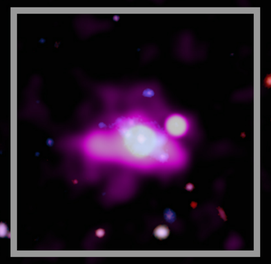
AGN enhancement and appearance of the ICM in protoclusters of galaxies at z>2 (What can we learn before the X-ray desert)



Paolo Tozzi
INAF-Osservatorio Astrofisico
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X-RAY & OPTICAL

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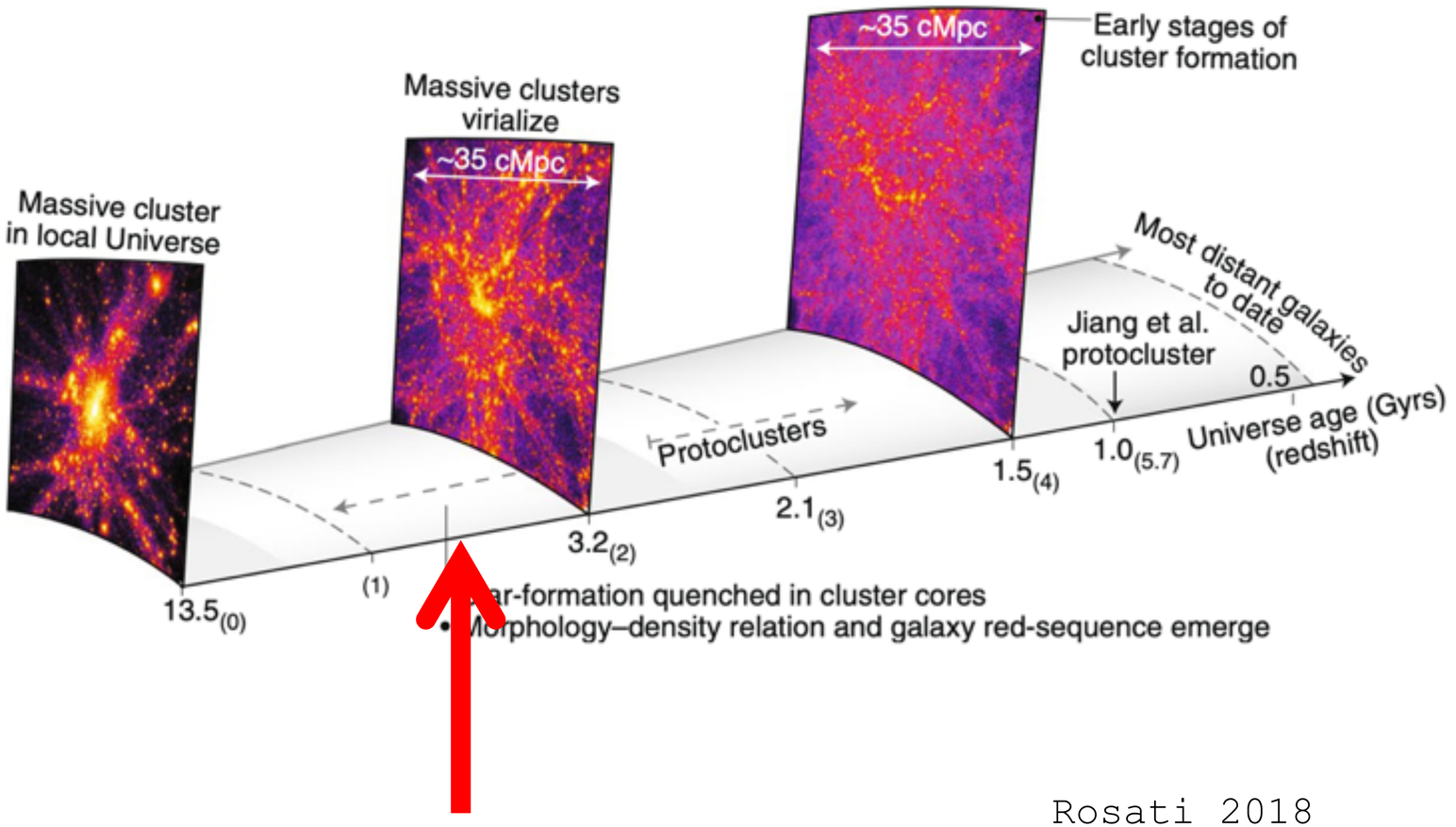
A schematic view of the cosmic evolution of a massive cluster



Rosati 2018

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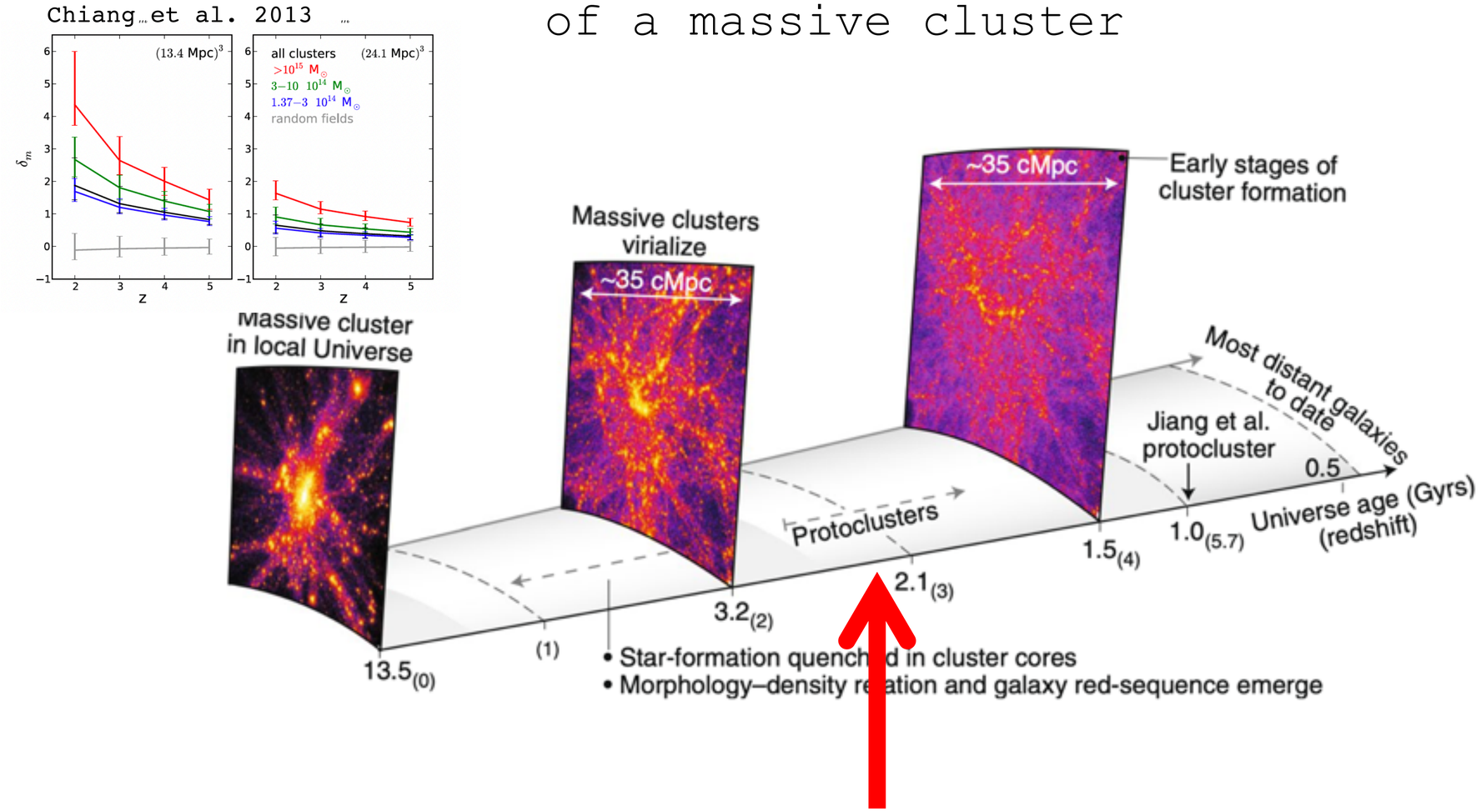

Rosati 2018

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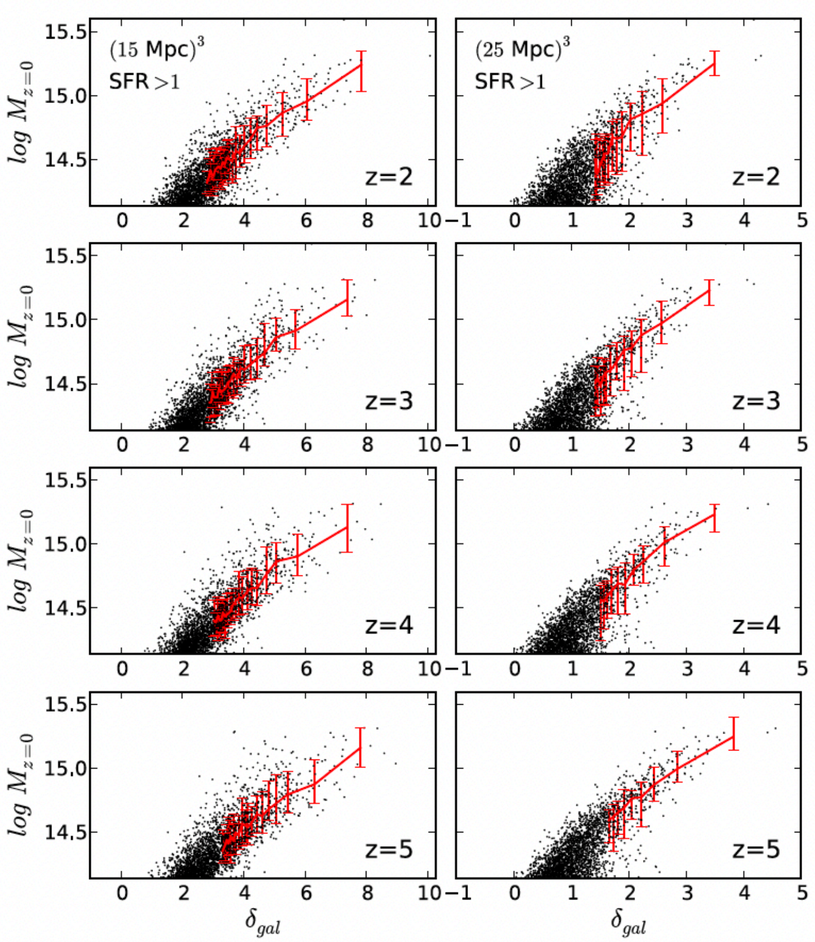
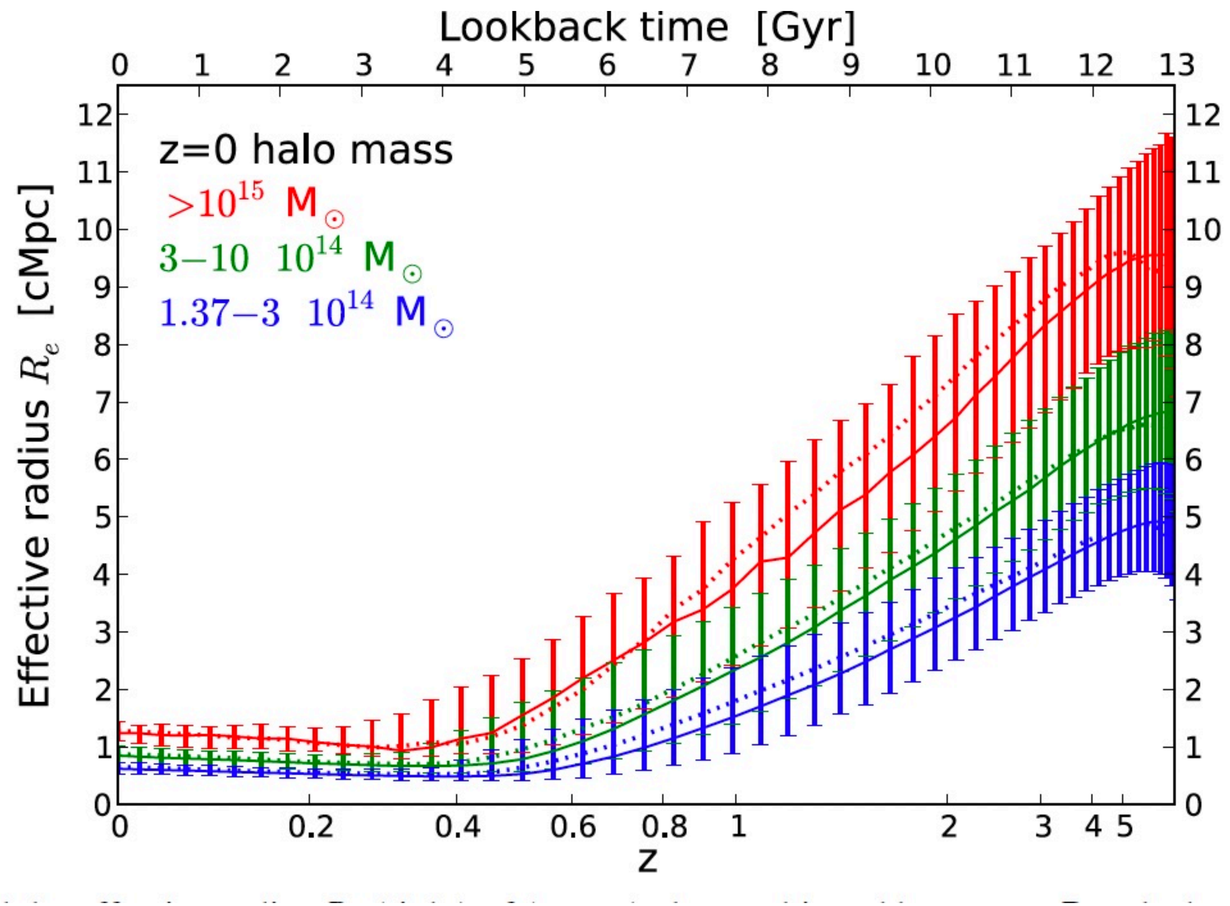
How to define and identify protoclusters





Chiang, Overzier & Gebhardt 2013

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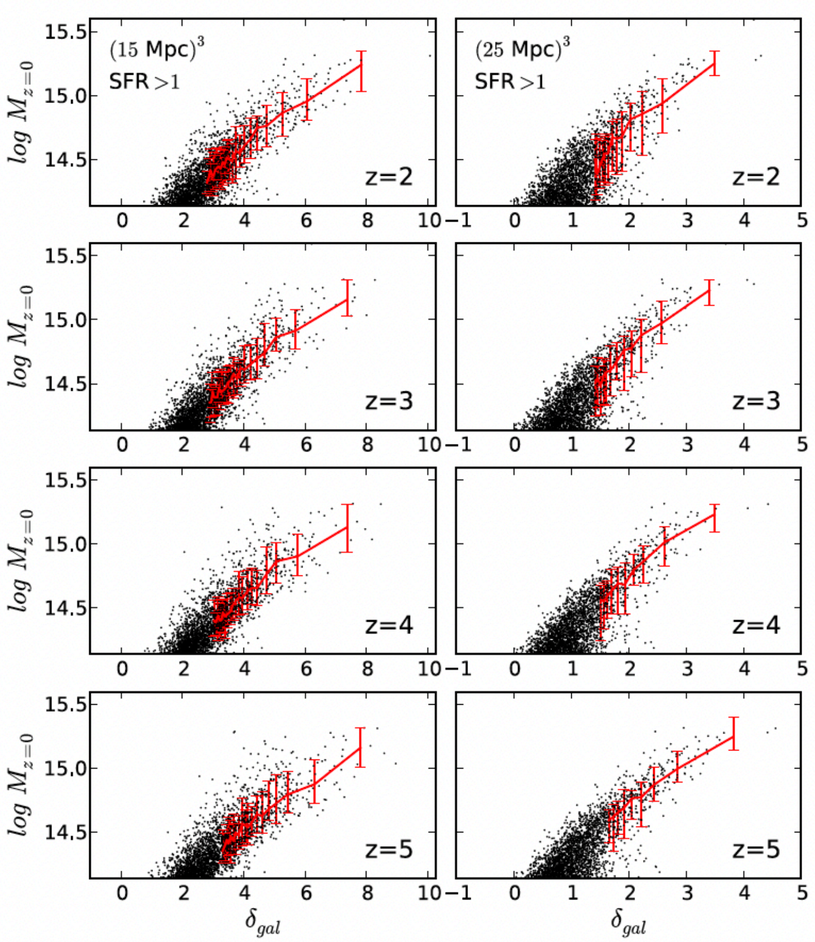

