SRG/eROSITA

0.3-2.3 keV - RGB

COSMOLOGICAL RESULTS FROM THE FIRST eROSITA ALL SKY SURVEY

E. ARTIS on behalf of the eROSITA Clusters & Cosmology group

22 May 2024

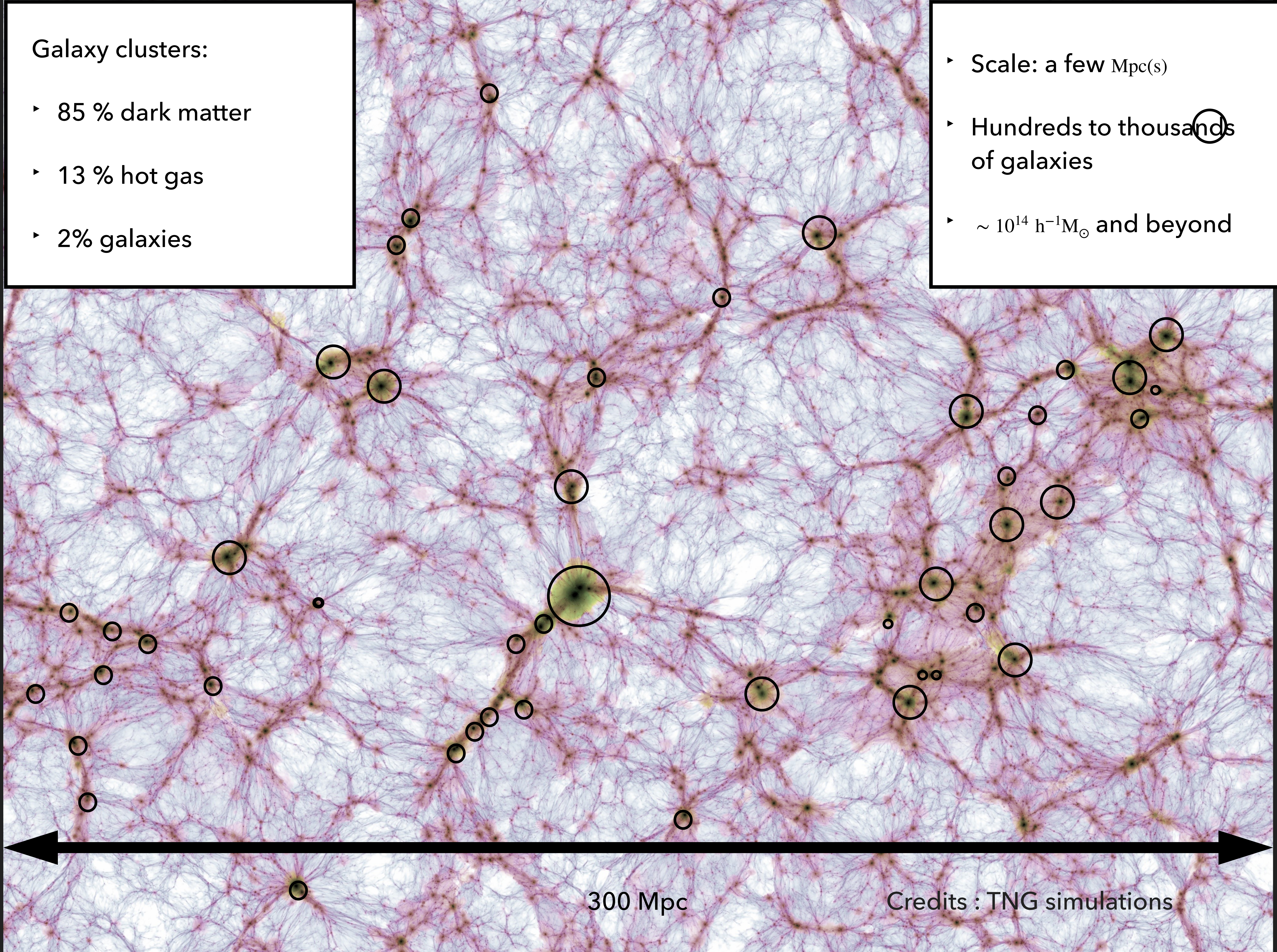
MAX PLANCK INSTITUTE FOR EXTRATERRESTRIAL PHYSICS

Dark Quest

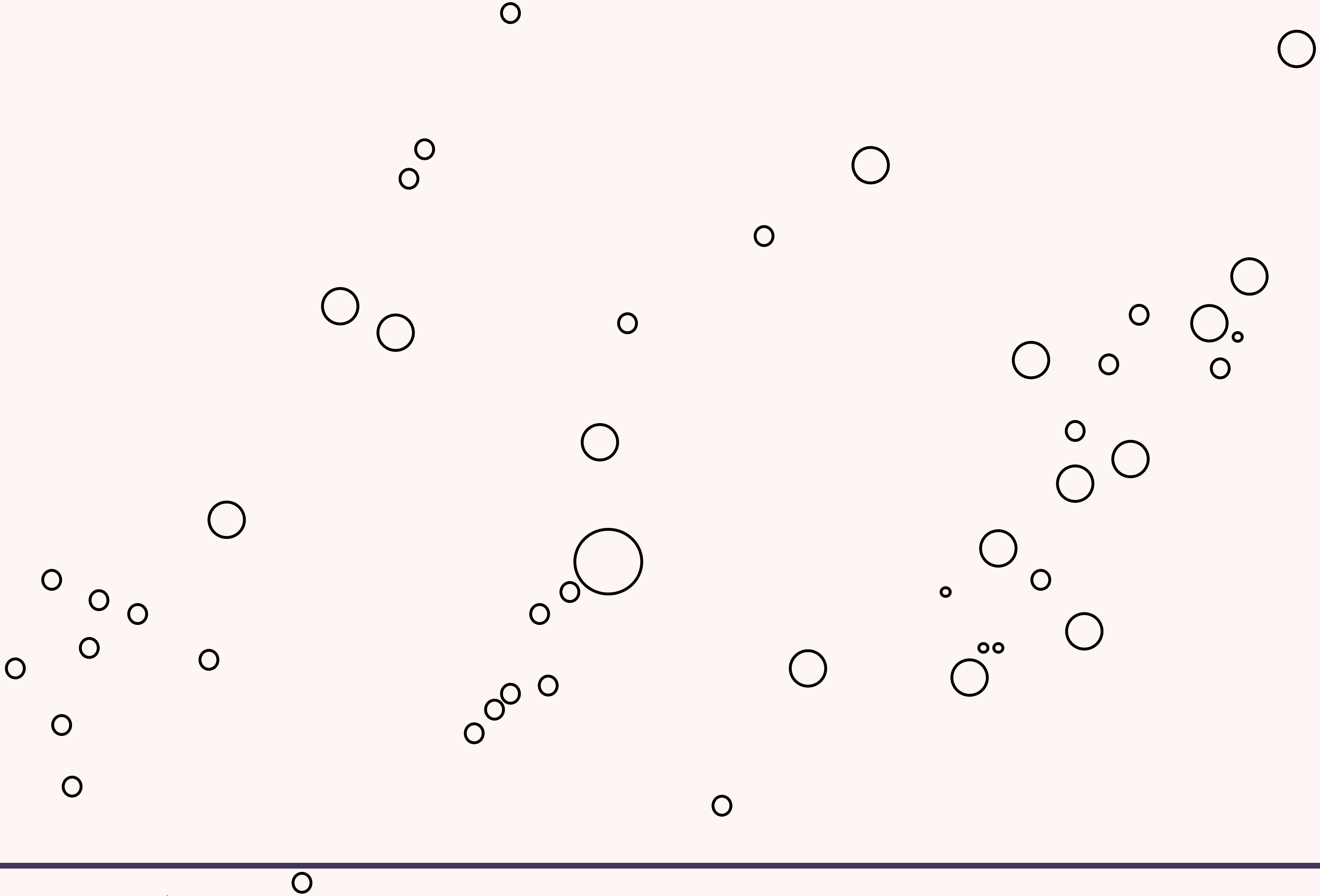
Galaxy clusters:

- 85 % dark matter
- 13 % hot gas
- 2% galaxies

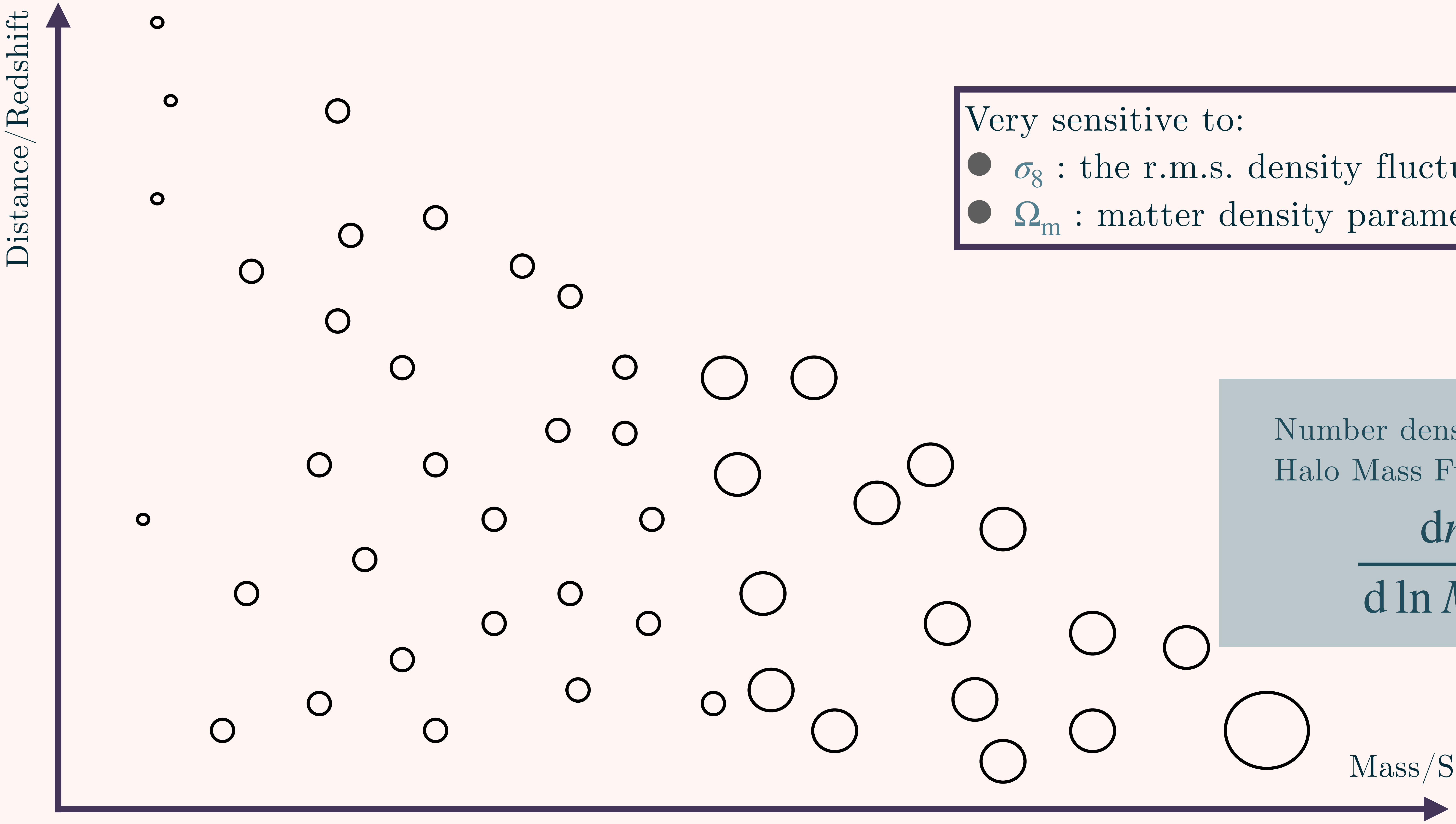
- Scale: a few Mpc(s)
- Hundreds to thousands of galaxies
- $\sim 10^{14}\ h^{-1}M_\odot$ and beyond



Credits : TNG simulations



CLUSTER ABUNDANCE AS A COSMOLOGICAL PROBE



Very sensitive to:

- σ_8 : the r.m.s. density fluctuation in 8 h^{-1}Mpc
- Ω_m : matter density parameter

Number density of clusters / Halo Mass Function

$$\frac{dn}{d\ln M dz}(M, z)$$

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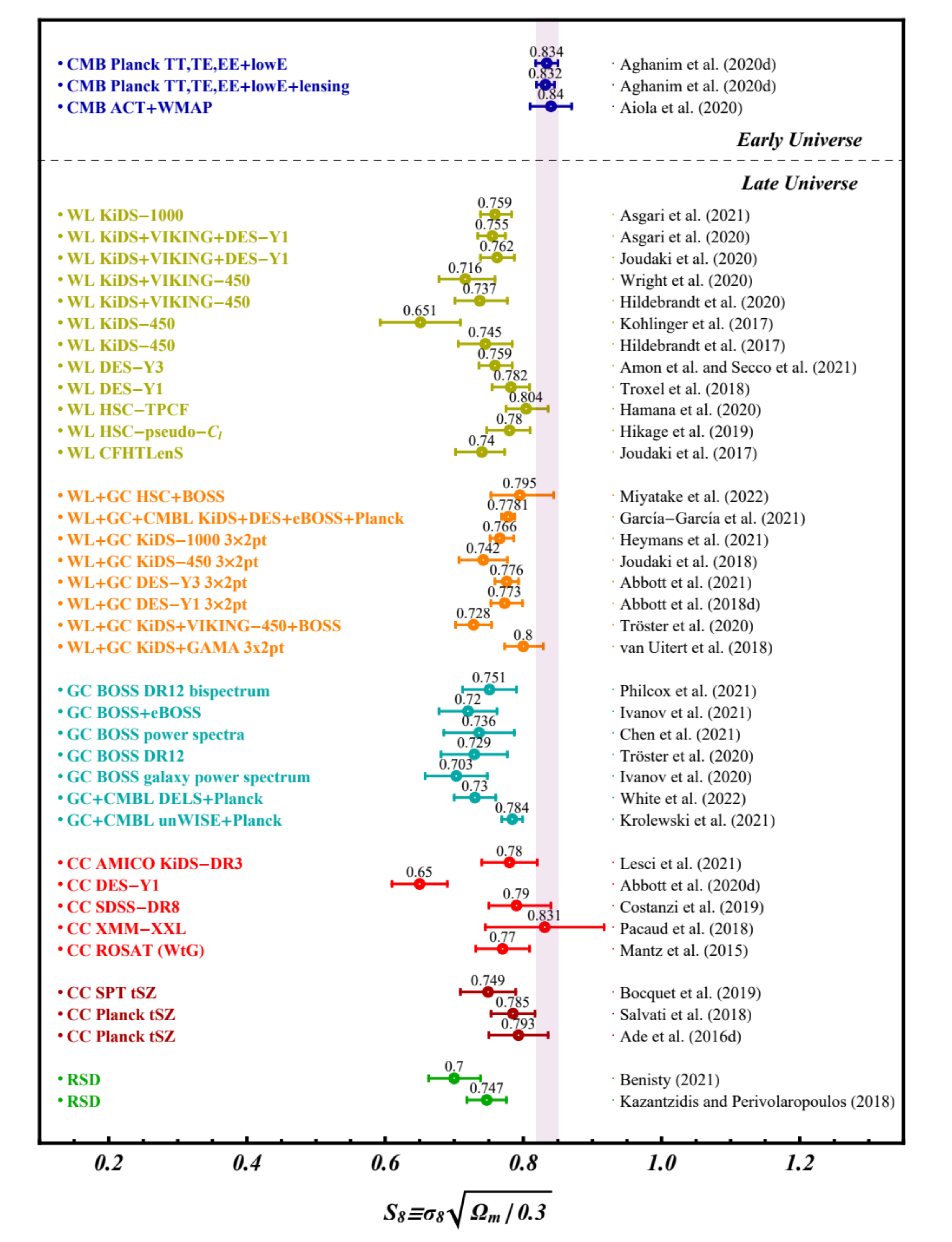

Abdalla et al., 2022

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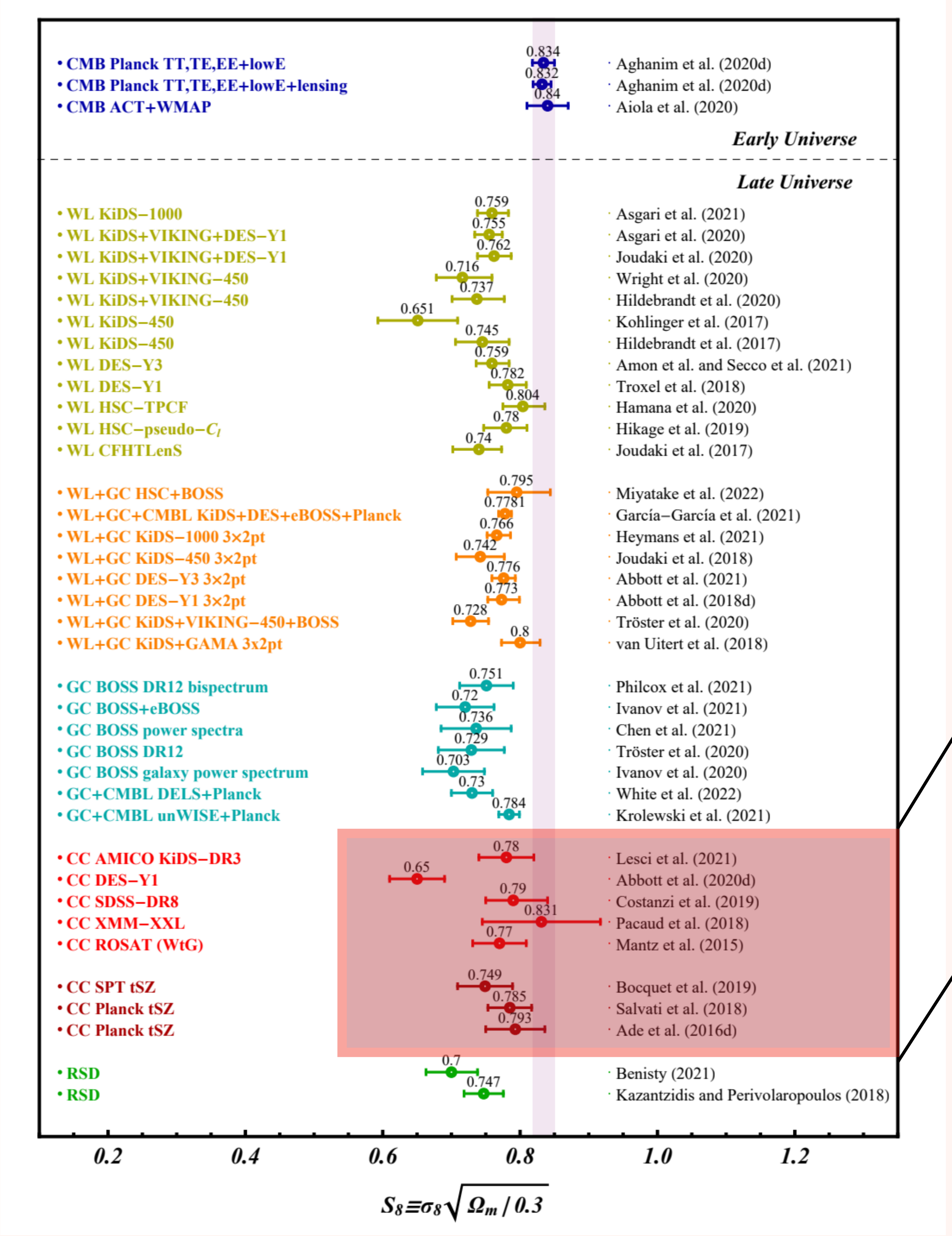
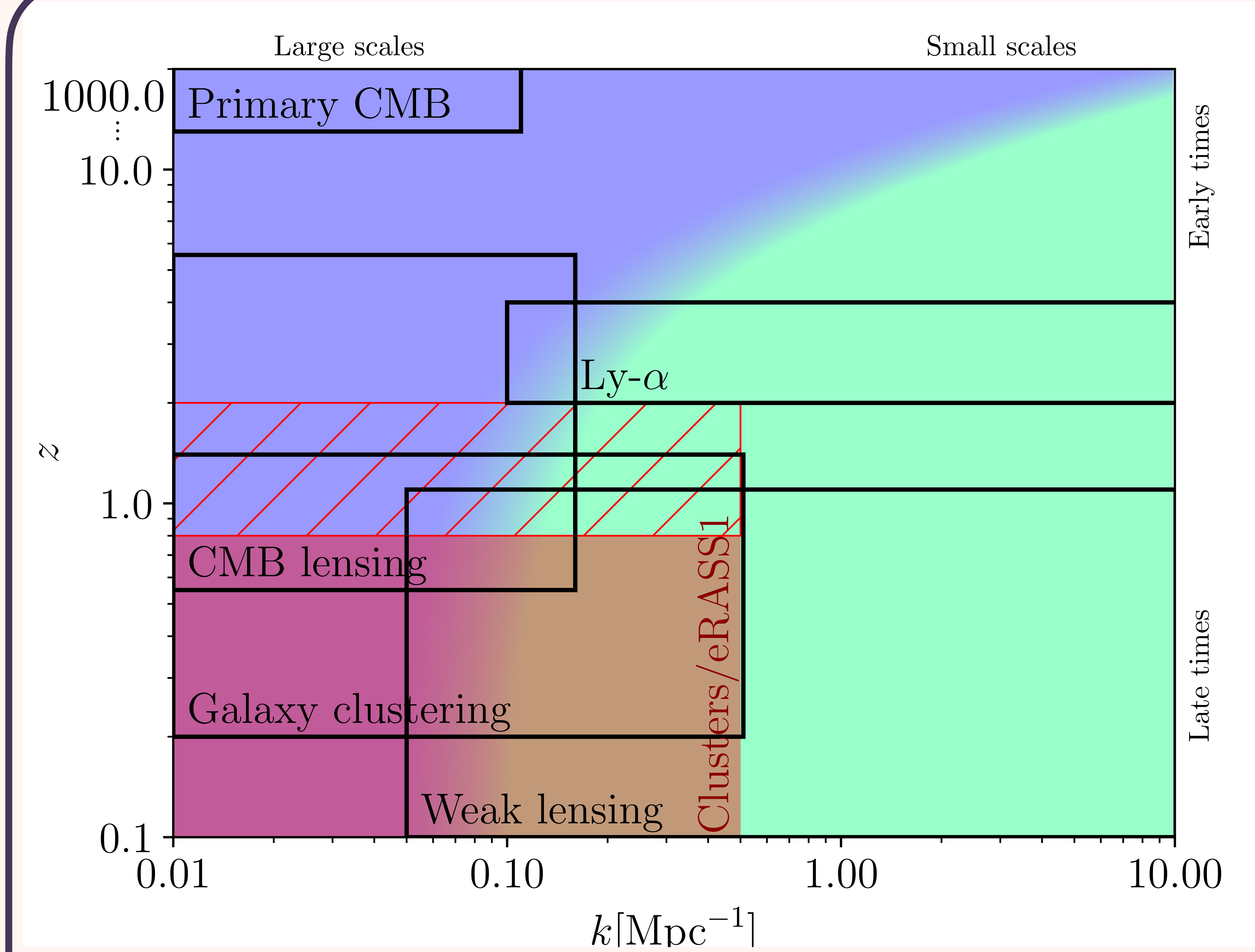


Abdalla et al., 2022

Measurements of S_8 by galaxy clusters

CLUSTER ABUNDANCE AS A COSMOLOGICAL PROBE



Redshift and scale sensitivity of the different redshift probes, adapted from Preston et al., 2023

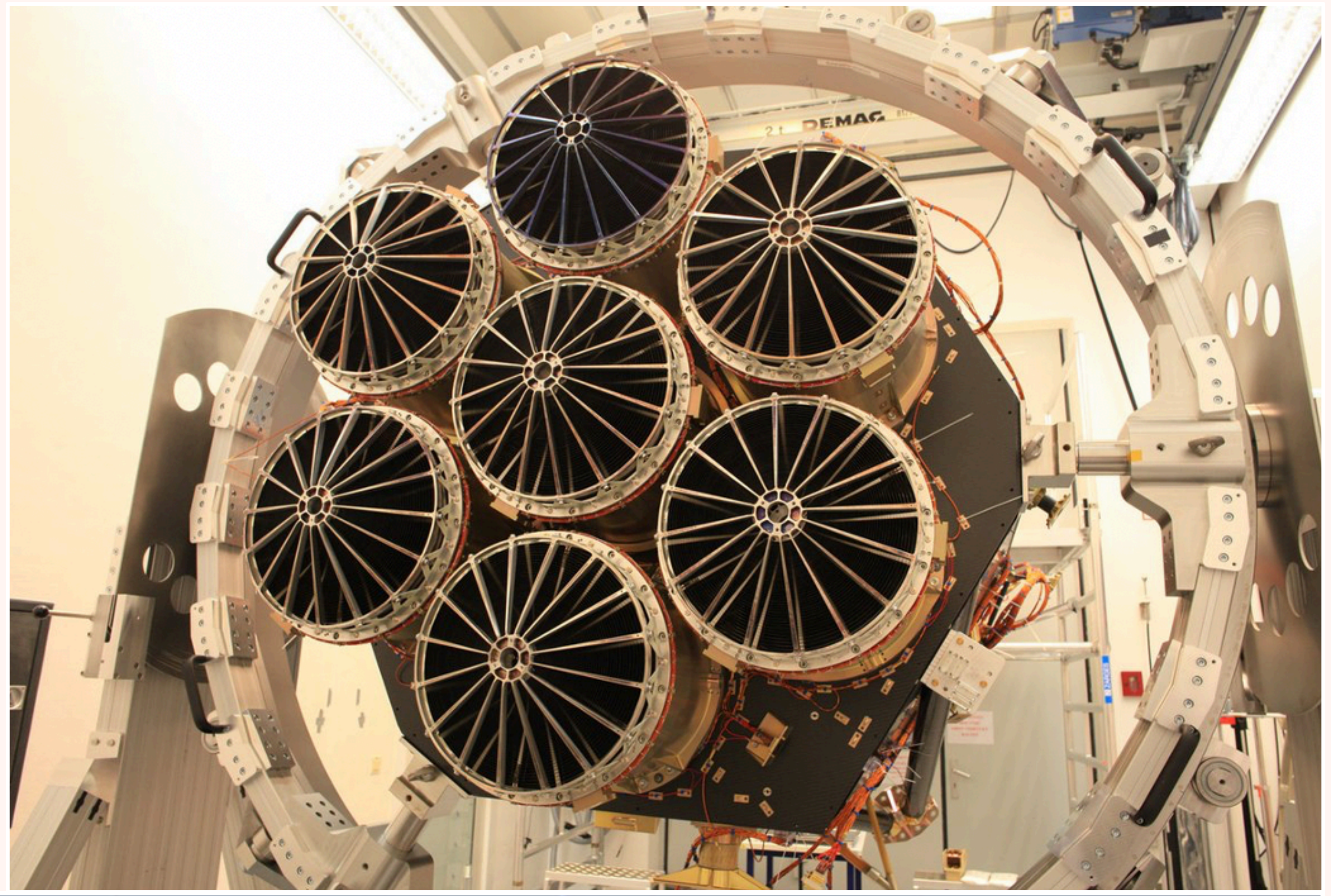
EA et al., 2024

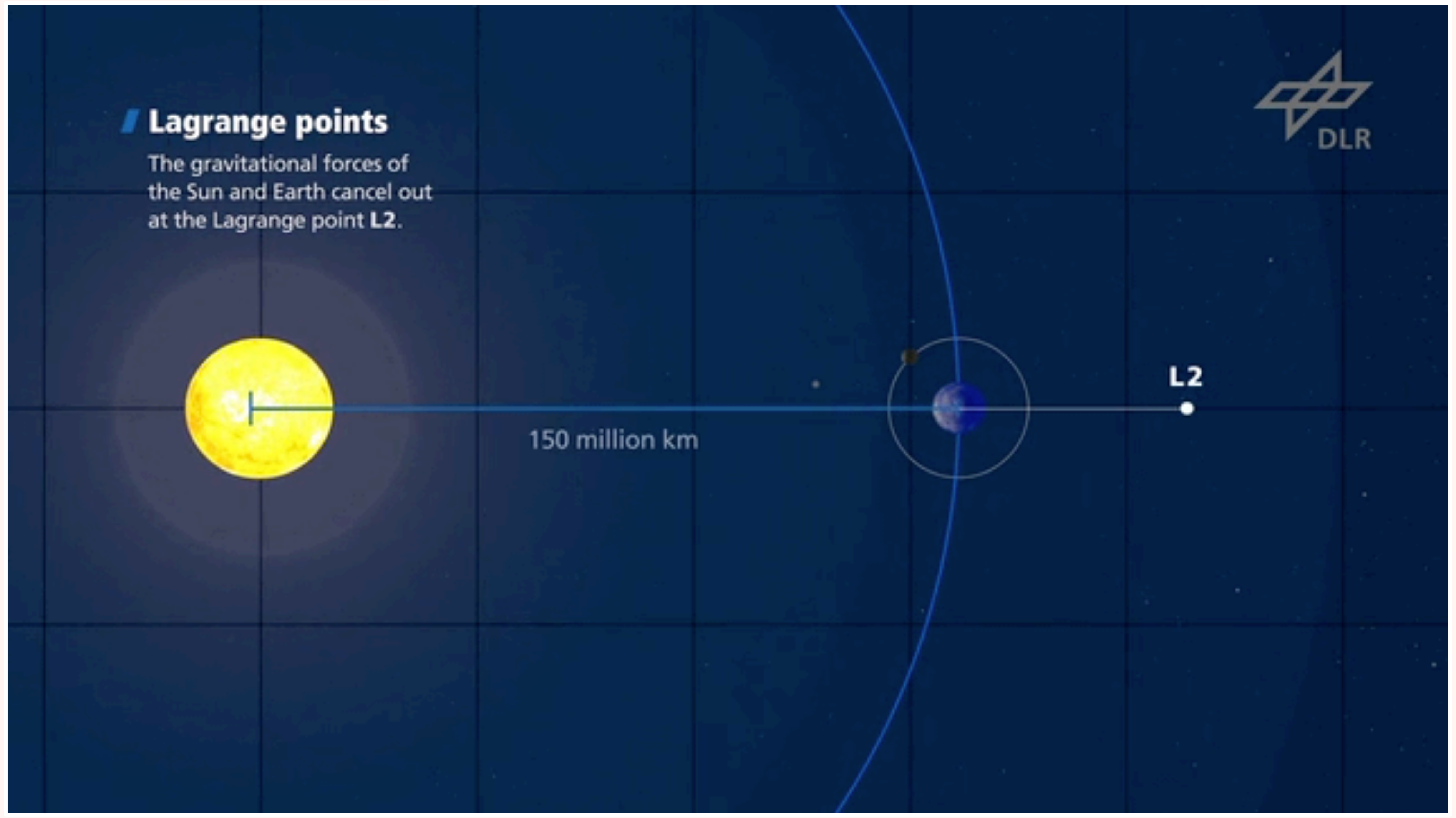
- **Cluster abundance probe redshift and scale ranges complementary to other probes**
- **If discrepancies are to arise, it is important that they are tested in these different regimes**

eROSITA X-RAY TELESCOP ON SRG

- **eROSITA = ex**tended **RO**entgen **S**urvey with an **I**maging **T**elescope **A**rray
- **X-ray all-sky survey** in **4** years (**8x6** month surveys)
- Expected lifetime **> 7 years**
- **Sensitive to 0.2 – 10 keV band**

