FROM CLUSTERS TO LOCAL GROUPS: EXTENDING X-RAY SCALING RELATIONS WITH eROSITA

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21 April 2026, INAF, Bologna


MOTIVATION
Galaxy Evolution Coffee
24 July 2025, ESO

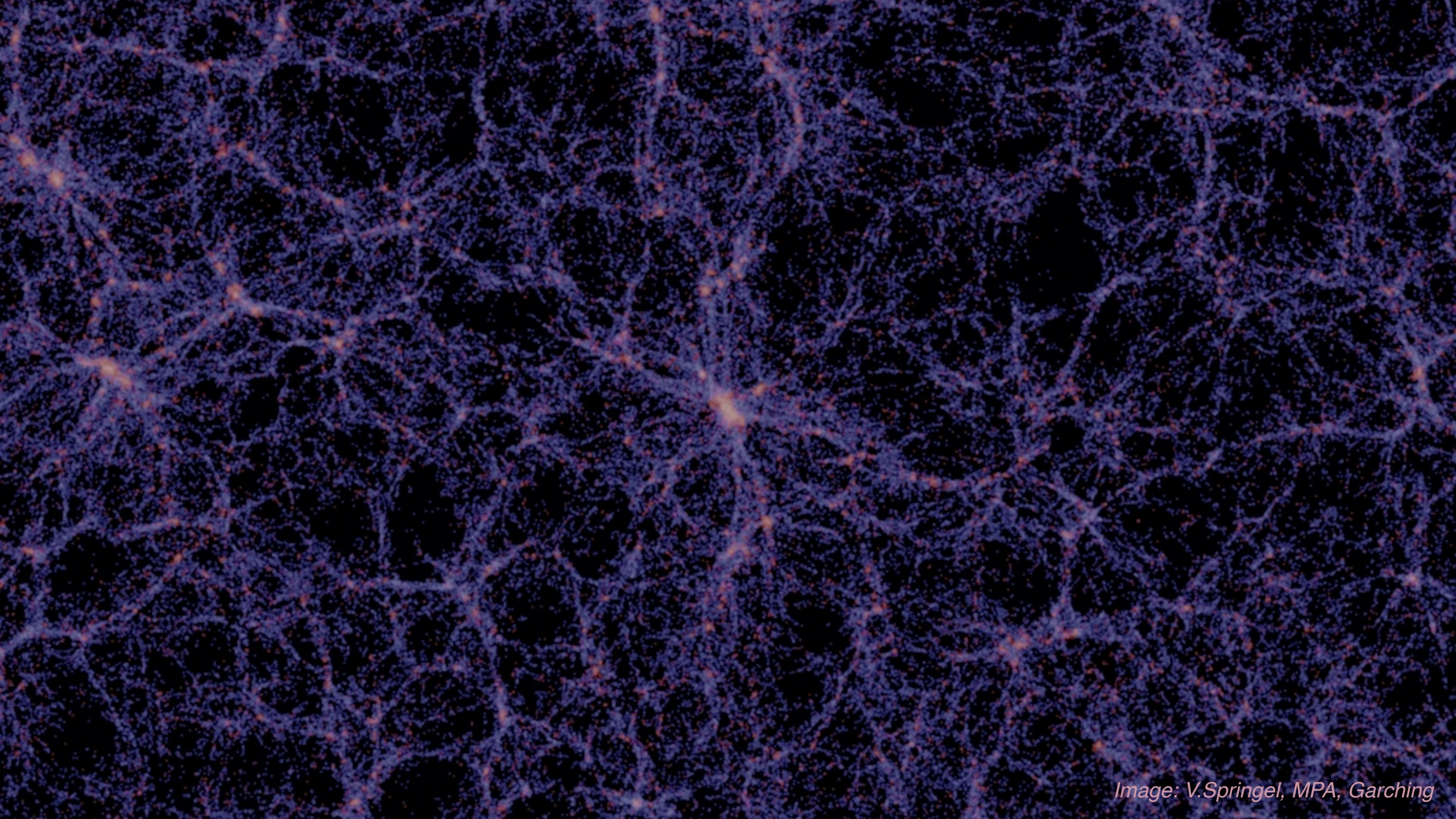
Image: V.Springel, MPA, Garching

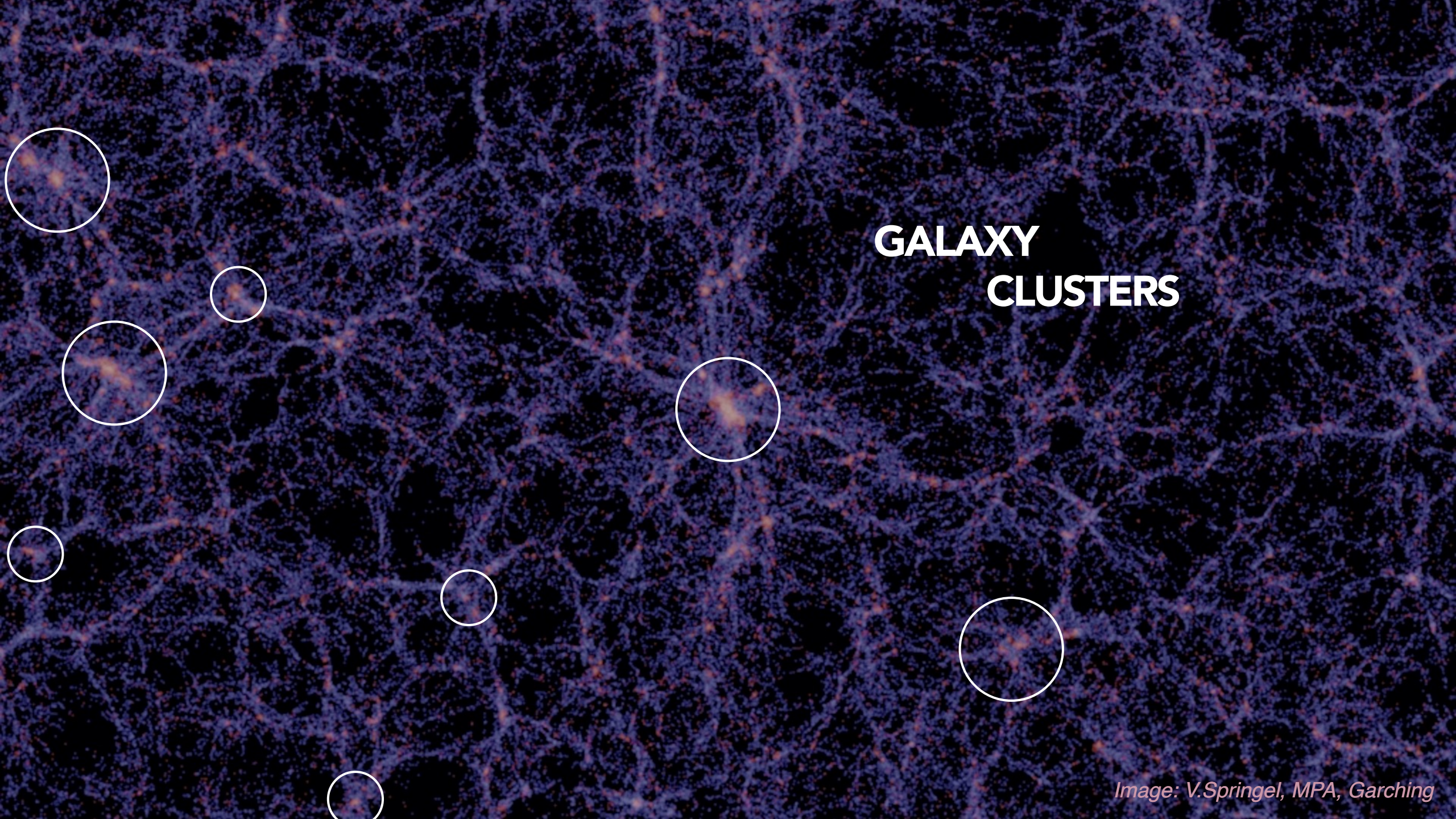

Image: V.Springel, MPA, Garching

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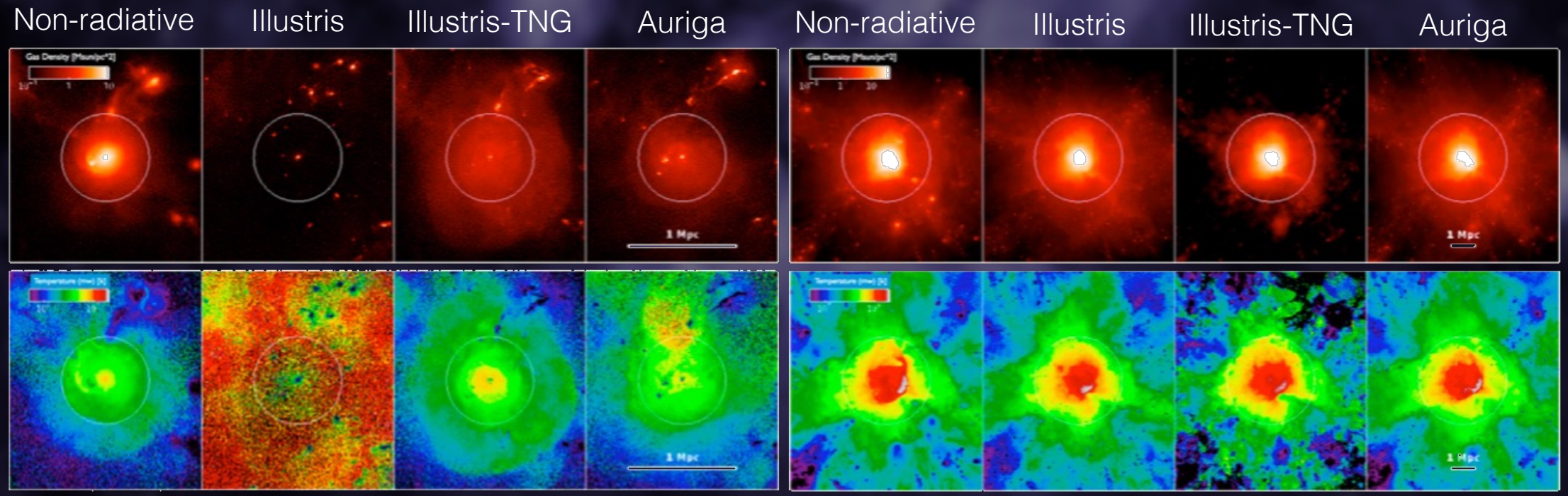
GALAXY GROUPS: THE ULTIMATE TESTING GROUND FOR NON-GRAVITATIONAL PROCESSES

Galaxy group: $M_h \sim 2 \times 10^{13}\, M_\odot$

Galaxy cluster: $M_h \sim 2 \times 10^{15}\, M_\odot$

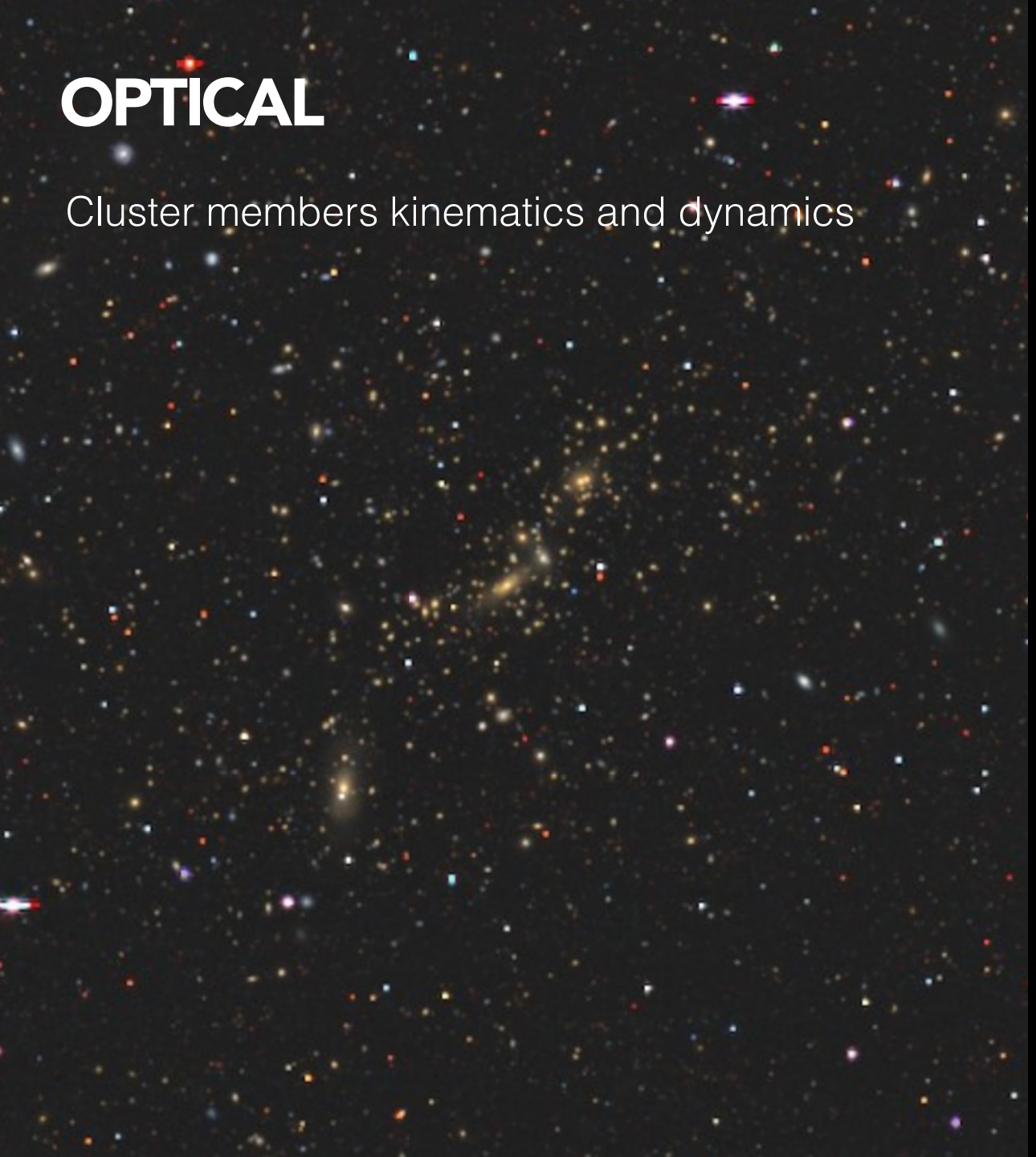


Plot by A. Pillepich

Feedback can affect strongly on the gas properties

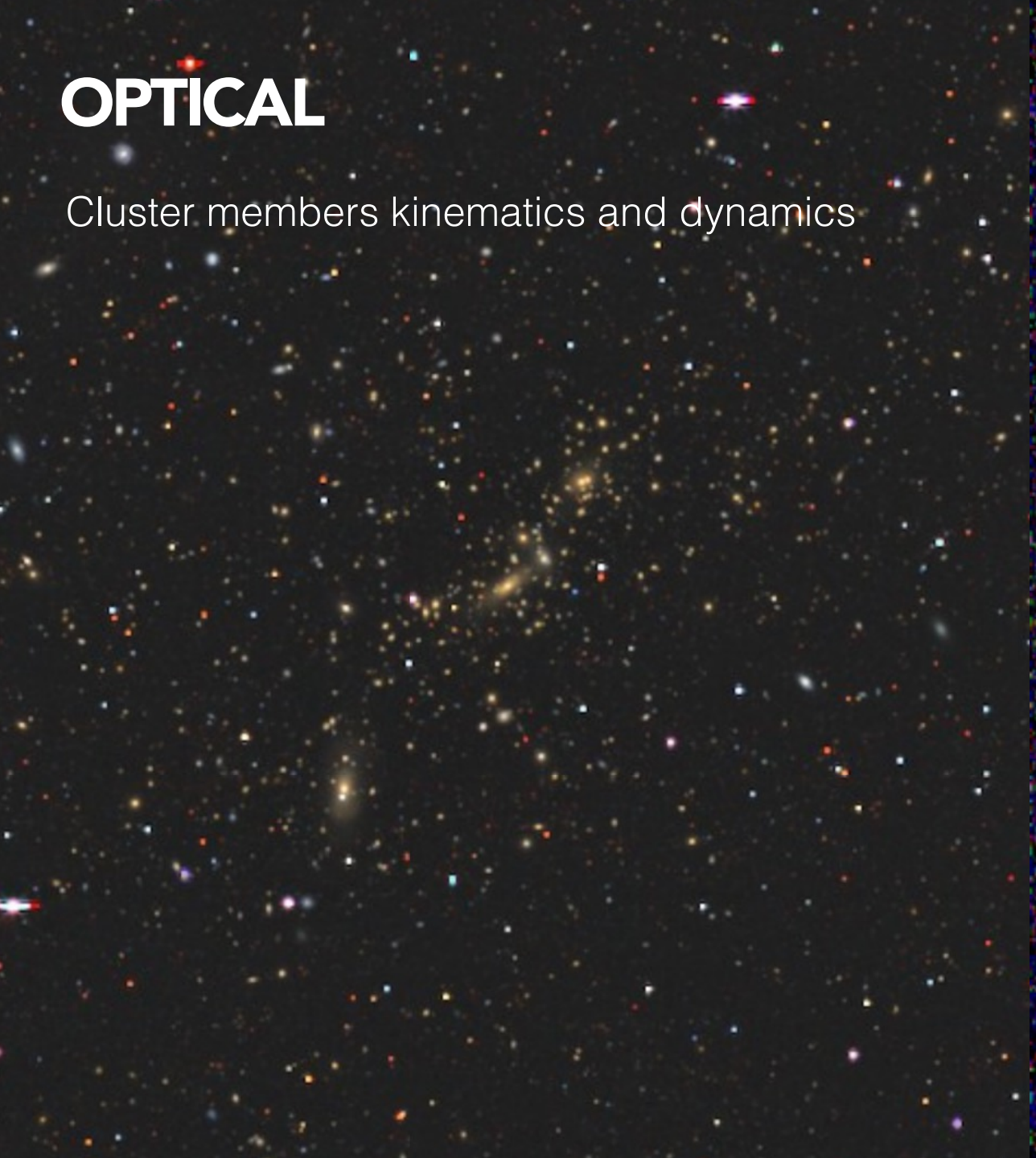
Feedback has marginal effect on temperature and density


OPTICAL



OPTICAL

Cluster members kinematics and dynamics


OPTICAL
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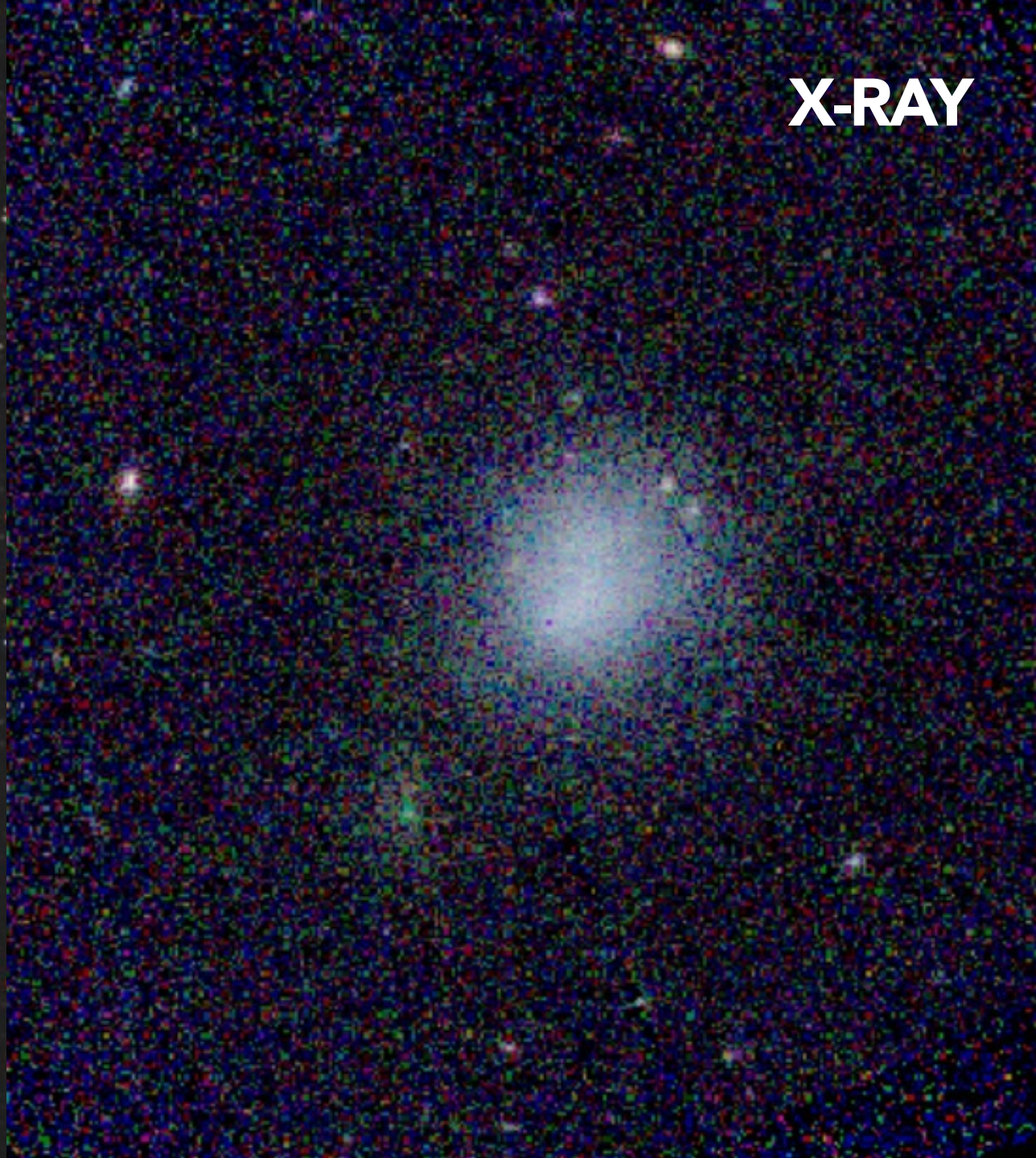
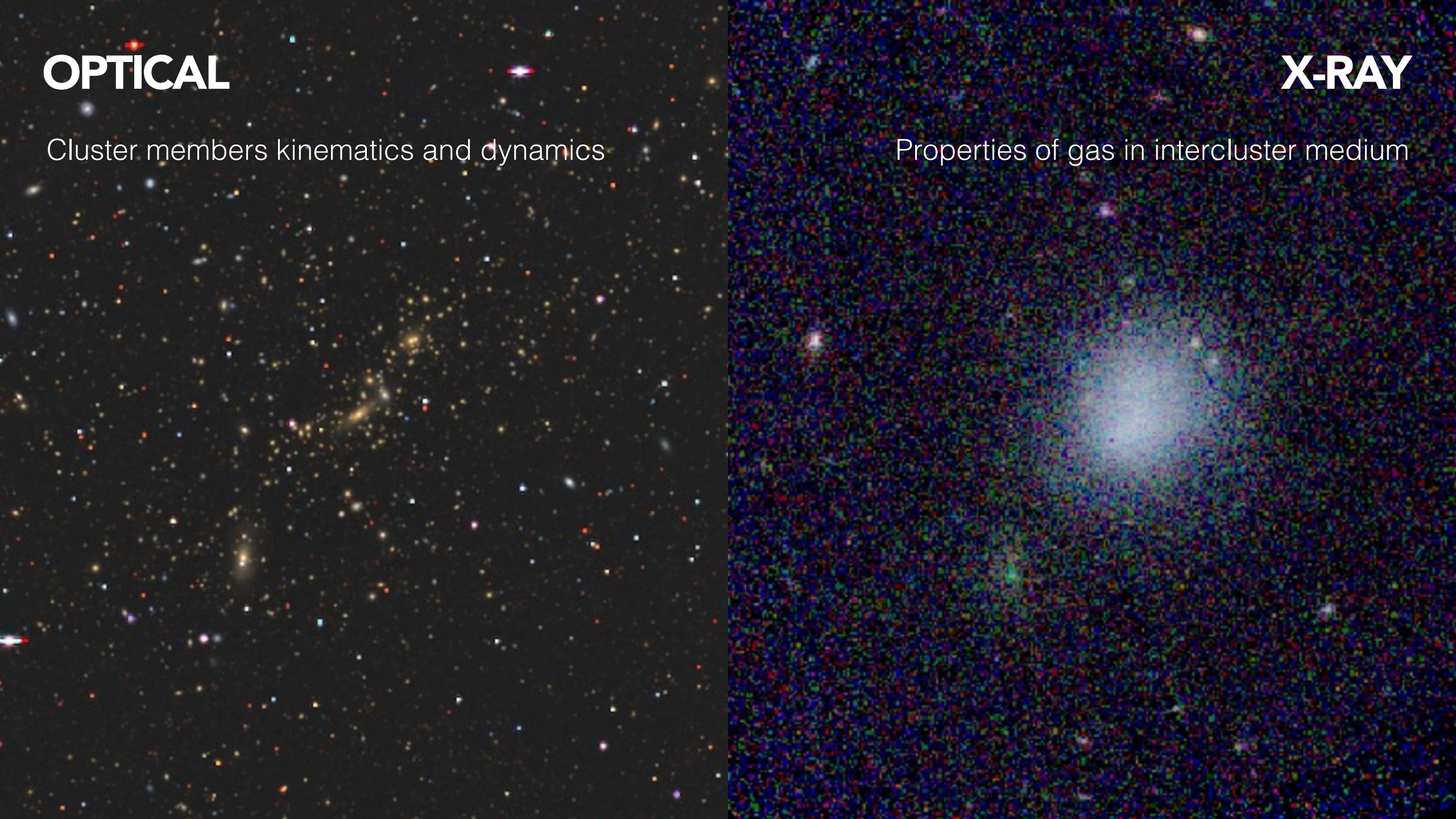
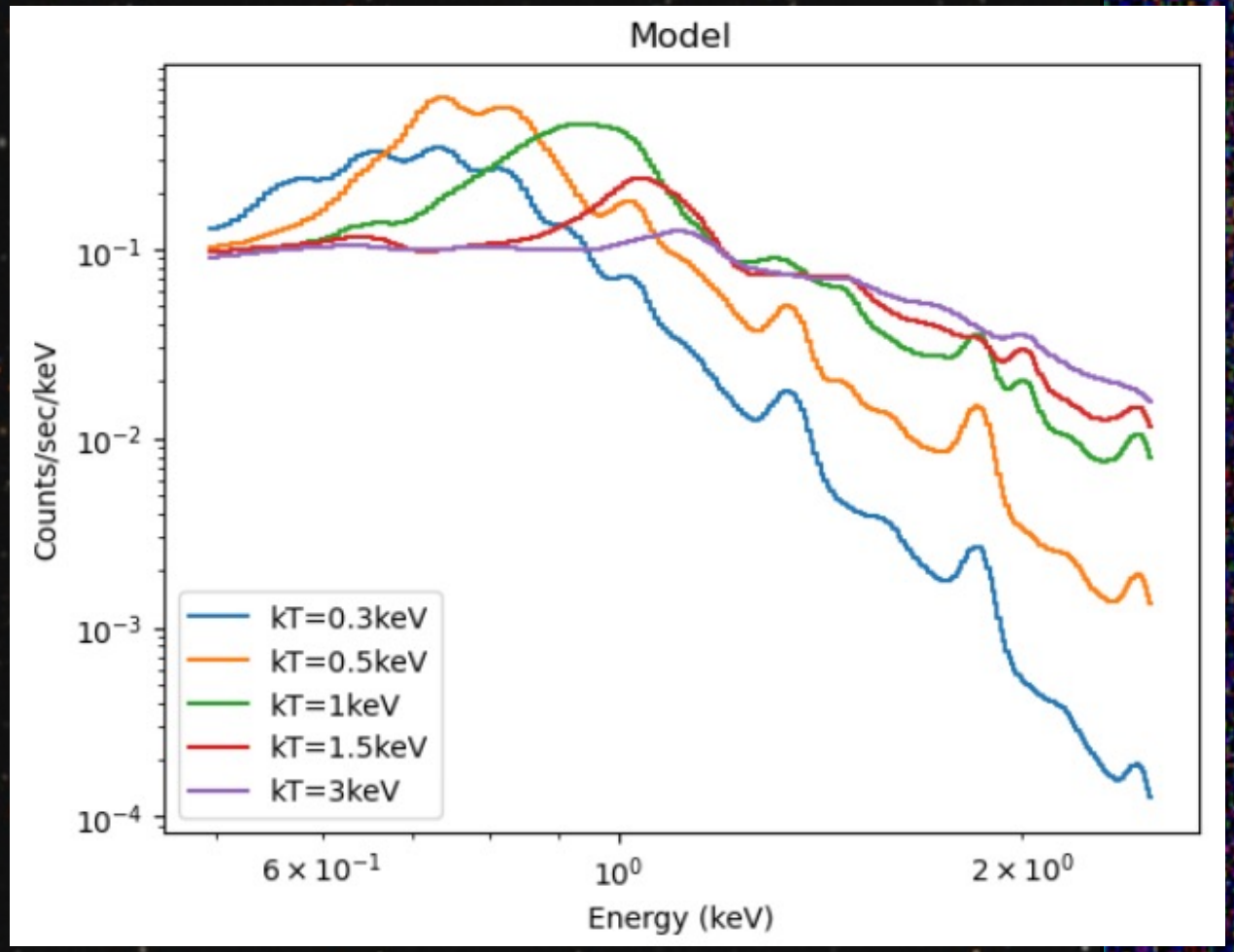

X-RAY


OPTICAL
Cluster members kinematics and dynamics
X-RAY
Properties of gas in intercluster medium

OPTICAL

Cluster members kinematics and dynamics



X-RAY

Properties of gas in intercluster medium

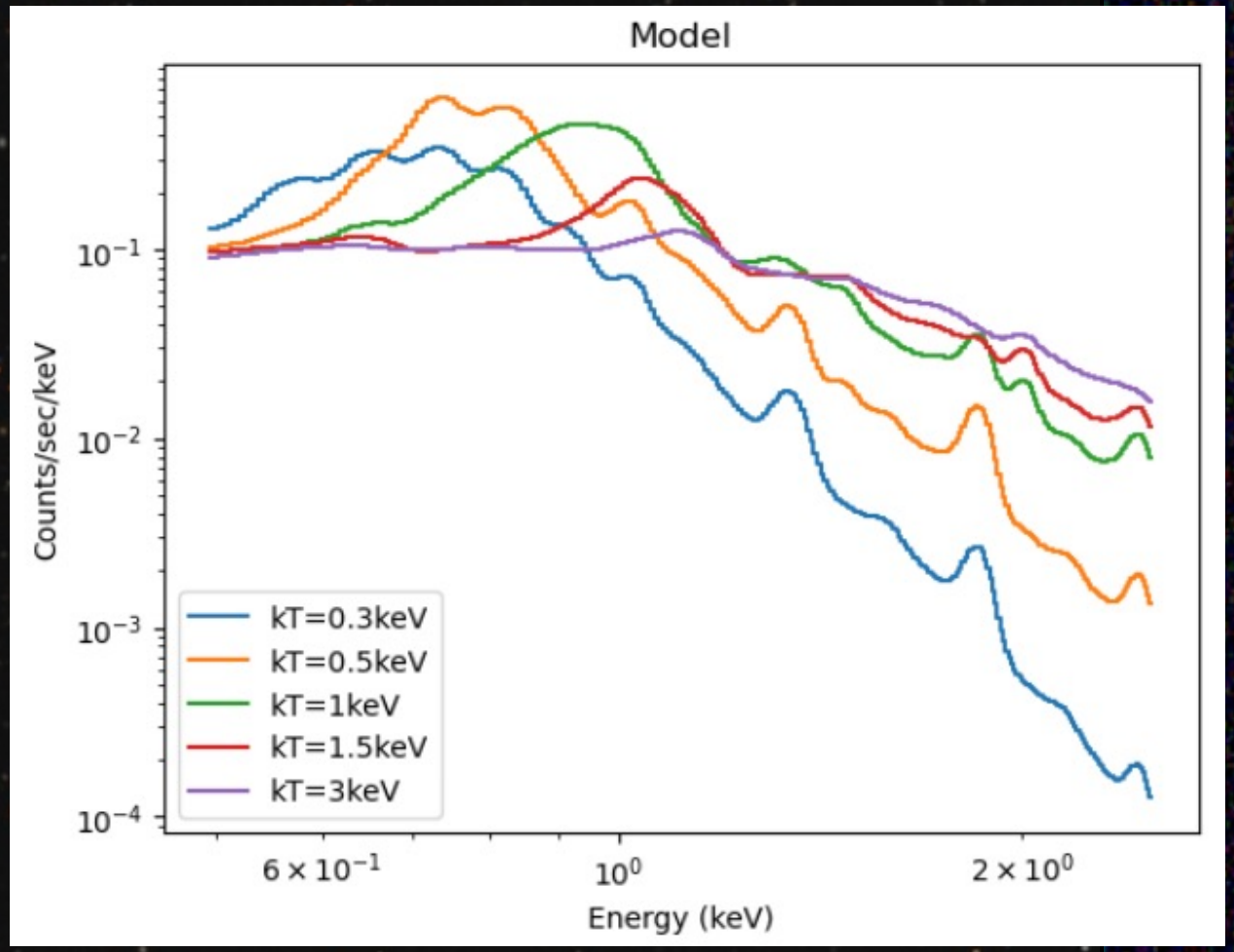
Estimation of the gas temperature by modeling X-ray spectrum

OPTICAL

Cluster members kinematics and dynamics

X-RAY

Properties of gas in intercluster medium



→ Temperature

→ Luminosity

→ Temperature and surf. brightness profiles

Estimation of the gas temperature by modeling X-ray spectrum

OPTICAL

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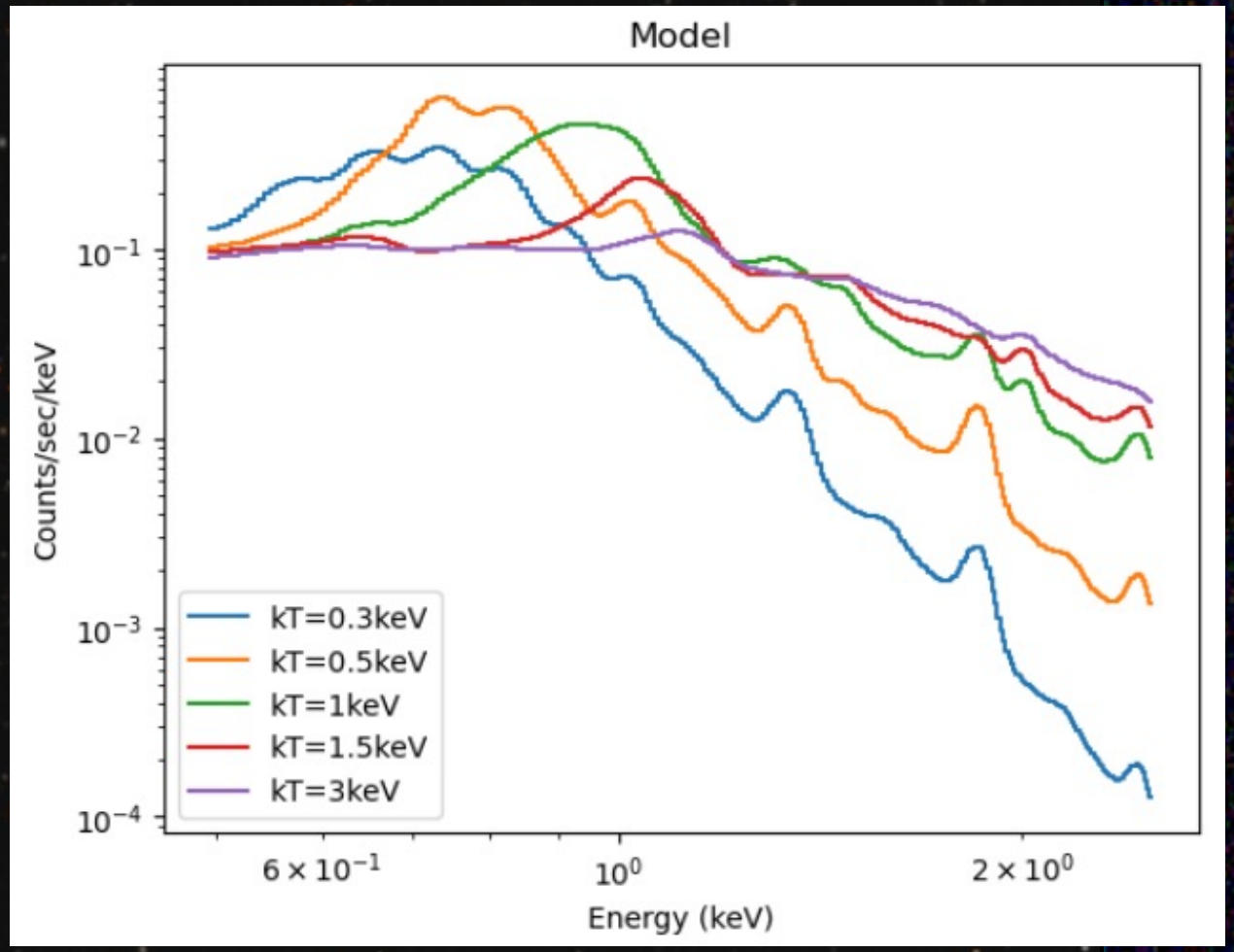


X-RAY

Properties of gas in intercluster medium

→ Temperature

→ Luminosity

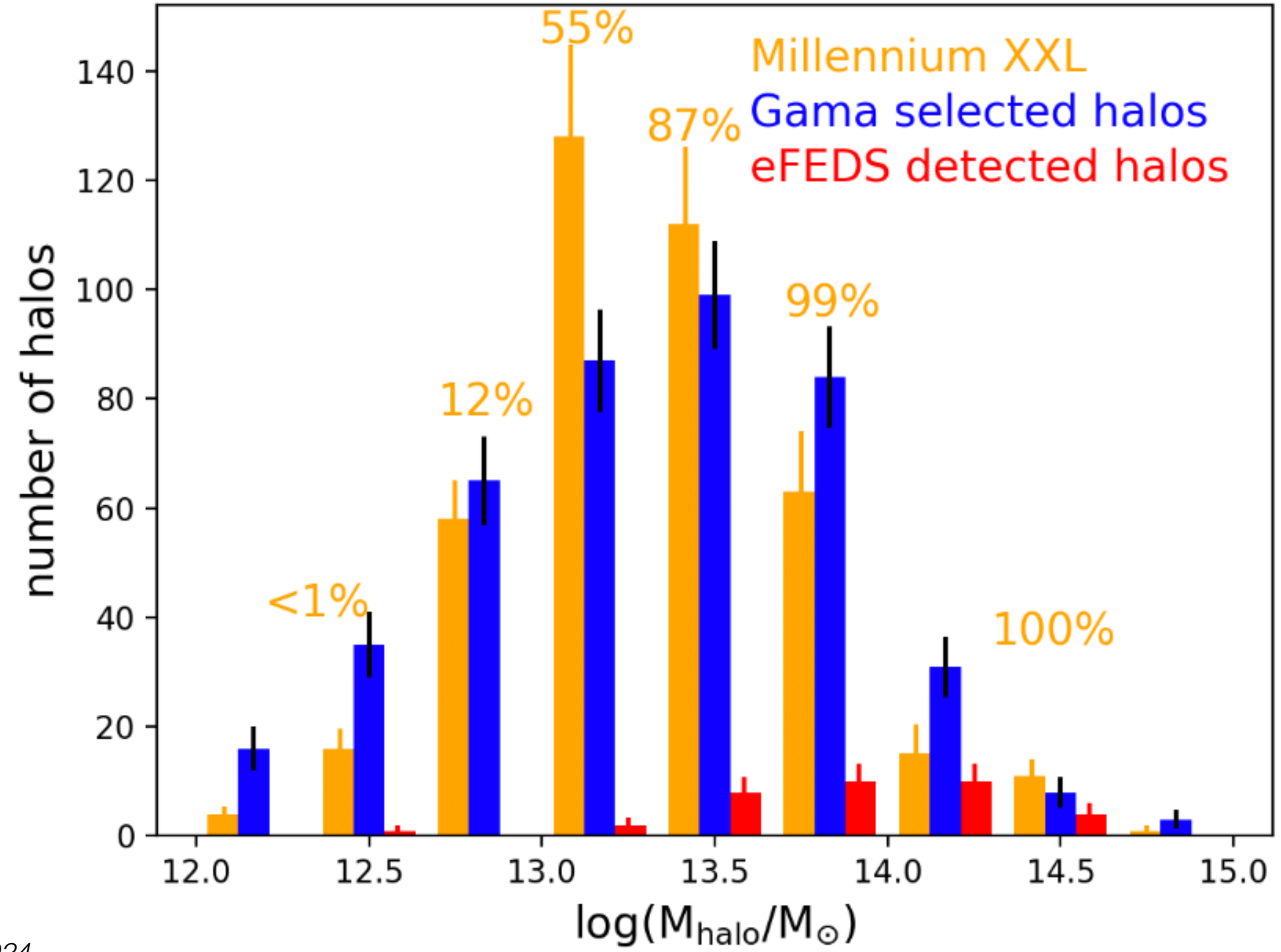
→ Temperature and surf. brightness profiles

