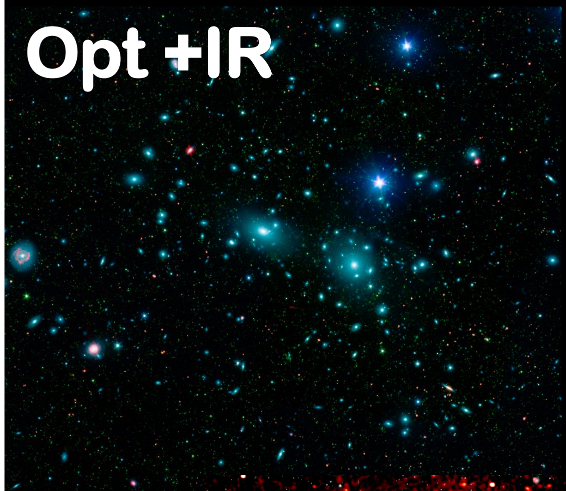








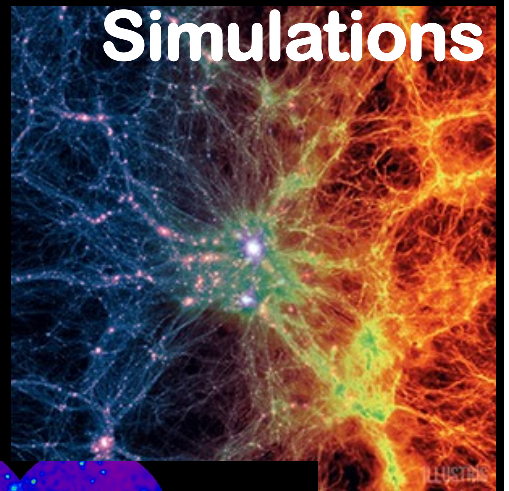


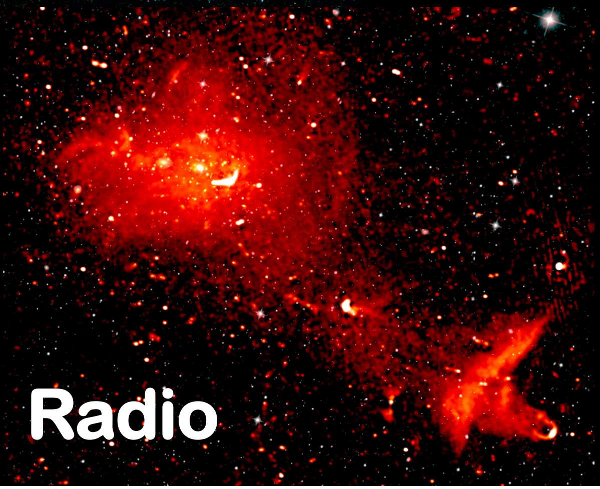


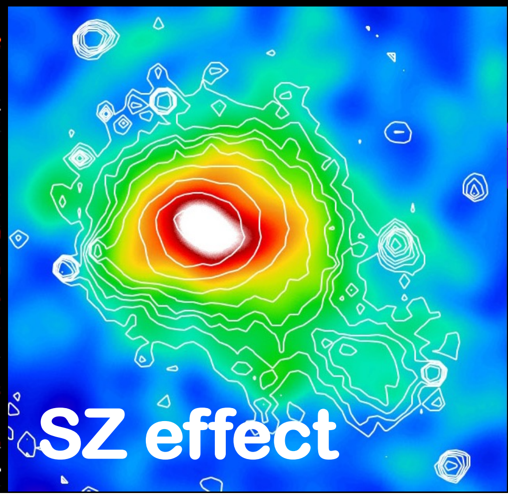
galaxy groups & clusters:

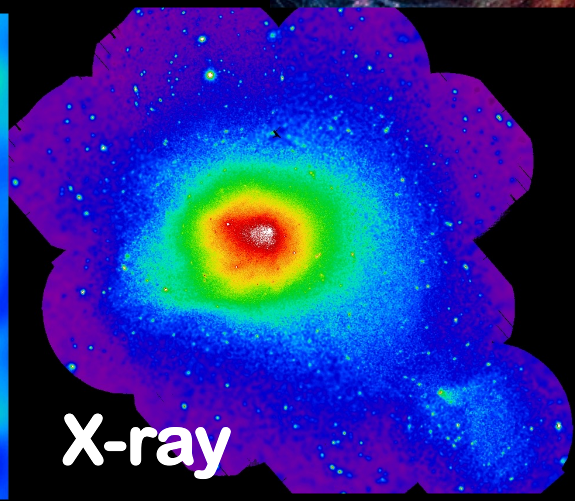
at the crossroad of

Astrophysics & Cosmology







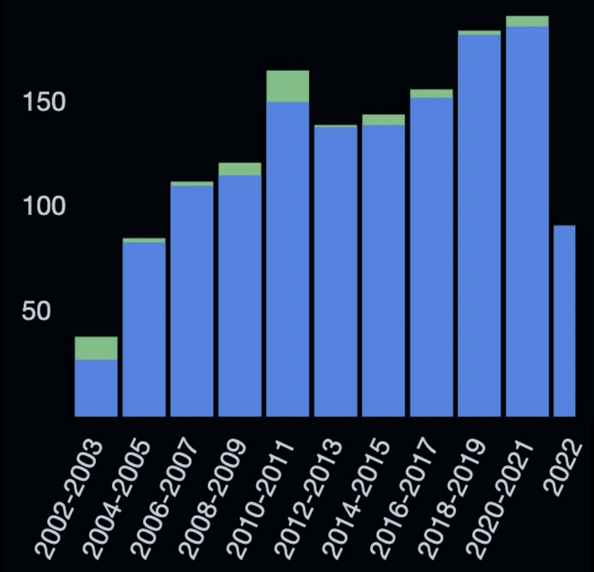


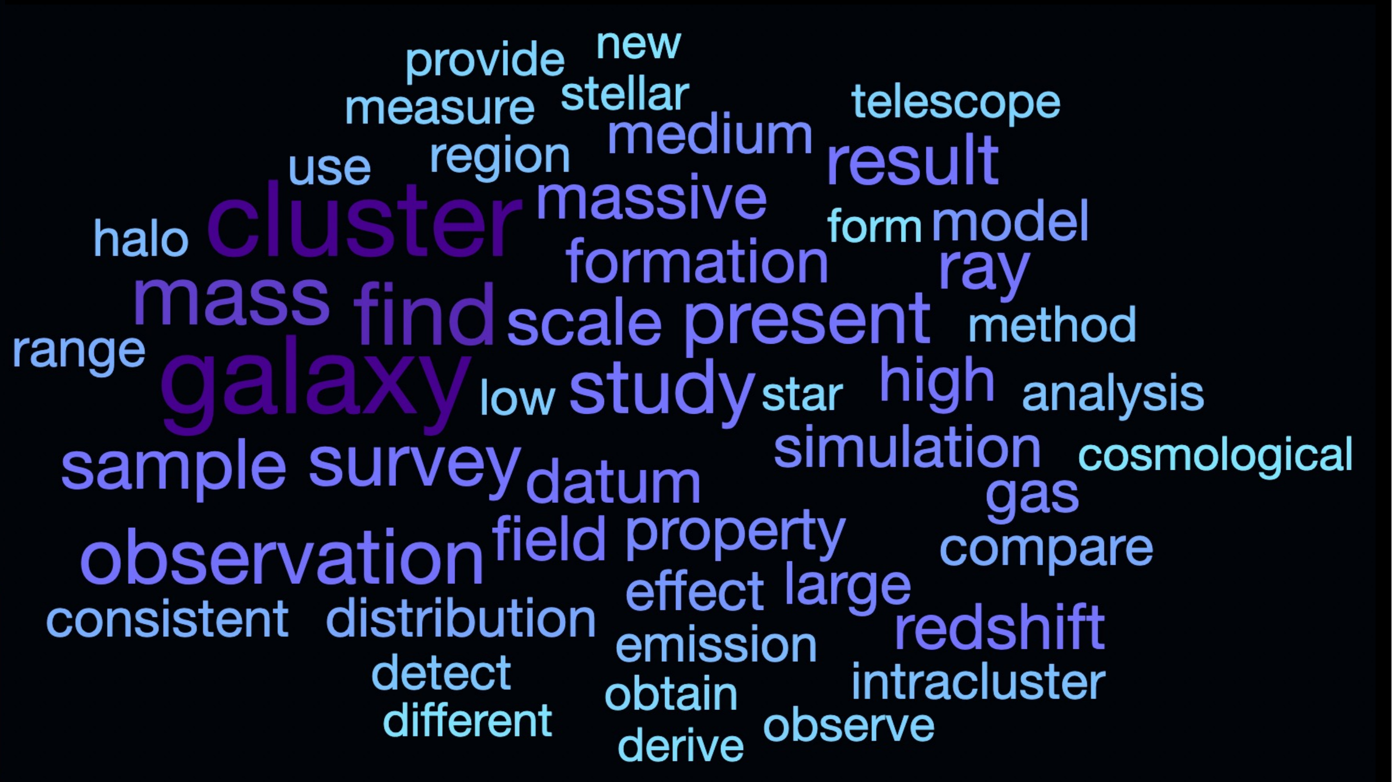
Fundamental questions

- **Astronet** **Chapter 1: "Origin & evolution of the Universe":** Are there deviations from general relativity, and on what scales? Are there deviations from the standard model of particle physics? Are there deviations from the standard cosmological model? What is the nature of dark matter? What is the origin of the accelerated expansion? Can we identify specific observational signatures of inflation? What can gravitational waves observations reveal about dark energy, dark matter and modifications of gravity on cosmological scales? **Sect.1.2.4 "The Formation of LSS":** Is there evidence in structure formation for deviations from general relativity or the cold dark matter and dark energy paradigm? What is the exact connection between the formation of stars and galaxies and their dark matter halo?
- **Snowmass2021 Cosmic Frontiers:** What is dark energy? What is the nature of cosmic inflation? What is dark matter? Is gravity well-described by Einstein's general relativity, or do we need new degrees of freedom to describe its action on cosmic scales?
- **Astro2020 Decadal:** C-Q1. what set the hot BB in motion? C-Q2. what are the properties of DM & dark sector? C-Q3. what physics drives the cosmic expansion and large scale evolution? D-Q1. how did IGM and first sources of radiation evolve from cosmic dawn through epoch of reionization? D-Q2. how do gas, metals, and dust flow into/through/out of galaxies? D-Q4: how do the histories of galaxies and their DM halos shape their observable properties?
- **ESA Cosmic Vision:** **M *Euclid*** What is the distribution of DM in the Universe? What is the history of expansion of the Universe? What does this tell us about the nature of DE? Does the DE equation of state evolve over time? How do LSS form in the Universe? **L2 "Hot & Energetic Universe"** How do baryons in groups and clusters accrete and dynamically evolve in the dark matter halos? What drives the chemical and thermodynamic evolution of the Universe's largest structures? What is the interplay of galaxies, SMBHs, and intergalactic gas evolution in clusters? Where are the missing baryons at low redshift, and what is their physical states?
- **Voyage 2050**: **L-missions**: New Physical Probes of the Early Universe. How did the Universe begin? How did the first cosmic structures and black holes form and evolve? ... This theme follows the breakthrough science from Planck and the expected scientific return from LISA; **M-Missions:** 3.1.12 Mapping the Cosmic Structure in Dark Matter, Missing Baryons, and Atomic and Molecular Lines; 3.1.13 Probing the Large Scale IGM in the Local Universe through Absorption Lines in the UV and X-rays

keyword:"cosmology: large-scale structure of Universe"
OR keyword:"galaxies: clusters: intracluster medium"
OR keyword:"galaxies: clusters: general"
year:2018-2022 AND aff:"INAF”

466/1,708 (~27%; 30% for citations)