- **20-30 times more sensitive than ROSAT**
- **Grasp; FOV*Effective Area @1keV:**
  - **5 × XMM-Newton**
  - **100 × Chandra ACIS**





Credit : E. Bulbul

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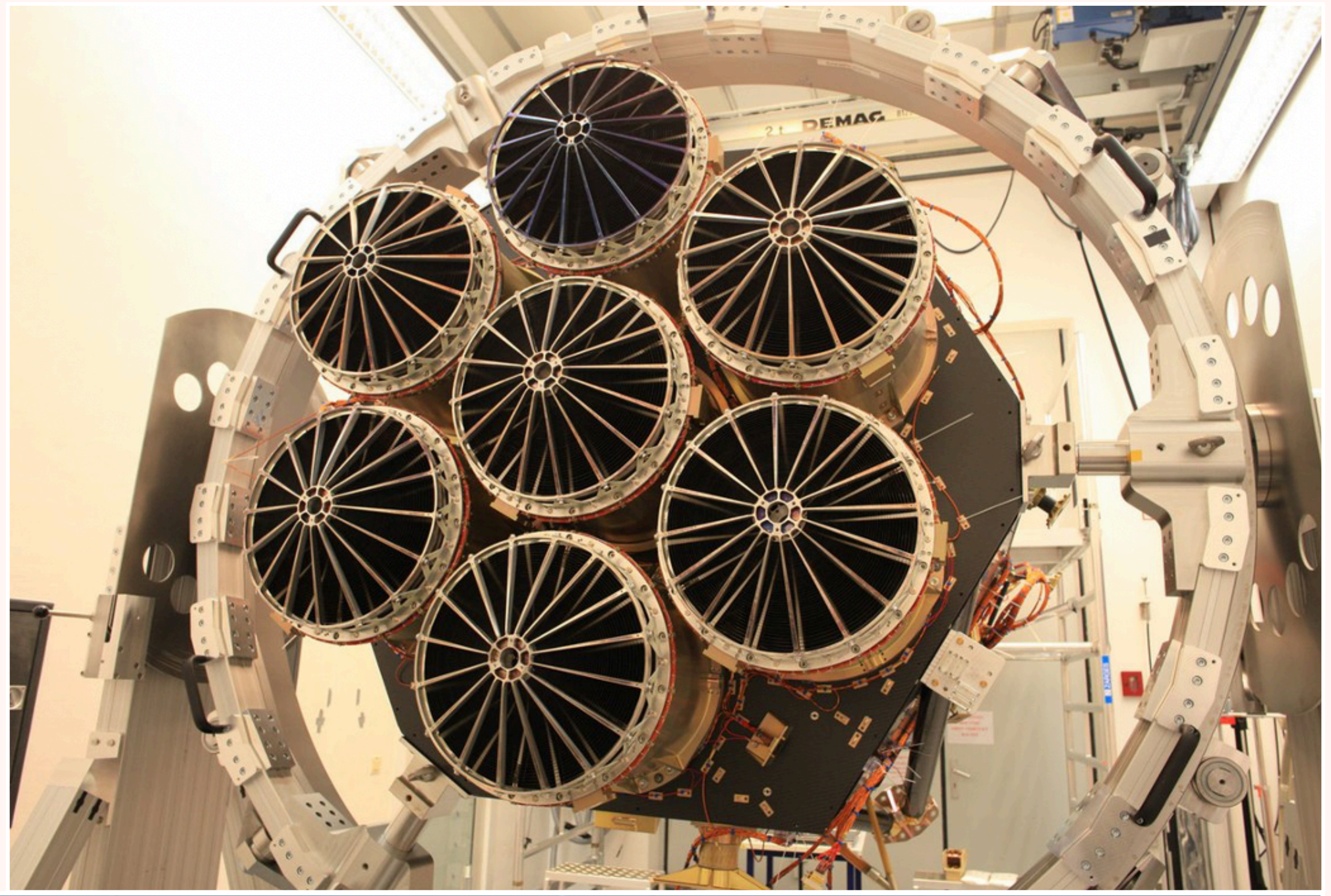

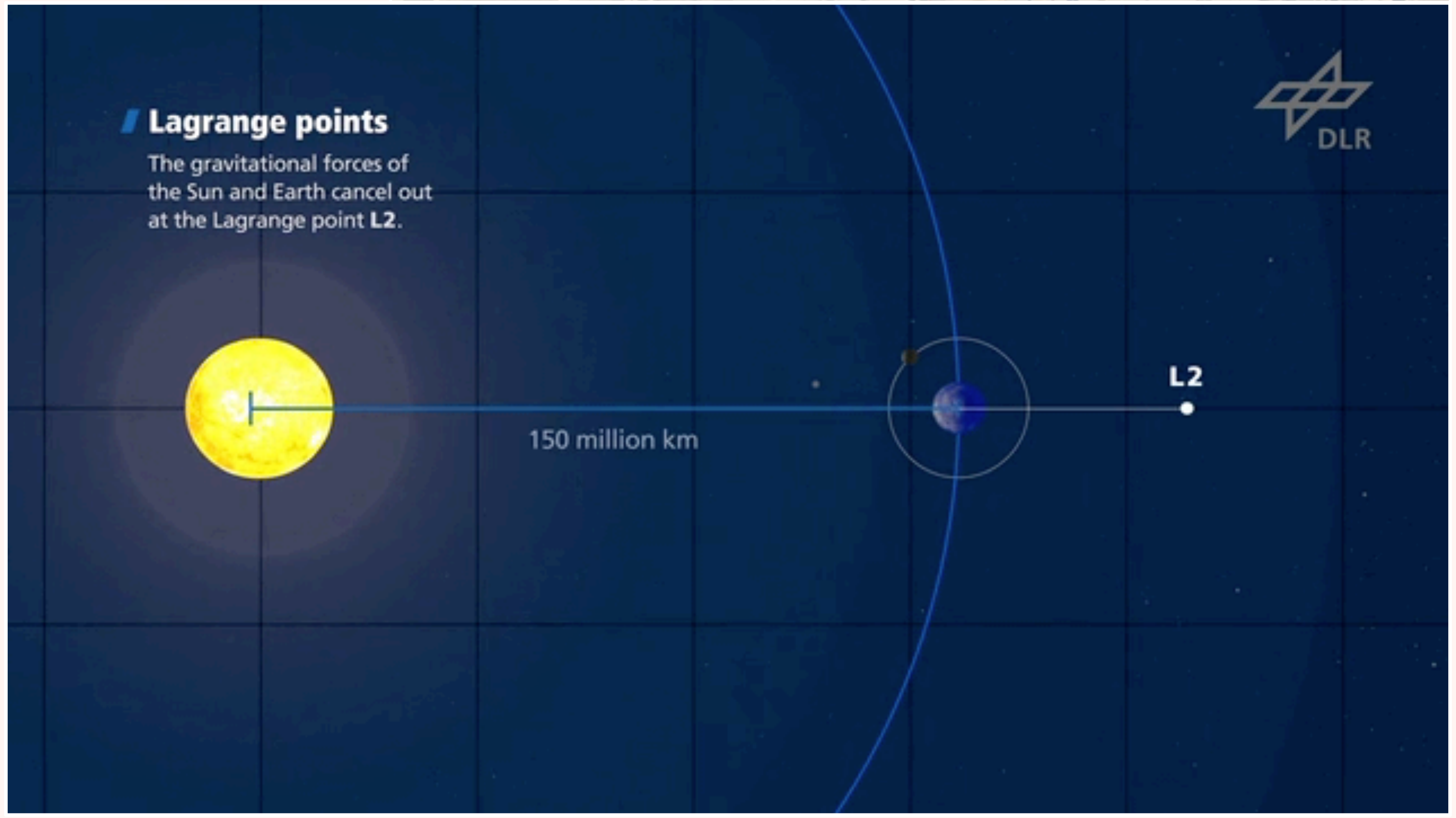

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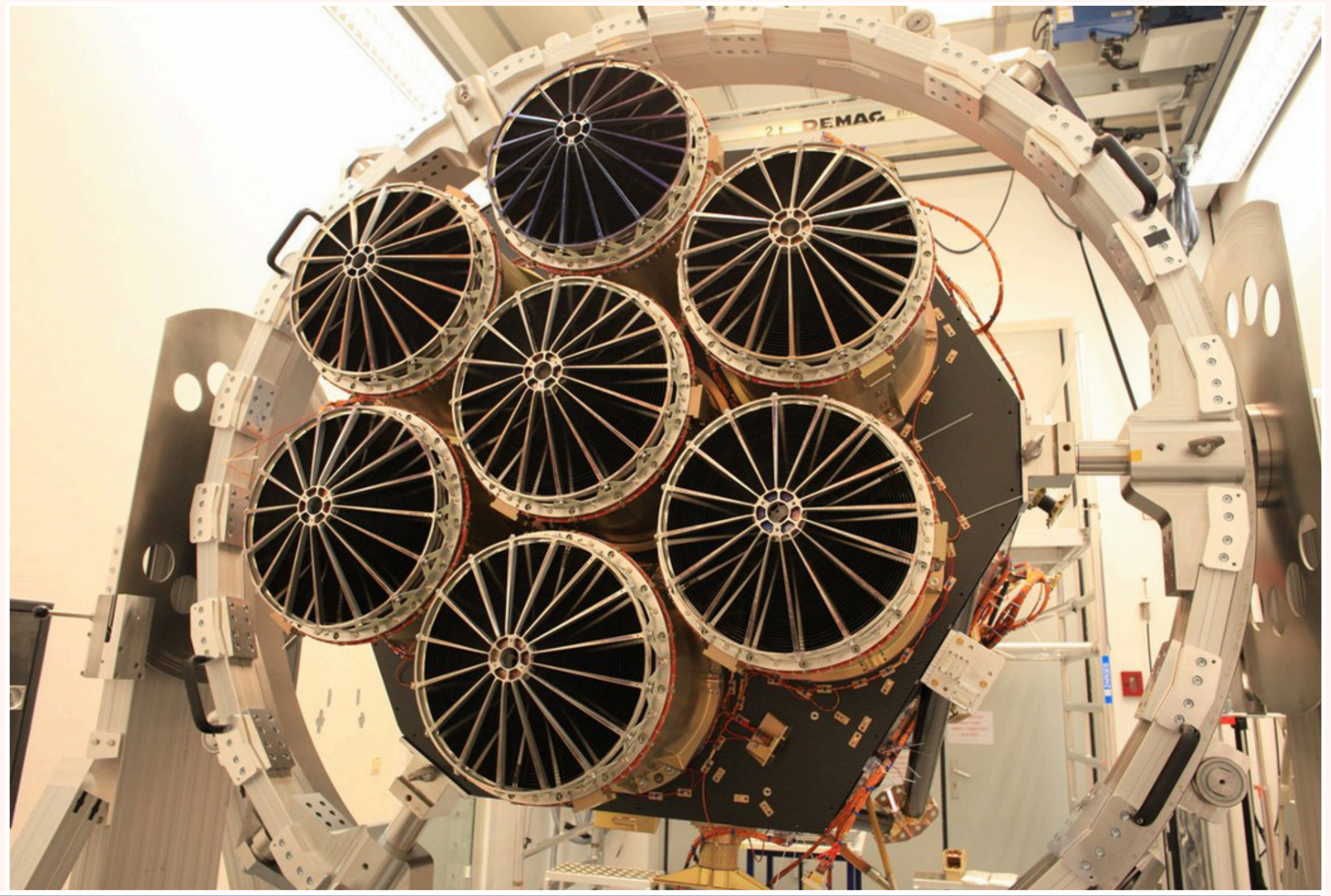

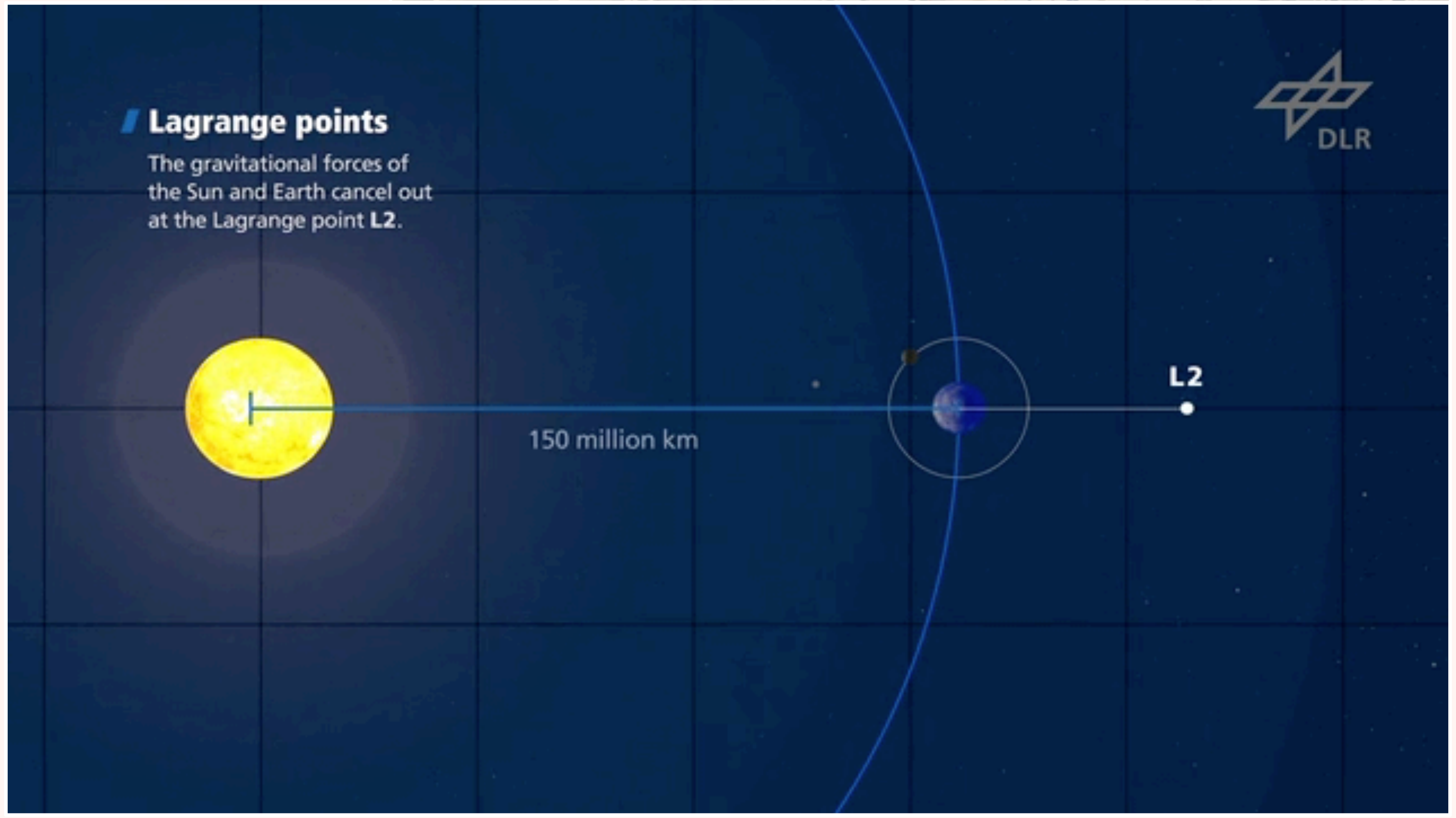

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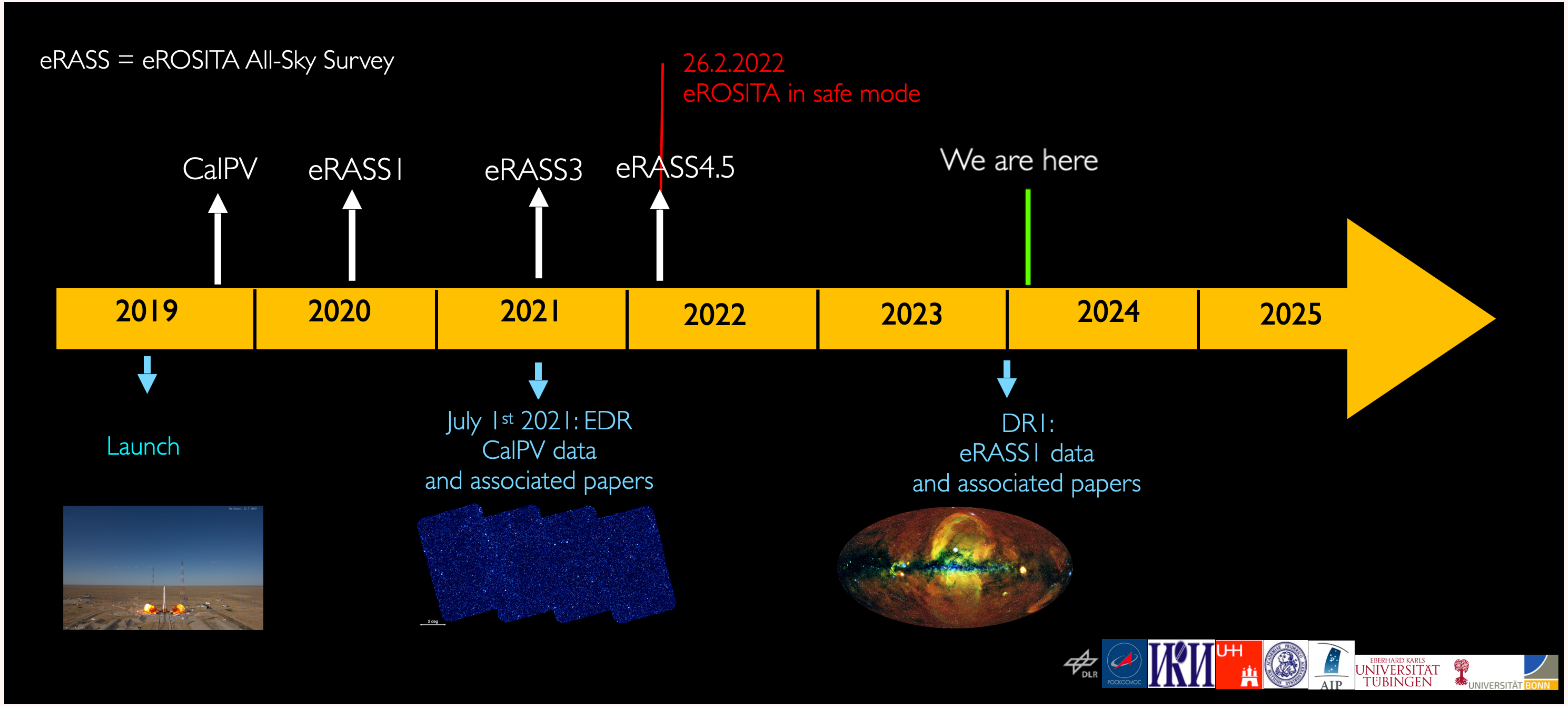
eROSITA SO FAR



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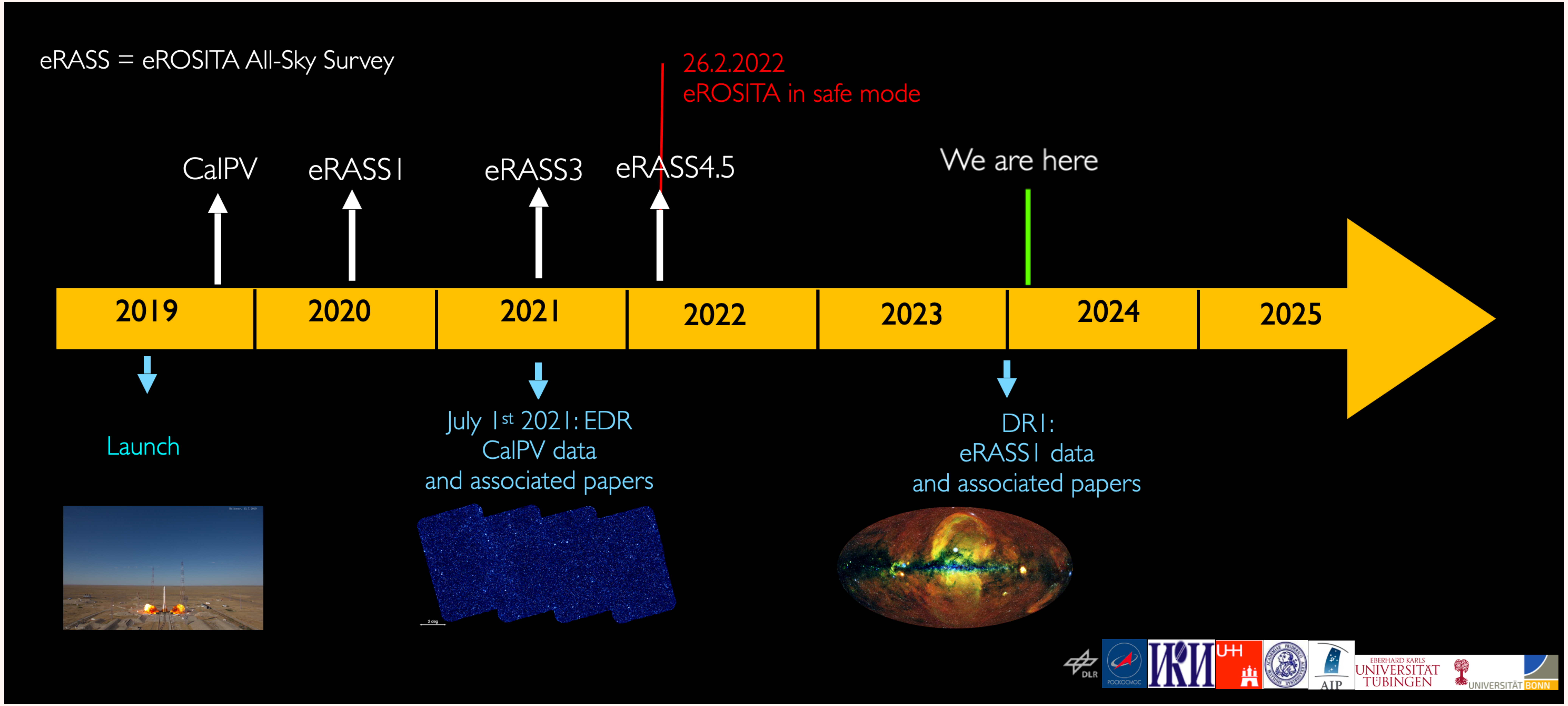


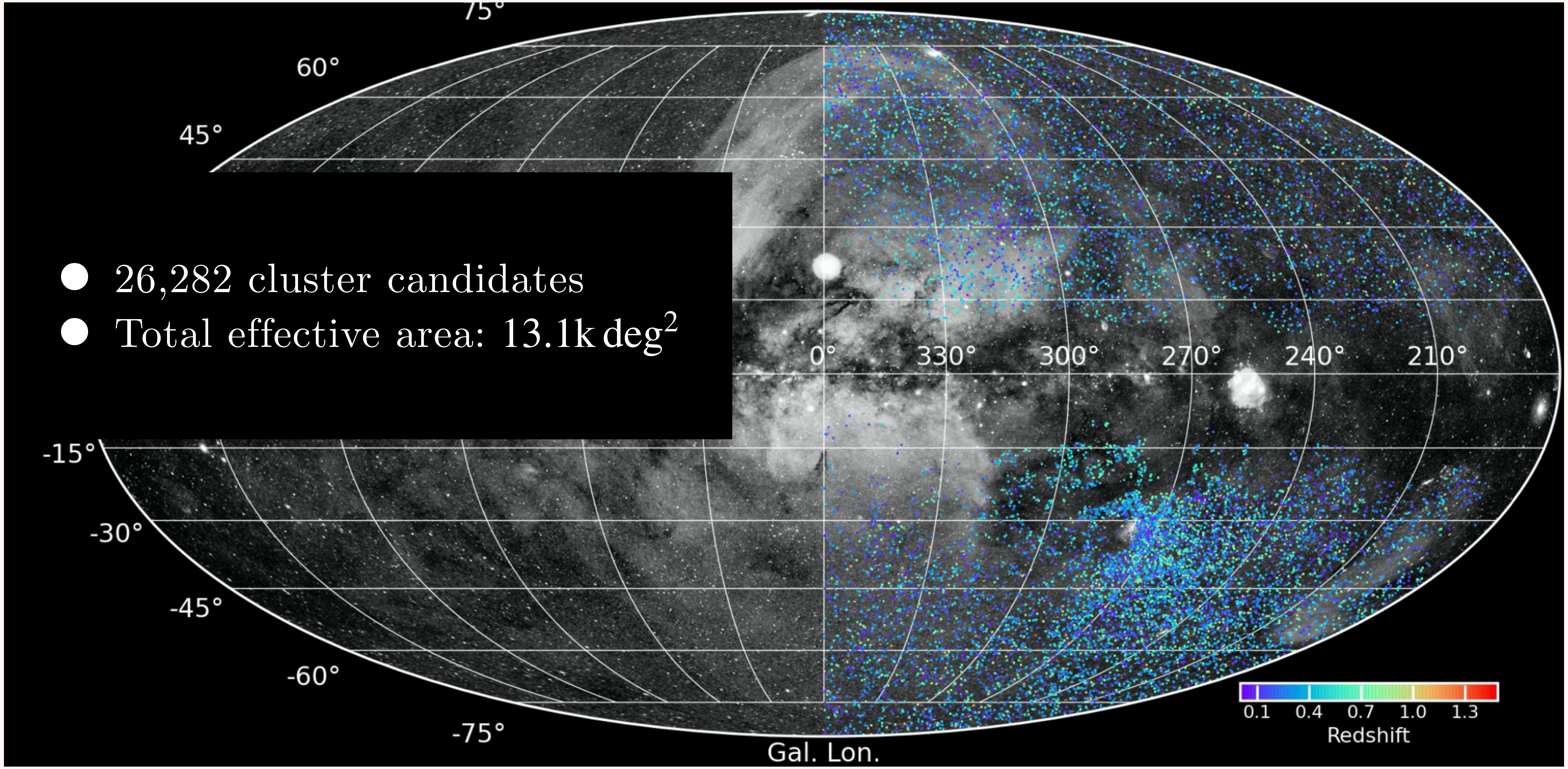
Cosmological results from eRASS1 only

Credit : E. Bulbul

THE eRASS1 CLUSTER CATALOG

Bulbul et al., 2024

- 26,282 cluster candidates
- Total effective area: $13.1\text{k}\,\text{deg}^2$



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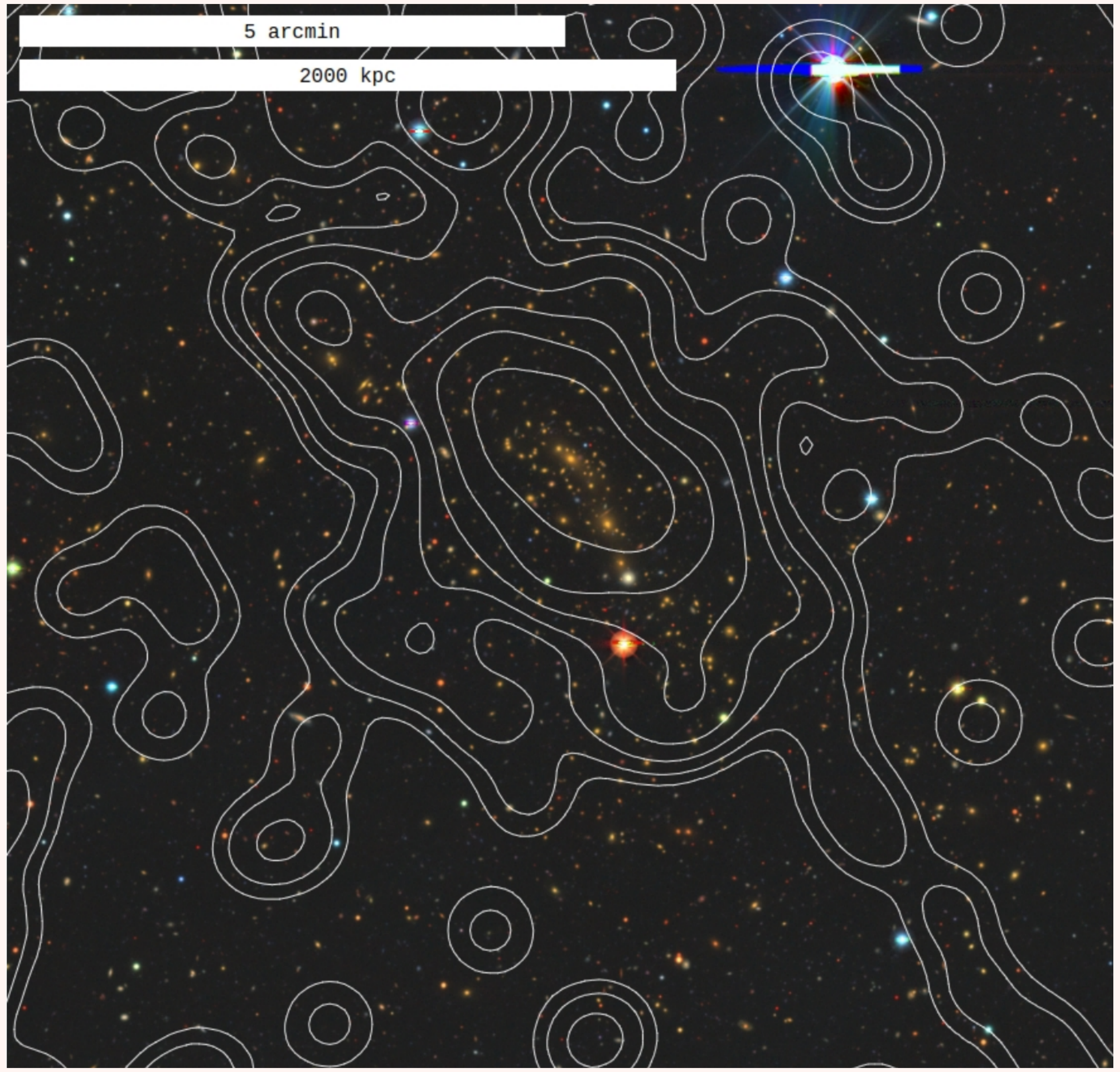
OPTICAL FOLLOW-UP WITH DESI LEGACY DR9 & 10

