Illuminating the link between Galaxy Formation and massive Cosmic Web Nodes at high redshift

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Talk Outline

The MQN01 Cosmic Structure at z~3: a unique laboratory to test galaxy formation and evolution from both the galaxy and the CGM/IGM side (in emission!)

The Galaxy-Side in MQN01: surprises from multi-wavelength osbservations

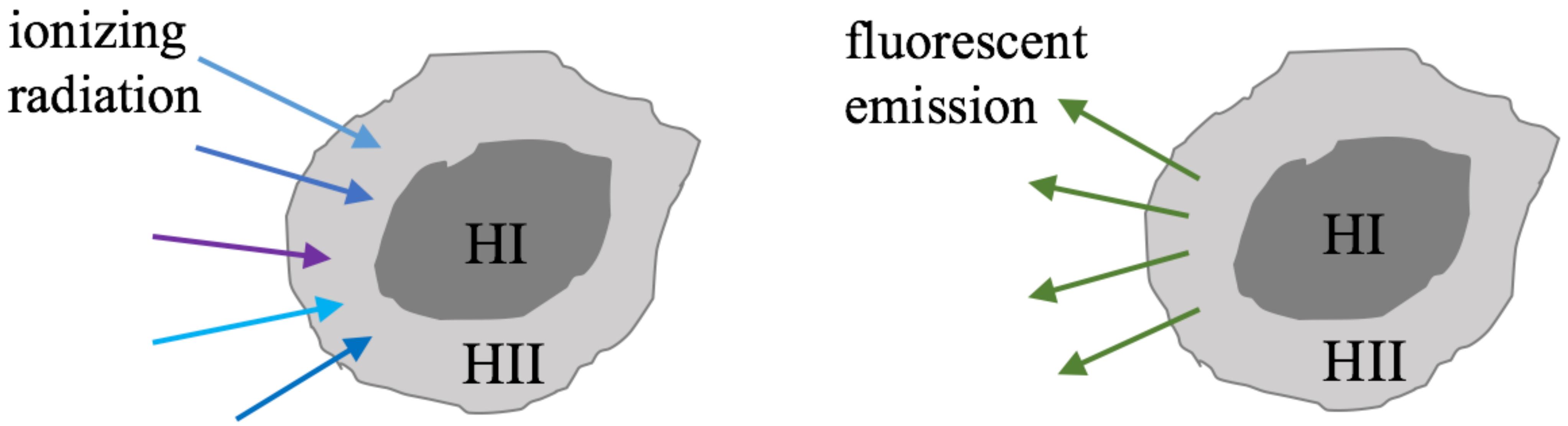
The CGM/IGM side in MQN01: the hot and the “cold” phase in emission

Summary and future outlook: connecting galaxy and the CGM/IGM properties

Introduction and key questions

The IGM/CGM in emission: methods

Direct detection *in emission*: Fluorescent Lyα (*Hogan & Weymann 1987;Gould & Weinberg 1996; Zheng & Miralda-Escude 2005; SC+05,07; Kollmeier+06,10; SC+12; Mas-Ribas+17; Gronke & Bird 2017; Mitchell+21; Byrohl+21; ++*)



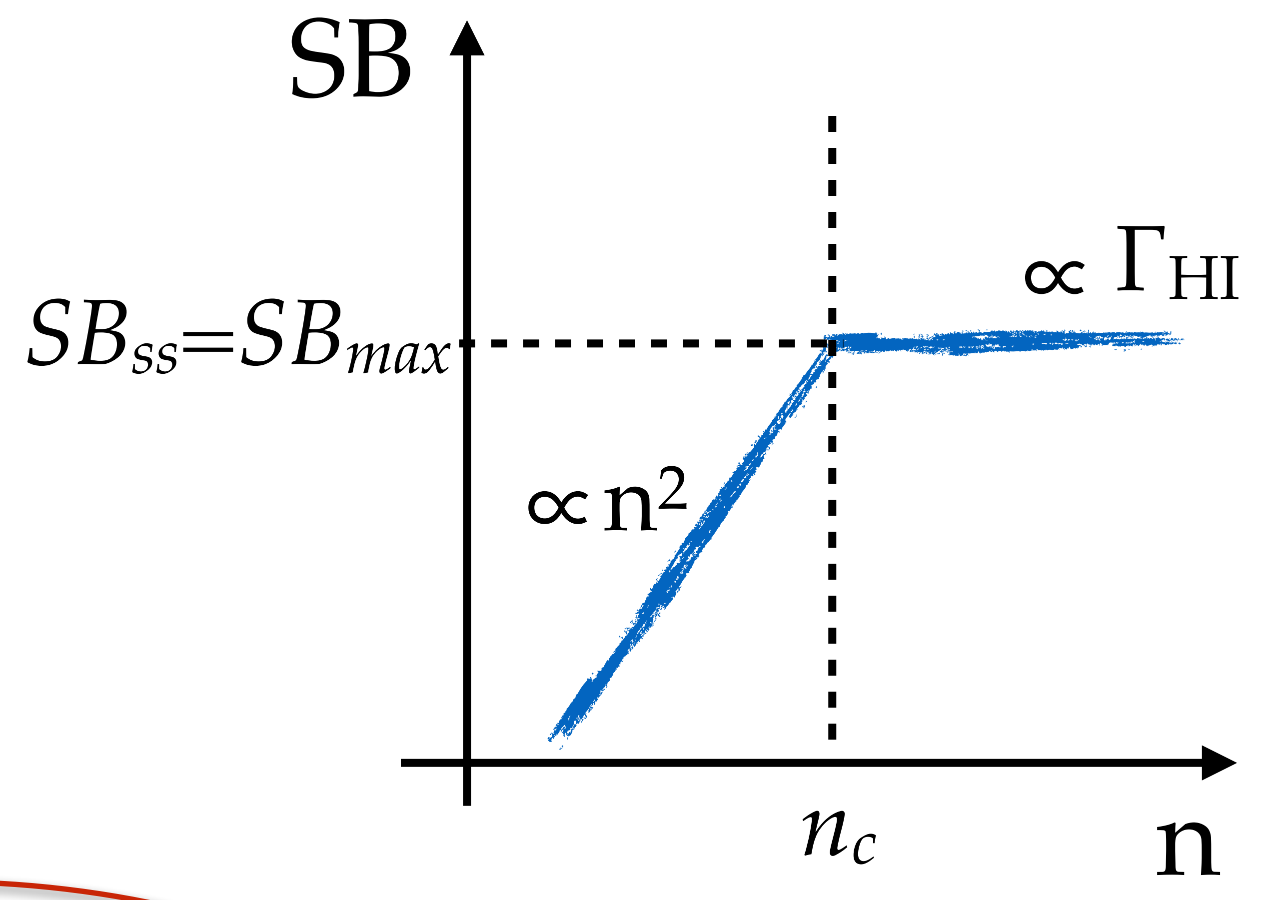
Two main regimes for **recombination radiation**:

- Self-shielded gas: "mirror" emission -> ~60% of incident ionizing radiation (Γ_{HI}) "converted" to Lyα (modulo Lyα RT effects).

$$n \gg n_c \equiv \Gamma_{HI}/\alpha(T) \qquad SB_{ss} \propto \Gamma_{HI}$$

- Fully ionized gas: proportional to *cold* ($T \sim 10^4$ K) gas density squared and gas "clumping factor" *C*

$$n \ll n_c \equiv \Gamma_{HI}/\alpha(T) \qquad SB_{ion} \propto \frac{1}{A}\int n^2 dV \propto < n >^2 \cdot L \cdot C \qquad C \equiv \langle n^2 \rangle / \langle n \rangle^2$$



For $\Gamma_{UVB} \sim 10^{-12}$ s^{-1} at z~3:

$n_c \sim 0.1$ cm^{-3}

$SB_{max} \sim 10^{-20}$ cgs/arcsec^2

Faint!

In **general:**

Ioinizations - Recombinations | Collisional excitations | Continuum photon-pumping

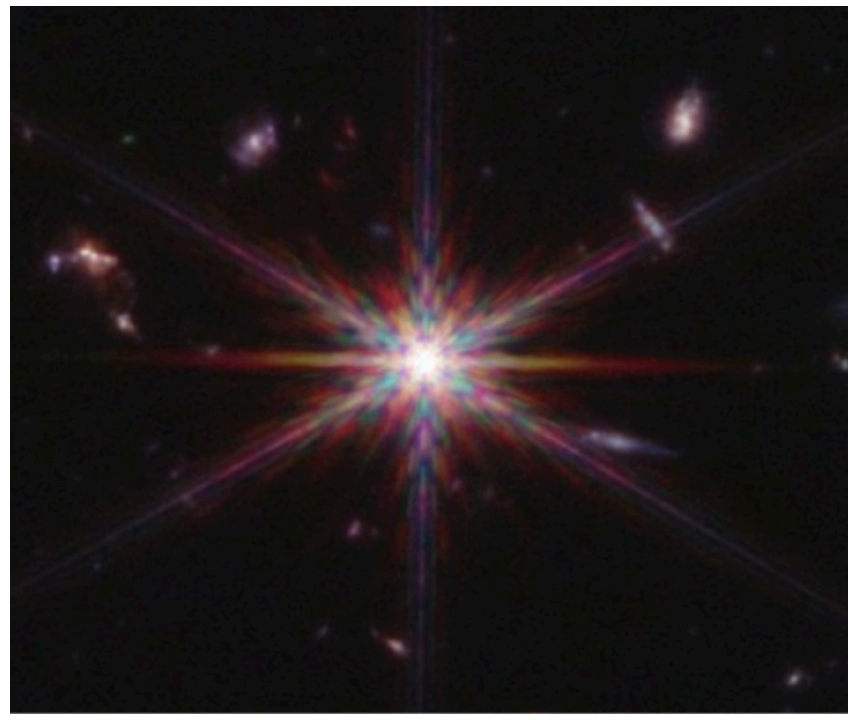
$$\frac{4\pi j_{Ly\alpha}}{h\nu_{Ly\alpha}} = n_e n_p\, \alpha^{eff}_{Ly\alpha}(T) + n_e n_{HI}\, q^{eff}_{Ly\alpha}(T) + P(I_\nu, n_{HI}, T)$$

ionized gas → partially ionized → neutral gas

Complicated!

How to solve both problems?

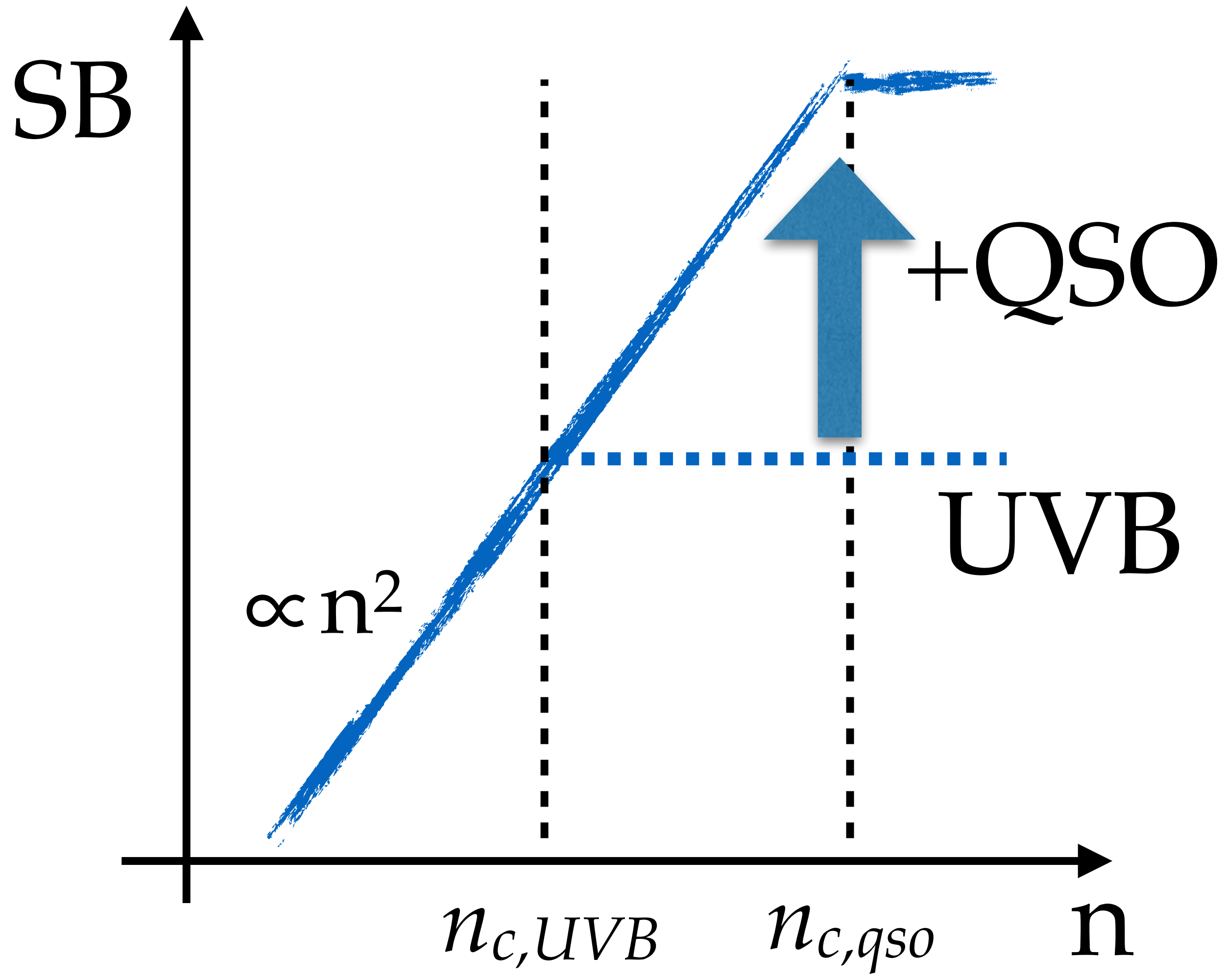
How to make IGM/CGM emission brighter and easier to interpret: Quasars!



$\Gamma_{UVB} \sim 10^{-12}\ s^{-1}$

$\Gamma_{QSO} \sim 10^{-6}\ s^{-1}$ at r=30 kpc from a bright z~3 QSO

(but everything else works as long as $\Gamma >> \Gamma_{UVB}$!)



- Hydrogen safely ionised for any reasonable density ($n << 10^5\ cm^{-3}$)!
- Collisional excitation term can be safely ignored
- Photon-pumping (scattering of QSO BLR) *can be shown* to be subdominant analytically and using non-resonant lines (Hα of H and HeII). See later in the talk.
- Max Lyα SB is high enough to detect emission on Mpc scales (if gas dense enough):

$$SB_{max} \simeq 10^{-17} \left[\frac{4}{1+z}\right]^4 \left[\frac{1\ \mathrm{pMpc}}{R}\right]^2 \mathrm{cgs\ arcsec^{-2}}$$

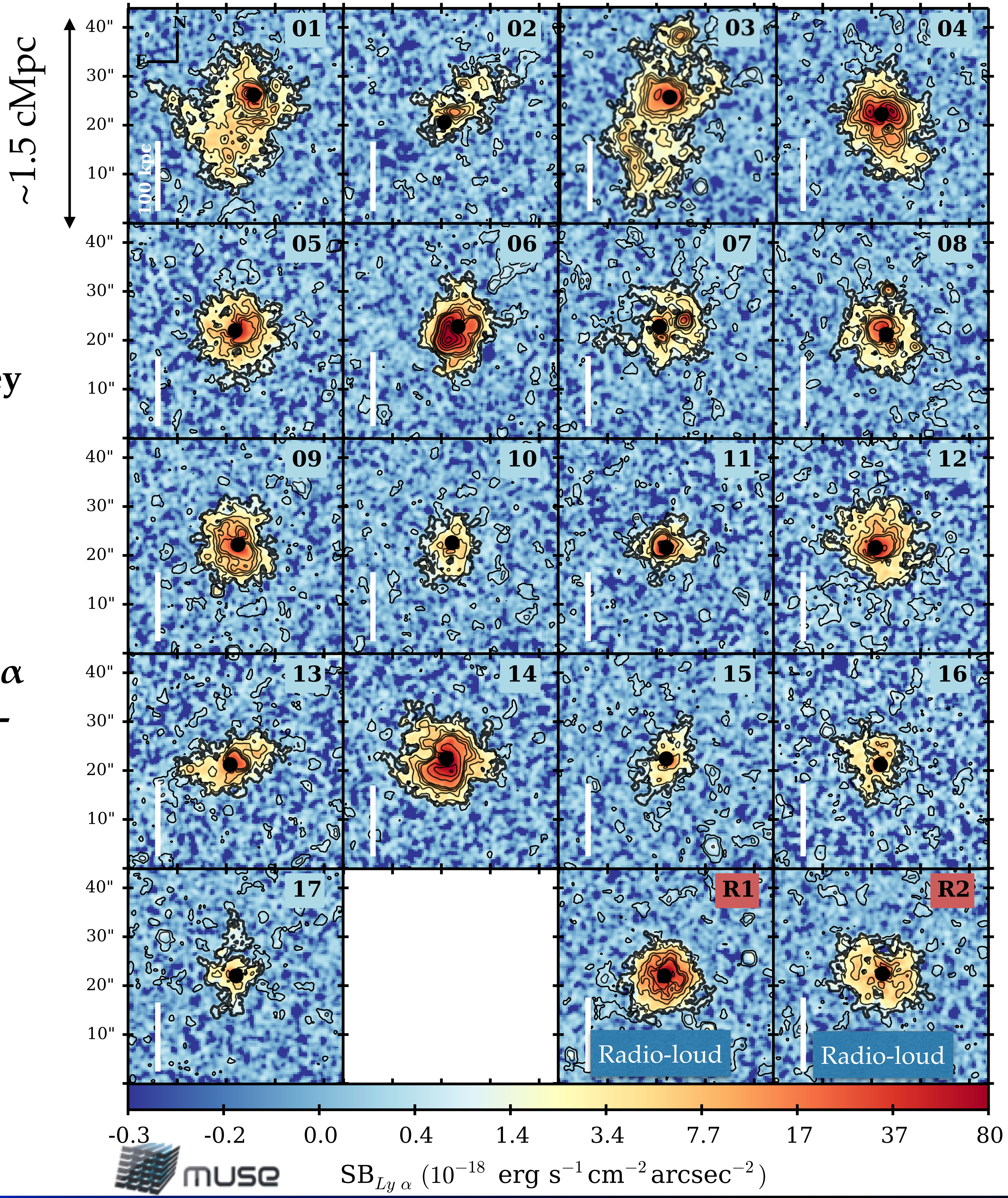
Compare with max SB from expected UVB at z=3 : $SB_{UVB} \sim 10^{-20}$ cgs/arcsec^{-2}

MUSE+KCWI Integral-Field Spectroscopy of radio-quiet QSO fields: ~100% detection of giant Lyα nebulae!

Borisova, SC+, 2016: MUSE Snaphost survey (only 1h per field!)

z~3

Optimally extracted Lyα images with QSO PSF-subtraction obtained with **CubExtractor** (SC+19)



More than 200 giant quasar nebulae discovered so far at 2<z<6.5 with MUSE & KCWI:

Borisova, SC+16; Fumagalli+16; North+17; Marino,SC+18, 19; Ginolfi+18; Farina+18; Husemann+18; Arrigoni-Battaia+18, 19; Cai, SC+19; Lusso+19; Drake+19; Mackenzie, SC+20; Fossati+21 … and many more!

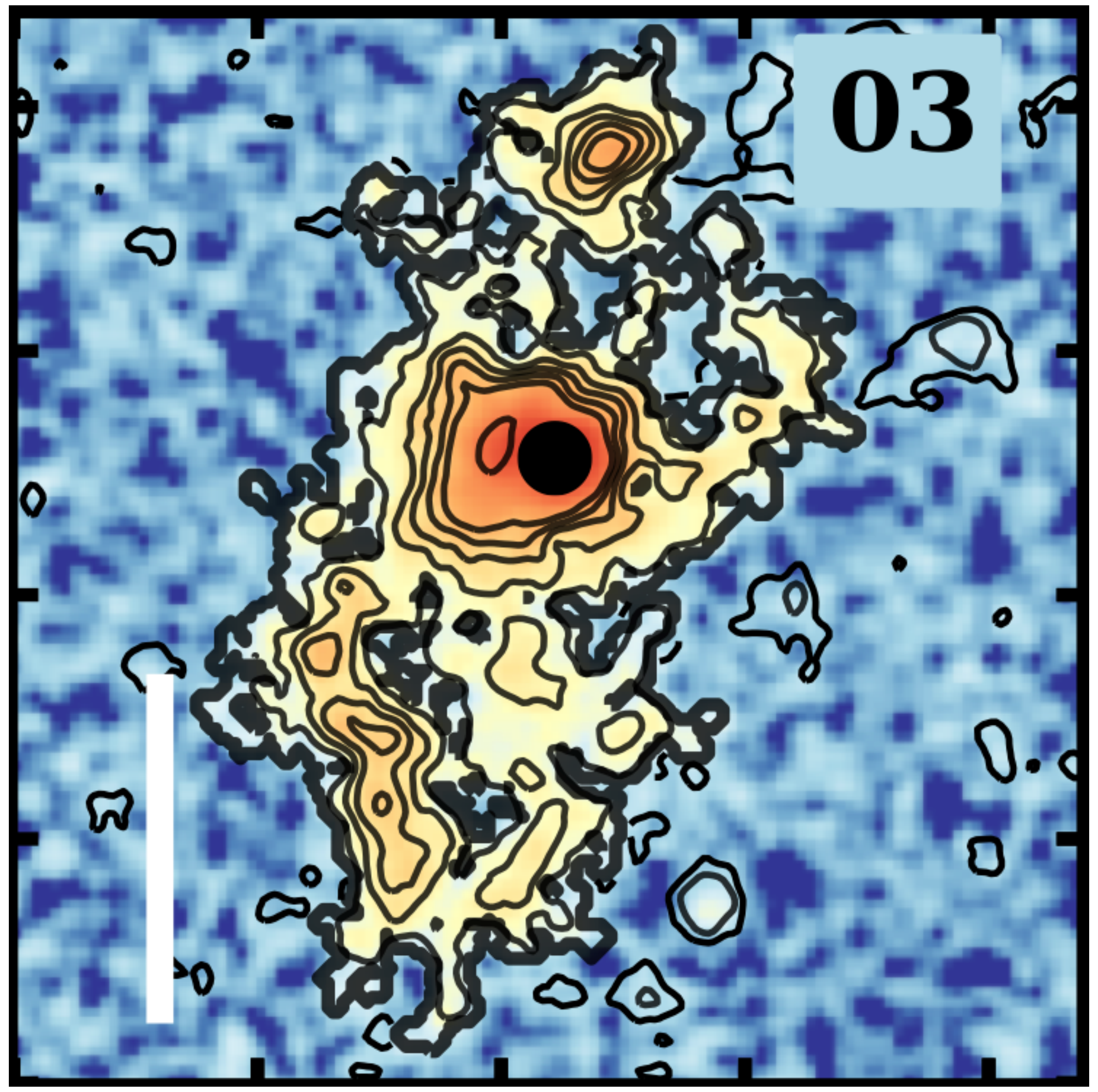
All nebulae larger than 500 ckpc with prevalence of **circular morphologies** and (more rarely) **filaments on larger scales.**

High SB: 10^{-18} - 10^{-17} cgs/arcsec^2 ! High densities (>> 1 cm^{-3}) and/or large clumping factors (C>>100) required for recombination radiation

$$SB_{ion} \propto \frac{1}{A}\int n^2 dV \propto <n>^2 \cdot L \cdot C$$

A 3D view of the Muse Quasar Nebula 3 (MQN03), 1.5 cMpc in size:

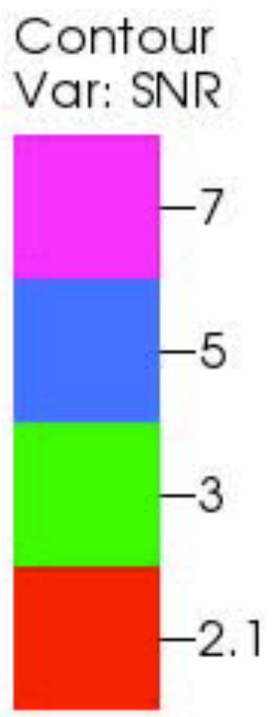
Borisova, SC+, 2016



A 3D view of the Muse Quasar Nebula 3 (MQN03), 1.5 cMpc in size:

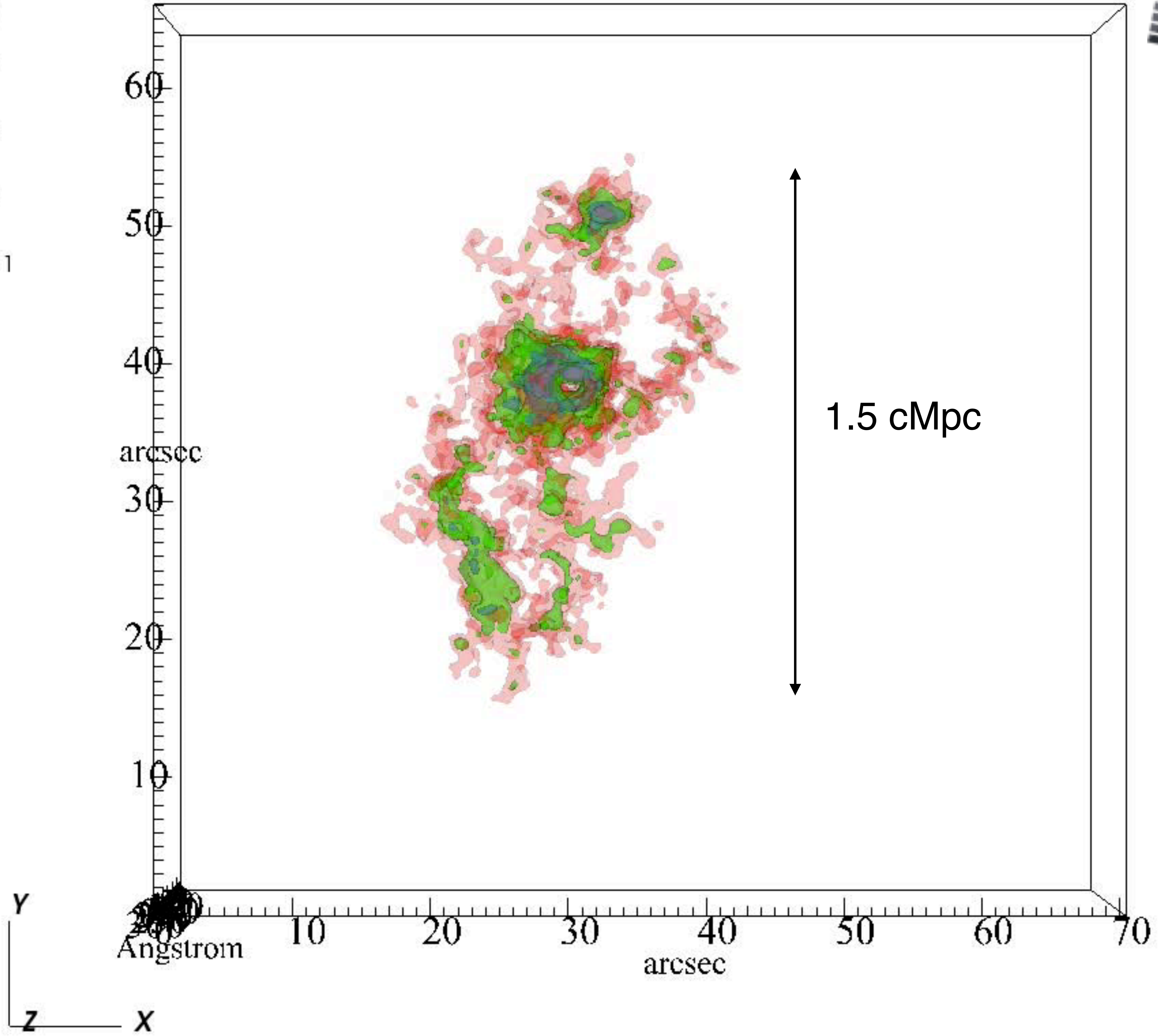
CubExtractor (SC+19) + VisIt
QSO PSF and continuum subtracted cube