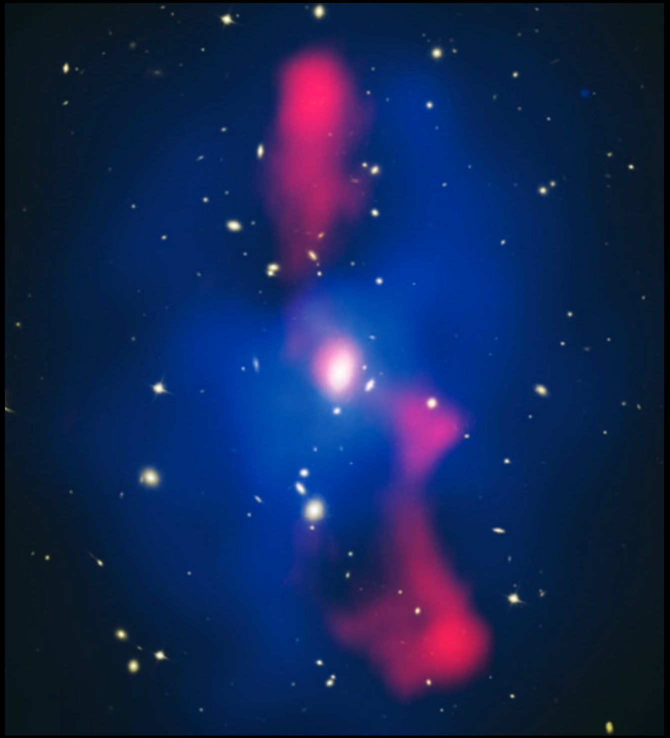
Outline

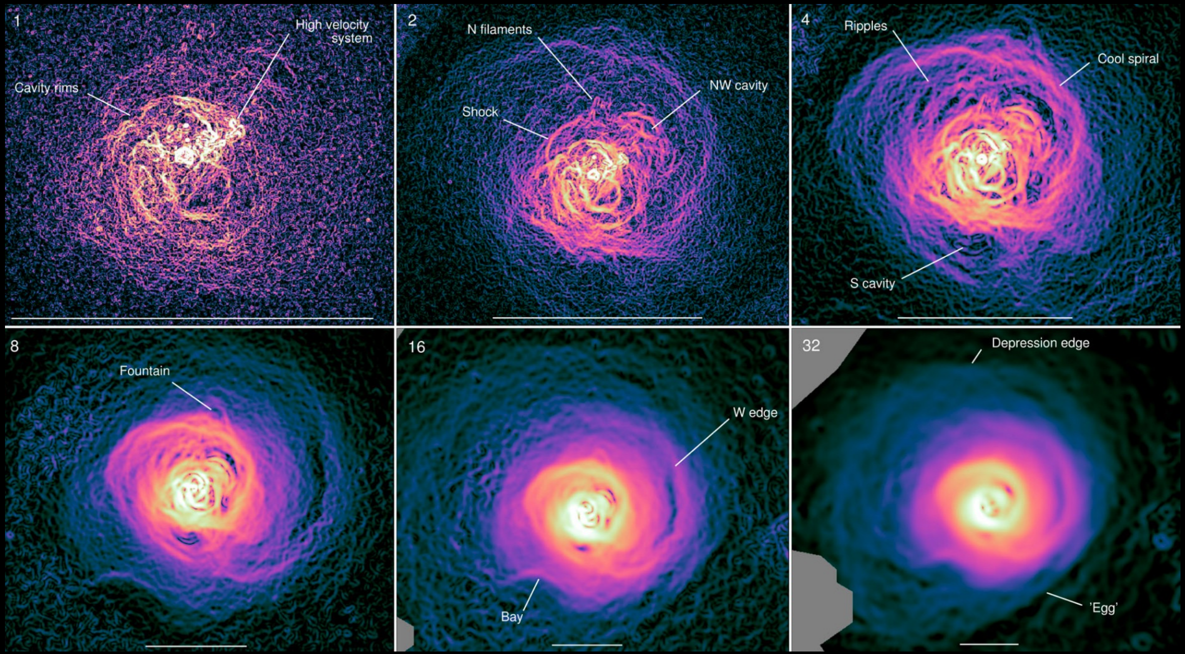
- **Formation**: transport & circulation of energy & baryons;
cores: feeding to & feedback from AGNs;
outskirts: accretion, splashback radius, clusters' pairs
- **Environment**: galaxy evolution in overdense regions;
metal circulation; role of groups
- **Plasma physics**: radio structures, high-res X-ray/SZ
- **Evolution**: how do the properties ensemble
(our knowledge limited to z~2) ?
- **Gravity:** mass proxies, scatter & bias;
DM & alternatives; substructures
- **Anomalies**: 3.5 keV, soft X-ray excess, anisotropy
- **role of AI**

Formation: core

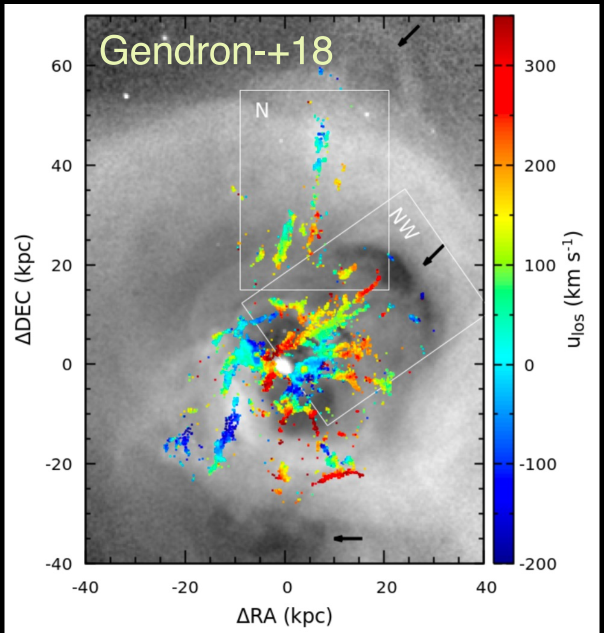
Cooling → fresh gas → ignite AGNs → outflows/AGN-driven jets → heating
(MS0735, McNamara+05**)**

When & how is the jet energy is delivered to the gas? Co-existence of the multiple phases of gas, from the hot, weakly magnetized plasma to the cold ionized and molecular gas indicates an active competition between efficient radiative cooling and energetic heating processes



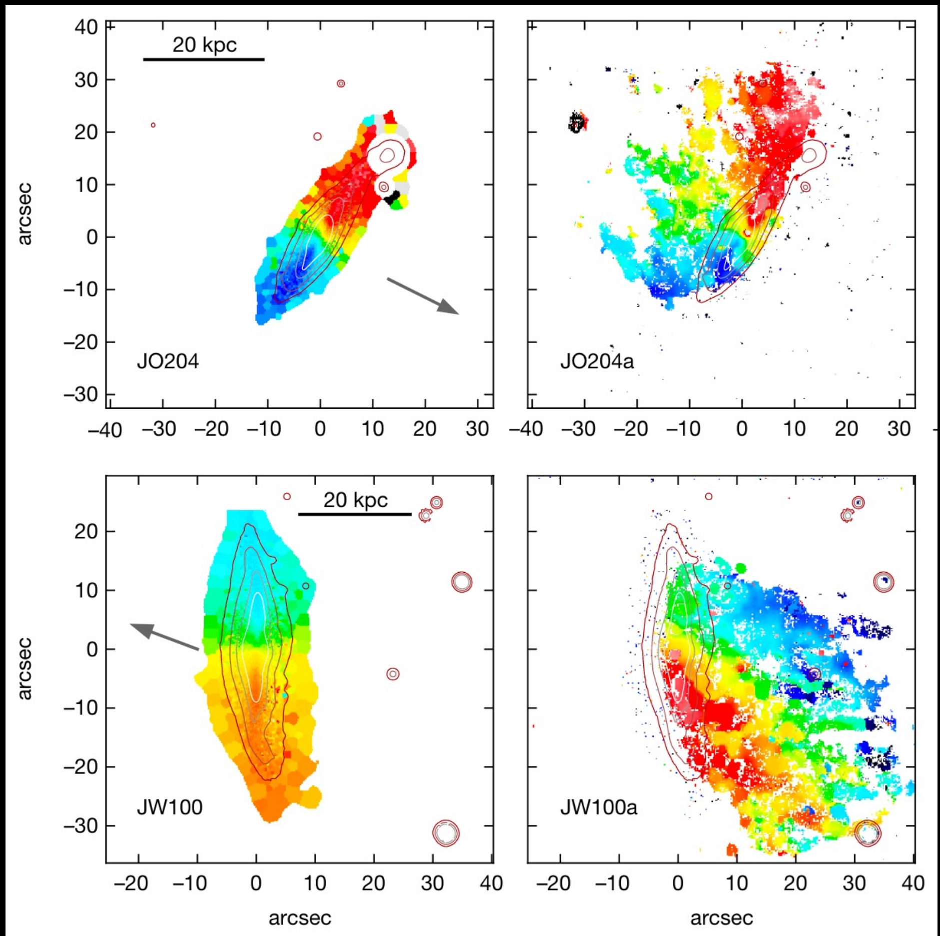


Perseus (Sanders+16; bar=4'~89 kpc)



Formation: core

But why only a small fraction of SMBH becomes AGN (by accreting matter)?
In overdense regions, several processes can remove gas from galaxies, with ram-pressure stripping being among the most efficient ones



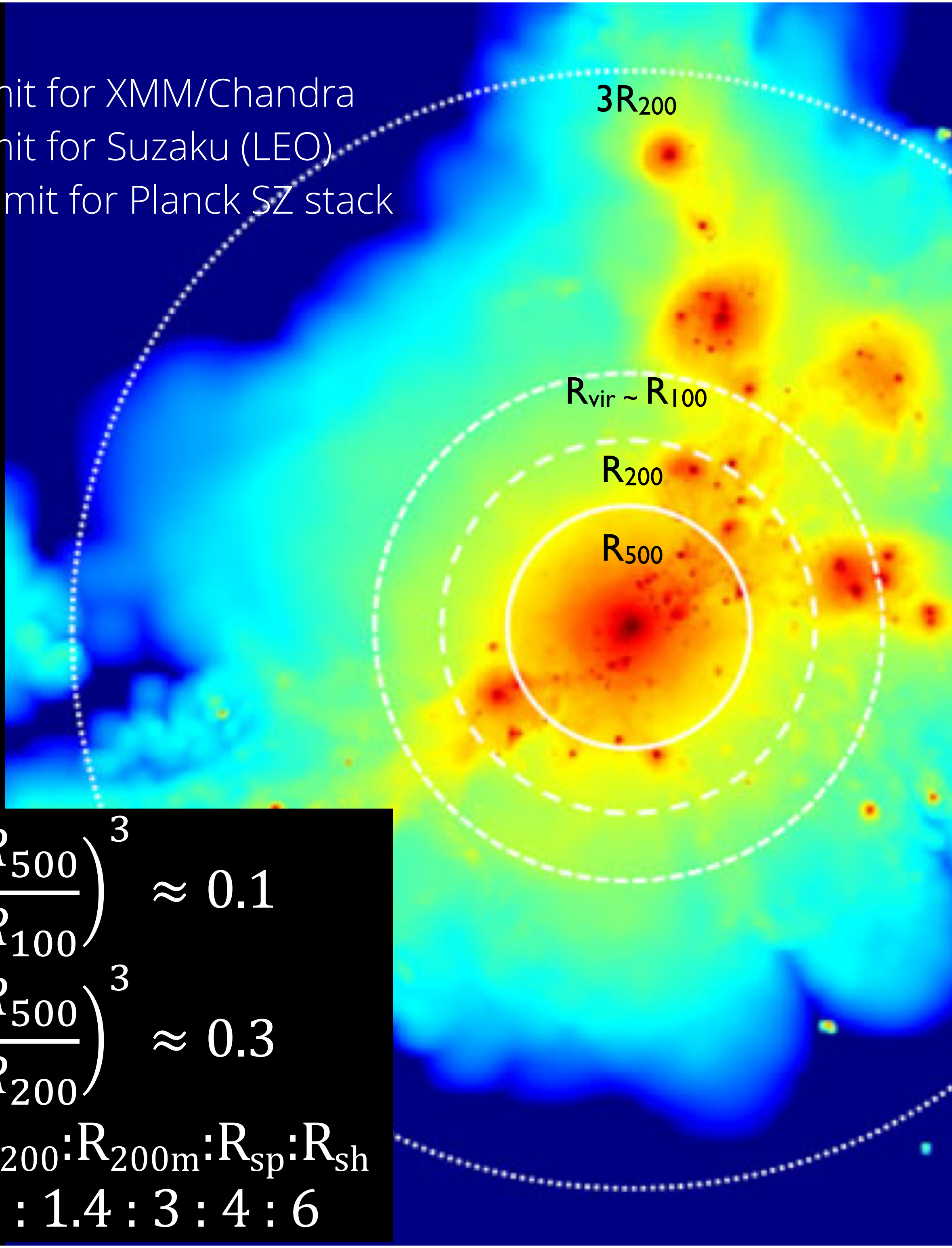
MUSE/GASP (Poggianti+17 Nat)

The special role of BCG: they are not just overgrown massive Ell, but expericence a special growth history (accretion of tidelly-stripped stars & ram-P stripped gas, cannibalism), that is also difficult to be reproduced through simulations; *details of their formation & how their properties relate to the environment are still unknown*

R$_{500}$ - limit for XMM/Chandra

R$_{200}$ - limit for Suzaku (LEO)