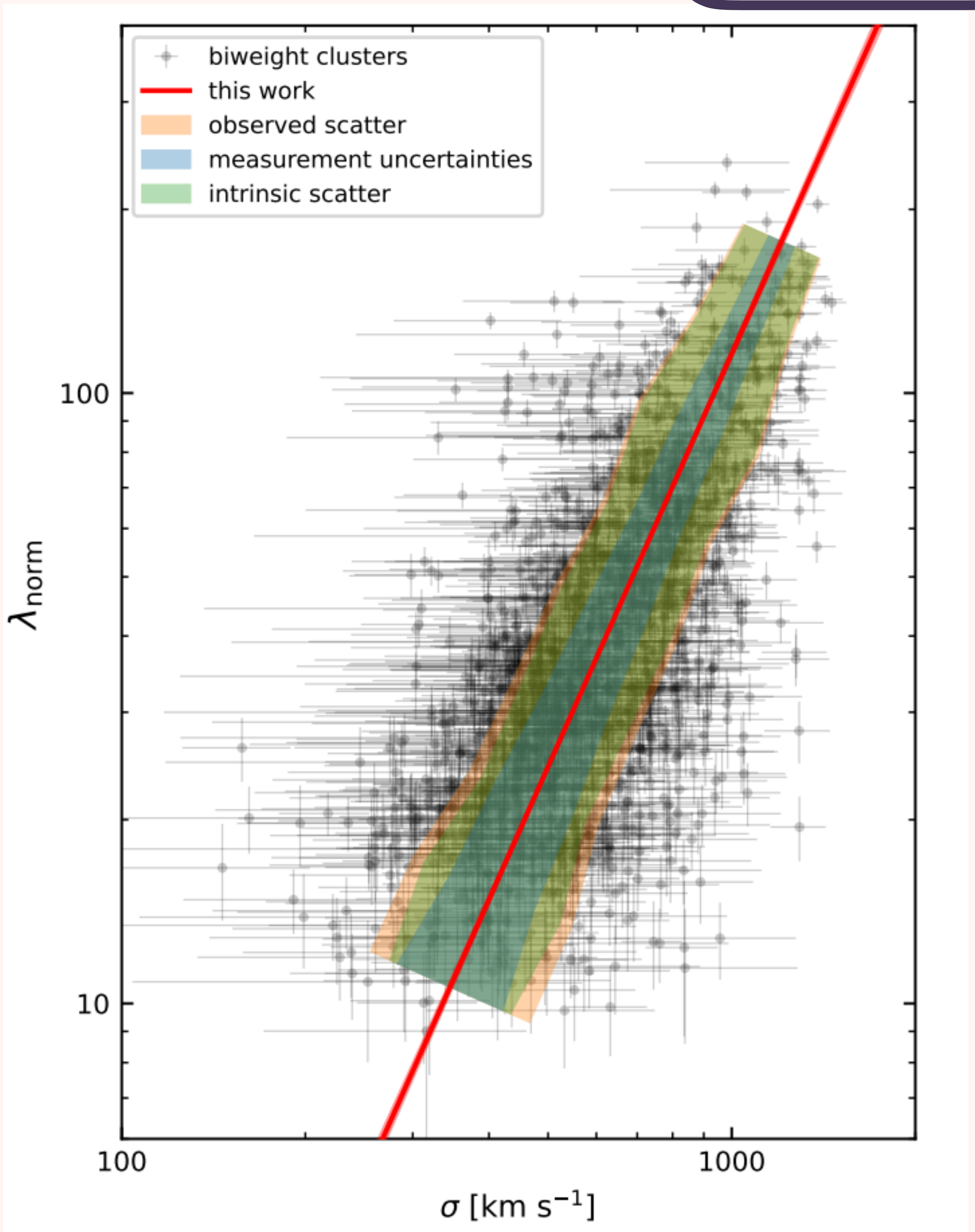


LS *grz* image of a cluster overlaid with eRASS1 X-ray contours

12,247 clusters with redshift measurement
86% purity

- Clean the catalog
- Get the photometric redshifts
- Get an additional mass proxy

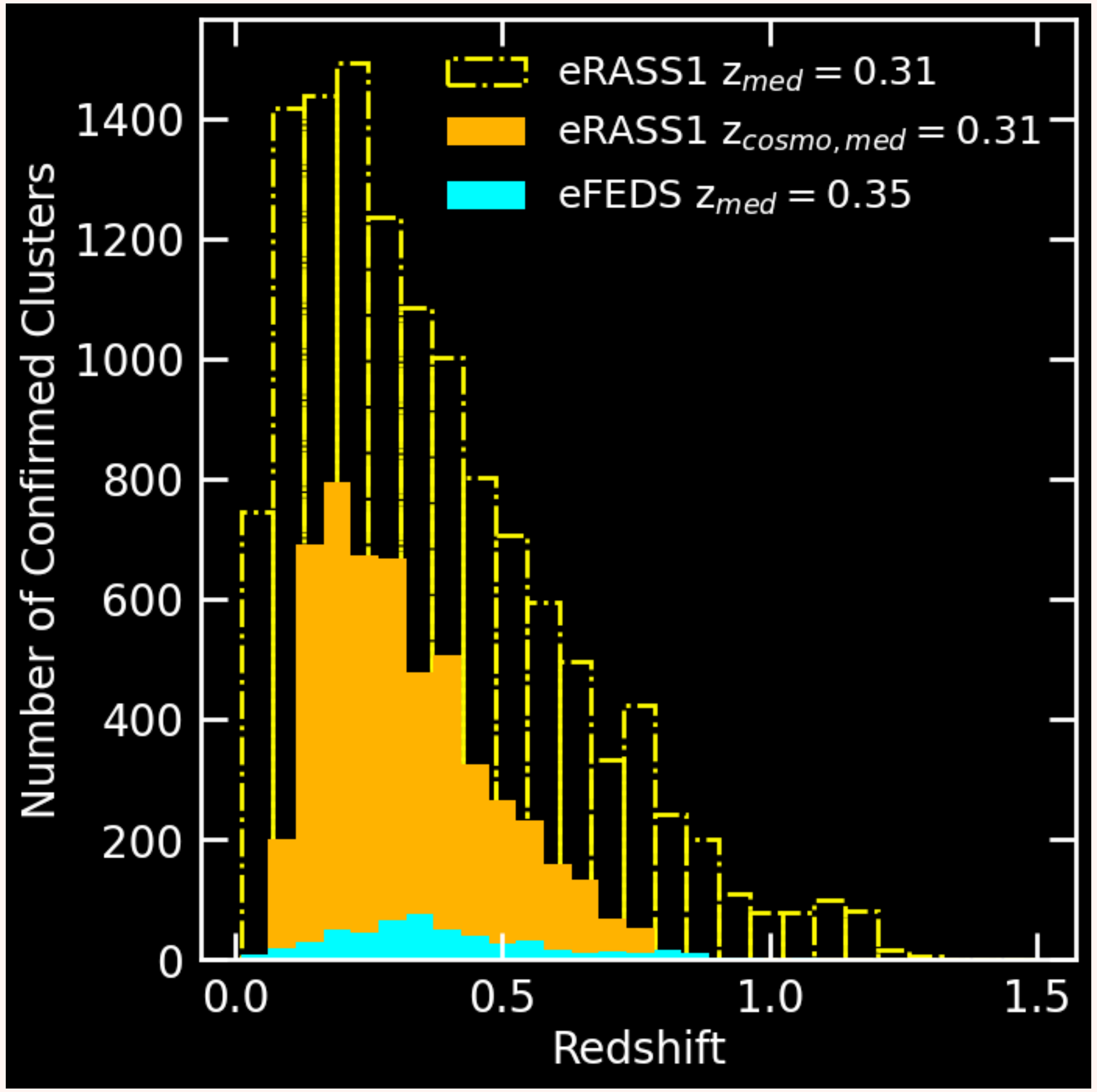
Kluge et al., 2024

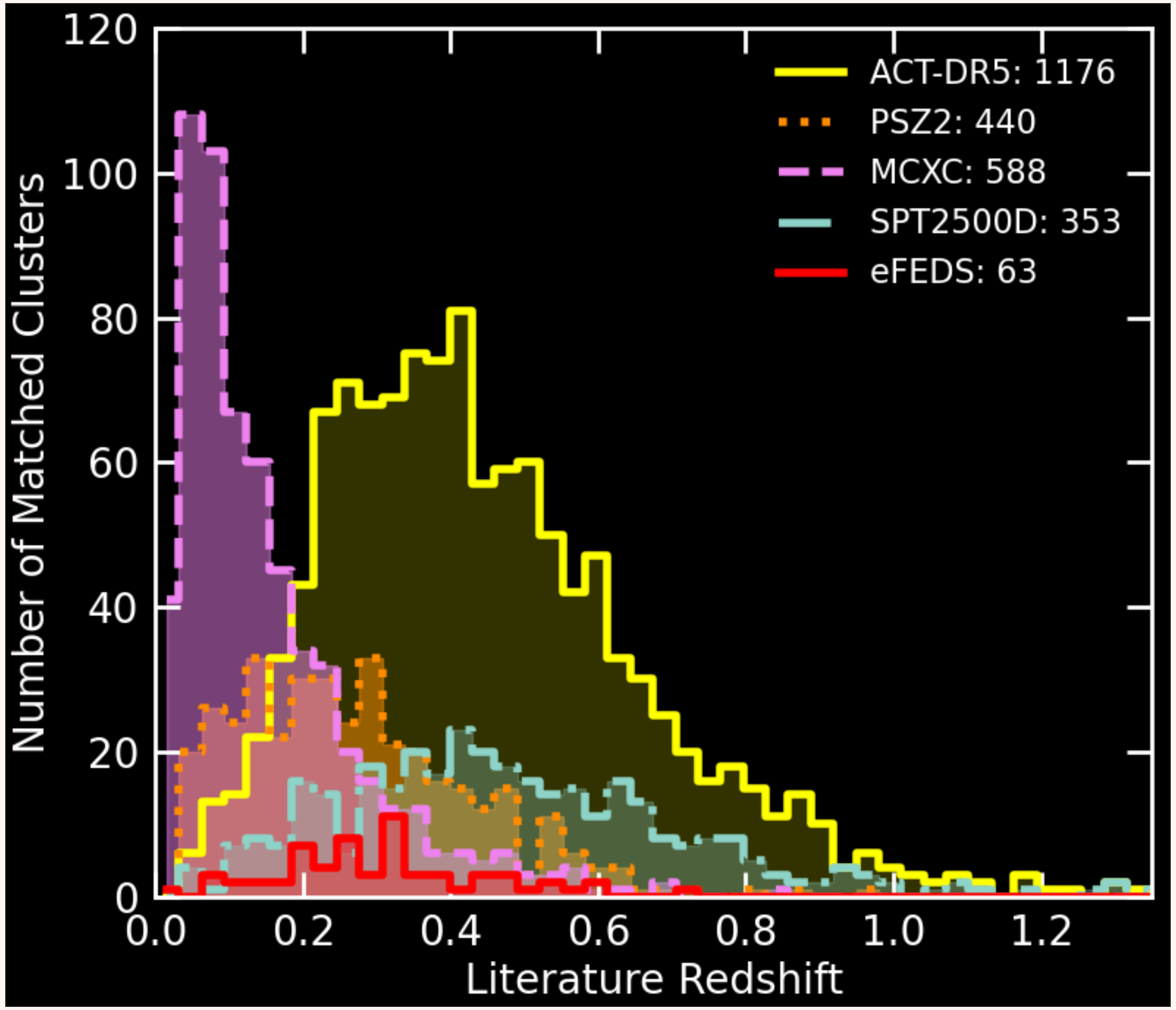


Richness vs velocity dispersion from a subsample of the catalog

THE eRASS1 CLUSTER CATALOG

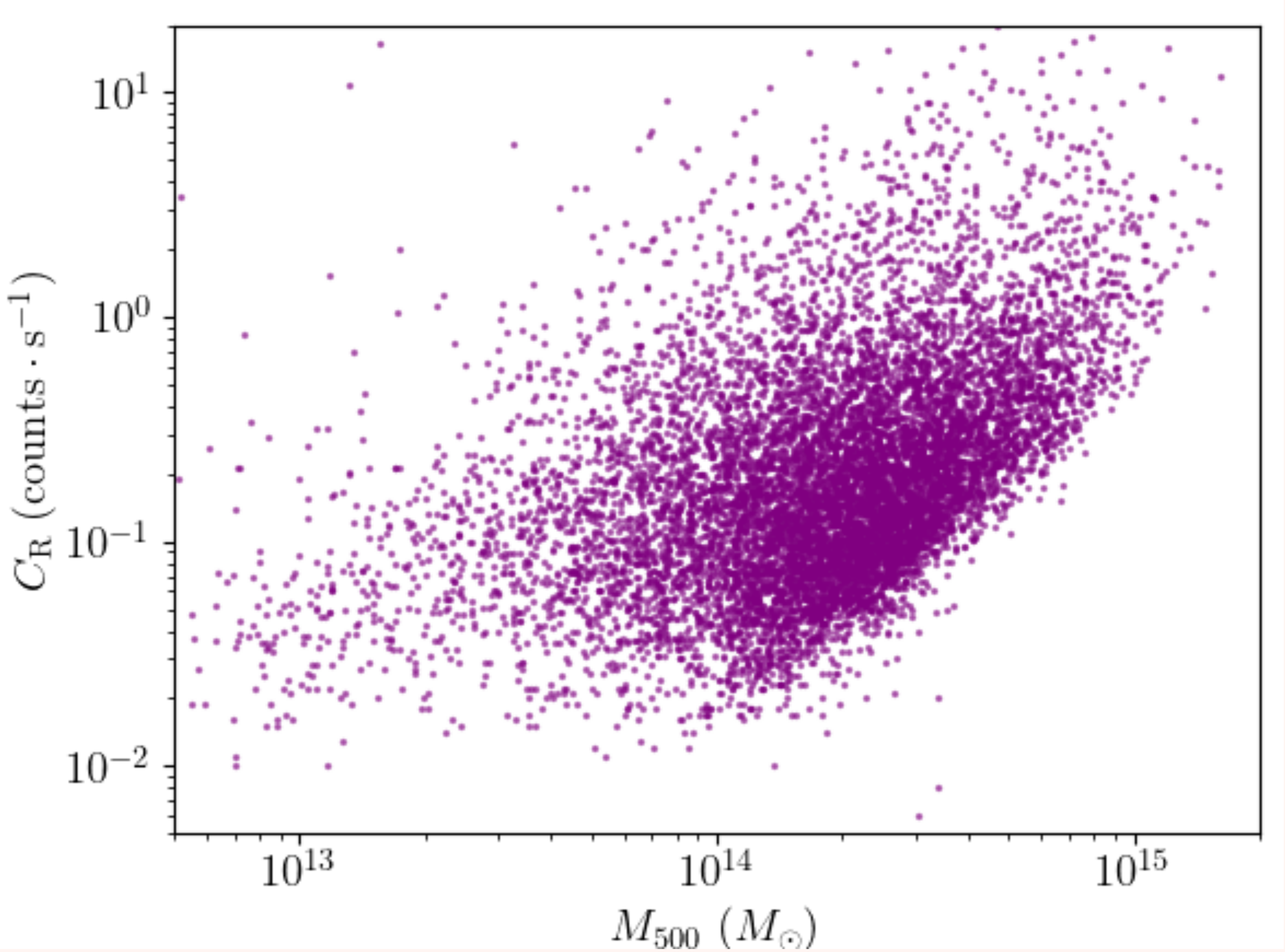
Bulbul et al., 2024

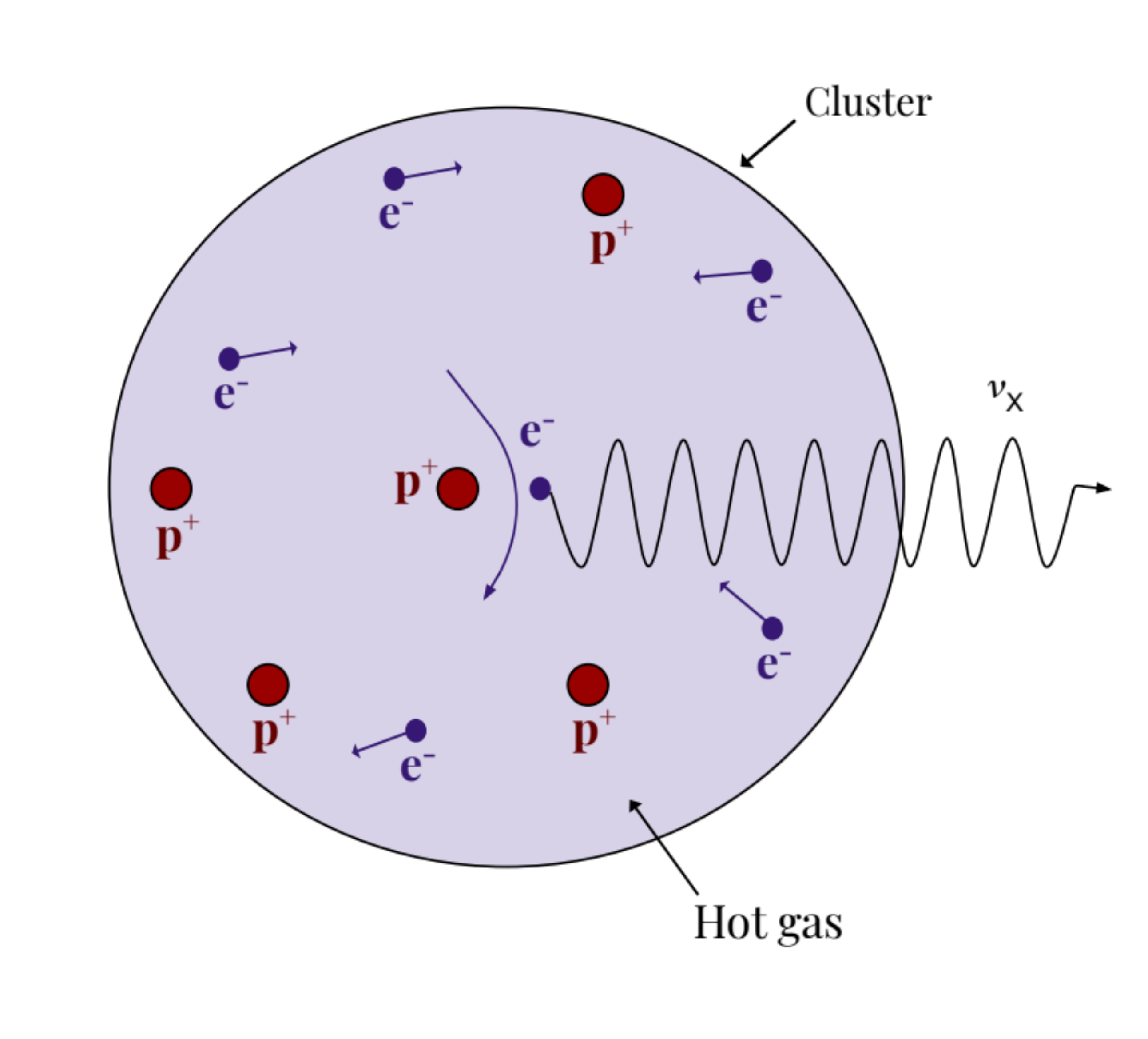




X-RAY OBSERVABLE

C_R fitted using MBproj2D (Sanders et al., 2018)

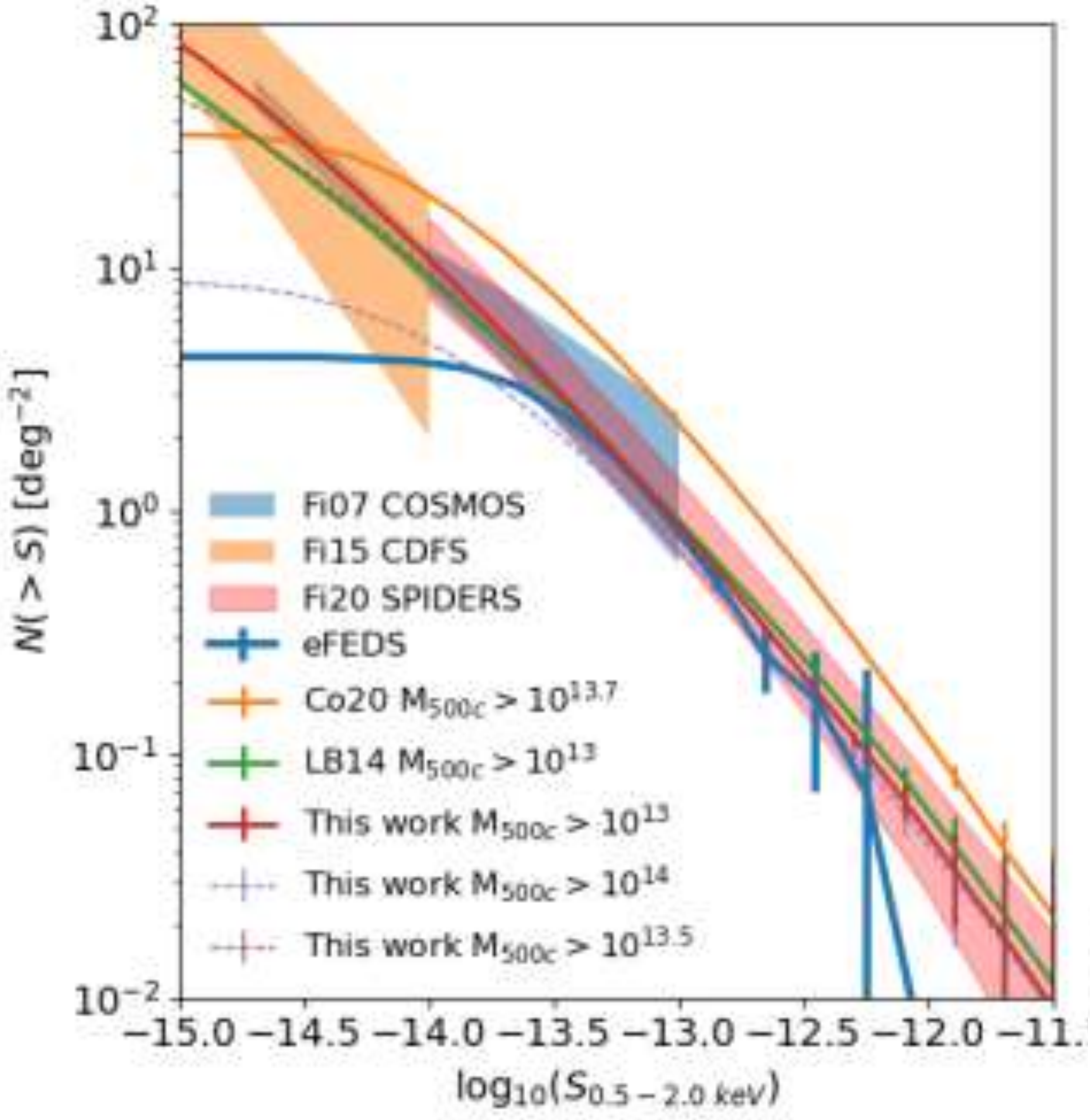


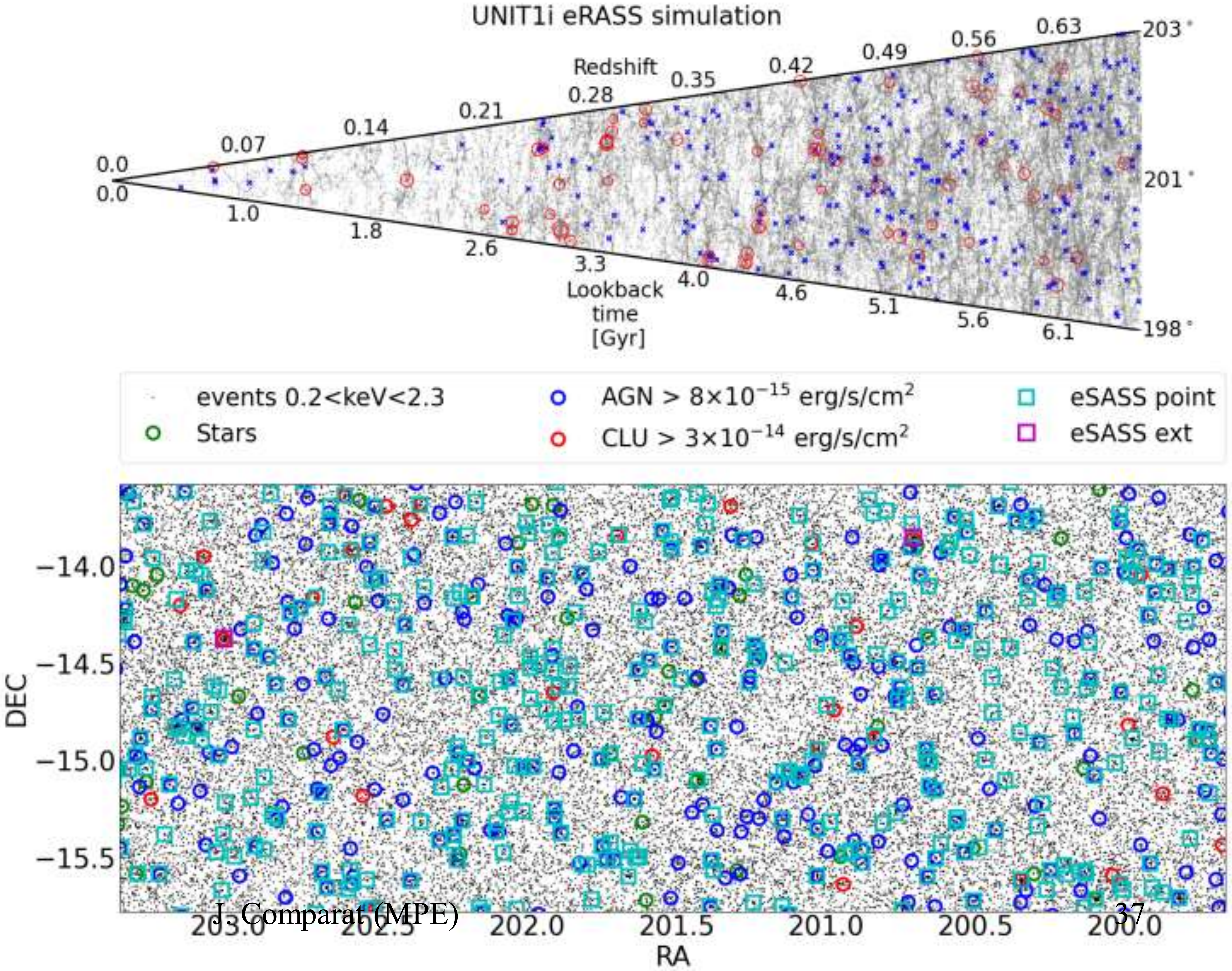


Bremsstrahlung radiation from clusters

Count rate to mass relation from the cluster catalog presented in Bulbul et al., 2024

