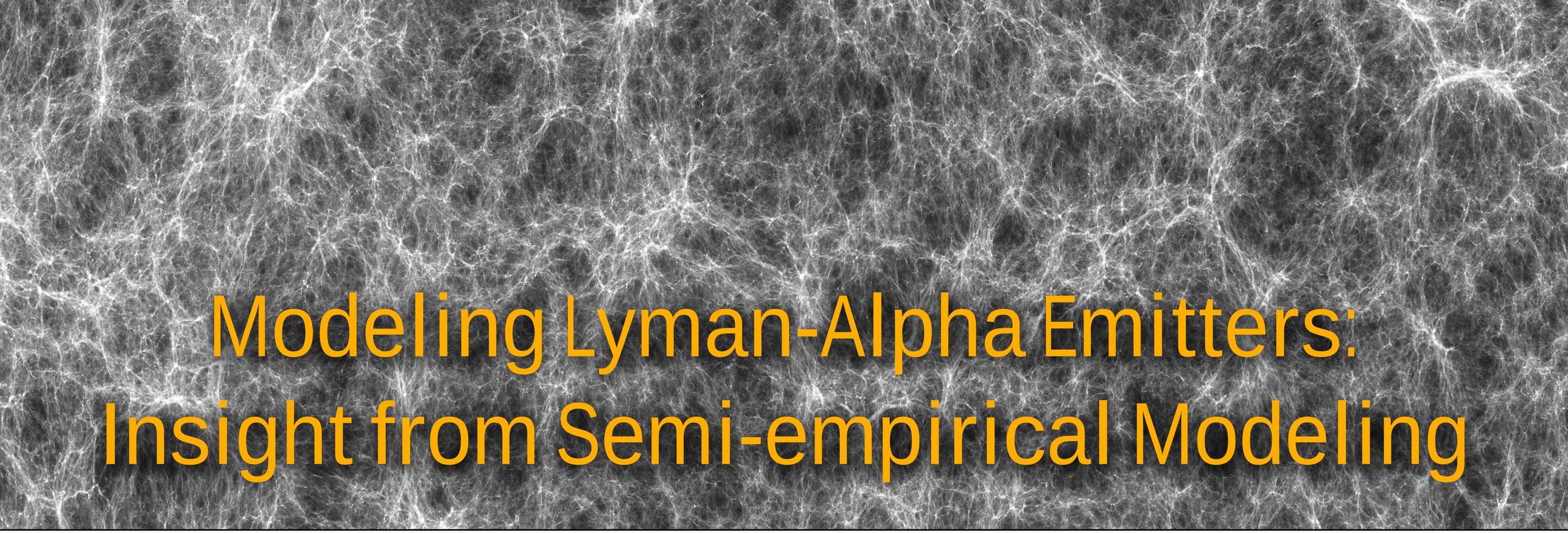


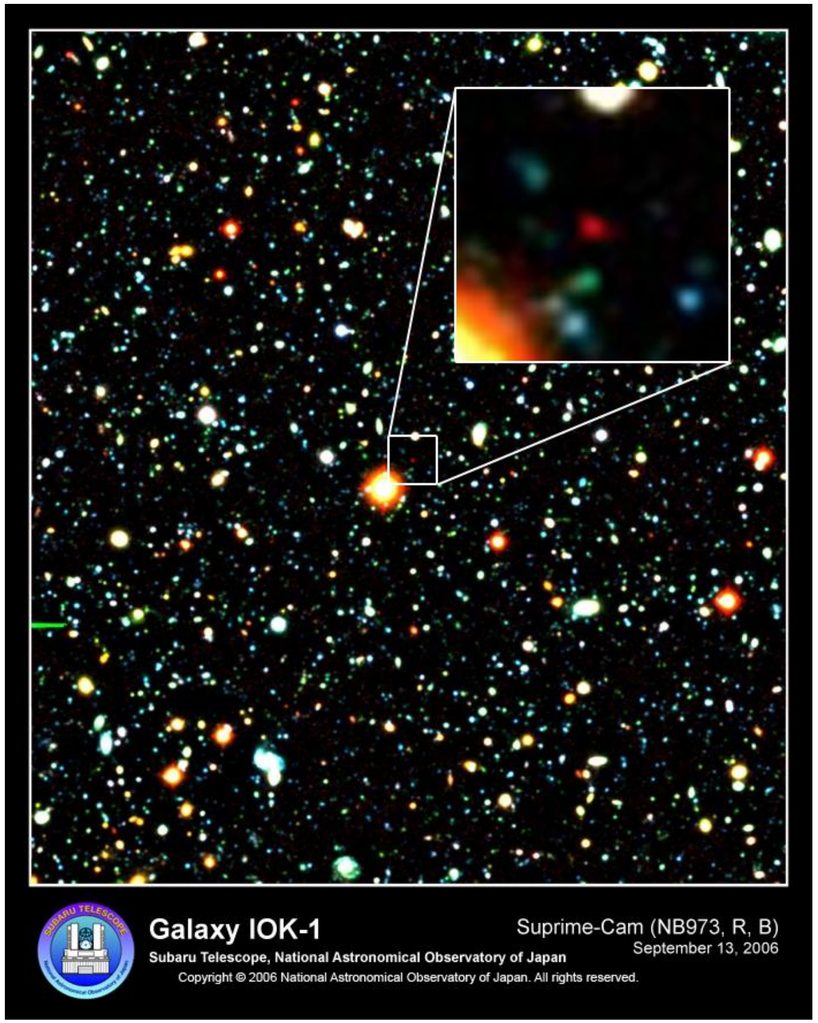
Modeling Lyman-Alpha Emitters: Insight from Semi-empirical Modeling

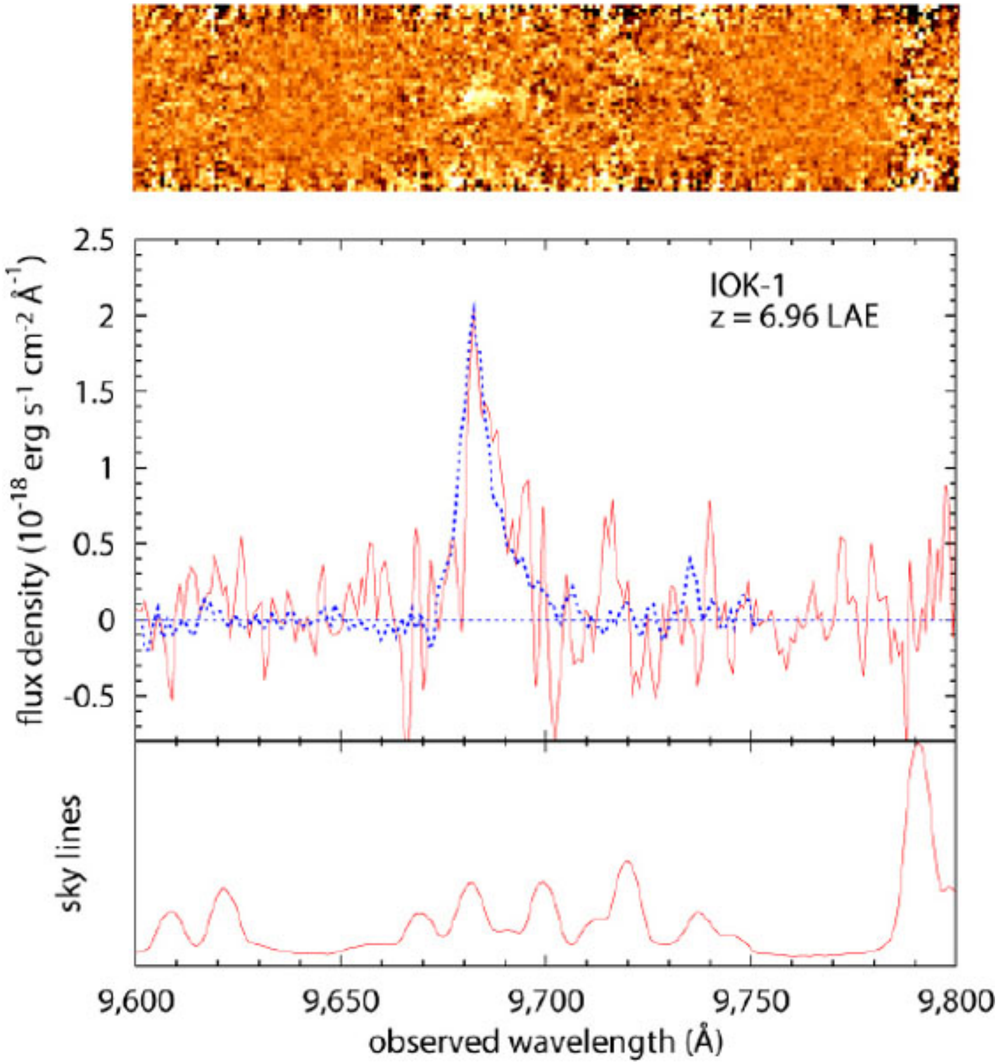
Jaehong Park, Changbom Park, Jaehyun Lee, Juhan Kim (KIAS),
HR5 & ODIN collaboration

Survey Science Group Workshop 2024, High1 Resort, 31/Jan/2024

Lyman Alpha Emitters (LAEs)

Partridge & Peebles (1967) first predicted that the Ly-α line should be a good tracer of star forming galaxies at distant Universe.

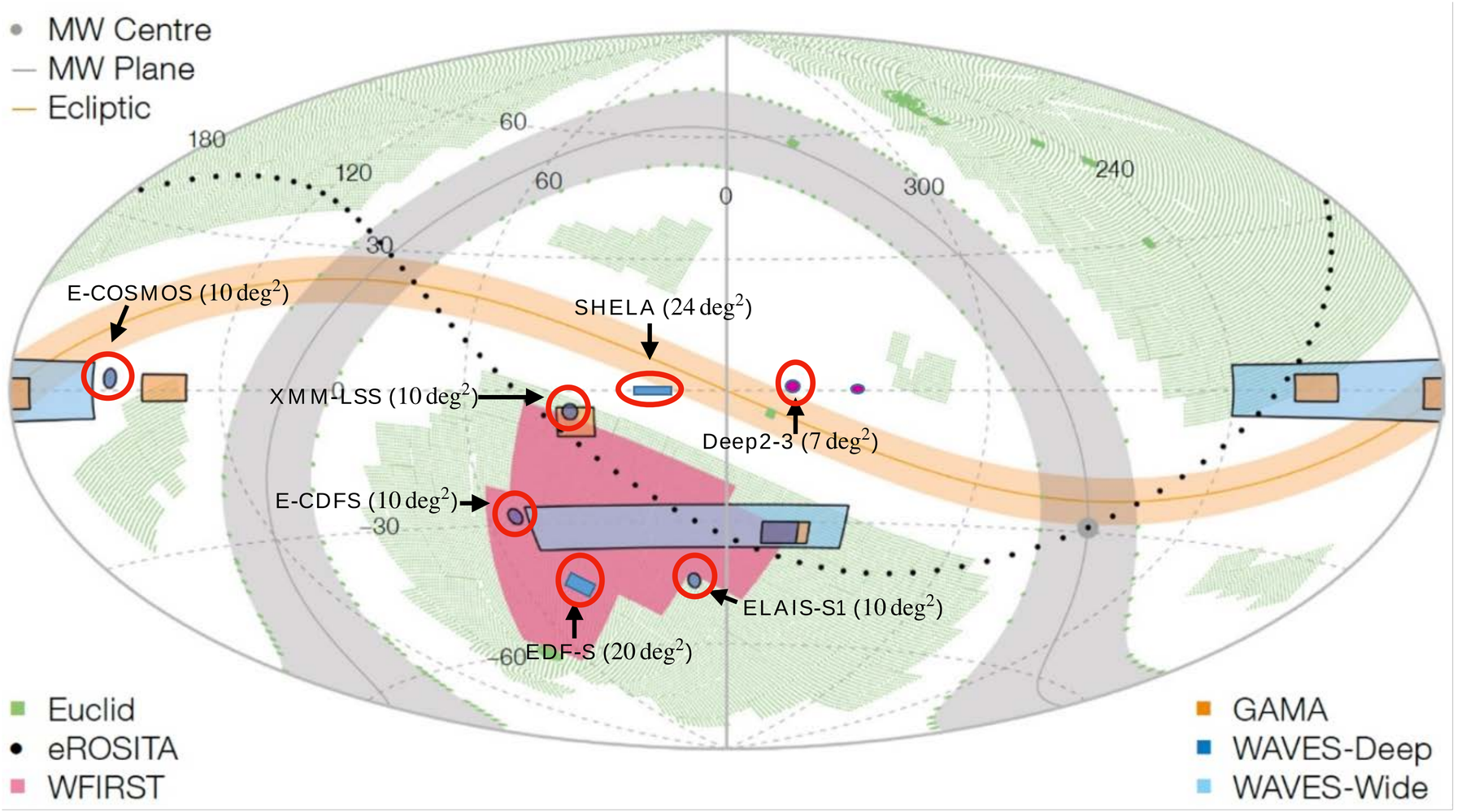




Iye et al., 2006

A new LAE survey

ODIN (One-Hundred-Degree^2 DECam Imaging in Narrow band) survey is a DECam survey to image an unprecedented volume (91 deg^2) with three custom narrow-band filters to sample Ly-α emission at z ~ 2.4, 3.1, and 4.5, straddling the crucial epoch in which the mass assembly in cluster galaxies reached its peak. PI: Kyung-soo Lee & Eric Gawiser