3R$_{500}$ - limit for Planck SZ stack

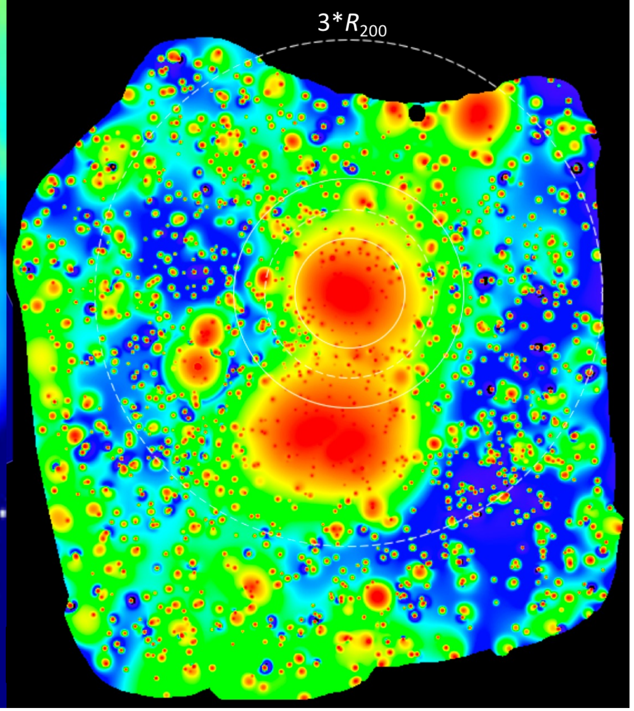


$$\left(\frac{R_{500}}{R_{100}}\right)^3 \approx 0.1$$

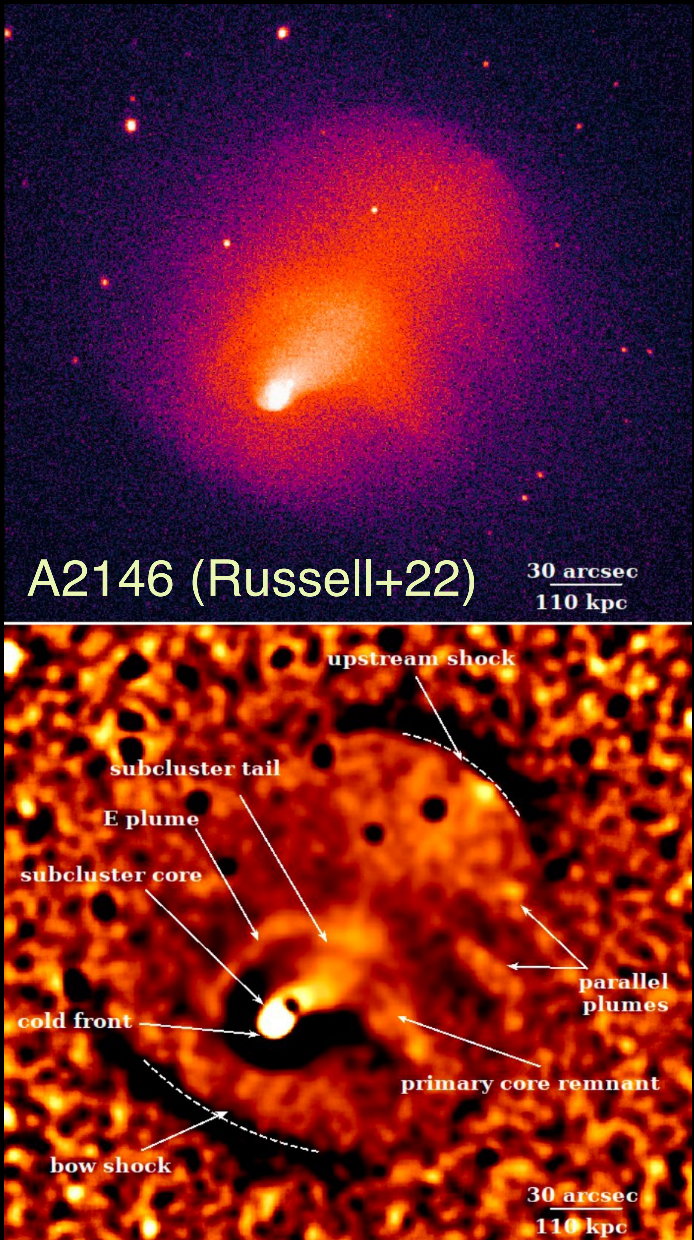
$$\left(\frac{R_{500}}{R_{200}}\right)^3 \approx 0.3$$

$$R_{500}:R_{200}:R_{200m}:R_{sp}:R_{sh} = 1:1.4:3:4:6$$

A3391-A3395/eROSITA
(Reiprich+21)

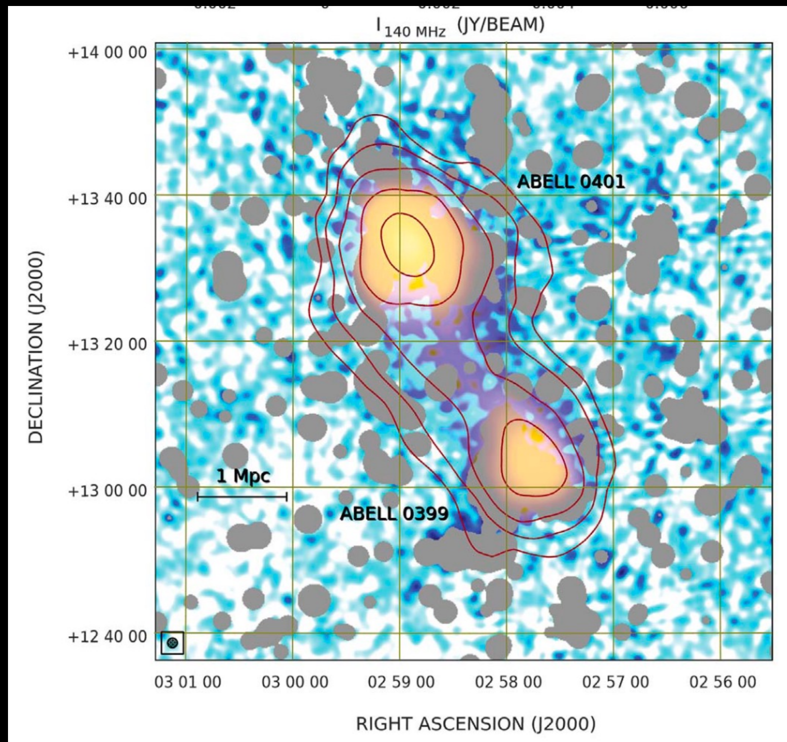


Formation: merging



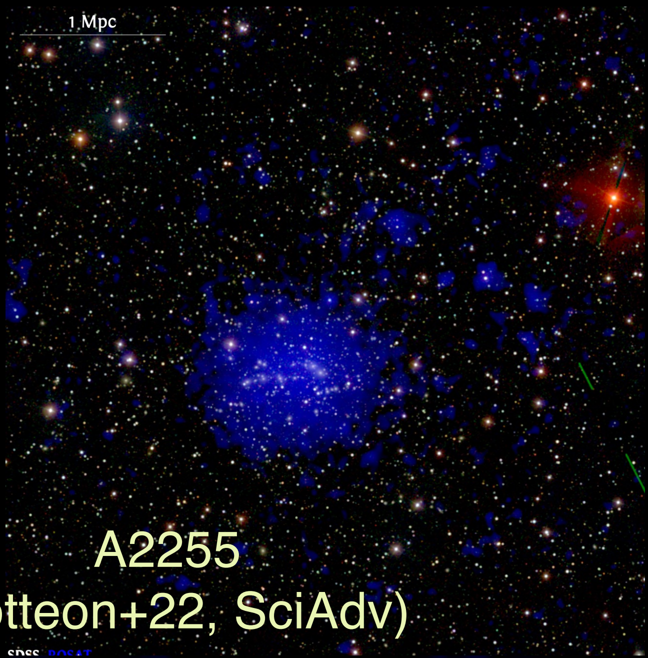
Merging clusters revealed a wealth of gas/galaxies motion-related phenomena subcluster infall, shocks, “cold fronts”, cool core sloshing, ram pressure stripping, bridges.

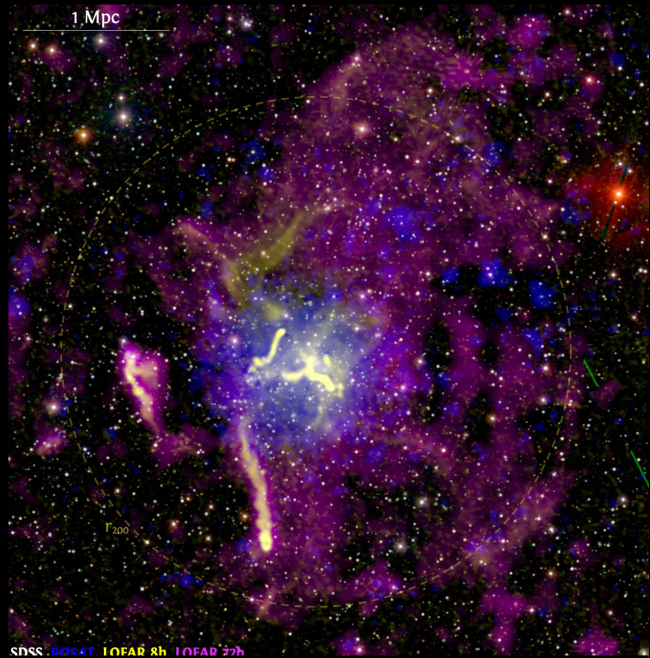
Questions: How relaxed are “relaxed” clusters? What is the fraction of turbulent and nonthermal pressure components (cosmic rays, magnetic fields) in the total gas pressure?



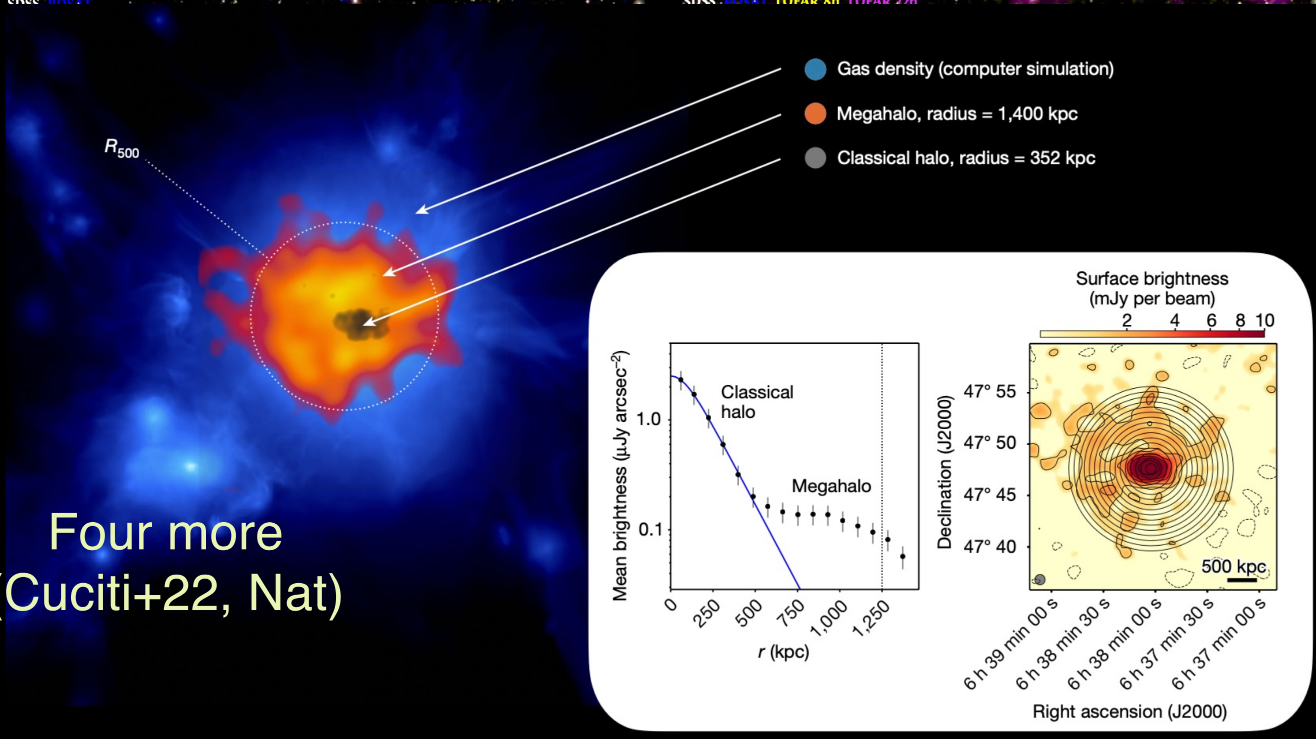
A399-A401 (Govoni+19 Sci; LOFAR+Planck)