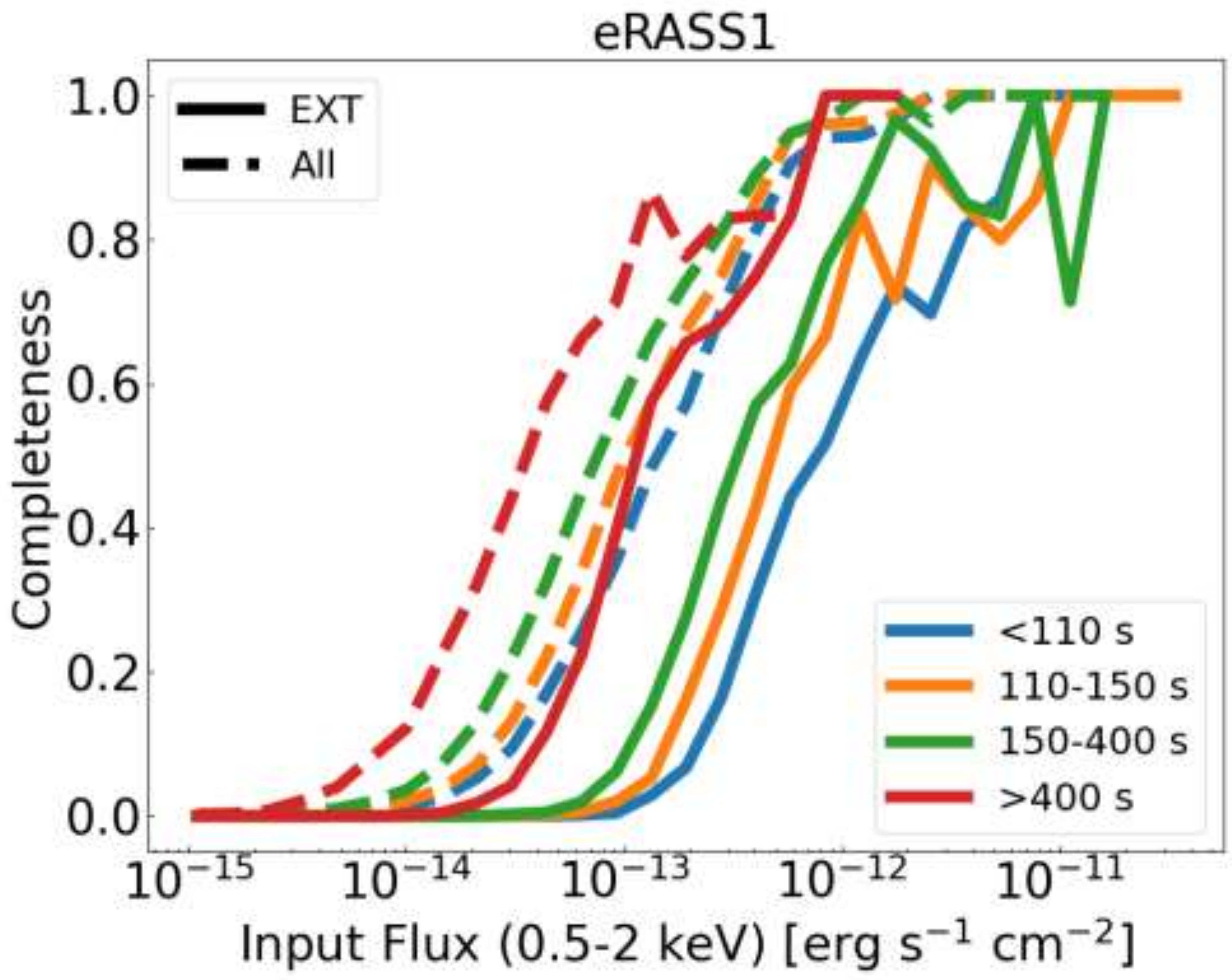
eRASS1 digital twin

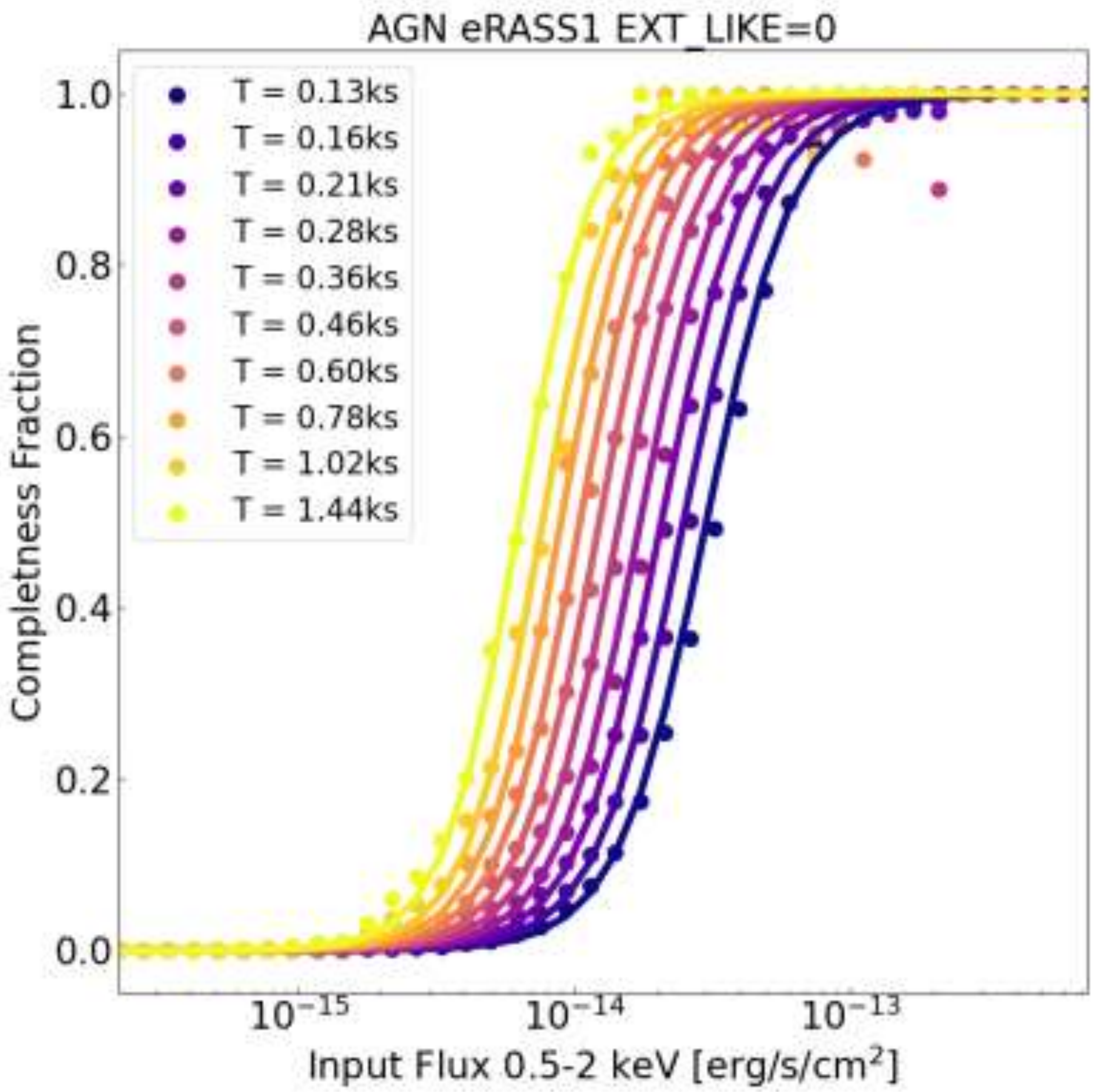




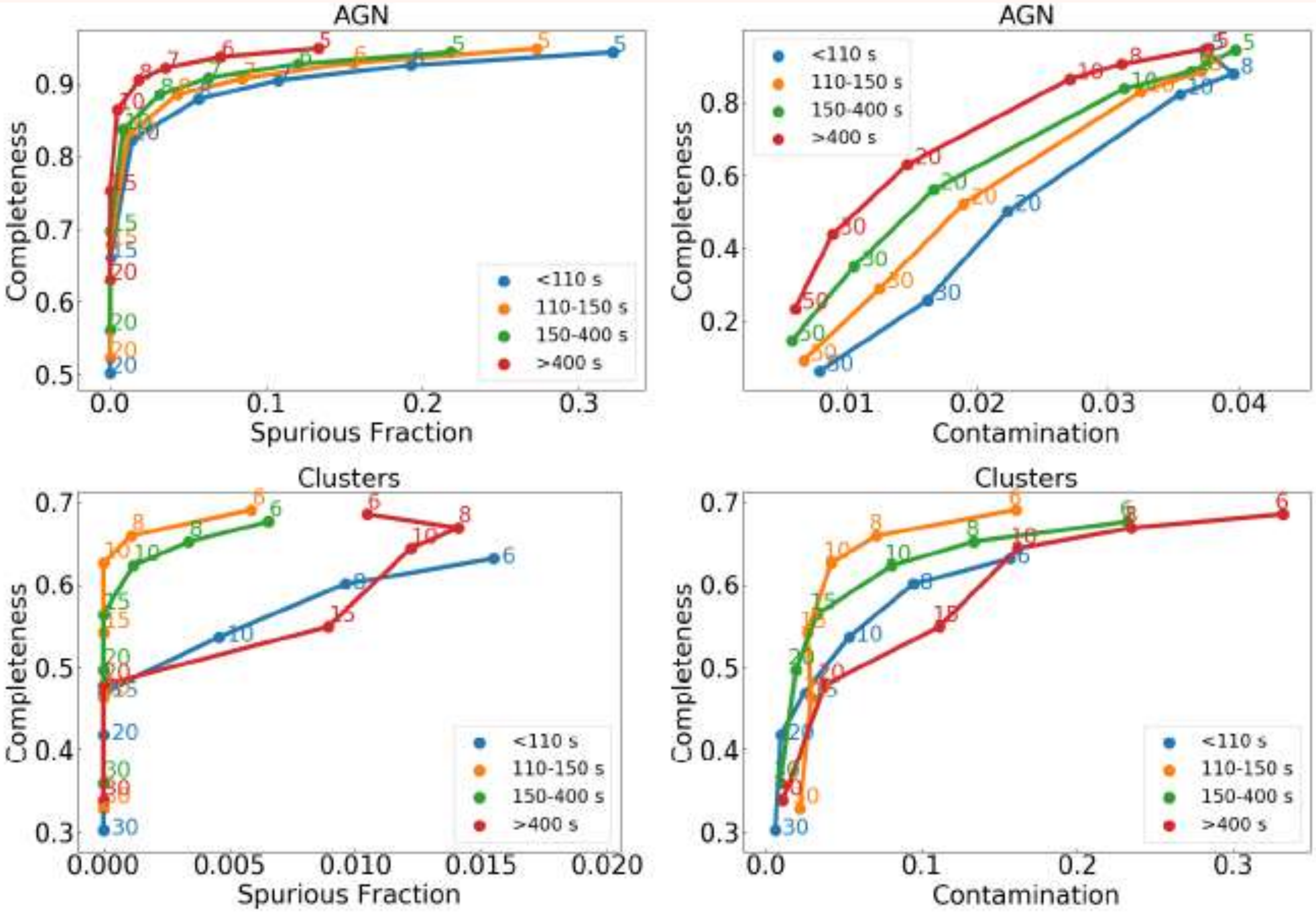
Comparat, Merloni et al., 2019
Comparat, Eckert et al. 2020
Seppi, Comparat et al. 2022

eRASS1 digital twin





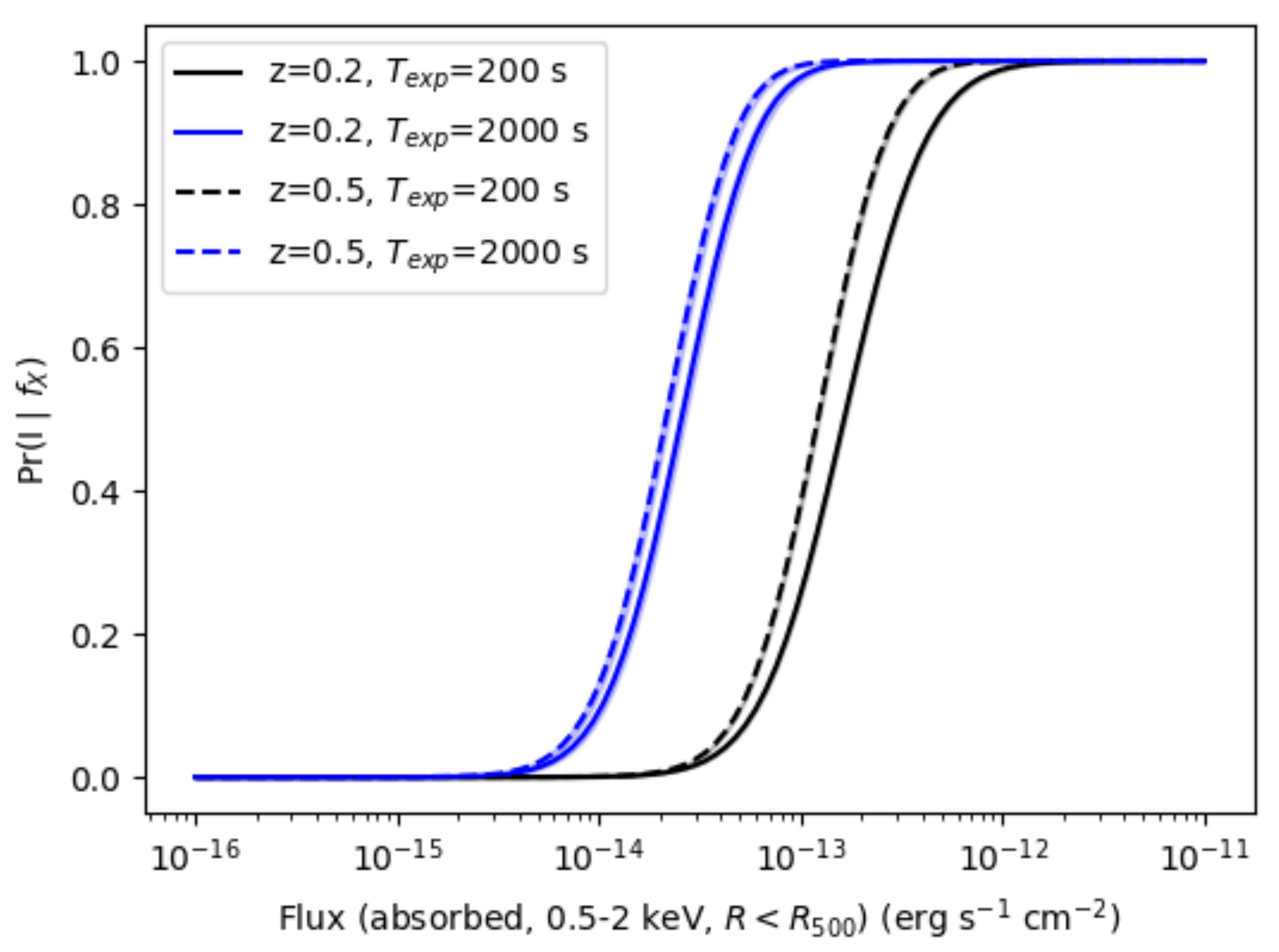
Seppi, Comparat et al. 2022. arXiv:2207.09242



Seppi, Comparat et al. 2022. arXiv:2207.09242

THE eRASS1 CLUSTER SELECTION FUNCTION

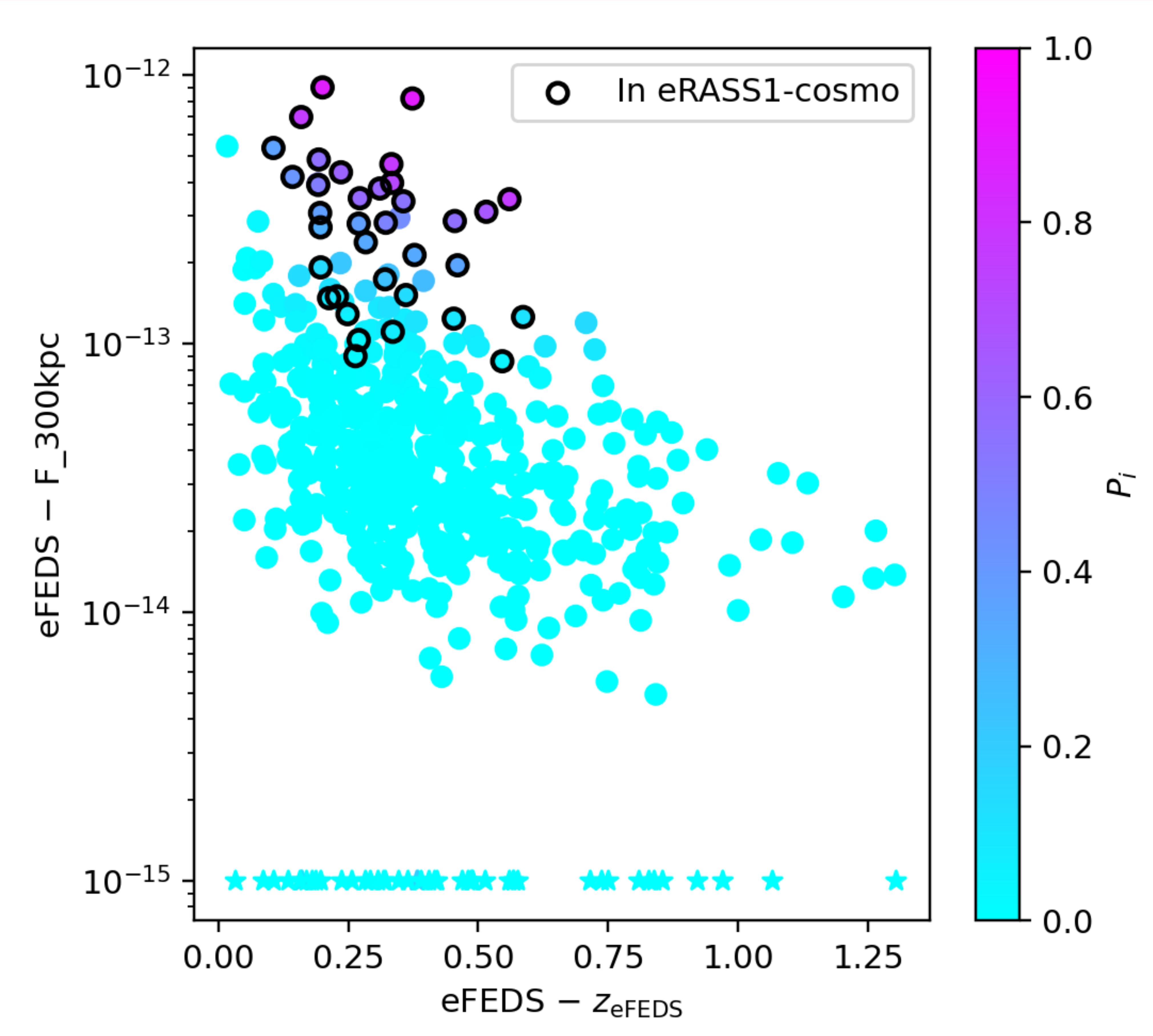
Clerc et al., 2024



- **Depends on the count rates, exposure times, hydrogen column density and background**
- **Quantity fitted on eRASS1 simulations**

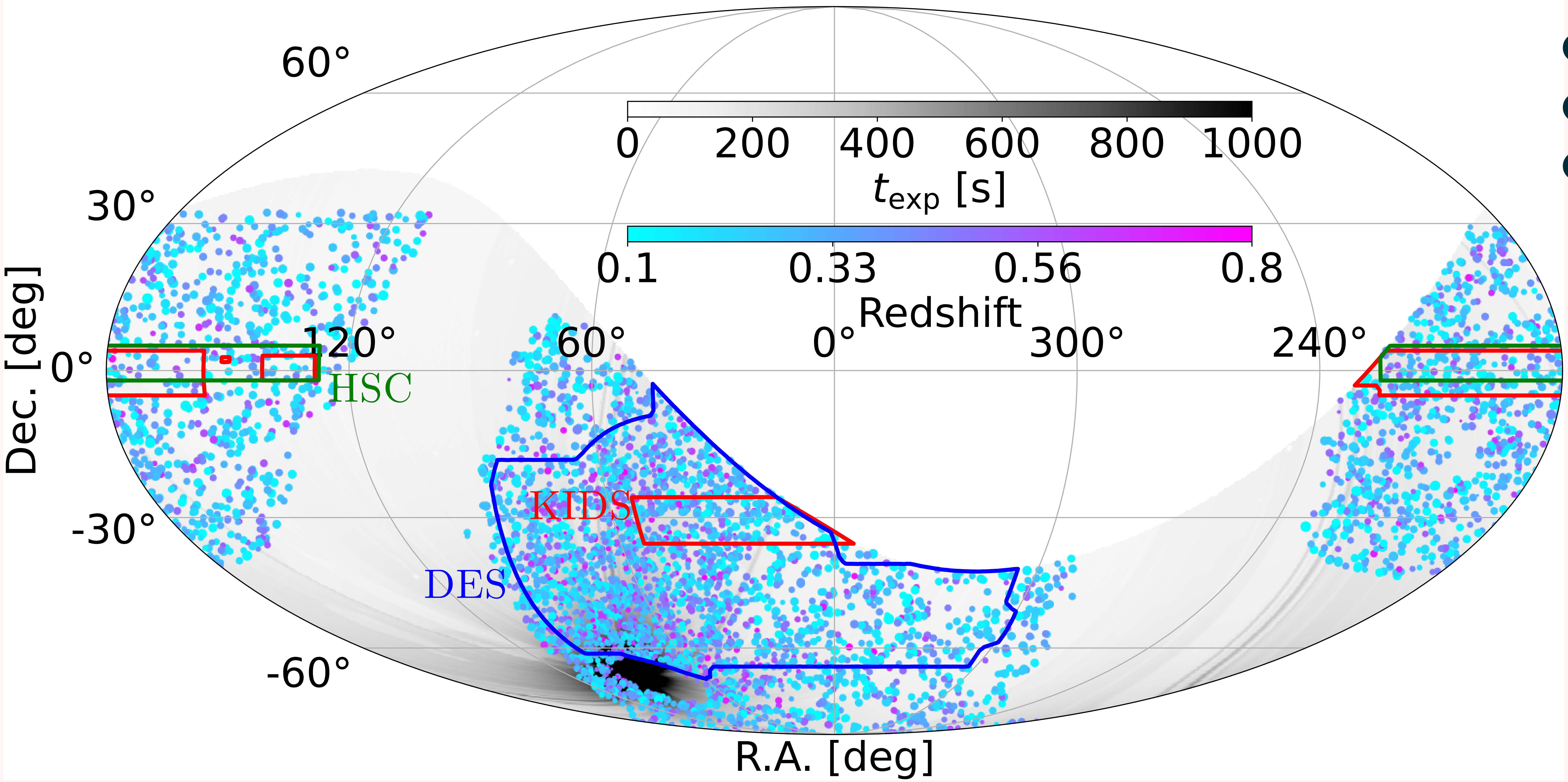
THE eRASS1 CLUSTER SELECTION FUNCTION

Clerc et al., 2024



The model is tested with eFEDS as a reference catalog

THE eRASS1 CLUSTER CATALOG



- 5,263 cluster candidates
- Total effective area: 12.8k $\deg^2$
- 95% purity

Ghirardini, Bulbul, EA et al., 2024

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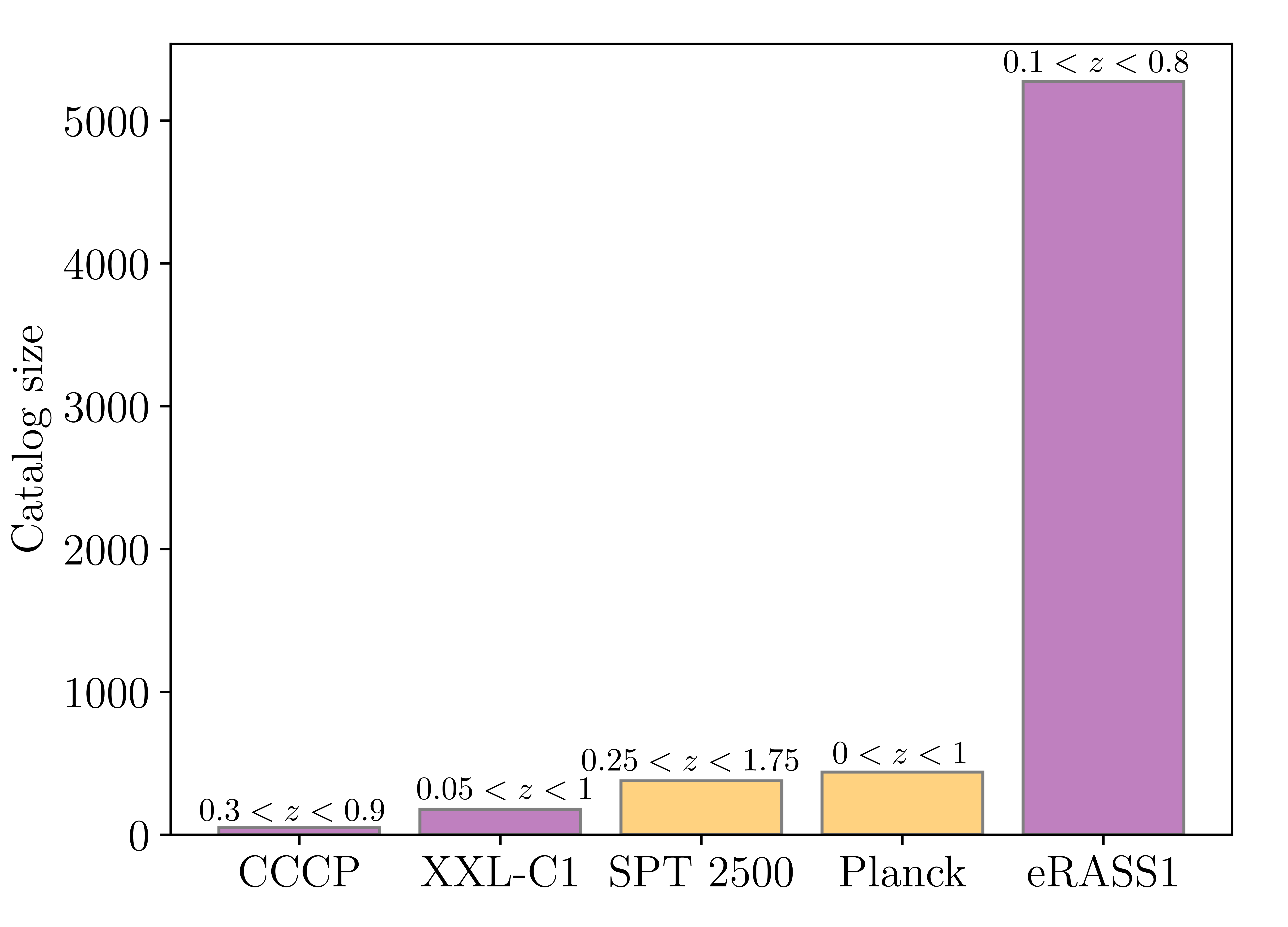
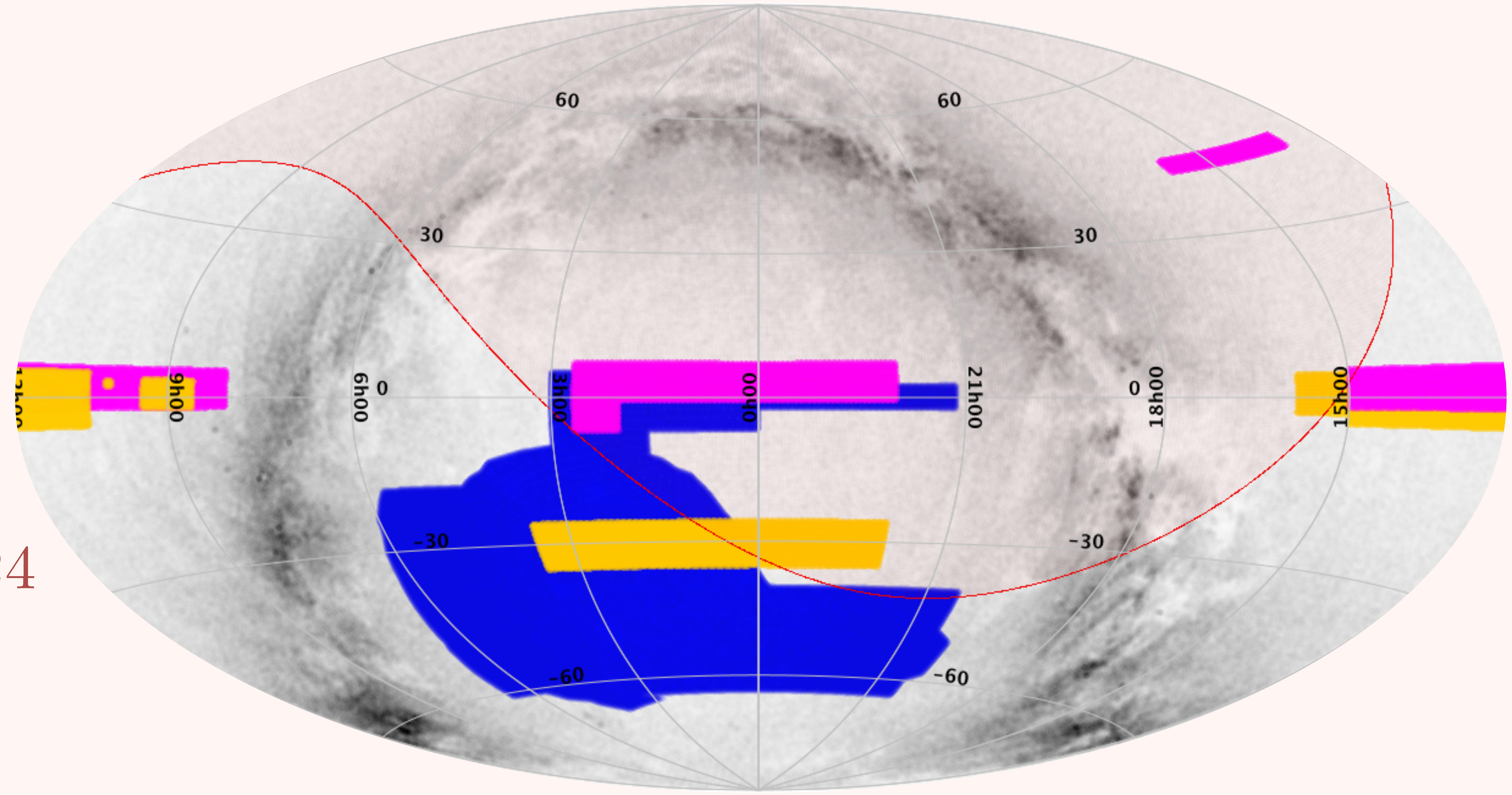


- 5,263 cluster candidates
- Total effective area: 12.8k $\deg^2$
- 95% purity

Largest ICM selected cosmology sample to date !