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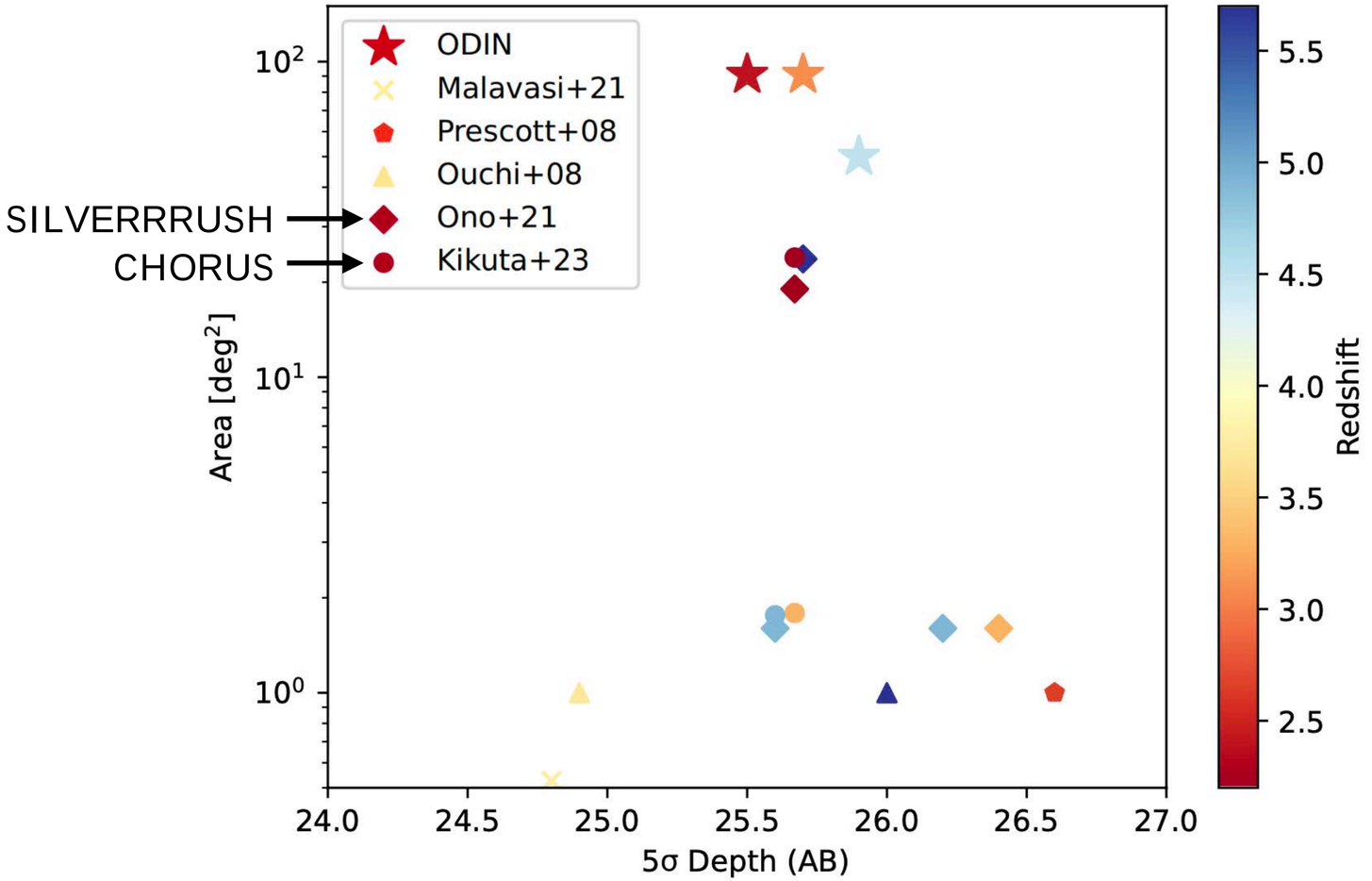


Lee et al., 2023. arXiv.2309.10191

A new LAE survey

Science Goal

ODIN probes the large-scale structure in three narrow cosmic slices straddling the epoch of "Cosmic Noon." Lee et al., 2023. arXiv.2309.10191

- Identify protoclusters and understand their properties and relation between LSS
- Identify Lyman-alpha blob and understand their properties and relation between LSS
- Physical properties of LAEs via LFs, SEDs, and clustering
- Reconstructing the expansion history of the Universe

A new LAE survey

Collaboration

~40 members from KIAS, KASI, SNU, CNU, APCTP (South Korea), Purdue Univ., Rutgers Univ., Penn State Univ., NOIRLab, Univ. of Michigan, U. Texas at Austin, Princeton Univ., Univ. of Maryland, Ohio State Univ., U.C. Santa Cruz, Siena College, Univ. of Massachusetts, Lawrence Berkeley National Laboratory (USA), P.U. Catolica, Perimeter Institute (Canada), Universidad Central de Chile, P.U. Catolica (Chile), IATE (Argentina)

Joint Projects

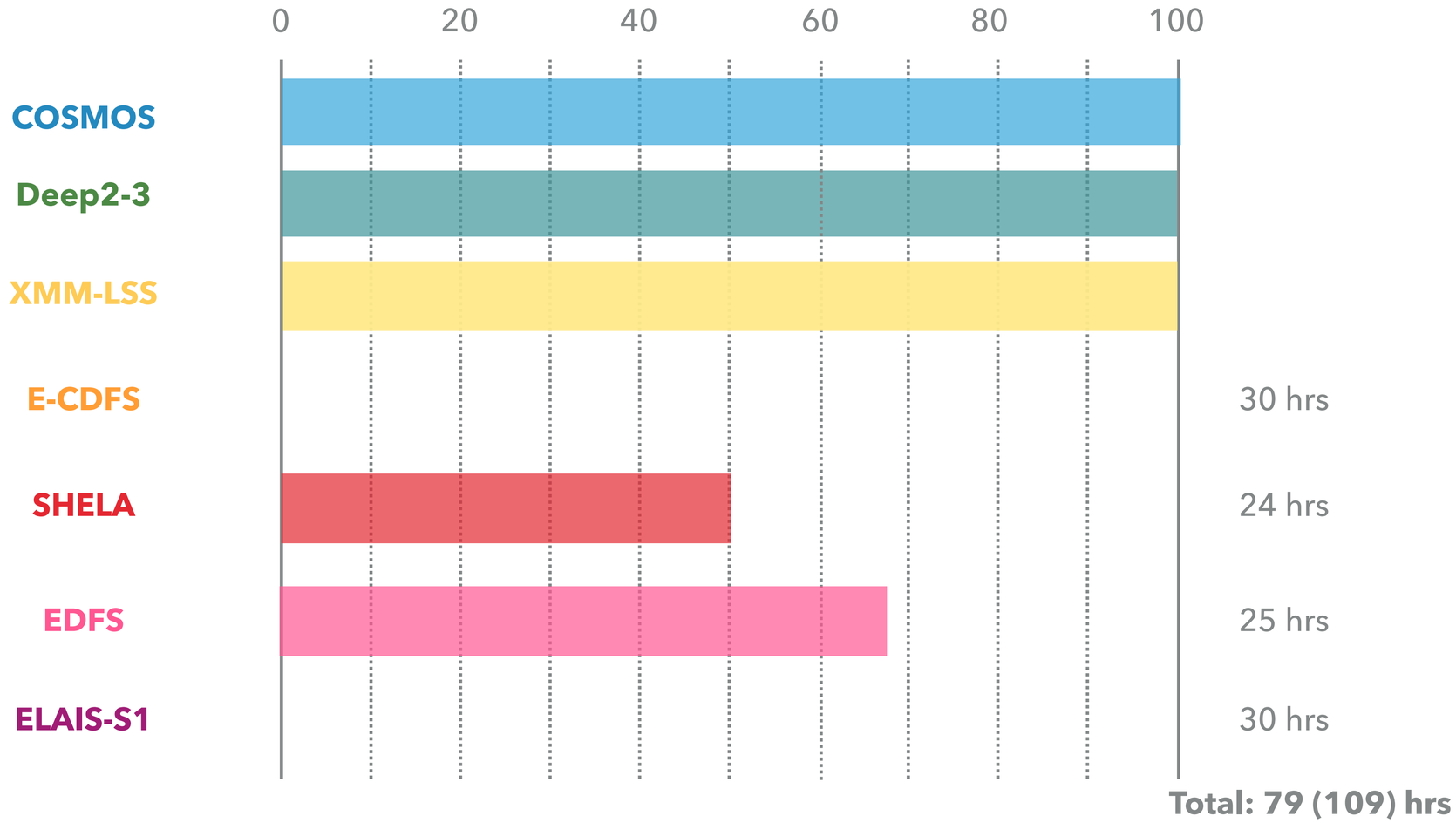
DESI-ODIN
HETDEX-ODIN
Spectroscopic follow-up is available.

A new LAE survey

Current status

N419 FILTER (Z=2.4)

Credit: Recent ODIN ZOOMFEST

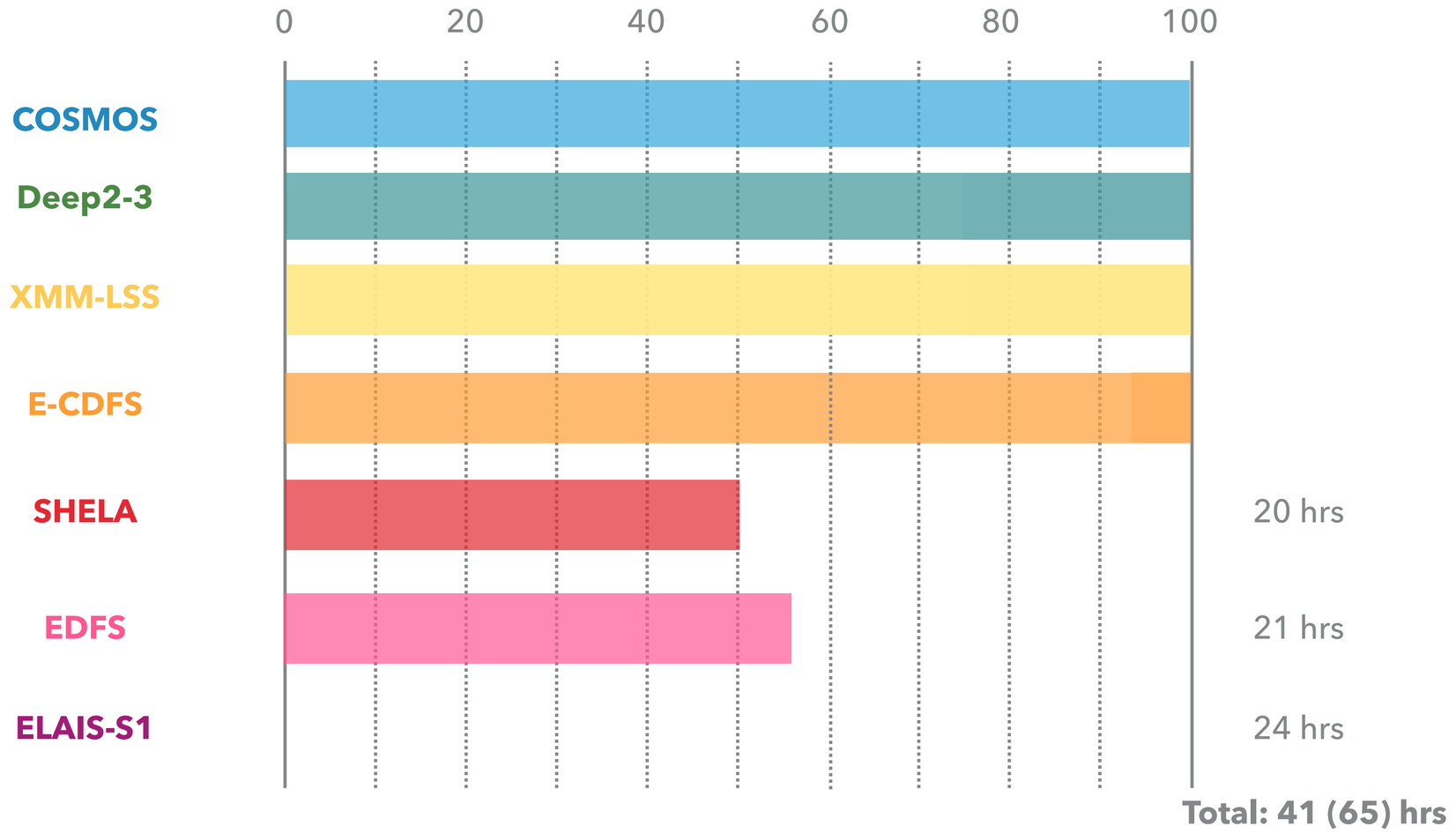


A new LAE survey

Current status

N501 FILTER (Z=3.1)

Credit: Recent ODIN ZOOMFEST

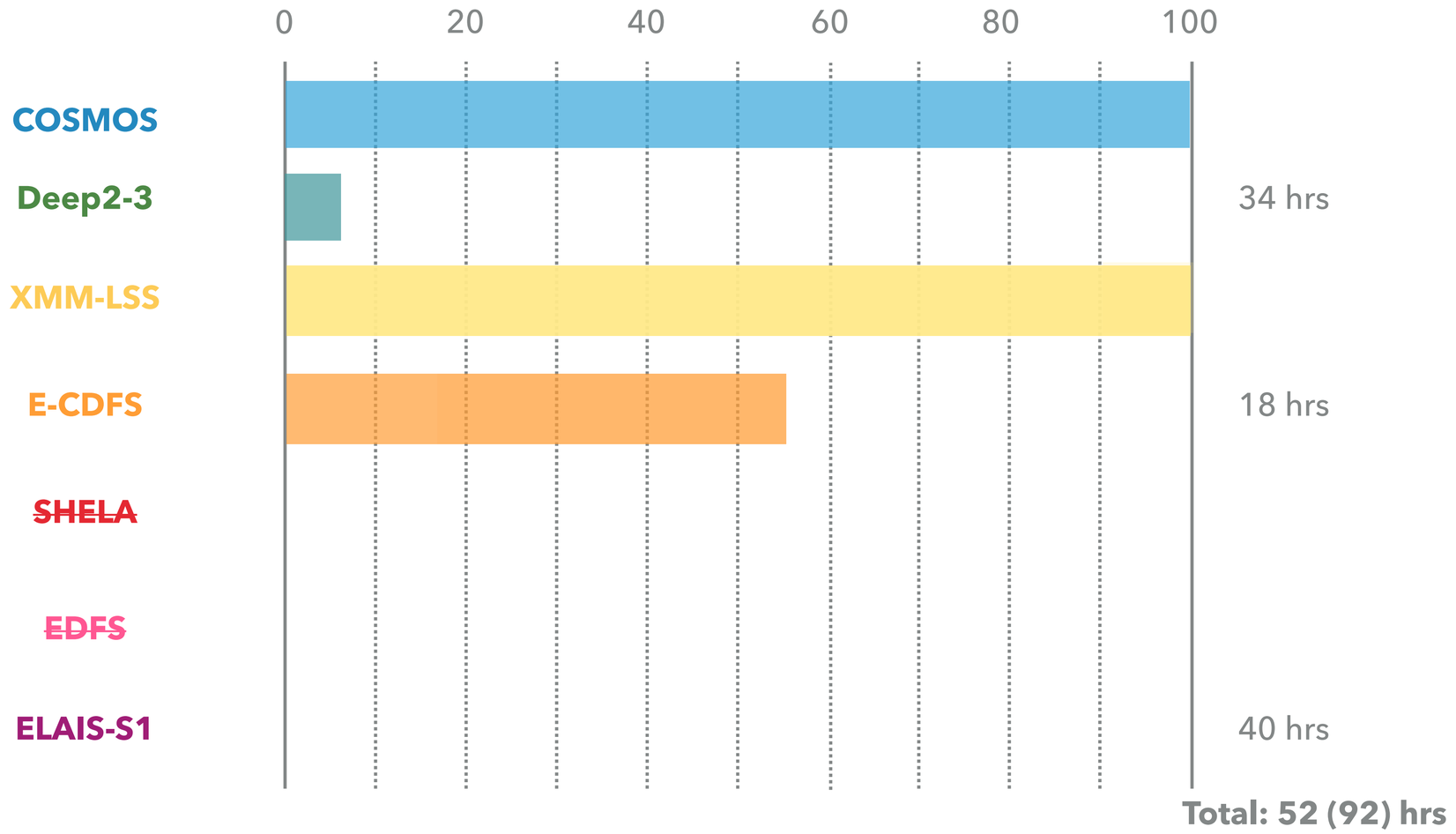


A new LAE survey

Current status

N673 FILTER (Z=4.5)