Plasma physics: radio structures





A2255
(Botteon+22, SciAdv)

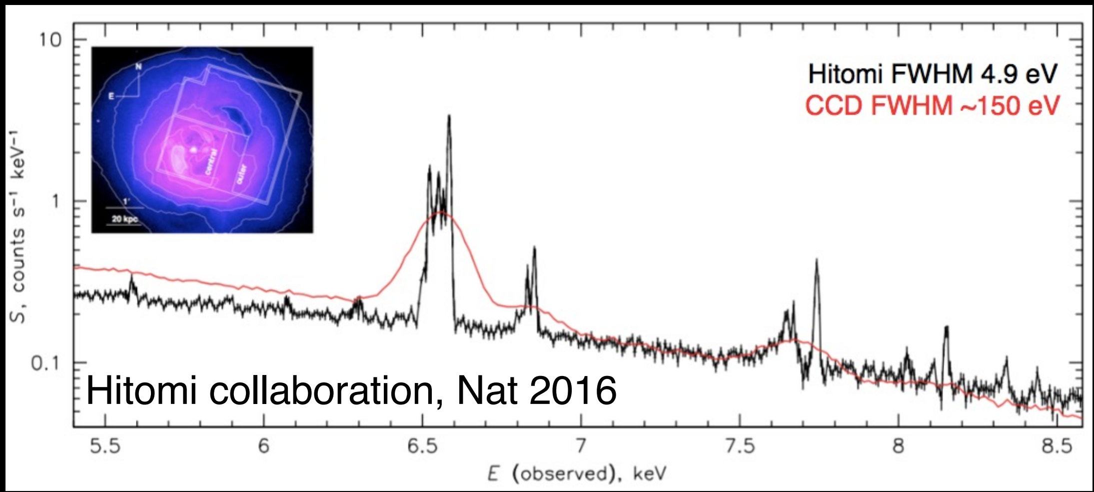


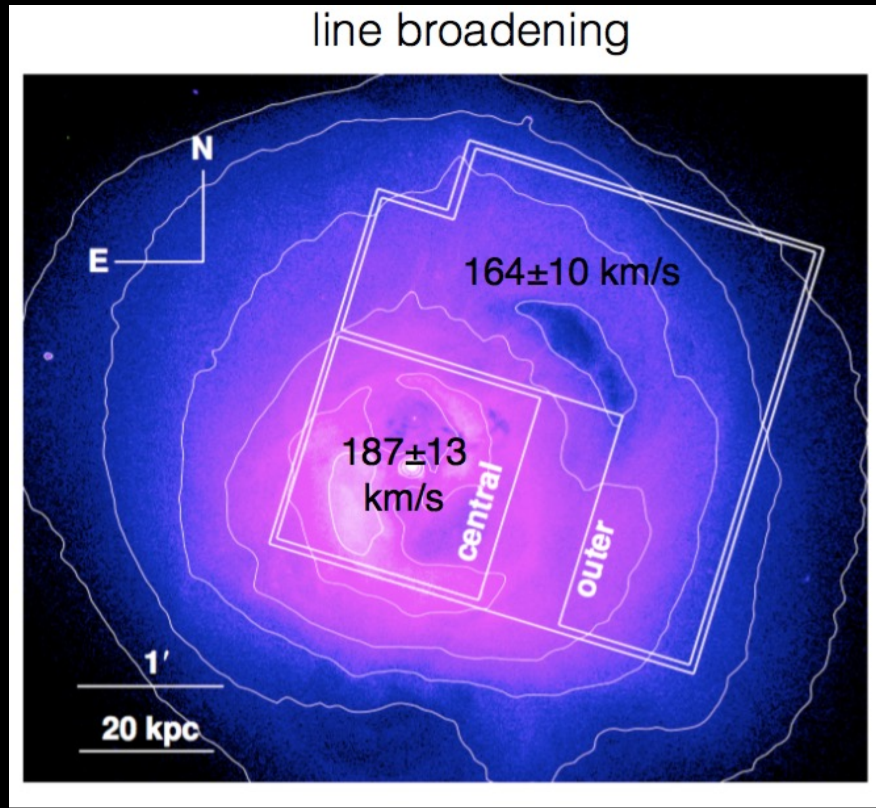
Four more
(Cuciti+22, Nat)

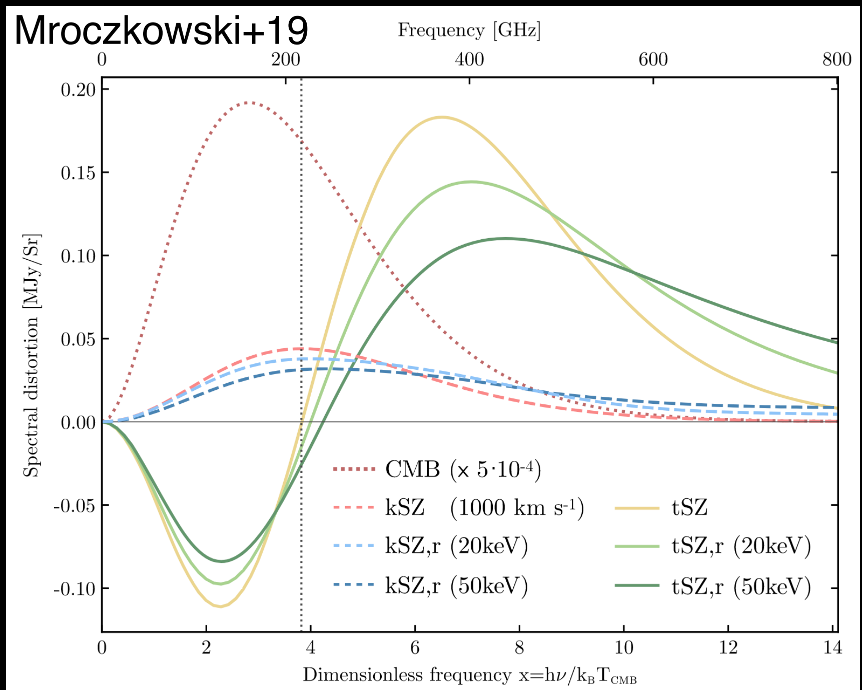
Relativistic electrons & B fields on large scales are responsible for these radio signals

How they are produced and maintained, how & by how much they depend on the halo properties, and how they are connected to the mass/energy components of the halo is still largely unknown

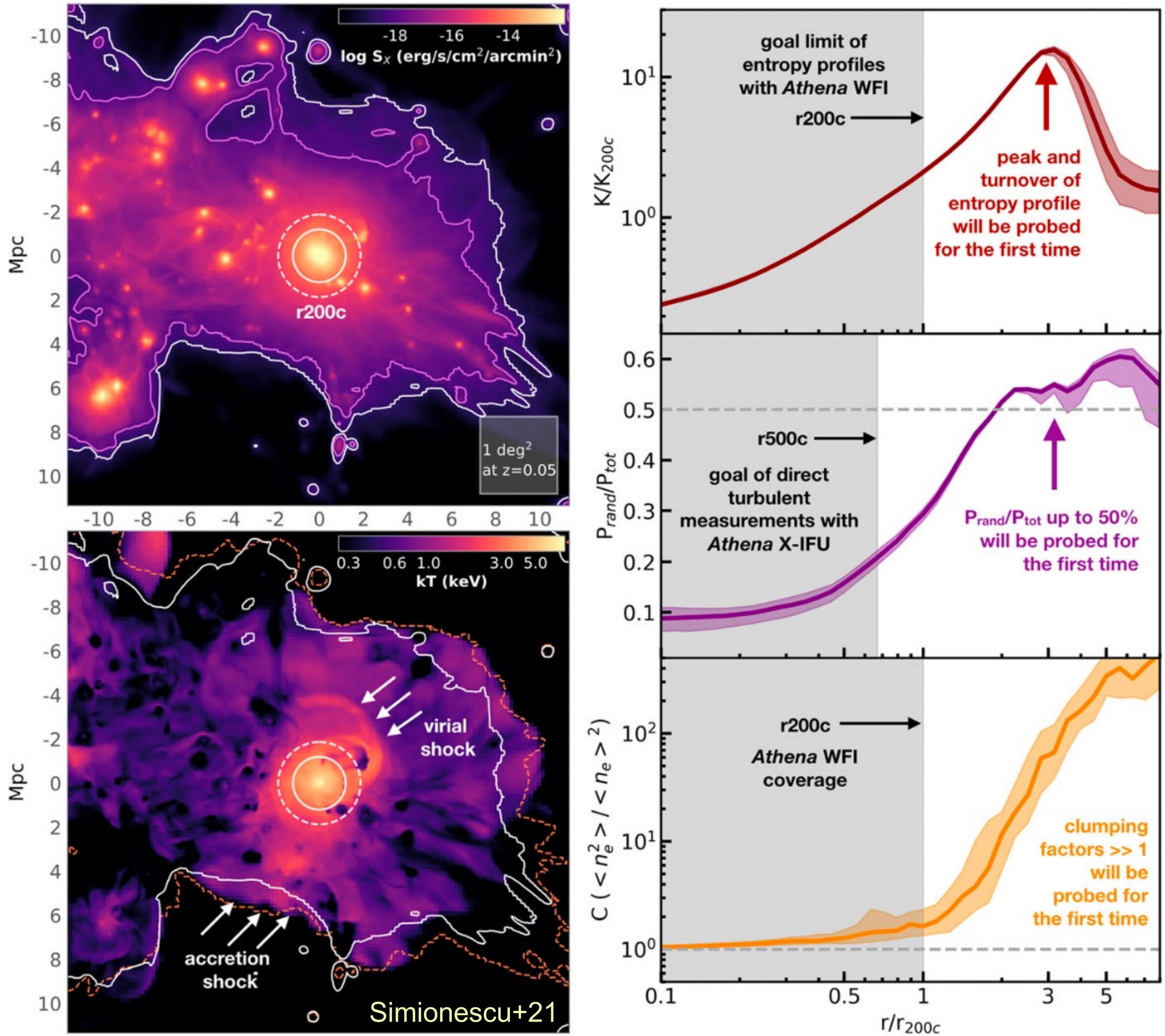
Plasma physics: X-ray & SZ high-res







- Estimate of the turbulence, bulk motion, non-thermal SZ signal (<10% of tSZ)
- Electron-Ion equilibration in outskirts
- Metallicity, possibly allowing the resolved contributions from single elements, to study the enrichment processes that are occurring



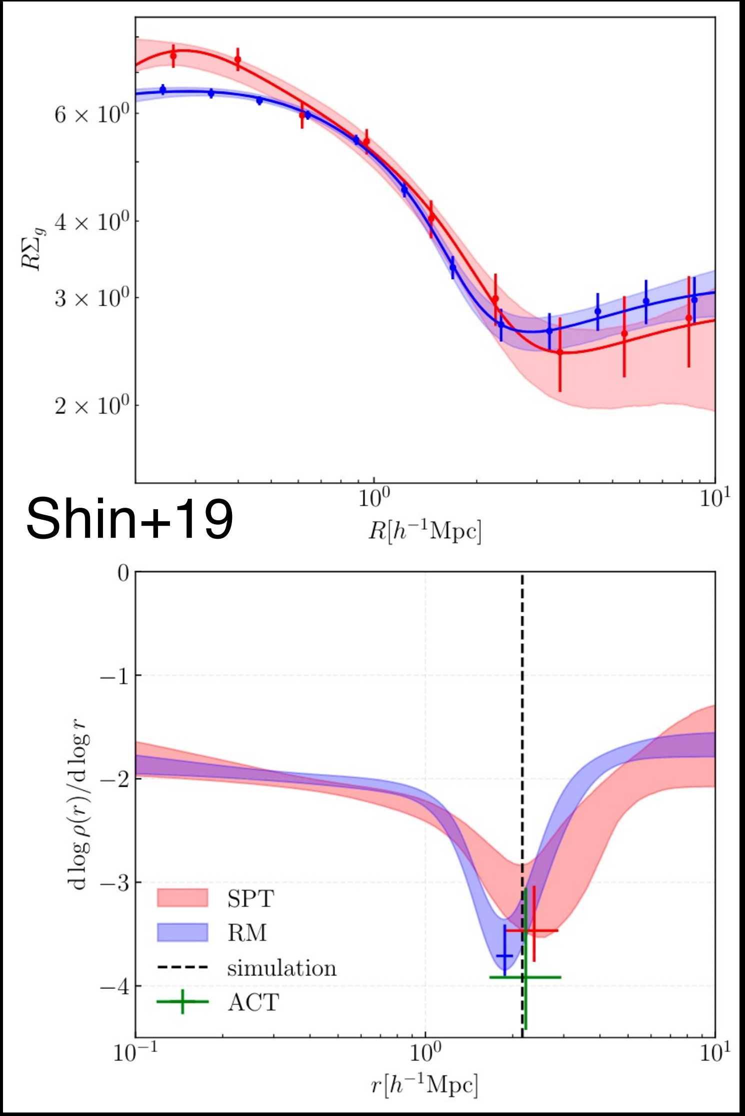
log S_X (erg/s/cm^2/arcmin^2)
-18 -16 -14
r200c
1 deg^2 at z=0.05
Mpc
kT (keV)
0.3 0.6 1.0 3.0 5.0
virial shock
accretion shock
Simionescu+21
goal limit of entropy profiles with *Athena* WFI
r200c
peak and turnover of entropy profile will be probed for the first time
K/K_{200c}
r500c
goal of direct turbulent measurements with *Athena* X-IFU
P_{rand}/P_{tot} up to 50% will be probed for the first time
P_{rand}/P_{tot}
r200c
Athena WFI coverage
clumping factors >> 1 will be probed for the first time
$C\ (<n_e^2>/<n_e>^2)$
r/r_{200c}

