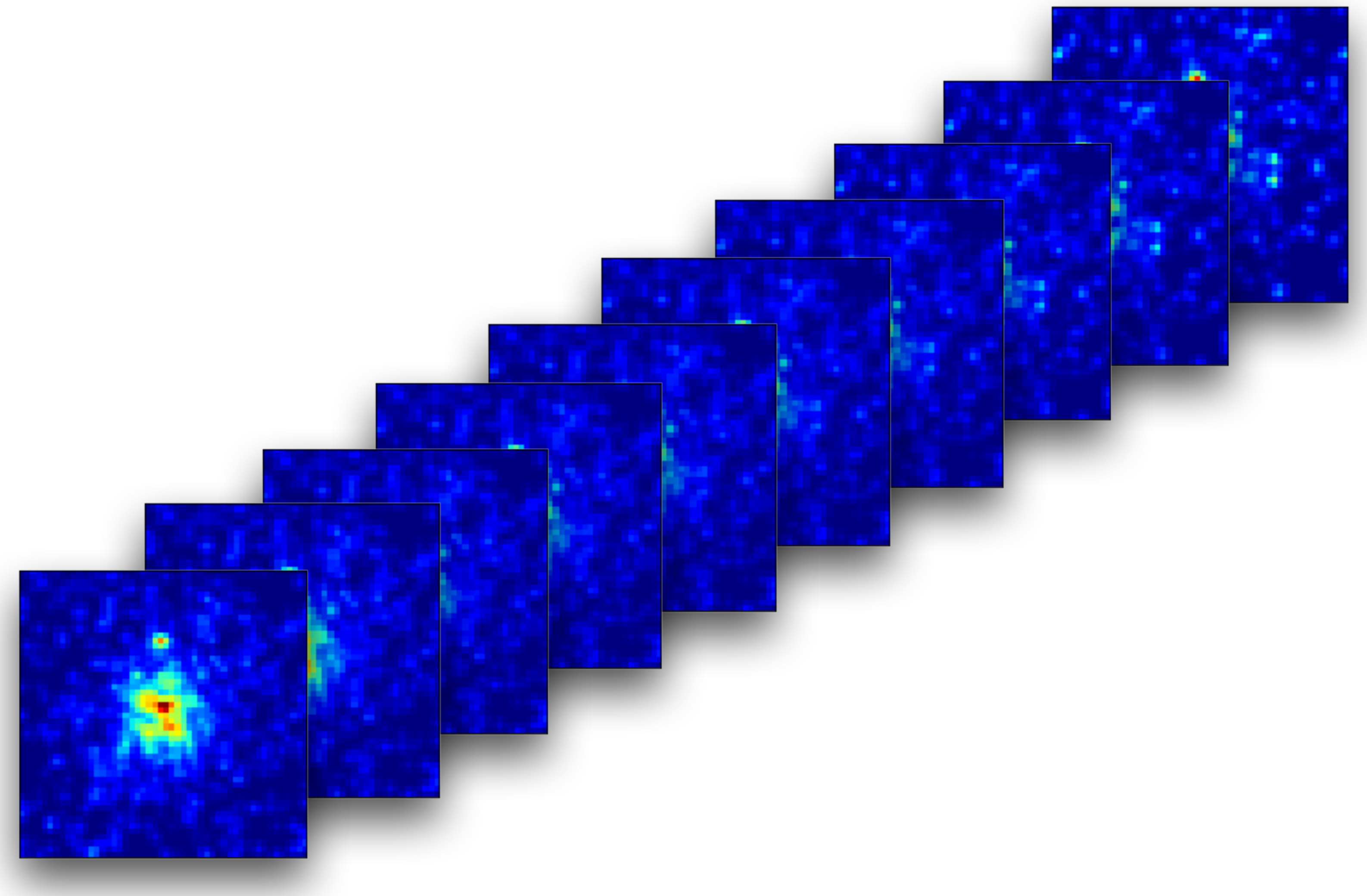
Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