→ Scaling relations with internal properties (halo mass, BCG stellar mass…)

→ Gas fraction

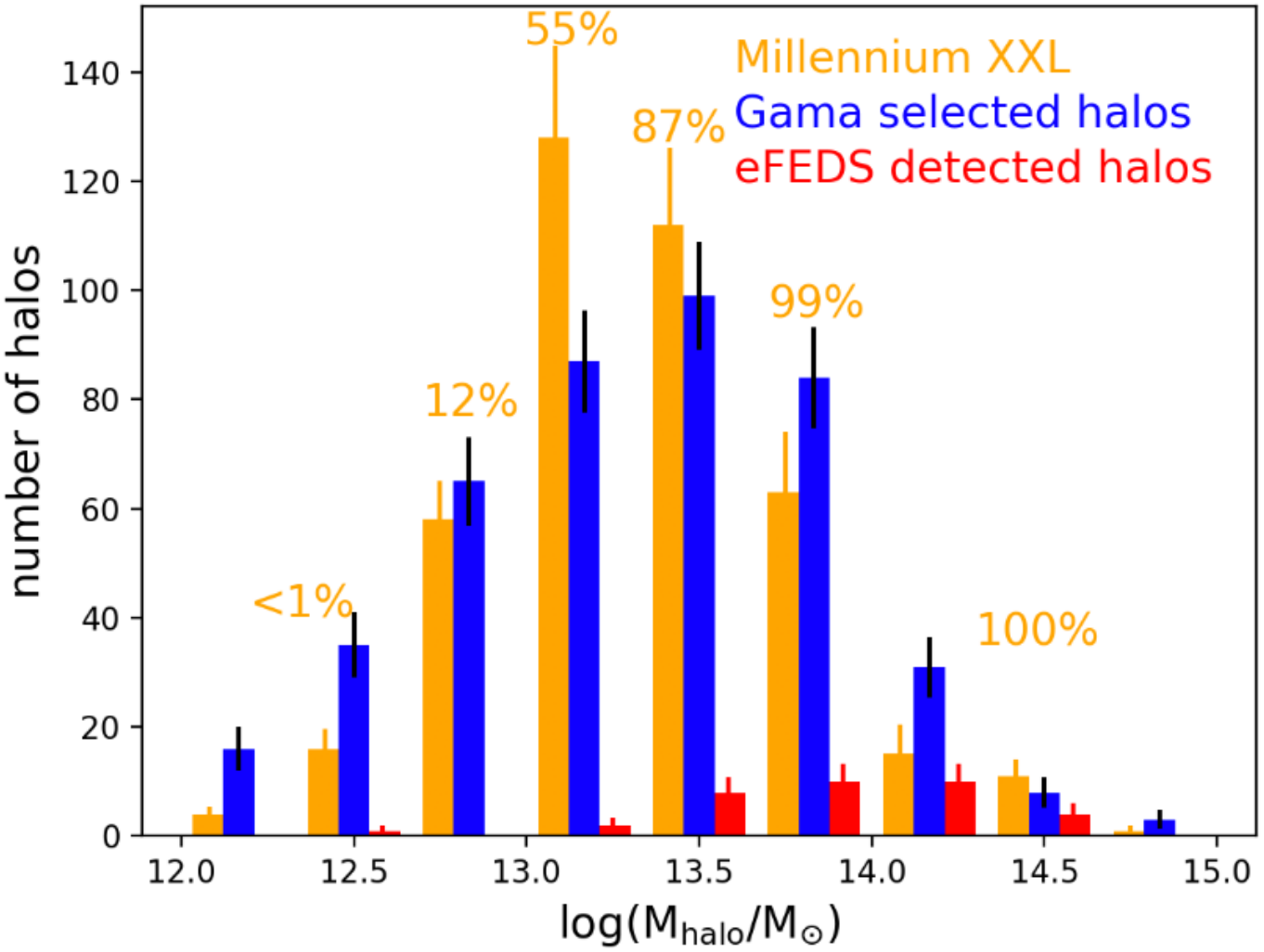
→ Entropy profile

Estimation of the gas temperature by modeling X-ray spectrum



Popesso et al. 2024

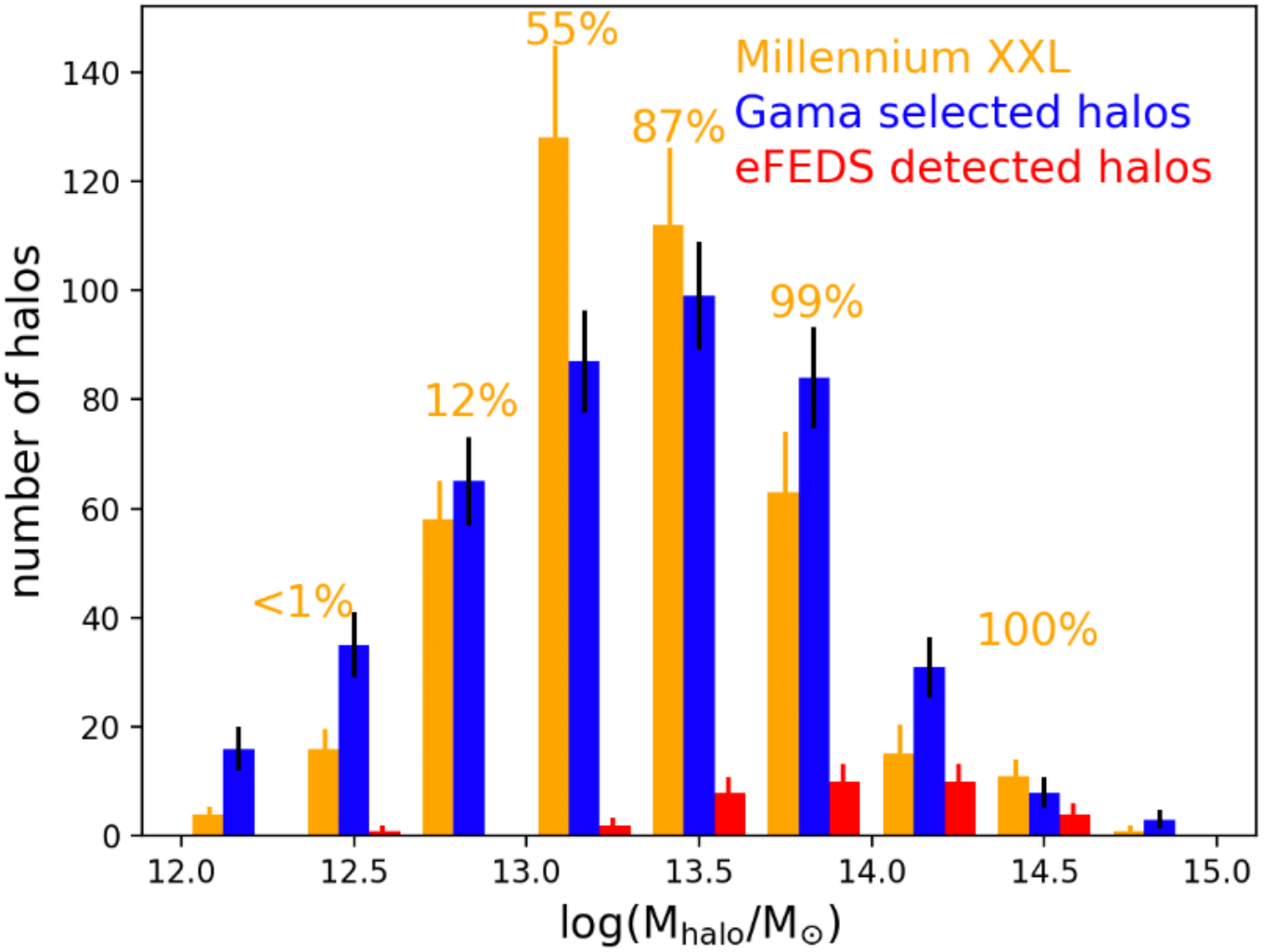
OBSERVATIONAL BIASES



Popesso et al. 2024

$M_h \sim 2x10^{13} M_\odot$

OBSERVATIONAL BIASES



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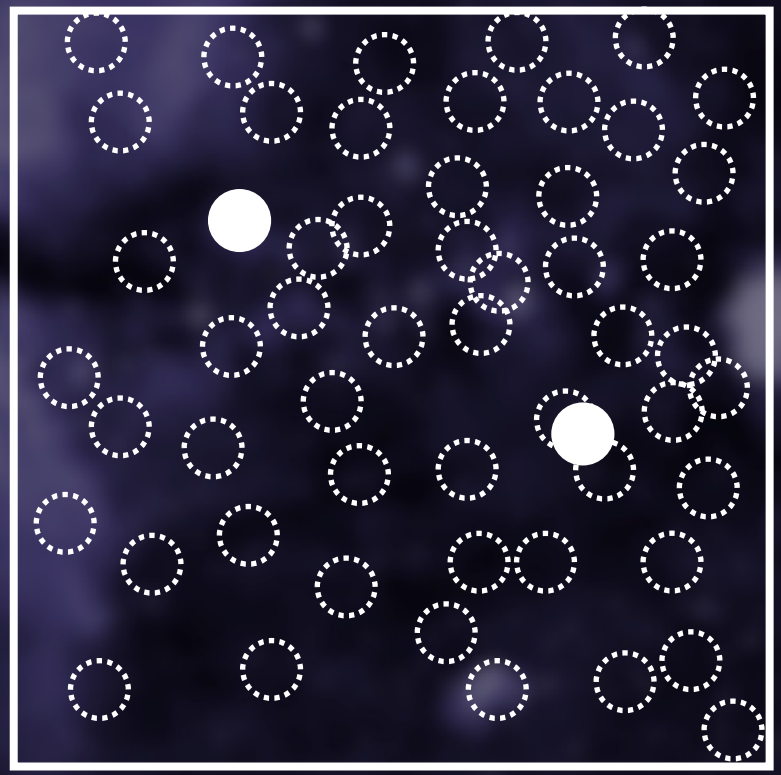

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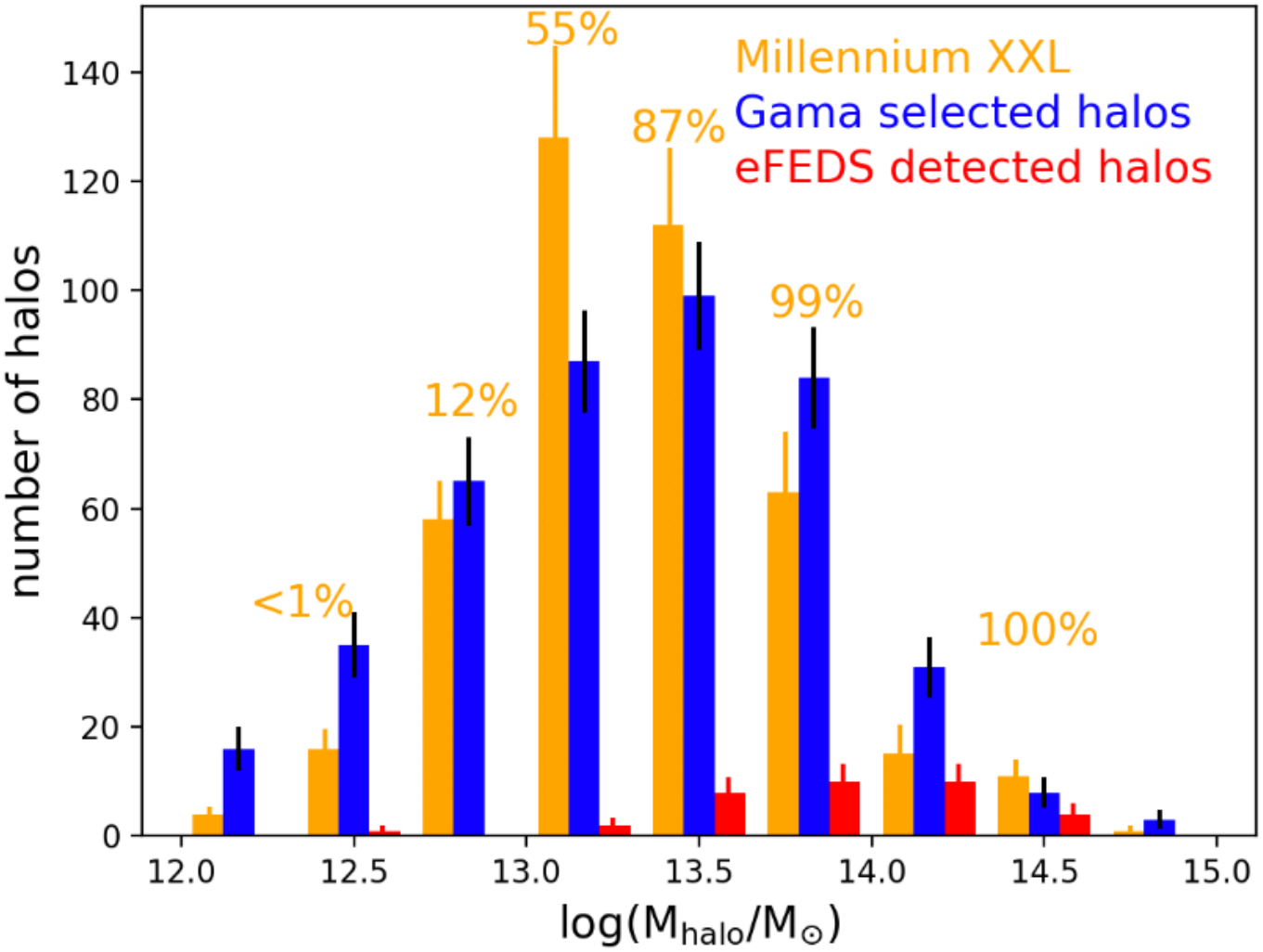
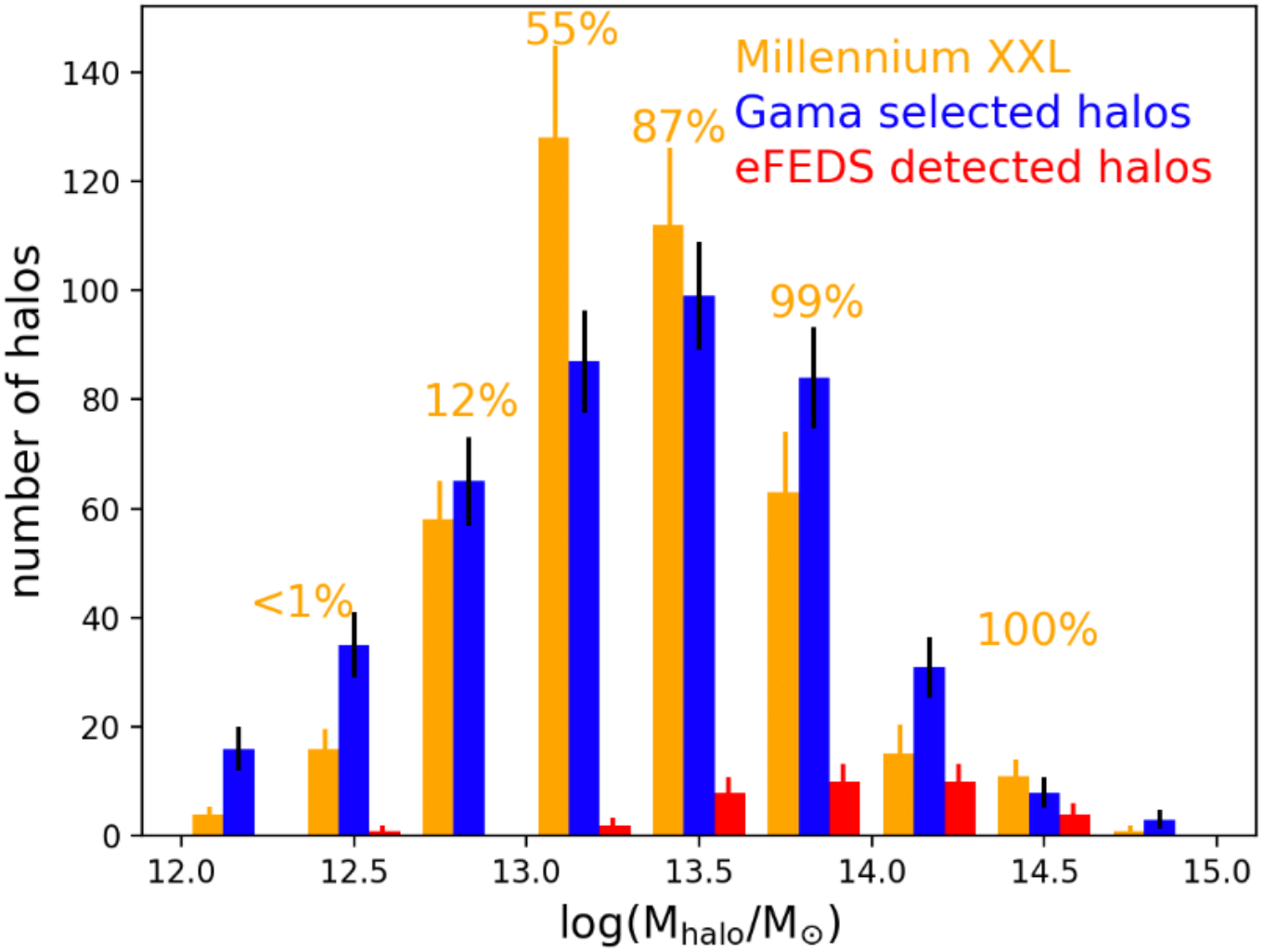


Popesso et al. 2024

Only the brightest groups can be studied with X-ray -> low-mass end of scaling relations populated poorly

OBSERVATIONAL BIASES



Popesso et al. 2024

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That might cause biases as far as selecting the brightest X-ray groups and then study their X-ray properties

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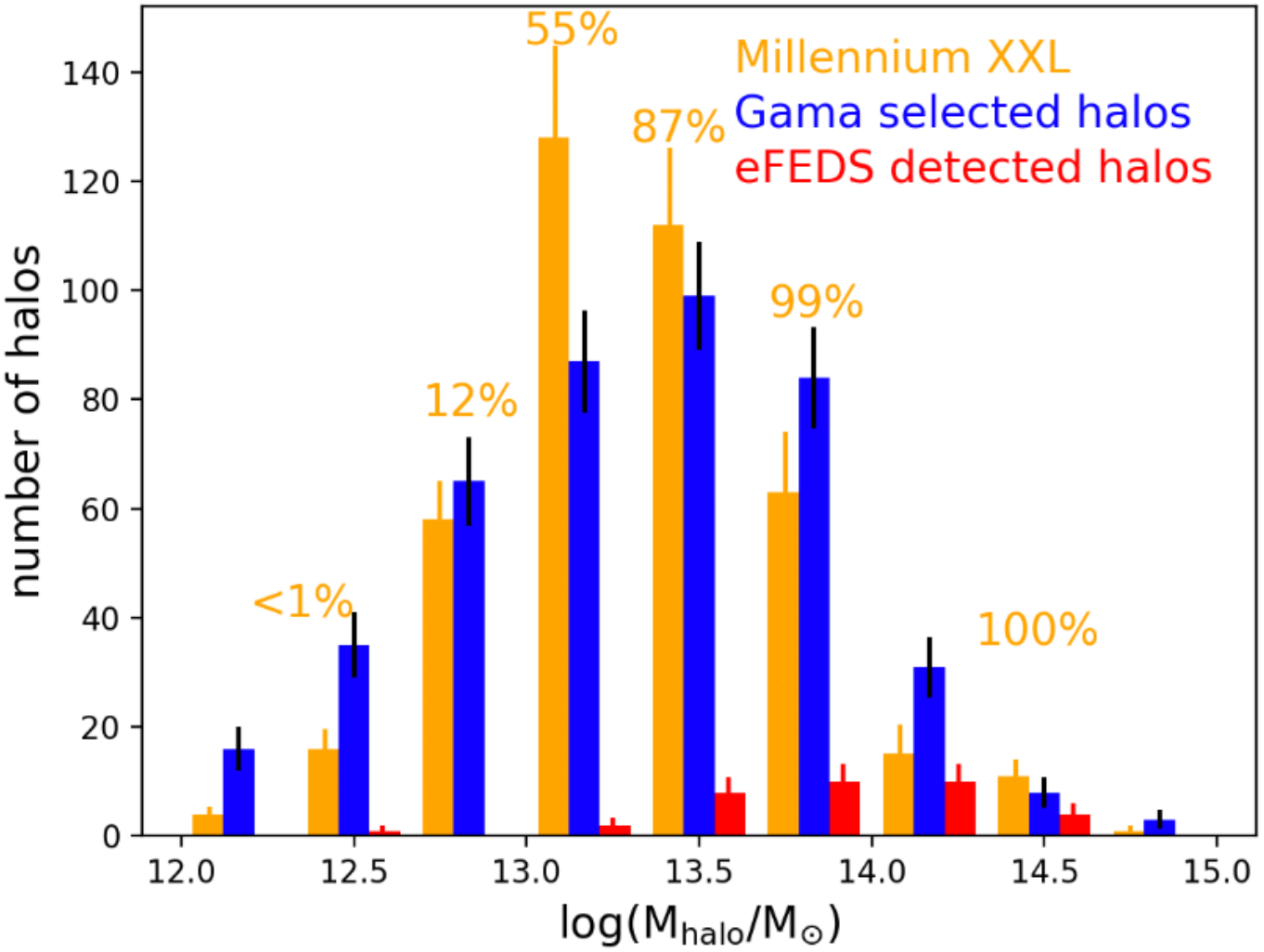

Popesso et al. 2024

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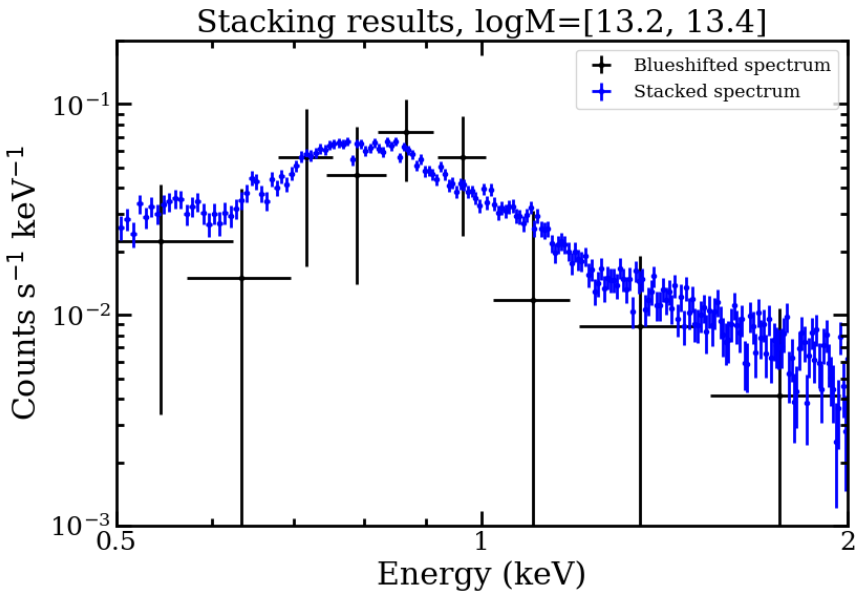
We should look for other approaches of sample selection and add X-ray faint groups

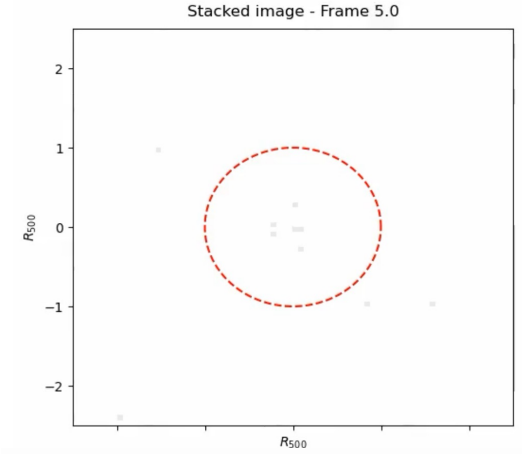

OUR METHODS
Galaxy Evolution Coffee
24 July 2025, ESO

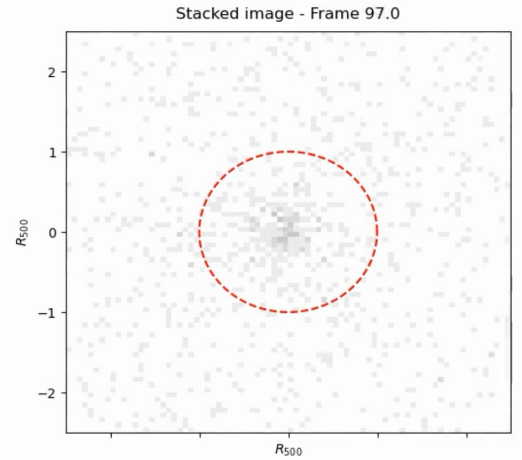
MAIN TECHNIQUE: STACKING

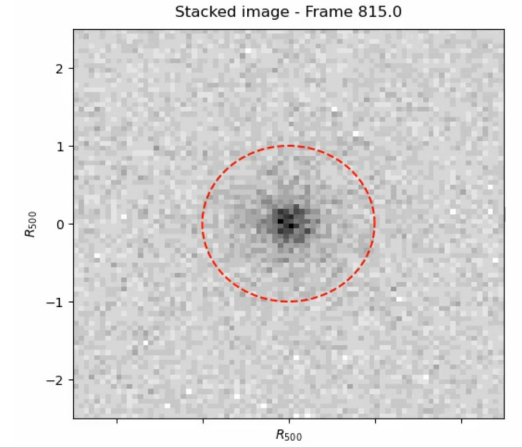
The use the sample of faint sources will lead to lack of photons that will not allow us to model the spectrum and estimate the temperature for most of the source

but it could be avoided by stacking all the sources together in the bins with same properties









ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

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ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

- Friend-of-friend algorithms
- Optical halo mass proxies
(total luminosity, total stellar mass)

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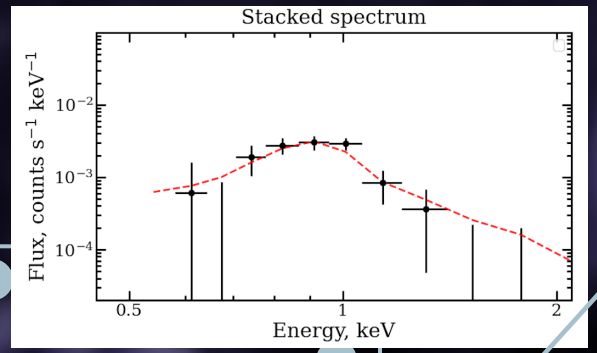
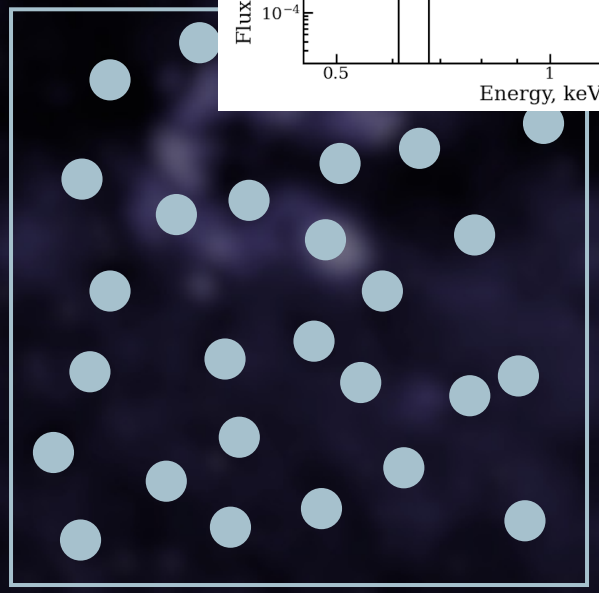
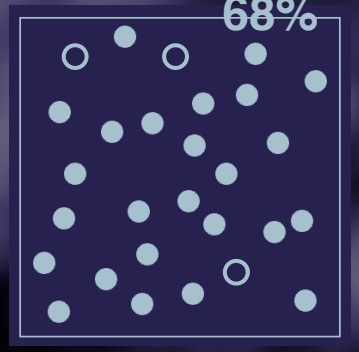
ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

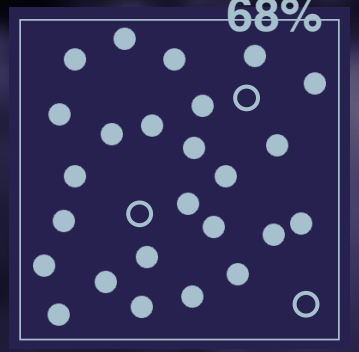
- Extraction of individual spectra/SB profile
- Blueshifting to rest-frame
- Stacking all of them within the bin
- Modeling

