X-ray Properties of Galaxy Clusters with *eROSITA*

Joseph Hall

Astro Lunch Meeting

30 July 2025

News?

X-ray Properties of Galaxy Clusters with *eROSITA*

Joseph Hall

Astro Lunch Meeting

30 July 2025

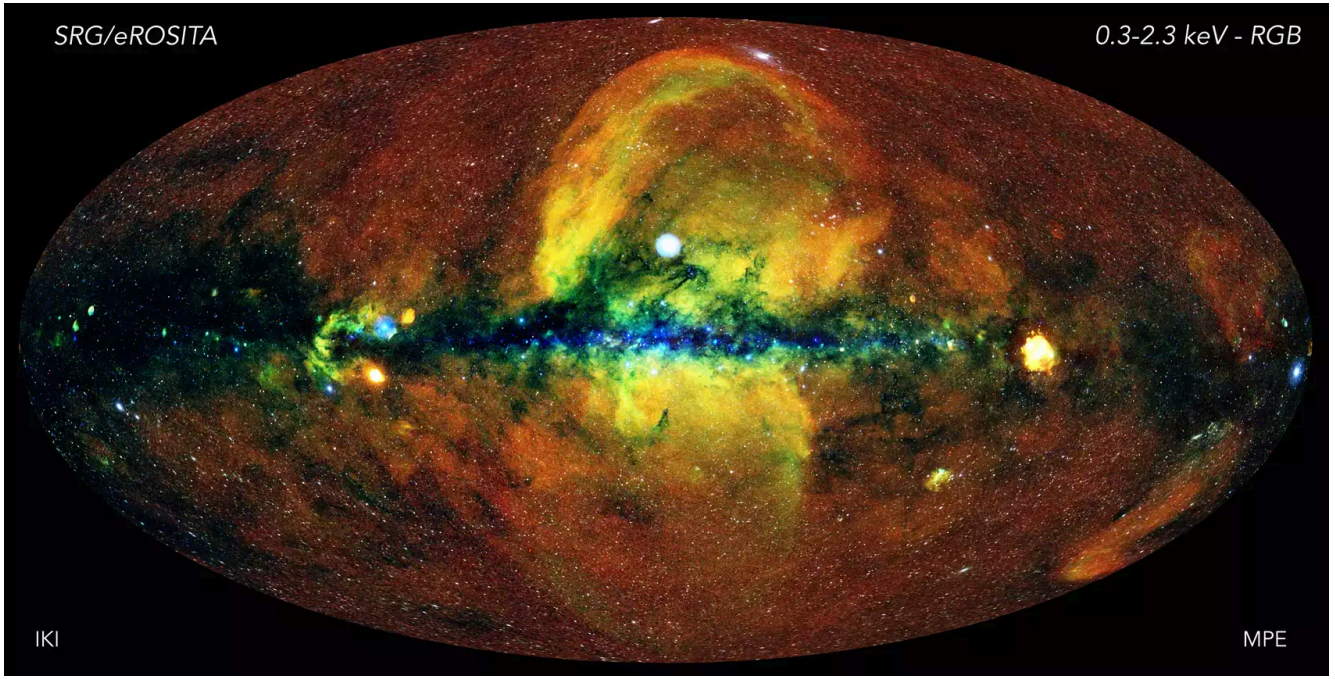
BACKGROUND

A New Era

This is an exciting time for wide field cosmological surveys:

A New Era

This is an exciting time for wide field cosmological surveys:



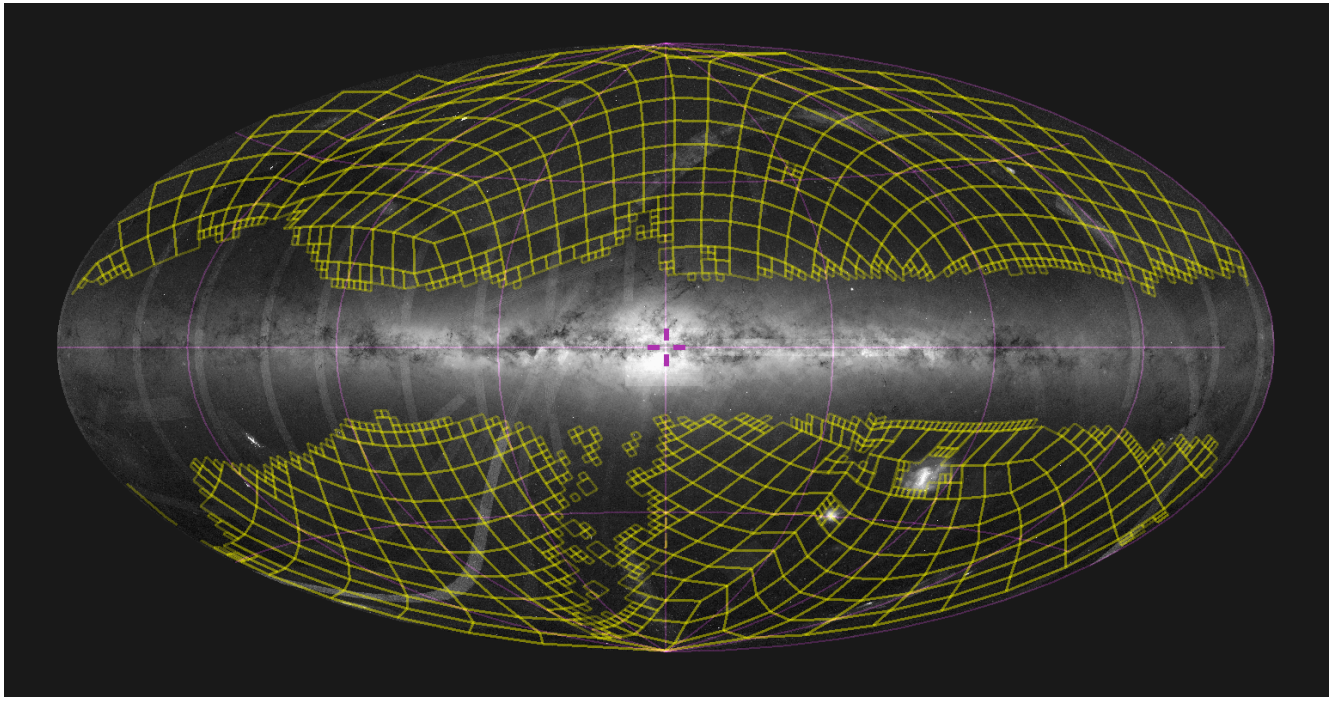
For 2.5 years from 2019 **eROSITA** mapped the X-ray sky, so far providing 2 data releases

Brunner et al. 2022, Merloni et al. 2024

Image Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)

A New Era

This is an exciting time for wide field cosmological surveys:



The optical sky has been well-mapped by **DES** and **DESI**, with **Euclid** Q1 data providing a preview of the full data coming next year

DES Collaboration 2021, *Dey et al. 2022*, *Euclid Collaboration 2025*
Image credit: Wen & Han 2024 via VizieR

Galaxy Clusters: They're Like Dragons.

Galaxy Clusters: They're Like Dragons.

They're the *largest gravitationally bound objects*, only 20% of their baryons are in stars, the rest is in the X-ray emitting **ICM**.

Image Credit: ESA/XMM-Newton/DSS-II/J. Sanders et al. 2019

Galaxy Clusters: They're Like Dragons.

They're the *largest gravitationally bound objects*, only 20% of their baryons are in stars, the rest is in the X-ray emitting **ICM**.

Studying the properties of the ICM allows us to construct **scaling relations** for samples of clusters.

Galaxy Clusters: They're Like Dragons.

They're the *largest gravitationally bound objects*, only 20% of their baryons are in stars, the rest is in the X-ray emitting **ICM**.

Studying the properties of the ICM allows us to construct **scaling relations** for samples of clusters.

Assuming that only gravity dictates these properties, the scaling relations can be fit by the **self-similar model**.

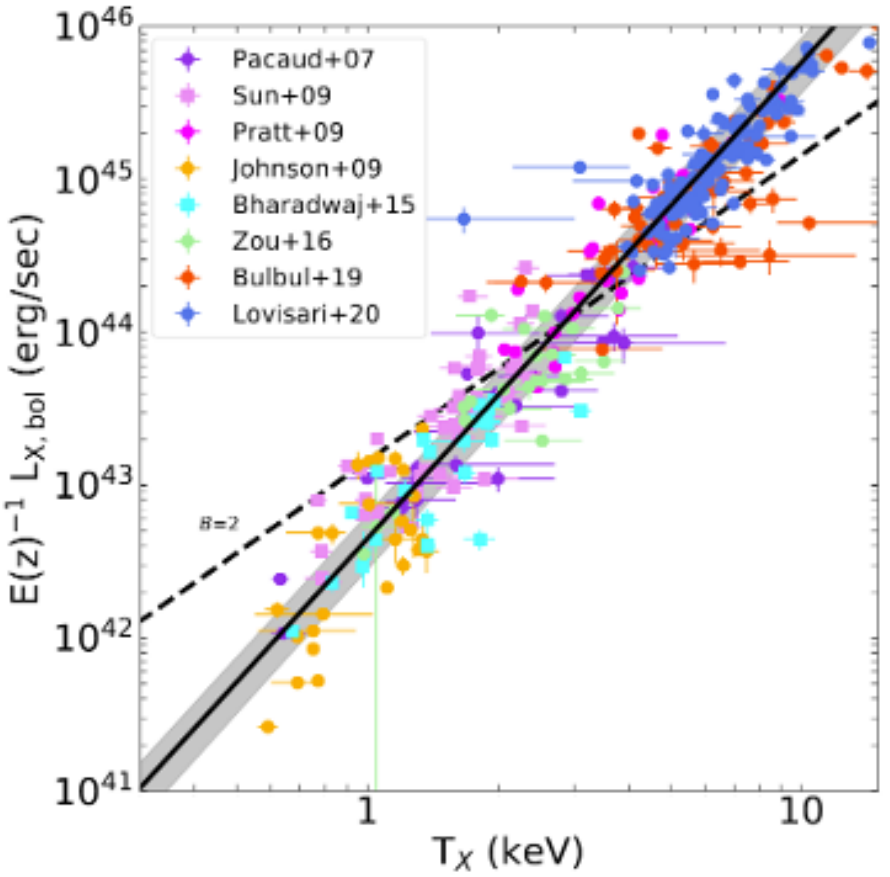


Image Credit: Lovisari & Maughan 2022

Galaxy Clusters: They're Like Dragons.

They're the *largest gravitationally bound objects*, only 20% of their baryons are in stars, the rest is in the X-ray emitting **ICM**.

Studying the properties of the ICM allows us to construct **scaling relations** for samples of clusters.

Assuming that only gravity dictates these properties, the scaling relations can be fit by the **self-similar model**.

Deviations from the model are the result of extra astrophysics.