PUNCH 4NFDI

ML Approach to Infer Galaxy Cluster Masses from eROSITA X-ray Images

arXiv:2305.00016

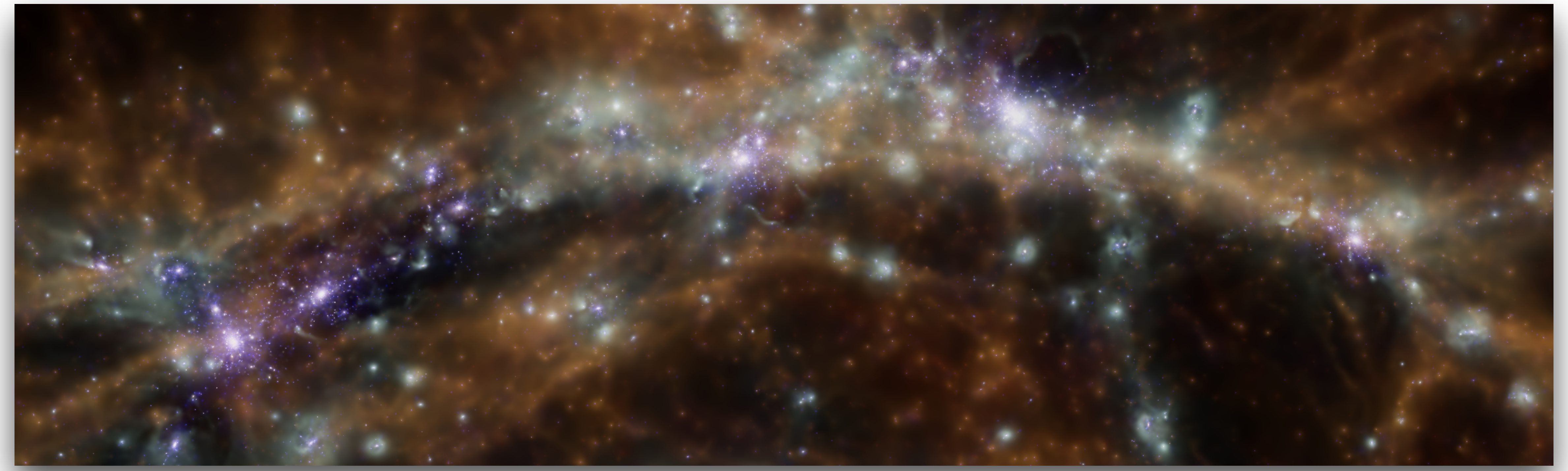


ML4Jets
08 Nov 2023

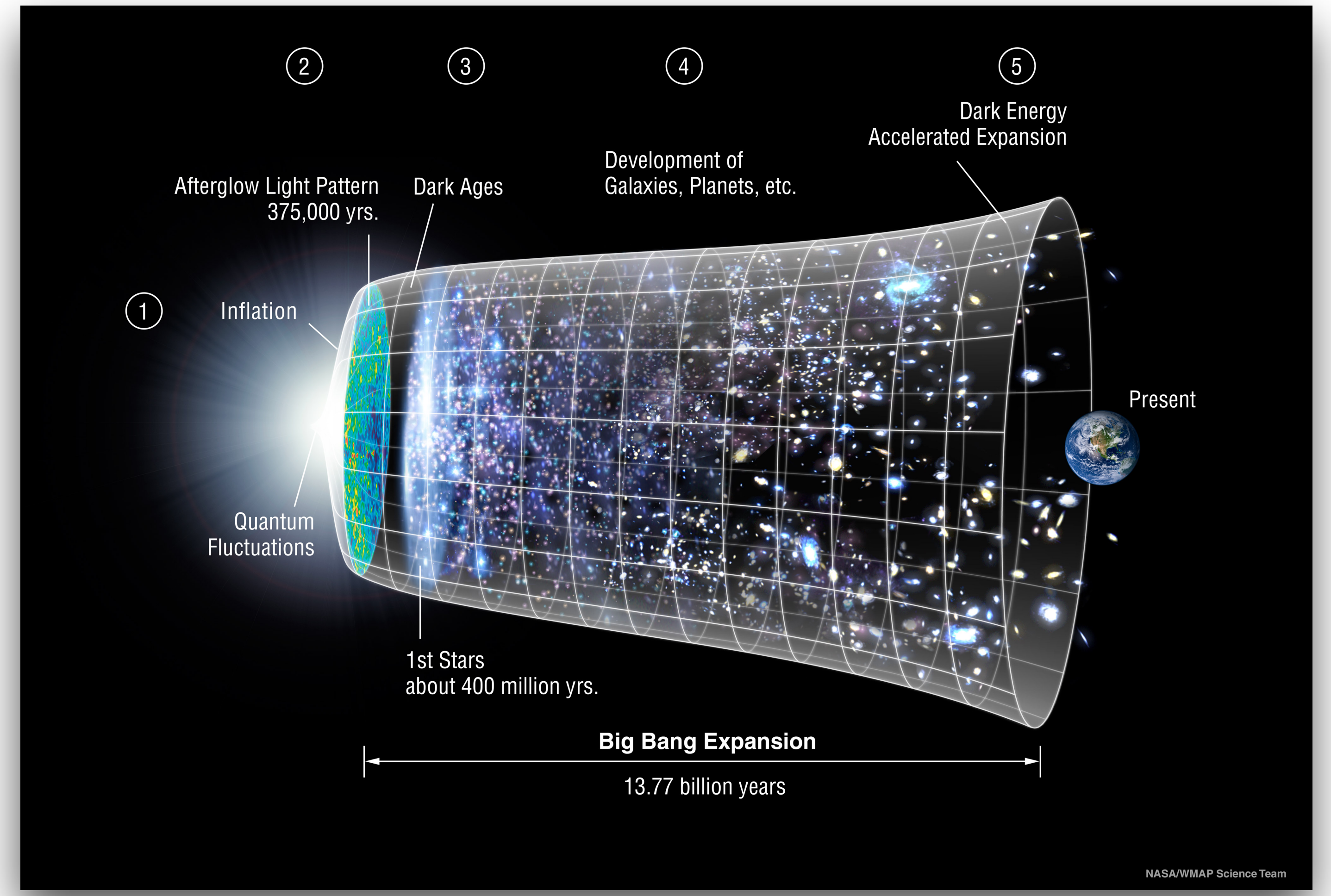
Sven Krippendorf, Nicolas Baron Perez, Esra Bulbul, Melih Kara et al.

Motivation

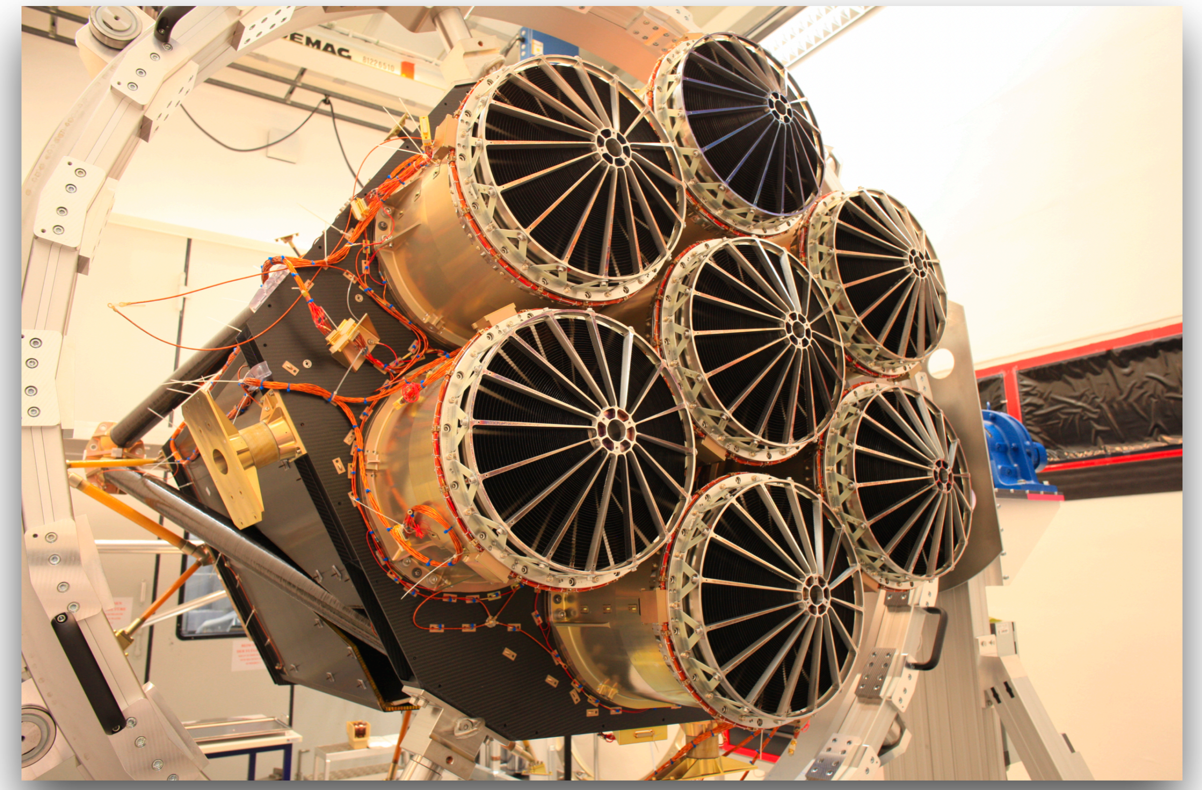
- What are galaxy clusters?
- Why measure their masses?
  - $n(M, z) \rightarrow \Omega_m, \sigma_8$
- eROSITA
  - Wide-field X-ray instrument
  - Surveys the whole sky every six months
  - 10^5 clusters expected