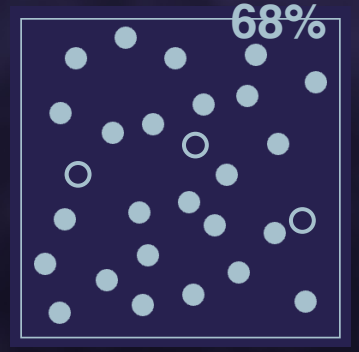
ESTIMATION OF STATISTICAL ERRORS

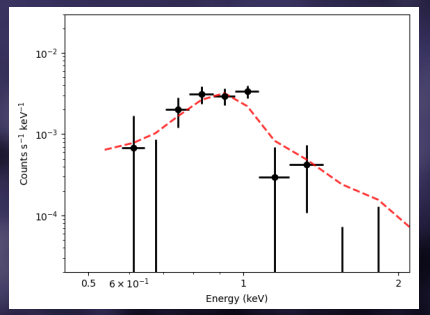


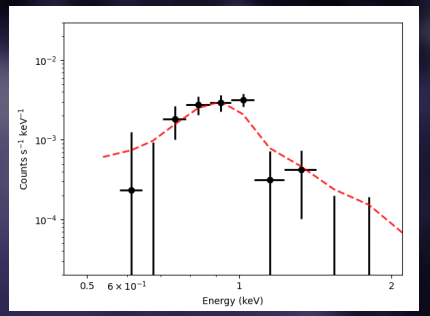


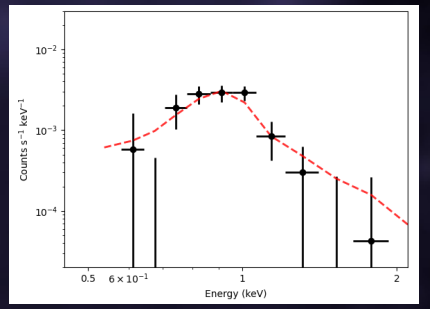




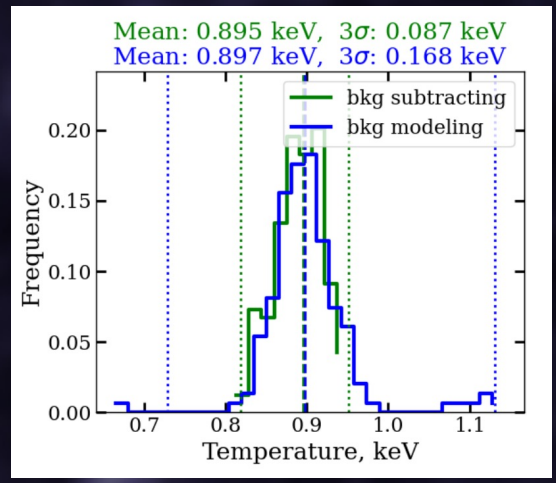






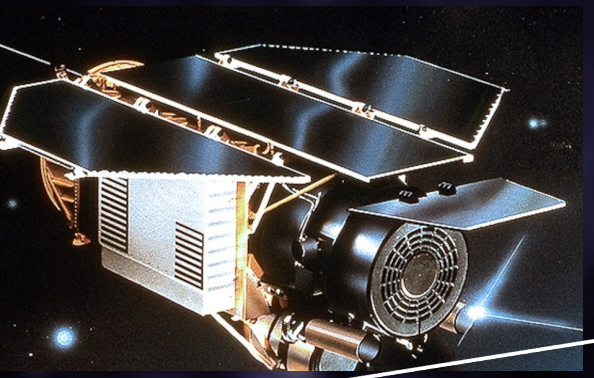


Slightly different temperatures for different subsamples

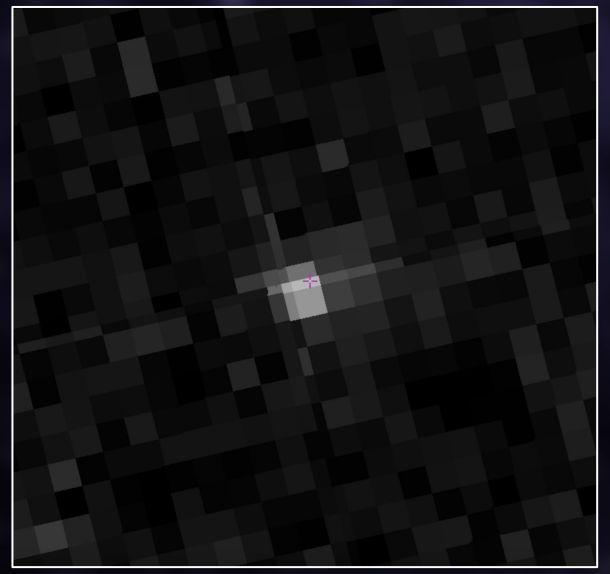


Temperatures by modeling with gadem model

ROSAT

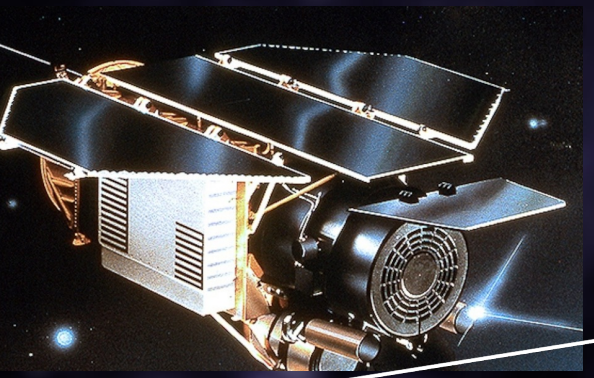


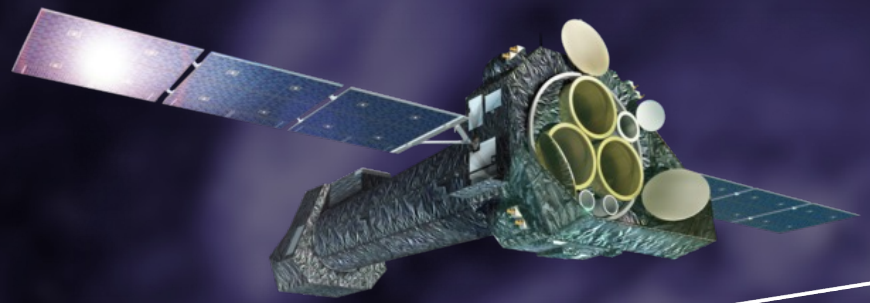
1990



ROSAT

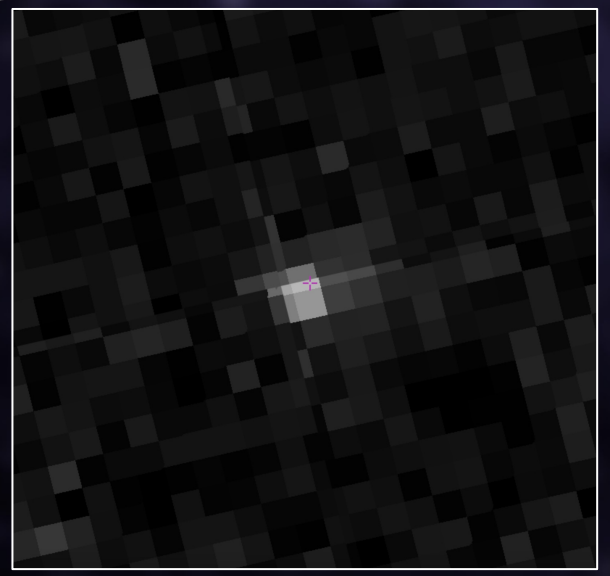
XMM-Newton

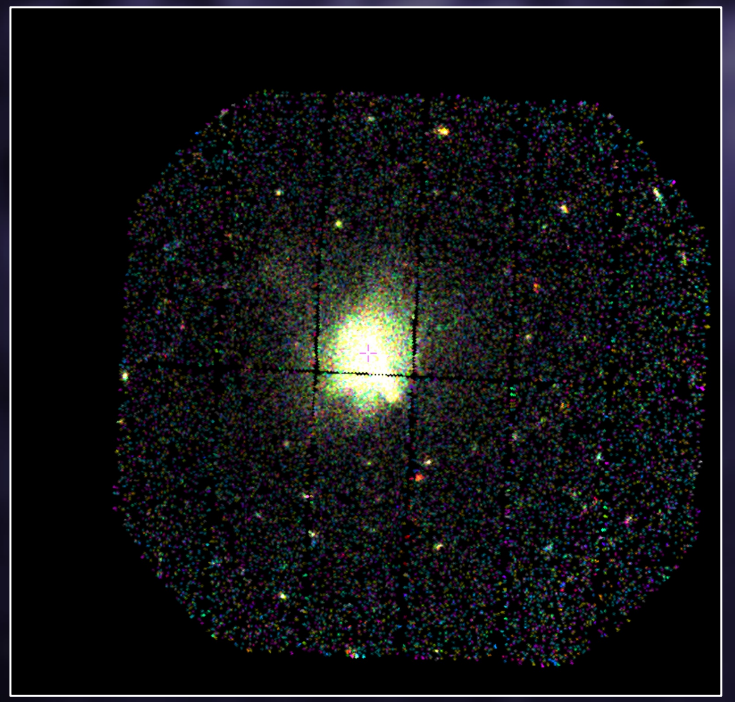




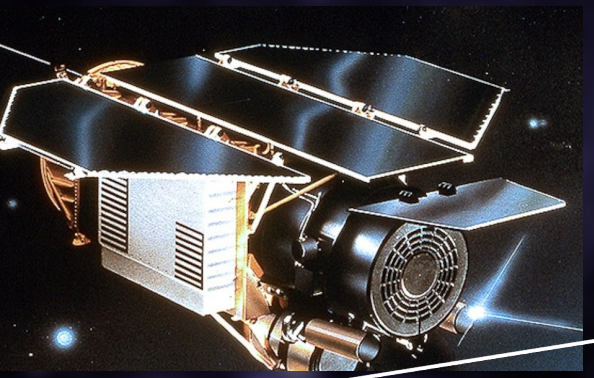
1990

2000

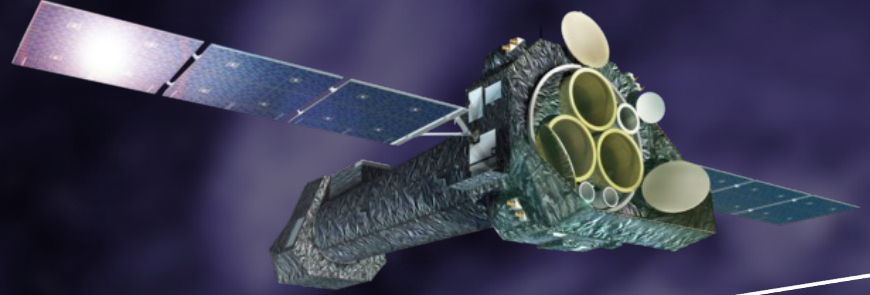


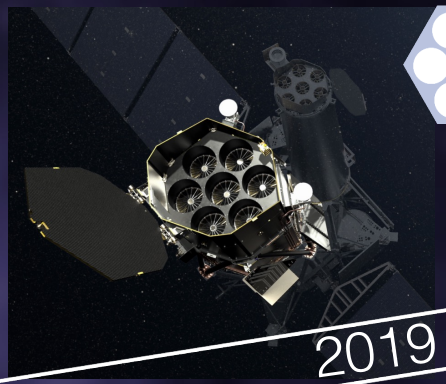


ROSAT



XMM-Newton



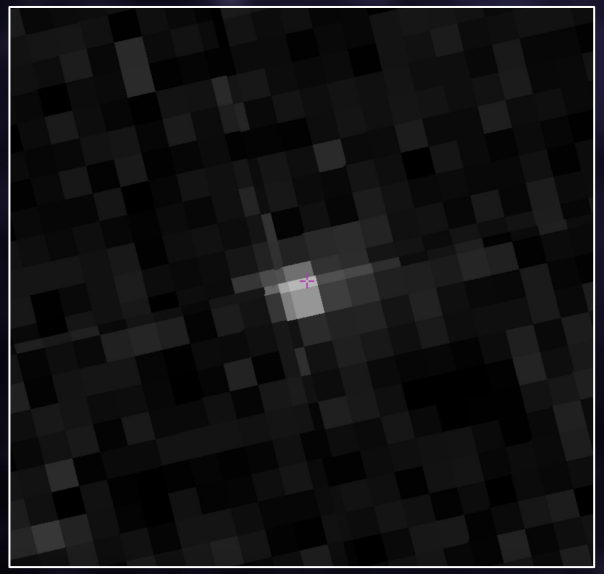


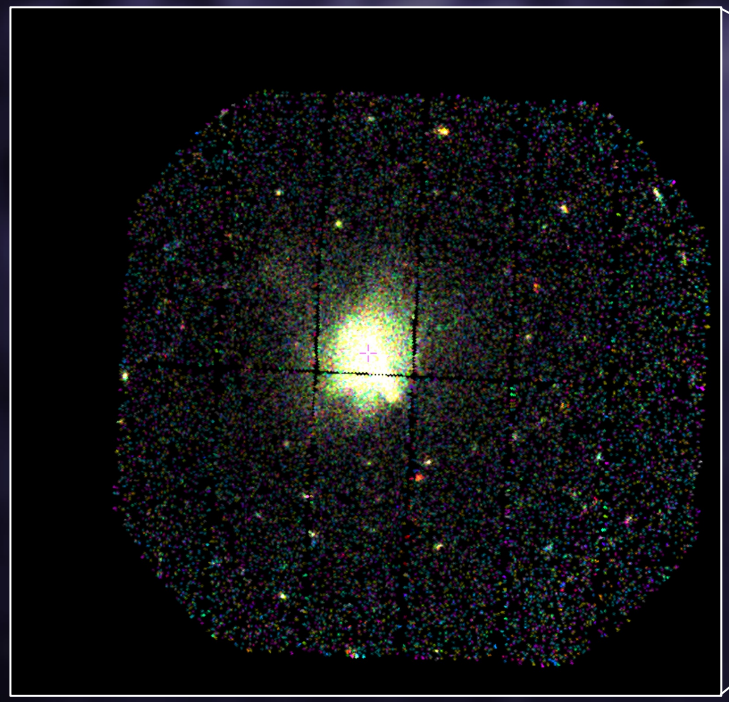
eROSITA

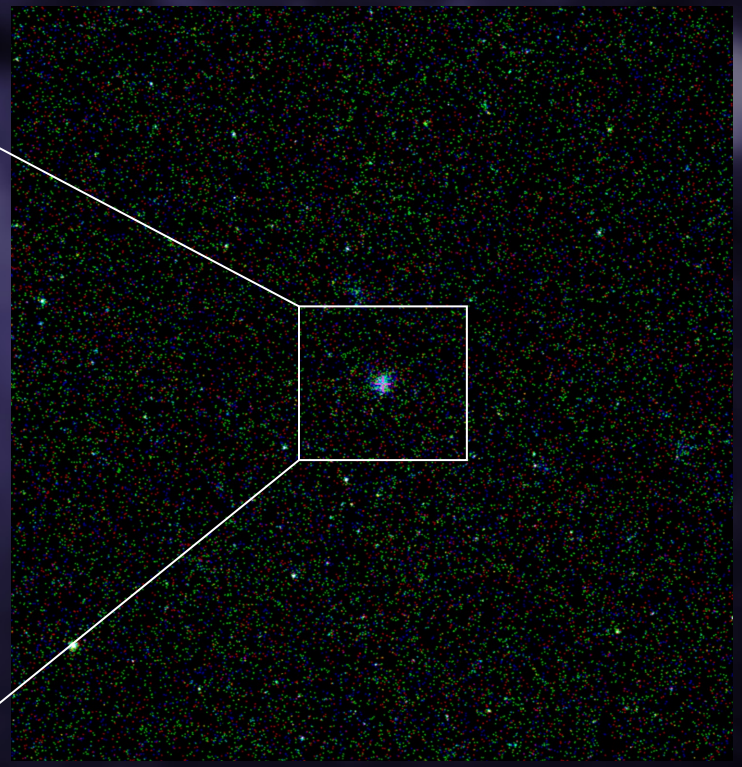
1990

2000

2019

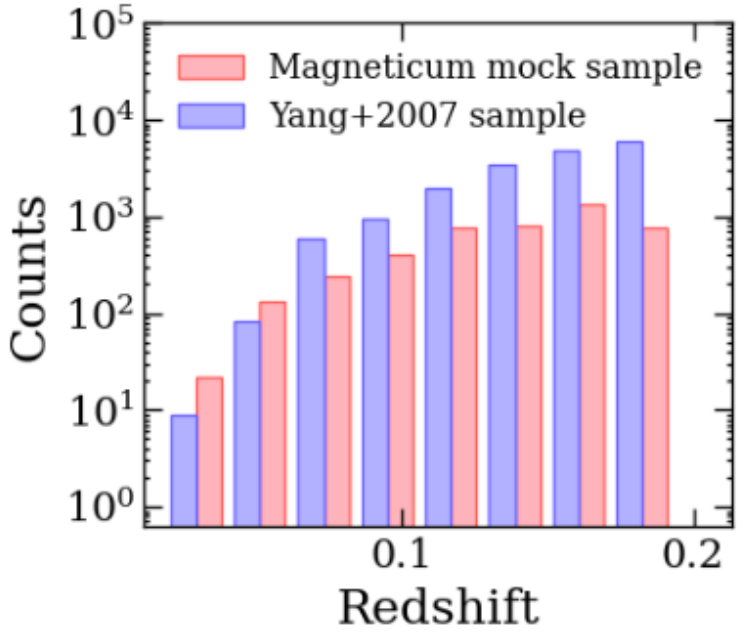


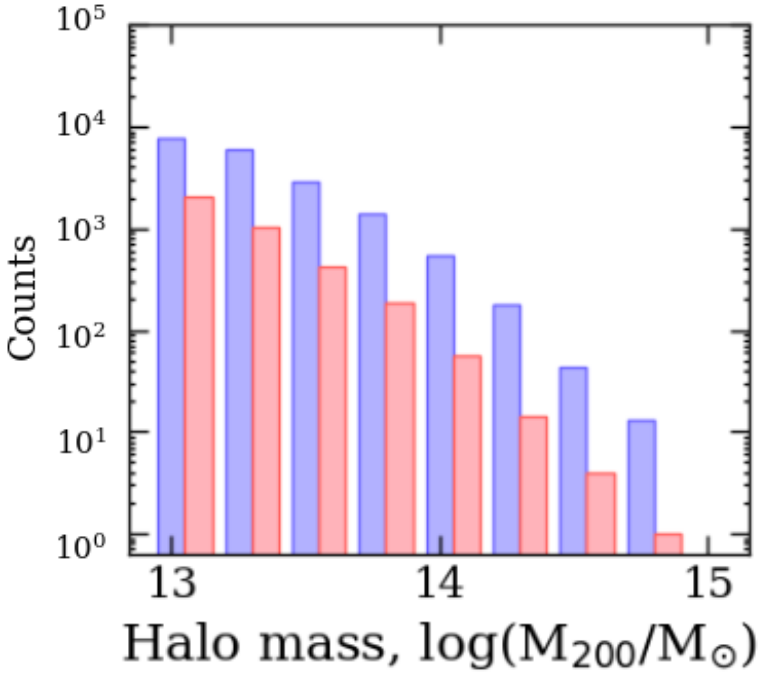




THE DATASET

- Yang+2007 groups sample selected by SDSS; all targets in SDSS field
- eRASS1 publicly available data





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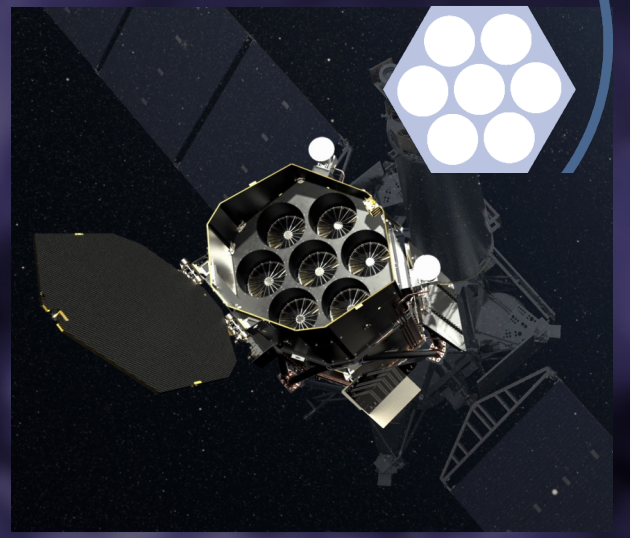

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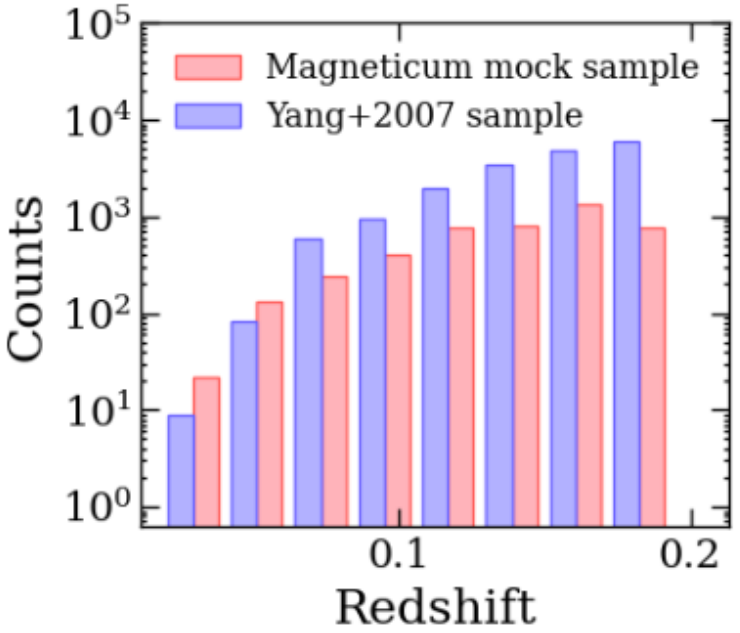
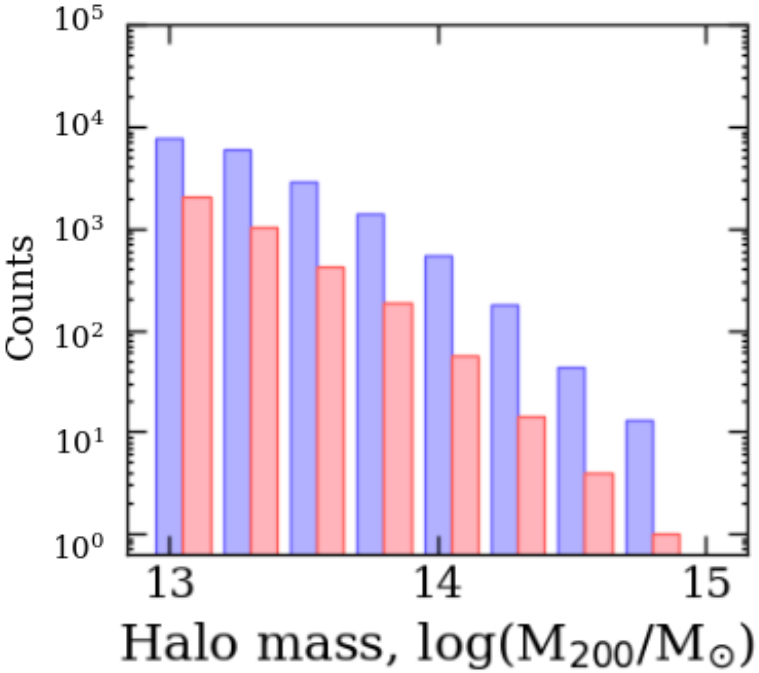
- Only local Universe up to z=0.2
- Removed all sources that contain other sources inside R_{500}
- Only sources without point-sources inside R_{500} in eRASS1 catalog





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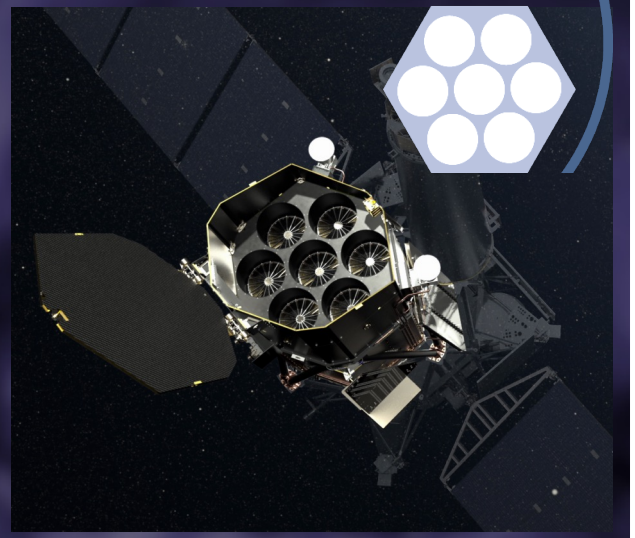

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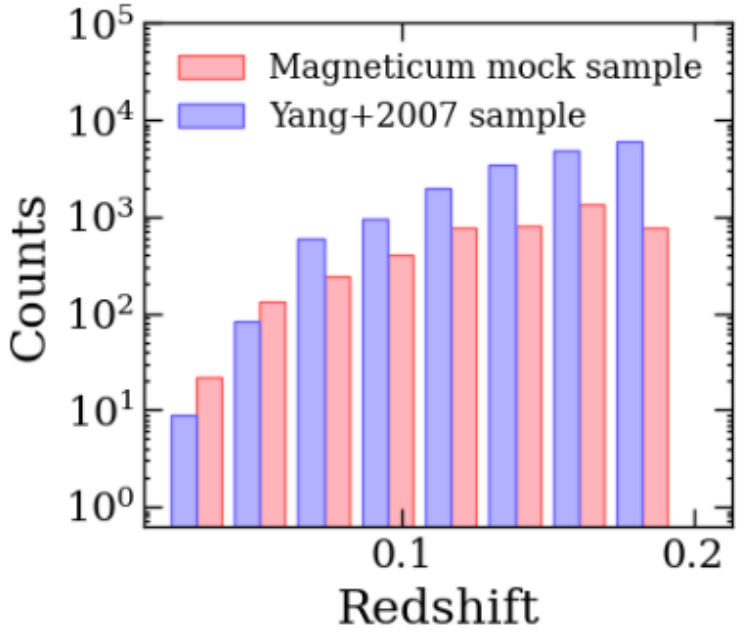
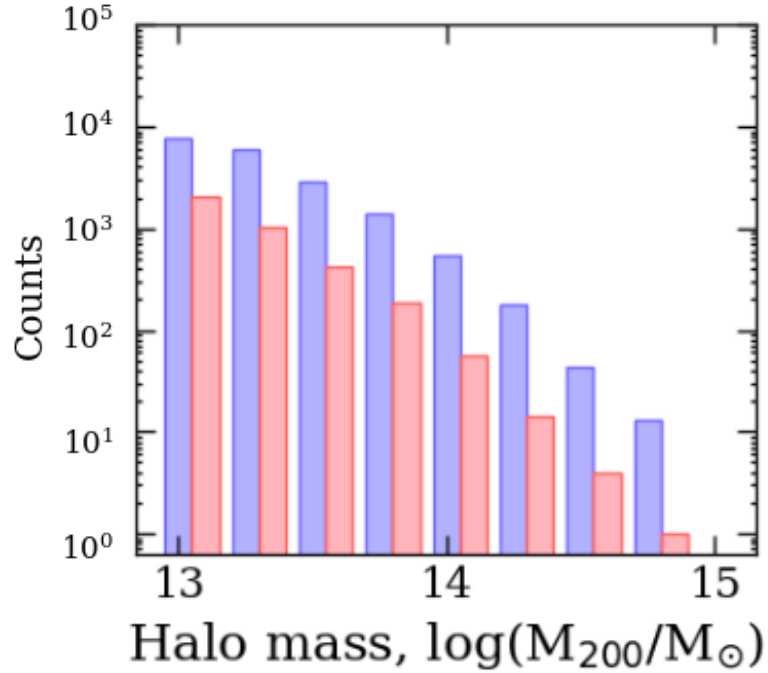
- The “mimic” sample with the same selection criteria from Magneticum for additional clarification





VALIDATION

Galaxy Evolution Coffee
24 July 2025, ESO

SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

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ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

IS IT RELIABLE?

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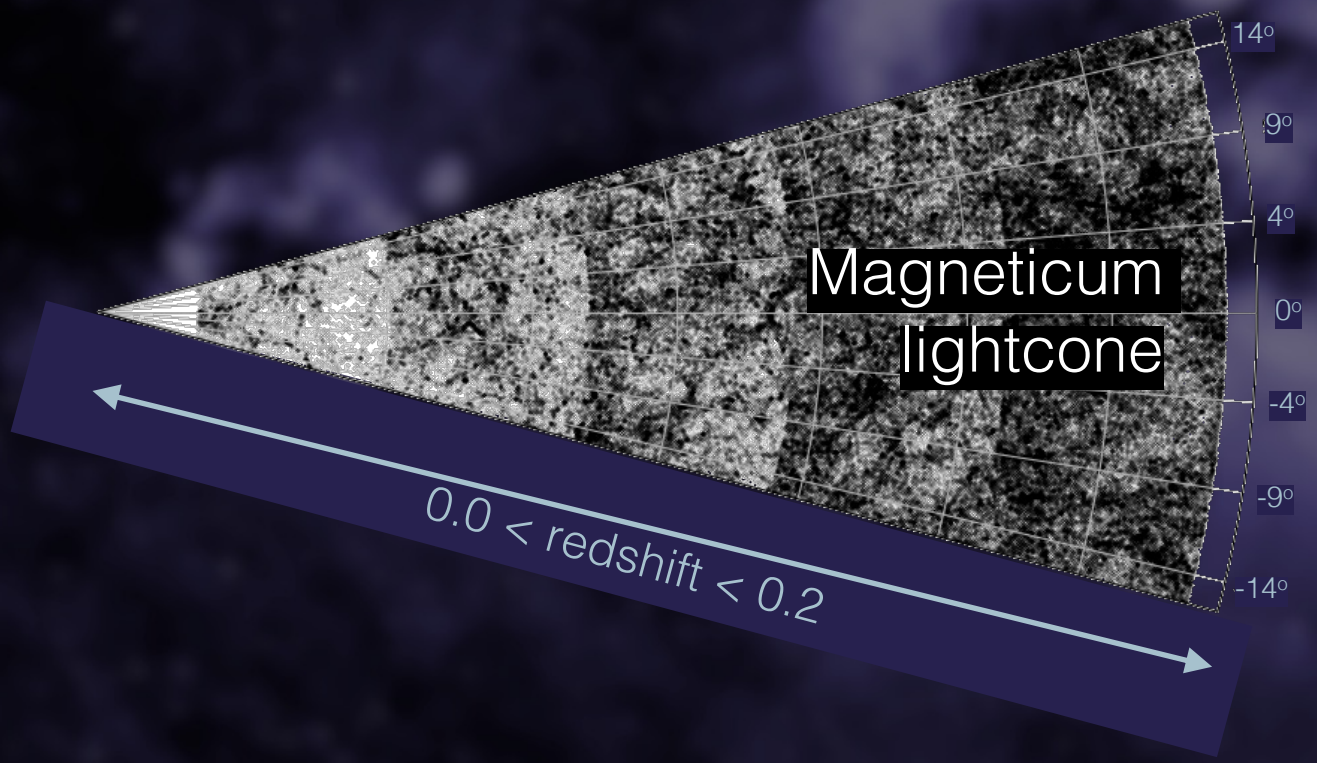
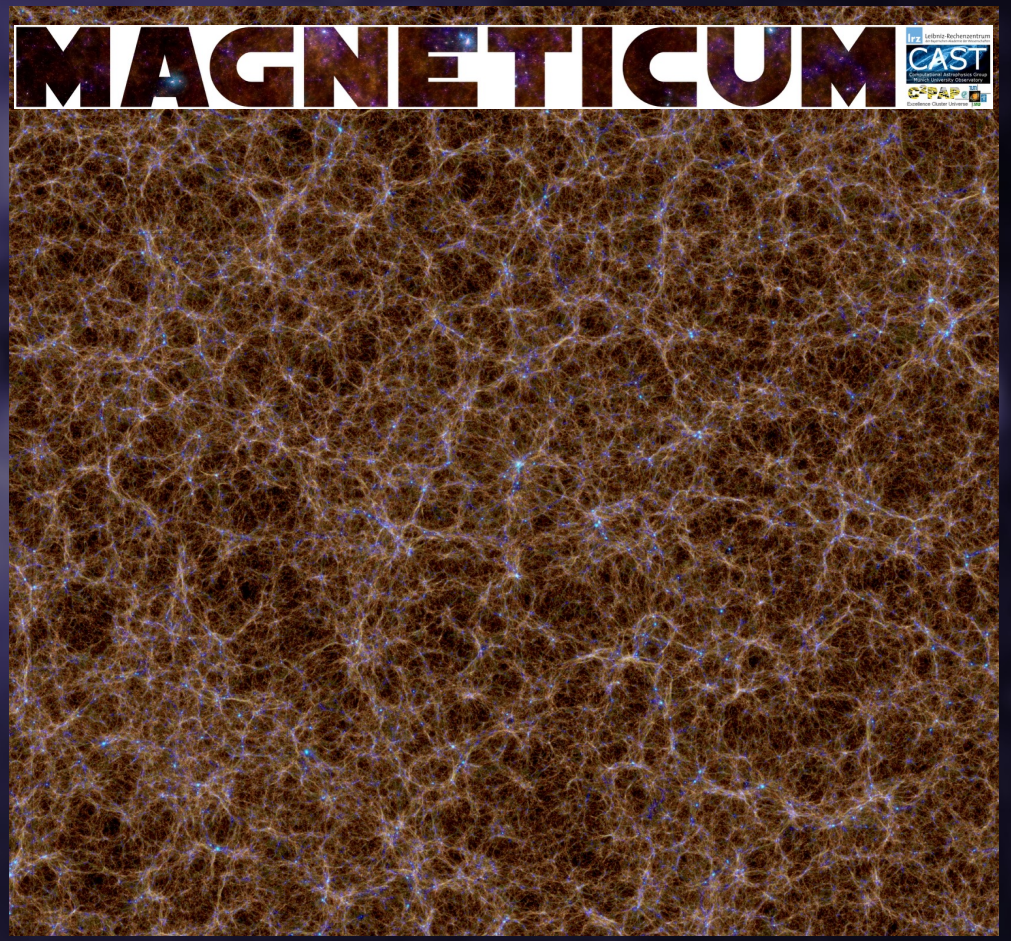
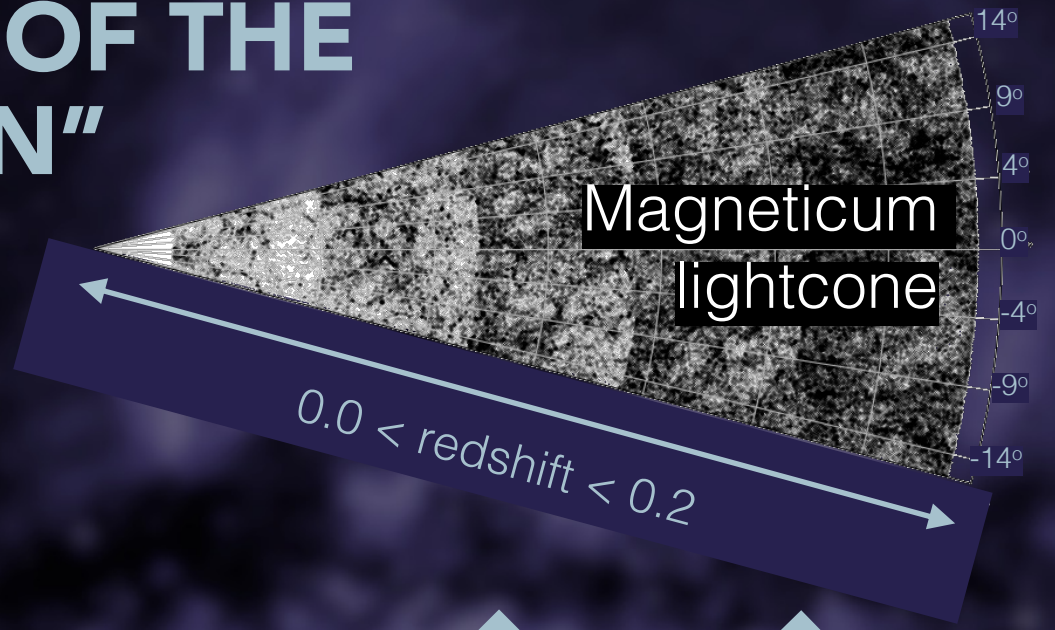
ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

ADVANTAGES OF THE "WELL-KNOWN" UNIVERSE

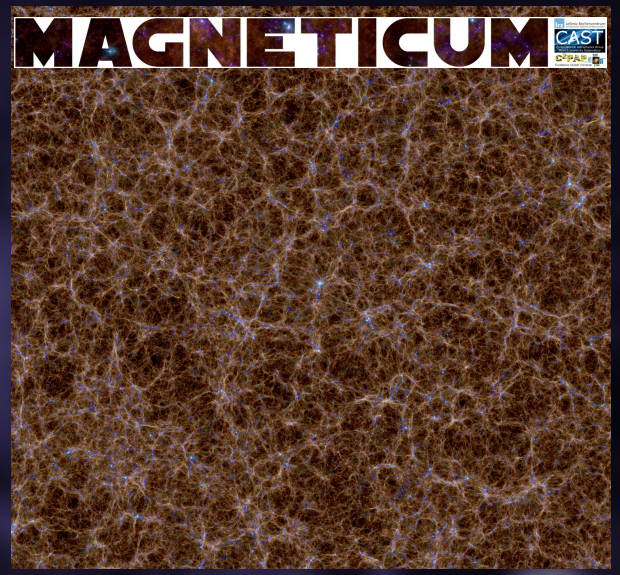




ADVANTAGES OF THE "WELL-KNOWN" UNIVERSE



Are optical catalogs reliable?



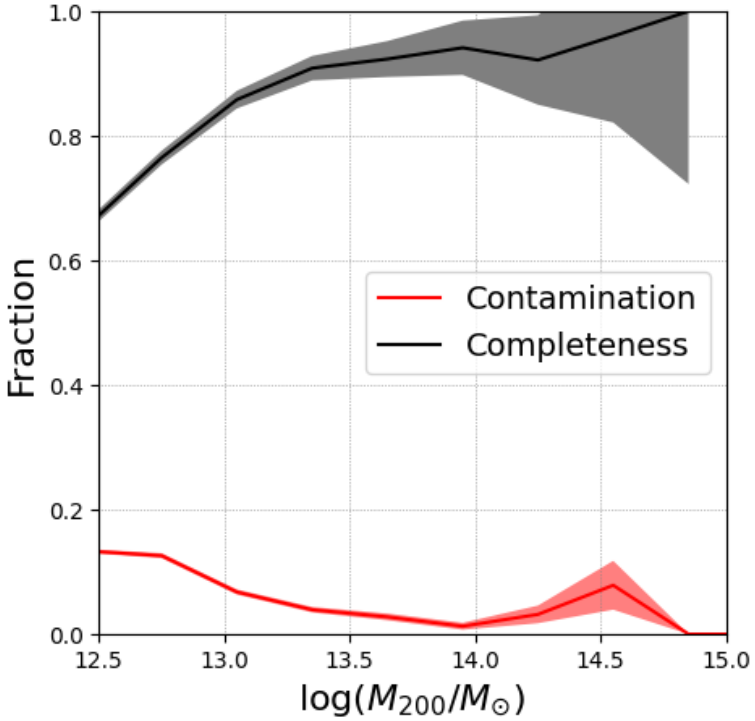
Ilaria Marini,
ESO

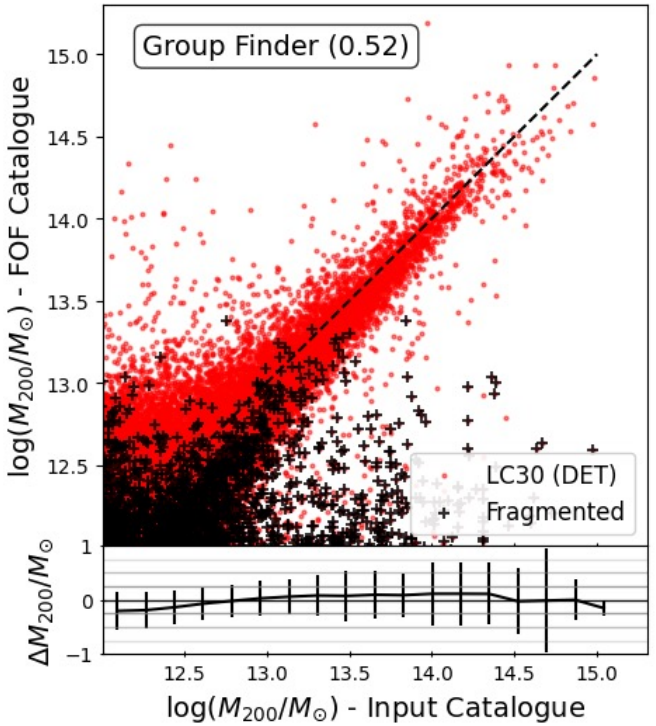
Marini et al. 2025a

Optical mock galaxy catalog

Are optical catalogs reliable?
Probably, yes

NEW WAY OF SAMPLE SELECTION





We used the group finder from the *Yang et al. (2007)* catalog of galaxy groups for the optical mock catalog to test how well it can reconstruct groups population. The method shows high completeness, low contamination, and can successfully reconstruct input halo masses.
For more information, see *Marini et al. 2025*

Optical group catalogs may be the good choice and appear as the new approach of the sample selection

SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

+

ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

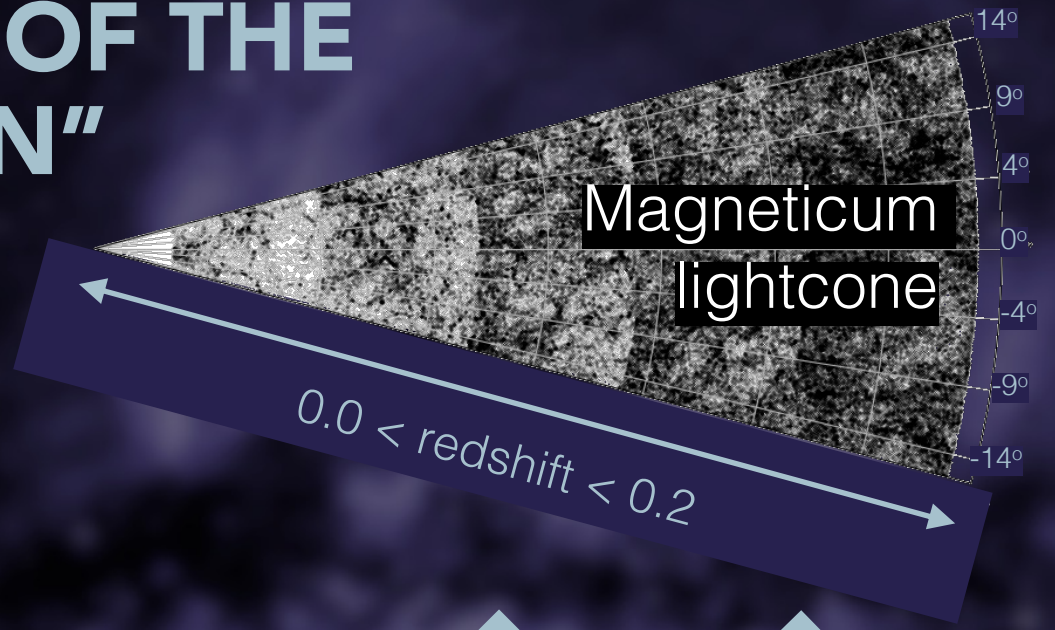
SAMPLE SELECTION BASED ON OPTICAL CLUSTER CATALOGS

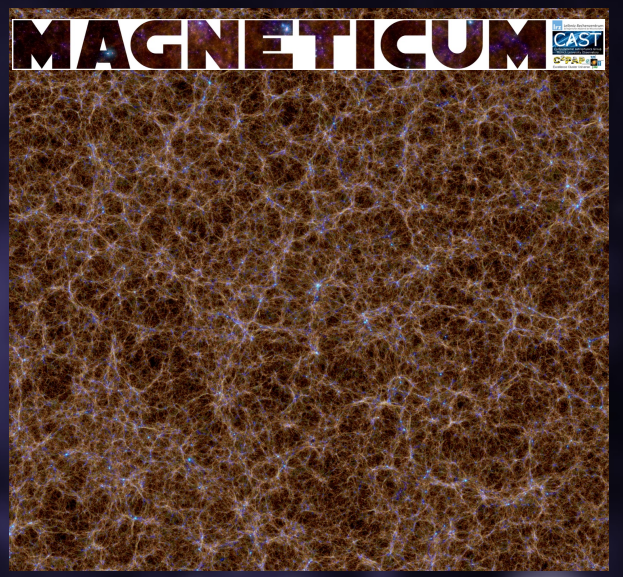
+

ANALYSIS OF GAS PROPERTIES BASED ON STACKED X-RAY DATA

IS IT RELIABLE?

ADVANTAGES OF THE "WELL-KNOWN" UNIVERSE



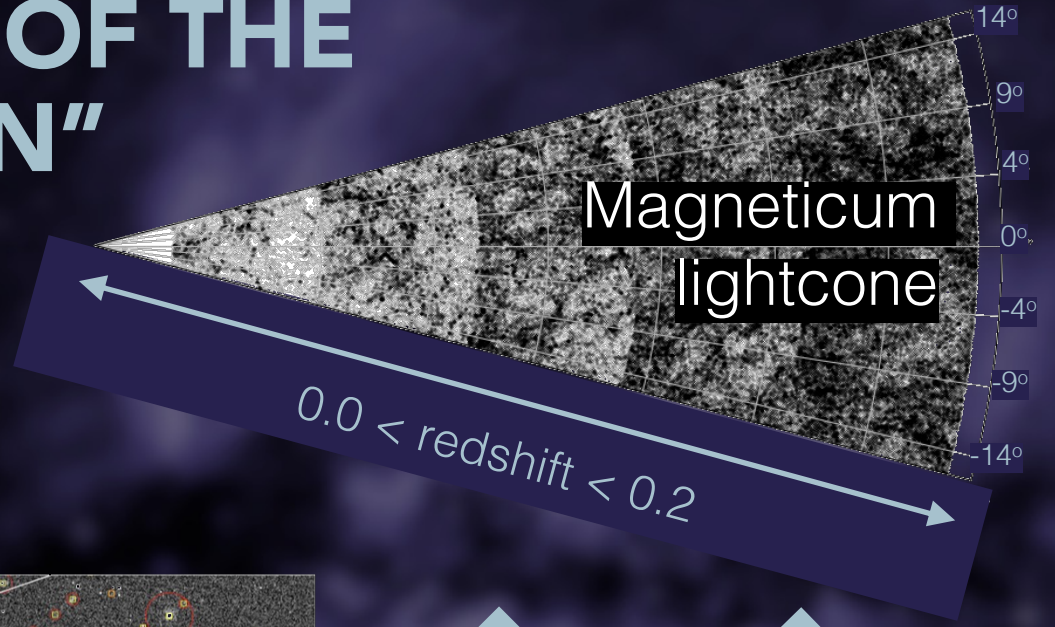


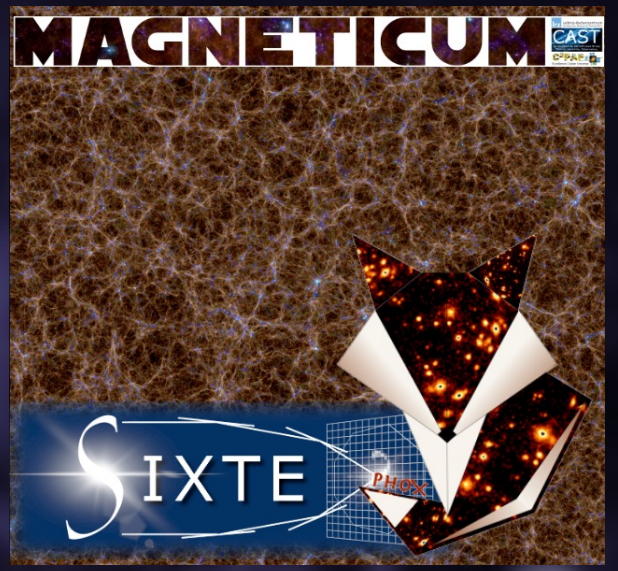
Ilaria Marini,
ESO

Marini et al. 2025a

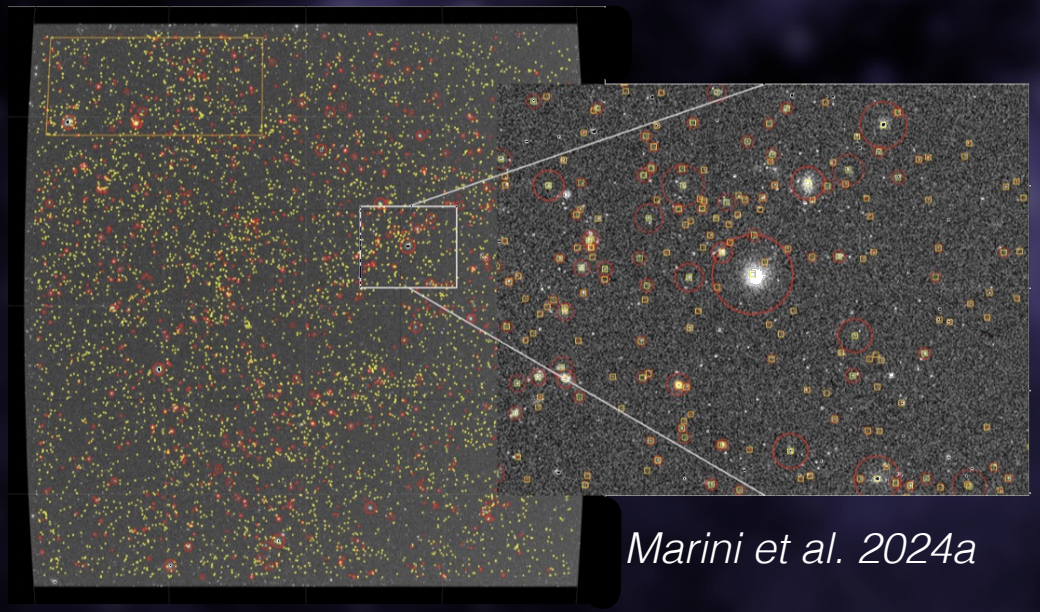
Optical mock galaxy catalog

ADVANTAGES OF THE "WELL-KNOWN" UNIVERSE





Is X-ray stacking reliable?