Borisova, SC+, 2016



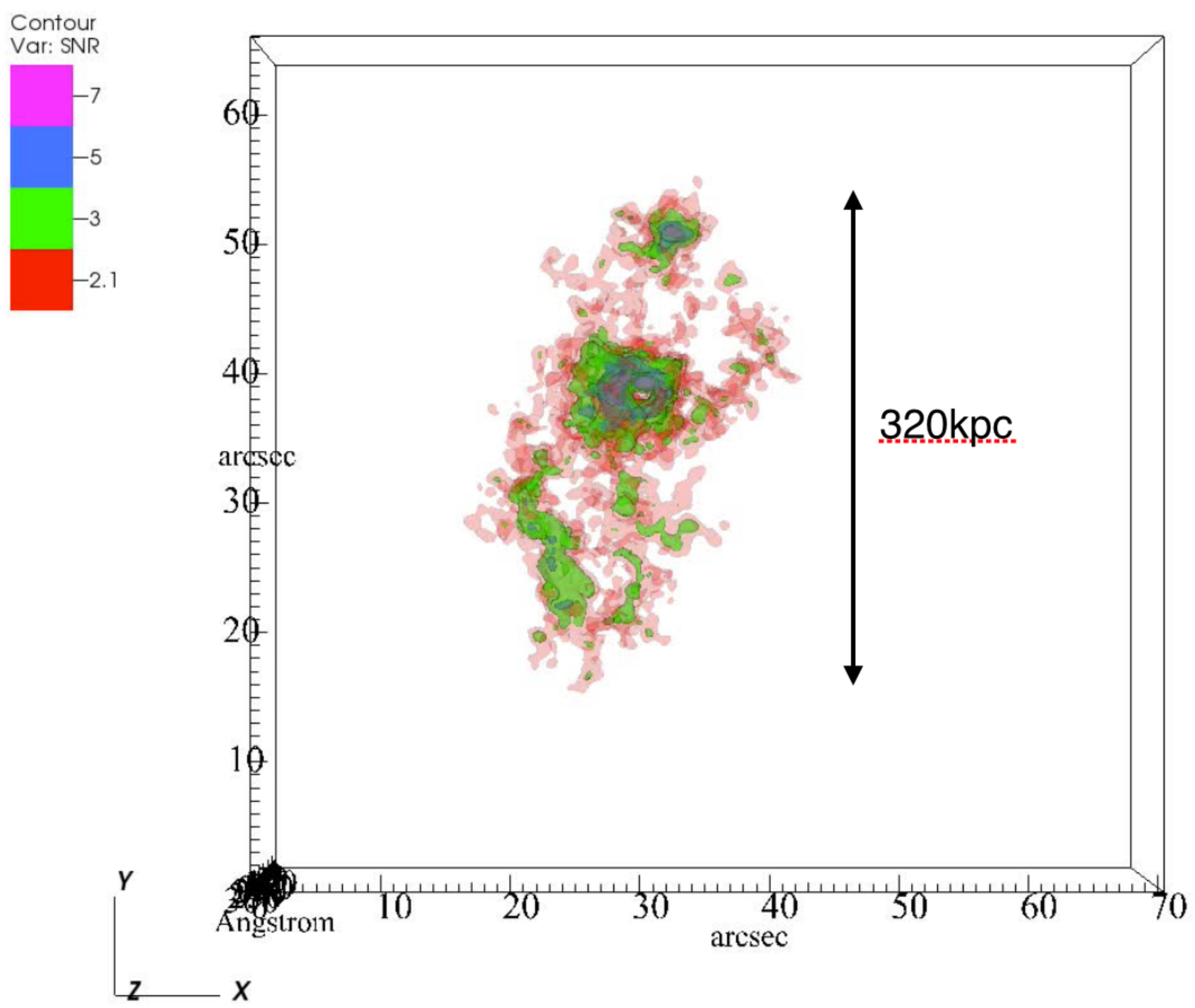
$2\sigma \sim 1 \times 10^{-18}$ cgs/arcsec^2

10A ~ 600km/s

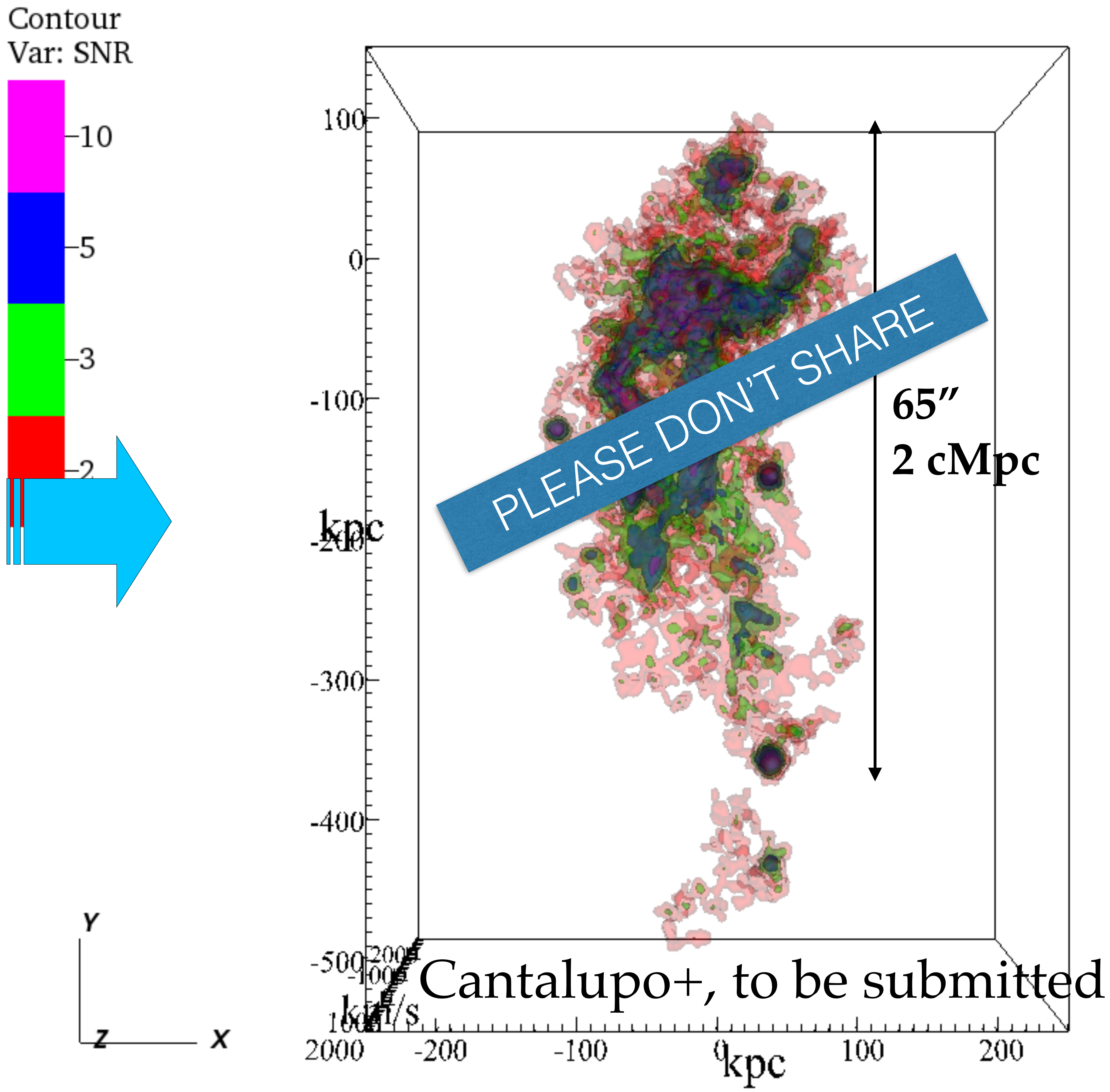


A MUSE-Mosaic on MQN03: tracing the largest filaments

data from multiple recent runs (1x3 mosaic: 15h-deep in the center):

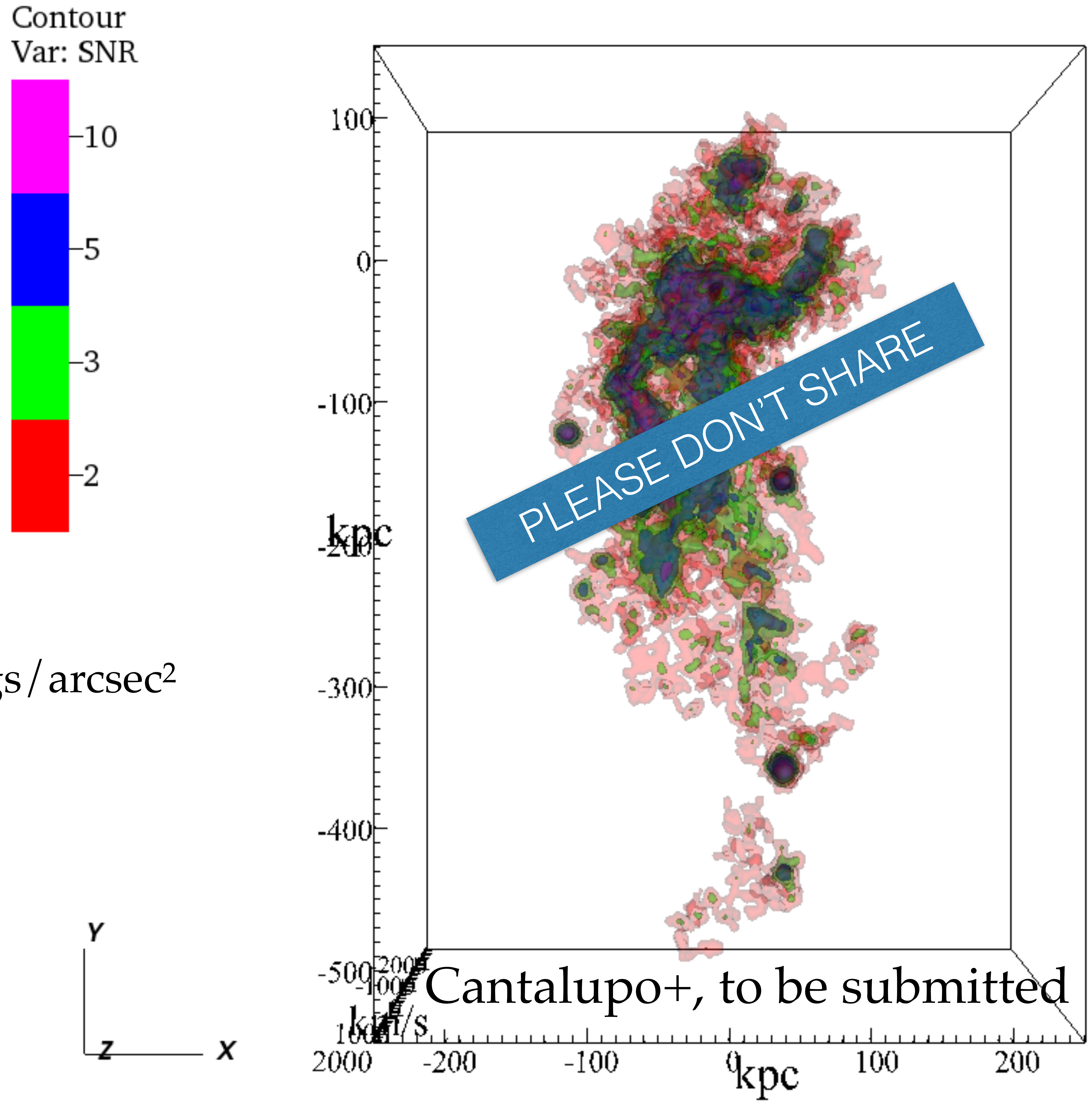


previous 1h-deep snapshot
(single pointing)



Cantalupo+, to be submitted

A MUSE-Mosaic on MQN03: tracing the largest filaments

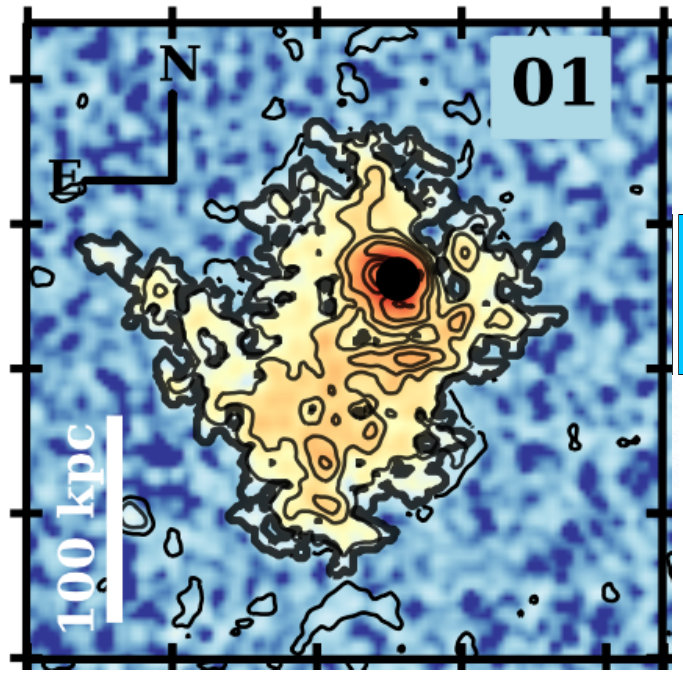


$1\sigma \sim 10^{-19}$ cgs/arcsec^2

Cantalupo+, to be submitted

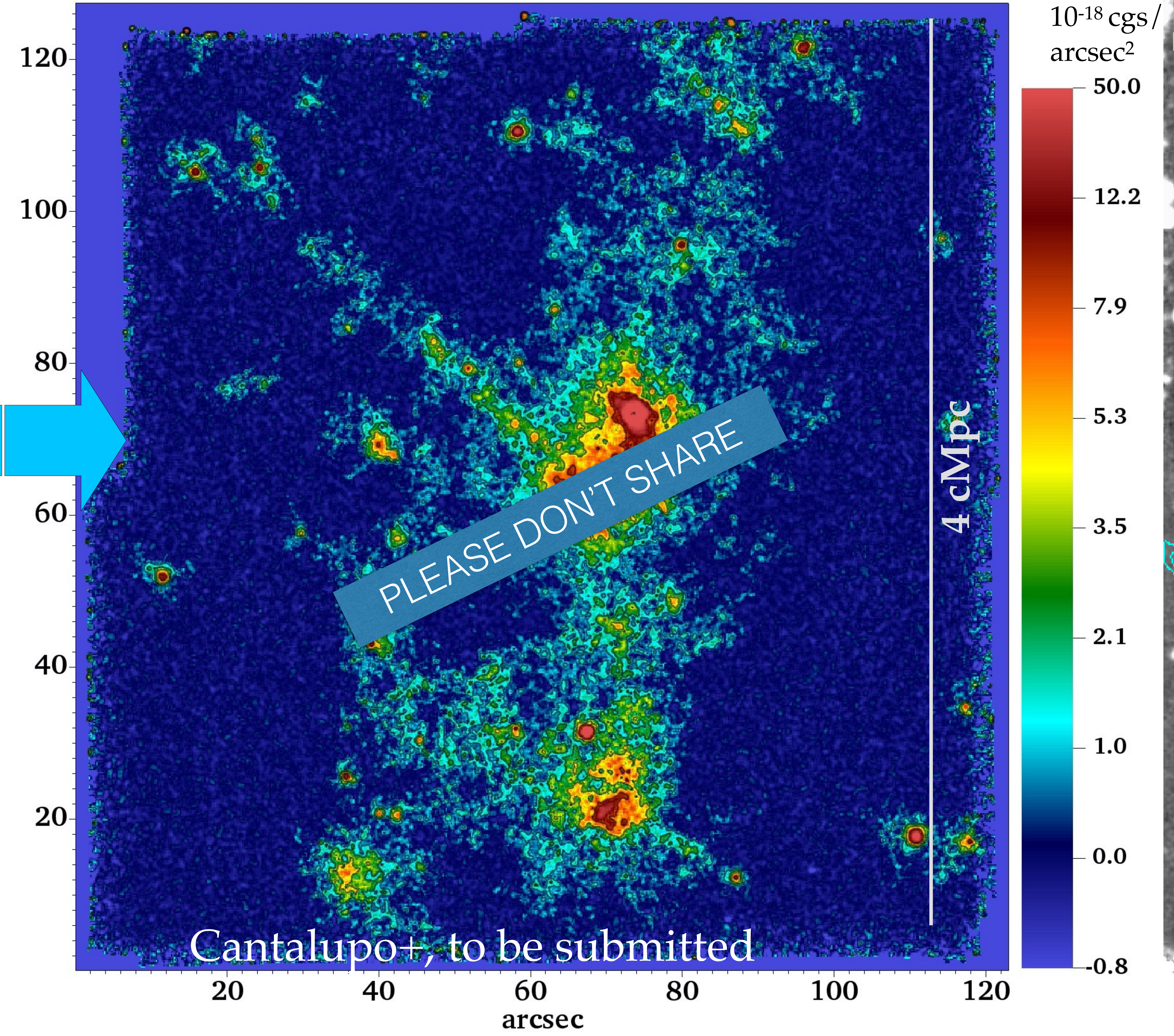
However: only a few galaxy associated with the filament (very mild overdensity…)

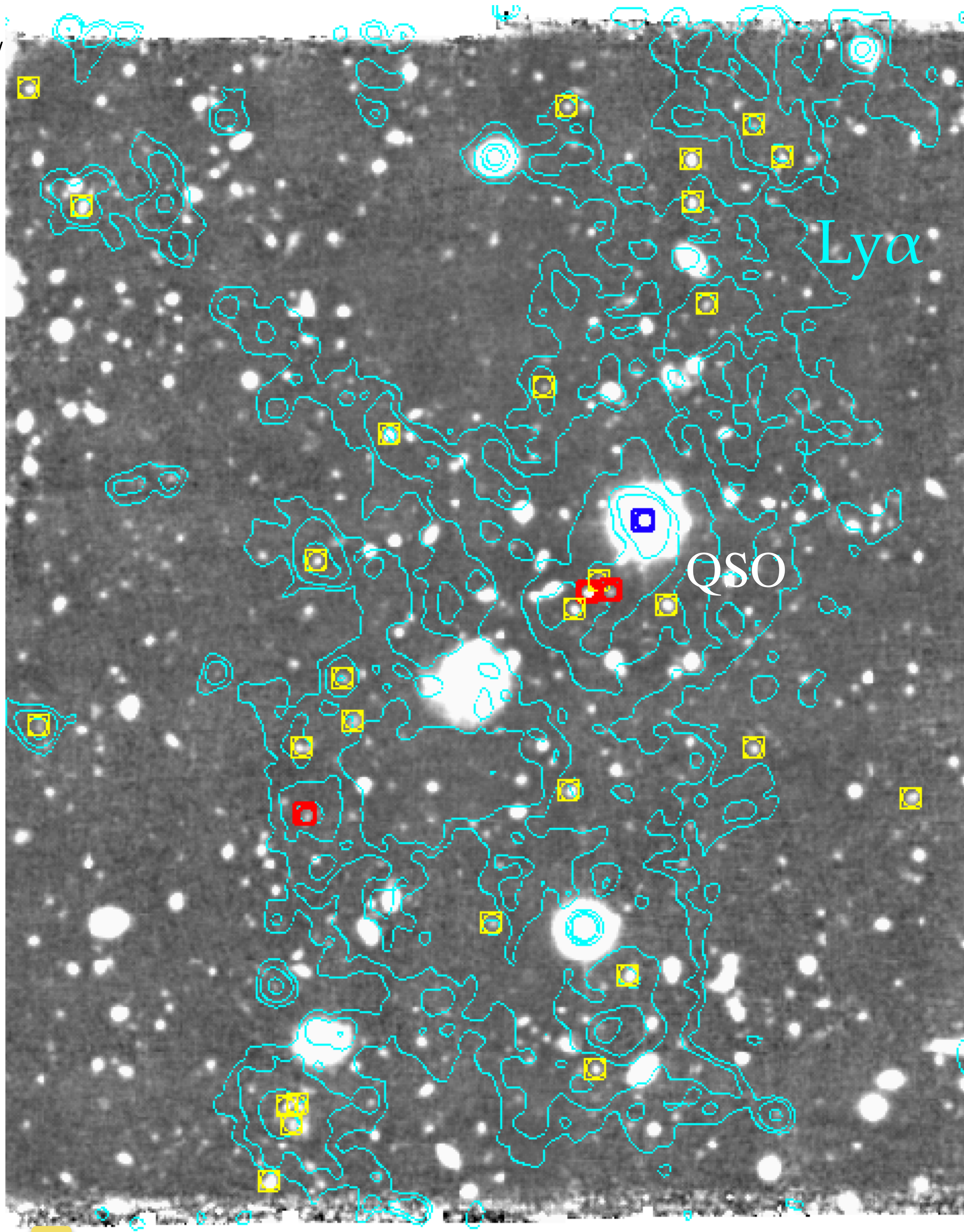
A 4x4 MUSE-Mosaic on MQN01: tracing a massive Cosmic Web node



1h

10h x 4 = 40h



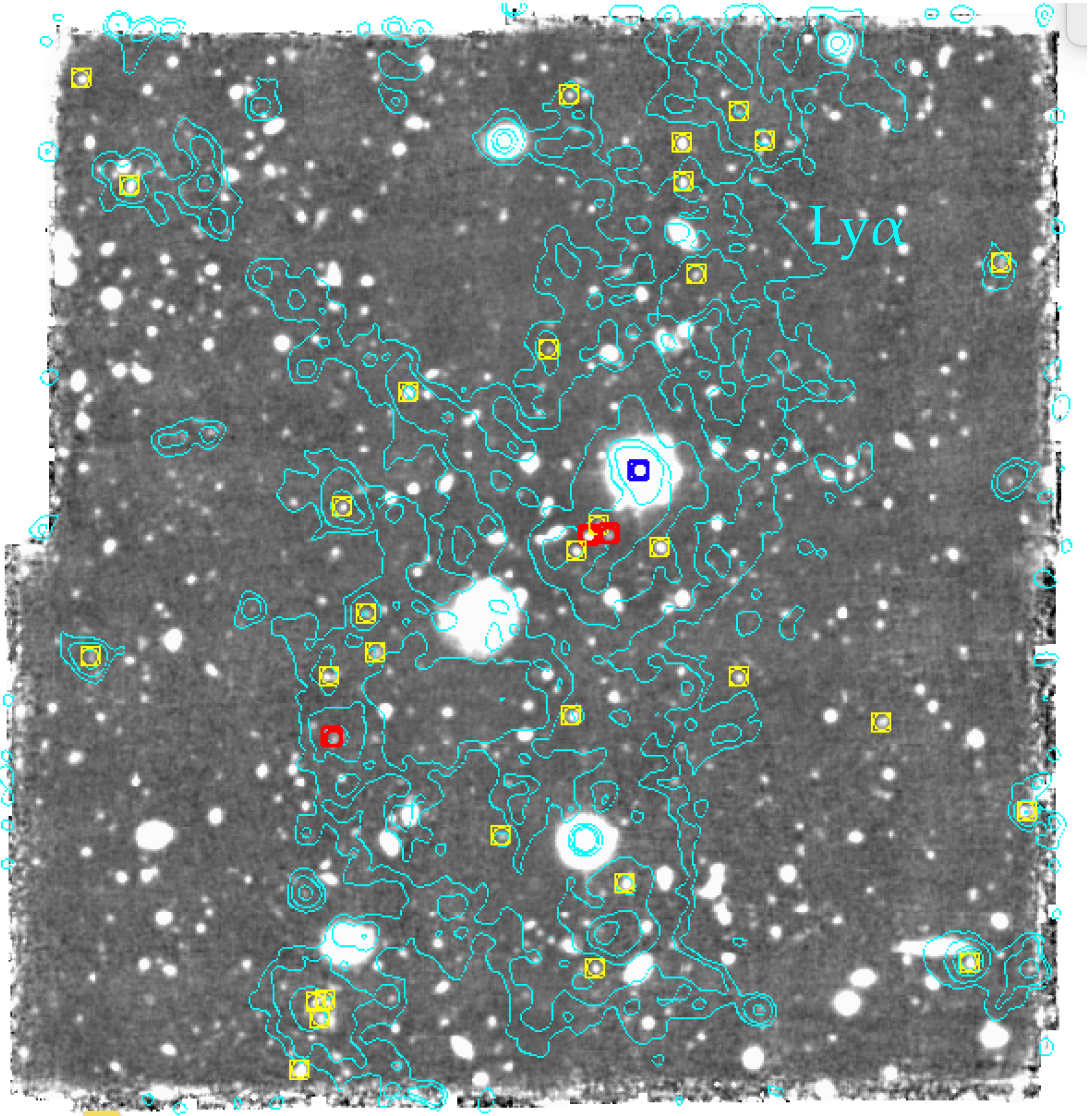


Absorption-line galaxies at MQN01 redshift

Type-II AGN at MQN01 redshift

Largest filaments associated with huge galaxy/AGN overdensity (see later)!