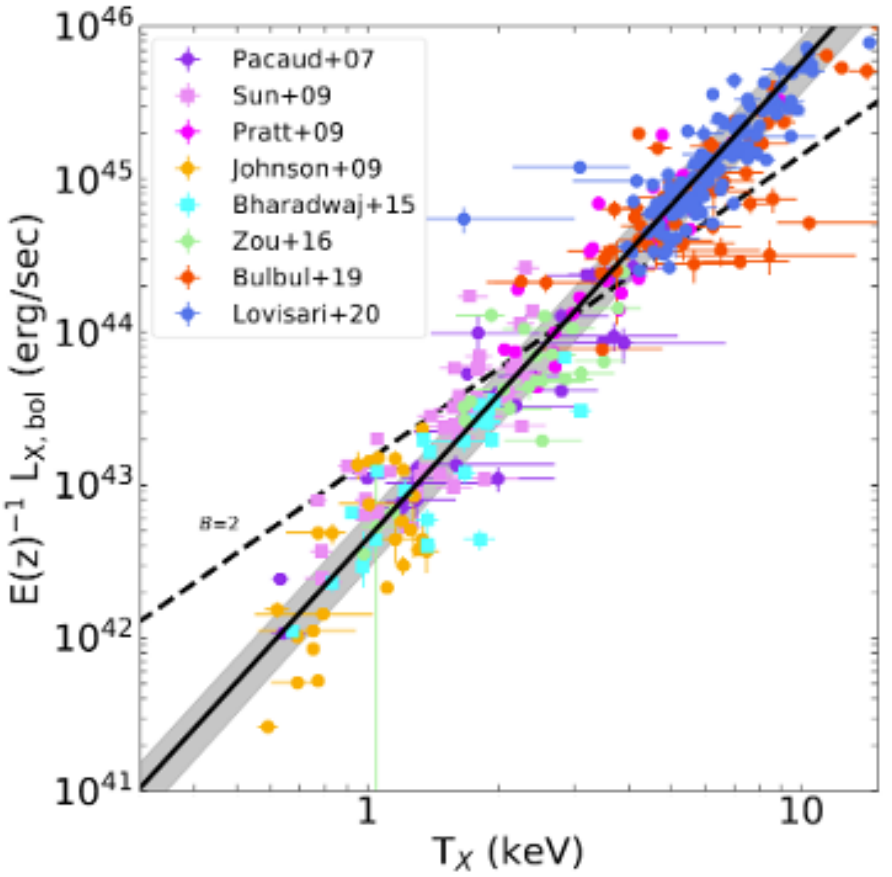


Image Credit: Lovisari & Maughan 2022

Cluster Cosmology

Counting the number of clusters in the universe can help to constrain cosmological parameters, particulary σ_8 and Ω_M

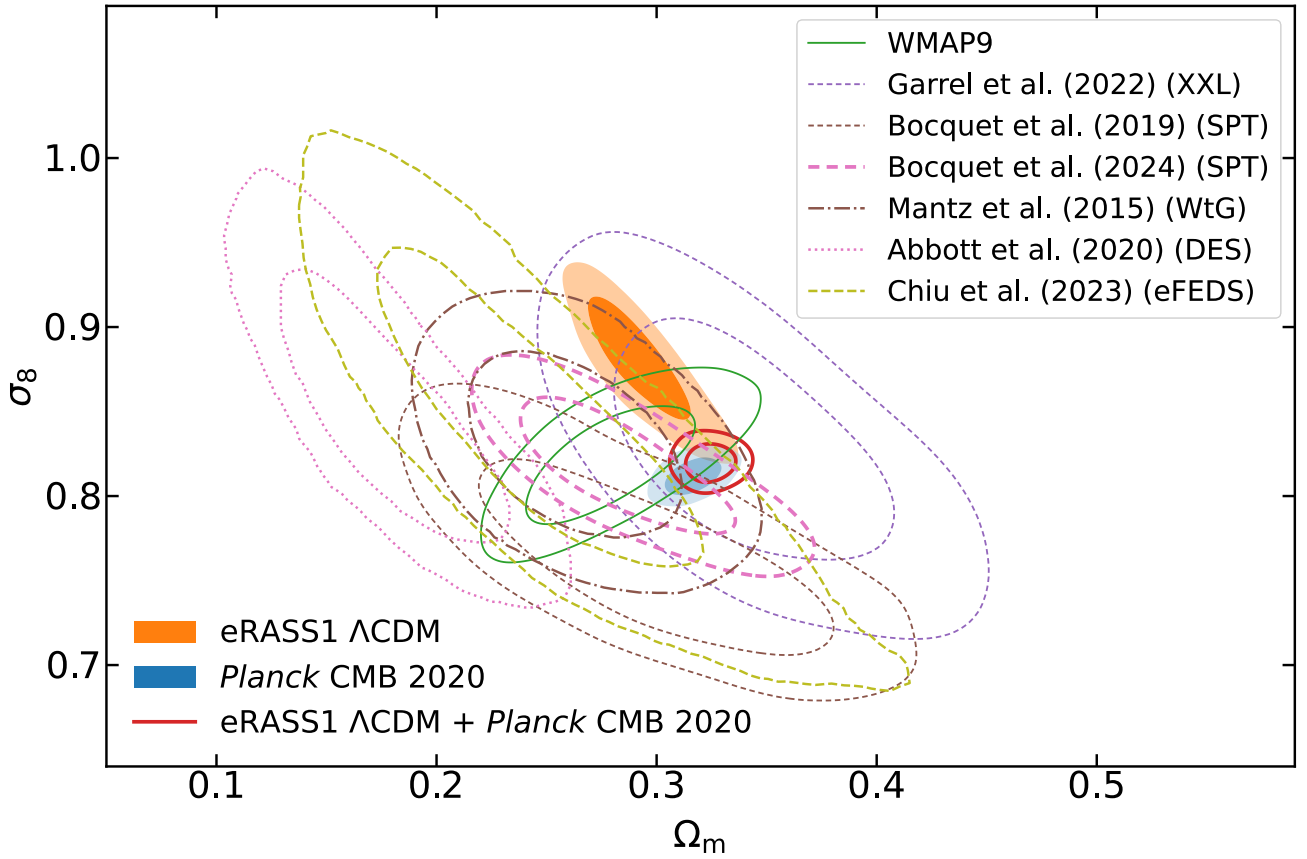


Image Credit: Ghirardini et al. 2024

Cluster Cosmology

Counting the number of clusters in the universe can help to constrain cosmological parameters, particulary σ_8 and Ω_M

To do this effectively we need accurate **selection functions**

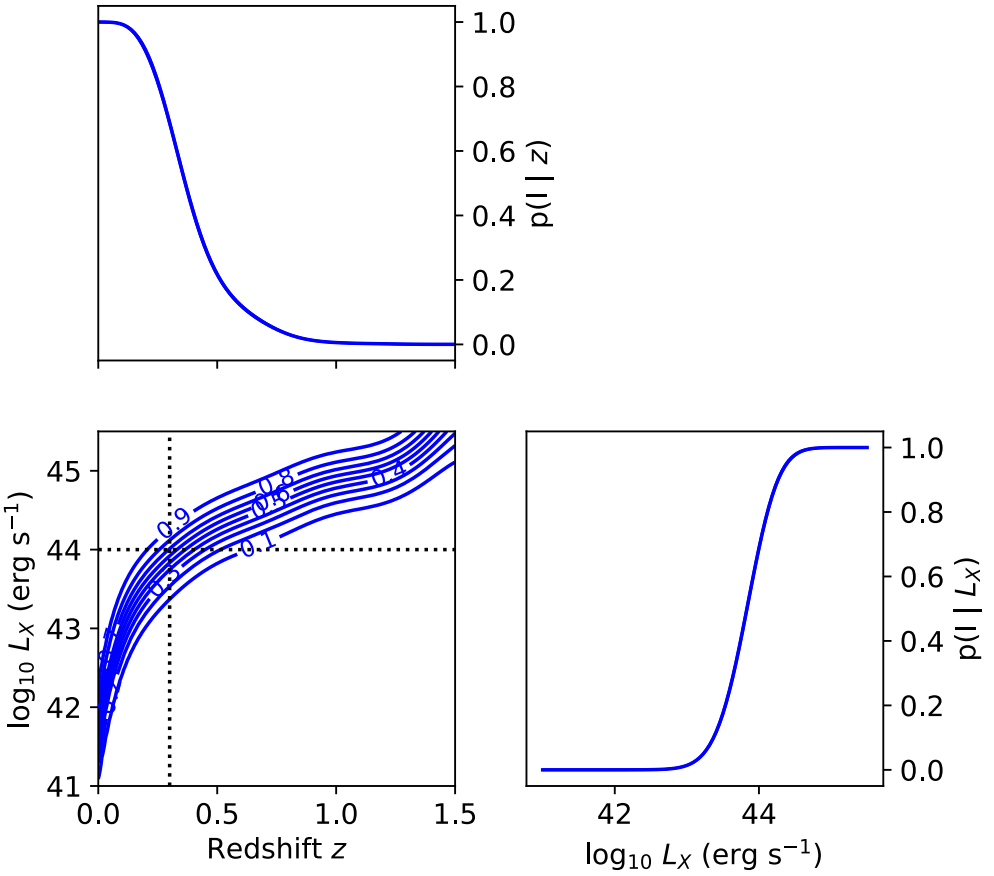


Image Credit: Clerc et al. 2024

Cluster Cosmology

Counting the number of clusters in the universe can help to constrain cosmological parameters, particulary σ_8 and Ω_M

To do this effectively we need accurate **selection functions**

These need to be taken from **large, unbiased samples**

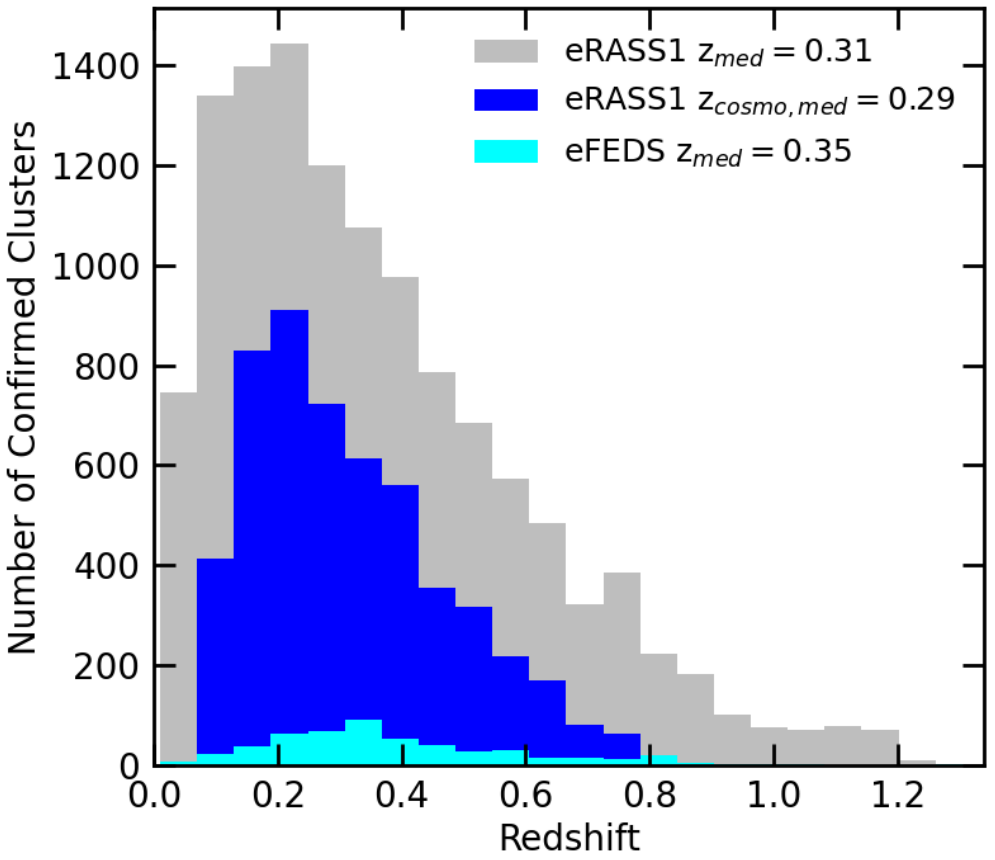


Image Credit: Bulbul et al. 2024

Cluster Cosmology

Counting the number of clusters in the universe can help to constrain cosmological parameters, particulary σ_8 and Ω_M

To do this effectively we need accurate **selection functions**

These need to be taken from **large, unbiased samples**

Andreon et al. (2016) found diffs in scaling rels for **optical and X-ray clusters**