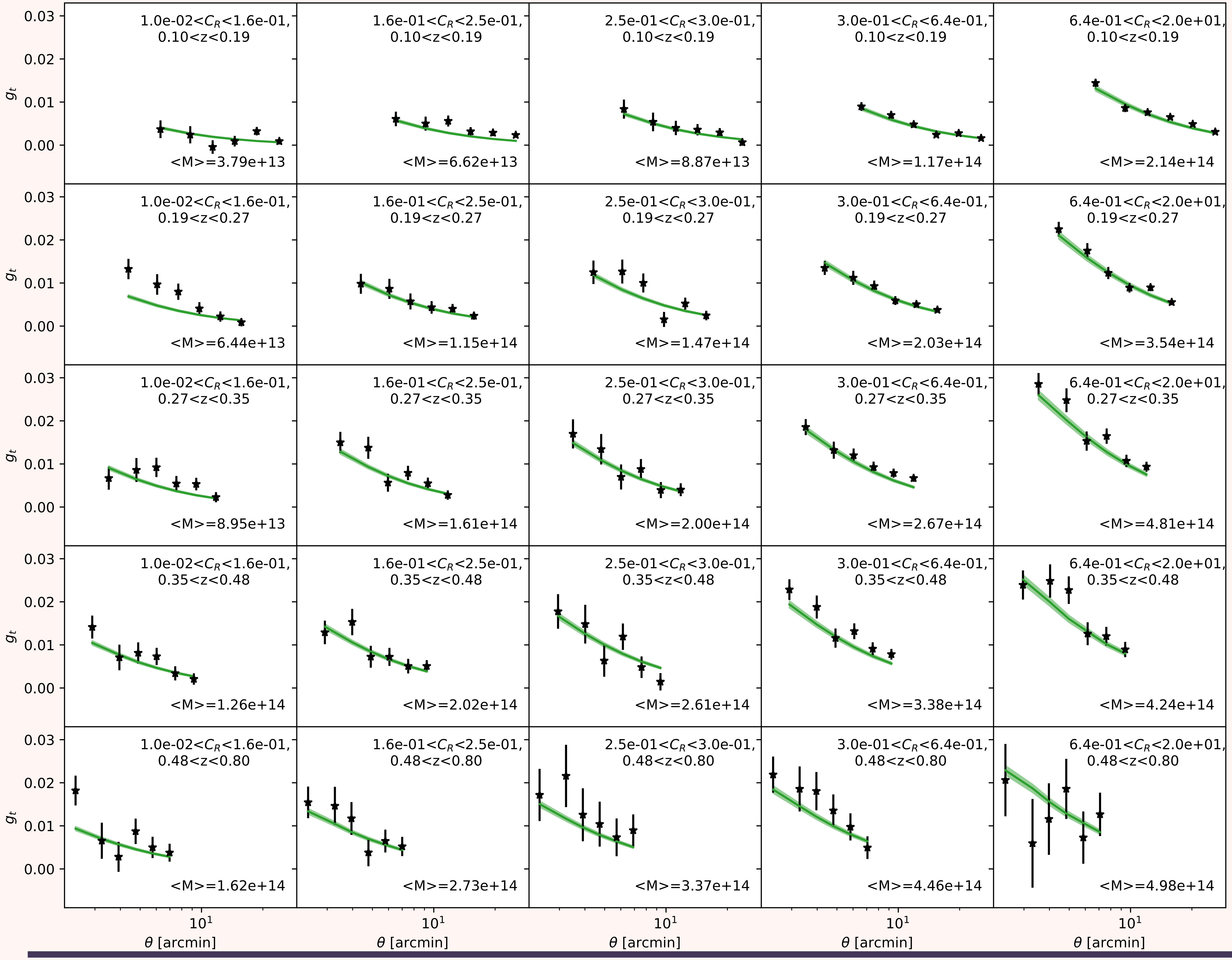
WEAK LENSING MASS CALIBRATION

Calibrate the $C_R - M$ and $\lambda - M$ relations



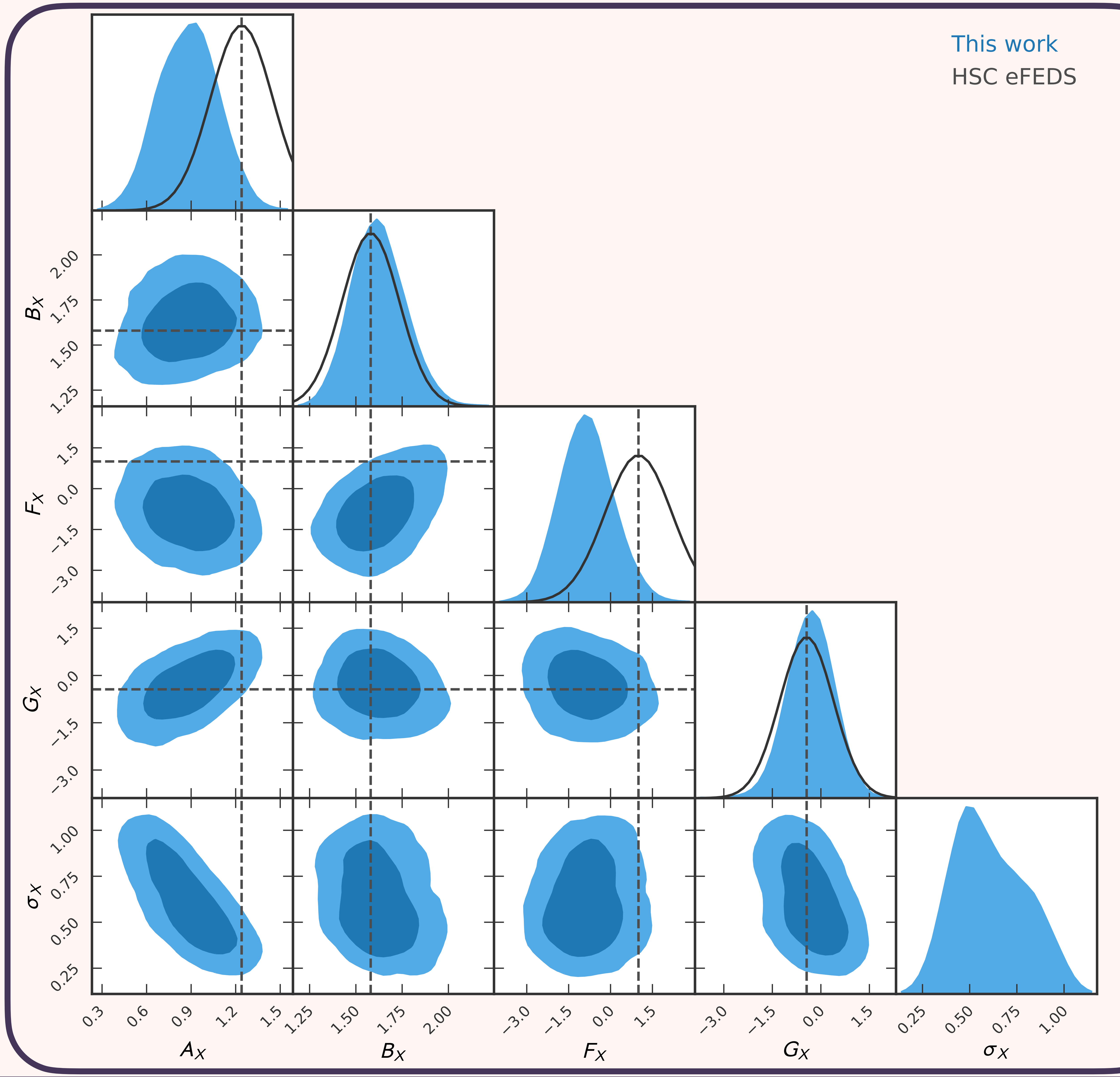
- **Dark energy Survey (DES)** Grandis et al., 2024
  - **2201 tangential shears**
- **Kilo Degree Survey (KIDS)** Kleinebreil et al., 2024
  - **96 tangential shears**
- **Hyper Supreme Cam Survey (HSC)** Chiu et al., 2024
  - **236 tangential shears**

Cosmological results from the first eROSITA All Sky Survey (eRASS1)



Grandis et al., 2024

Each individual shear profile is directly integrated in the cluster abundance likelihood



Grandis et al., 2024

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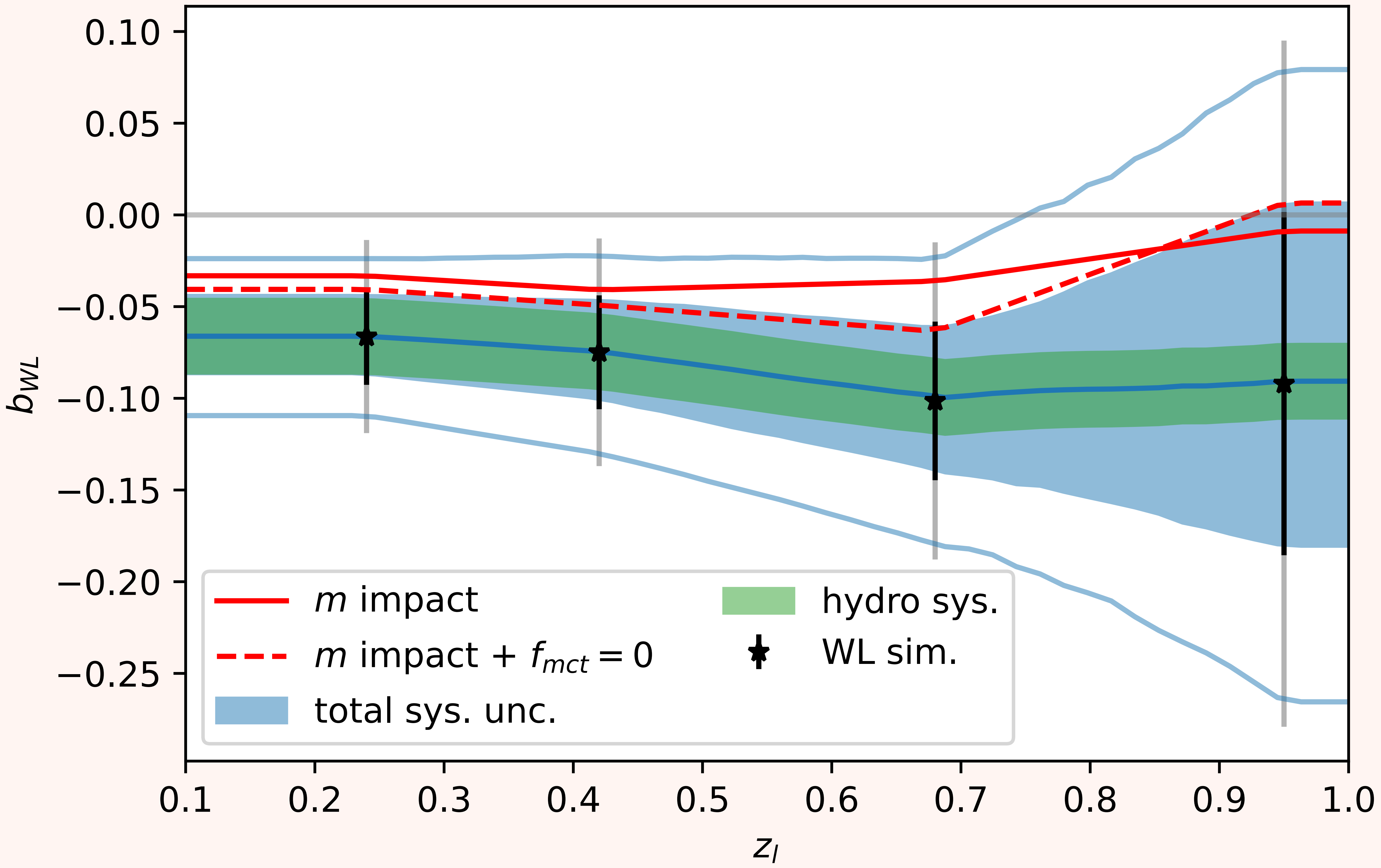

Grandis et al., 2024

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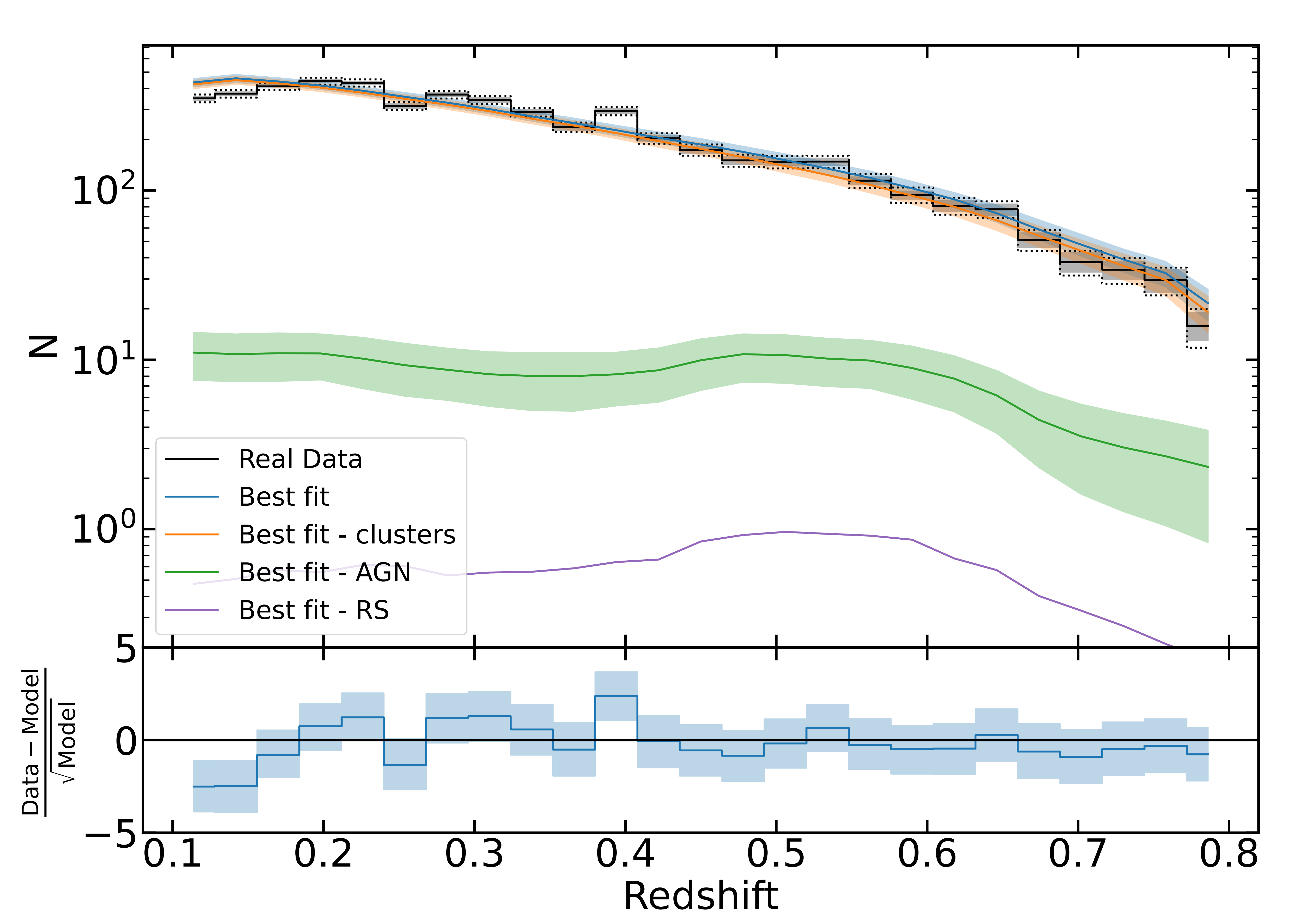
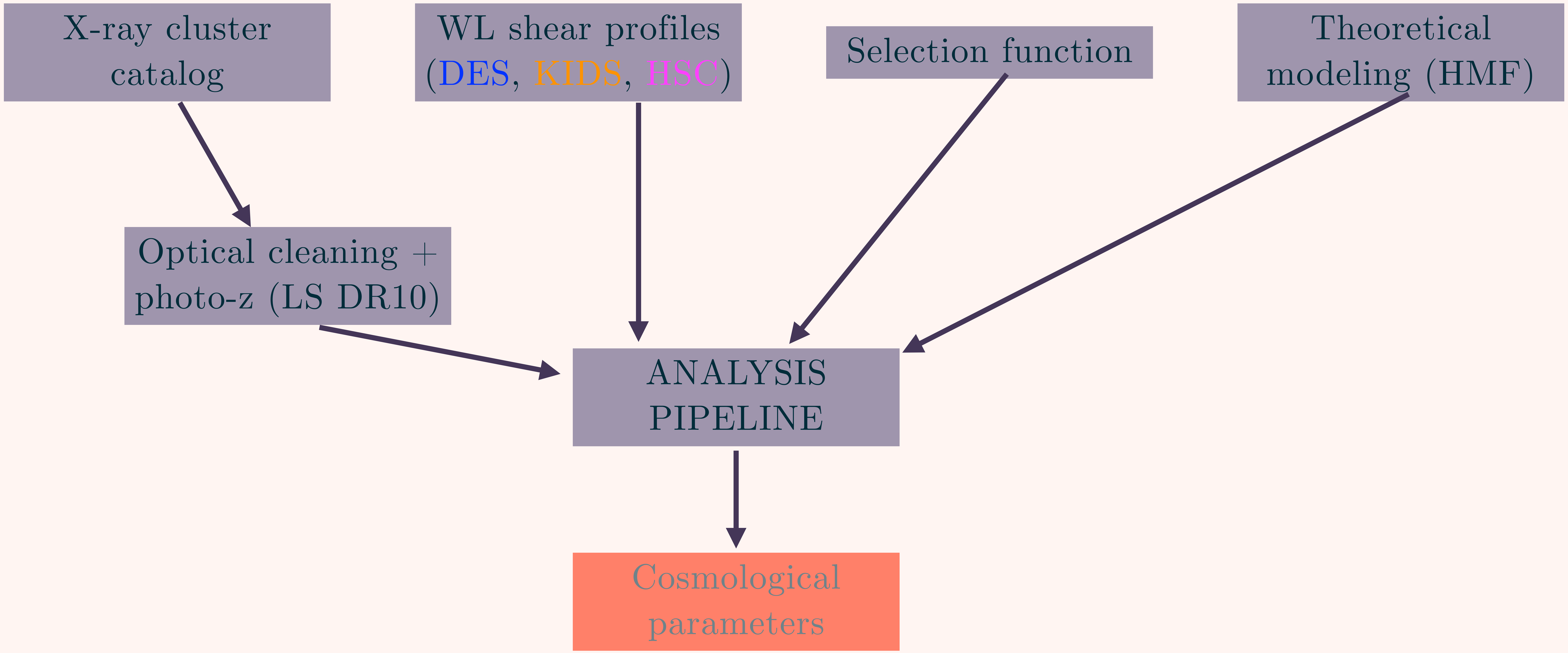
MIXTURE MODEL: REMOVING THE CONTAMINATION FRACTION

Ghirardini, Bulbul, EA et al., 2024



We account for AGN contamination and noise fluctuation. The fraction of these objects is fitted in the global likelihood

OVERVIEW : eRASS1 CLUSTER ABUNDANCE PIPELINE



Parameter	Units	Description	Prior
• Cosmology			
Ω_m	-	Mean matter density at present time	$\mathcal{U}(0.05, 0.95)$
$\log_{10} A_s$	-	Amplitude of the primordial power spectrum	$\mathcal{U}(-10, -8)$
H_0	$\frac{\mathrm{km}/\mathrm{s}}{\mathrm{Mpc}}$	Hubble expansion rate at present time	$\mathcal{N}(67.77, 0.6)$
Ω_b	-	Mean baryon density at present time	$\mathcal{U}(0.046, 0.052)$
n_s	-	Spectra index of the primordial power spectrum	$\mathcal{U}(0.92, 1.0)$
w_0	-	Dark energy equation of state. Fixed to -1 in ΛCDM	$\mathcal{U}(-2.5, -0.33)$
$\sum m_\nu$	eV	Summed neutrino masses. Fixed to 0 eV in ΛCDM	$\mathcal{U}(0, 1)$
• X-ray scaling relation			
A_X	-	Normalization of the $M - C_R$ scaling relation	$\mathcal{U}(0.01, 3)$
B_X	-	Mass slope of the $M - C_R$ scaling relation	$\mathcal{U}(0.1, 5)$
D_X	-	Luminosity distance evolution of the $M - C_R$ scaling relation	Fixed to -2
E_X	-	Scale factor evolution of the $M - C_R$ scaling relation	Fixed to 2
F_X	-	Redshift evolution of the mass slope of the $M - C_R$ scaling relation	$\mathcal{U}(-5, 5)$
G_X	-	Redshift evolution of the normalization of the $M - C_R$ scaling relation	$\mathcal{U}(-5, 5)$
σ_X	-	Intrinsic scatter of the $M - C_R$ scaling relation	$\mathcal{U}(0.05, 2)$
• Weak lensing mass calibration			
A_{WL}	-	Scatter in the weak lensing bias from the first principal component	$\mathcal{N}(0, 1)$
B_{WL}	-	Scatter in the weak lensing bias from the second principal component	$\mathcal{N}(0, 1)$
C_{WL}	-	Standardize mass slope of the weak lensing bias	$\mathcal{N}(0, 1)$
D_{WL}	-	Redshift dependent intrinsic scatter in the weak lensing bias	$\mathcal{N}(0, 1)$
ρ_{M_{WL}, C_R}	-	Intrinsic correlation between weak lensing mass and count rate	$\mathcal{U}(-0.9, 0.9)$
• Richness mass calibration			
$\log A_\lambda$	-	Normalization of the $M - \lambda$ scaling relation	$\mathcal{U}(1.4, 6)$
B_λ	-	Mass slope of the $M - \lambda$ scaling relation	$\mathcal{U}(0, 2)$
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• Contamination modeling			
f_{AGN}	-	Fraction of AGN contaminants in the extended source sample	$\mathcal{U}(0, 0.1)$
f_{RS}	-	Fraction of RS contaminants in the extended source sample	$\mathcal{U}(0, 0.15)$
• Redshift uncertainty			
σ_z	-	Relative error on the measured redshift	$\mathcal{TN}(0.0050, 0.0011, 0, 1)$
b_z	-	Systematic bias in our redshift estimate	$\mathcal{N}(1.005, 0.037)$
c_z	-	Fraction of objects for which we measure a shifted redshift	$\mathcal{TN}(0.0013, 0.0010, 0, 1)$
$c_{shift,z}$	-	Amount of redshift shift for c_z fraction of objects	$\mathcal{U}(-0.1, 0.1)$

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A_{WL}	-	Scatter in the weak lensing bias from the first principal component	$\mathcal{N}(0, 1)$
B_{WL}	-	Scatter in the weak lensing bias from the second principal component	$\mathcal{N}(0, 1)$
C_{WL}	-	Standardize mass slope of the weak lensing bias	$\mathcal{N}(0, 1)$
D_{WL}	-	Redshift dependent intrinsic scatter in the weak lensing bias	$\mathcal{N}(0, 1)$
$\rho_{M_{\mathrm{WL}}, C_R}$	-	Intrinsic correlation between weak lensing mass and count rate	$\mathcal{U}(-0.9, 0.9)$
• Richness mass calibration			
$\log A_\lambda$	-	Normalization of the $M - \lambda$ scaling relation	$\mathcal{U}(1.4, 6)$
B_λ	-	Mass slope of the $M - \lambda$ scaling relation	$\mathcal{U}(0, 2)$
C_λ	-	Redshift evolution of the normalization of the $M - \lambda$ scaling relation	$\mathcal{U}(-2, 2)$
D_λ	-	Redshift evolution of the mass slope of the $M - \lambda$ scaling relation	$\mathcal{U}(-2, 2)$
σ_λ	-	Intrinsic scatter of the $M - \lambda$ scaling relation	$\mathcal{U}(0.05, 2)$
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f_{AGN}	-	Fraction of AGN contaminants in the extended source sample	$\mathcal{U}(0, 0.1)$
f_{RS}	-	Fraction of RS contaminants in the extended source sample	$\mathcal{U}(0, 0.15)$
• Redshift uncertainty			
σ_z	-	Relative error on the measured redshift	$\mathcal{TN}(0.0050, 0.0011, 0, 1)$
b_z	-	Systematic bias in our redshift estimate	$\mathcal{N}(1.005, 0.037)$
c_z	-	Fraction of objects for which we measure a shifted redshift	$\mathcal{TN}(0.0013, 0.0010, 0, 1)$
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Parameter	Units	Description	Prior
• Cosmology			
Ω_m	-	Mean matter density at present time	$\mathcal{U}(0.05, 0.95)$
$\log_{10} A_s$	-	Amplitude of the primordial power spectrum	$\mathcal{U}(-10, -8)$
H_0	$\frac{\text{km}/\text{s}}{\text{Mpc}}$	Hubble expansion rate at present time	$\mathcal{N}(67.77, 0.6)$
Ω_b	-	Mean baryon density at present time	$\mathcal{U}(0.046, 0.052)$
n_s	-	Spectra index of the primordial power spectrum	$\mathcal{U}(0.92, 1.0)$
w_0	-	Dark energy equation of state. Fixed to -1 in ΛCDM	$\mathcal{U}(-2.5, -0.33)$
$\sum m_\nu$	eV	Summed neutrino masses. Fixed to 0 eV in ΛCDM	$\mathcal{U}(0, 1)$
• X-ray scaling relation			
A_X	-	Normalization of the $M - C_R$ scaling relation	$\mathcal{U}(0.01, 3)$
B_X	-	Mass slope of the $M - C_R$ scaling relation	$\mathcal{U}(0.1, 5)$
D_X	-	Luminosity distance evolution of the $M - C_R$ scaling relation	Fixed to -2
E_X	-	Scale factor evolution of the $M - C_R$ scaling relation	Fixed to 2
F_X	-	Redshift evolution of the mass slope of the $M - C_R$ scaling relation	$\mathcal{U}(-5, 5)$
G_X	-	Redshift evolution of the normalization of the $M - C_R$ scaling relation	$\mathcal{U}(-5, 5)$
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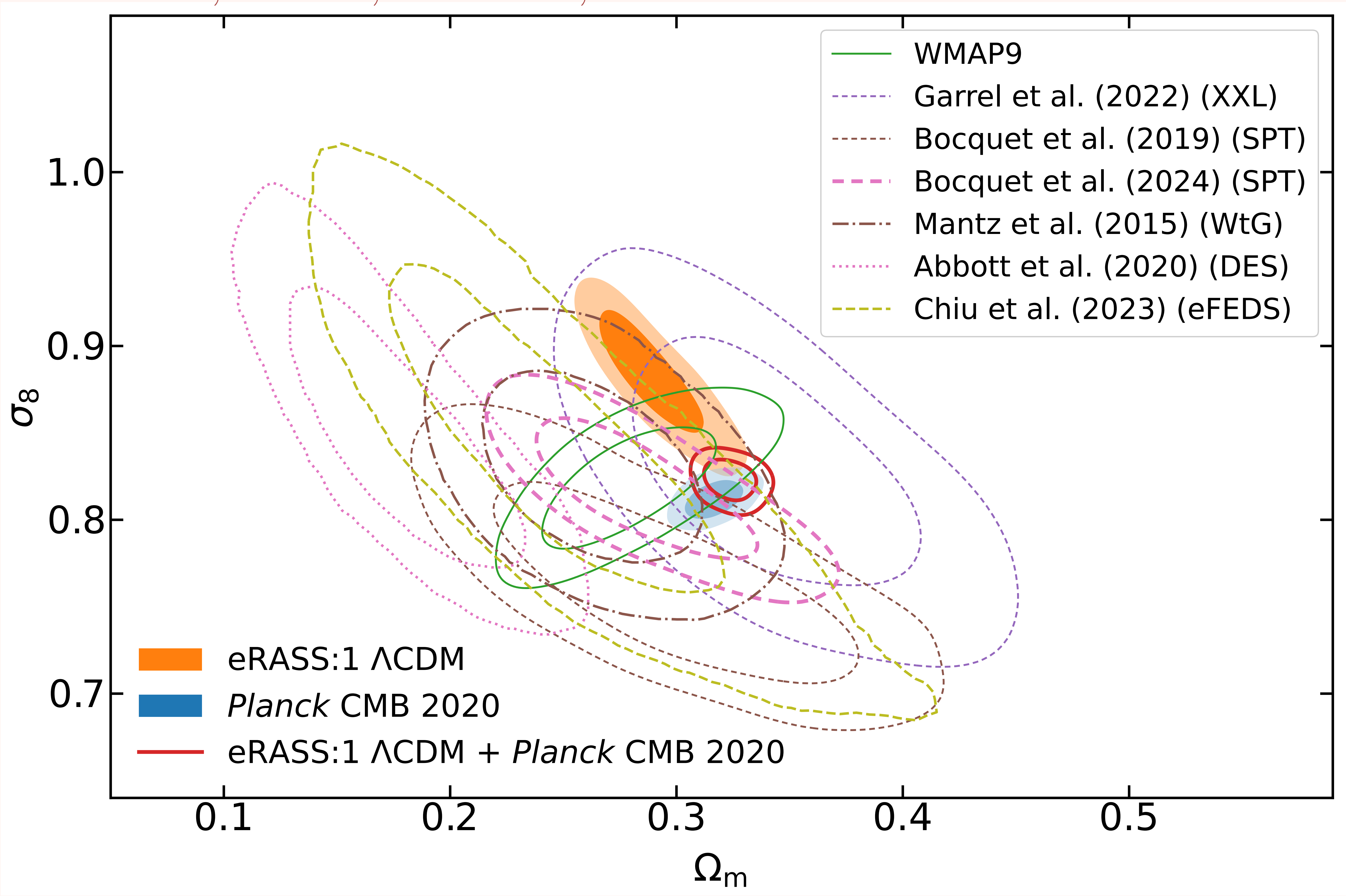
eRASS1 COSMOLOGICAL RESULTS : ΛCDM

