Faint high-redshift galaxies and their Lyman-alpha emission

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together with
The MUSE Collaboration

muse
multi unit spectroscopic explorer

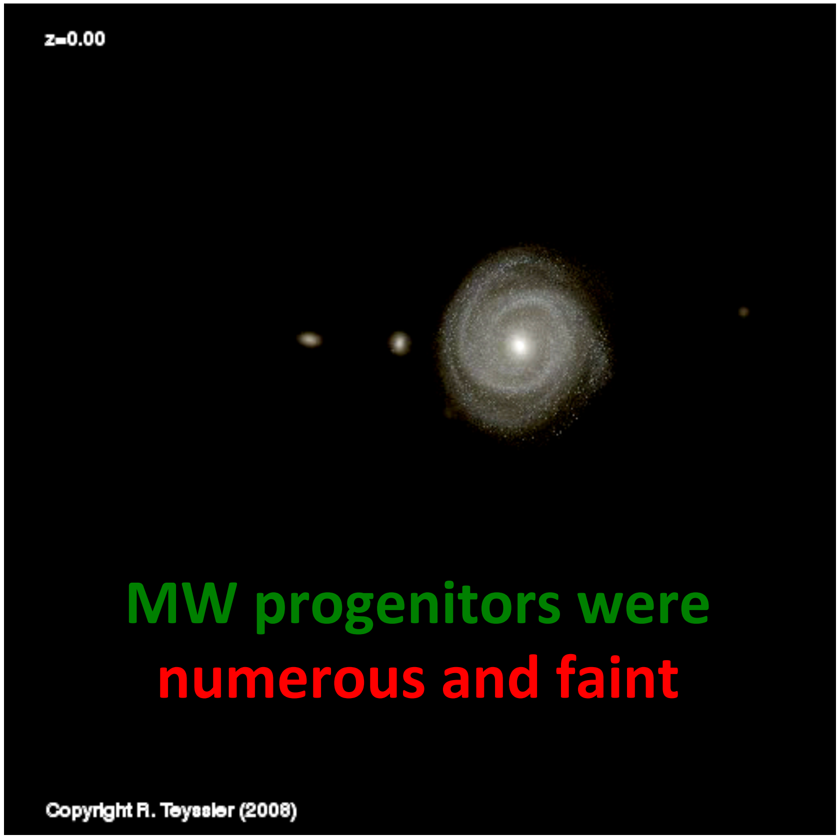
AIP

Content

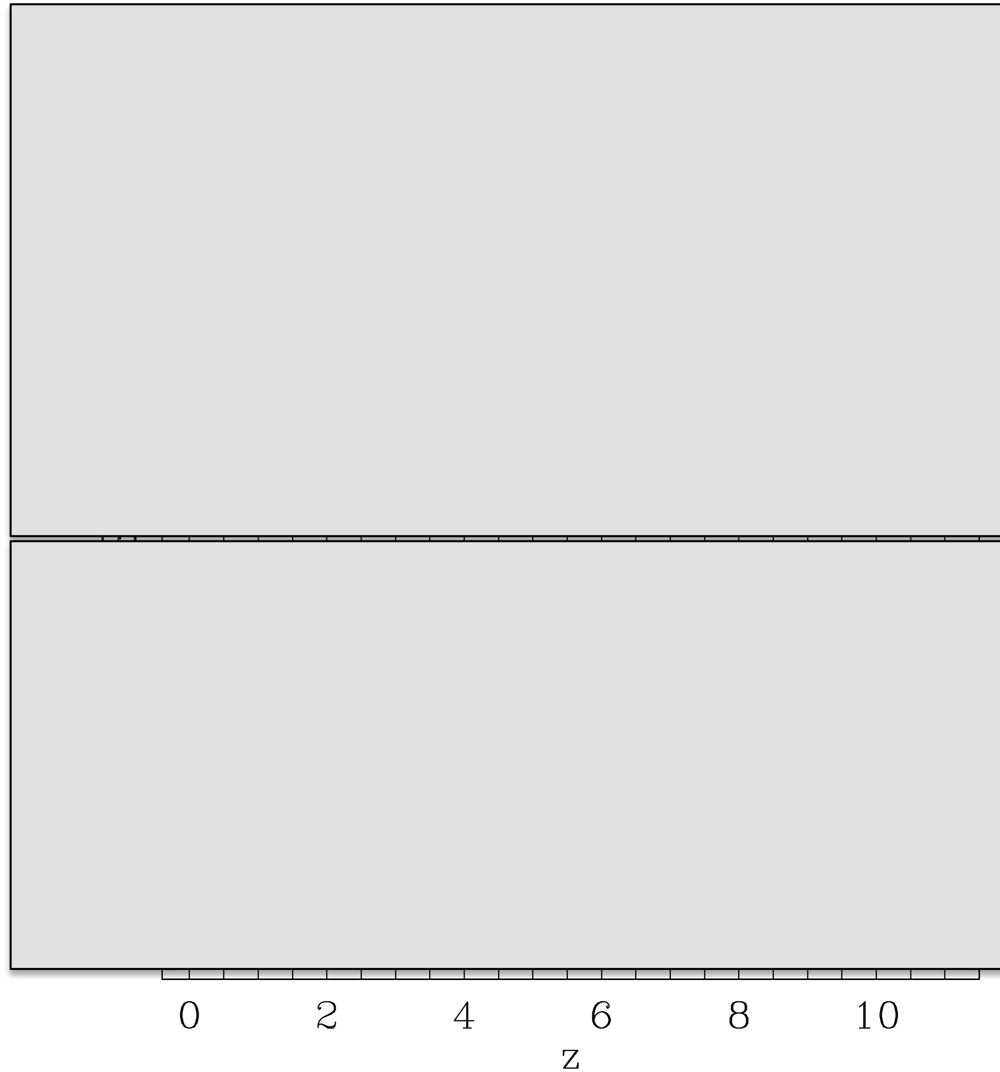
- Motivation: Lyman-α emission as a probe of the high-z universe
- Blind surveys in Deep Fields with MUSE
- Properties of faint Ly-α selected galaxies
- Extended Ly-α emission around high-z galaxies
- Implications for the demographics of Ly-α emitters
- What is the origin of extended Ly-α haloes?

operational definition:
high z → $z \gtrsim 3$

Progenitors of Milky Way-type galaxies



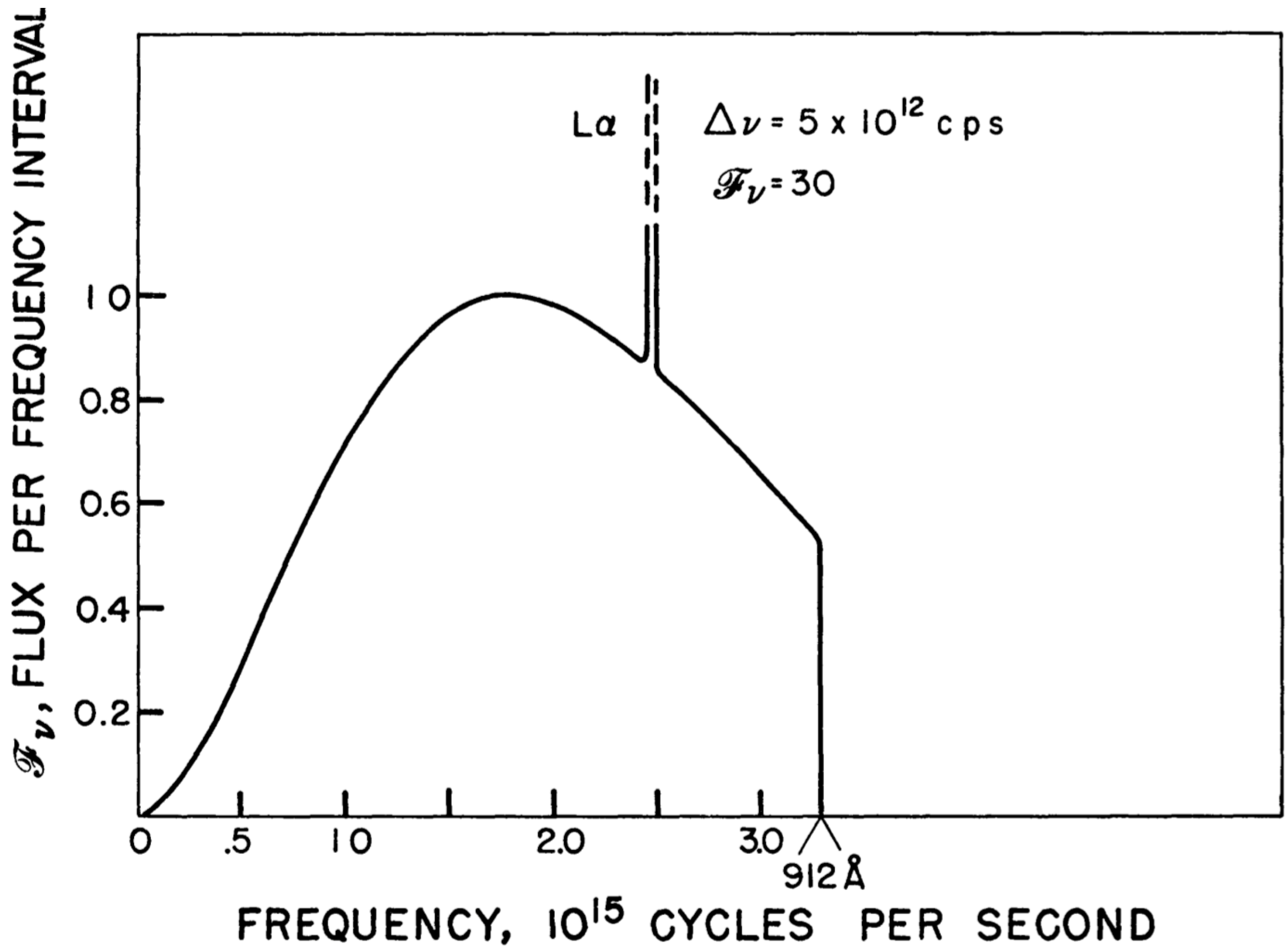
The growth history of a `simulated MW´:



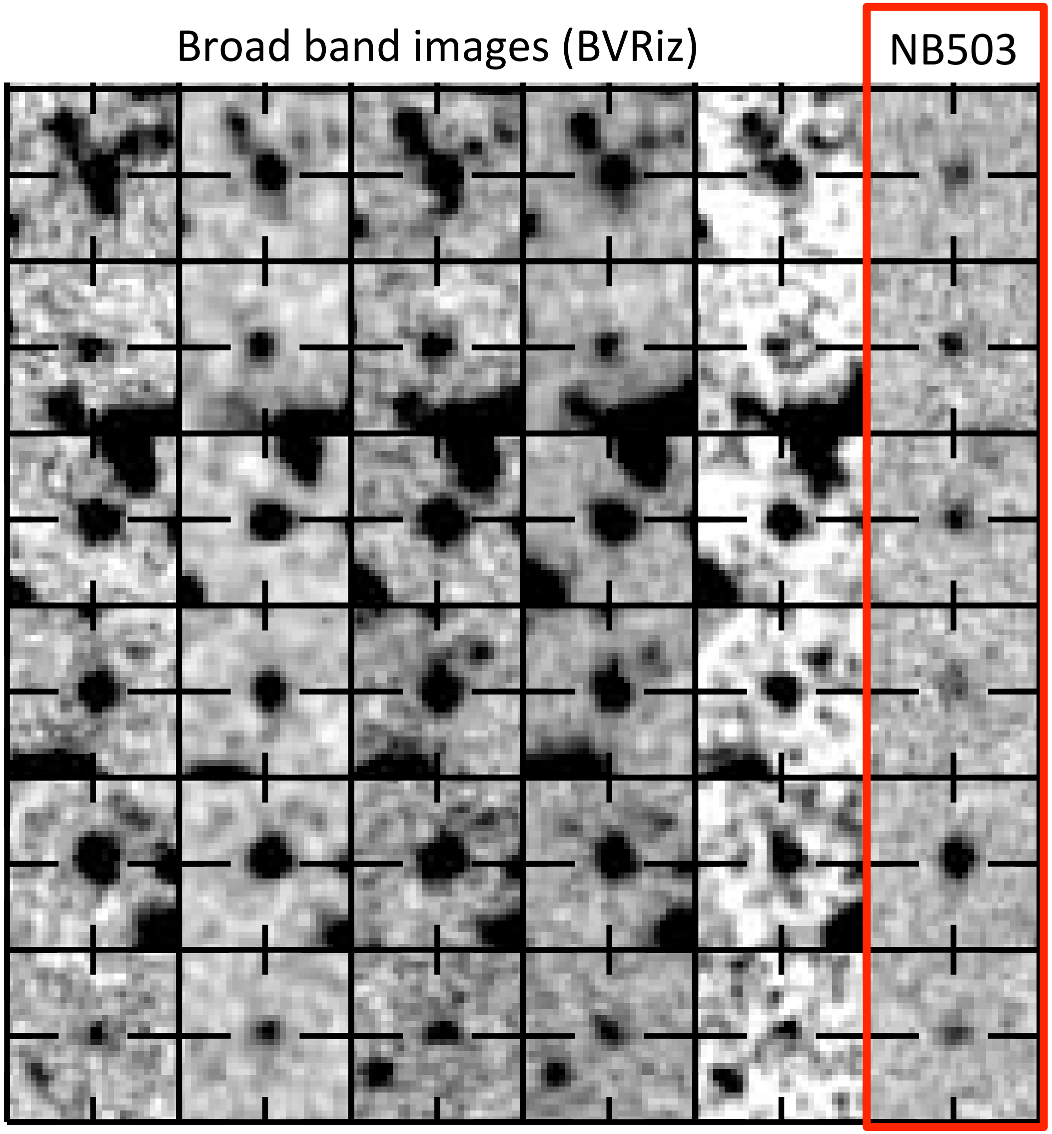
Yajima+ 2012 (also Dayal & Libeskind 2012)

ARE YOUNG GALAXIES VISIBLE?

R. B. Partridge and P. J. E. Peebles
Palmer Physical Laboratory, Princeton University
Received August 5, 1966; revised September 8, 1966



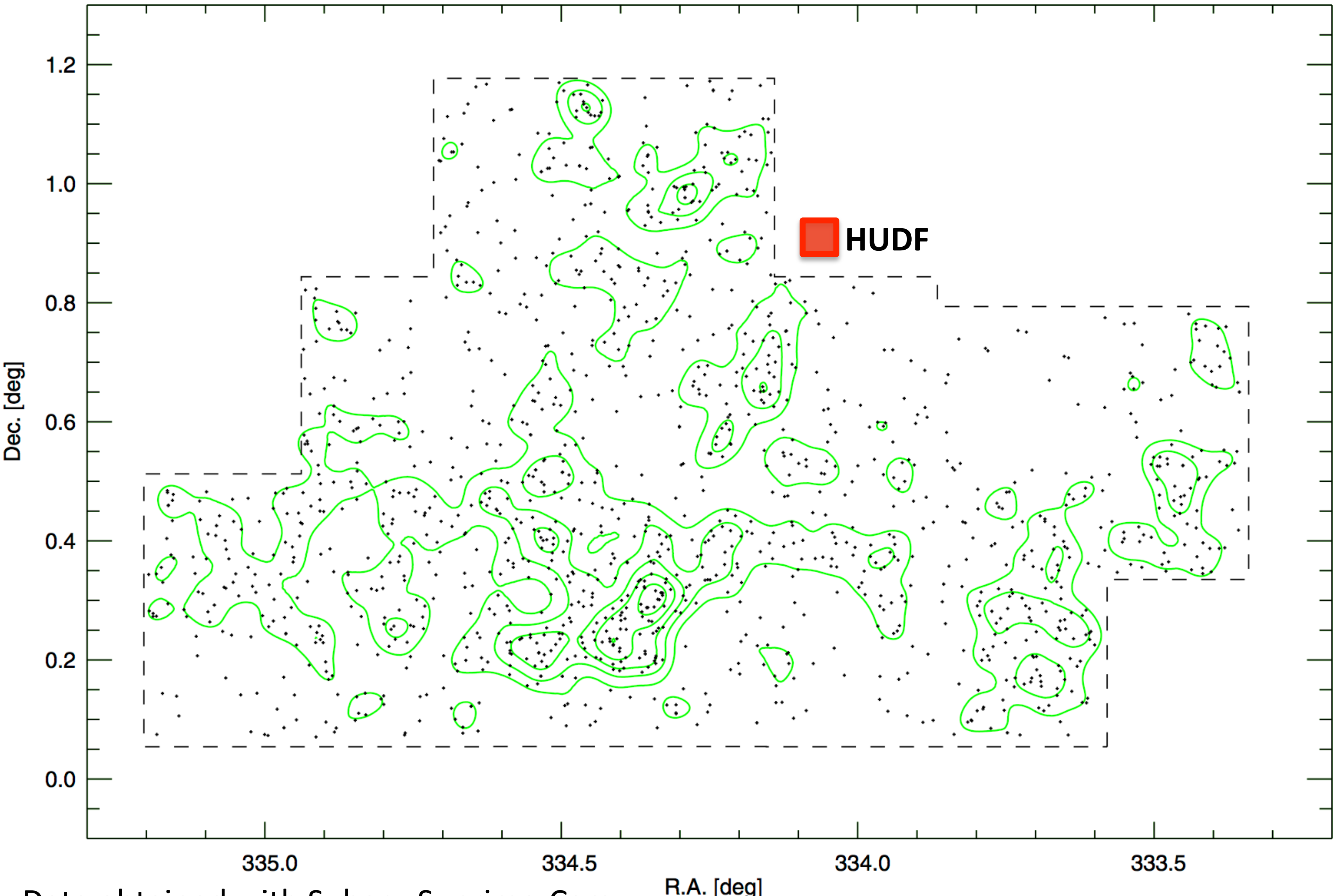
High-redshift Ly-α emitters from narrowband imaging



+ spectroscopic follow-up!