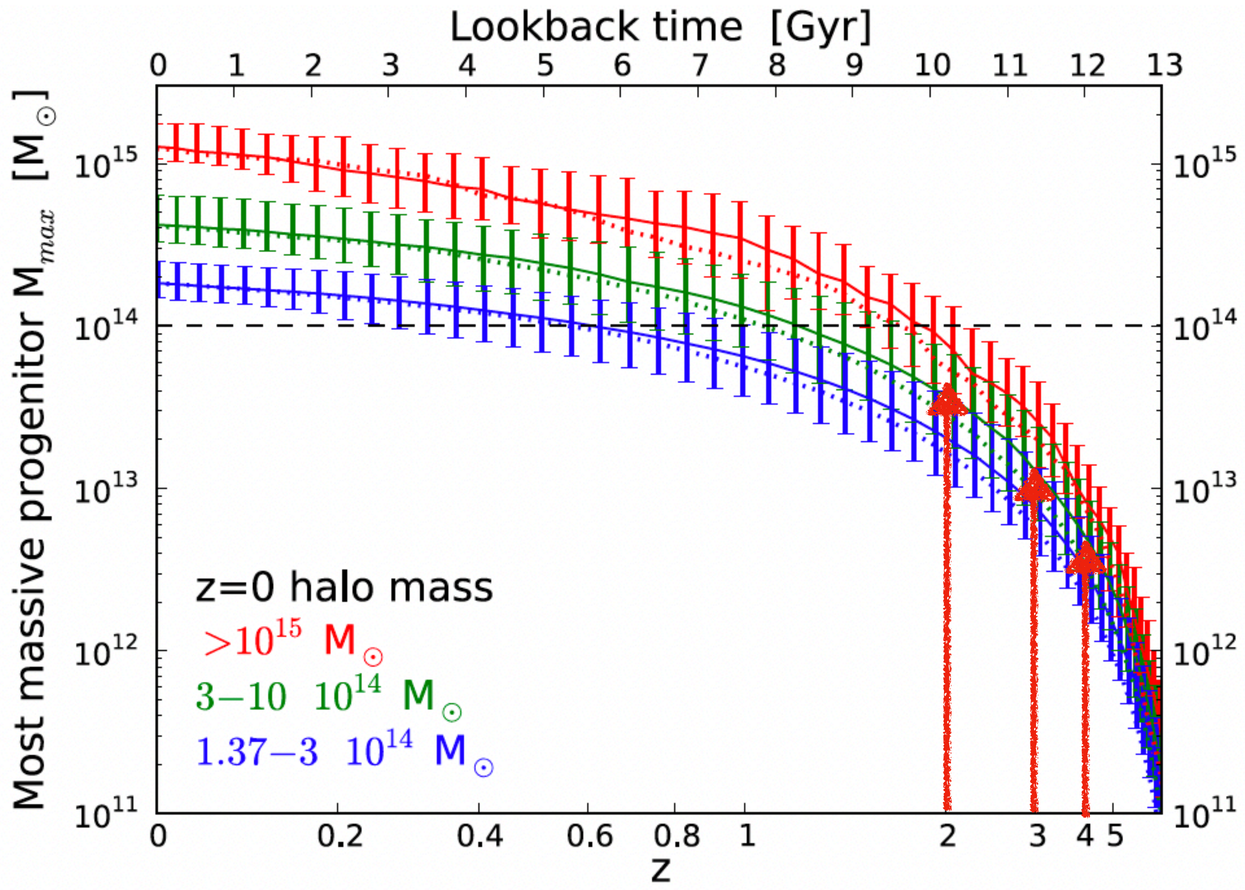

Chiang, Overzier & Gebhardt 2013

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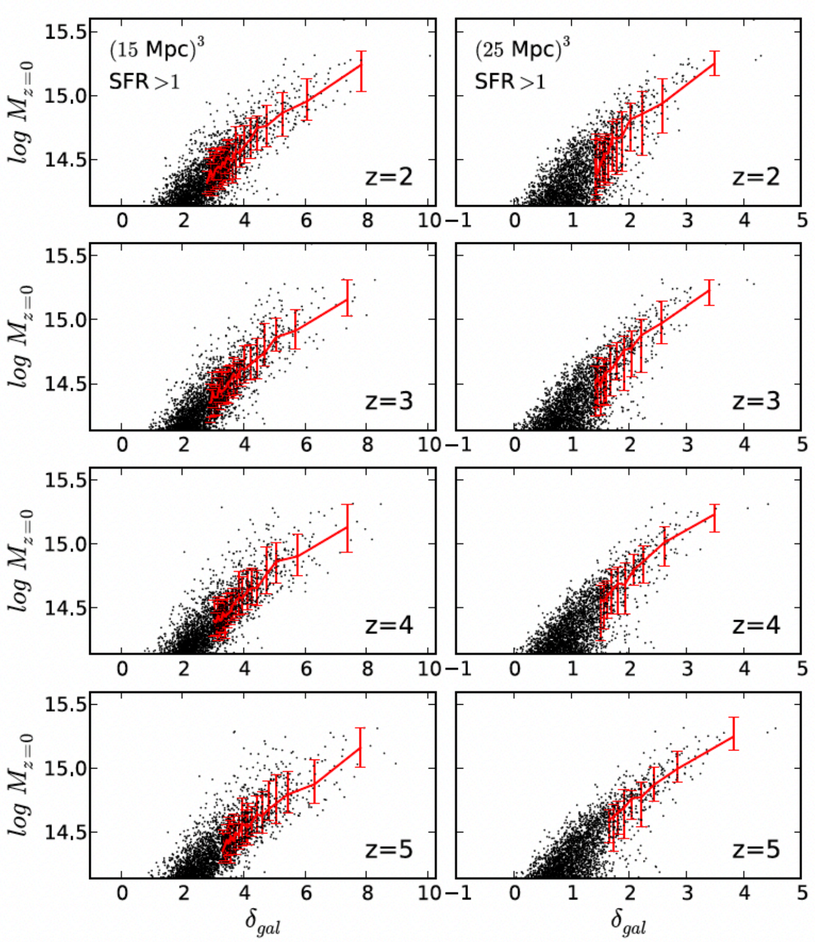

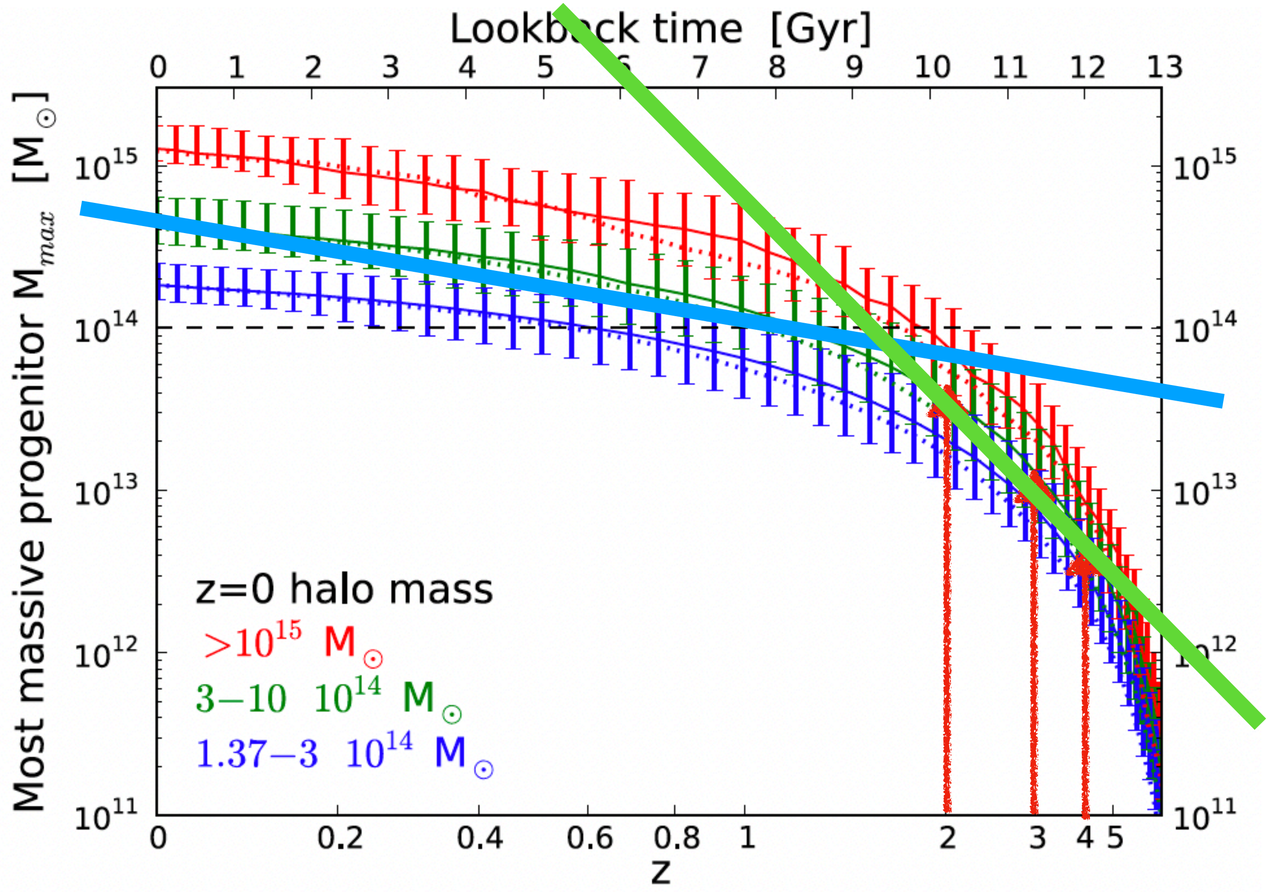

Chiang, Overzier & Gebhardt 2013

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Protoclusters (overdensities at z>2, Delta <<200) are ideal laboratories to study galaxy properties in dense environments, and environmental dependence of galaxy formation and evolution in the early universe. Galaxy evolution in dense environment at high-z is expected to be accelerated.

Protoclusters magnify details of the assembly processes:

Infalling of galaxies from the cosmic web (or simply increase in the environ density)
Triggering of star formation
Interactions between galaxies
Coevolution of galaxies and their SMBH
Formation of the BCG
First stages of gravitational heating of the proto-ICM
Feedback and enrichment of the proto-ICM
Build up of the ICL

(see review by Overzier 2016 ARAA)

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X-ray observables in protoclusters and high-z clusters

i) X-ray emitting AGN

ii) thermal emission from shocked or heated diffuse intra cluster medium

iii) non thermal diffuse emission due to IC from relativistic electron.

iv) population of HMXB in starbursting galaxies.

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The Spiderweb Galaxy

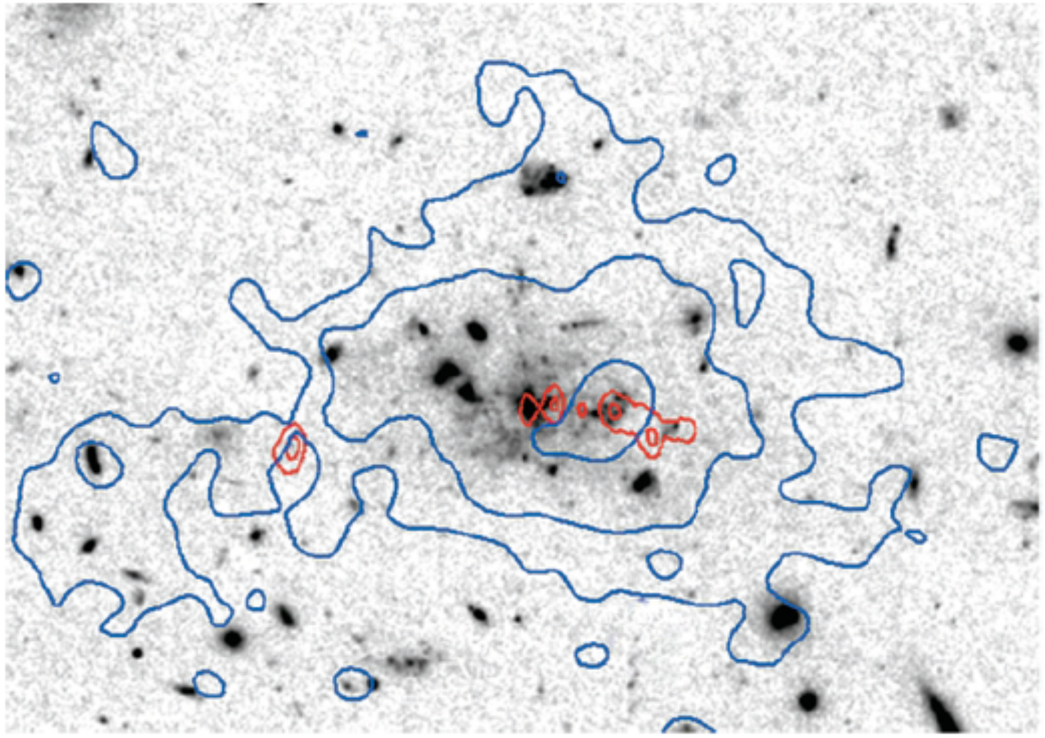

FIG. 2.—VLT Lyα contours (*blue*, resolution ~1″ FWHM) delineating the gaseous nebula and the VLA 8 GHz contours (*red*, resolution ~0″.3) delineating the nonthermal radio emission are superimposed on the composite (g_{475} + I_{814}) ACS image. The image shows a 33″ × 23″ region rotated 10° from north. The gaseous nebula extends for >200 kpc and is comparable in size with the envelopes of cD galaxies in the local universe.

Miley et al. 2006

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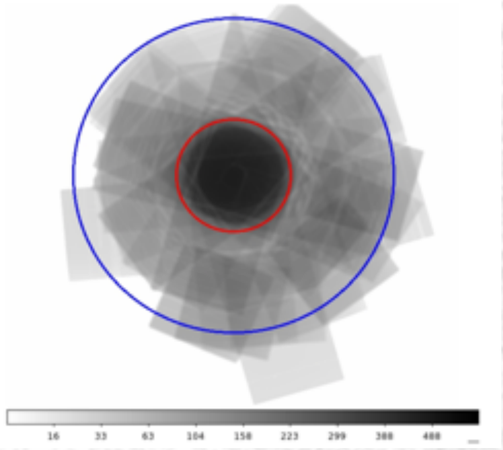

715 ks with Chandra ACIS-S

At z~2.156 - 5 arcmin ~ 2.5 Mpc

PT et al. 2022, A&A, 662, 54

AXIS - Galaxies SWG - September 2022

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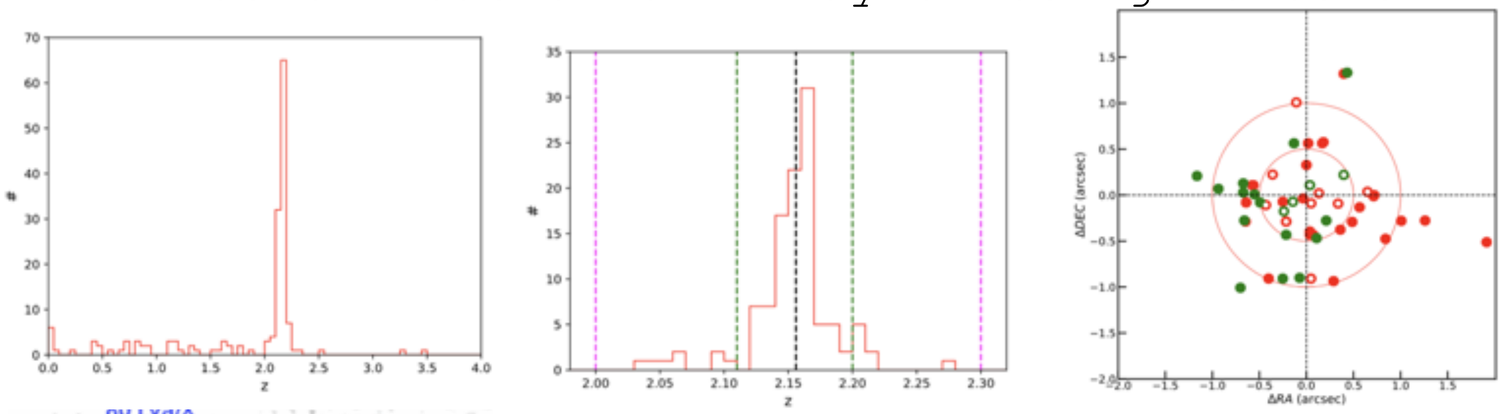
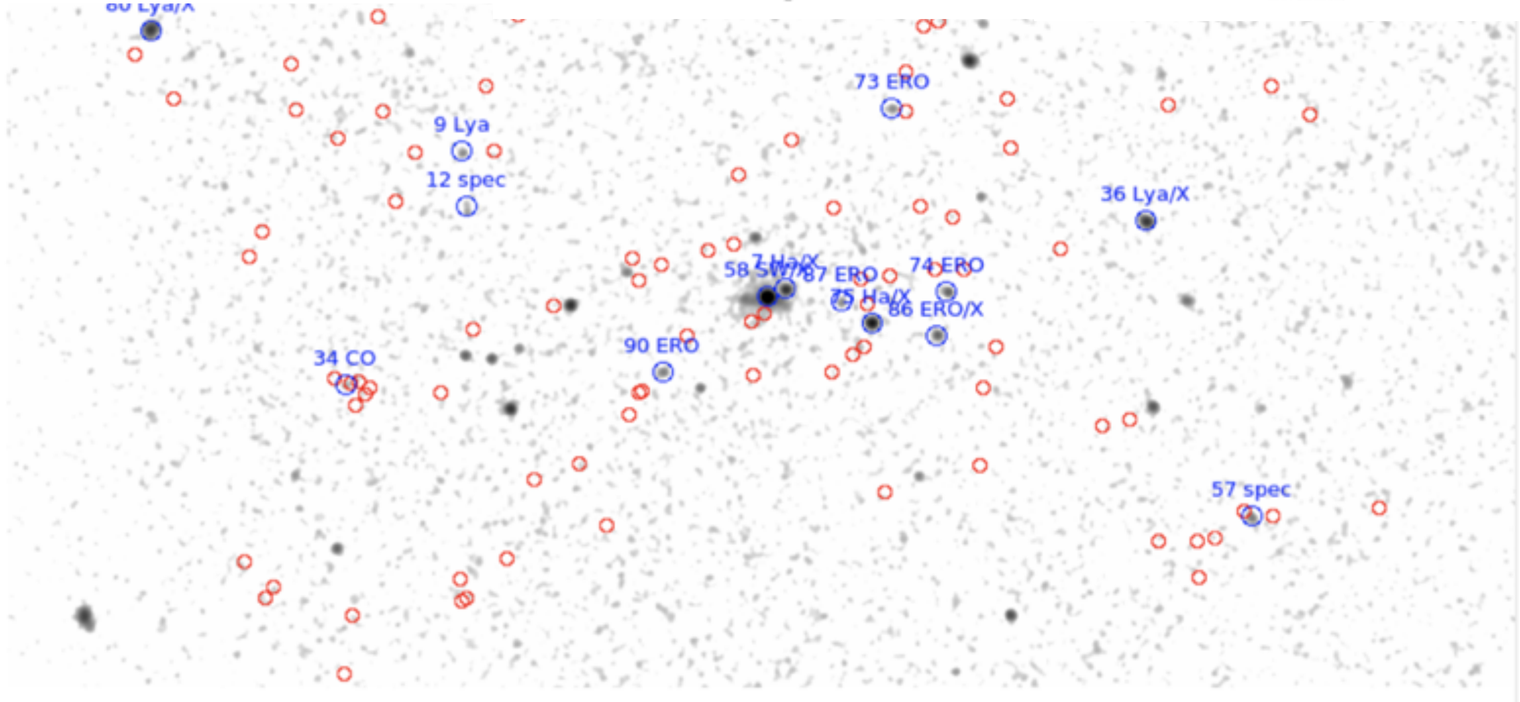
Identification of X-ray emitting members