Credit: Recent ODIN ZOOMFEST



A new LAE survey

Current status

ODIN DATA/CATALOG SUMMARY (UPDATED)

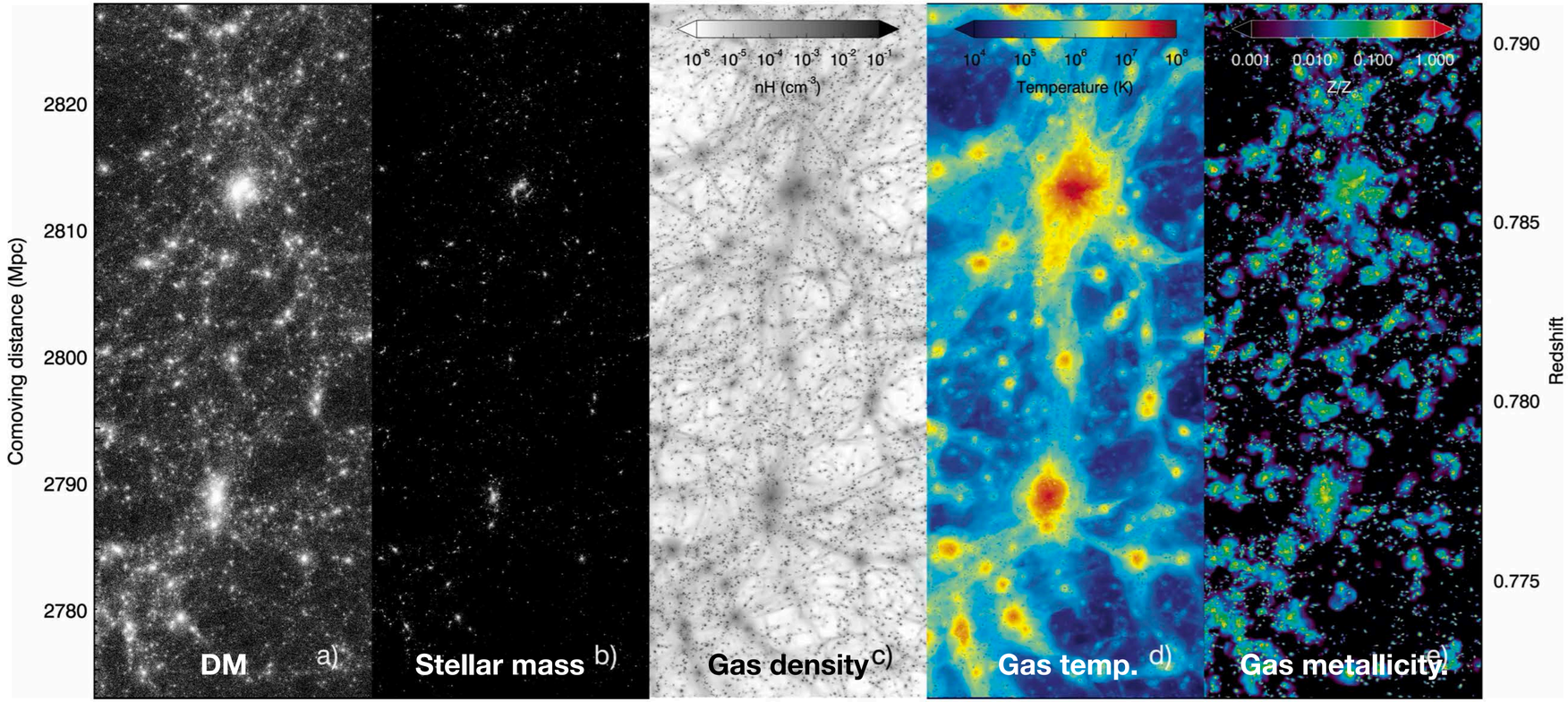
Credit: Recent ODIN ZOOMFEST

Done Almost Done Preliminary Not Done

Filter	Field	obs	Reduction	catalog	LAE	LAB
N419	COSMOS					
	Deep2-3					
	XMM-LSS					
	SHELA-P12					
	SHELA-P78					
N501	COSMOS					
	Deep2-3					
	XMM-LSS					
	SHELA-P12		STM in progress			
	SHELA-P78					
	CDFS					
N673	COSMOS					
	XMM-LSS					

Cosmological Simulations

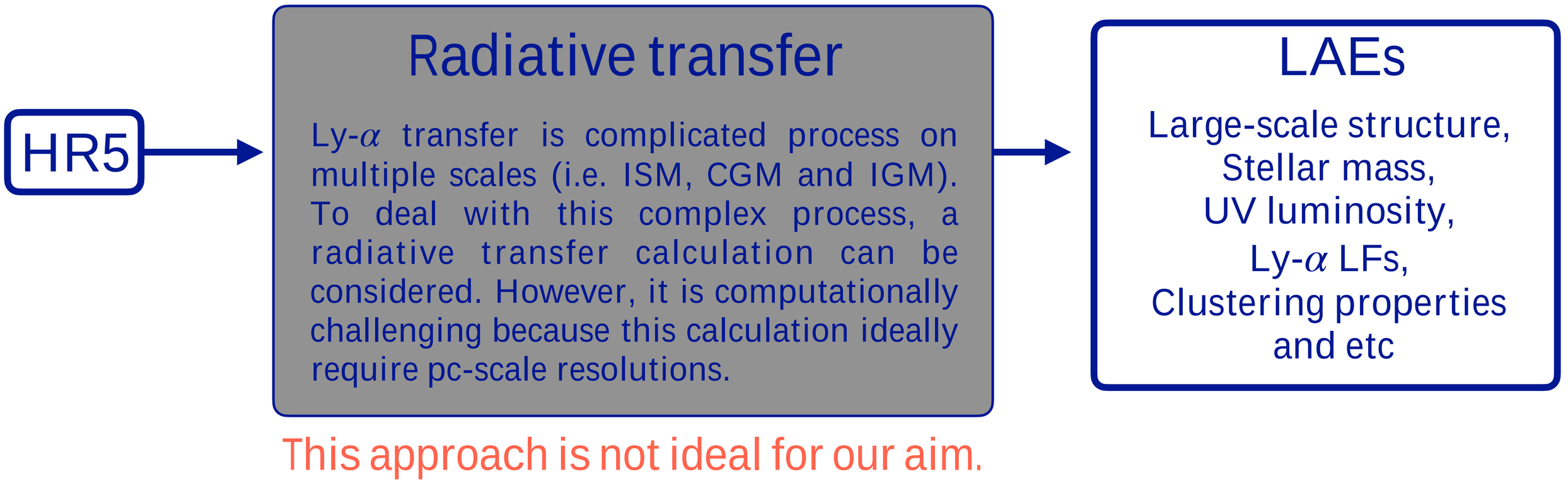
Horizon Run 5 (HR5) : Cosmological hydrodynamical simulation
- Total box size: 1 cGpc^3
- Zoom-in region: 1049 cMpc x 119 cMpc x 127 cMpc
- Resolves down to 1kpc



Lee et al., 2021

The full simulation box of 1cGpc^3 provides the long-wavelength modes of the density power spectrum, which gives the large scale power up to ~ 100 cMpc scale.

Modelling LAEs using an empirical approach



This approach is not ideal for our aim.

Modelling LAEs using an empirical approach

HR5

An empirical approach

Alternatively we can utilize an empirical relation between UV luminosity and Ly-α Equivalent width (e.g., Dijkstra&Wyithe, 2012, Gronke+2014, Mason+2018, Weinberger+2019, Morales+2021).
Although this approach might not capture the intricate details of physical properties, but it allows us to overcome the computational challenges.

LAEs

Large-scale structure,
Stellar mass,
UV luminosity,
Ly-α LFs,
Clustering properties
and etc

Insight from an empirical study

Started from the general assumption that the observed number of LAEs and LBGs (i.e., UV-selected galaxies) are connected.

Ly-a luminosity function ← UV luminosity function (e.g. a Schechter function)

$$\Phi(L_\alpha)\mathrm{d}L_\alpha = \mathrm{d}L_\alpha \times F \times \int_{M_{\min}}^{M_{\max}} \mathrm{d}M_{\mathrm{UV}}\,\phi(M_{\mathrm{UV}})\,P(L_\alpha|M_{\mathrm{UV}})$$

The conditional probability density function of Ly-a for a given M_{UV}

$$P(L_\alpha|M_{\mathrm{uv}}) = \begin{cases} P(x|M_{\mathrm{UV}})\dfrac{\partial \mathrm{REW}}{\partial L_\alpha}, & x \in (x_{\min}, x_{\max}), \\ 0, & \text{otherwise}, \end{cases}$$

$$P(\mathrm{REW}|M_{\mathrm{UV}}) = \mathcal{N}\exp\left[\frac{-\mathrm{REW}}{\mathrm{REW_c}(M_{\mathrm{UV}})}\right]$$

Free parameters

$$\mathrm{REW_c}(M_{\mathrm{UV}}) = \mathrm{REW_{c,0}} + (\mathrm{d\,REW_c}/\mathrm{d}M_{\mathrm{UV}})\Delta M + (\mathrm{d\,REW_c}/\mathrm{d}z)\Delta z$$

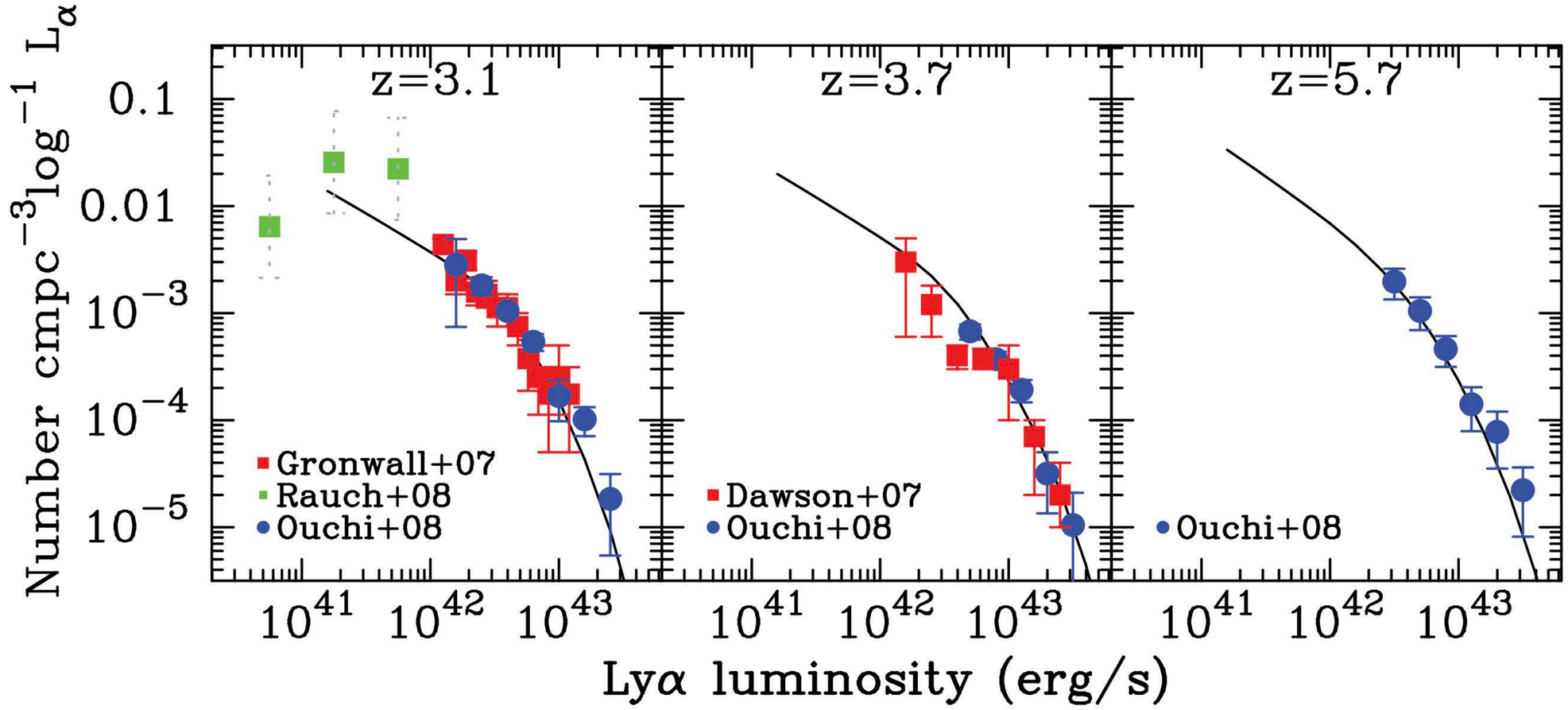
$$\Delta M \equiv M_{\mathrm{UV}} + 21.9 \text{ and } \Delta z = z - 4.0$$

Dijkstra & Wyithe (2012)

Insight from an empirical study

With 3 Free parameters

+ 9 UV LF parameters (3 Schechter parameters x 3 redshifts)
+ 1 normalization parameter (F)



Dijkstra & Wyithe (2012)

Modelling LAEs in HR5: An empirical approach

Following Weinberger+2019, we draw a random rest-frame equivalent width (REW) from the conditional probability $P(L_\alpha | M_{\rm UV})$ (e.g., Dijkstra & Wyithe 2012, Gronke+2014, Mason+2018)

HR5

$$L_{\alpha,\rm obs} = C \times \mathrm{REW} \times L_{\rm UV,\nu}$$

where $C \equiv (\nu_\alpha/\lambda_\alpha)(\lambda_{\rm UV}/\lambda_\alpha)^{-\beta-2}$

ν_α : the Ly-α transition frequency

λ_α : the corresponding Ly-α wavelength

$\lambda_{\rm UV}$: the rest-frame wavelength at UV luminosity

β : the UV spectral index

Modelling LAEs in HR5: An empirical approach

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Dust modelling

Observed UV luminosity

SED ← Stellar population Synthesis model

Intrinsic UV luminosity

HR5

FSPS (Flexible Stellar Population Synthesis; Conroy, Gunn, & White 2009, Conroy & Gunn 201)

Taking an empirical dust-correction model following Illustris TNG simulations (Vogelsberger+2020)