Ouchi+ 2008

High-redshift Ly-α emitters from narrowband imaging



Data obtained with Subaru Suprime-Cam
Yamada+ 2012

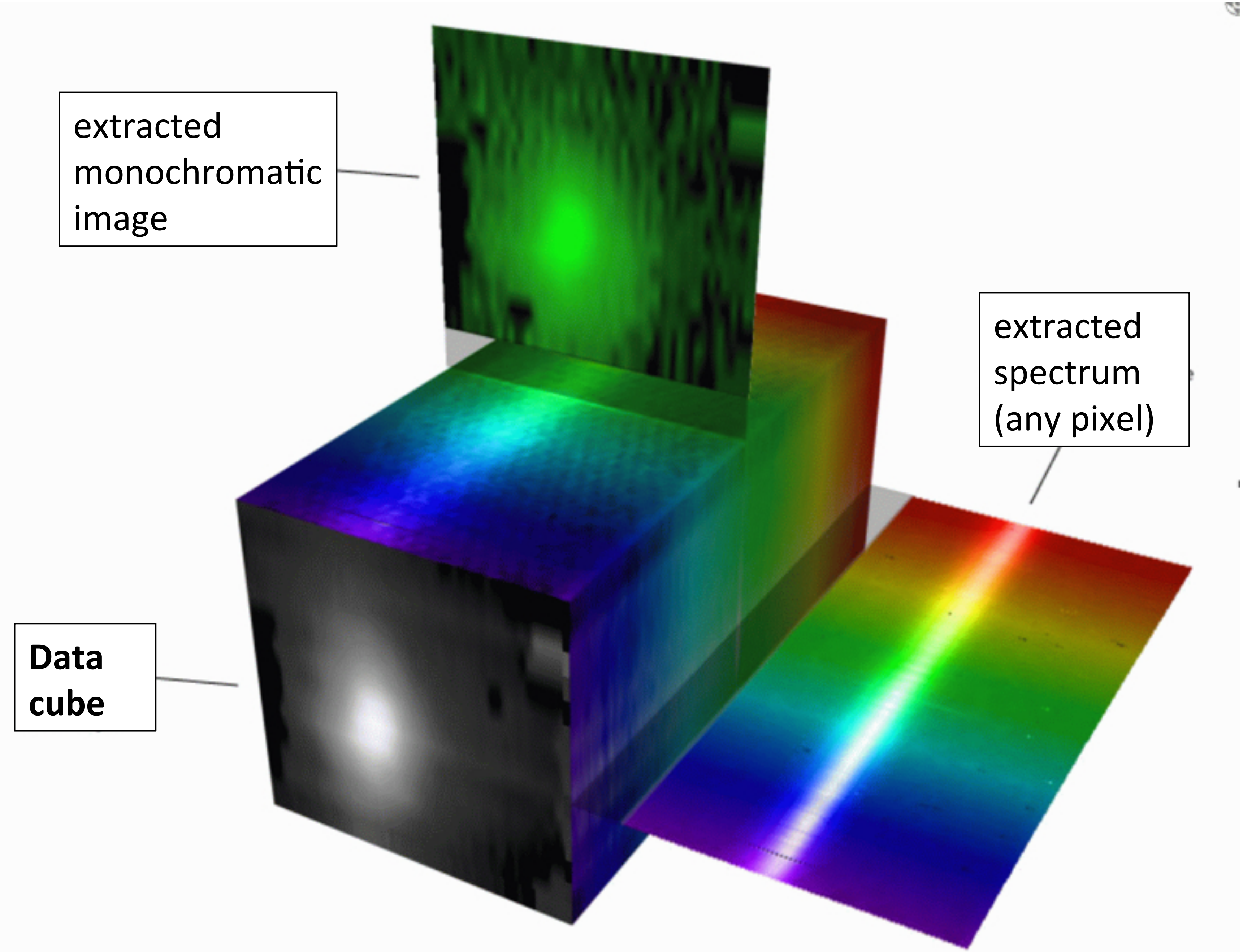

MUSE: 300 × 300 spaxels, 0.2″ × 0.2″ per spaxel

muse
multi unit spectroscopic explorer

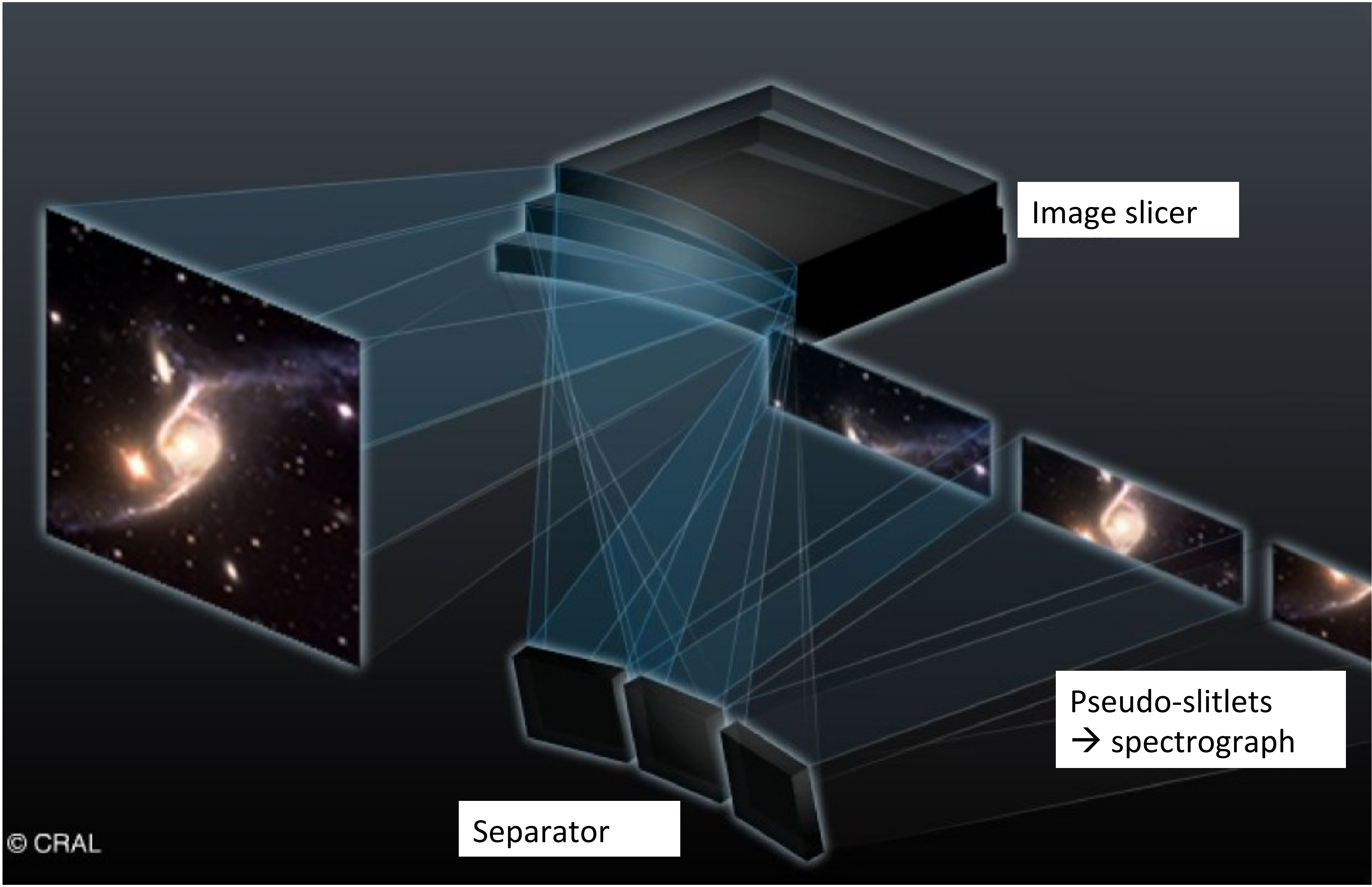
MUSE in a nutshell:

- 2nd generation instrument for ESO VLT
- Integral Field Spectrograph in optical domain:
  - 1' × 1' field of view (in Wide Field Mode)
  - 0.2" × 0.2" spatial pixels
  - → 90,000 spectra on 24 spectrographs
  - (Ground-layer) Adaptive Optics support
- developed by consortium of 6 institutes + ESO
- in operation since 2014; with AO since 2017

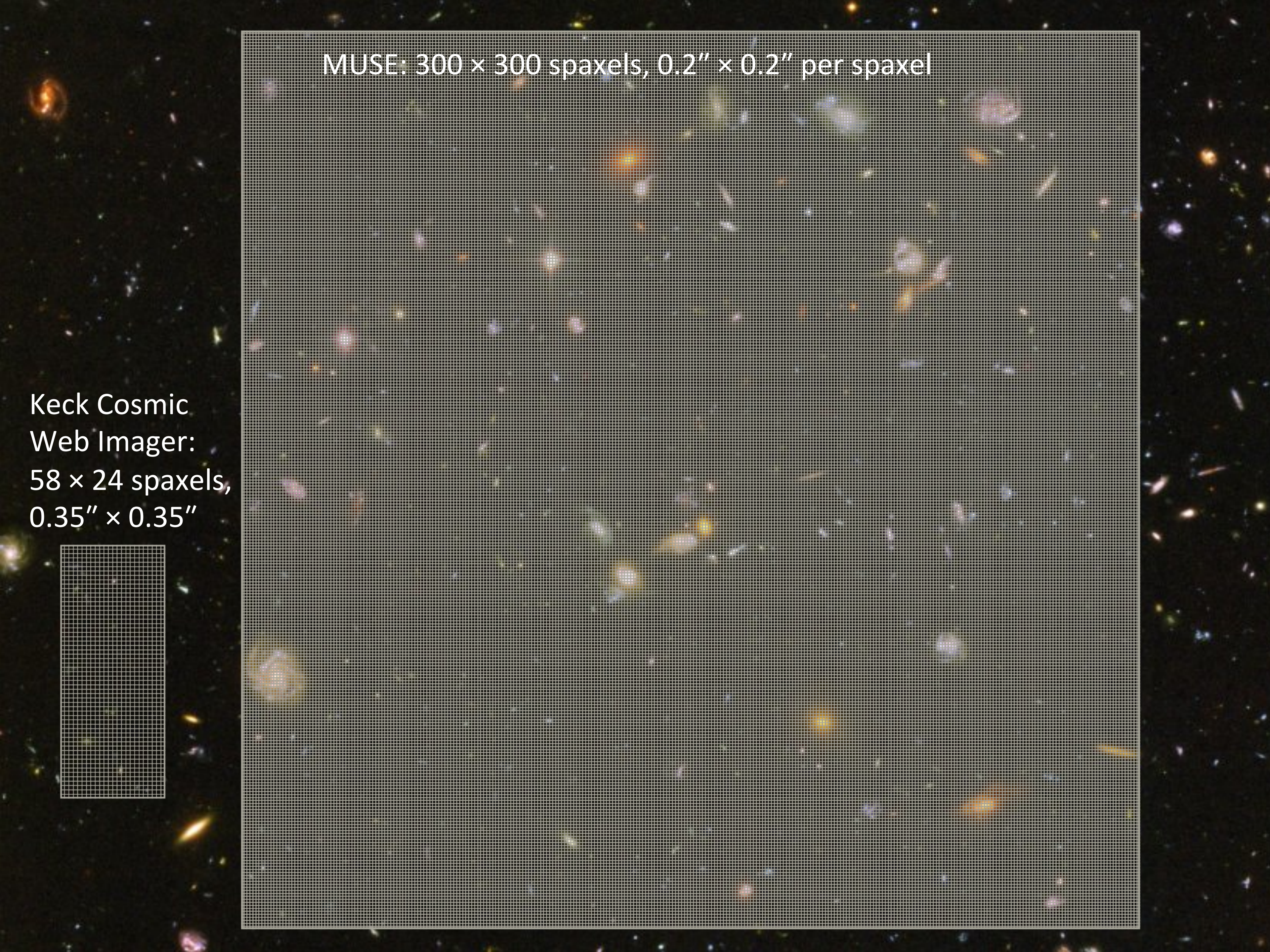
Integral field spectroscopy: The concept



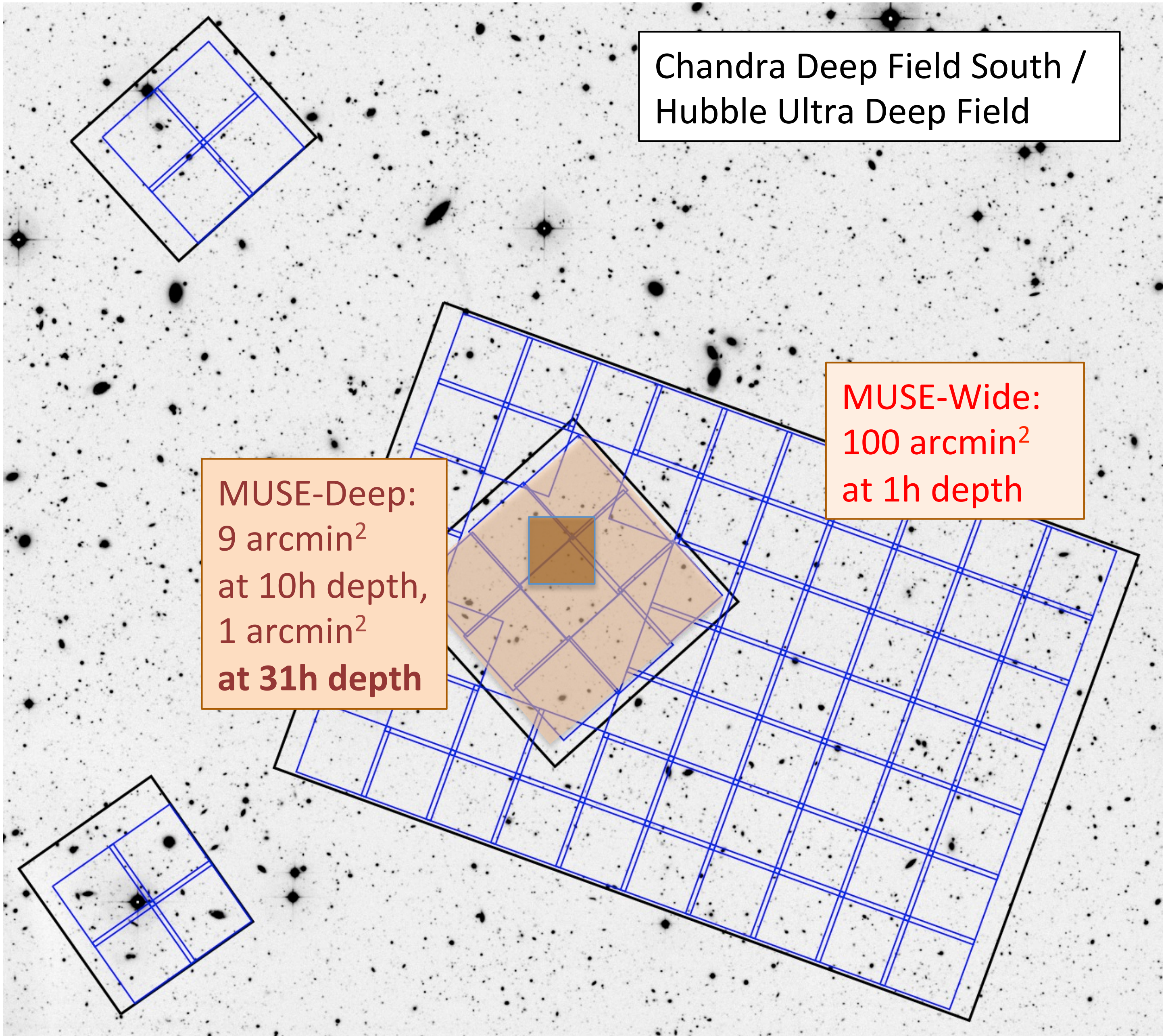
The MUSE principle: Slicing the focal plane

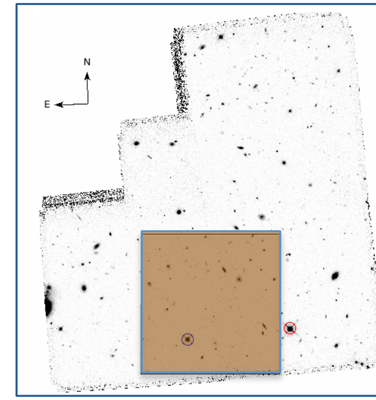



ETH


MUSE: 300 × 300 spaxels, 0.2″ × 0.2″ per spaxel
Keck Cosmic Web Imager: 58 × 24 spaxels, 0.35″ × 0.35″

MUSE-Deep and MUSE-Wide





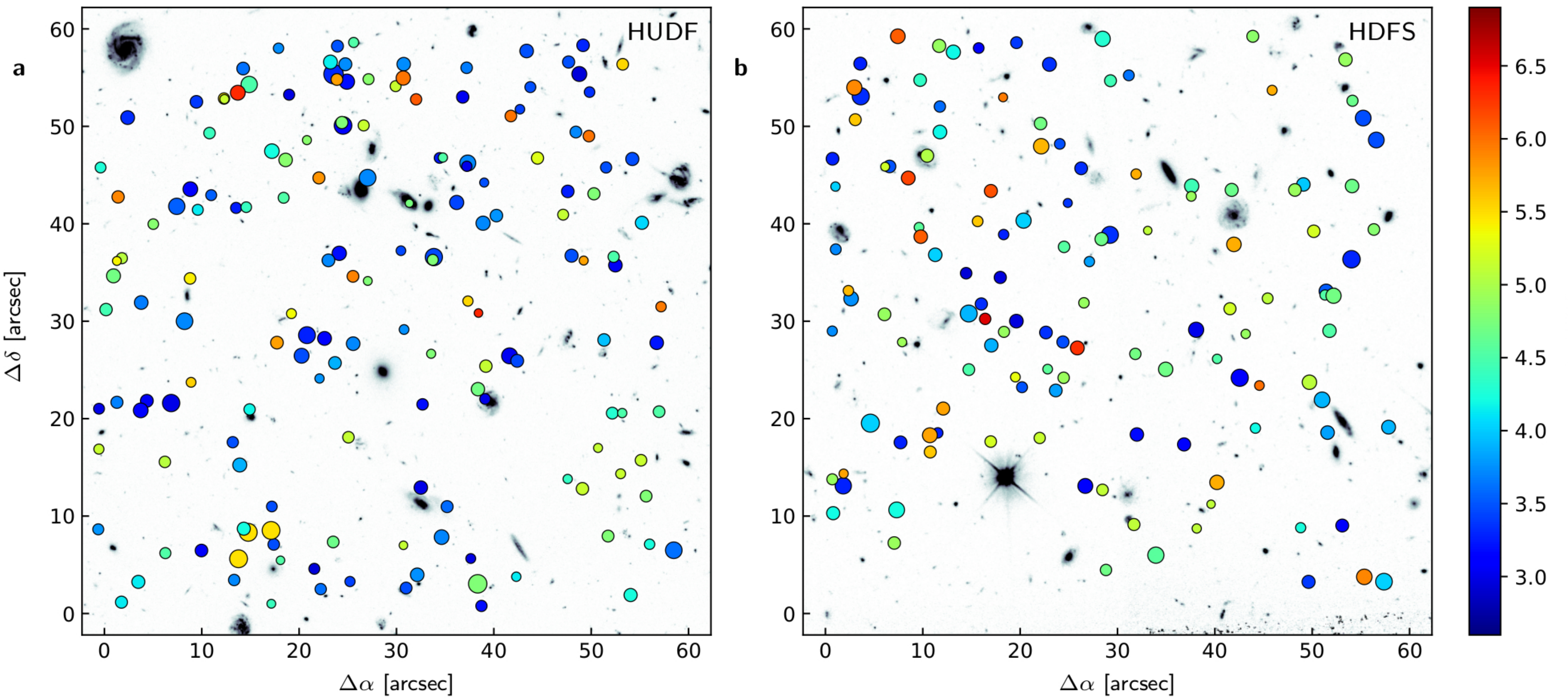
+ Hubble Deep Field South:
1 arcmin^2
at 27h depth

The Hubble Deep Field South, observed with MUSE

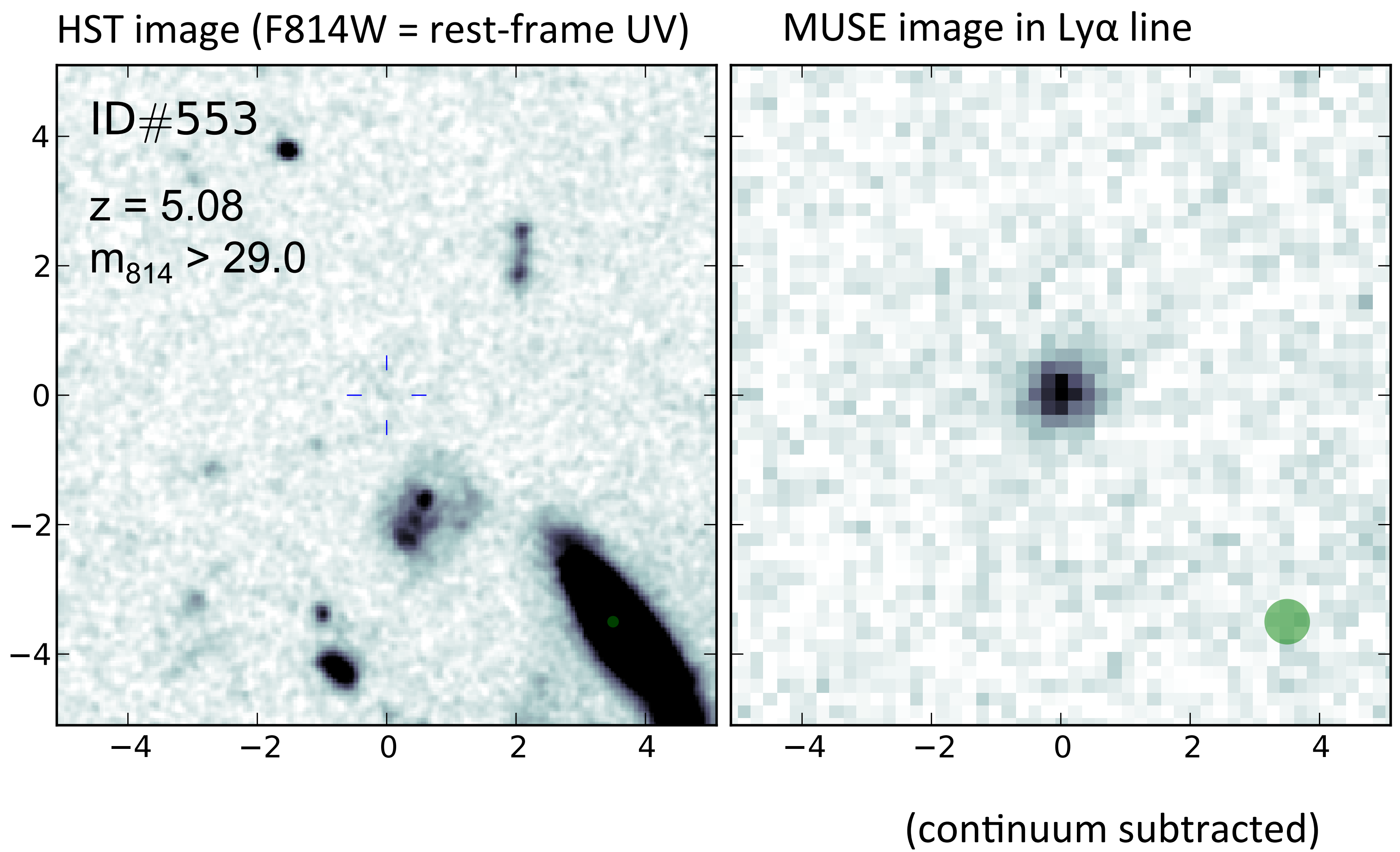
Hubble:

MUSE:

300 Lyα emitters with spectra within 2 arcmin²

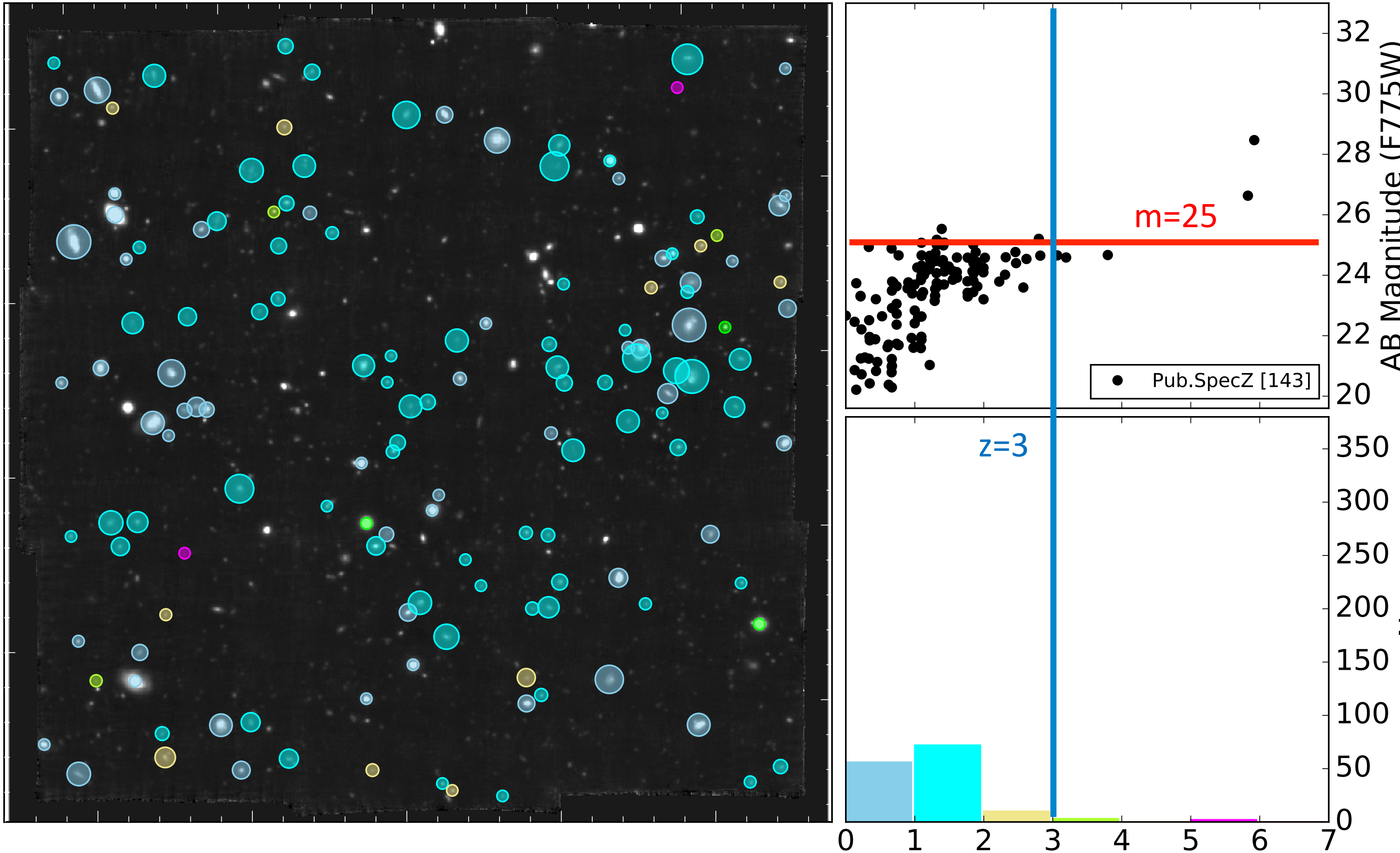


Wisotzki+ 2018


HST image (F814W = rest-frame UV)
MUSE image in Lyα line
ID#553
z = 5.08
m814 > 29.0
(continuum subtracted)

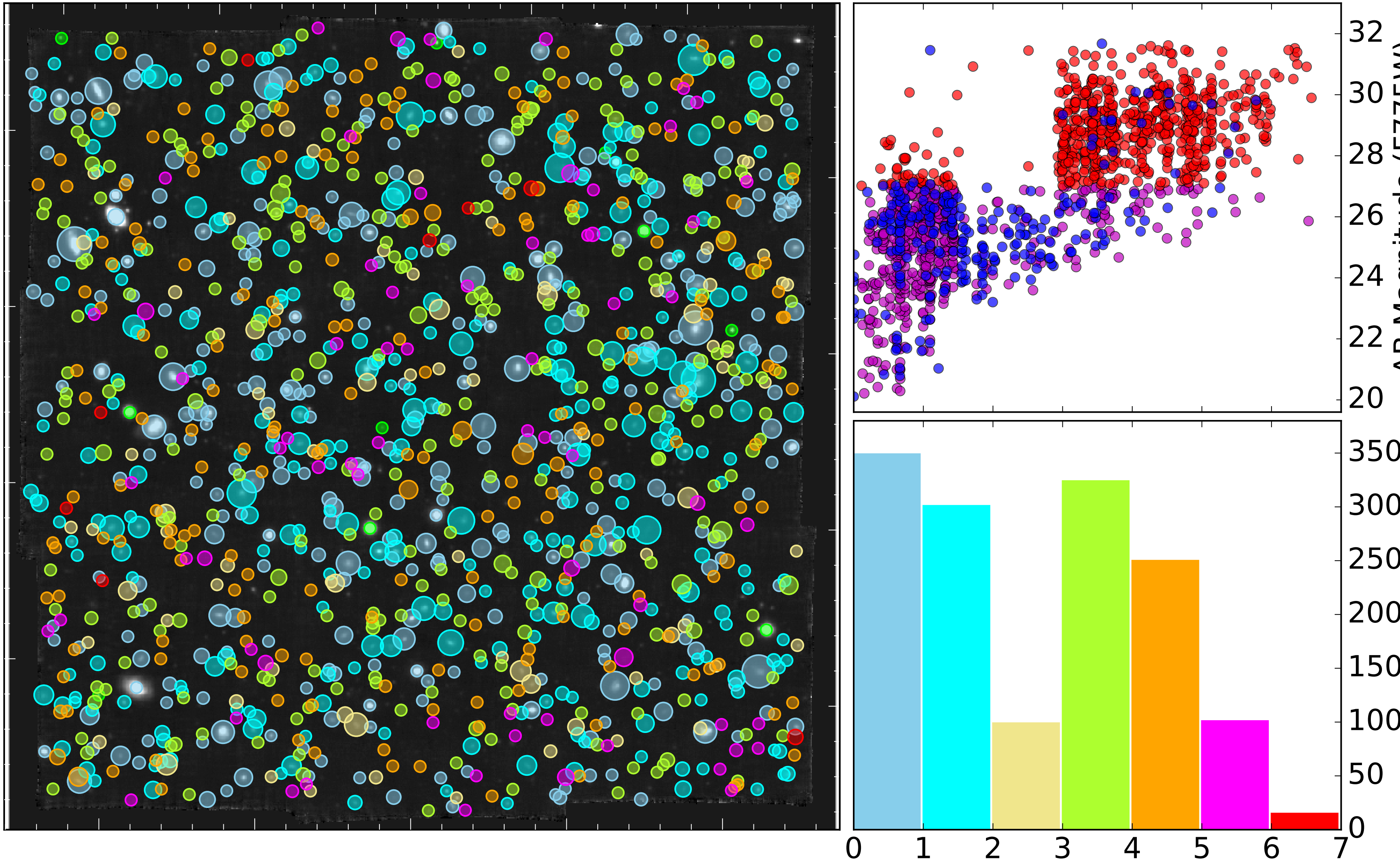
Redshifts in the MUSE-Deep UDF mosaic

Previous spectroscopic redshifts within MUSE footprint: **143**

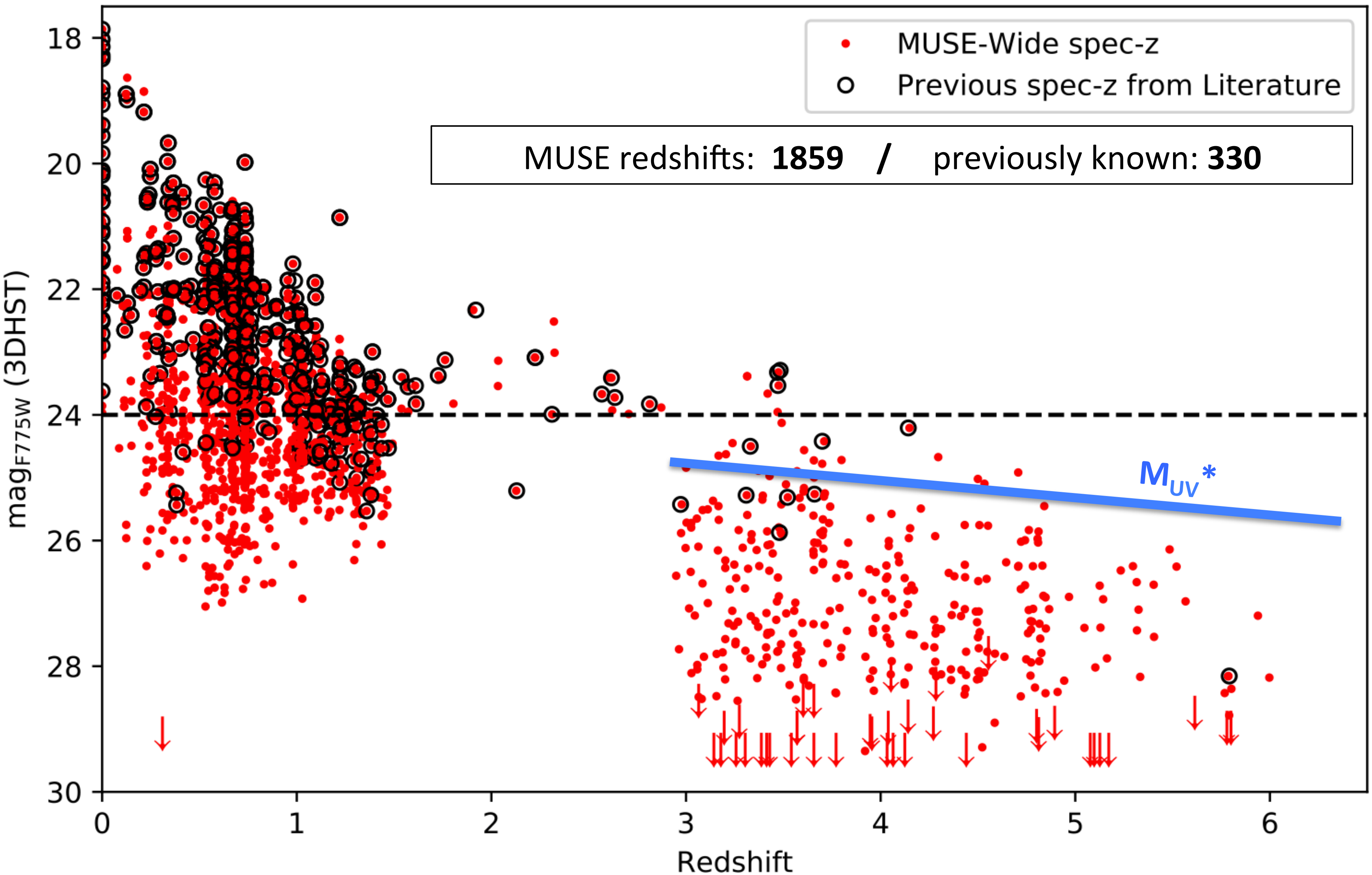


Redshifts in the MUSE-Deep UDF mosaic

MUSE redshifts combined: **1443** / previously known: **143**

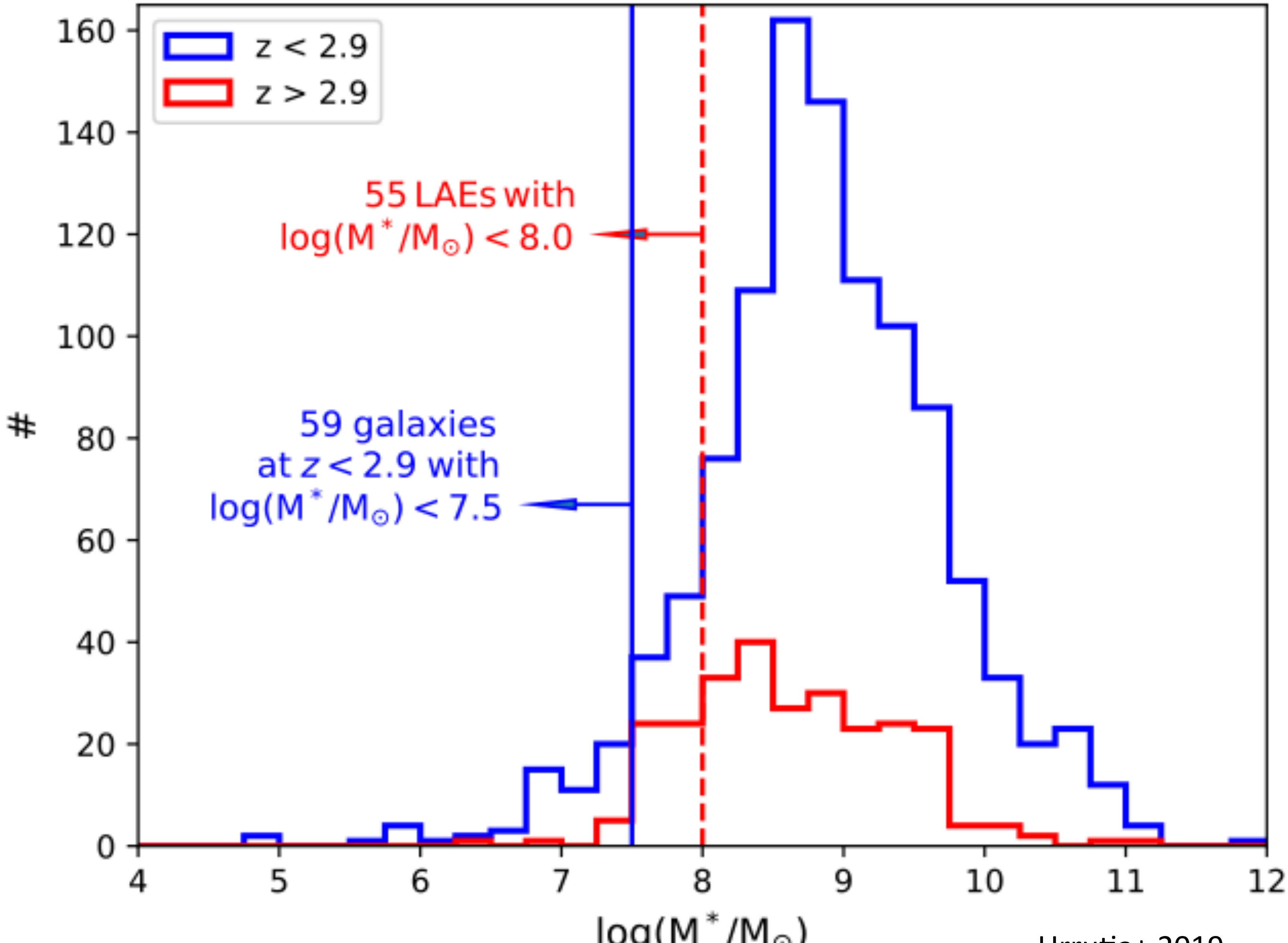


Magnitudes and redshifts in MUSE-Wide DR1 (44 arcmin^2 in CDFS)



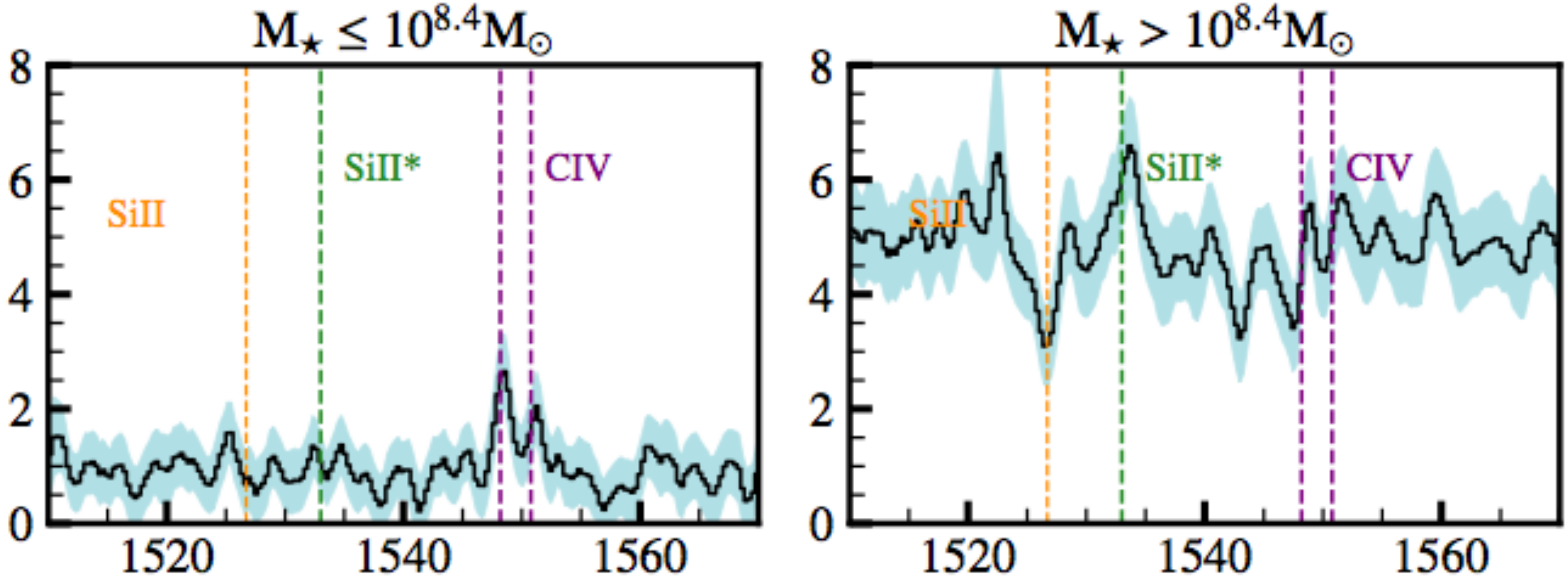
Urrutia+ 2019

Stellar masses of galaxies in MUSE-Wide



Urrutia+ 2019

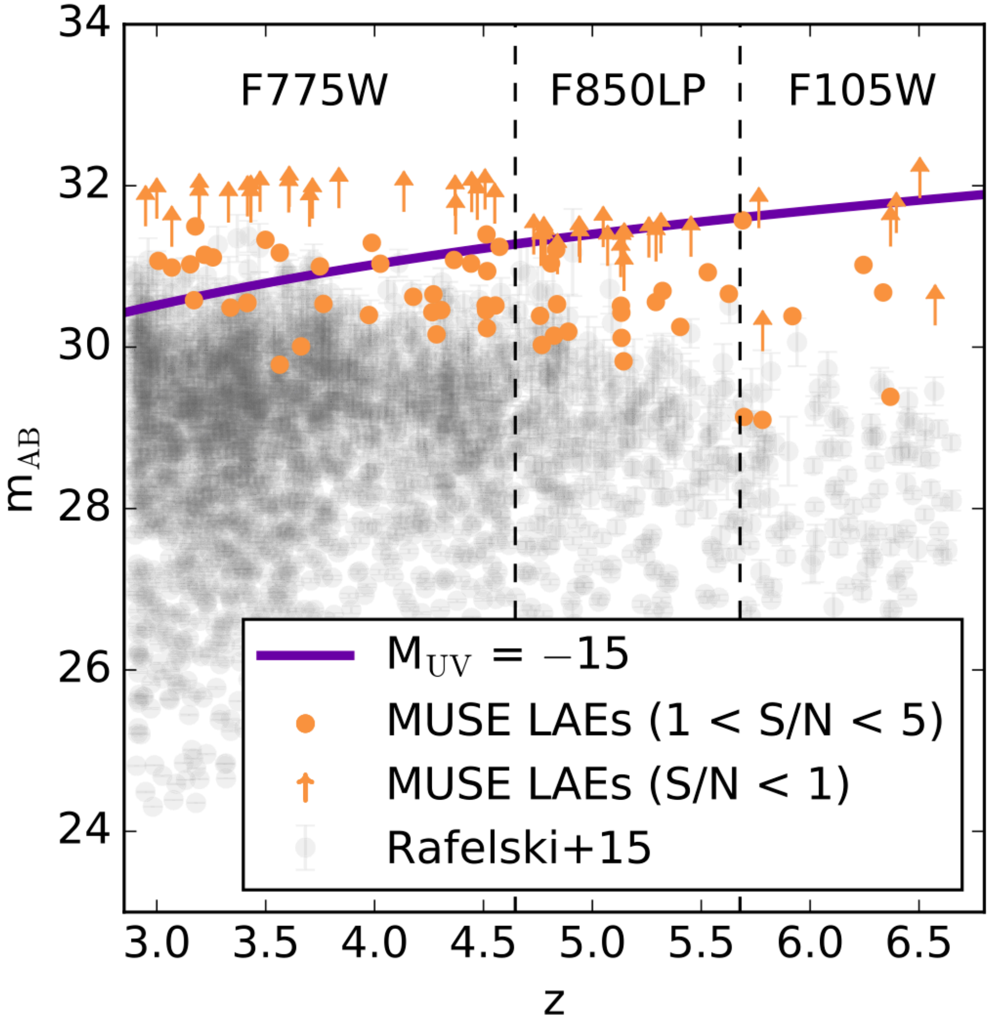
Spectral stacks of LAEs (z > 2.9) as function of stellar mass