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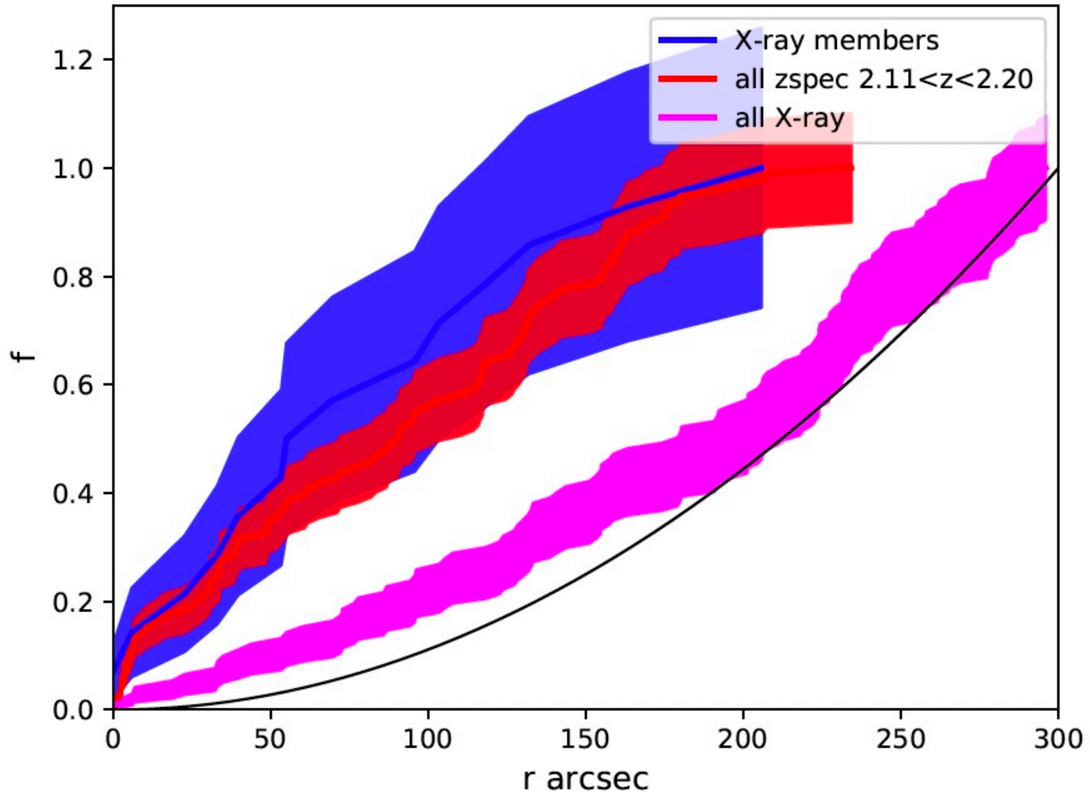

Fig. 9. Fraction of sources within a given radius from the Spiderweb Galaxy. X-ray cluster members (shown in blue) have the same distribution as all the spectroscopically confirmed protocluster members in the $2.11 < z < 2.20$ range (shown in red). On the other hand, the distribution of all the X-ray sources (dominated by the field) is clearly less

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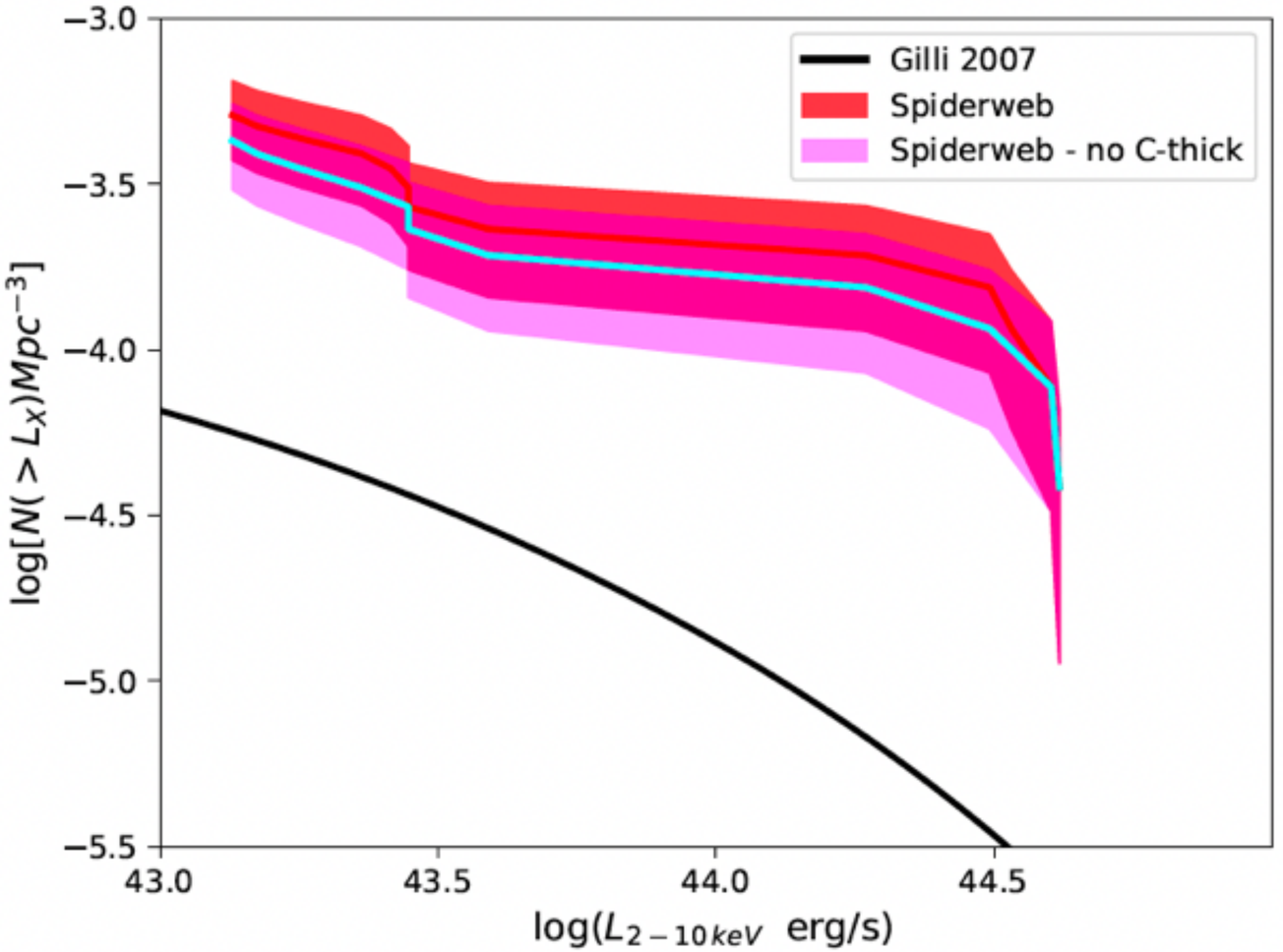
Strong excess (Spiderweb Galaxy is excluded)



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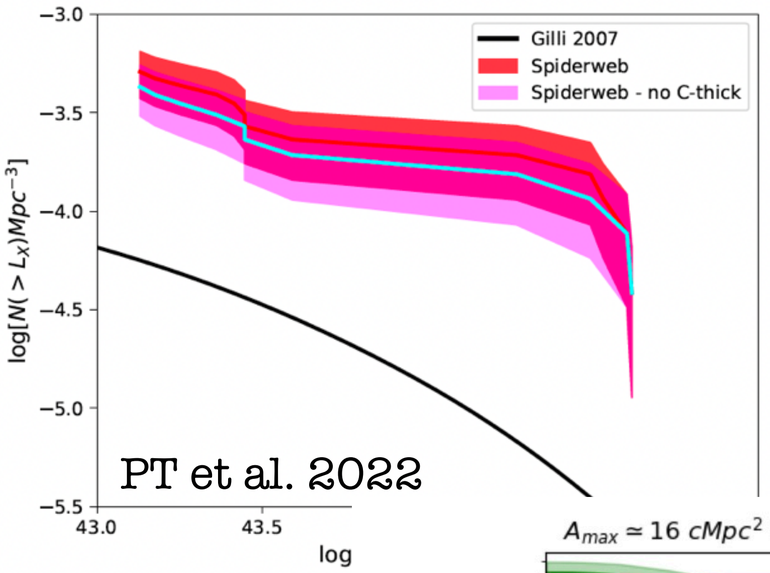
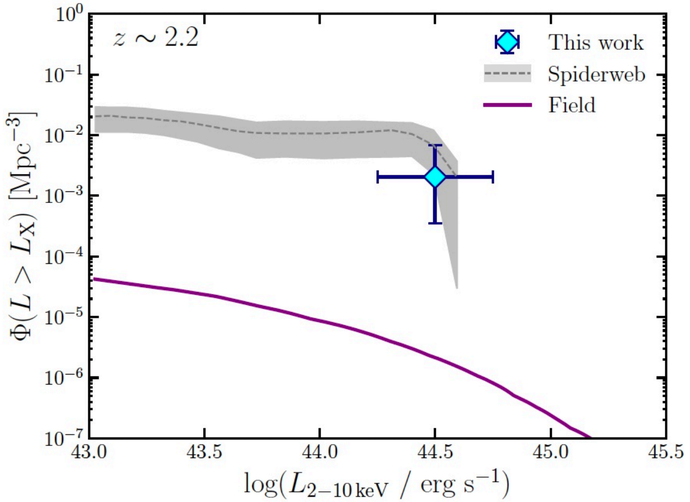
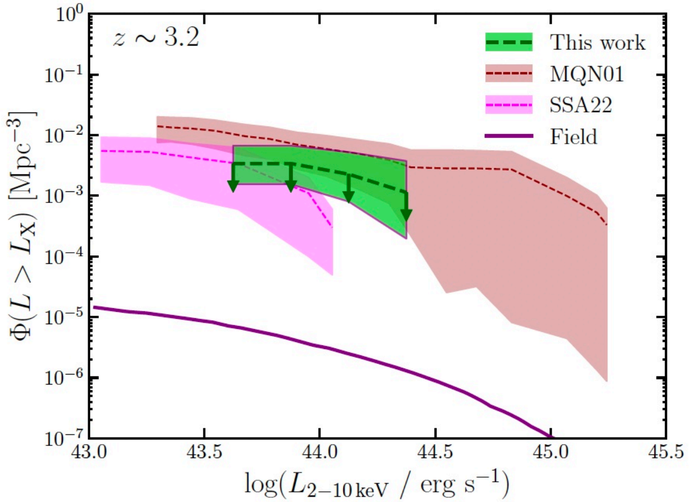
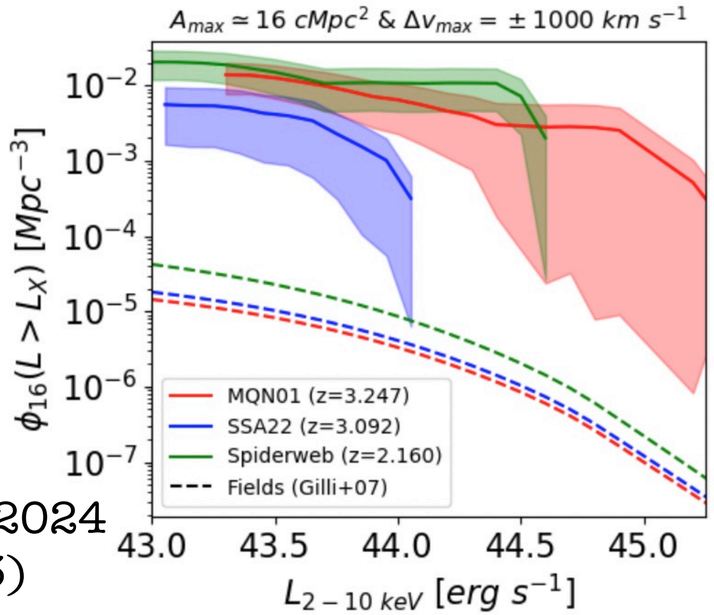


PT et al. 2022

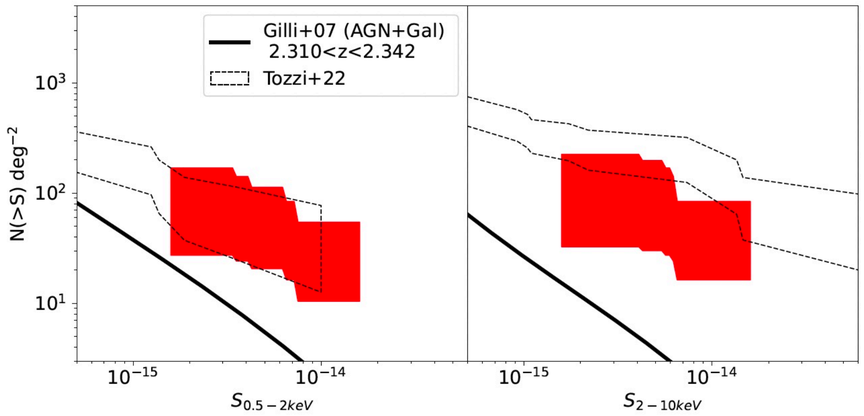




Vito et al. 2024
Traina et al. 2025



Travascio et al. 2024
(MQN01 z~3)



Wu et al. 2025 (BOSS1441)

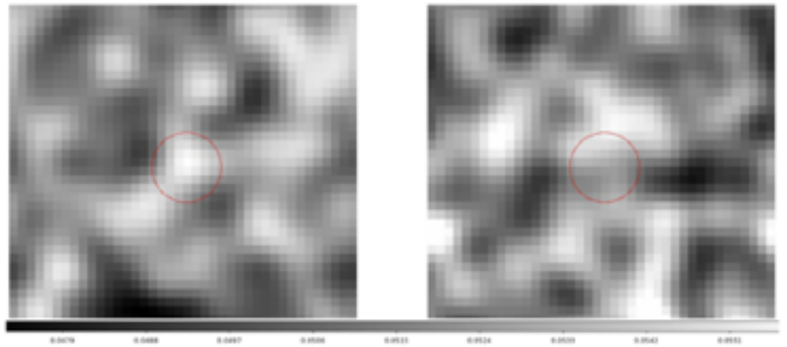


Fig. 17. Left panel: stacked image of the 82 spectroscopically confirmed protocluster members in the soft band. The size of the cutout is 20 × 20 arcsec, while the red circle shows the 2 arcsec radius region used to perform aperture photometry on the stacked image. Right panel: same as in the left panel in the hard band.

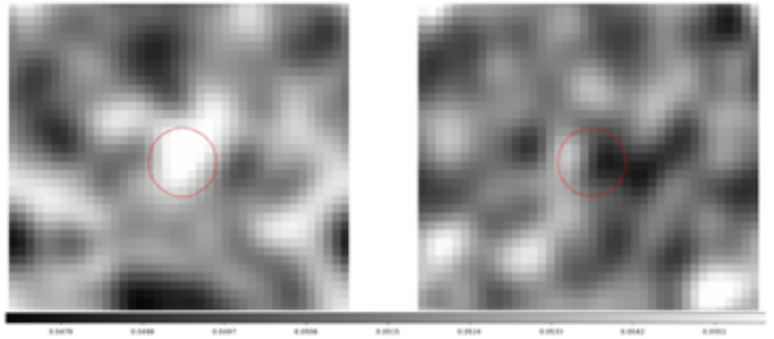


Fig. 18. Left panel: stacked image of the 81 color or narrow-band selected protocluster member candidates in the soft band. The red circle shows the 2 arcsec radius region used to perform aperture photometry on the stacked image. Right panel: same as in the left panel in the hard band.

No low-LX hidden in other members or member candidates

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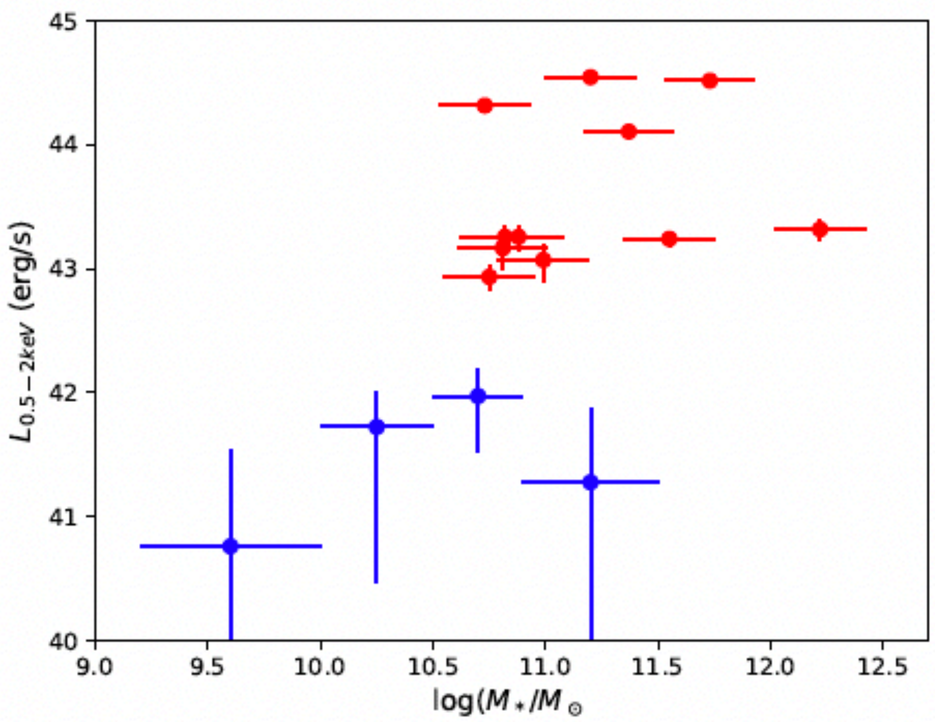
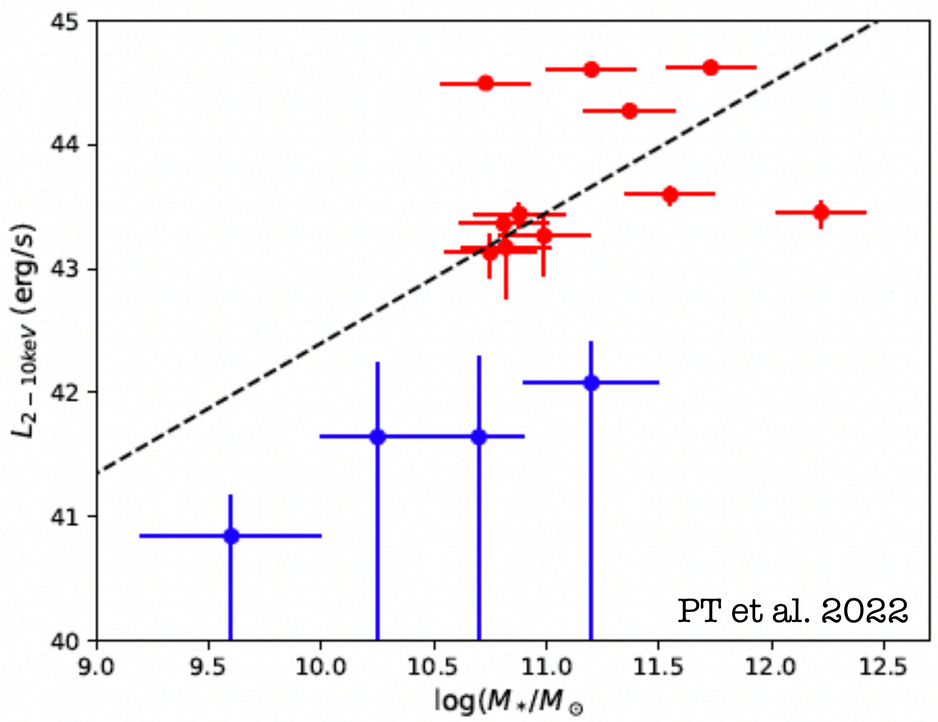
Possible cumulative signal from SF galaxies?





