Illuminating the most massive Cosmic Web Nodes and their relation with galaxies at z~3 with the help of Quasars

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In collaboration with:

CosmicWeb Research Group, including:

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Introduction and Motivation

Detecting the Cosmic Web and CGM in Emission

The MUSE Quasar Nebulae Survey:
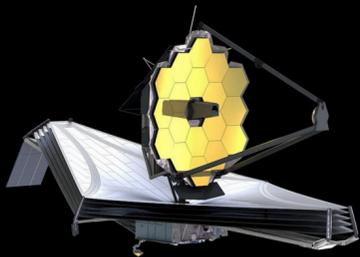Mpc scale filaments and galaxy over densities

The Galaxy-Environment-Cosmic Web connection:
surprises from multi-wavelength observations

Summary and future outlook

The "bright" Universe:
light-dominated view
stars and quasars: ~100%

JADES Collaboration

observations

The "dark" Universe:
mass-dominated view
dark matter: ~ 84%
cosmic gas: ~ 15%
(mostly hydrogen)
stars: ~1%

How do galaxies get their gas?
What are the density, morphology and
temperature of the "Circum Galactic Medium"?
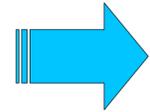
How are galaxies connected to each other ?
What are the morphology and the small scale
properties of the "Cosmic Web" and how
"environment" affects galaxy properties?

S. Cantalupo 2014

simulations

If $M_{vir} >$ few times $10^{11}\,M_\odot$ $(t_{cool} > t_{ff})$:

➡ Stable "hot" halo at T_{vir}
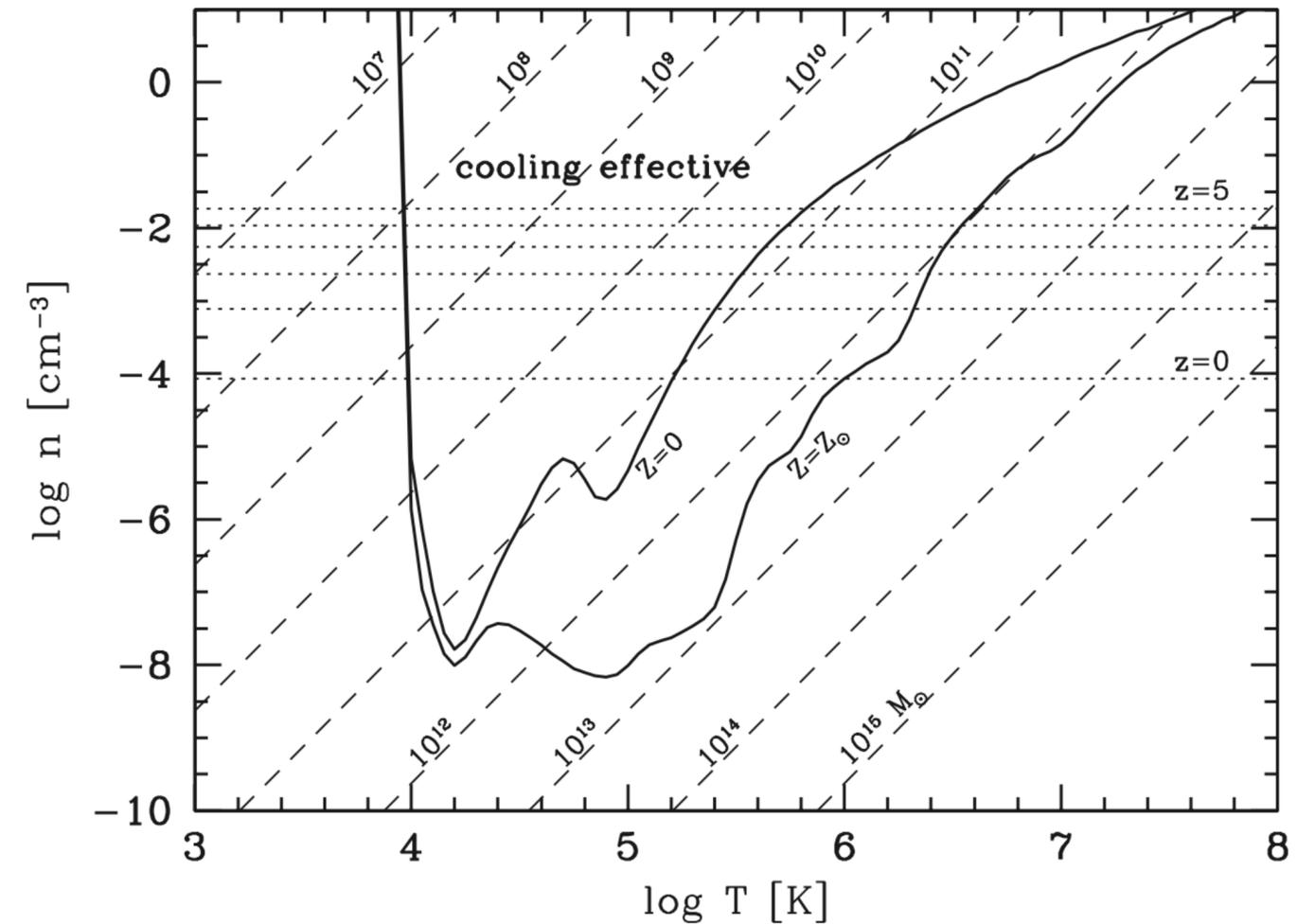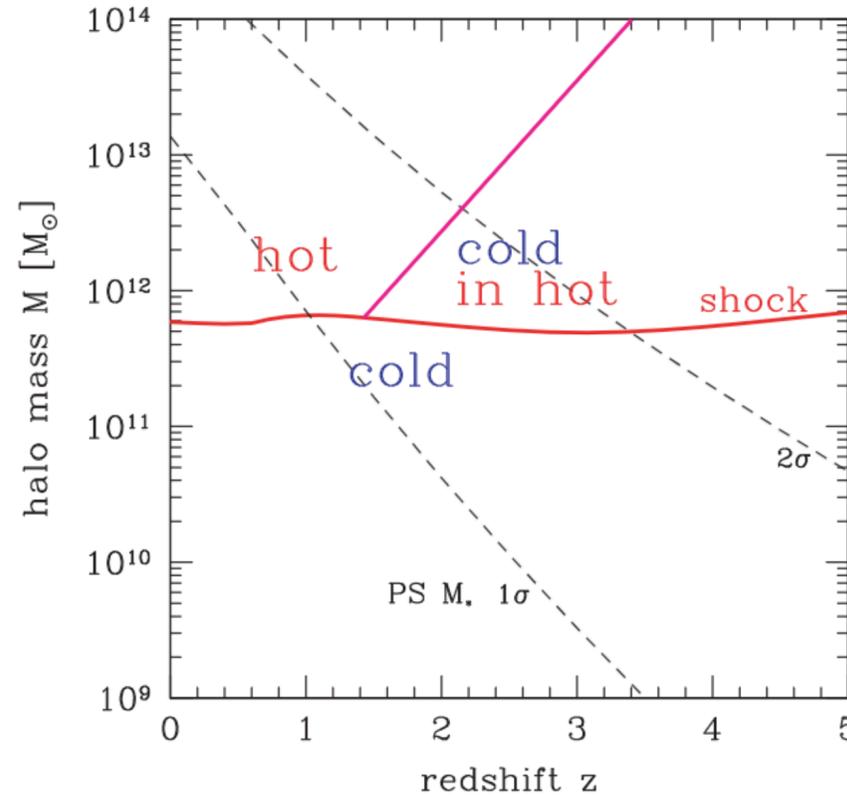
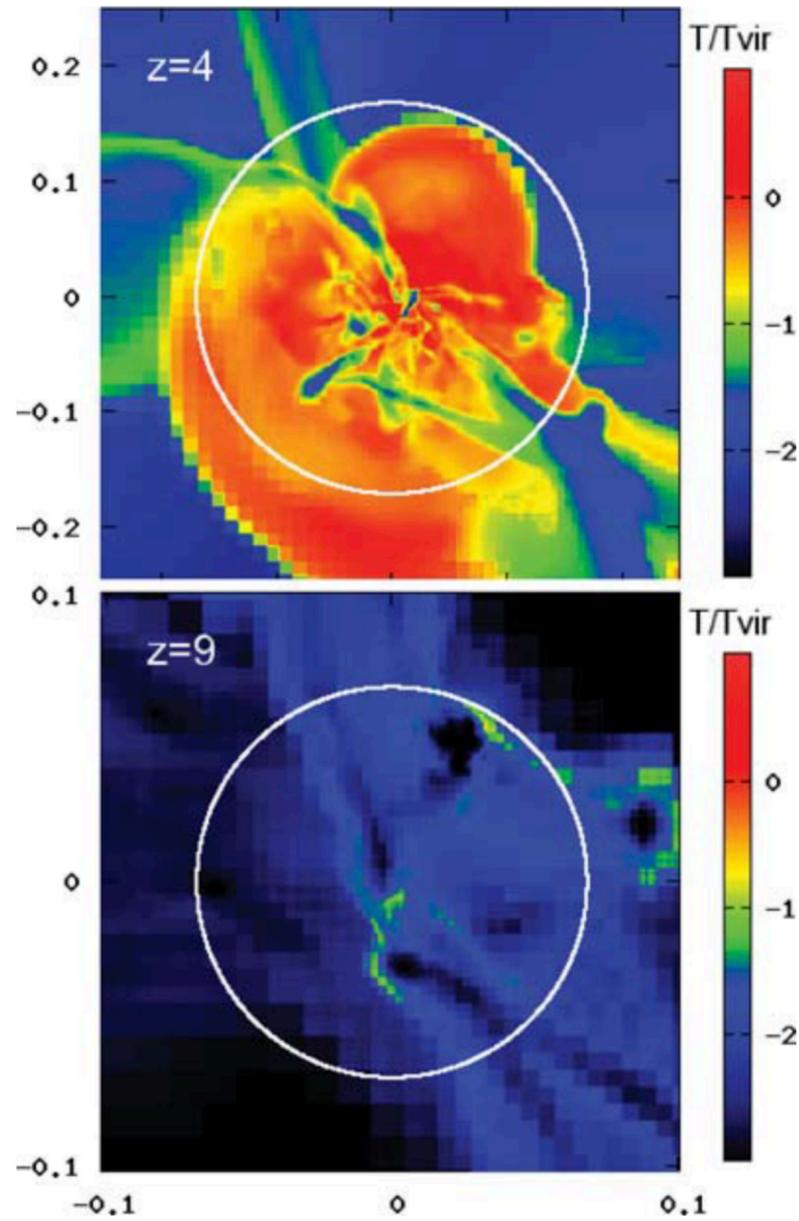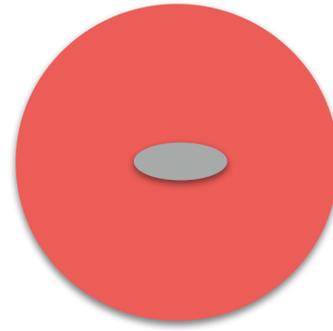Fig. 8.6. Cooling diagram showing the locus of $t_{cool} = t_{ff}$ in the n–T plane. The upper and lower curves correspond to gas with zero and solar metallicity, respectively. The tilted dashed lines are lines of constant gas mass (in $M_\odot$), while the horizontal dotted lines show the gas densities expected for virialized halos ($\delta = 200$) at different redshifts. All calculations assume $f_{gas} = 0.15$ $\Omega_{m,0} = 0.3$, and $h = 0.7$. Cooling is effective for clouds with n and T above the locus.
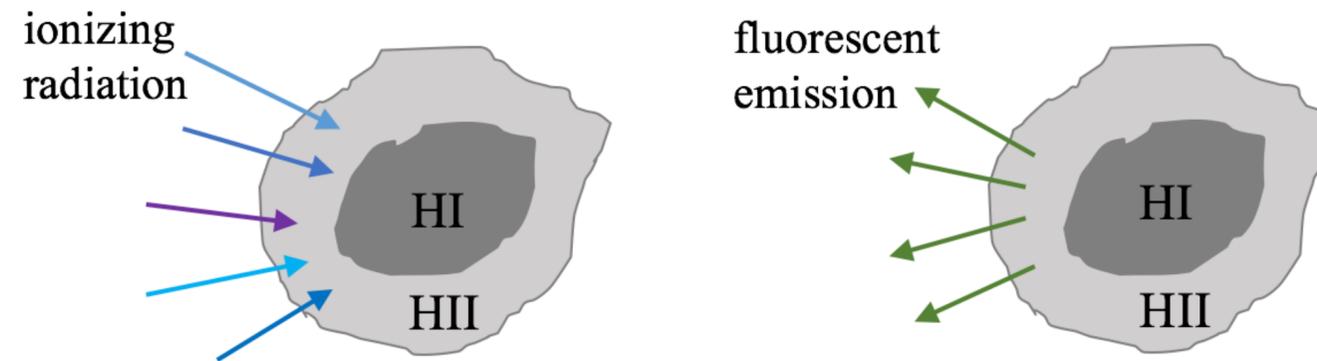
Dekel & Birnboim 2006

Mo, Van Den Bosch & White 2012
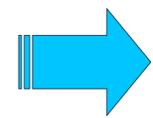
➡ "Cold streams" in hot haloes. Is it really the case?
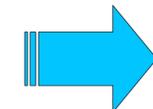
➡ Direct imaging needed!

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; ++*)
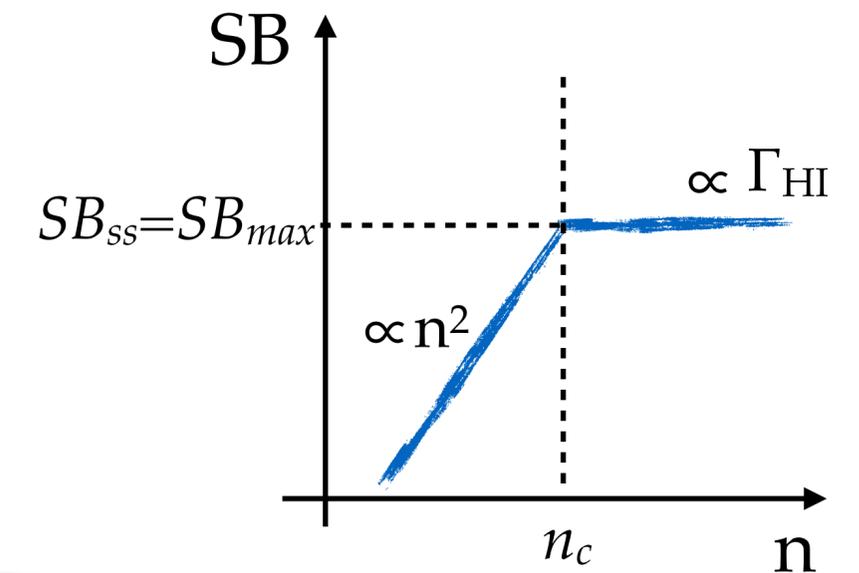

Two main regimes for **recombination radiation**:

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

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

➡ Fully ionized gas: proportional to *cold* (T~10^4 K) gas density squared and gas "clumping factor" C

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

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

n_c ~ 0.1 cm^{-3}

SB_{max}~10^{-20} cgs/arcsec^2

Faint!

In **general**:

Ioinizations - Recombinations

Collisional excitations

Continuum photon-pumping

$$\frac{4\pi j_{\rm Ly\alpha}}{h\nu_{\rm Ly\alpha}} = n_{\rm e} n_{\rm p} \; \alpha_{\rm Ly\alpha}^{\rm eff}(T) + n_{\rm e} n_{\rm HI} \; q_{\rm Ly\alpha}^{\rm eff}(T) + P(I_\nu, n_{\rm HI}, T)$$

Complicated!

ionized gas → partially ionized → neutral gas

How to solve both problems?
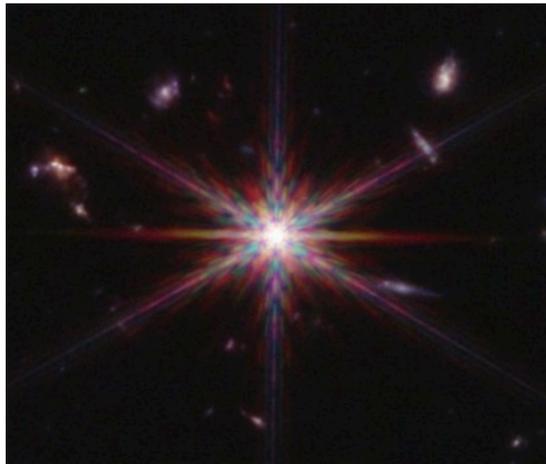
$\Gamma_{UVB} \sim 10^{-12}$ s^{-1}

$\Gamma_{QSO} \sim 10^{-6}$ s^{-1} at r=30 kpc from a bright z~3 QSO
(but everything else works as long as $\Gamma \gg \Gamma_{UVB}$!)
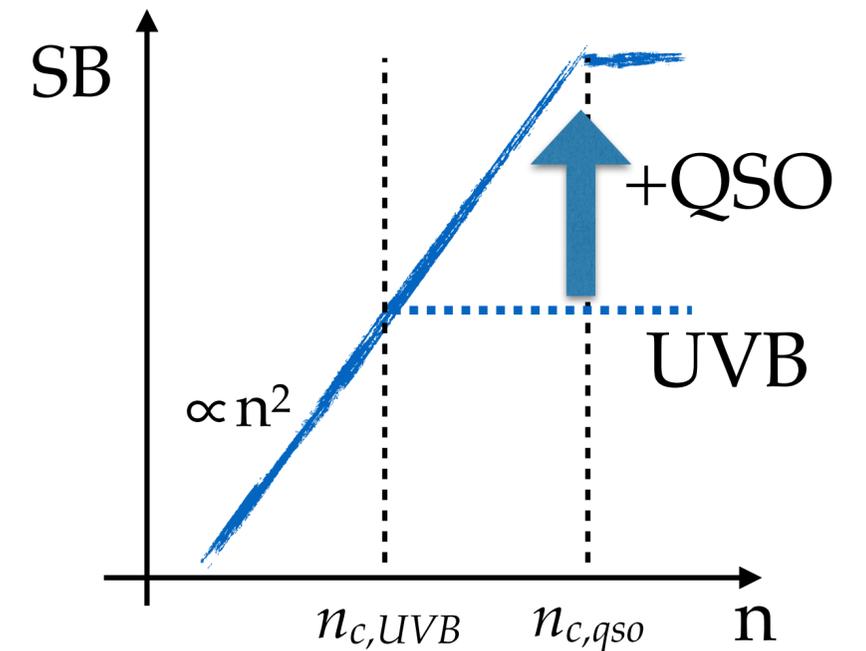
Hydrogen safely ionised for any reasonable density (n $\ll 10^5$ cm^{-3})!

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):

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

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

SB

$\propto n^2$

+QSO

UVB

$n_{c,UVB}$ $n_{c,qso}$ n

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

~1.5 cMpc

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)

$SB_{Ly\,\alpha}$ (10^{-18} erg s^{-1} cm^{-2} arcsec^{-2})
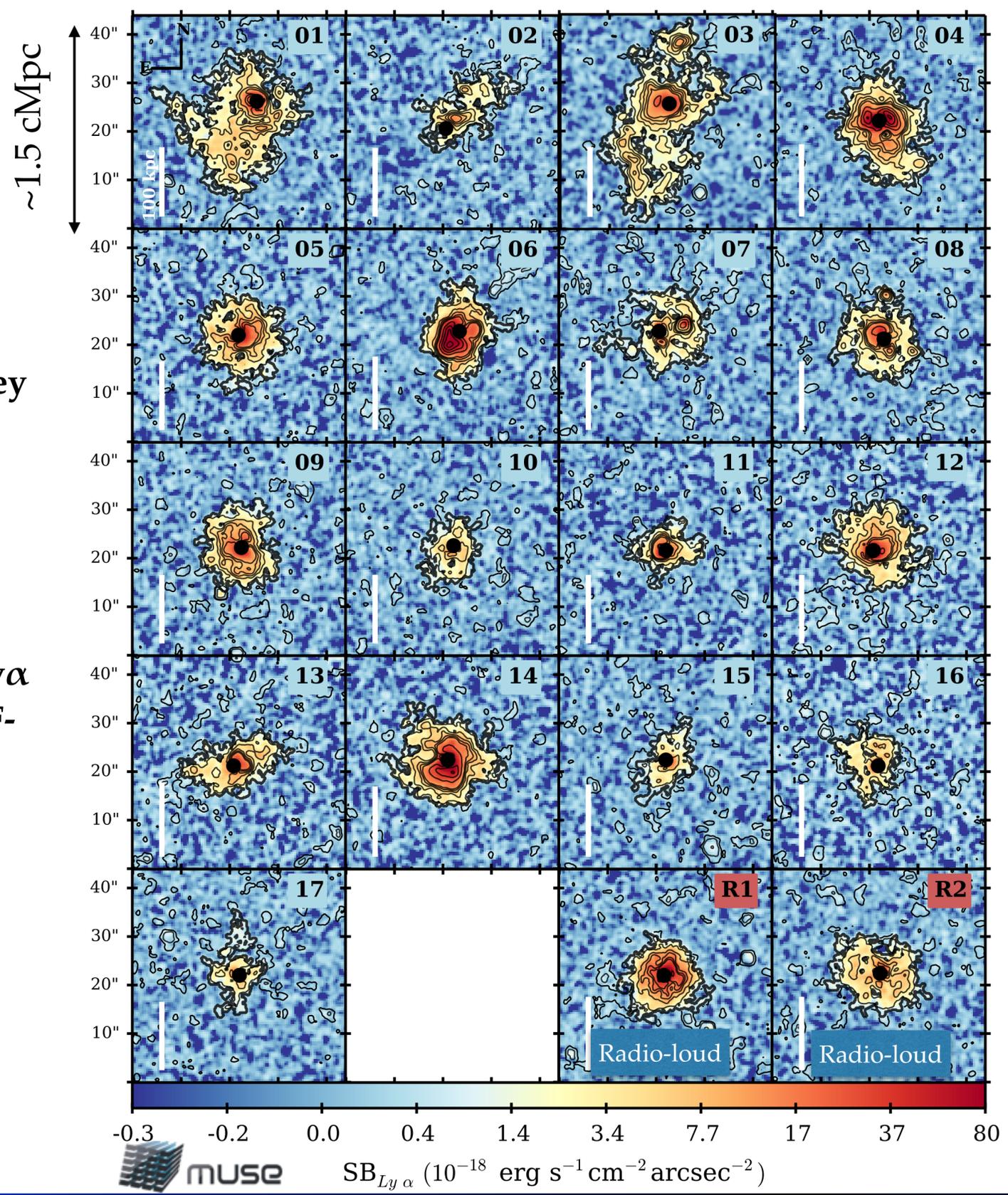
More than 200 giant quasar nebulae discovered so far at 2<z<6.5 with MUSE & KCWI:

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

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

Borisova, SC+, 2016

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

CubExtractor (SC+19) + VisIt
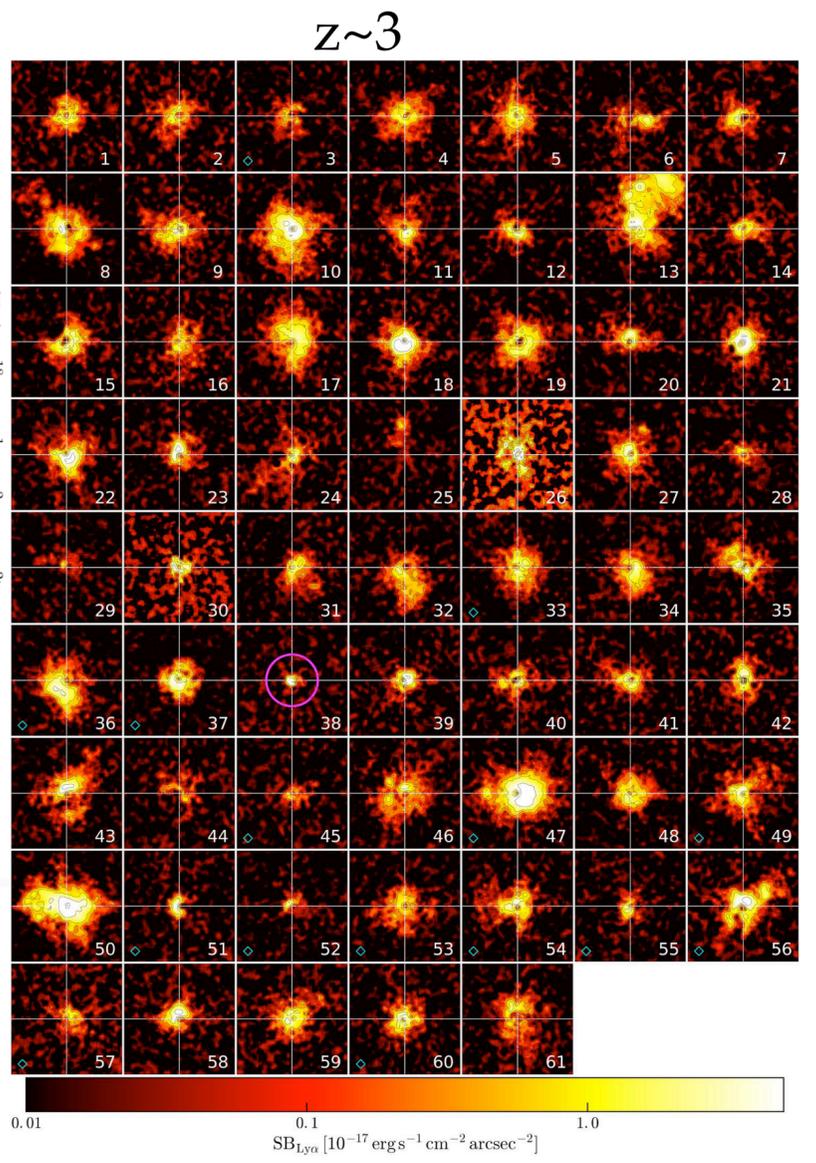QSO PSF and continuum subtracted cube
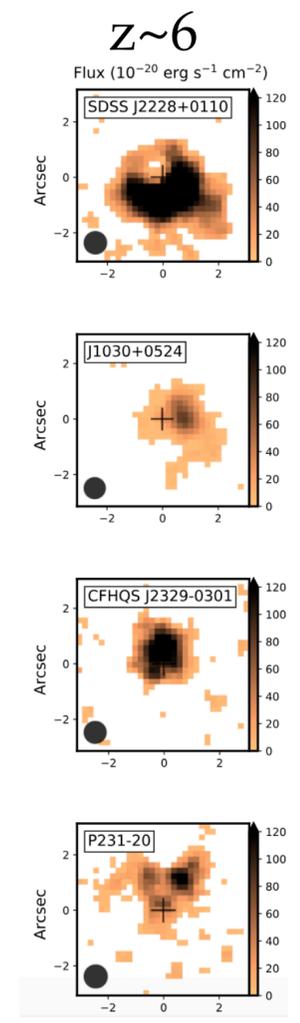
Borisova, SC+, 2016
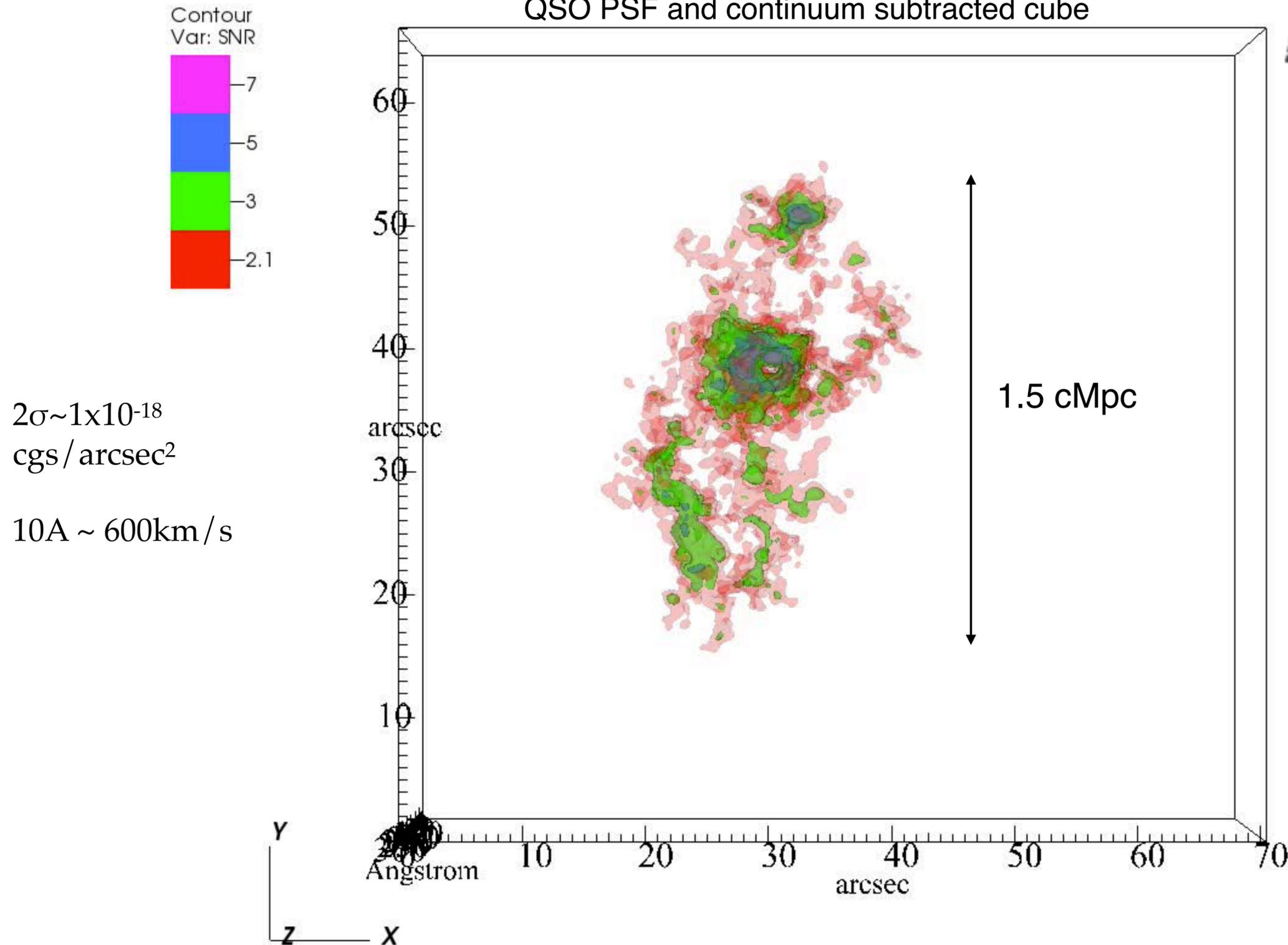
Contour
Var: SNR