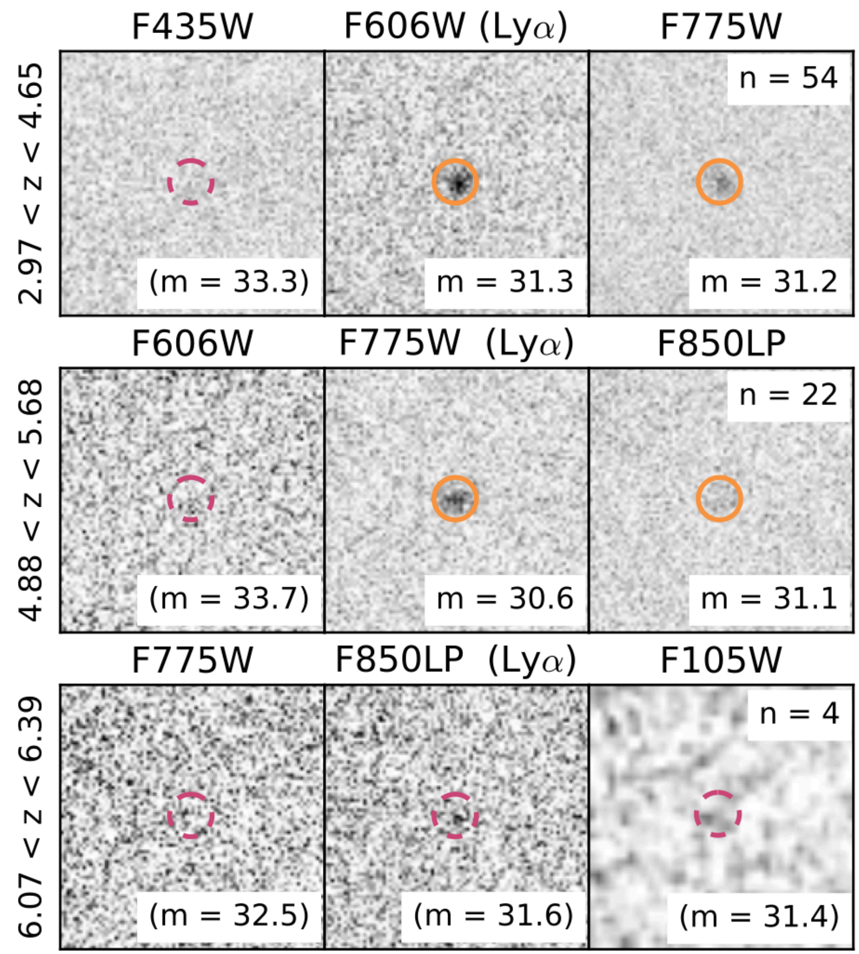
Feltre+ 2020, submitted

Lyman-α emitters undetected by HST

LAEs & counterparts in the Hubble Ultra-Deep Field:

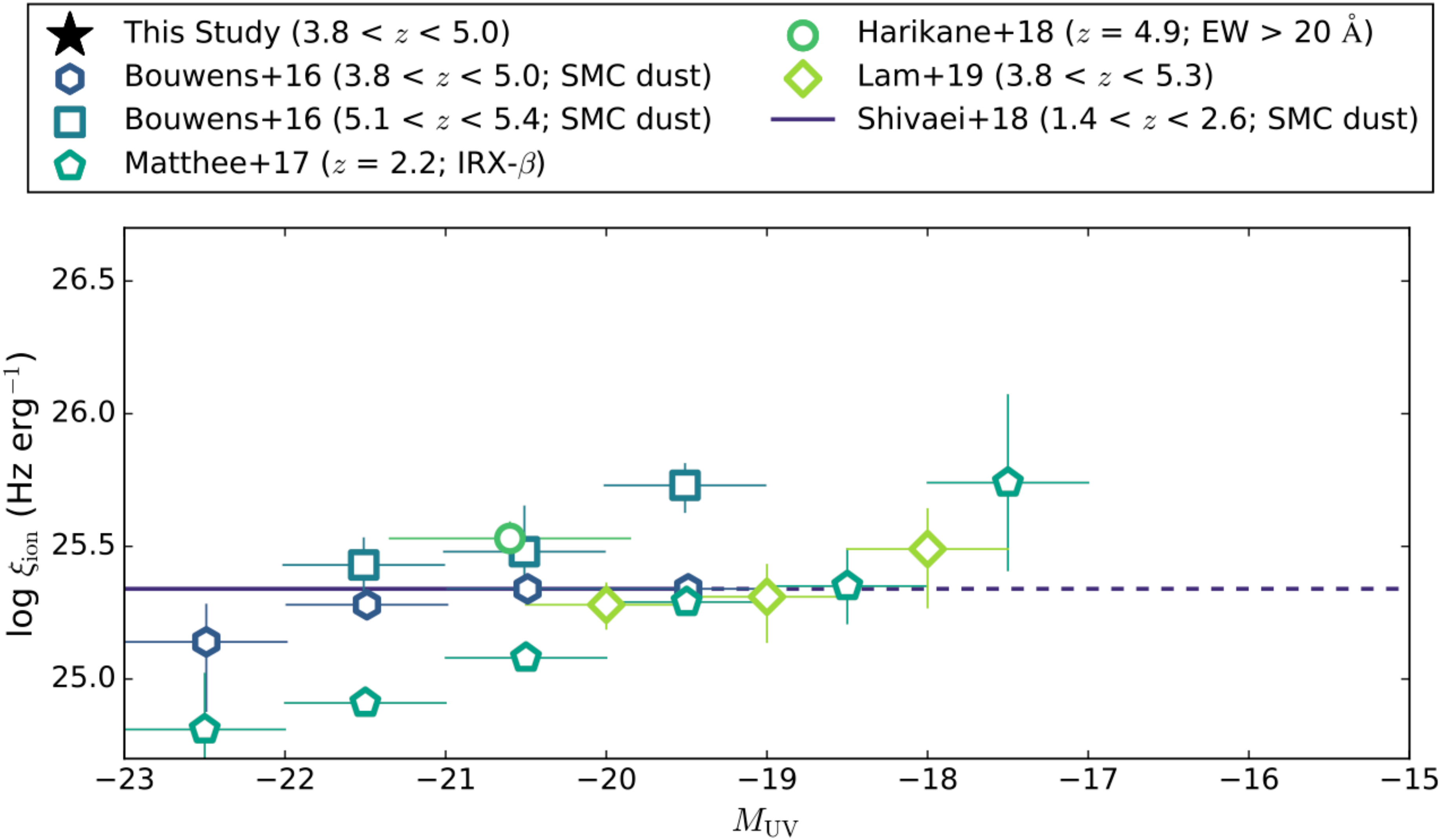


HST image stacks:



Maseda+ 2018

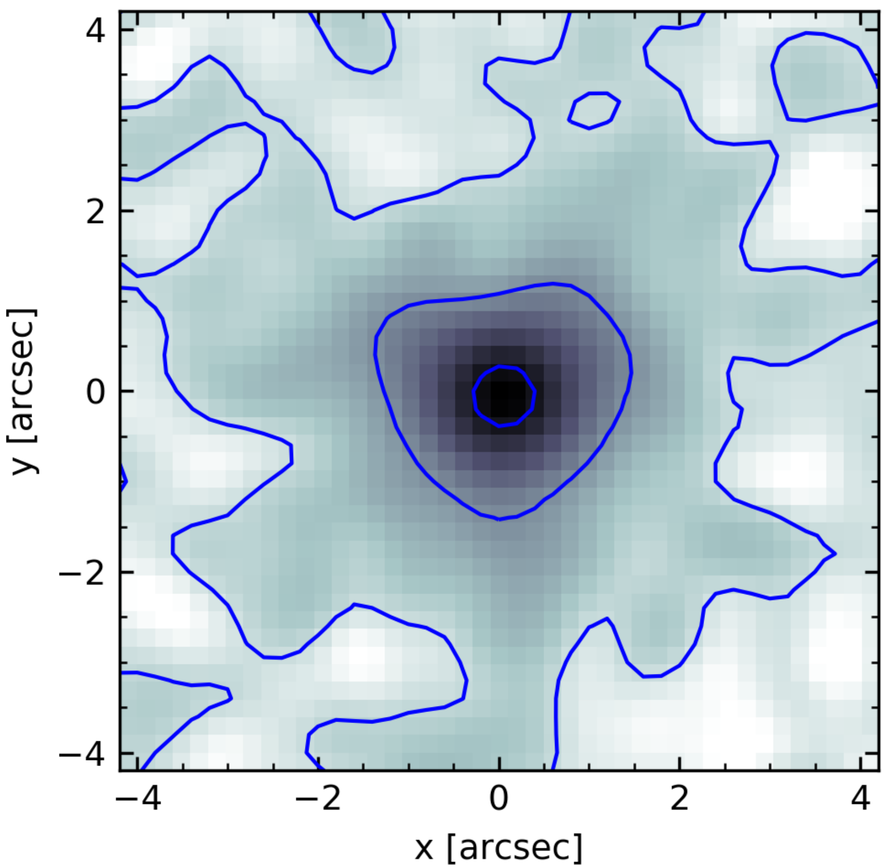
Faint LAEs have an elevated ionizing photon production efficiency

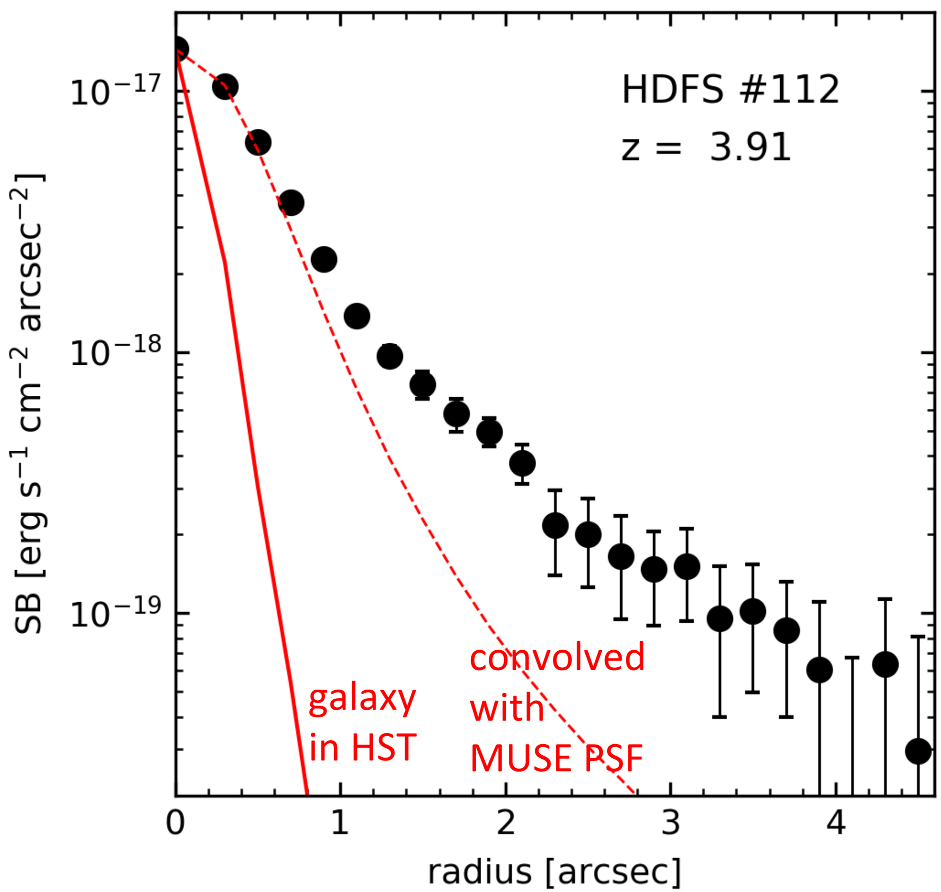


Maseda+ 2020

Extended Lyα emission around low-mass galaxies

in 30h exposure with MUSE
with 0.7 arcsec Seeing:

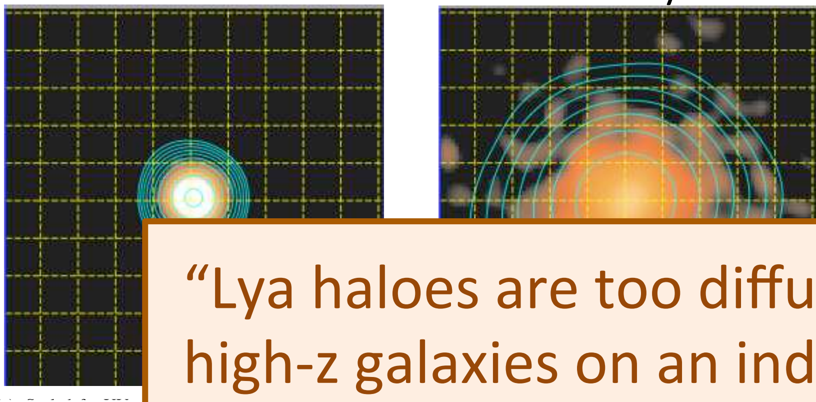


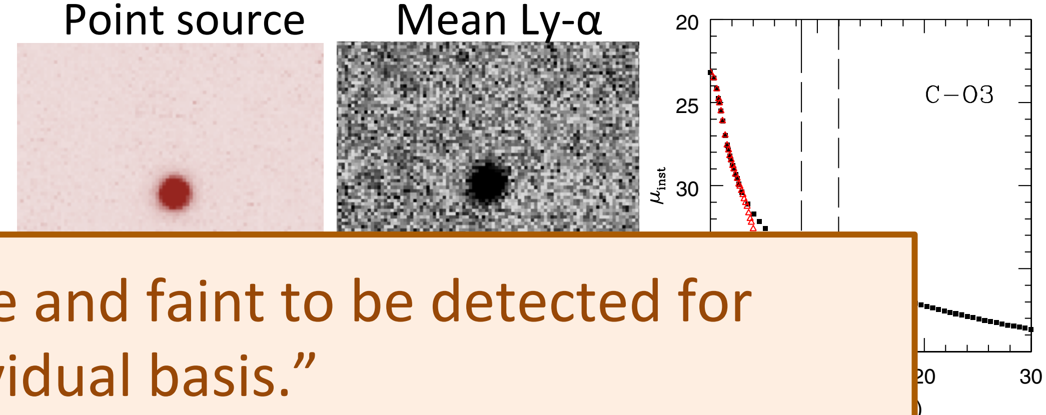


Wisotzki+ 2016

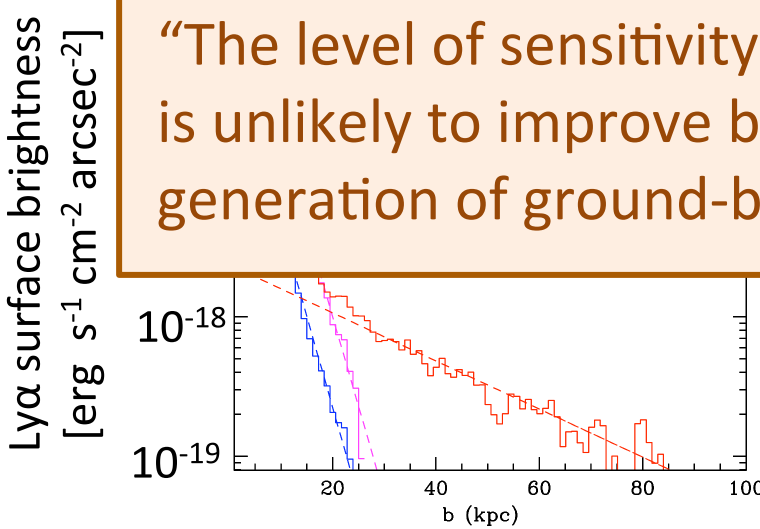
Previous searches for extended Lyman-α emission from normal galaxies:

Narrowband imaging and stacking of 100s ... 1000s of galaxies

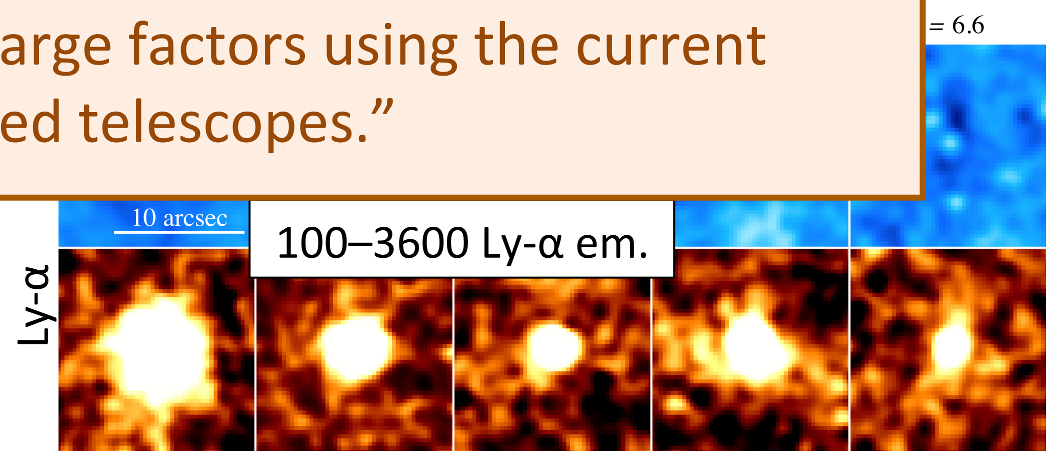




> "Lya haloes are too diffuse and faint to be detected for high-z galaxies on an individual basis."
>
> "The level of sensitivity to low surface brightness emission is unlikely to improve by large factors using the current generation of ground-based telescopes."