Tracing a massive Cosmic Web node: multi-wavelength campaign



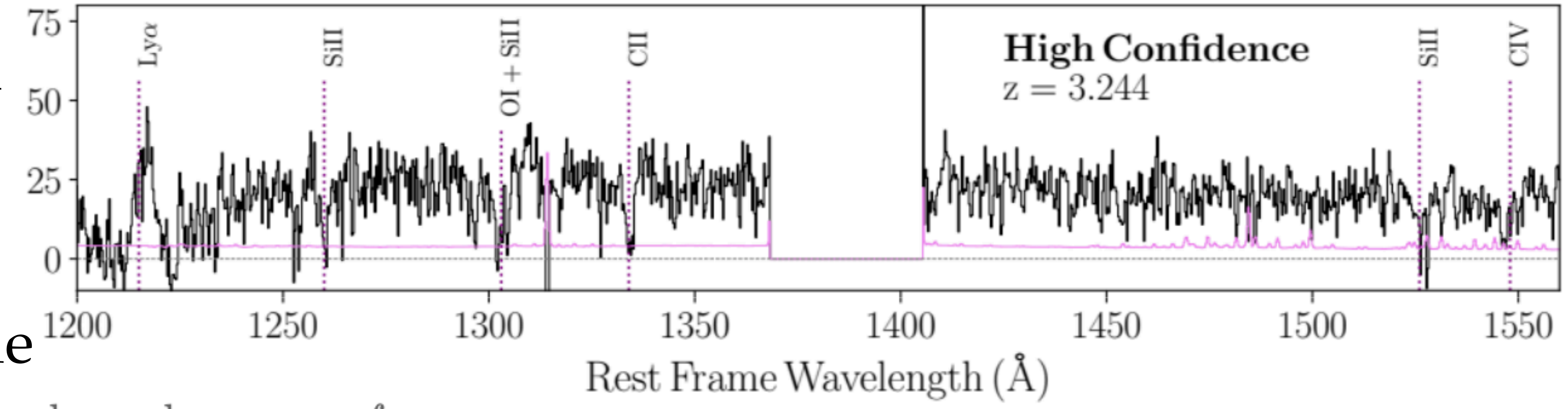
Absorption-line galaxies at MQN01 redshift
Type-II AGN at MQN01 redshift

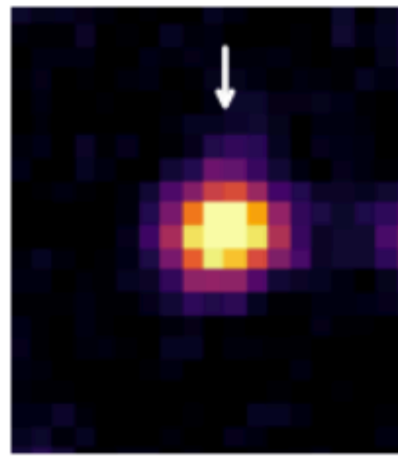
Unique laboratory to study galaxy - cosmic web filaments' properties connection! In addition to the MUSE original mosaic:

- **650ks of Chandra** X-ray observations to trace AGN population over 20 cMpc (PI: SC);
- **FORS+HAWKI** u-b-v-r-z-H-CH4-K imaging (**23h**) to detect LBG and massive galaxies over 20 cMpc;
- **45h of ALMA** to detect CO(4-3) and dust continuum and trace dust-obscured galaxy population (PI: SC)
- **24h of JWST NIRSpec** to detect Hα emission from filaments and galaxies to measure kinematics and densities (PI: SC)
- Deep **HST (22 orbits)** + **JWST NIRCam** (PI:SC) to study galaxy morphology and relate it to filaments properties.
- Additional **80h of MUSE** (PI:SC) to extend mosaic observations on larger scales (recently completed)

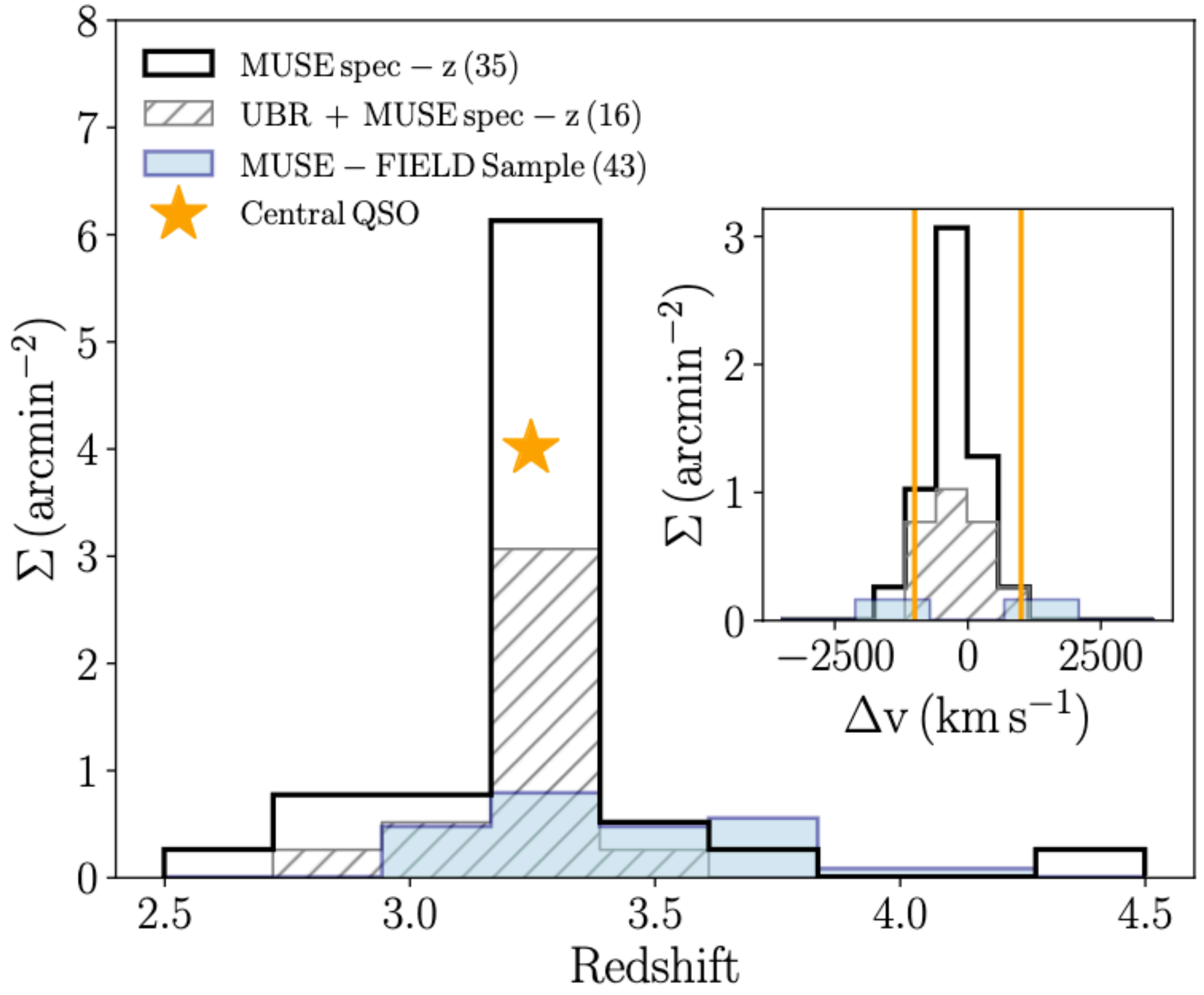
Continuum-selected Star Forming Galaxies in MQN01: the power of MUSE

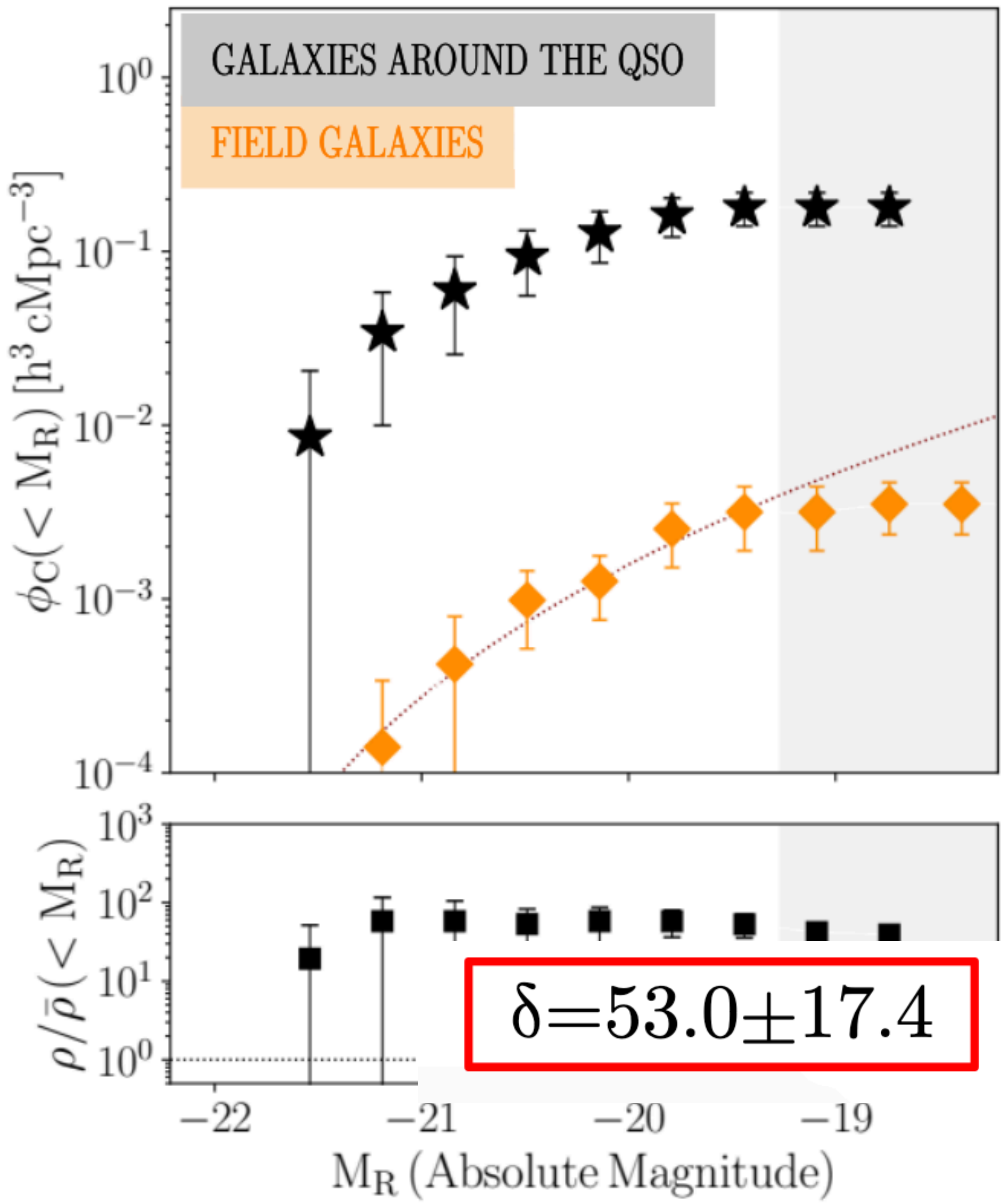
- 21 absorption line galaxies with secure redshift in 4x4 $cMpc^2$ and +-1000 km/s around the quasar!
- FIELD comparison sample selected from other MUSE cubes with same depth and same technique

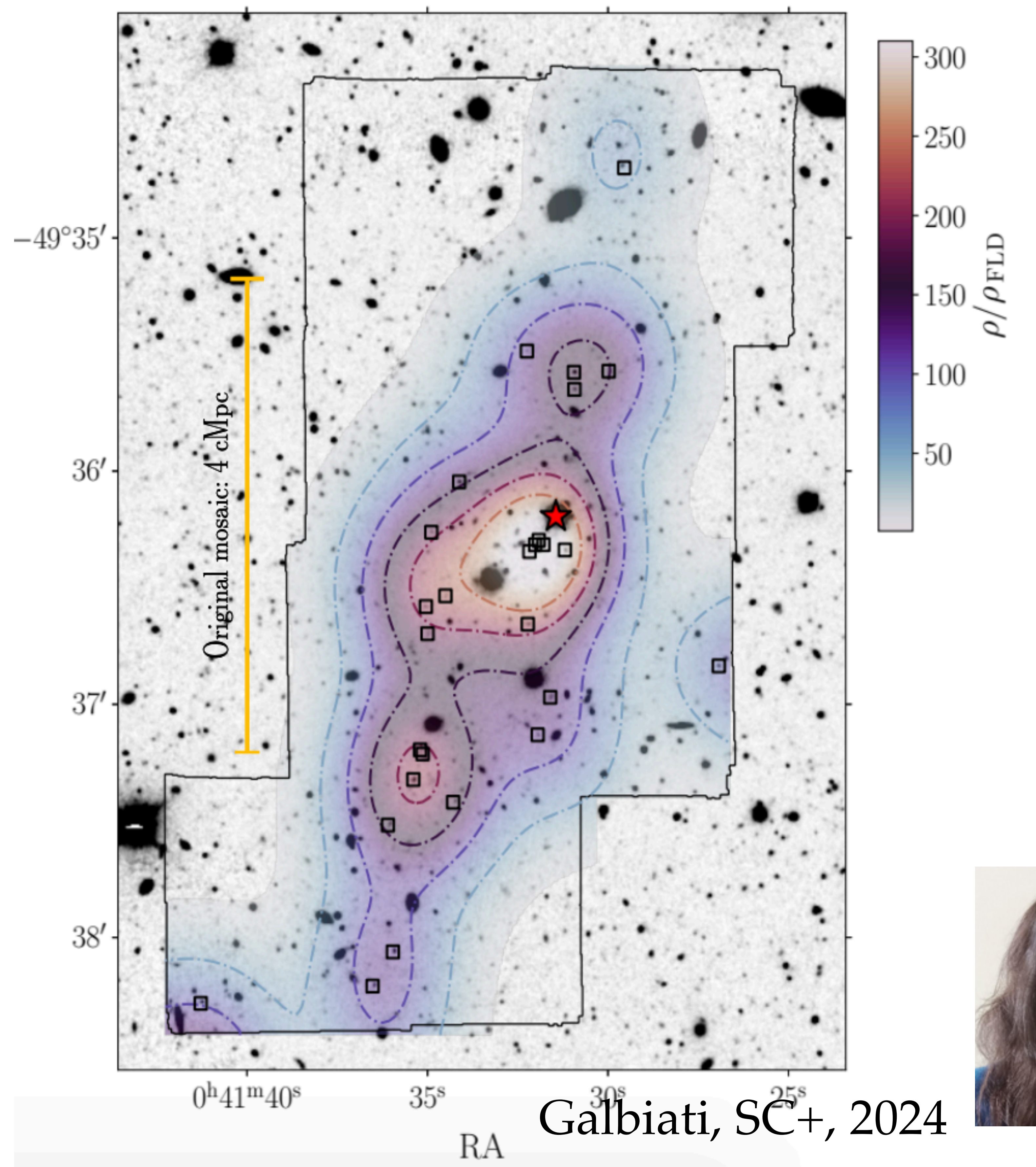




MUSE white-light

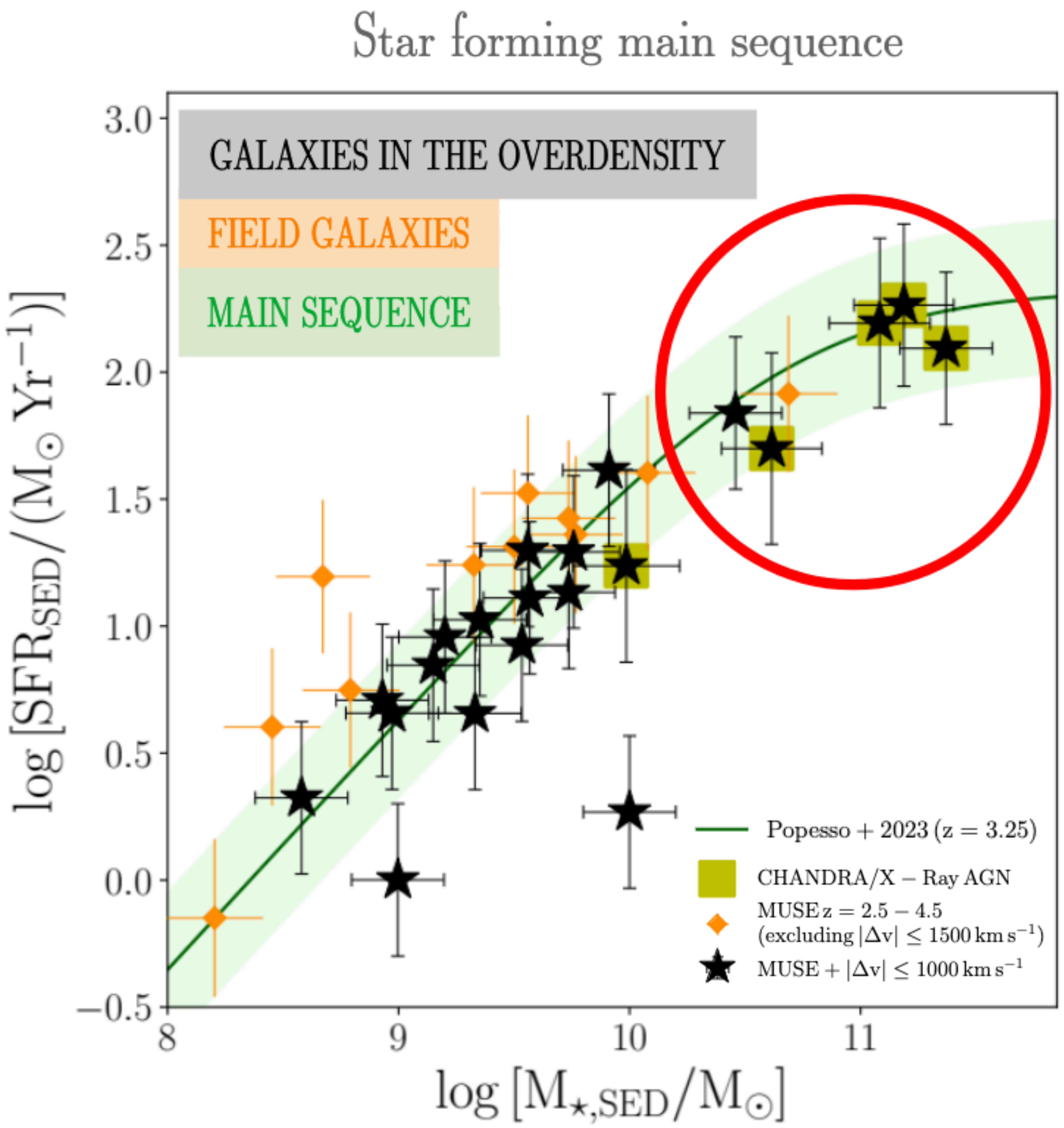


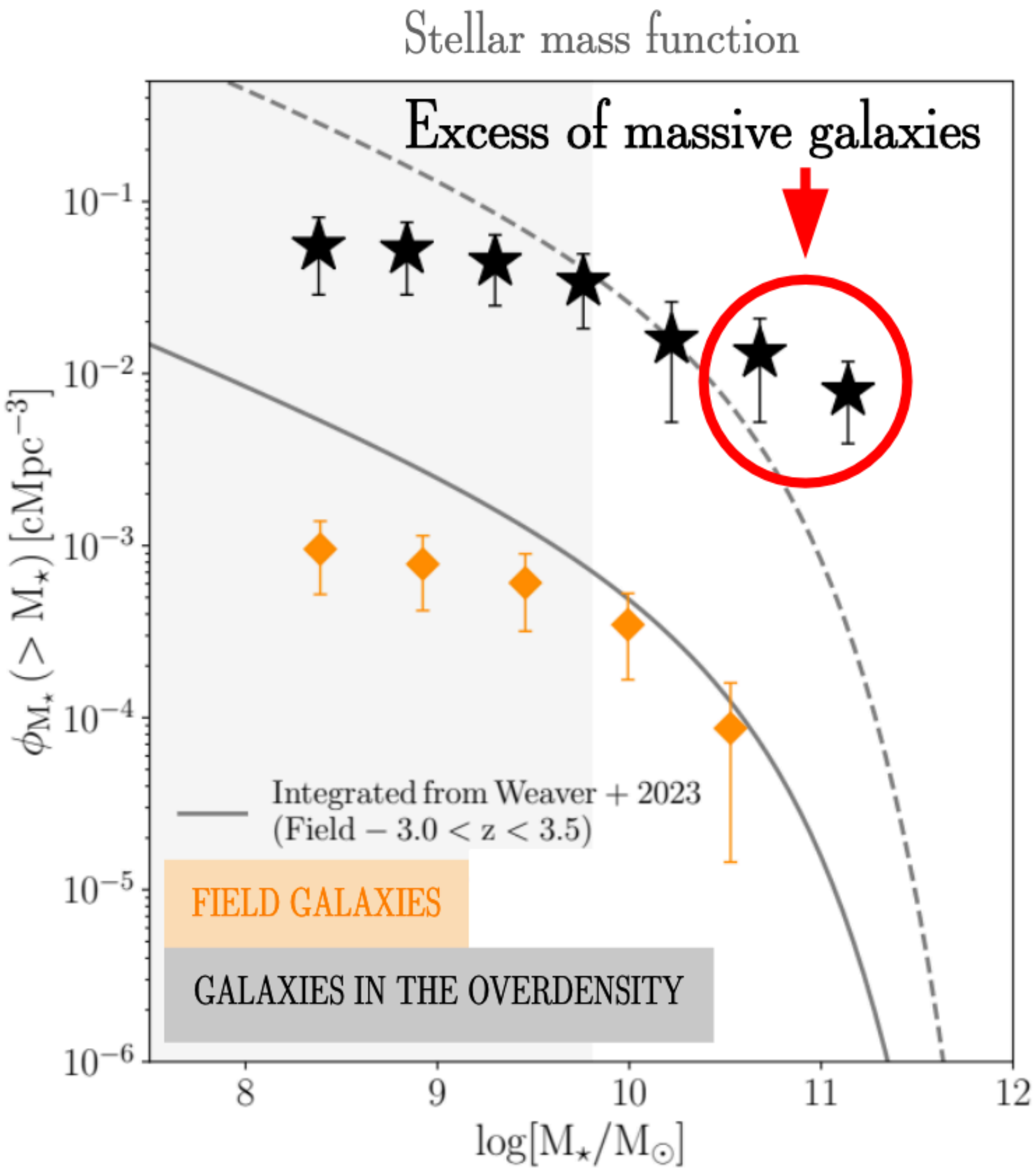




Galbiati, SC+, 2024

How does “environment” affect the SFR and Stellar Masses of continuum-selected SF galaxies?



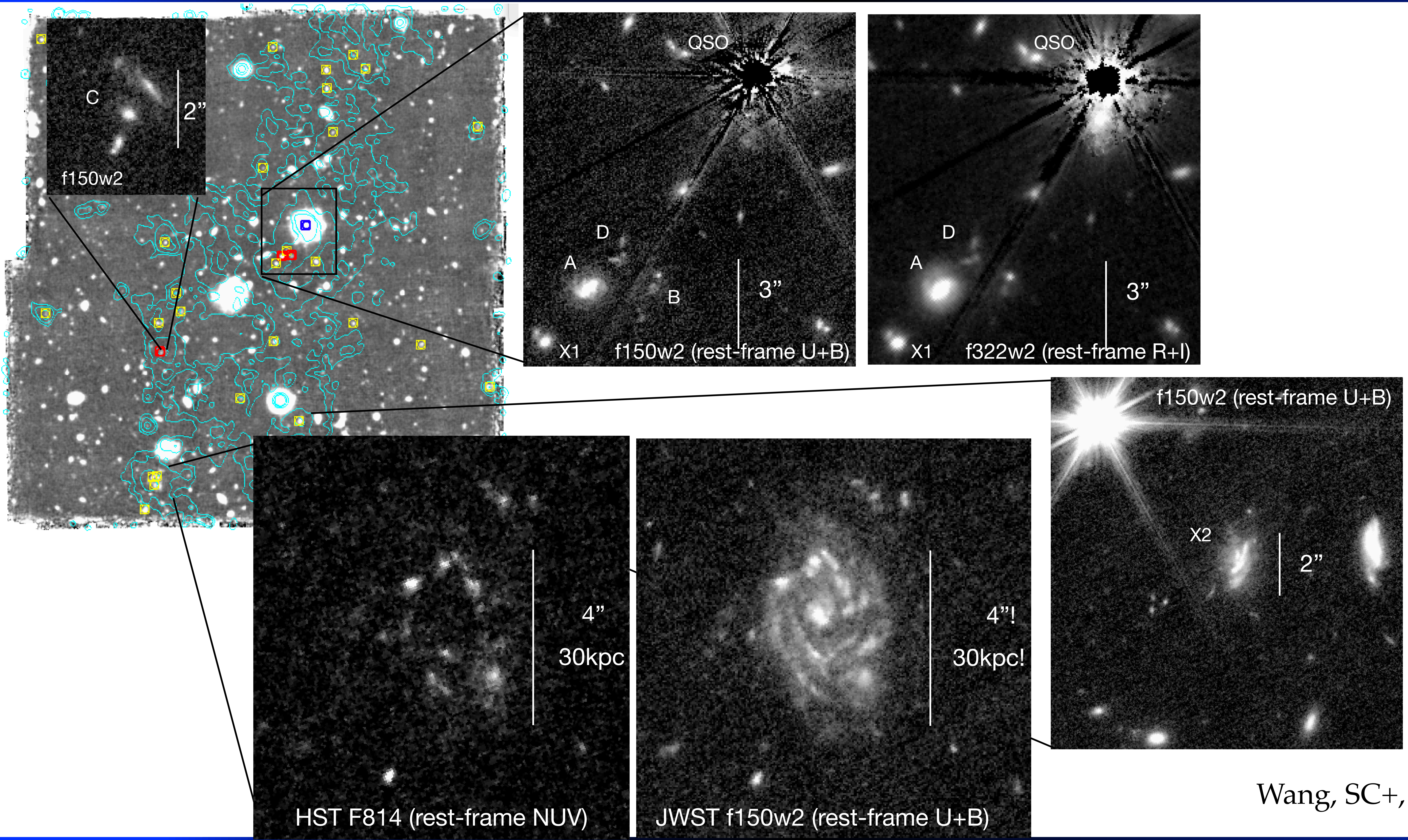


No clear differences in the SFR (maybe a hint of bending). Continuum-selected SF galaxies in MQN01 have SFR similar to the field and as expected for “main sequence”

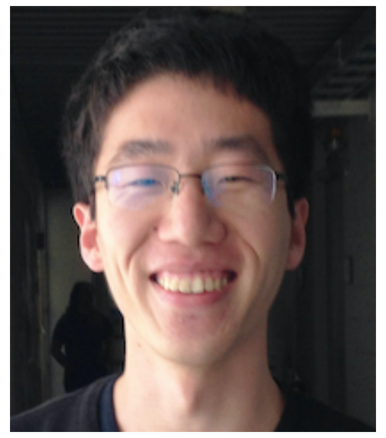
However: different Mass Function! They must have formed *earlier* or more *efficiently*

Galbiati, SC+, 2024

JWST/NIRCAM & HST: galaxy morphologies in a massive Cosmic Web node at z=3.25



Wang, SC+, 2025

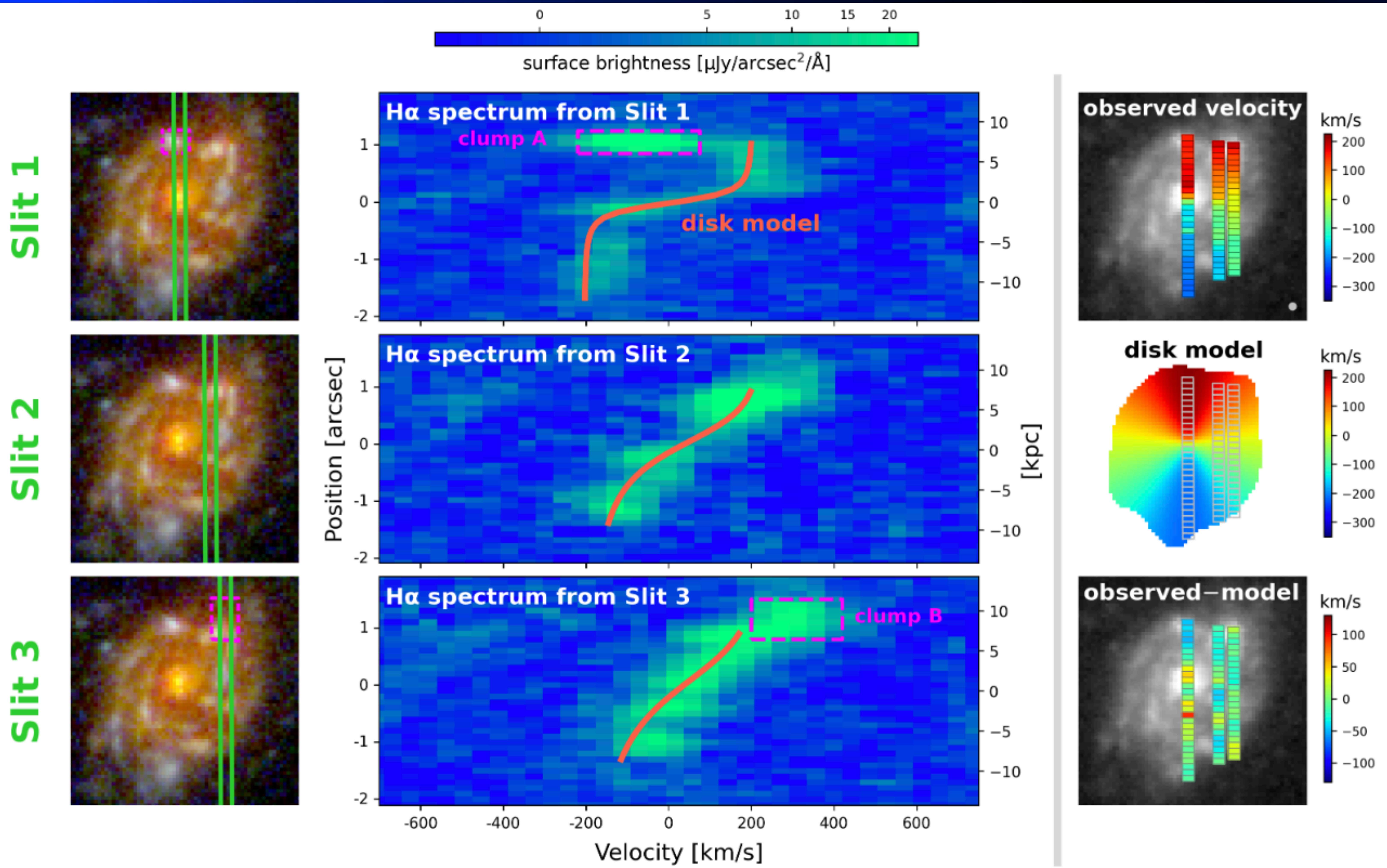


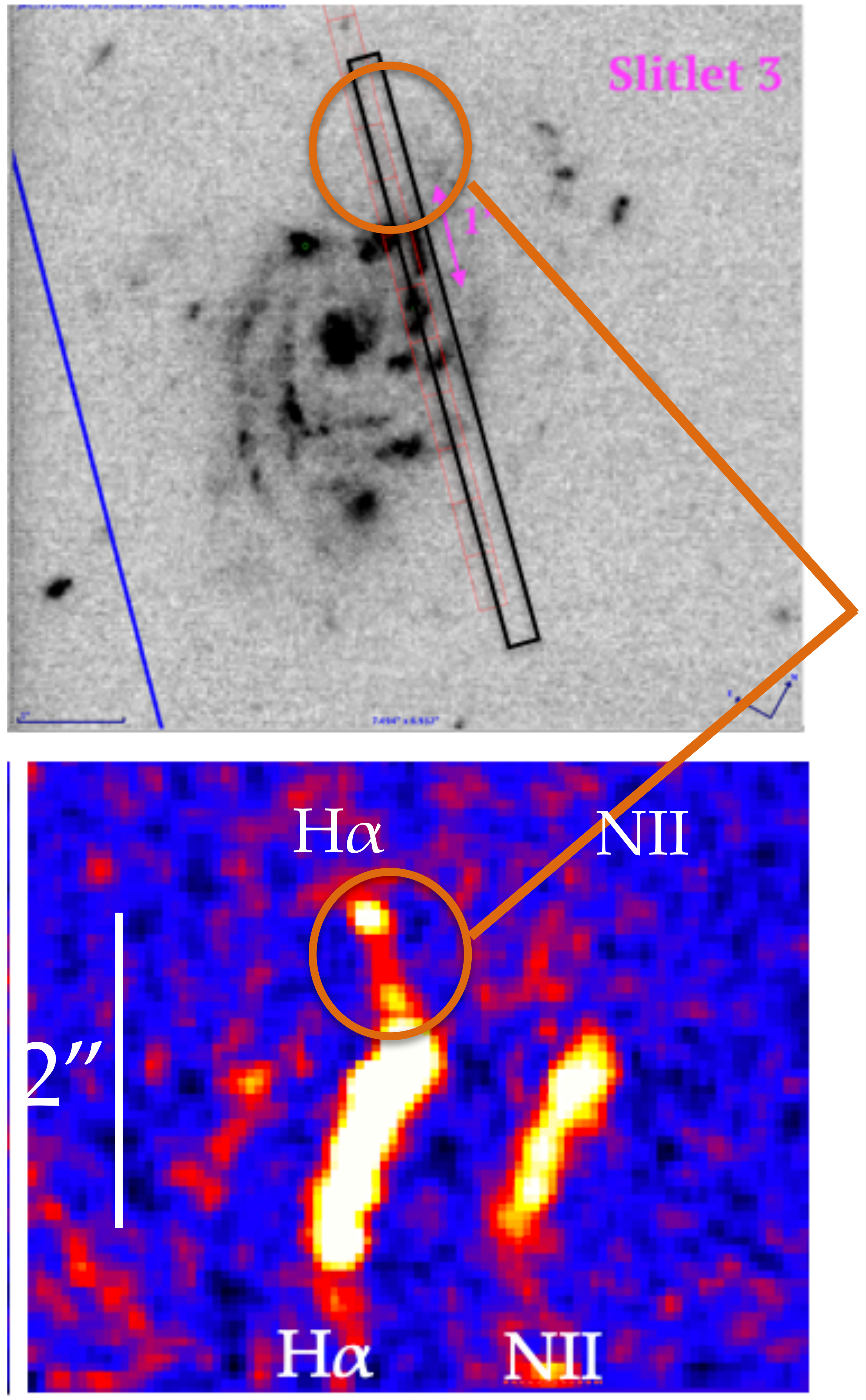
JWST/NIRCAM & HST: grand design spiral galaxy in a massive Cosmic Web node at z=3.25!