7
5
3
2.1

arcsec

1.5 cMpc

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

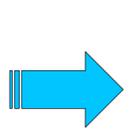$10A \sim 600 km/s$

Y

Angstrom

10   20   30   40   50   60   70
arcsec

Z — X

z~2

z~3

z~6
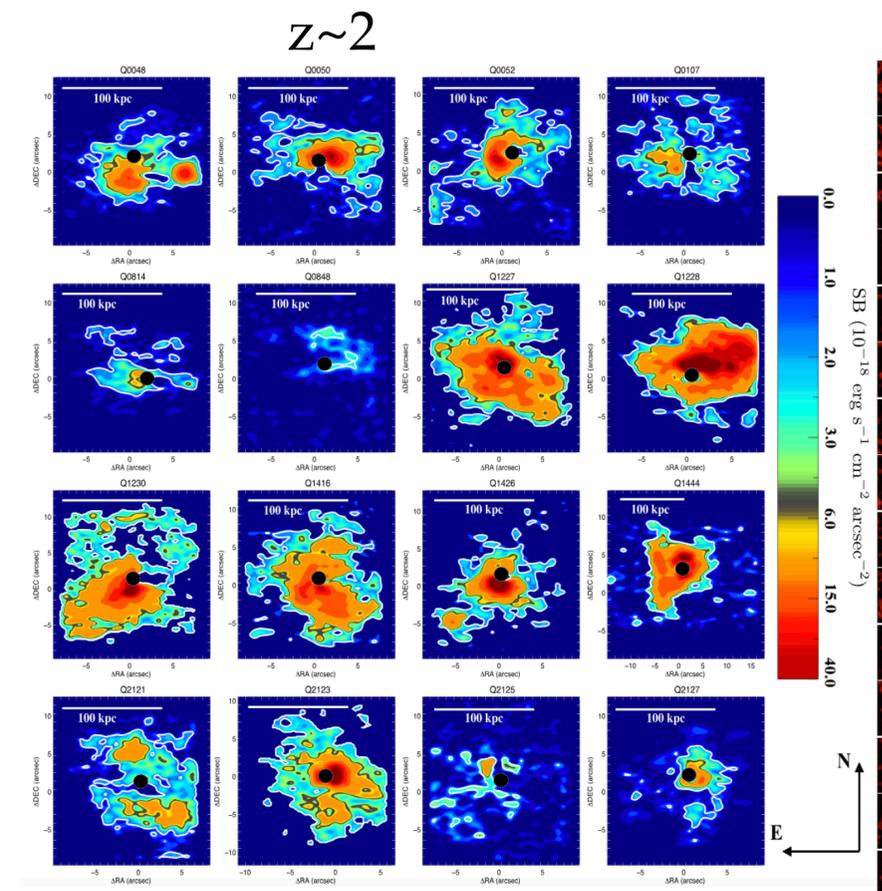
Cai,SC+19

Arrigoni-Battaia+19

Drake+19

Fossati+21
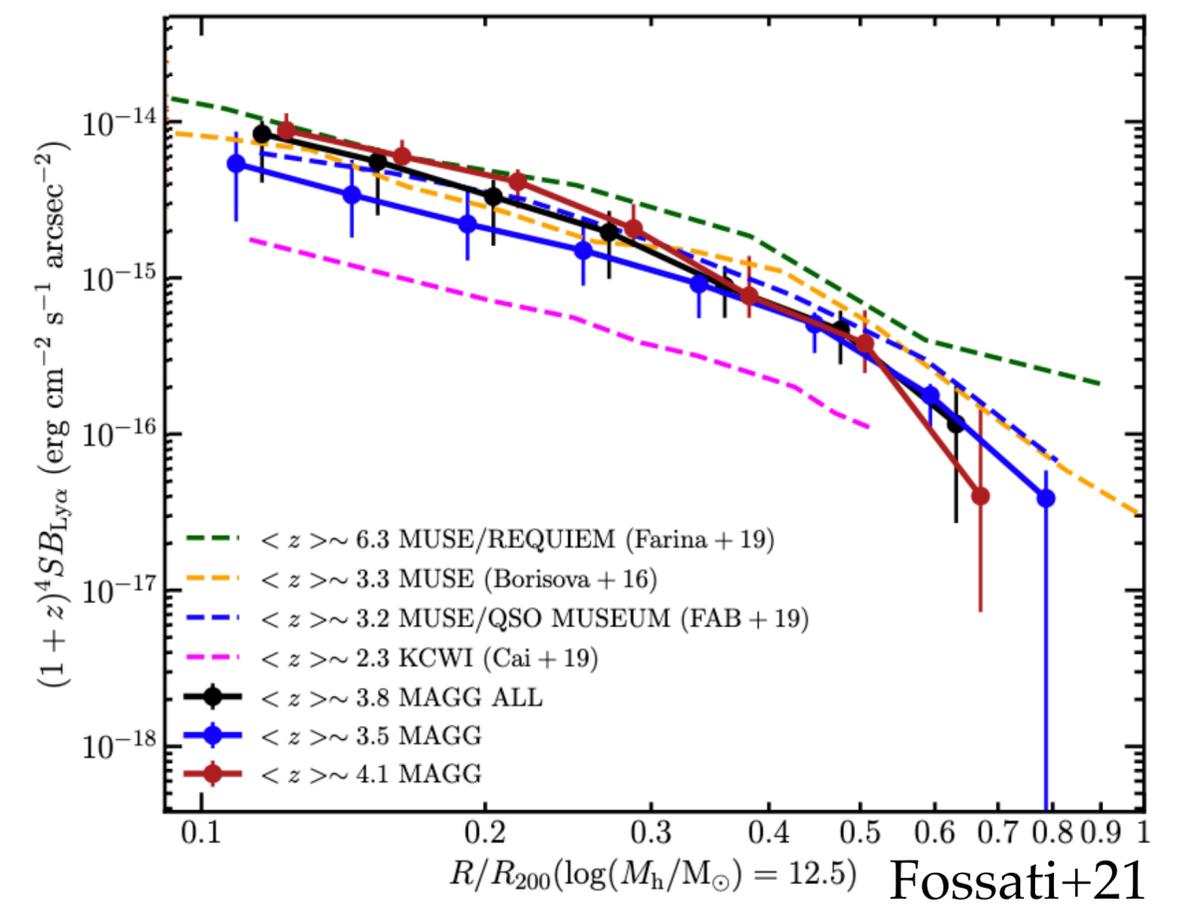
High densities (>0.1-1 cm^{-3}) and high clumping factors required if Lyα produced by recombination radiation for typical quasar host haloes of ~10^{12} M$_\odot$ (from clustering and kinematics, e.g. De Beer+23, Eftekharzadeh+15, Trainor & Steidel 2013) . Non-resonant lines (e.g., H-Hα) needed to confirm it!
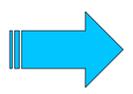
H-Hα only observable at z=2.3 from ground (z~3 requires JWST, see later), otherwise we must use He$^+$-Hα (HeII1640)

Multiple (non-resonant) emission lines with different n_c needed: observing the Slug Nebula at z~2.3 in Hydrogen Hα (infrared) and HeII-Hα (optical, with MUSE)
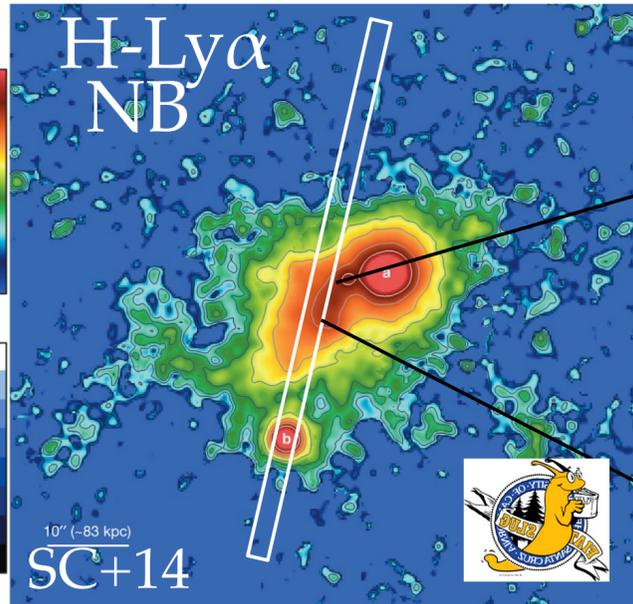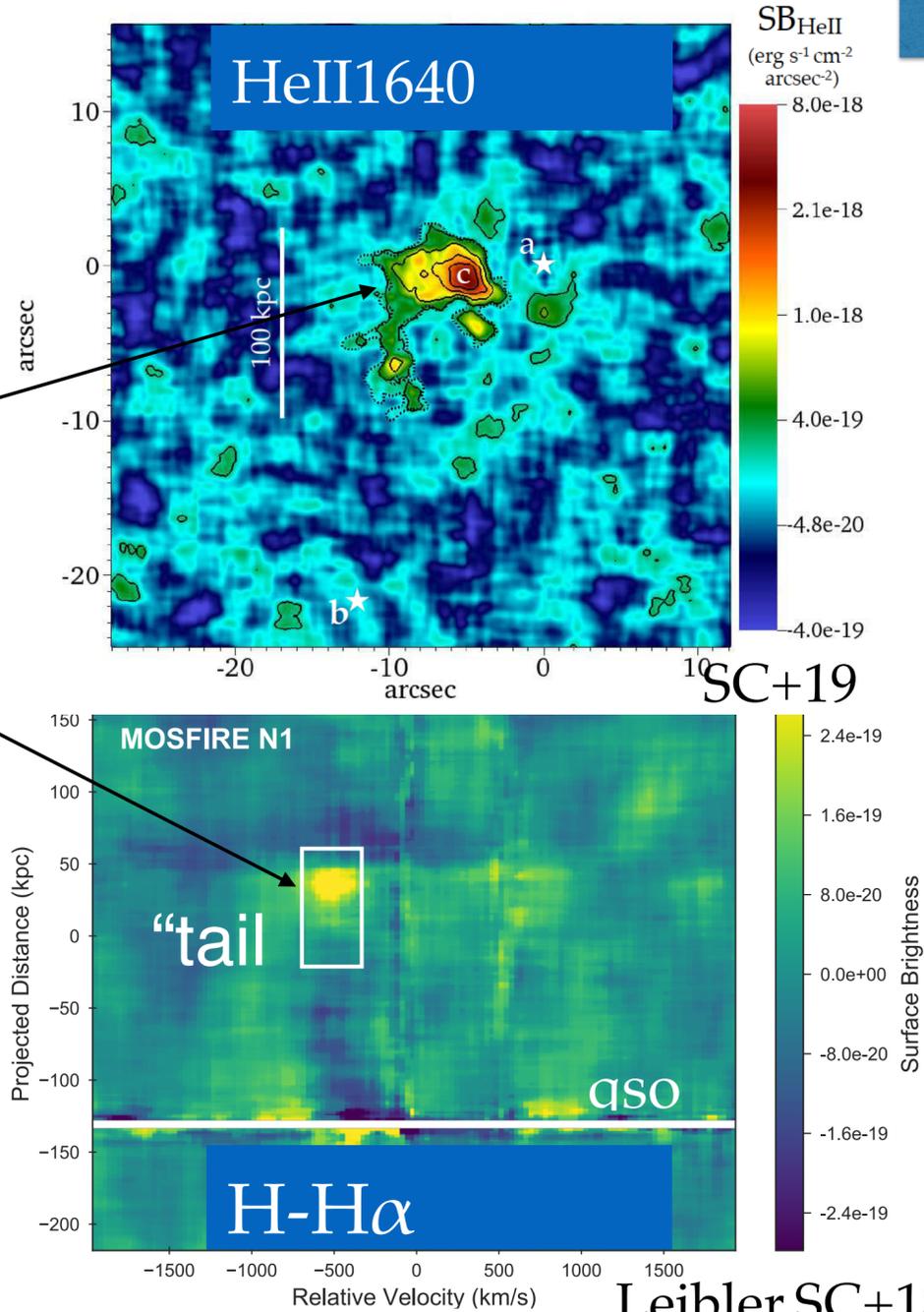
Very low HeII/Lyα ratio (<0.08 instead of exp. 0.3)! Cannot be explained by single-density photo-ionisation models!

H-Lyα NB

SC+14

Lyα/Hα ~ 5-8 consistent with recombination radiation

HeII1640

SB_{HeII} (erg s^{-1} cm^{-2} arcsec^{-2})

100 kpc

SC+19

MOSFIRE N1

"tail

qso

H-Hα

Leibler,SC+18

"region c"
"bright tail"

r=270kpc

σ

r=900kpc

<n>=0.10 cm^{-3}
<n>=0.05 cm^{-3}
<n>=0.02 cm^{-3}

$SB_{Ly\alpha}$ (erg s^{-1} cm^{-2} arcsec^{-2})

Log-normal density distribution

NB: Clumping factor is related to σ by C=exp(σ²)
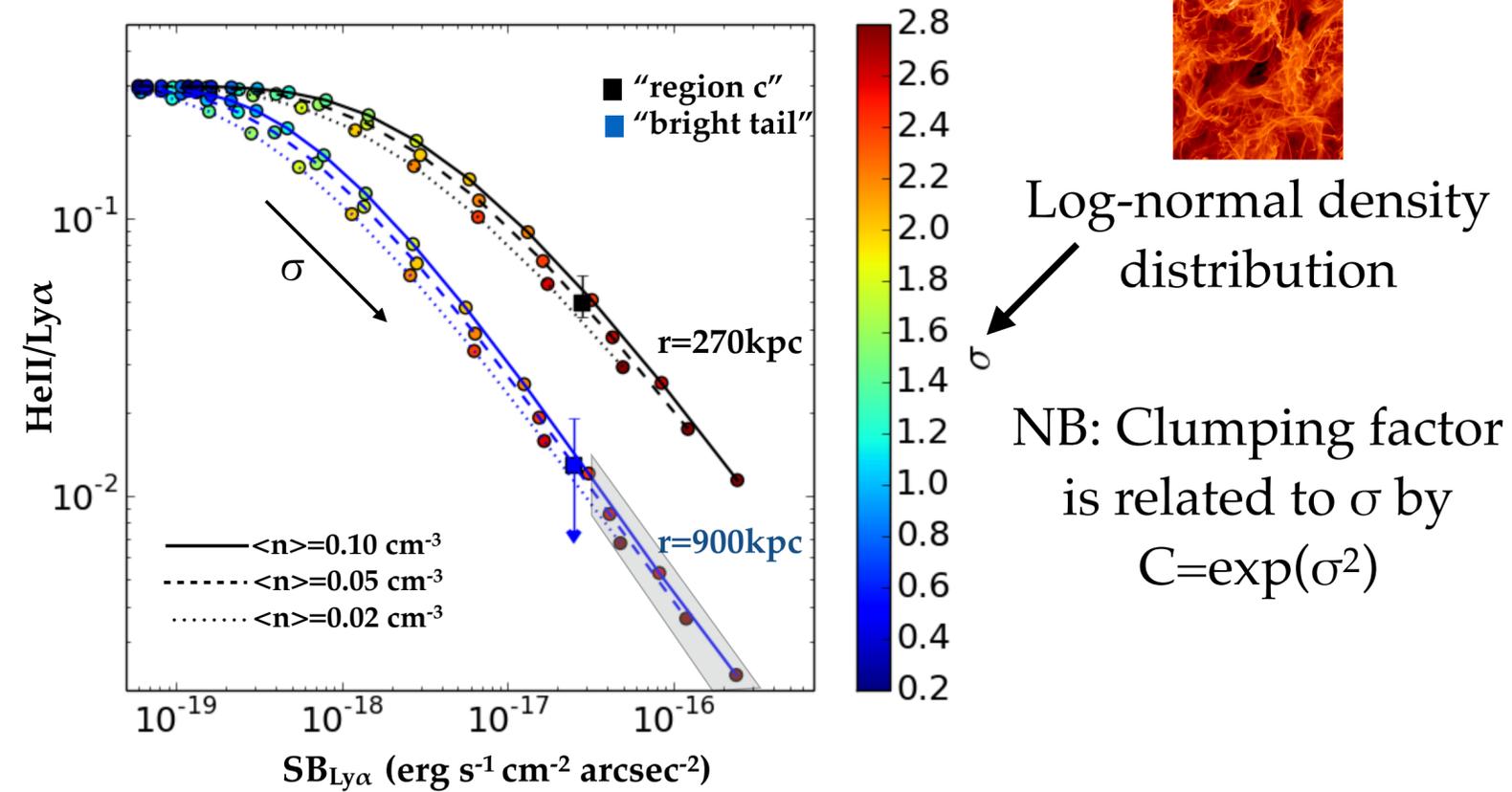
Consistent with broad density distribution / turbulent CGM if **log-normal σ >2.5 (C>500)** —> as large as the ISM (!)   **How common is that?**

SC+19

16 over 28 nebulae detected in HeII1640 (MAGG Sample, 5-10h)!

Photo-ionisation models with log-normal PDF

$SB_{HeII}/SB_{Ly\alpha}$

10^{-1}

Observations

σ

10^0 10^1

HeII   Lyα   HeII   Lyα   HeII   Lyα   HeII   Lyα
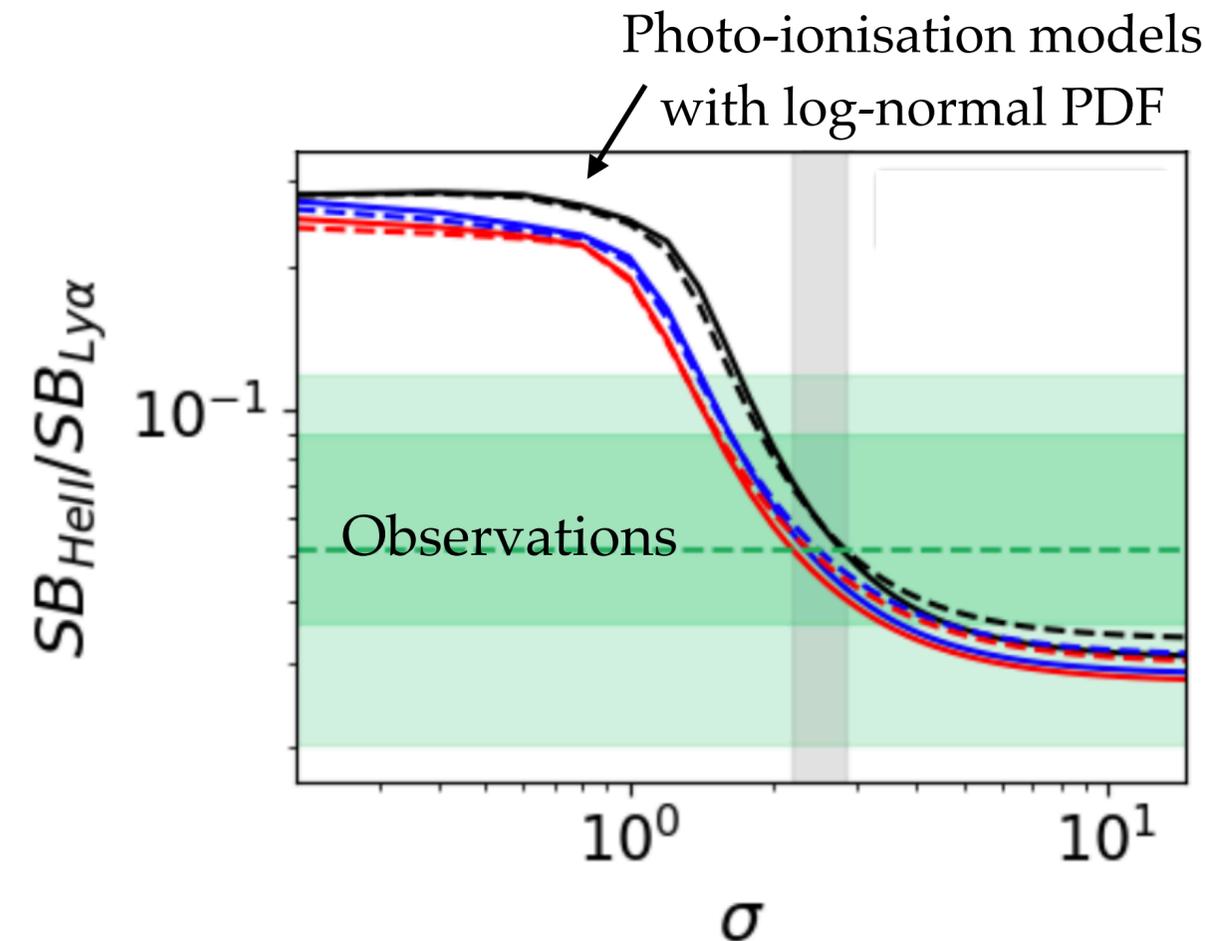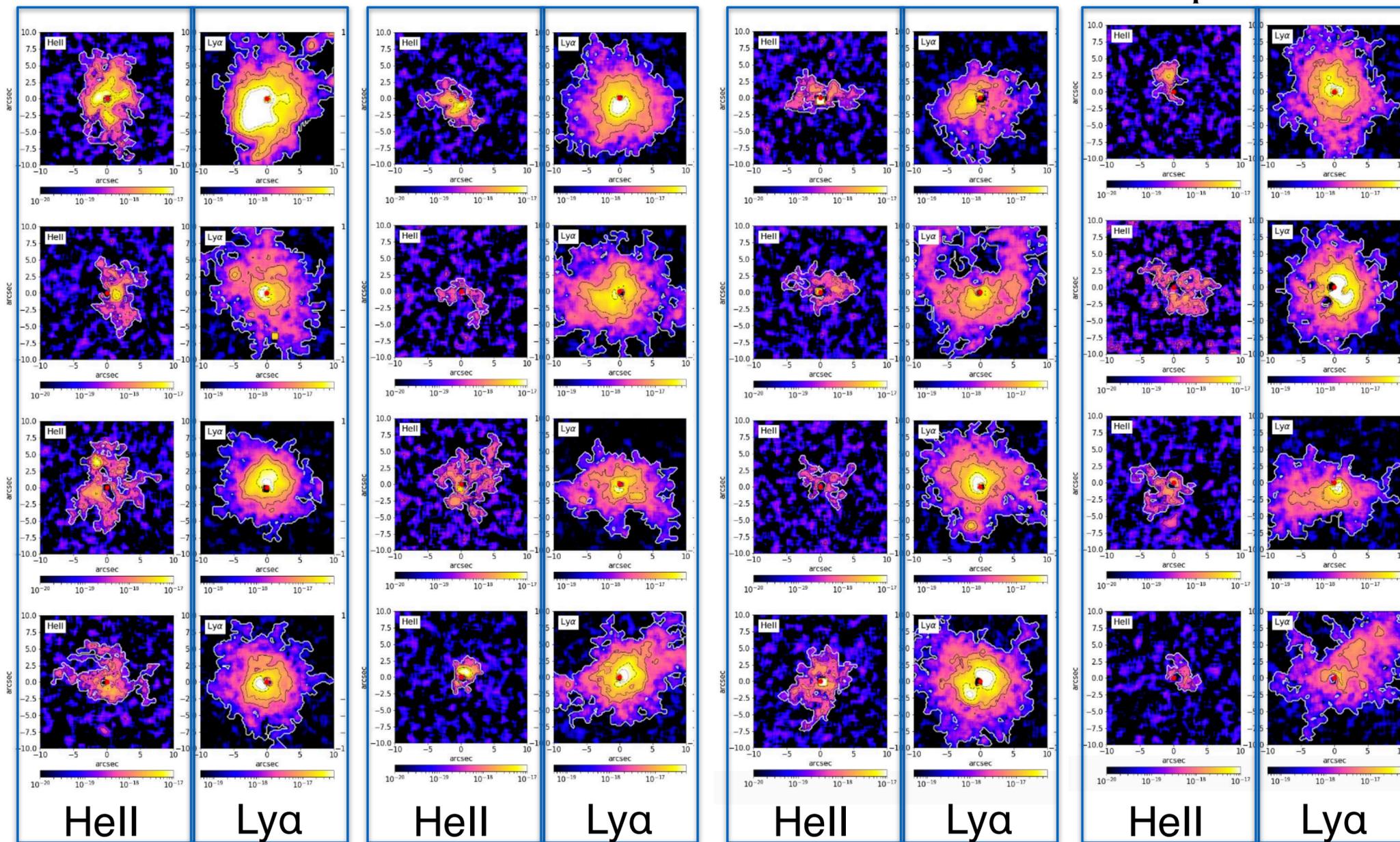
➤ Large σ and clumping factor requirement confirmed (e.g., σ>2.5) for a statistical sample (assuming Lyα recombination radiation)

➤ Similar velocity dispersion profiles between HeII and Lyα —> Lyα can be used for kinematics!

➤ Hα needed to break degeneracy with emission mechanism

Travascio, SC+, in prep.

A double Hα (H+He⁺) ongoing survey around bright QSOs with KCWI and MOSFIRE at z~2.2
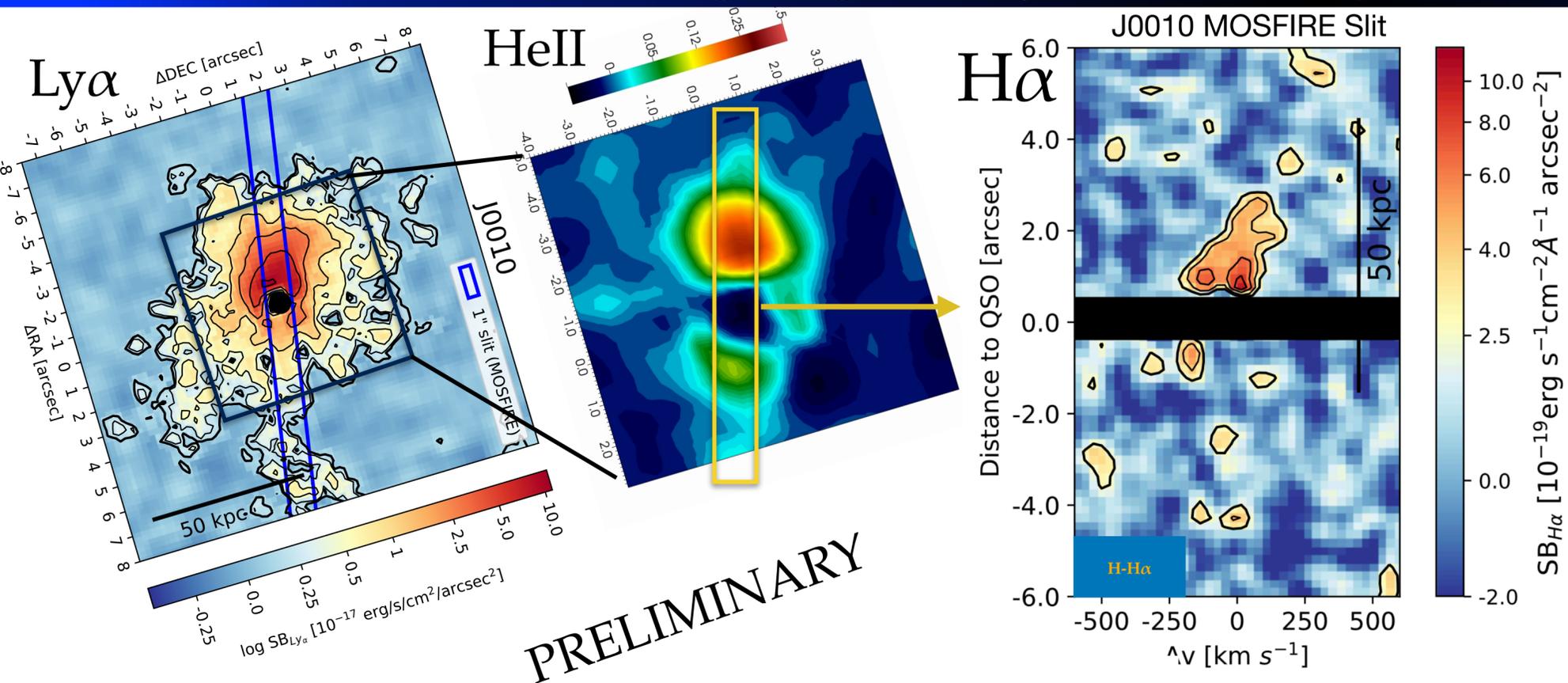
~10 quasar nebulae (5 observed so far), 2+ hours per field with KCWI

HeII1640 and Hα always detected (so far)

Lyα/Hα consistent with recombination

HeII1640/Hα~0.5 implying (again):

σ>2.5 or C>500

PRELIMINARY
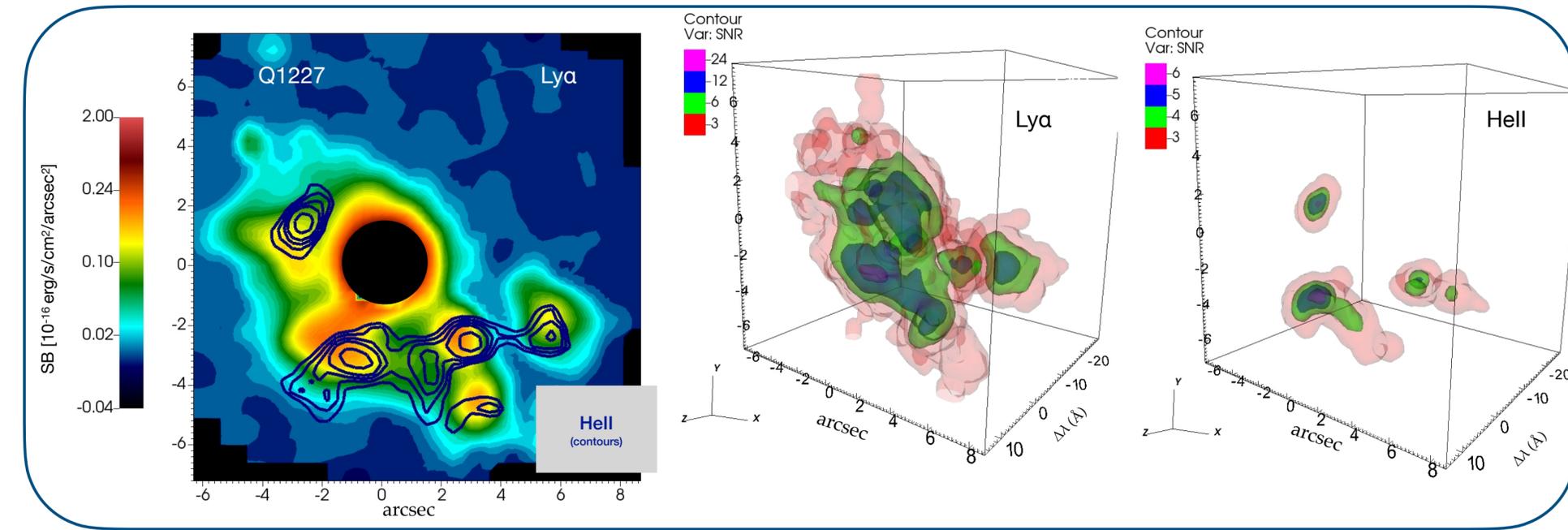
Travascio, SC+, in prep. (see also: Langen, SC+2023)

A 3D view of the Cosmic Web

CubEx optimally extracted Lyα image
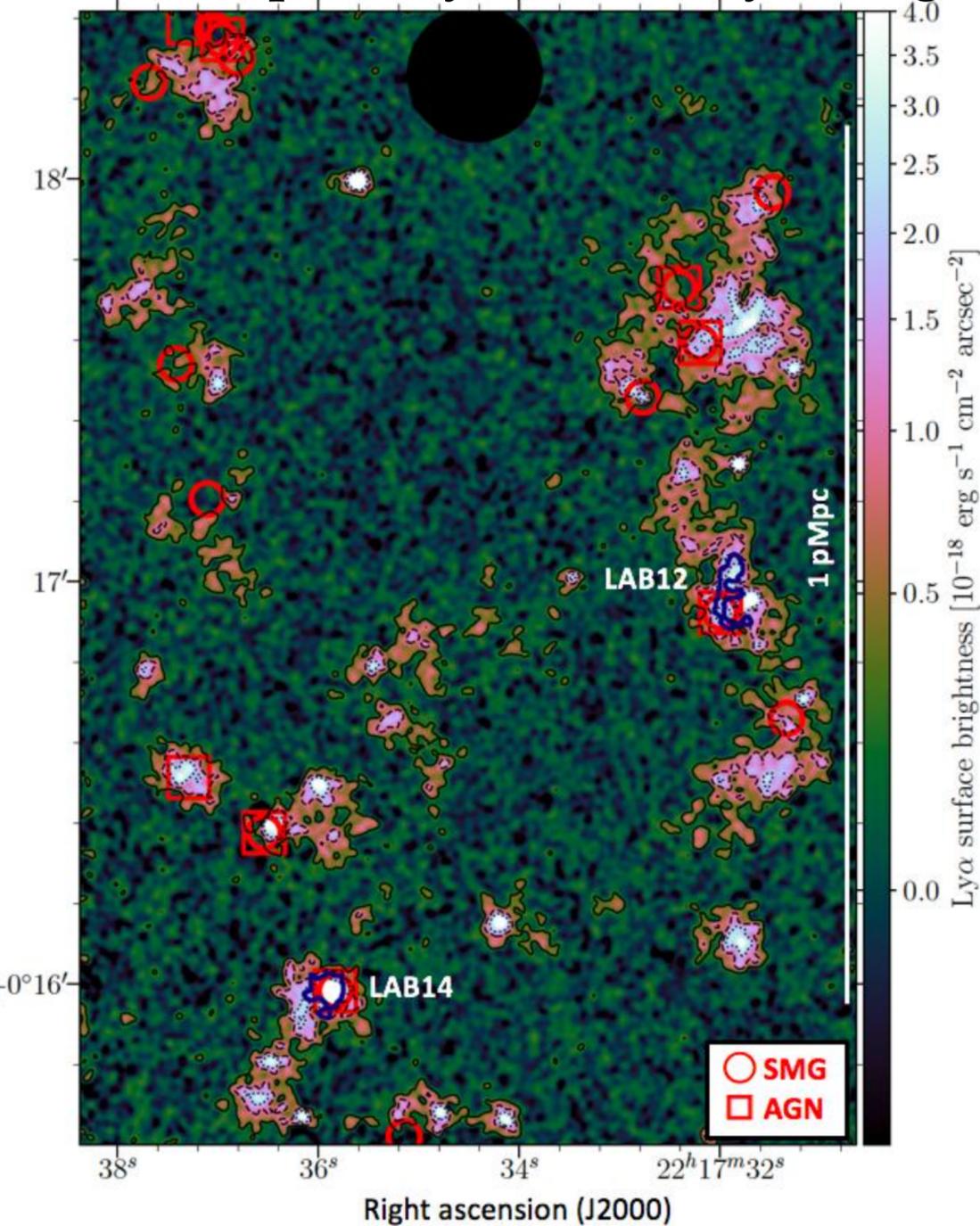
Umehata+2019, Science