Modelling LAEs in HR5: An empirical approach

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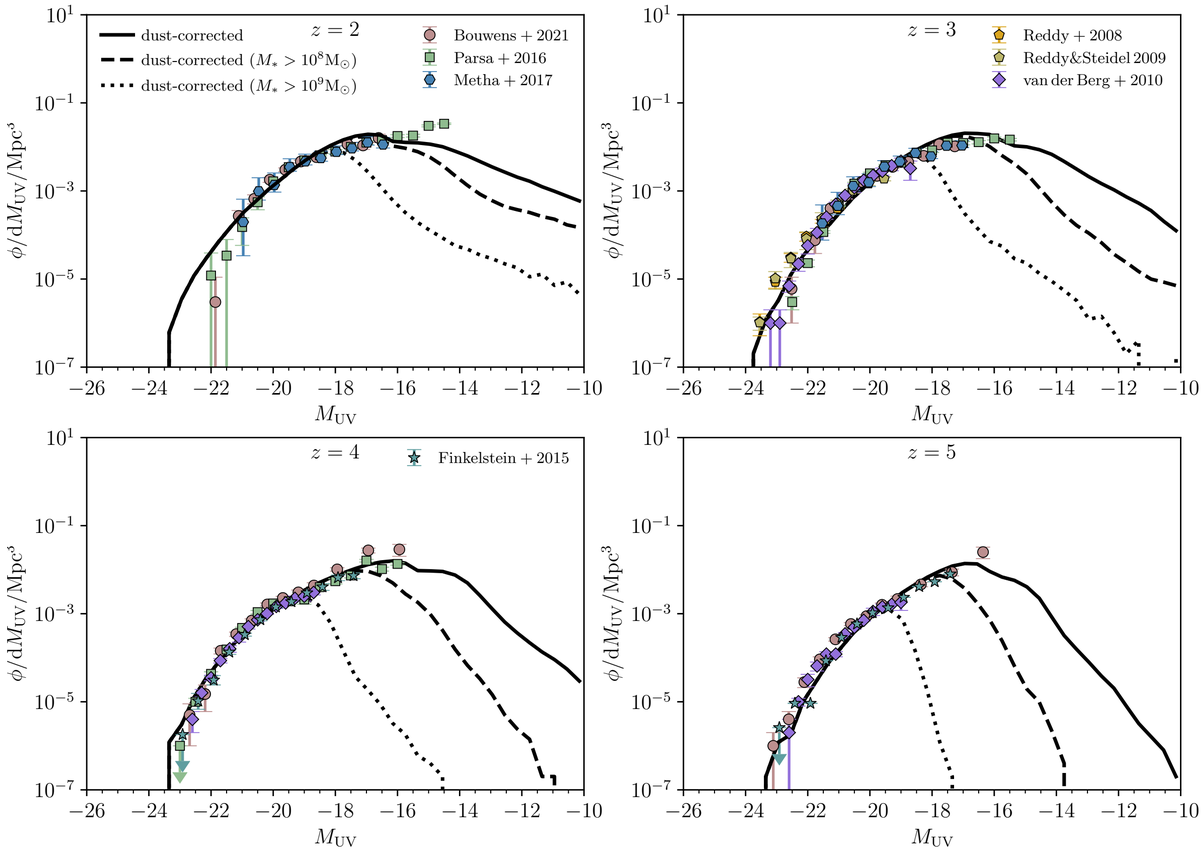

Modelling LAEs in HR5: An empirical approach

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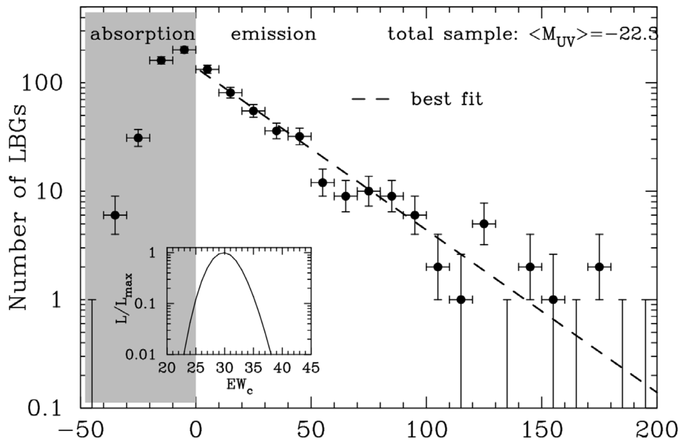
HR5



Empirical relation

$$P(\mathrm{REW}\,|\,M_{\rm UV}) = \frac{A(M_{\rm UV})}{EW_{\rm c}(M_{\rm UV})} \exp\left[\frac{-\mathrm{REW}}{\mathrm{REW_C(M_{UV})}}\right] H(REW) + \left[1 - A(M_{\rm UV})\right] \delta(REW),$$

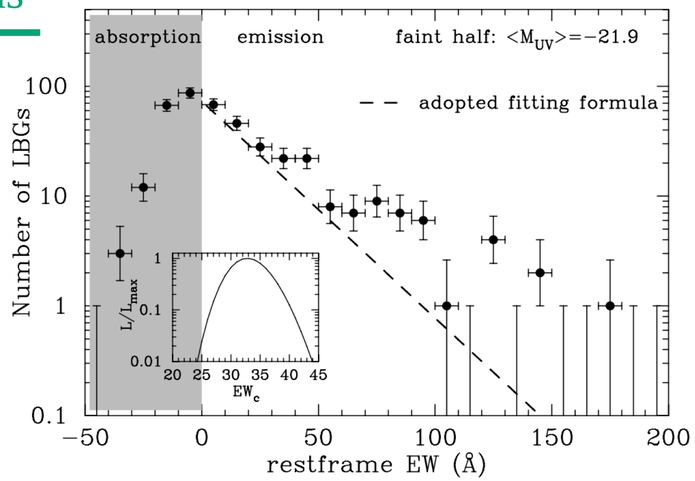
where $\mathrm{REW_c}(M_{\rm UV}) = \underset{\rm EW1}{31} + \underset{\rm EW2}{12}\tanh\left[4(M_{\rm UV} + 20.25)\right]$ and

$$A(M_{\rm UV}) = \underset{\rm A1}{0.65} + \underset{\rm A2}{0.1}\tanh\left[3(M_{\rm UV} + 20.25)\right]$$

We adopt Mason+2018 model to reproduce Ly-a luminosity functions without the unphysical normalization parameter.

EW distribution from observations

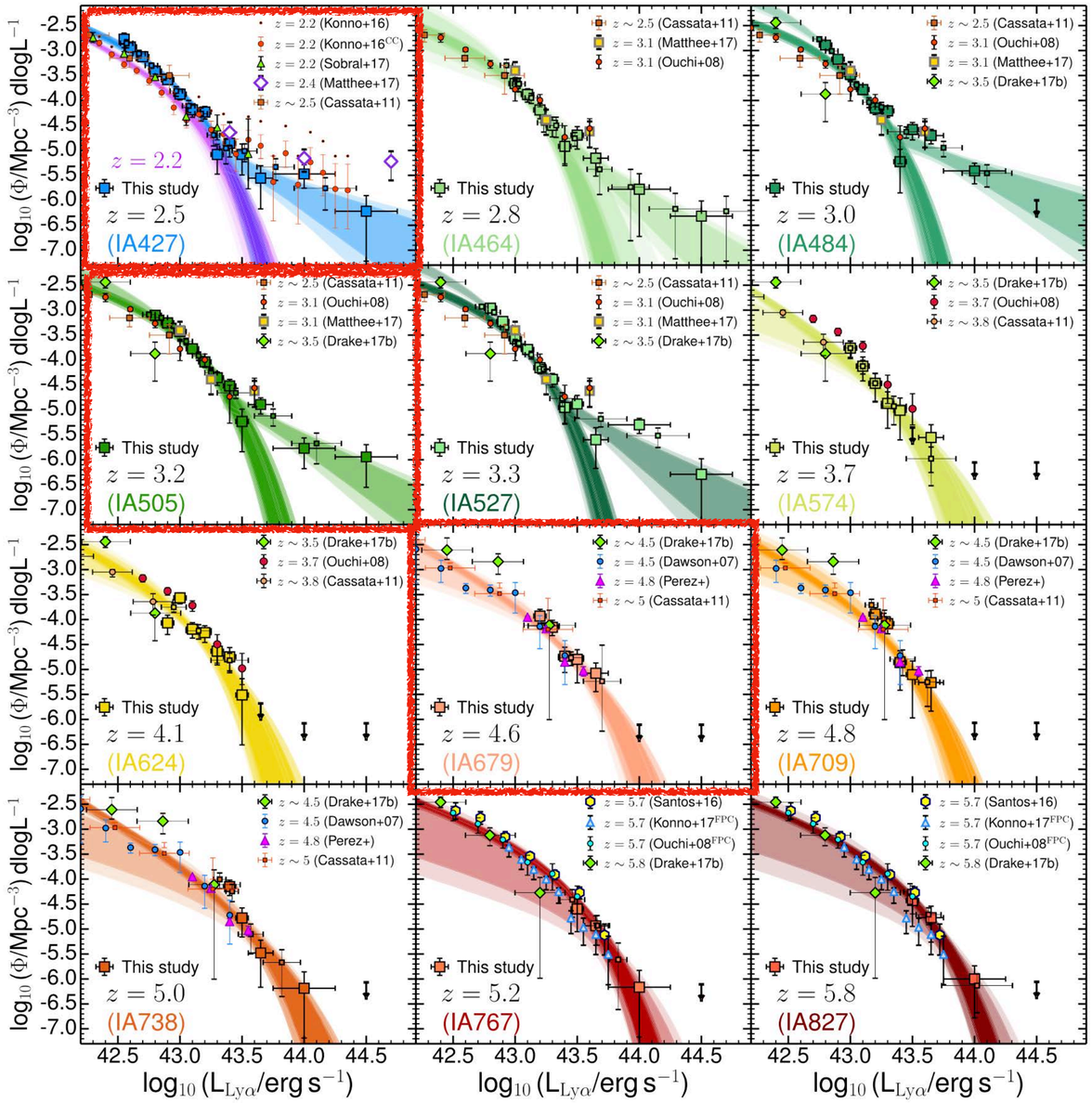
EW distribution depends on Muv and redshift (e.g., Shapley+2003, Stark+2010 and Cassata+2015)



Dijkstra & Wyithe (2012)

Modelling LAEs in HR5: An empirical approach

Finding Best-fit: SC4K data ($z \sim 2$ to 6; Sobral et al. 2018)



Modelling LAEs in HR5: An empirical approach

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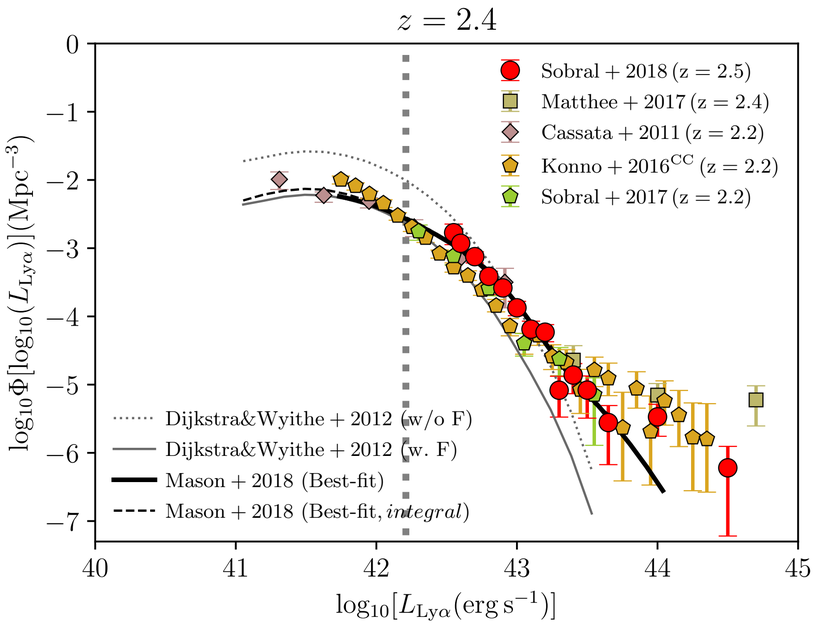
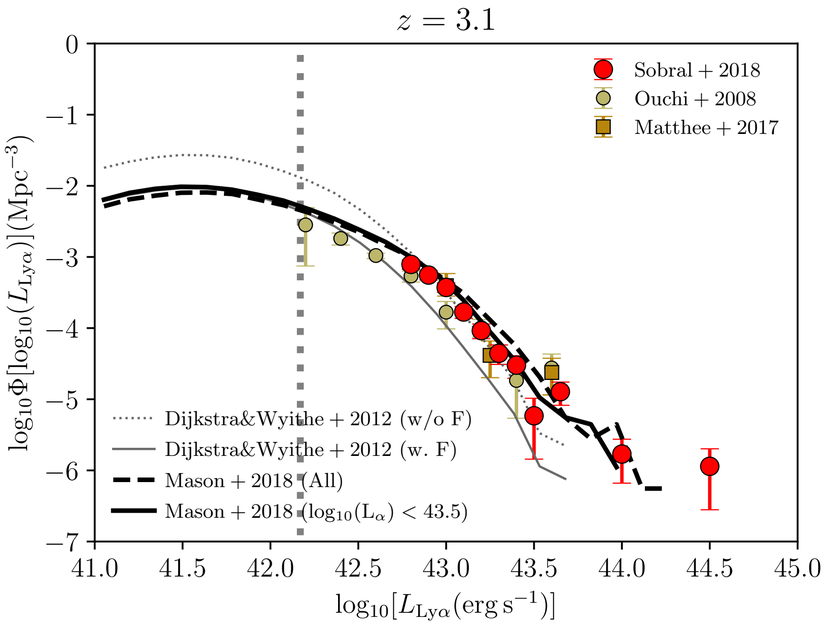
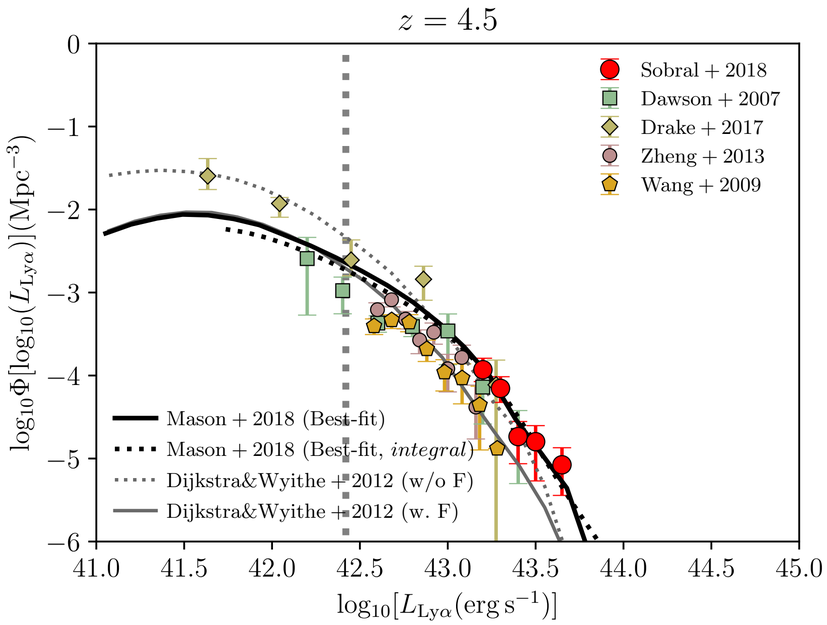