Marini et al. 2024a

30 deg

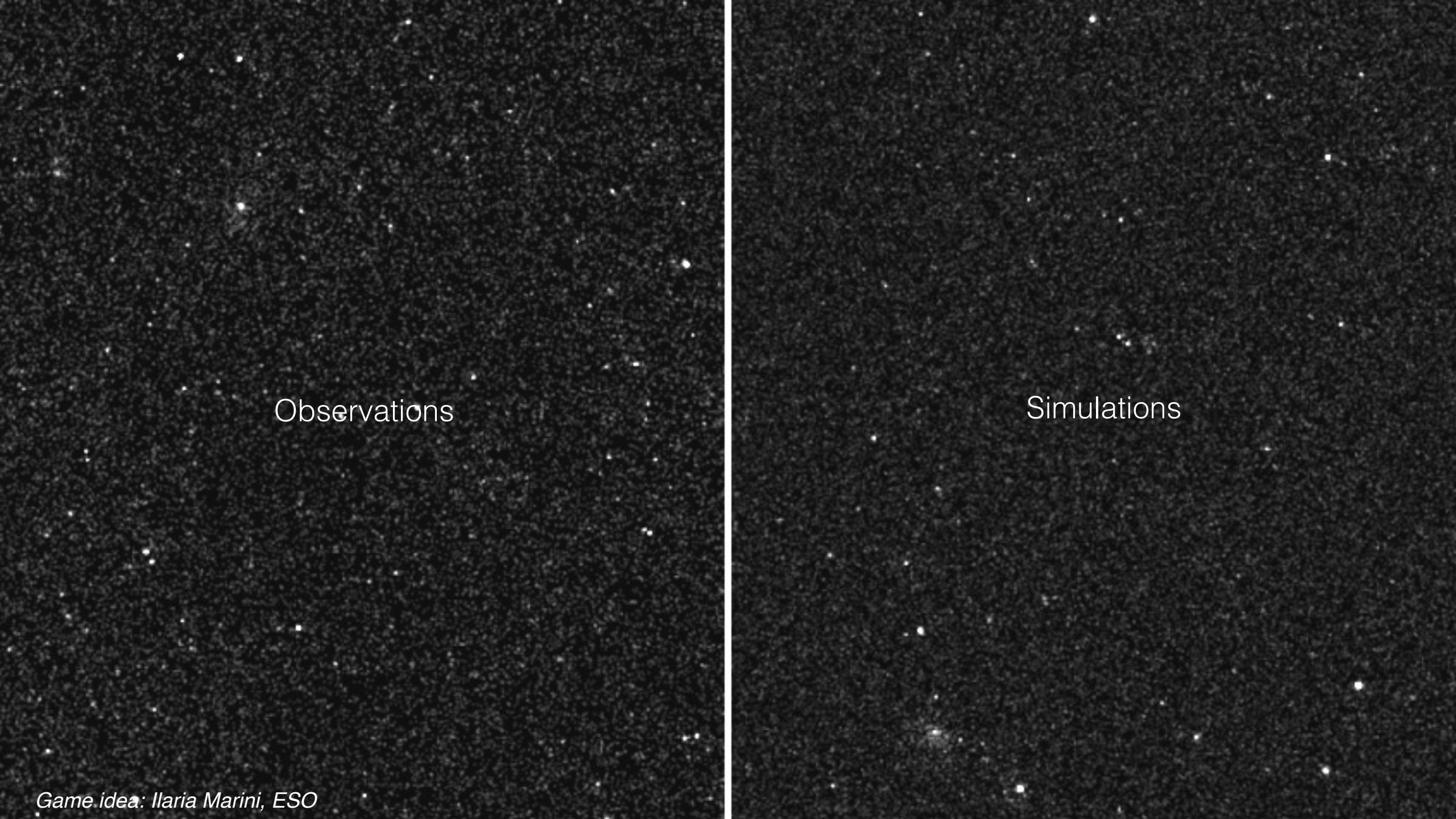
Ilaria Marini,
ESO

Marini et al. 2025a

X-ray mock observations (eRASS4 depth)

Optical mock galaxy catalog


Game idea: Ilaria Marini, ESO

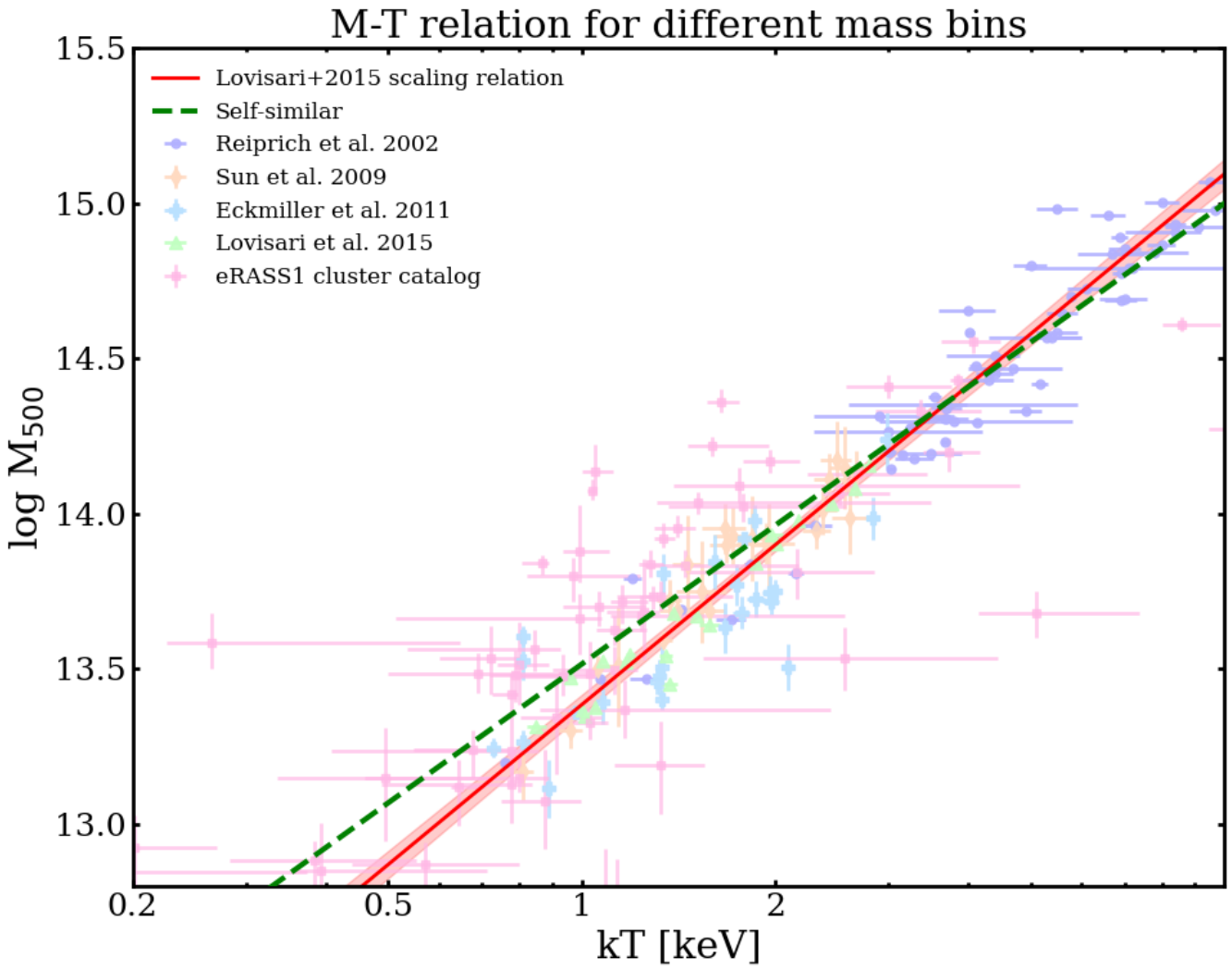


Game idea: Ilaria Marini, ESO

RESULTS

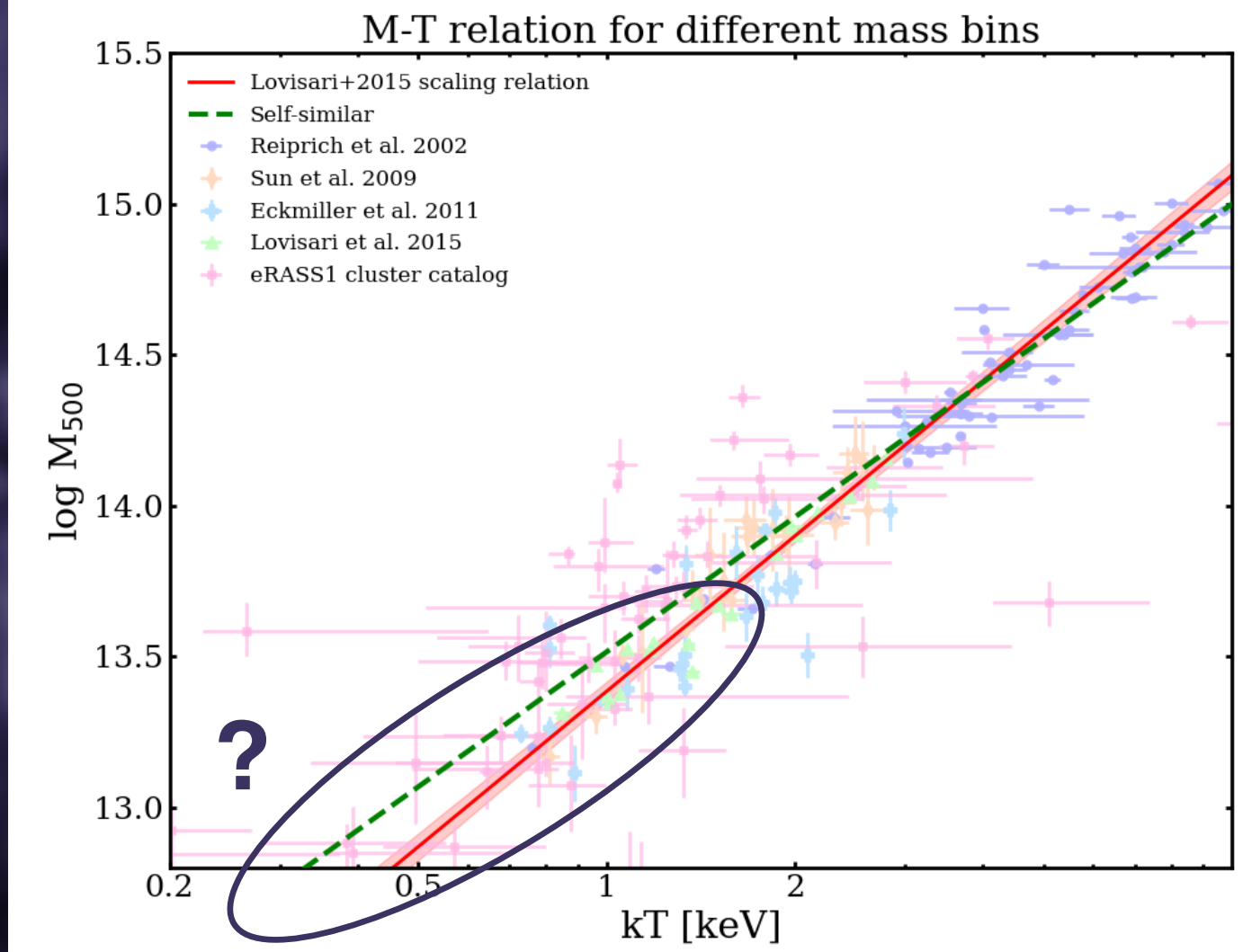
Toptun et al. 2025:

SPECTRAL STACKING to estimate the temperature



Toptun et al. 2025:

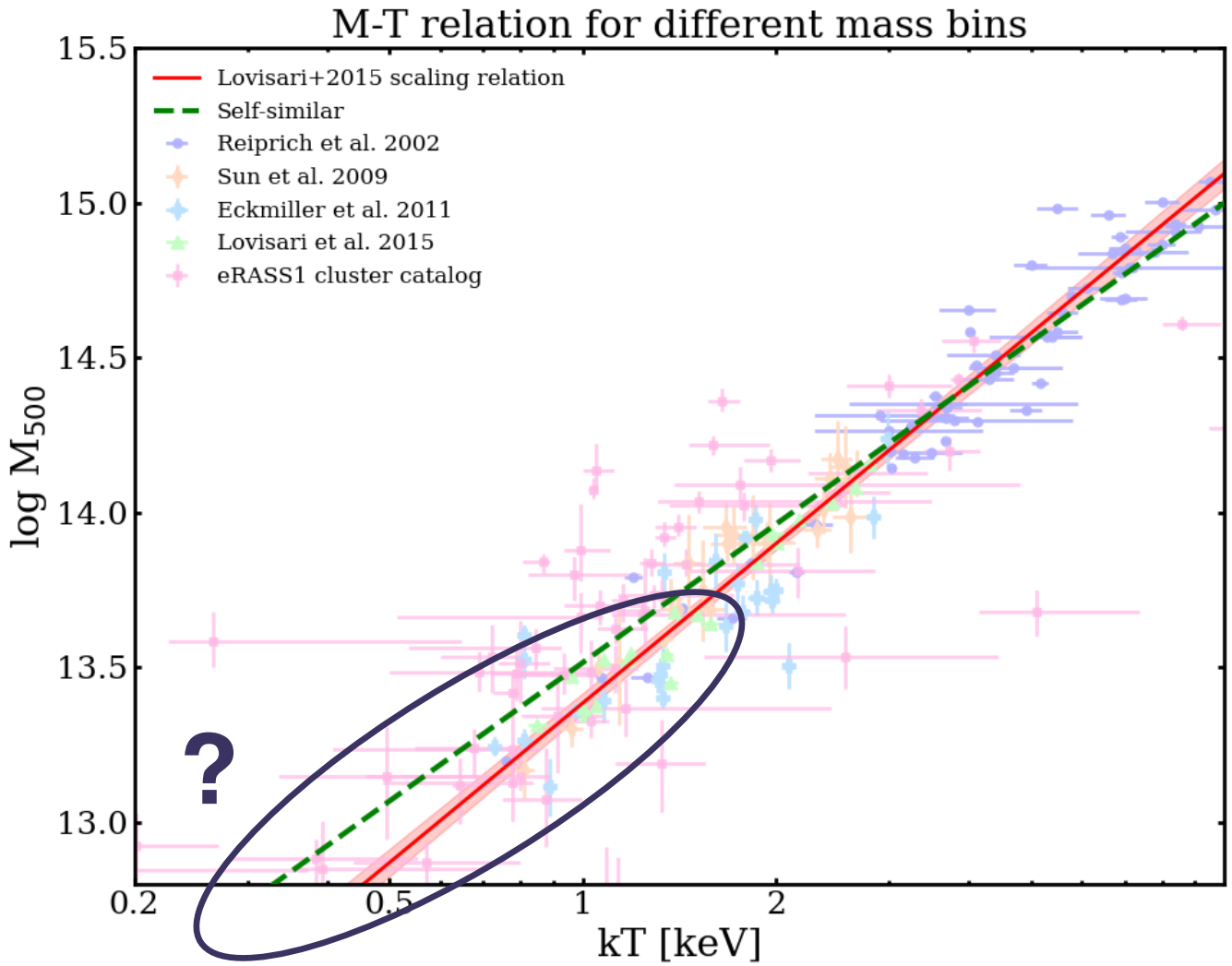
SPECTRAL STACKING to estimate the temperature



Toptun et al. 2025:

SPECTRAL STACKING to estimate the temperature

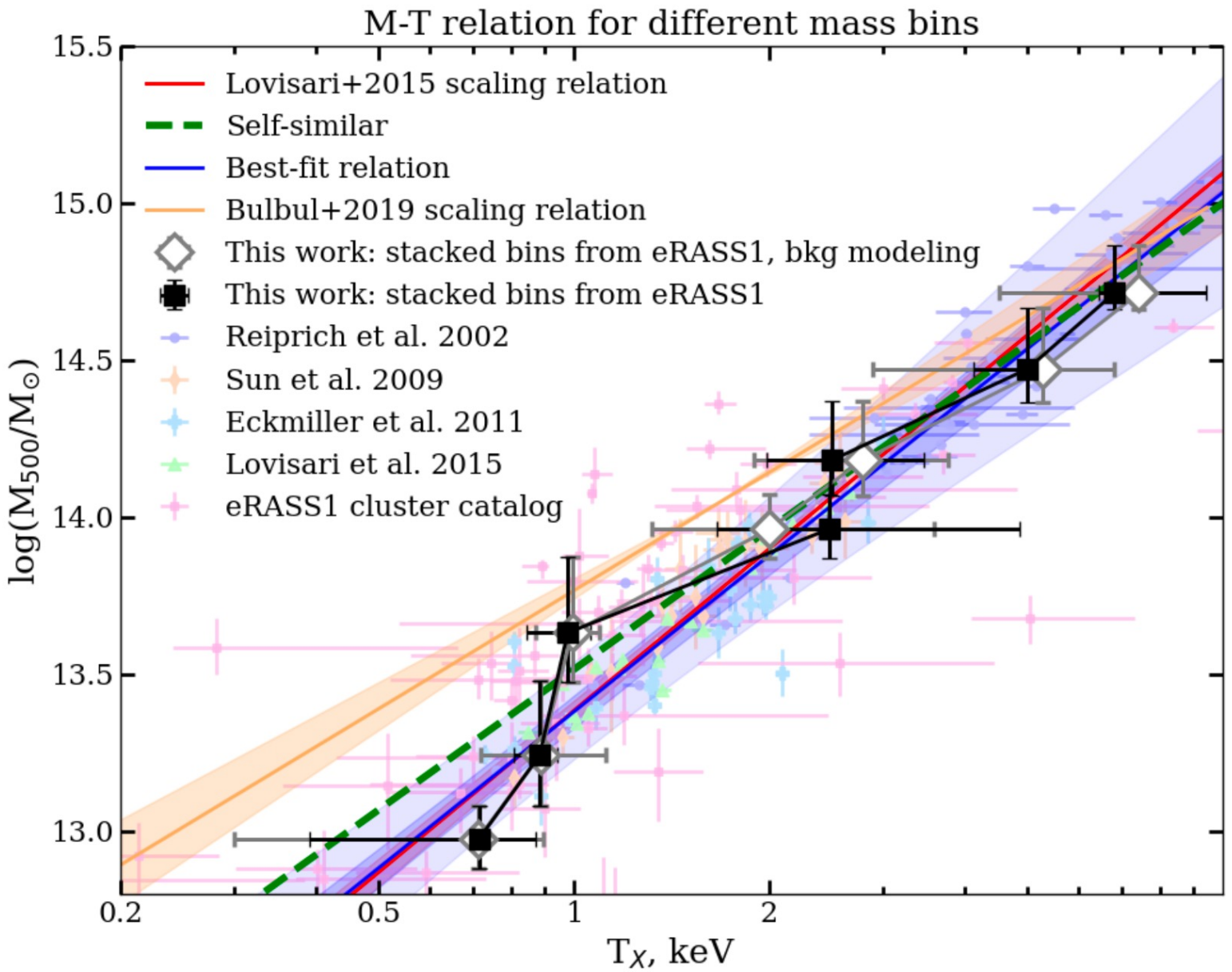
dividing the sample into mass bins
↓
result: stacked X-ray spectrum in each bin
↓
temperatures by modeling spectra with gadem model
↓
test on mock observations



RELATION REVEALED

Stacking + wide-field data allows us to look up to $\log M_{500} \approx 13.0$

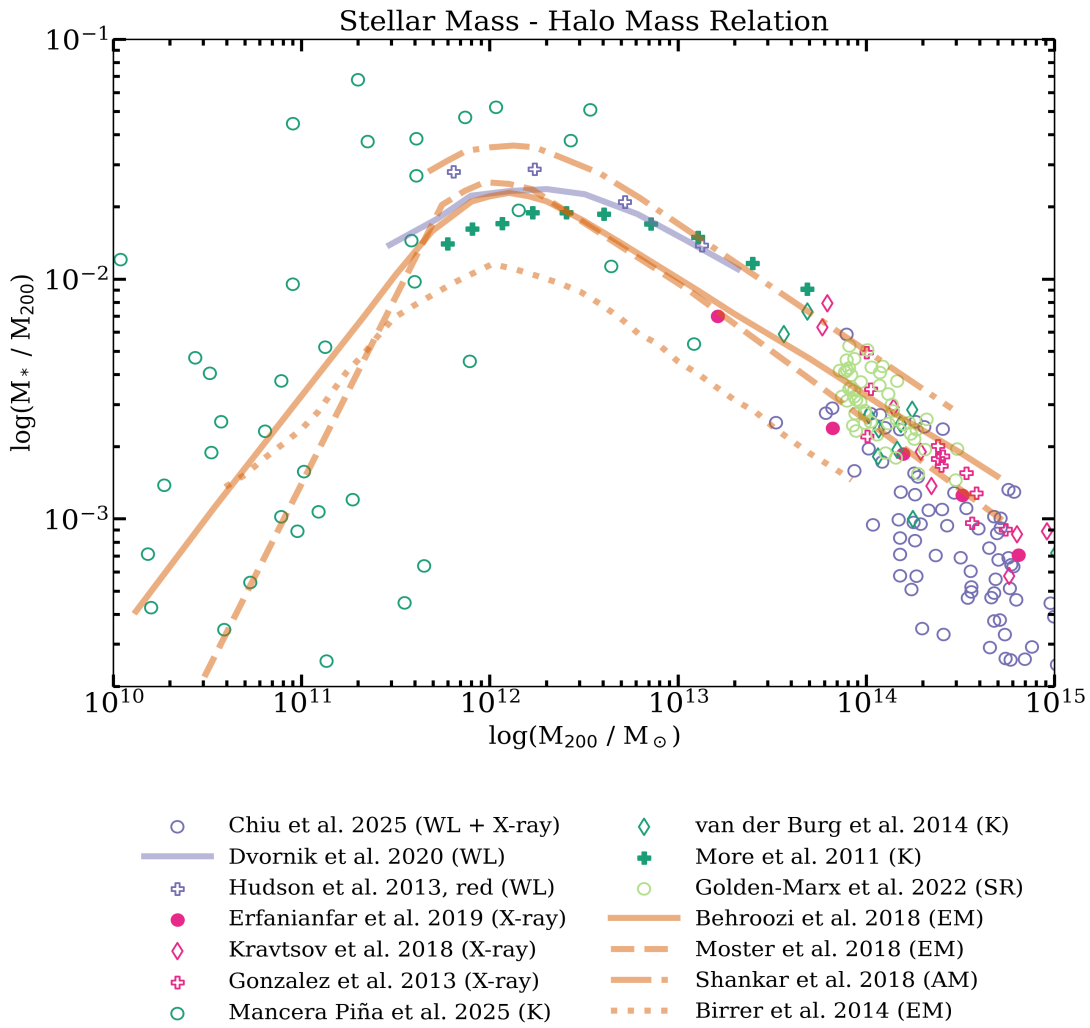
No significant impact of feedback into average temperature inside R_{500}



Toptun et al. 2025

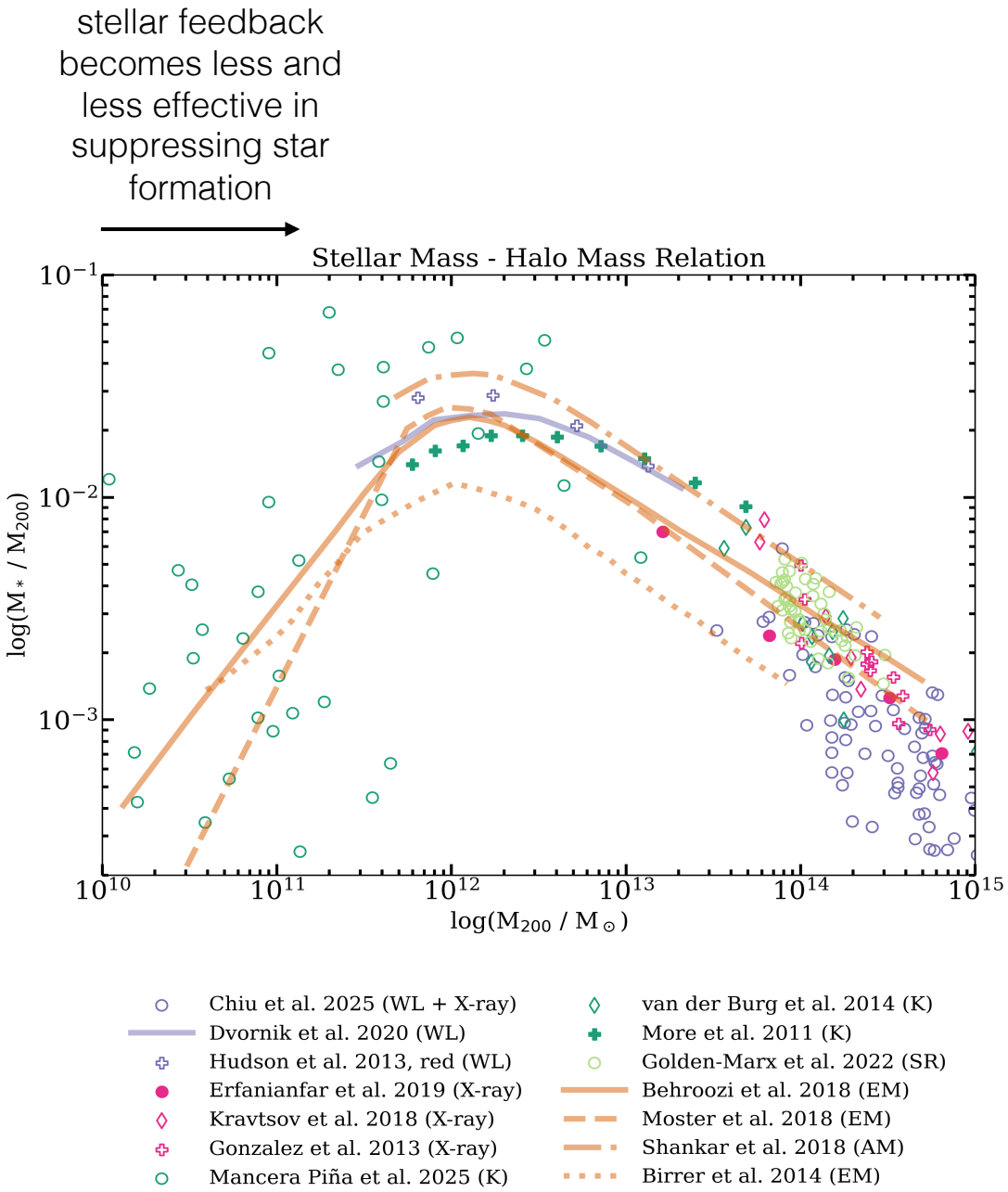
Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION



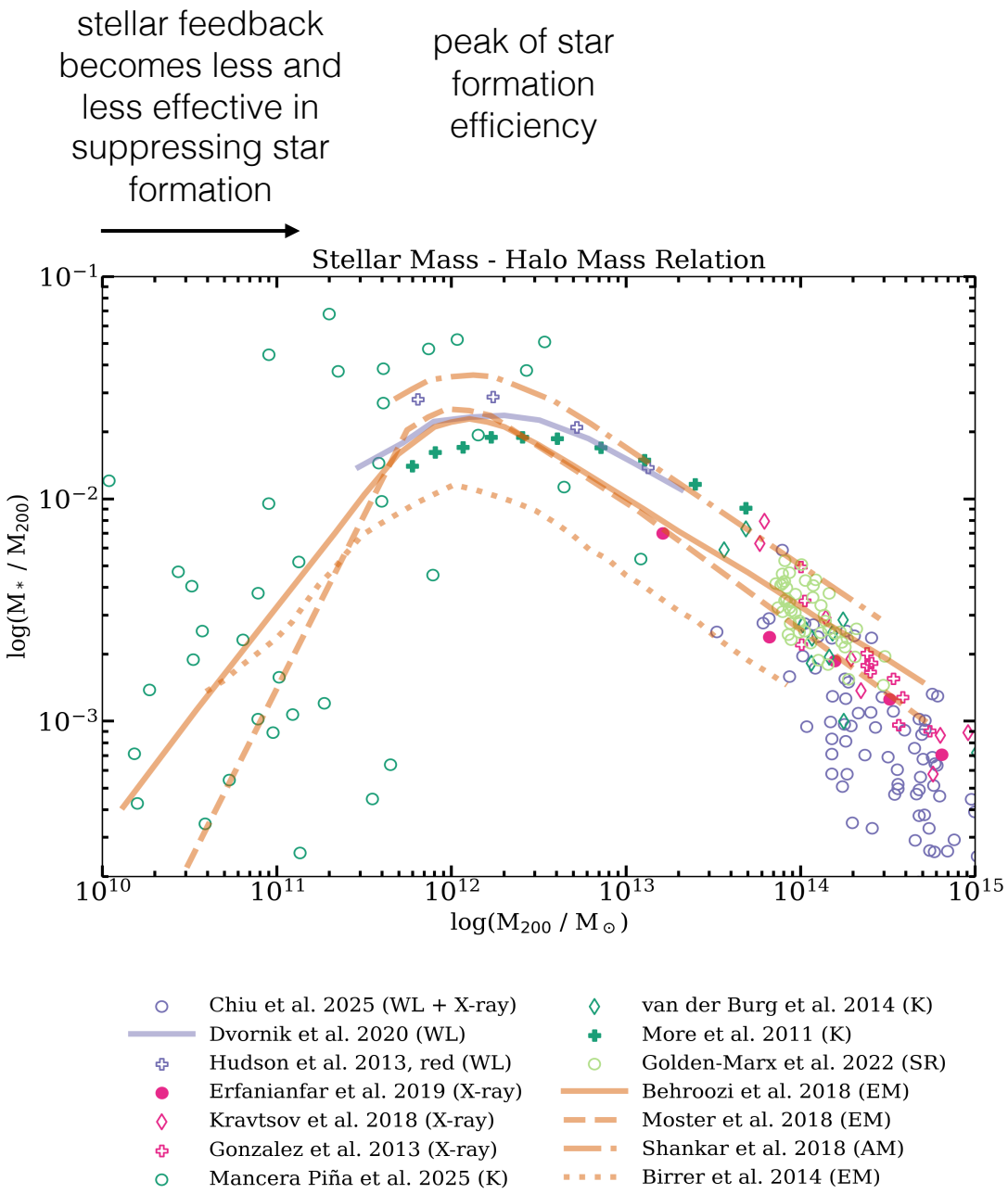
Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION



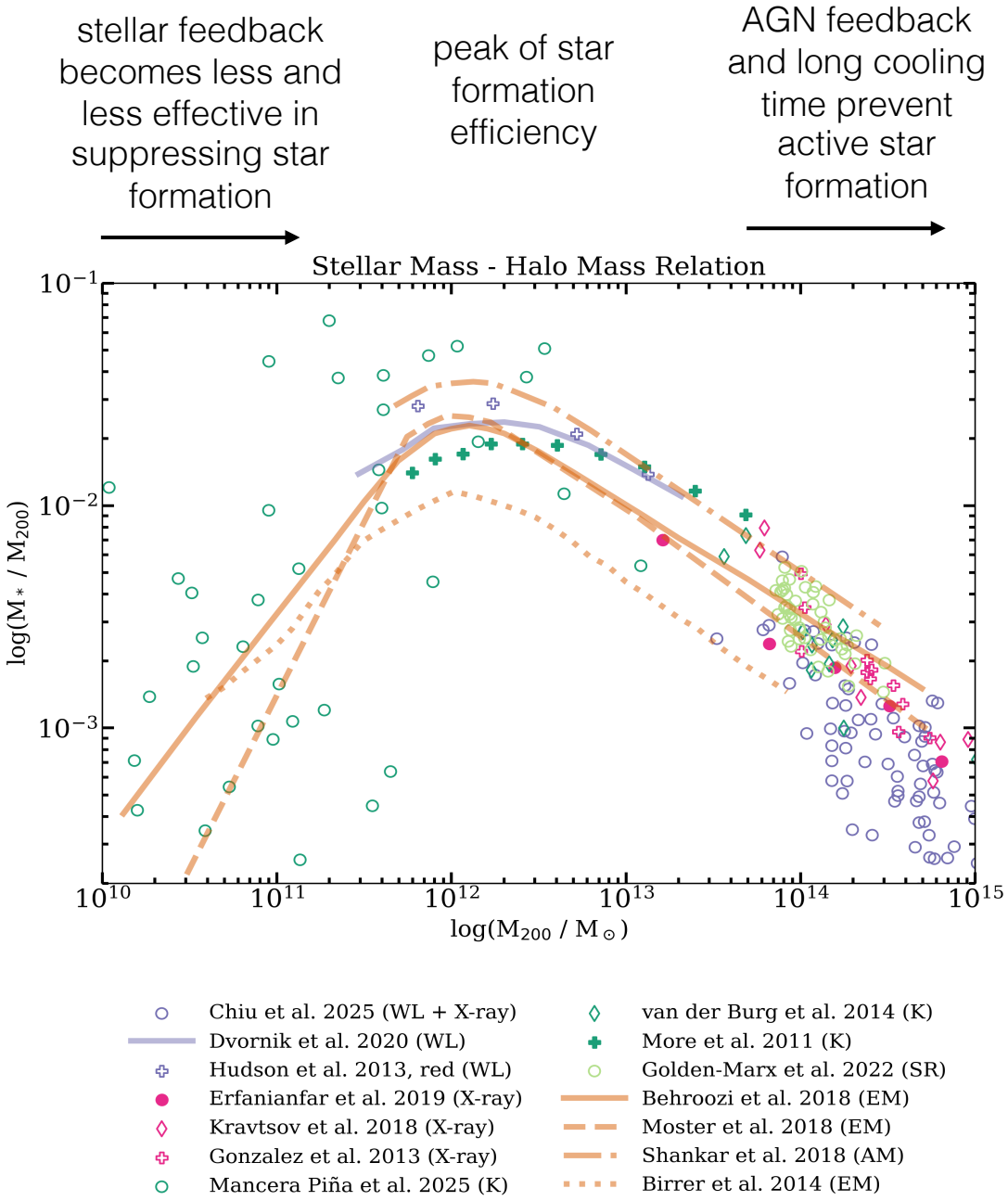
Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION



Toptun et al. 2026 (in prep.)