HST F814 (rest-frame far-UV) + JWST f150w2 (rest-frame U+B) + f322w2 (rest-frame R+I)

Wang, SC+, 2025

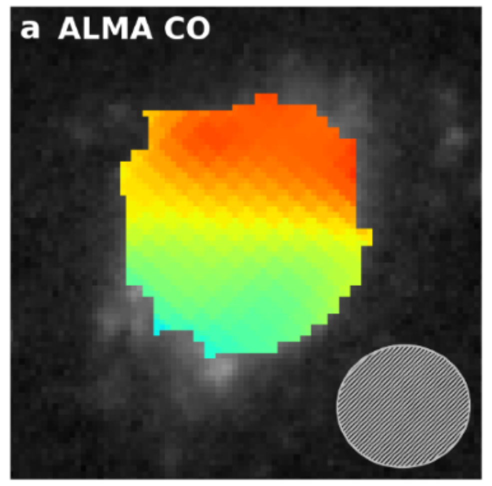
Hα spectroscopy of the Big Wheel Galaxy

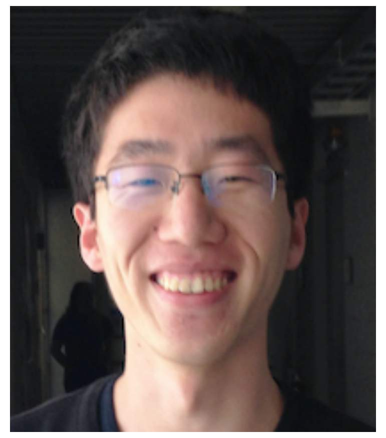




CGM gas in emission (accretion?)

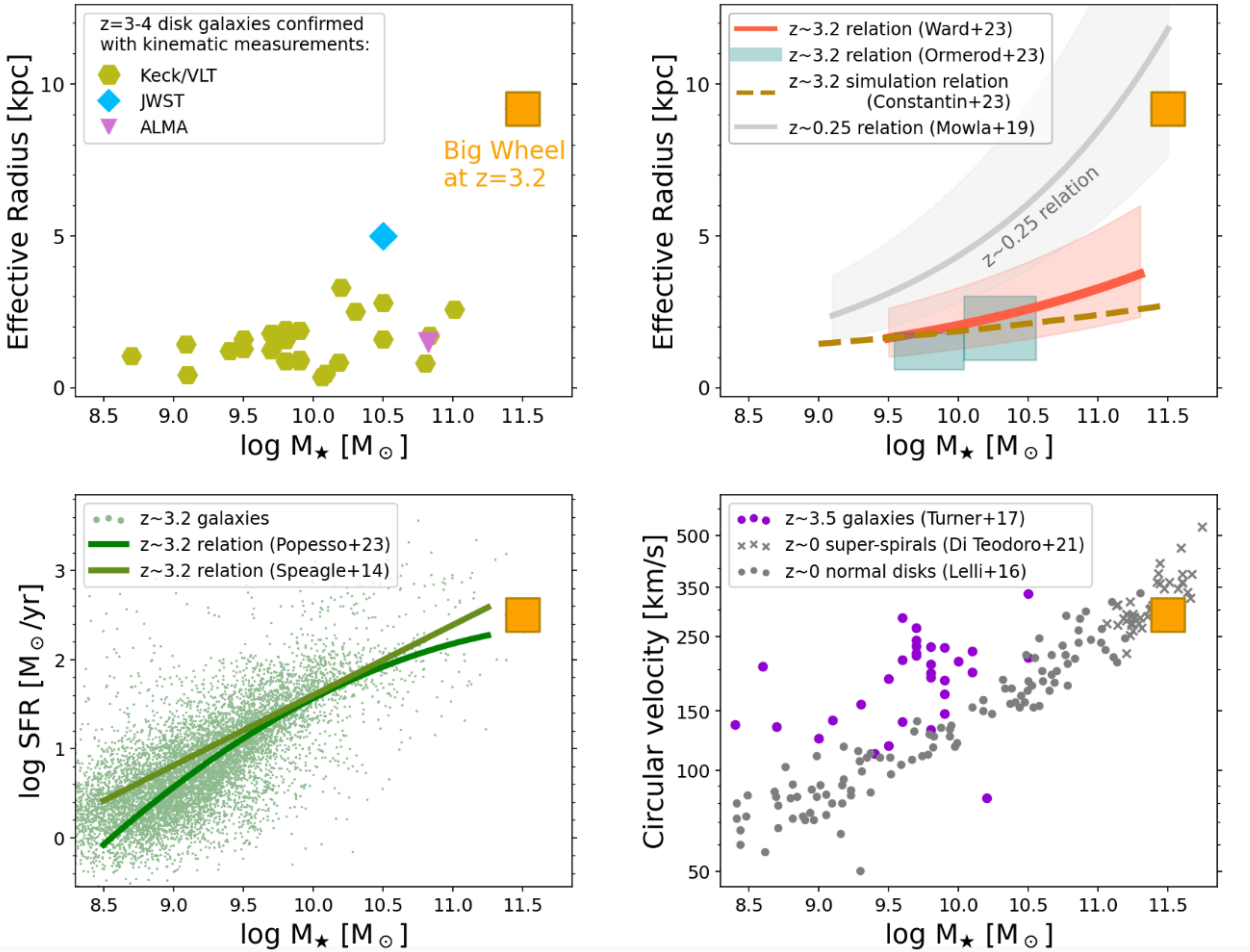
Beautifully rotating disk galaxy (consistent with lower-res ALMA data)! Also "super-cold" with V/σ~10 (see later)





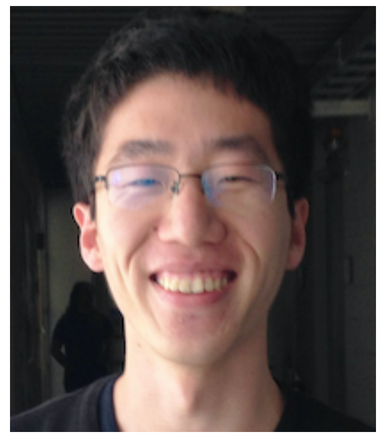
Wang, SC+, 2025

A giant, unexpected rotating disk galaxy at z=3.25!



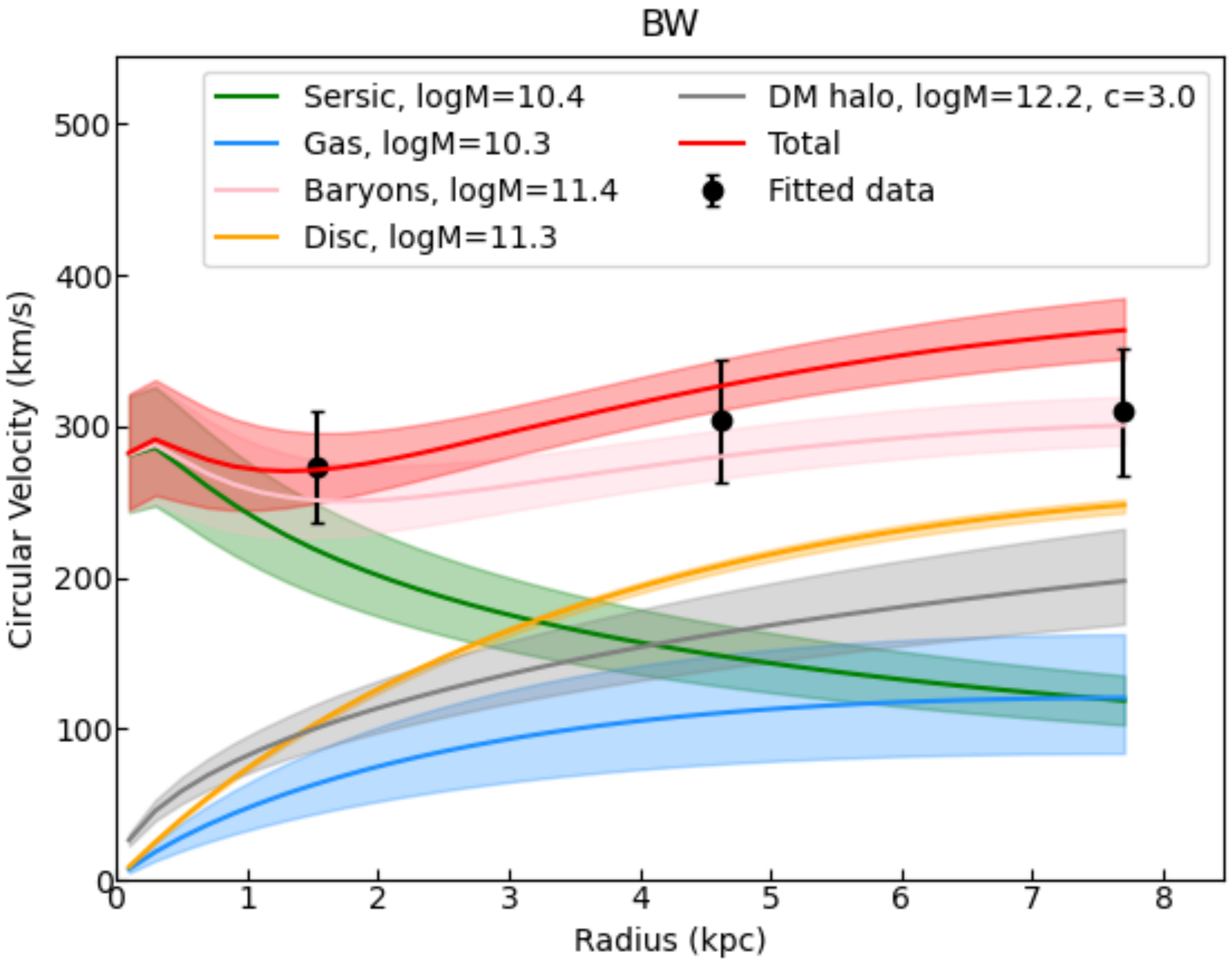
- Sitting on the **local** size mass-relation and **local** Tully-Fisher relation!
- Three times larger than expected for its stellar mass
- Still on or close to the Main Sequence at z~3
- Living in one of the largest over density of galaxies found so far

Wang, SC+, 2025

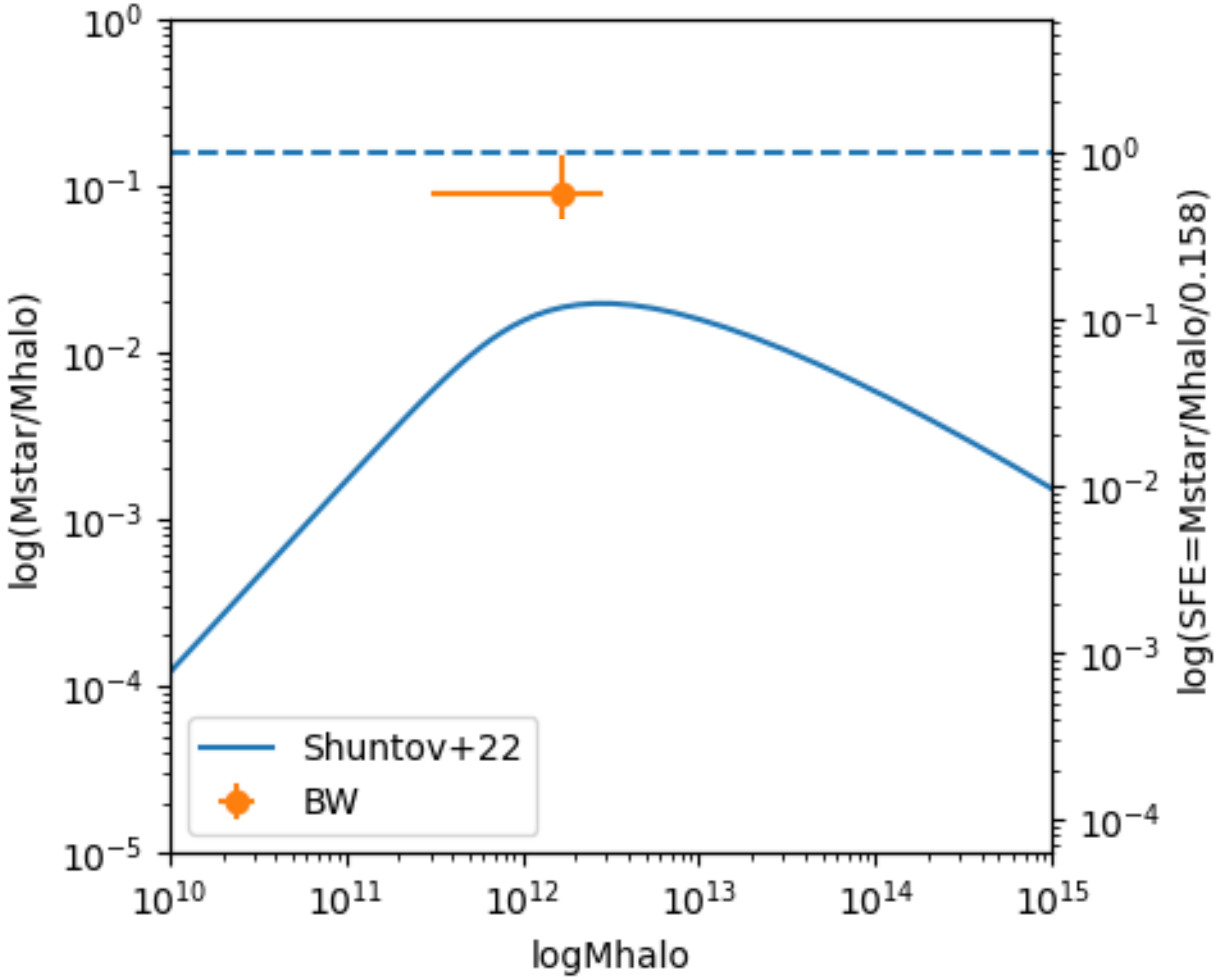


Dynamical decomposition of the Big Wheel: big galaxy, small halo!

PRELIMINARY



Can be fit without a DM halo up to a distance of 1.5 times R_e (considering $H\alpha$) !

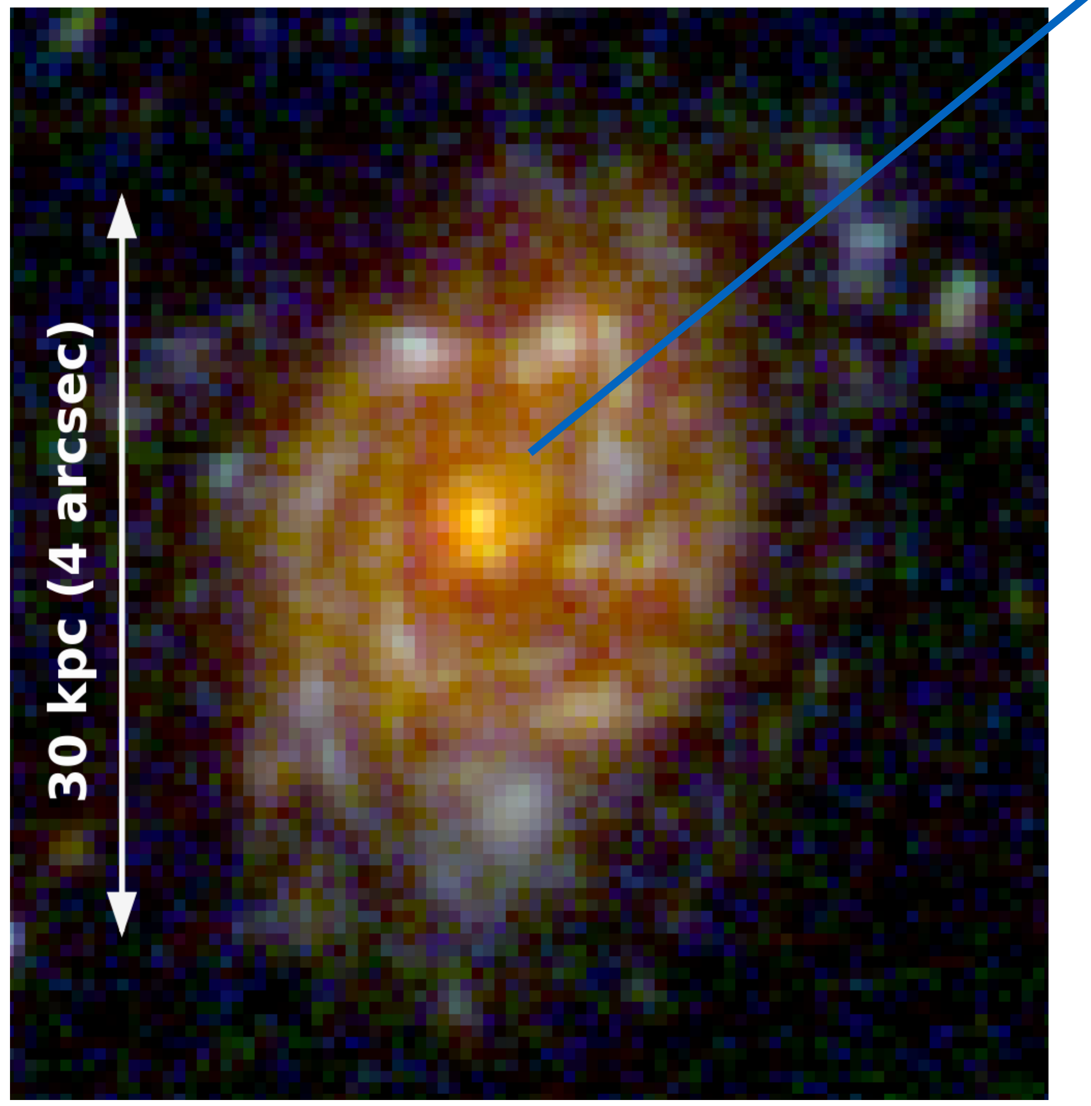


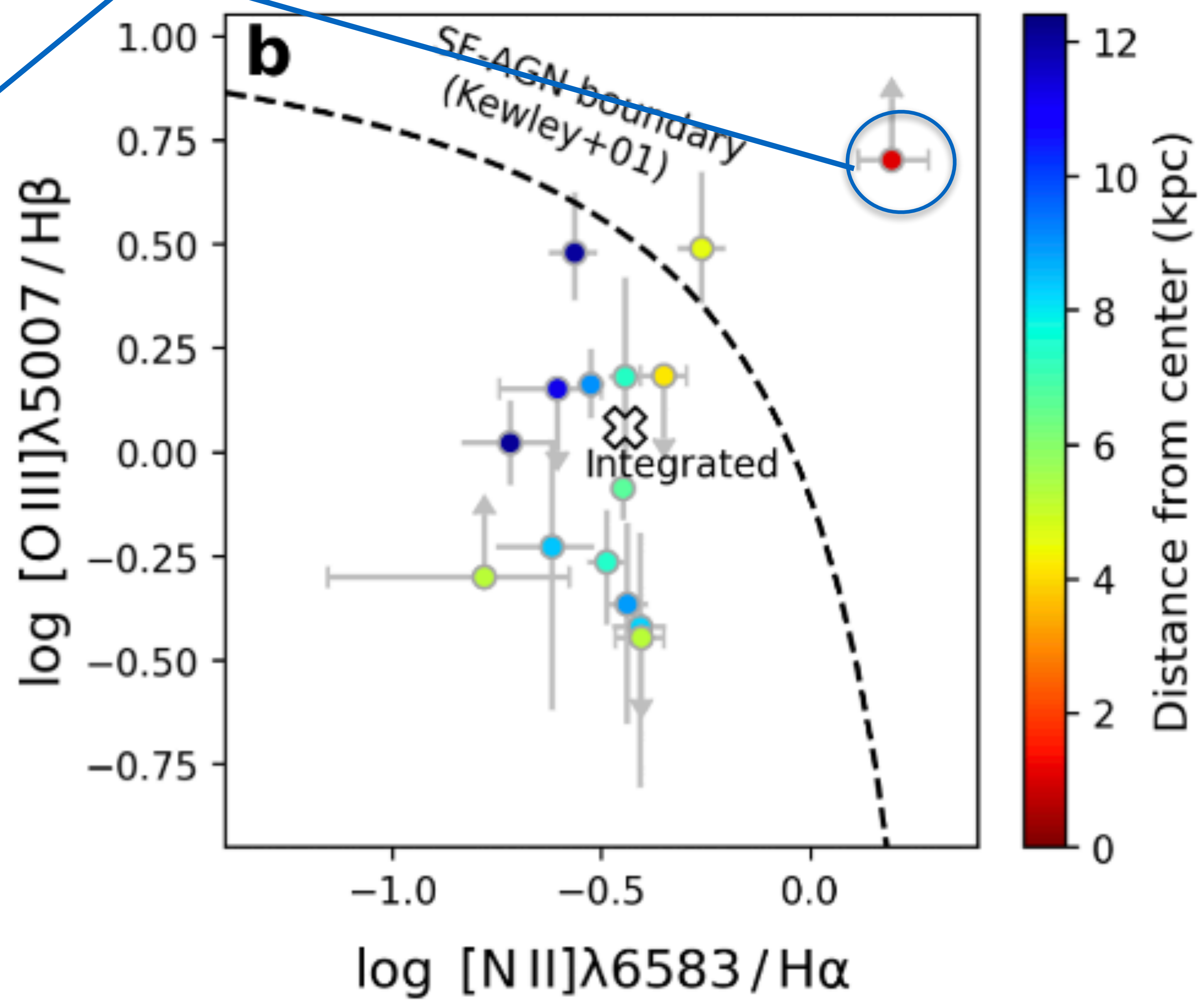
The Big Wheel has been forming at the maximum possible efficiency!

Quadri, SC, Bacchini+ in prep.