Formation: outskirts

galaxy clusters continue to grow and accrete matter from the cosmic web

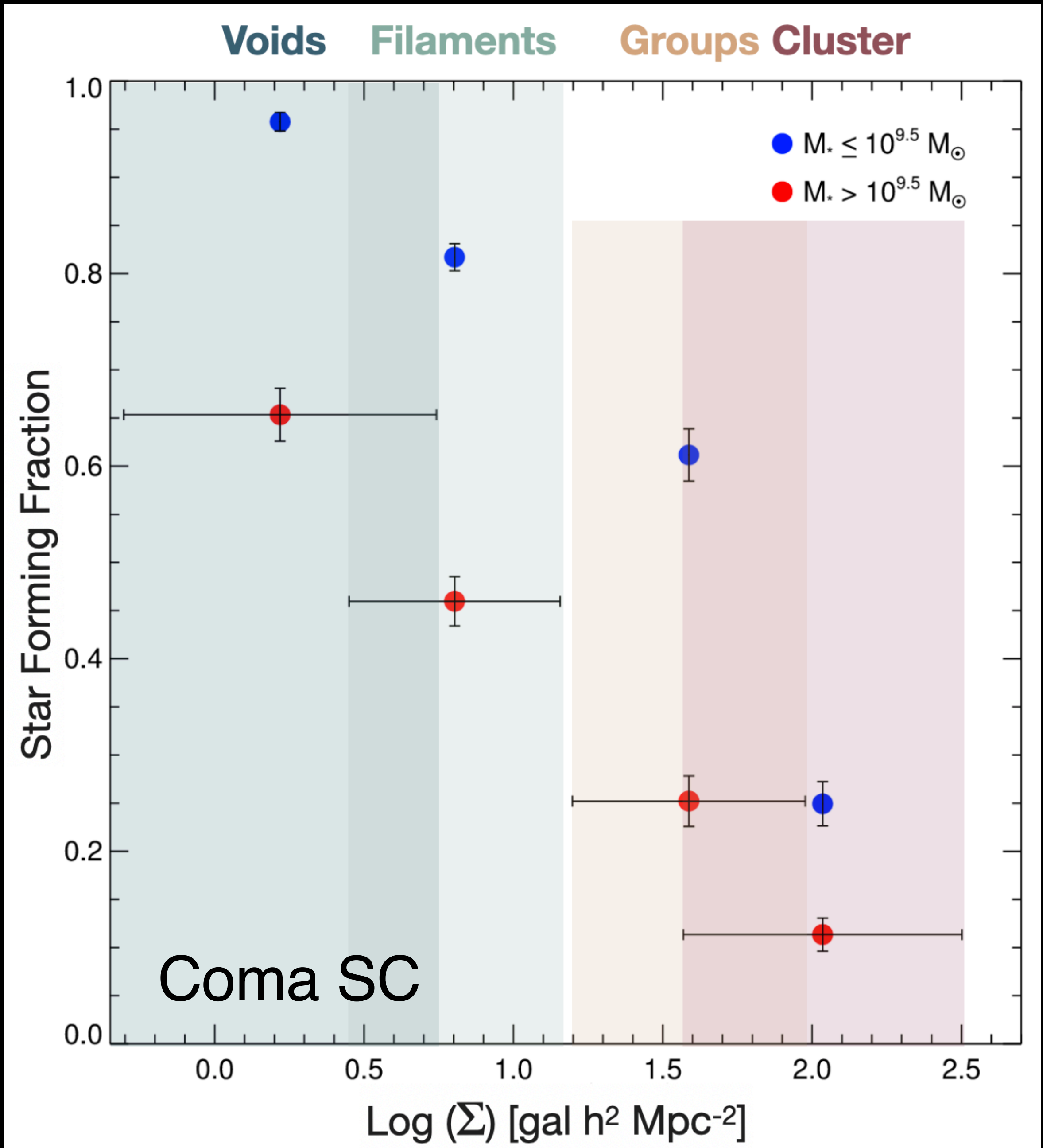
Physically Significant Scales and Radii: accreting DM forms the so-called "splashback radius" (Diemer & Kravtsov 14); it depends on the MAR of the DM halo (More+15); accretion (or "external") shock radius defines the spatial extent of the hot gas in DM halos; "internal shocks" due to mergers and filamentary accretion

Questions: How do electrons get heated in cluster outskirts? What is the role of magnetic fields in mediating the equilibration between different particle species in the plasma? Does the ideal fluid approximation, which is often employed in numerical simulations of large-scale structure formation, break down? If so, at what point? What is the extent and importance of the filamentary structure around clusters predicted by CDM-based simulations? What proportion of galaxies live in filaments (as opposed to groups, clusters, voids...)? How does that depend on galaxy properties?



Shin+19

Environment

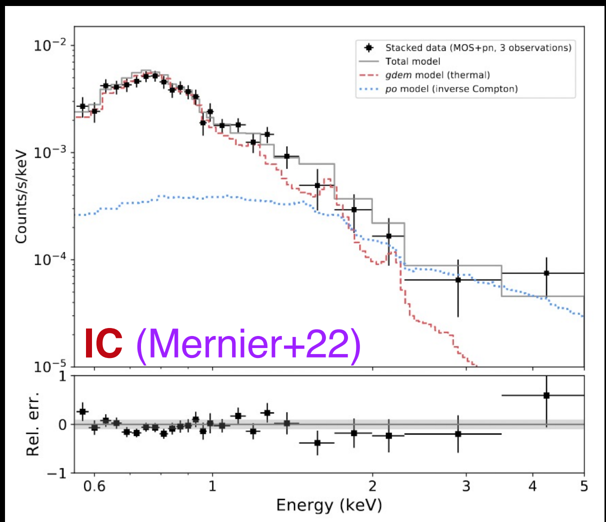


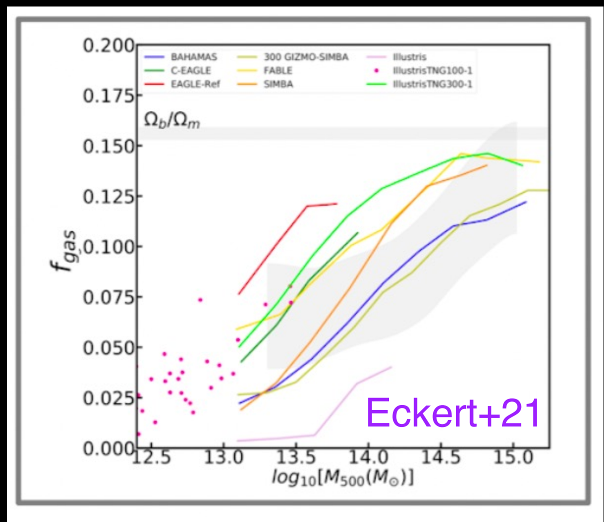
Environment is one of the primary drivers of galaxy evolution, capable of transforming galaxies from SF to quiescent via multiple mechanisms.

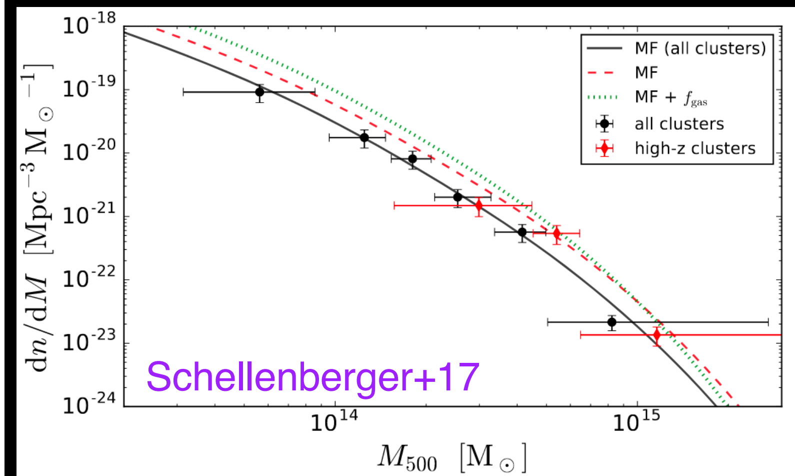
We still do not have a clear view of how environmental quenching proceeds in the most extreme environments, galaxy clusters and their progenitor proto-clusters (*interaction with ICM/outside-in; gravitational; internal/inside-out*; e.g. Boselli+21, Alberts & Noble 22)

Galaxy Groups

Galaxy groups are more than an intermediate scale between clusters and halos hosting individual galaxies; they are crucial laboratories to test a range of astrophysical processes from plasma physics (impact of thermal/non-thermal emission) to how galaxies form (half of all massive galaxies live in groups up to z~1.5, e.g. Boselli+21) & evolve (being building blocks in the hierarchical scenario) to LSS statistics for cosmology (@z=0, ~30/210 more objects in the mass range M_{500} = 1e13 M_{sun}-M_{cut} than in $M_{500} > M_{cut}$, and M_{cut} = 1/2e14M_{sun})