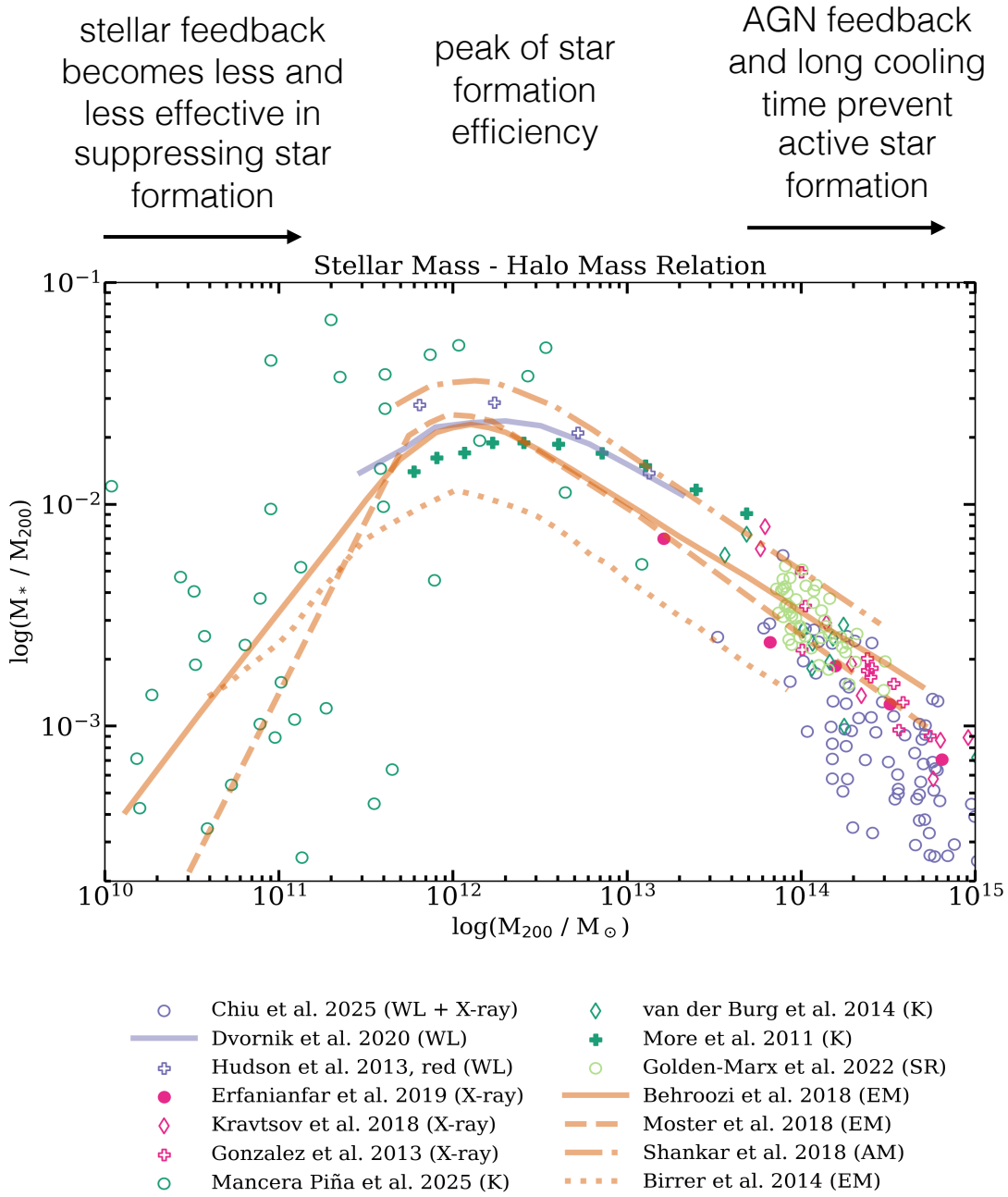
STELLAR-TO-HALO MASS RELATION



Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION

dividing the sample into stellar mass (GSWLC catalog) bins to estimate average temperature in each bin



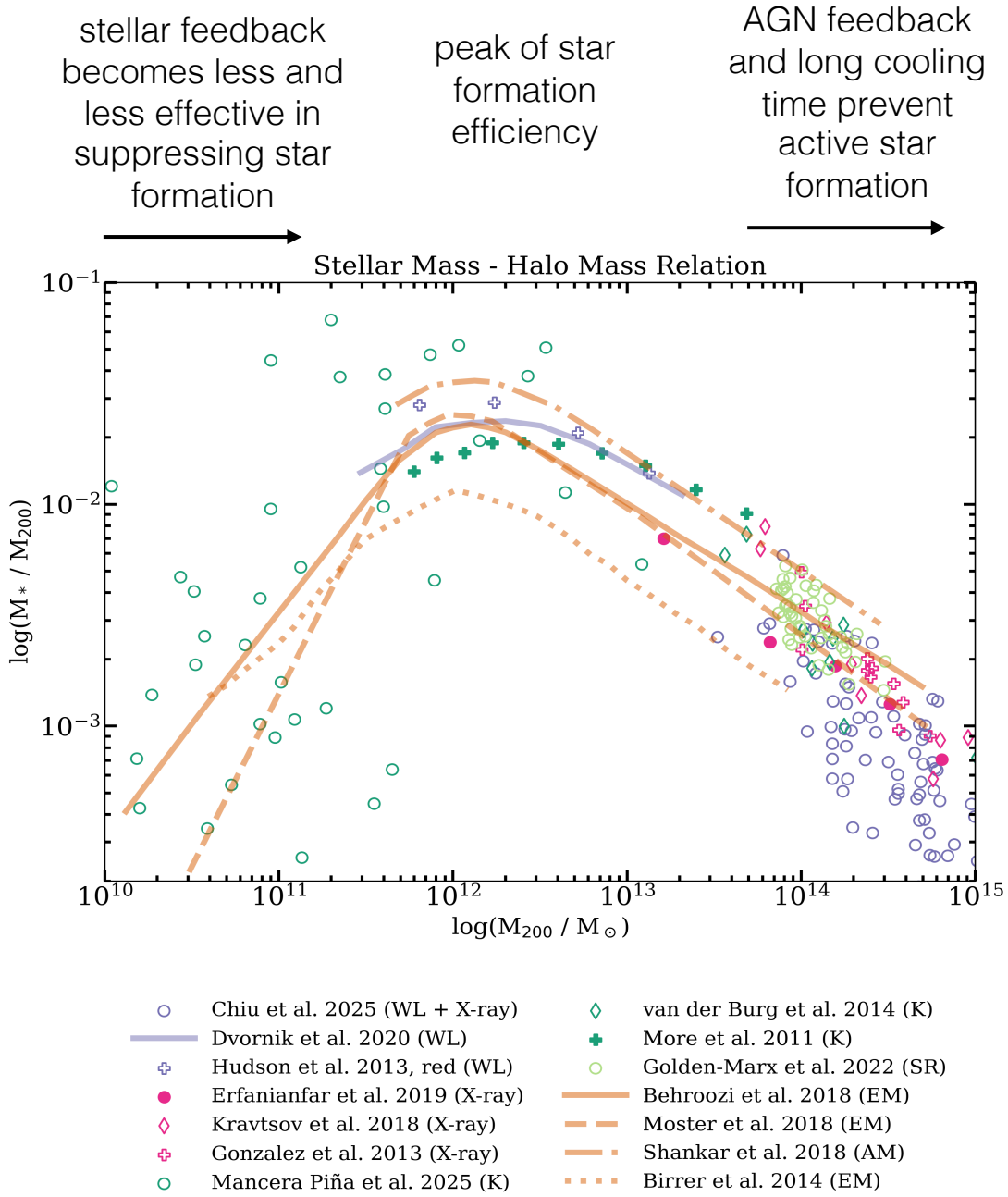
Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION

dividing the sample into stellar mass (GSWLC catalog) bins to estimate average temperature in each bin

↓

from the M-T relation (Toptun et al. 2025) we can estimate M_{halo} from the temperature



Toptun et al. 2026 (in prep.)

STELLAR-TO-HALO MASS RELATION

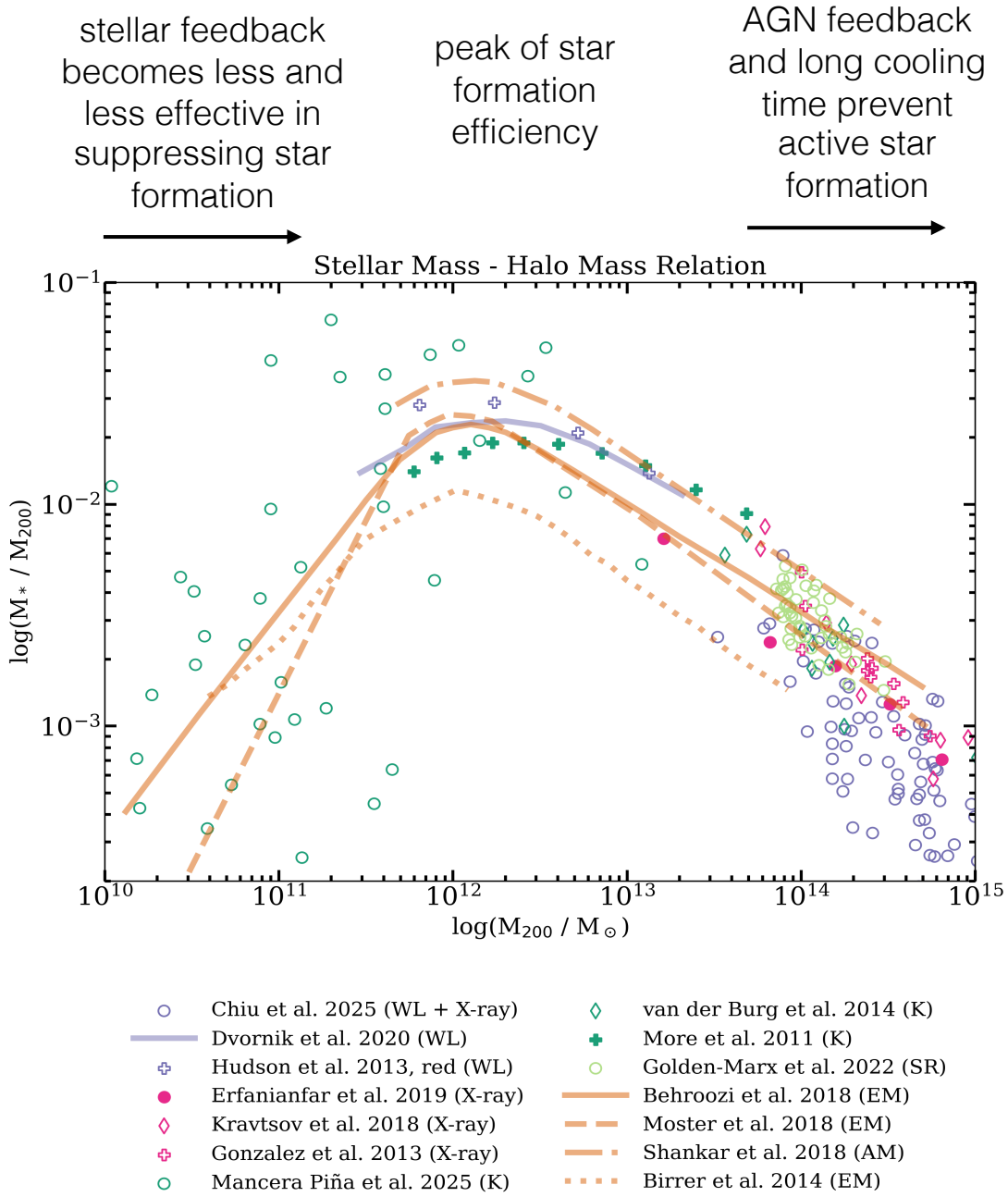
dividing the sample into stellar mass (GSWLC catalog) bins to estimate average temperature in each bin

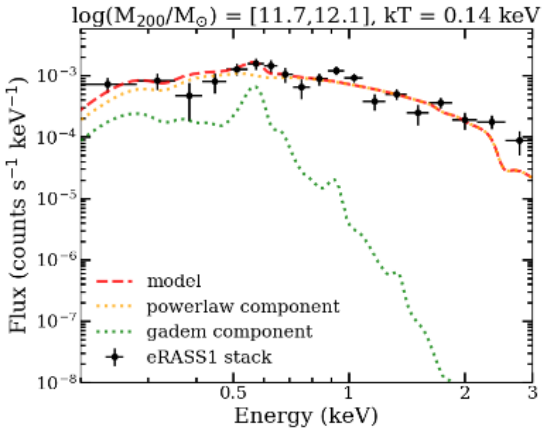
↓

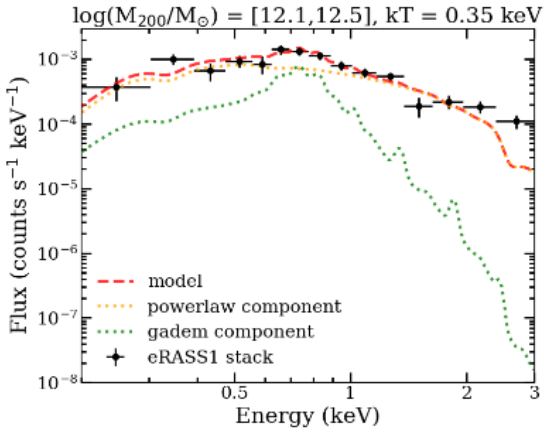
from the M-T relation (Toptun et al. 2025) we can estimate M_{halo} from the temperature

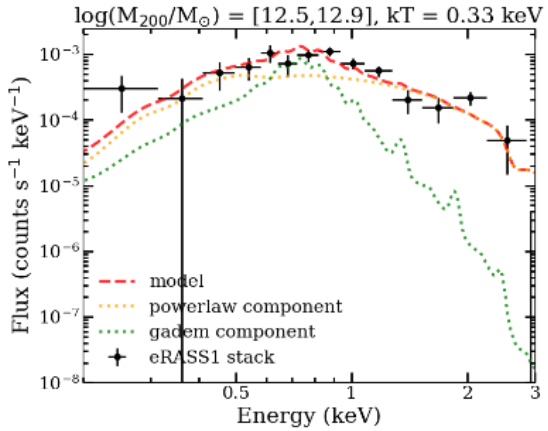
↓

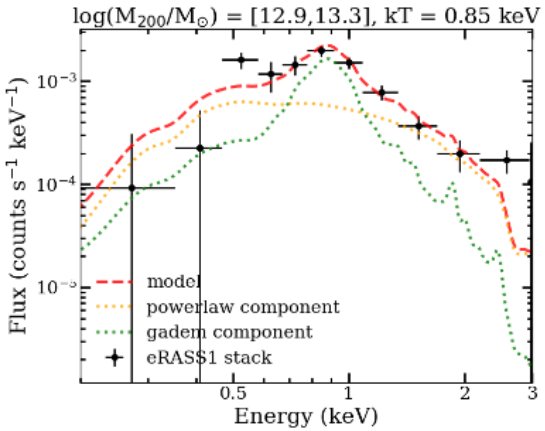
stellar-to-halo mass relation based on independent halo mass estimates

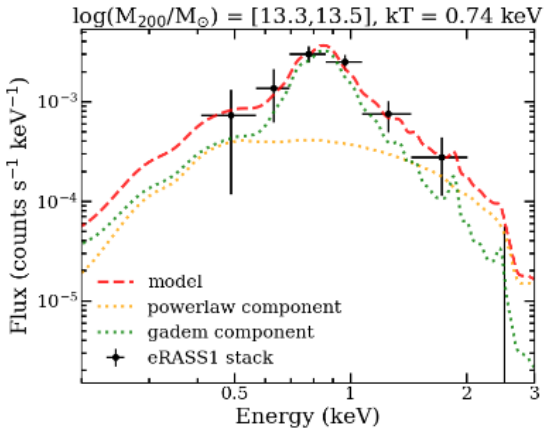


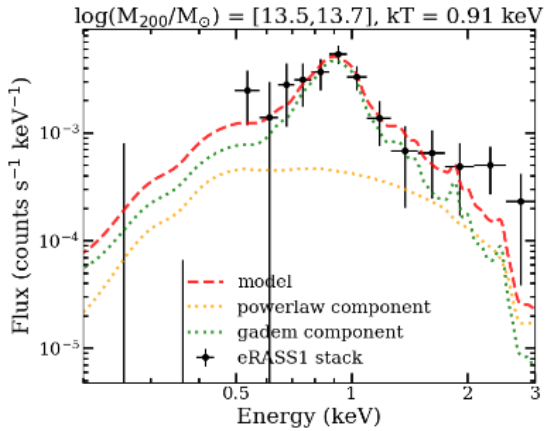

log(M200/M⊙) = [11.7,12.1], kT = 0.14 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

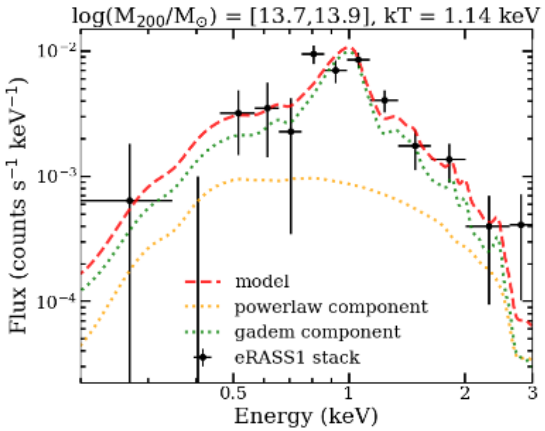

log(M200/M⊙) = [12.1,12.5], kT = 0.35 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

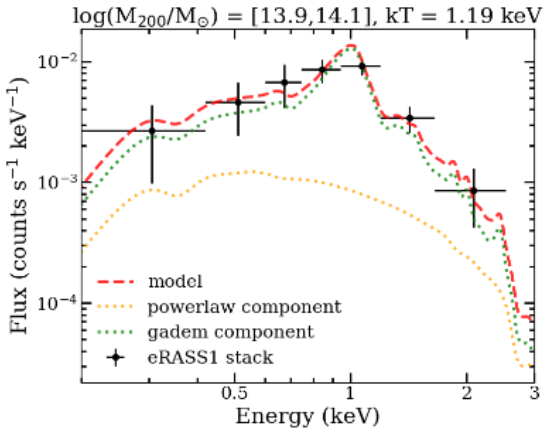

log(M200/M⊙) = [12.5,12.9], kT = 0.33 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

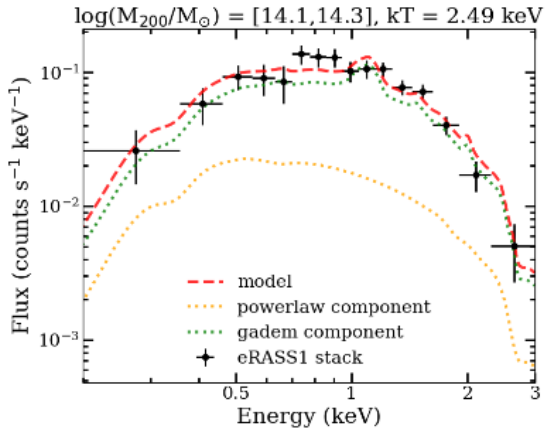

log(M200/M⊙) = [12.9,13.3], kT = 0.85 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack


log(M200/M⊙) = [13.3,13.5], kT = 0.74 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

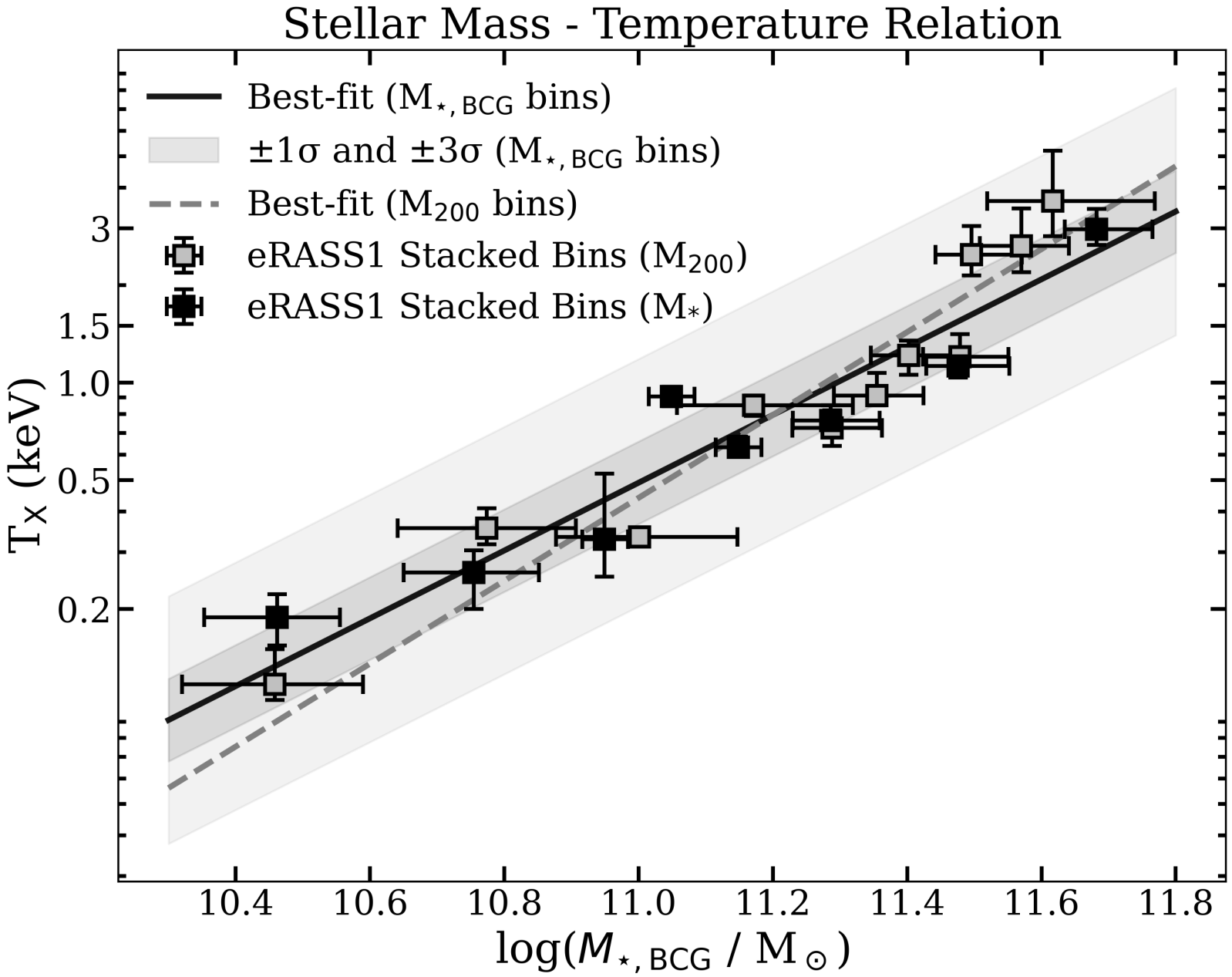

log(M200/M⊙) = [13.5,13.7], kT = 0.91 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack


log(M200/M⊙) = [13.7,13.9], kT = 1.14 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack


log(M200/M⊙) = [13.9,14.1], kT = 1.19 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack


log(M200/M⊙) = [14.1,14.3], kT = 2.49 keV
Flux (counts s⁻¹ keV⁻¹)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

SPECTRA

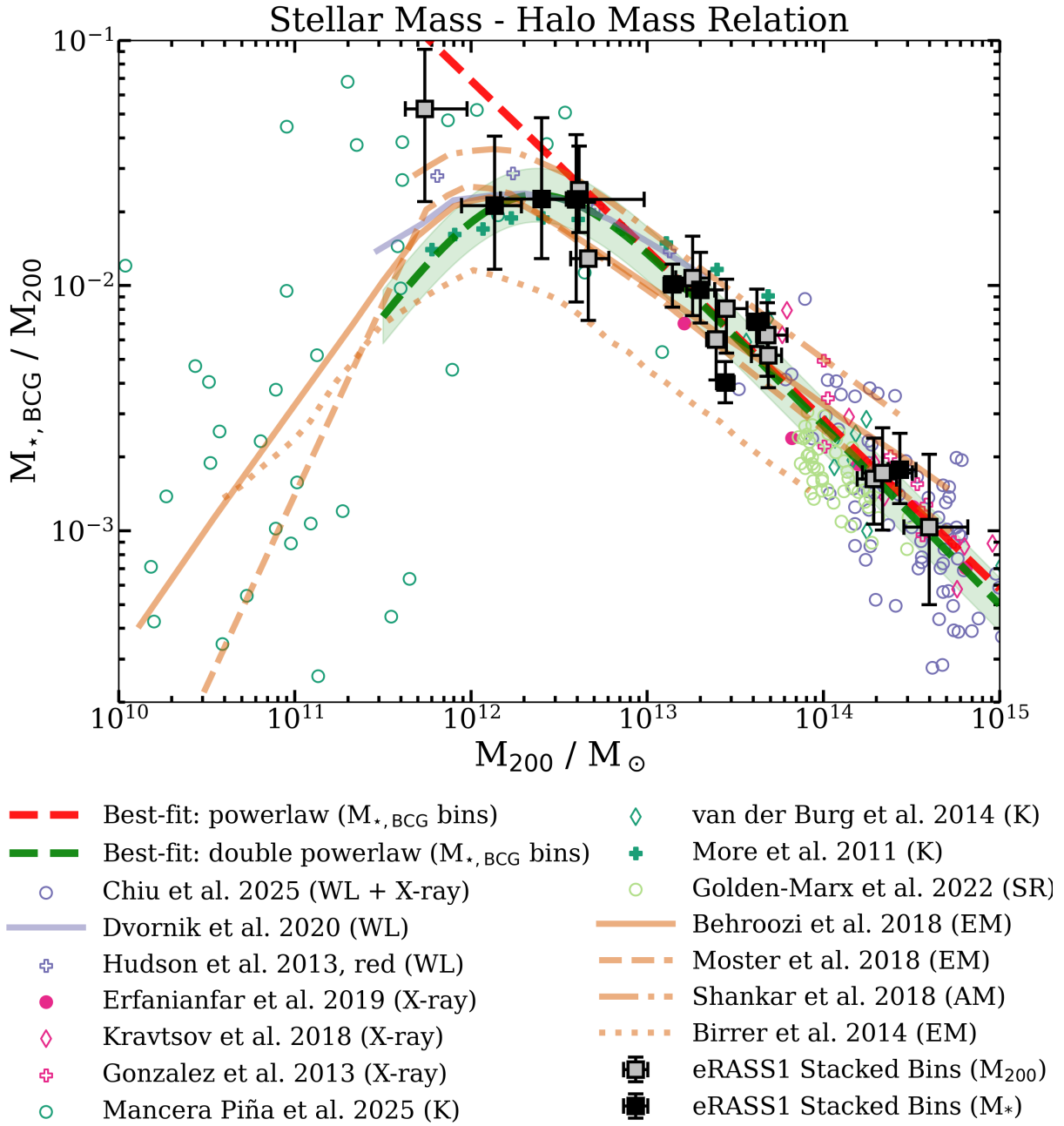


BCG STELLAR MASS TO TEMPERATURE

Toptun et al. 2026

STELLAR-TO-HALO MASS RELATION: RESULTS

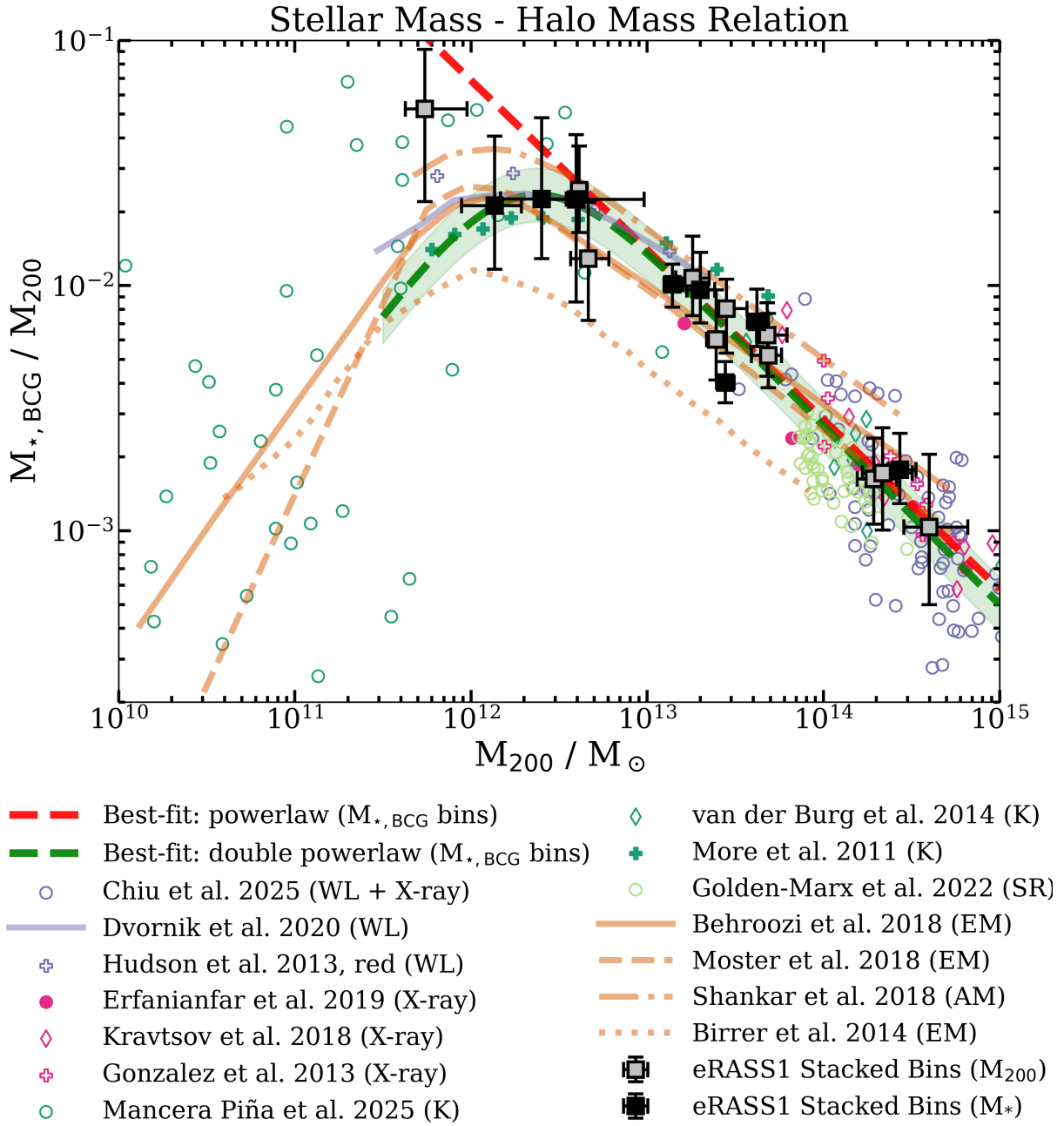
- Widest known coverage of SHMR with halo masses estimated independently from optical data



Toptun et al. 2026

STELLAR-TO-HALO MASS RELATION: RESULTS

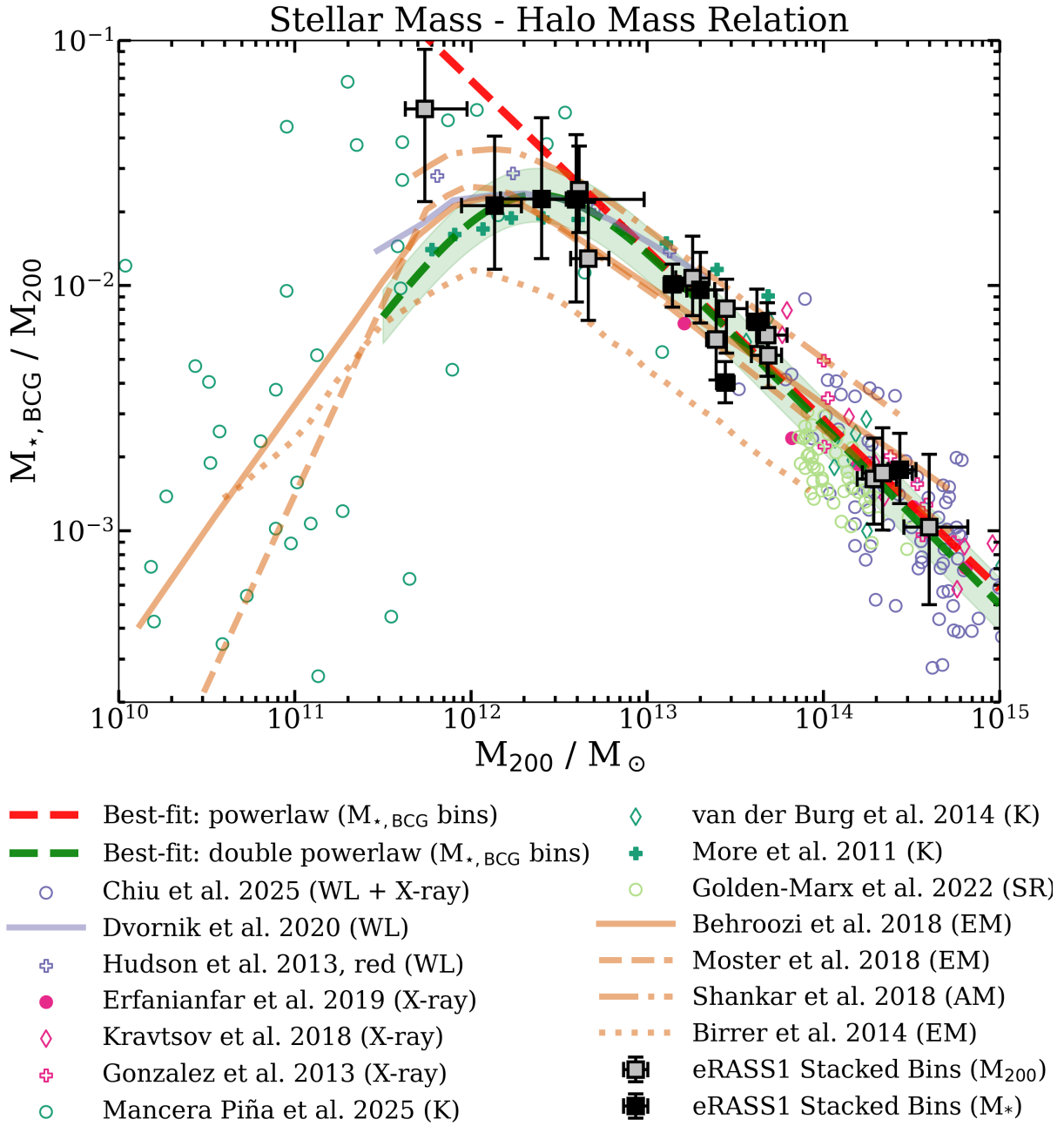
- Widest known coverage of SHMR with halo masses estimated independently from optical data
- Consistent with previous studies based on weak lensing, individual X-rays, cluster dynamics, predictions of semi-empirical models and abundance matching



Toptun et al. 2026

STELLAR-TO-HALO MASS RELATION: RESULTS

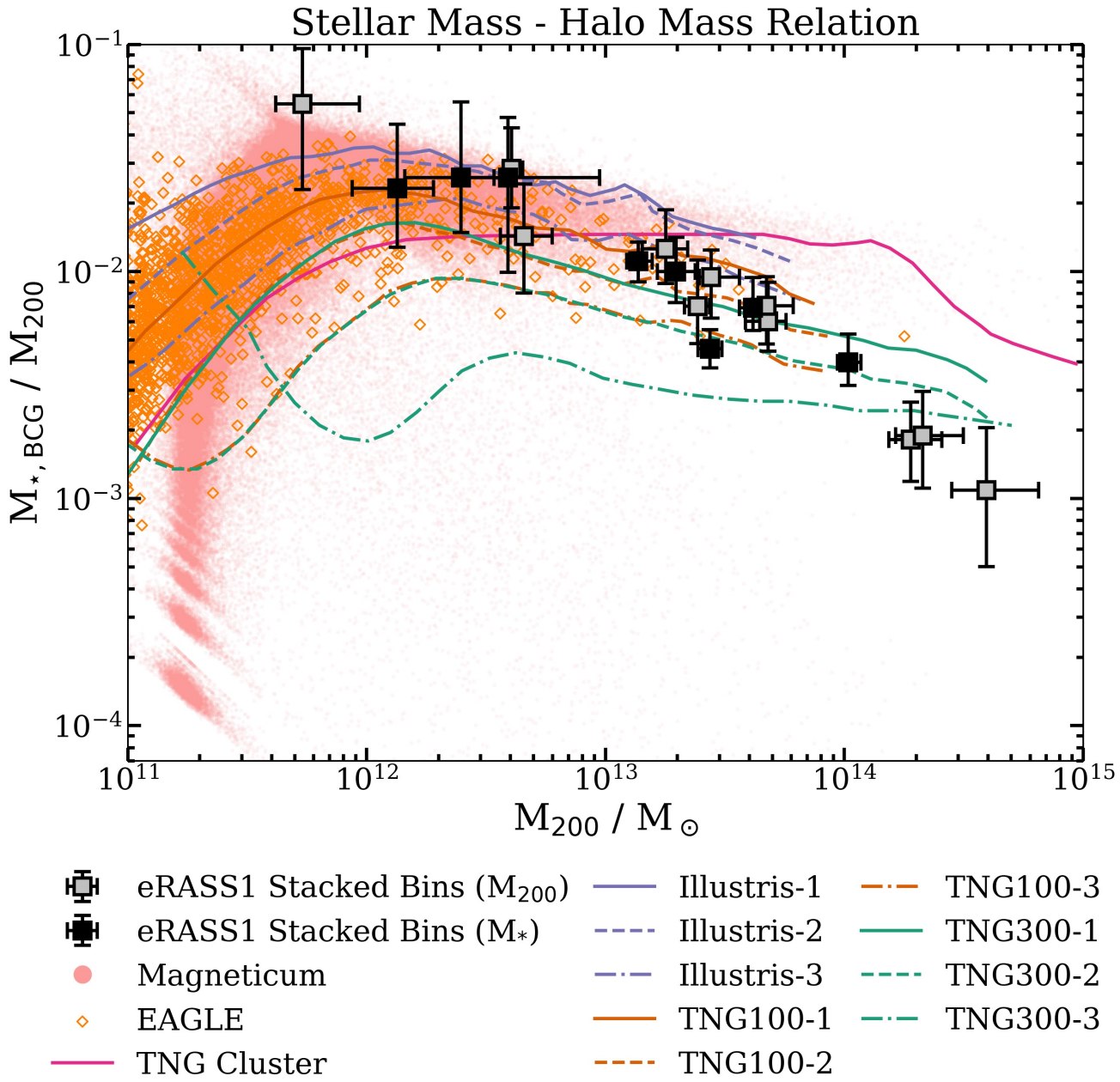
- Widest known coverage of SHMR with halo masses estimated independently from optical data
- Consistent with previous studies based on weak lensing, individual X-rays, cluster dynamics, predictions of semi-empirical models and abundance matching
- We can trace the efficiency peak around 10^{12} M_{sun}



Toptun et al. 2026

STELLAR-TO-HALO MASS RELATION: RESULTS

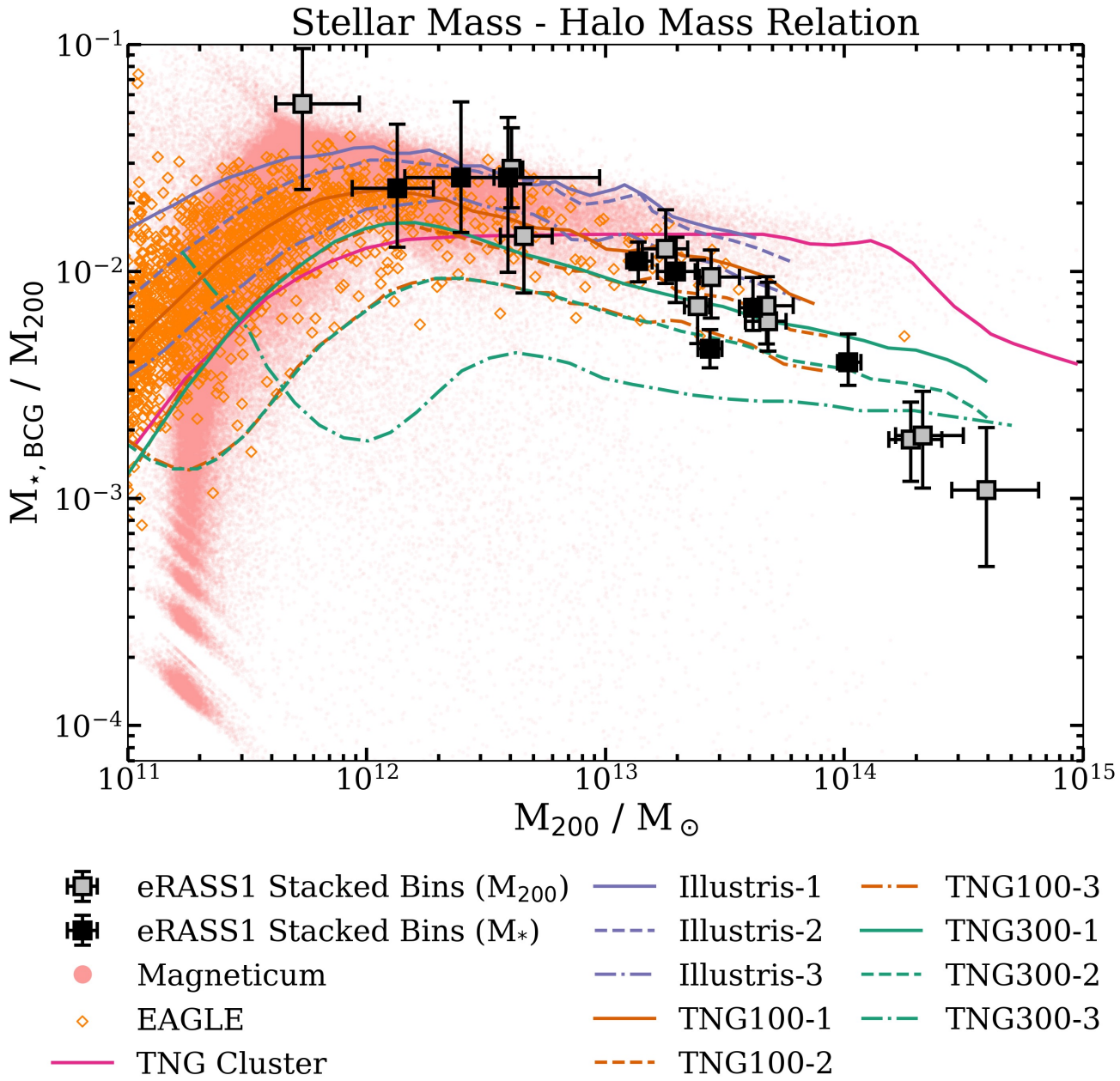
- Simulations tends to overpredict the M_*/M_{200} at higher masses