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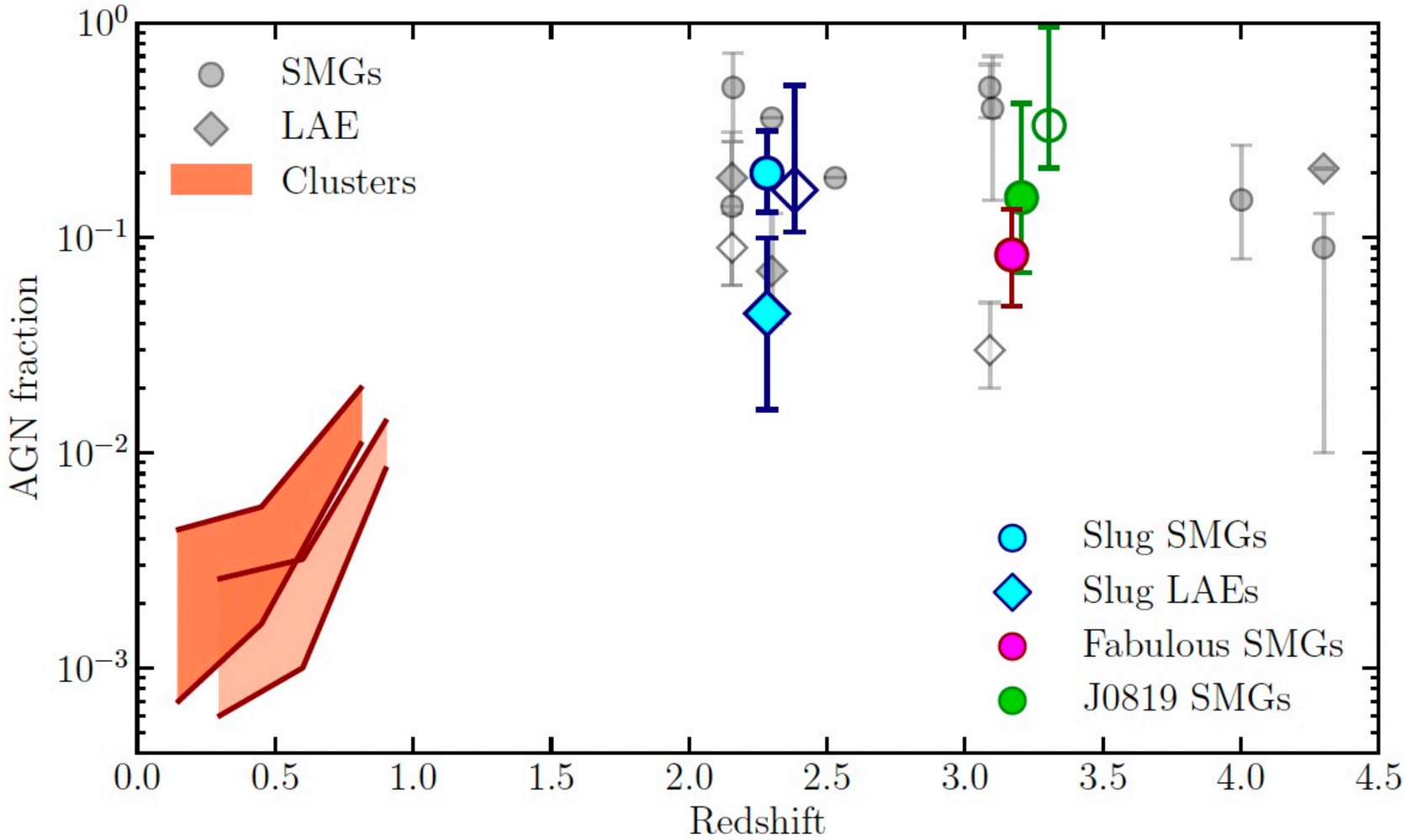

Fig. 3. Fractions of X-ray selected AGN with respect to different population of galaxies (i.e., SMGs, LAEs) in the Slug, Fabulous and J0819 protoclusters, compared to other protoclusters (Lehmer et al. 2009; Digby-North et al. 2010; Smail et al. 2014; Chen et al. 2016; Macuga et al. 2019; Umehata et al. 2019; Vito et al. 2020; Polletta et al. 2021; Tozzi et al. 2022b; Monson et al. 2023; Pérez-Martínez et al. 2023; Vito et al. 2024; Travascio et al. 2025) and the X-ray AGN fractions in local clusters (Martini et al. 2006; Bufanda et al. 2017). Empty blue and green points are the fractions computed for spectroscopically confirmed members (see Table 5).

Vito et al. 2024
Traina et al. 2025

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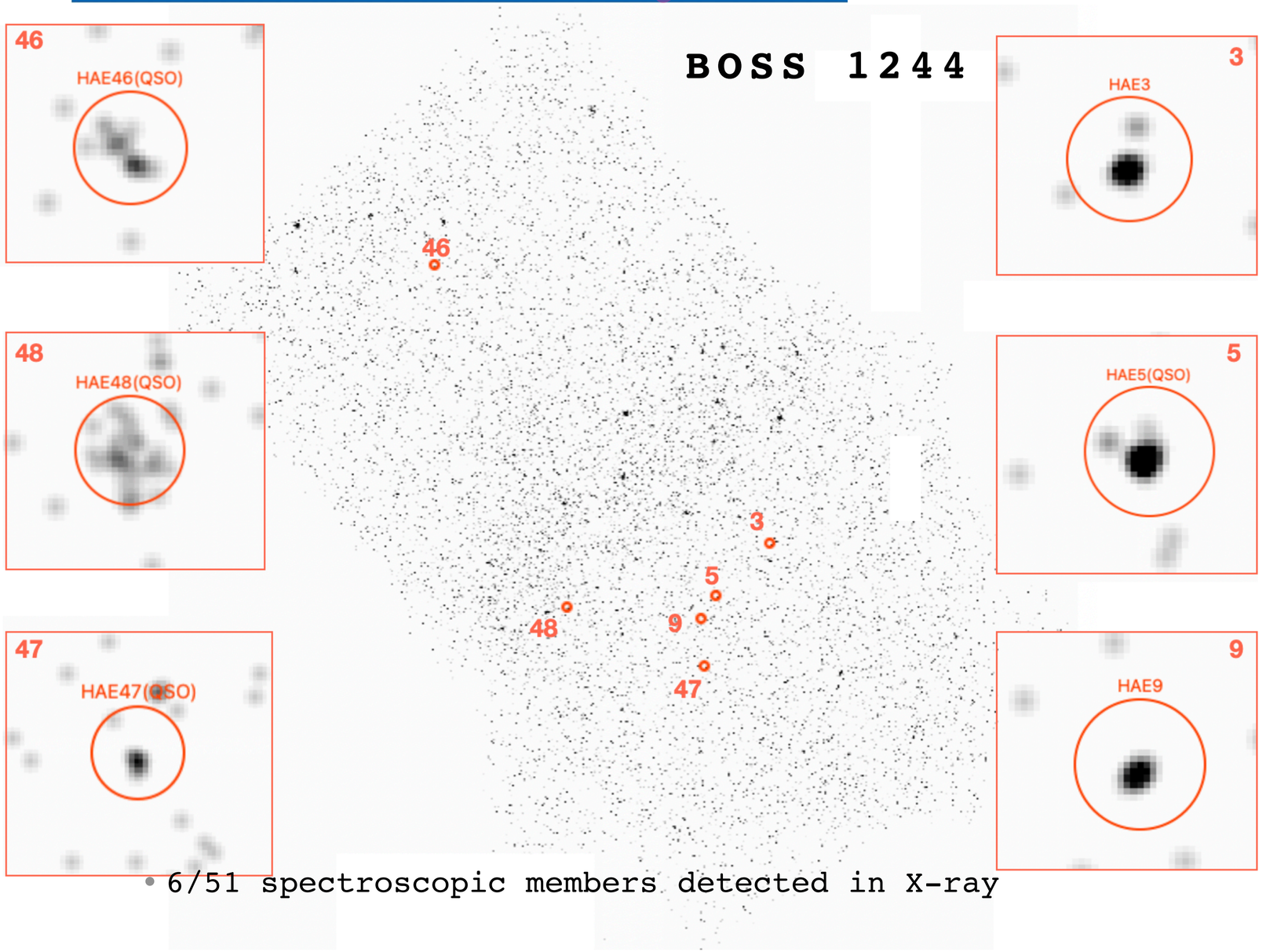
BOSS 1244



Lepore, M., et al. 2025 in preparation

- 6/51 spectroscopic members detected in X-ray

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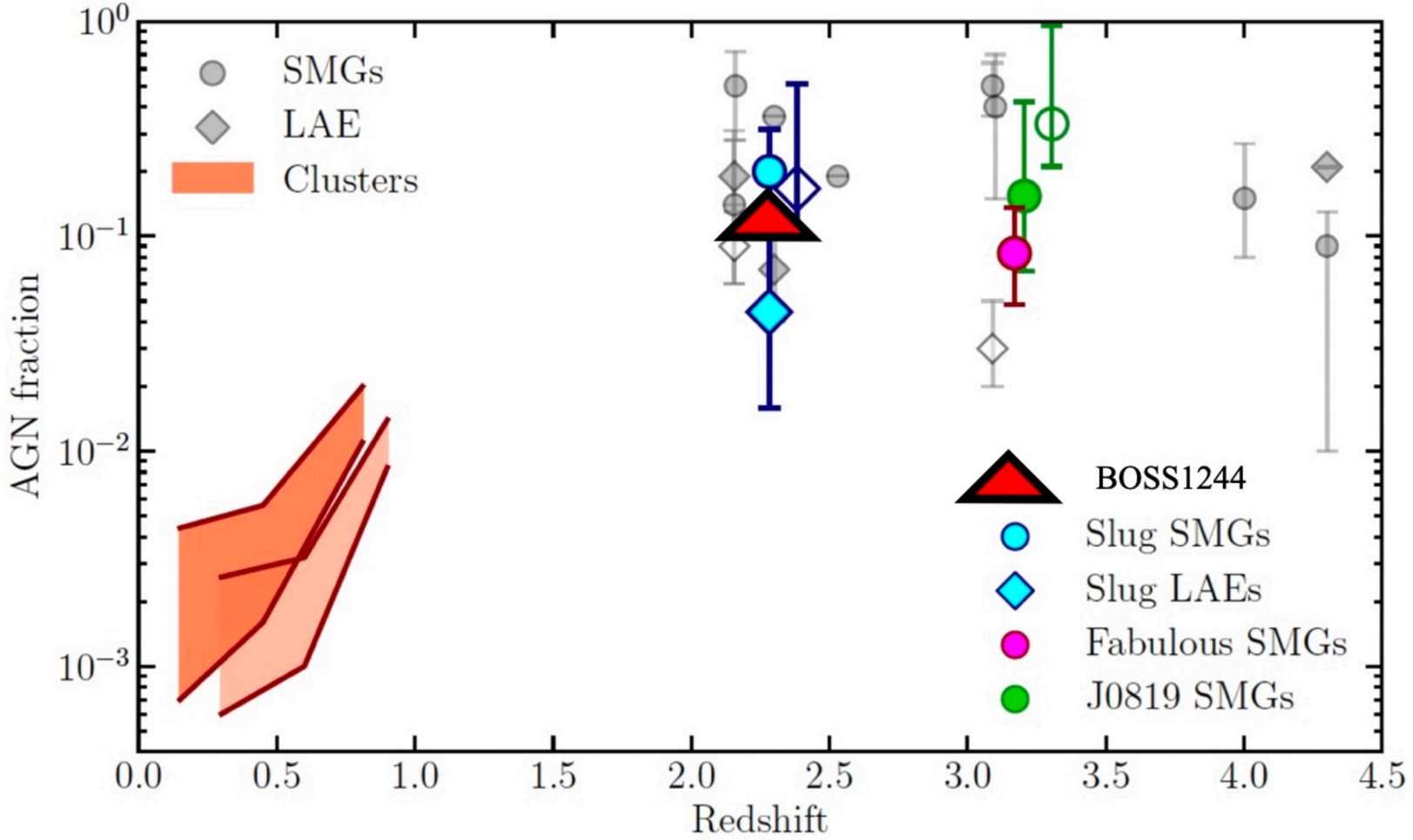

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Vito et al. 2024
Traina et al. 2025

- The f_AGN is ~13% of the spec confirmed members in the mass range $log(M_*/M_\odot) > 10.5$
- Synergy with NIR, MIR (JWST) and submm (ALMA) data for SF and cold gas
- Martinez-Perez et al. 2025, Shimakawa et al. 2025

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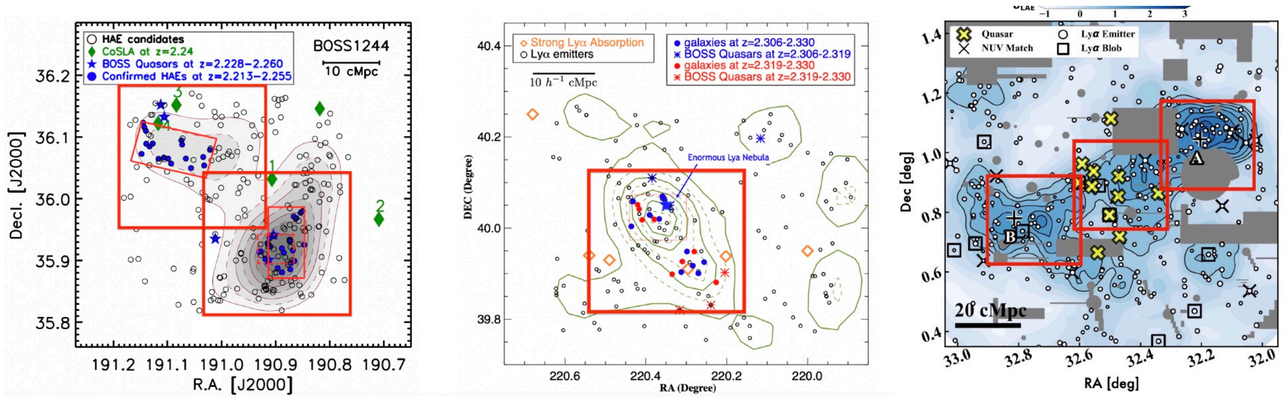

Figure 2: Left: BOSS1244 field adapted from [12]. The thin red boxes show the regions of the spectroscopic survey, while the black and blue circles are HAE candidates and HAE spectroscopically confirmed members, respectively. The blue stars are BOSS AGNs. Center: BOSS1441 field, adapted from [11]. The orange diamonds represent Lyα absorption systems and the red asterisks represent BOSS QSOs. Right: BOSS0210 LAE overdensity map, adapted from [15]. Circles and yellow crosses represent the LAE candidates and the BOSS QSOs, respectively. The red thick boxes show the ACIS-I FoVs of this proposal.