Steidel+ 2011

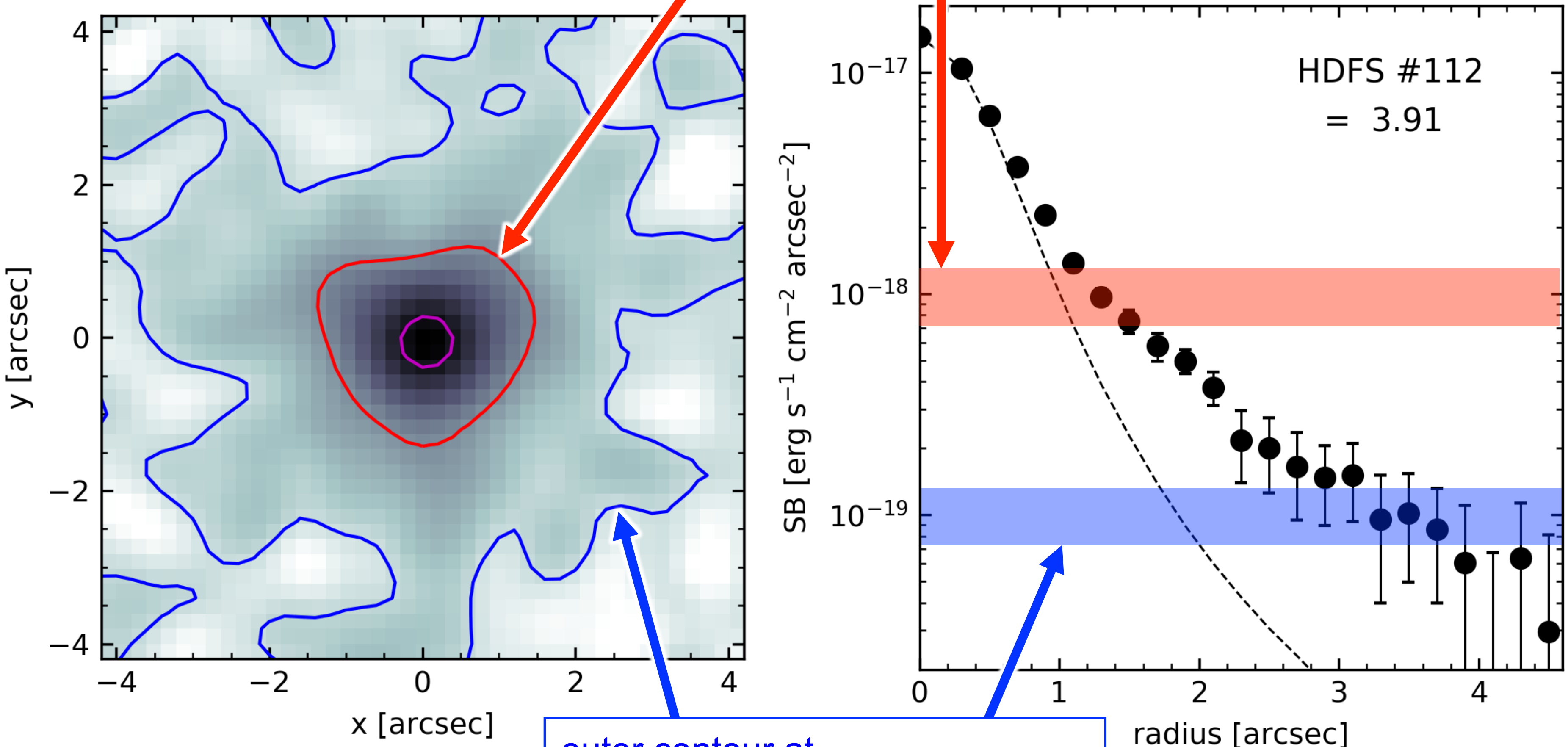


Momose+ 2014

Extended Lyα emission

in 30h exposure with MUSE
with 0.7 arcsec Seeing:

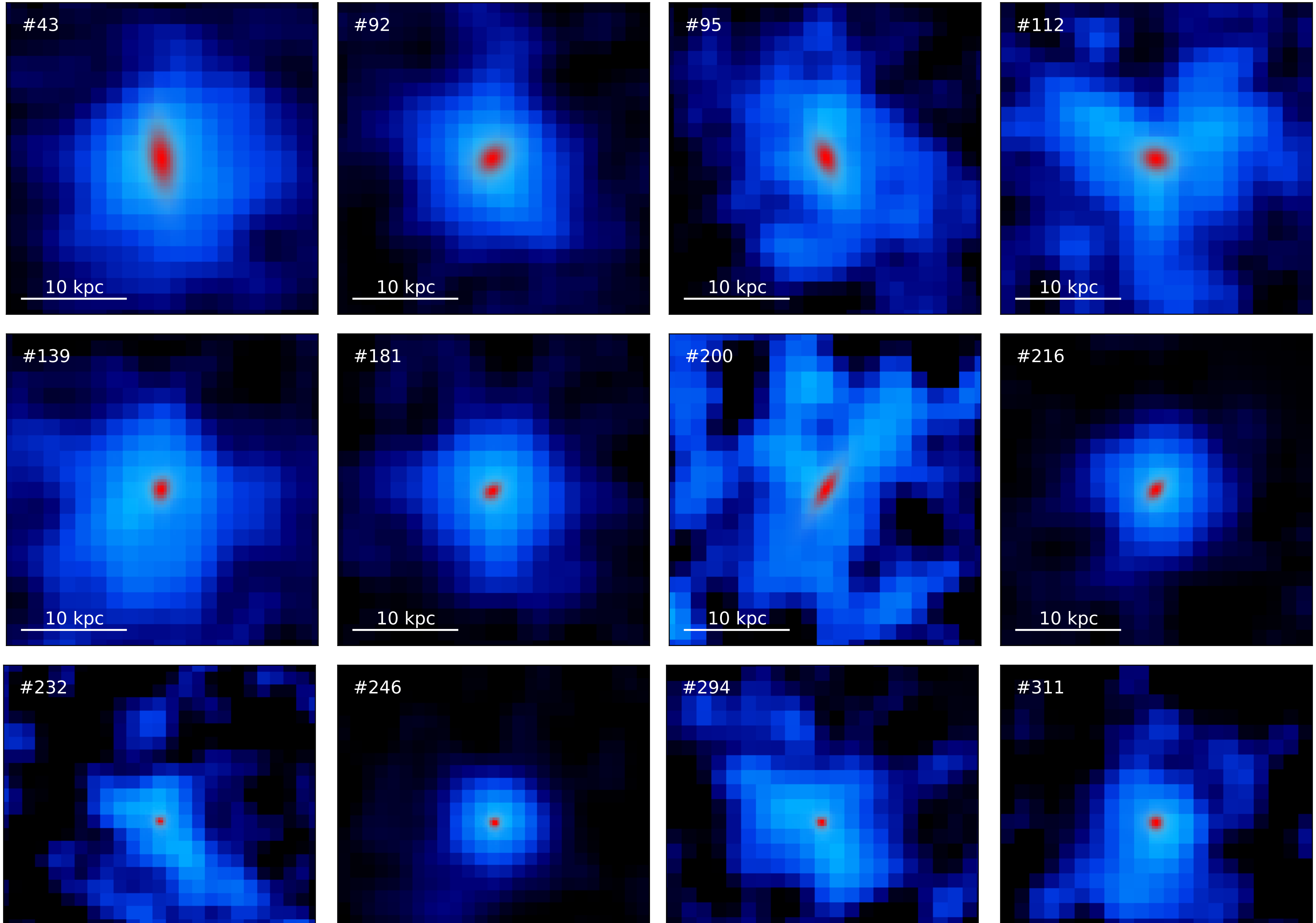
Typical limit of narrowband imaging:
~1 × 10^{-18} erg s^{-1} cm^{-2} $arcsec^{-2}$ (1σ)



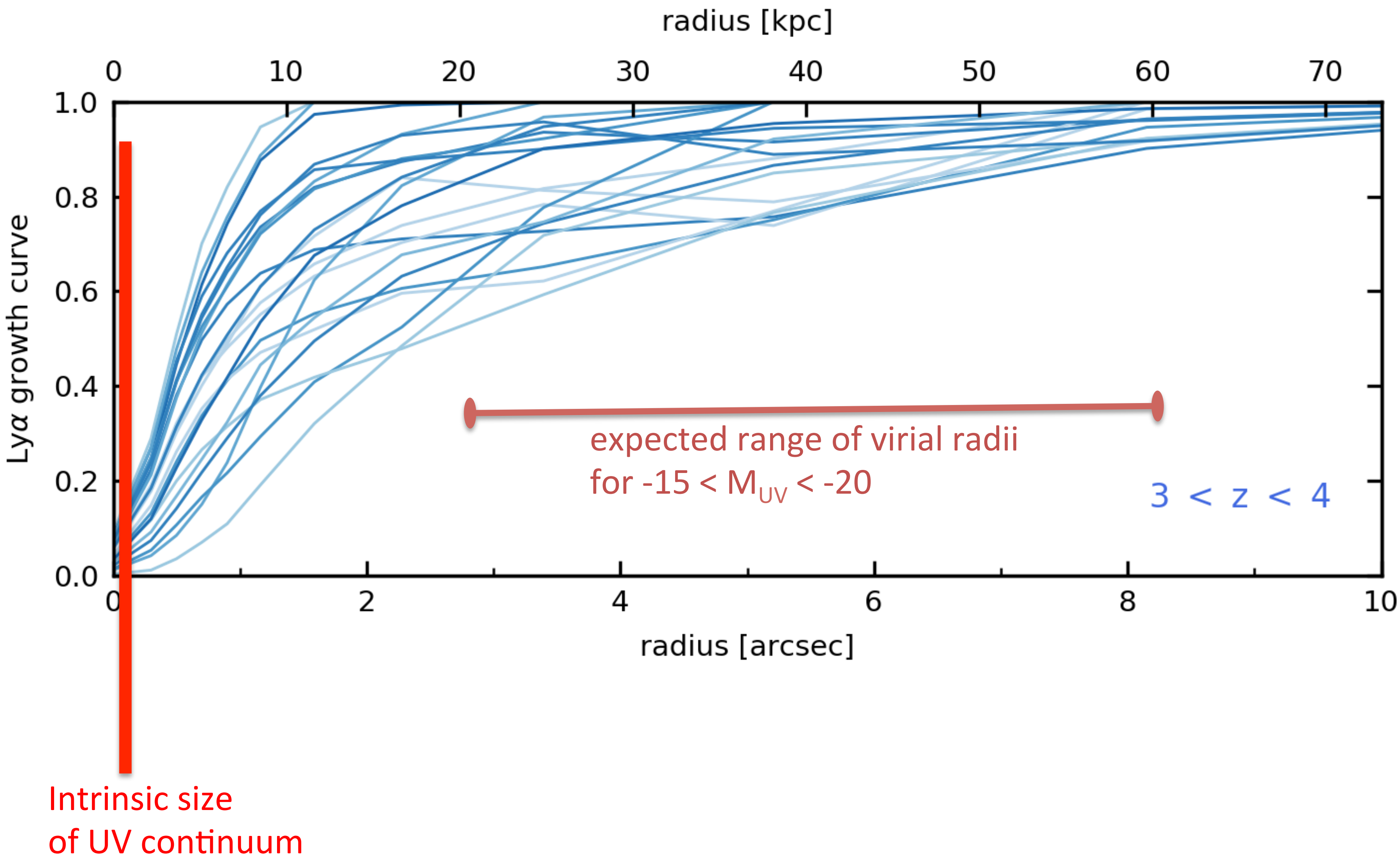
outer contour at
1 × 10^{-19} erg s^{-1} cm^{-2} $arcsec^{-2}$

Wisotzki+ 2016

Lyα haloes around individual galaxies at z>3 are ubiquitous

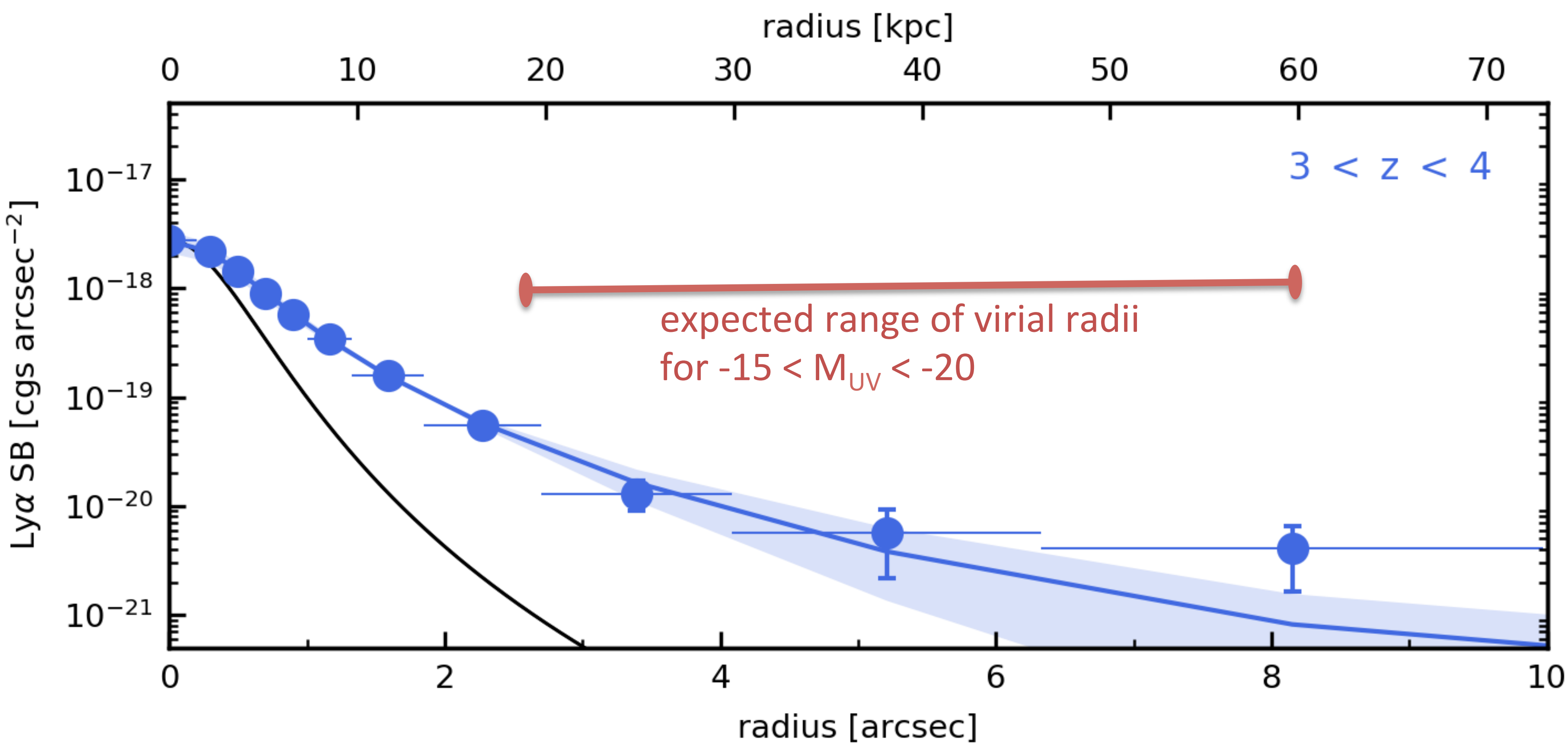


Growth curves of Lyman-α haloes in MUSE Deep data



Going even fainter: Stacking of extremely faint LAEs

Surface brightness profile of median-stacked image:



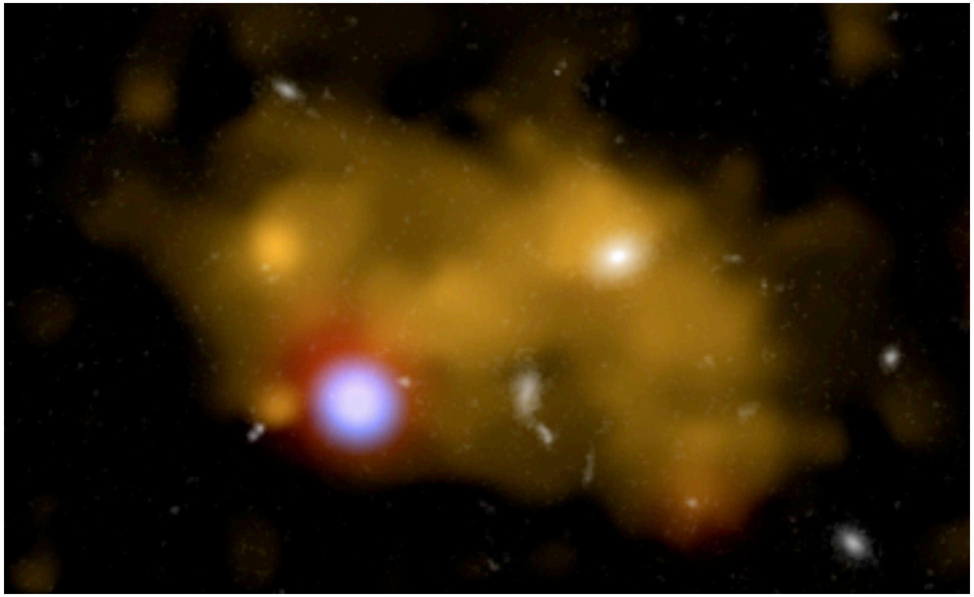
Extended Lyα emission ≈ filling the DM halo!

Wisotzki+ 2018

Lyα "haloes" vs. Lyα "blobs"

Lyα blobs:

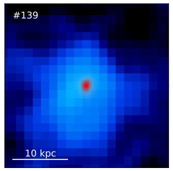
- Giant nebulae (>100 kpc at SB > 10^{-18} erg s^{-1} cm^{-2} $arcsec^{-2}$)
- known since 20 years.
- Rare!
- Often the "main" galaxy is unclear;
- very often related to AGN.



Hayashino+ 2004

Lyα haloes:

- 1–2 orders of magnitude fainter than blobs!
- also much smaller;
- extremely common;
- always around a galaxy;
- normal, low-mass star-forming systems.



Wisotzki+ 2016

Questions arising:

1. Why does more than ~50% of the Lyα emission come from extended regions? How is it produced (and powered)?

2. What are the implications for the demographics of Lyα emitting galaxies?

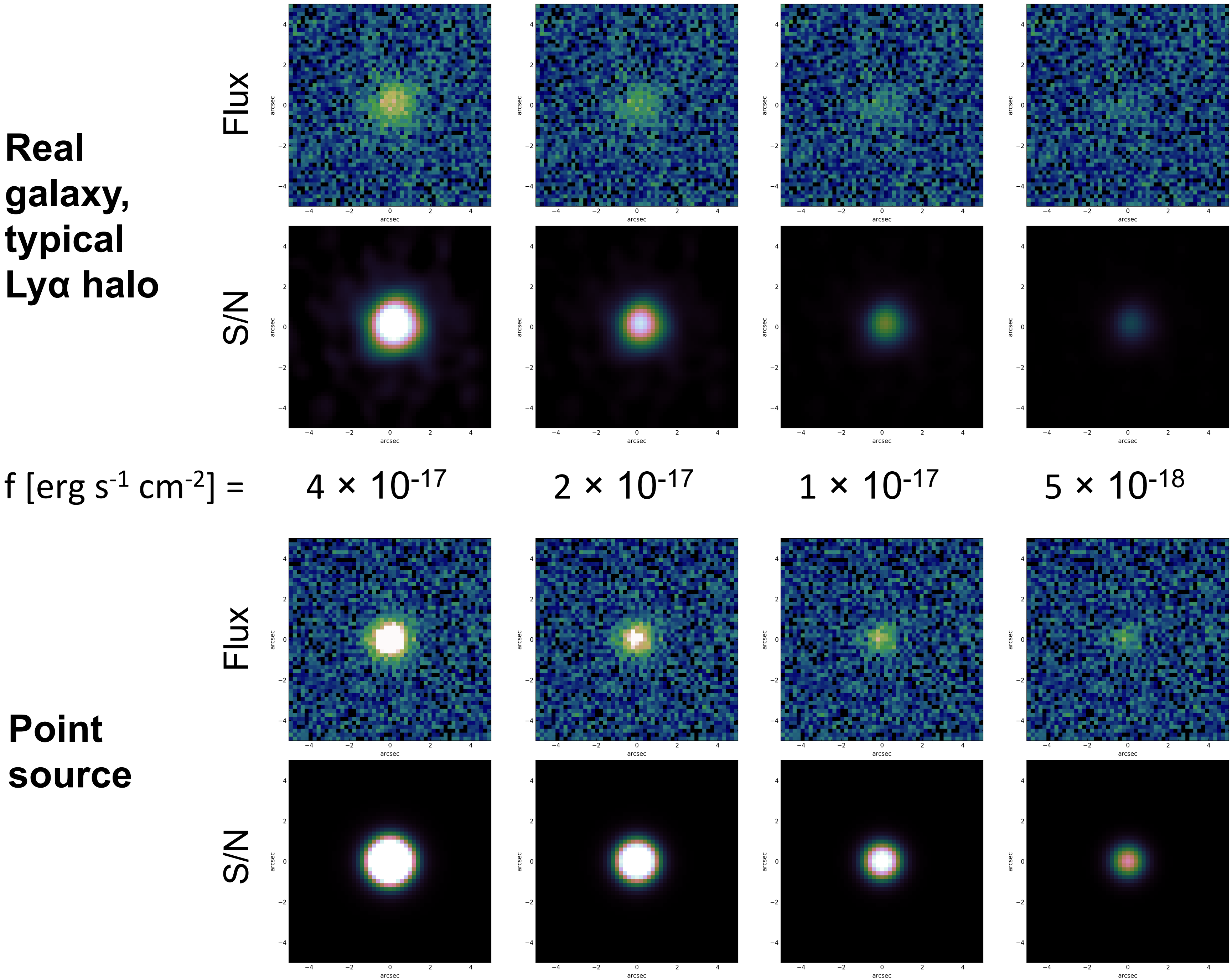
Questions arising:

1. Why does more than ~50% of the Lyα emission come from such extended regions? How is it powered?

2. **What are the implications for the demographics of Lyα emitting galaxies?**

Lyman-α haloes and the Lyα luminosity function

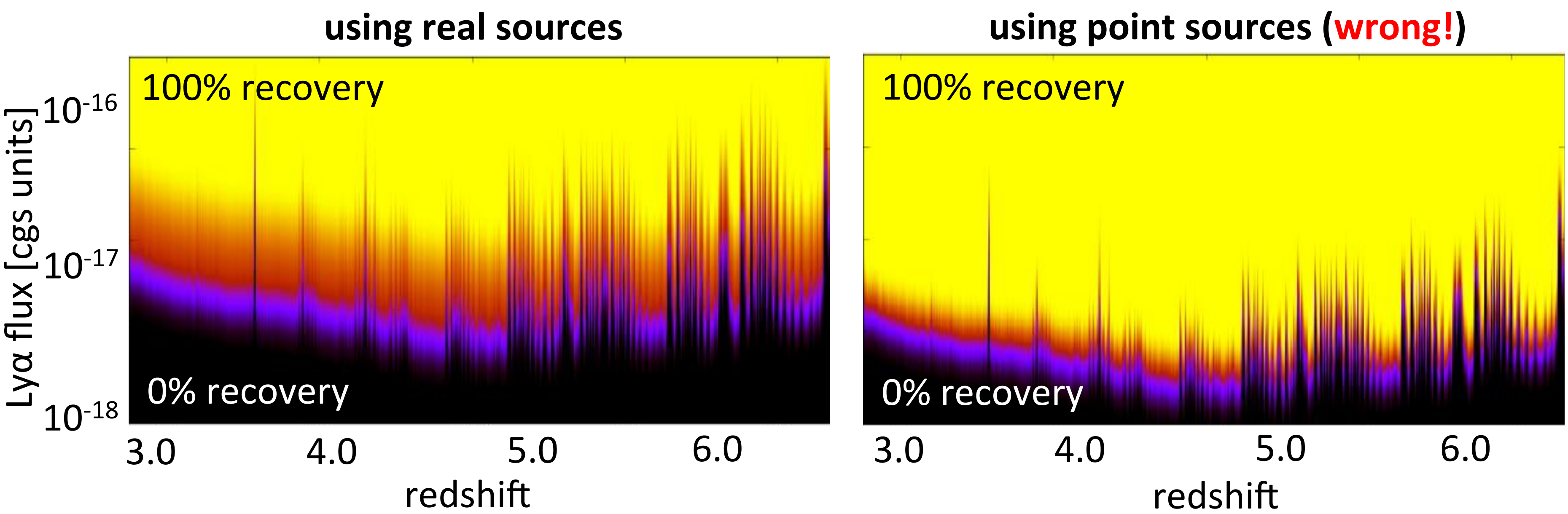
- Extended nature of Lyα haloes relevant for demographics in 2 ways:
  - Measurements through small apertures or spectrograph slits loose a large fraction of the total Lyα flux
    - Lyα luminosities / equivalent widths / escape fractions biased low!
  - Extended sources are harder to detect that point sources at given total flux
    - Huge impact on actual flux limits and selection function of Lyα emitter surveys (not just MUSE, but all!)



Real galaxy, typical Lyα halo
Flux
S/N
f [erg s-1 cm-2] =
4 × 10-17
2 × 10-17
1 × 10-17
5 × 10-18
Point source
Flux
S/N
arcsec

Reassessing the Lyα luminosity function at z > 3

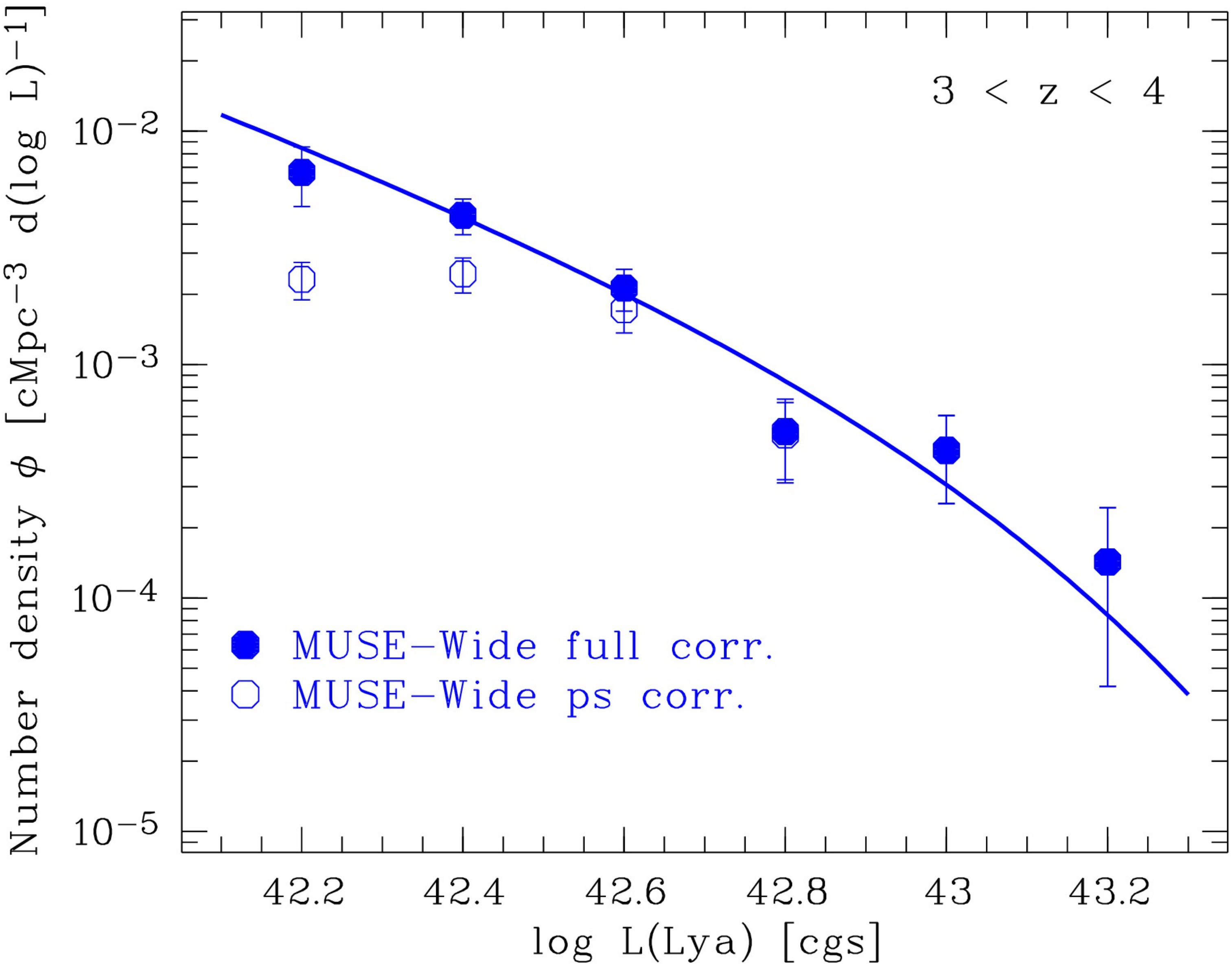
Selection function for MUSE-Wide from fake source insertion experiments:



⇒ Lyα surveys are (generally!) less deep than thought.

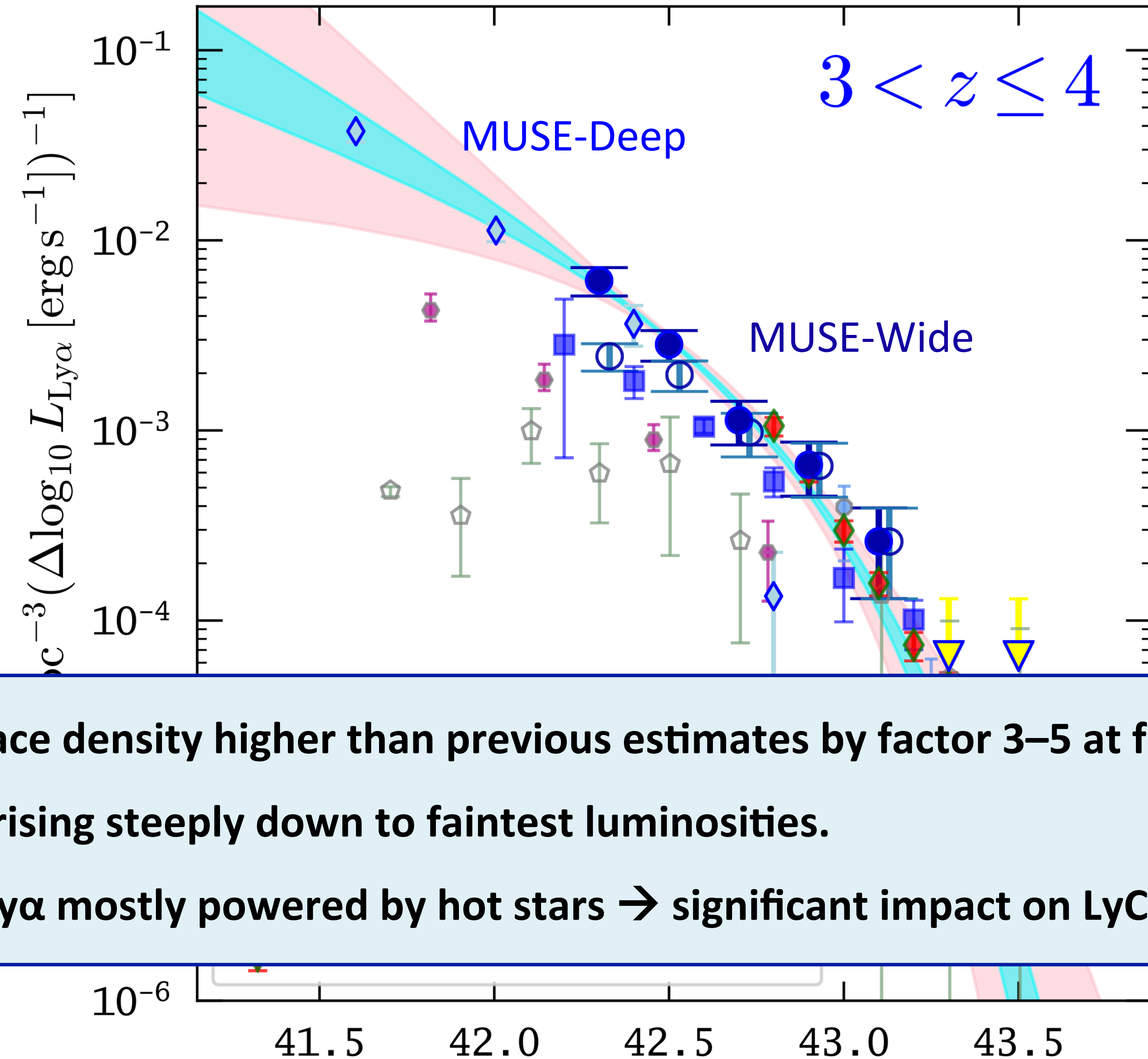
Herenz+ 2019

Reassessing the Lyα luminosity function at z > 3



Herenz+ 2019

Reassessing the Lyα luminosity function at z > 3



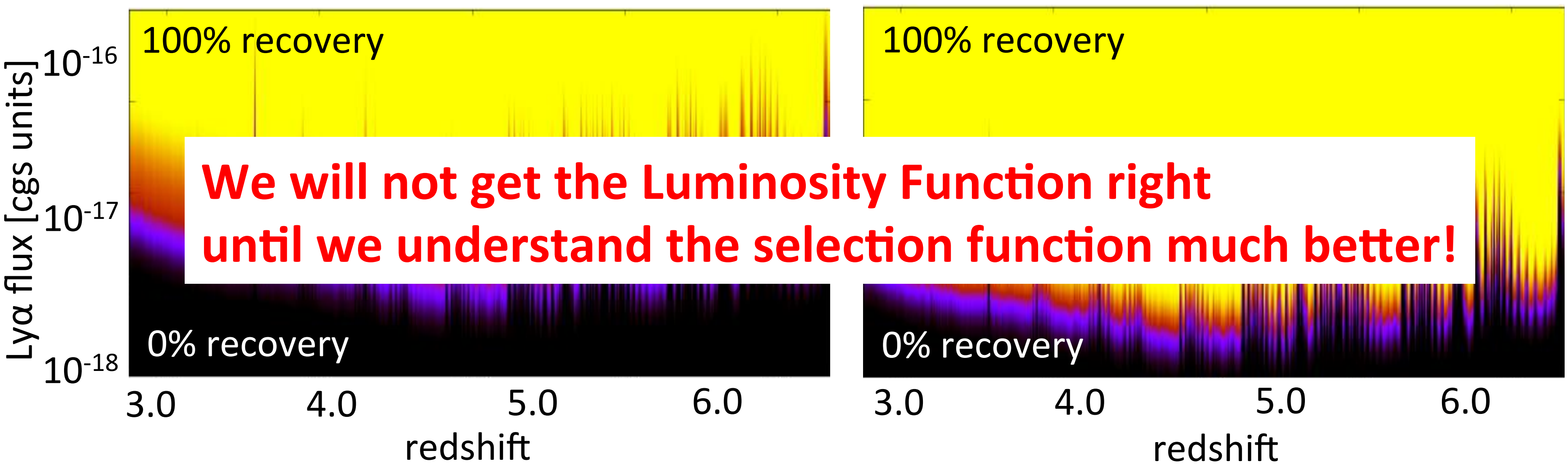
- **Space density higher than previous estimates by factor 3–5 at faint end.**
- **LF rising steeply down to faintest luminosities.**
- **If Lyα mostly powered by hot stars → significant impact on LyC production**

Drake+ 2017;
Herenz+ 2019

How well do we know the LAE selection function?

Selection function for MUSE-Wide from fake source insertion experiments:

using real sources (but which?) | **using point sources (wrong!)**



We will not get the Luminosity Function right until we understand the selection function much better!

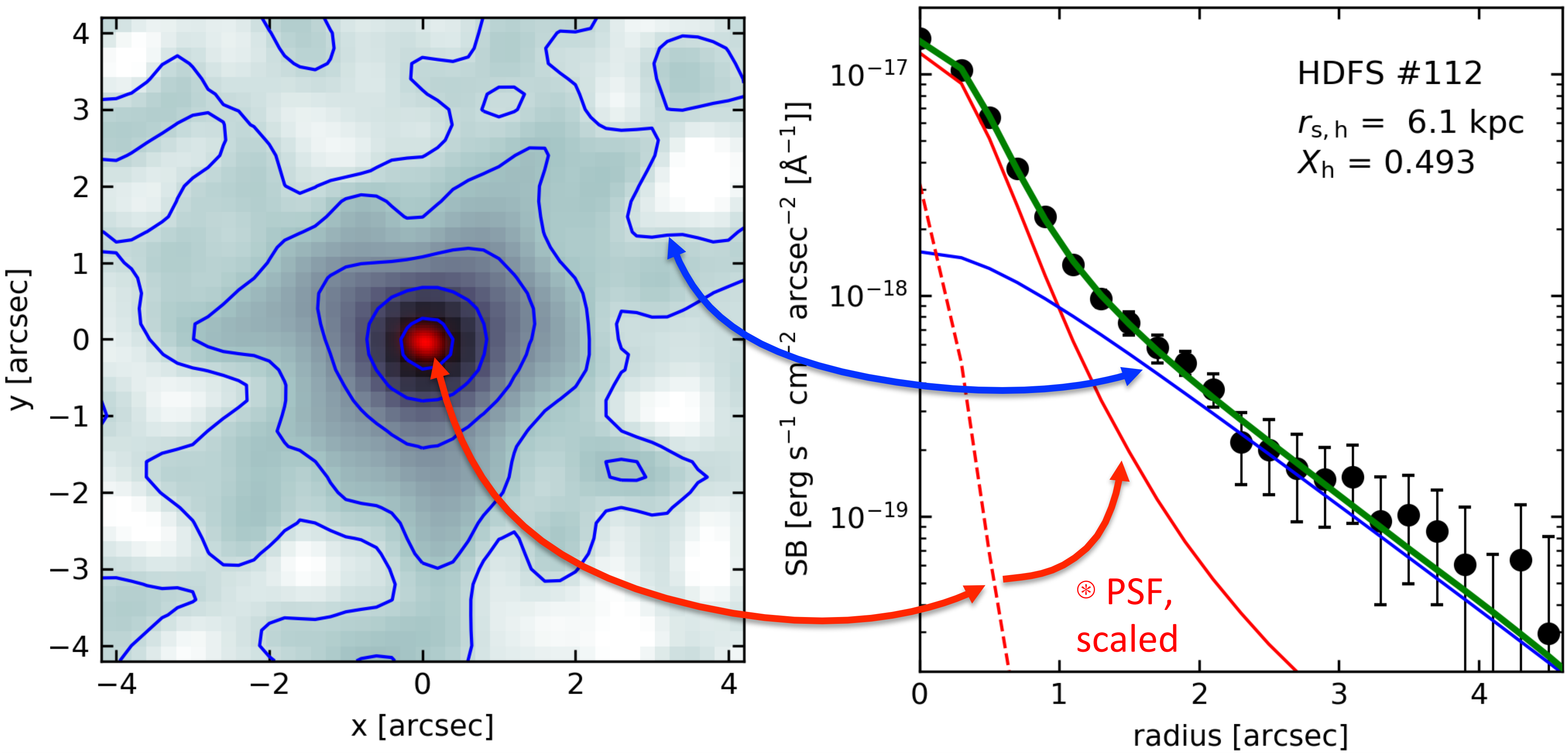
Questions arising:

1. **Why does more than ~50% of the Lyα emission come from such extended regions? How is it produced (and powered)?**

2. What are the implications for the demographics of Lyα emitting galaxies?

A typical Lyα halo at z≈4: A closer look

Phenomenological model: Compact core ≈ UV continuum + extended exponential

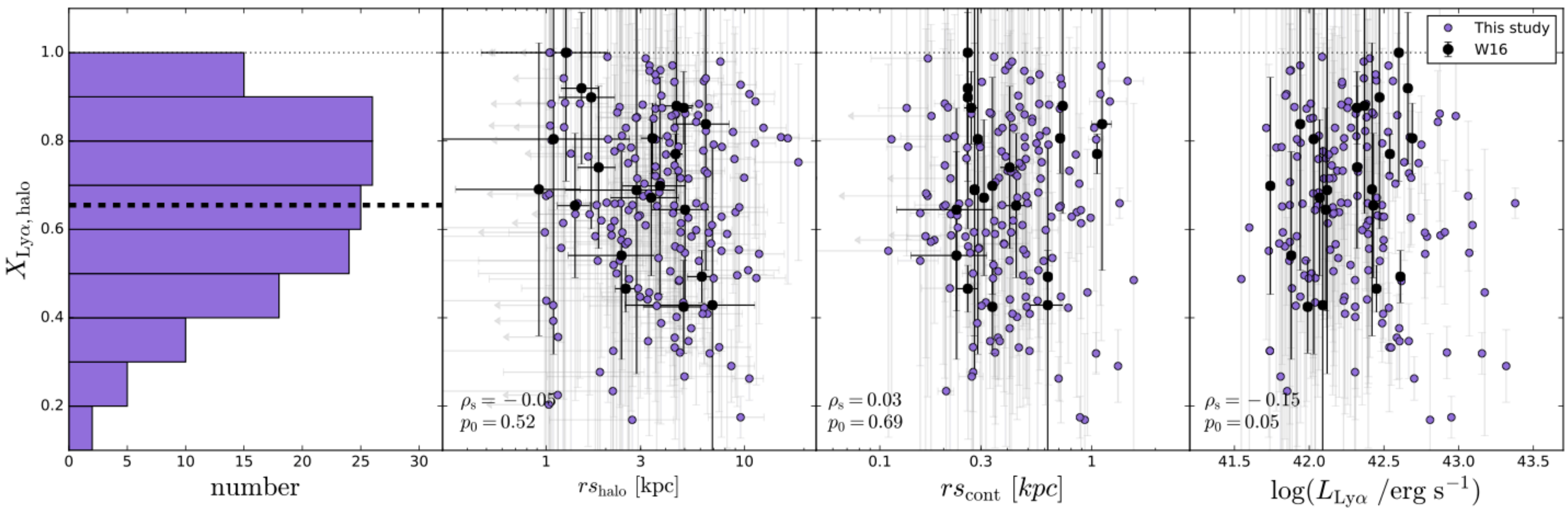


2 parameters for extended emission:

- **Flux fraction in the halo, $X_h = F_h/F_{total}$**
- **Scale length of halo**

Most of the observed Lyα photons come from the halo!