Toptun et al. 2026

STELLAR-TO-HALO MASS RELATION: RESULTS

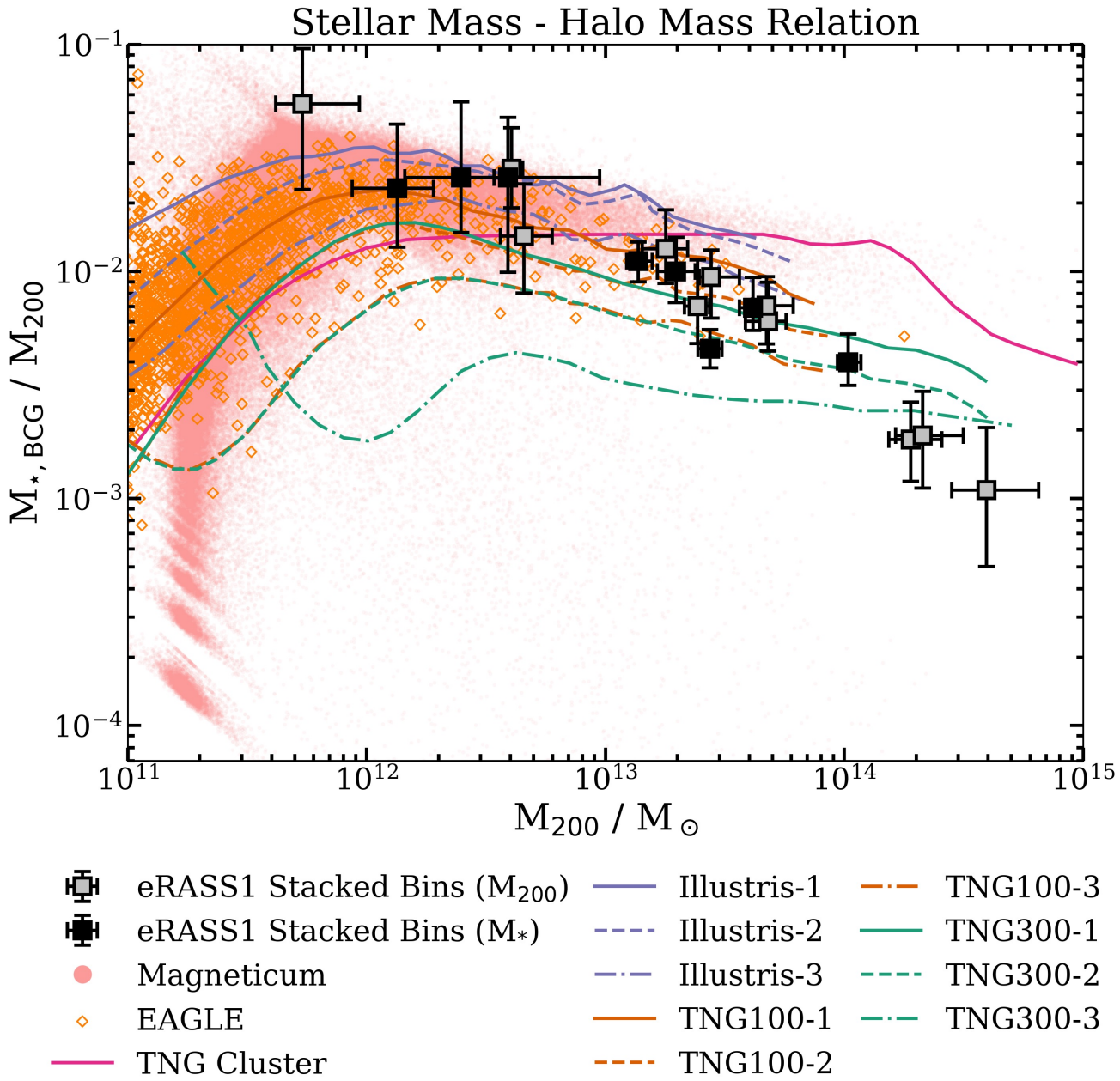
- Simulations tends to overpredict the M_*/M_{200} at higher masses
- For groups they are in place within the uncertainties



Toptun et al. 2026

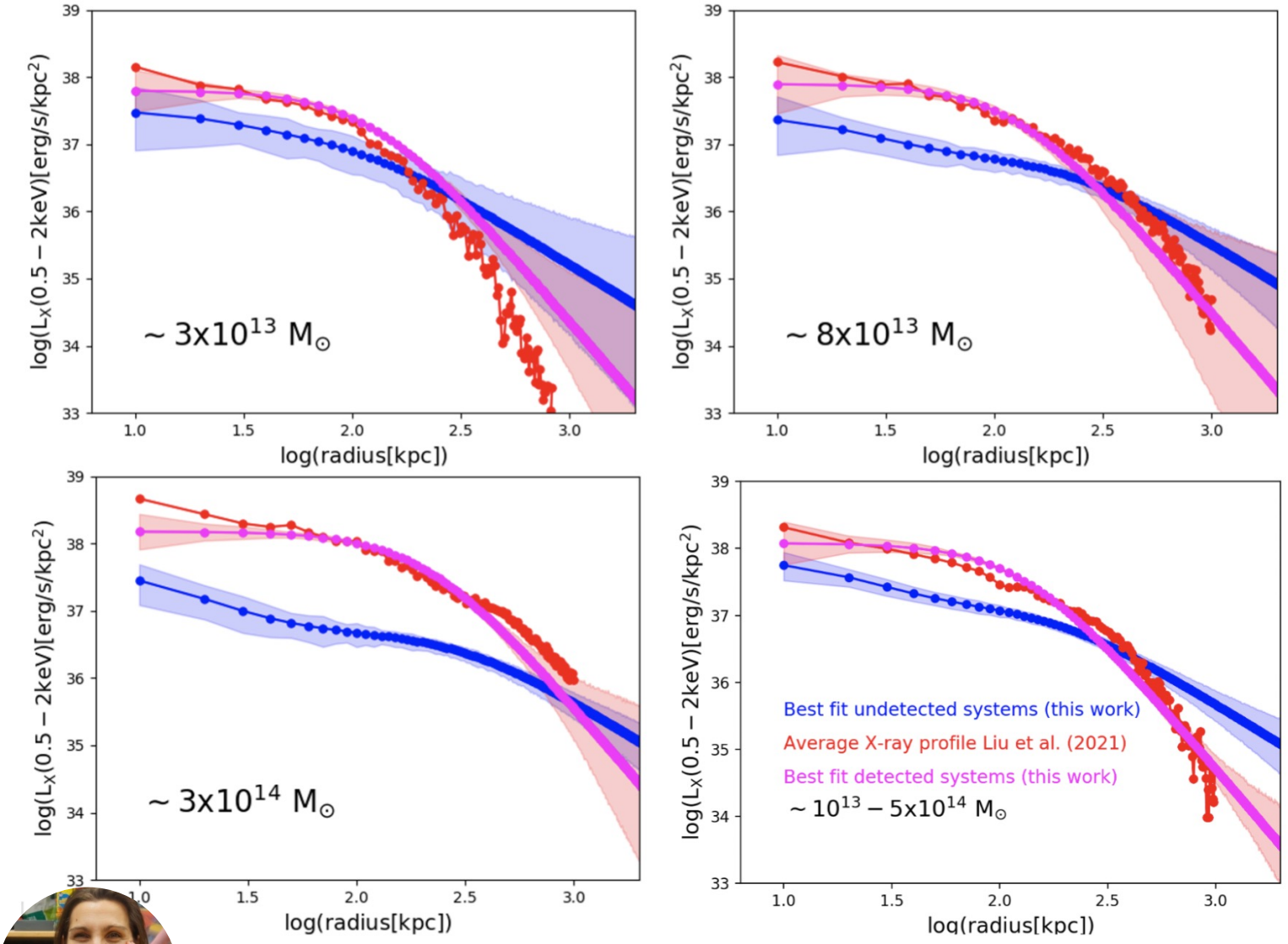
STELLAR-TO-HALO MASS RELATION: RESULTS

- Simulations tends to overpredict the M_*/M_{200} at higher masses
- For groups they are in place within the uncertainties
- Additional constraints on the simulations are needed to reproduce the Universe on the full mass range



SURFACE BRIGHTNESS PROFILES STACKING

Tontun+2024 (in prep)

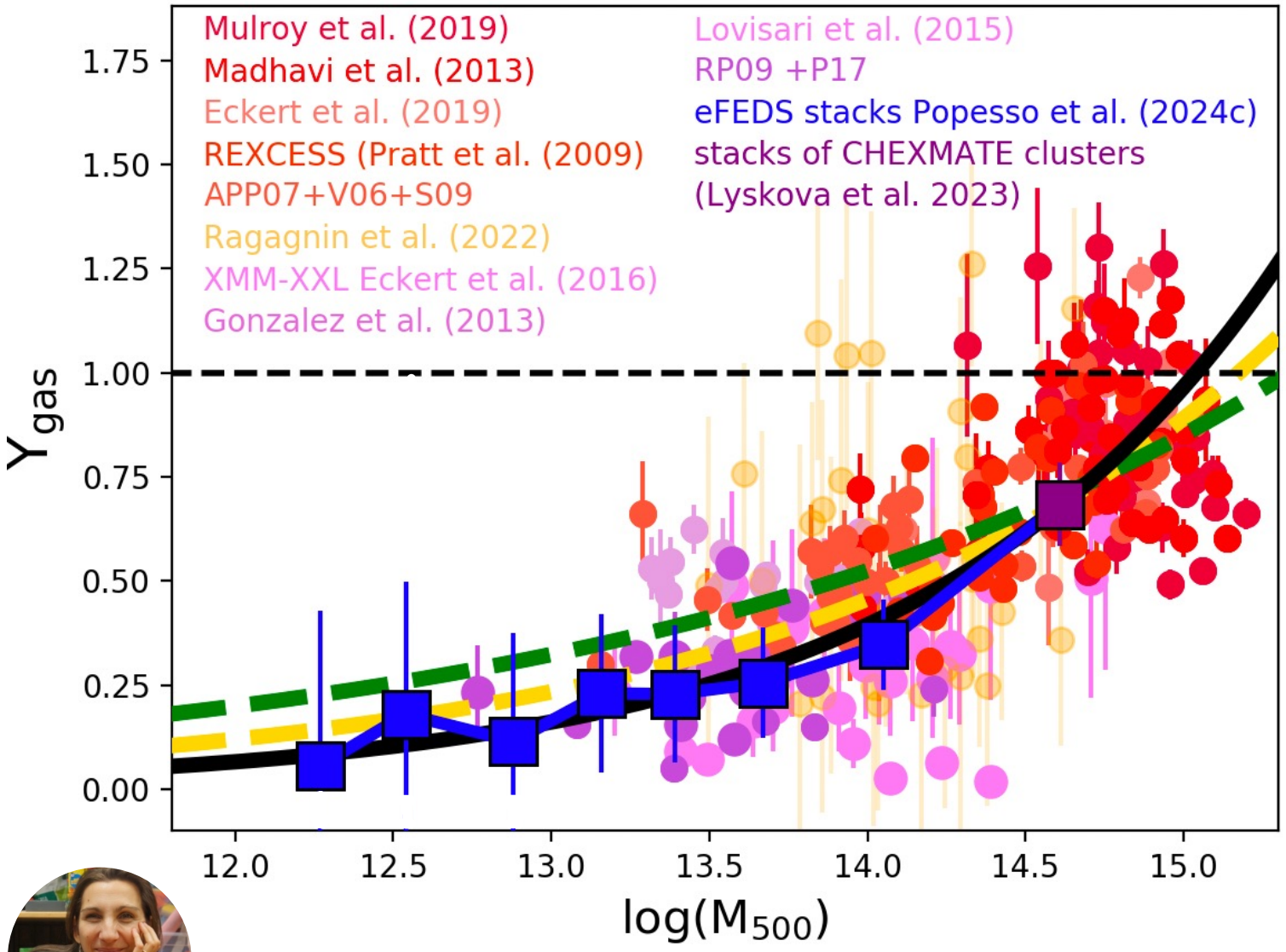


X-ray faint systems tend to have shallower surface brightness profiles: insights into their internal structure?

Popesso et al. 2024

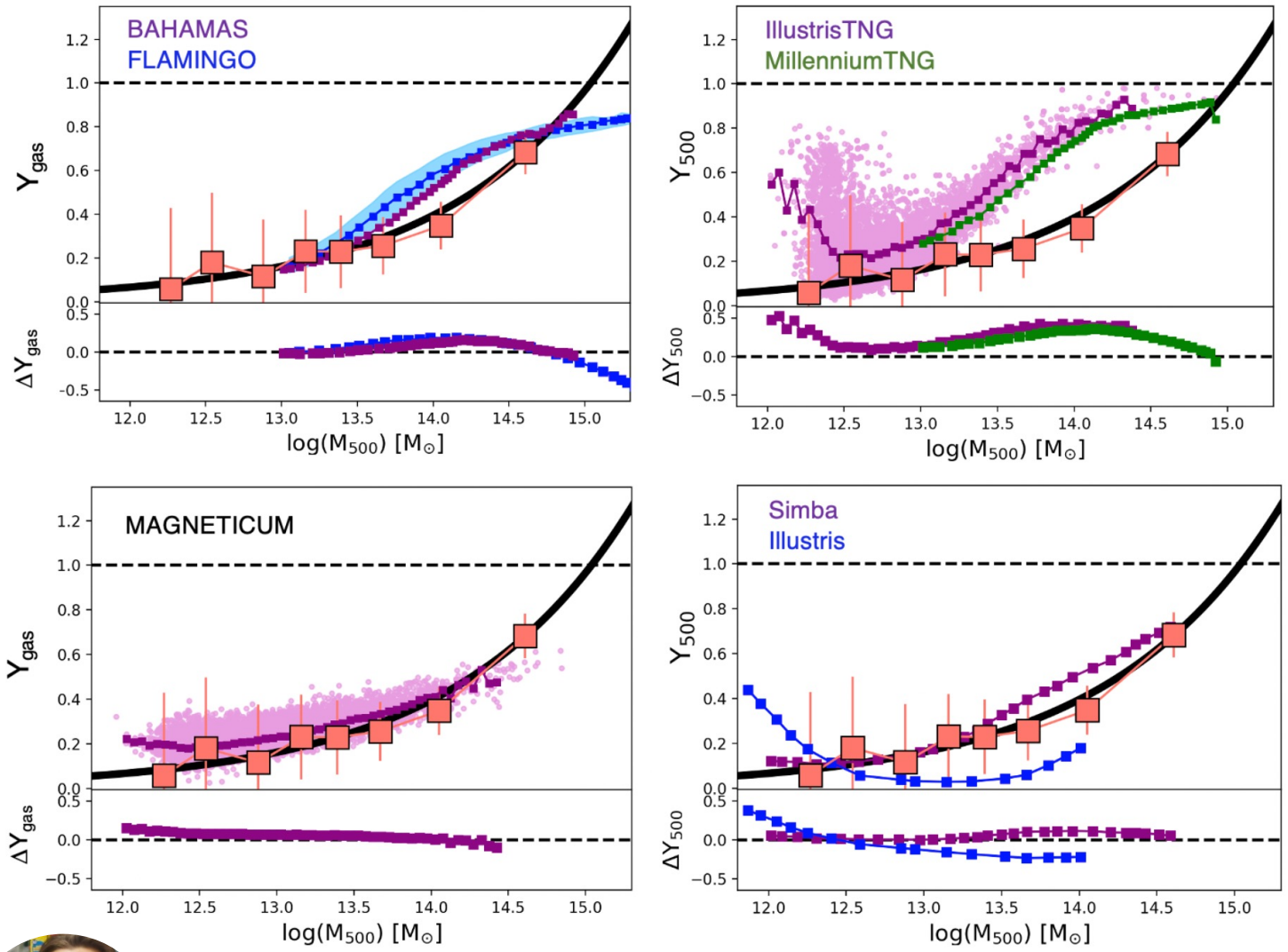
Based on eFEDS+GAMA data

GAS FRACTION



Popesso et al. 2026

Including X-ray faint optical groups lowers the average gas fraction, likely due to reduced gas content in halos that are most affected by AGN feedback



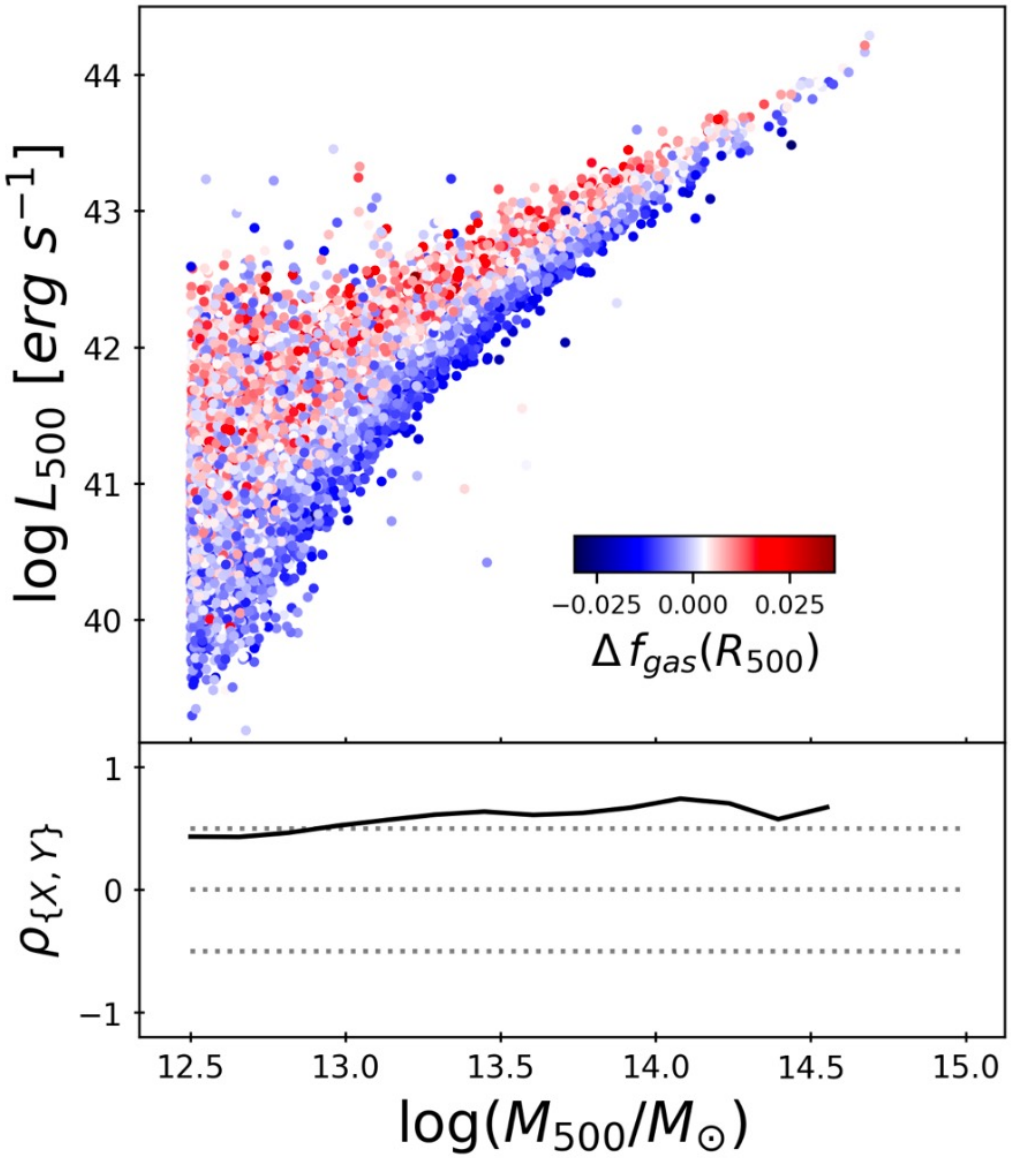
Popesso et al. 2024b

GAS FRACTION

Simulations tend to overpredict gas mass fraction

↓

Mechanisms of AGN feedback in simulations are still can't reproduce real processes fully



ASSEMBLY HISTORY

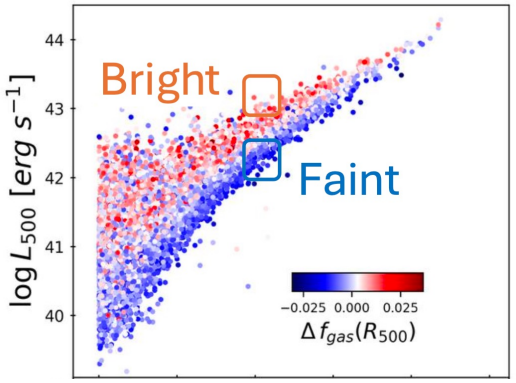
Toptun+2024 (in prep)

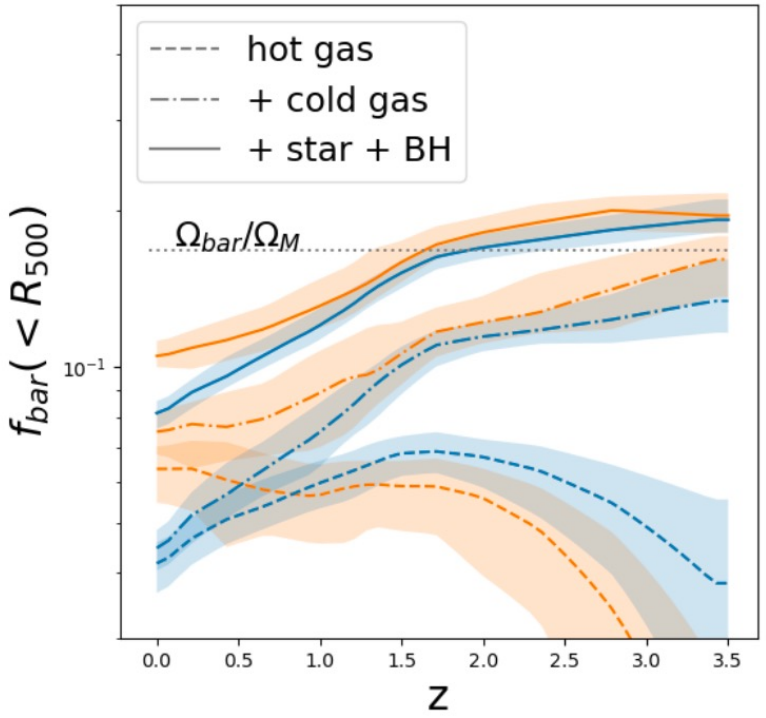
Why some of the groups of the same halo mass are brighter and some are not?

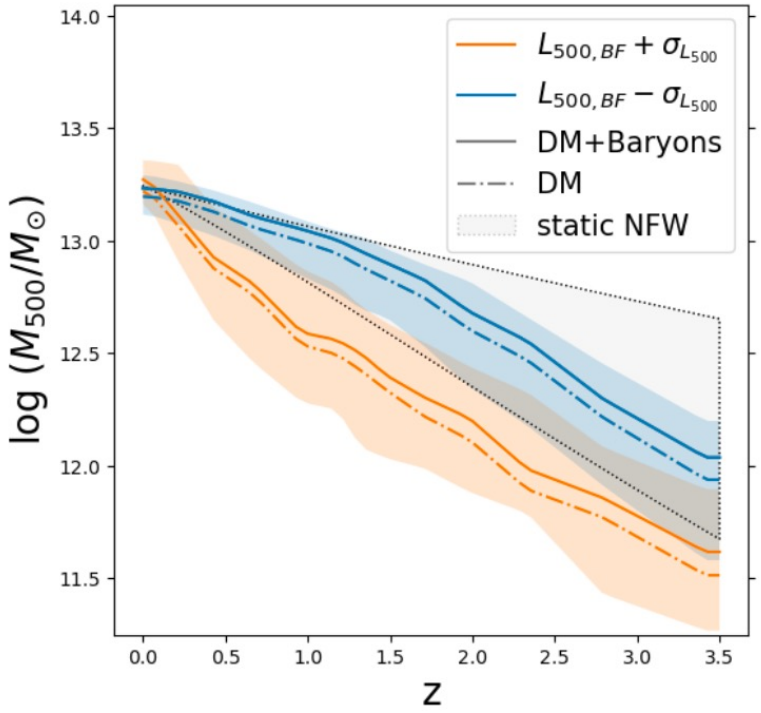
Brighter halos have higher gas fraction then fainter one. But what causing this difference?

Marini et al. 2025b

MAGNETICUM







Marini et al. 2025b

ASSEMBLY HISTORY

Toptun+2024 (in prep)

At z>1.5 AGN feedback lowering the gas fraction

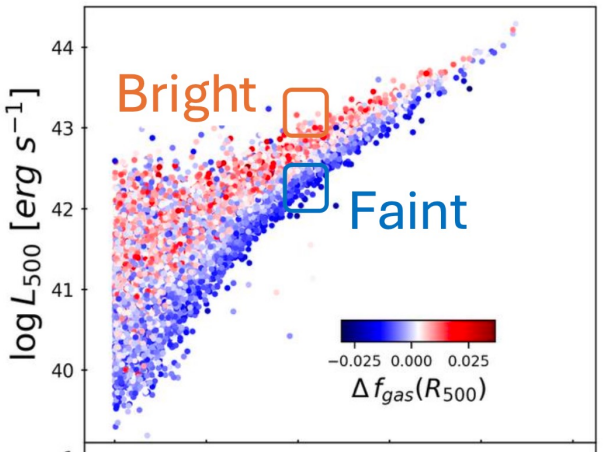
At z<1.5 late-time gas-rich mergers restoring the hot gas and boosting Lx

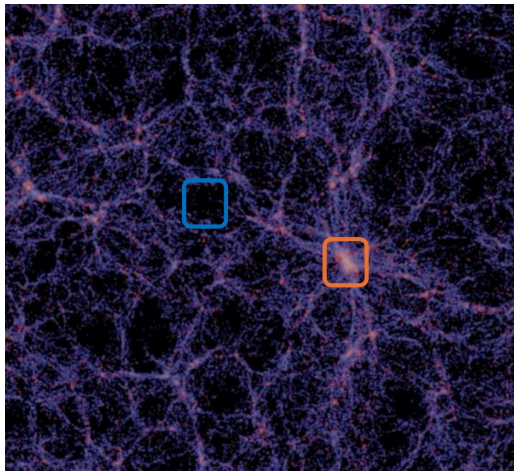
MAGNETICUM

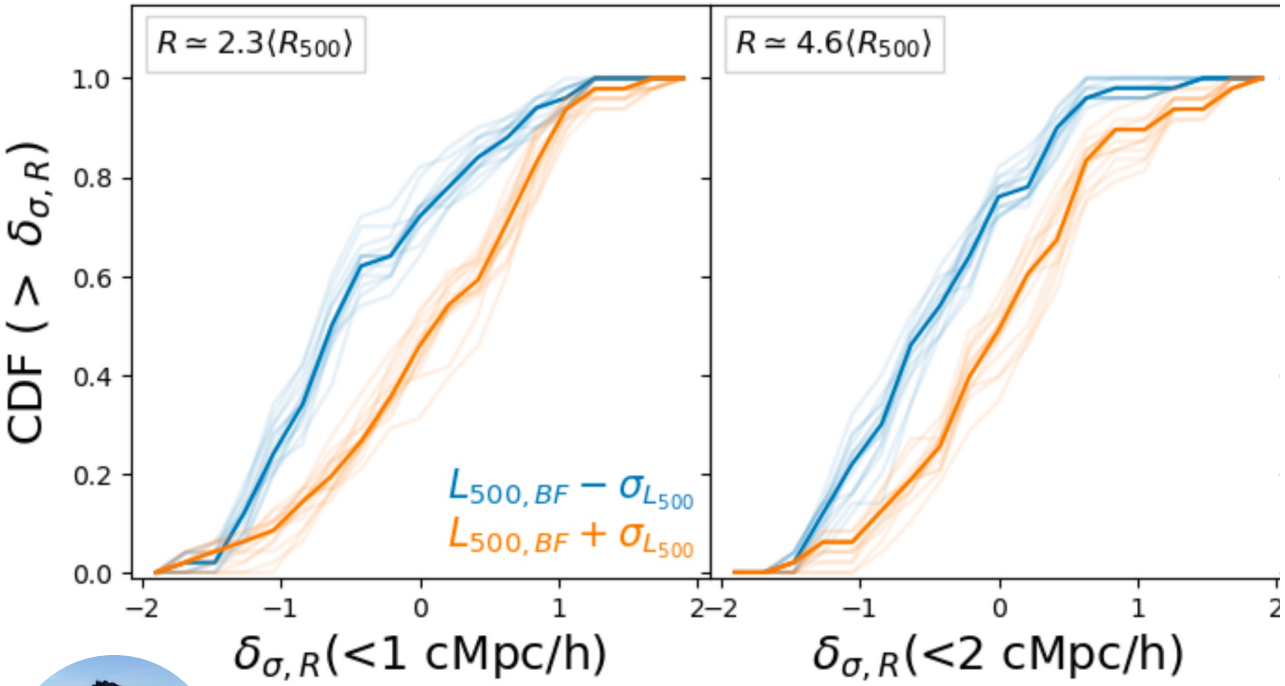
ASSEMBLY HISTORY

Toptun+2024 (in prep)

Gas content correlates with BH mass, stars, metals and environment

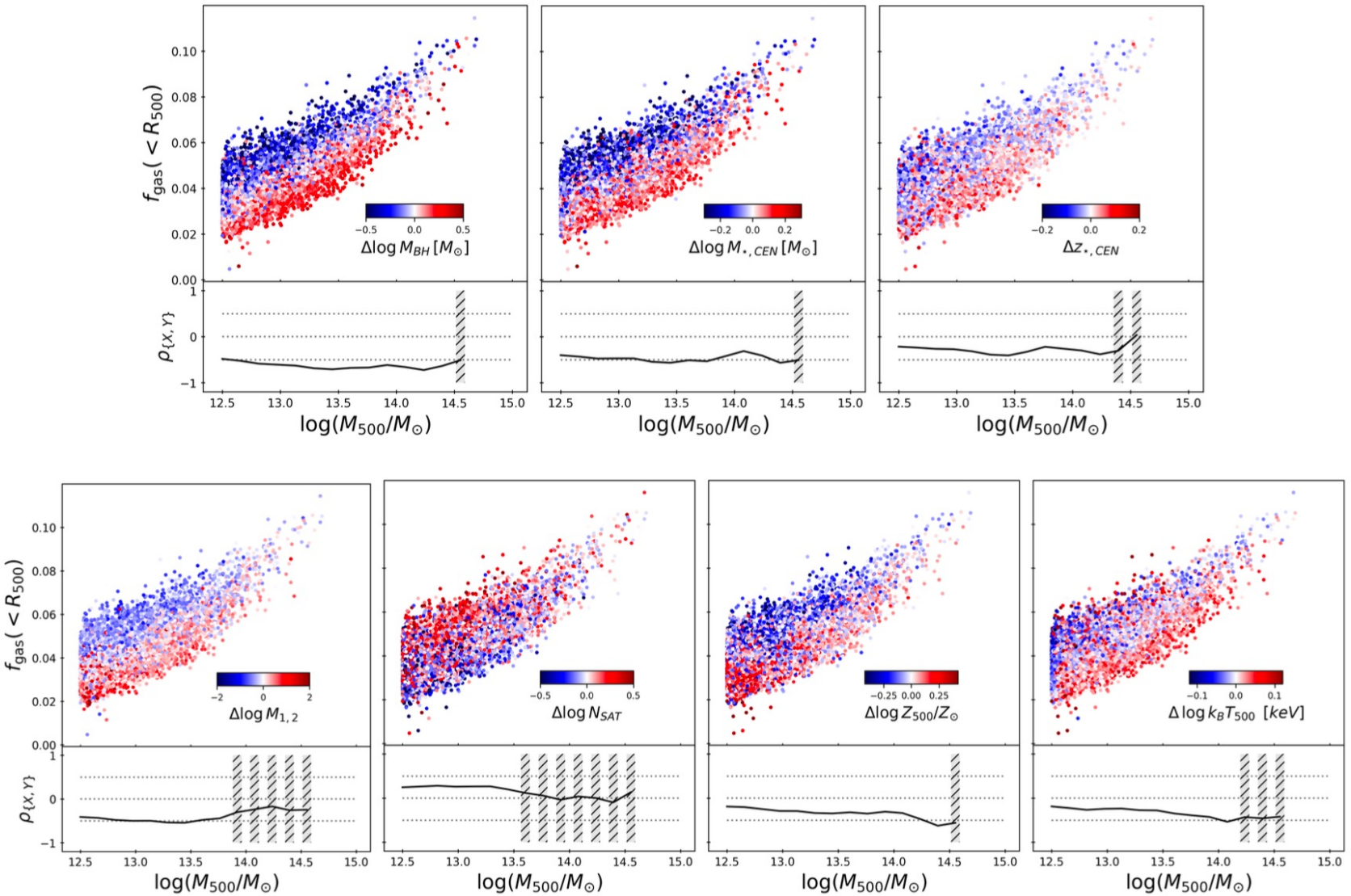






Marini et al. 2025b

MAGNETICUM



ASSEMBLY HISTORY

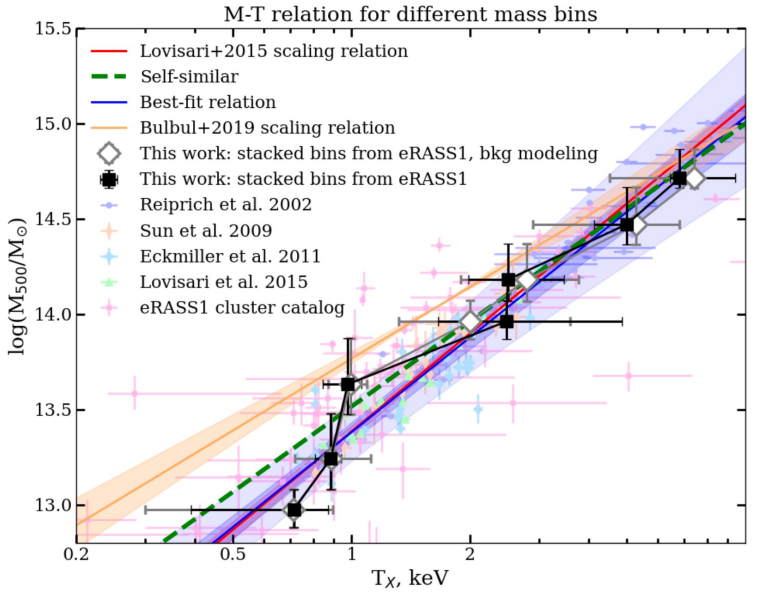
Gas content correlates with BH mass, stars, metals and environment

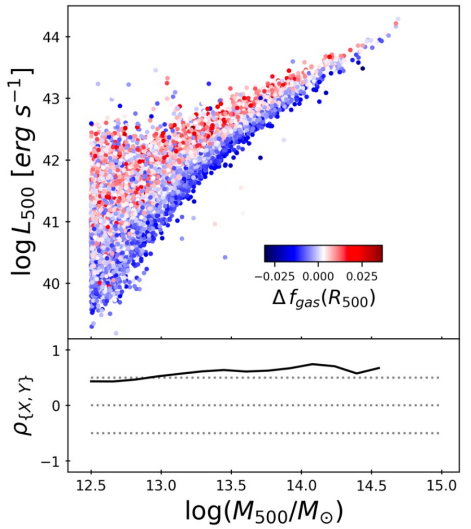
Marini et al. 2025b

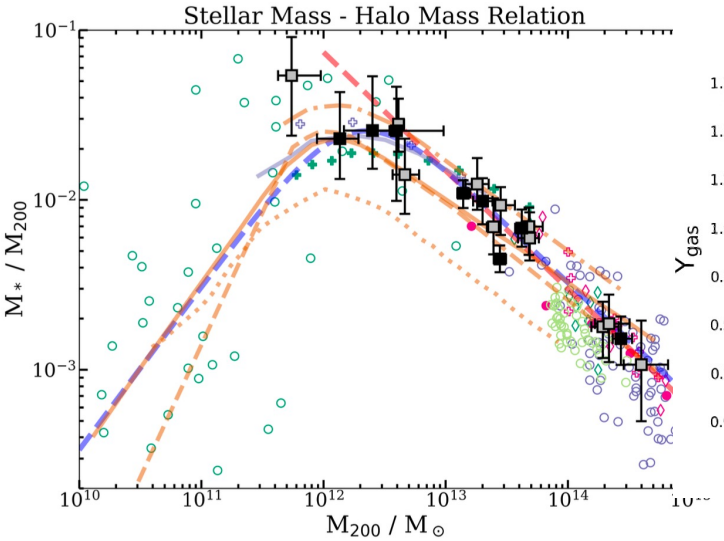
MAGNETICUM

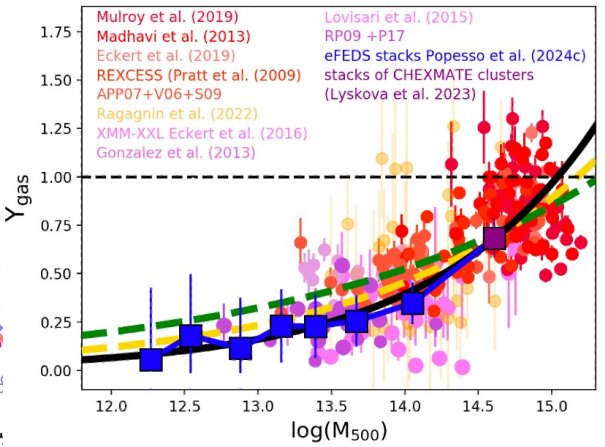
- Stacking + optical selection is reliable technique that allows us to dig much deeper than from we did from individual observations

RESULTS & TAKE-HOME MESSAGES









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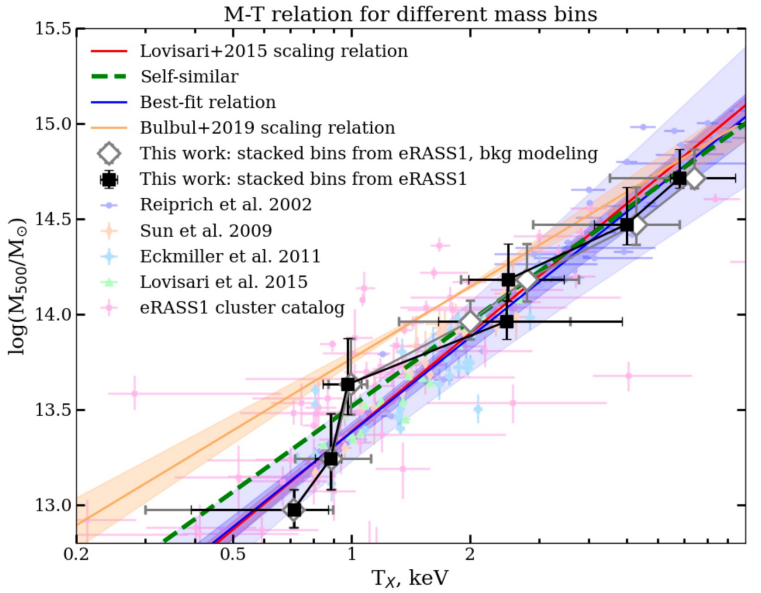
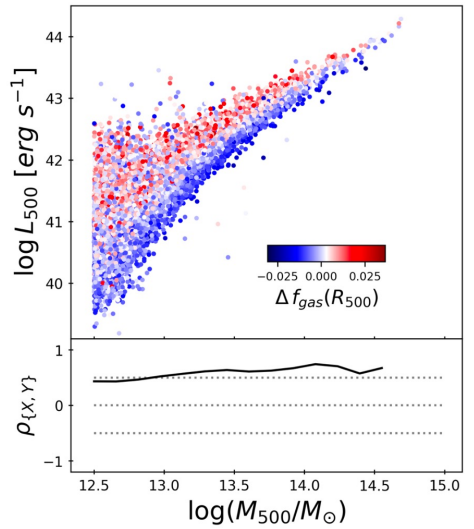
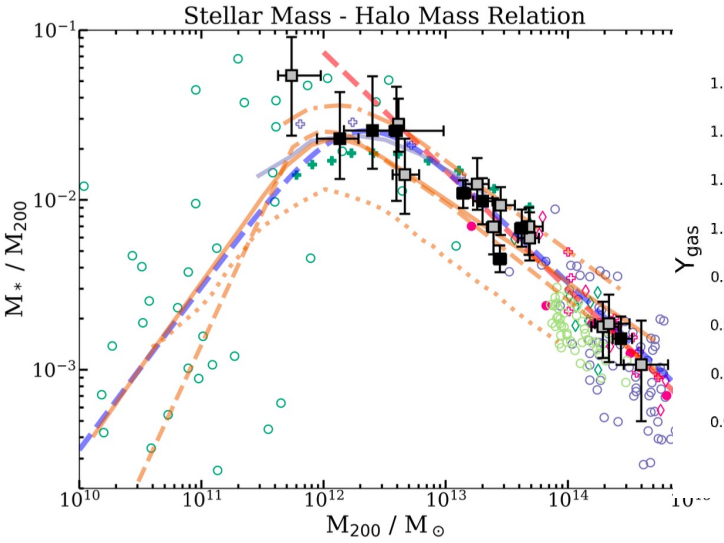
21 April 2026
Questions and ideas are welcome!