How about active black-hole in the Big Wheel? Spatially resolved BPT diagram + Chandra

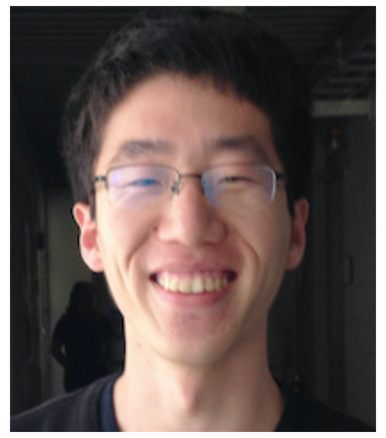
Seyfert-like AGN in the center ($\log(L_x/(\mathrm{erg/s}))\sim43.5$)



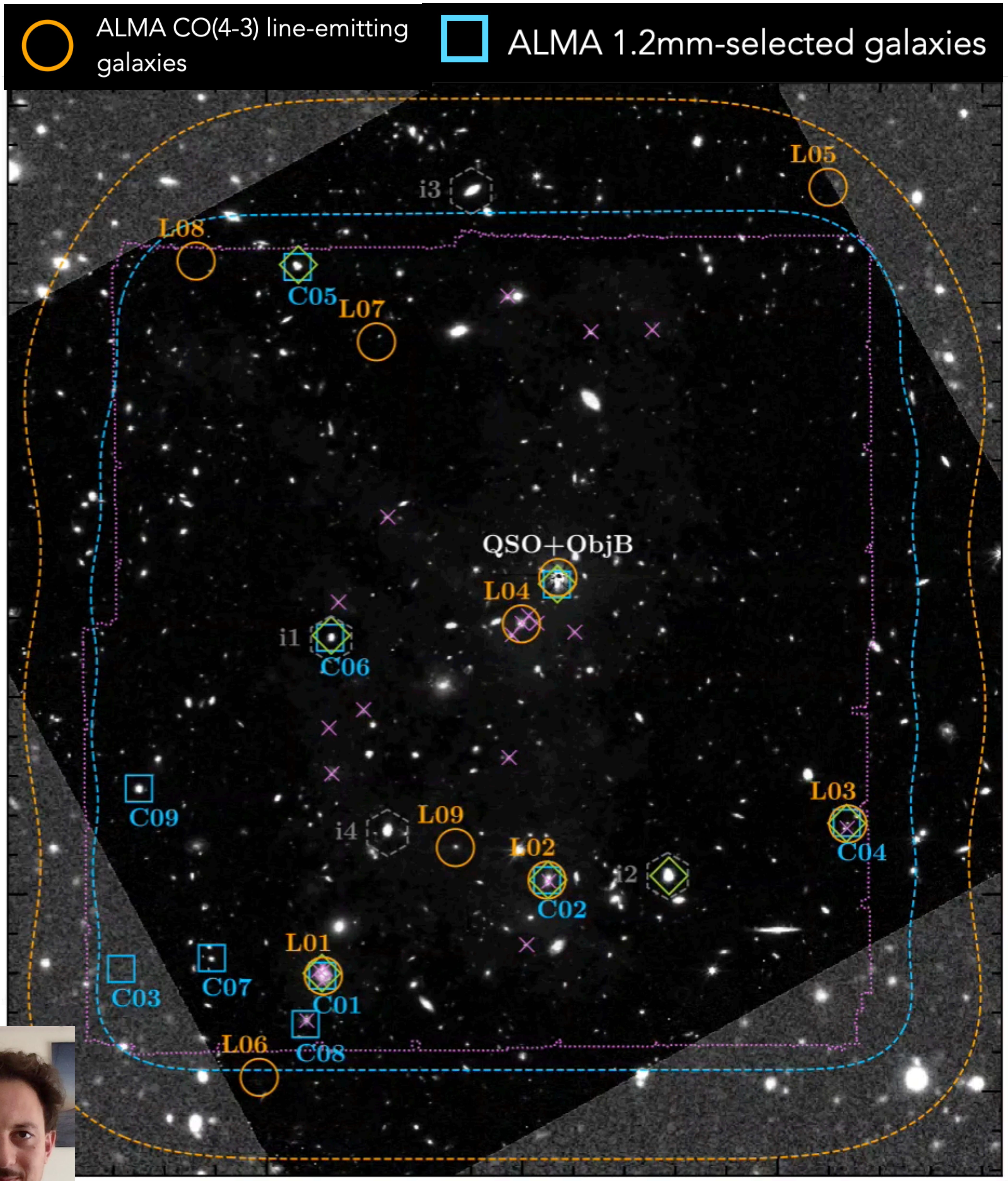


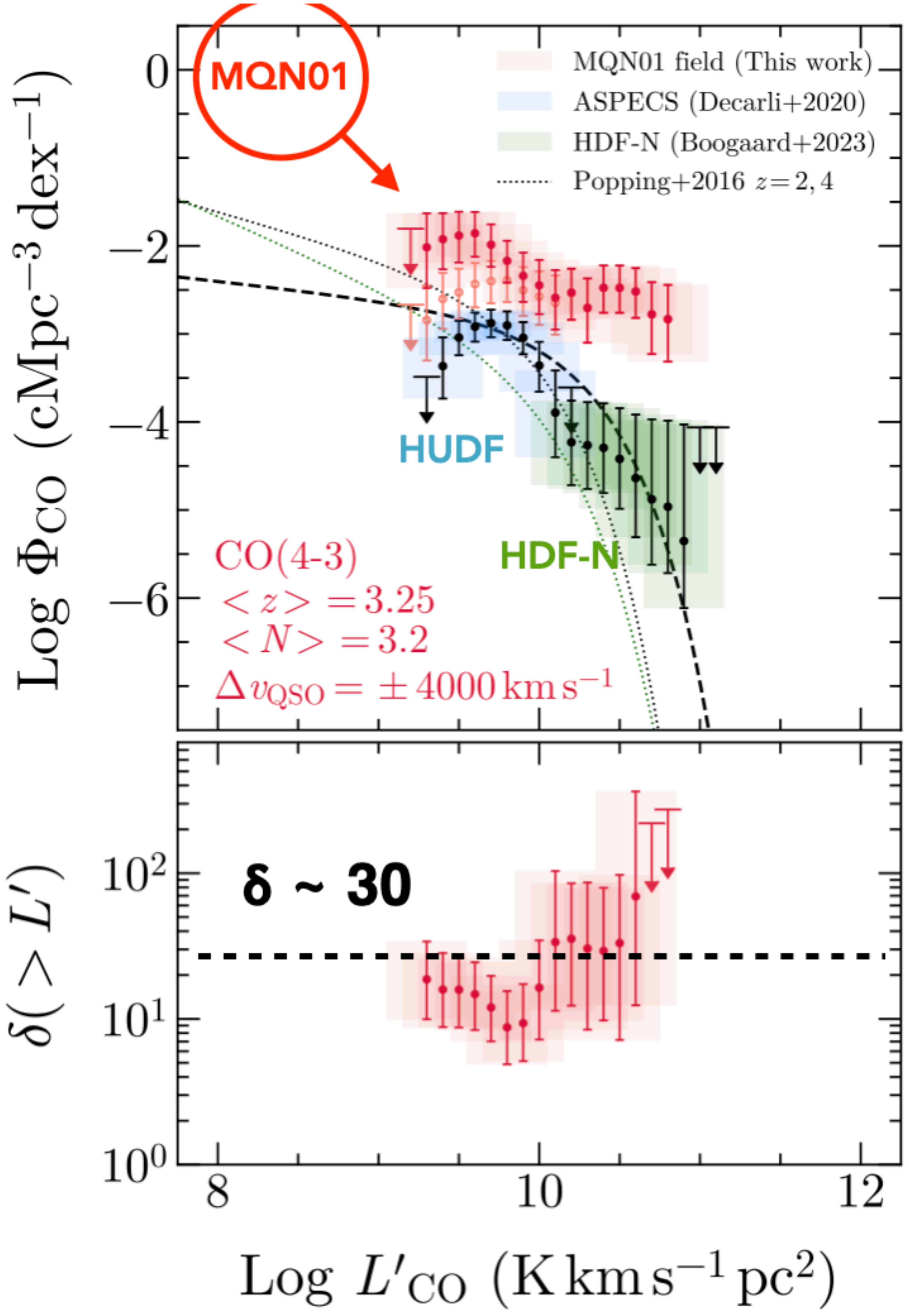
Faint AGN: either not currently accreting at full power or "small" BH mass…

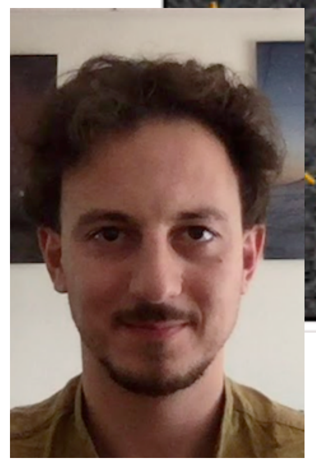
Wang, SC+, 2025



Different tracers same result: large overdensity of CO(4-3) emitters and more surprises…

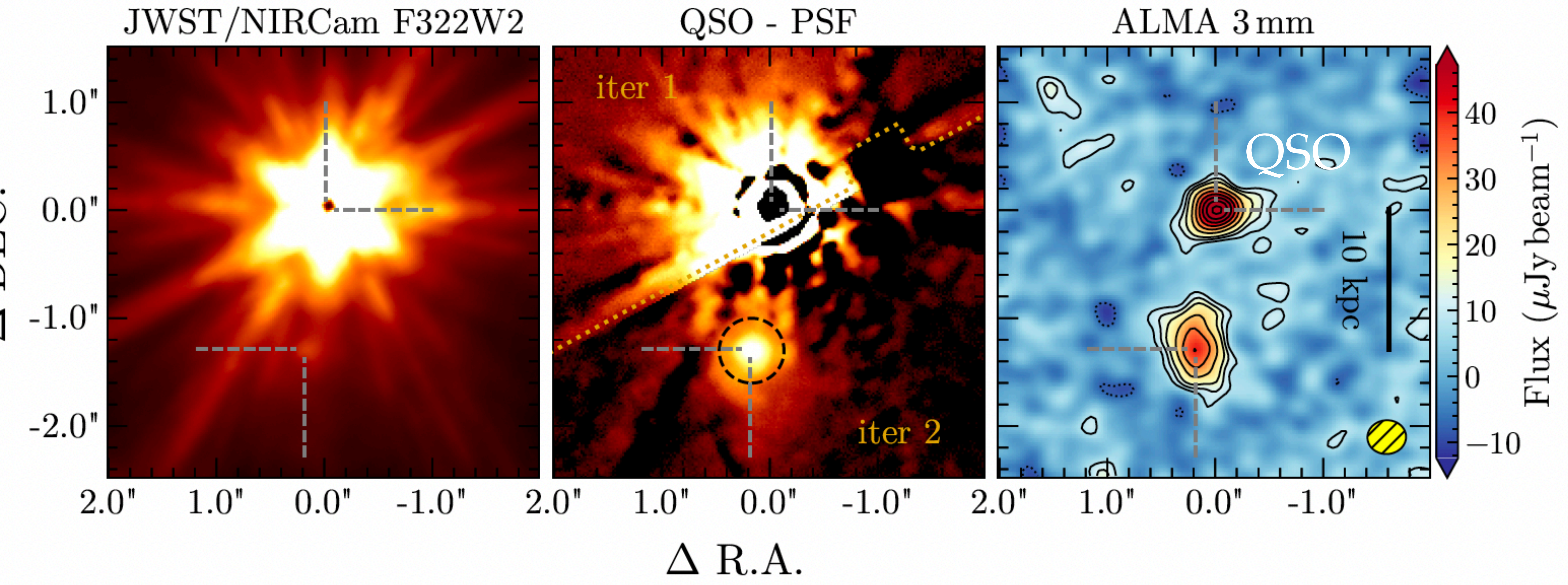




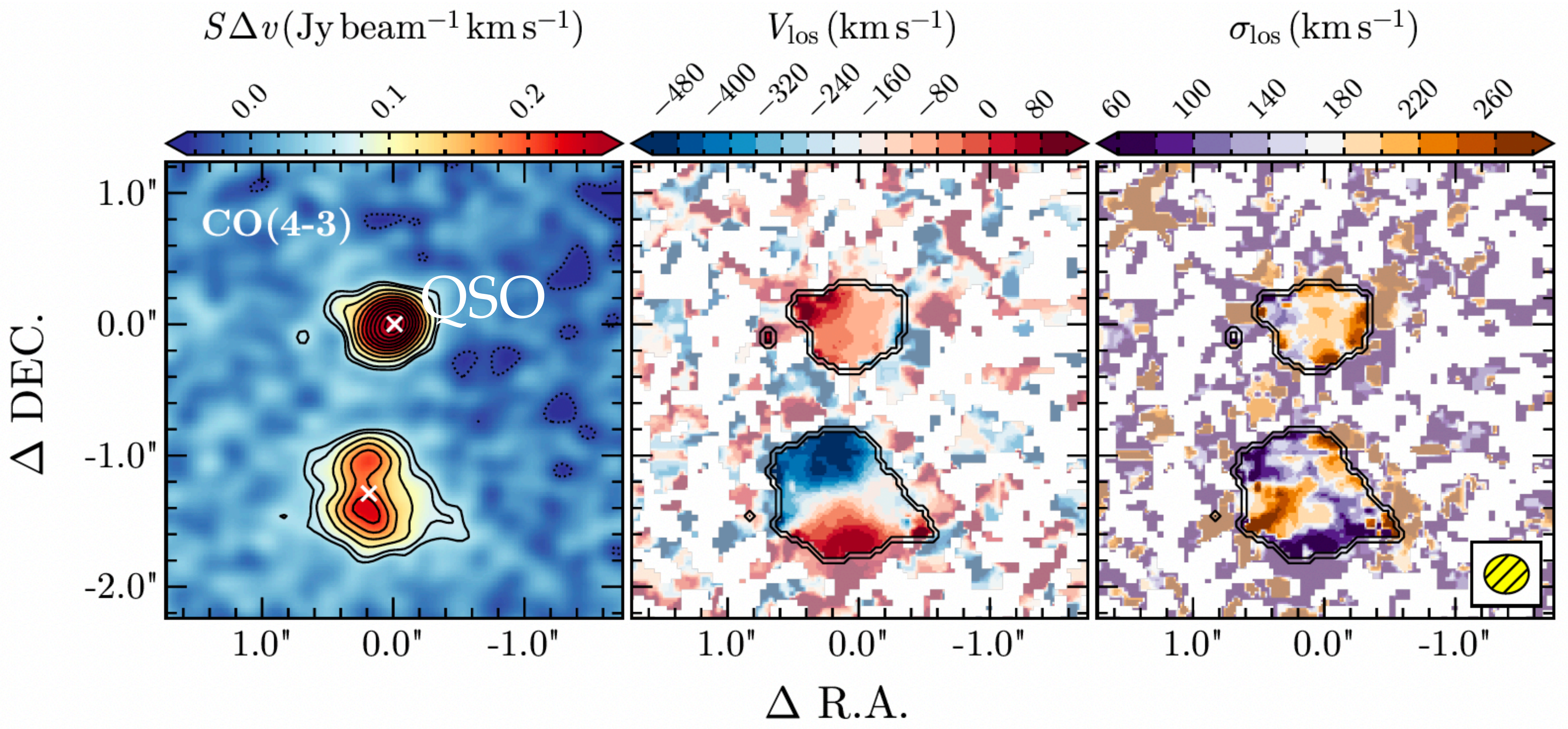


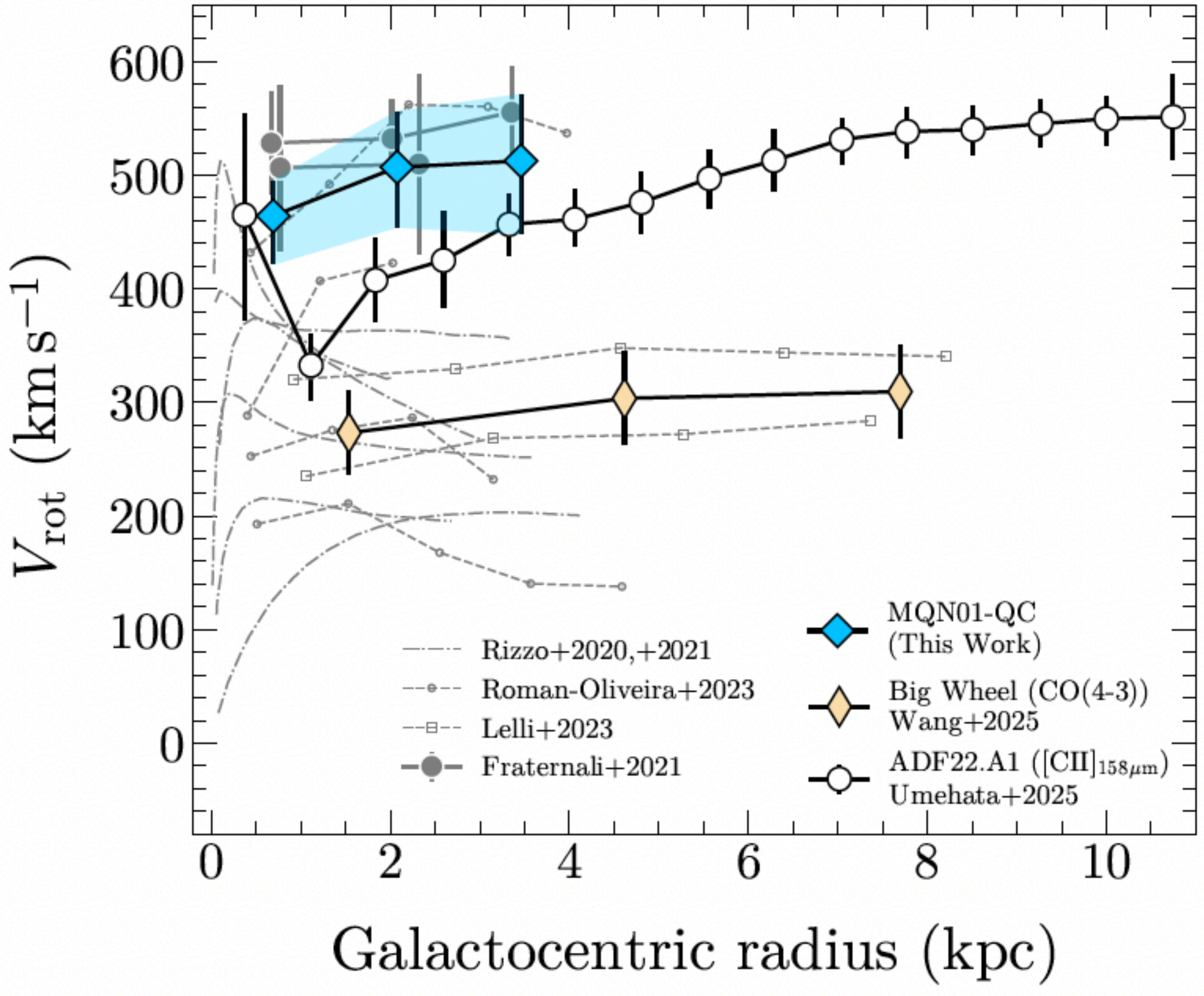
Pensabene,SC+, 2024

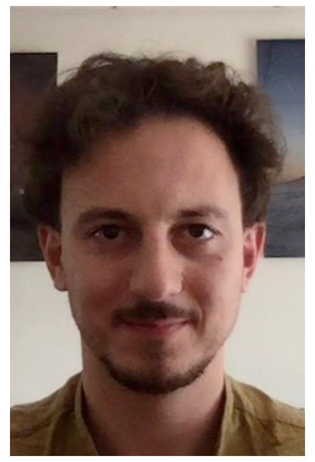
Surprises from ALMA observations: a massive "companion" hidden in the QSO PSF (~1" distance)



A massive (M_{star}~10^{11} $M_{\odot}$), happily rotating super-cold disk (V/σ~10) ~10kpc away from the brightest z~3 QSO and at the center of a huge overdensity!

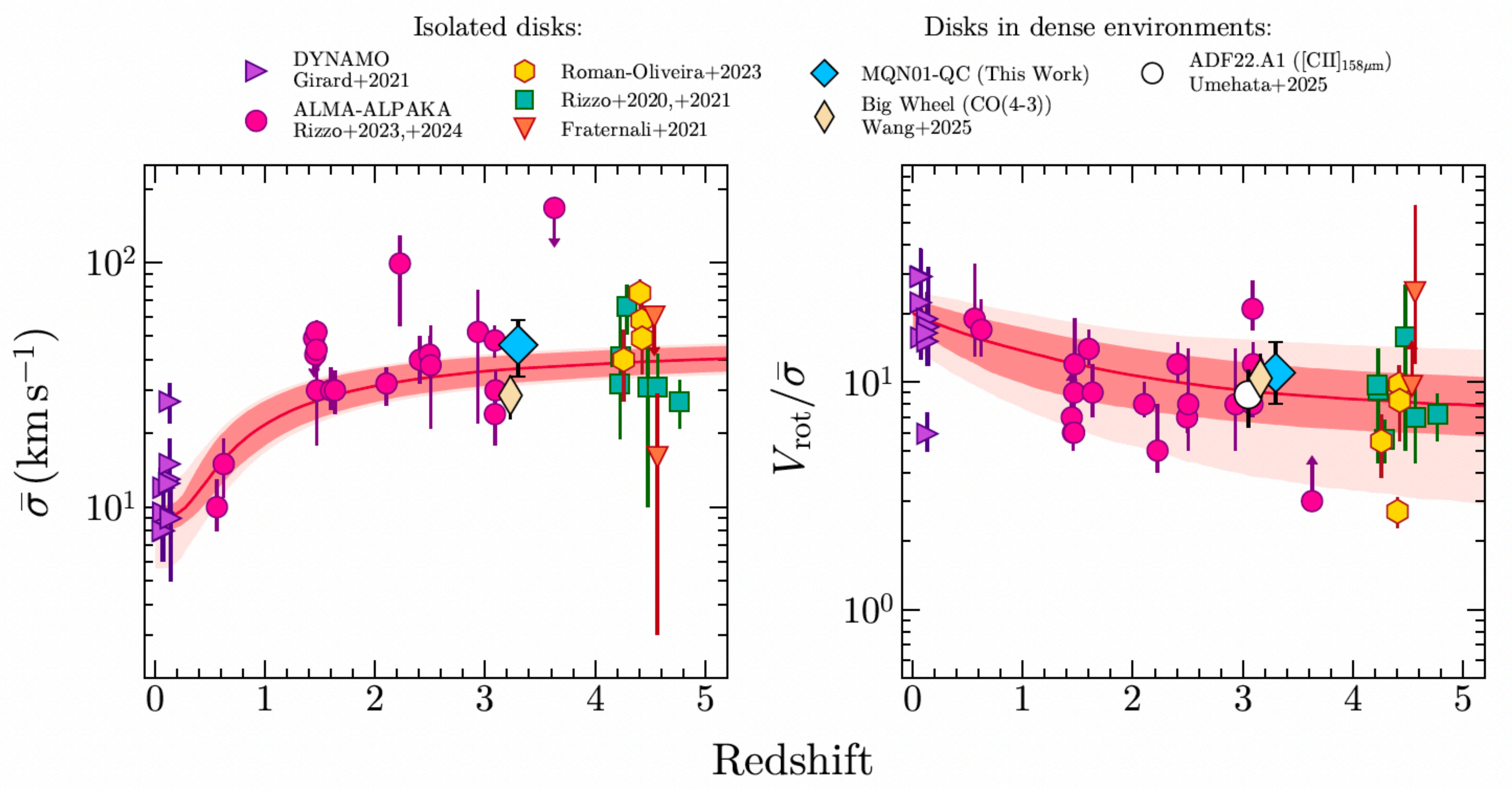




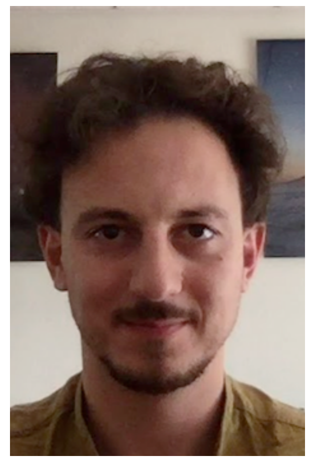


Pensabene,SC+, 2025

How does "environment" affects galaxy disks kinematics?

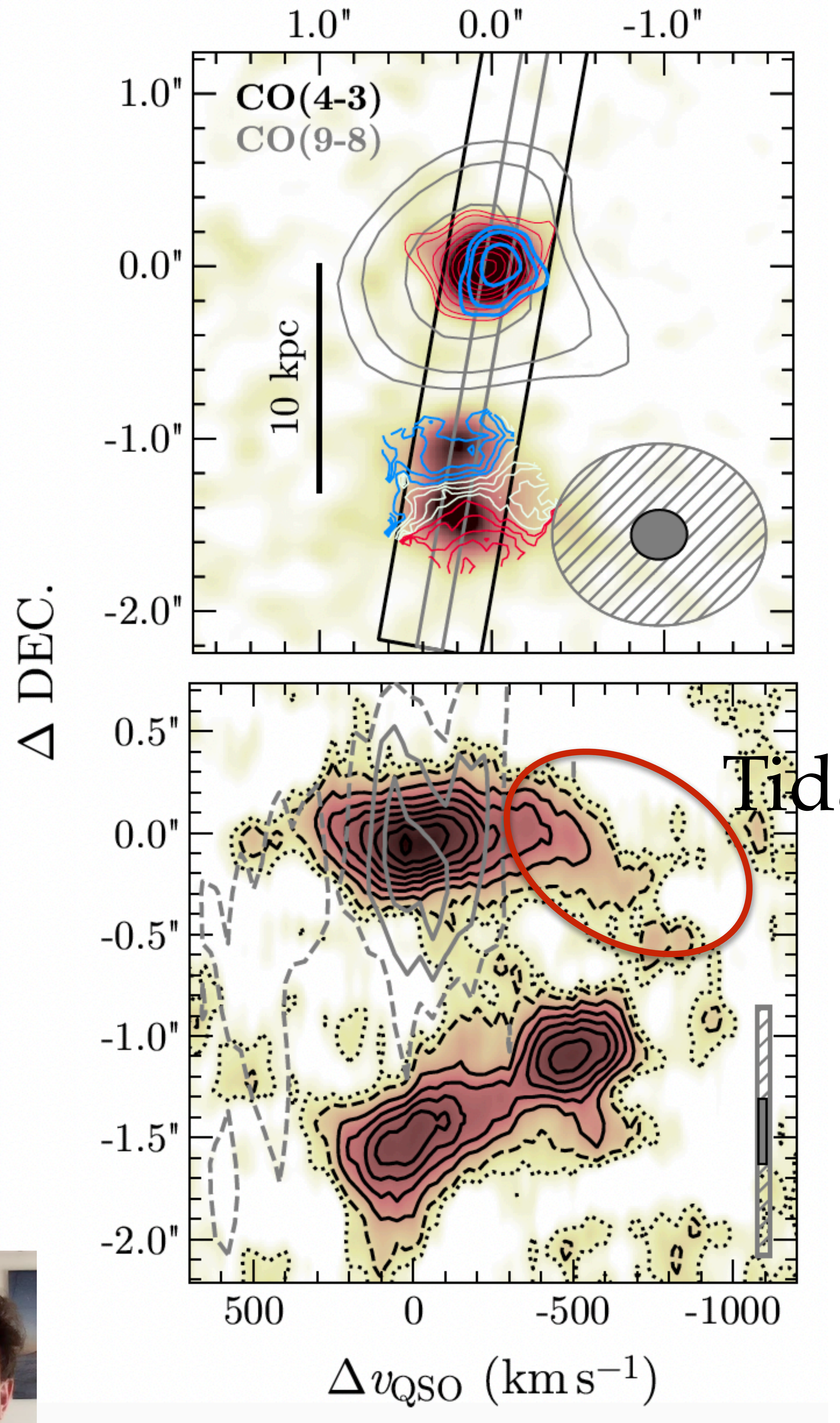


Super-cold disks (V/σ~10) are also present in the densest environments!
Are massive, super-cold disks resilient to mergers or even promoted by them?



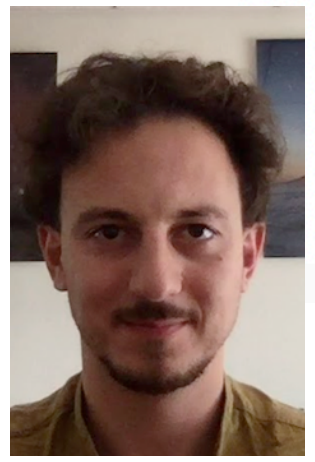
Pensabene,SC+, 2025

The disk is unaffected by the interaction. How about the QSO host?



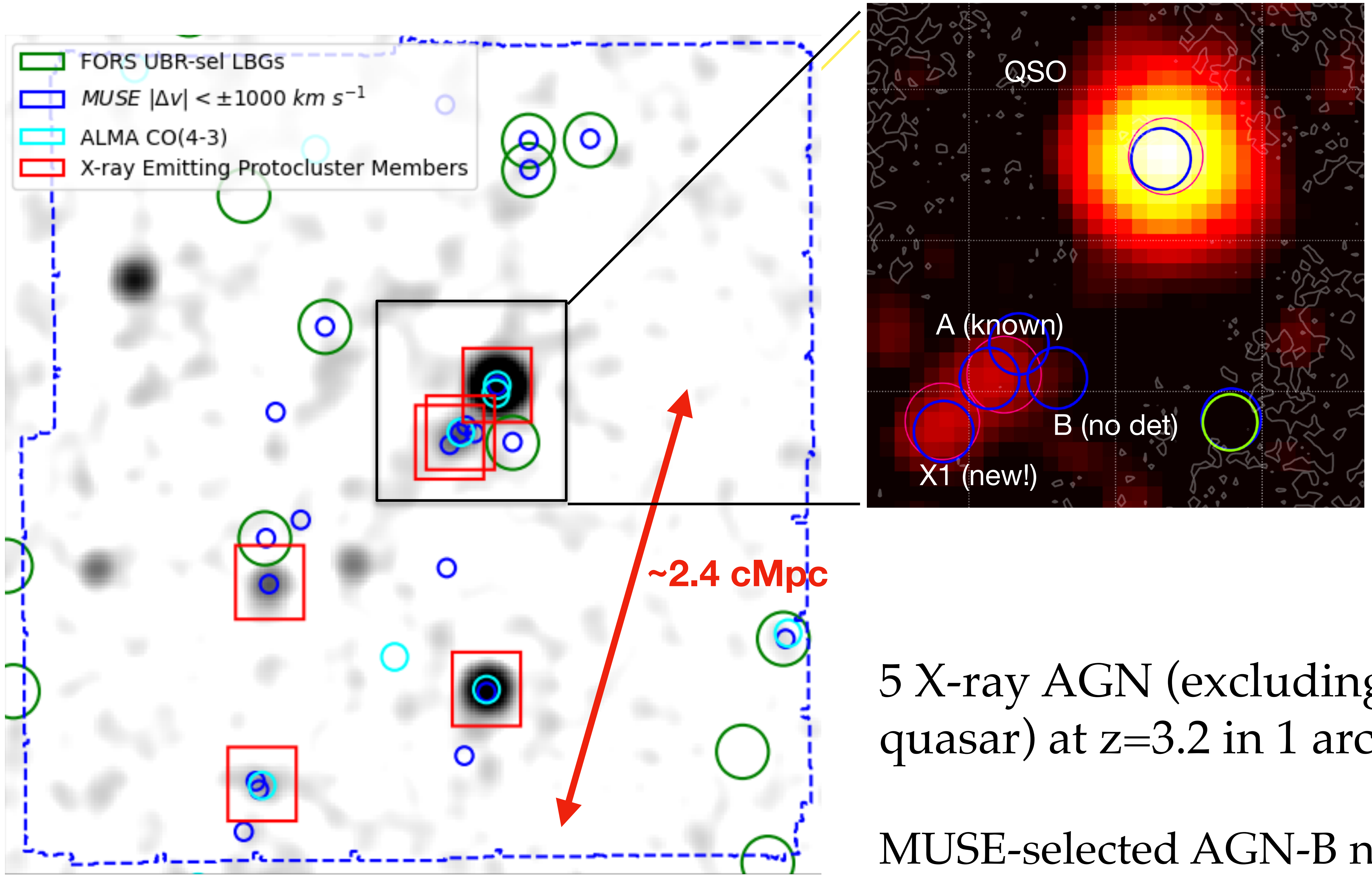
Is the QSO (the brightest in the Universe at z~3!) the actual **satellite galaxy** in the system?