CubEx 3D Lyα emission distribution
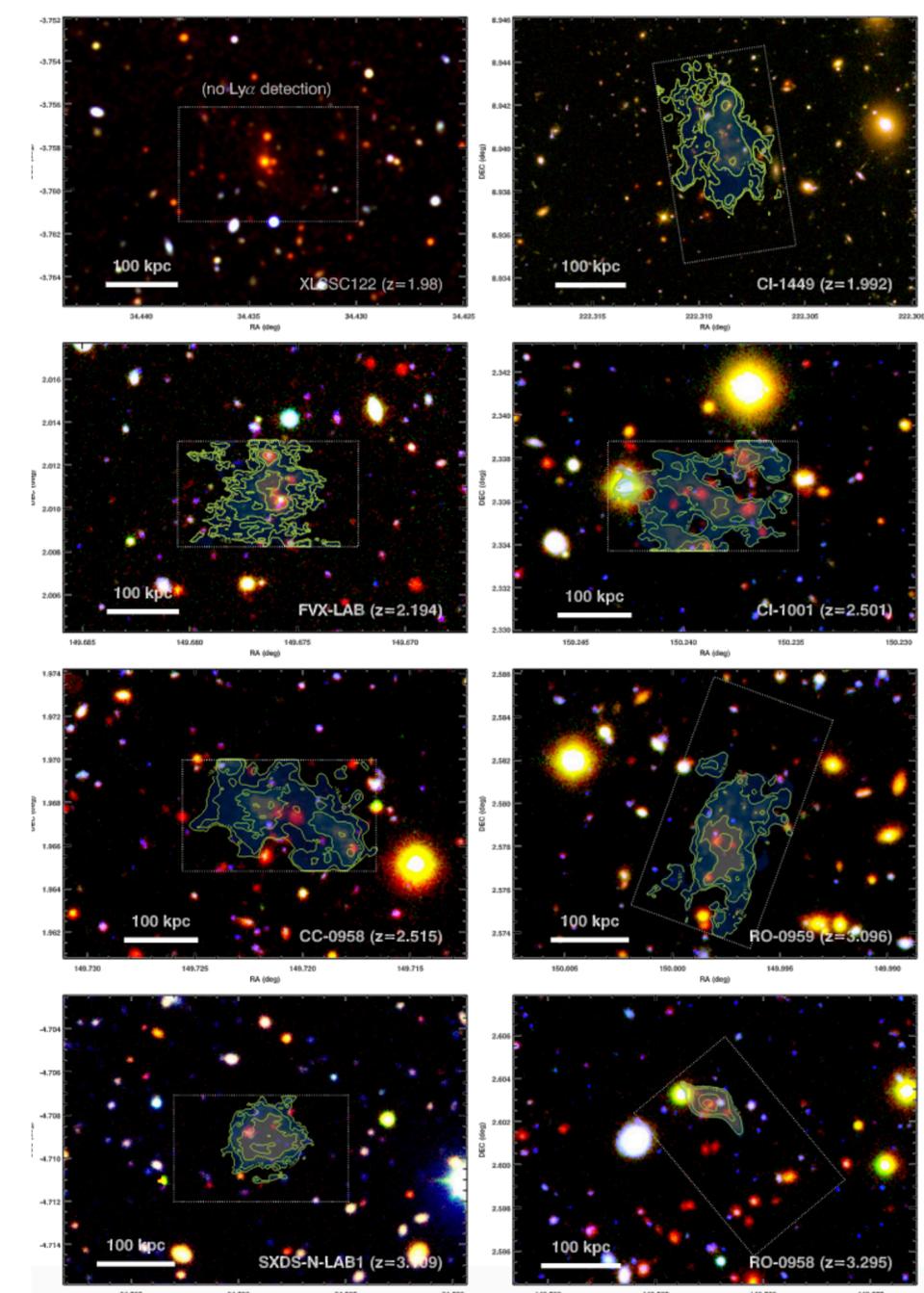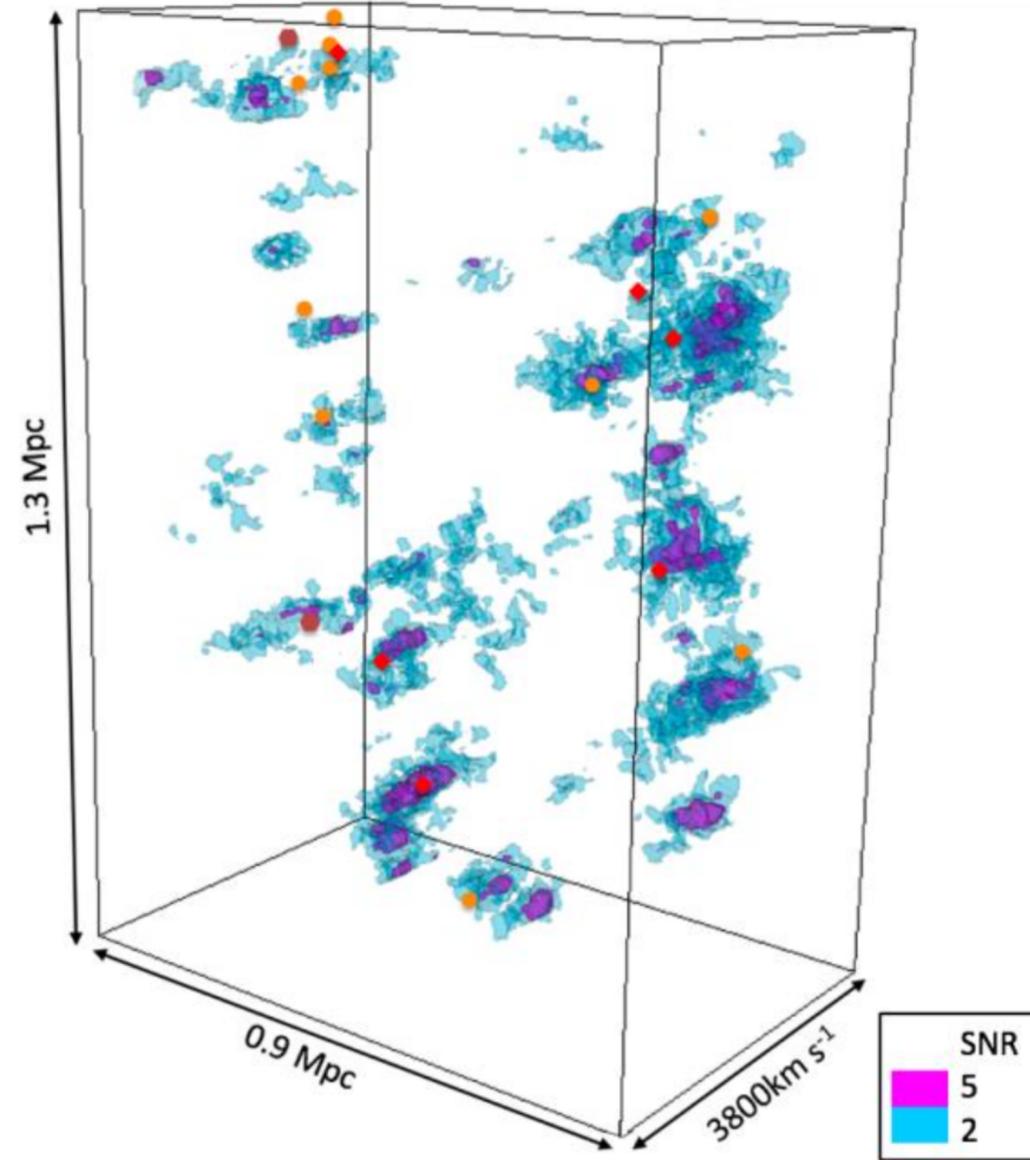
Galaxy groups (Daddi+2022)

Overdensity of galaxies + bright quasar / AGN are likely needed… let's explore again the MQN sample

data from multiple recent runs (1x3 mosaic: 15h-deep in the center):
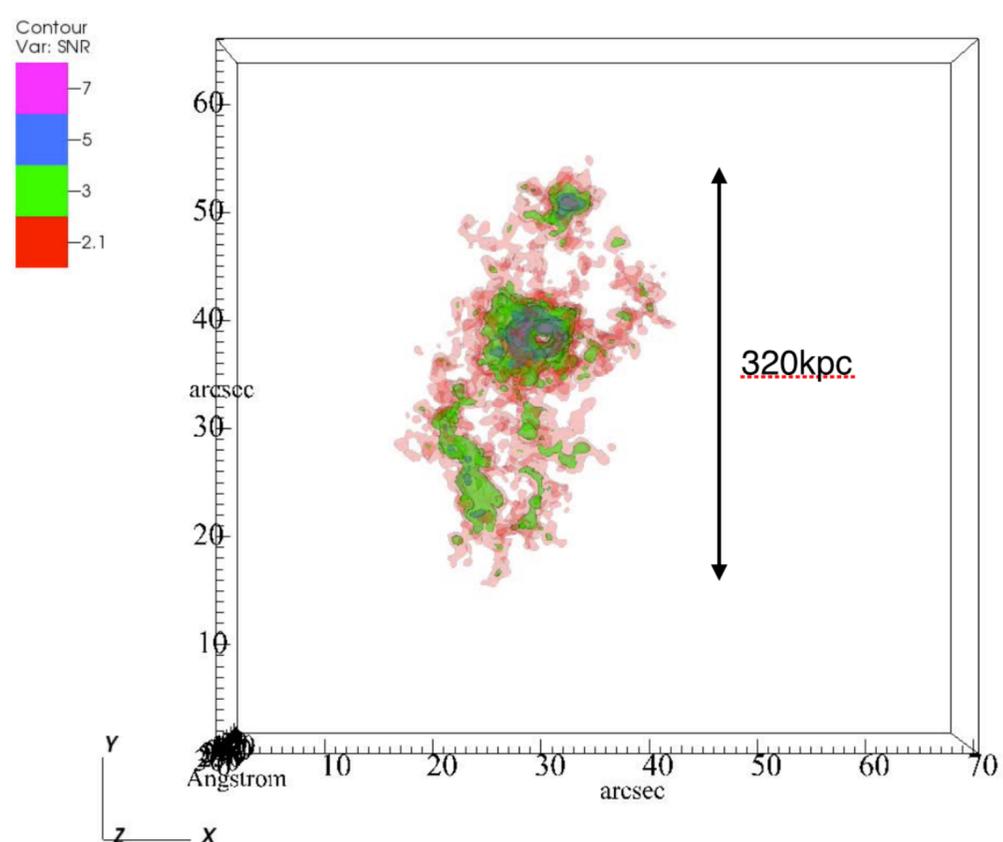
previous 1h-deep snapshot
(single pointing)
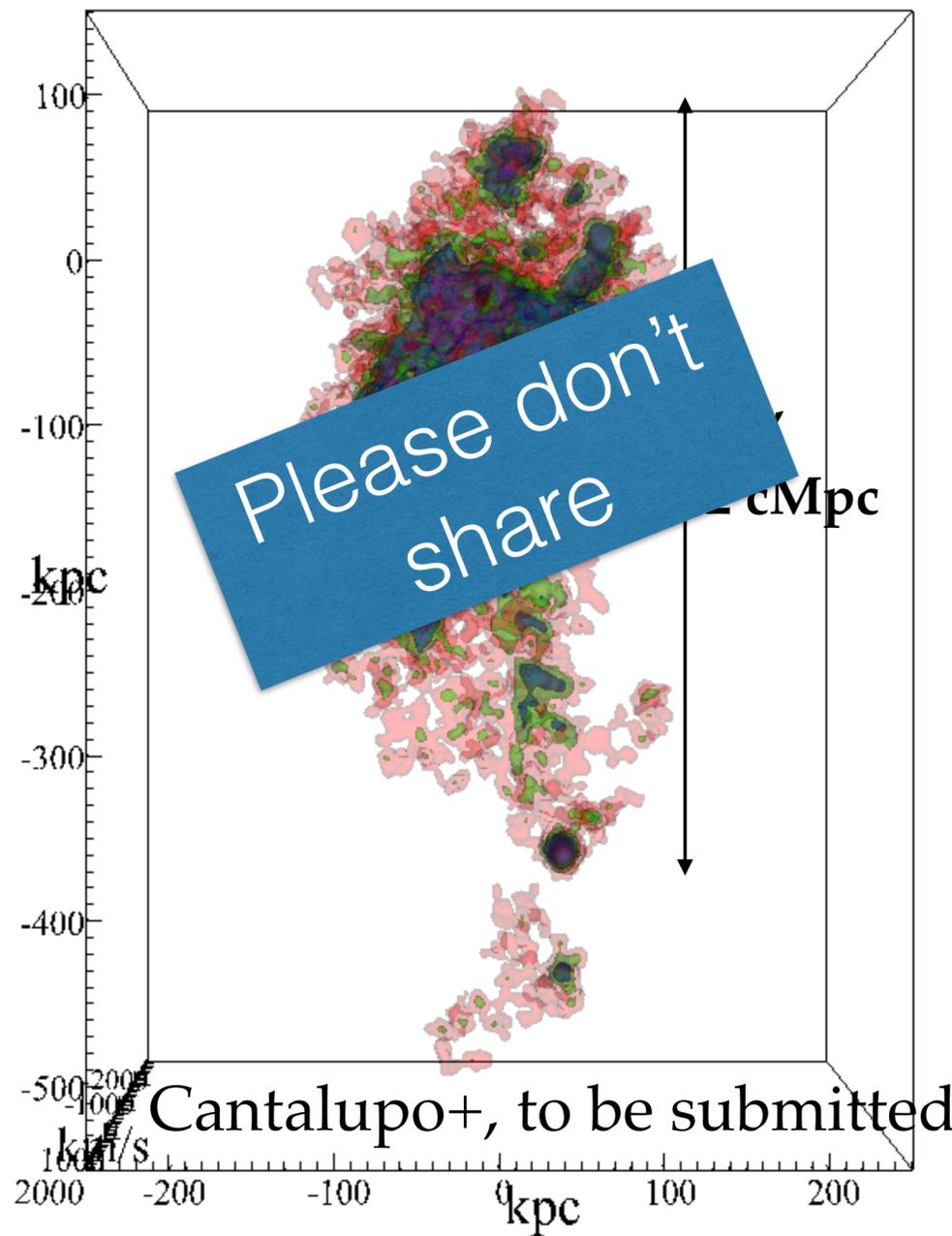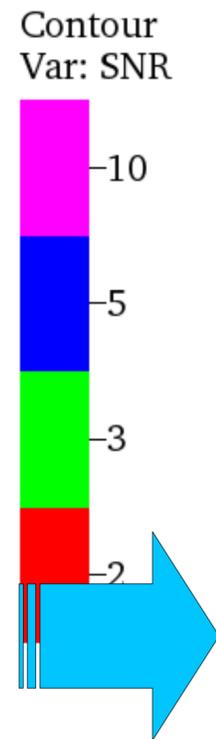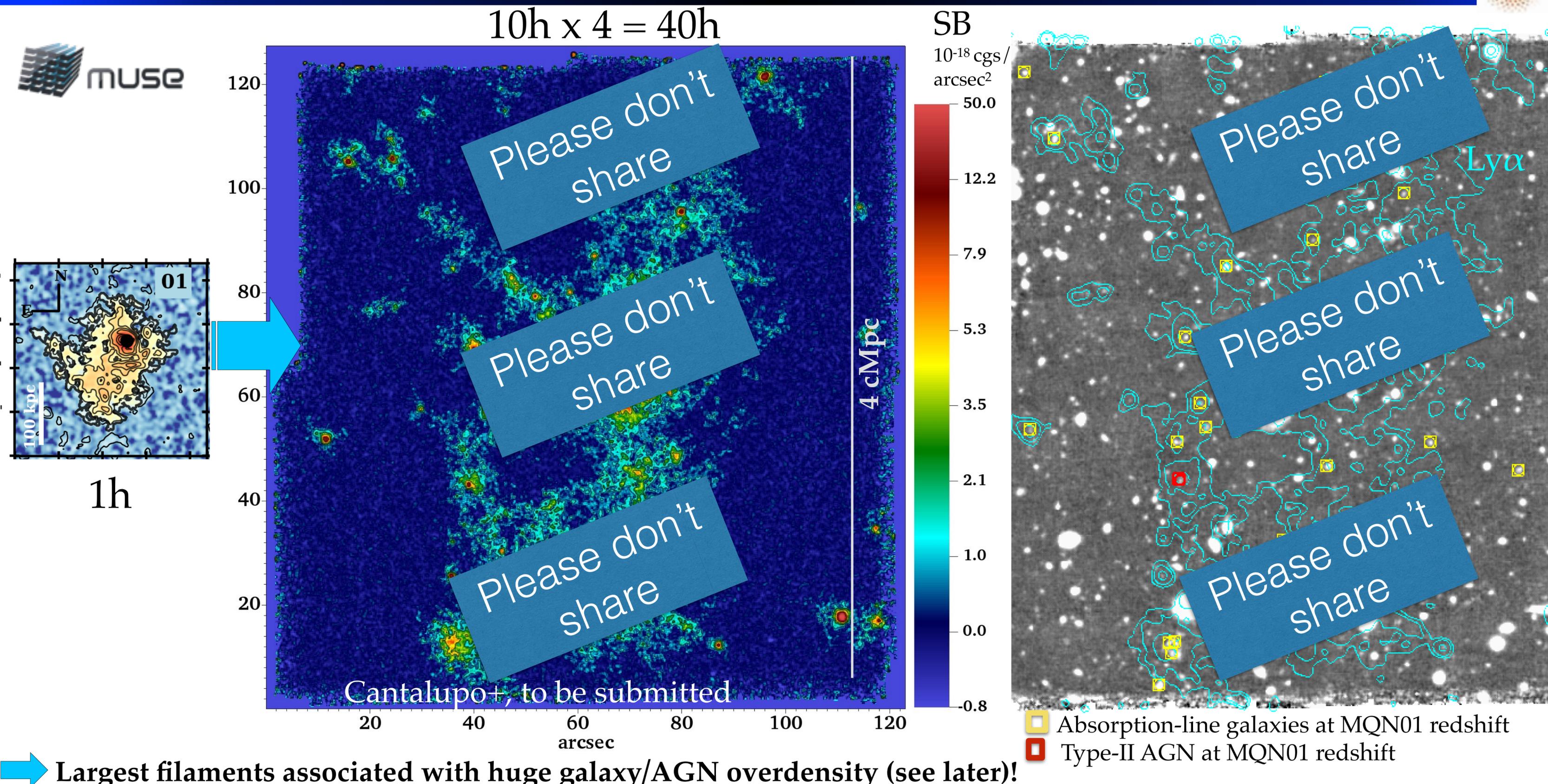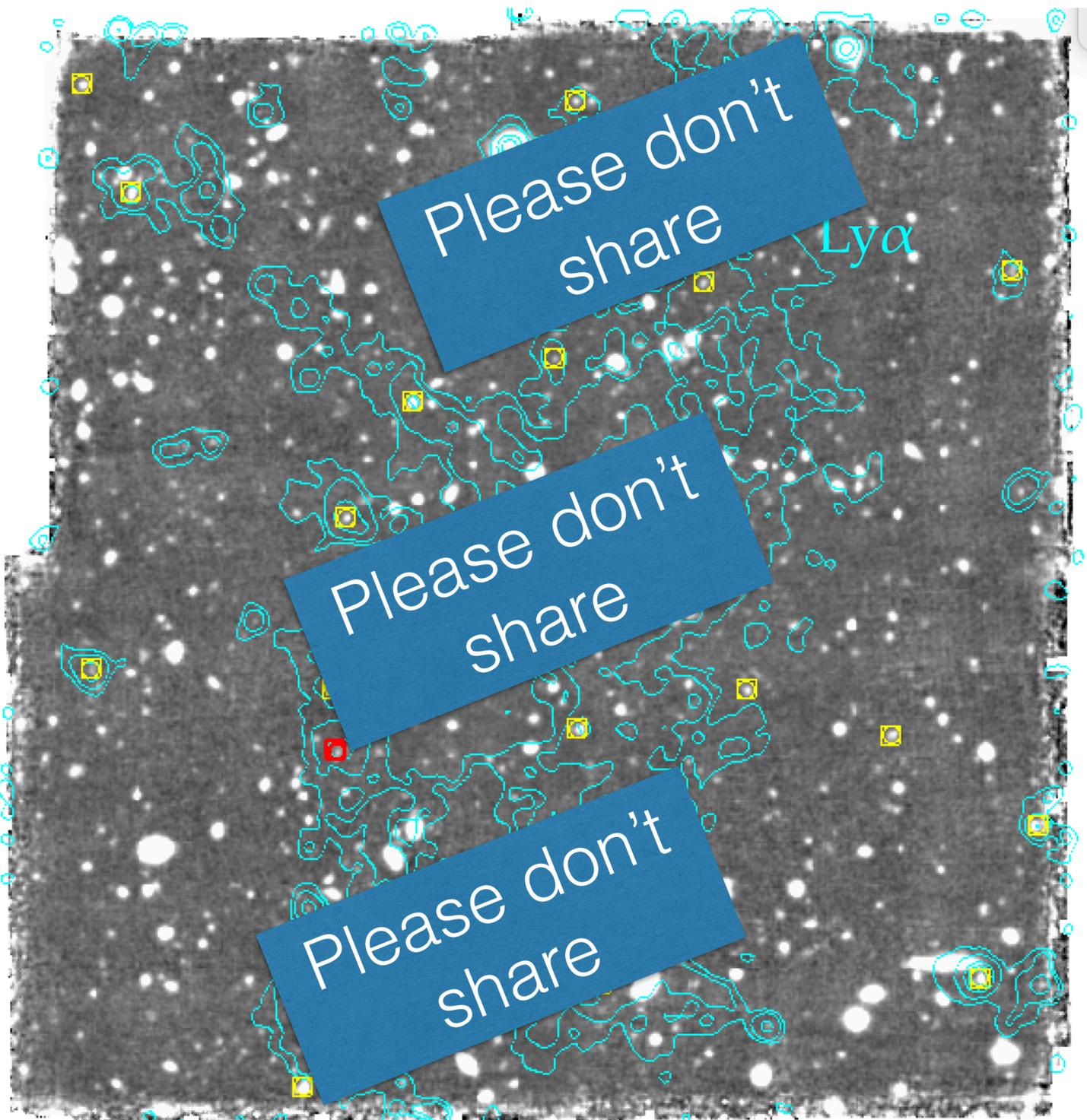
Please don't share

cMpc

Cantalupo+, to be submitted

10h x 4 = 40h

SB

10^{-18} cgs / arcsec^2

50.0

12.2

7.9

5.3

3.5

2.1

1.0

0.0

-0.8

4 cMpc

Lyα

1h

100 kpc

01

N

E

Cantalupo+, to be submitted

arcsec

Absorption-line galaxies at MQN01 redshift

Type-II AGN at MQN01 redshift

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

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)

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

➤ 21 CASF galaxies (of which 5 X-ray detected AGN! See later) with secure redshift in 4x4 cMpc² and +-1000 km/s around the quasar!

➤ FIELD comparison sample selected from other MUSE cubes with same depth and same technique

High Confidence
$z = 3.244$

Rest Frame Wavelength (Å)

MUSE white-light

UBR color selection of LBGs
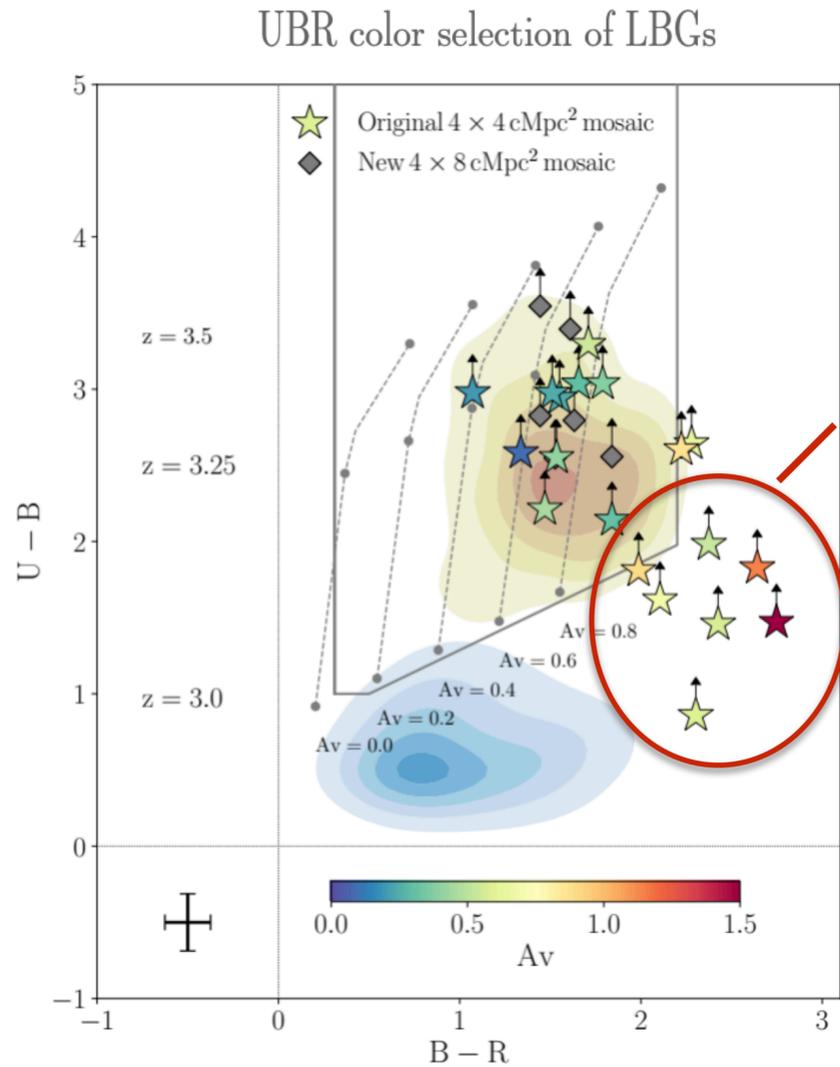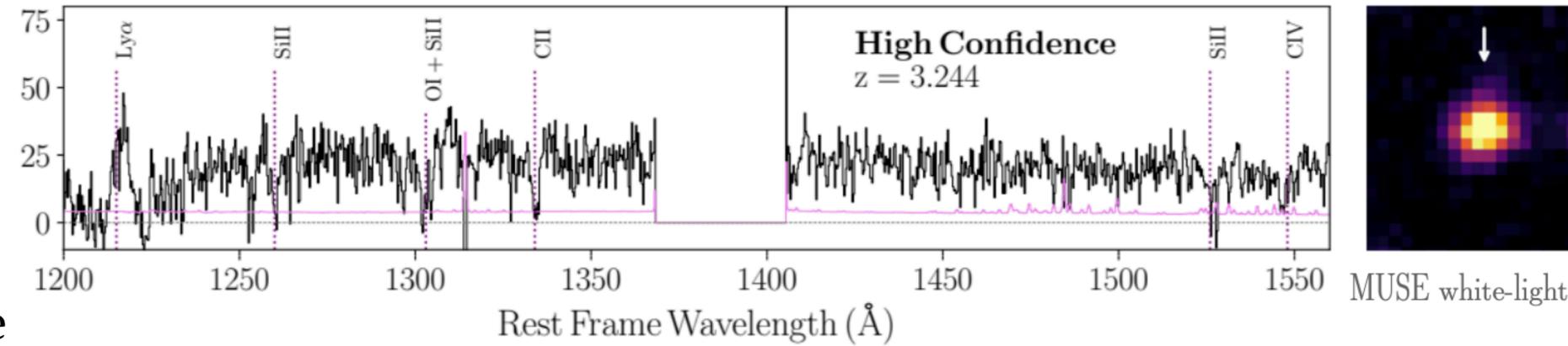
Standard LBG selection misses the most massive SF galaxies and AGN (at the center of the overdensity)!