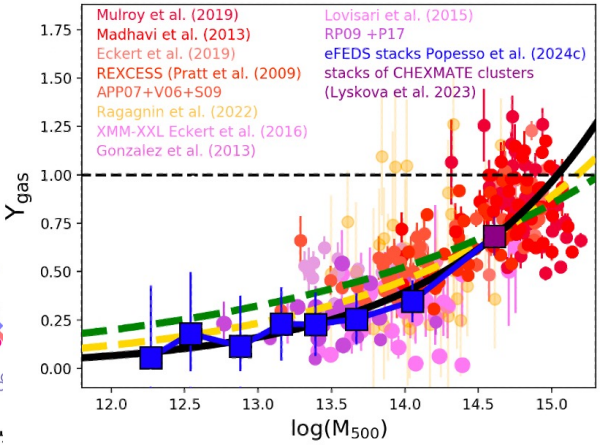
RESULTS & TAKE-HOME MESSAGES

- Stacking + optical selection is reliable technique that allows us to dig much deeper than from we did from individual observations
- Galaxy groups halos are different and having (probably) different evolutionary paths









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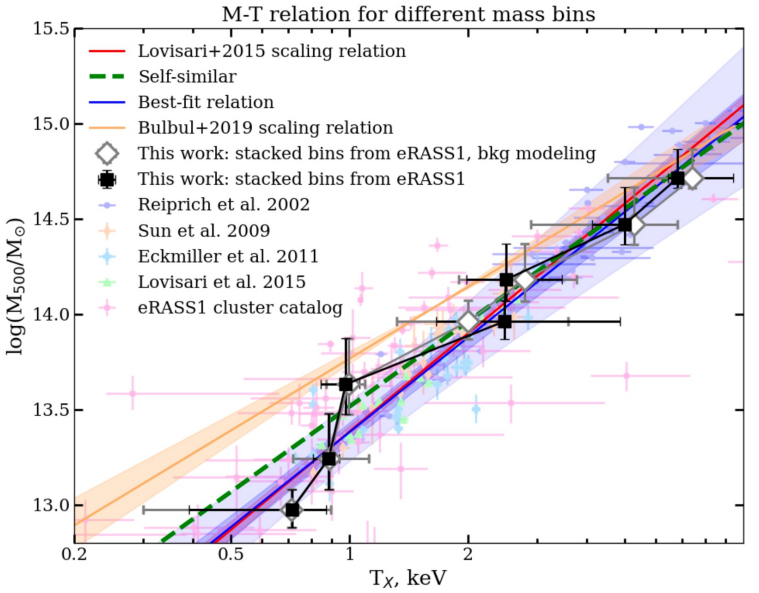
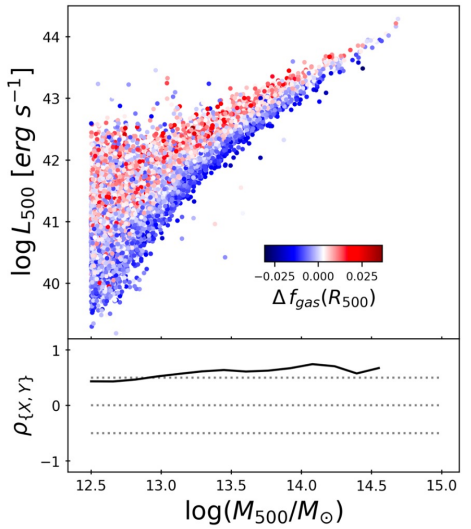
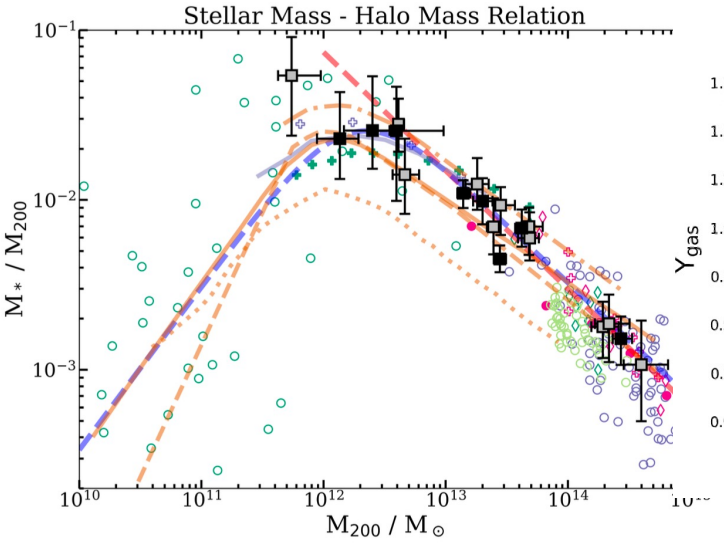
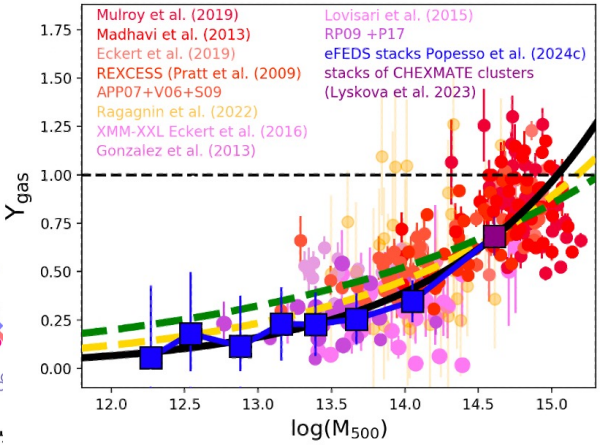
RESULTS & TAKE-HOME MESSAGES

- Stacking + optical selection is reliable technique that allows us to dig much deeper than from we did from individual observations
- Galaxy groups halos are different and having (probably) different evolutionary paths
- Average temperature inside R_{500} is consistent with self-similar predictions + gas fraction is lower
  → moving forward to entropy profiles to trace the feedback mechanisms









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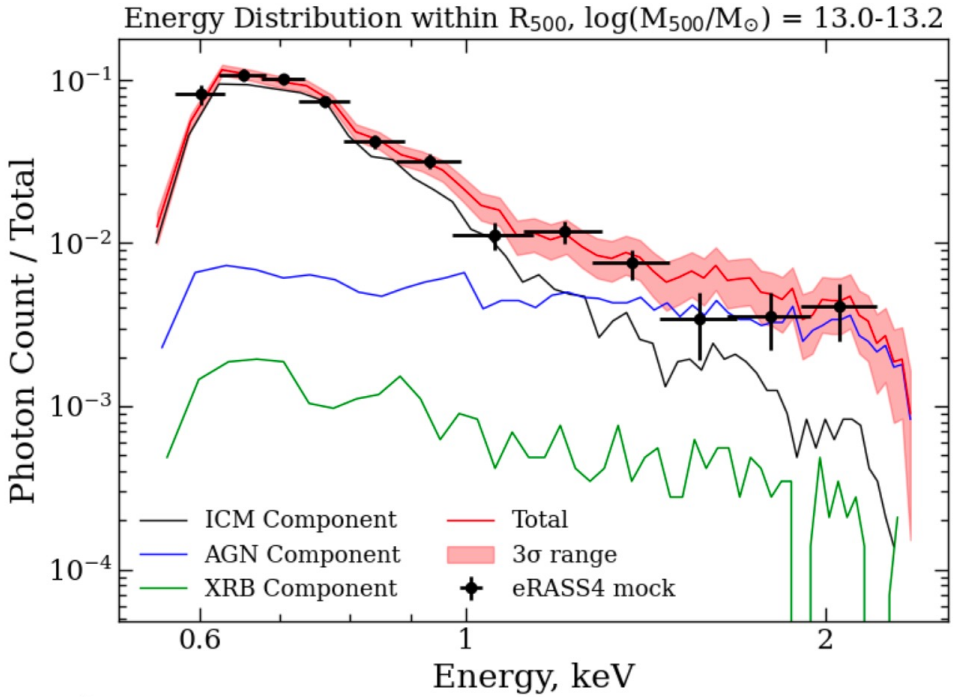
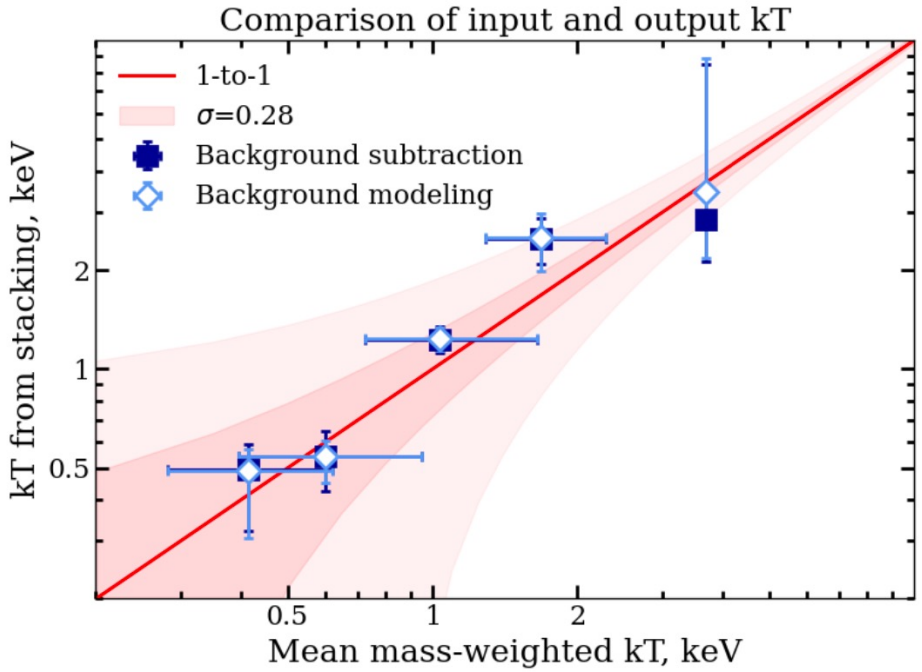
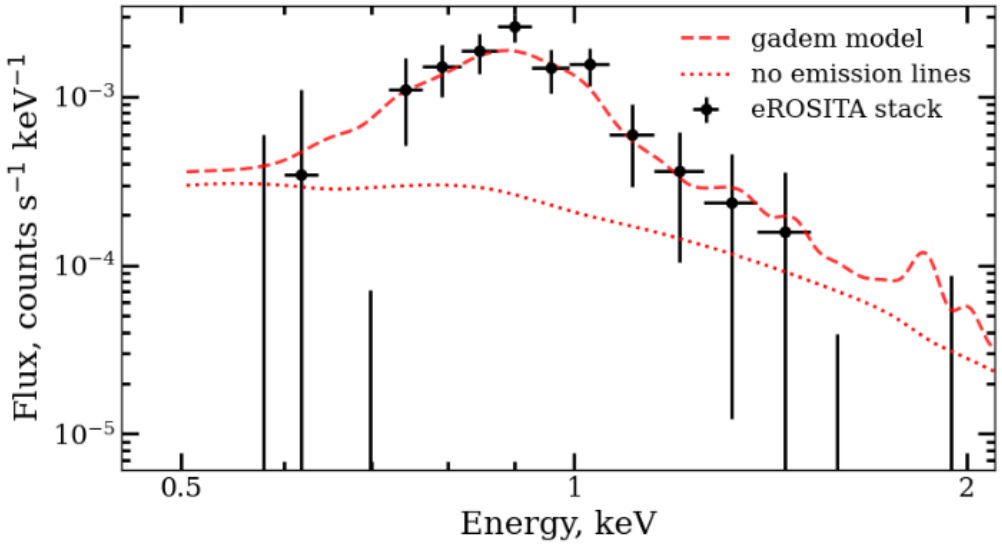


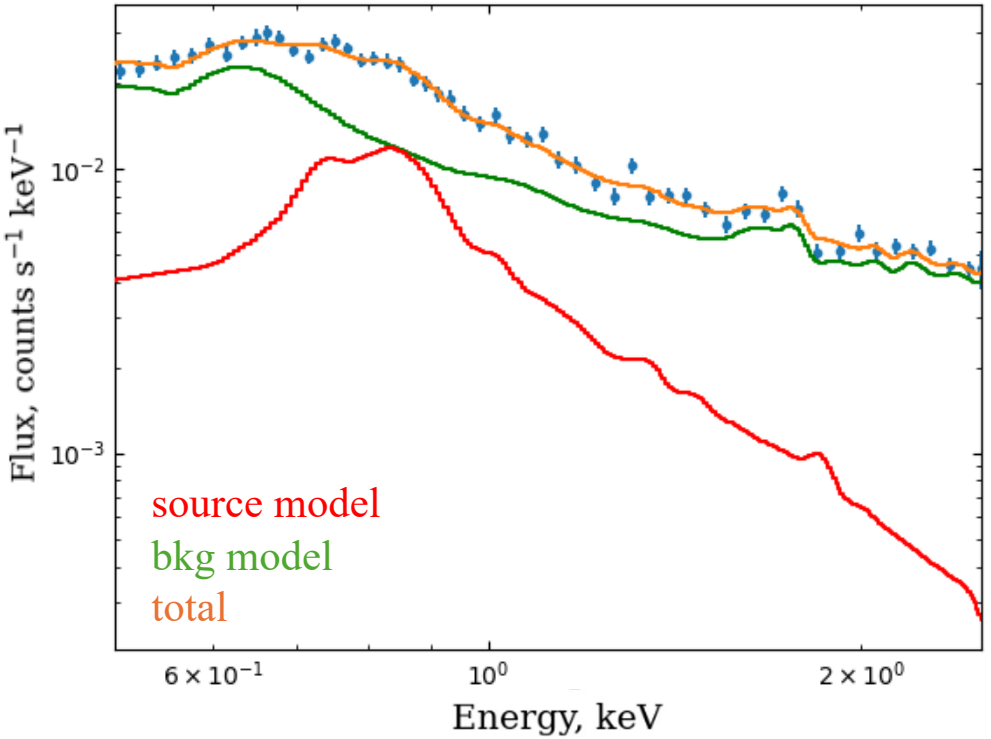


Toptun et al. 2025

Thanks to the simulations, we can compare input temperatures and spectra with the results after stacking to test our ability to reconstruct them accurately



subtracted background

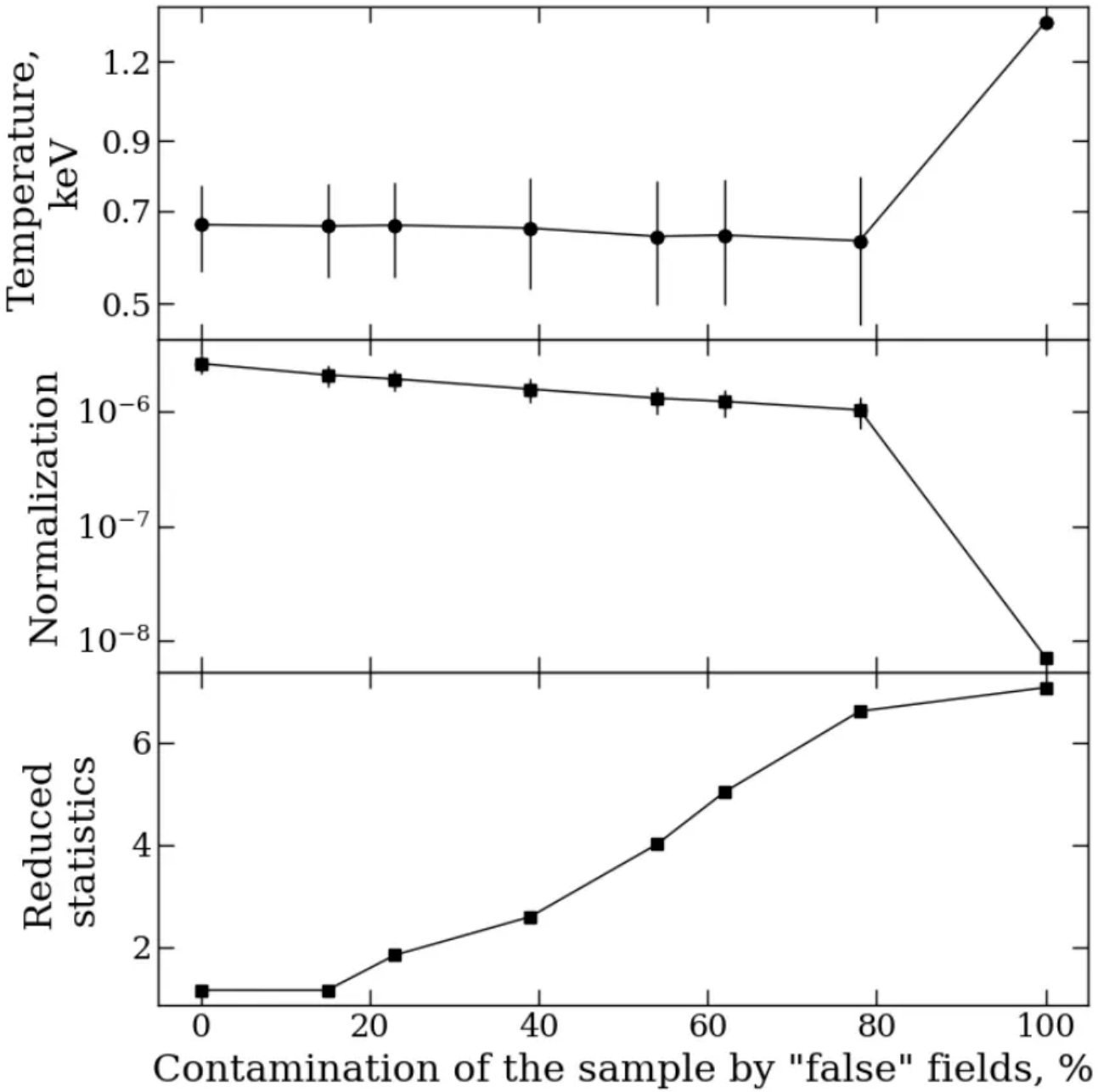


background modeling

TWO WAYS OF SPECTRAL MODELING

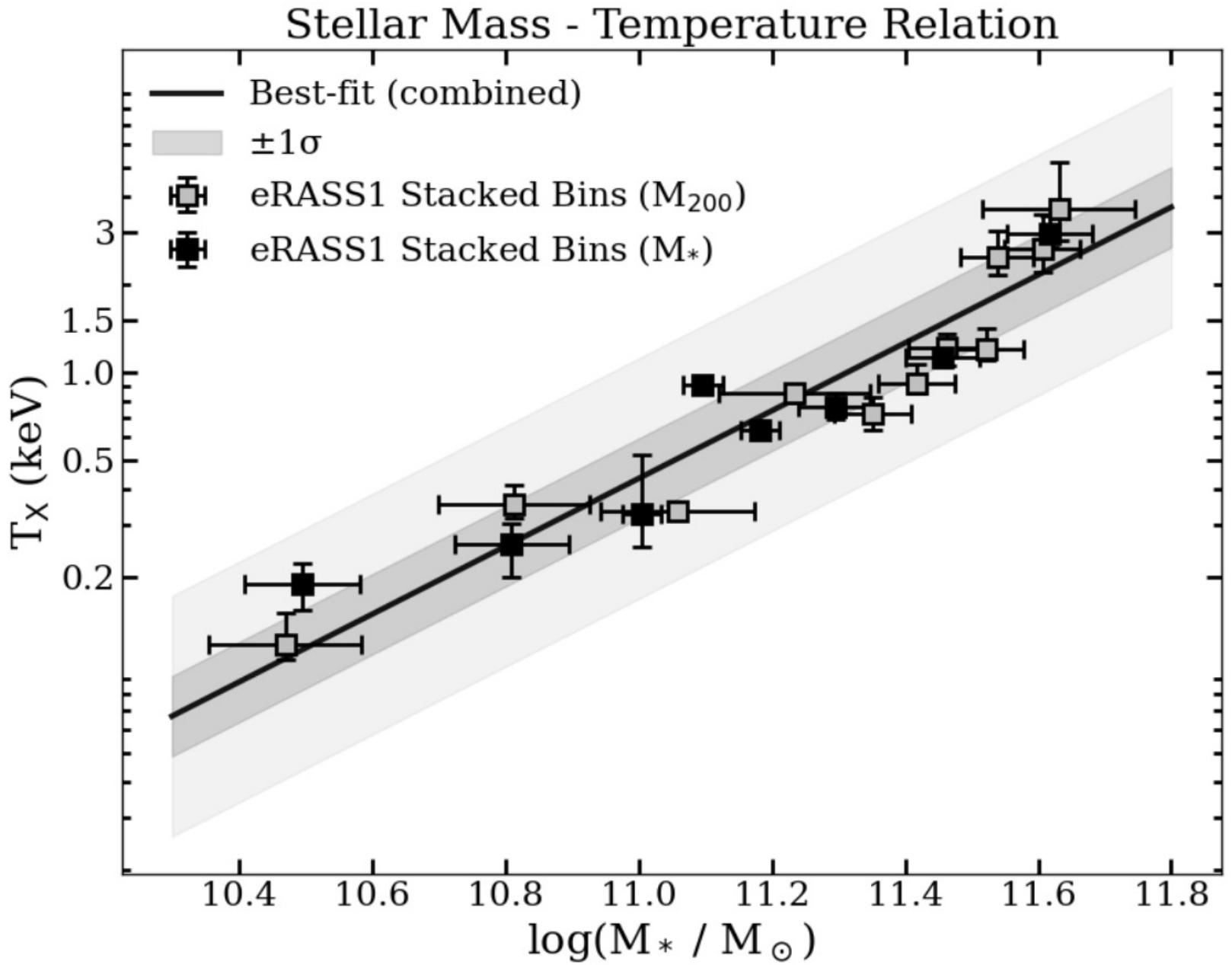
to check the consistency

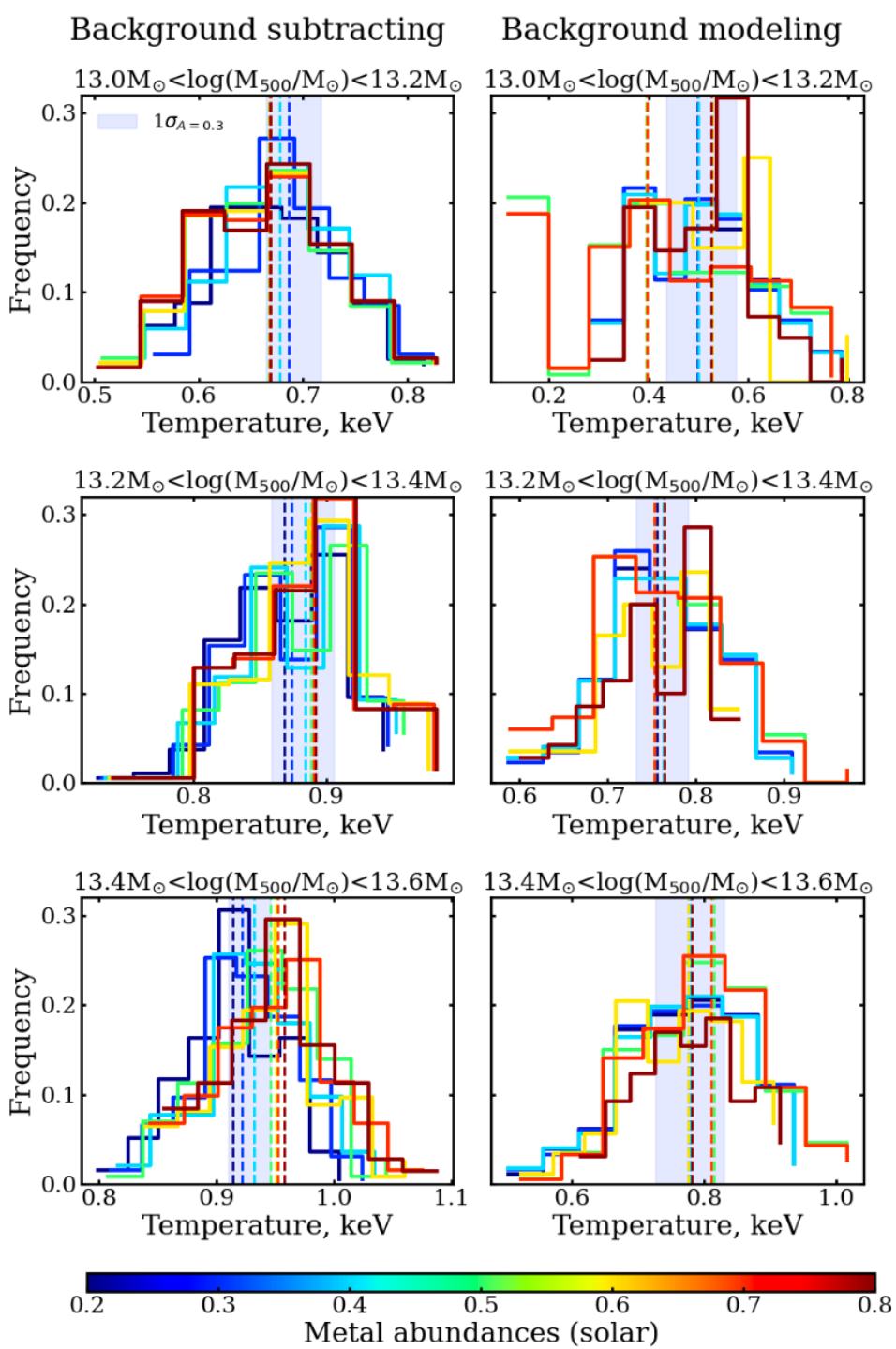
Toptun et al. 2025

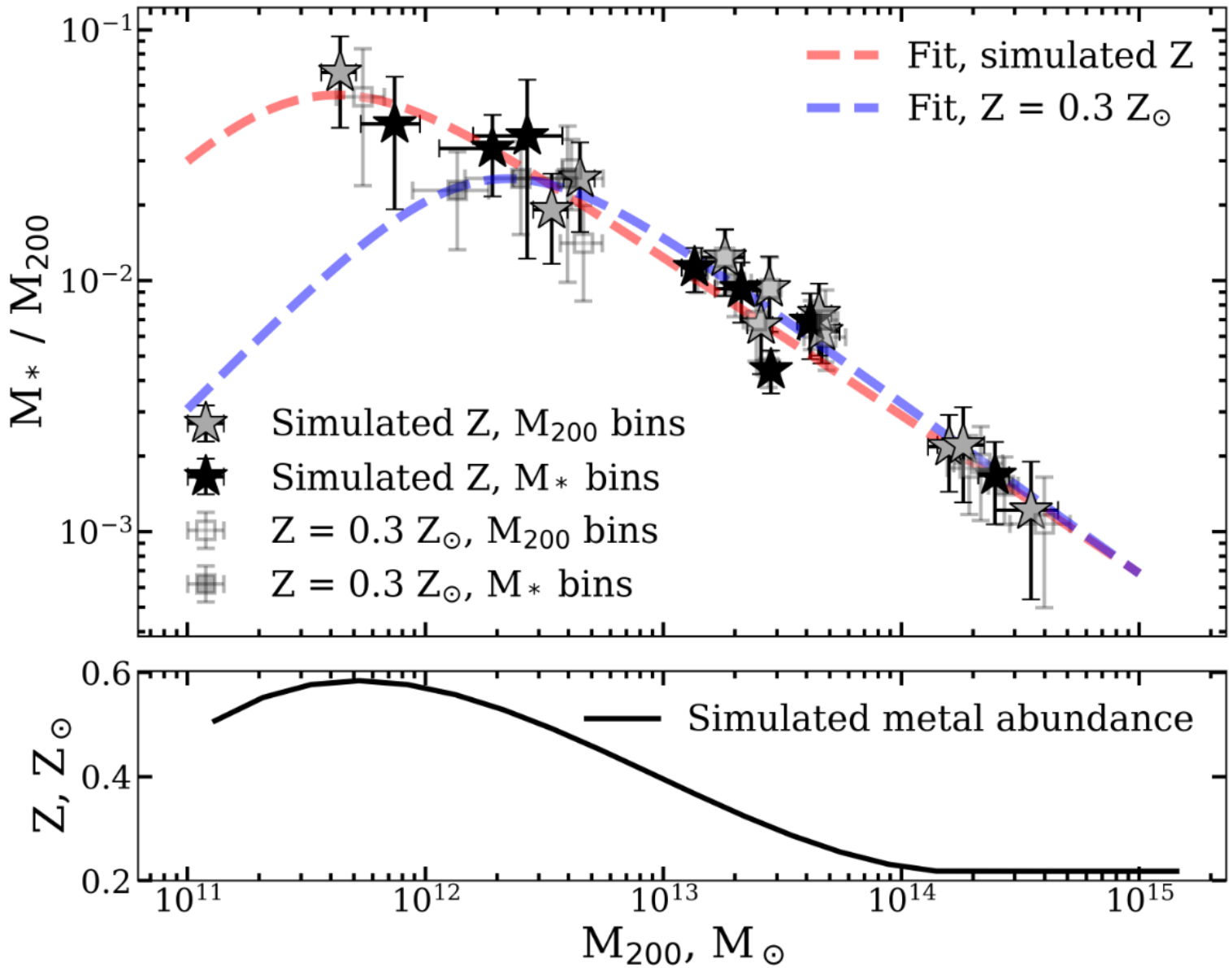


Comparison of the results for samples with different amount of “false-positive” sources shows us that

- temperature measurements are stable towards contamination
- but luminosities can be strongly affected

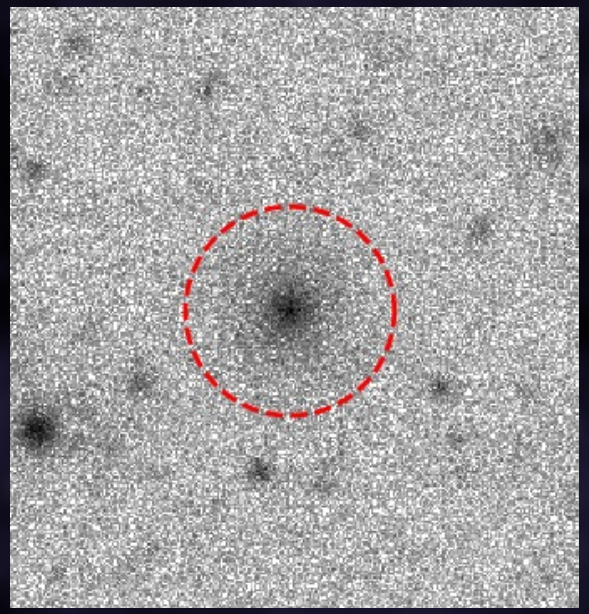

Stellar Mass - Temperature Relation
Best-fit (combined)
±1σ
eRASS1 Stacked Bins (M200)
eRASS1 Stacked Bins (M*)
3
1.5
1.0
0.5
0.2
TX (keV)
10.4
10.6
10.8
11.0
11.2
11.4
11.6
11.8
log(M* / M⊙)


Background subtracting
Background modeling
13.0M⊙<log(M500/M⊙)<13.2M⊙
13.2M⊙<log(M500/M⊙)<13.4M⊙
13.4M⊙<log(M500/M⊙)<13.6M⊙
1σA=0.3
Frequency
Temperature, keV
Metal abundances (solar)

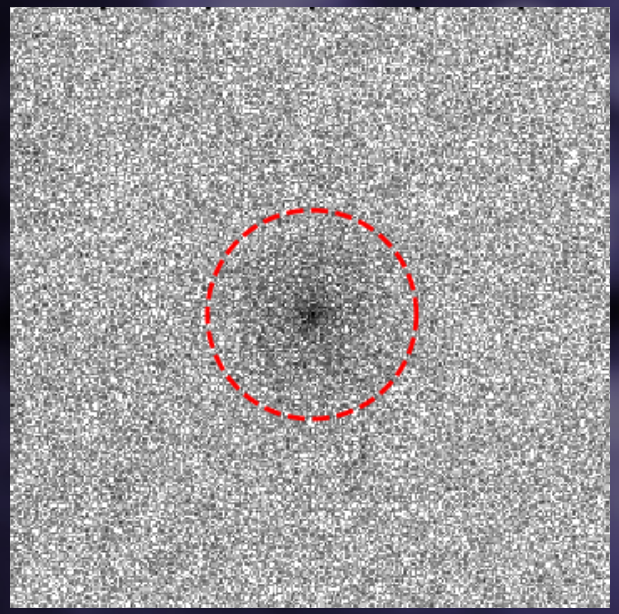

Fit, simulated Z
Fit, Z = 0.3 Z⊙
Simulated Z, M200 bins
Simulated Z, M* bins
Z = 0.3 Z⊙, M200 bins
Z = 0.3 Z⊙, M* bins
M* / M200
Simulated metal abundance
Z, Z⊙
M200, M⊙

MAIN TECHNIQUE: STACKING

Example on simulated stacked data, logM500=13.4



before

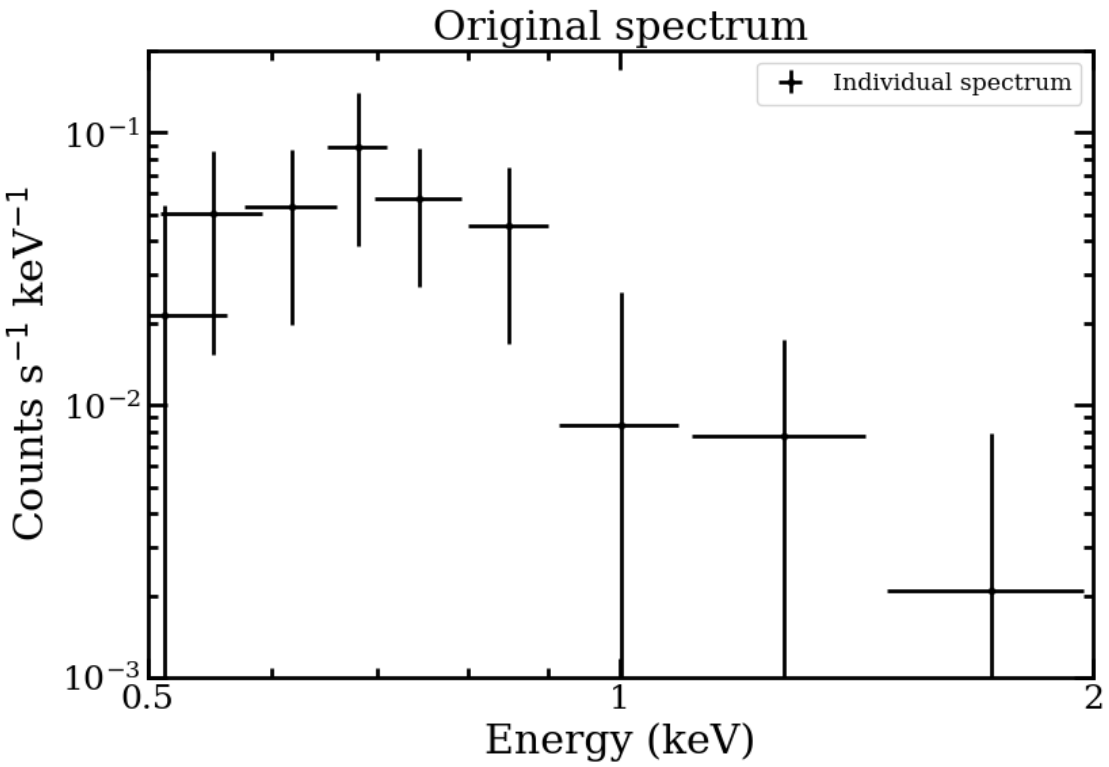


after

All point sources, previosly detected in produced event list (for simulations) or in eRASS1 catalog (for observations) masked with size of average eROSITA psf to clean source and background spectra from bright AGN's photons