K. Dolag, USM



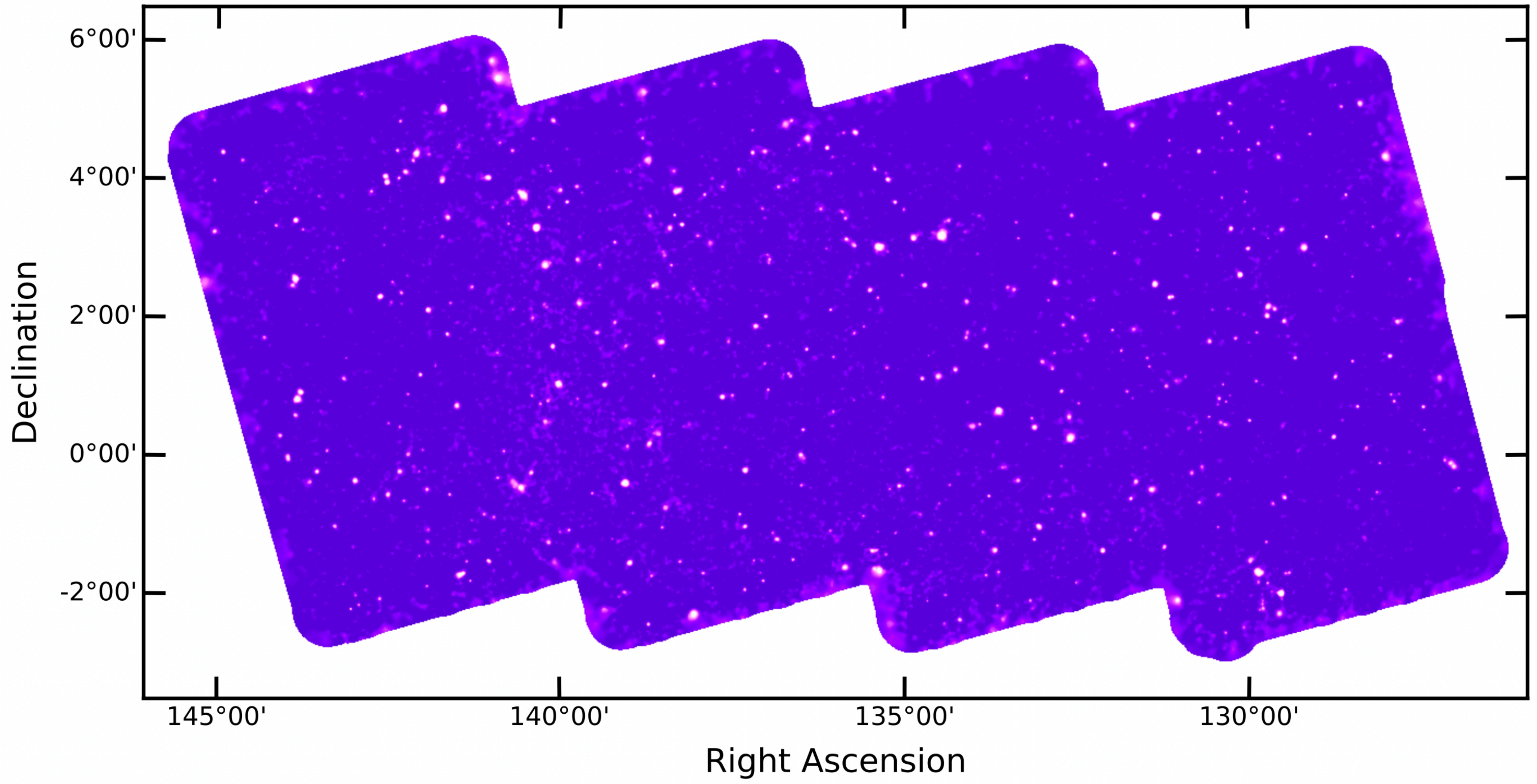
NASA / WMAP Science Team



Predehl et al., 2021

eROSITA Observations

- eFEDS observation
  - Mini survey with $\sim 140\,\text{deg}^2$
  - 542 detected clusters
- Mock observations
  - Dark matter simulations with flat ΛCDM cosmology
  - Mass: $10^{13} \lesssim M / M_{\odot} \lesssim 10^{15}$
  - Redshift: $z \lesssim 1.5$