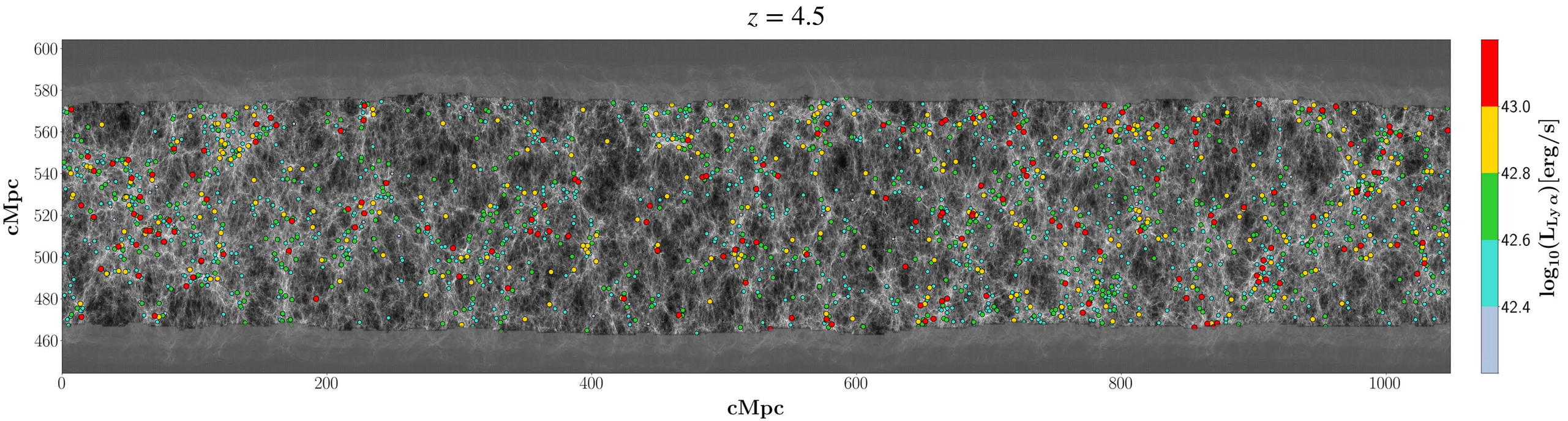




Best-fit parameters

Mason+2018	$z = 2.4$	$z = 3.1$	$z = 4.5$
$A1 = 0.65$	$A1 = 0.6$	$A1 = 0.4$	$A1 = 0.3$
$A2 = 0.1$	$A2 = 0.1$	$A2 = 0.1$	$A2 = 0.1$
$EW1 = 31$	$EW1 = 24.5$	$EW1 = 34.7$	$EW1 = 52.4$
$EW2 = 12$	$EW2 = 4.8$	$EW2 = 7.1$	$EW2 = 10.3$

Modelling LAEs in HR5: An empirical approach



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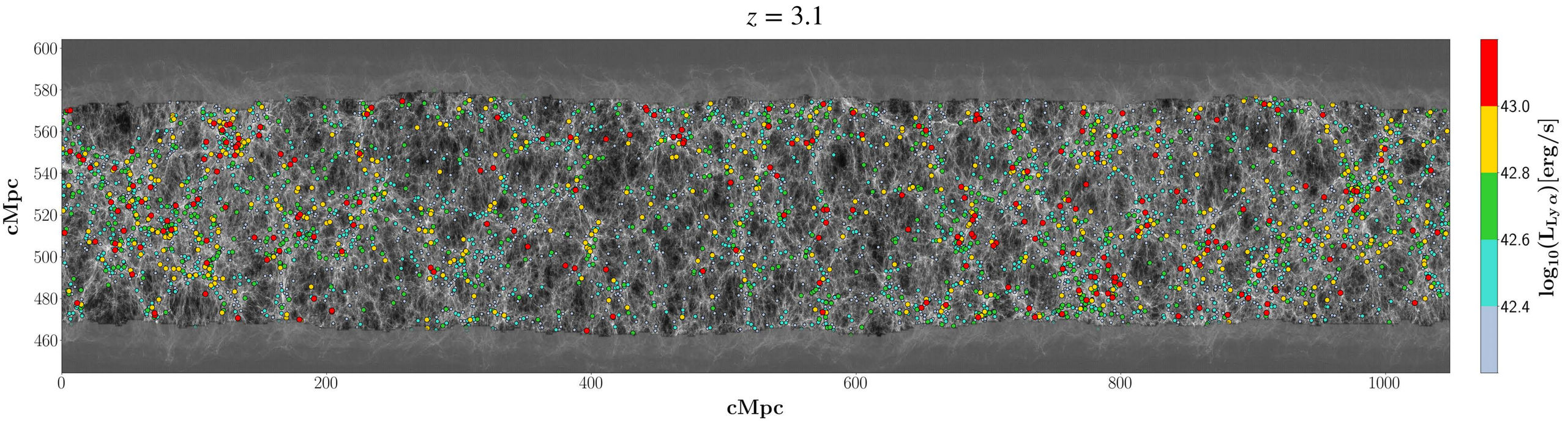
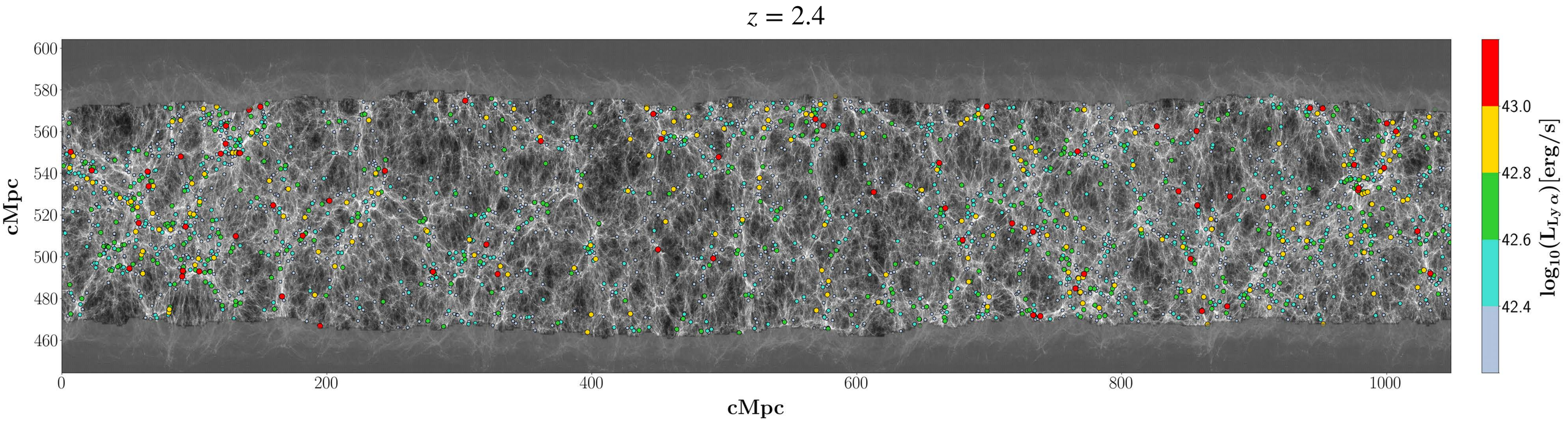
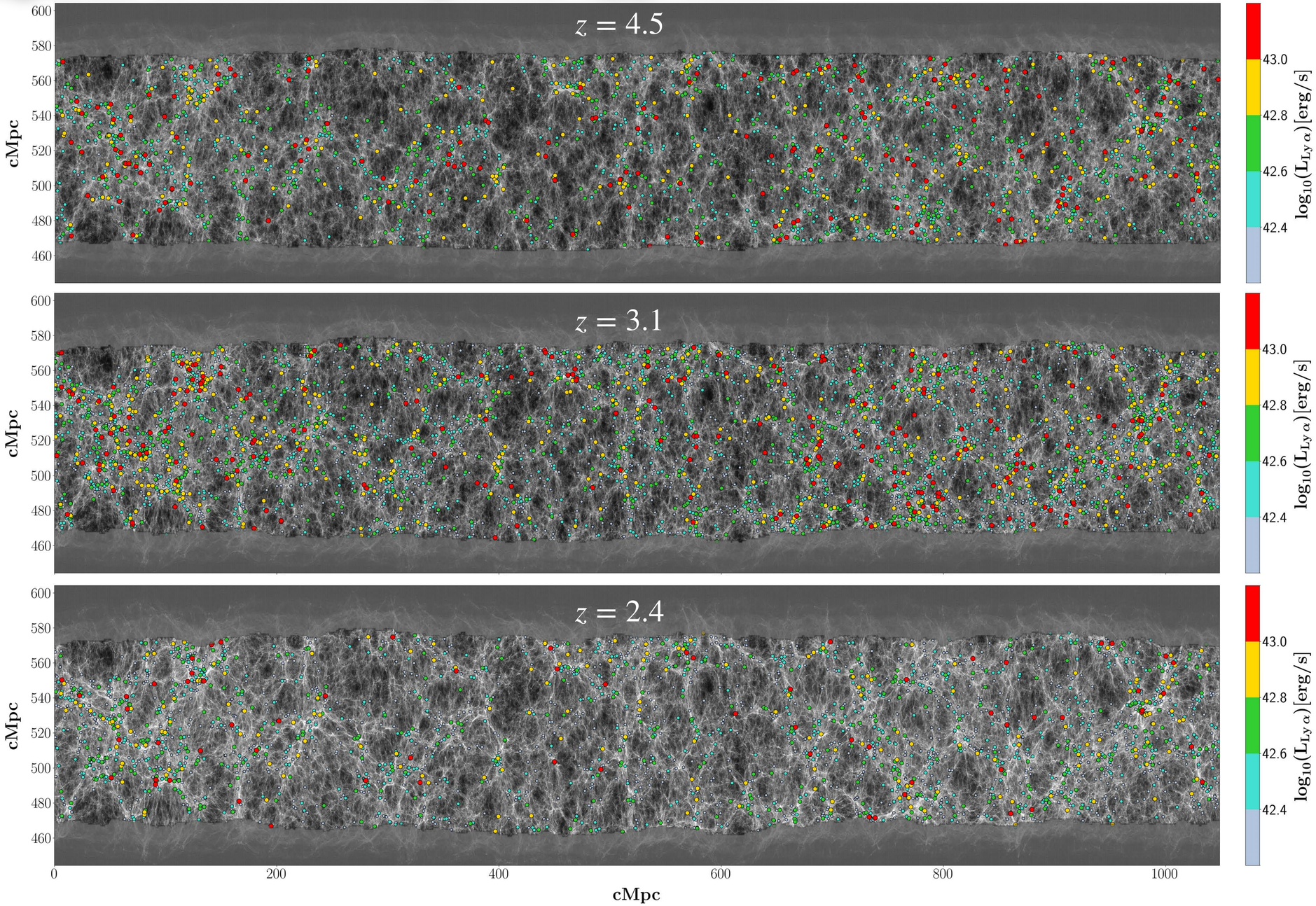


Modelling LAEs in HR5: An empirical approach

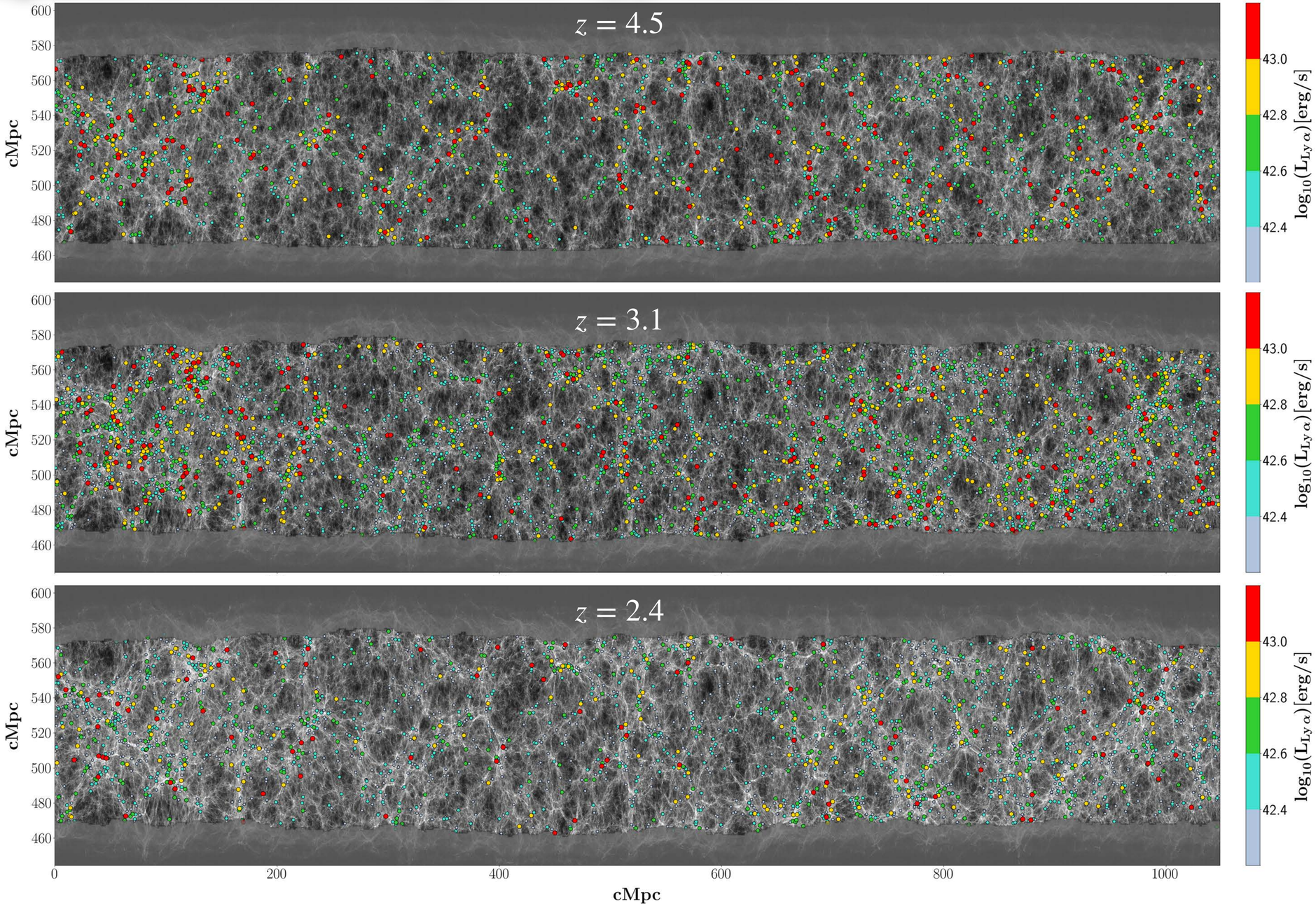


LAE catalogs are now available.
100 catalogs with different random generations from Mason+2018 model.