M. Lepore LP Chandra AO27

Table 1: List of *Chandra* pointings. (1): object ID; (2): Right ascension; (3): Declination; (4) redshift; (5): Galactic hydrogen column density; (6): galaxy overdensity[1]; (7): Proposed time (ks); (8): Archival time (ks); (9): GTO time (ks). *RA and Dec refer to the ACIS-I FoV center as shown in Fig.2.*

ID	RA	Dec	redshift	N_{HGal} $10^{20}/cm^2$	δ_g	t_{exp} prop	t_{exp} arch	t_{exp} GTO
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1244NE	12:44:19.2	+36:04:48.0	2.246 ± 0.001	1.33	10.9 ± 2.5	**140**	30	–
1244SW	12:43:31.2	+35:55:12.0	2.230 ± 0.002	1.27	22.9 ± 4.9	–	30	120 [2]
1441	14:41:24.0	+40:00:00.0	2.32 ± 0.02	1.07	10.8 ± 2.6	**110**	45[3]	–
0210E	02:08:48.0	+01:00:00.0	2.177 ± 0.023	2.93	–	**170**	–	–
0210C	02:09:48.0	+00:54:00.0	2.177 ± 0.023	2.93	–	–	–	150[4]
0210W	02:11:00.0	+00:46:48.0	2.177 ± 0.023	2.93	–	**170**	–	–
Total time						590	105	270

[1] Overdensity of LAEs for BOSS1441 and overdensity of HAEs for BOSS1244

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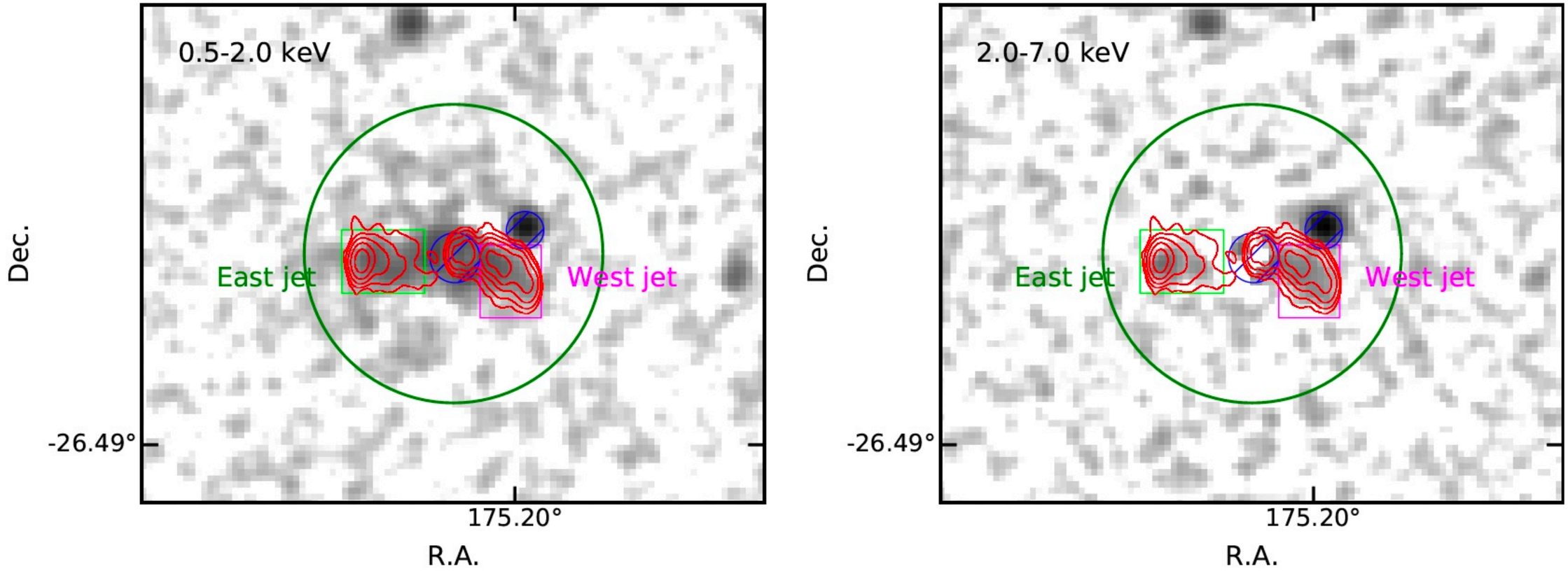
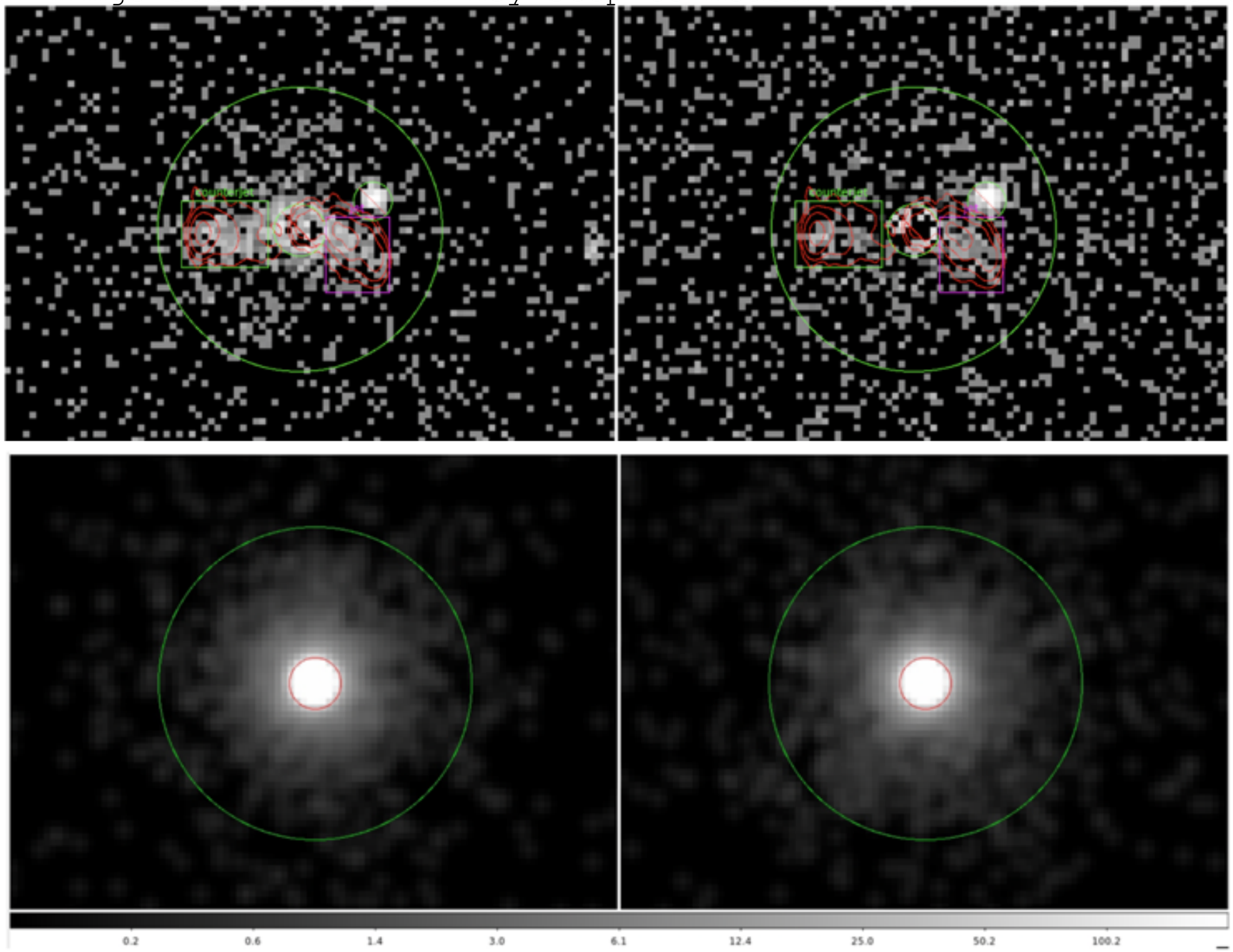


- Diffuse emission in the soft (left) and hard (right) band in the Spiderweb. Red contours are 10 GHz JVLA contours (Carilli et al. 2022)

PSF wings subtraction: a key step to measure the diffuse emission



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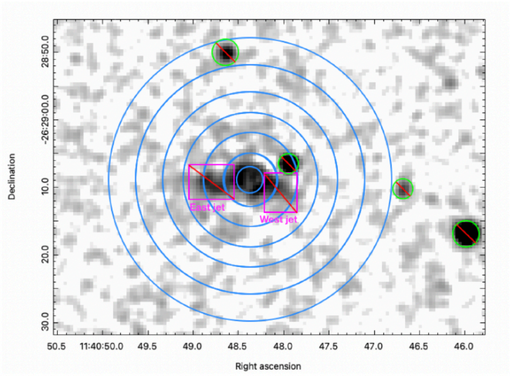
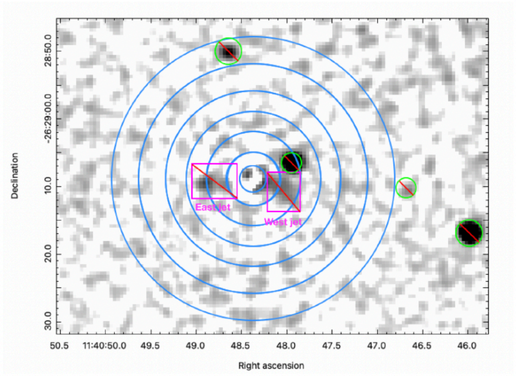
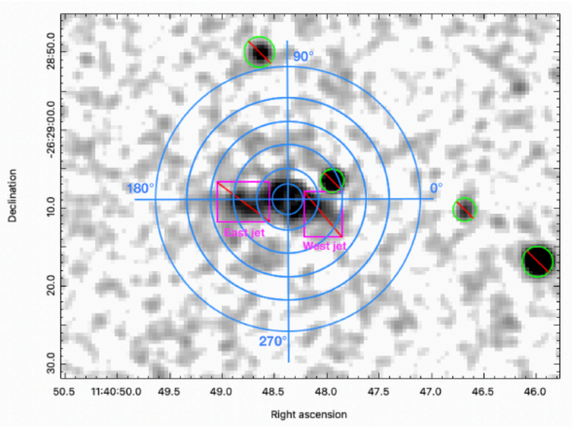
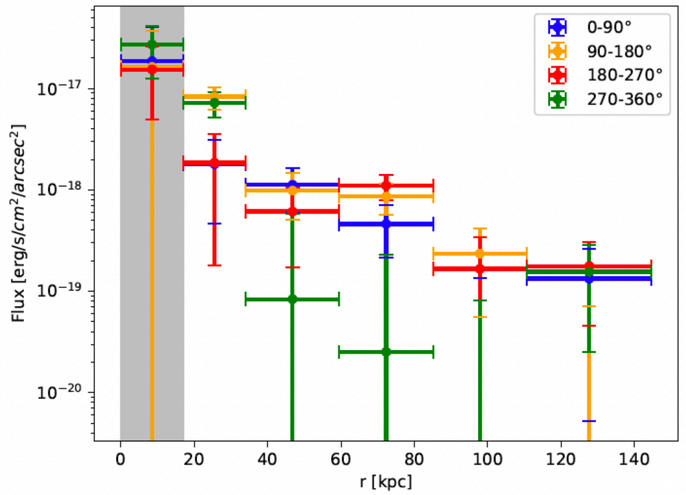
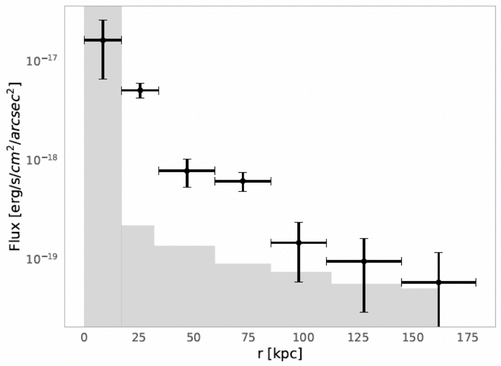
Lepore et al. 2024

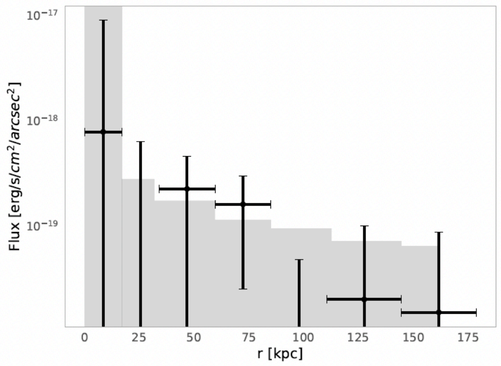












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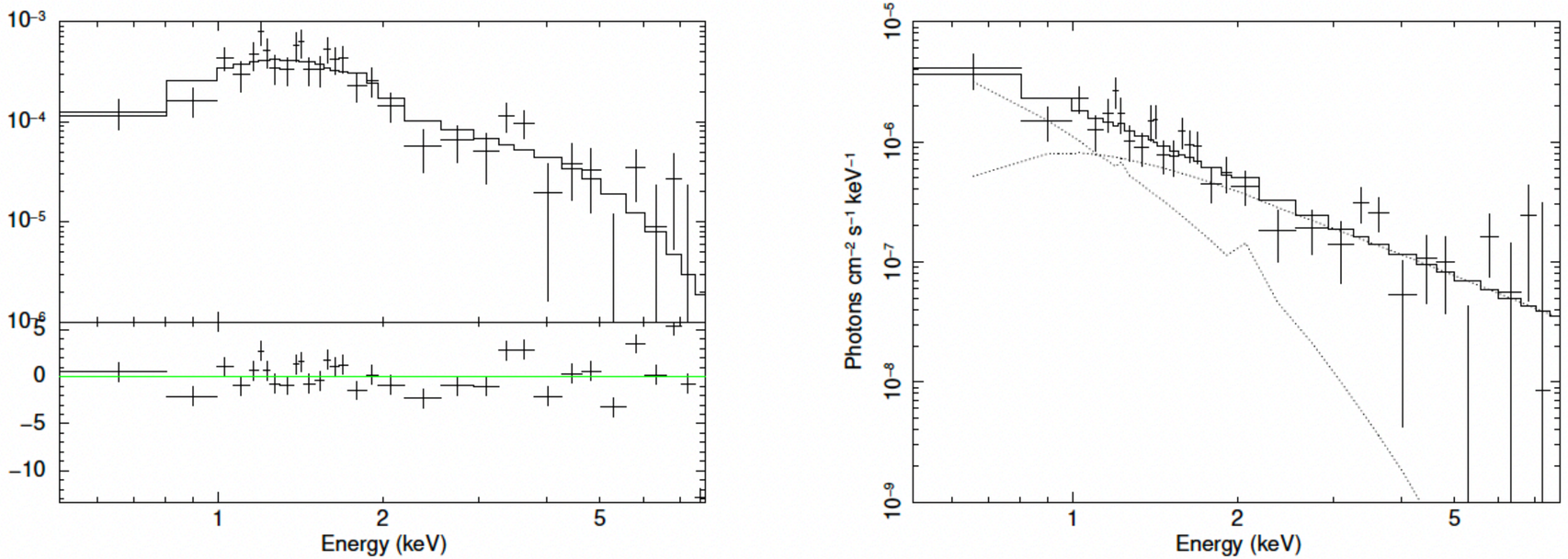

Fig. 14. *Left*: spectrum (folded with the instrument spectral response) of the isotropic diffuse emission (after removing the central, AGN-dominated region, and the jet regions) fitted with a thermal `mekal` model plus the AGN contamination. *Right*: unfolded spectrum with the two model components shown with dotted lines. The AGN contamination (absorbed power law) is dominant at energies >1.5 keV, while the thermal component is dominant below 1 keV.

PT et al. 2022

kT = 2.0 +0.7 -0.4 keV

M_{ICM} = 1.67 +-0.17 $10^{12} M_\odot$

M_{tot}(<100 kpc) = $1.5^{+0.5}_{-0.3}$ $10^{13} M_\odot$

M_{500} = 3.0+-1.1 $10^{13} M_\odot$

Consistent with the low-mass case simulation of Saro et al. (2009)

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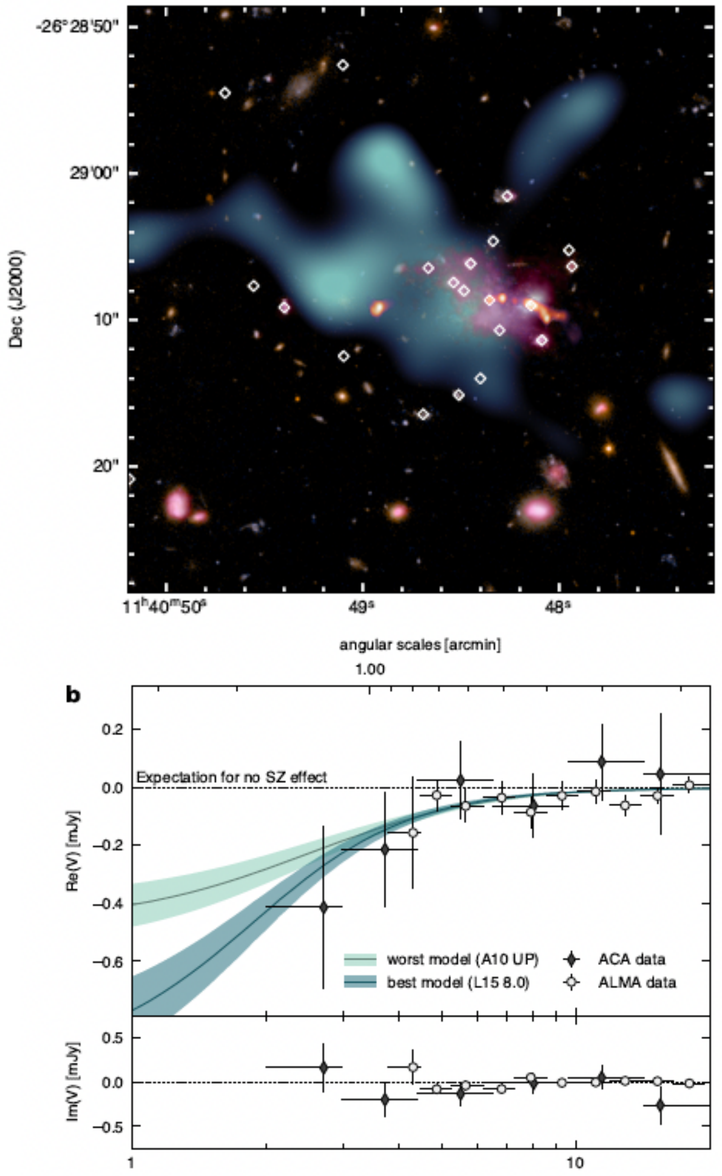