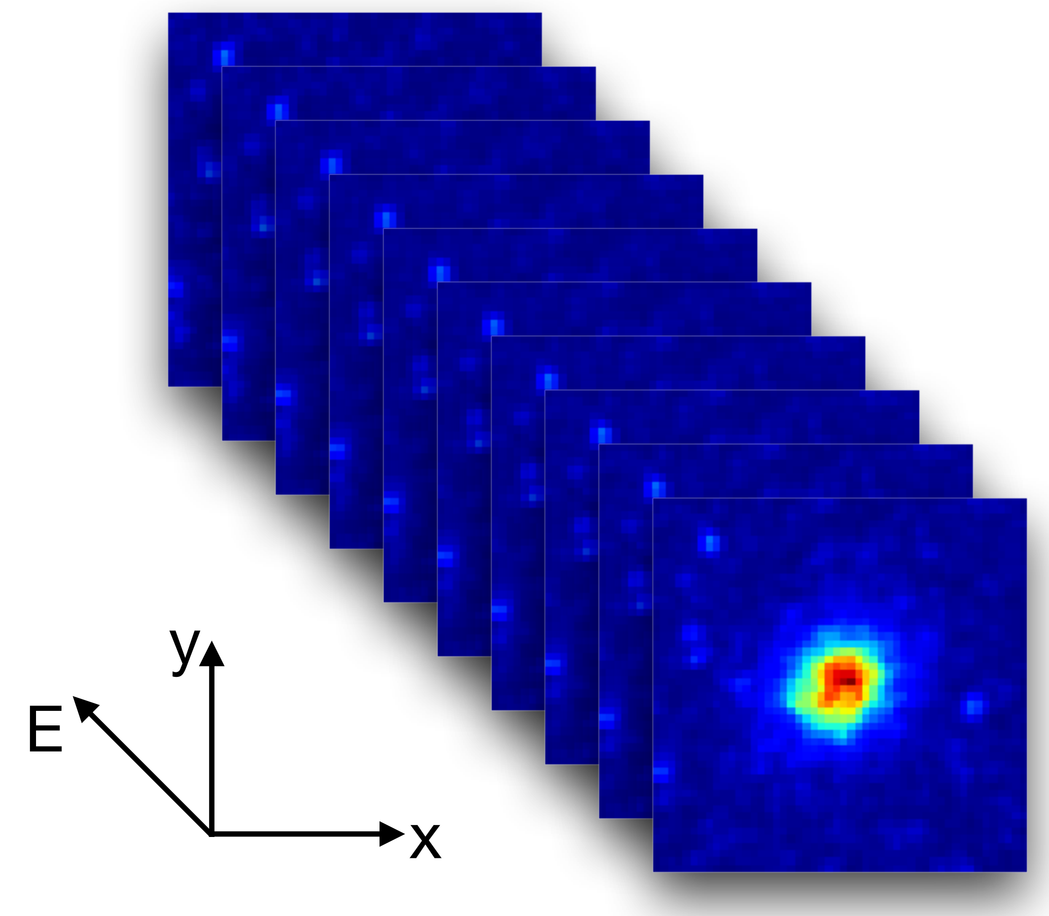


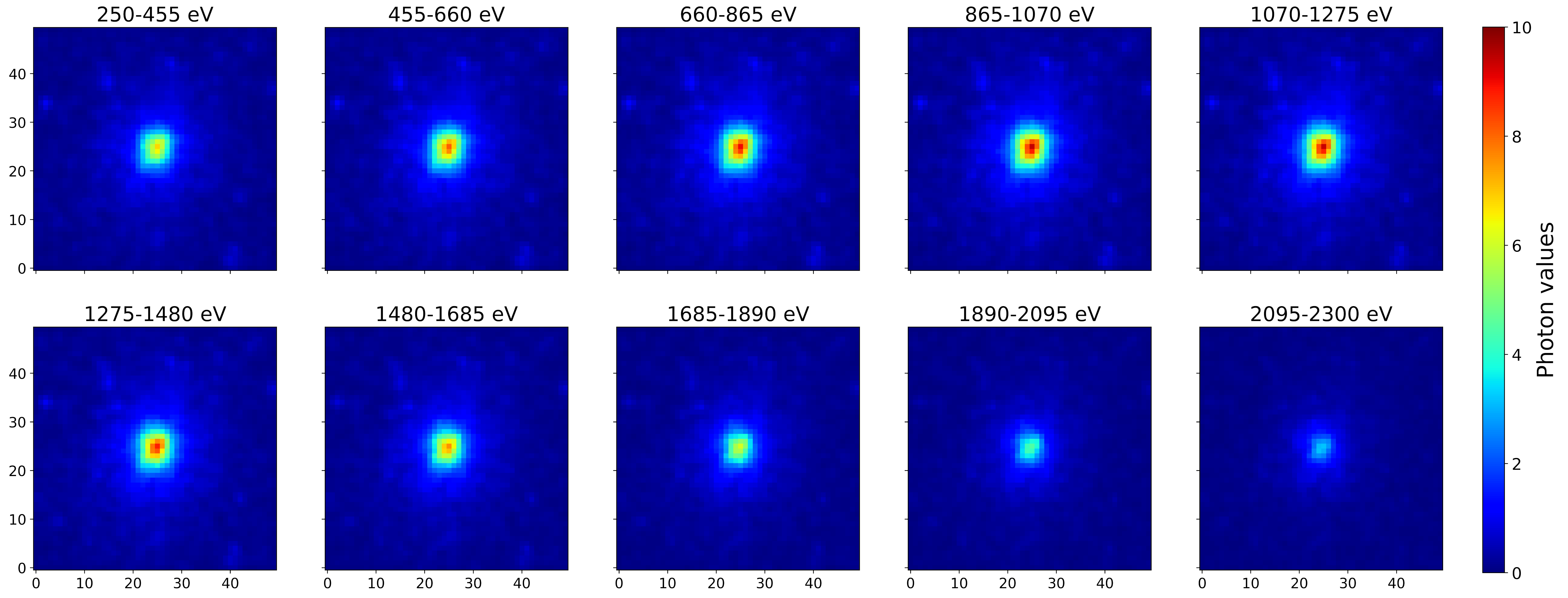
Liu et al., 2022

Input Data

Energy-band Images

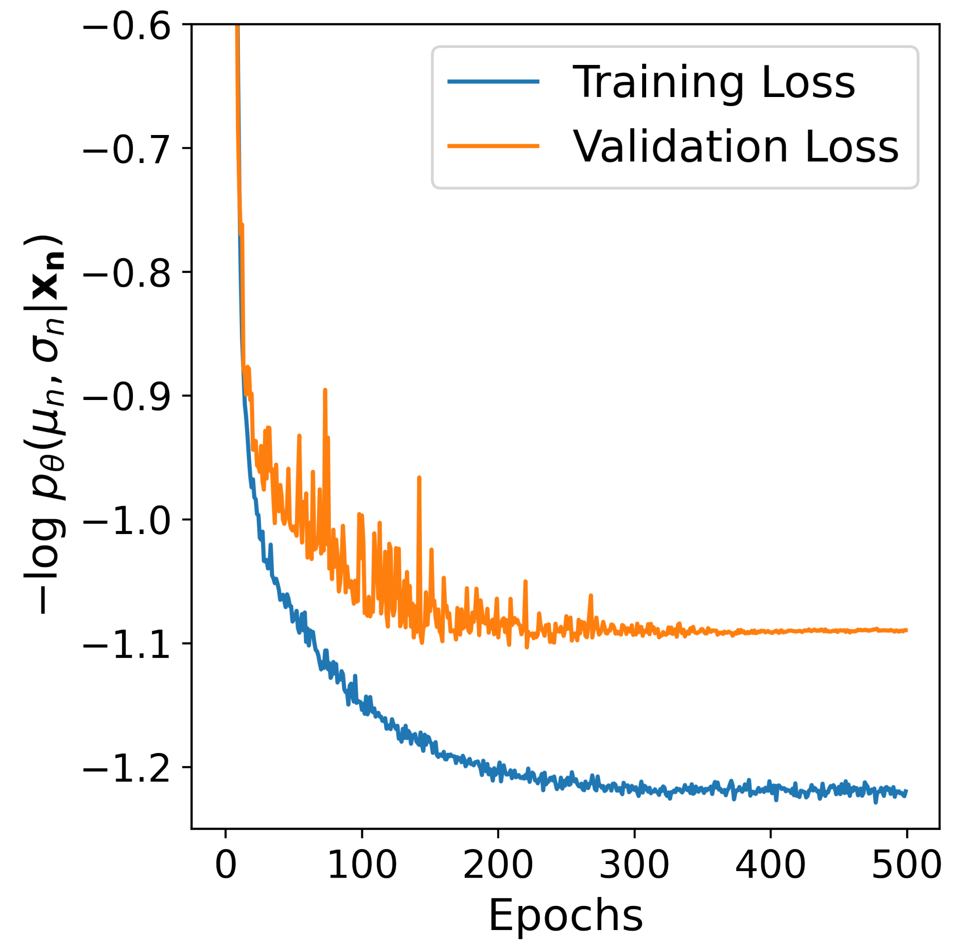
- EBI: Spatial information in ten energy channels
  - Squared region of 300 pixels centred at the cluster
  - Resized to 50x50x10 to reduce memory requirements
  - Gaussian smoothed to account for low-count clusters
- Cluster sample of ~ 8000 clusters

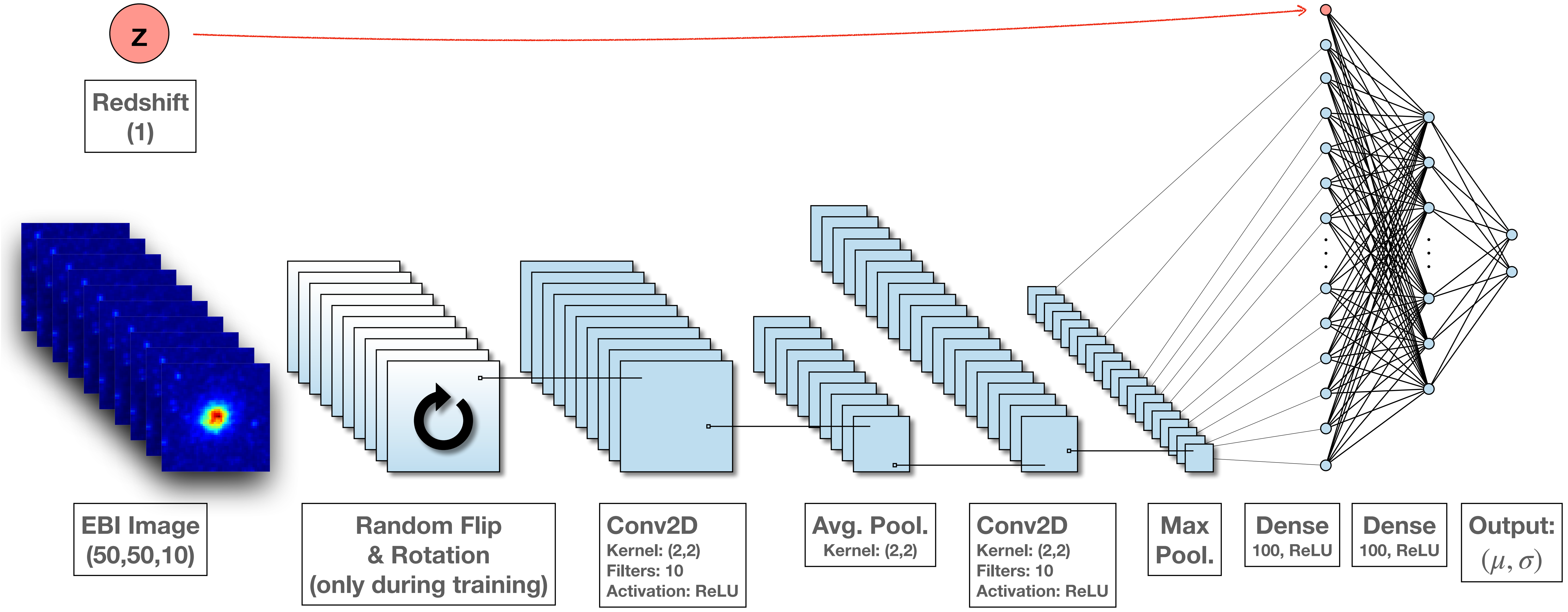




CNN Architecture

- Deep ensemble with 30 CNNs
- Preprocessing: Accounts for overfitting
- Redshift is concatenated to the first dense layer
- Gaussian negative log-likelihood loss: $\mathscr{L}(\mathbf{y}\ \ \mathbf{x}) = \dfrac{\log\ \sigma_\theta^2(\mathbf{x})}{2} + \dfrac{\left(\mathbf{y} - \mu_\theta(\mathbf{x})\right)^2}{2\,\sigma_\theta^2(\mathbf{x})}$