Cleaning the exposures from point sources

MAIN TECHNIQUE: STACKING

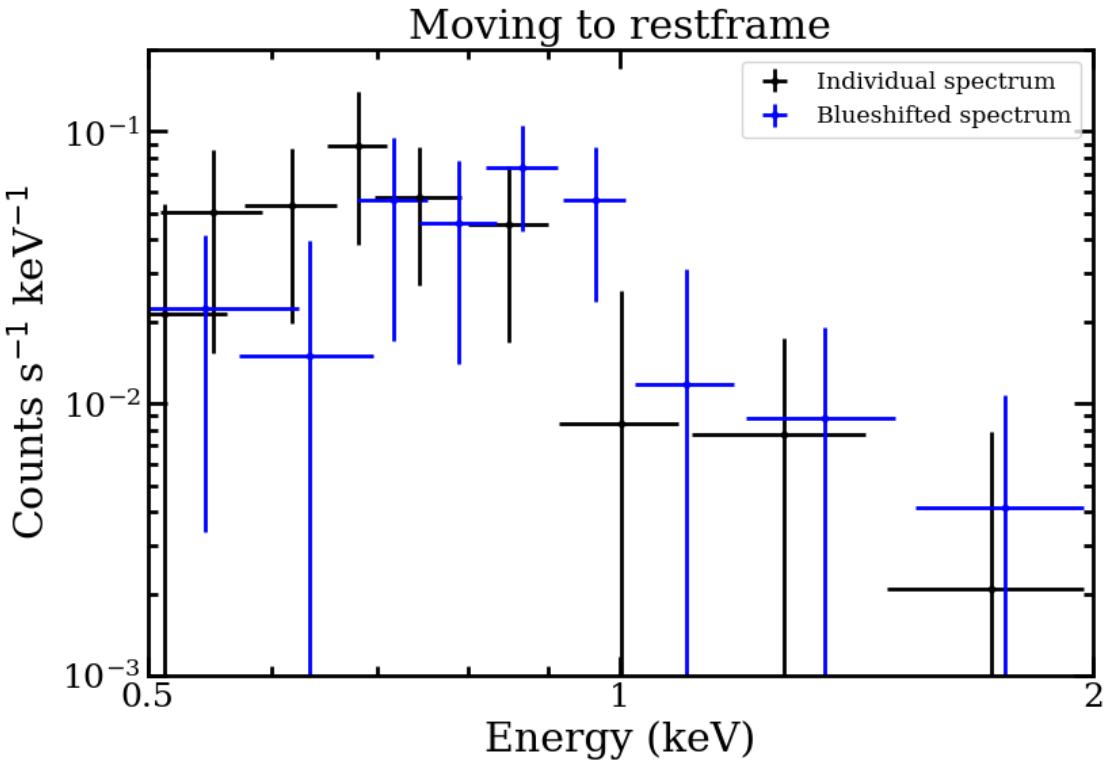


Using eSASS with radius of extraction R500

Cleaning the exposures from point sources

Extracting individual spectra

MAIN TECHNIQUE: STACKING



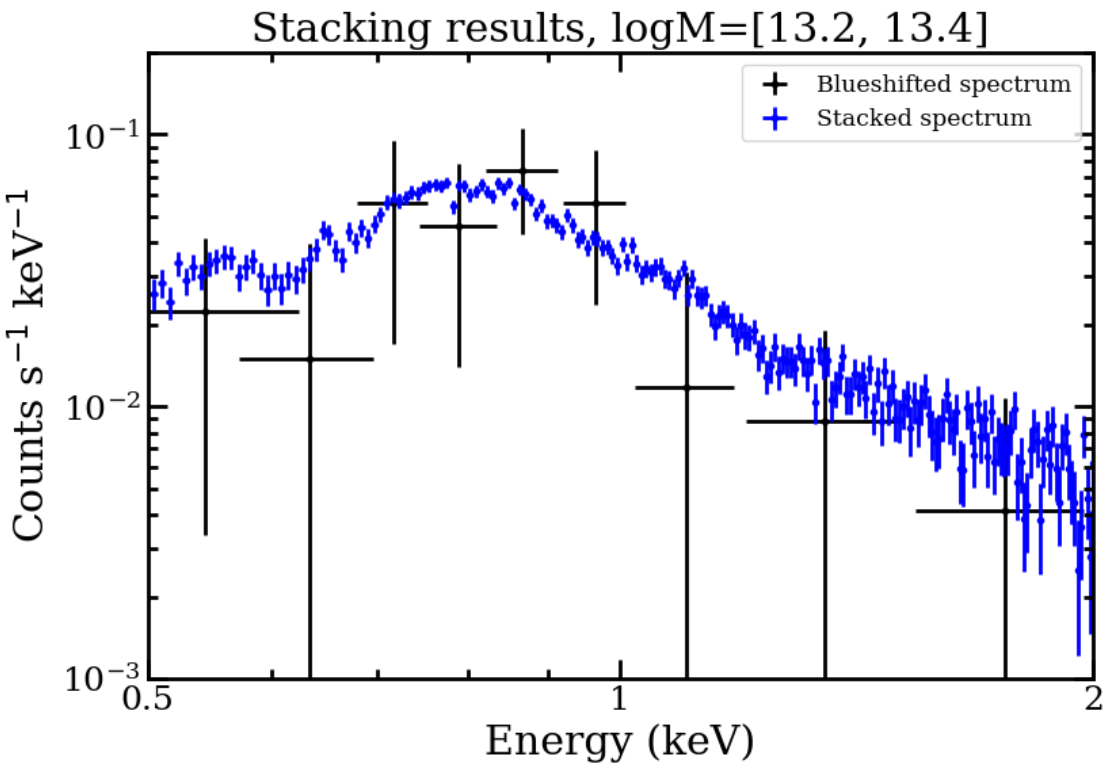
Moving to restframe (red) to avoid "blurring" of stacked spectra

Cleaning the exposures from point sources

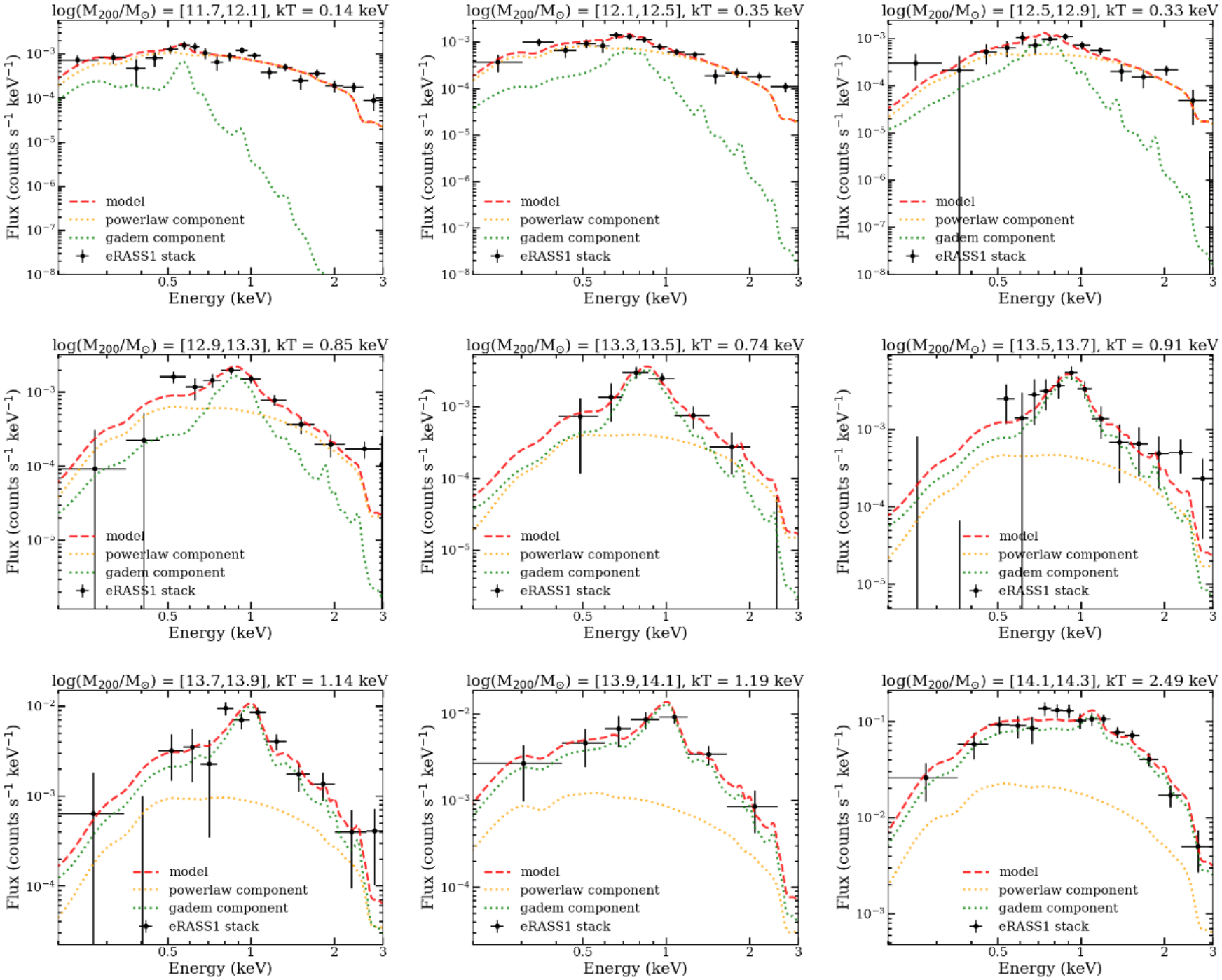
Extracting individual spectra

Moving spectra to restframe

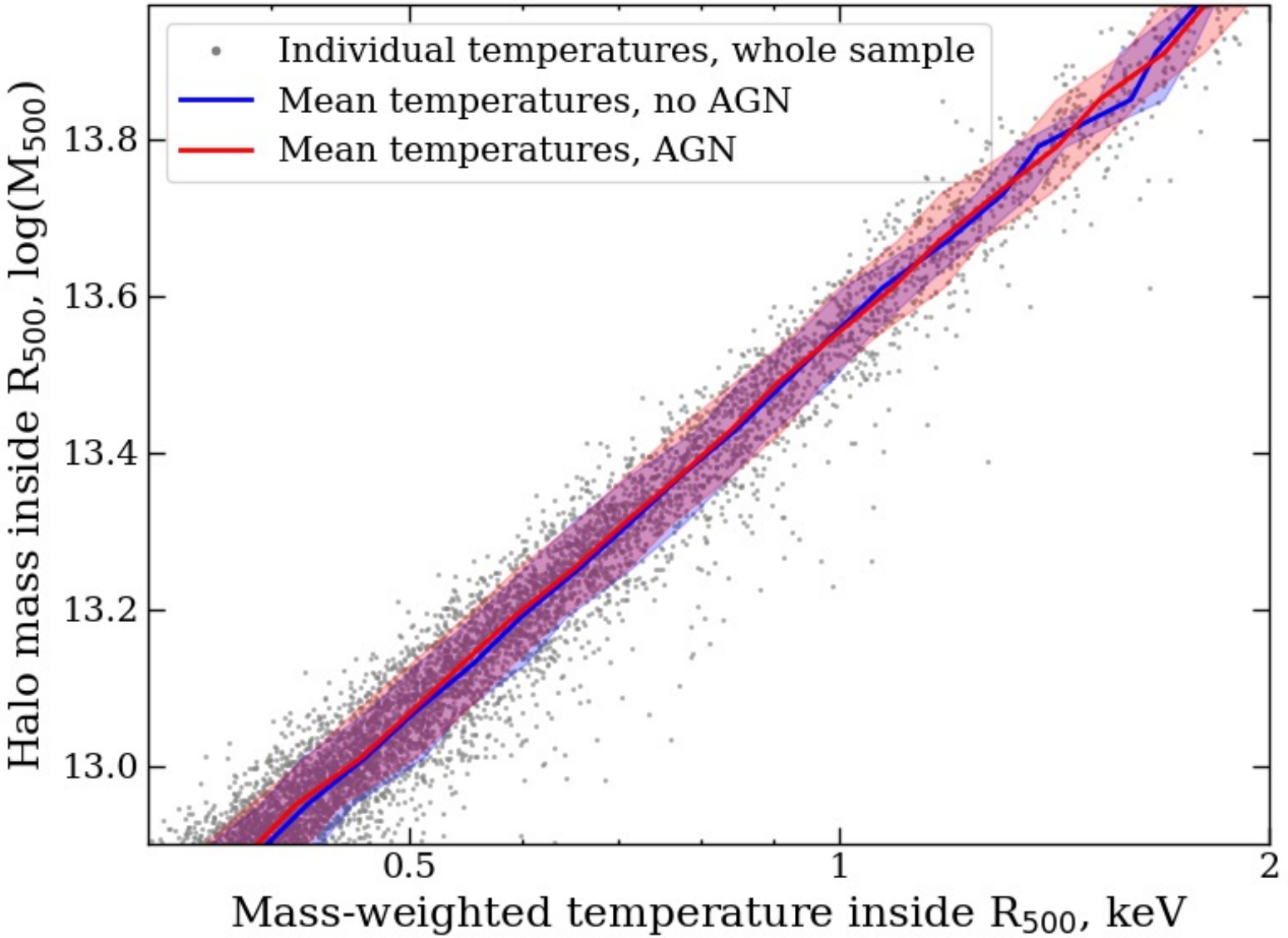
MAIN TECHNIQUE: STACKING



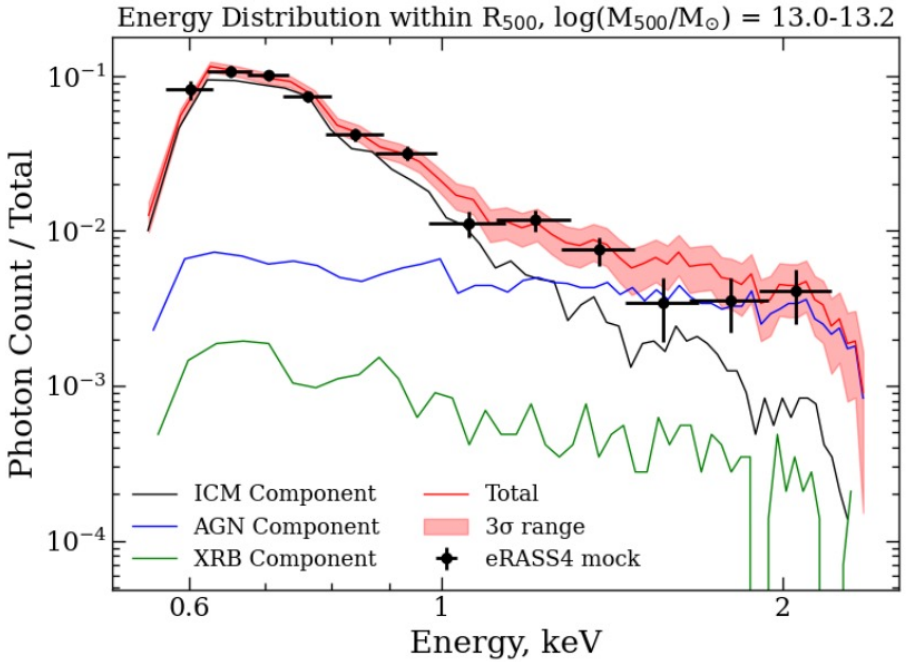
Result: significant increasing of signal-to-noise with saving of original spectrum shape

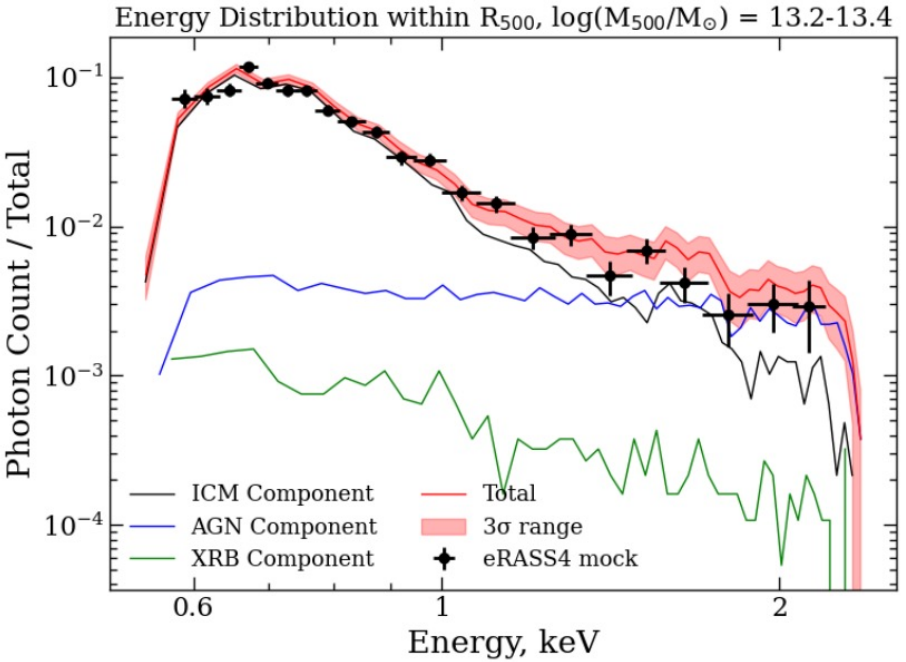

log(M200/M⊙) = [11.7,12.1], kT = 0.14 keV
log(M200/M⊙) = [12.1,12.5], kT = 0.35 keV
log(M200/M⊙) = [12.5,12.9], kT = 0.33 keV
log(M200/M⊙) = [12.9,13.3], kT = 0.85 keV
log(M200/M⊙) = [13.3,13.5], kT = 0.74 keV
log(M200/M⊙) = [13.5,13.7], kT = 0.91 keV
log(M200/M⊙) = [13.7,13.9], kT = 1.14 keV
log(M200/M⊙) = [13.9,14.1], kT = 1.19 keV
log(M200/M⊙) = [14.1,14.3], kT = 2.49 keV
Flux (counts s−1 keV−1)
Energy (keV)
model
powerlaw component
gadem component
eRASS1 stack

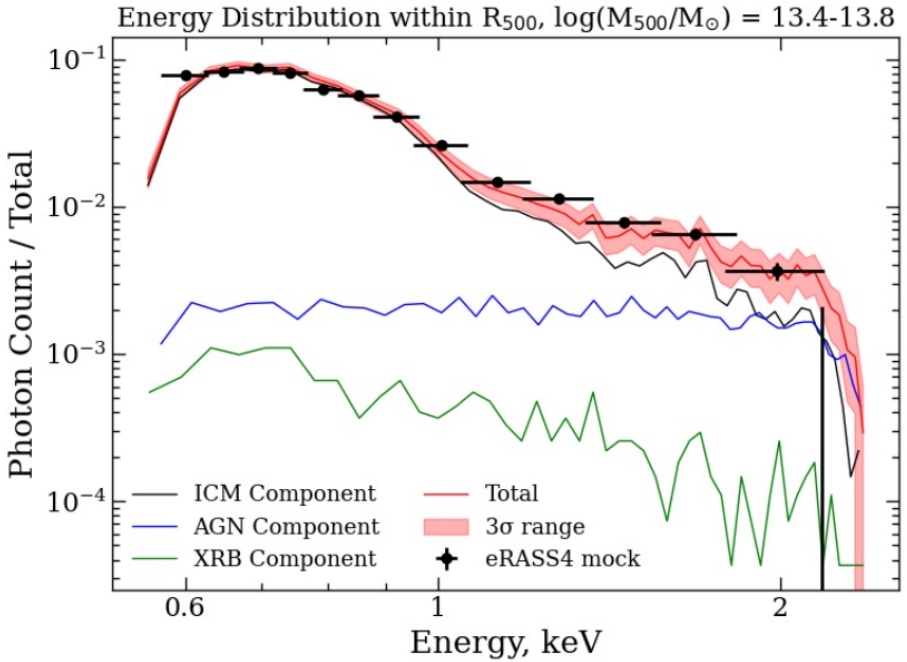
IMPACT OF AGN

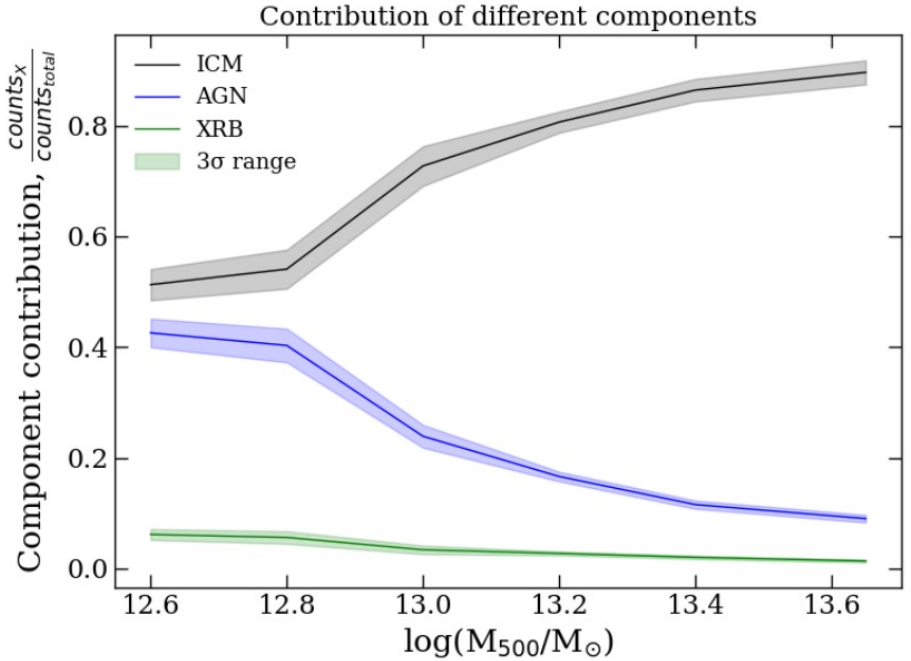


IMPACT OF AGN

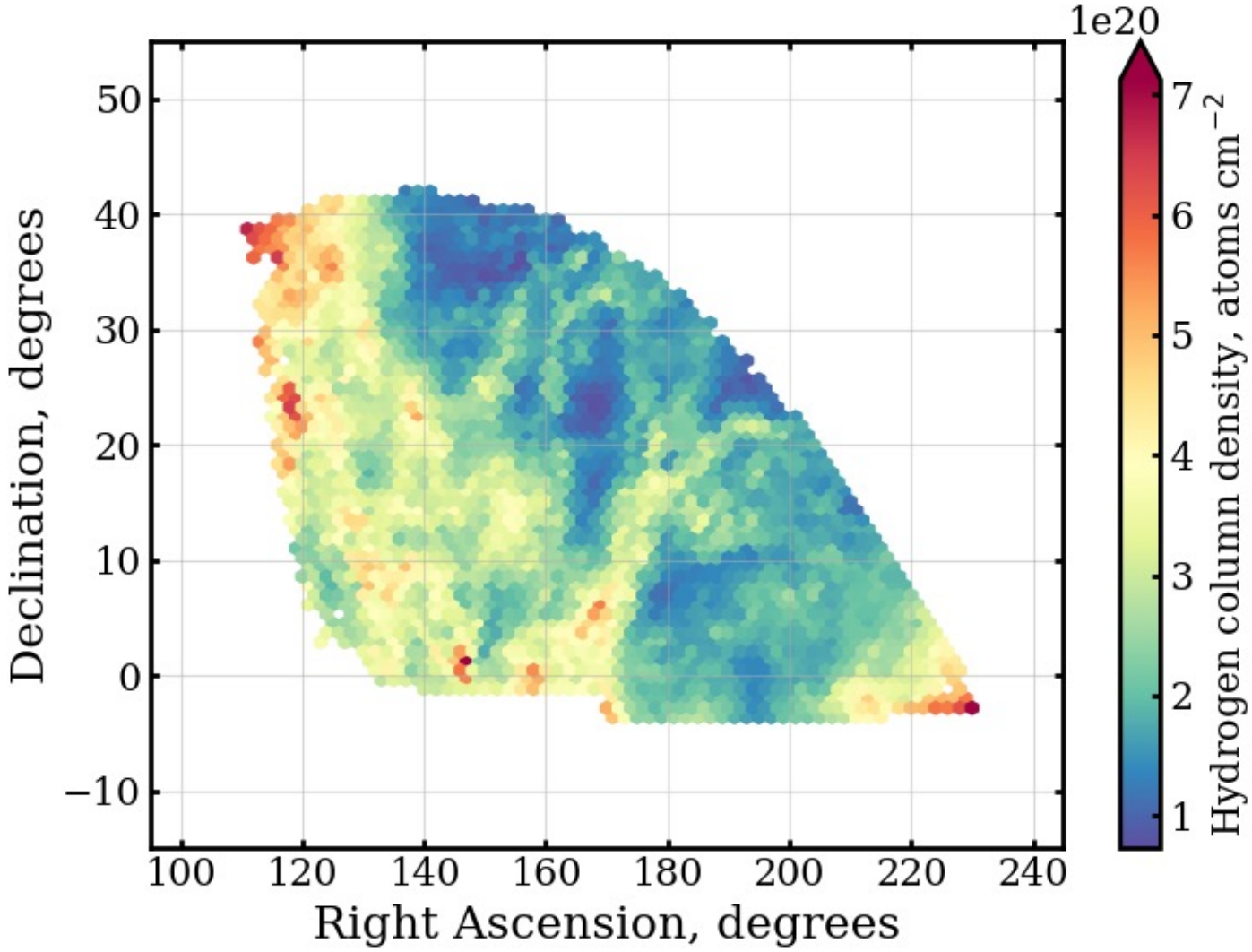


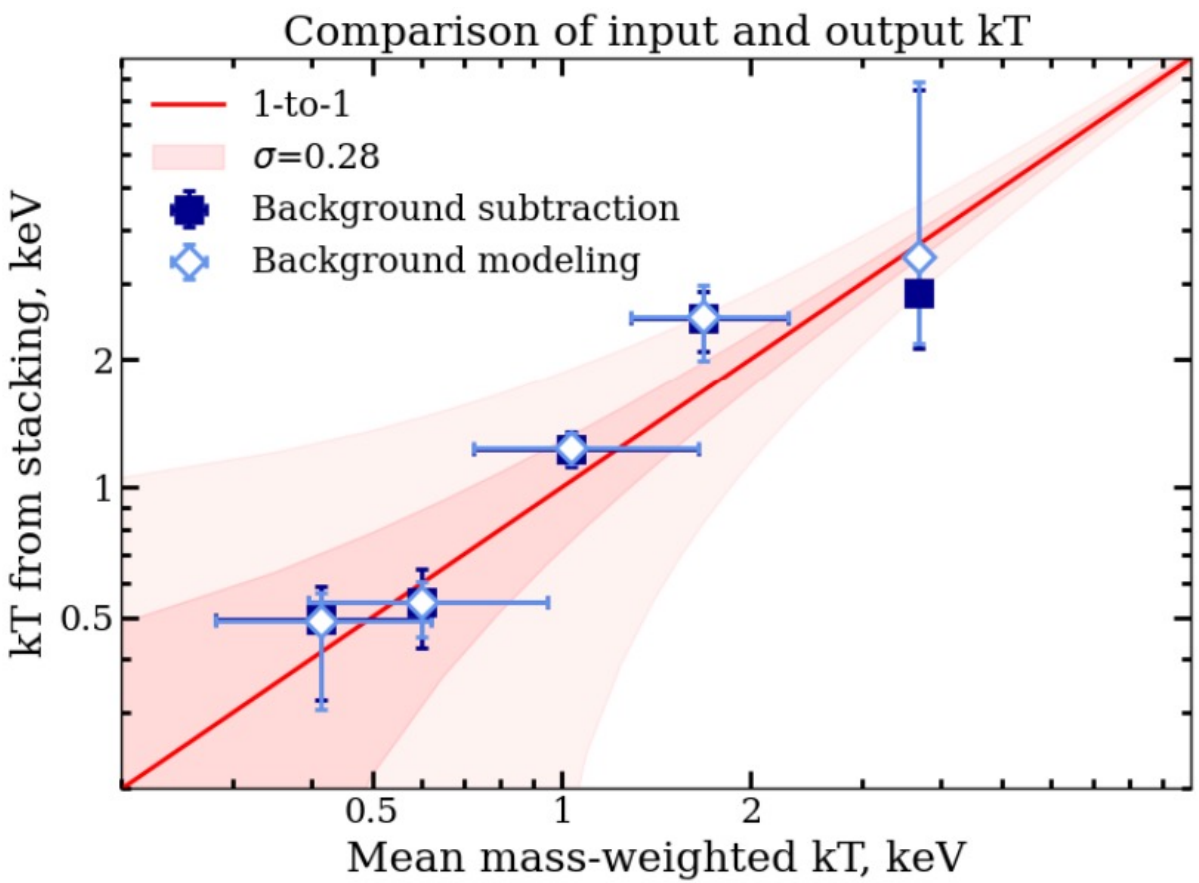


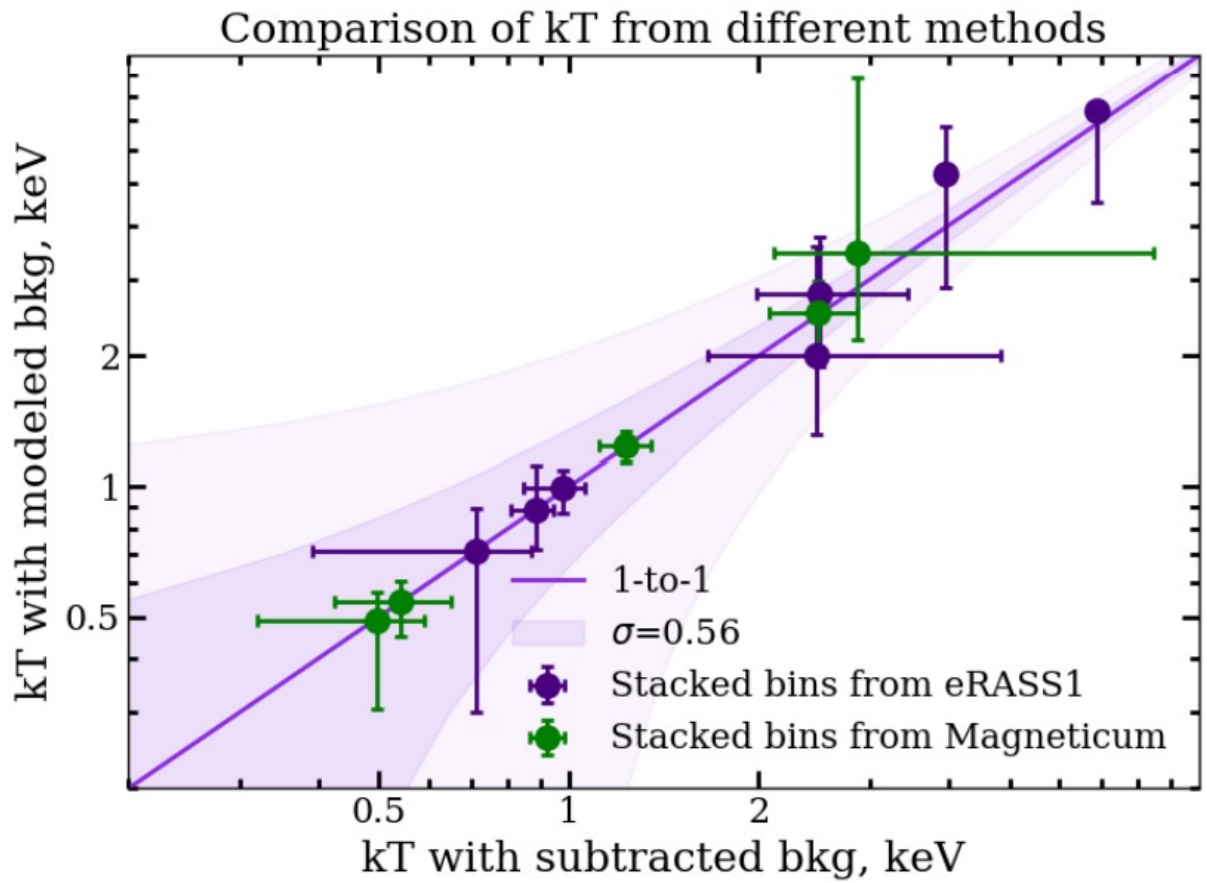




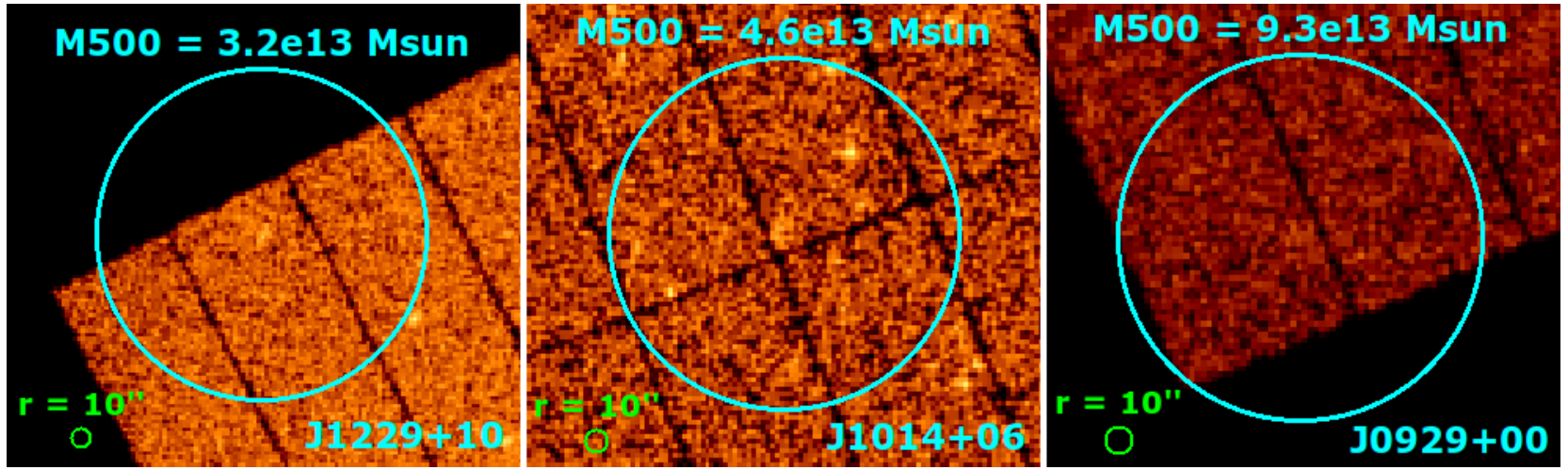
FOREGROUND ABSORPTION



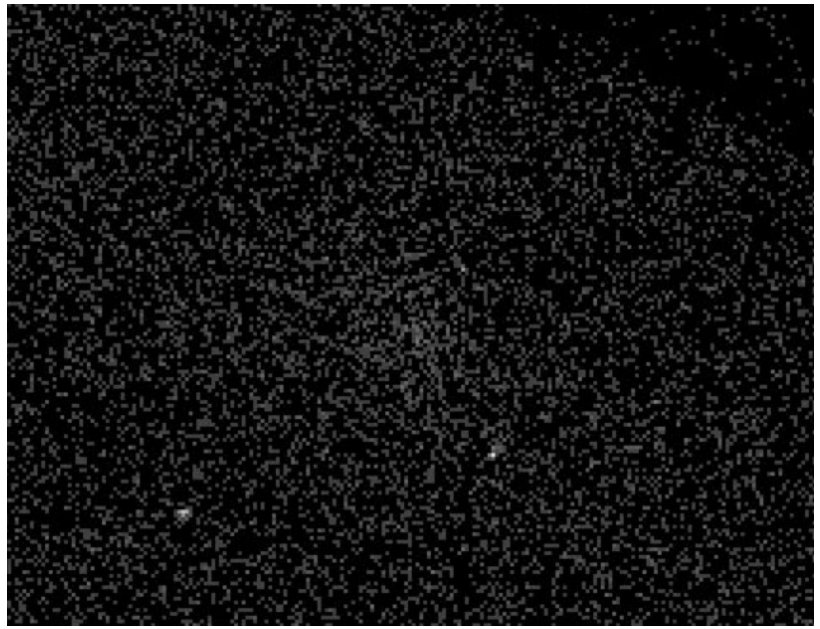

Comparison of input and output kT
1-to-1
σ=0.28
Background subtraction
Background modeling
kT from stacking, keV
Mean mass-weighted kT, keV
0.5
1
2


Comparison of kT from different methods
1-to-1
σ=0.56
Stacked bins from eRASS1
Stacked bins from Magneticum
kT with modeled bkg, keV
kT with subtracted bkg, keV
0.5
1
2

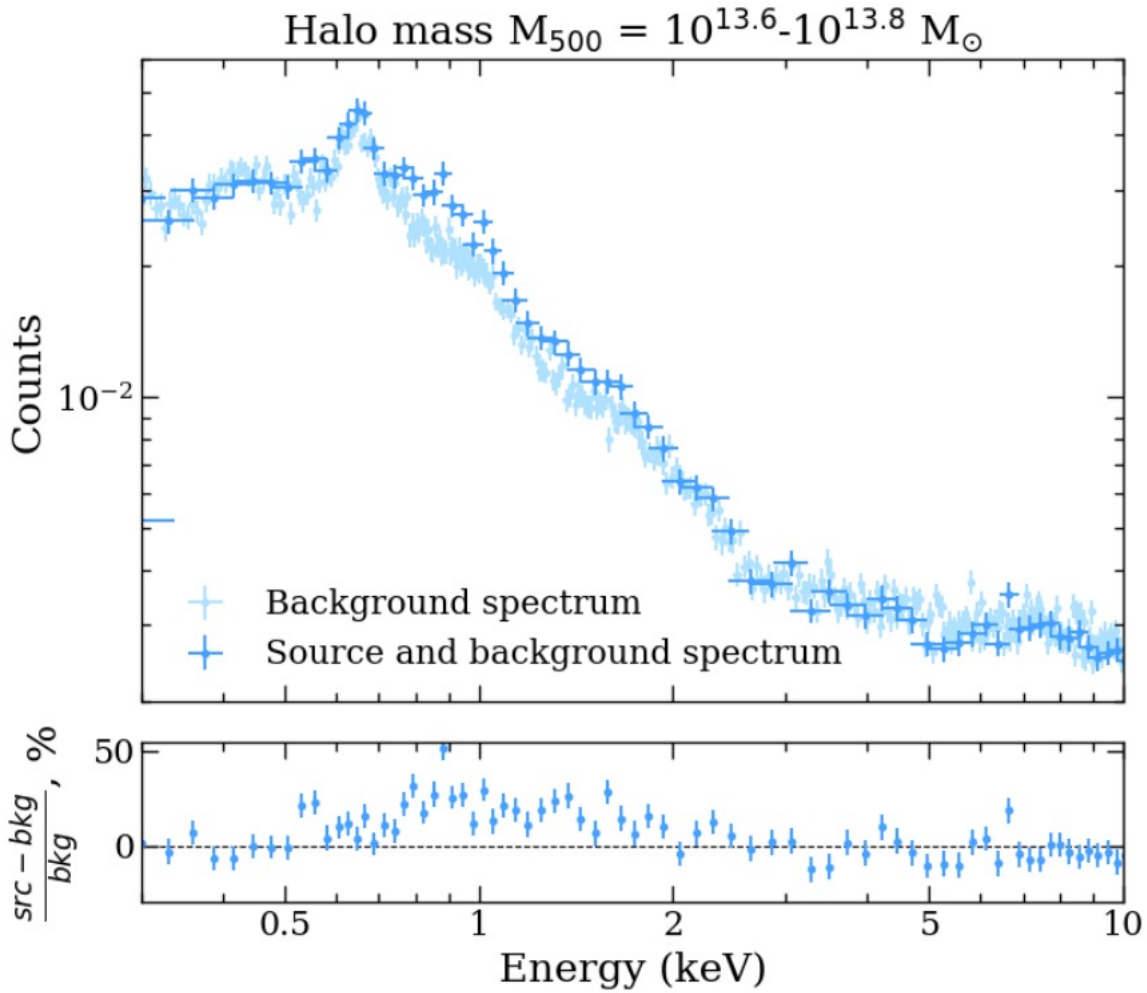
ARCHIVAL DATA



XMM-Newton



Chandra


Halo mass $M_{500} = 10^{13.6}$-$10^{13.8}$ $M_\odot$
Counts
10^{-2}
Background spectrum
Source and background spectrum
$\frac{src - bkg}{bkg}$, %
50
0
0.5
1
2
5
10
Energy (keV)