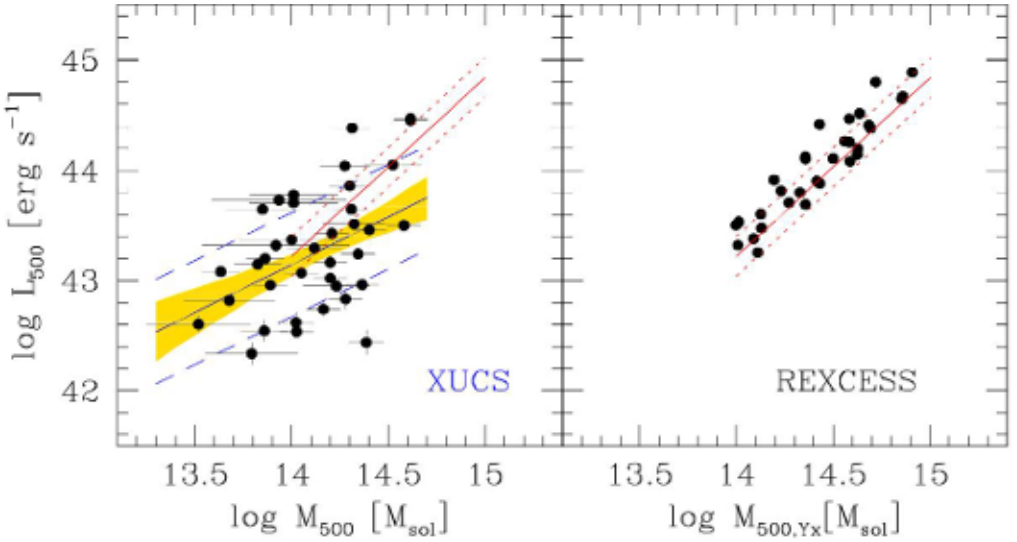
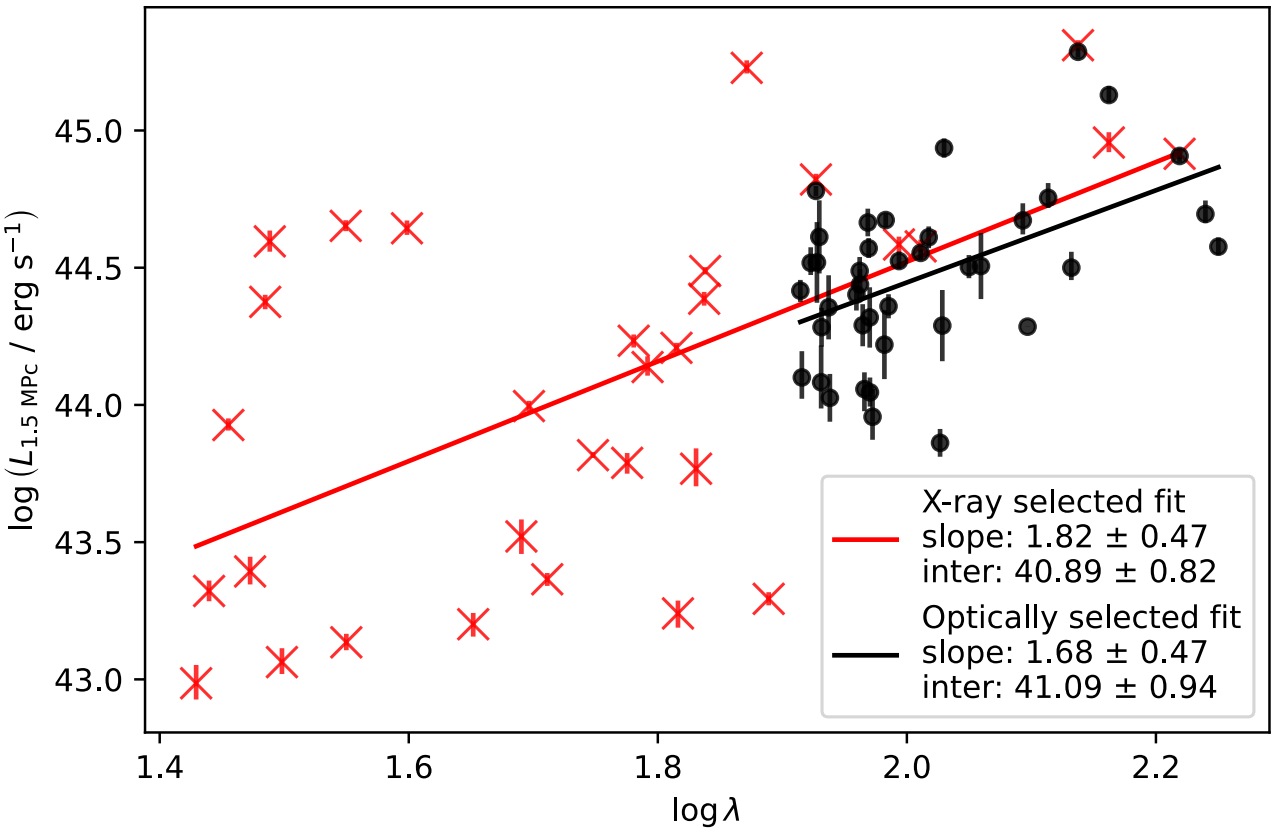


Image Credit: Andreon et al. 2016

Combining eROSITA data with clusters found in wide optical surveys gives the ideal platform to test these biases

Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

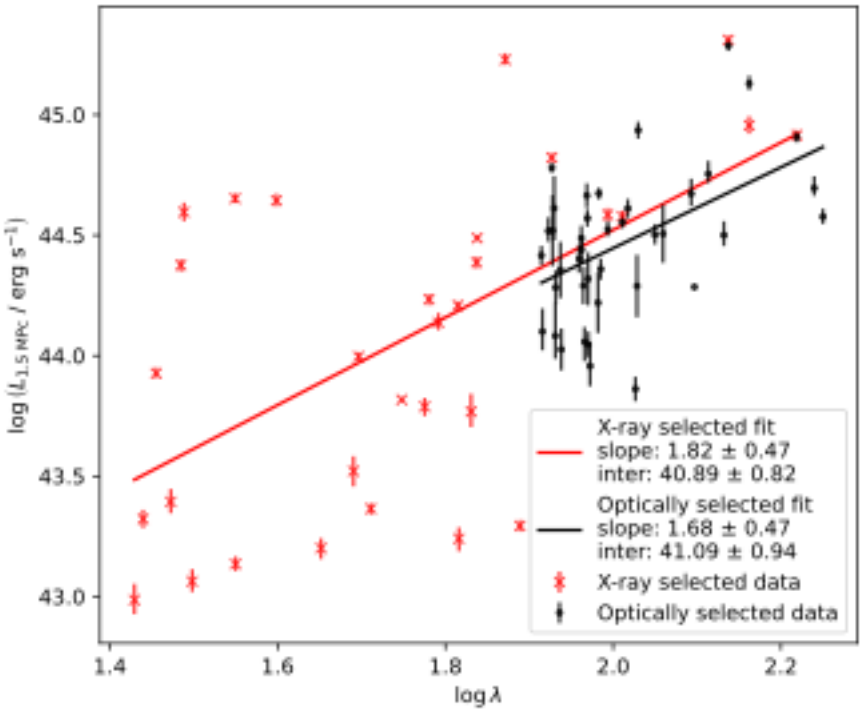


Bulbul et al. 2024, Rykoff et al. 2014

Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

They are not great…



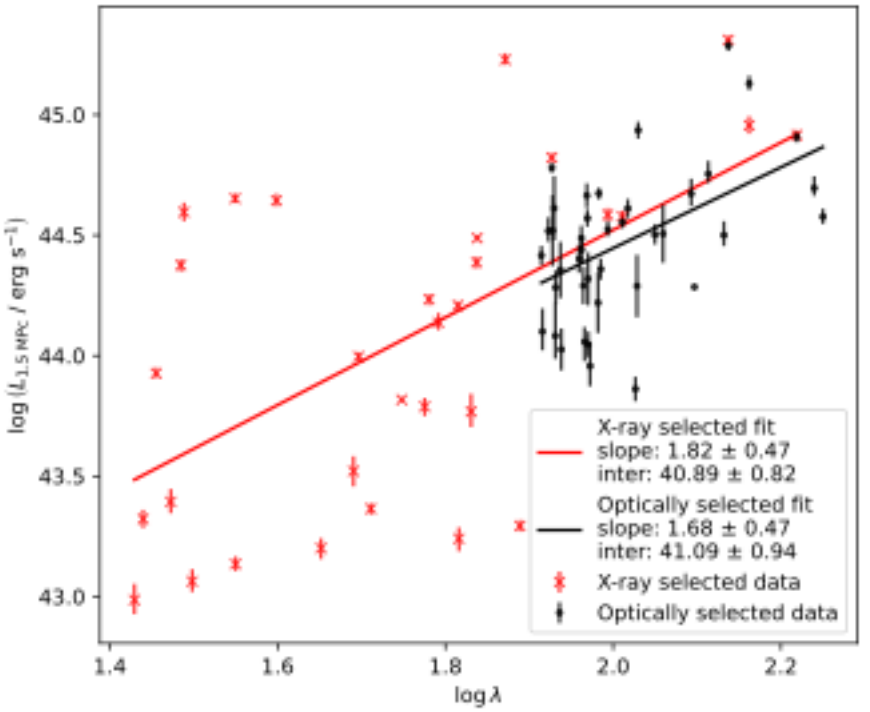
Bulbul et al. 2024, Rykoff et al. 2014

Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

They are not great…

- Flux rather than **Luminosity (L)** selected X-ray clusters



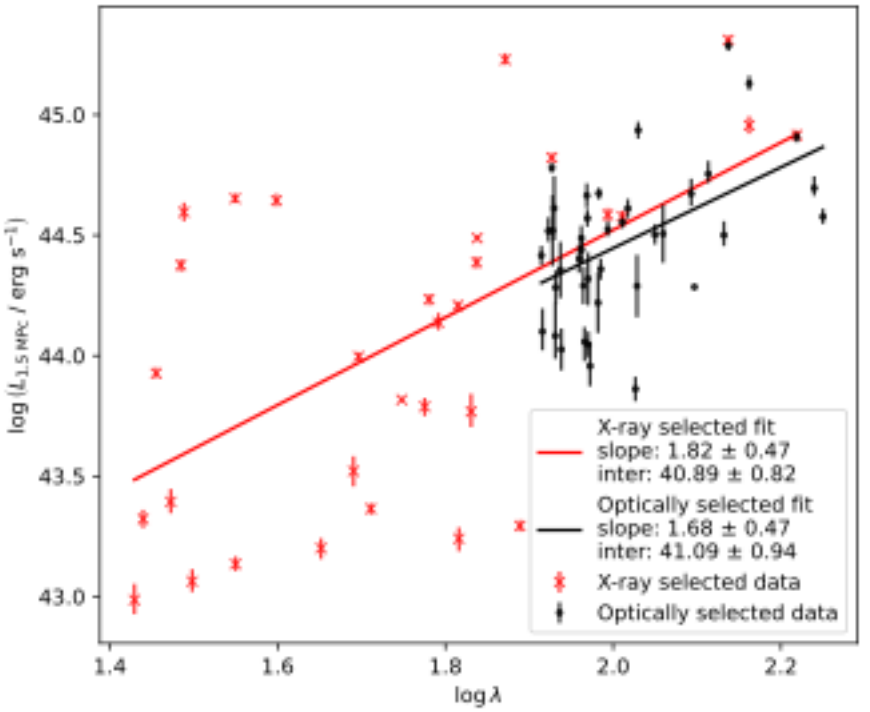
Bulbul et al. 2024, Rykoff et al. 2014

Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

They are not great…

- Flux rather than **Luminosity (L)** selected X-ray clusters
- Optical sample poorly overlaps X-ray



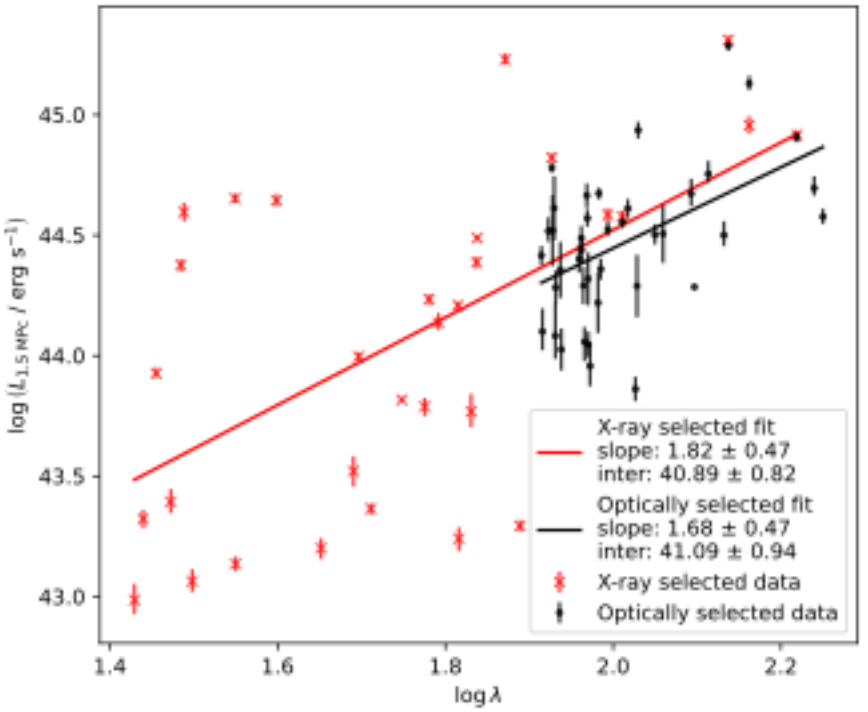
Bulbul et al. 2024, Rykoff et al. 2014

Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

They are not great…

- Flux rather than **Luminosity (L)** selected X-ray clusters
- Optical sample poorly overlaps X-ray
- Bad scaling relation fitting