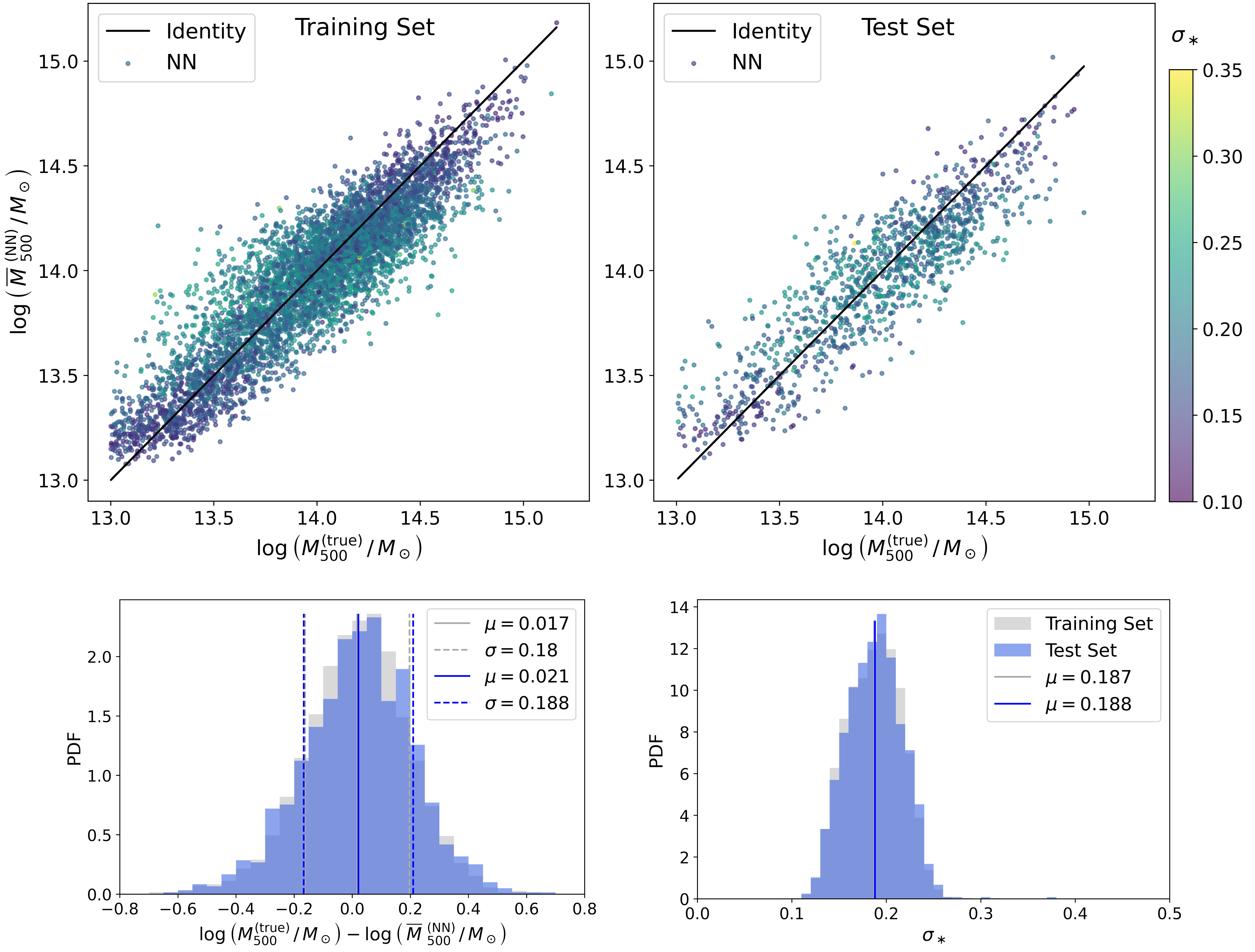




Results

eFEDS Simulation

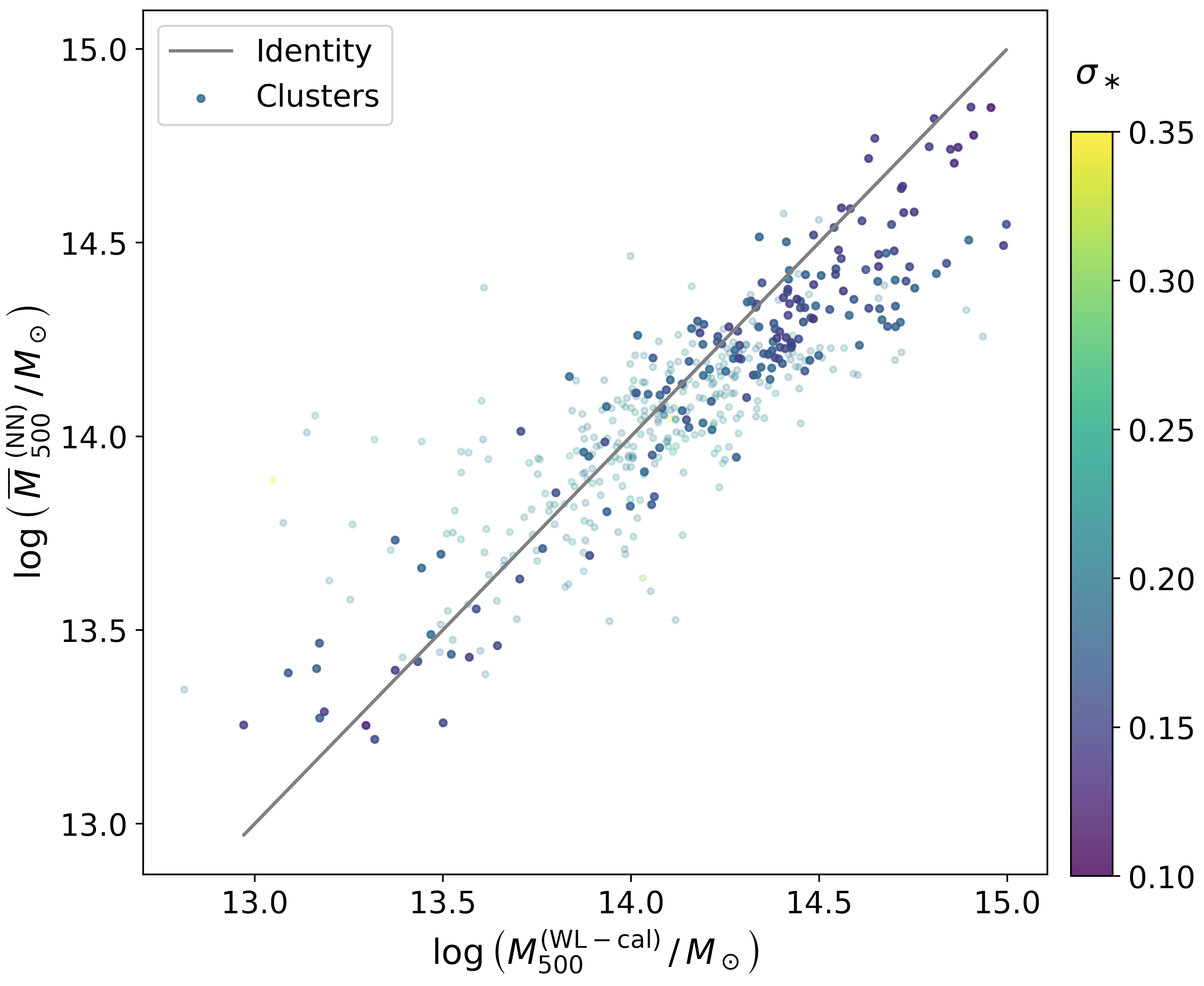
- Mass scatter with traditional method: $\sigma = 19.7\,\%$
- **Our mass scatter:** $\sigma = 18.8\,\%$
- Mean predicted uncertainty ~18.8%
- Clusters with smaller uncertainty have smaller scatter