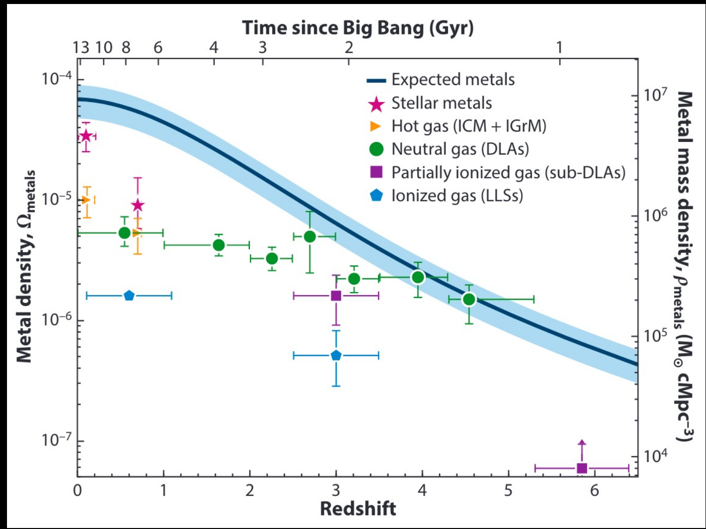


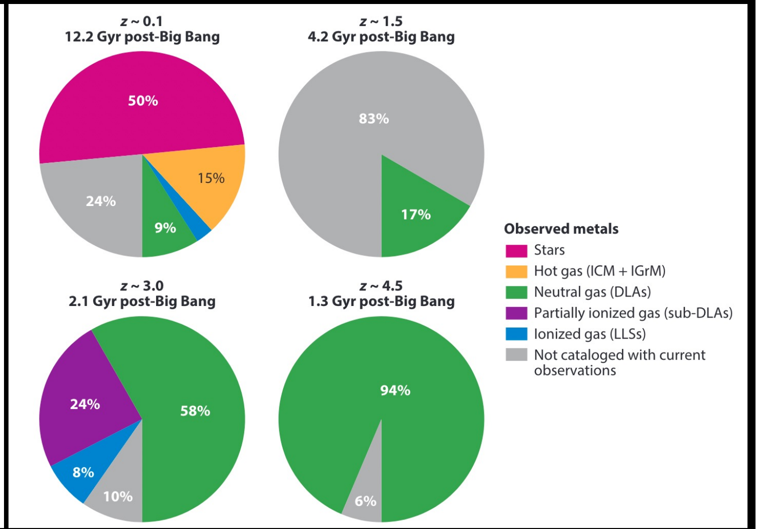


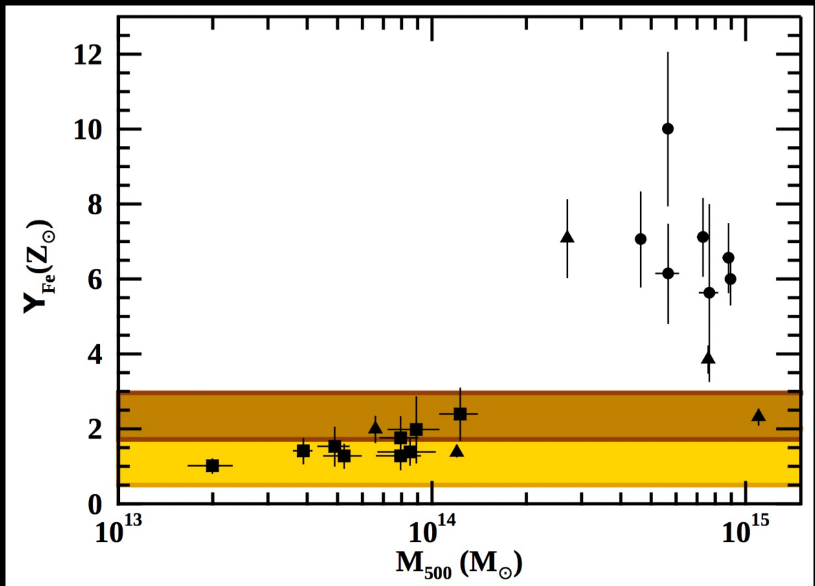


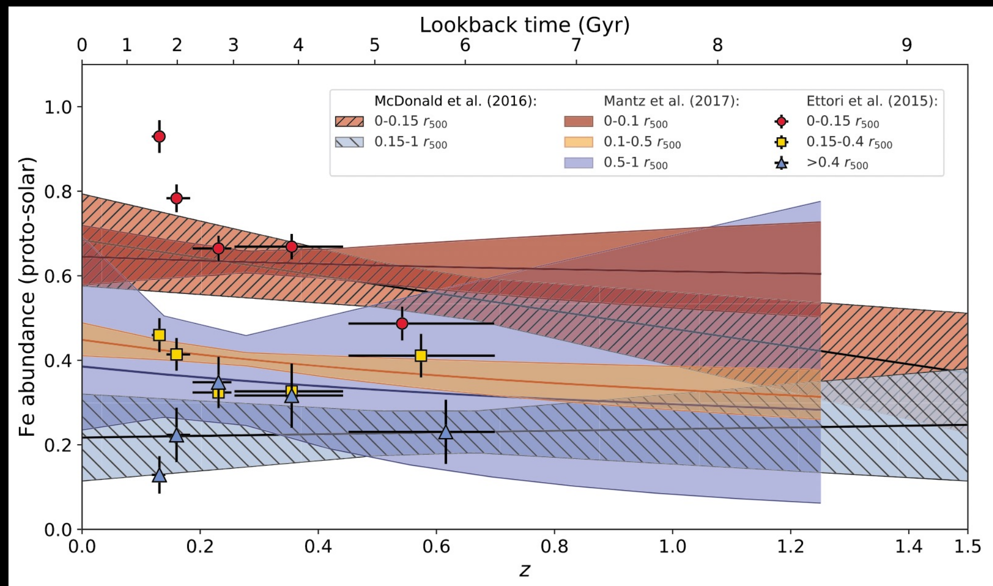
Metals

Missing metal problem: @z ≈ 0.1, half of the metals are in stars, and the metals in the hot gas (ICM+IGrM) become comparable with the metals in the neutral gas at z<1; **at 1<z<3, contributors need to be better characterized** (Peroux & Howk 20)









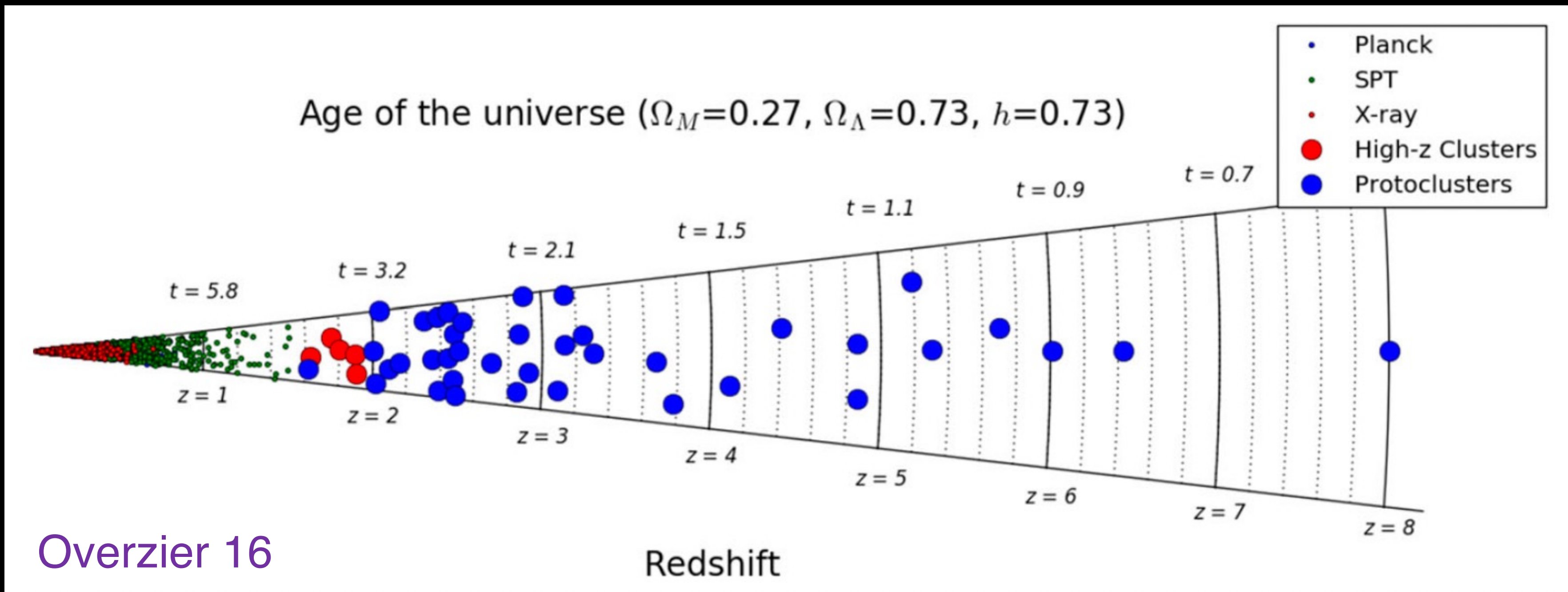
ICM seems to host more metals than expected from stars, with no evolution with z (Gastaldello+21; Mernier+18)

Evolution: properties at z>2

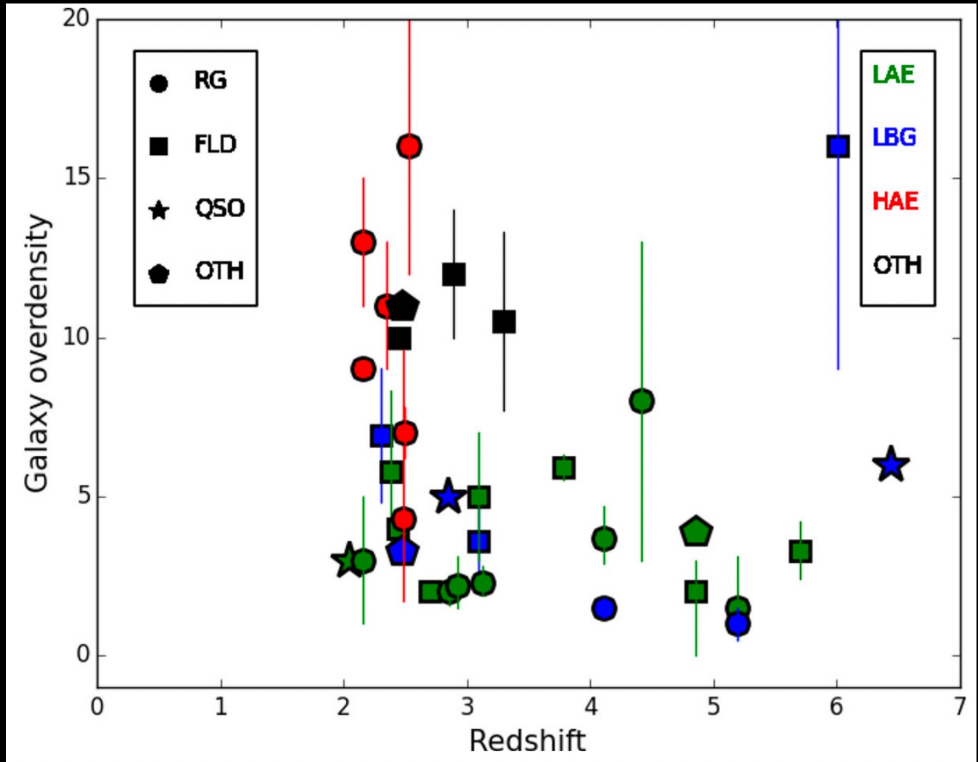
Our knowledge on the GCs properties is limited to z<2
(i.e. the last 10 Gyrs)

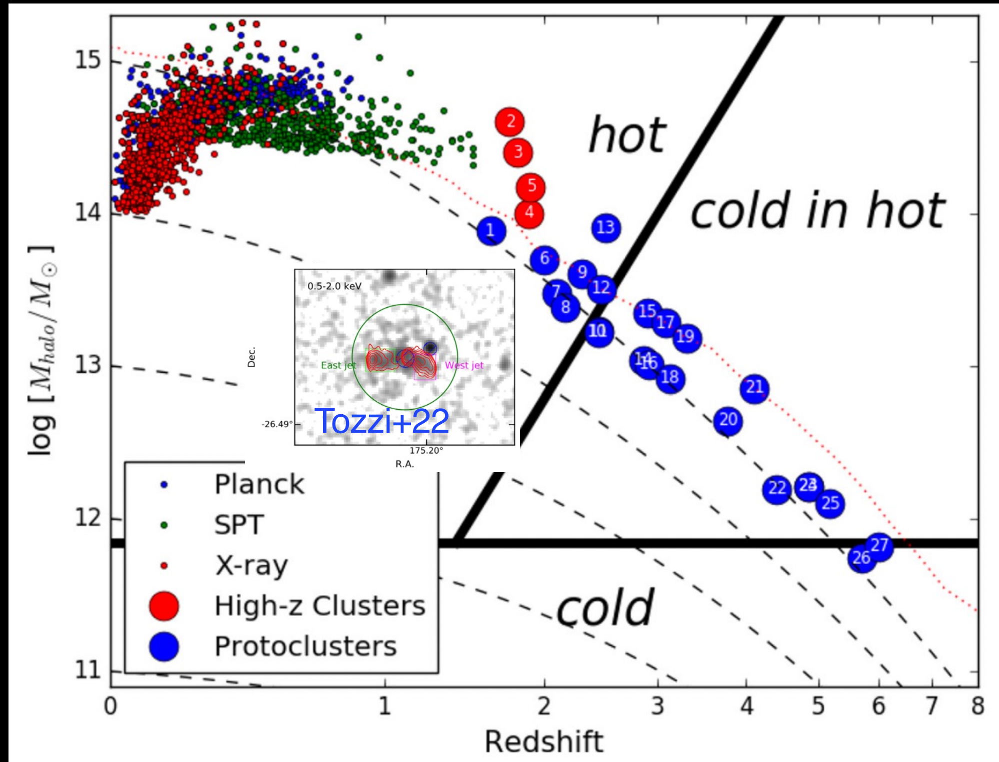
how do these properties ensemble (*galaxy transformation, environmental effects, BCG, collapse & virialization*) ?