Cumulative luminosity function

GALAXIES AROUND THE QSO

FIELD GALAXIES

$\delta = 53.0 \pm 17.4$

2D overdensity of confirmed spec-z galaxies

Galbiati, SC+, 2025

Star forming main sequence

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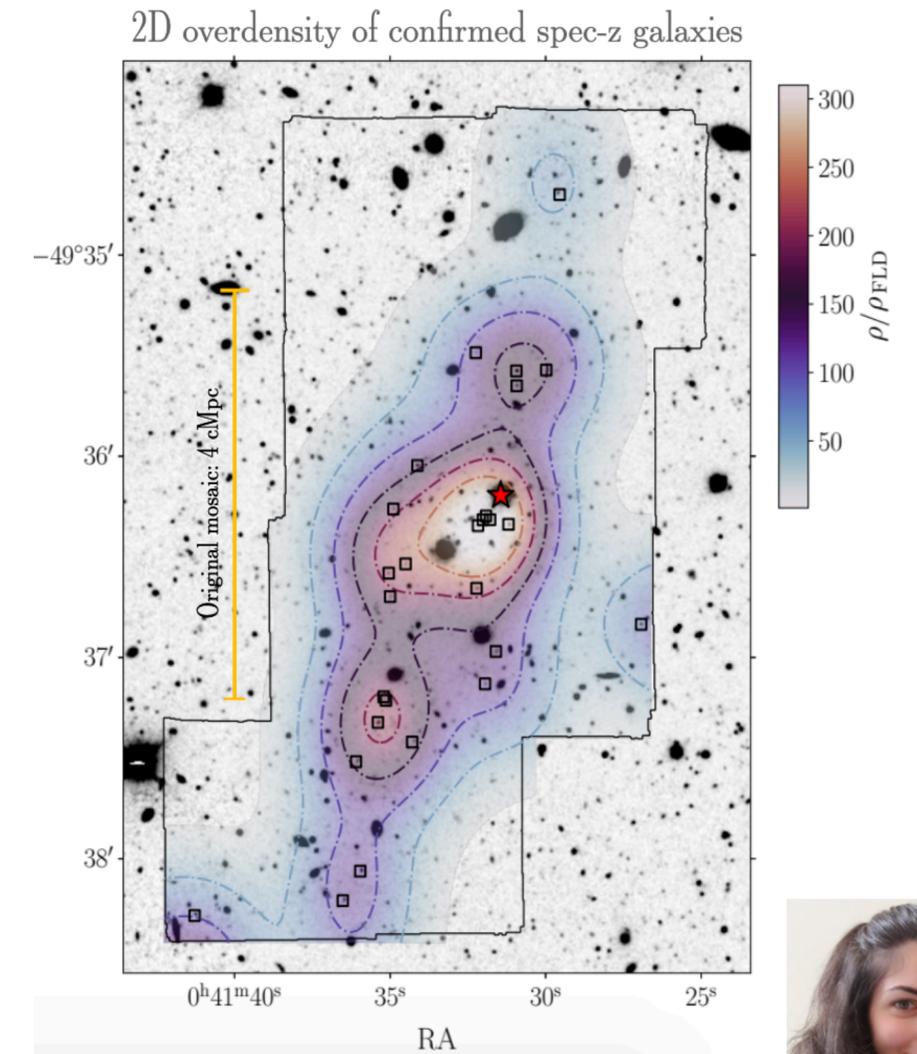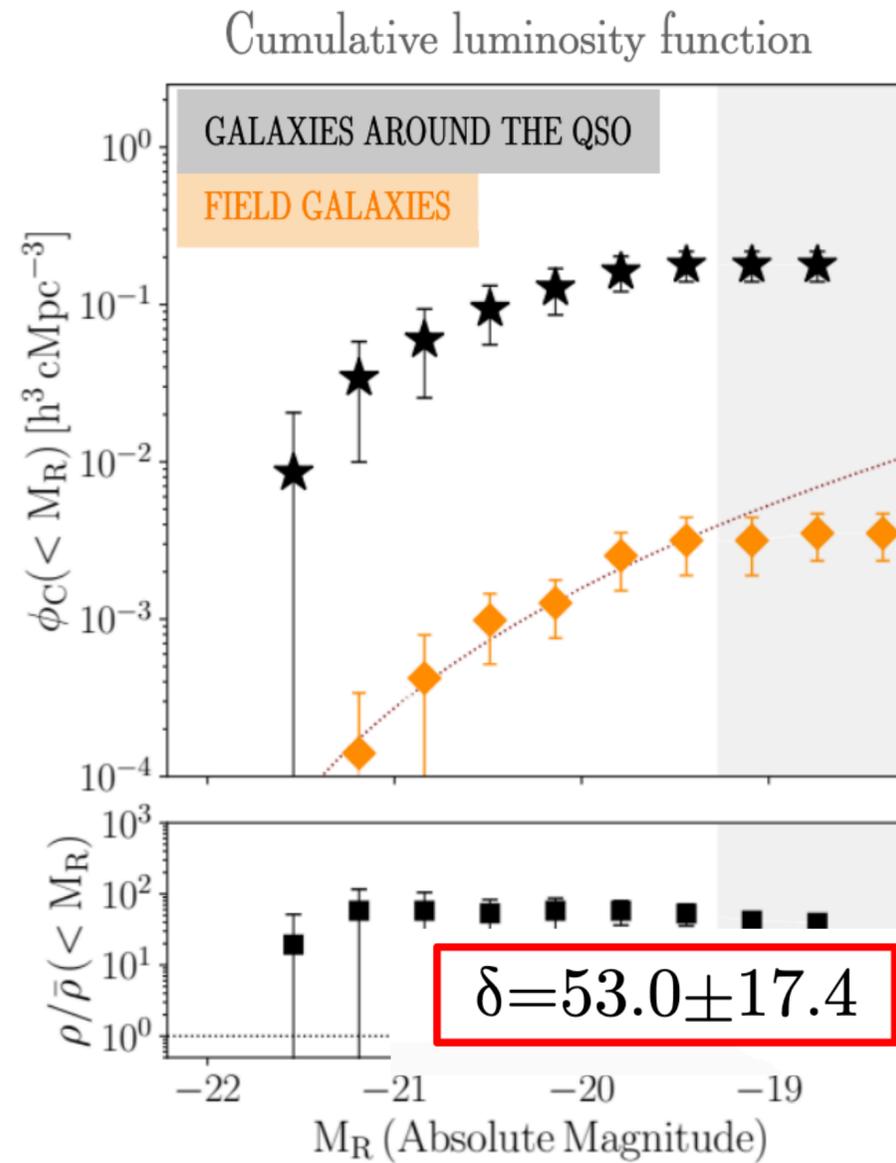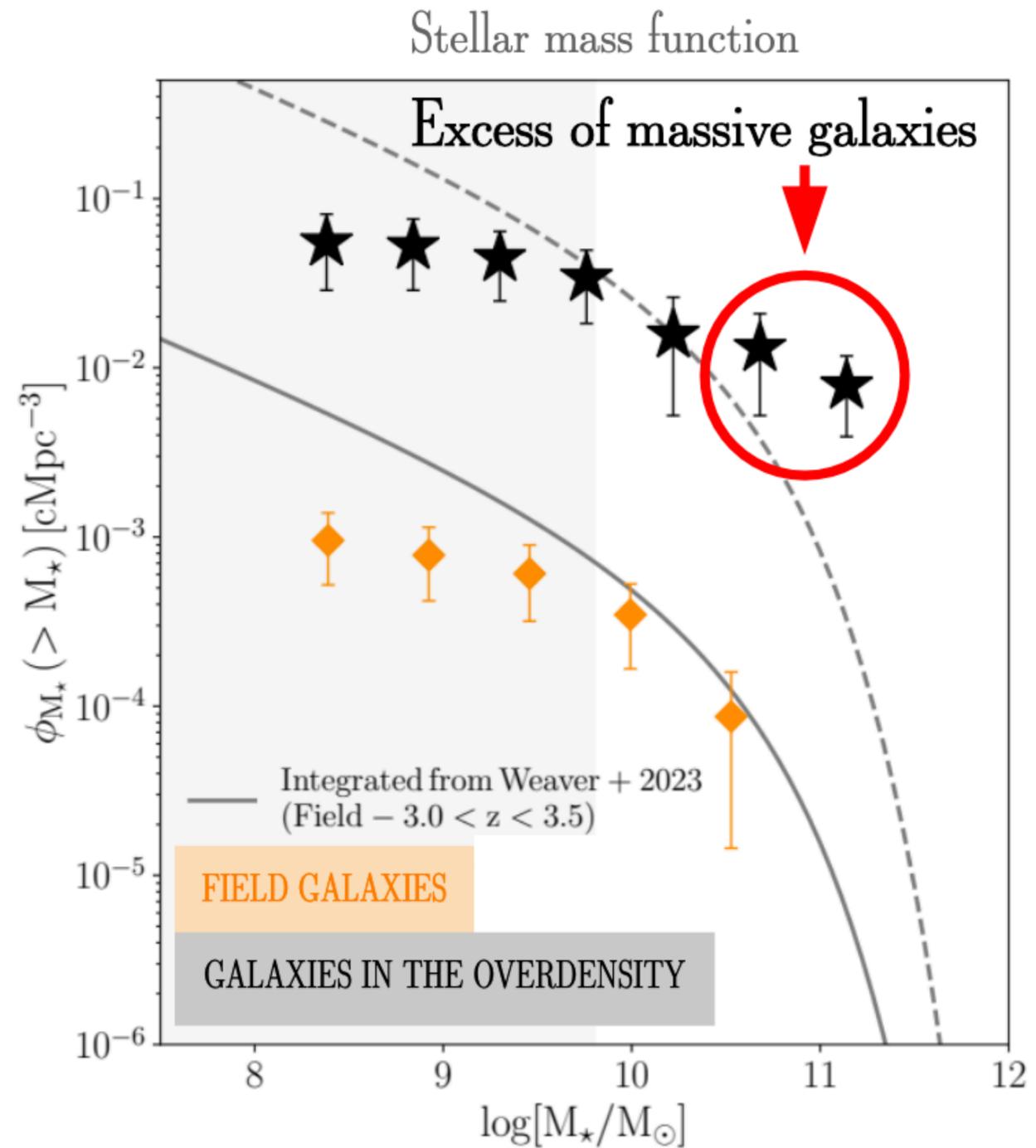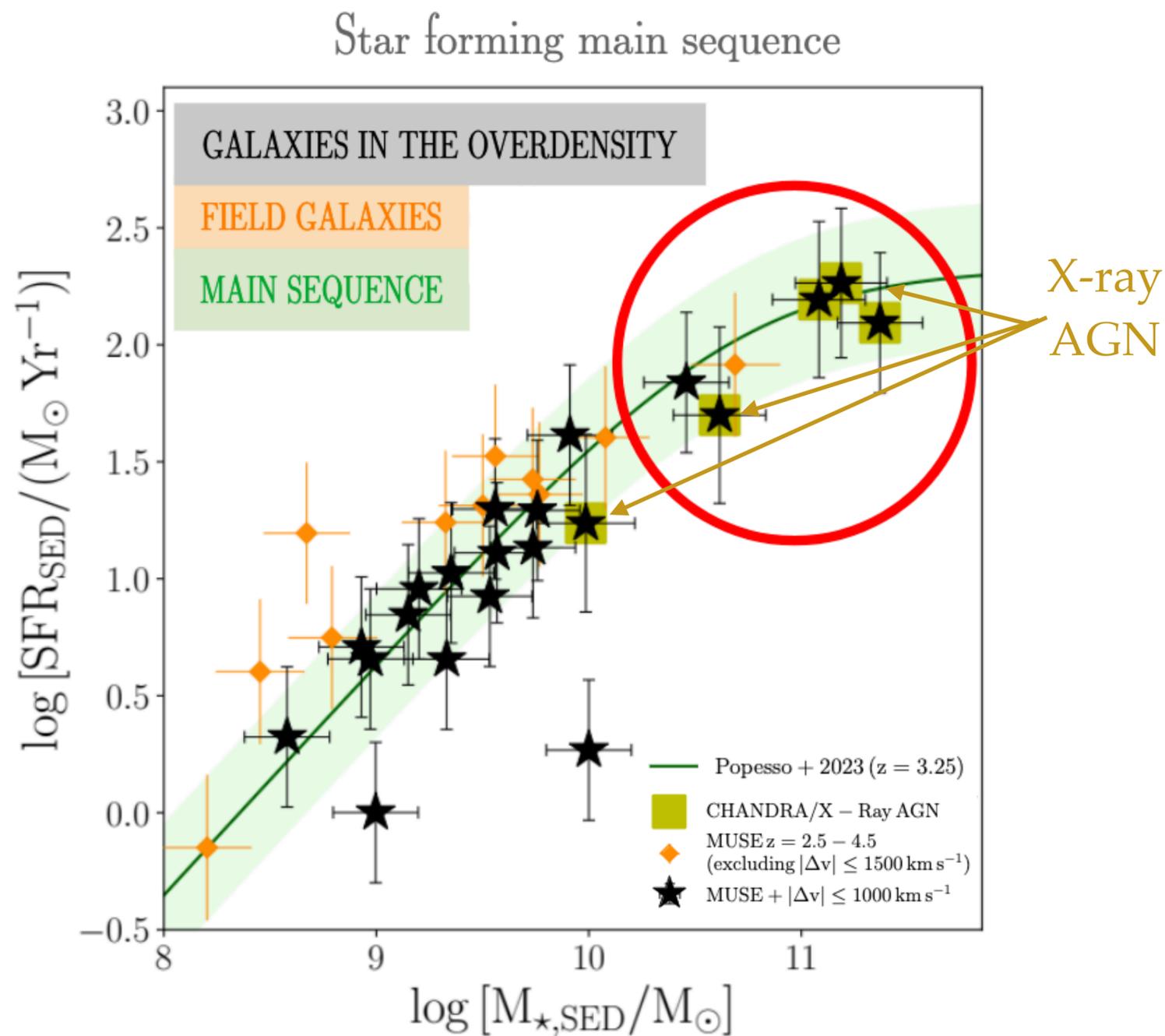
No clear differences in the SFR (maybe a hint of bending). Continuum-selected SF galaxies in MQN01 have SFR similar to the field and as expected for "main sequence"

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

Galbiati, SC+, 2025

Full OIII, Hβ, NII and Hα spectroscopic information for ~10 galaxies from deep JWST NIRSpec (see later)
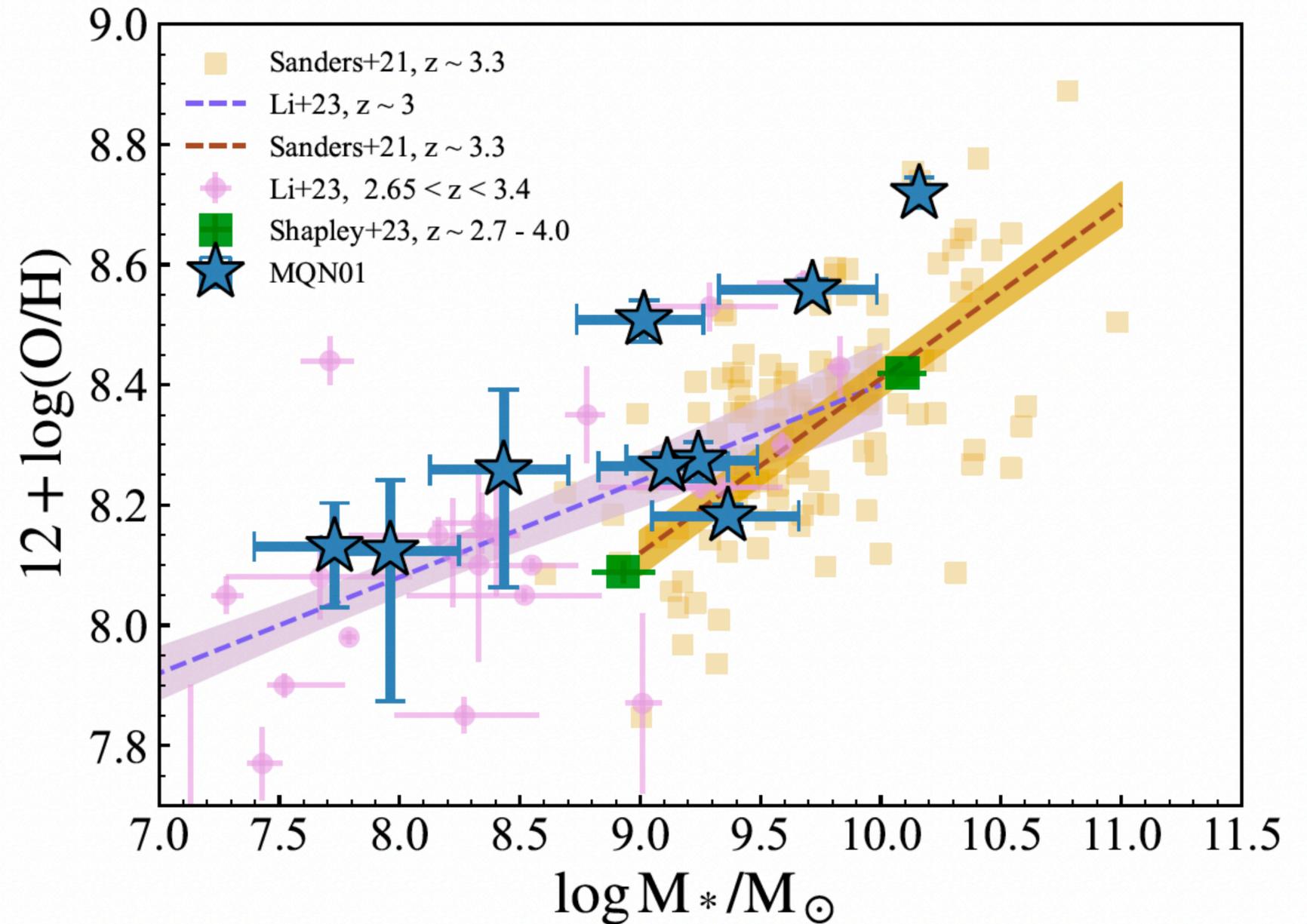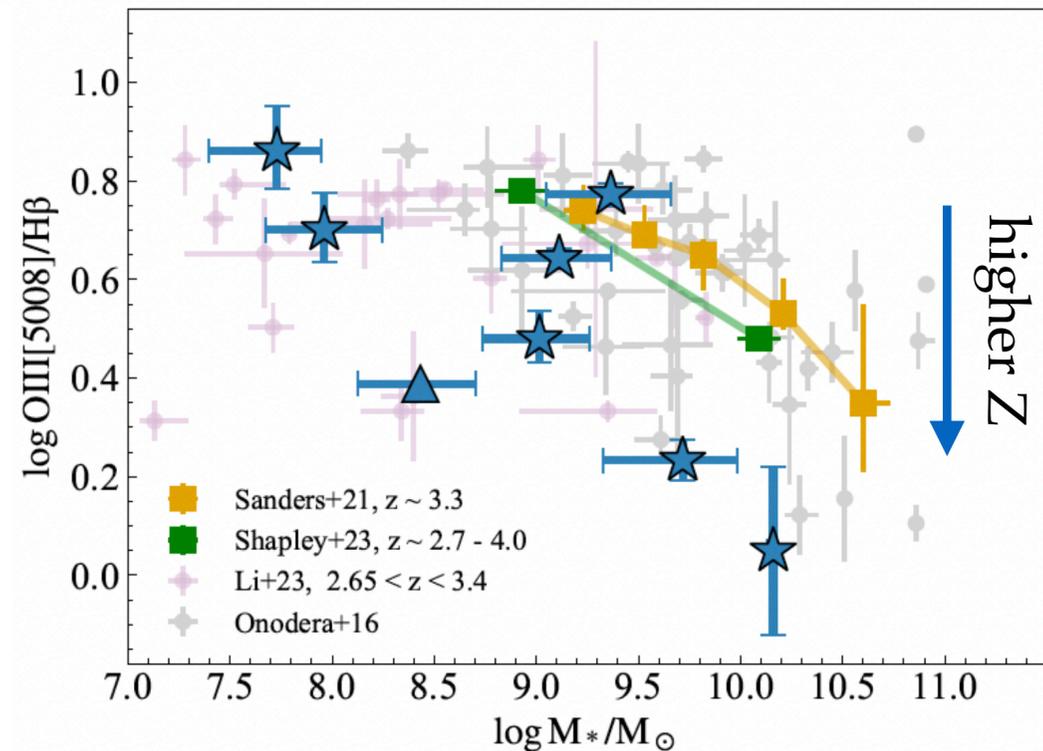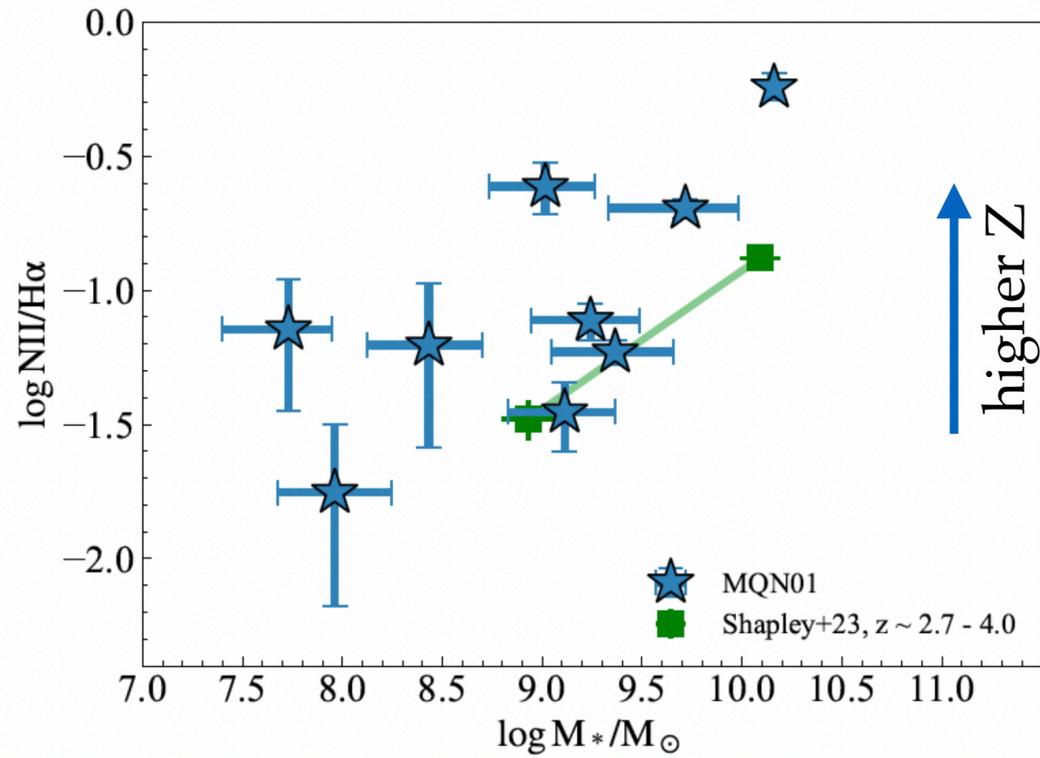
Higher metallicity than field galaxies, consistent with earlier/more efficient formation!

Wang X.,SC+, submitted (arXiv:2511.19608)
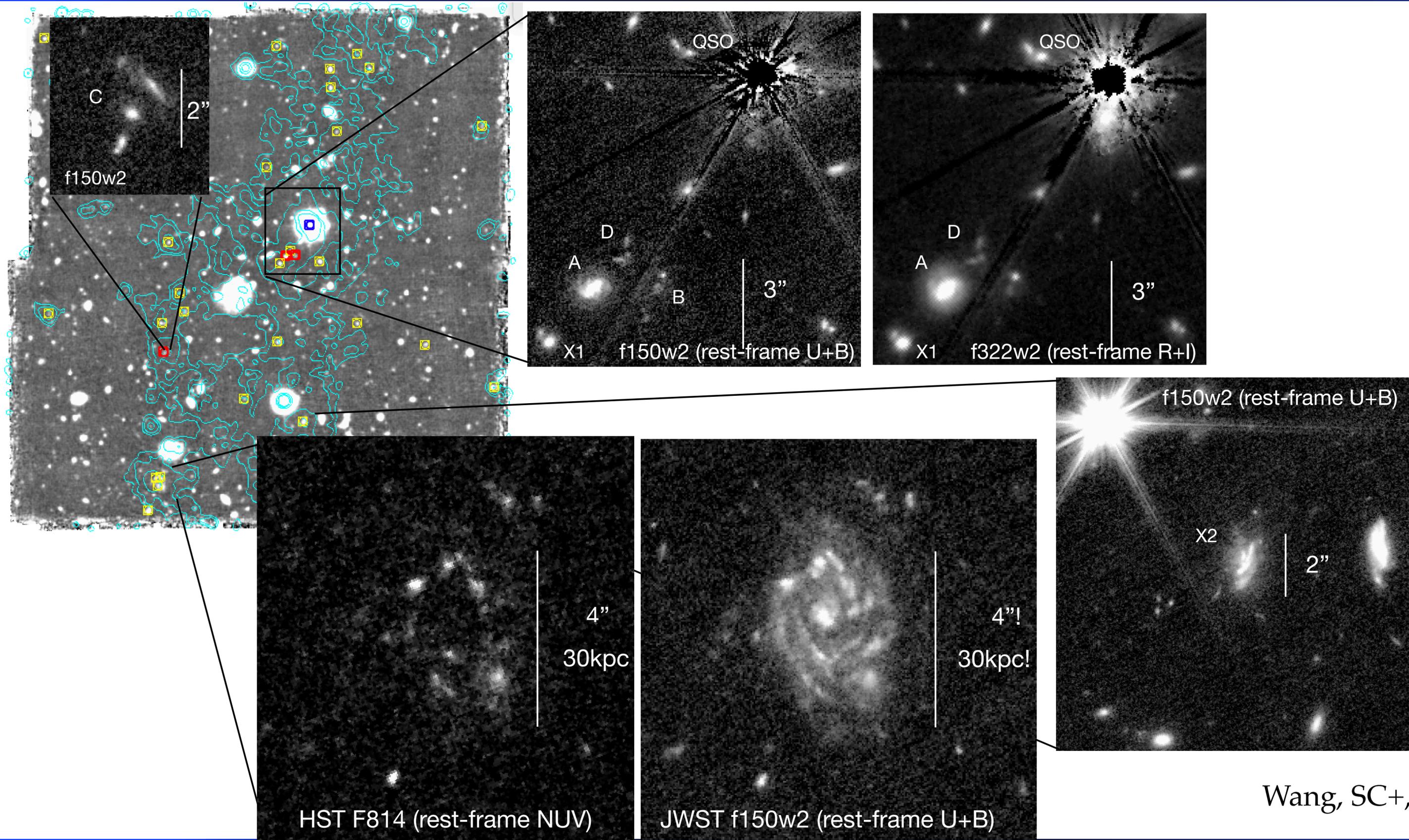
C

f150w2

2"

QSO

D

A

B

X1   f150w2 (rest-frame U+B)

3"

QSO

D

A

X1   f322w2 (rest-frame R+I)

3"

f150w2 (rest-frame U+B)

X2

2"

HST F814 (rest-frame NUV)

4"

30kpc

JWST f150w2 (rest-frame U+B)

4"!

30kpc!

Wang, SC+, 2025

a

QSO

0.5 arcmin

b

Big Wheel

30 kpc (4 arcsec)
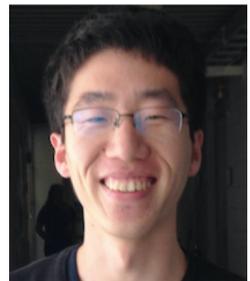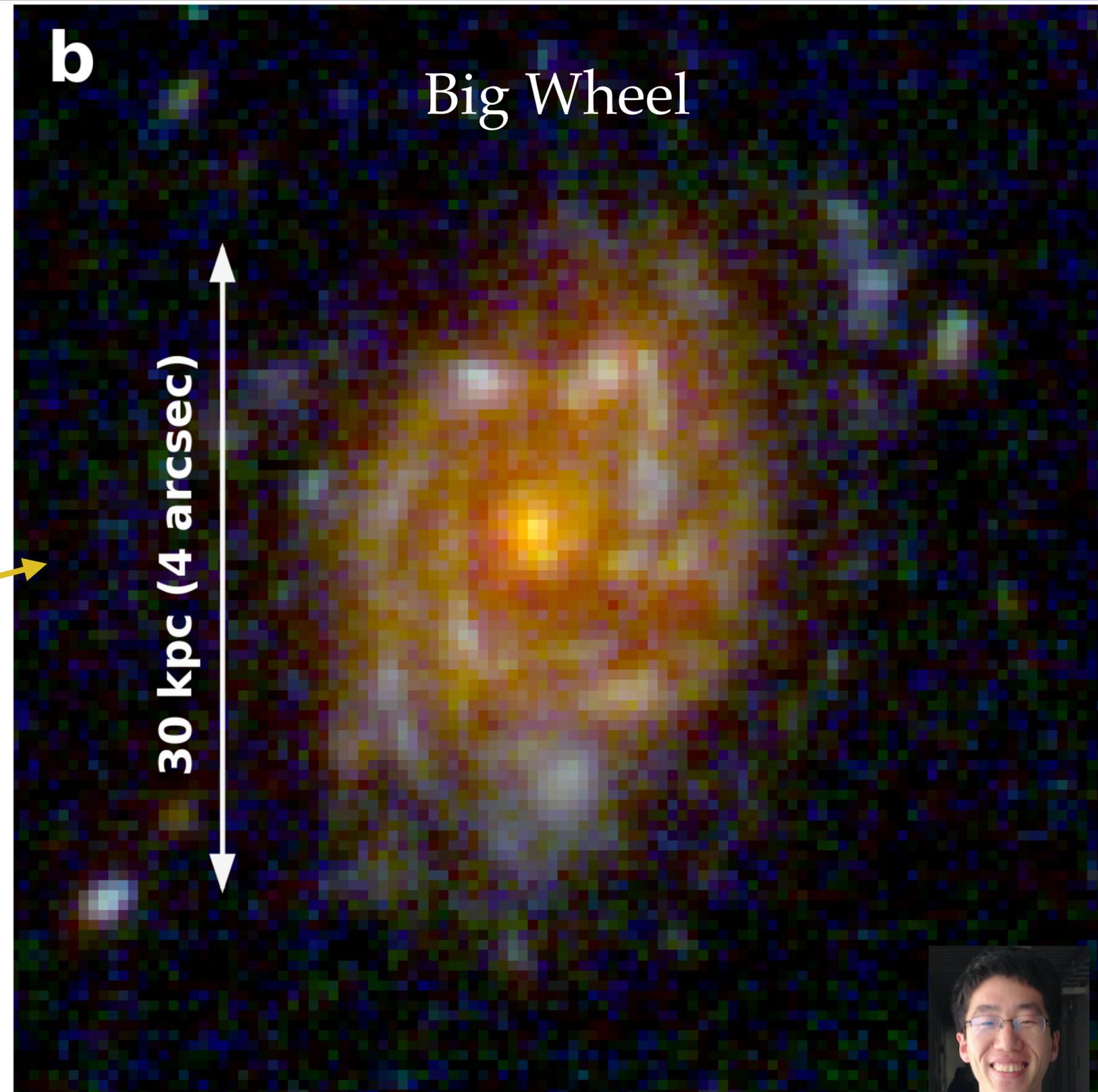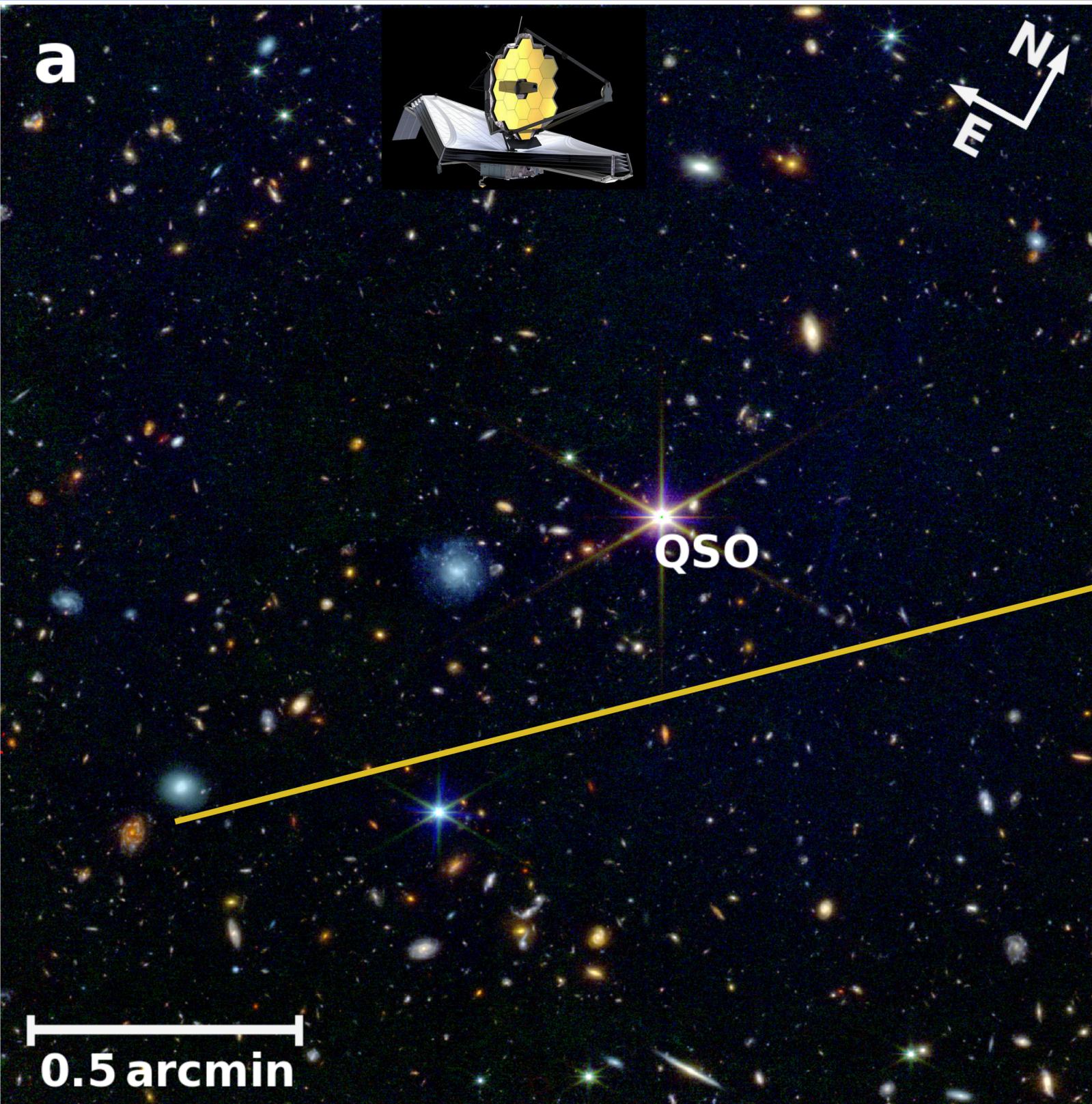
HST F814 (rest-frame far-UV) + JWST f150w2 (rest-frame U+B) + f322w2 (rest-frame R+I)

Wang, SC+, 2025

surface brightness [μJy/arcsec²/Å]

Hα spectrum from Slit 1

clump A

disk model

Position [arcsec]

Hα spectrum from Slit 2

Hα spectrum from Slit 3

clump B

Velocity [km/s]