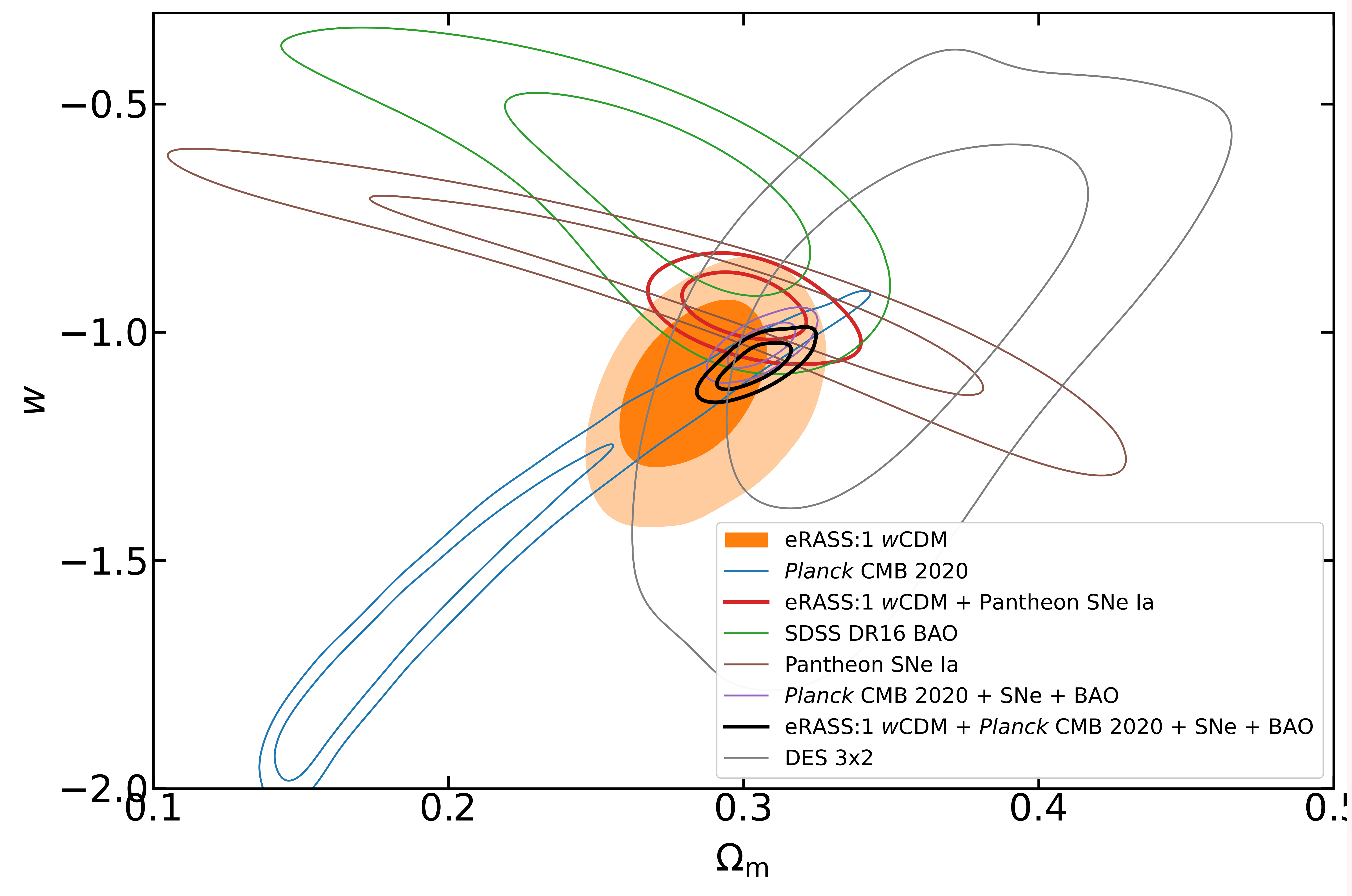
Ghirardini, Bulbul, EA et al., 2024



- $\Omega_{\rm m} = 0.29^{+0.01}_{-0.02}$ **(7% precision)**
- $\sigma_8 = 0.88 \pm 0.02$ **(2% precision)**

eRASS1 COSMOLOGICAL RESULTS : *w*CDM

Ghirardini, Bulbul, EA et al., 2024



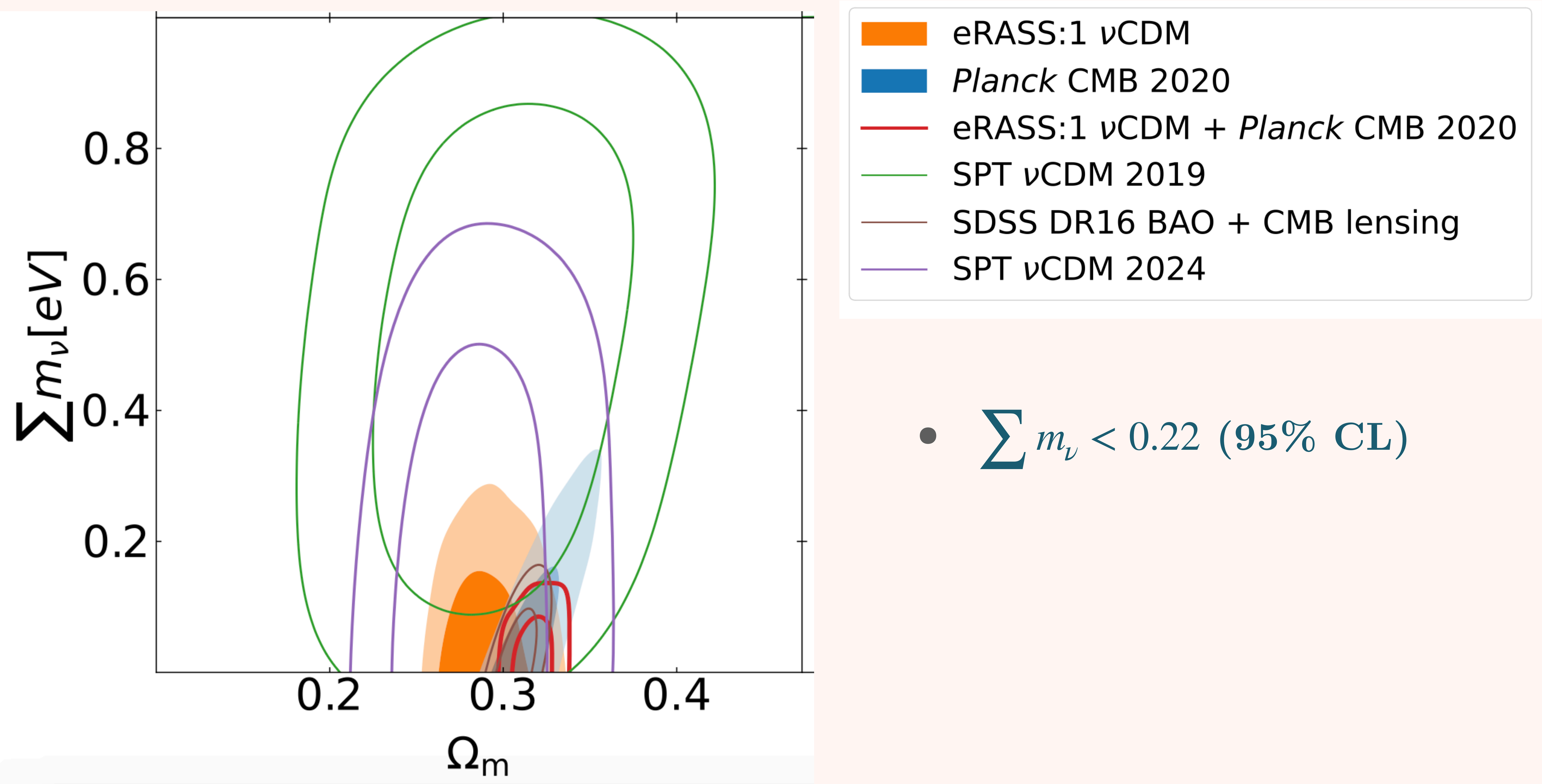
DE equation of state

$$p = w\rho$$

$$w = -1.12 \pm 0.12$$

eRASS1 COSMOLOGICAL RESULTS : νCDM

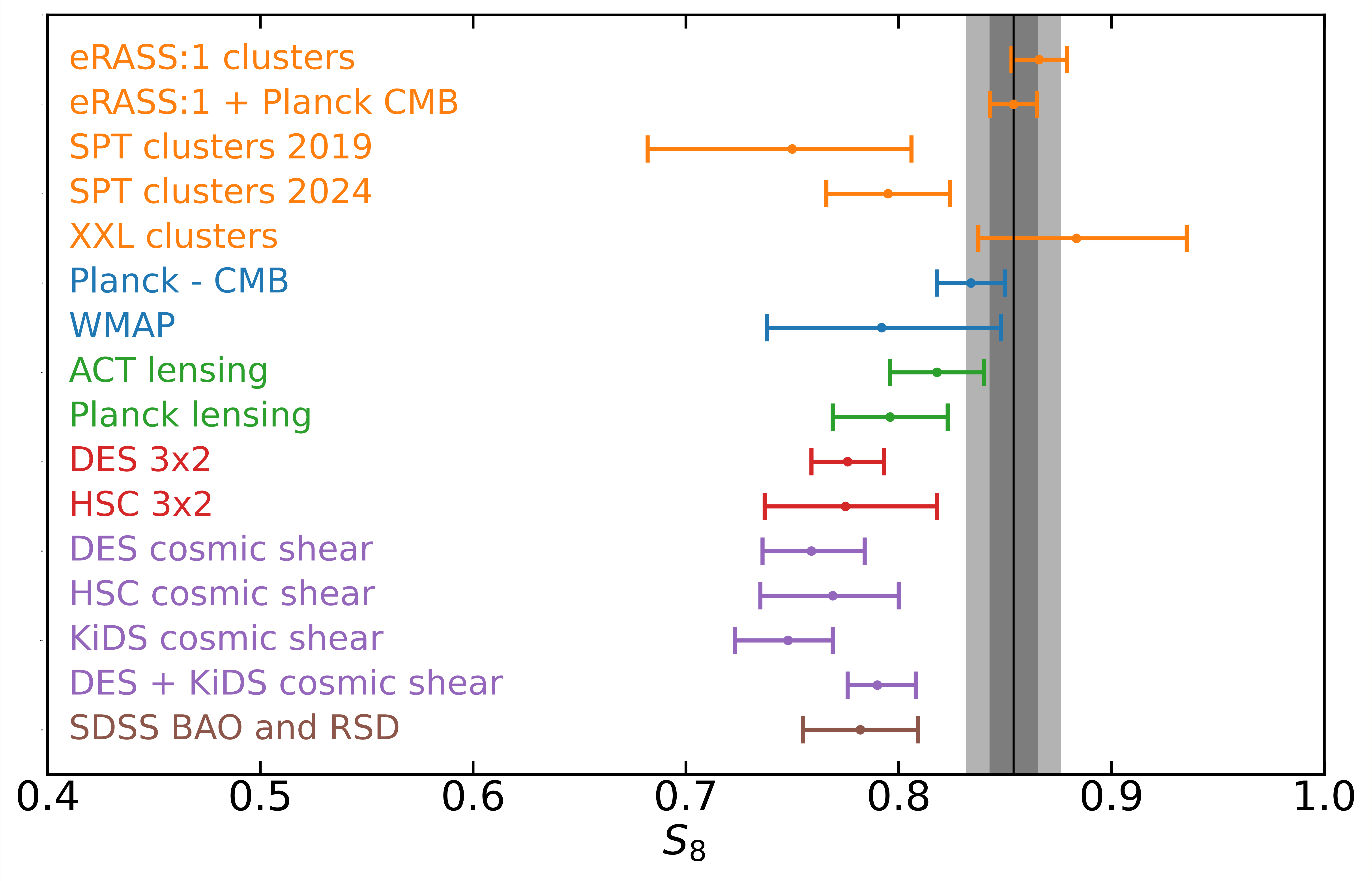
Ghirardini, Bulbul, EA et al., 2024



- $\sum m_\nu < 0.22$ **(95% CL)**

IMPACT ON THE S_8 TENSION

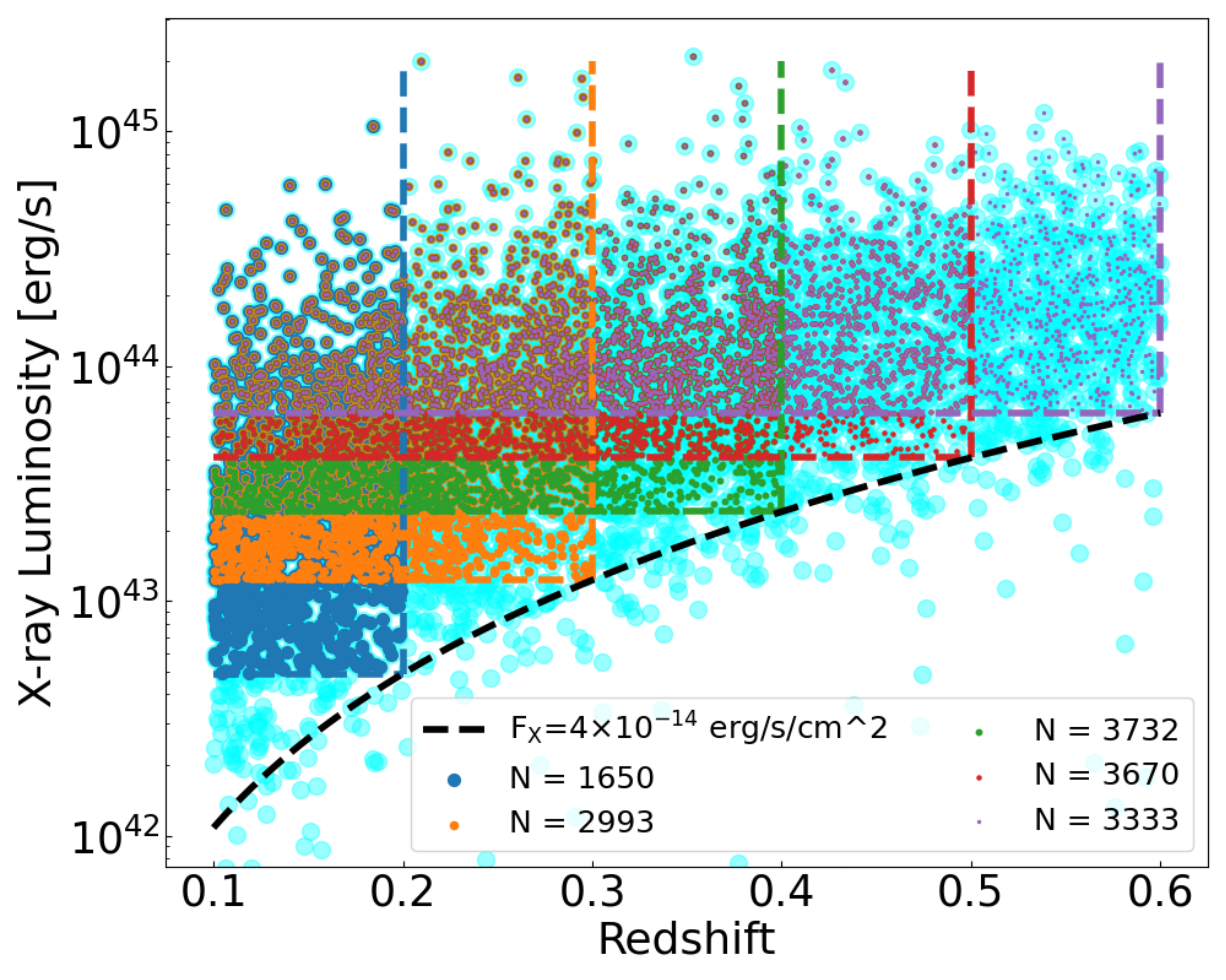
Ghirardini, Bulbul, EA et al., 2024



eRASS1 cluster abundance is in good agreement with the CMB

MORE : CLUSTER 2PT CORRELATION FUNCTION

Seppi et al., 2024

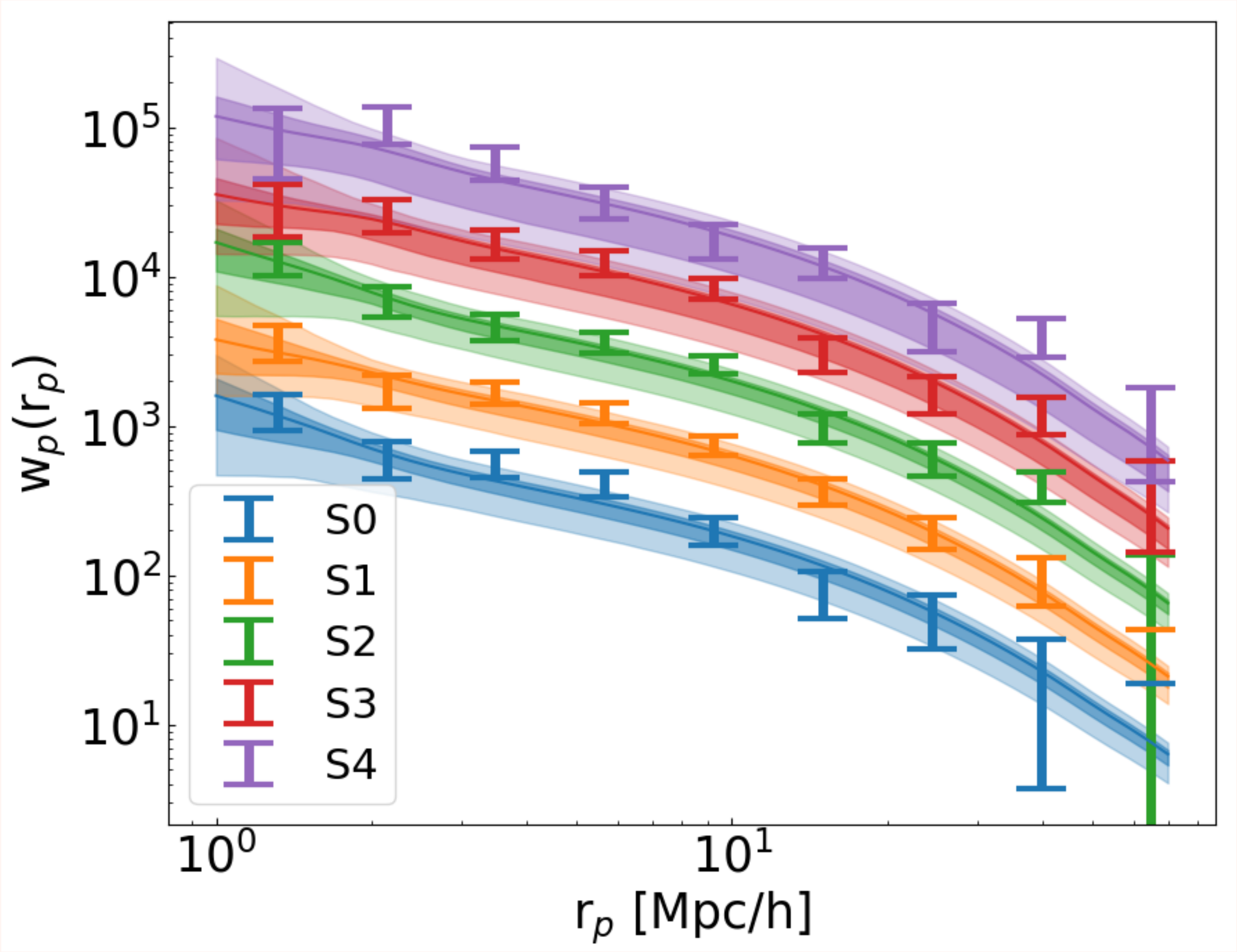


Riccardo Seppi

Volume limited selection of the eRASS1 cluster sample

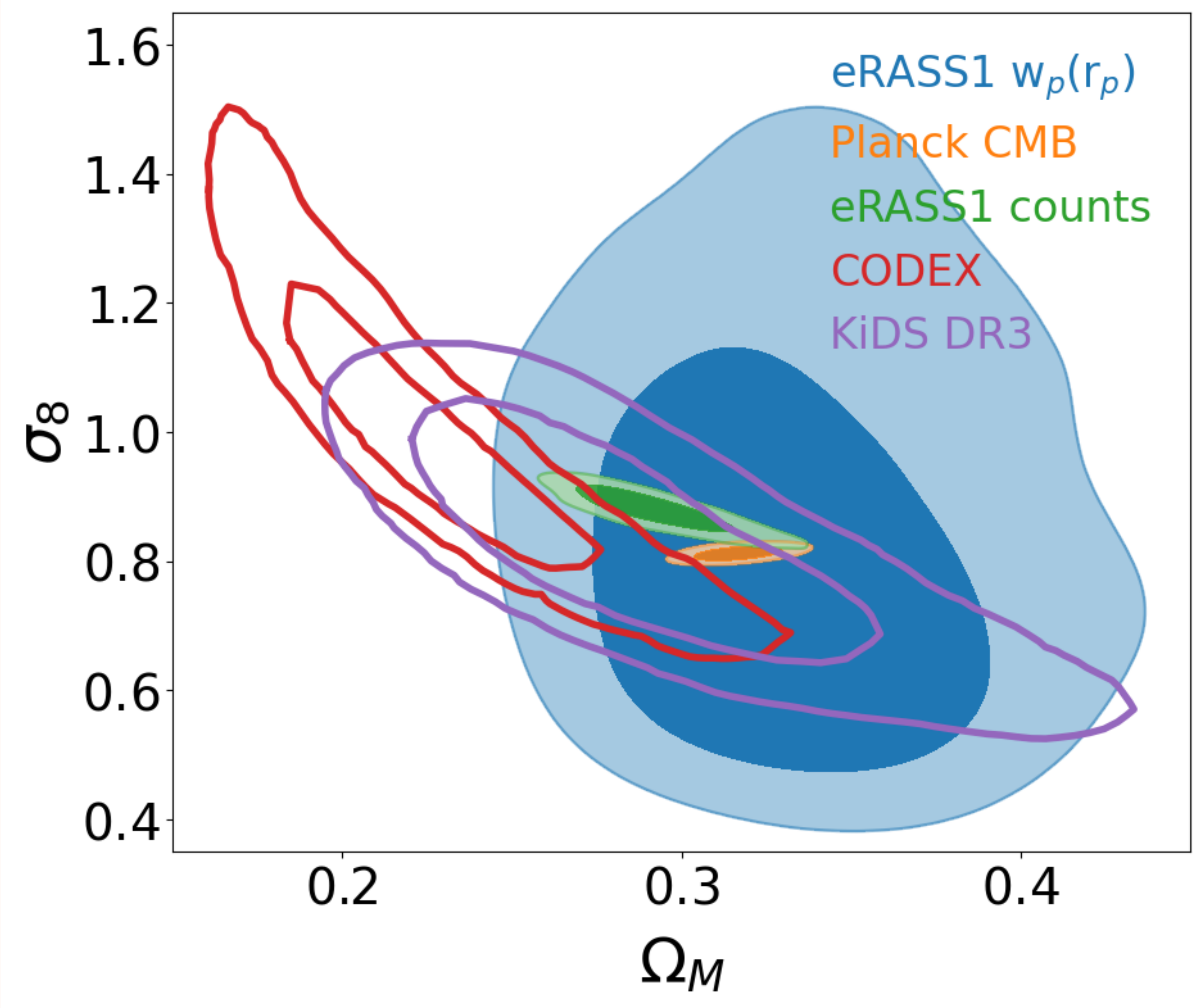
CLUSTER 2PT CORRELATION FUNCTION

Seppi et al., 2024



Projected correlation function of the 4 volume selected eRASS1 cluster samples

CLUSTER 2PT CORRELATION FUNCTION



Seppi et al., 2024

Cosmological results obtained from the eRASS1 clusters correlation function

EVEN MORE : $f(R)$ GRAVITY

EA et al., 2024

Einstein-Hilbert action

$$S_{\mathrm{EH}} = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} + \mathscr{L}_{\mathrm{m}} \right) \longrightarrow \tilde{S}_{\mathrm{EH}} = \int d^4x \sqrt{-g} \left(\left[\frac{R + f(R)}{16\pi G} \right] + \mathscr{L}_{\mathrm{m}} \right)$$

Einstein equations

$$G_{\mu\nu} - f_R R_{\mu\nu} - \left(\frac{f}{2} - \Box f_R \right) g_{\mu\nu} - \nabla_\mu \nabla_\nu f_R = 8\pi G T_{\mu\nu}$$

Hu & Sawicki, 2007

$$f(R) = -2\Lambda - f_{R0} \frac{\overline{R_0}^2}{R} \quad \text{with} \quad f_{R0} \ll 1$$

Impacts:

- The halo mass function
- The gravitationnal collapse of structures

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Impacts:

- The halo mass function
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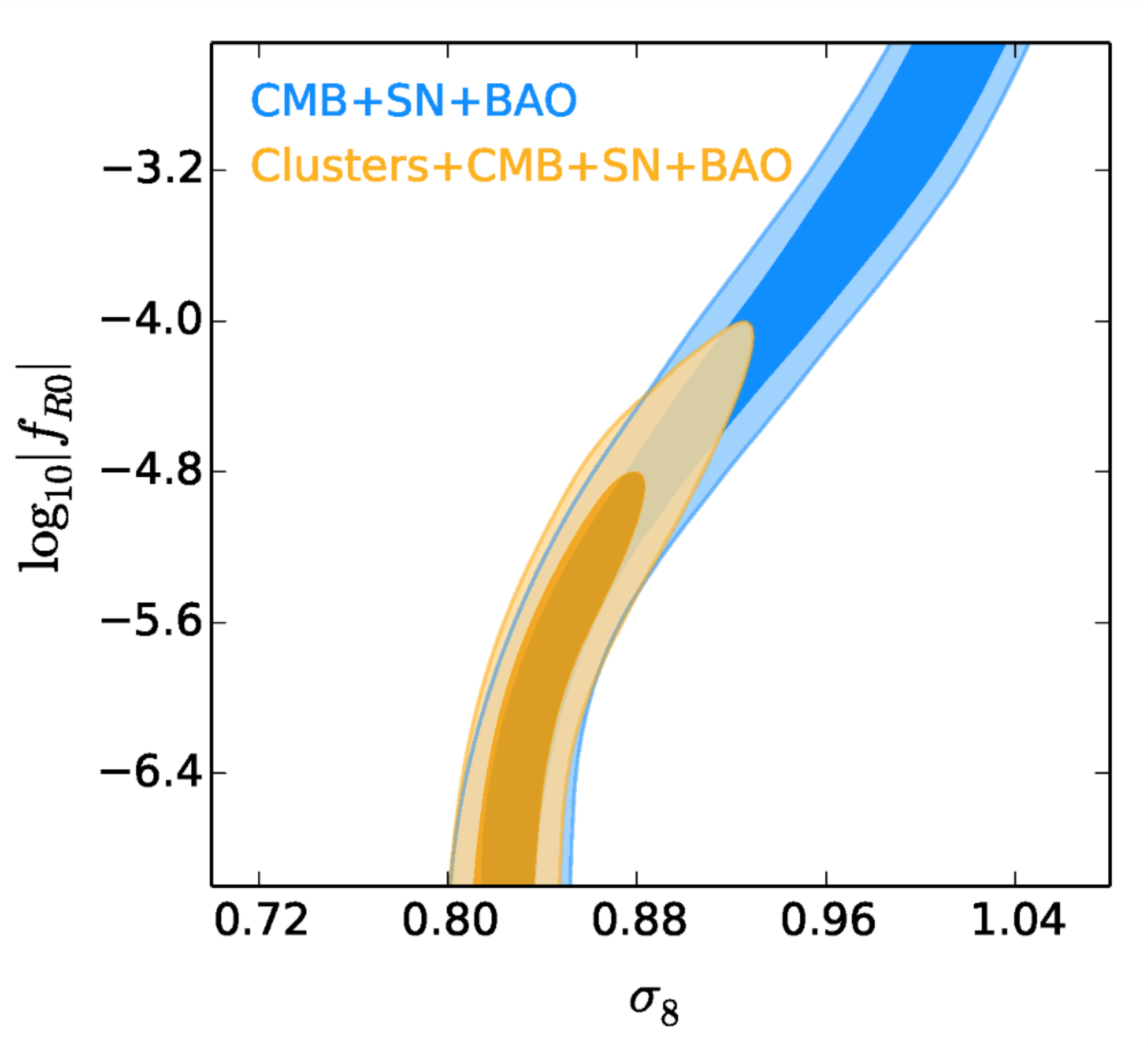
EVEN MORE : *f*(*R*) GRAVITY

EA et al., 2024



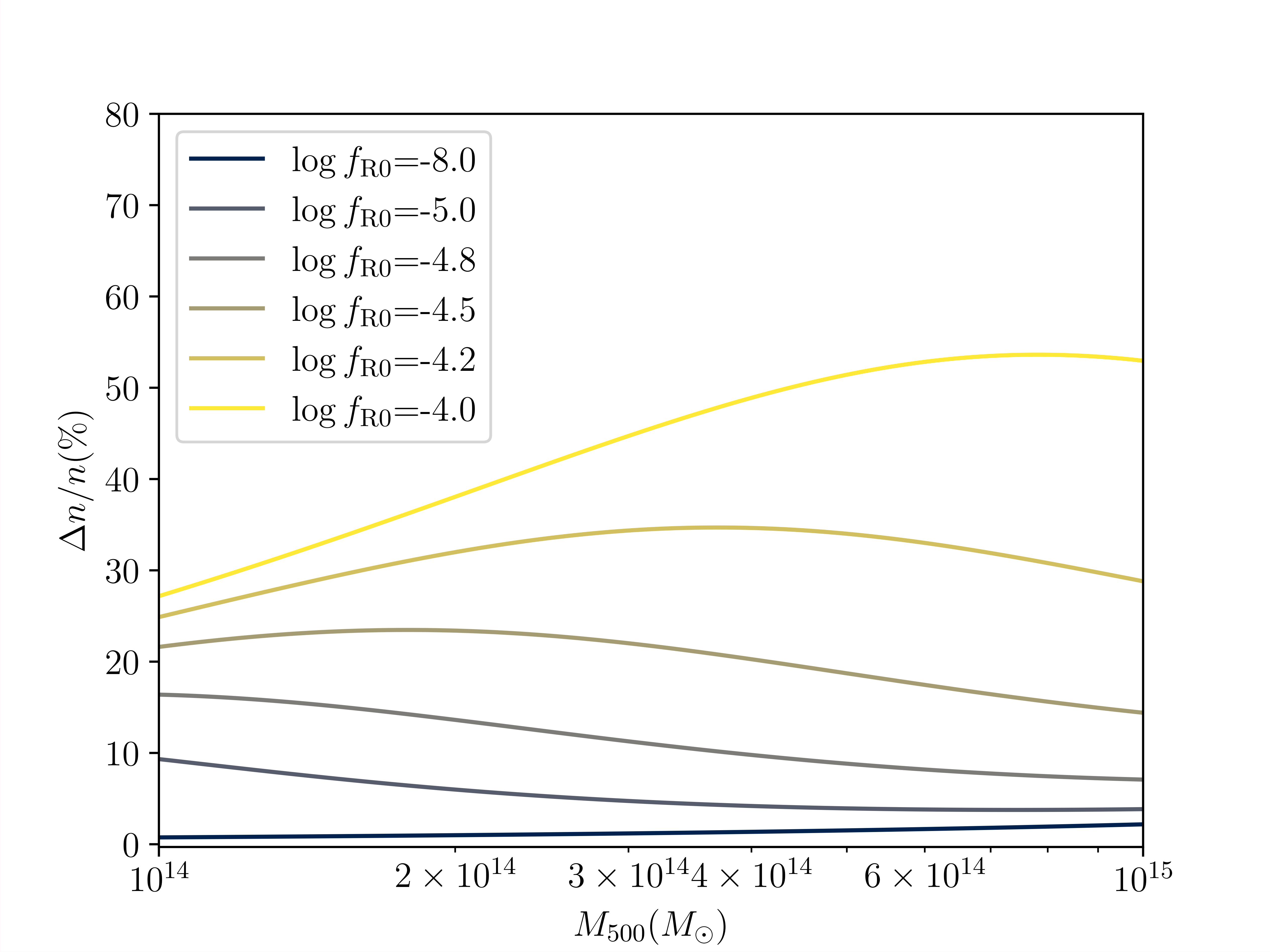
Latest constraints on the Hu-Sawicki parameterization of *f*(*R*) gravity from Cataneo et al., 2014 .