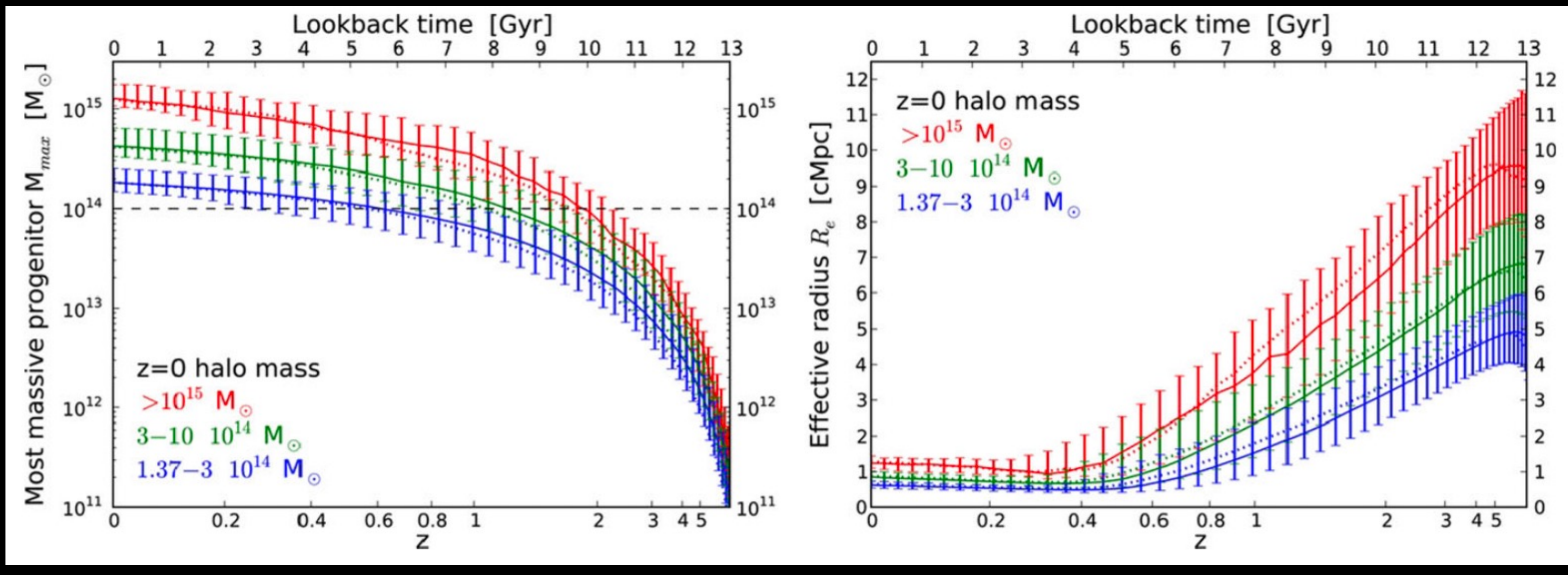
Problems: difficult to identify proto-clusters (biased-tracer: SF, dust content; RG, QSO, Lya abs) & convince the TAC that they are "real"; mix of evolutionary stages



Evolution: properties at z>2







Cosmology from the Galaxy Clusters: **complementarity**

- **Number counts & clustering ➔** $\{\Omega_m; \Lambda, w\}$
- **Mass distribution ➔** *(SI)DM / MOND*
- **Cosmography with SL ➔** $\{\Omega_m; \Lambda, w; H_0\}$
- **Concentration/sparsity ➔** $\{\Omega_m; \sigma_8\}$
- **Triaxial shape ➔** consistency with ΛCDM
- **X/SZ pressure profiles ➔** H_0
- **Gas mass fraction ➔** $\{\Omega_m; \Lambda, w\}$

➔ Reliable & robust **(i) selection function, (ii) estimate of the mass distribution**: massive investment in exposure time and/or dedicated instruments, efficient strategy, and simulations

Formation: models of gravity

- ***The largest gravitationally-bound structures in the universe***

- ***"dunkle Materie"*** (Zwicky 1933)

~80% of total mass; ~15% hot gas; few % stars

➔Laboratories to test predictions for DM models (C/SI/fuzzy, decaying DM, MOND; role of substructures)

Dark Matter ***hot*** **ICM**

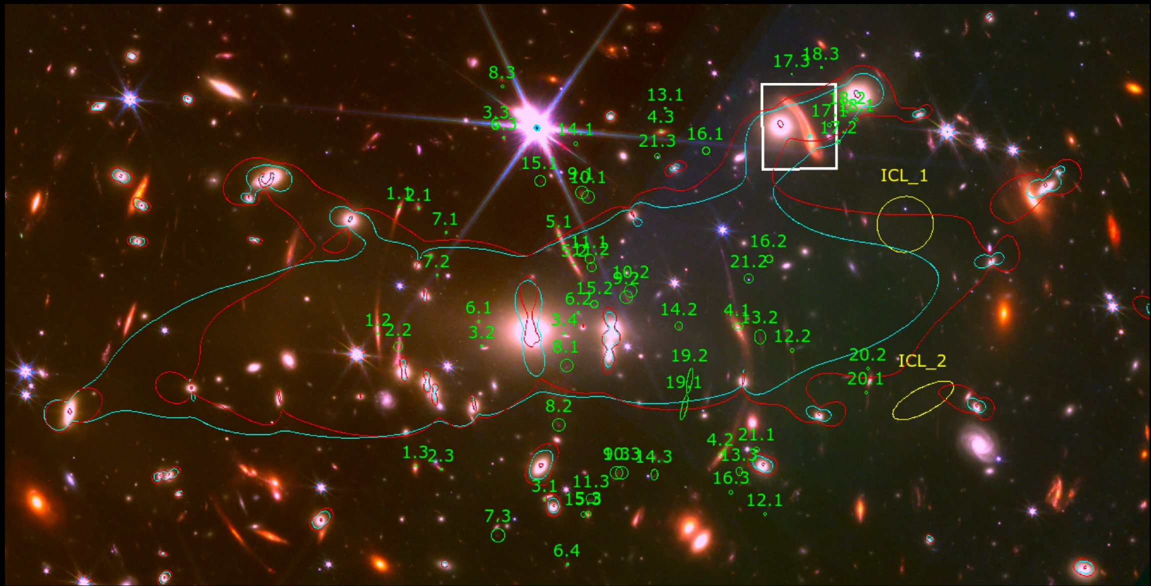
Bullet cluster

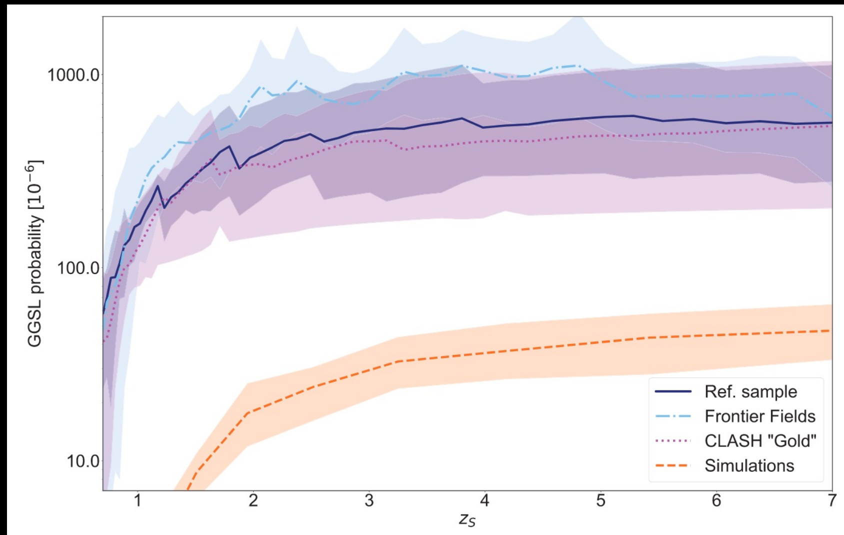
A2744

MACSJ0025

Formation: models of gravity

- What is the cluster "true" mass?
- What are the bias & scatter of observable mass proxies?
- Cosmic telescopes

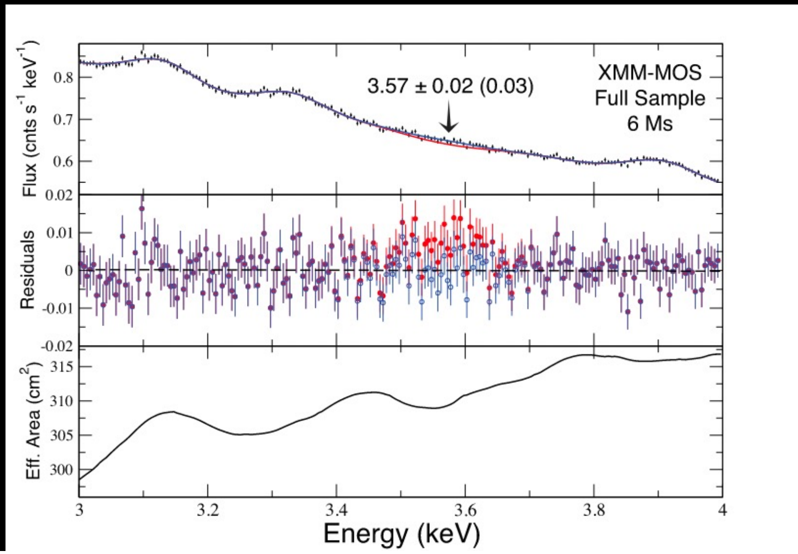


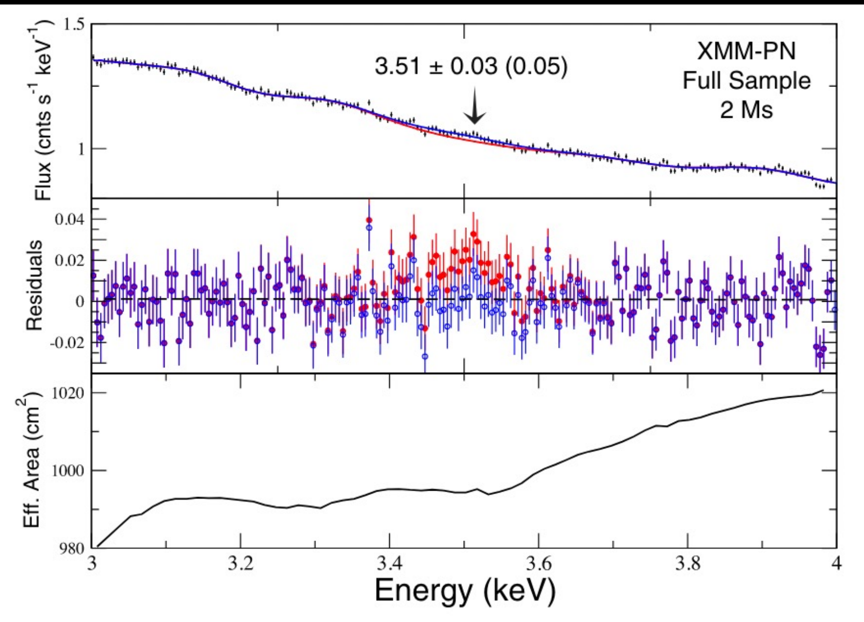


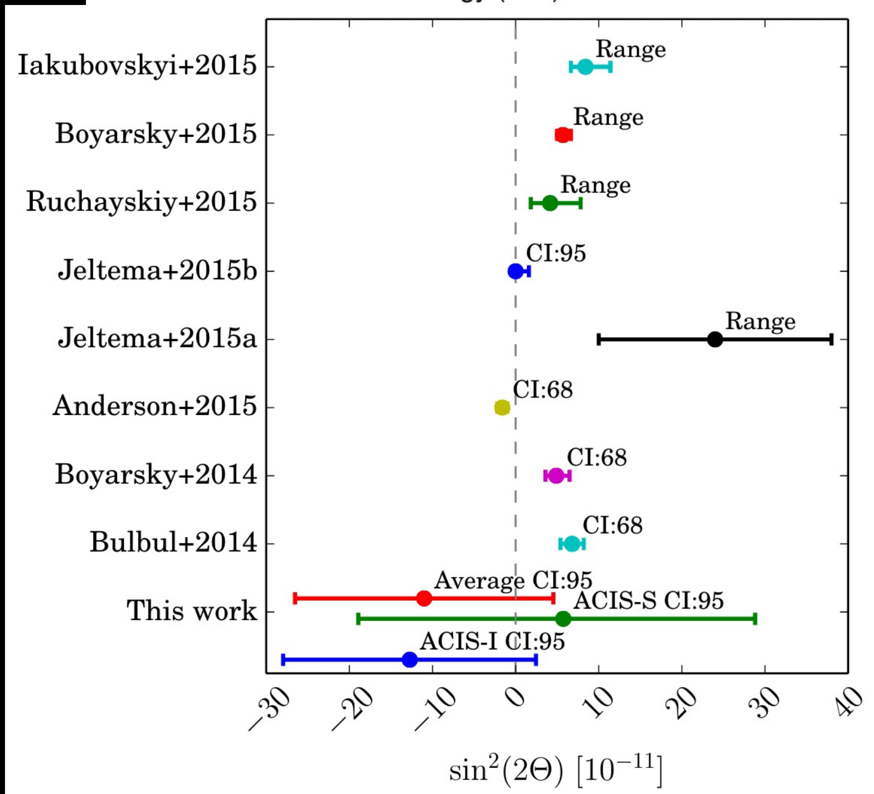
SMACSJ0723 (Mahler+22; **JWST discovered 16/21 multiple image systems**; more constraints for gravitational lensing reconstruction, more efficient techniques required)