Bulbul et al. 2024, Rykoff et al. 2014

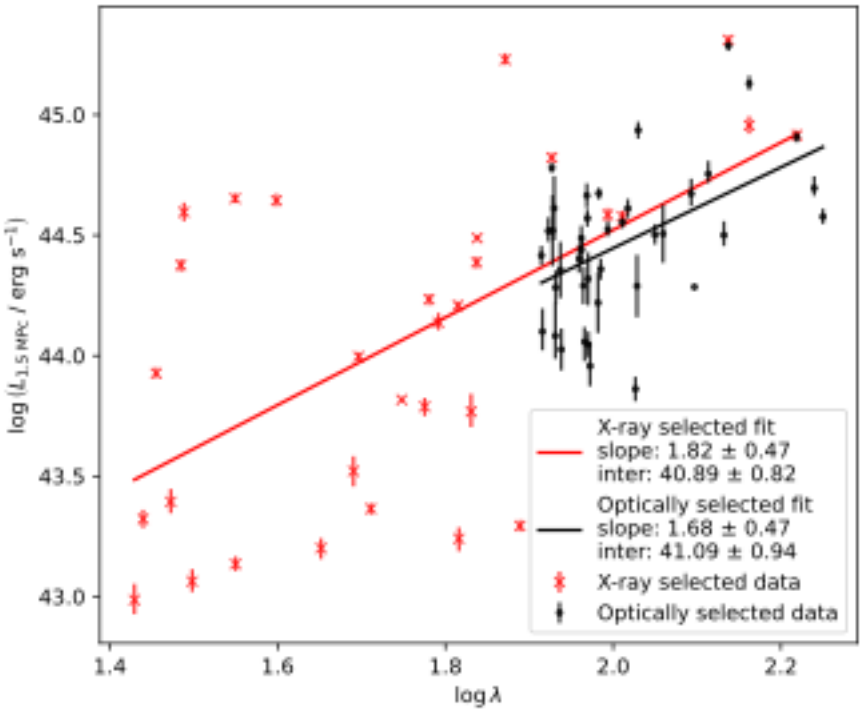
Last Update

In September, I presented these results from eRASS flux selected clusters and **richness (λ)** selected from the SDSS survey analysed by a pipeline I wrote.

They are not great…

- Flux rather than **Luminosity (L)** selected X-ray clusters
- Optical sample poorly overlaps X-ray
- Bad scaling relation fitting

Over the past year I have been addressing these issues



Bulbul et al. 2024, Rykoff et al. 2014

SAMPLE SELECTION

Choosing a Catalogue – X-rays

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

Choosing a Catalogue – X-rays

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

For the **X-ray selected** sample, I continued using the primary eRASS1 cluster catalogue of >12,000 clusters.

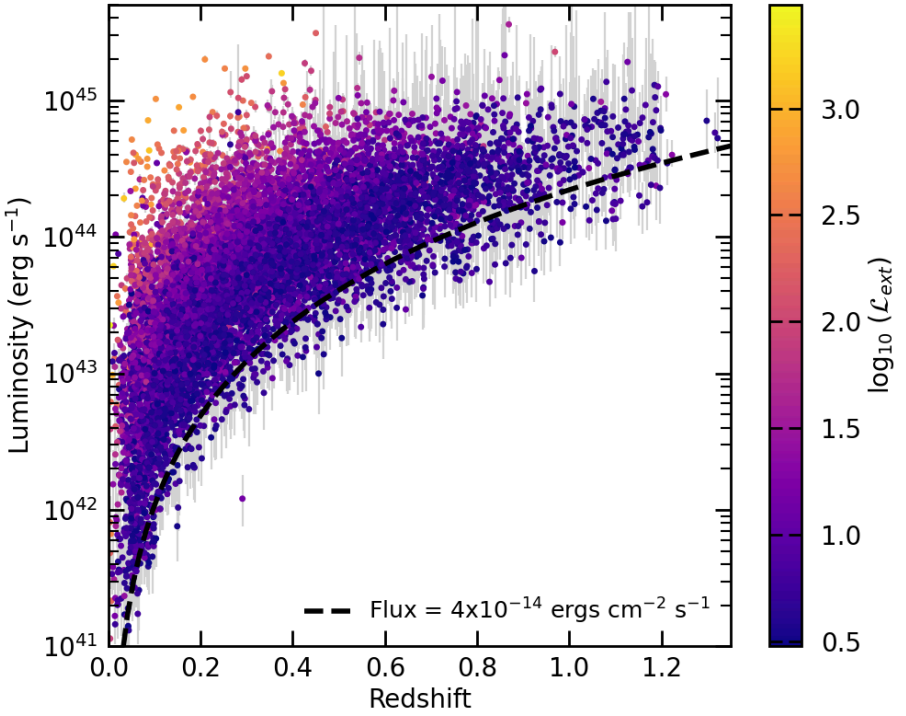


Image Credit: Bulbul et al. 2024

Choosing a Catalogue – X-rays

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

For the **X-ray selected** sample, I continued using the primary eRASS1 cluster catalogue of >12,000 clusters.

Comparisons with the eRASS1 digital twin estimate full catalogue purity of **86%** and completeness of **~90%**.

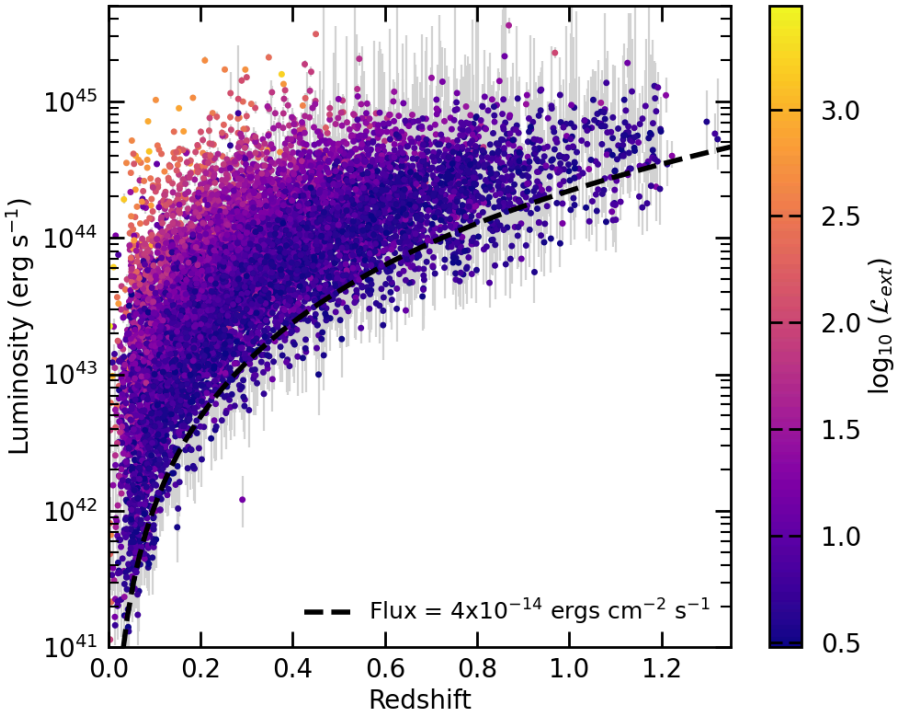


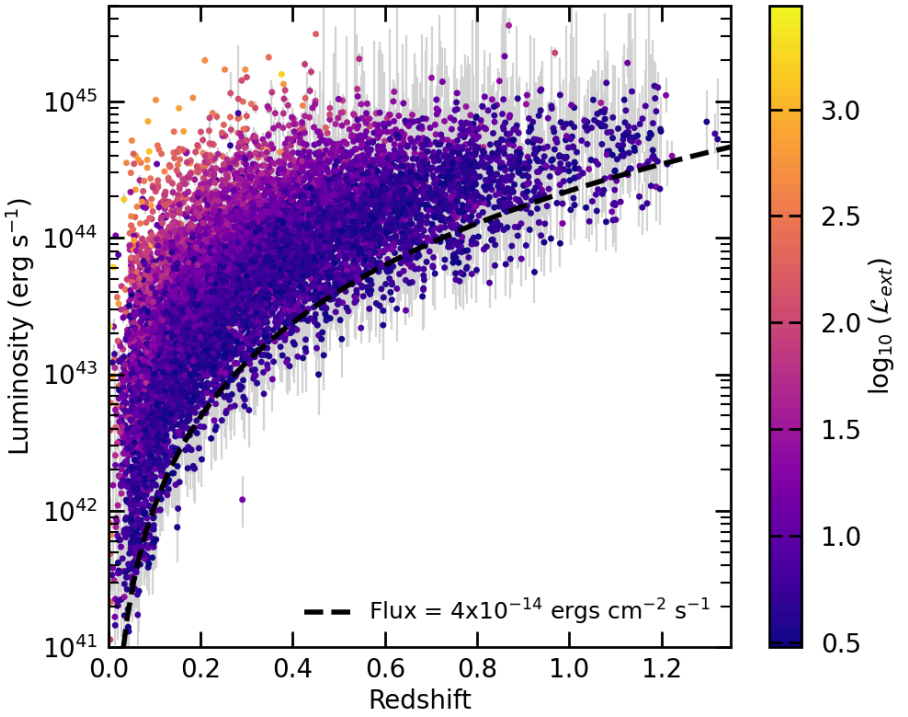
Image Credit: Bulbul et al. 2024

Choosing a Catalogue – X-rays

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

For the **X-ray selected** sample, I continued using the primary eRASS1 cluster catalogue of >12,000 clusters.

Comparisons with the eRASS1 digital twin estimate full catalogue purity of **86%** and completeness of **~90%**.



Recent work in Balzer et al. (2025) has identified **1,000s** more clusters in the eRASS1 data

Image Credit: Bulbul et al. 2024

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

At first, I considered using catalogues based on **DES** data, as it covers the southern eROSITA sky and was well used at a conference

DES MOC

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

At first, I considered using catalogues based on **DES** data, as it covers the southern eROSITA sky and was well used at a conference

But the only catalogue available in September was for “Science Validation” and contained a mere **787 clusters**.

Not nearly enough!

Choosing a Catalogue – Optical

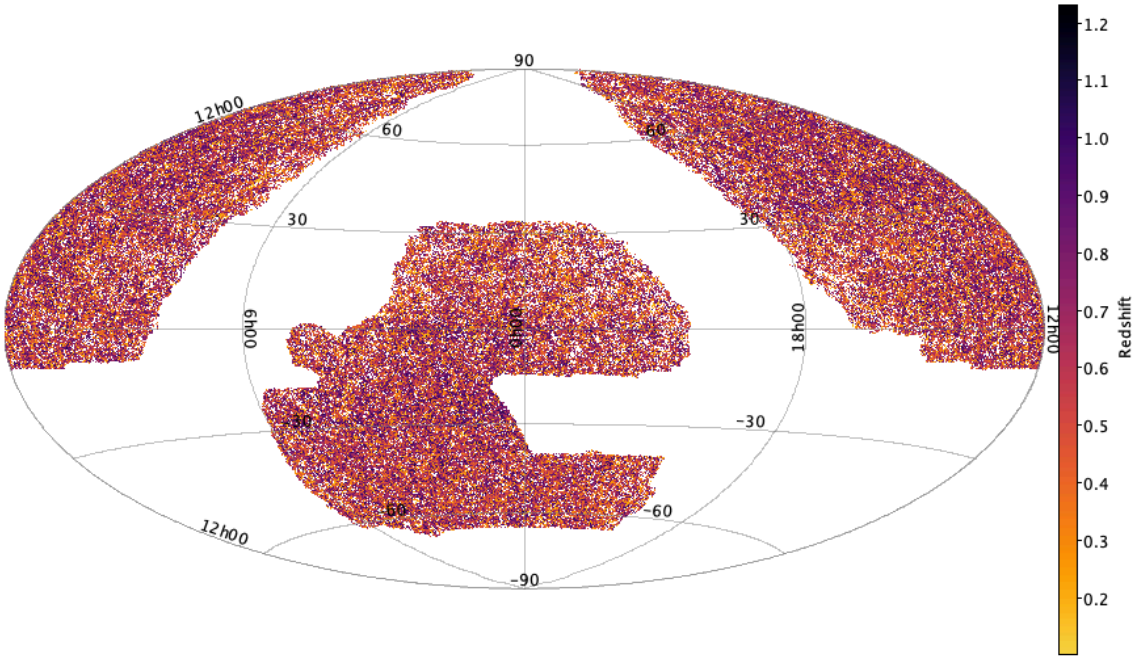
For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

Next looked at the **DESI** catalogues, which cover more of the sky and have many more clusters.