Impacts:

- The halo mass function
- The gravitationnal collapse of structures

$f(R)$ GRAVITY

EA et al., 2024

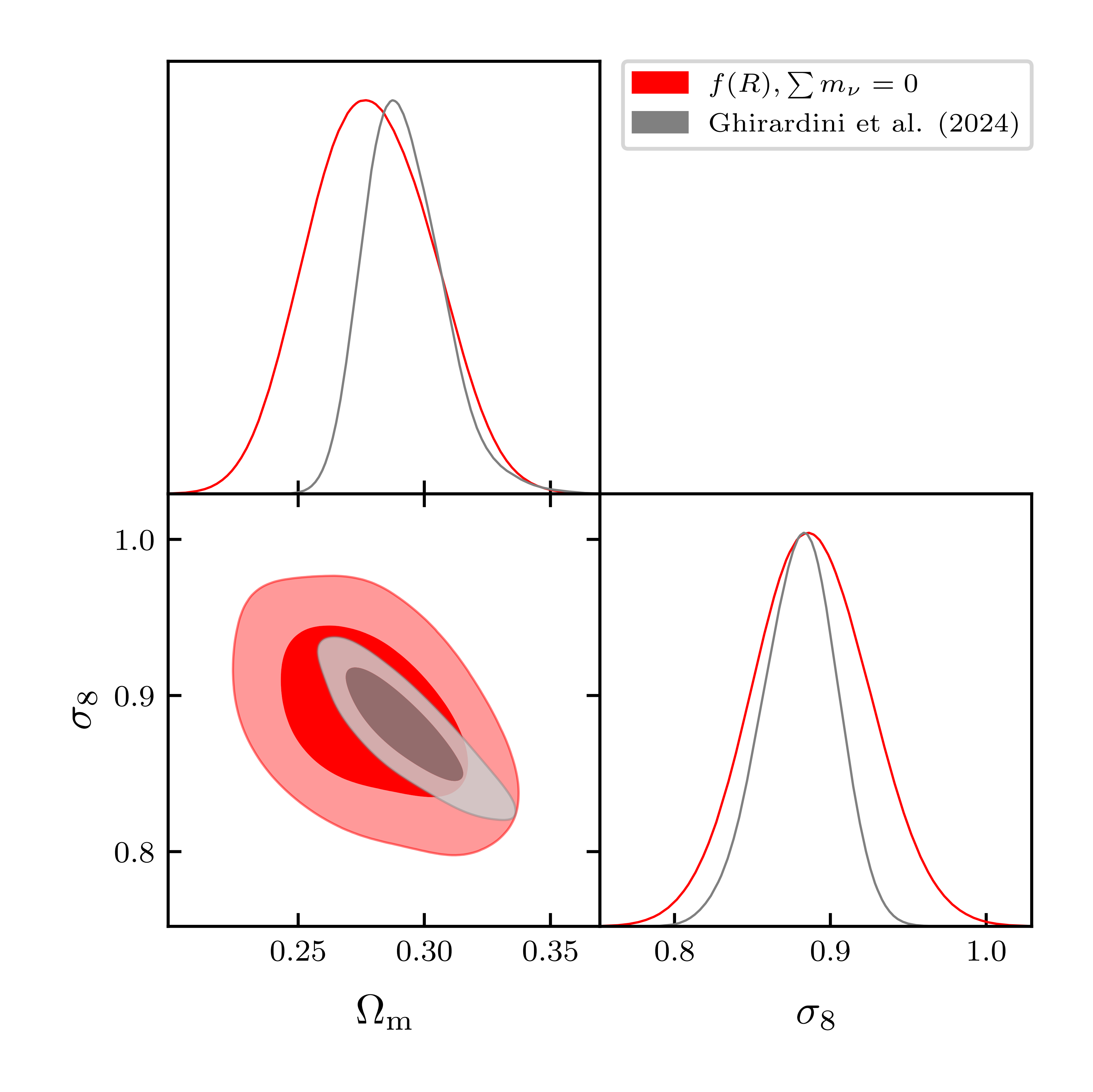


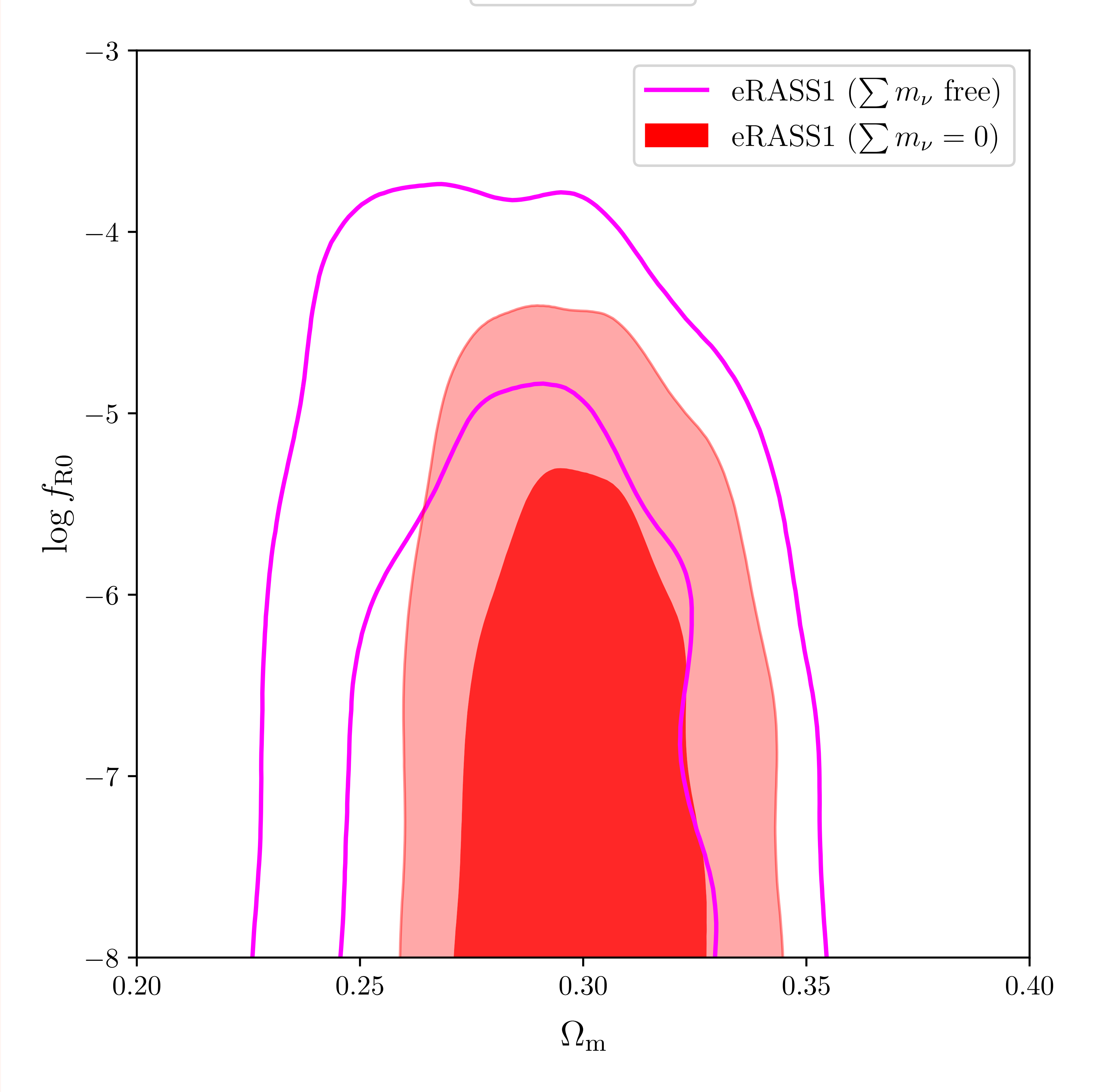
f_{R0} increases the number of massive clusters

$f(R)$ GRAVITY

EA et al., 2024

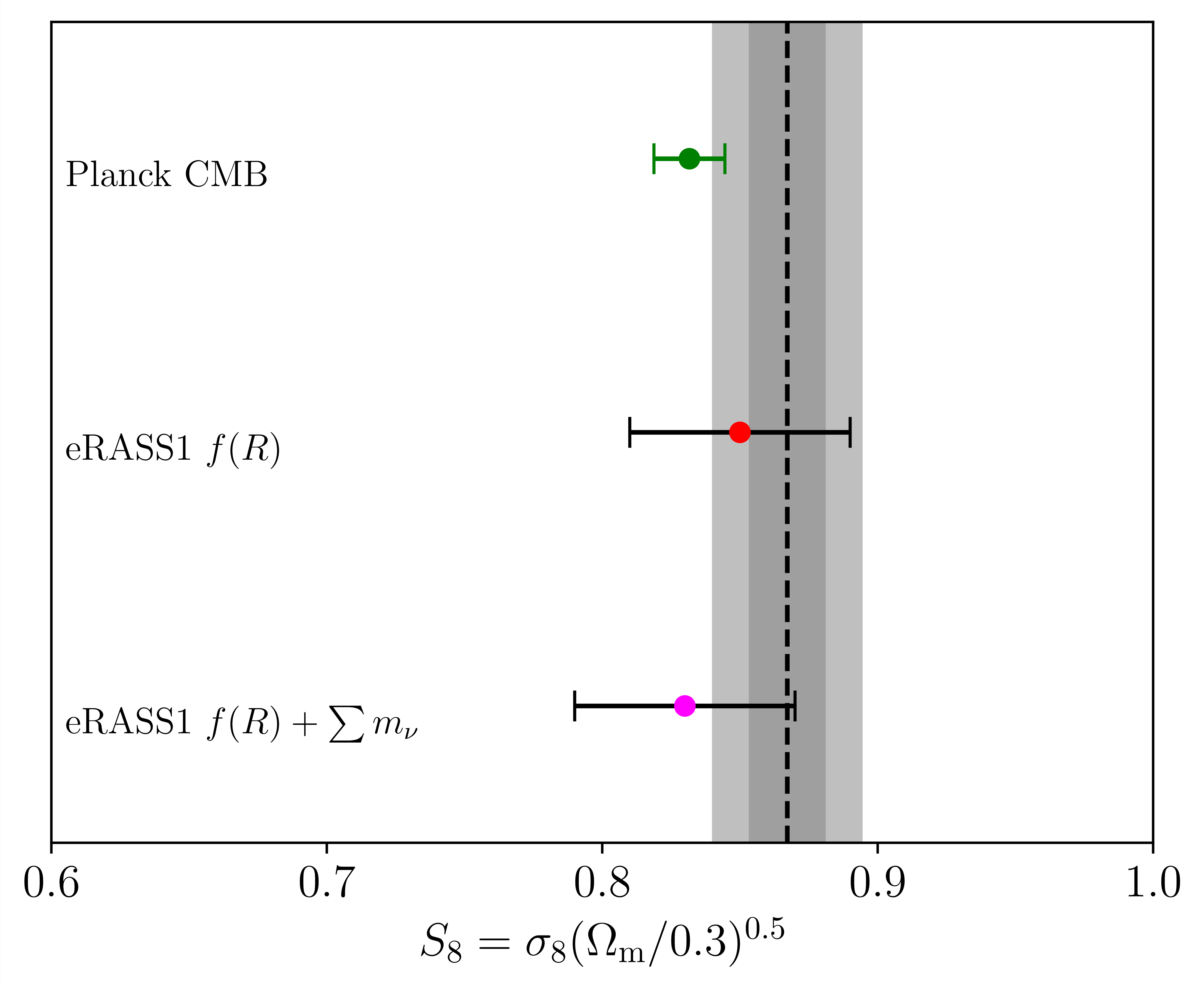
$\log|f_{R0}| < 4.12$ with clusters only



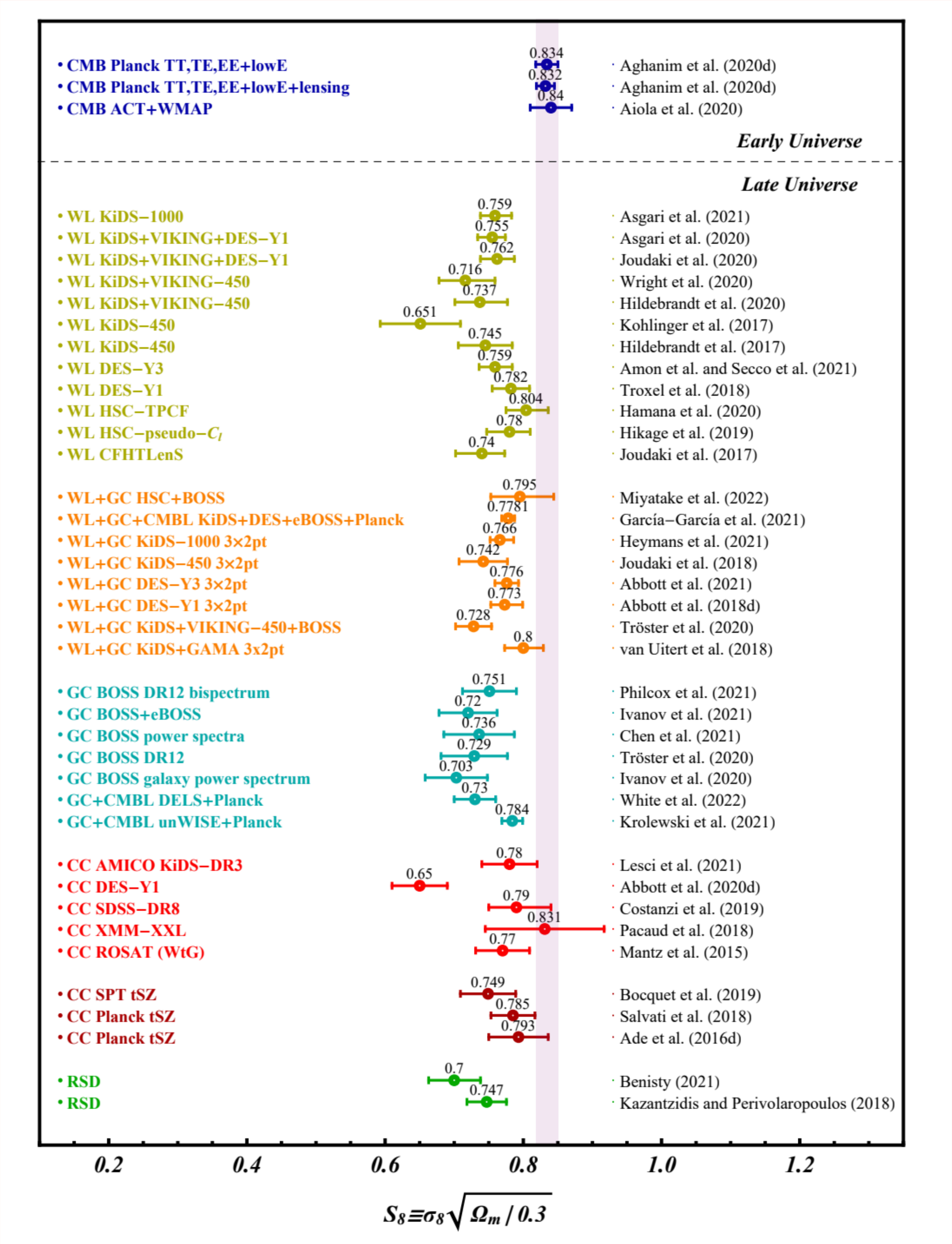


$f(R)$ COSMOLOGICAL CONSTRAINTS

EA et al., 2024



WHAT IS NEXT?

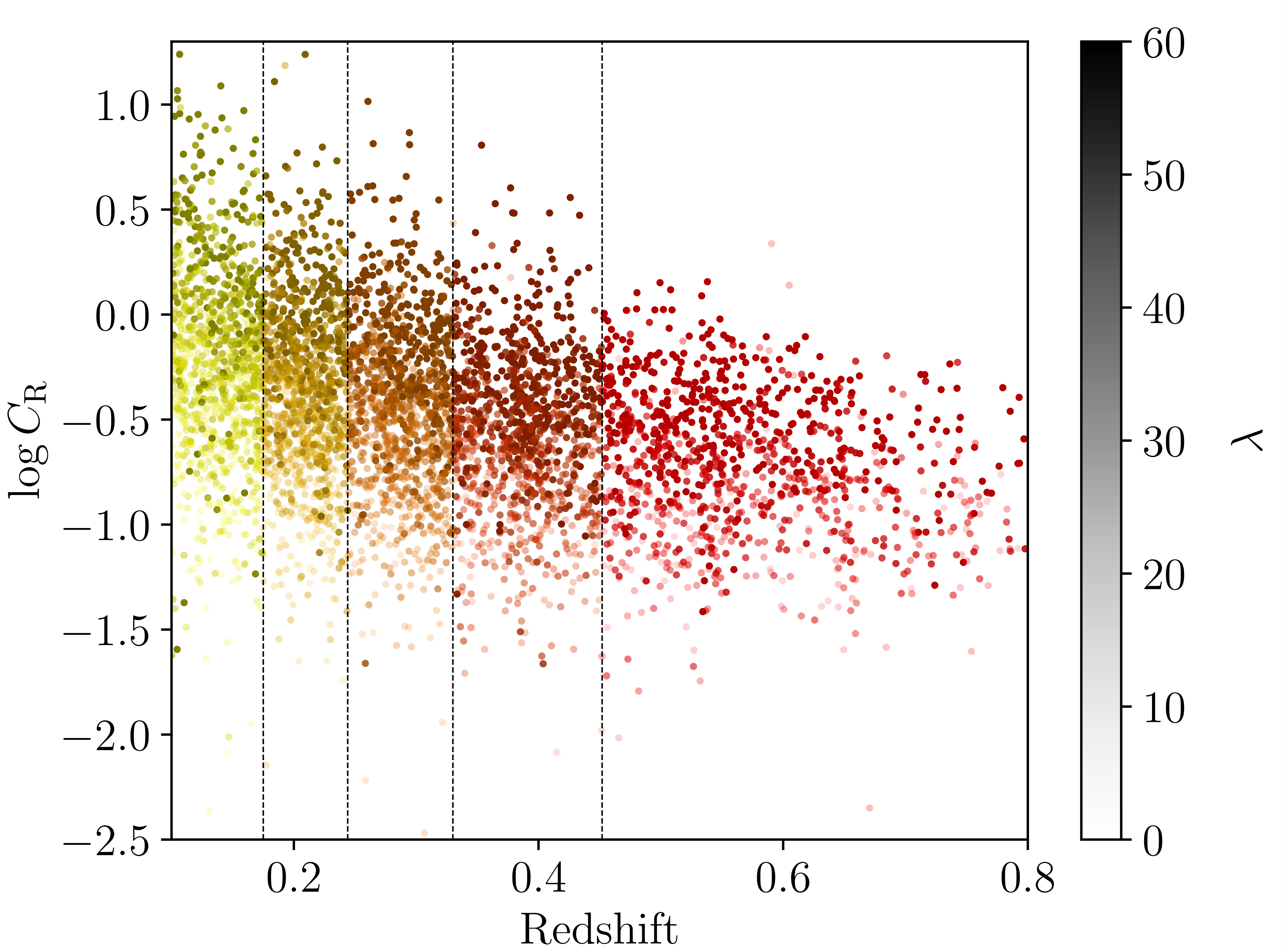


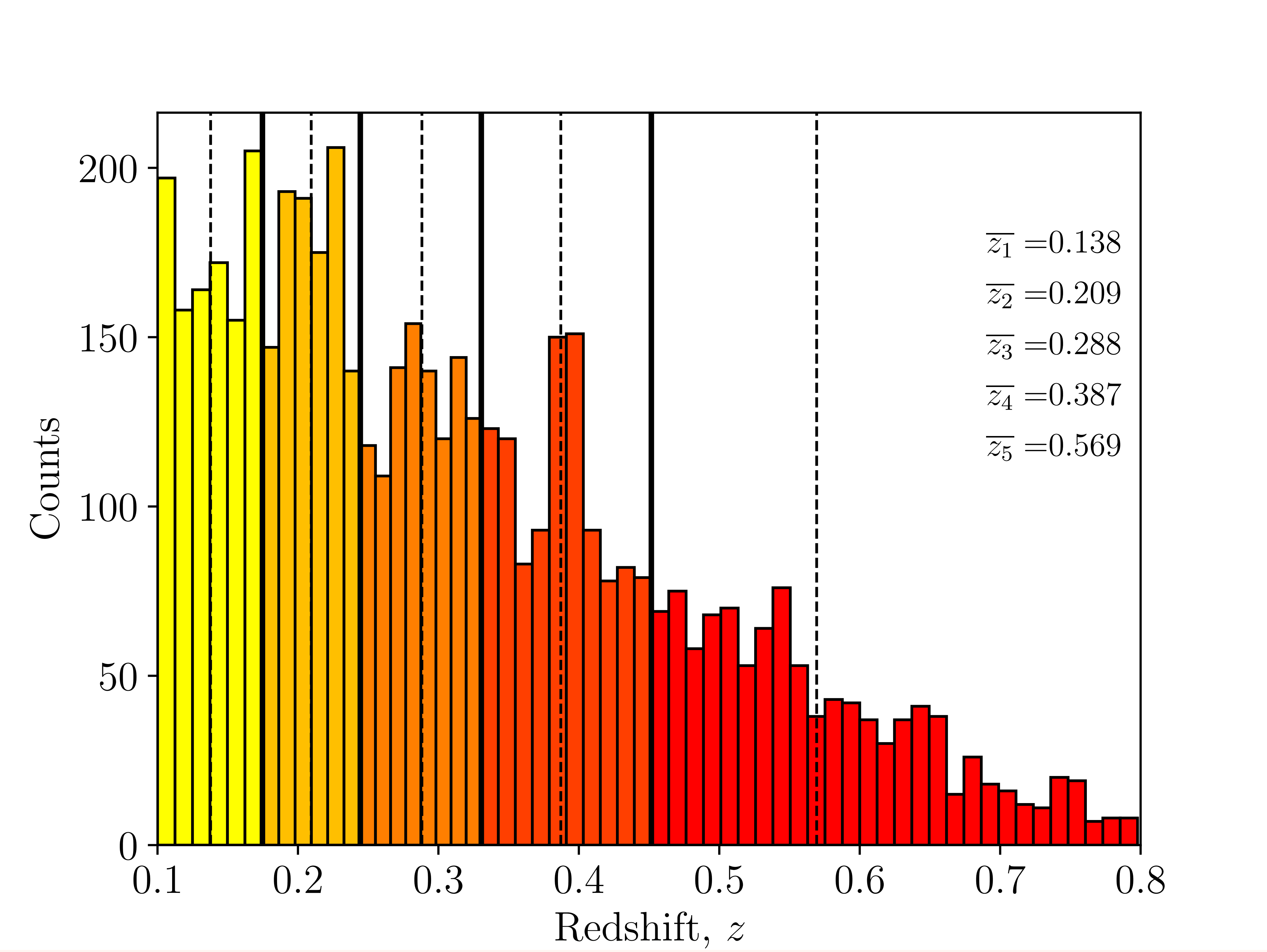
Abdalla et al., 2022

REDSHIFT EVOLUTION OF THE COSMOLOGICAL PARAMETERS

Preliminary

Redshift distribution of the clusters in each bin

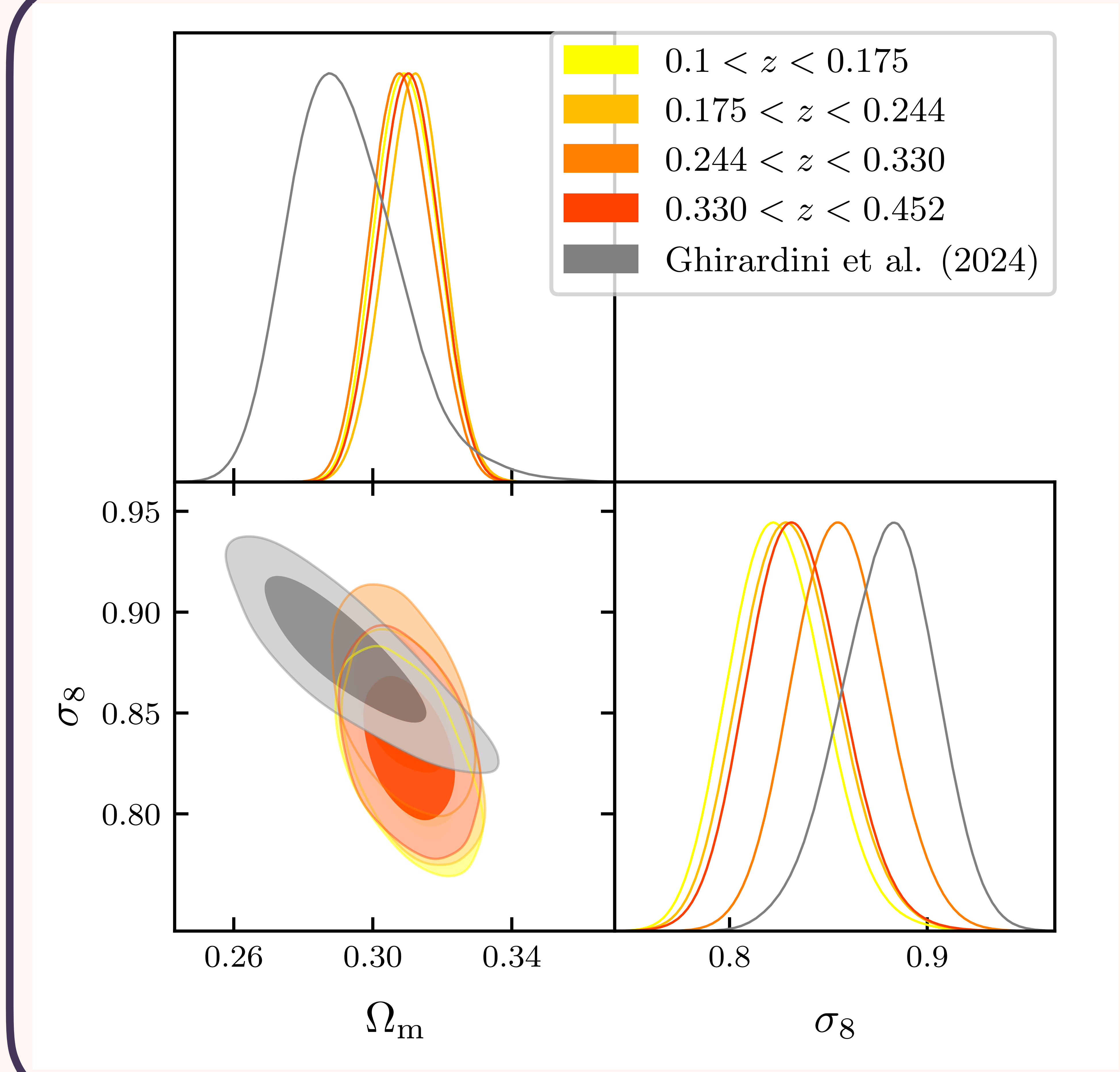




REDSHIFT EVOLUTION OF THE COSMOLOGICAL PARAMETERS

Preliminary

eRASS1 cluster abundance + θ*



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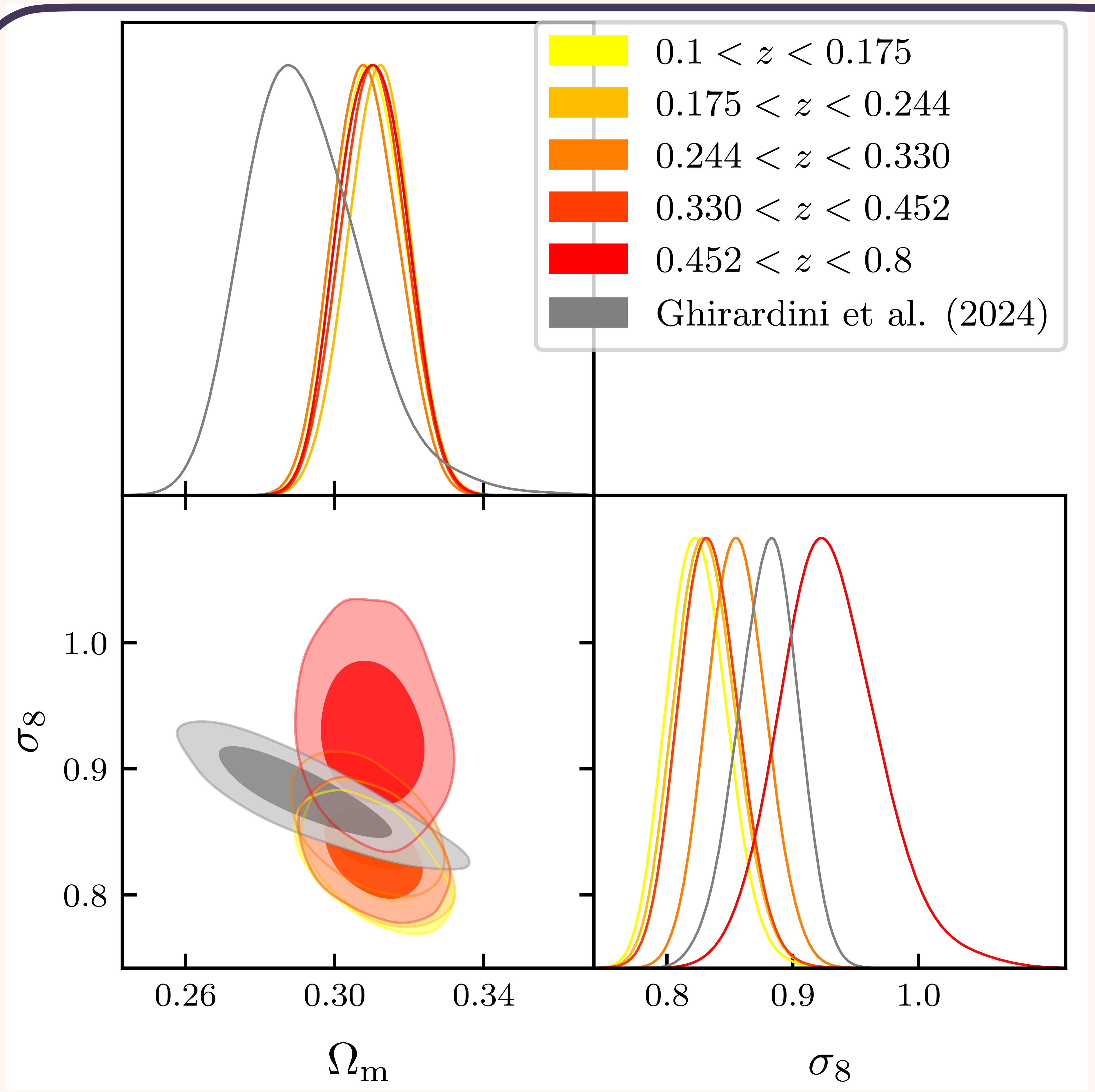

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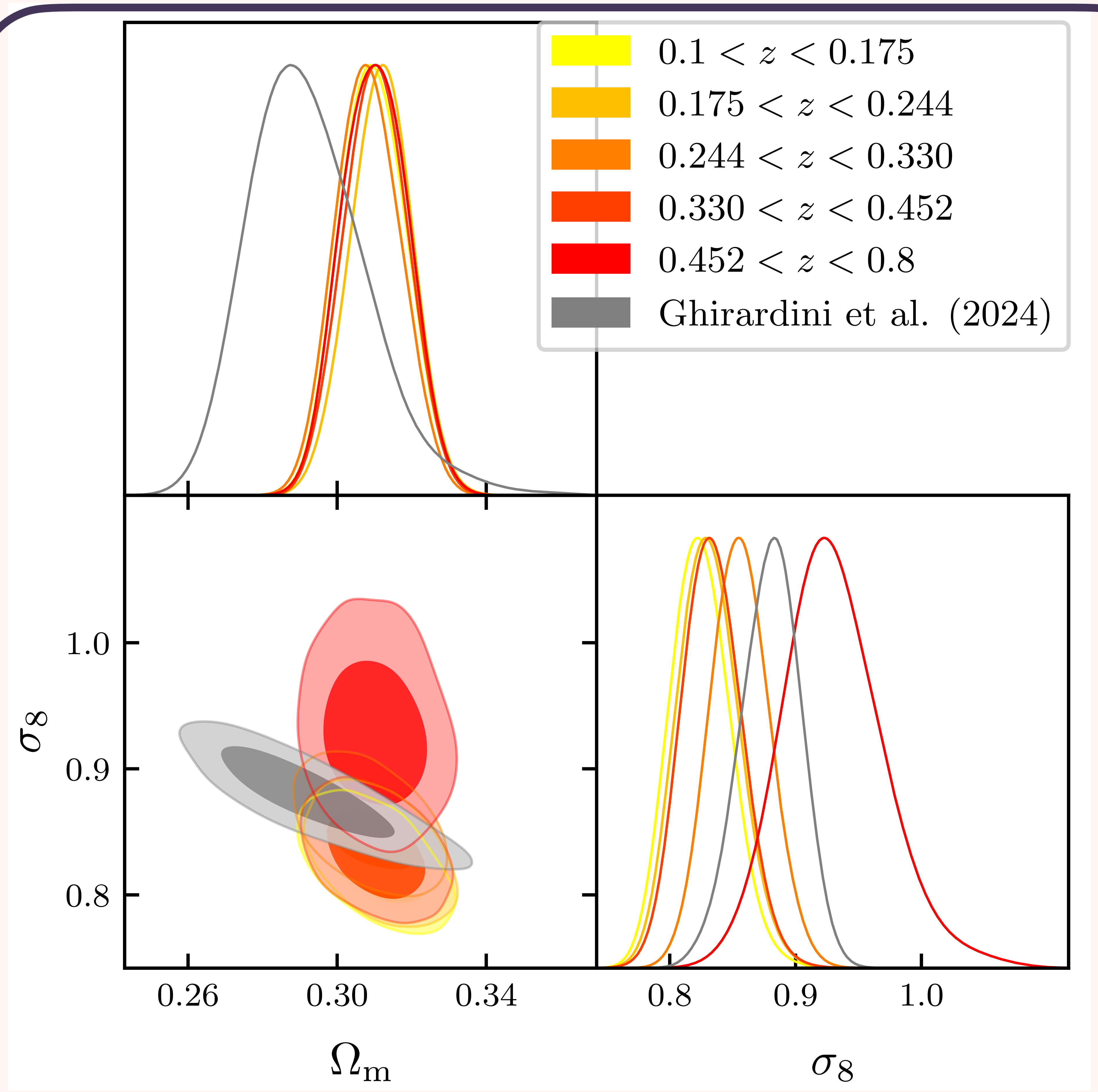