[kpc]

observed velocity
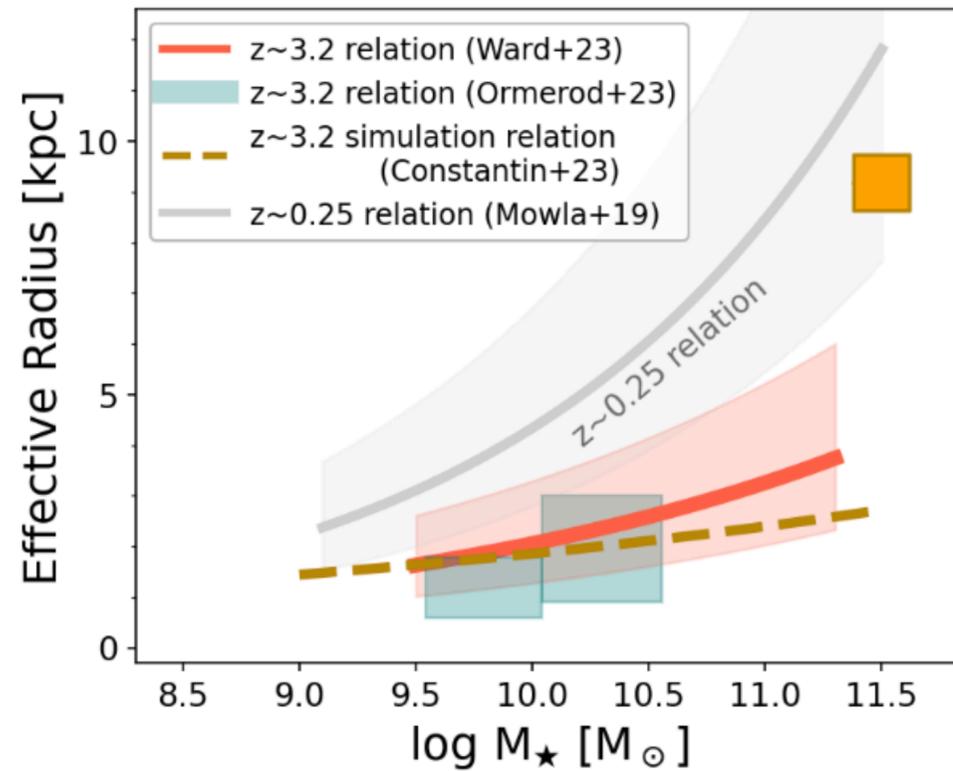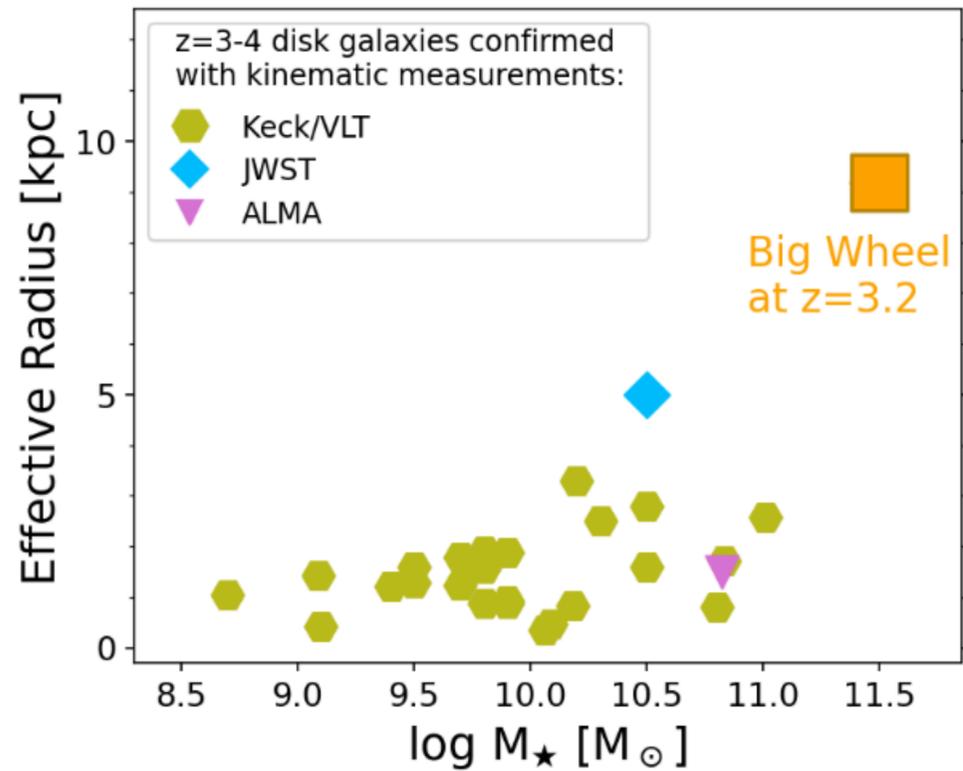
km/s

disk model

km/s

observed−model

km/s

Slitlet 3
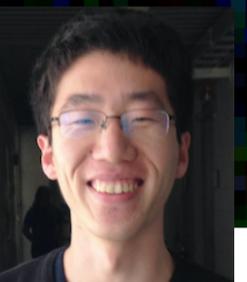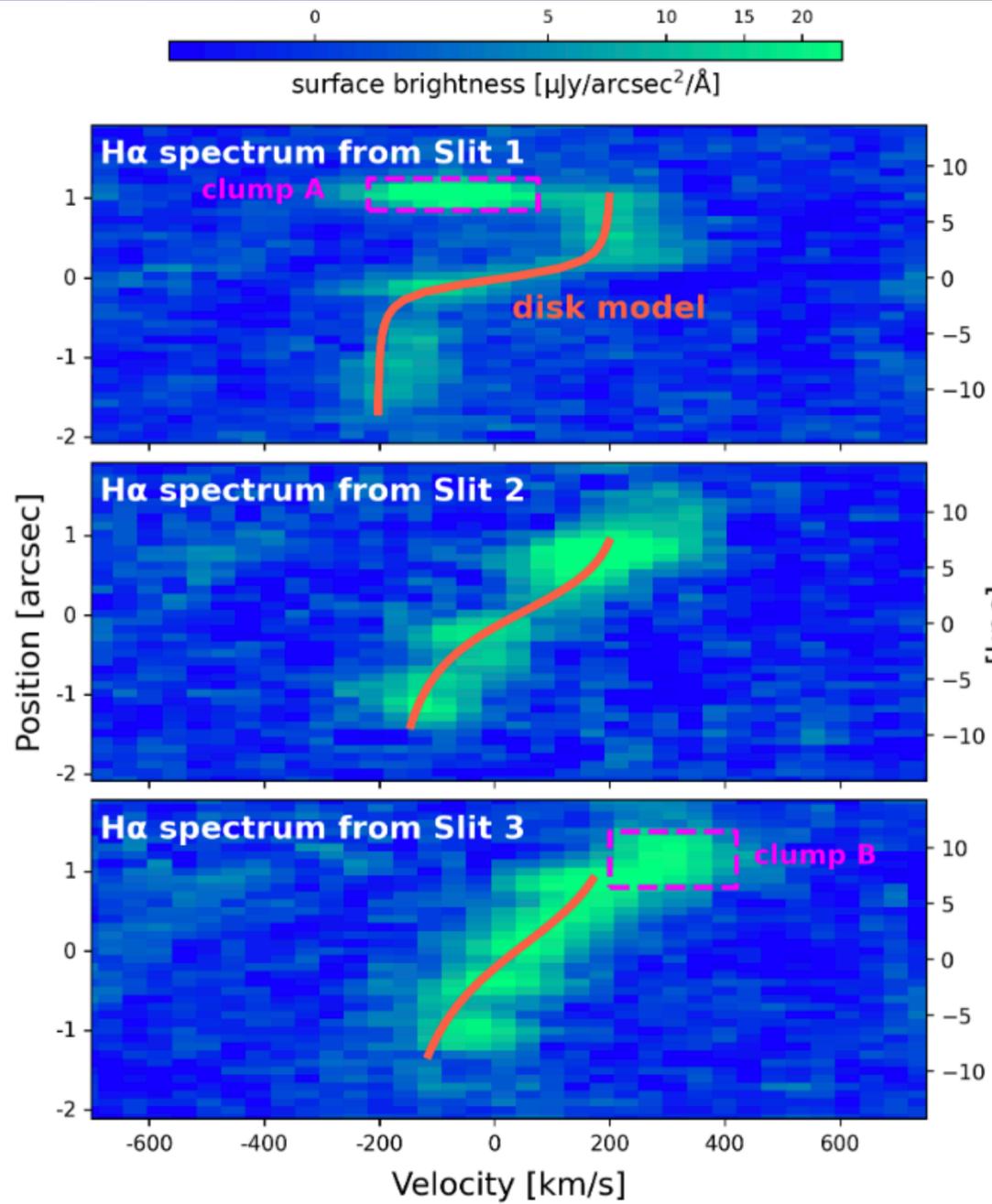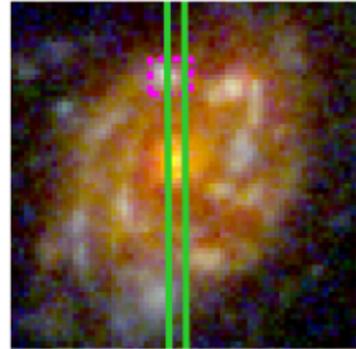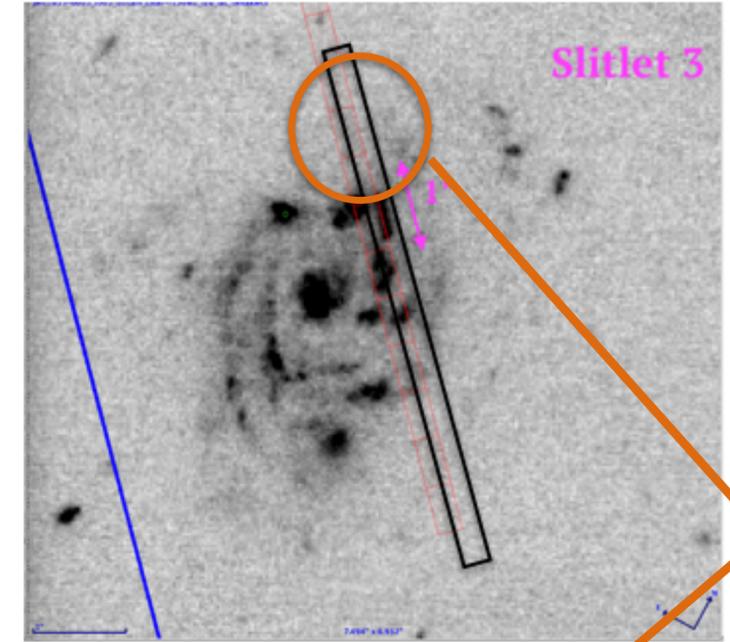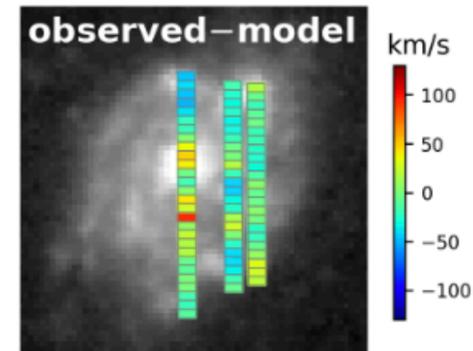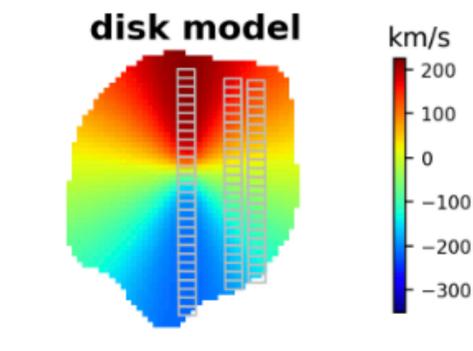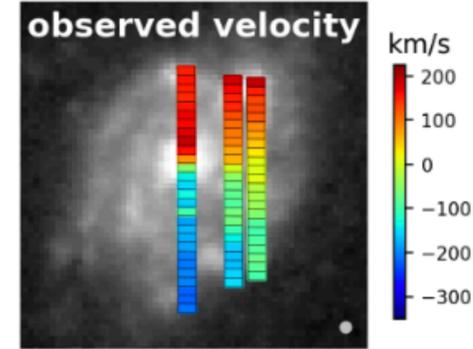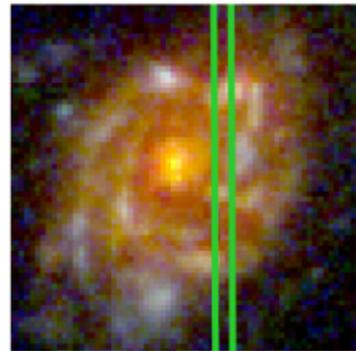
CGM gas
in emission
(accretion?)

Hα   NII

2"

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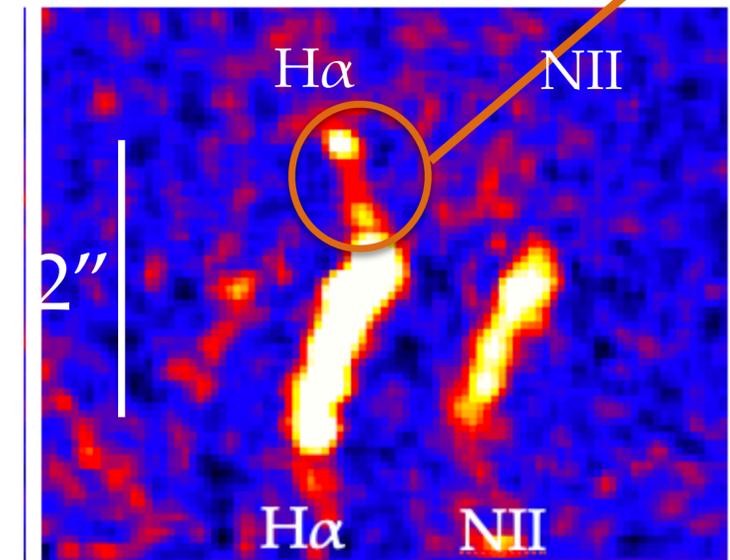
Beautifully rotating disk galaxy
(consistent with lower-res ALMA data)!
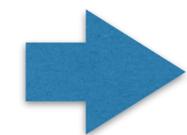Also "super-cold" with V/σ~10
(see later)

a ALMA CO

Wang, SC+, 2025
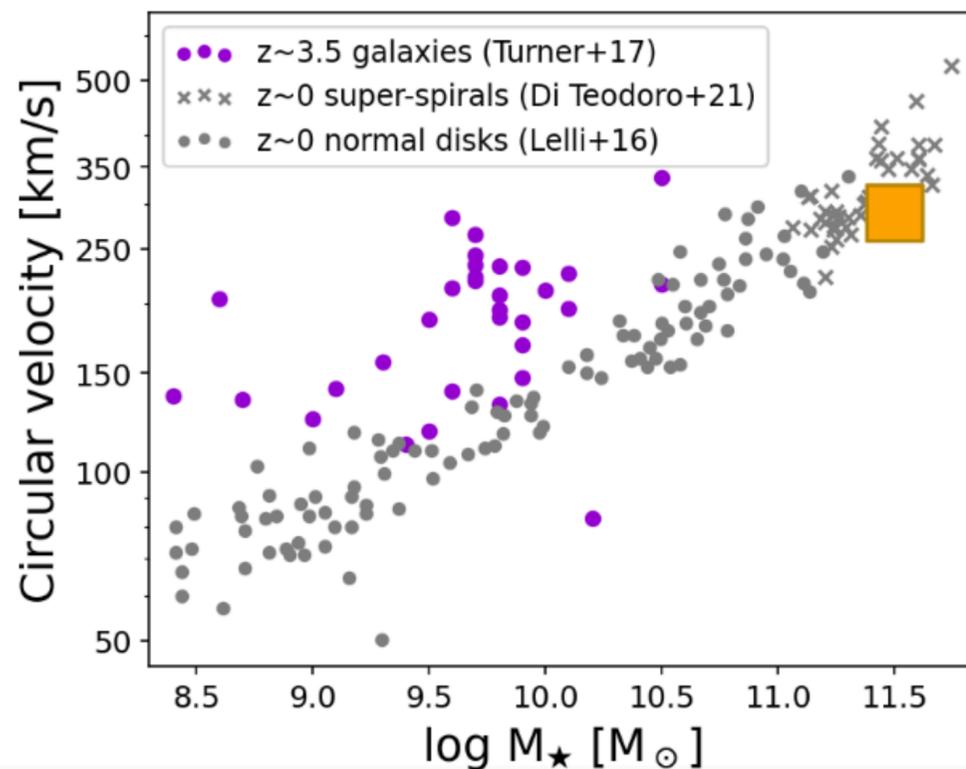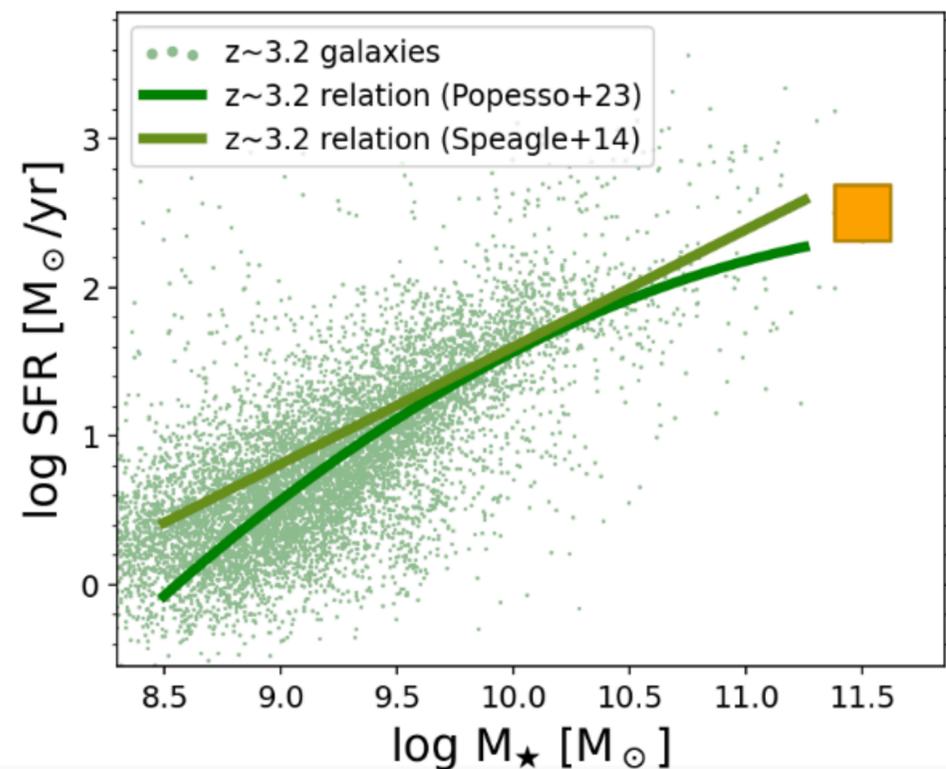
Sitting on the **local** size mass-relation and **local** Tully-Fisher relation!

Three times larger than expected for its stellar mass

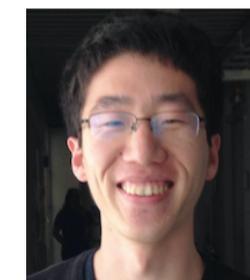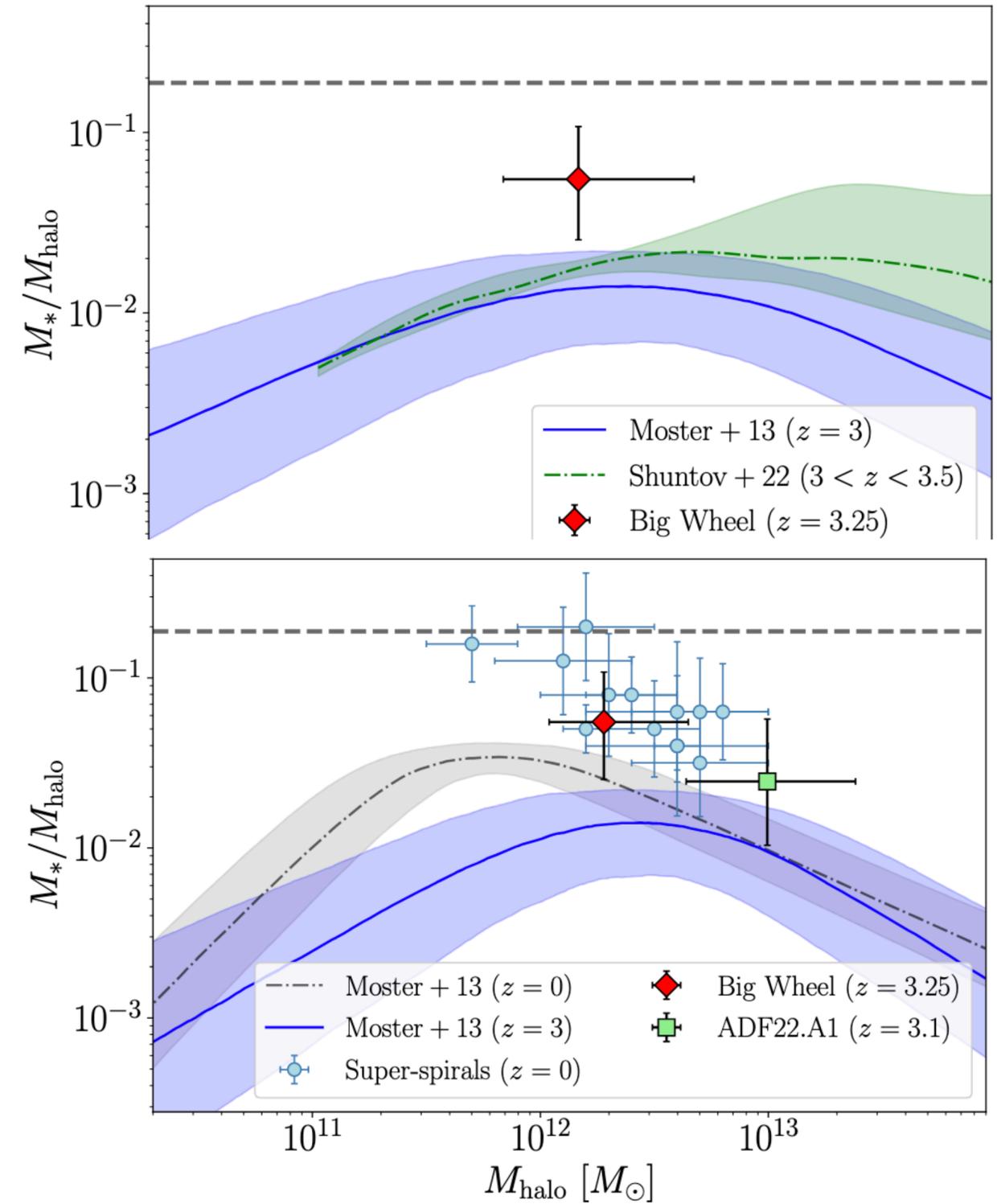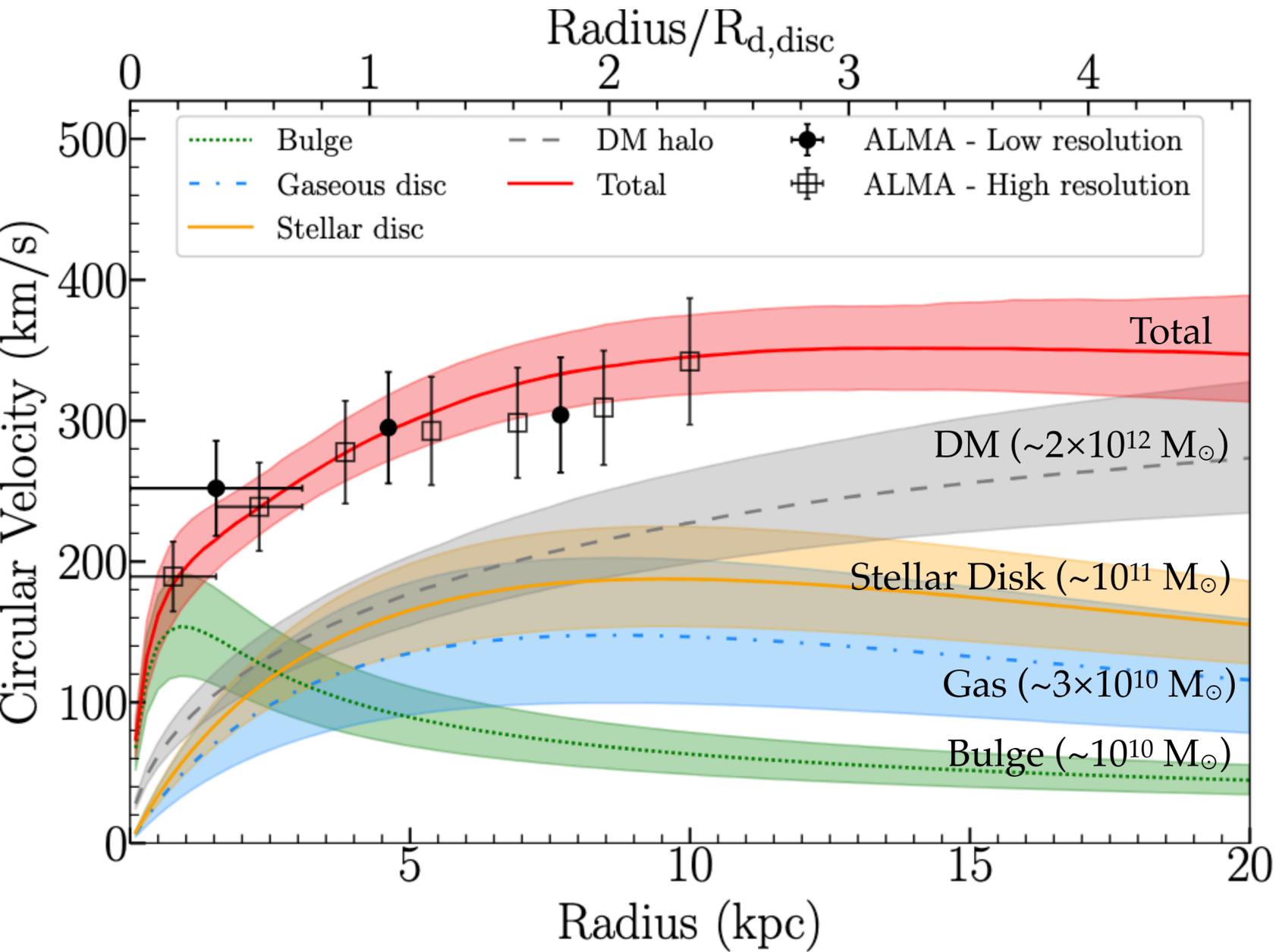Still on or close to the Main Sequence at z~3
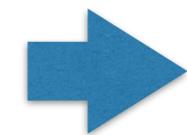
Living in one of the largest over density of galaxies found so far

Wang, SC+, 2025
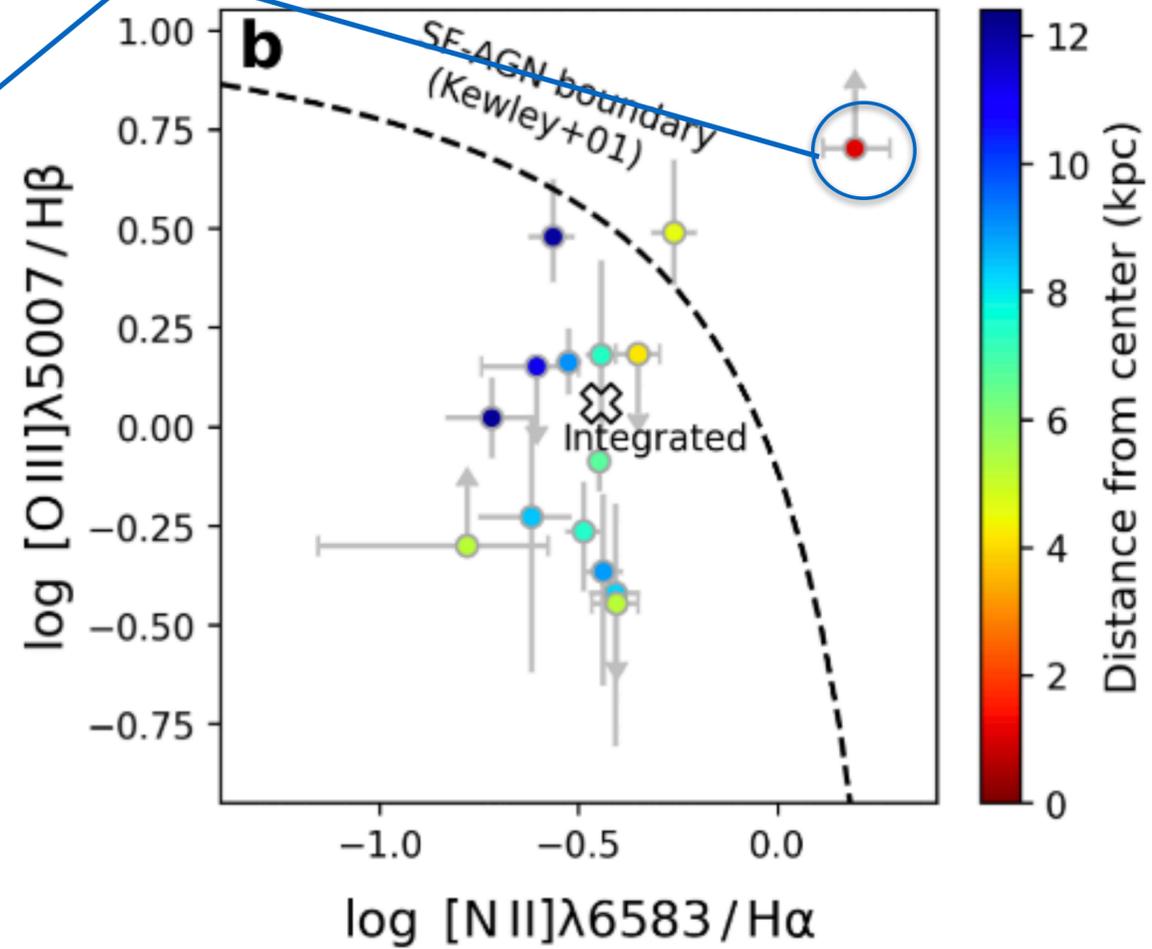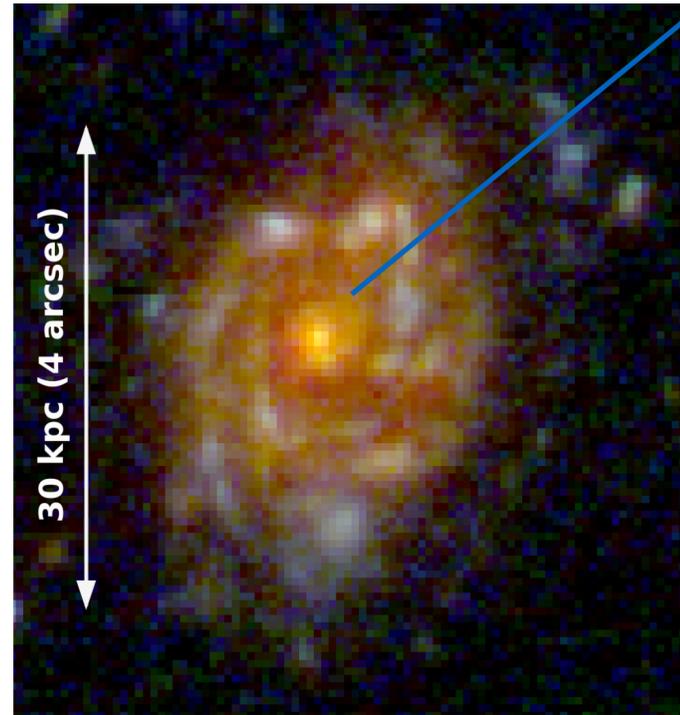
Quadri, SC, Bacchini+ to be submitted

Again, the Big Wheel is more similar to local Super-Spirals also in Stellar-to-Halo-Mass.