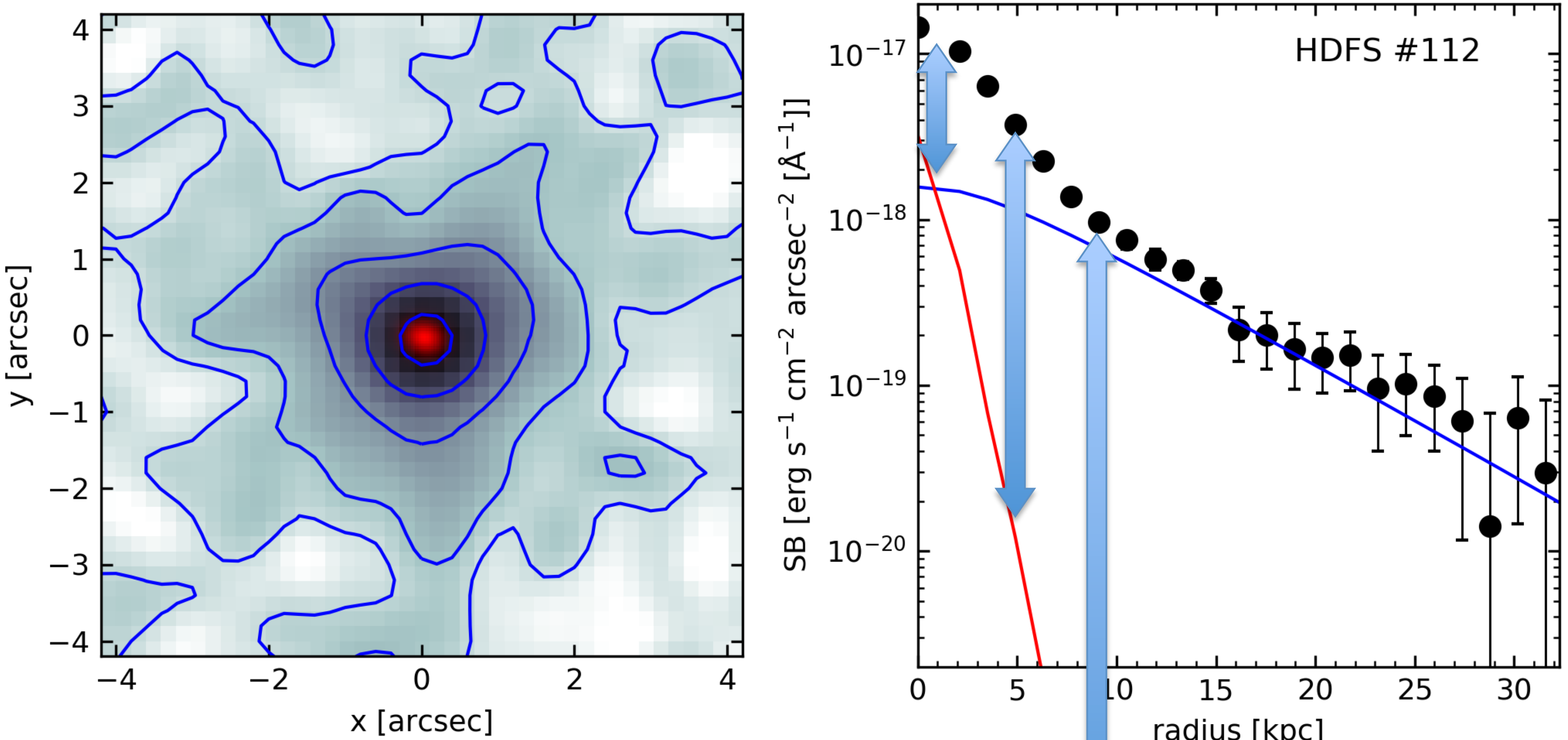
- Lyα halo luminosity fraction: $X_h = L_{halo} / L_{total}$
- Measured values: $10\% < X_h < 100\%$, average: 65%
- **No** correlation with sizes or luminosities!



Leclercq+ 2017

A typical Lyα halo at z≈4: A closer look

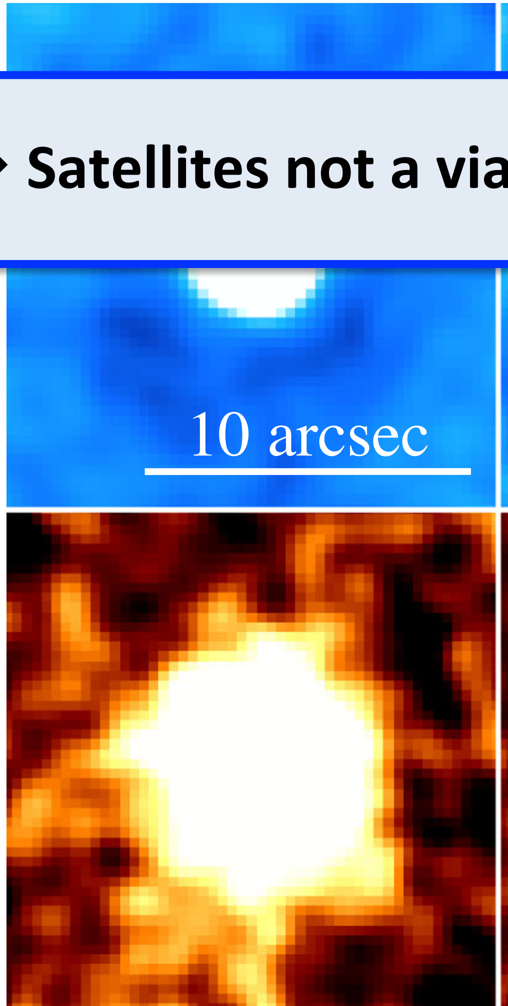
Equivalent width increase from ~10 Å at r=0 ➞ >10^4 Å at r > 10 kpc



→ **Extended Lyα emission cannot be produced in situ by stars!**

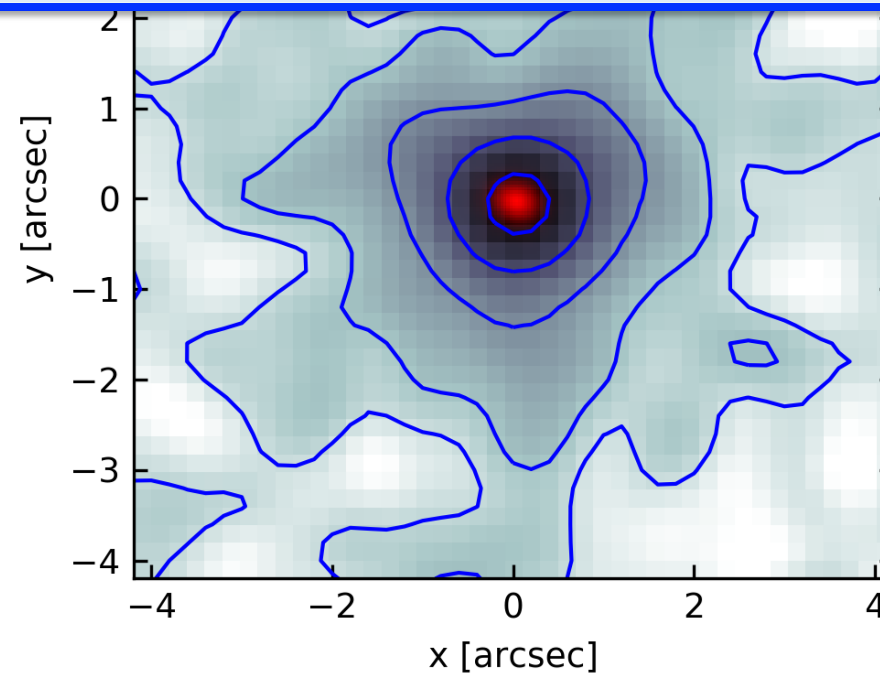
Can Lyα haloes be faked by satellite galaxies?

Stack of >3000 LAEs:



Momose+ 2014

Single LAE:



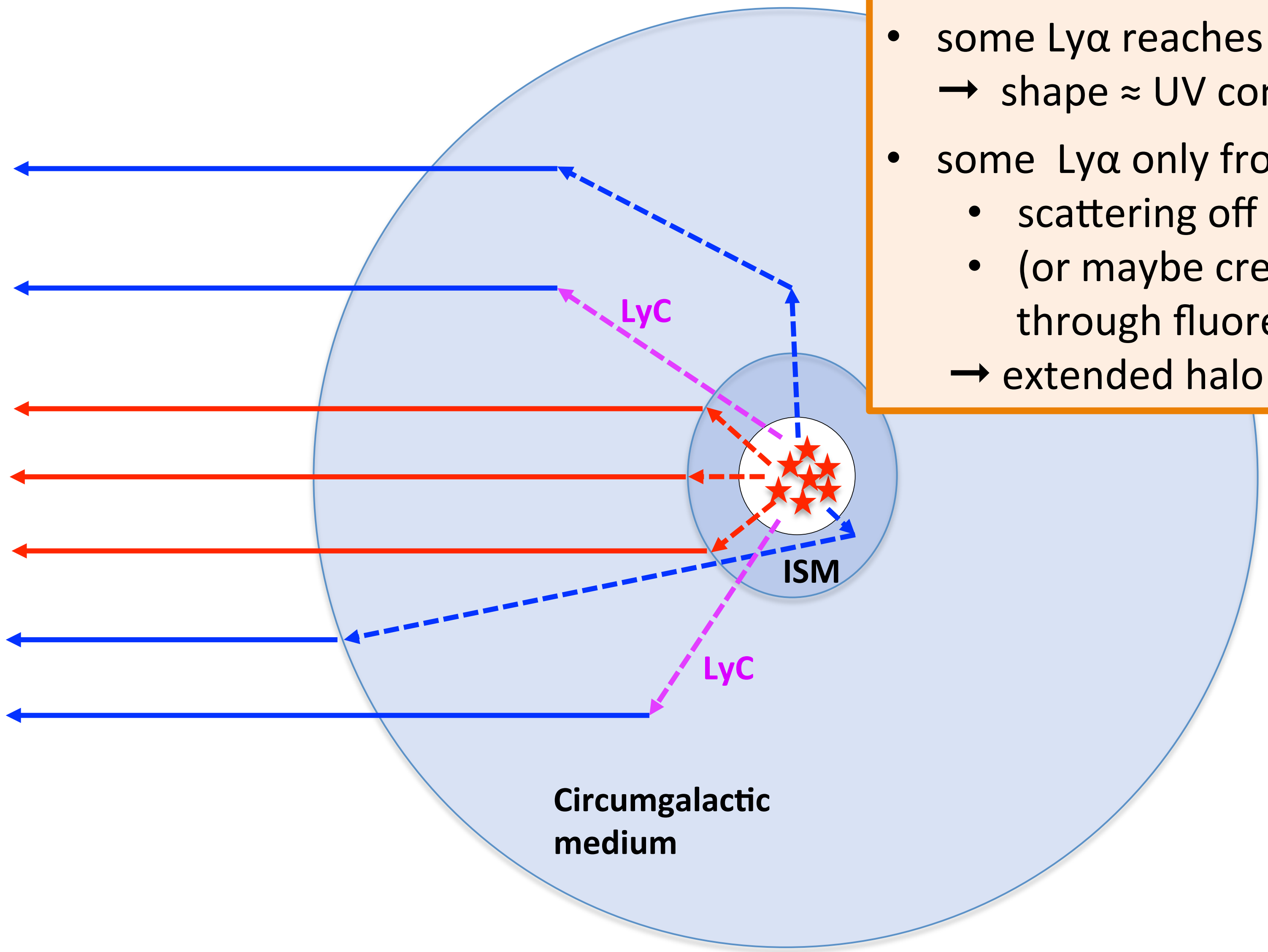
→ Satellites not a viable explanation for individual Lyα haloes!

Origin of the extended Lyα emission

1. **Lyα from recombination inside galaxies, then scattered outwards?**
   - Required: Young stars in the galaxies; enough circumgalactic H I
   - A simple expanding shell + Radiative Transfer model can roughly reproduce the observed Lyα spectra, but it fails on the radial profiles.
   - Other models do OK for the radial profiles, but don't get the spectra right.
   - Extended haloes also not predicted in galaxy formation simulations.

   → Plausible scenario, but physics still to be understood!

Lyα escape from galaxies: A two-stage challenge!



After the ISM there is the CGM!

- some Lyα reaches us from ISM:
  → shape ≈ UV continuum
- some Lyα only from CGM:
  - scattering off H I
  - (or maybe created in situ through fluorescence)

  → extended halo

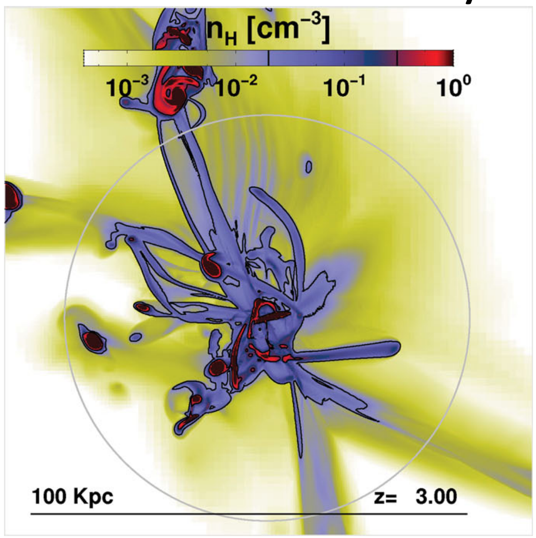
Origin of the extended Lyα emission

1. **Lyα from recombination inside galaxies, then scattered outwards?**

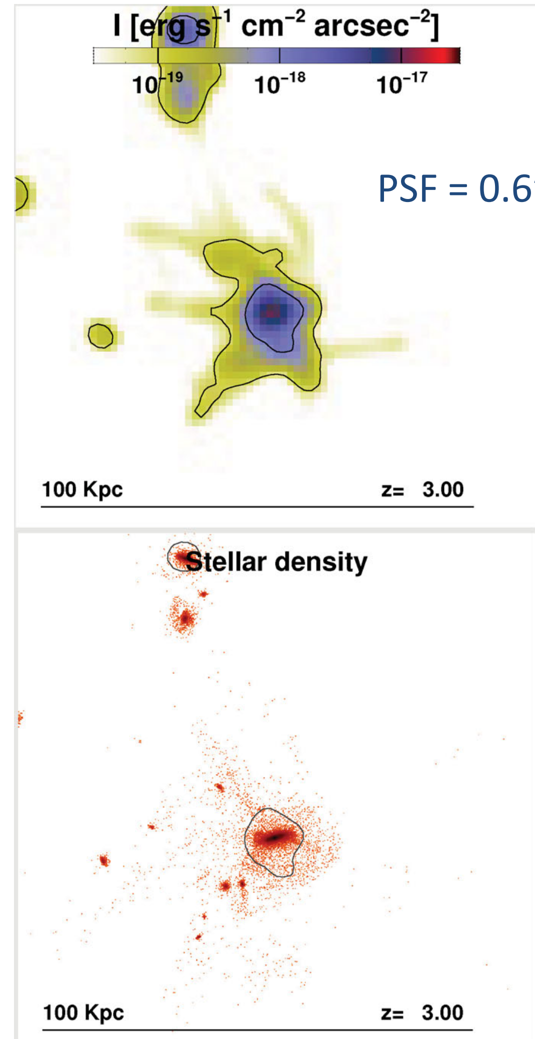
2. **Lyα from collisional excitation in accreting intergalactic gas?**
   - Predicted by simulations, but very uncertain;
   - could maybe explain “Lyα blobs” residing in very overdense locations;
   - but probably subdominant in low-mass haloes;

Lyα cooling radiation in numerical simulations

Gas column density



Lyα surface brightness



PSF = 0.6″

Rosdahl & Blaizot 2012

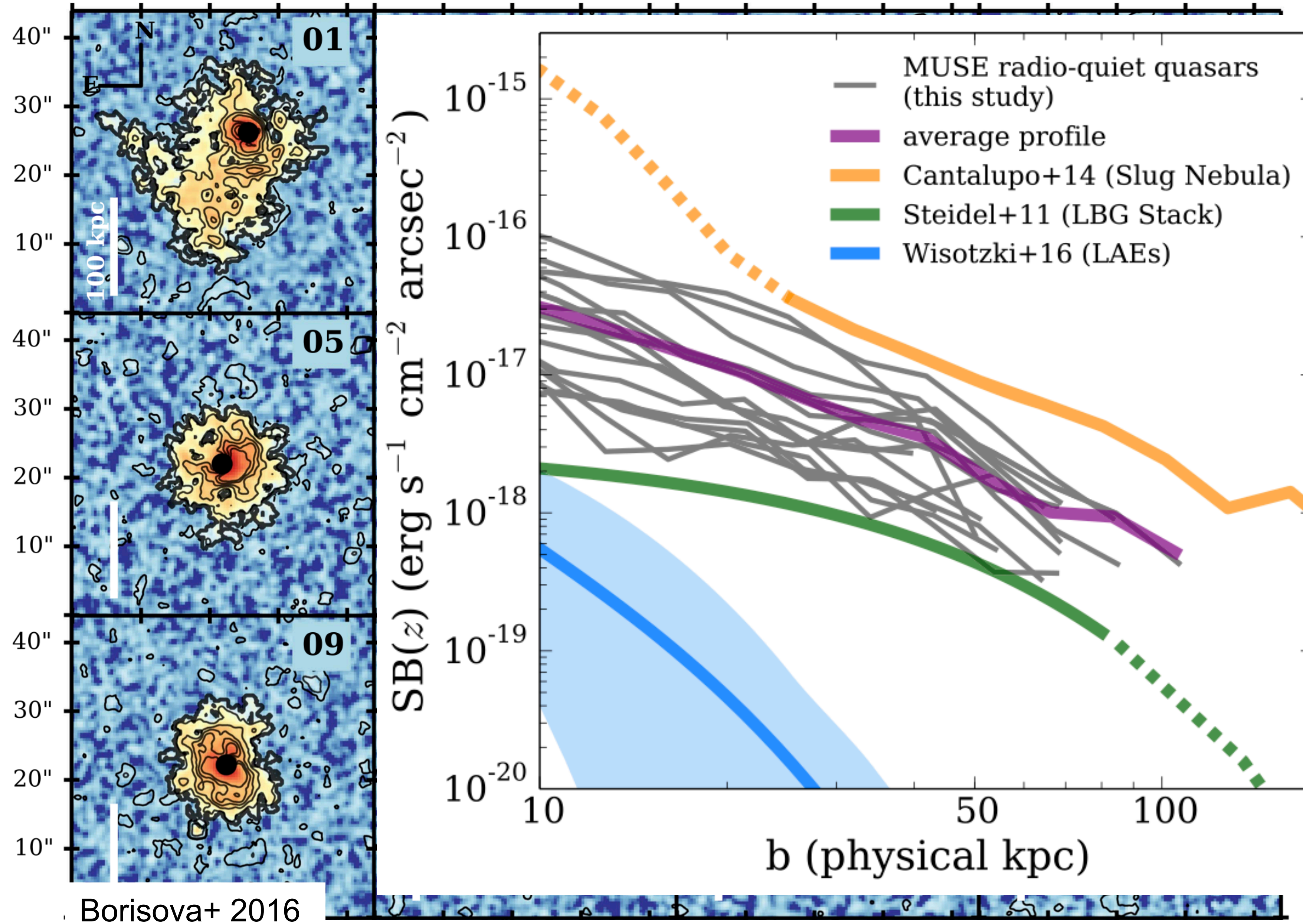
Origin of the extended Lyα emission

1. **Lyα from recombination inside galaxies, then scattered outwards?**

2. **Lyα from collisional excitation in accreting intergalactic gas?**

3. **Lyα from UV fluorescence?**
   - requires that enough Lyman Continuum photons escape from galaxies;
   - → Lyα nebulae around luminous quasars!
   - not clear whether relevant for `normal’ LAE haloes
   - At transition to IGM: Fluorescence by UV background becomes relevant.