Modelling LAEs in HR5: An empirical approach

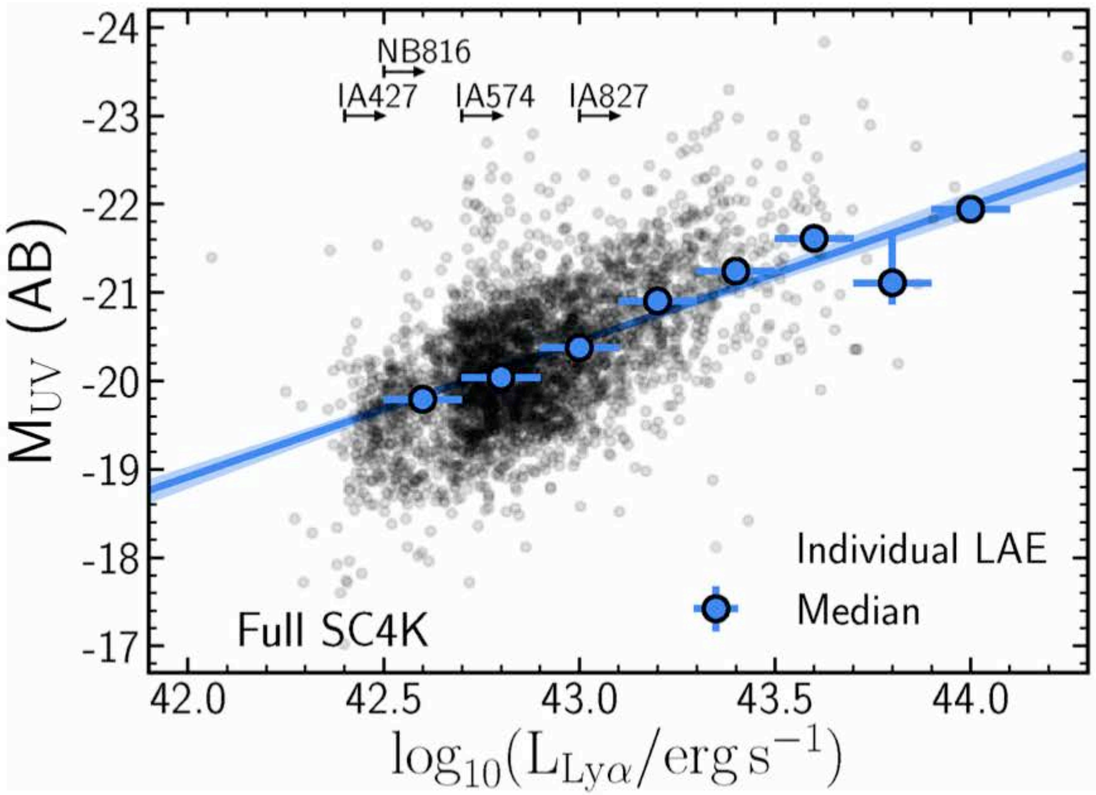


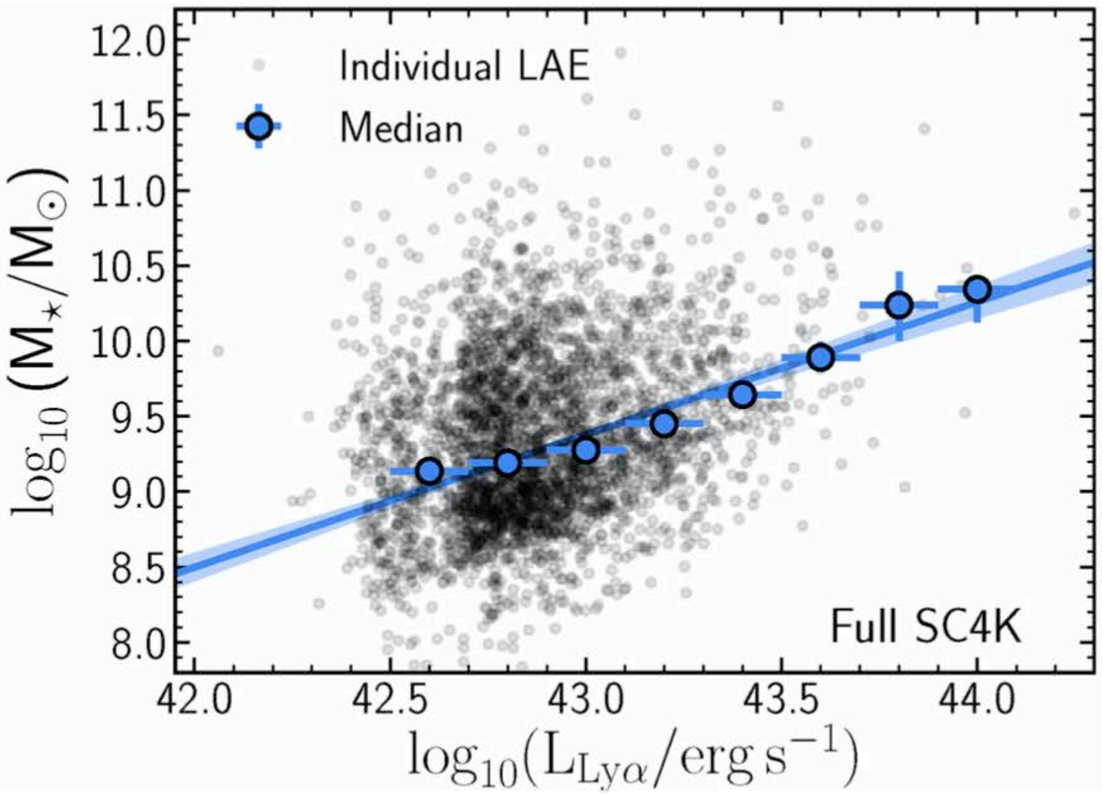
Modelling LAEs in HR5: An empirical approach



Modelling LAEs in HR5: An empirical approach

Comparing results with SC4K data ($z \sim 2$ to 6; Santos et al. 2021)

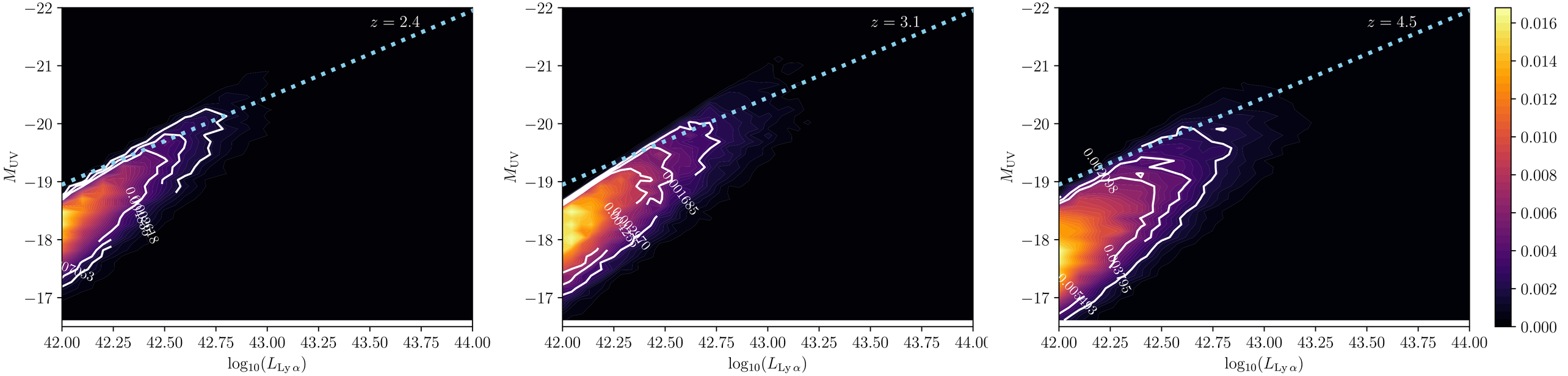




Modelling LAEs in HR5: An empirical approach

Comparing results with SC4K data ($z \sim 2$ to 6; Santos et al. 2021)

L_α vs $M_{\rm UV}$



EW cut : 50 Å

Modelling LAEs in HR5: An empirical approach

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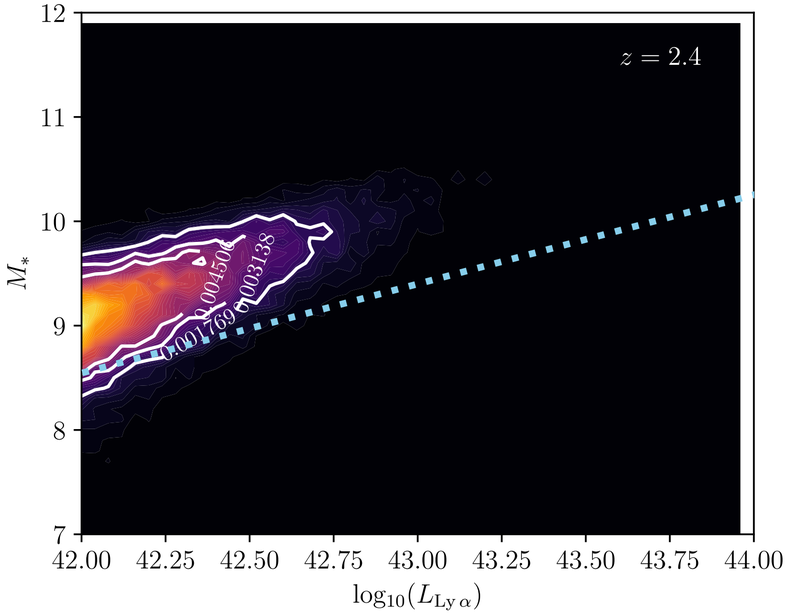
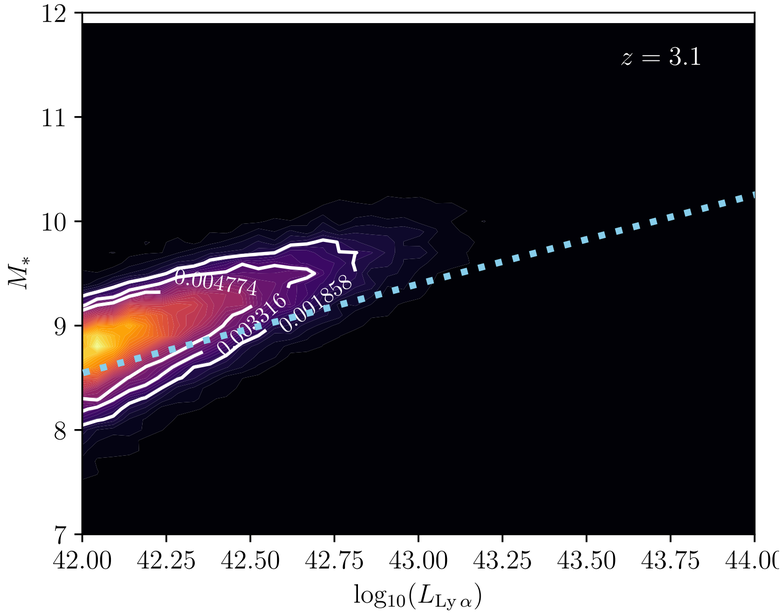
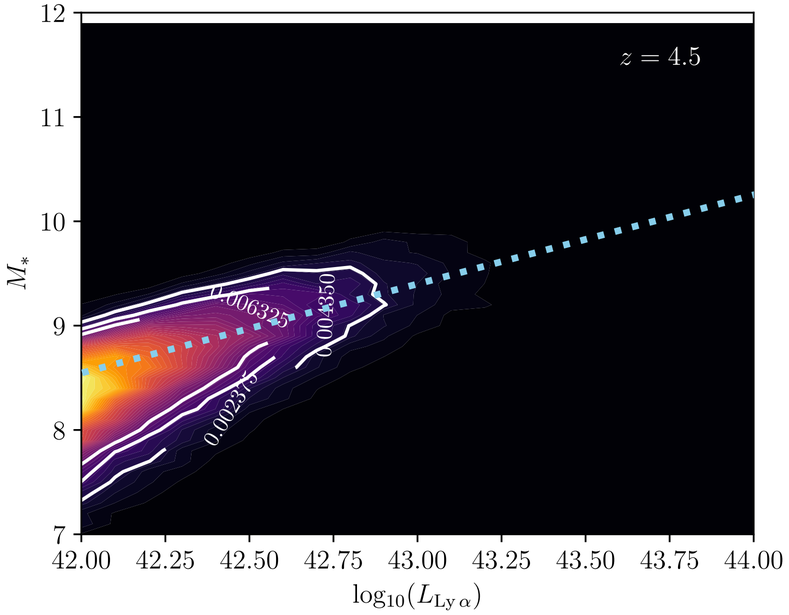
L_α vs M_*