The Big Wheel has been forming at the maximum possible efficiency without strong ejective feedback!?
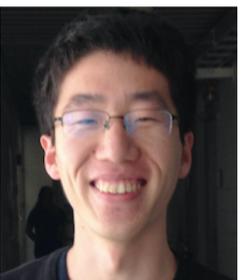
Seyfert-like AGN in the center $(\log(L_x/(erg/s))\sim43.5)$

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

Wang, SC+, 2025
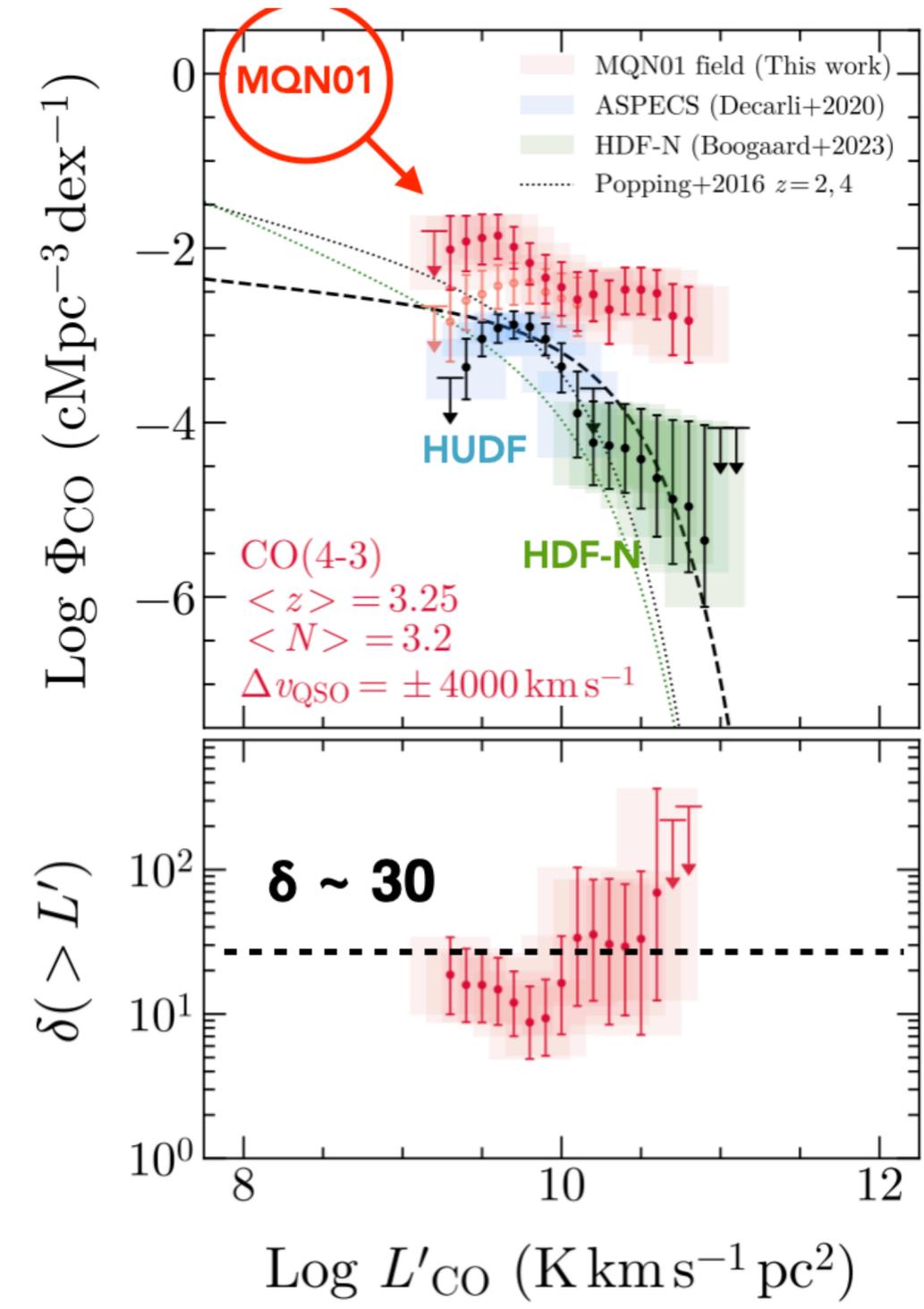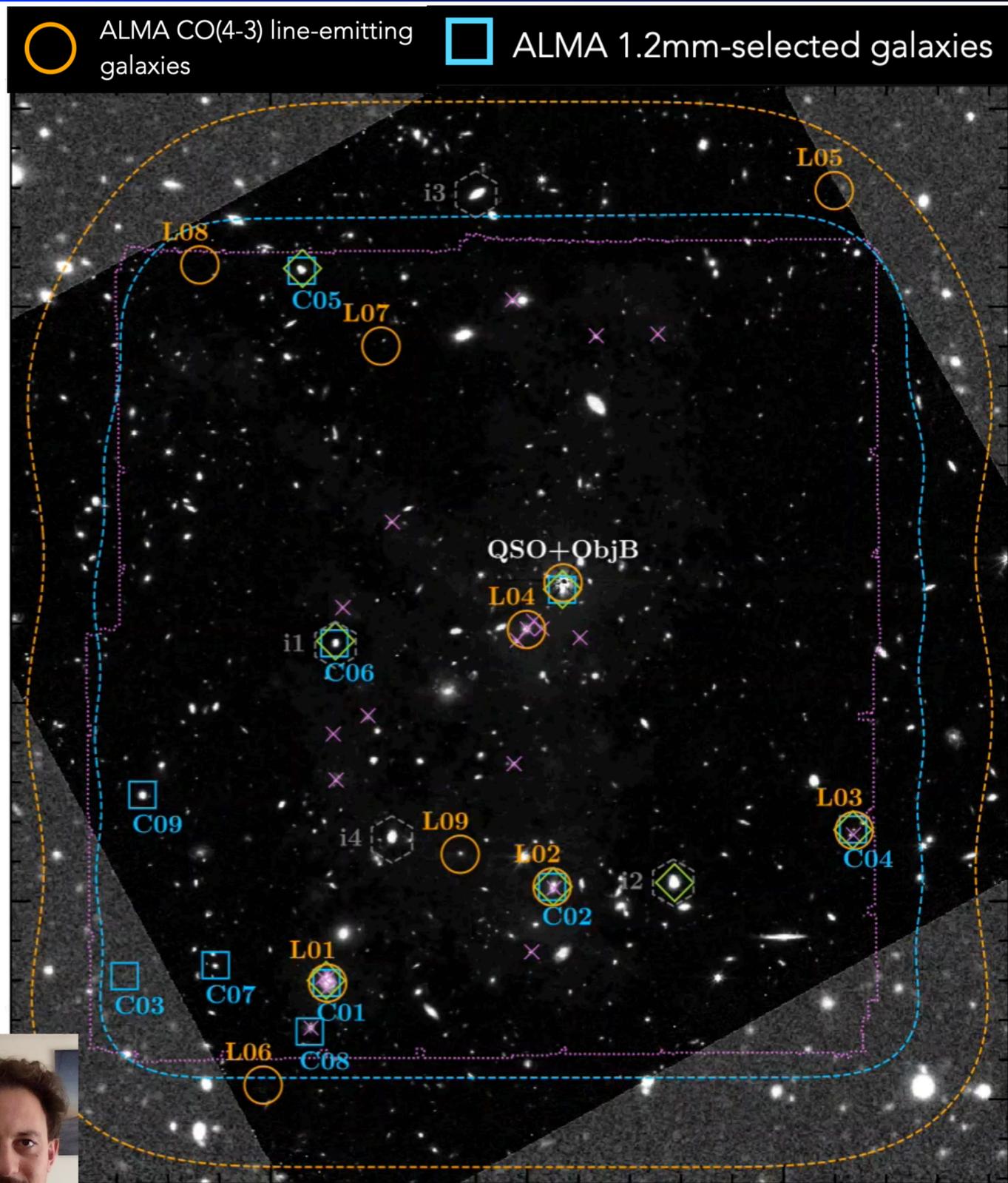
Pensabene,SC+, 2024
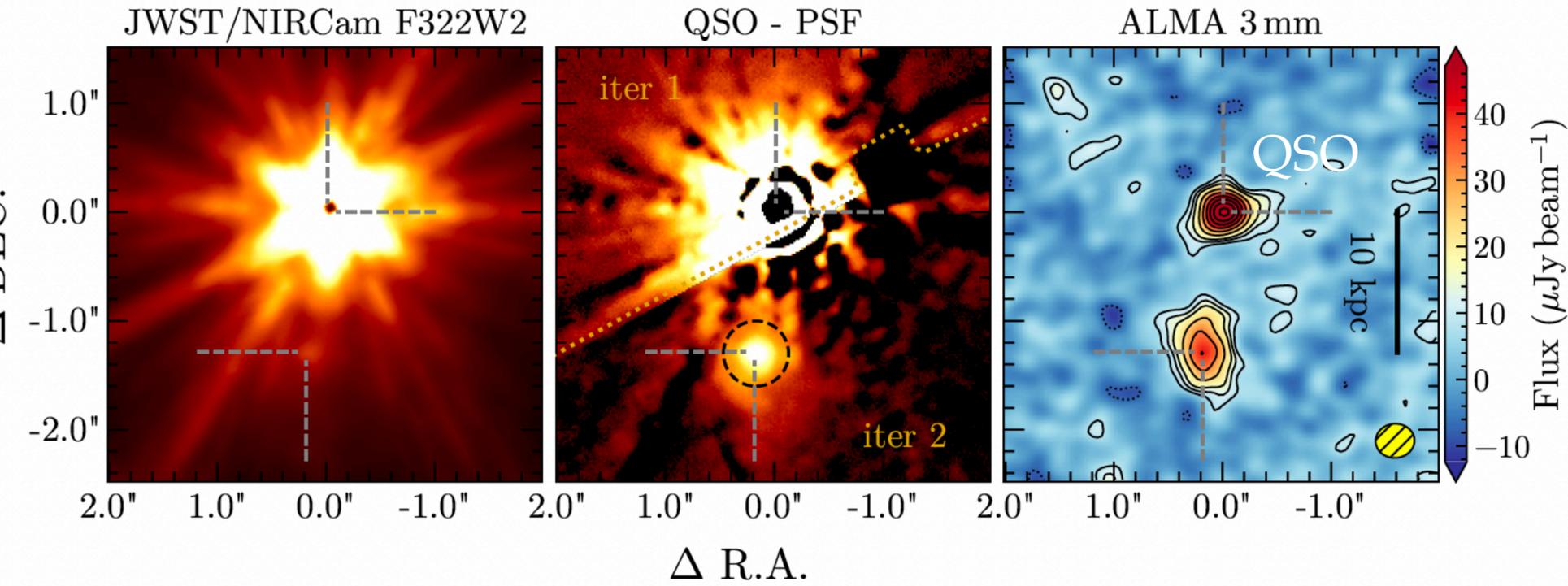
A massive ($M_{star} \sim 10^{11} \, M_\odot$), happily rotating super-cold disk ($V/\sigma \sim 10$) ~10kpc away from the brightest z~3 QSO and at the center of a huge overdensity!
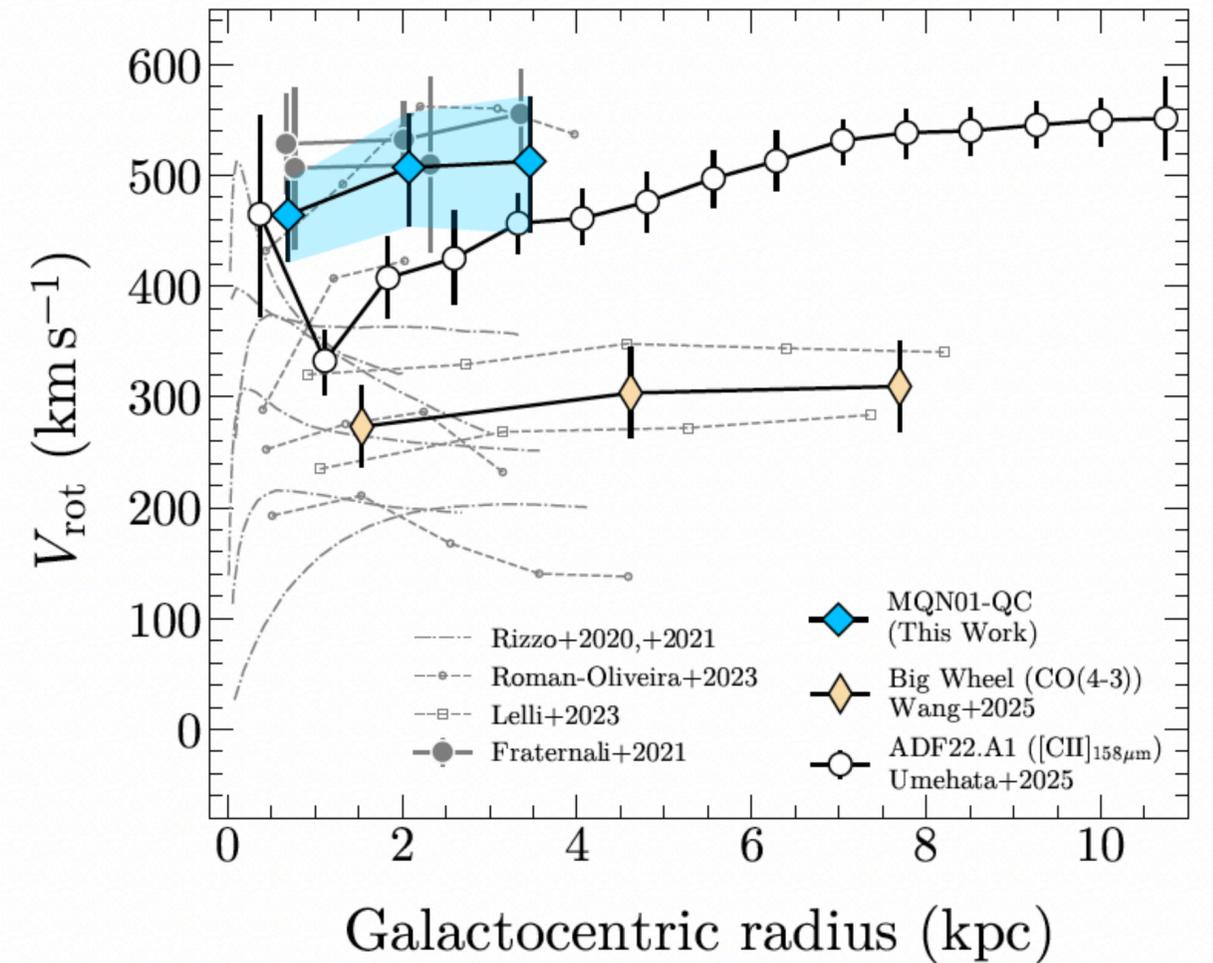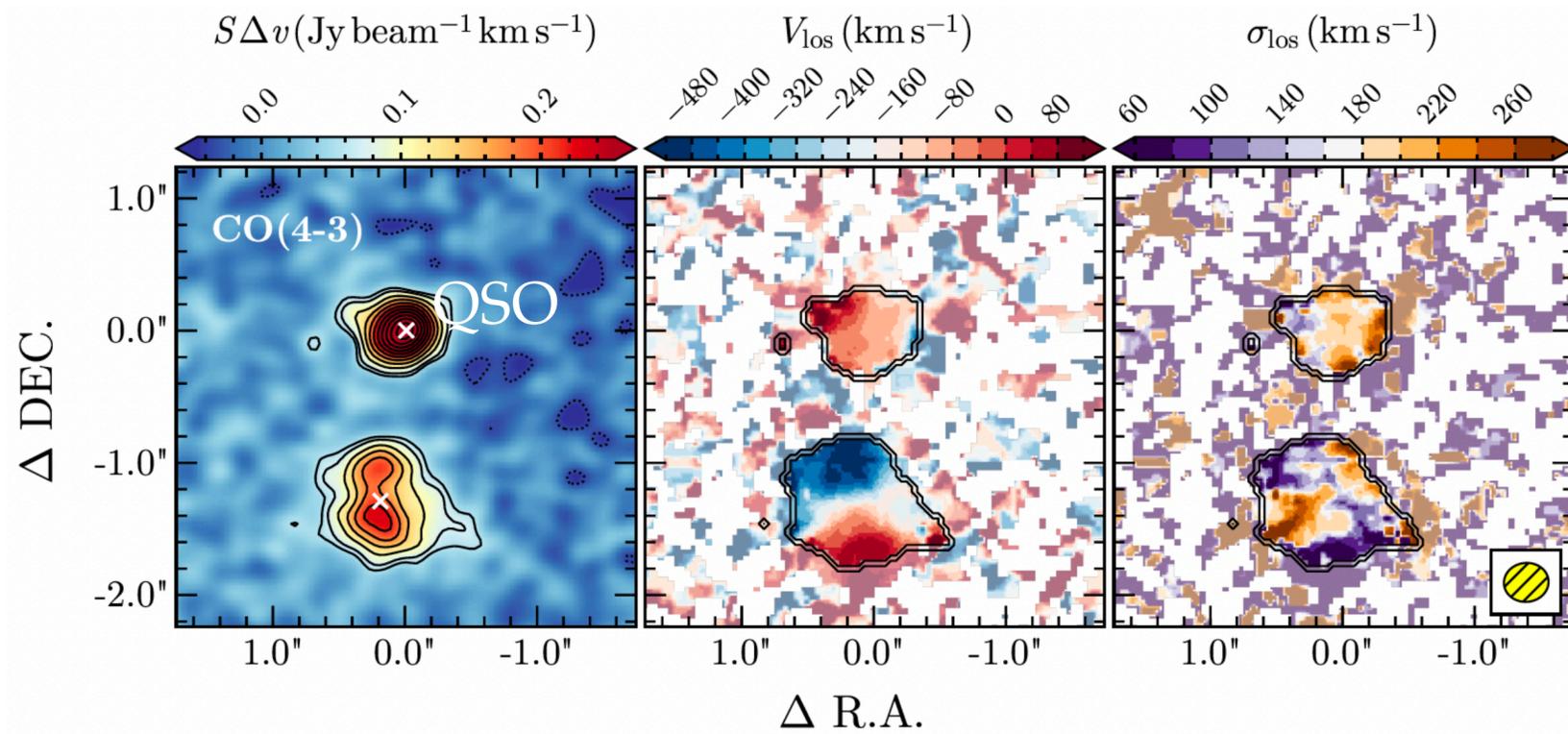
Pensabene, SC+, 2025

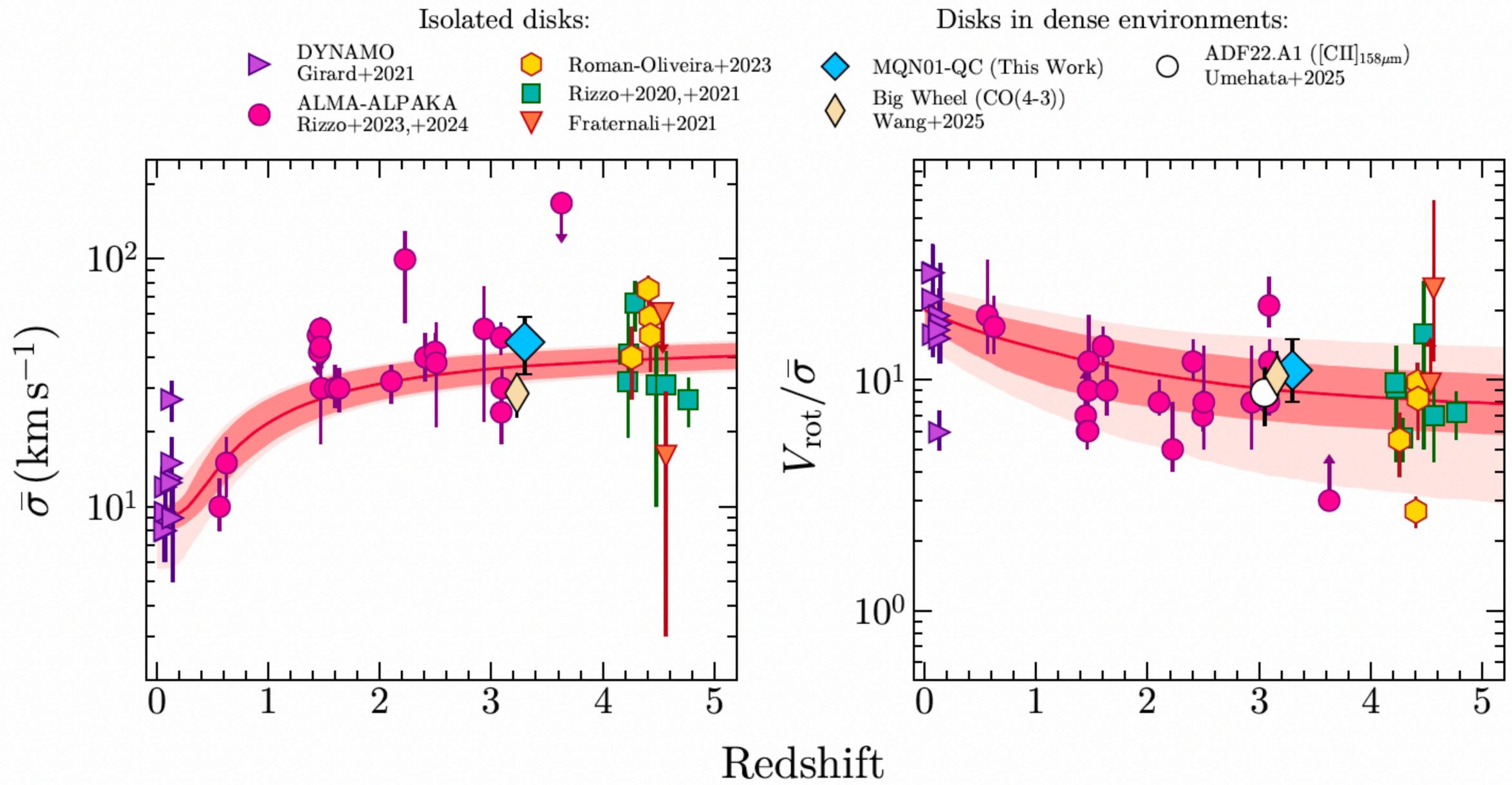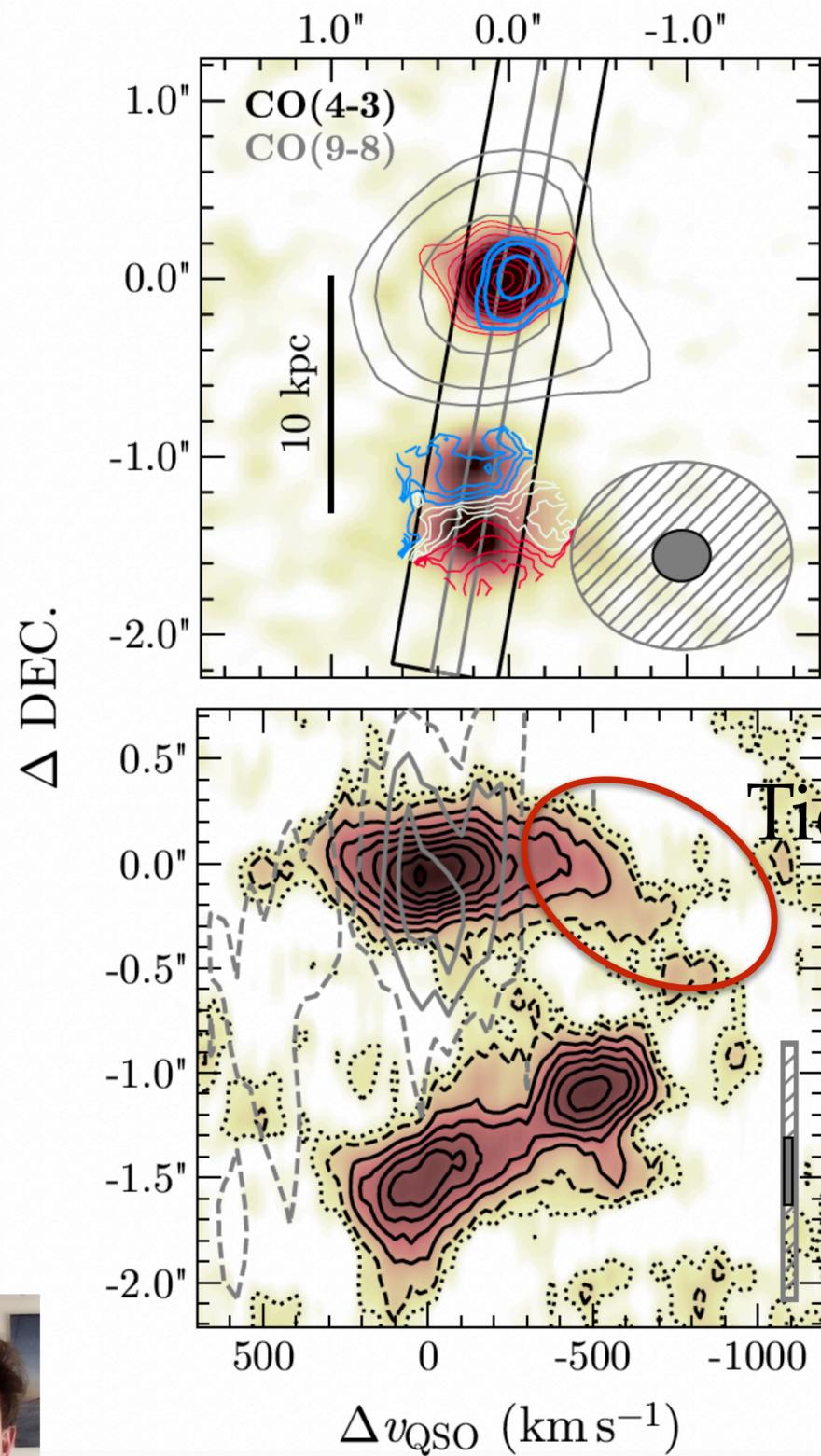Super-cold disks (V/σ~10) are also present in the densest environments!
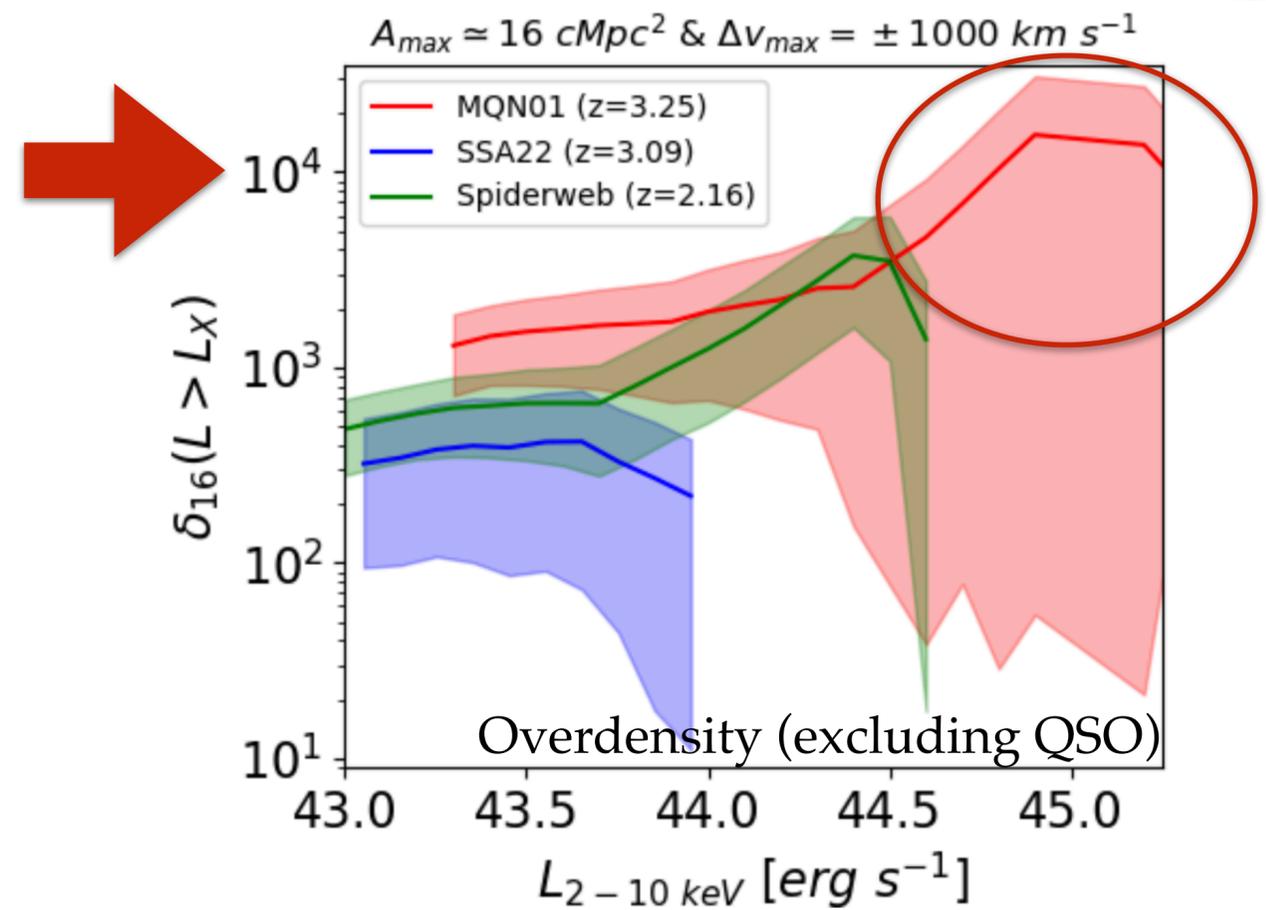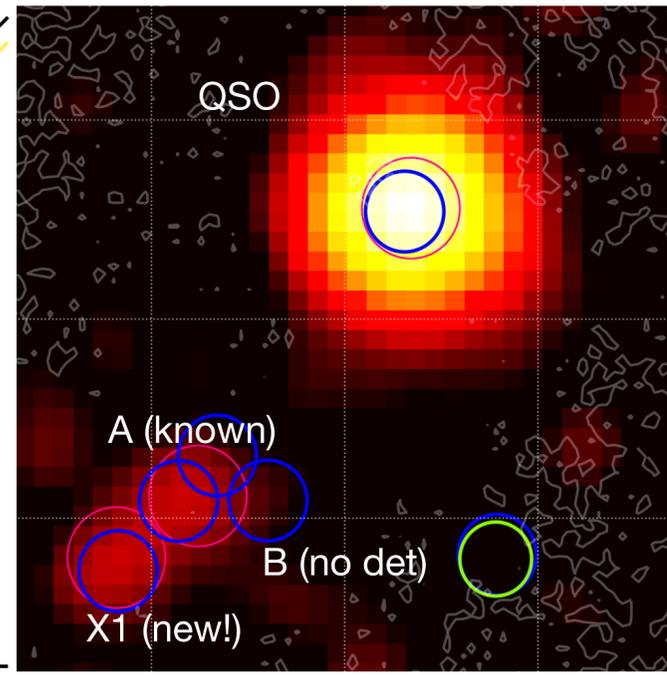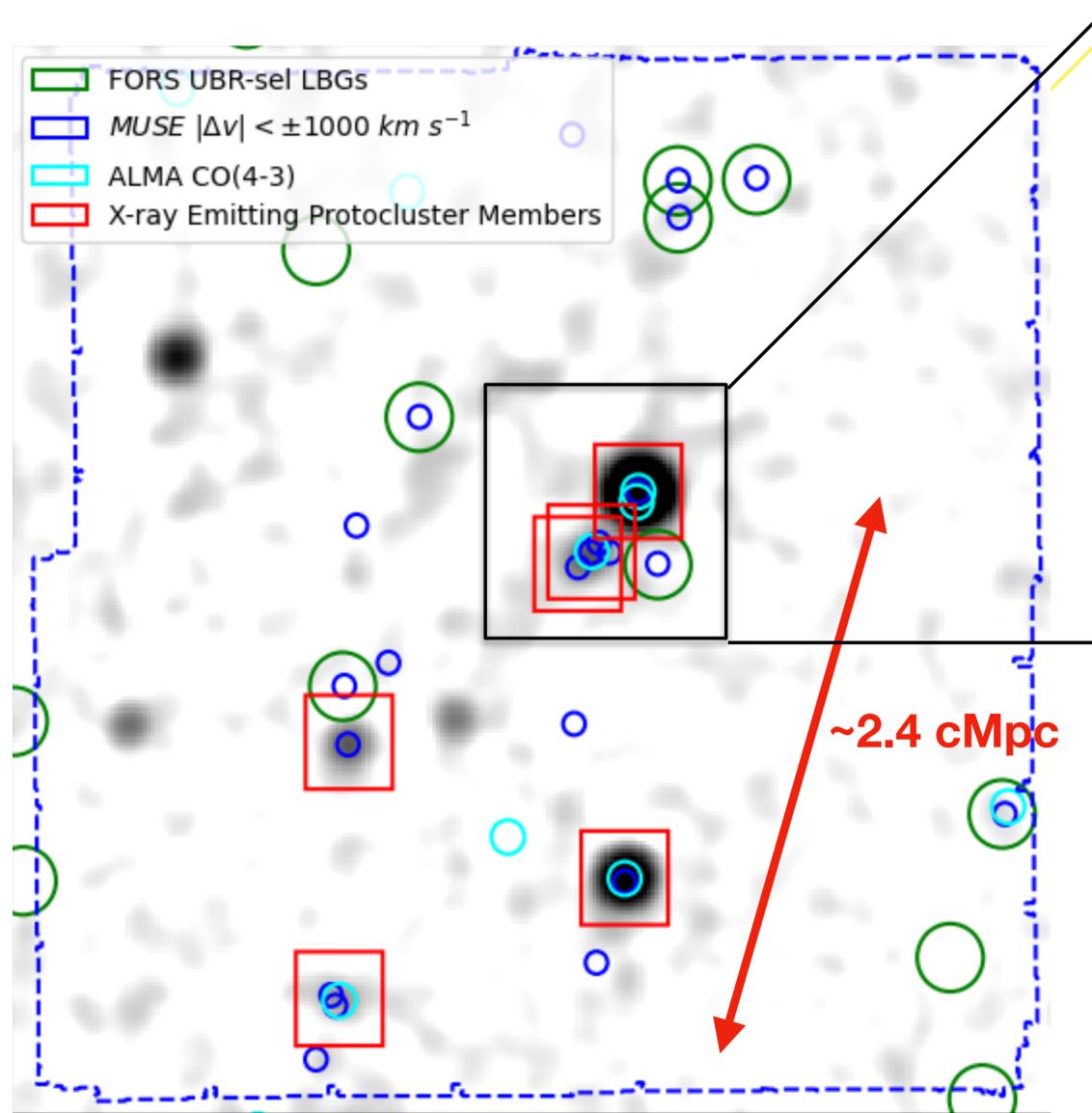Are massive, super-cold disks resilient to mergers or even promoted by them?