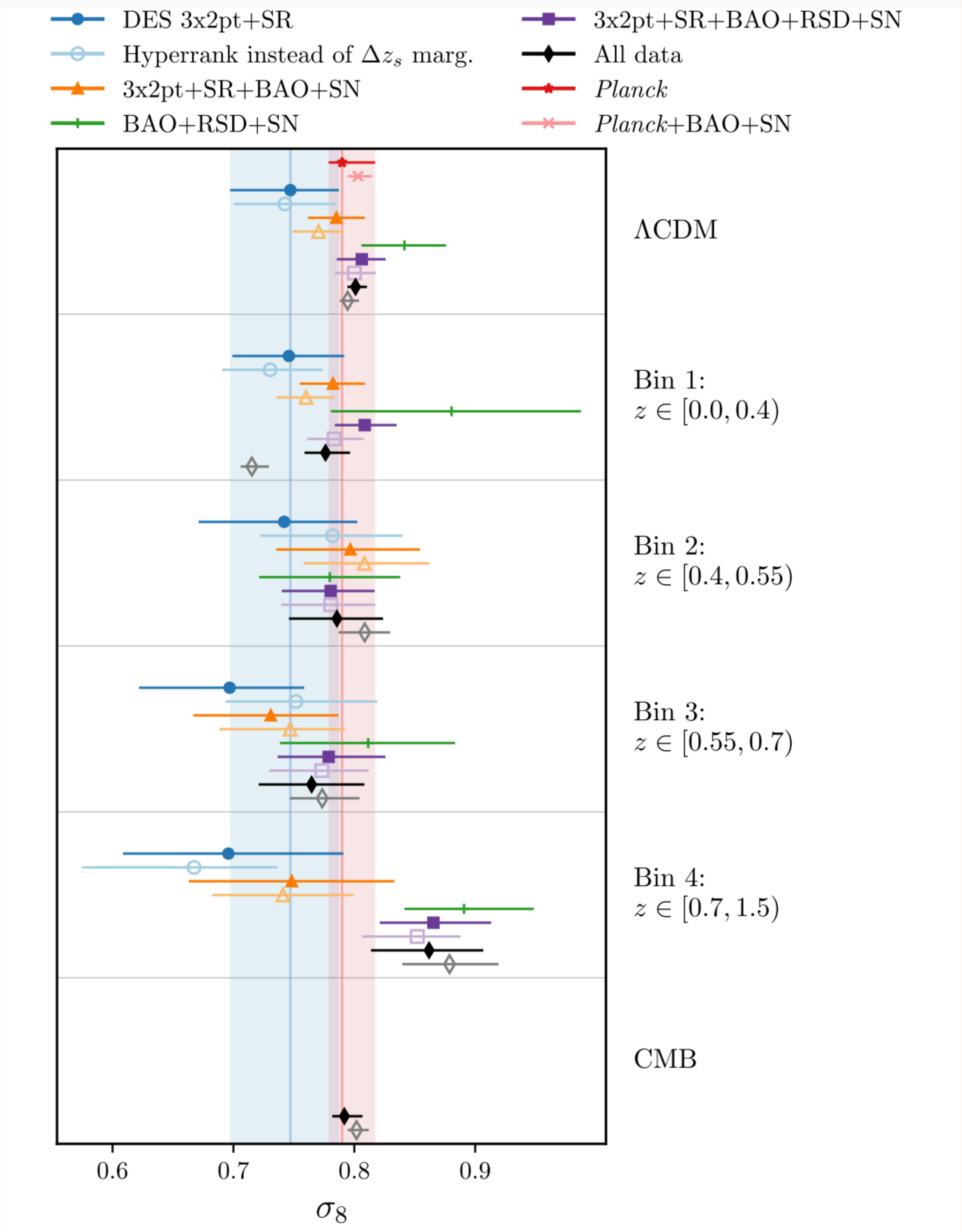

Abbott et al., 2023

REDSHIFT EVOLUTION OF THE COSMOLOGICAL PARAMETERS

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Abbott et al., 2023

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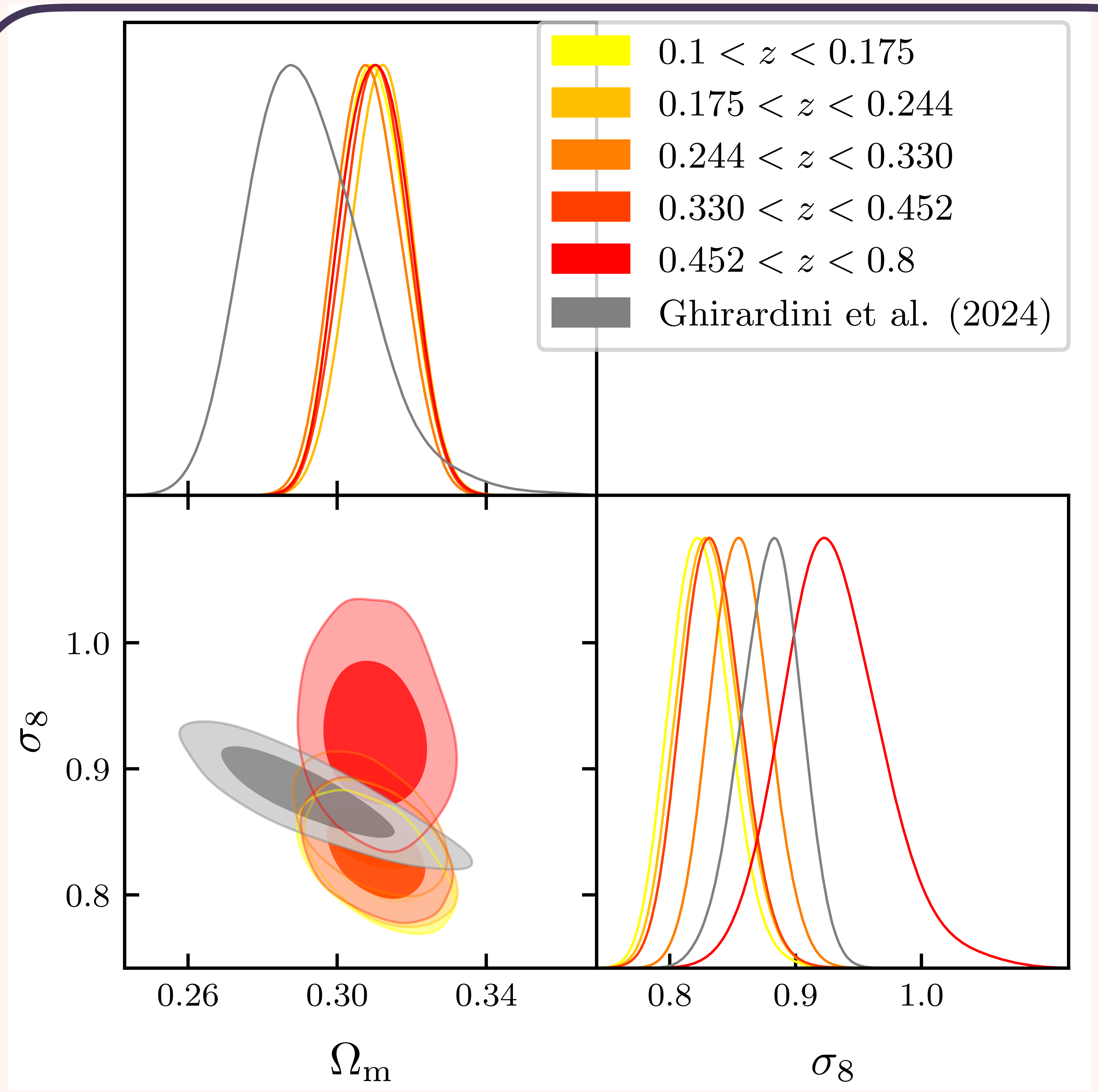

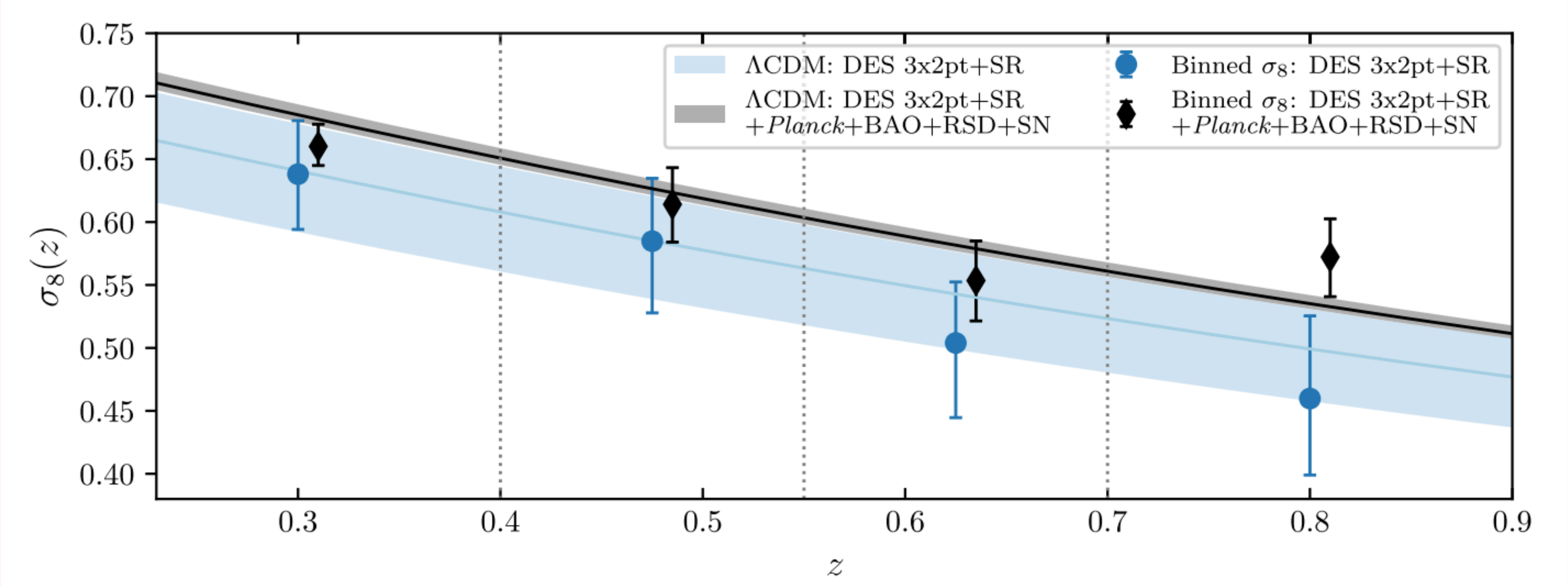

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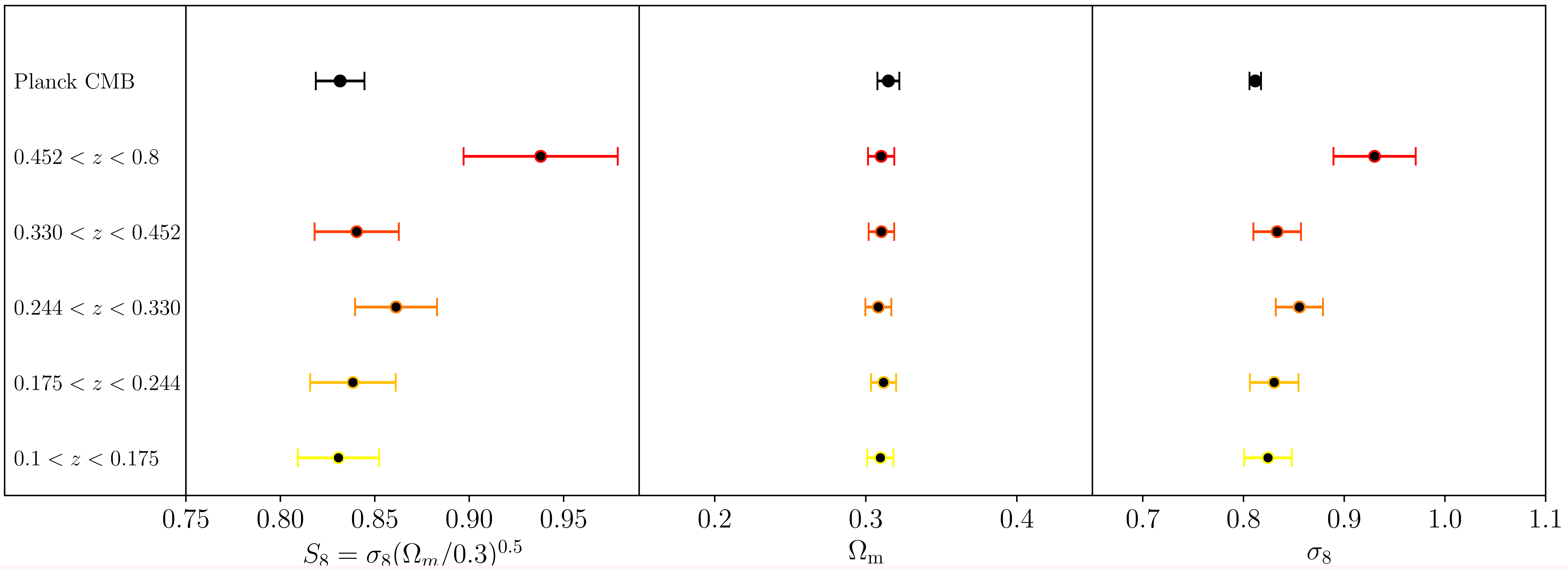

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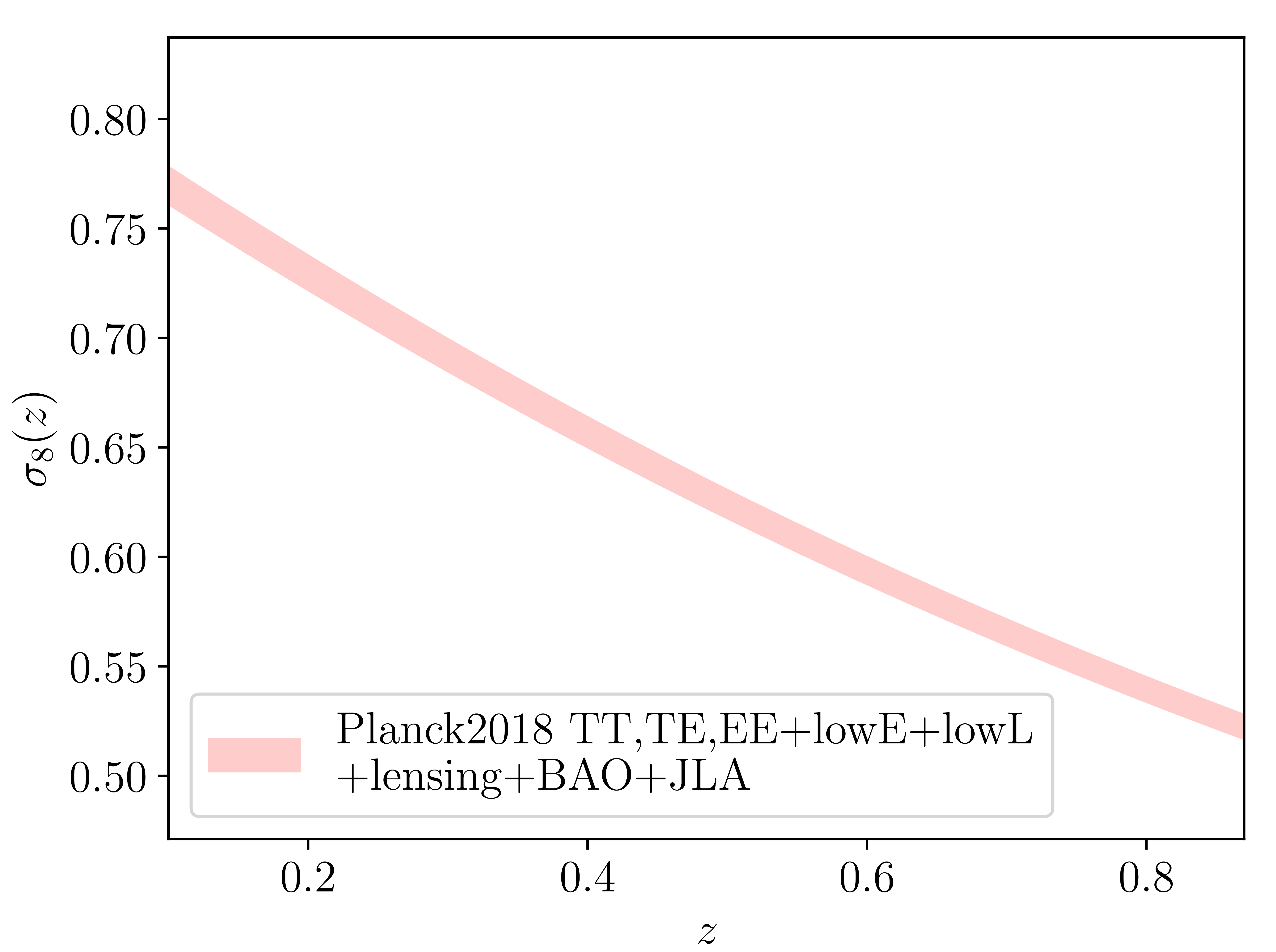

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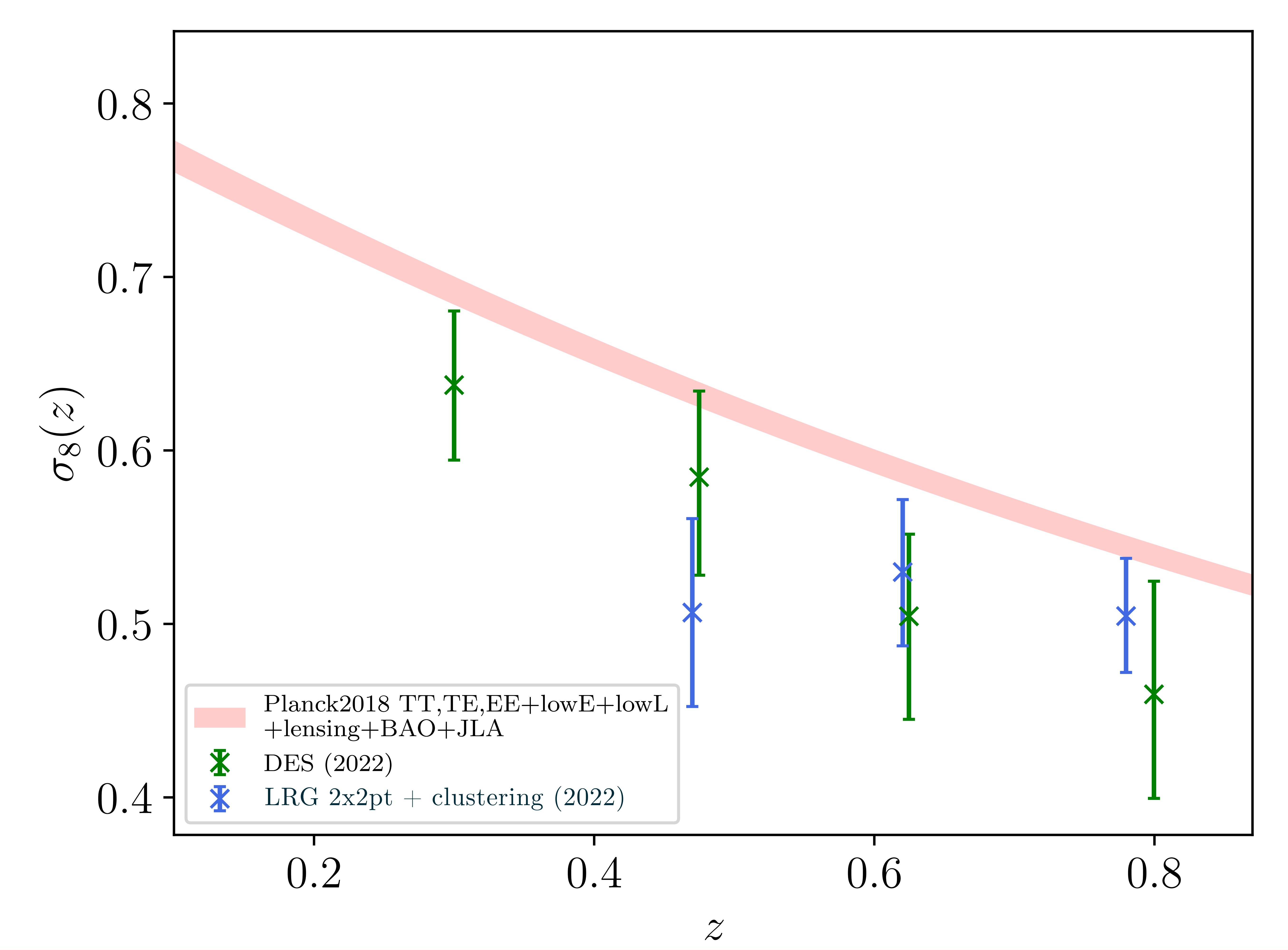

DES weak lensing shear and **DESI targeted LRG 2x2pt + CMB** are in tension with Planck best fit model

REDSHIFT EVOLUTION OF THE COSMOLOGICAL PARAMETERS

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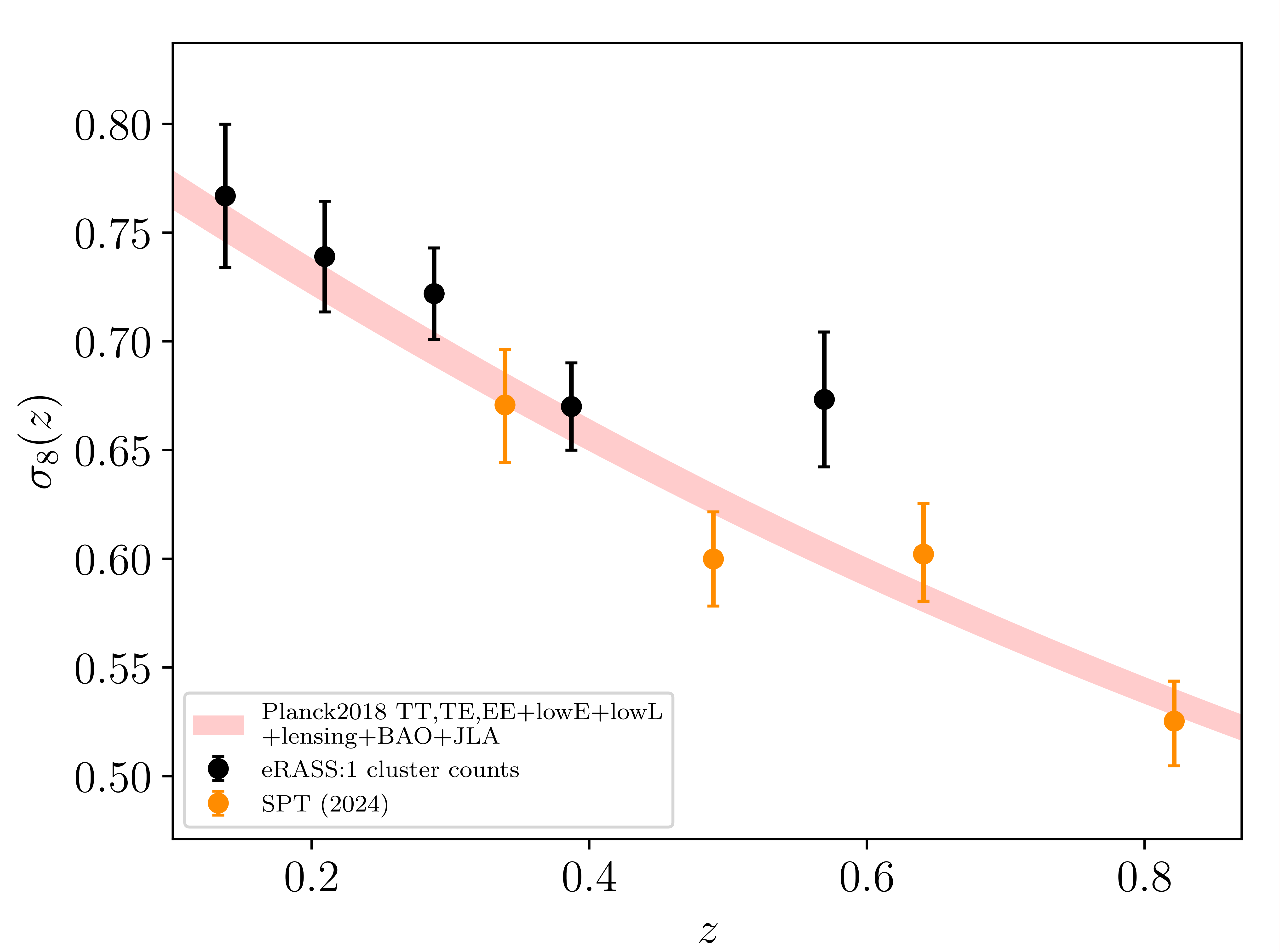

Cluster abundance in good agreement with the predicted growth from Planck CMB

REDSHIFT EVOLUTION OF THE COSMOLOGICAL PARAMETERS

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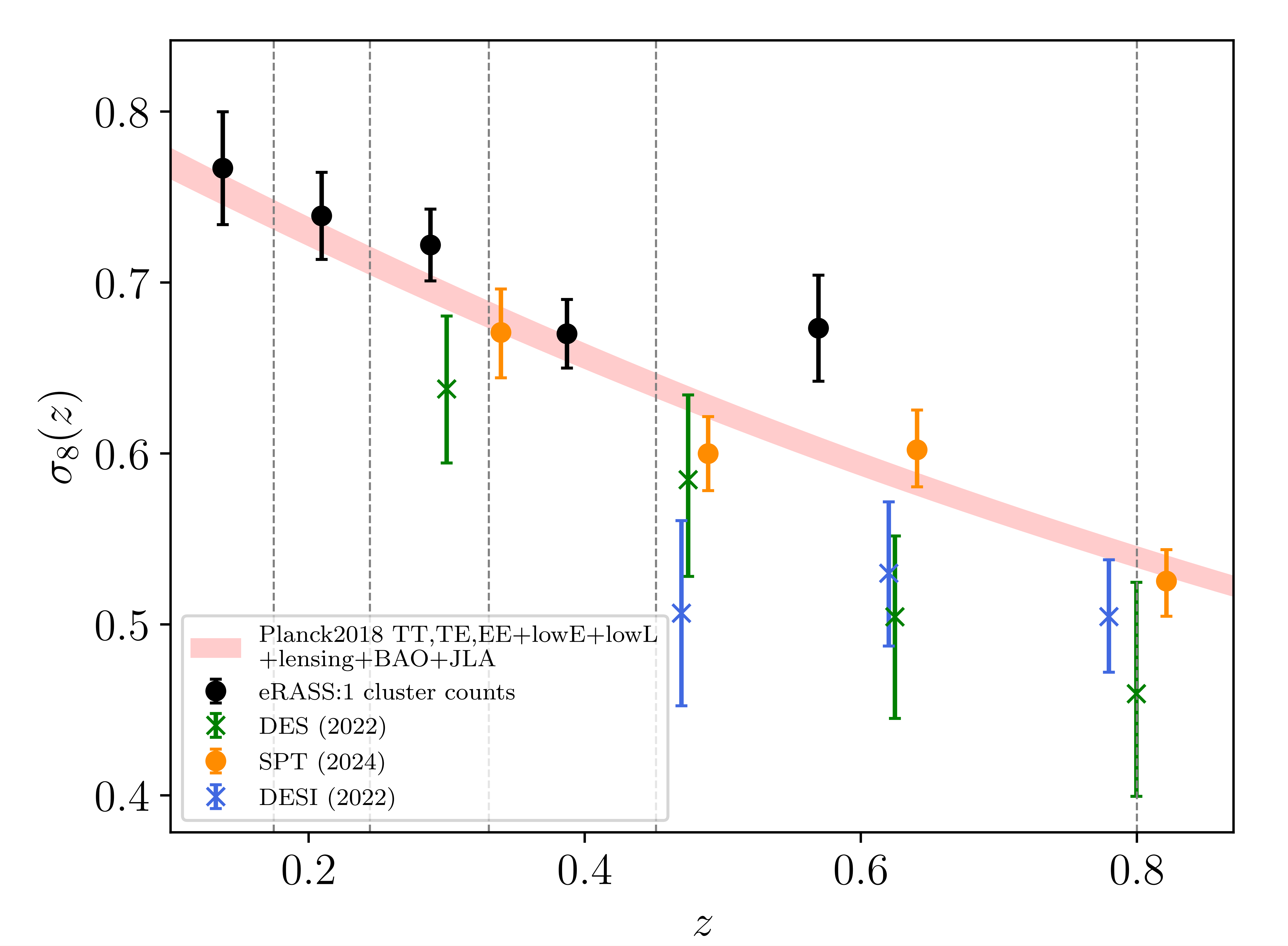

SUMMARY

- **We measured the cosmological parameters with eRASS1, the largest ICM selected cluster sample to date**
  - $\Omega_{\rm m} = 0.29^{+0.01}_{-0.02}$ **(7% precision)**
  - $\sigma_8 = 0.88 \pm 0.02$ **(2% precision)**
  - $\sum m_\nu < 0.22$ **(95% CL)**
- **We do not find traces of the S_8**
- **More results to come on the growth of structures**

Thank you!