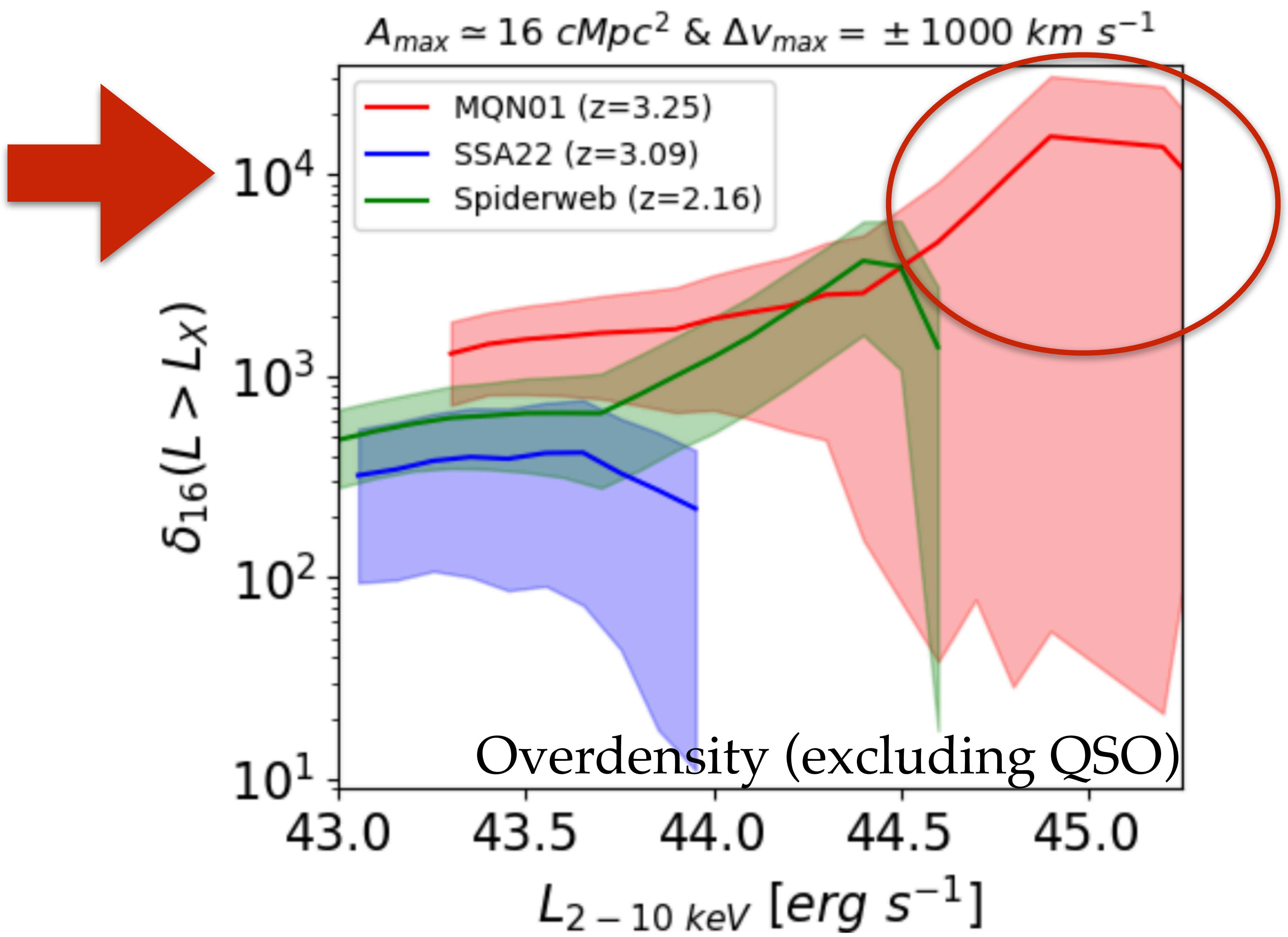
Tidal tail or outflow?



Pensabene,SC+, 2025

Chandra deep X-ray observations: even larger overdensity and more surprises…

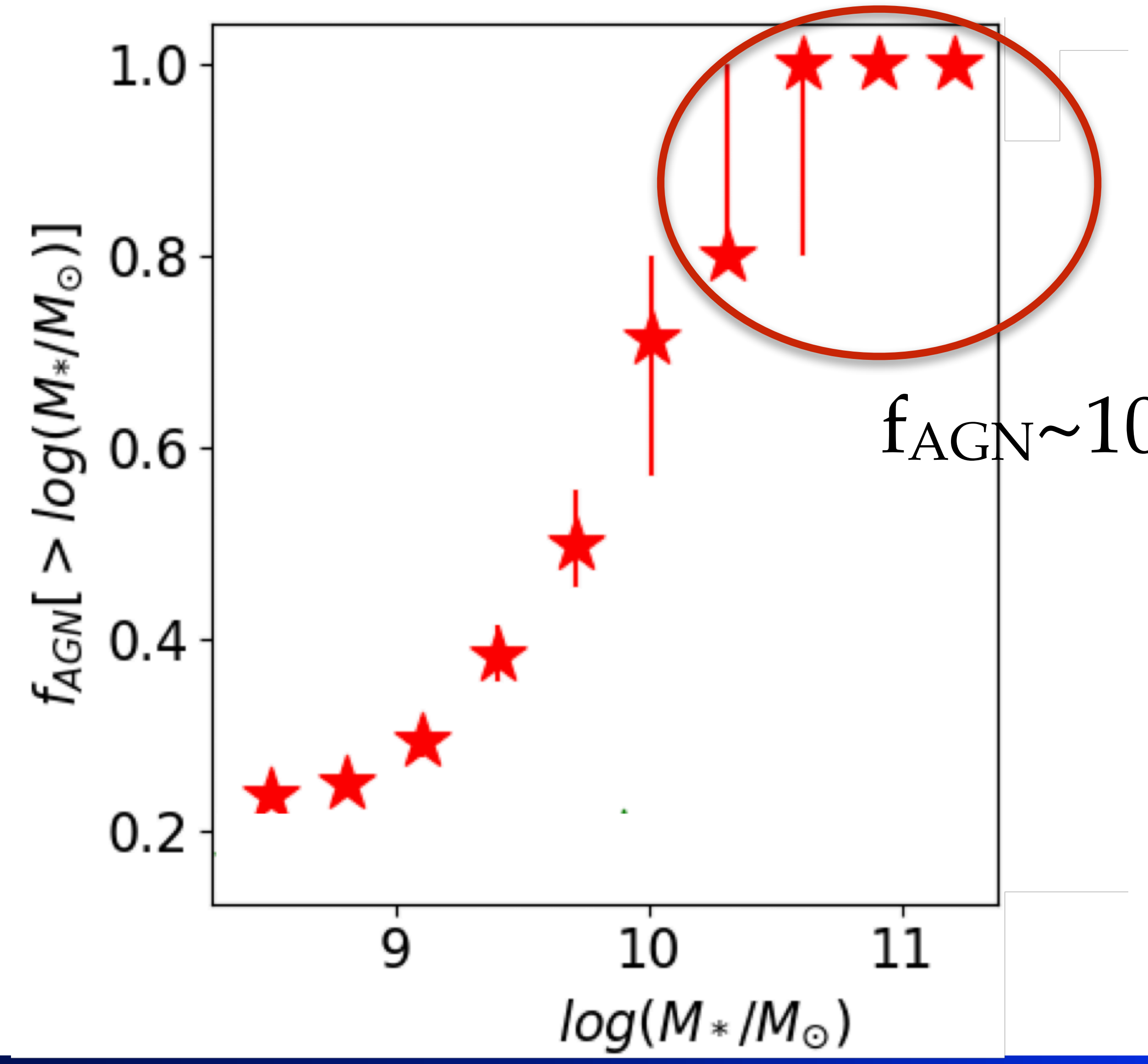




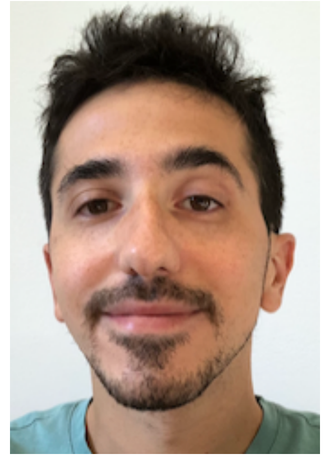
5 X-ray AGN (excluding the quasar) at z=3.2 in 1 arcmin² !!

MUSE-selected AGN-B not X-ray detected. Two new sources.

Potential AGN quadruplet in 10"!



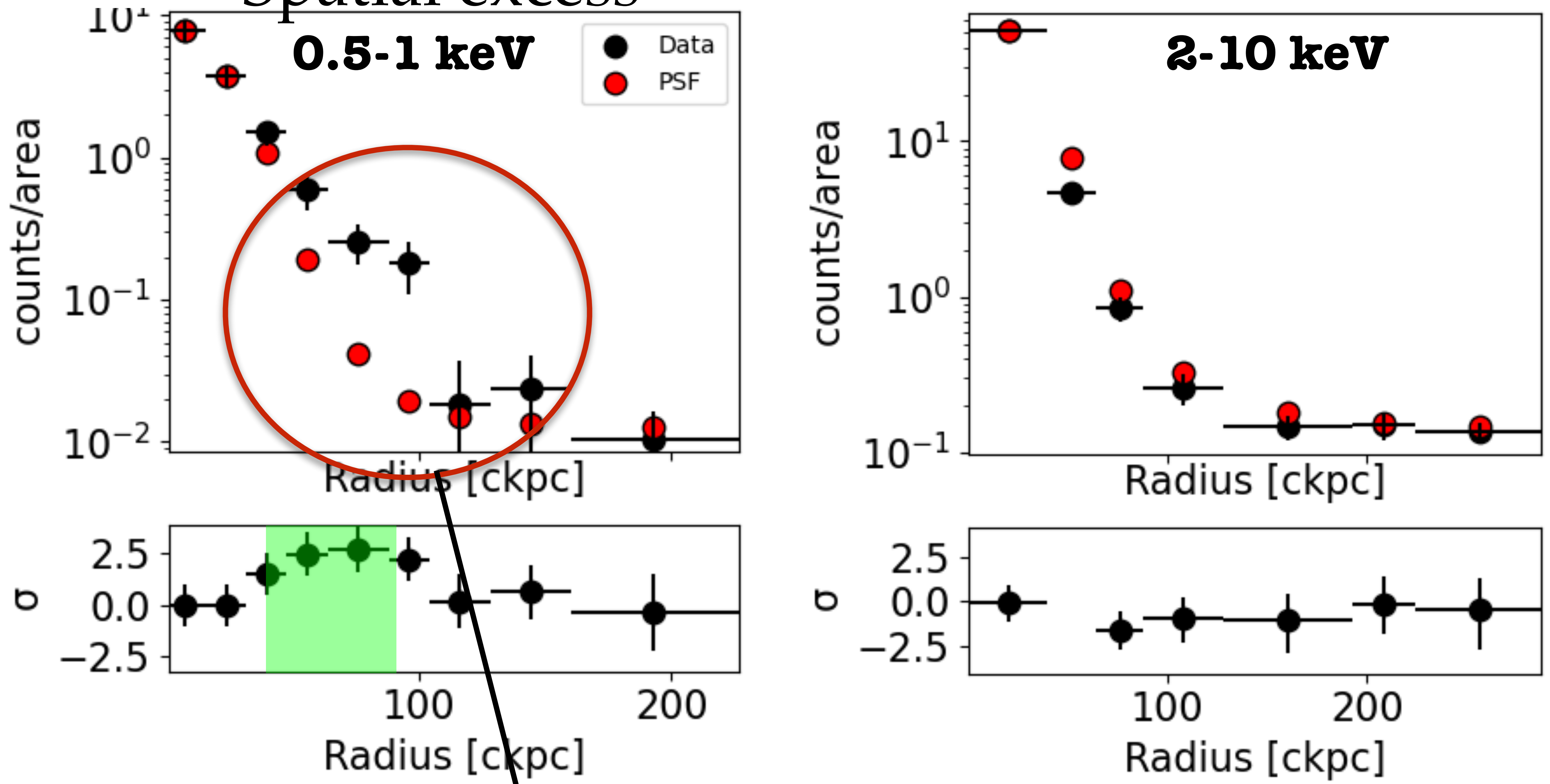
f_{AGN}~100%!



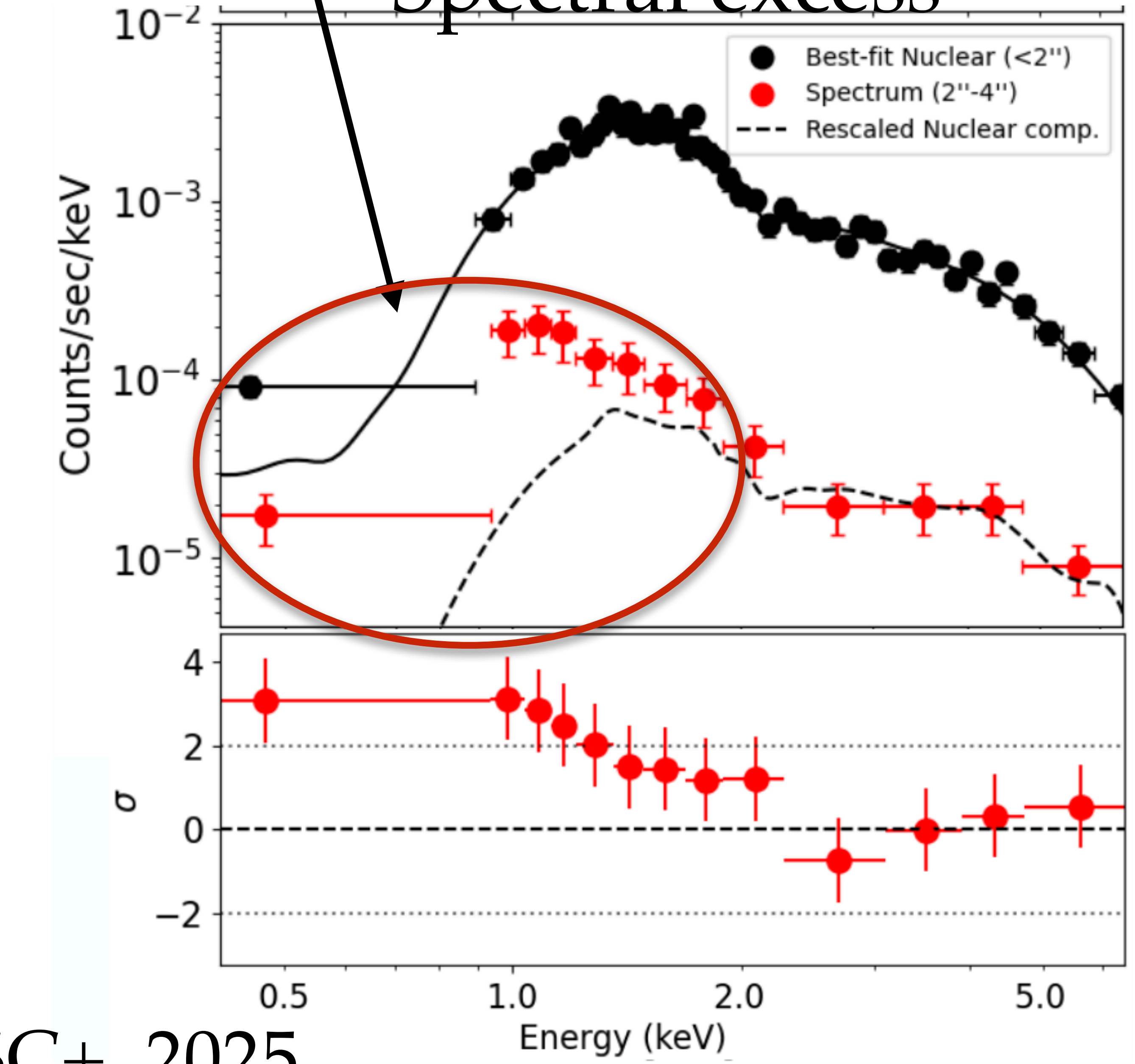
Travascio, SC+, 2024

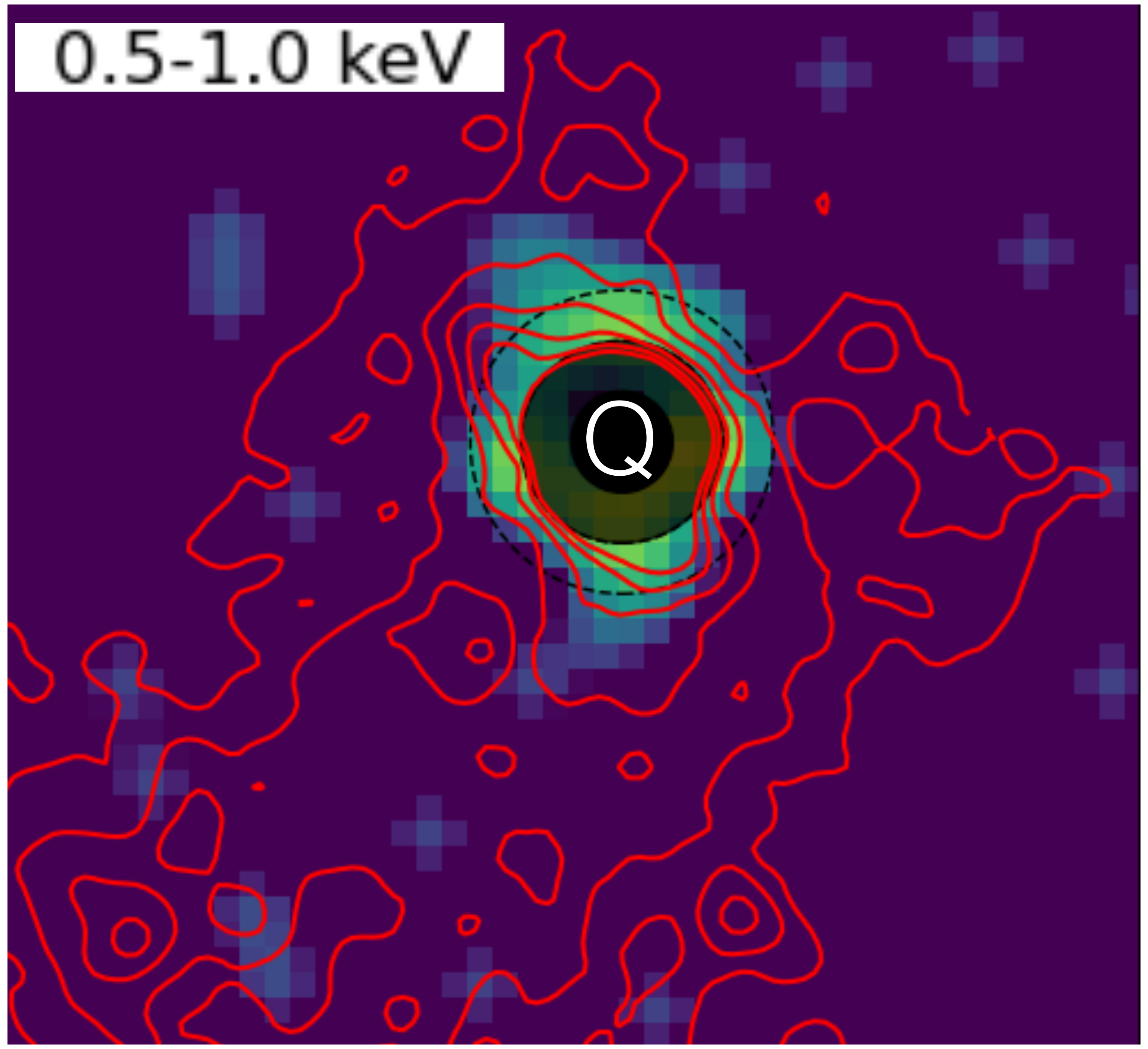
Chandra deep X-ray observations: even larger overdensity and more surprises…

Spatial excess

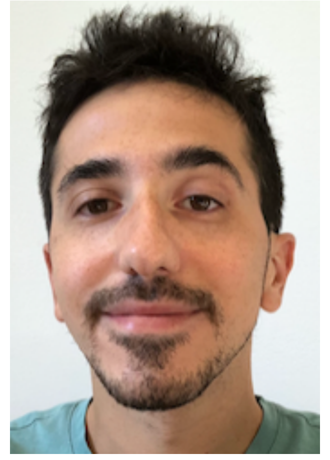


Spectral excess





Lyα contours



Travascio, SC+, 2025

- First detection of hot CGM / proto-ICM at z>3 (+ "warm/cold" component!)
- Spectrum consistent with thermal emission with T~2x10^7 K —> M_{vir} ~3x10^{13} M_{sun}
- Other emission mechanisms (e.g., Compton up-scattering) much less plausible.

Characterizing in detail the hot CGM properties

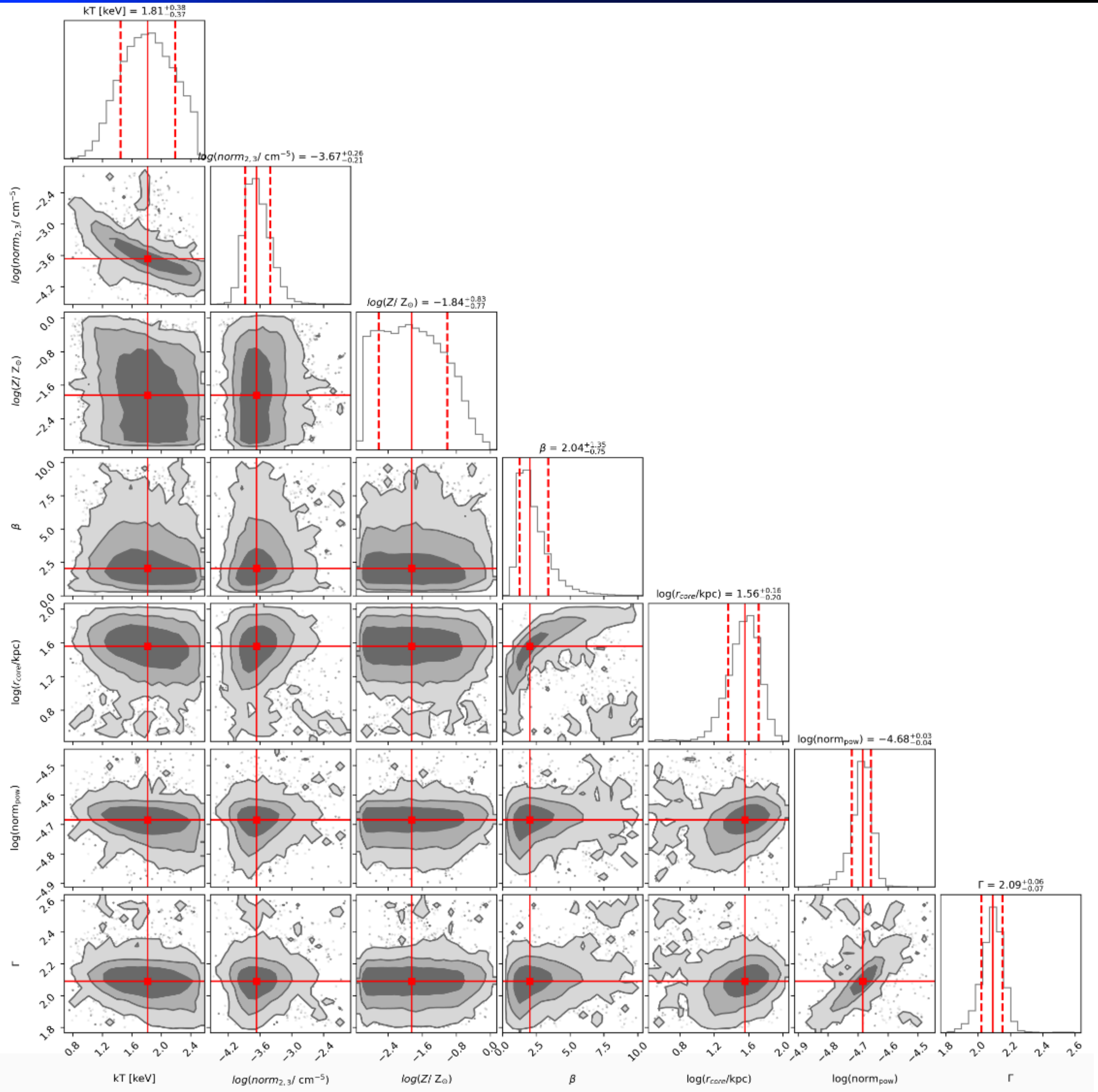


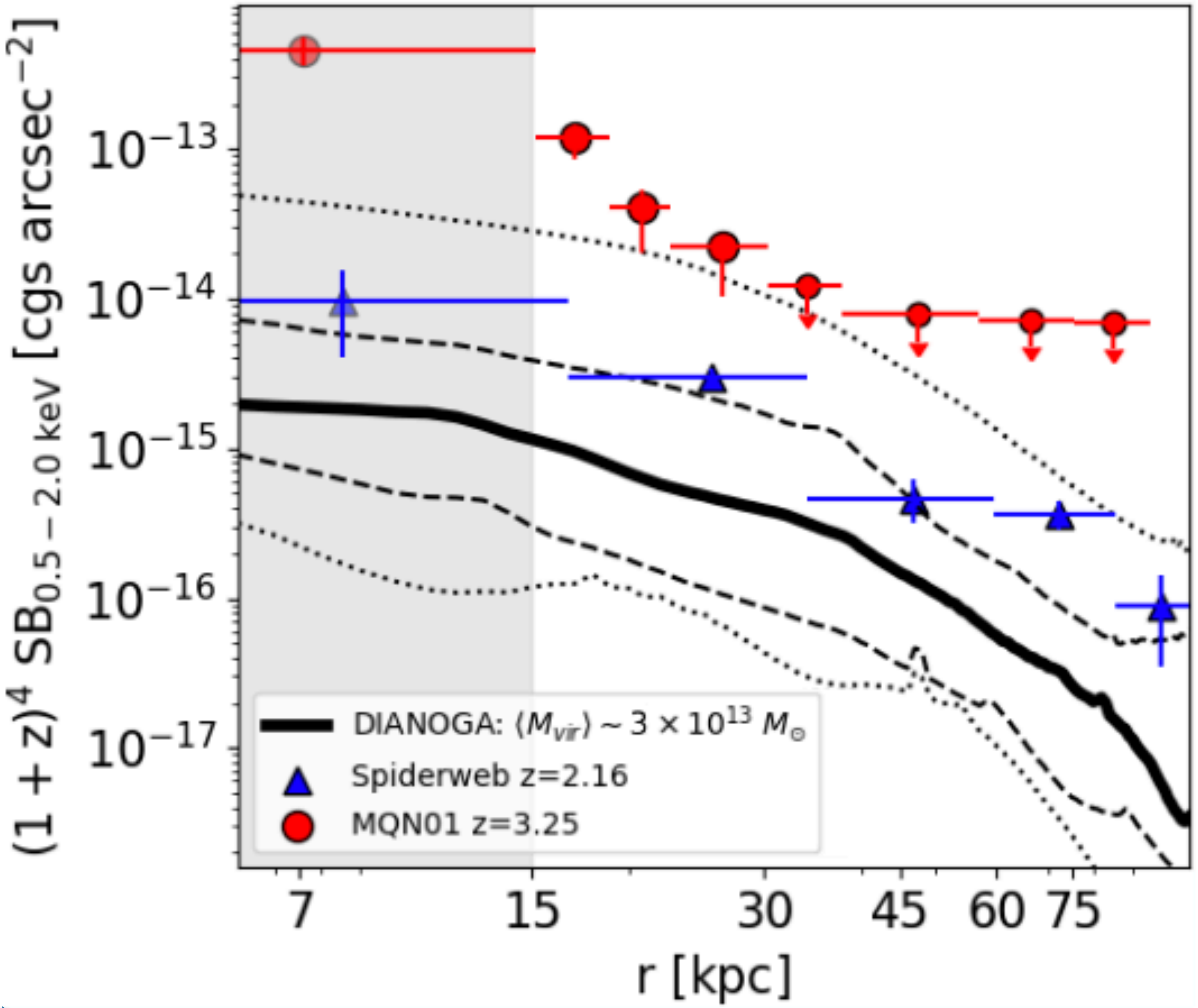
Table 1. Median, 16th, and 84th percentiles of the posterior distributions from the MCMC analysis, along with the derived physical properties of the hot gas halo.