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

Next looked at the **DESI** catalogues, which cover more of the sky and have many more clusters.

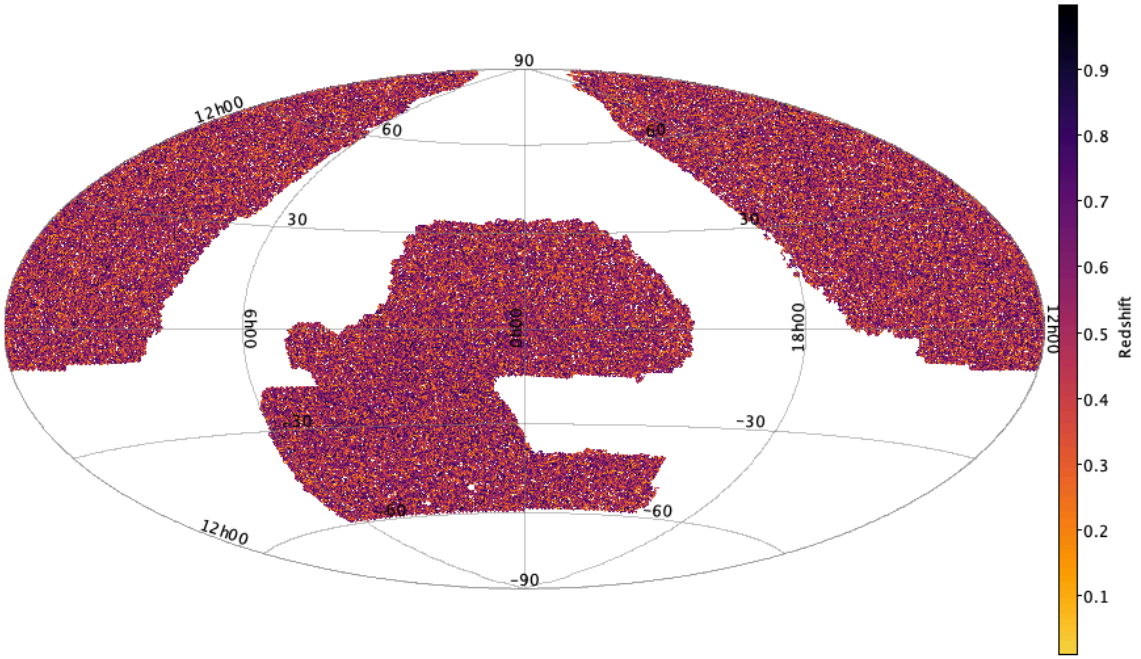


Yantovski-Barth et al. (2023) – ~300,000 clusters

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

Next looked at the **DESI** catalogues, which cover more of the sky and have many more clusters.

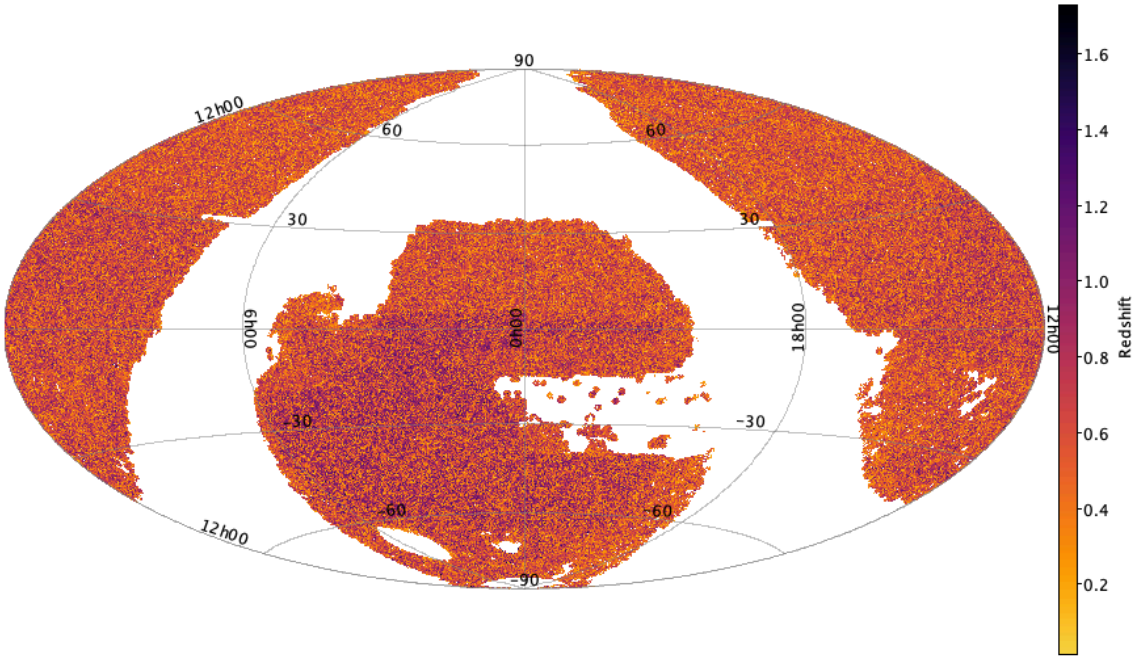


Zou et al. (2021) – 540,432 clusters

Choosing a Catalogue – Optical

For my samples, the catalogues I chose to use needed to have high **completeness** and **purity**.

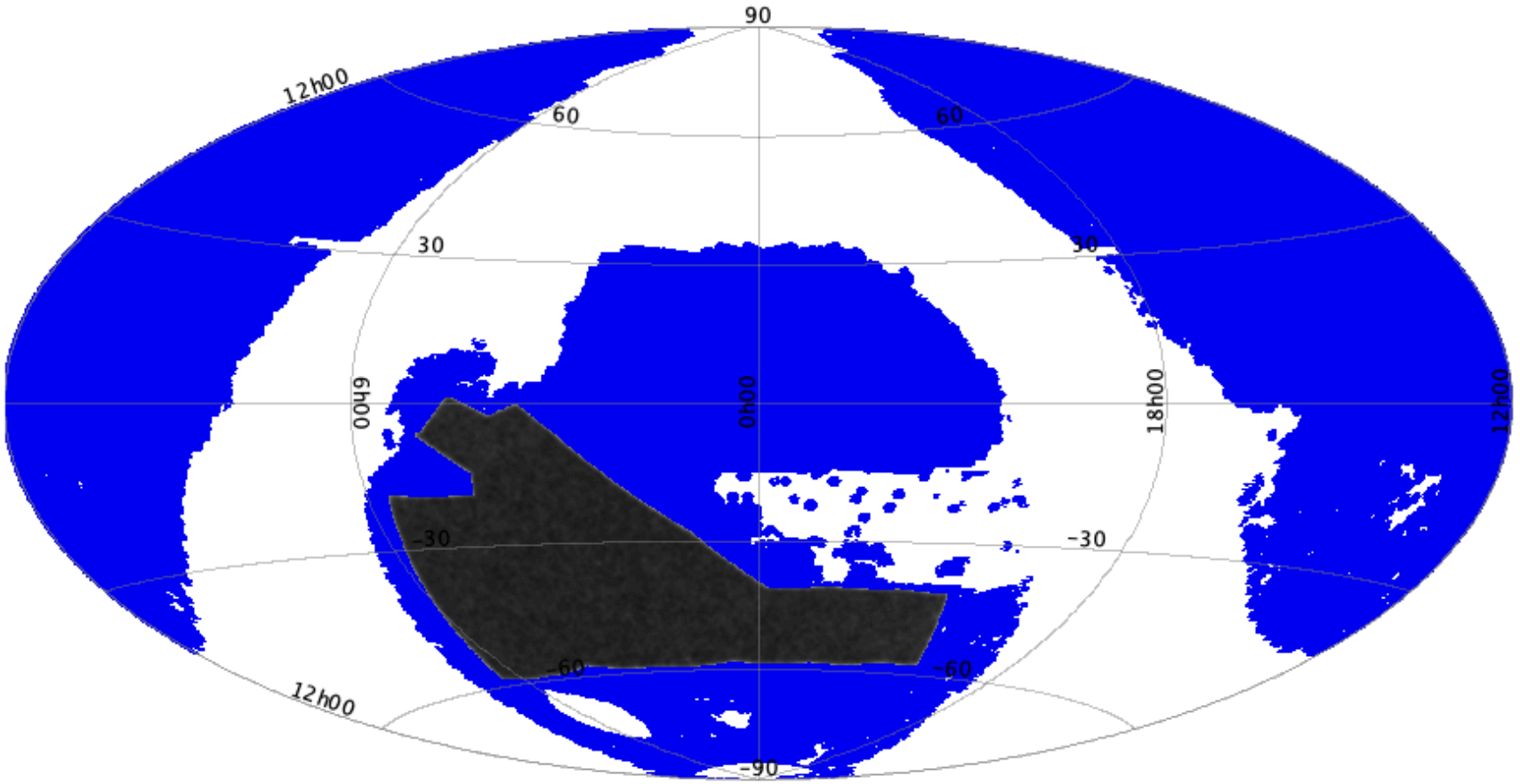
Next looked at the **DESI** catalogues, which cover more of the sky and have many more clusters.



Wen & Han (2024) – >1.5 million clusters

Choosing a Catalogue – Optical

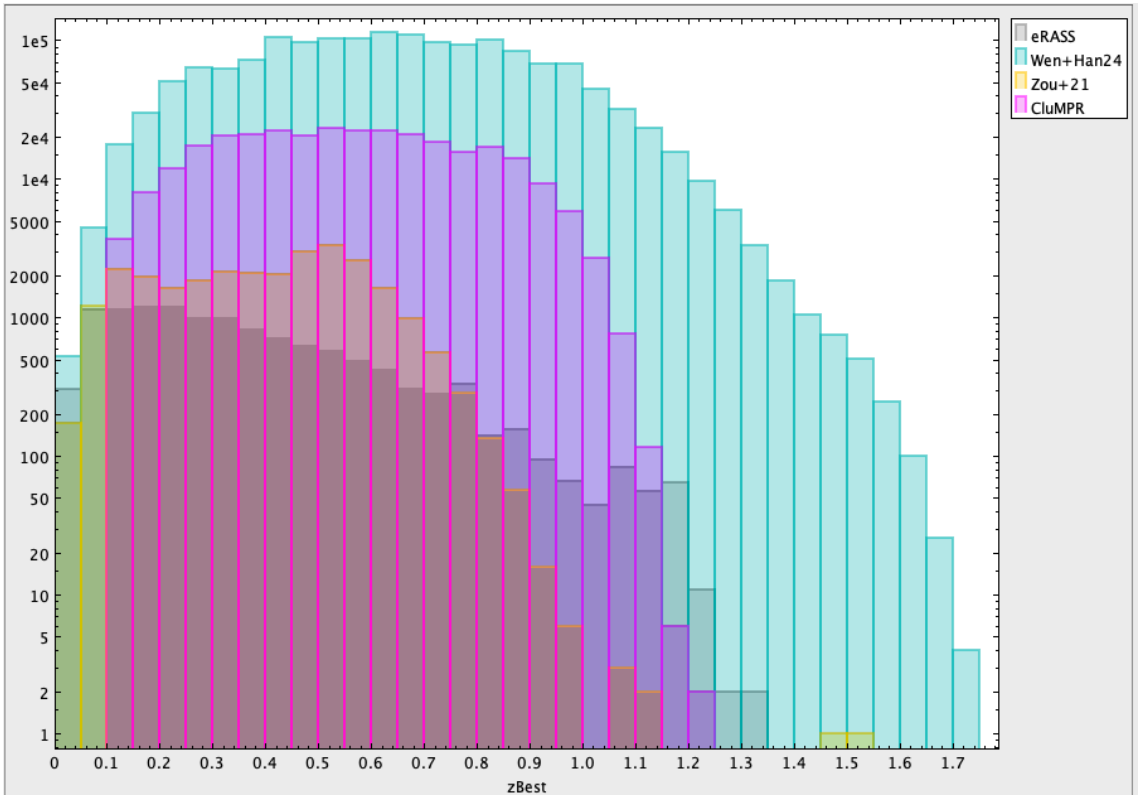
To decide which of these three to use, I selected a sample of each from a region on the sky they overlapped with each other.