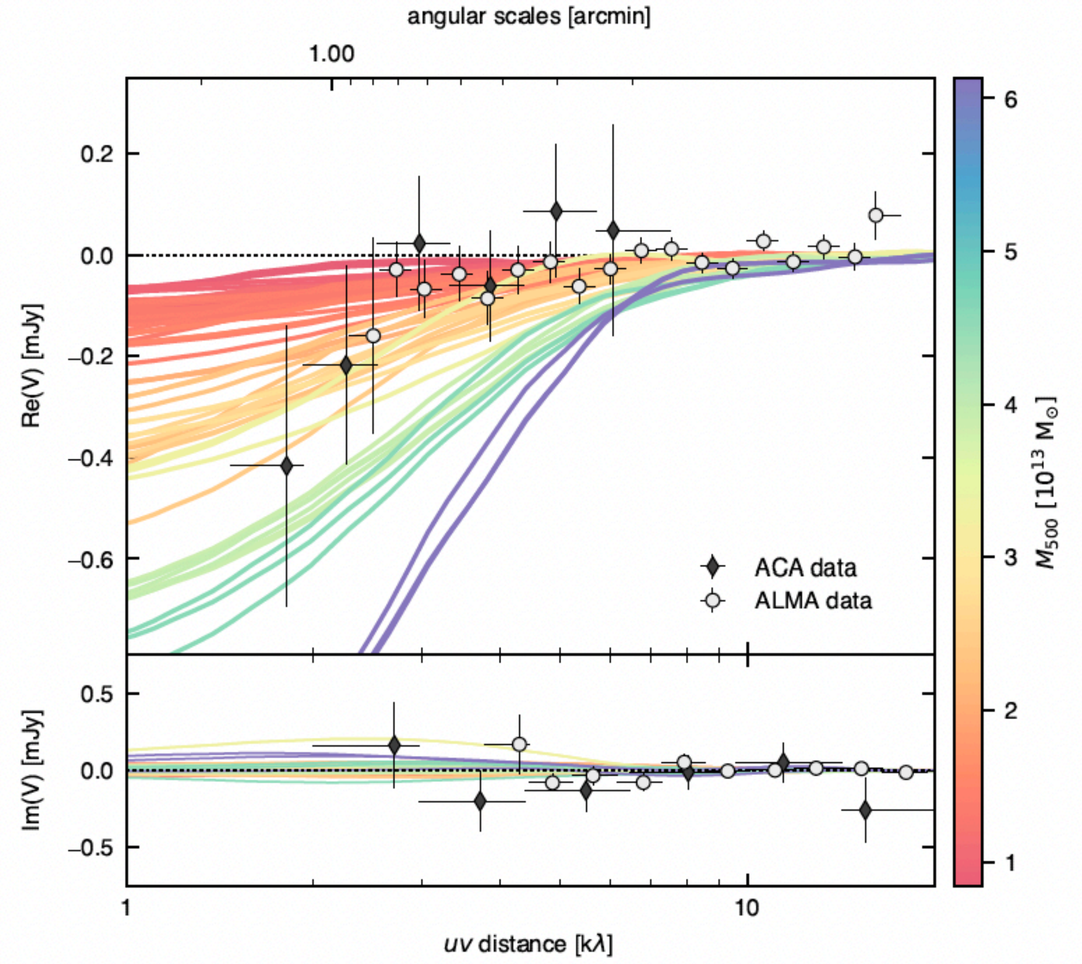

Di Mascolo et al. 2023

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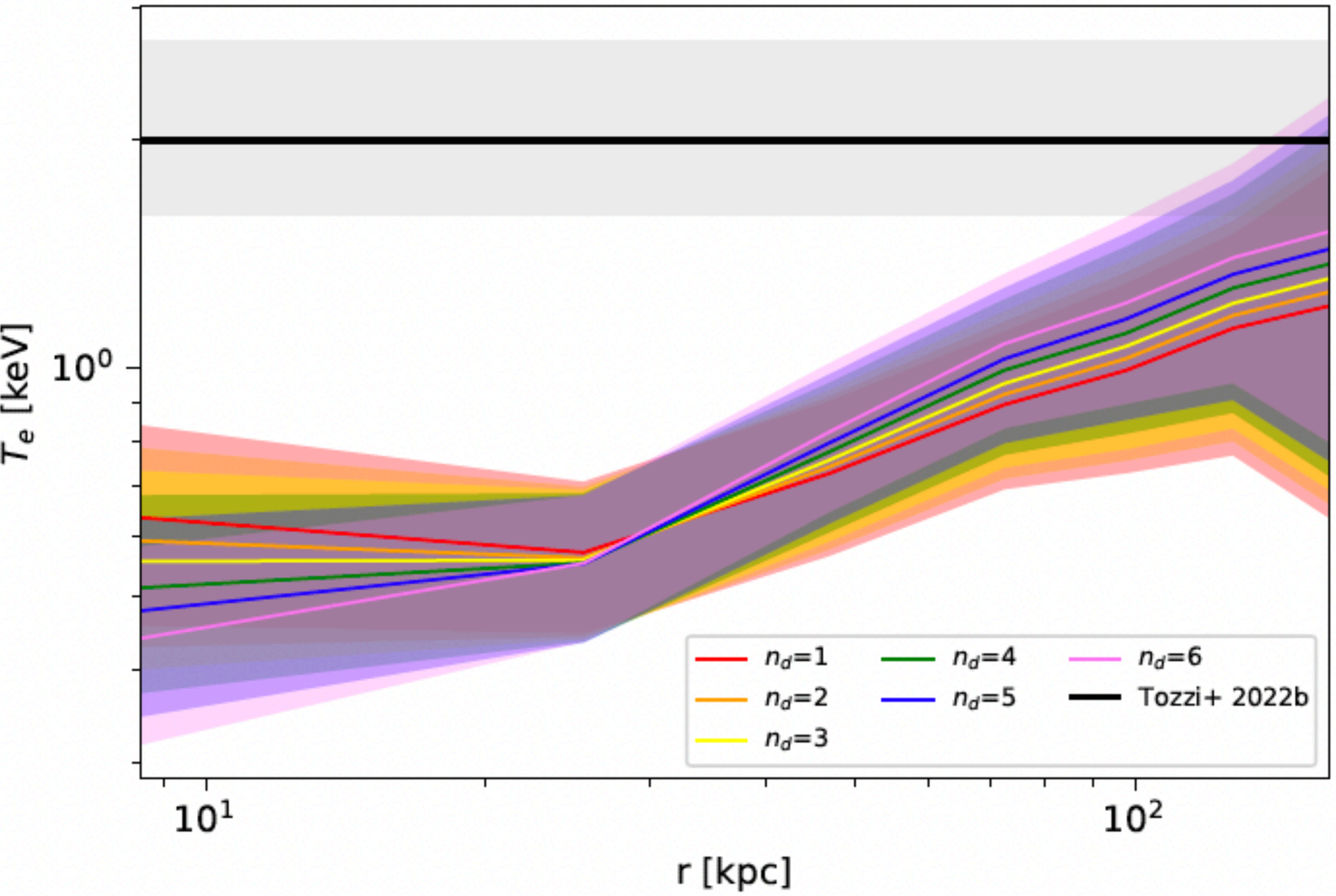
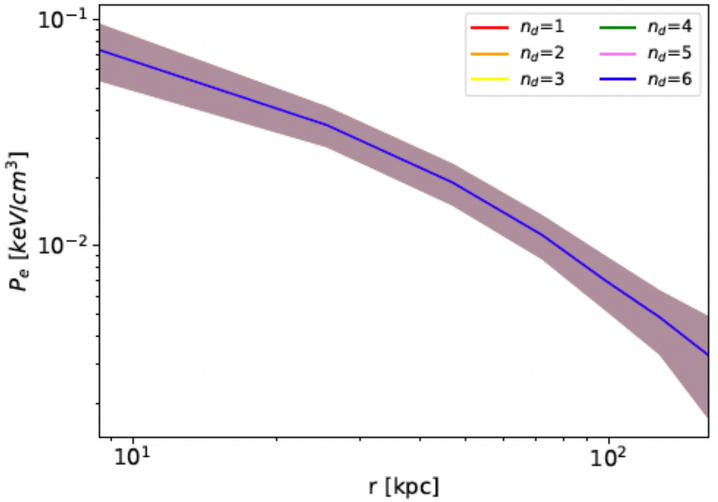
Temperature gradient in the ICM





Lepore et al. 2023

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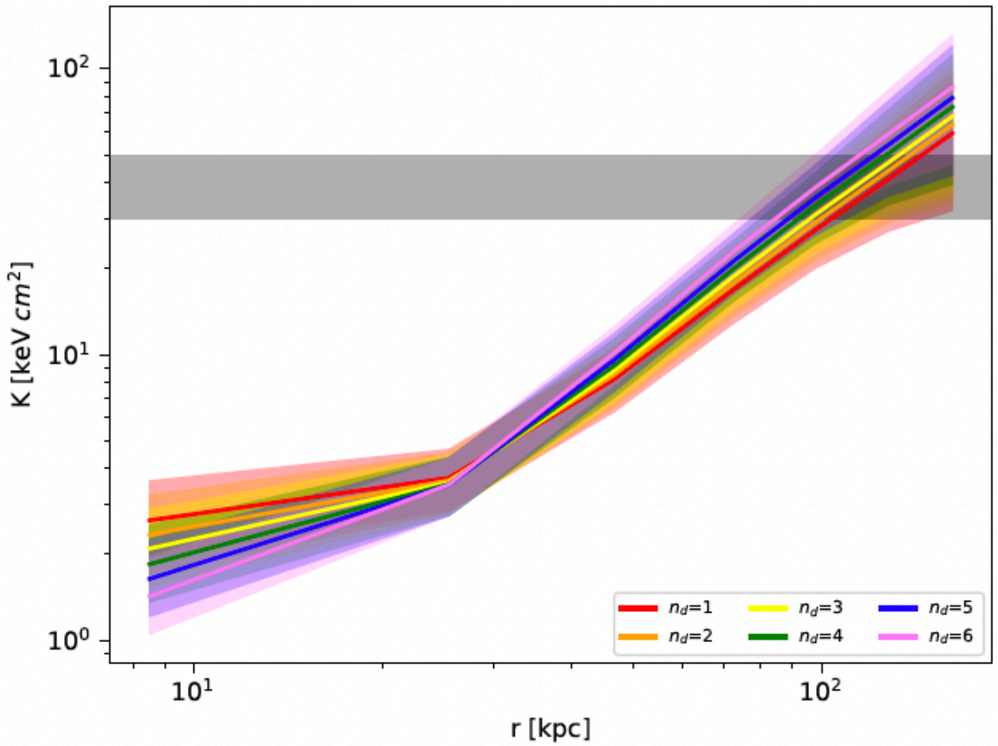
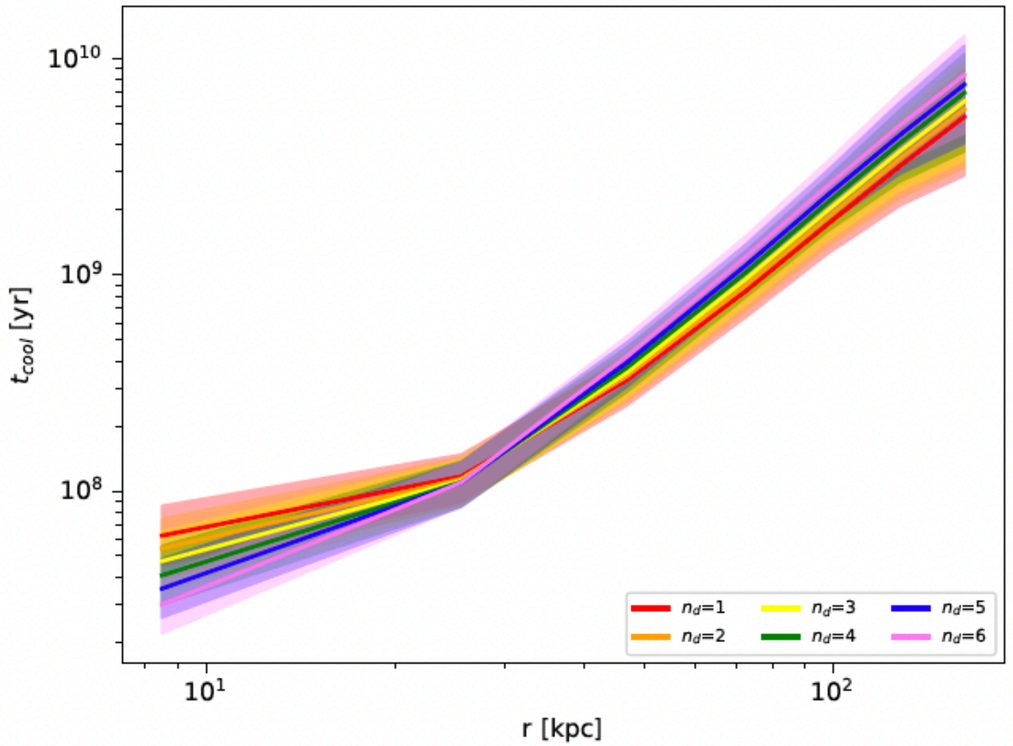
Cool core (cooling flow?) in the Spiderweb





~ adiabatic cooling flow of 250-1000 M/yr (optimal value 760 M/yr)

SFR values:

1390+-150 M/yr (Seymour et al. 2012)

1150+-580 M/yr (Rawlings et al. 2013)

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Table 2. Best-fit values for the reference spectral analysis of the diffuse emission.

Region	kT (mekal) keV	F_S erg s^{-1} cm^{-2}	F_H erg s^{-1} cm^{-2}	$L_{0.5-2\,keV}$ erg s^{-1}	$L_{2-10\,keV}$ erg s^{-1}
Isotropic	$1.98^{+0.70}_{-0.43}$	$(2.5 \pm 0.6) \times 10^{-15}$	$(2.4 \pm 0.9) \times 10^{-16}$	$(7.7 \pm 1.8) \times 10^{43}$	$(7.3 \pm 1.7) \times 10^{43}$
Region	Γ –	F_S erg s^{-1} cm^{-2}	F_H erg s^{-1} cm^{-2}	$L_{0.5-2\,keV}$ erg s^{-1}	$L_{2-10\,keV}$ erg s^{-1}
West jet	1.90 ± 0.20	$(1.32 \pm 0.21) \times 10^{-15}$	$(1.78 \pm 0.28) \times 10^{-15}$	$(4.1 \pm 0.7) \times 10^{43}$	$(5.5 \pm 0.9) \times 10^{43}$
East jet	2.51 ± 0.21	$(1.89 \pm 0.25) \times 10^{-15}$	$(1.02 \pm 0.13) \times 10^{-15}$	$(1.18 \pm 0.15) \times 10^{44}$	$(6.4 \pm 0.8) \times 10^{43}$

Notes. We note that in this table, flux and luminosity values of the isotropic (thermal) emission have not been corrected by the geometrical factor, but directly correspond to the best-fit values obtained from the extraction region. Error bars refer to 1σ c.l. on a single parameter.

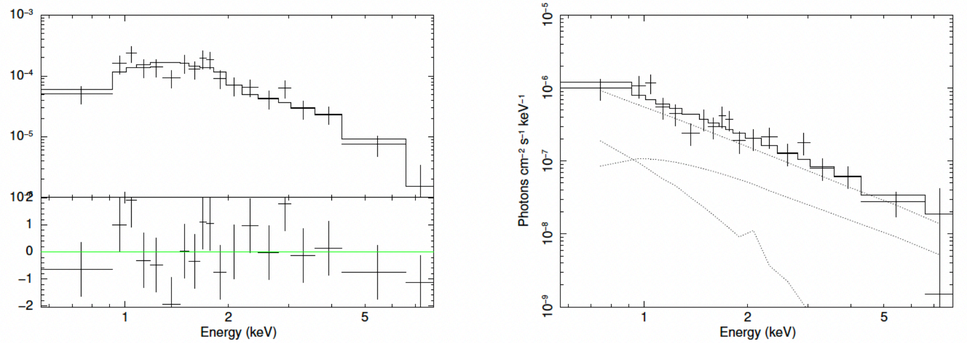

Fig. 15. *Left*: spectrum (folded with the instrument spectral response) of the emission in the west jet region (including the AGN contamination and the residual thermal emission from the ICM) fitted with a power law. *Right*: unfolded spectrum with the three components in the model shown with dotted lines. The lowest dotted line corresponds to the thermal emission from the overlapping ICM, while the line in the middle accounts for the AGN wings contamination. The IC from the relativistic population in the west jet is shown by the unabsorbed power law that is dominating at any energy.

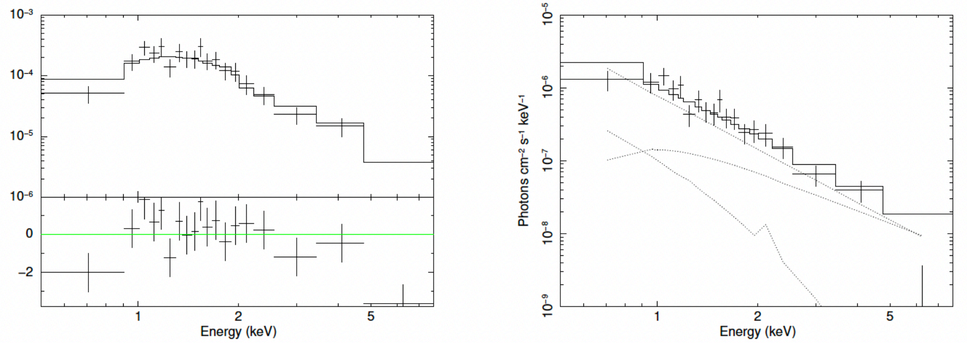

Fig. 16. *Left*: spectrum (folded with the instrument spectral response) of the emission in the east jet region (including the AGN contamination and the residual thermal emission from the ICM) fitted with a power law. *Right*: unfolded spectrum with the three components in the model shown with dotted lines. The lowest dotted line corresponds to the thermal emission from the overlapping ICM, while the line in the middle accounts for the AGN wings contamination. The IC from the relativistic population in the east jet is shown by the unabsorbed power law that is dominating at any energy.