Pensabene,SC+, 2025

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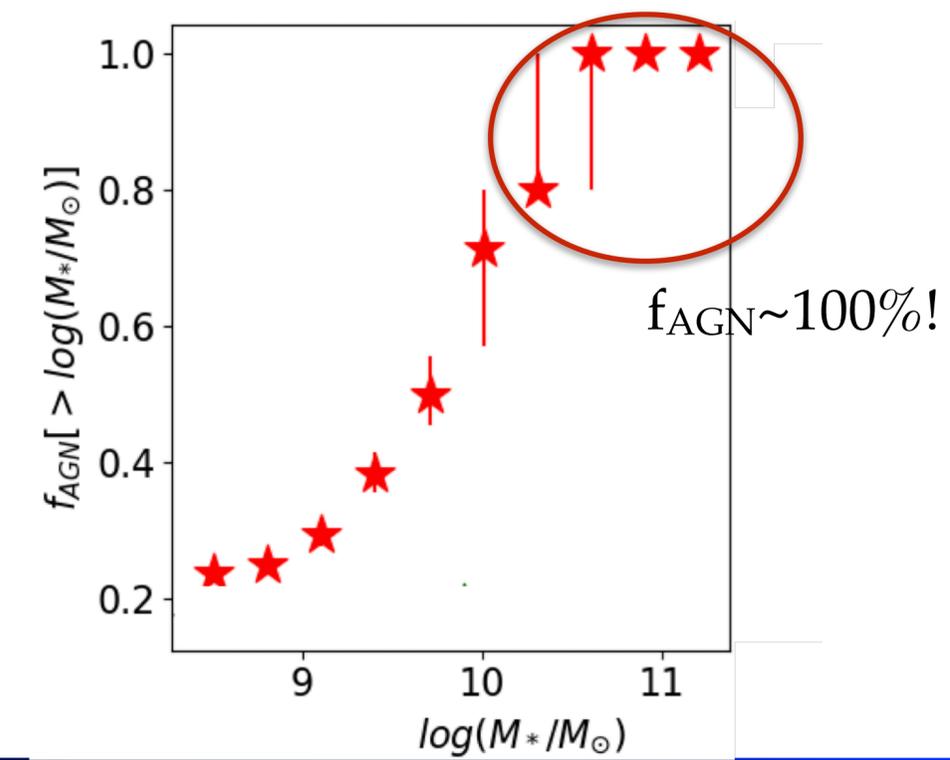
Tidal tail or outflow?

Pensabene,SC+, 2025

Legend:
- FORS UBR-sel LBGs
- *MUSE* $|\Delta v| < \pm 1000\ km\ s^{-1}$
- ALMA CO(4-3)
- X-ray Emitting Protocluster Members

QSO

A (known)

B (no det)

X1 (new!)

~2.4 cMpc

$A_{max} \simeq 16\ cMpc^2\ \&\ \Delta v_{max} = \pm 1000\ km\ s^{-1}$

- MQN01 (z=3.25)
- SSA22 (z=3.09)
- Spiderweb (z=2.16)

$\delta_{16}(L > L_X)$

$L_{2-10\ keV}\ [erg\ s^{-1}]$

Overdensity (excluding QSO)

5 X-ray AGN (excluding the quasar) at z=3.2 in 4 arcmin^2 !!

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

Potential AGN quadruplet in 10″!

$f_{AGN}[> log(M_*/M_\odot)]$

$log(M_*/M_\odot)$

$f_{AGN} \sim 100\%$!

Travascio, SC+, 2024

Spatial excess

Spectral excess

Travascio, SC+, 2025

Lyα contours
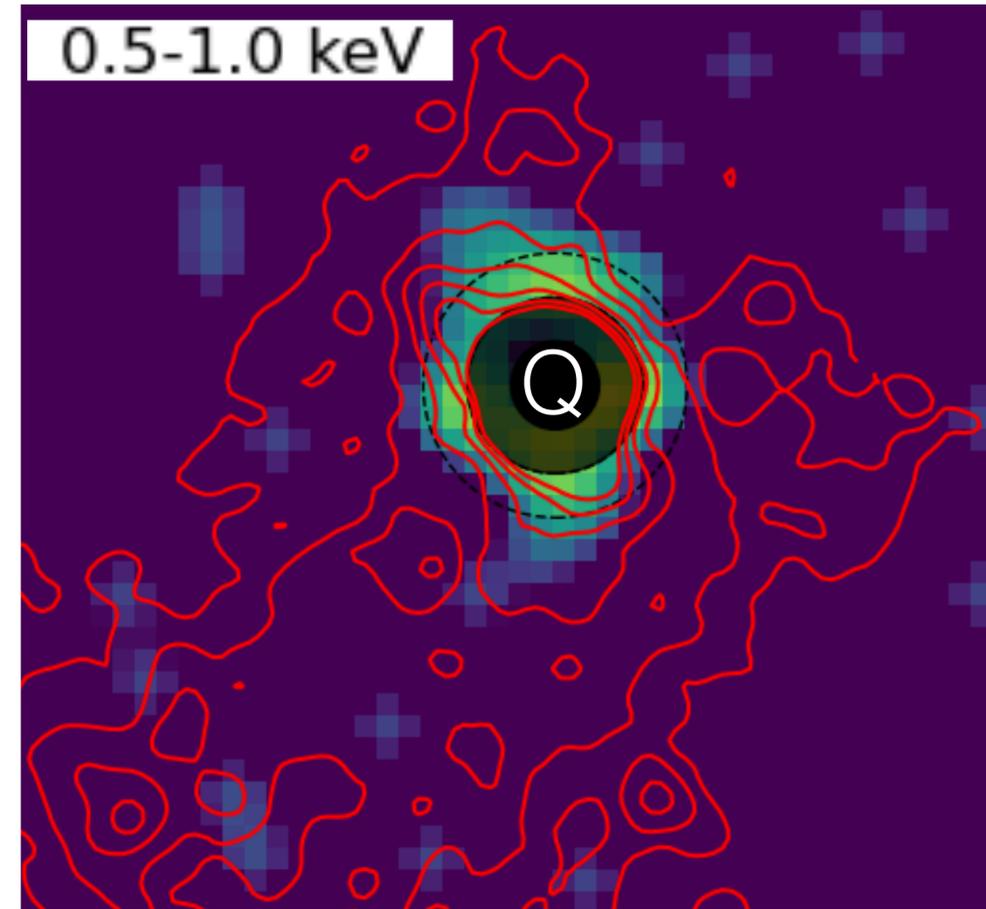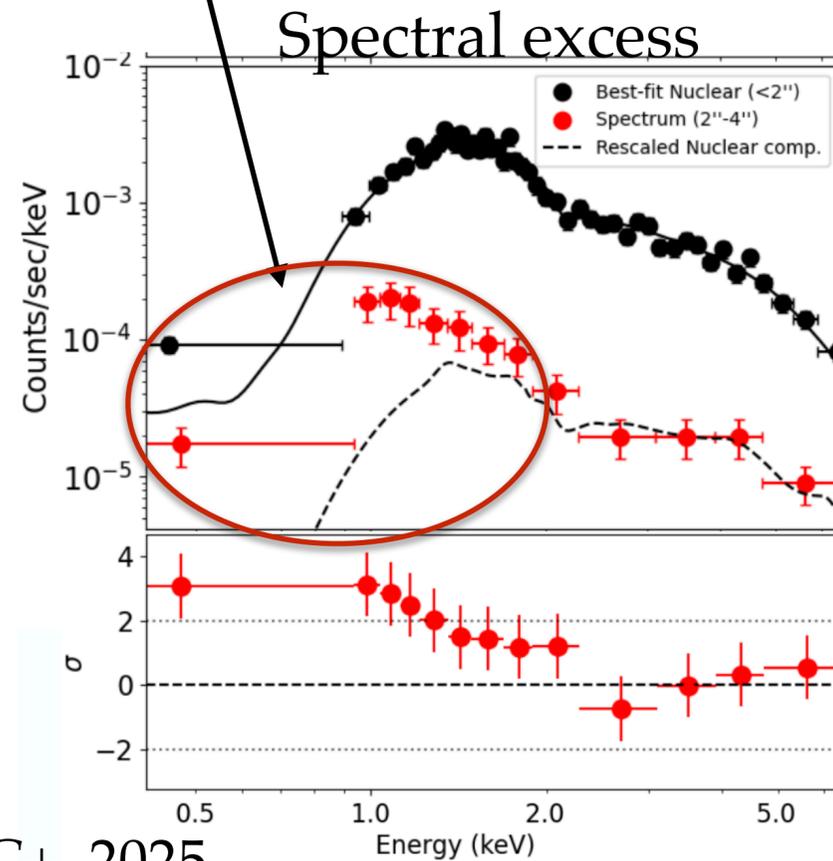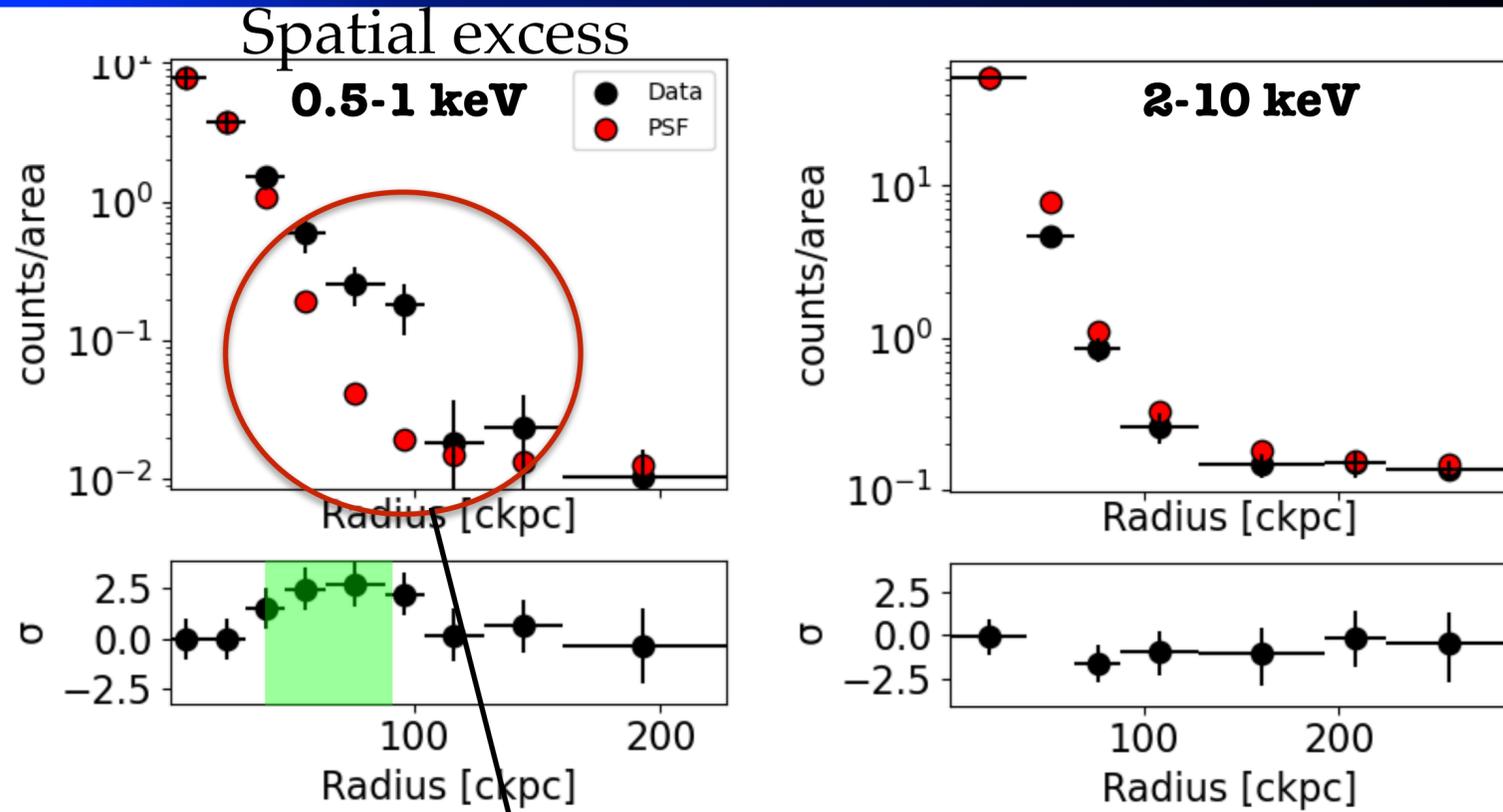
First detection of hot CGM / proto-ICM at z>3 (+ "warm/cold" component!)

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.

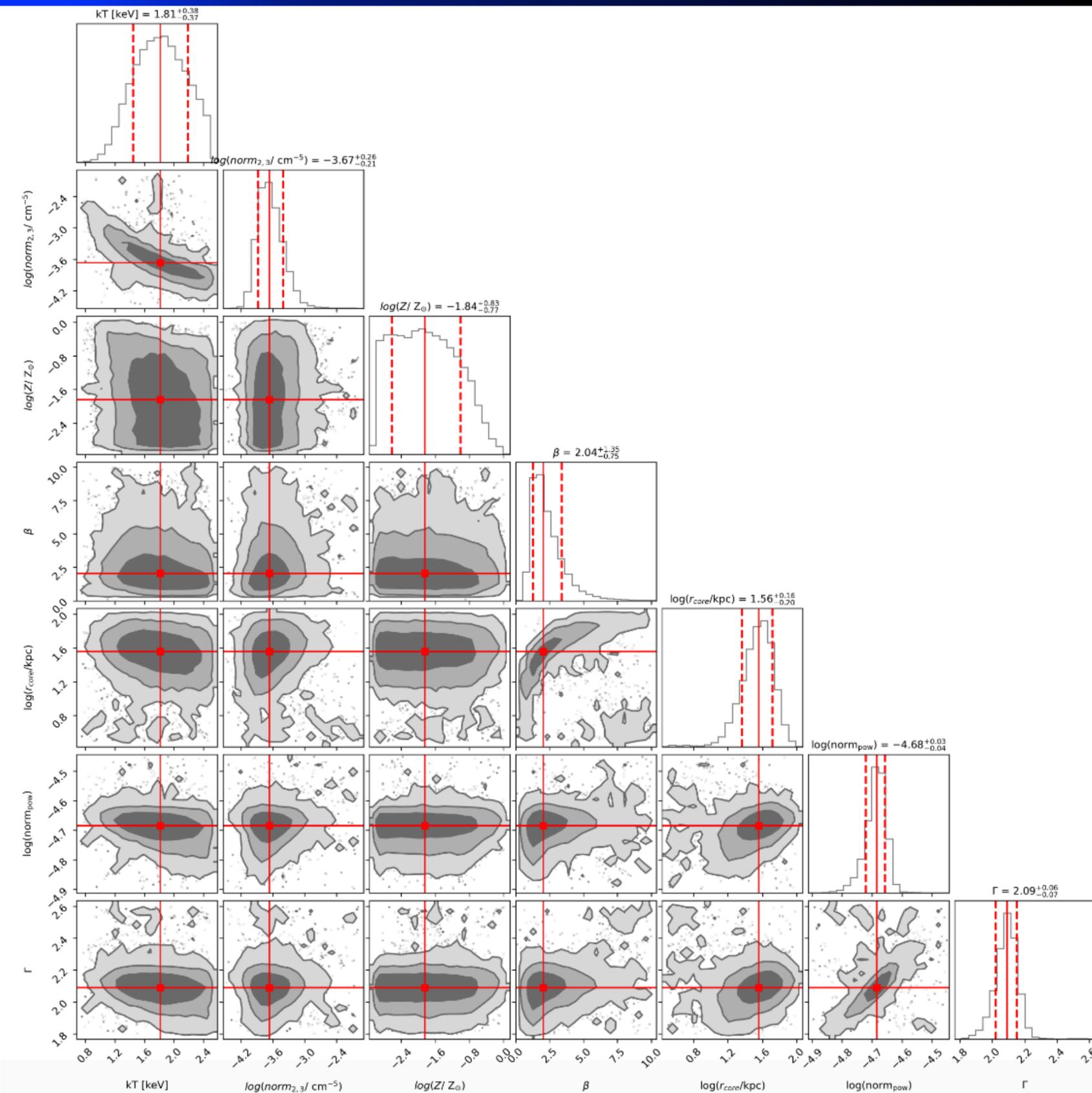**Table 1.** Median, 16th, and 84th percentiles of the posterior distributions from the MCMC analysis, along with the derived physical properties of the hot gas halo.

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

† parameter used as marginalization (not constrained)

Travascio, SC+, 2025

Left panel legend:
- DIANOGA: $\langle M_{vir} \rangle \sim 3 \times 10^{13} \, M_\odot$
- Spiderweb z=2.16 (blue triangle)
- MQN01 z=3.25 (red circle)

Axes: $(1+z)^4 \, SB_{0.5-2.0 \, keV}$ [cgs arcsec^{-2}] vs r [kpc]

Right panel legend:
- Best − Fit β − model MQN01
- Spiderweb (L24, Fig. 7)
- DIANOGA Hot Halos

Axes: $n_e(r)$ [cm^{-3}] vs r [kpc]
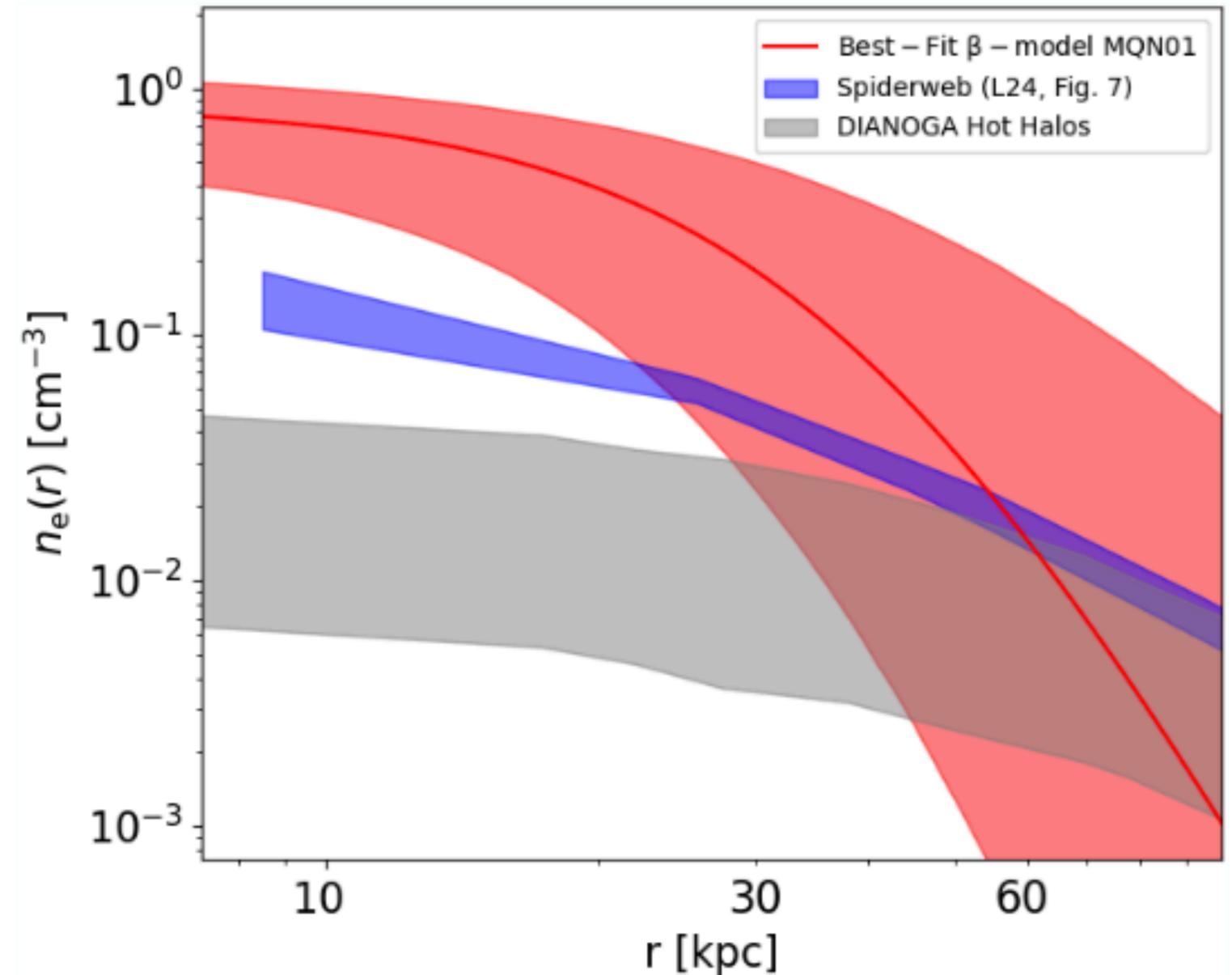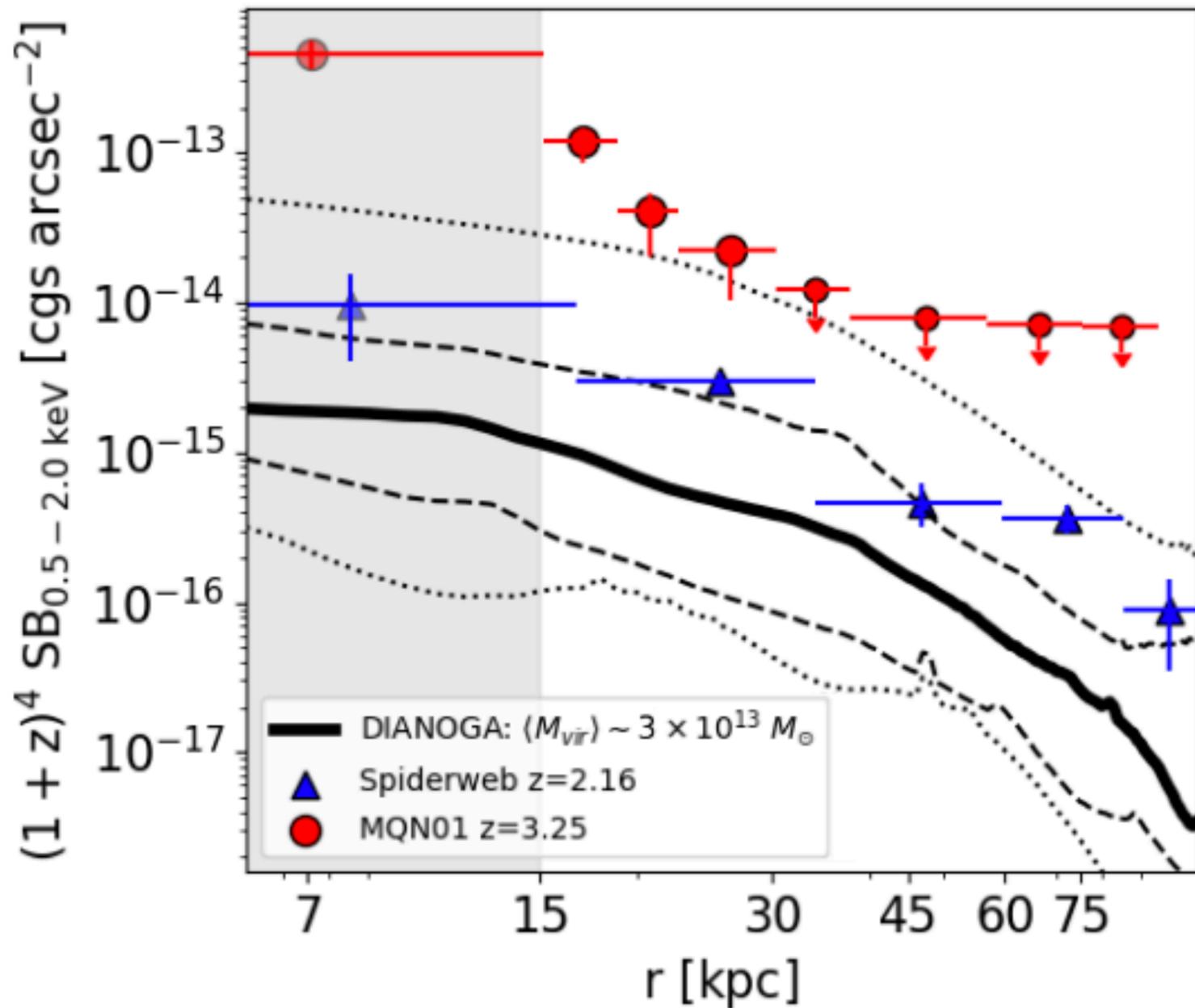
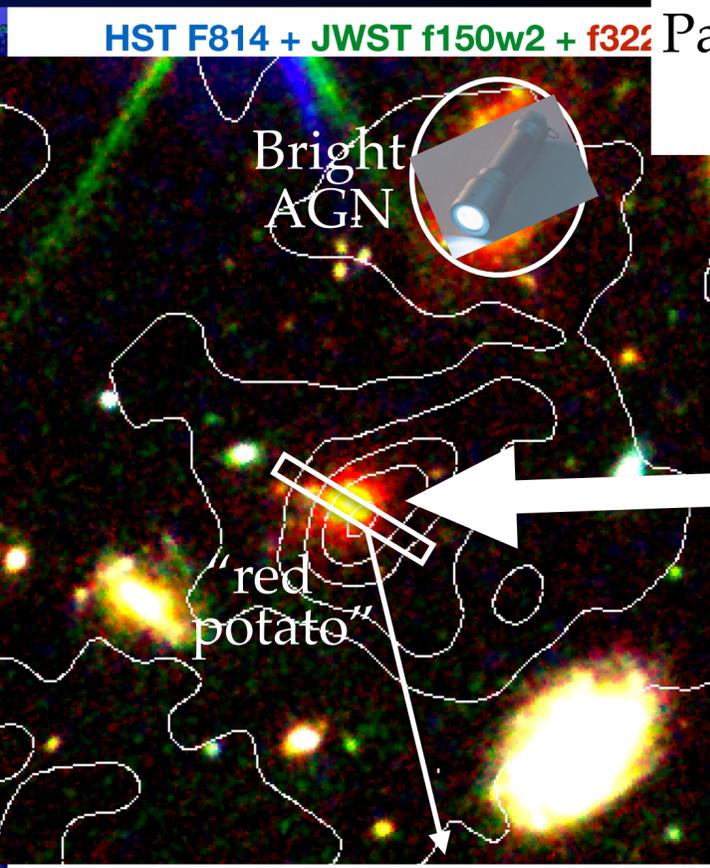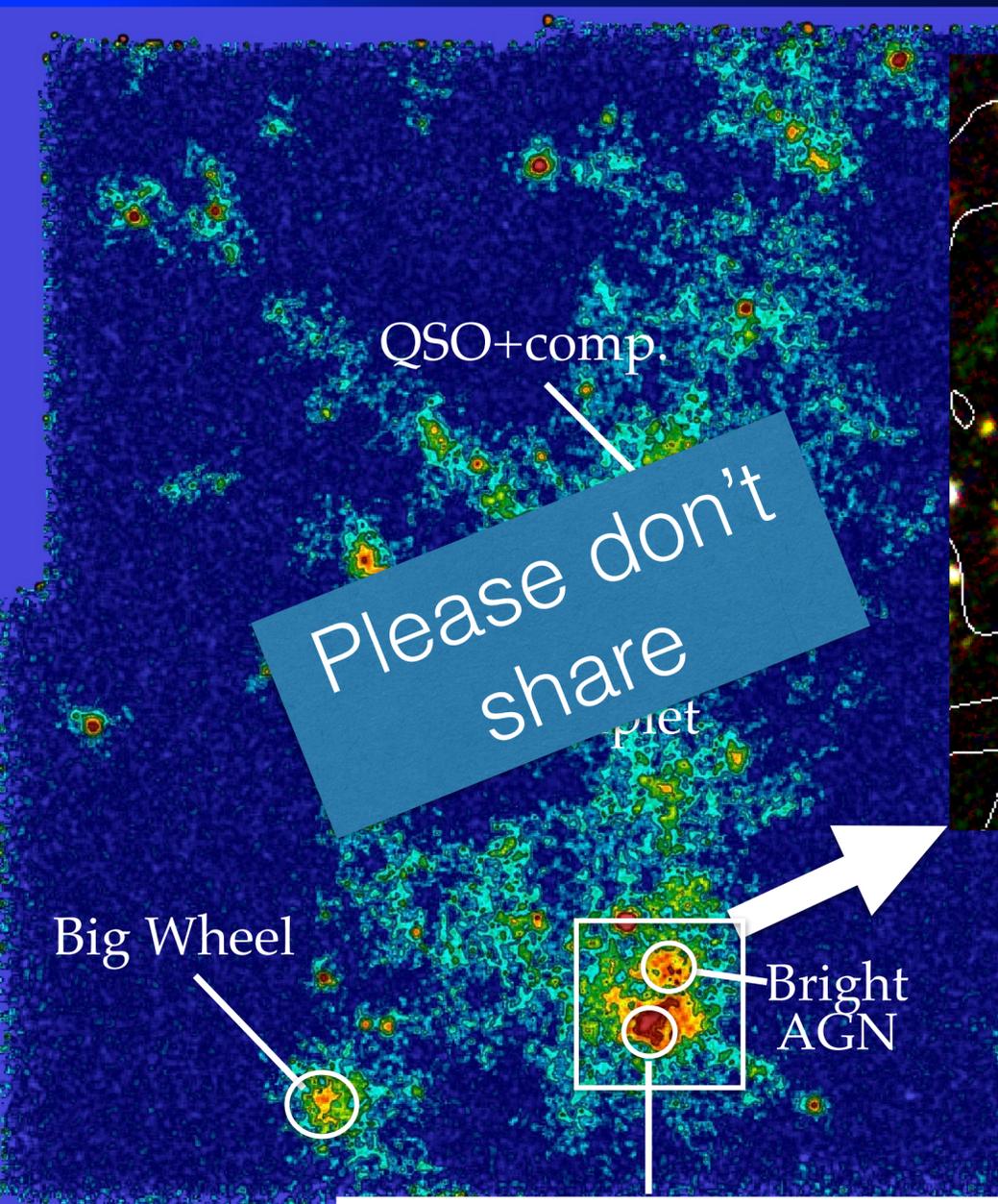▶ 100x brighter and >10x denser (in the inner CGM) than typical DIANOGA haloes!