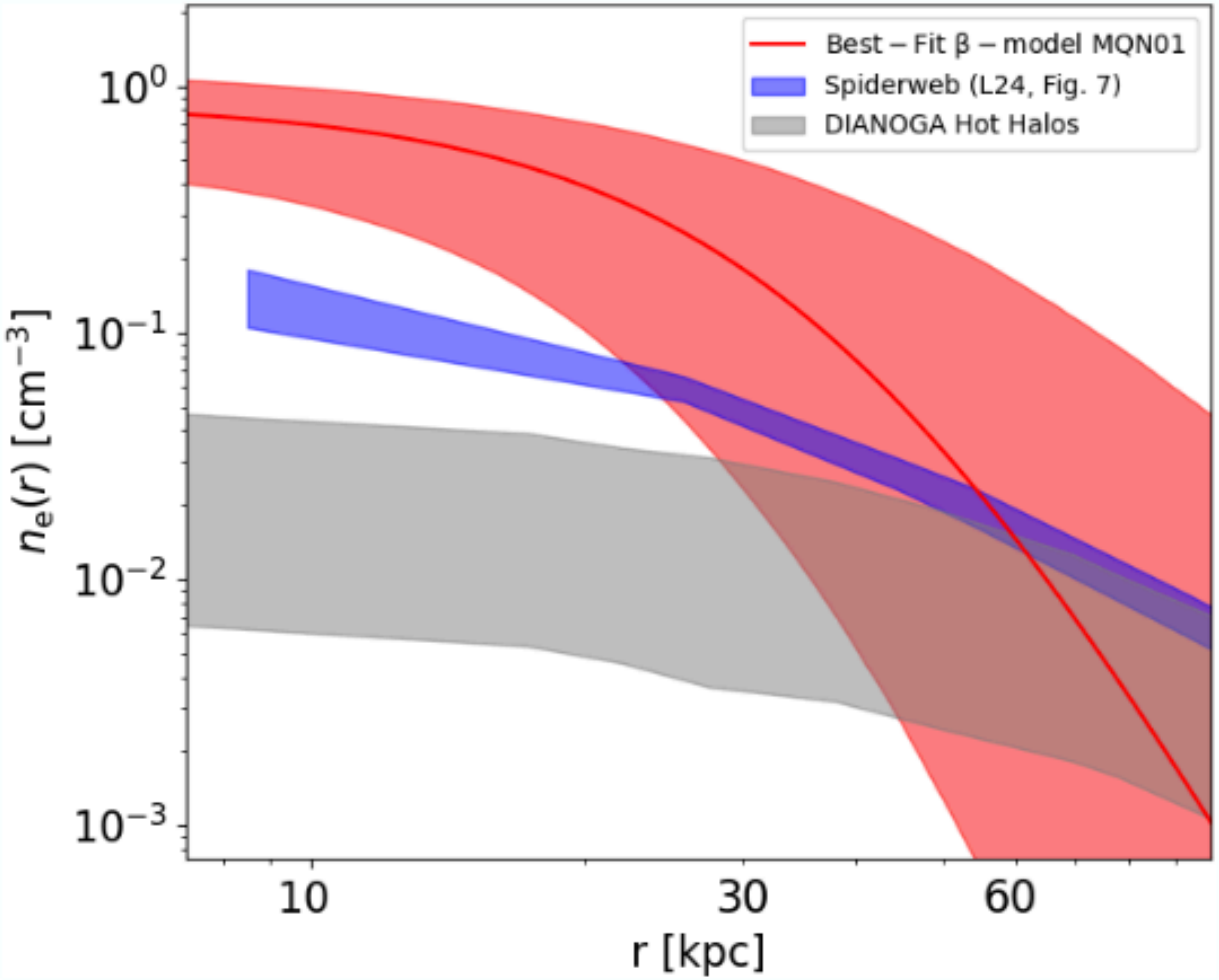
Parameter	Units	Value
kT	[keV]	$1.81^{+0.38}_{-0.37}$
norm	[10^{-4} cm^{-5}]	$2.13^{+1.75}_{-0.82}$
Z†	[$Z_\odot$]	$0.014^{+0.083}_{-0.012}$
β		$2.04^{+1.35}_{-0.75}$
$r_{\rm core}$	[kpc]	36^{+16}_{-13}
$norm_{\rm pow}$	[10^{-5}]	$2.07^{+0.15}_{-0.18}$
Γ		$2.09^{+0.06}_{-0.07}$
T	[10^7 K]	$2.1^{+0.4}_{-0.4}$
$M_{\rm vir}$	[10^{13} $M_\odot$]	3 ± 1
$R_{\rm vir}$	[kpc]	190^{+19}_{-20}
$n_{e,0}$	[cm^{-3}]	$0.86^{+0.48}_{-0.19}$
$M_{\rm hot\ gas}(R_{\rm vir})$	[10^{12} $M_\odot$]	$2.6^{+1.7}_{-0.6}$
$M_{\rm hot}/M_{\rm vir}$		$0.083^{+0.098}_{-0.030}$
$f_{\rm hot}$		$0.56^{+0.65}_{-0.20}$

† parameter used as marginalization (not constrained)

Travascio, SC+, 2025

Characterizing in detail the hot CGM properties + comparison with DIANOGA simulations

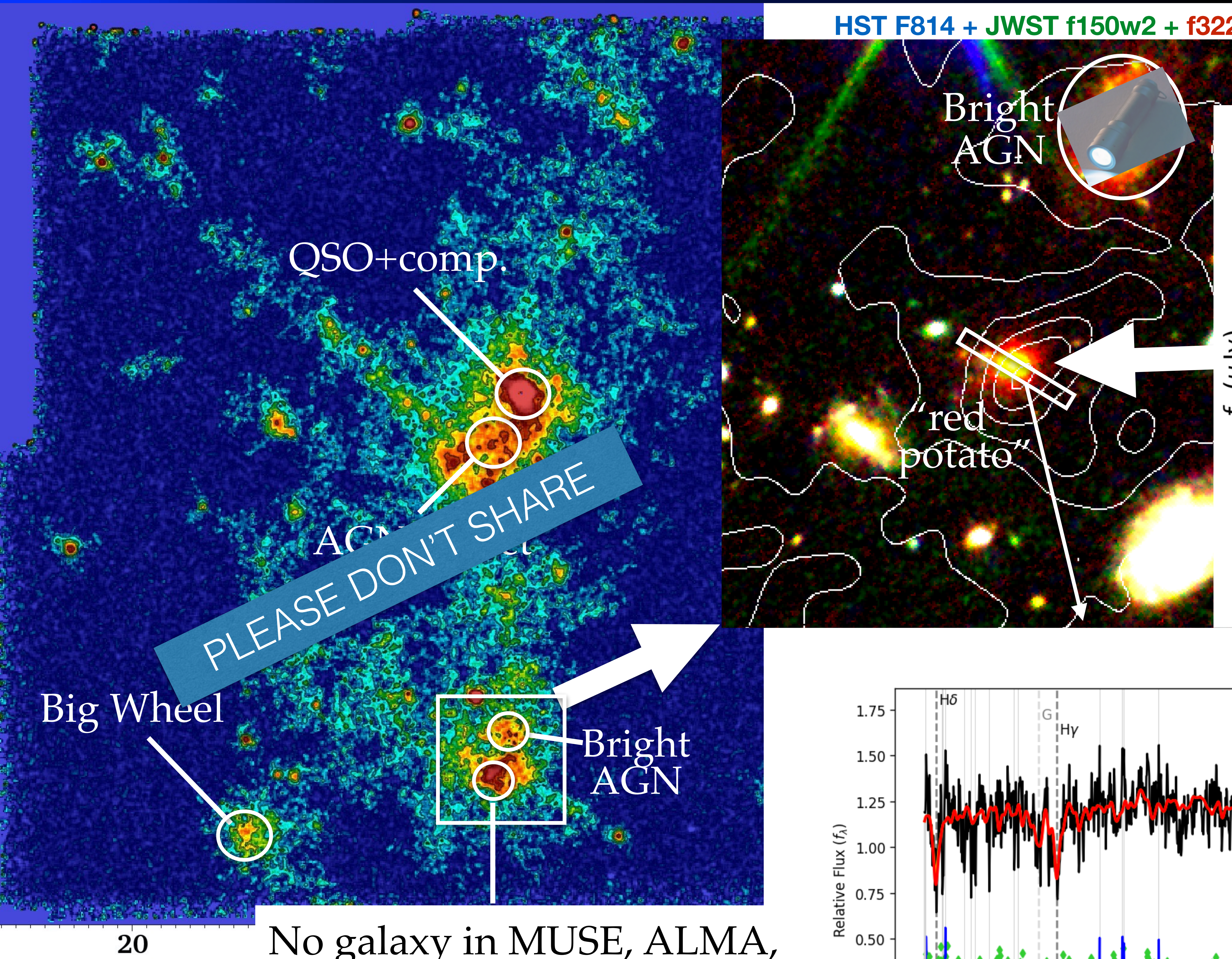




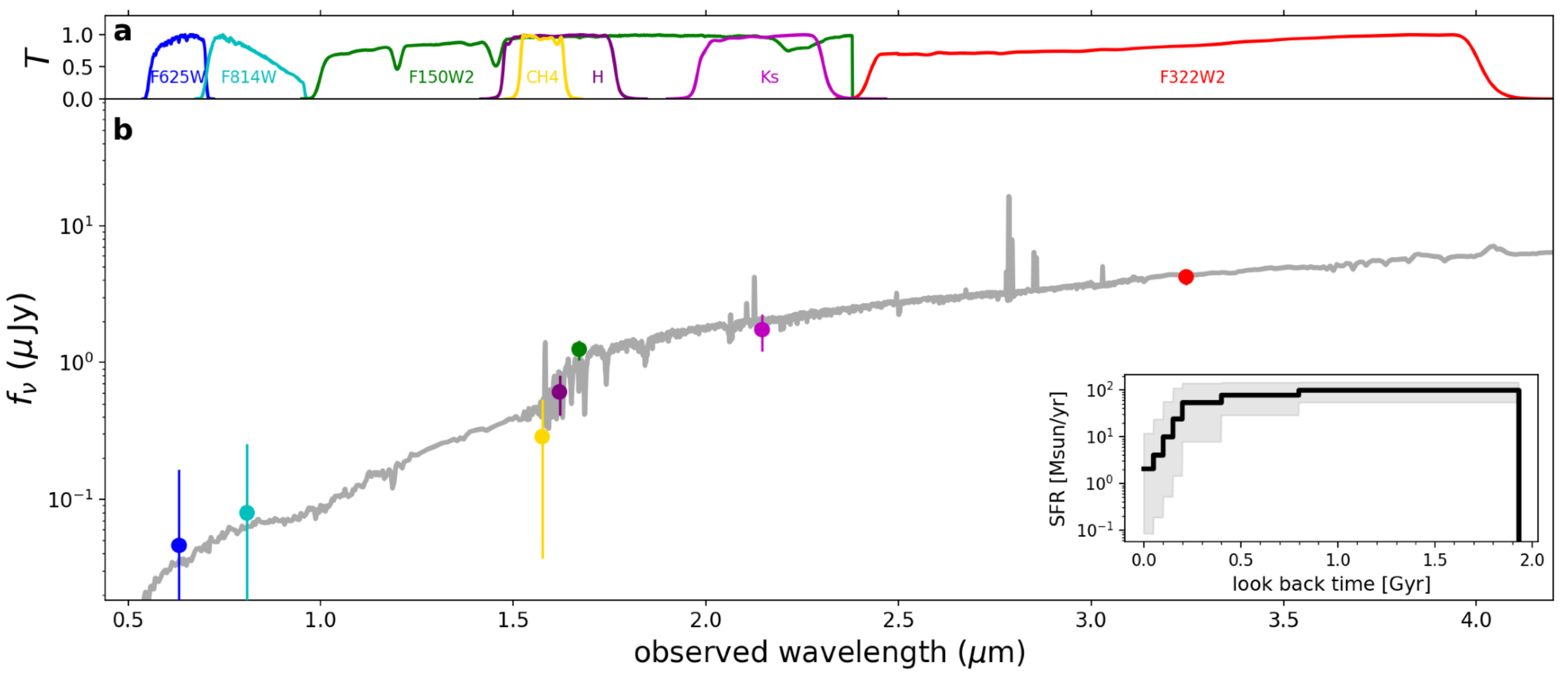
- 100x brighter and >10x denser (in the inner CGM) than typical DIANOGA haloes!
- Enough pressure to pressure-confine dense cold Ly-alpha emitting gas (“clumps”)
- $1 < t_{cool}/t_{ff} < 10$ suggesting possible thermal instabilities in the inner hot CGM

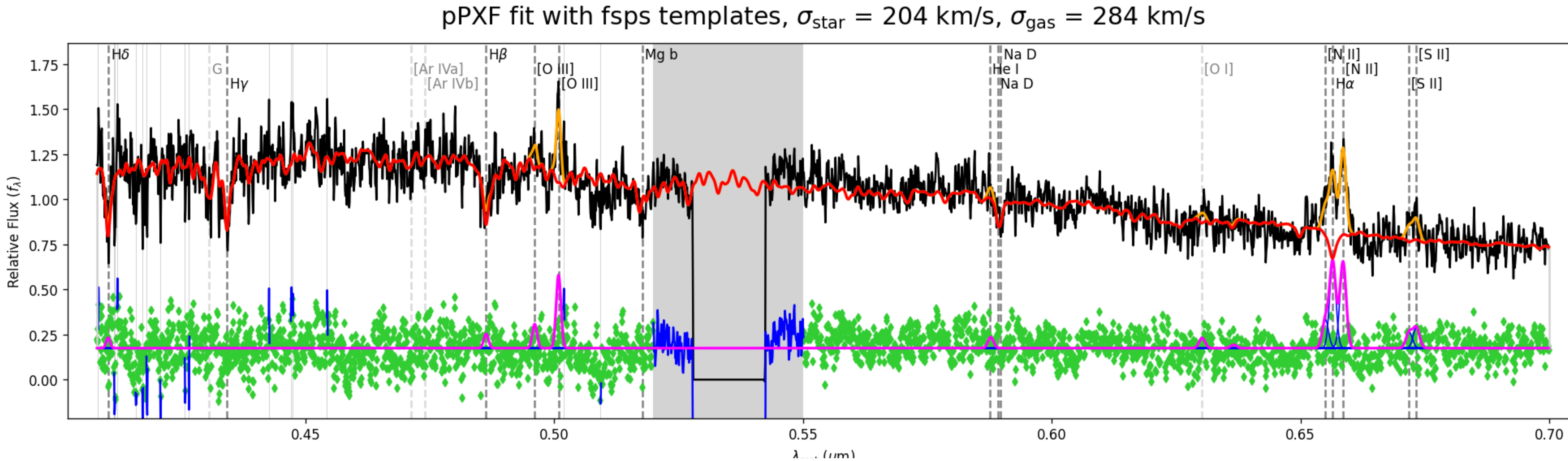
Travascio, SC+, 2025

The mystery of the 2nd brightest Lyα-emitting region in MQN01:

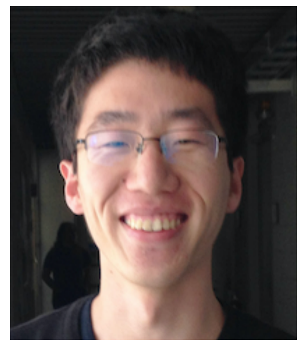


Passive (not dusty!) galaxy with M_{star}~10^{11} $M_\odot$ and SFR<3 $M_\odot$/yr (sSFR at least one dex below the main sequence)





No galaxy in MUSE, ALMA, Chandra… but in JWST…



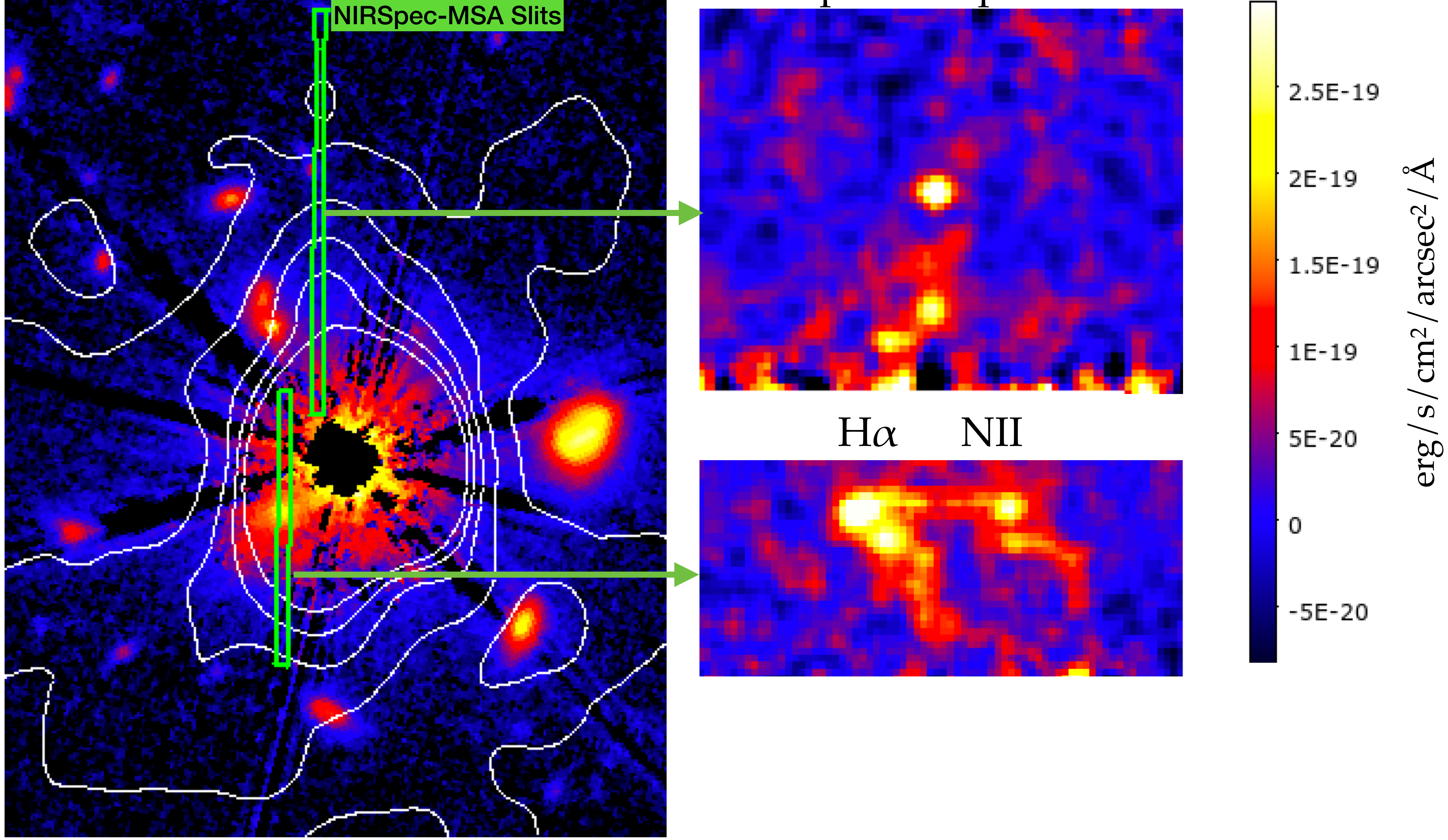
Wang, SC+, in prep.

Redshift and SED confirmed by Balmer absorption lines.
What is a passive galaxy doing in the middle of a large gas reservoir?

Back to the CGM: bright and clumpy CGM Hα emission detected with JWST around MQN01 QSO+companion!

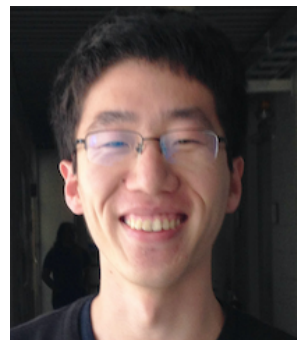
NIRCam image + Lyα contours

NIRSpec 2D Spectrum



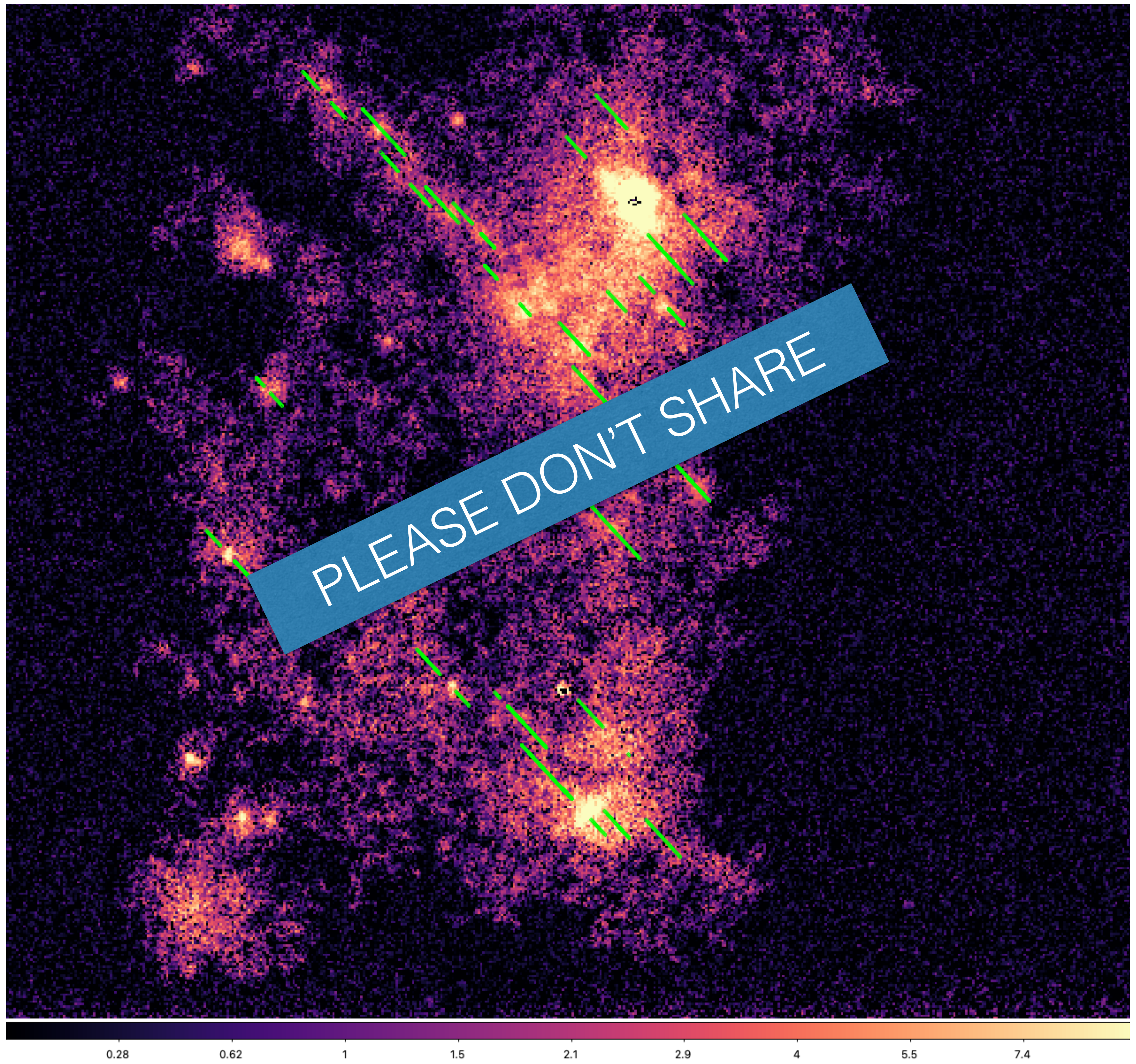
Hα SB as high as Lyα SB (!)
(but MSA slit width smaller than MUSE spatial resolution)

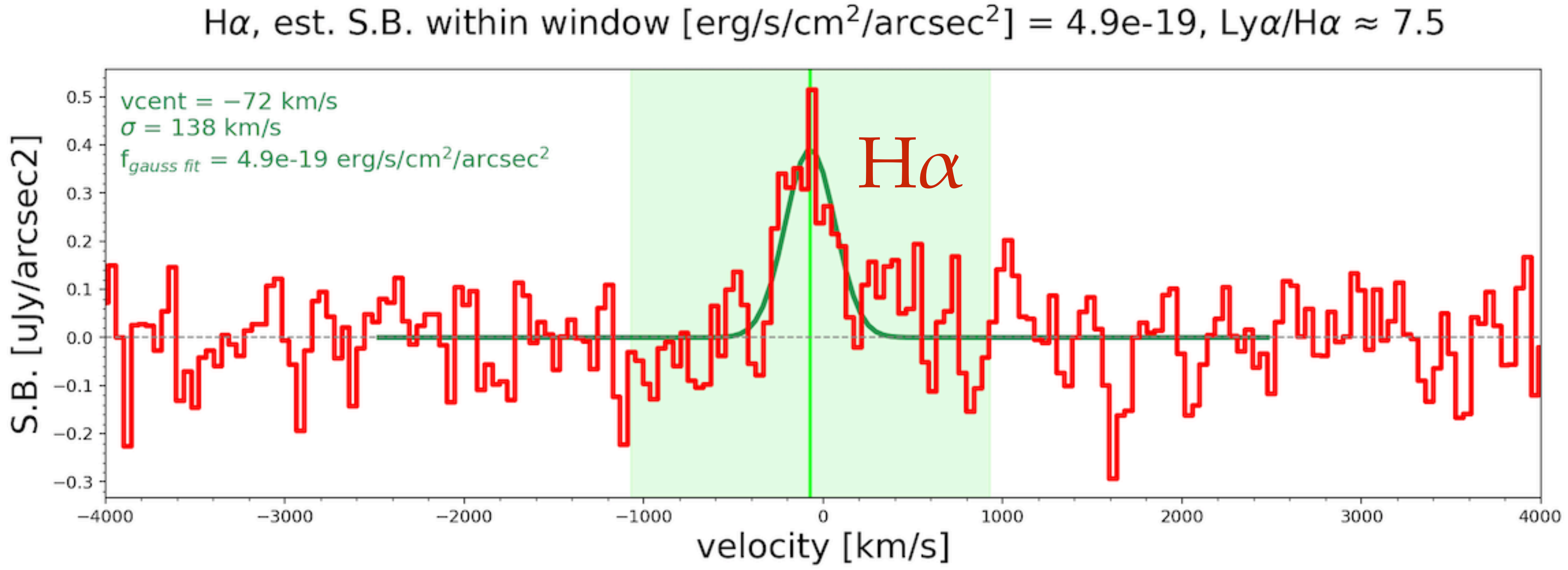
IFU observations needed to get proper line ratio and emission 2D morphology (JWST IFU required)

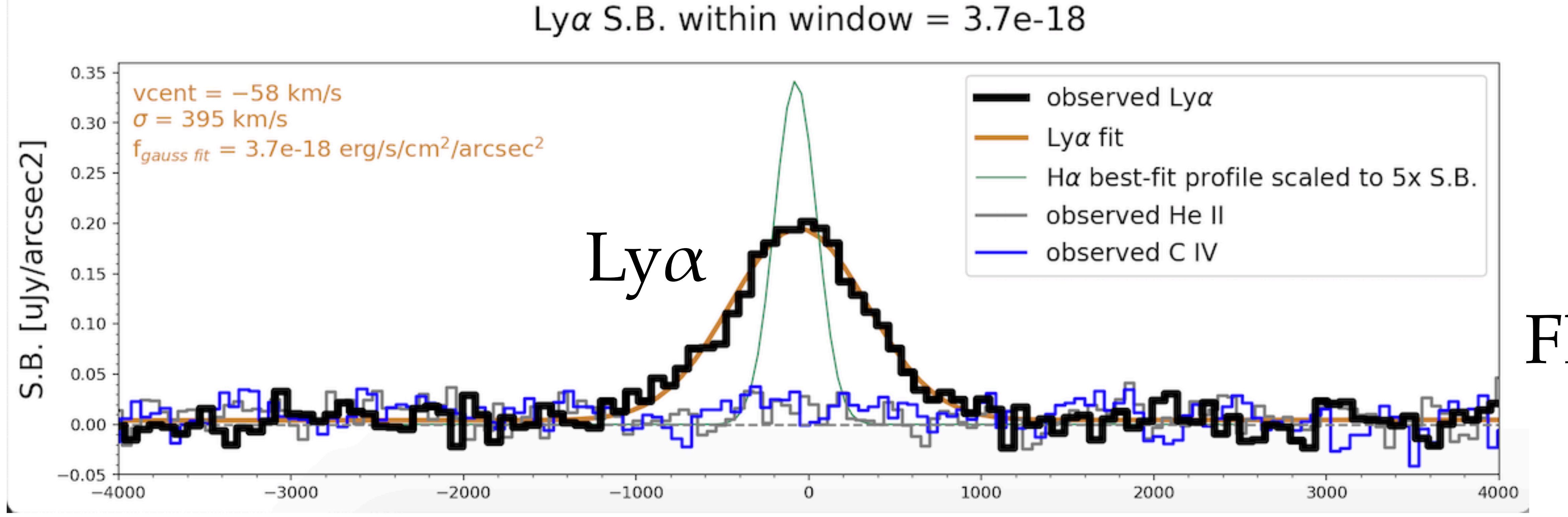


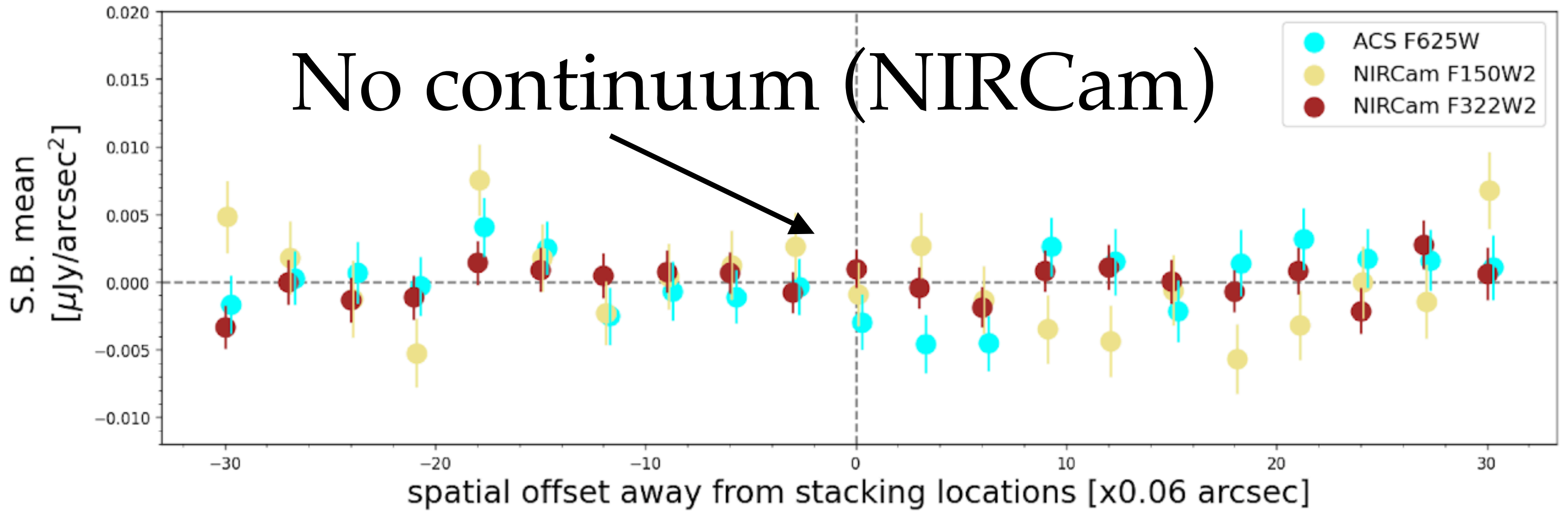
Wang, SC+, in prep.