Results

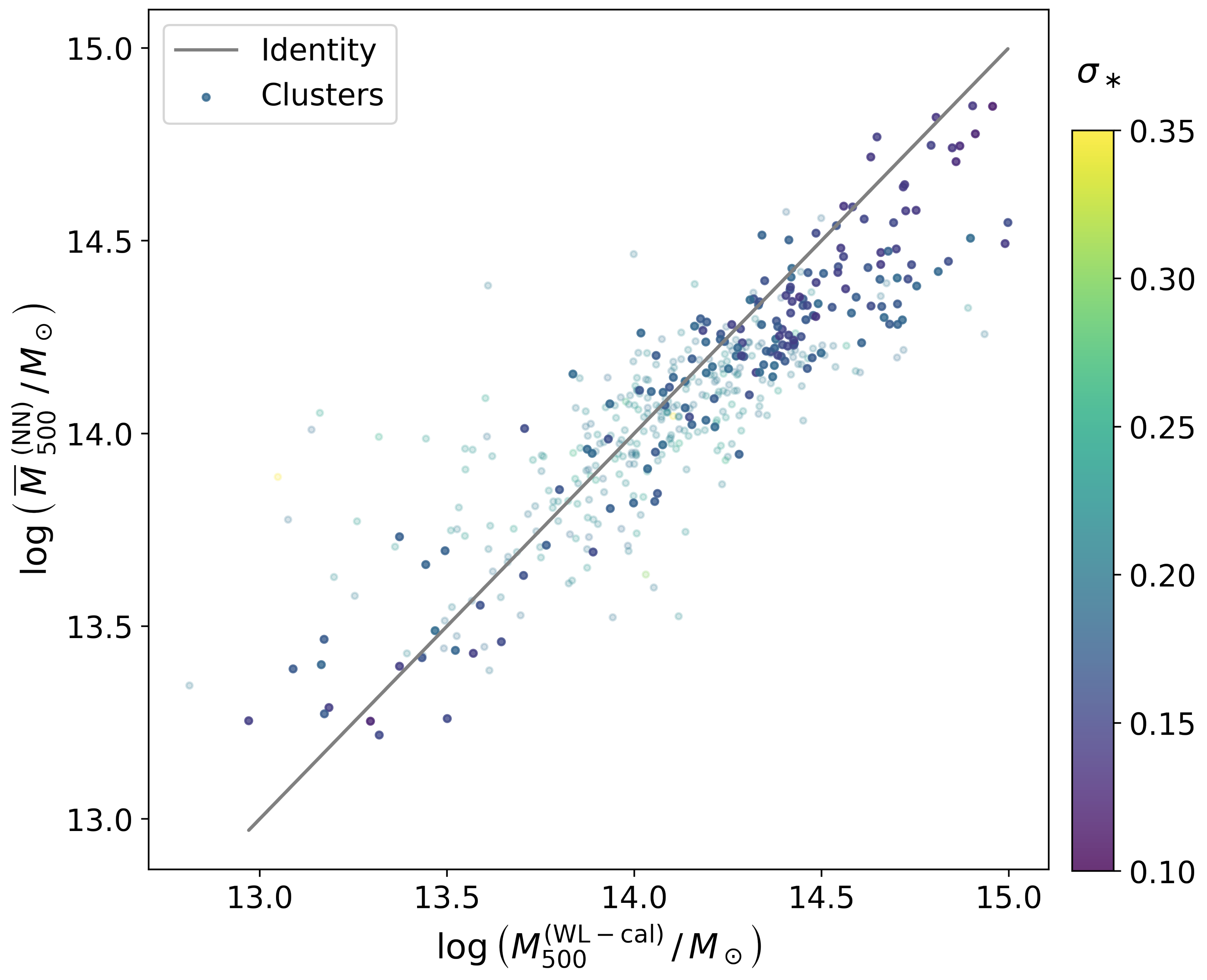
eFEDS Observation

- Comparison with masses from traditional method
- Both mass estimates are comparable

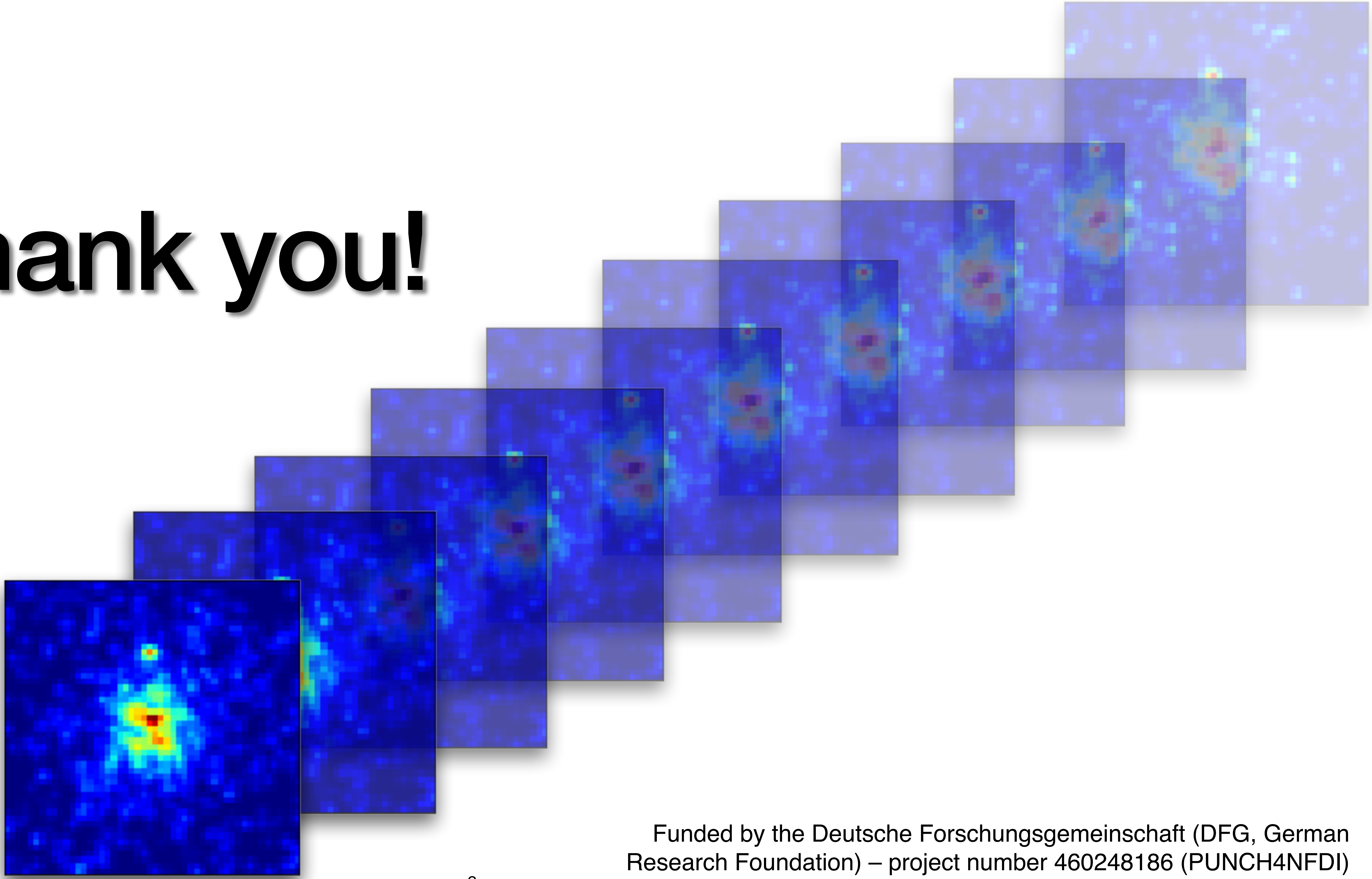


Conclusions

- CNN can handle real observation images with all kinds of contamination
- Uncertainty associated with ML mass estimates can be provided
- ML approach reduces the mass scatter by 4.8% in comparison to traditional methods



Thank you!