Choosing a Catalogue – Optical

To decide which of these three to use, I selected a sample of each from a region on the sky they overlapped with each other.

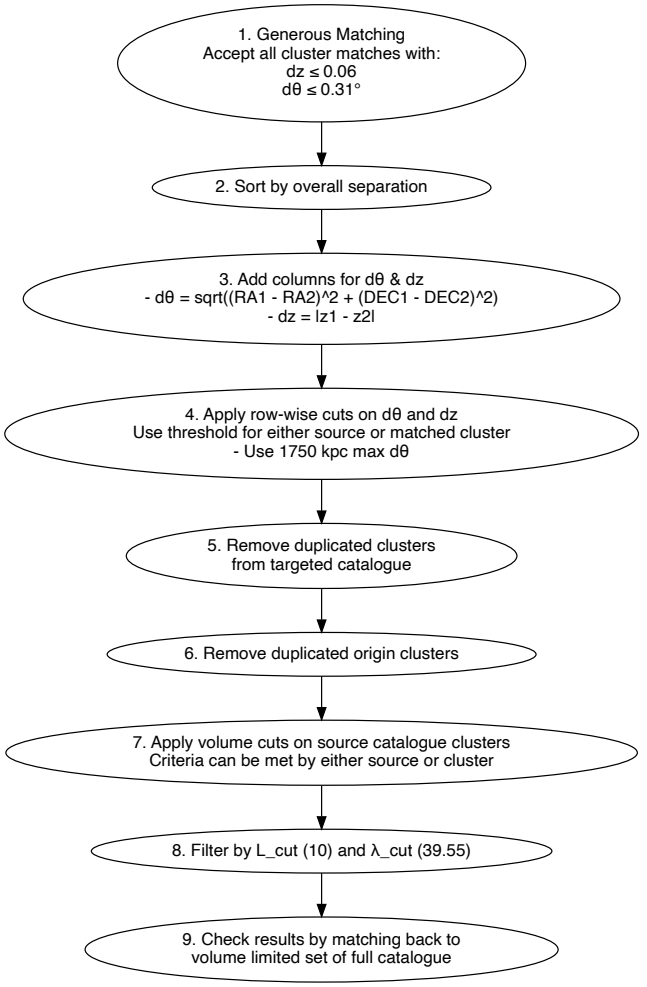
I then checked the **redshift** overlap with the eRASS1 catalogue:



Choosing a Catalogue – Optical

To decide which of these three to use, I selected a sample of each from a region on the sky they overlapped with each other.

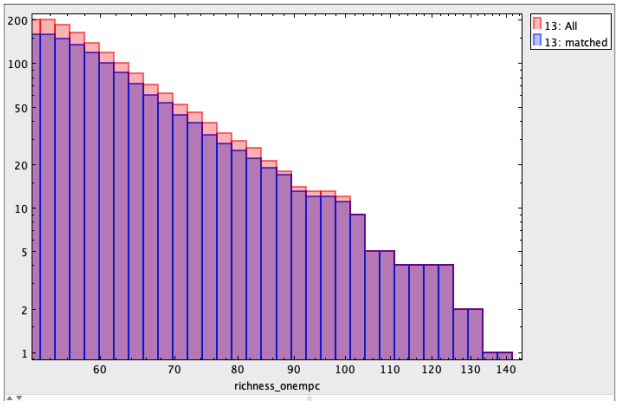
And then cross-matched to it to estimate **purity and completeness**:

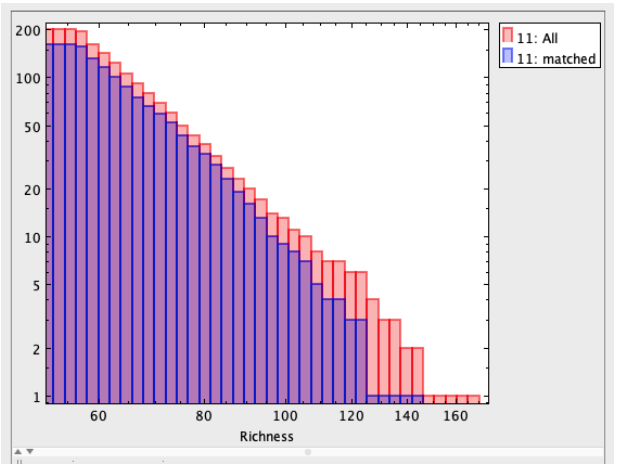


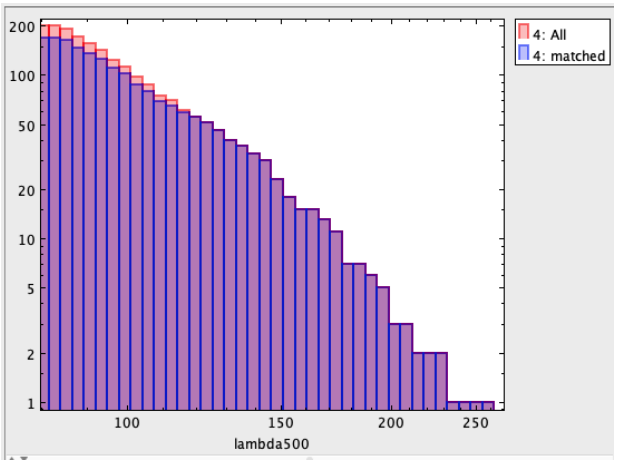
Choosing a Catalogue – Optical

To decide which of these three to use, I selected a sample of each from a region on the sky they overlapped with each other.

And then cross-matched to it to estimate **purity and completeness**







Yantovski-Barth et al. (2023) *Zou et al. (2021)* *Wen & Han (2024)*

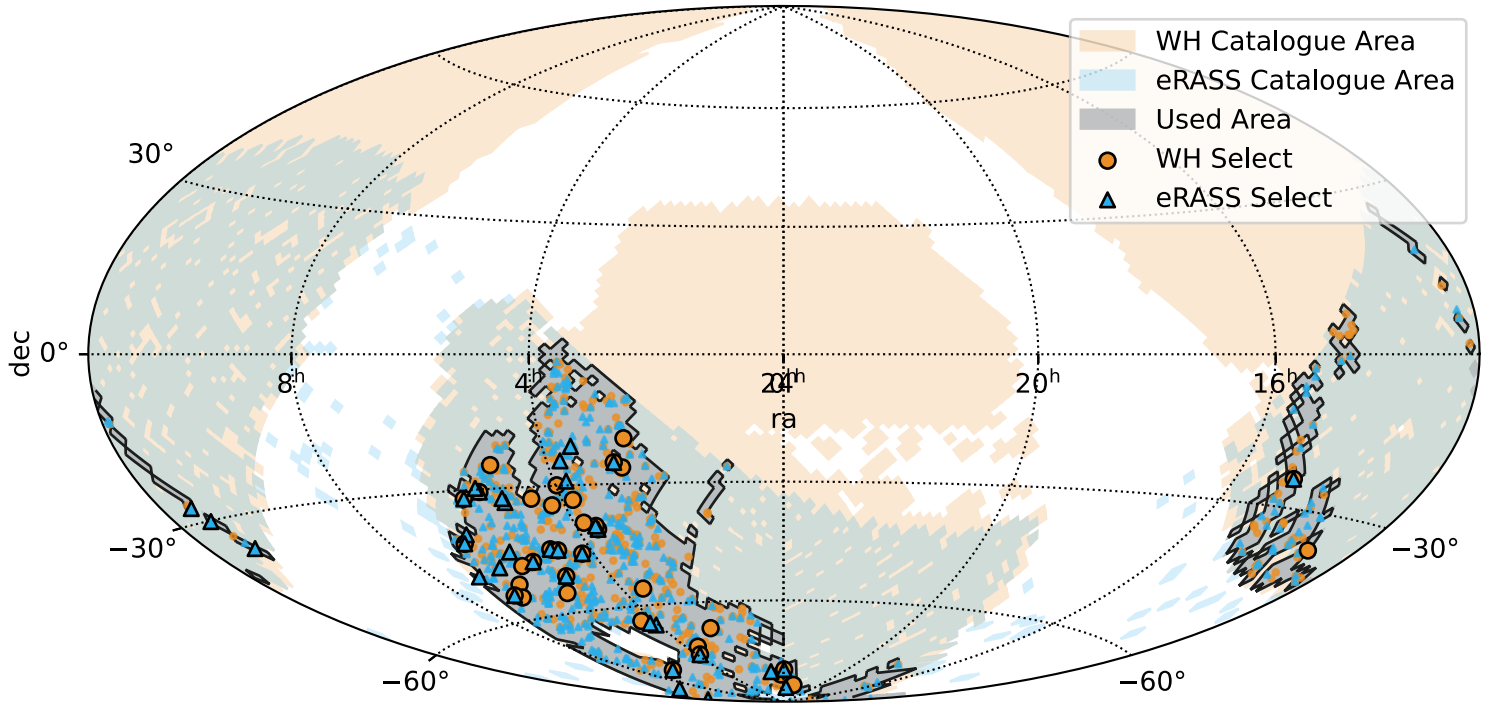
Wen & Han (2024) is the best optical catalogue for the work I want to do.

Final Samples

Redid the cross-matching but changed the search area to be where the eRASS1 exposure > 170 s & where the **eRASS sky** intersects with the **Wen & Han field** for $0.1 < z < 0.2$.

Final Samples

Redid the cross-matching but changed the search area to be where the eRASS1 exposure > 170 s & where the **eRASS sky** intersects with the **Wen & Han field** for $0.1 < z < 0.2$.



DATA ANALYSIS

X-rays Generate and Analyse

A mission agnostic platform for processing and analysing X-ray data.

Turner et al. 2022, 2024a, 2024b

X-rays Generate and Analyse

A mission agnostic platform for processing and analysing X-ray data.

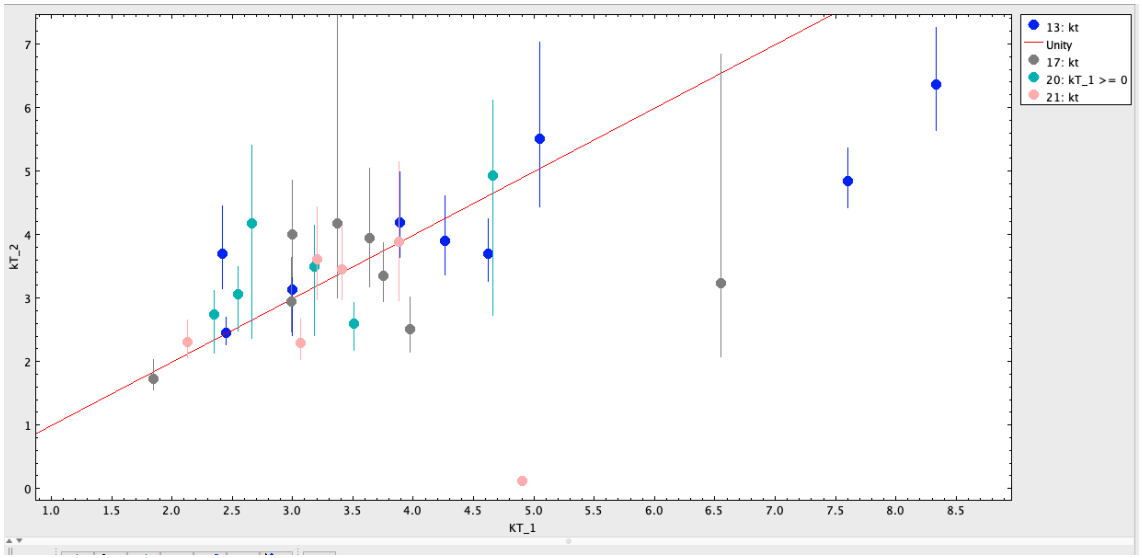
More advanced and mature than my pipeline and can handle data from other missions.

Turner et al. 2022, 2024a, 2024b

X-rays Generate and Analyse

A mission agnostic platform for processing and analysing X-ray data.

More advanced and mature than my pipeline and can handle data from other missions.



Validated XGA results by comparing its cluster temperatures with those from the eRASS catalogue.

Turner et al. 2022, 2024a, 2024b

Scaling Relations – Set-up

I measured luminsoities (L) with **XGA** and took richnesses (λ) from the **Wen & Han (2024)** catalogue for all clusters in the samples.

Scaling Relations – Set-up

I measured luminsoities (L) with **XGA** and took richnesses (λ) from the **Wen & Han (2024)** catalogue for all clusters in the samples.