Lyα nebulae around quasars



Borisova+ 2016

Origin of the extended Lyα emission

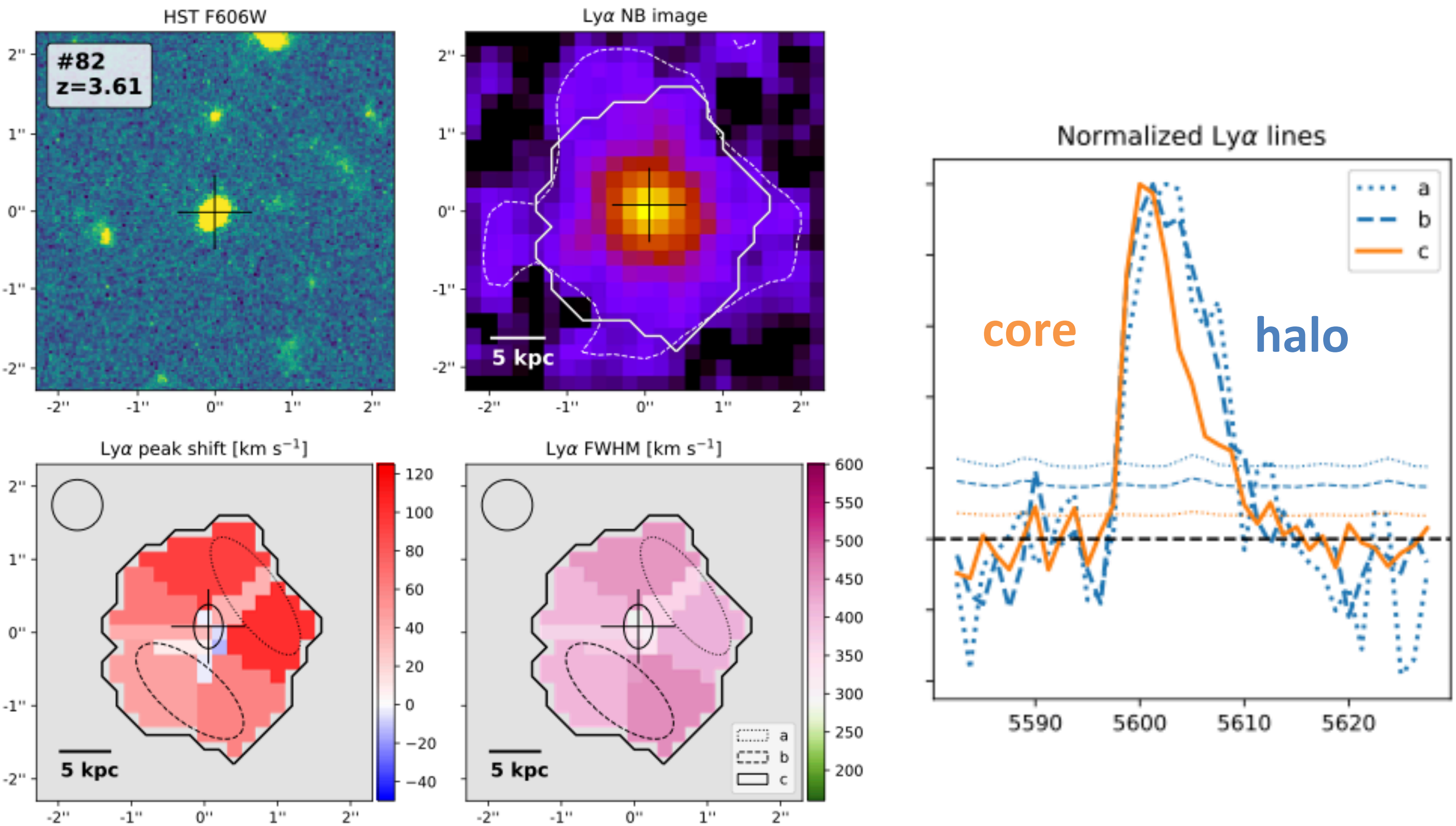
1. **Lyα from recombination inside galaxies, then scattered outwards?**
2. **Lyα from collisional excitation in accreting intergalactic gas?**
3. **Lyα from UV fluorescence?**

All still very uncertain!

→ Further insights from spatially resolved spectra of Lyα haloes.

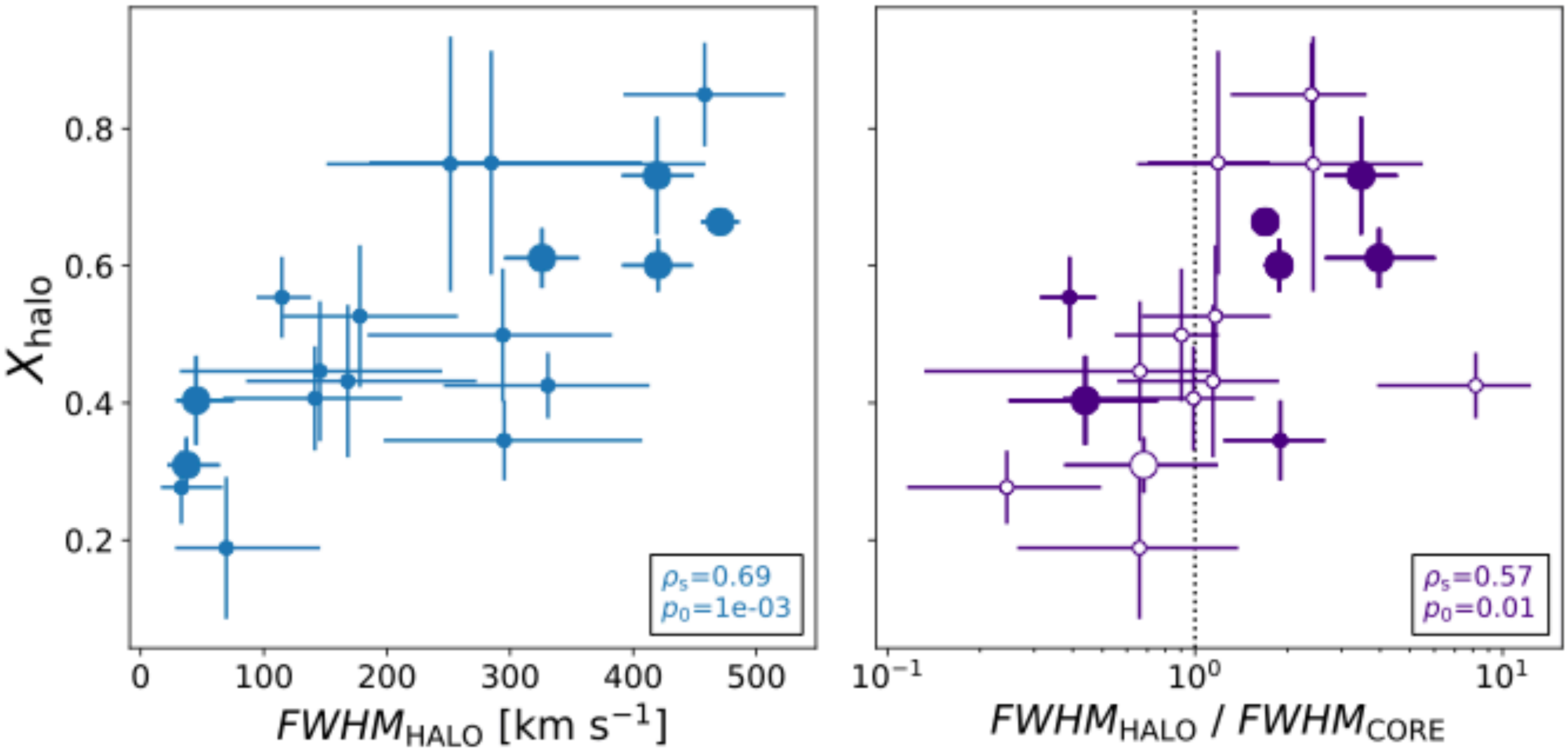
- Also provided by (the same) MUSE Deep Field data
- but very high S/N requirements → only brightest LAEs possible

Evidence for a scattering origin of Ly haloes from spatially resolved MUSE spectroscopy



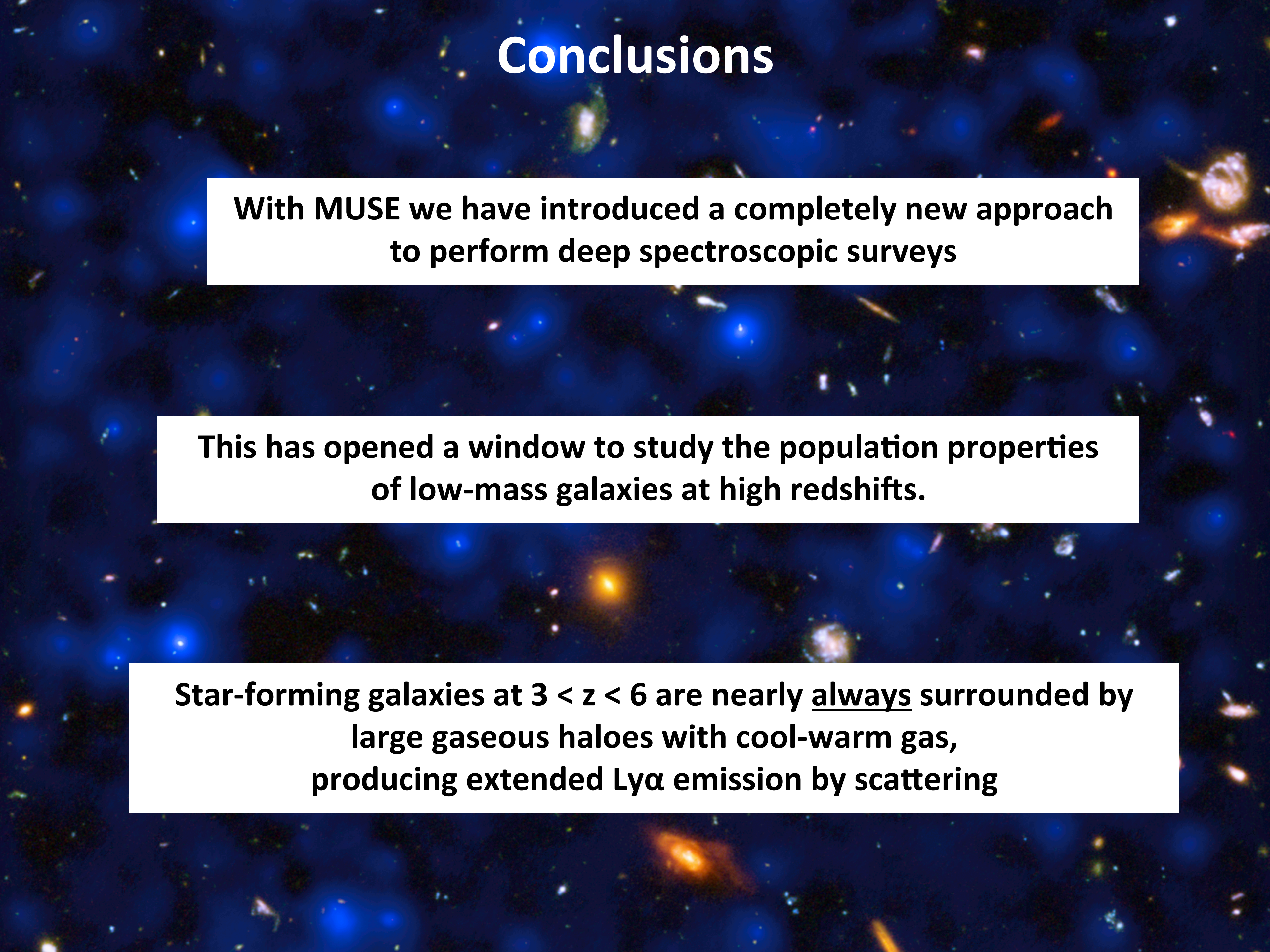
Leclercq+ 2020

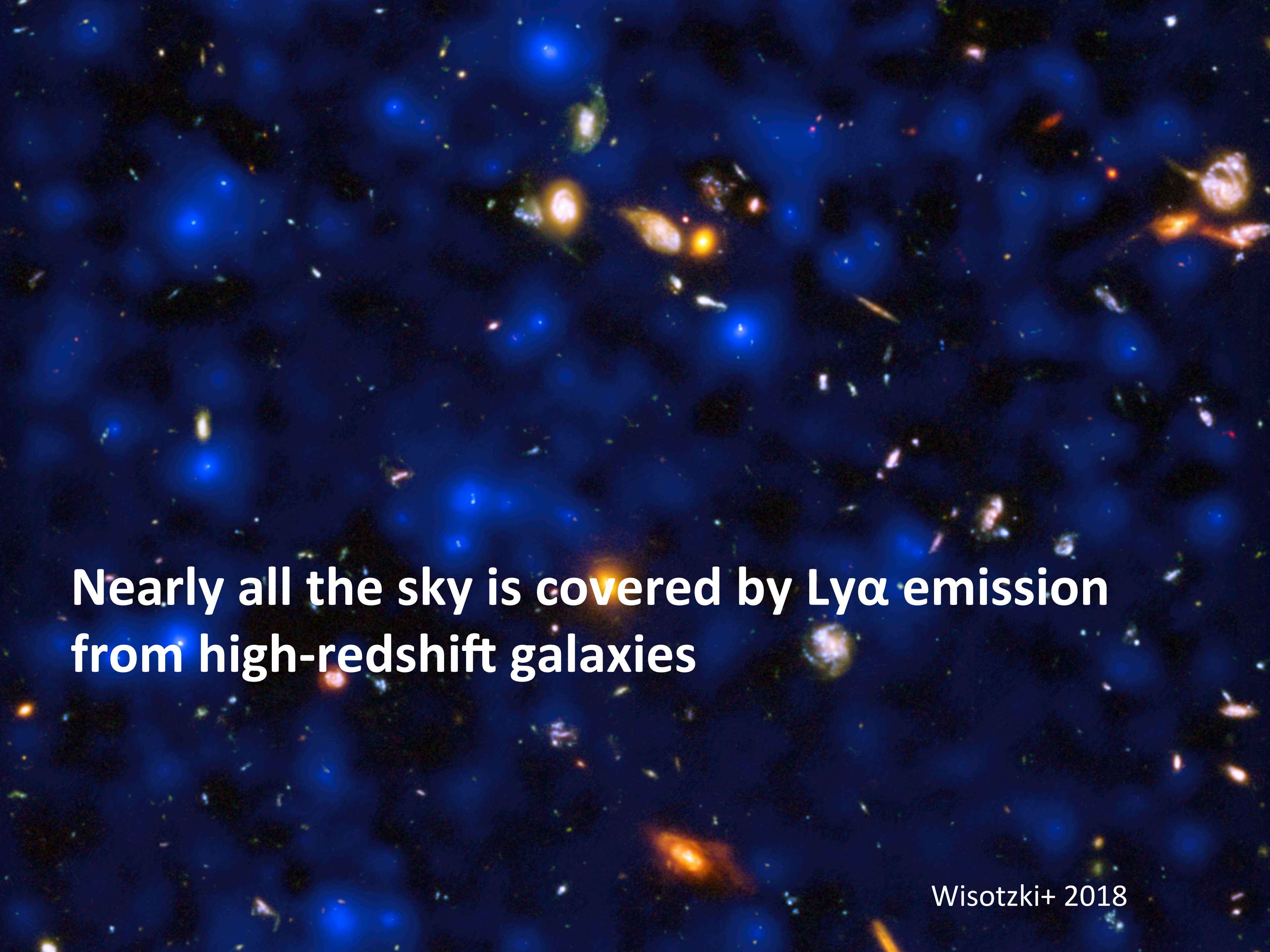
Evidence for a scattering origin of Ly haloes from spatially resolved MUSE spectroscopy



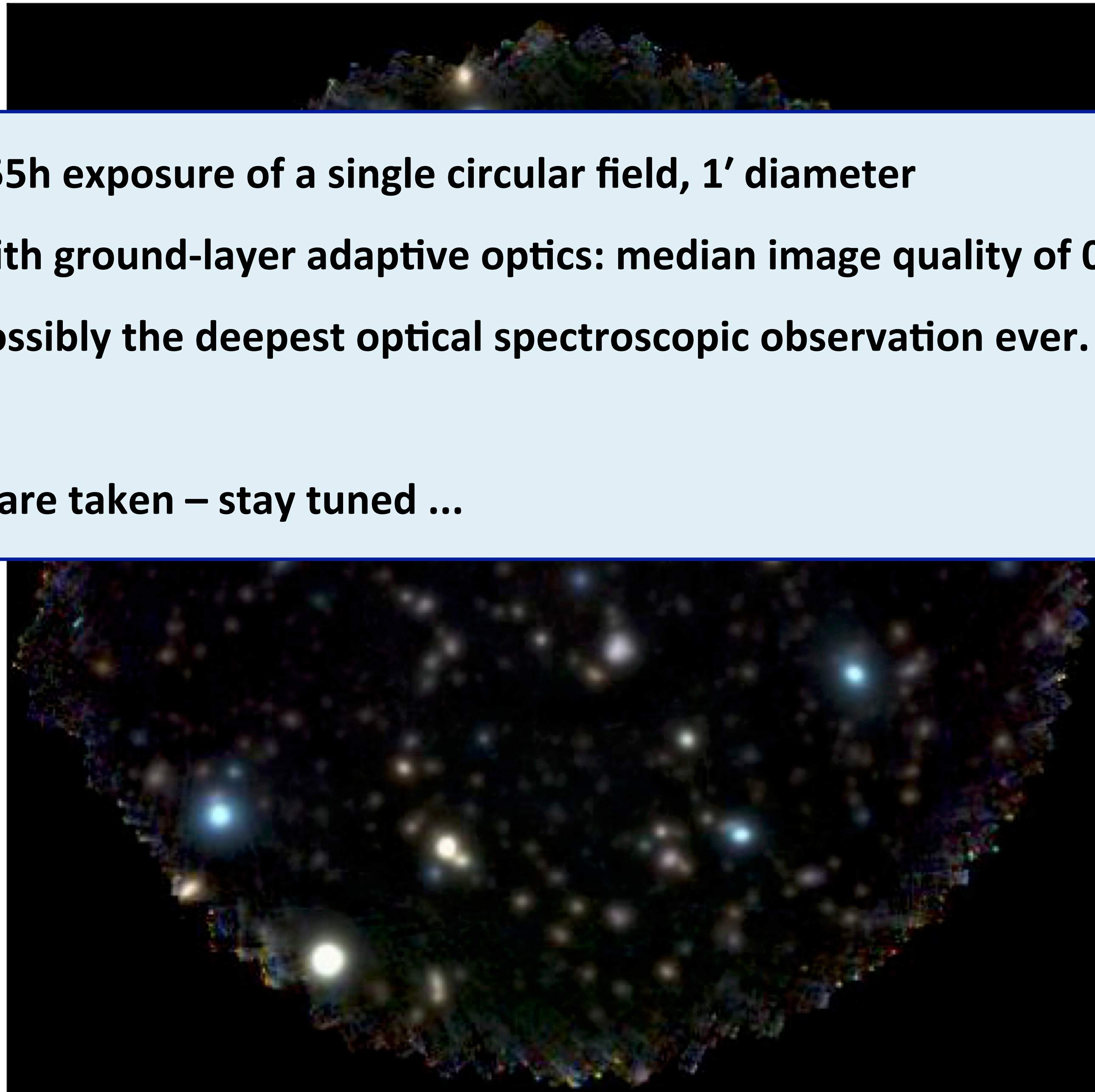
→ **The broader the line in the halo, the higher the luminosity fraction in the halo!**

Leclercq+ 2020


Conclusions
With MUSE we have introduced a completely new approach to perform deep spectroscopic surveys
This has opened a window to study the population properties of low-mass galaxies at high redshifts.
Star-forming galaxies at 3 < z < 6 are nearly always surrounded by large gaseous haloes with cool-warm gas, producing extended Lyα emission by scattering


Nearly all the sky is covered by Lyα emission
from high-redshift galaxies
Wisotzki+ 2018

The next step: The MUSE eXtremely Deep Field (MXDF)



- **155h exposure of a single circular field, 1′ diameter**
- **with ground-layer adaptive optics: median image quality of 0.48″**
- **possibly the deepest optical spectroscopic observation ever.**

Data are taken – stay tuned ...