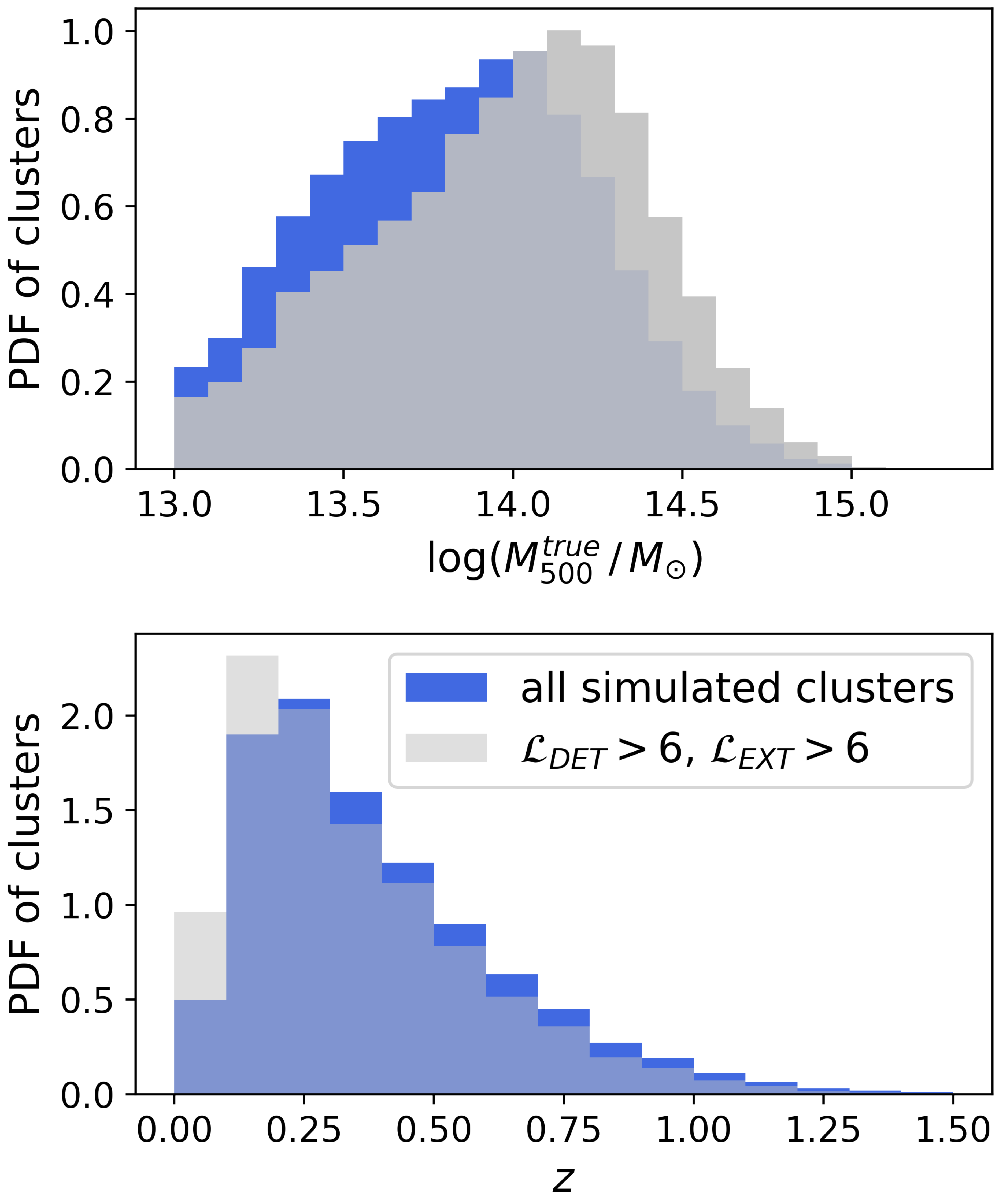
Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 460248186 (PUNCH4NFDI)

Backup

eROSITA

Simulated Observation (eFEDS)

- Based on dark matter simulations with flat ΛCDM cosmology
- 18 realisations of the eFEDS field
- Mass range: $10^{13.0} \lesssim M / M_\odot \lesssim 10^{15.2}$
- Redshift range: $0.01 \lesssim z \lesssim 1.51$
- Cuts: Detection likelihood > 5 and extent likelihood > 6
  - Likelihoods come from fitting a Gaussian kernel or β-model
  - Cluster sample of ~ 8000 clusters