Uncertainties were taken from the XGA results for L and as the square root era on the number of galaxies in the cluster for λ

Scaling Relations – Set-up

I measured luminsoities (L) with **XGA** and took richnesses (λ) from the **Wen & Han (2024)** catalogue for all clusters in the samples.

Uncertainties were taken from the XGA results for L and as the square root era on the number of galaxies in the cluster for λ

Produced two scaling relations for each of the cluster samples: $L - T$ & $L - \lambda$

Scaling Relations – Set-up

I measured luminsoities (L) with **XGA** and took richnesses (λ) from the **Wen & Han (2024)** catalogue for all clusters in the samples.

Uncertainties were taken from the XGA results for L and as the square root era on the number of galaxies in the cluster for λ

Produced two scaling relations for each of the cluster samples: $L - T$ & $L - \lambda$

Accounted for cluster evolution by dividing L for each cluster by:

$$E(z)^{\gamma} = \left(\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\lambda}\right)^{\gamma}.$$

Scaling Relations – Fitting

Rather than simple least squares regression I used Sereno (2015)'s **LI**near **R**egression in **A**stronomy (LIRA) package.

Scaling Relations – Fitting

Rather than simple least squares regression I used Sereno (2015)'s **LI**near **R**egression in **A**stronomy (LIRA) package.

Improvement as it does **Bayesian** linear regression and can account for intrinsic scatters and biases from selection effects.

Scaling Relations – Fitting

Rather than simple least squares regression I used Sereno (2015)'s **LI**near **R**egression in **A**stronomy (LIRA) package.

Improvement as it does **Bayesian** linear regression and can account for intrinsic scatters and biases from selection effects.

To aid LIRA and **reduce degeneracies**, I set pivots on my data at: $L_0 = 10^{43}$ erg s^{-1}, $kT_0 = 3.55$ keV, and $\lambda_0 = 109$.

Scaling Relations – Fitting

Rather than simple least squares regression I used Sereno (2015)'s **LI**near **R**egression in **A**stronomy (LIRA) package.

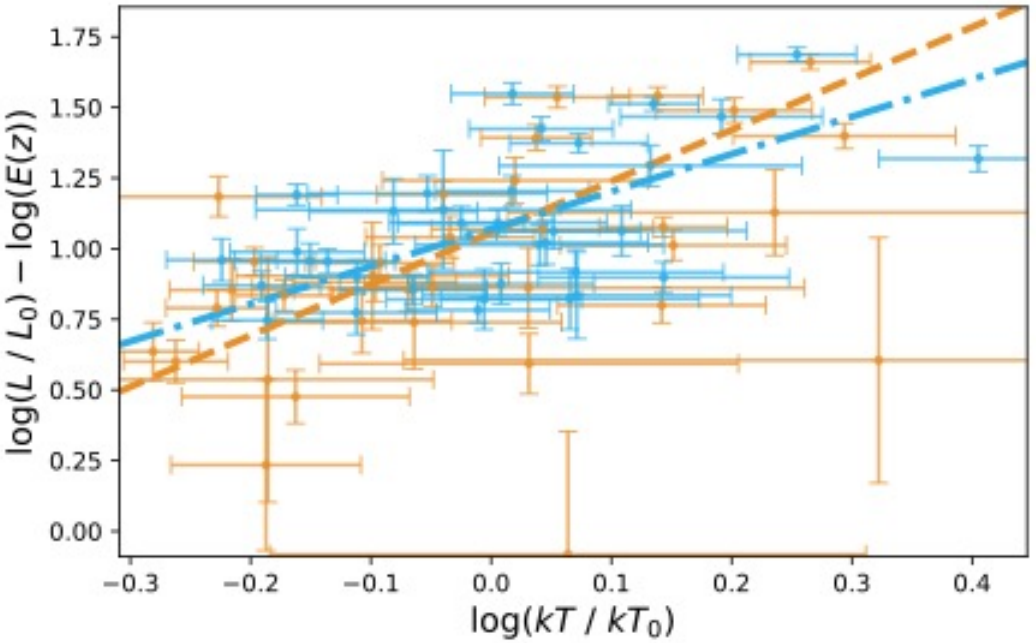
Improvement as it does **Bayesian** linear regression and can account for intrinsic scatters and biases from selection effects.

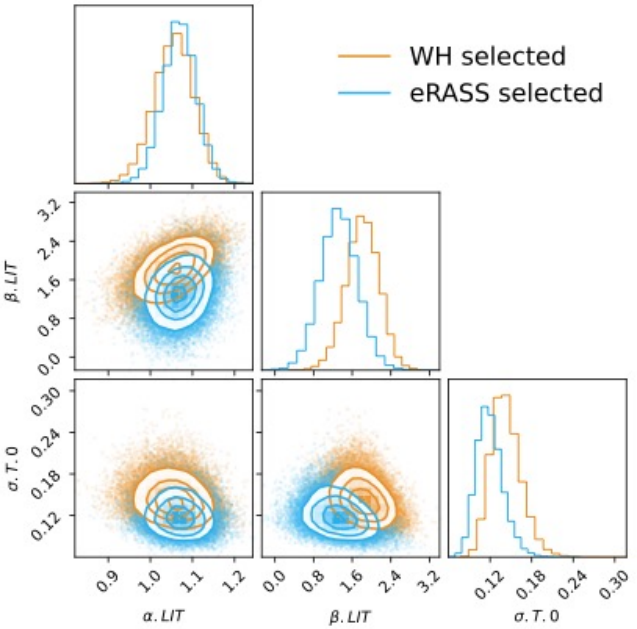
To aid LIRA and **reduce degeneracies**, I set pivots on my data at: $L_0 = 10^{43}$ erg s^{-1}, $kT_0 = 3.55$ keV, and $\lambda_0 = 109$.

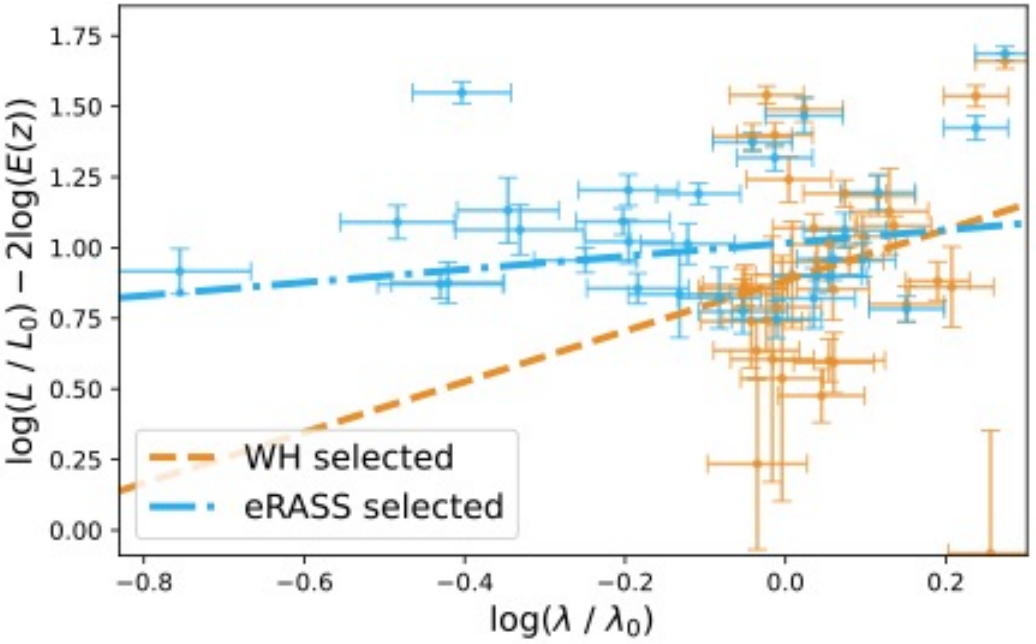
For bias modelling, I set these thresholds: $L_{\text{thresh}} = 10^{43.5}$ erg s^{-1} and $\lambda_{\text{thresh}} = 10$ for the **eRASS selected** clusters, and $\lambda_{\text{thresh}} = 43.7$ for the **optically selected** sample.

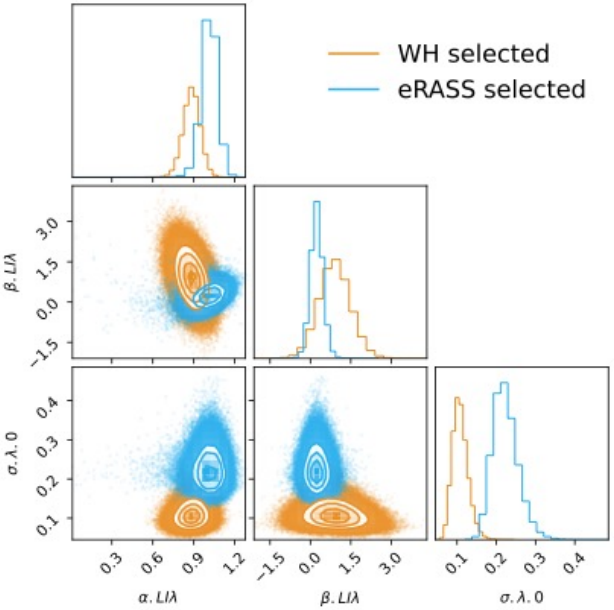
RESULTS

Results


log(L / L0) − log(E(z))
log(kT / kT0)


WH selected
eRASS selected
α. LIT
β. LIT
σ. T. 0

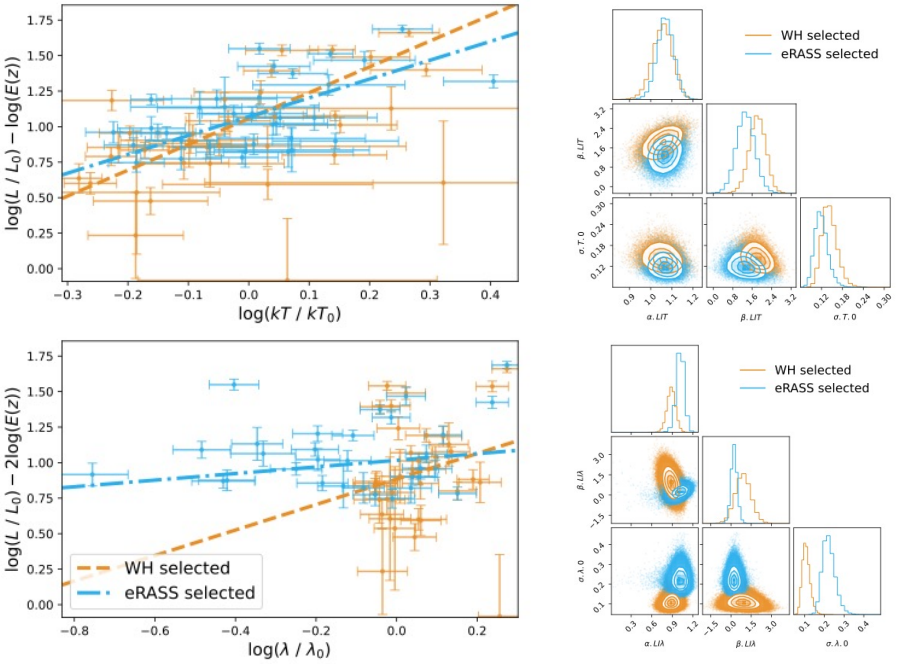

log(L / L0) − 2log(E(z))
log(λ / λ0)
WH selected
eRASS selected


WH selected
eRASS selected
α. LIλ
β. LIλ
σ. λ. 0

Discussion

The optical sample has a **steeper slope (β)** for both relations.