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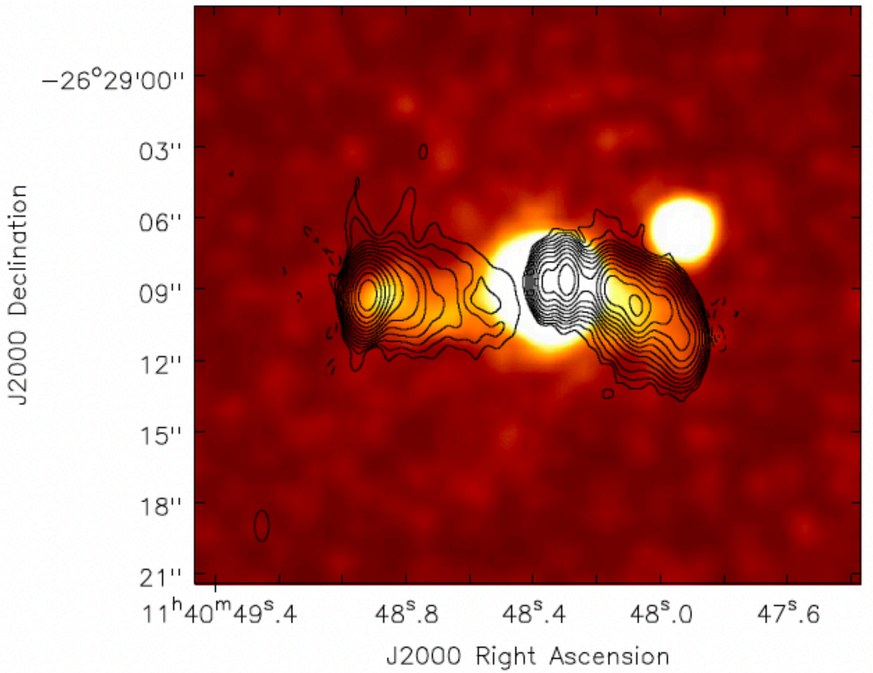

Figure 2. Contour image of the 2 GHz to 4 GHz VLA image of the Spiderweb galaxy, at a resolution of $1\farcs3 \times 0\farcs6$, major axis north–south. The contour levels are a geometric progression in a factor of two, starting at 20 μJy beam^{-1}. Negative contours are dashed. The color scale is the same Chandra Observatory total X-ray emission (0.5–7 keV) as shown in Figure 1.

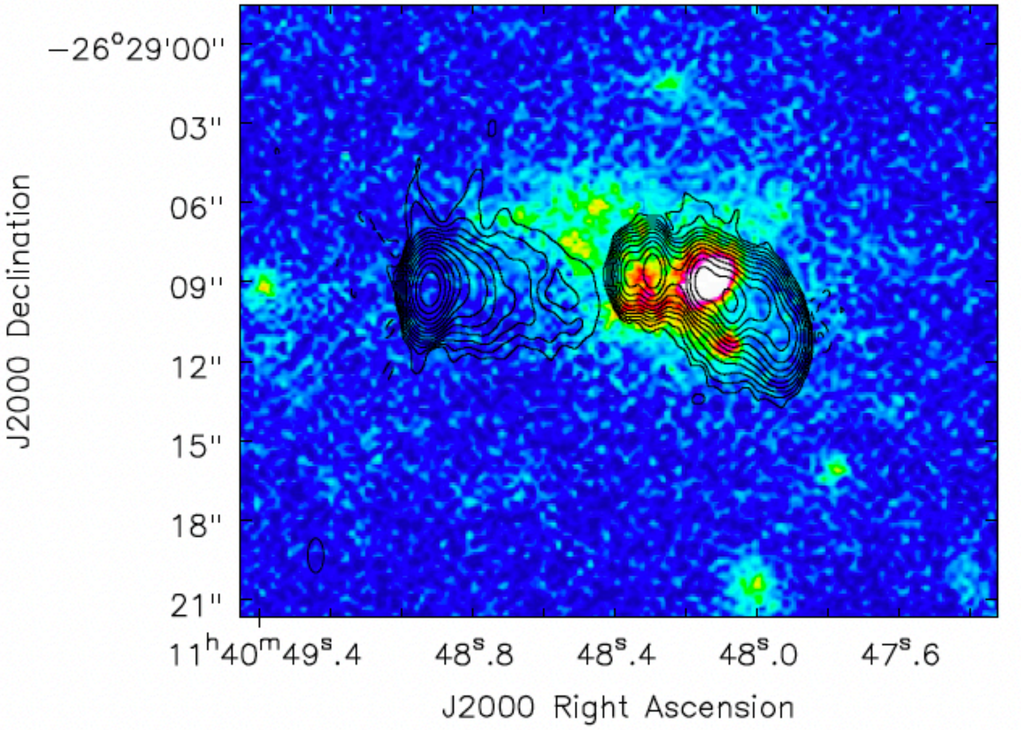

Figure 3. Same contour image as in Figure 1. The color image is the ESO narrowband filter image, roughly centered on the Lyα emission line from the Spiderweb galaxy at $z = 2.16$ (M. Nonino et al. 2022, in preparation).

Carilli et al. 2022
Anderson et al. 2022

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AXIS Deep Extragalactic Survey

The Extragalactic Surveys will find >20,000 AGN over cosmic time, >50x more than the Chandra Deep Field.

The Galactic Plane Survey will discover >1M new sources in crowded fields, 10x deeper and 5x wider than current best X-ray surveys.

The AXIS Science Pillars

Astro 2020 asks... Why X-rays?	...AXIS answers Why AXIS?
Pillar 1: "What seeds supermassive black holes and how do they grow?"	AXIS determines the origin of massive black holes X-rays identify clean census of black holes in distant JWST galaxies AXIS' PSF and large area enable imaging of distant, faint sources
Pillar 2: "How do gas, metals, and dust flow into, through, and out of galaxies?"	AXIS shows how supernovae and AGN transform galaxies X-rays uniquely probe the million-degree gas that drives gas flows High contrast imaging separates diffuse gas and bright sources
Pillar 3: "What powers the diversity of explosive phenomena across the electromagnetic spectrum?"	AXIS discovers explosive transients both near and distant X-rays uniquely encode information on transient progenitors AXIS enables transient alerts, TDAMM surveys and fast followup

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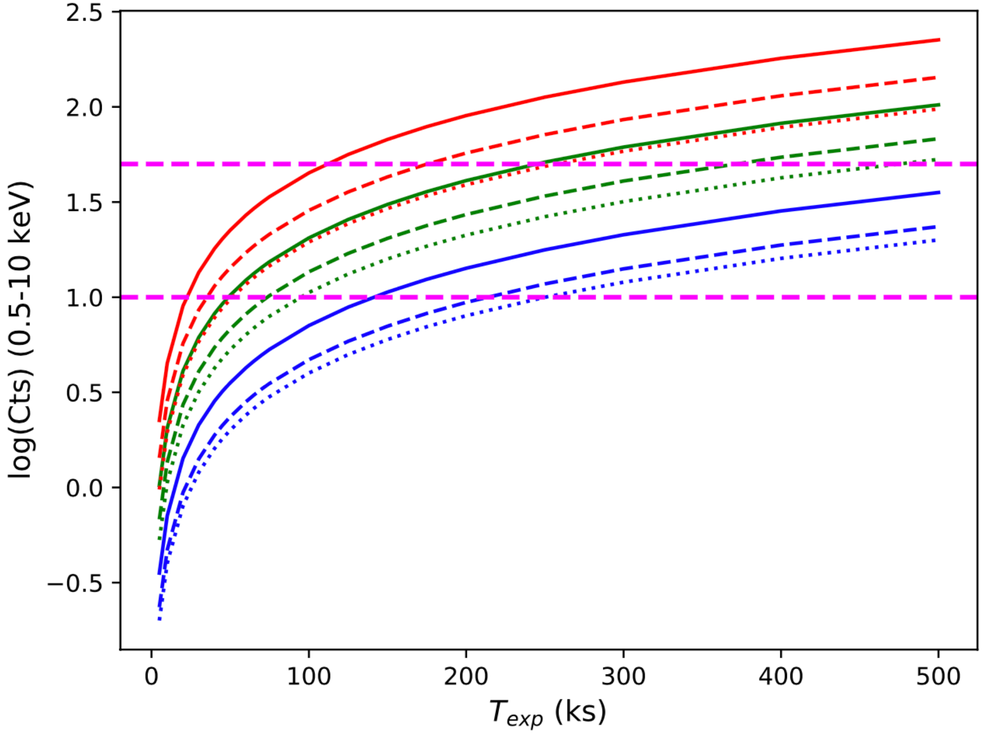
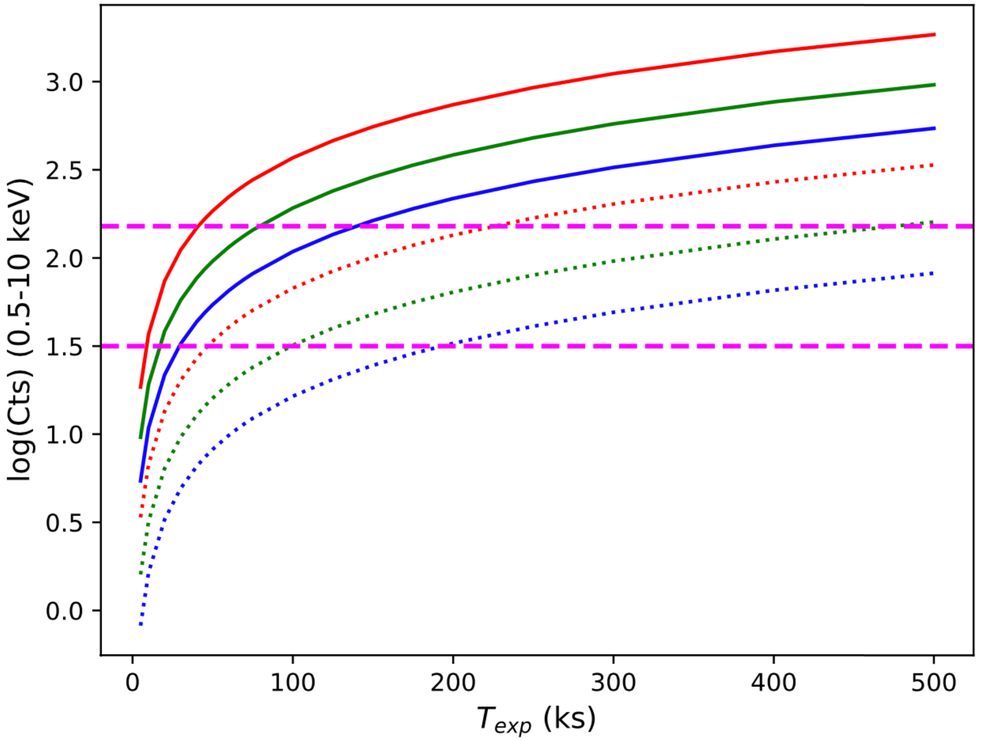
Detection of AGN with AXIS



Detection of proto-ICM with AXIS



AXIS GO Science Book, Ed. H. Russel & L. Lopez
See also https://axis.umd.edu/

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A small protocluster program with AXIS (1.16 Ms)

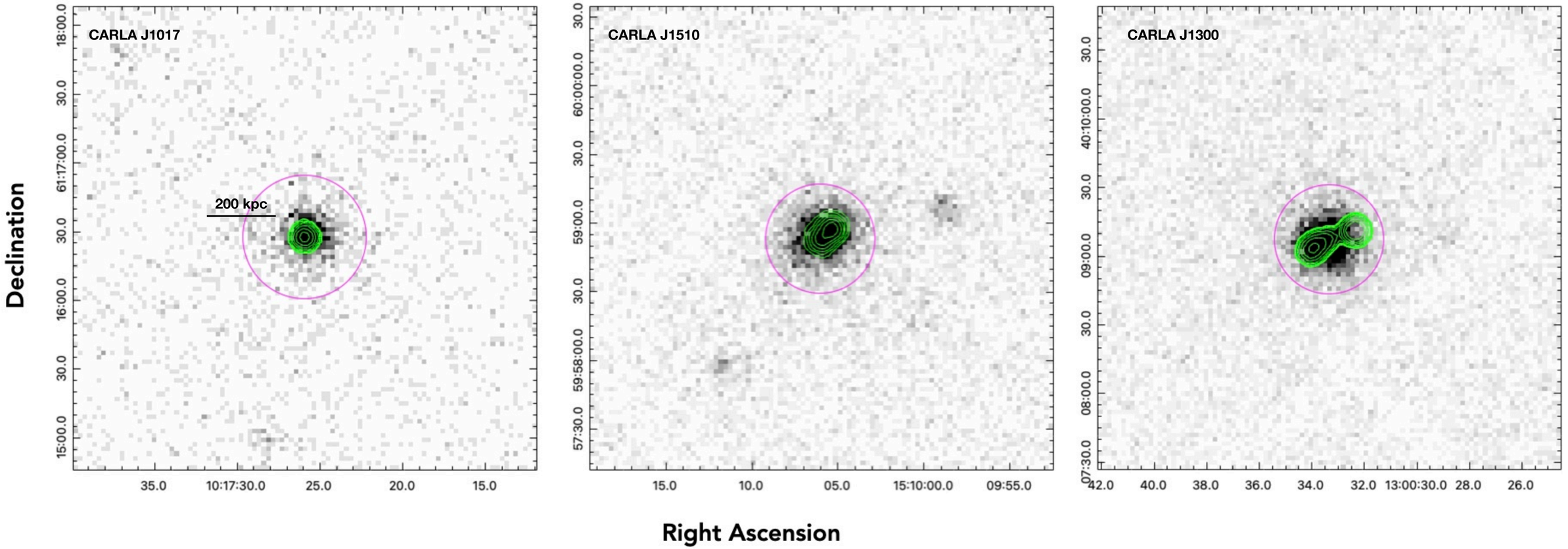
Table 3. Test sample of protoclusters suitable for this science case. (1): Object ID; (2): Right ascension; (3): Declination; (4) Redshift; (5): Galactic hydrogen column density in units of 10^{20} cm^{-2}; (6): Galaxy overdensity; (7) Reference to the discovery paper; (8), (9): Exposure time in ks for AXIS observations for AGN and ICM.

Protoclusters with radio beacon								
ID	RA	Dec	z	N_{HGal}	δ_g	Ref.	t_{exp} AGN	t_{exp} ICM
MRC0156-252	29:38:21.9	-24:59:32.1	2.02	1.10	17.8 ± 2.4^a	[141]	130	40
USS1707+105	17:10:06.5	10:31:06.2	2.35	6.18	12 ± 2^b	[177]	200	100
MRC2104-242	21:06:58.2	-24:05:11.3	2.49	4.16	14.0 ± 2.1^a	[141]	200	100
Protoclusters without dominant galaxy								
ID	RA	Dec	z	N_{HGal}	δ_g	Ref.	t_{exp} AGN	t_{exp} ICM
BOSS1244	12:43:31.2	+35:55:12.0	2.23	1.27	22.9 ± 4.9^c	[361]	180	80
HS1700+643	17:00:55.00	+64:11:26.7	2.30	2.11	6.9 ± 2.1^d	[373]	200	100
SSA22	22:17:34.0	+00:05:01	3.09	4.23	7.6 ± 1.4^e	[372]	250	180

[a]Density of IRAC sources from [141], [b]Density of Hα emitters from [177], [c]Density of Hα emitters from [361], [d]Density of IRAC sources from [373], [e]Density of Lyman Break Galaxies from [392]