PRELIMINARY





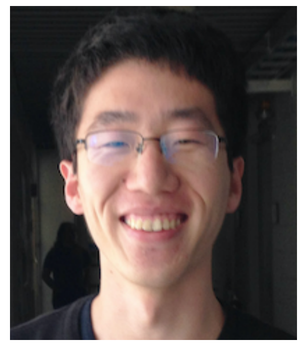




Lyα/Hα~8 (broader Lyα)

No continuum
In deep stack

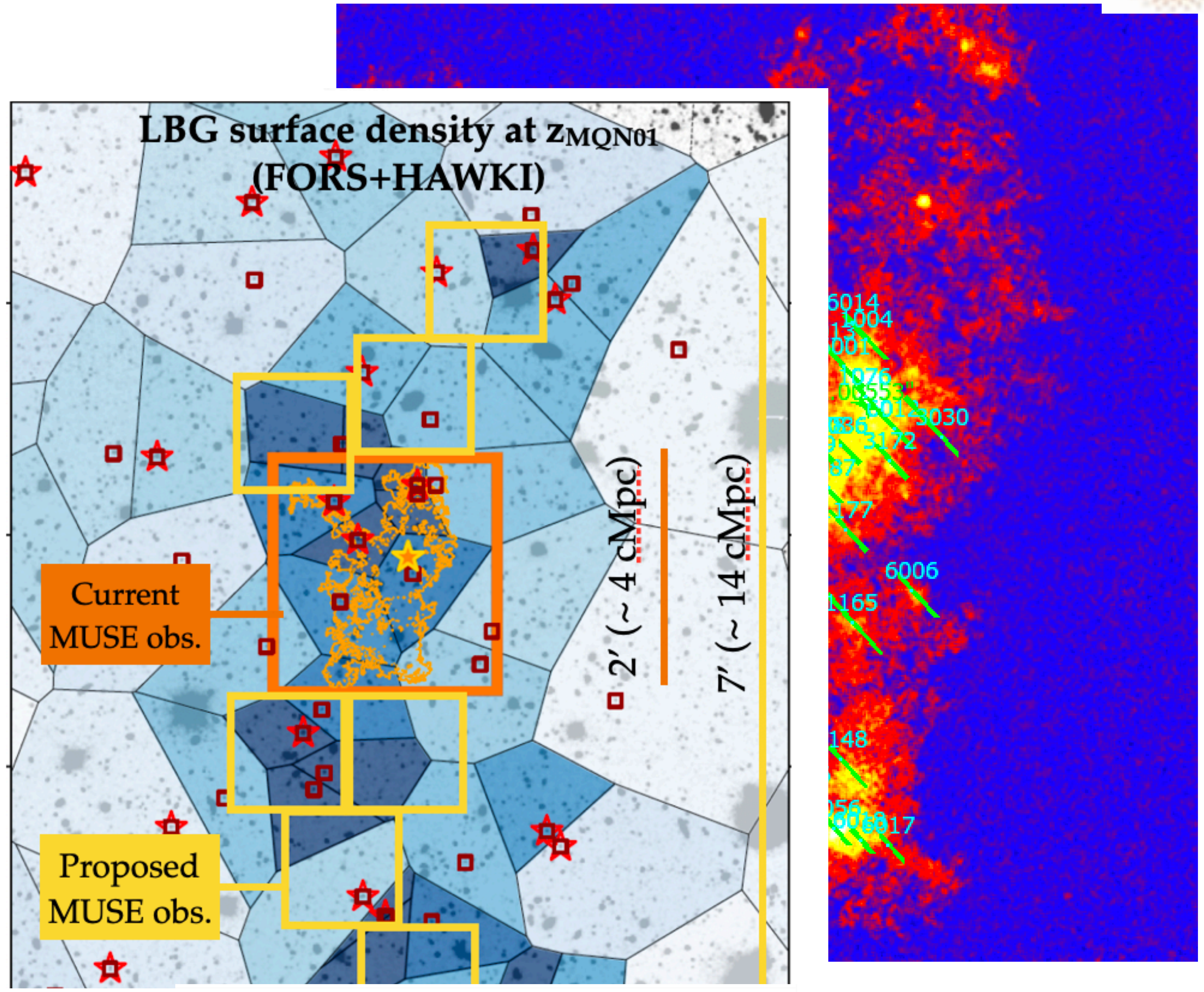
Consistent with Fluorescent emission
SB can be used to directly constrain "warm" gas density!



Wang, SC+, in prep.

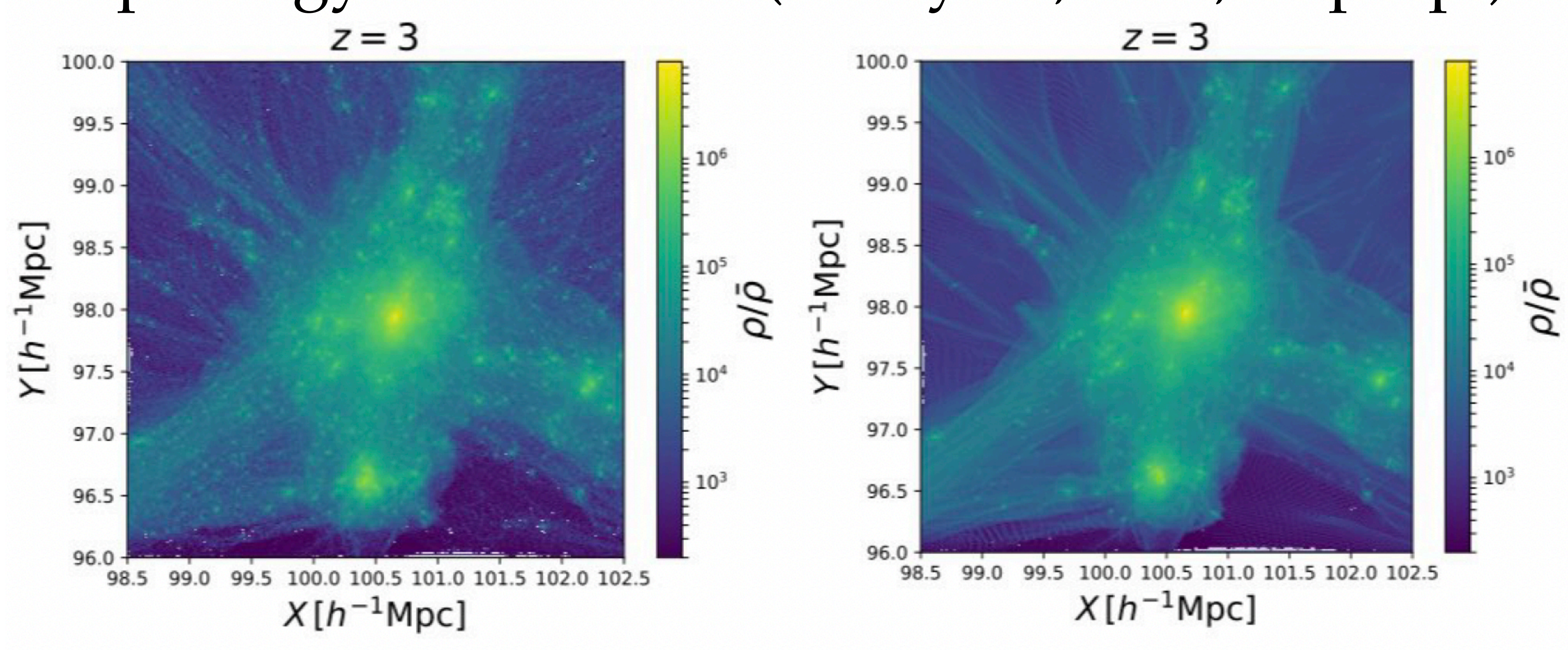
MQN01: ongoing / next explorations

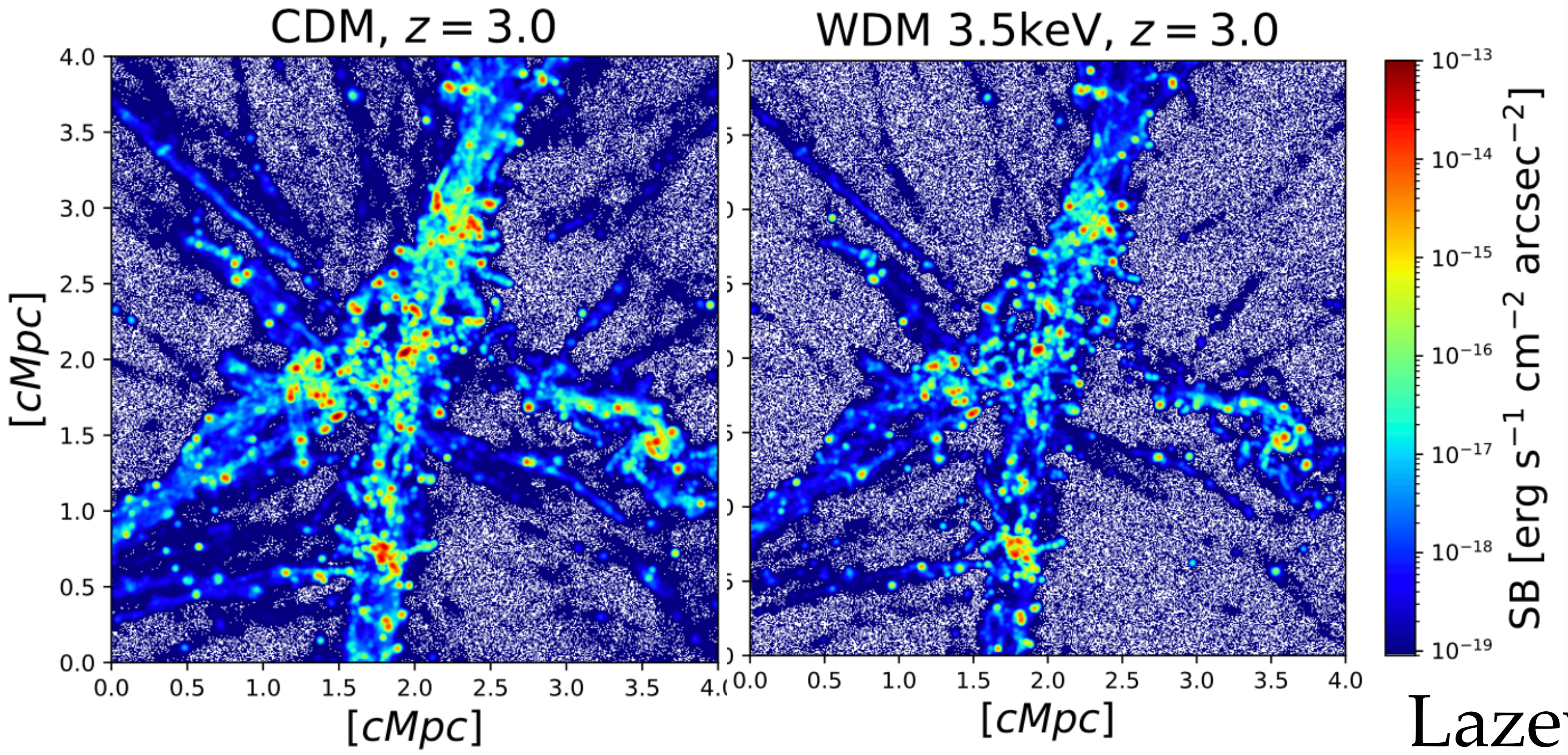
Correlate galaxy properties (SFR, Stellar Mass, molecular gas mass, metallicity, morphology, orientation, kinematics, AGN, …) with gaseous filaments' properties (density, clumpiness, morphology, kinematics,…)



80+ hours of MUSE obtained to map full structure in Lyα emission (observations recently completed).

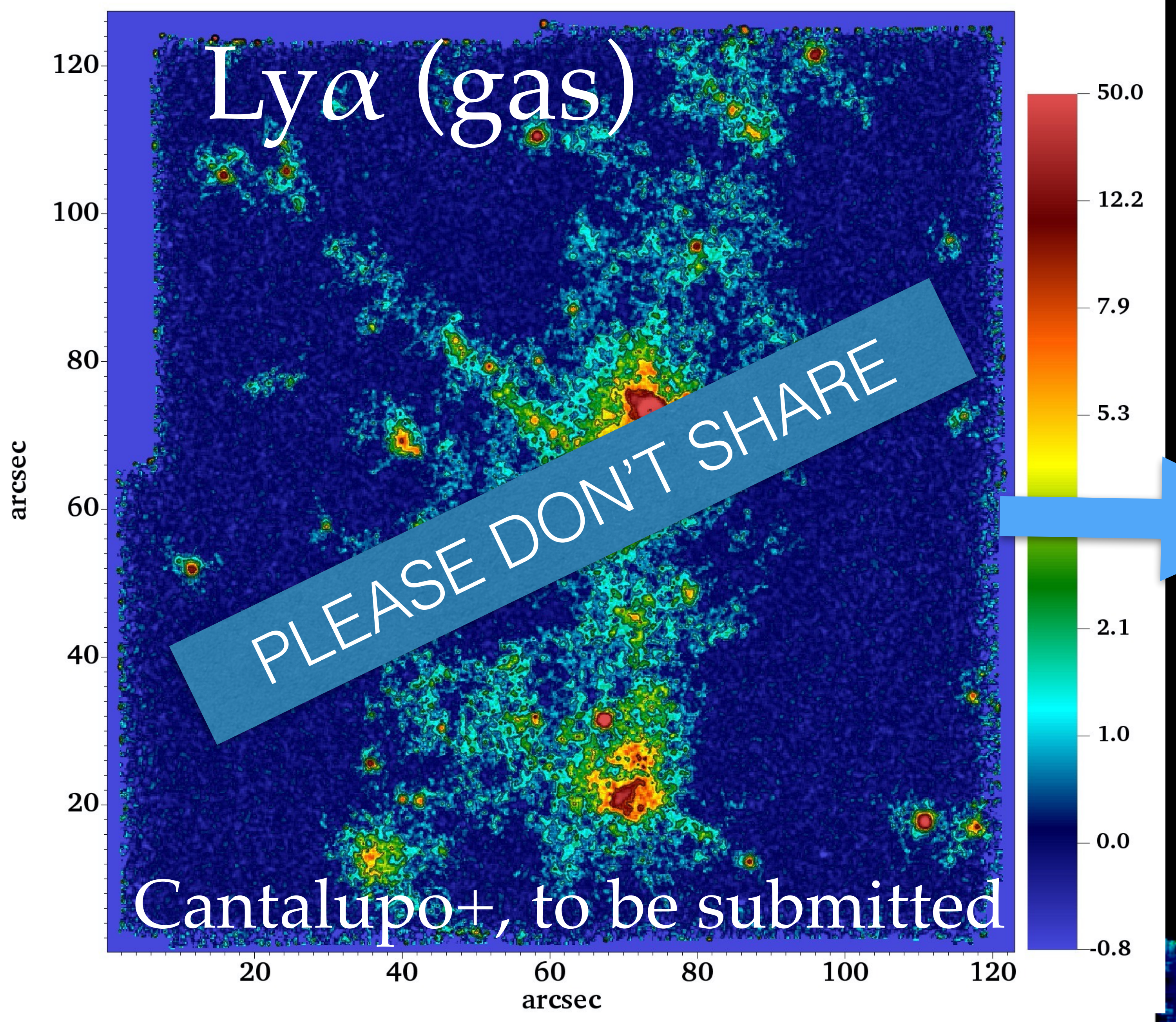
Constraining dark matter properties using clumpiness and morphology of filaments (Lazeyras, SC+, in prep.)

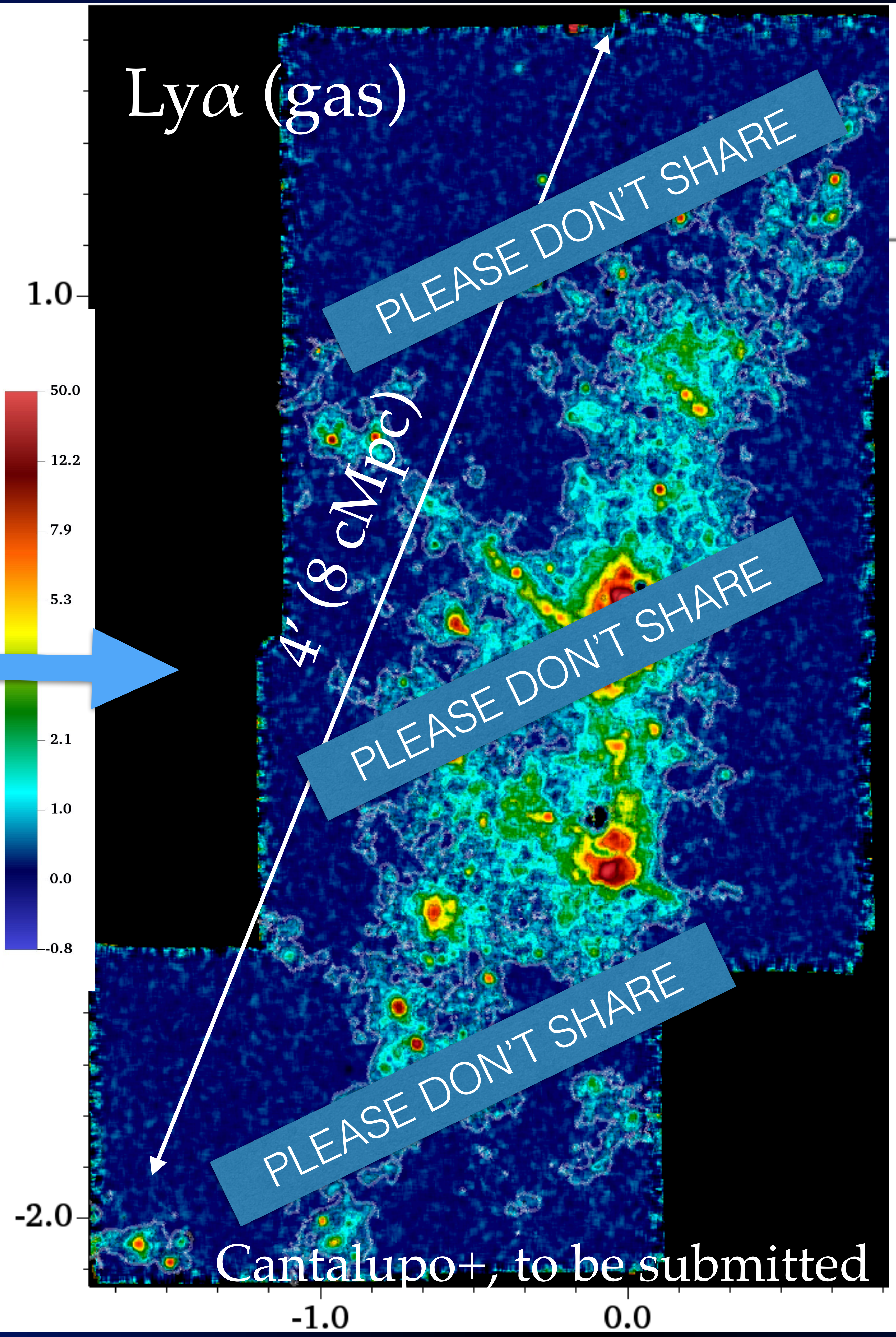


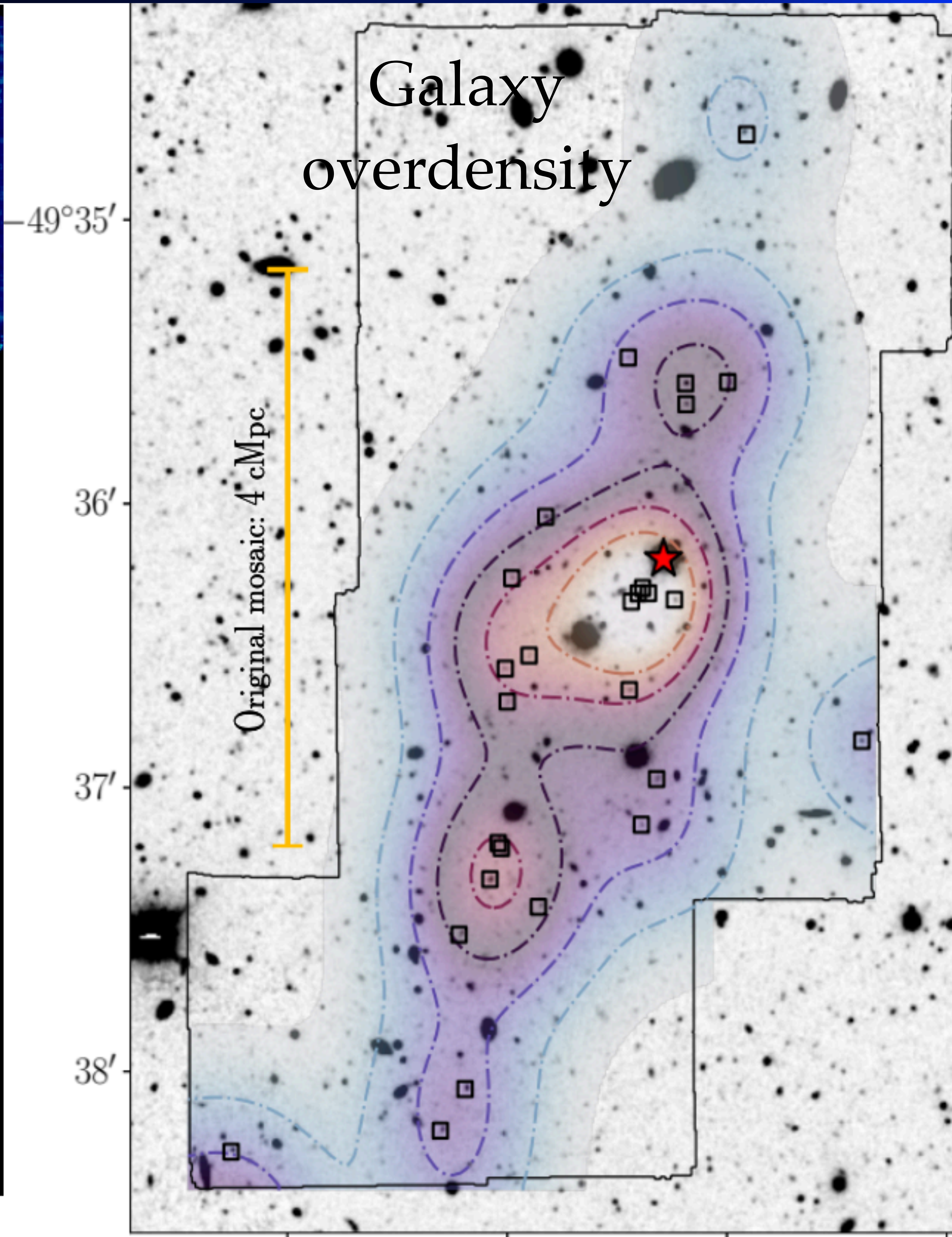


Lazeyras, SC+, in prep.

MQN01: extending the MUSE Mosaic… and doubling the Lyα filament size!







Summary, some open questions and future outlook

- MQN01 is one of the most "over-dense" laboratory found so far to study, all in a single volume, how different physical processes shape the properties of high-z galaxies detected with different tracers

- Galaxy side: many surprises! Including: i) massive super-cold disks, one very close to the QSO, the other (the Big Wheel) as large as local super-spirals; ii) passive galaxy in the middle of a cold gas reservoir (Red Potato); iii) 100% AGN fraction for massive SF galaxies
  What is the role of environment (including filaments seen in emission) on galaxy disks and AGN formation?

- First detection of the CGM hot phase of a massive halo at z>3! X-ray emission brighter than expected from simulations
  Is the difference due to excess of QSO ejective feedback in (some) models or (other) missing physics?

- Finally, the first detection of IGM fluorescent Hα emission, confirming that MQN01 Lyα emission is produced by recombination radiation, suggesting very high densities ($n>1$ cm^{-3}) / clumping factors (>100) even in the IGM
  What is the origin of these high densities? What is their effect on galaxy formation and evolution?

- Next steps, include:
  - new window on galaxy formation and evolution: directly connecting galaxy and filaments properties
  - Resolving the small scale physics of CGM and IGM with JWST (and ERIS)
  - Constraining structure formation and dark matter properties with filaments

Stay tuned!