Parameter	$L-T$		$L-\lambda$	
	WH	eRASS	WH	eRASS
α	$1.055^{+0.046}_{-0.049}$	$1.070^{+0.039}_{-0.039}$	$0.884^{+0.060}_{-0.062}$	$1.016^{+0.053}_{-0.057}$
β	$1.819^{+0.336}_{-0.342}$	$1.325^{+0.384}_{-0.337}$	$0.897^{+0.584}_{-0.573}$	$0.233^{+0.227}_{-0.222}$
σ	$0.141^{+0.024}_{-0.019}$	$0.118^{+0.020}_{-0.017}$	$0.107^{+0.021}_{-0.017}$	$0.22^{+0.035}_{-0.028}$

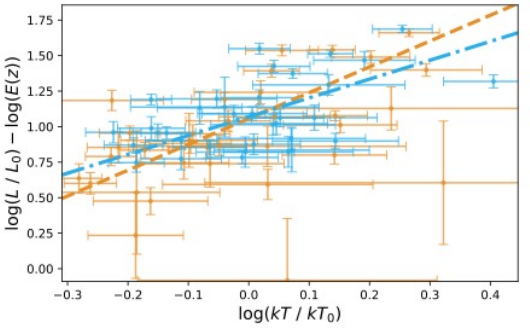


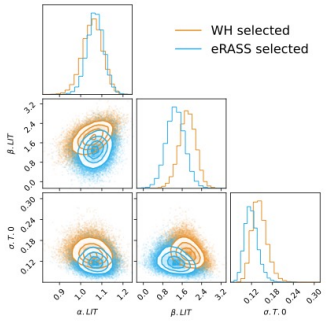
Discussion

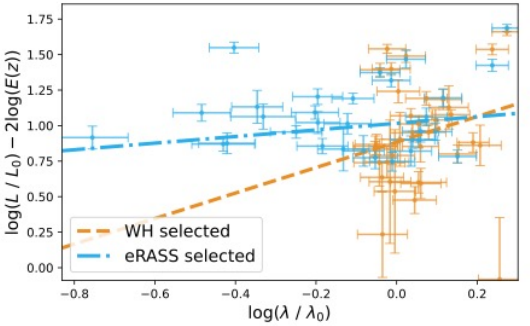
The optical sample has a **steeper slope (β)** for both relations.

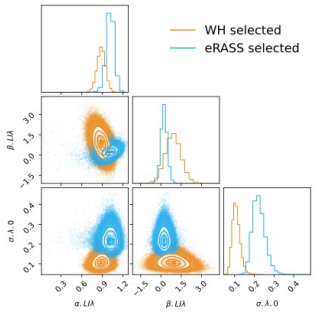
BUT the errors on these results are still very large…

Parameter	$L-T$		$L-\lambda$	
	WH	eRASS	WH	eRASS
α	$1.055^{+0.046}_{-0.049}$	$1.070^{+0.039}_{-0.039}$	$0.884^{+0.060}_{-0.062}$	$1.016^{+0.053}_{-0.057}$
β	$1.819^{+0.336}_{-0.342}$	$1.325^{+0.384}_{-0.337}$	$0.897^{+0.584}_{-0.573}$	$0.233^{+0.227}_{-0.222}$
σ	$0.141^{+0.024}_{-0.019}$	$0.118^{+0.020}_{-0.017}$	$0.107^{+0.021}_{-0.017}$	$0.22^{+0.035}_{-0.028}$









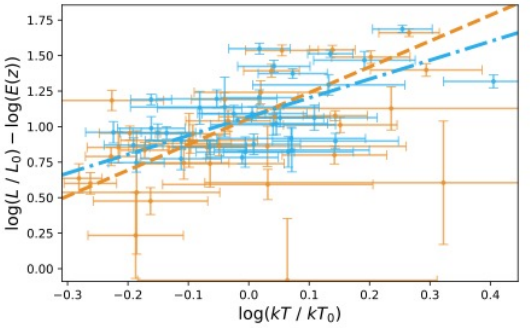
Discussion

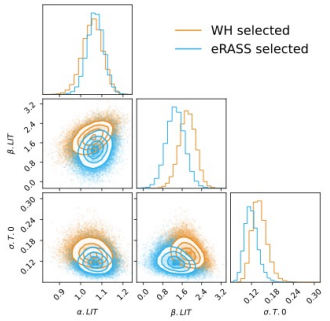
The optical sample has a **steeper slope (β)** for both relations.

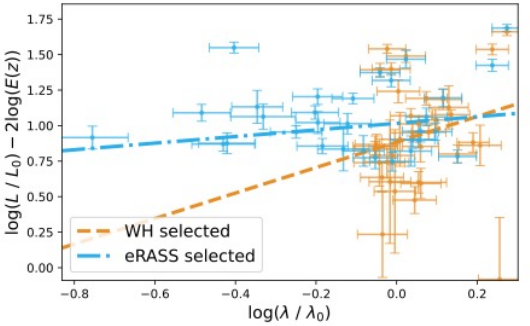
BUT the errors on these results are still very large…

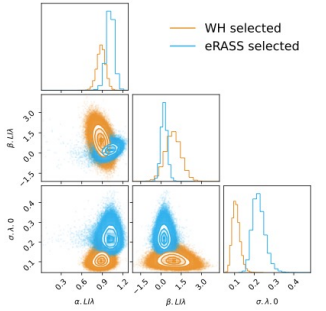
Differences in **scatter (σ)** are significant, which needs further investigation.

Parameter	$L-T$		$L-\lambda$	
	WH	eRASS	WH	eRASS
α	$1.055^{+0.046}_{-0.049}$	$1.070^{+0.039}_{-0.039}$	$0.884^{+0.060}_{-0.062}$	$1.016^{+0.053}_{-0.057}$
β	$1.819^{+0.336}_{-0.342}$	$1.325^{+0.384}_{-0.337}$	$0.897^{+0.584}_{-0.573}$	$0.233^{+0.227}_{-0.222}$
σ	$0.141^{+0.024}_{-0.019}$	$0.118^{+0.020}_{-0.017}$	$0.107^{+0.021}_{-0.017}$	$0.22^{+0.035}_{-0.028}$









Discussion

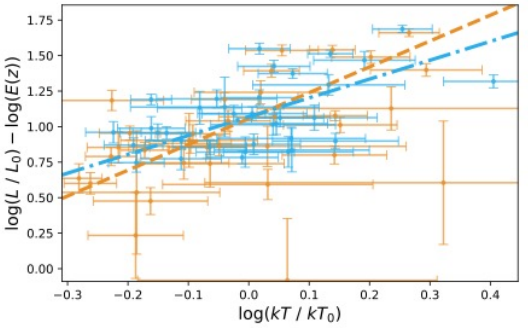
The optical sample has a **steeper slope (β)** for both relations.

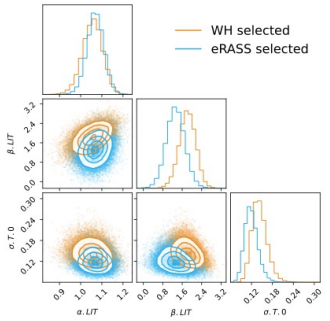
BUT the errors on these results are still very large…

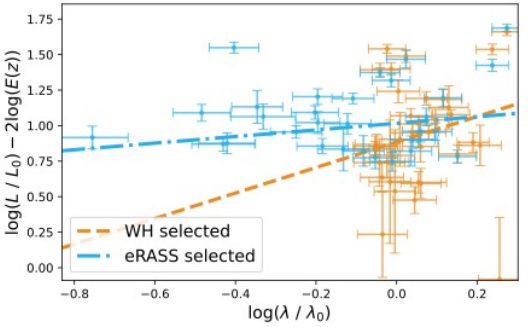
Differences in **scatter (σ)** are significant, which needs further investigation.

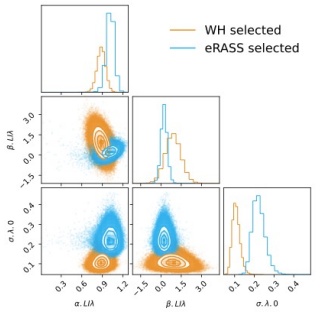
Similar to Andreon et al. (2016), we see a lot of high λ, low L clusters in the optical sample missed by the X-ray

Parameter	$L-T$		$L-\lambda$	
	WH	eRASS	WH	eRASS
α	$1.055^{+0.046}_{-0.049}$	$1.070^{+0.039}_{-0.039}$	$0.884^{+0.060}_{-0.062}$	$1.016^{+0.053}_{-0.057}$
β	$1.819^{+0.336}_{-0.342}$	$1.325^{+0.384}_{-0.337}$	$0.897^{+0.584}_{-0.573}$	$0.233^{+0.227}_{-0.222}$
σ	$0.141^{+0.024}_{-0.019}$	$0.118^{+0.020}_{-0.017}$	$0.107^{+0.021}_{-0.017}$	$0.22^{+0.035}_{-0.028}$



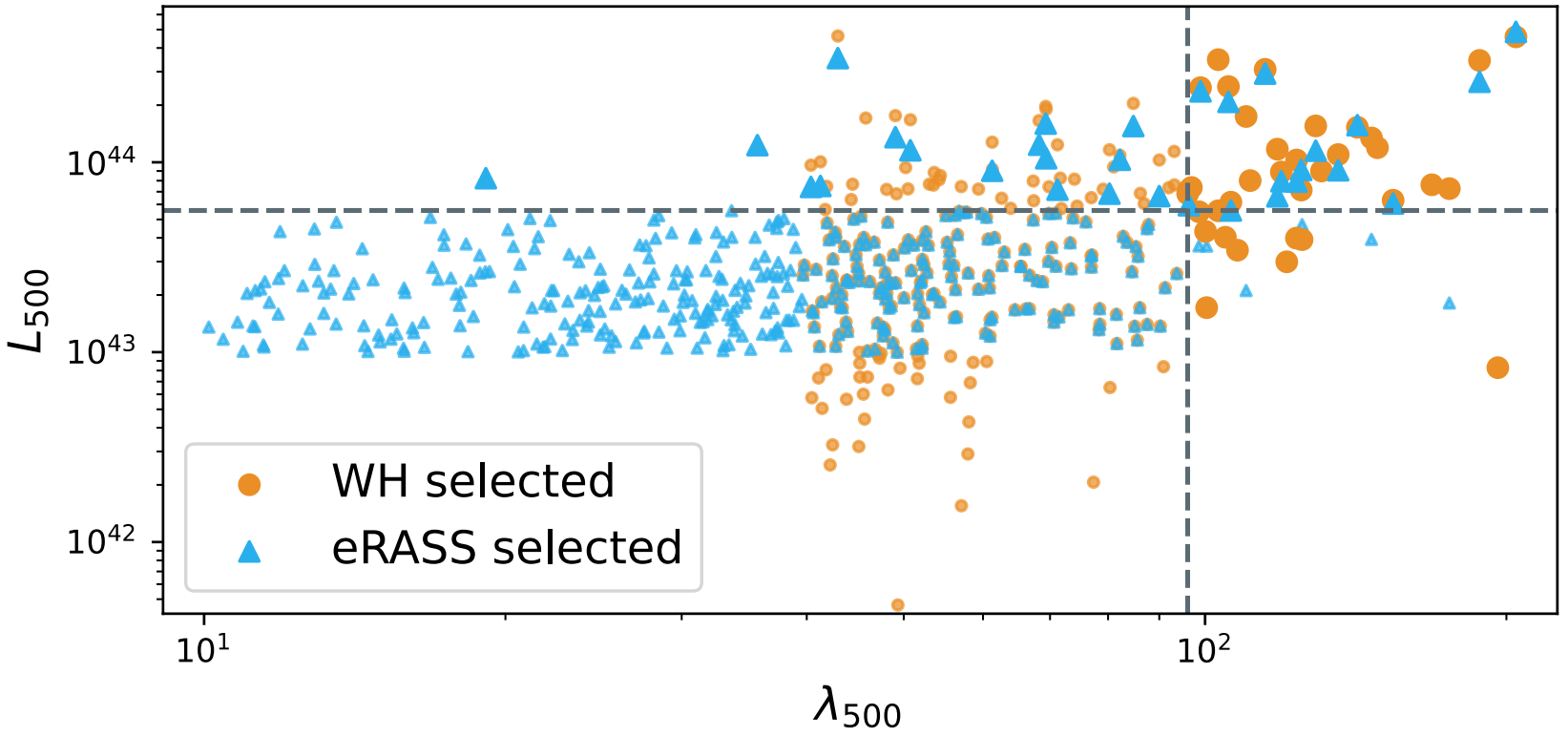






Future Work

My samples are currently very **incomplete**. I have used only 35 from each selection method of a possible 500 that I identified during sample selection:



SUMMARY

- Previous works have suggested that we are missing clusters, impacting cosmology
- I am trying to investigate this by comparing scaling relations of cluster properties
- Currently, the results are inconclusive but indicate that there might be something going on
- The more complete sample will help

SUMMARY

- Previous works have suggested that we are missing clusters, impacting cosmology
- I am trying to investigate this by comparing scaling relations of cluster properties
- Currently, the results are inconclusive but indicate that there might be something going on
- The more complete sample will help

ANY QUESTIONS?