AXIS GO Science Book, Ed. H. Russel & L. Lopez
See also https://axis.umd.edu/

ARLA SAMPLE



Radio-Loud QSO
$z = 2.801$

MOS1 16 ks
MOS2 18 ks
pn 15 ks

Radio-Loud QSO
$z = 1.725$

MOS1 42 ks
MOS2 42 ks
pn 27 ks

Radio-Loud QSO
$z = 1.675$

MOS1 52 ks
MOS2 52 ks
pn 18 ks

XMM Observation of CARLA clusters - **M. Lepore et al. in preparation**

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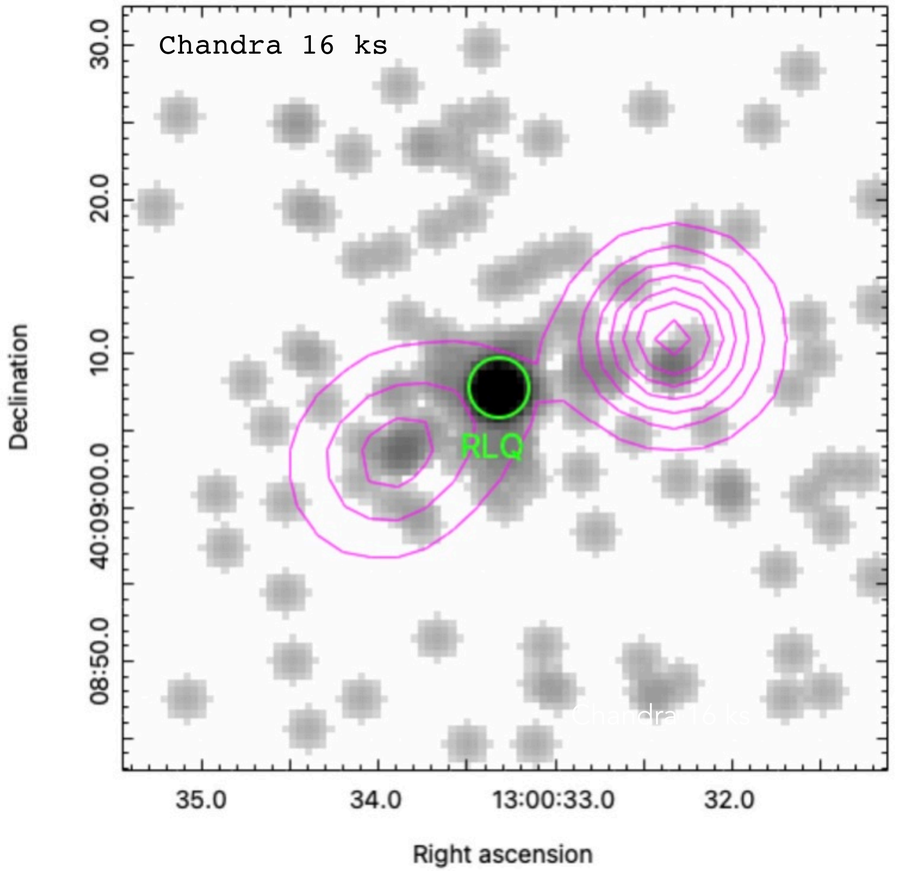
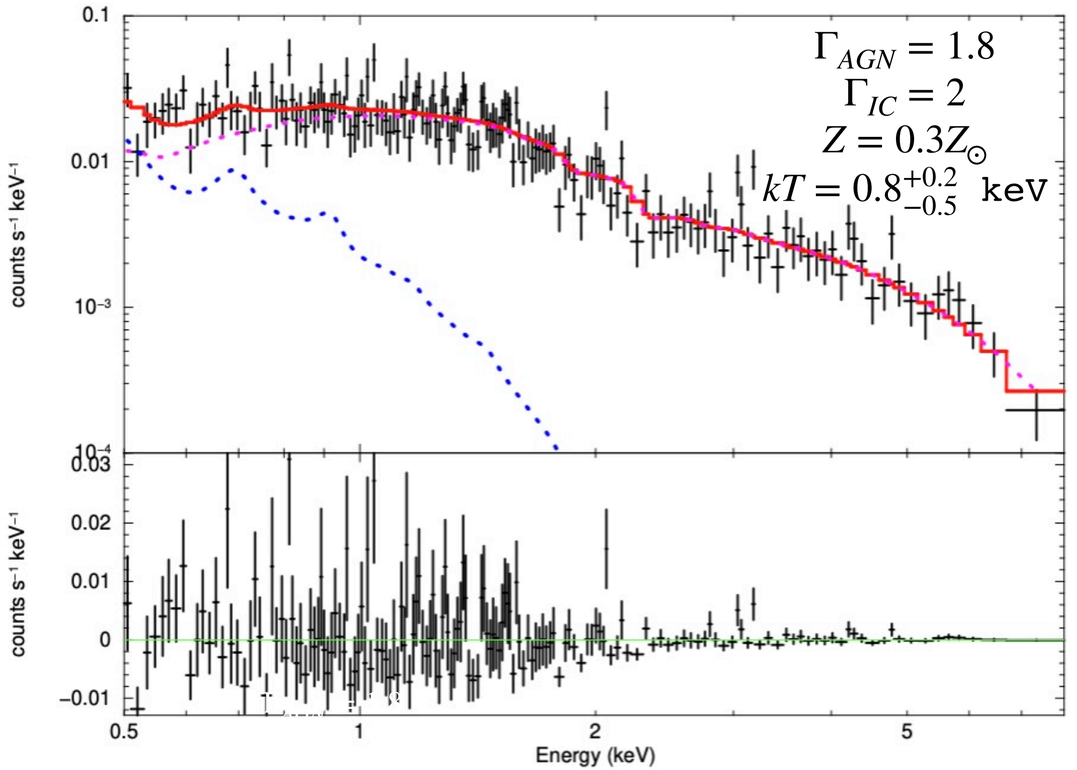
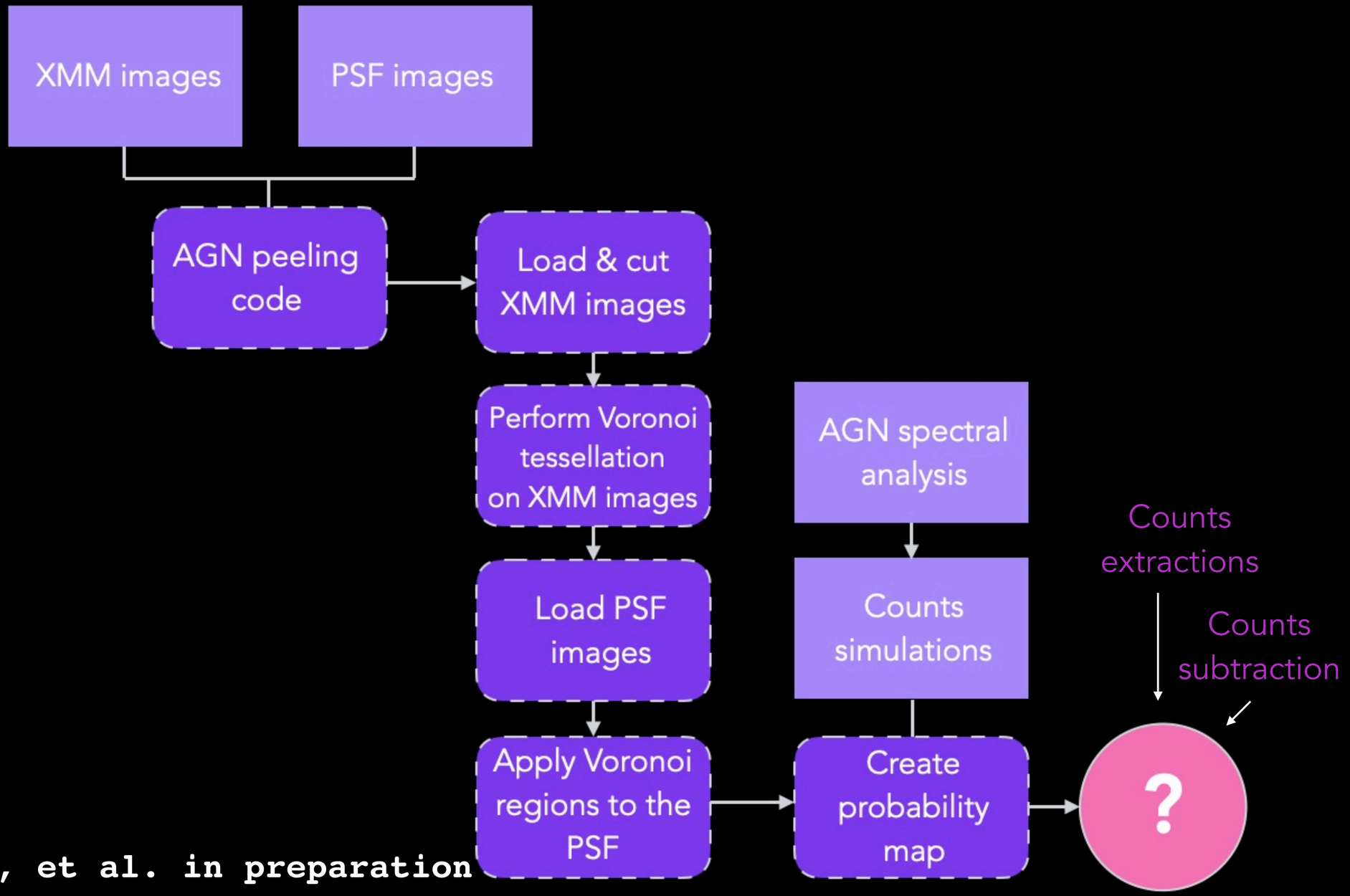




Lepore, M., et al. in preparation

The presence of thermal emission is detected from spectral analysis only at 2σ confidence level

THE CARLA SAMPLE: AGN PEELING CODE



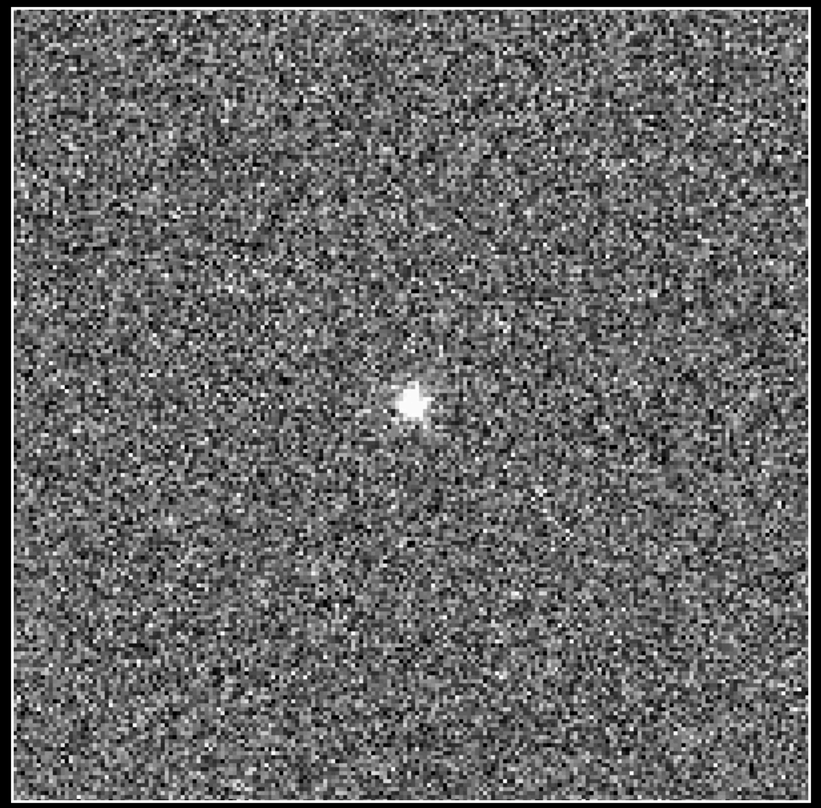
Lepore, M., et al. in preparation

THE CARLA SAMPLE: AGN PEELING

Cluster AGN Removal for ICM Tracing and analYsis

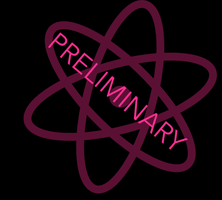
Lepore et al., in prep

AGN + background simulated image



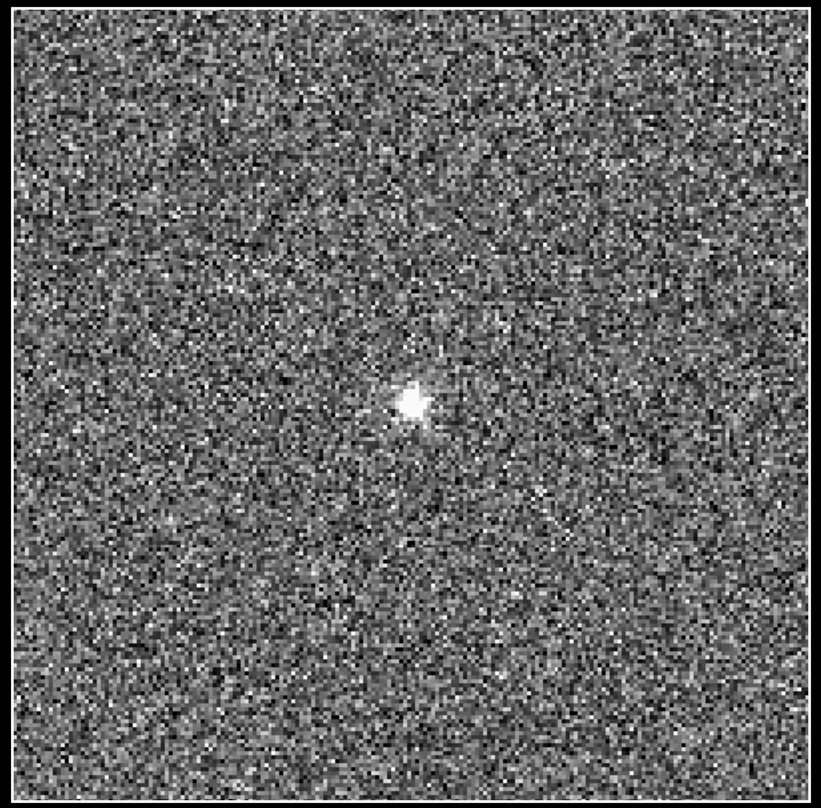
Lepore, M., et al. in preparation

THE CARLA SAMPLE: AGN PEELING



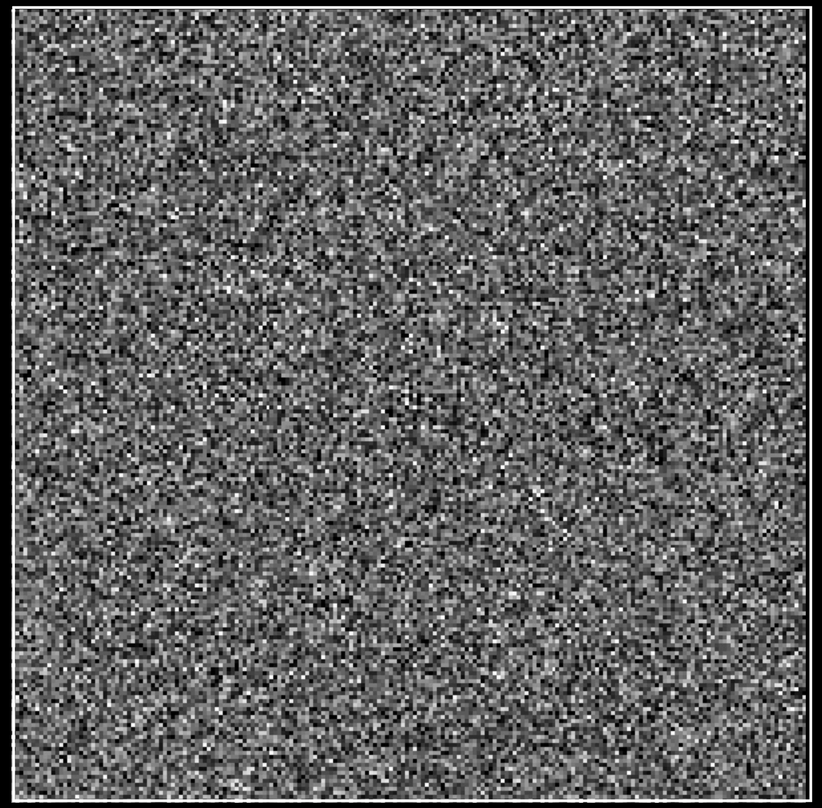
Cluster AGN Removal for ICM Tracing and analYsis

AGN + background simulated image



N-step subtraction

Output: AGN-subtracted residual

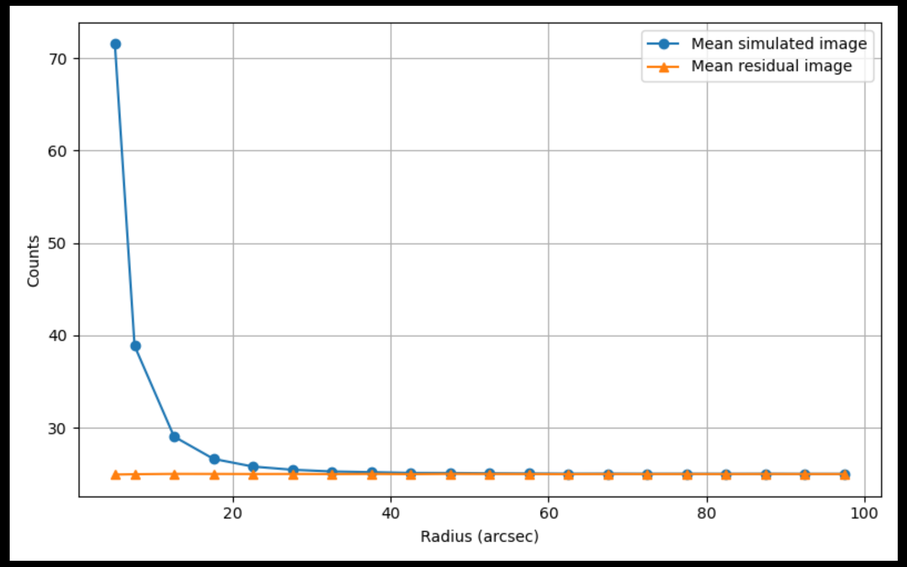


Simulated X-ray AGN removal using Voronoi-based PSF sampling and N-step probabilistic subtraction

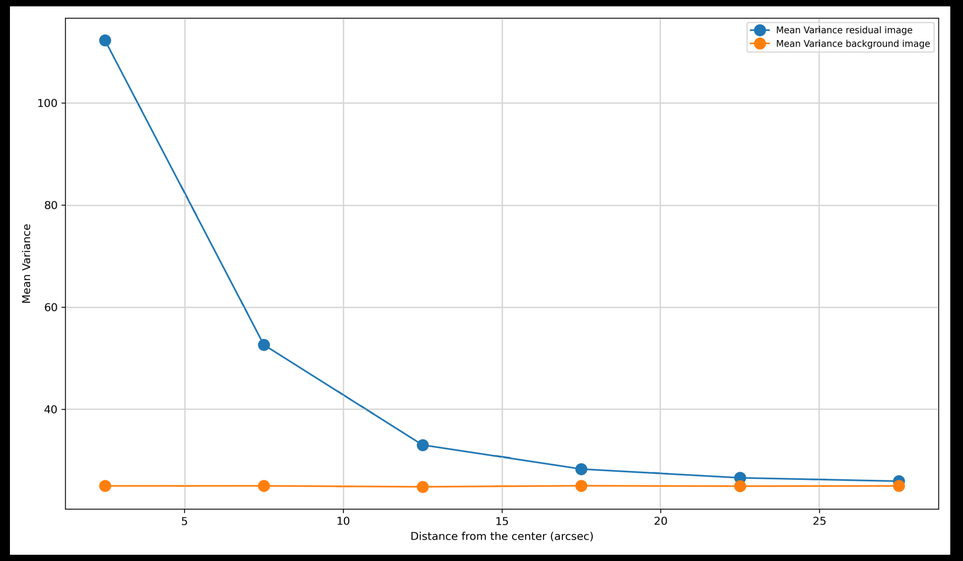
Lepore, M., et al. in preparation

THE CARLA SAMPLE: CLARITY

Cluster AGN Removal for ICM Tracing and analYsis



Photometry in 20'' from the center



Mean Variance

Simulated X-ray AGN removal using Voronoi-based PSF sampling and N-step probabilistic subtraction

Lepore, M., et al. in preparation

Conclusions

X-ray are key to explore several energetic phenomena during the transition from protoclusters to clusters (2<z<3):

Nuclear emission in member galaxies
Heating of the diffuse baryons (proto ICM) and their chemical enrichment
Possible cooling flows around strong beacons
IC emission from relativistic jets (strong synergy with radio observations)
HMXB emission associated to SF
Indirectly: feedback processes from AGN onto diffuse baryons

But protoclusters are not classic X-ray targets. Most of the “X-ray science” need ancillary data (spectroscopy, NIR imaging, Radio, etc), to begin with a clean selection based on stellar mass and large FOV.

High angular resolution and FOV are both very important (see AXIS).
However, significant results can be obtained in complex sources (Spiderweb-like) with XMM, by combining spatial and spectral information.