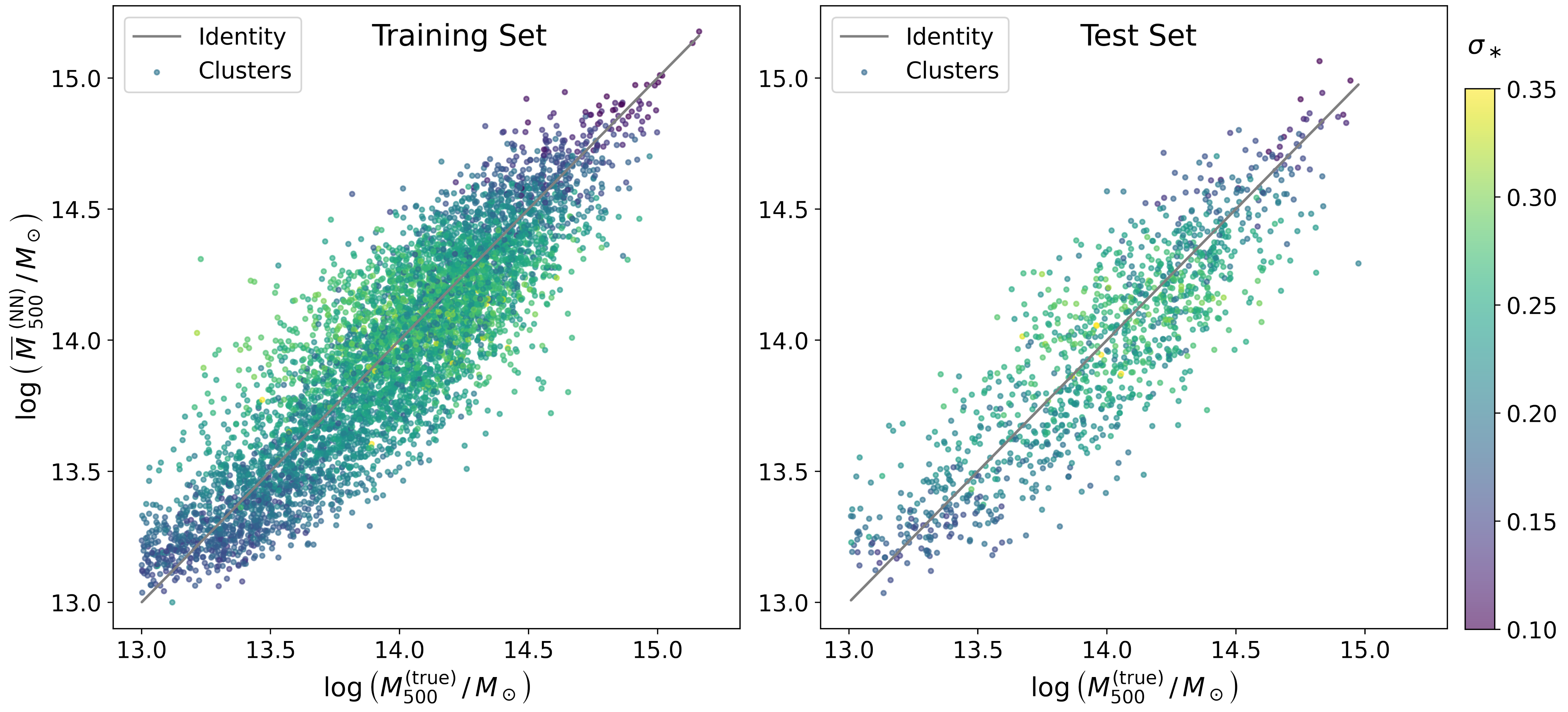


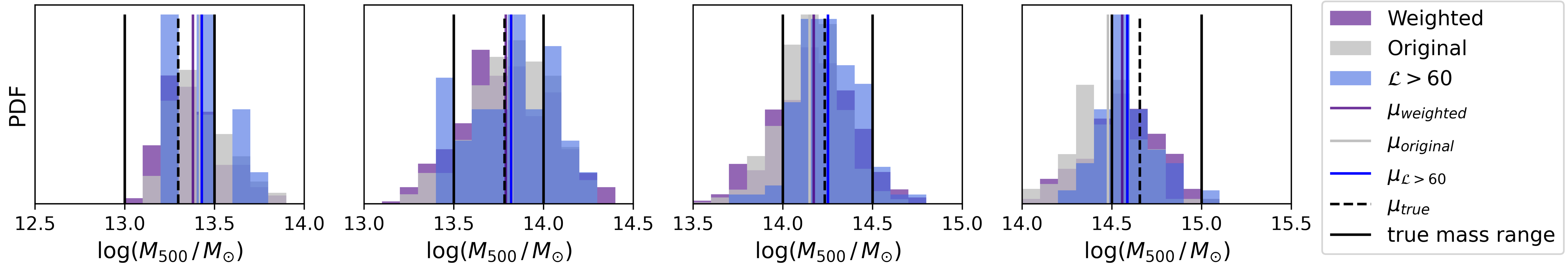
Results

eFEDS Simulation

- Training with uniform weighted sample
  - Scatter increases but follows ideal slope
  - Prediction is stable to different mass distributions in training set
- Training with high detection and extent likelihood subset ($\mathscr{L}_{DET}$, $\mathscr{L}_{EXT} > 60$)
  - Scatter decreases significantly (~15.2%)
- Improved bias in low and high mass regime

Uniform weighted sample





Results

eFEDS Observation

- Comparison with masses from traditional method (based on count-rate η)
- Both mass estimates are comparable

$$\left\langle \ln\left(\frac{L_X}{\text{ergs}}\middle| M_{500}\right)\right\rangle = \ln\left(3.36^{+0.53}_{-0.49}\right) + \ln\left(10^{43}\right) +$$
$$\left[\left(1.44^{+0.14}_{-0.13}\right) + \left(-0.07^{+1.26}_{-0.79}\right)\ln\left(\frac{1+z}{1+z_{\text{piv}}}\right)\right] \times \ln\left(\frac{M_{500}}{M_{\text{piv}}}\right)$$
$$+2\times\ln\left(\frac{E(z)}{E(z_{\text{piv}})}\right) + \left(-0.51^{+0.93}_{-0.75}\right)\times\ln\left(\frac{1+z}{1+z_{\text{piv}}}\right),$$

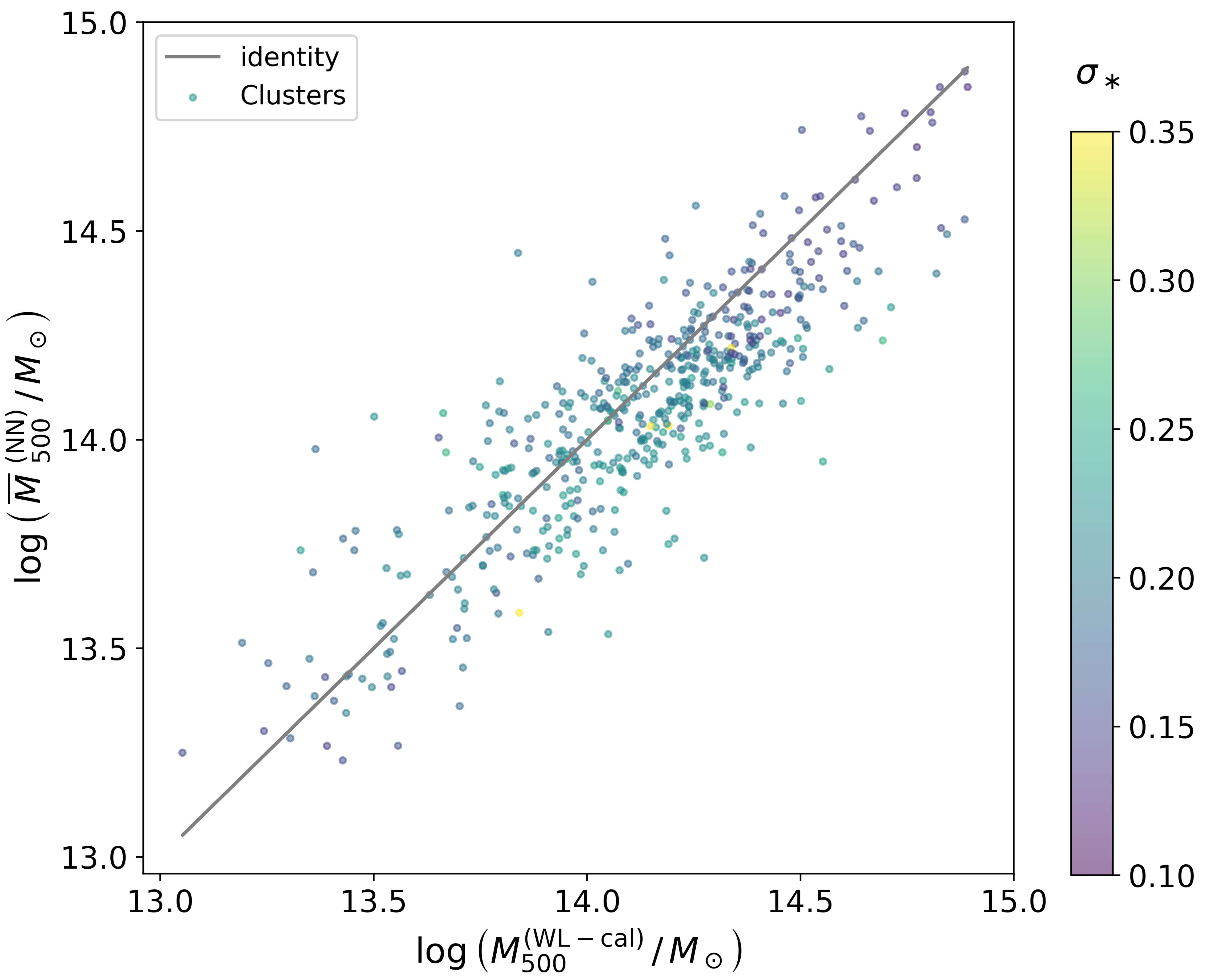


Table C.1: **Importance of redshift for our ensemble NN mass predictors:**

Noise-level	Training Set	Test Set
$\sigma_N = 0$	$\sigma = 0.180$	$\sigma = 0.188$
$\sigma_N = 0.01$	$\sigma = 0.178$	$\sigma = 0.186$
$\sigma_N = 0.1$	$\sigma = 0.191$	$\sigma = 0.204$
$\sigma_N = 0.2$	$\sigma = 0.208$	$\sigma = 0.224$

We show the respective standard deviations between the true and predicted masses observed on the training and test set. We find that increasing the noise level leads to worse predictions.