Excess of galaxy-galaxy strong lensing (GGSL) in clusters compared to expectations from the ΛCDM model CLASH sample (Meneghetti+20, Sci)

Plasma physics/Anomalies: 3.5 keV





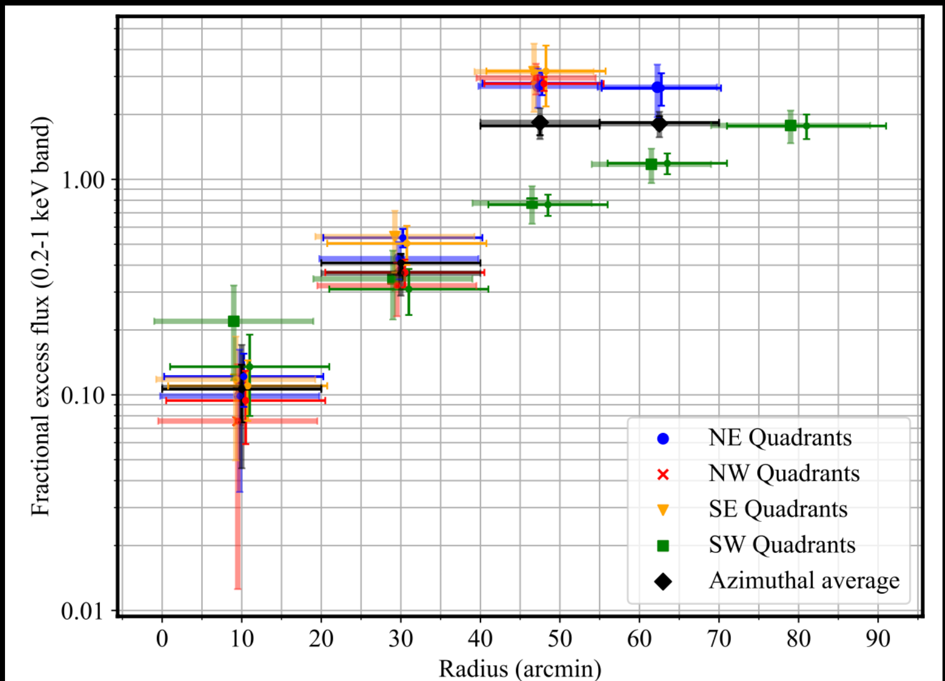


3.5 keV line: an anomalous X-ray line discovered in both galaxy clusters and the Andromeda galaxy, using XMM-Newton/Chandra data (**Bulbul+14**). Interpretation: decay mode of sterile neutrino DM; signal prop to particle mass & mixing angle with active ν (**Hofman+16;** *weak evidence*)

Anomalies: soft excess

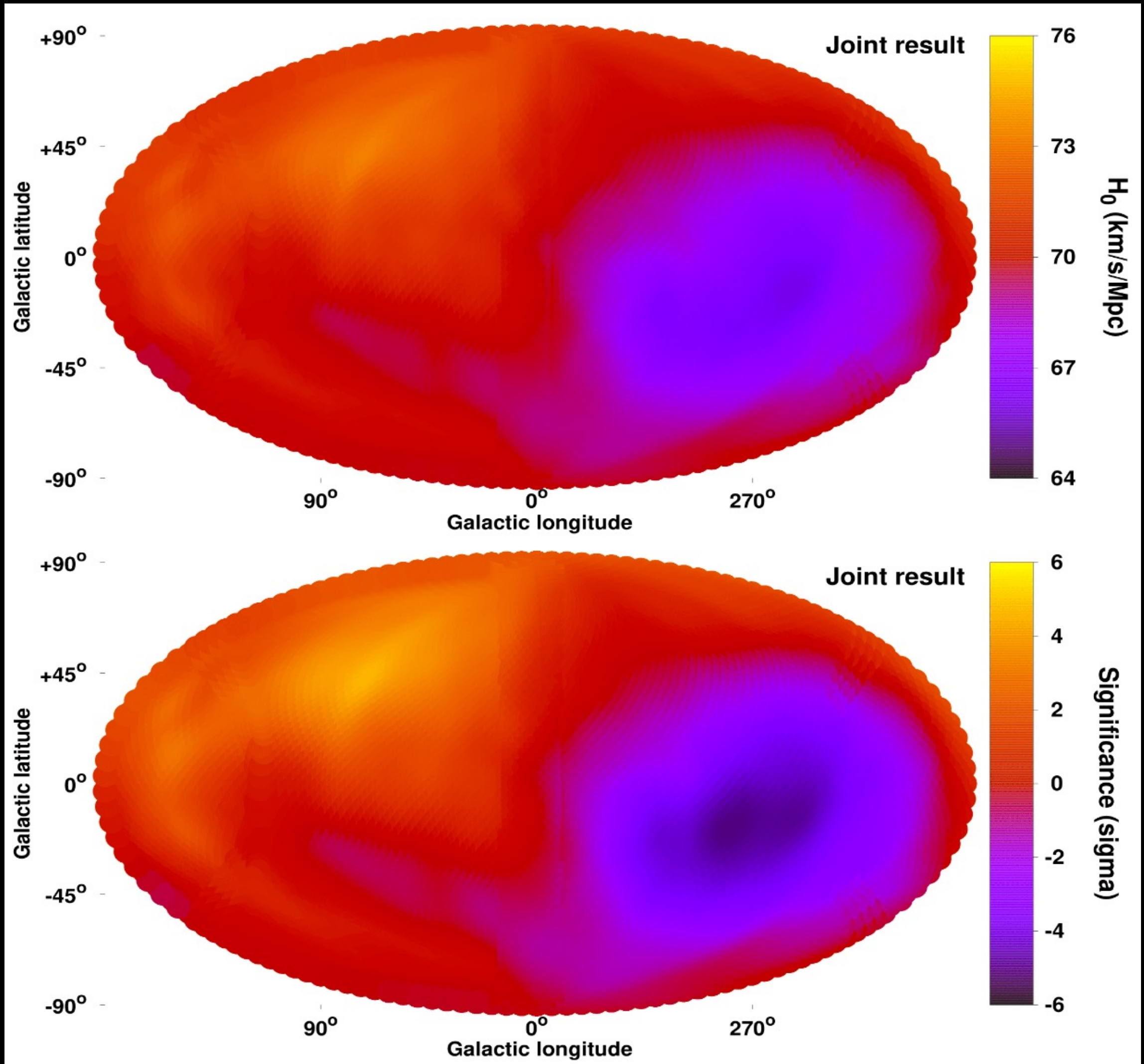
The Coma cluster was one of two clusters where an **excess of soft X–ray radiation,** above the contribution from ICM, was originally detected by the EUVE mission (Lieu+96; Bowyer+96).

This excess of radiation was subsequently confirmed by ROSAT for the Coma cluster (and for several other nearby clusters (Bonamente+02-09), by several other X–ray instruments including XMM-Newton (e.g. Kaastra+03; Nevalainen+03,07) and BeppoSAX (Bonamente+01). Some of the early EUVE measurements were subject to re-analyses that revised downward some of the soft excess fluxes (e.g. Bowyer+99), but there remain a preponderance of evidence that the cluster soft excess is a genuine astrophysical phenomenon



consistent with a thermal origin from warm gas at sub-virial temperatures, $\log T(K) \leq 7$, such as emission from WHIM filaments that converge towards the Coma cluster (Bonamente+22)

Anomalies: anisotropies

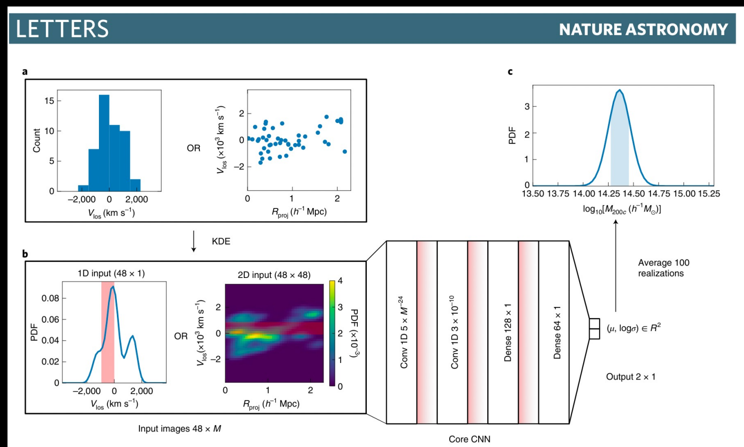


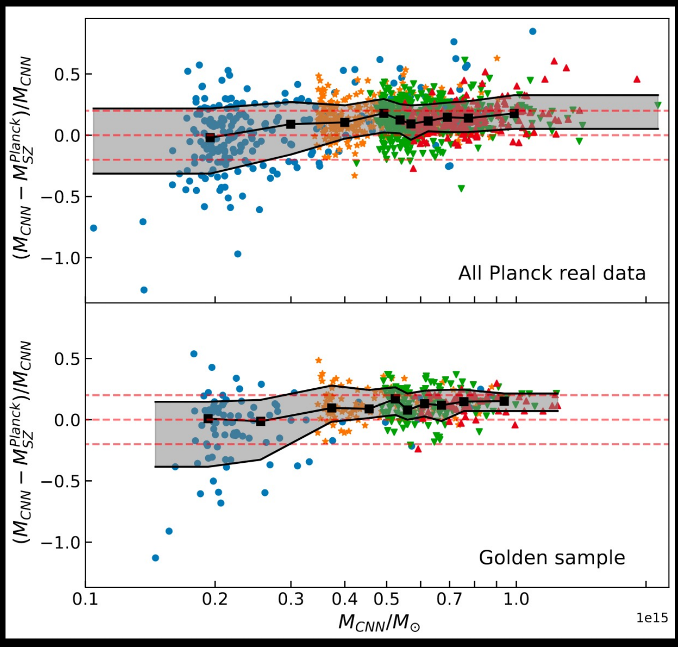
Using up to 570 clusters with measured properties at X-ray, microwave, and infrared wavelengths, to construct 10 different cluster scaling relations, Migkas+21 detect an apparent 9% spatial variation in the local H_0 between (l, b)~(280°, -15°) and the rest of the sky, violating the hypothesis of isotropy.

The observed anisotropy has a nearly dipole form & a significance > 5σ.
This result could also be attributed to a ~900 km/s bulk flow which seems to extend out to at least ~500 Mpc.

Role of AI

- Astronomy is entering the era of big data (eROSITA, Euclid, LSST; radio astronomy; archival dataset; large set of hydro/cosmo simulations)
- Machine Learning algorithms for a ***data driven science*** (analyze data and make predictions without assuming any previous known behaviour; Non-linear interpolation; Parameter estimation; Symbolic regression; Generative models; Anomaly detection)
- ML will impact optimization of Pipelines (transients, anomalies, low SNR regime / eROSITA, full forward models through Likelihood-Free Inference)





Recent applications on GCs: neural network-base for high-res X-ray spec /1905.13434; **DL for M_{tot}:** 1810.07703…2206.14834, 2207.12337, 2209.10333 **(Ho+22, de Andres+22 NatAst)**; building DM blocks: 2203.08827; to enhance eROSITA obs by improving follow-up selection: 2207.14324

CLUSTER3

https://sites.google.com/view/cluster3bo/home

- CLUSTER1 (Torino, 2017), CLUSTER2 (Napoli, 2018), CLUSTER3 (Bologna, 20-23 September 2022)

- ~100 participants: 50% staff; 30% PostDoc; 20% PhD +students

- "Manifesto di Torino" ➔ "Bologna Manifesto" (in prep.???): requests for more interconnection (common seminars); long postdoc positions; *Scuole Lucchin* (last one: 2016); new research areas such as: (i) *plasma physics and its observable in the radio,* ***microwave*** *(SZ; community @INAF is small), X-band (also with high-res spectroscopic facilities);* *(ii) cluster cosmology (driver of many international projects ➔ larger samples available; very appealing topic with students; Quantum gravity?!?)*

Outline

- **Formation**: transport & circulation of energy & baryons;
cores: feeding to & feedback from AGNs;
outskirts: accretion, splashback radius, clusters' pairs
- **Environment**: galaxy evolution in overdense regions;
metal circulation; role of groups
- **Plasma physics**: radio structures, high-res X-ray/SZ
- **Evolution**: how do the properties ensemble
(our knowledge limited to z~2) ?
- **Gravity:** mass proxies, scatter & bias;
DM & alternatives; substructures
- **Anomalies**: 3.5 keV, soft X-ray excess, anisotropy
- **role of AI**

➔ JWST, Euclid, LSST, WEAVE@WHT,
LOFAR/MeerKAT/SKA,
MISTRAL/AtLAST/US instruments,
XRISM/Athena/US probe, CTA…