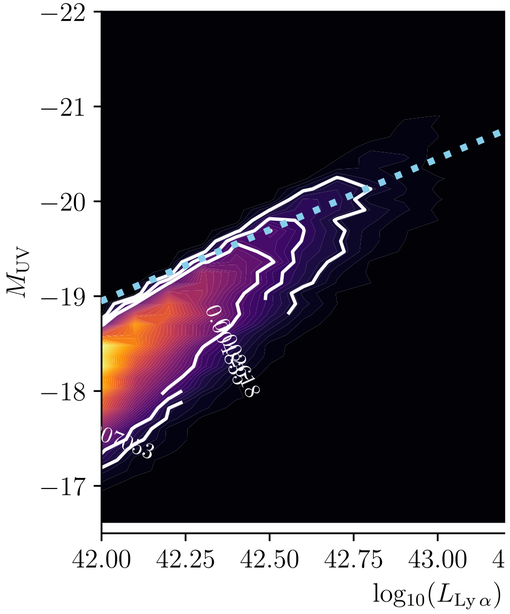


EW cut : 50 Å

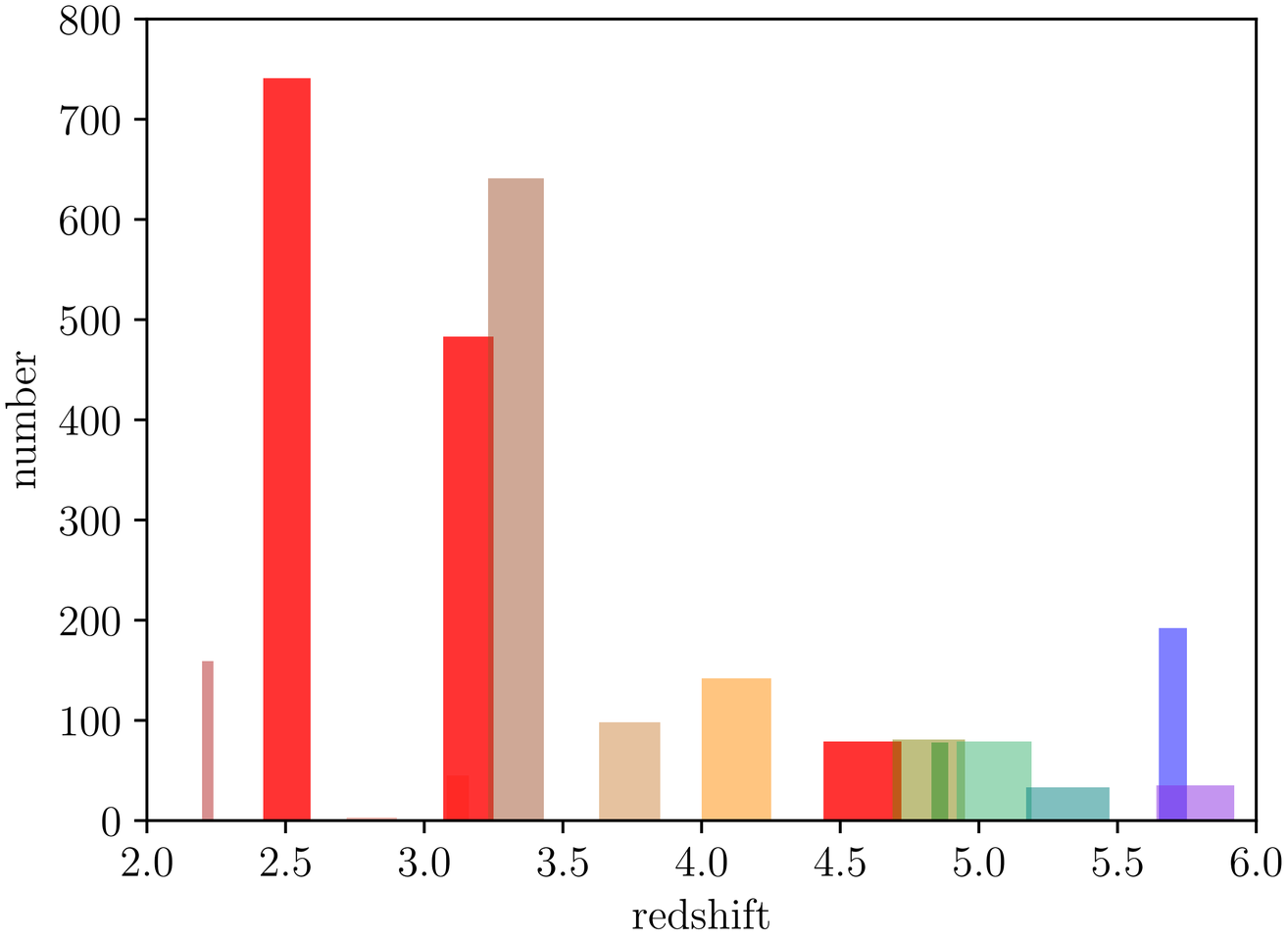
Modelling LAEs in HR5: An empirical approach

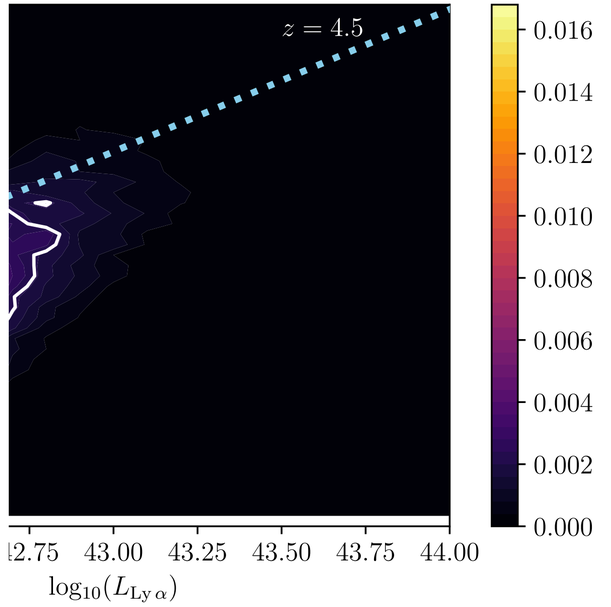
Comparing results with SC4K data ($z \sim 2$ to 6; Santos et al. 2021)

L_α vs M_*



EW cut : 50 Å

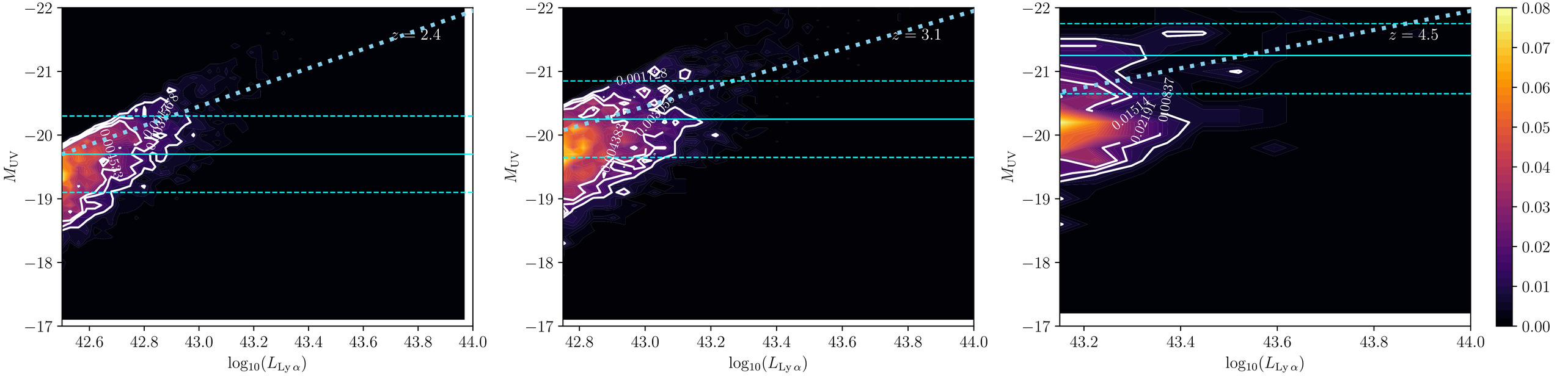




Modelling LAEs in HR5: An empirical approach

Comparing results with SC4K data ($z \sim 2$ to 6; Santos et al. 2021)

L_α vs $M_{\rm UV}$



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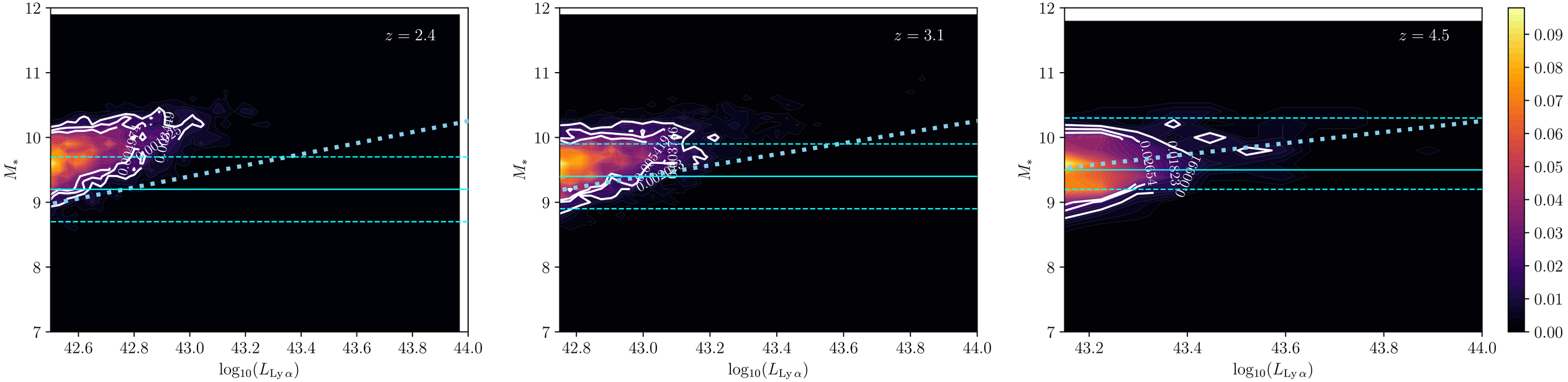
Modelling LAEs in HR5: An empirical approach

Comparing results with SC4K data ($z \sim 2$ to 6; Santos et al. 2021)

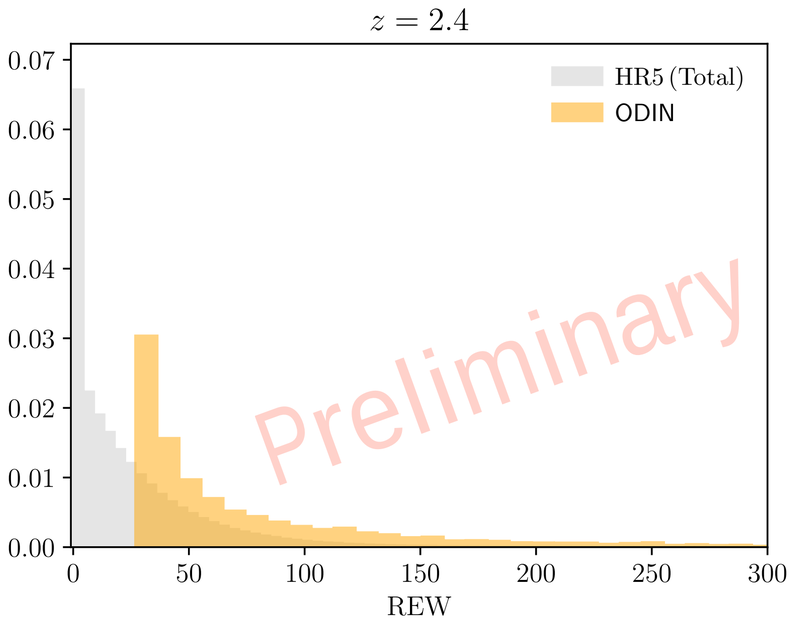
L_α vs M_*

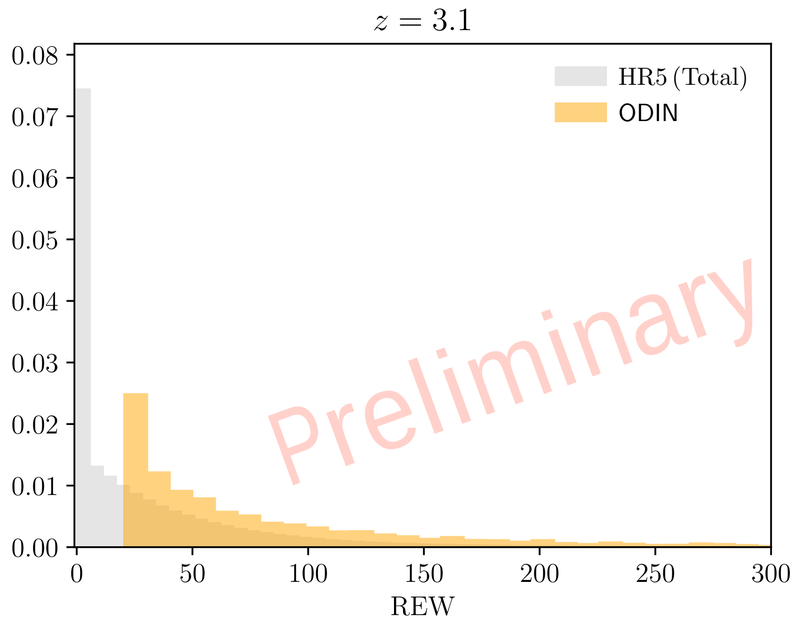


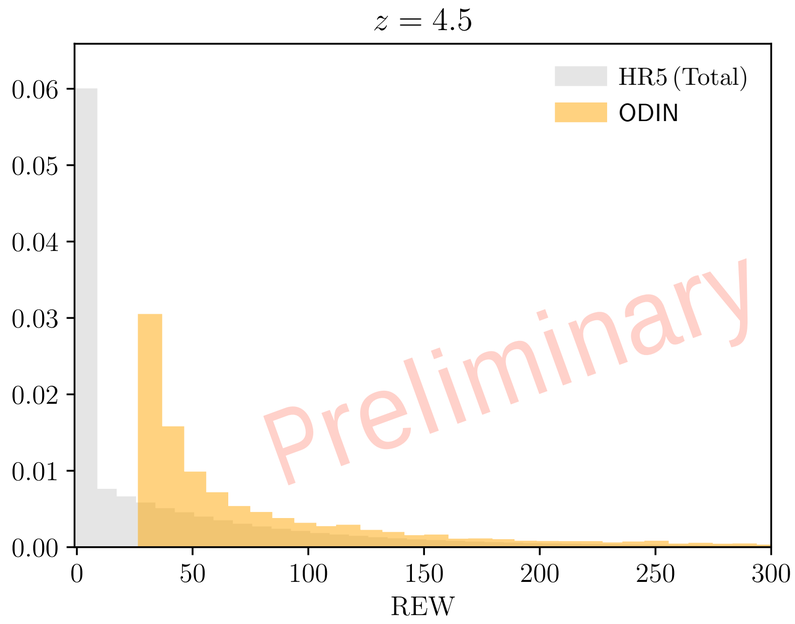
EW cut : 50 Å

Modelling LAEs in HR5: An empirical approach

REW distribution (ODIN data)



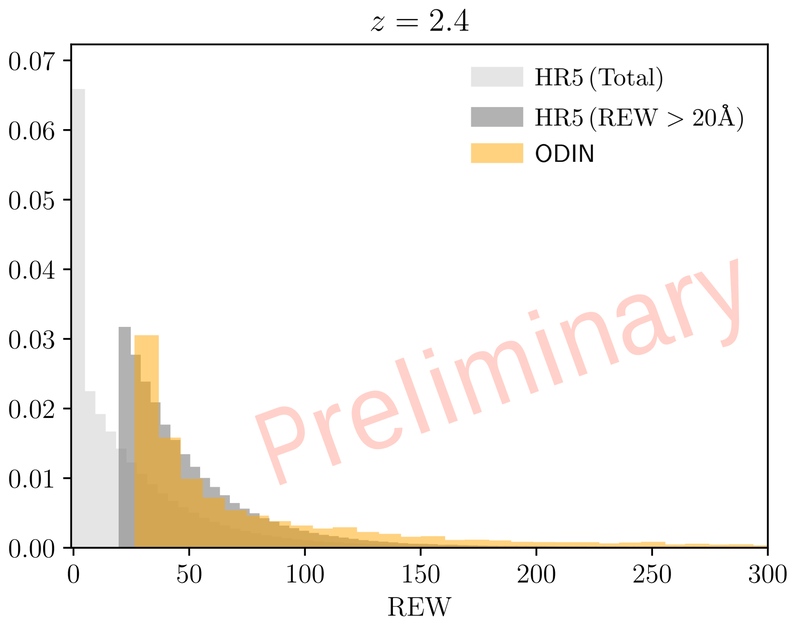


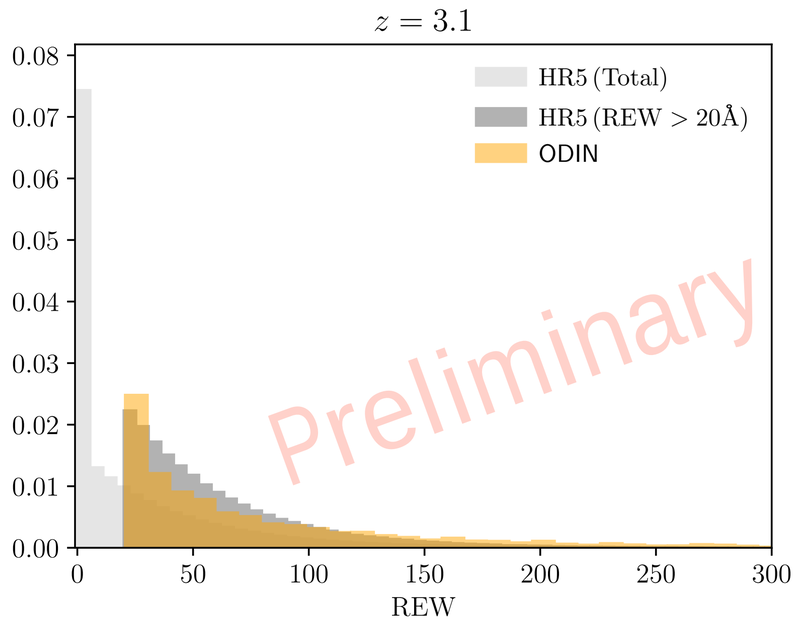


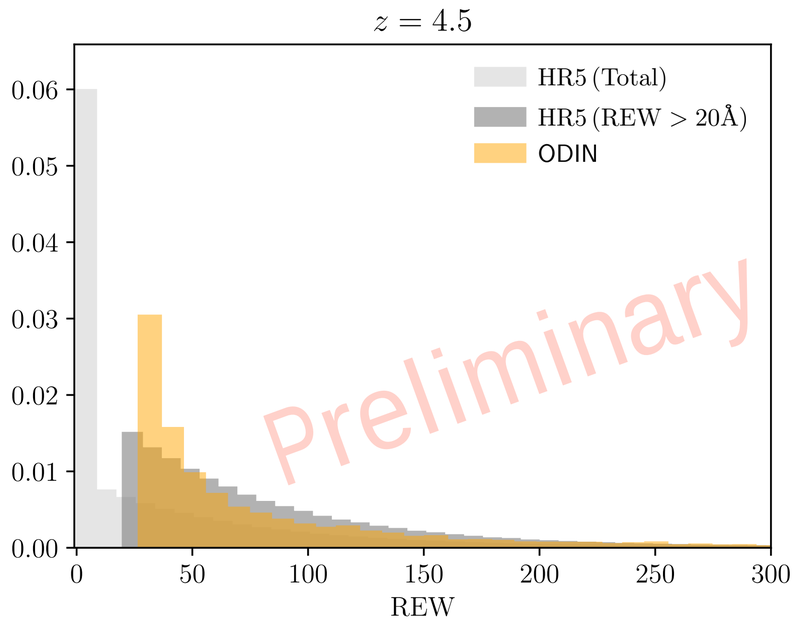
EW cut : 20 Å

Modelling LAEs in HR5: An empirical approach

REW distribution (ODIN data)



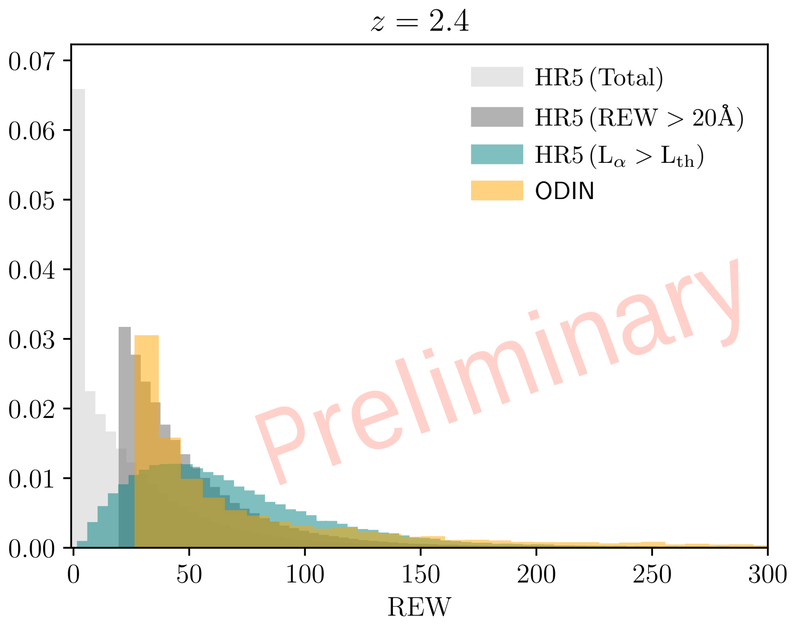


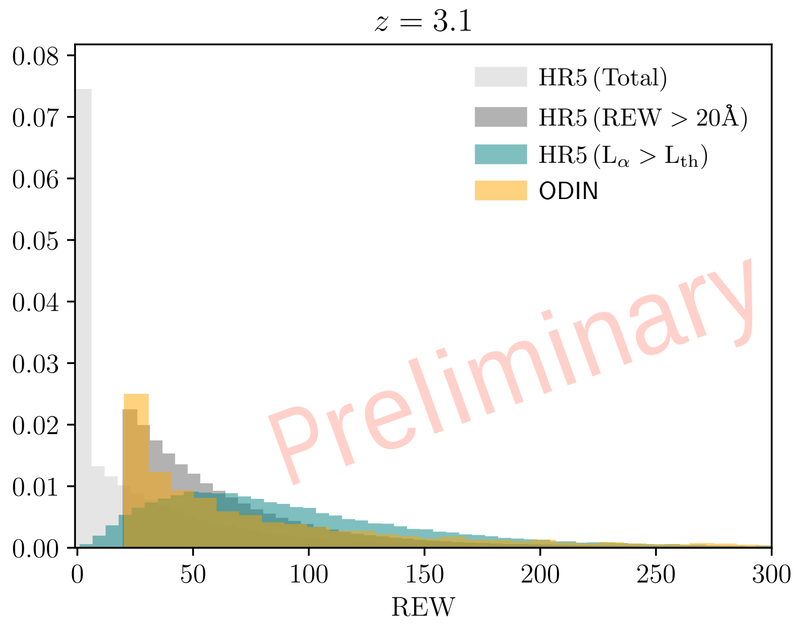


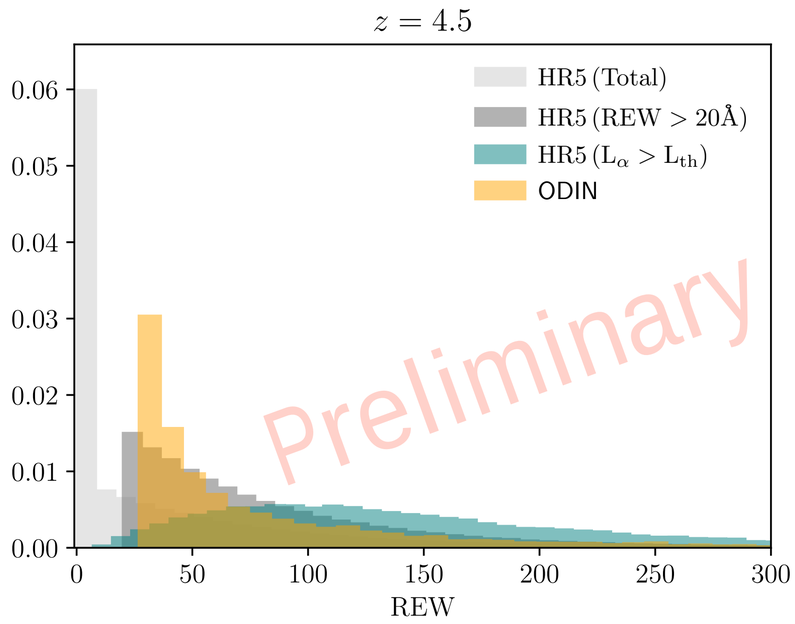
EW cut : 20 Å

Modelling LAEs in HR5: An empirical approach

REW distribution (ODIN data)



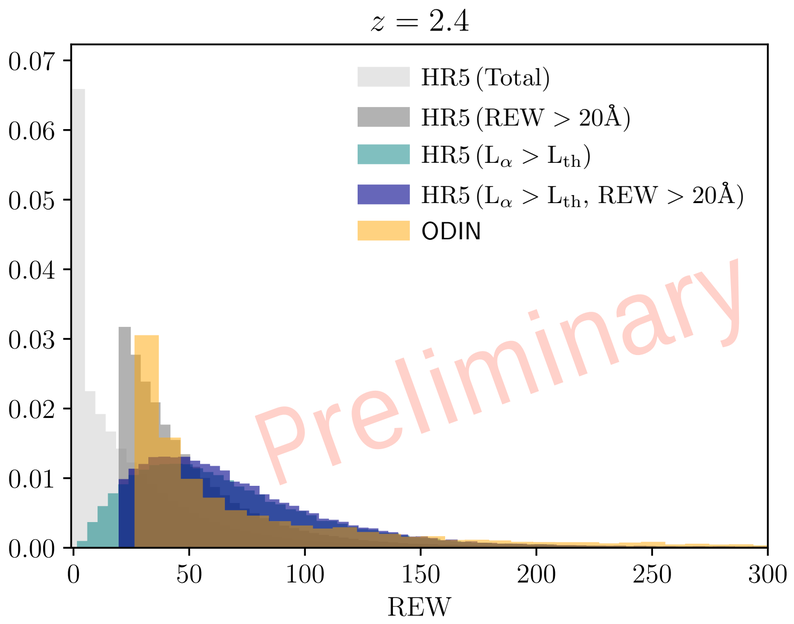


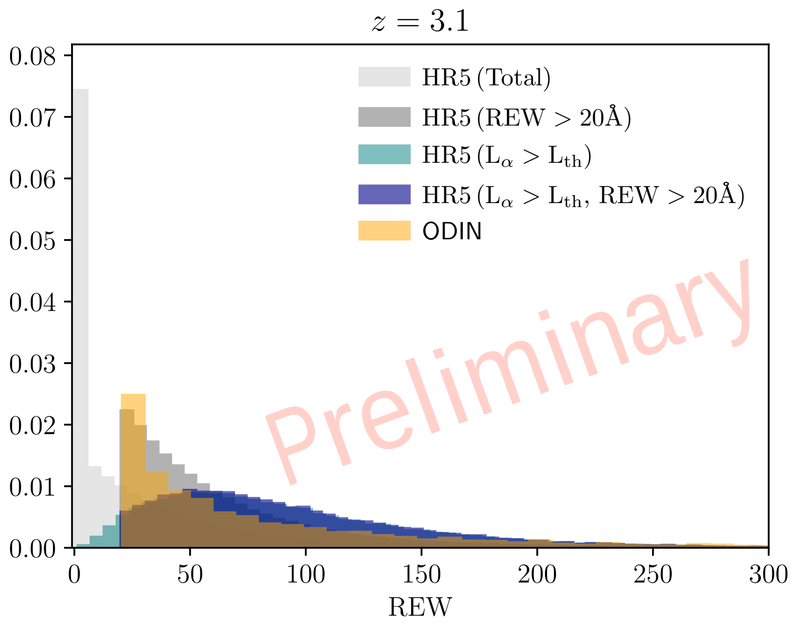


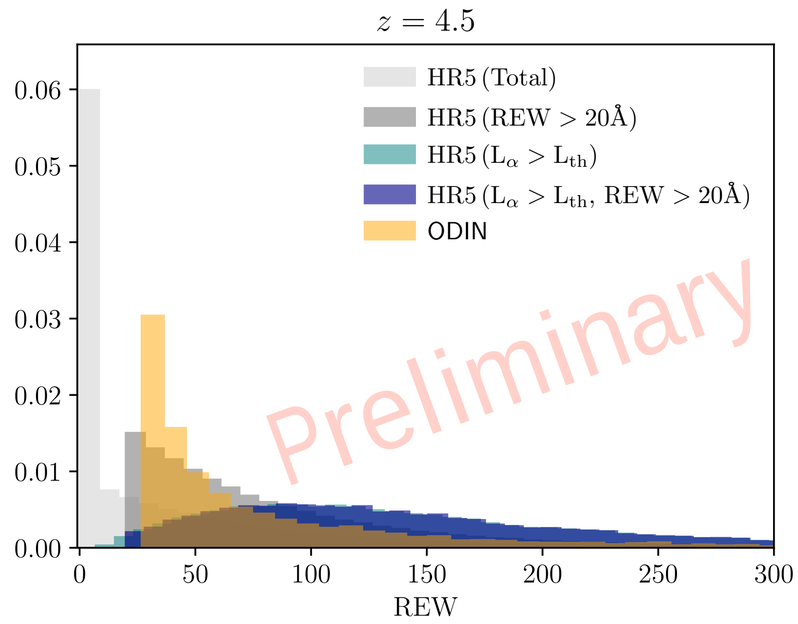
EW cut : 20 Å

Modelling LAEs in HR5: An empirical approach

REW distribution (ODIN data)







EW cut : 20 Å

Summary

- We aim to model LAEs in HR5 to investigate their properties and compare the predicted LAEs with observational LAEs from the ODIN survey.
- As the first step, we adopt an empirical approach that uses the probability distribution of the rest-frame EW to relate Ly-a luminosity and UV luminosity.
- We generated LAE catalogs using the Mason+2018 model and predicted Ly- LFs at z=2.4, 3.1, and 4.5, which are consistent with observations.
- We need further investigation (e.g. angular correlation function, bias, HOD, and etc)