▶ Enough pressure to pressure-confine dense cold Ly-alpha emitting gas ("clumps")

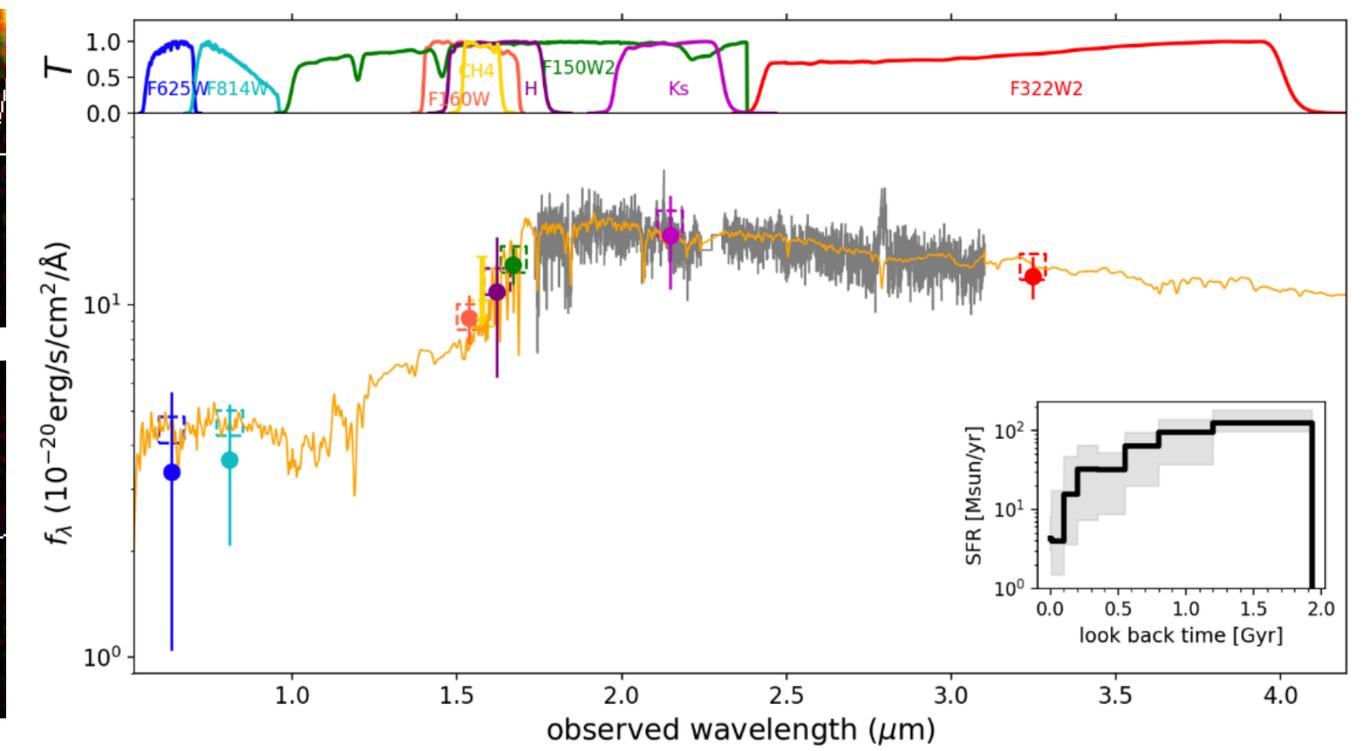▶ $1 < t_{cool}/t_{ff} < 10$ suggesting possible thermal instabilities in the inner hot CGM
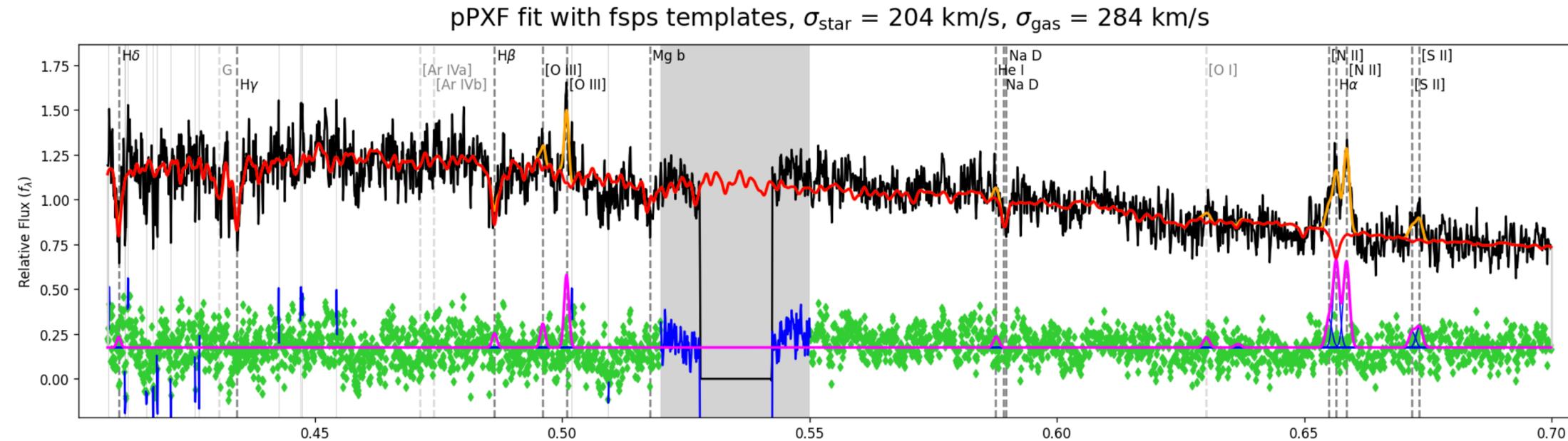
Travascio, SC+, 2025

Passive (not dusty!) galaxy with $M_{star} \sim 10^{11}\,M_\odot$ and SFR$<3\,M_\odot/$yr

(sSFR at least one dex below the main sequence)

HST F814 + JWST f150w2 + f322

Bright AGN

QSO+comp.

Please don't share

Big Wheel

Bright AGN

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

pPXF fit with fsps templates, $\sigma_{star} = 204$ km/s, $\sigma_{gas} = 284$ km/s

Wang W, SC+, submitted (arXiv:2601.20473)
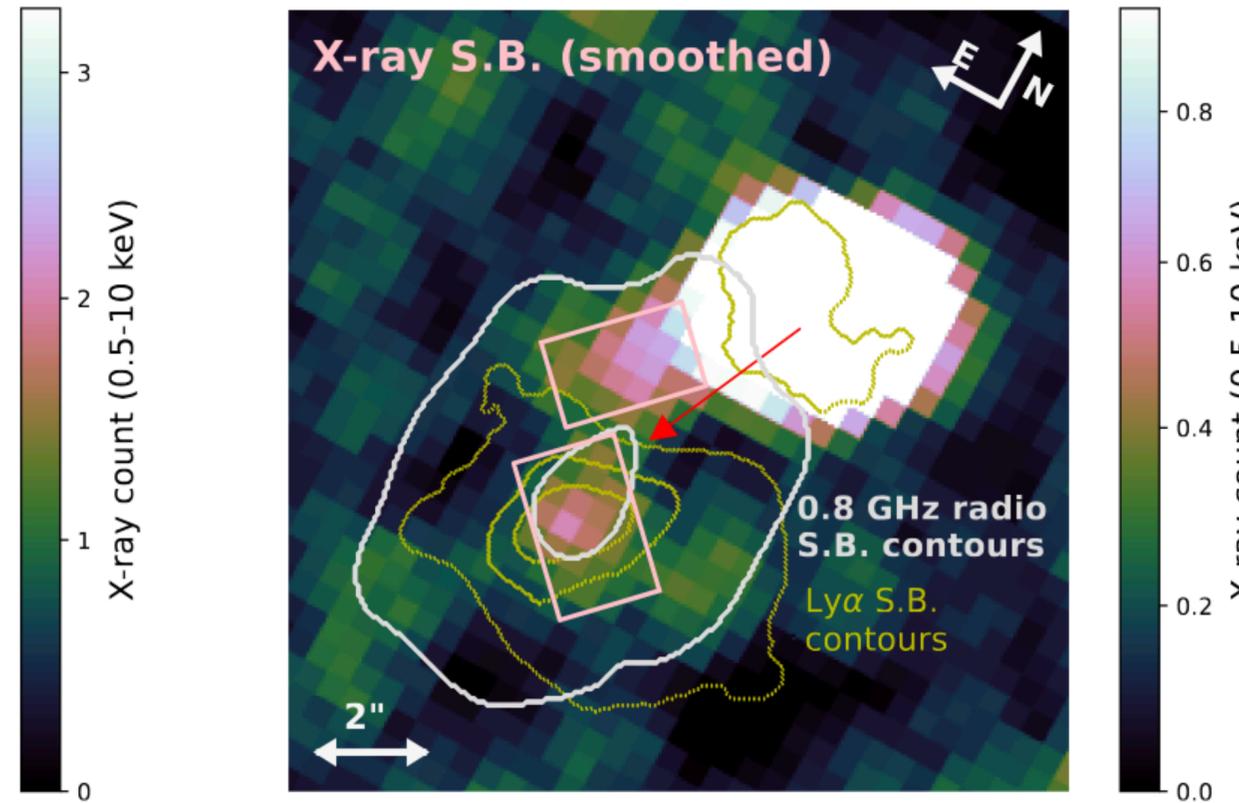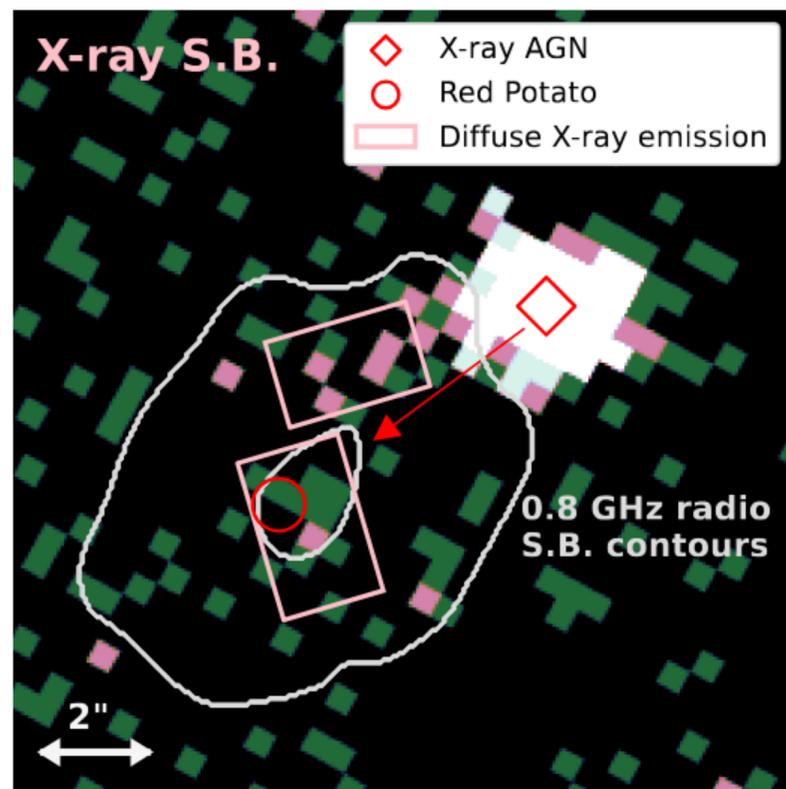
Redshift and SED confirmed by Balmer absorption lines.
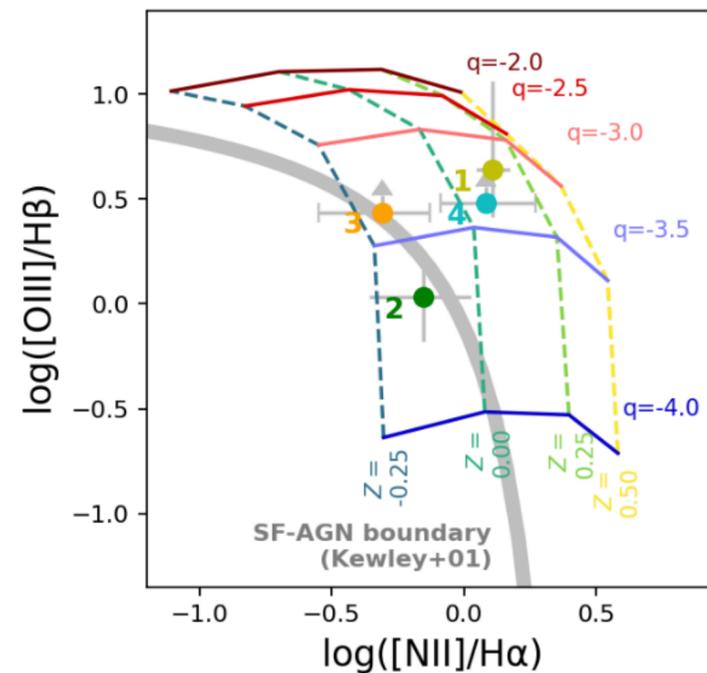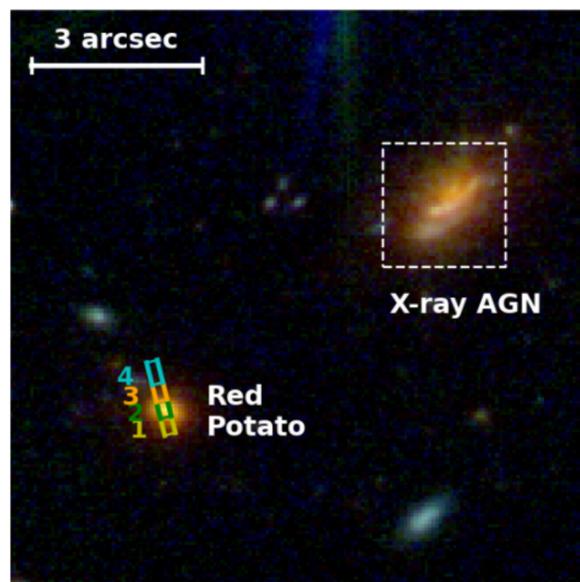What is a passive galaxy doing in the middle of a large gas reservoir?
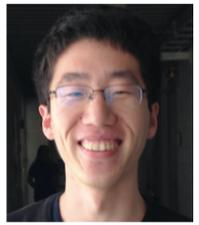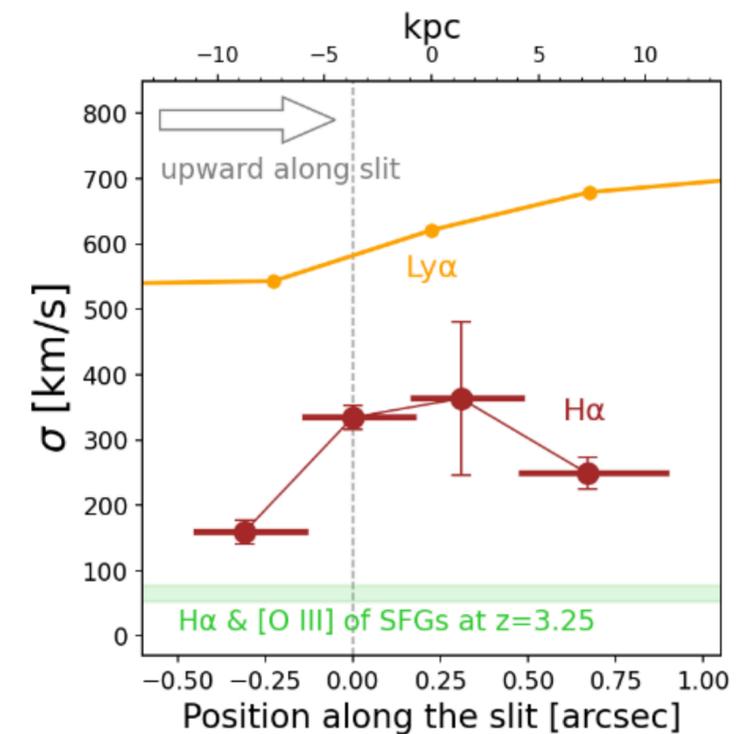
Evidences for a "external" AGN jet:
- radio detection in ASKAP (20" beam)
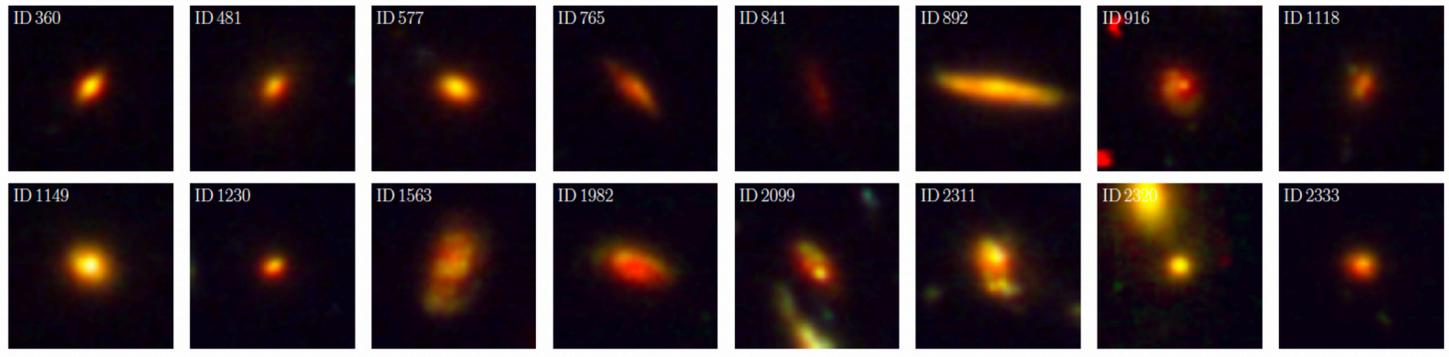- X-ray (low SNR) detection

Hα kinematics suggests "turbulent" CGM around the Red Potato:

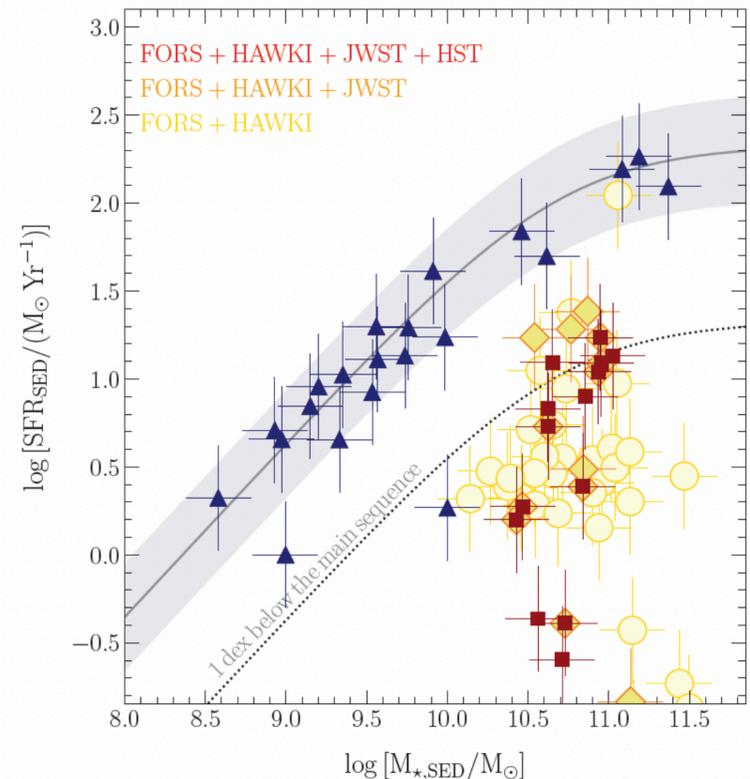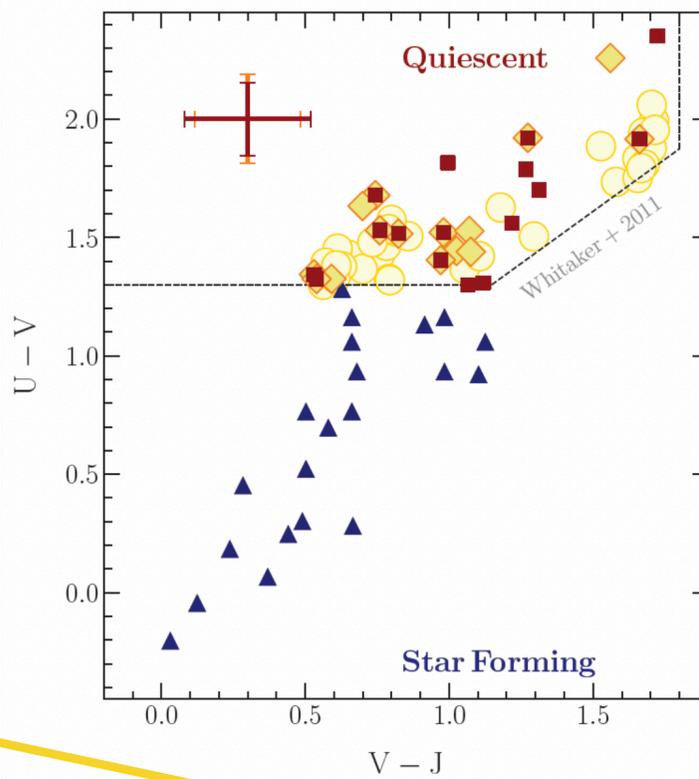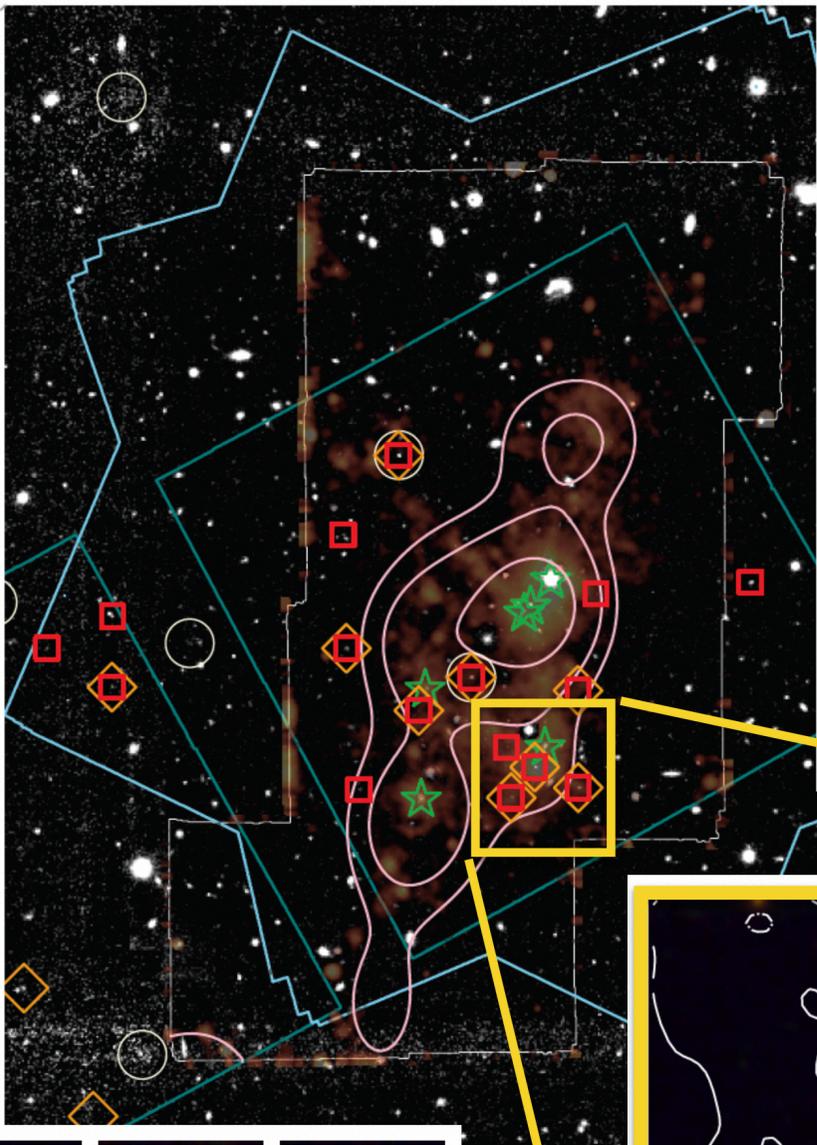There is no active AGN in Red Potato:
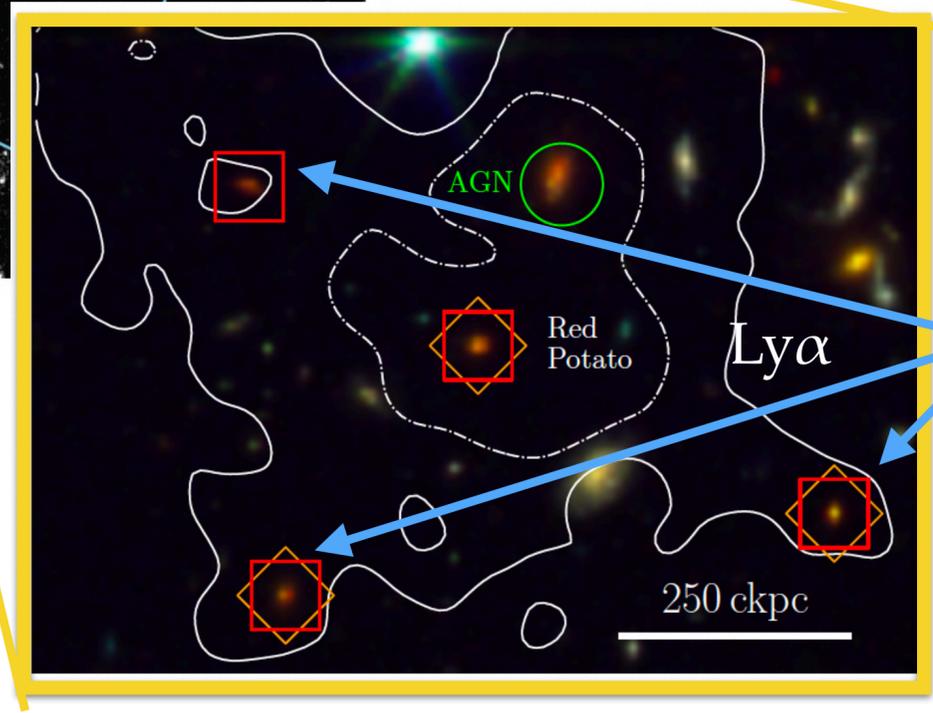- Resolved BPT suggests "external illumination"

Wang W, SC+, submitted (arXiv:2601.20473)

Searching for passive and massive galaxies in MQN01 through rest-frame optical/NIR photometry

Some passive galaxies have disk morphology!
(no dust using deep ALMA data)

Passive galaxies within/
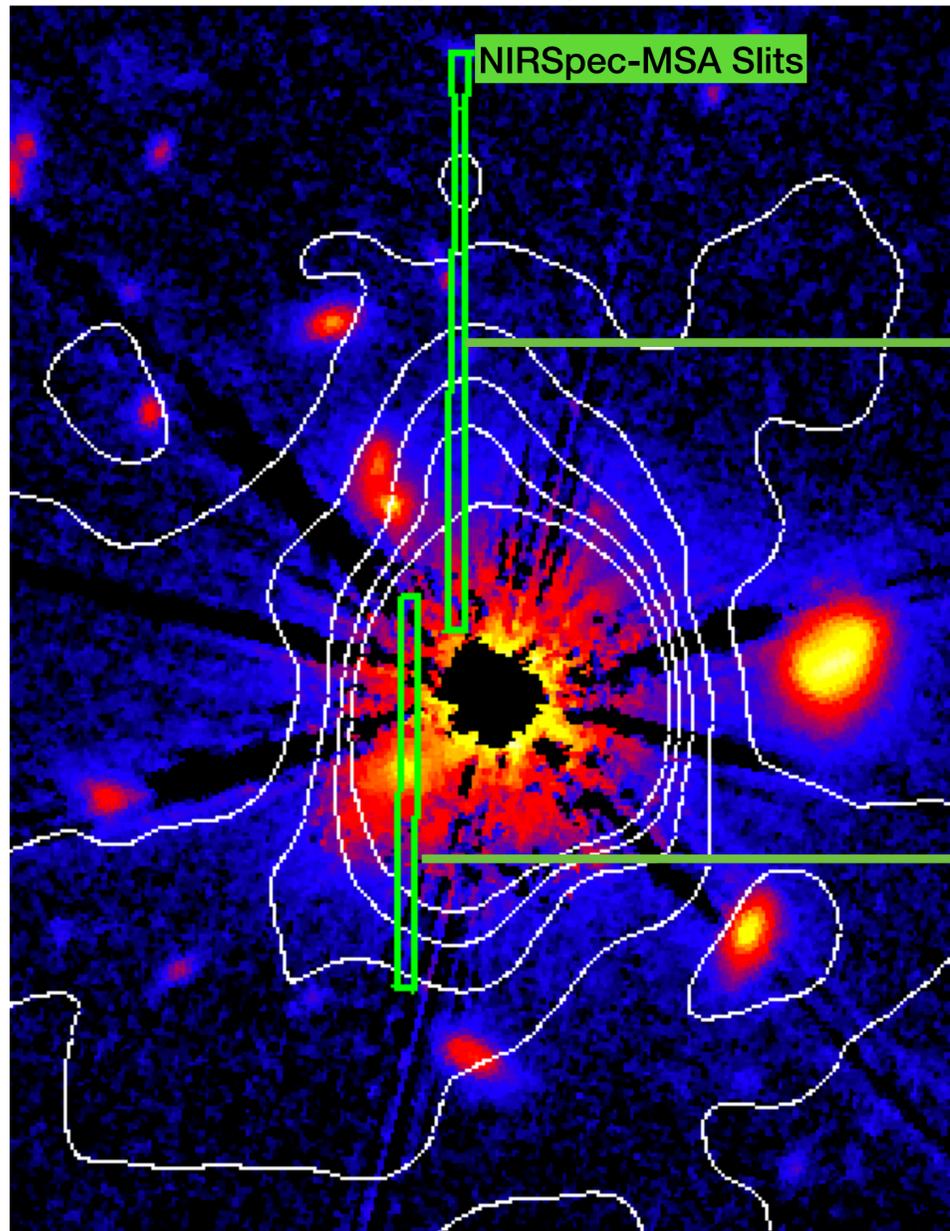along gas filaments!

Galbiati, SC+, in prep.

NIRCam image + Lyα contours

NIRSpec-MSA Slits

NIRSpec 2D Spectrum

Hα   NII

$\mathrm{erg\,/\,s\,/\,cm^2\,/\,arcsec^2\,/\,\mathring{A}}$
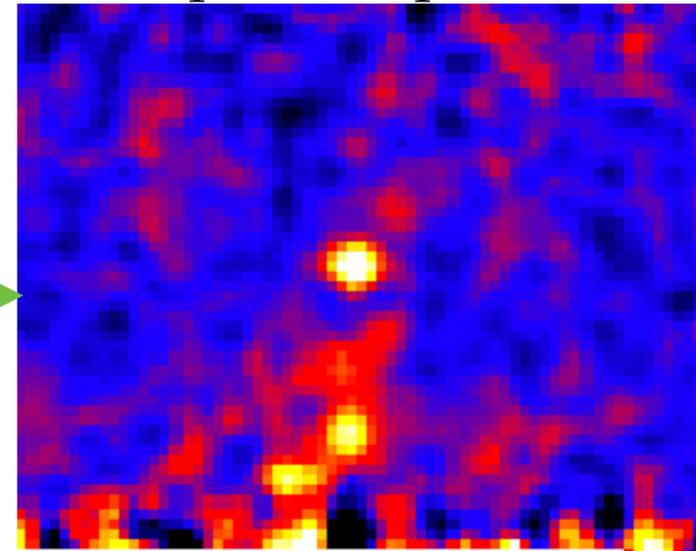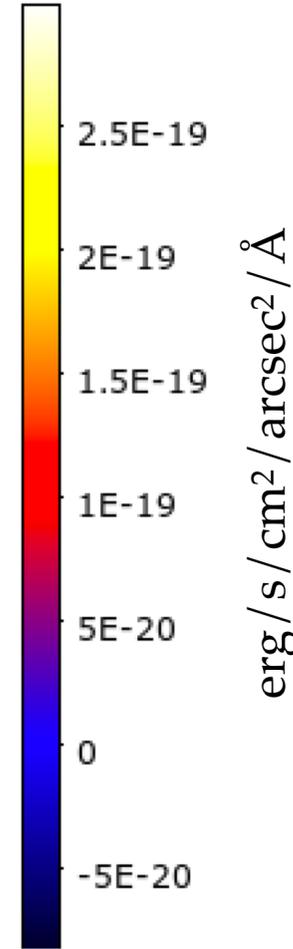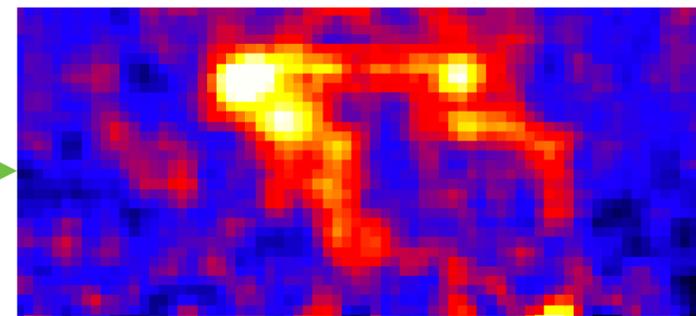
Hα SB as high as Lyα SB (!)
(but MSA slit width smaller than
MUSE spatial resolution)

IFU observations needed to get
proper line ratio and emission 2D
morphology (JWST IFU required)
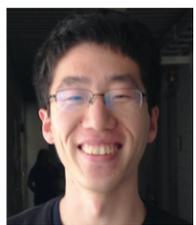
Wang, SC+, in prep.

PRELIMINARY

Lyα/Hα~8
(broader Lyα)
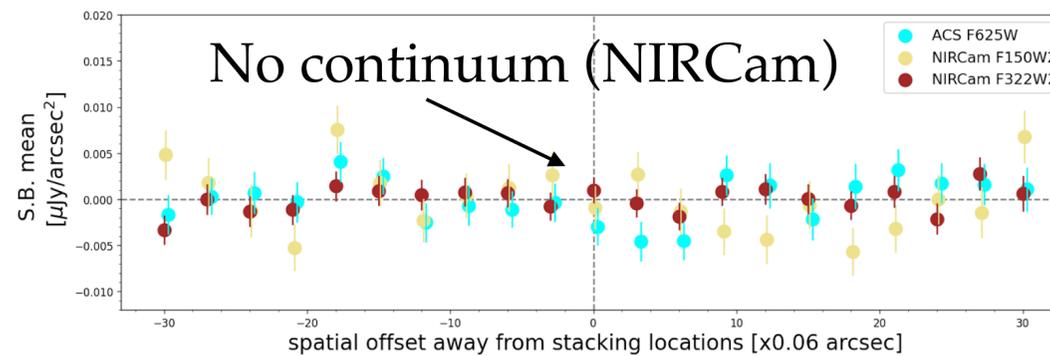
No continuum
In deep stack
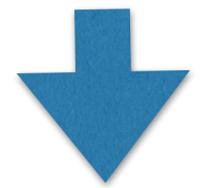
Consistent with
Fluorescent emission
SB can be used to
directly constrain
"warm" gas density!
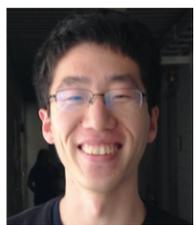
Wang, SC+, in prep.

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

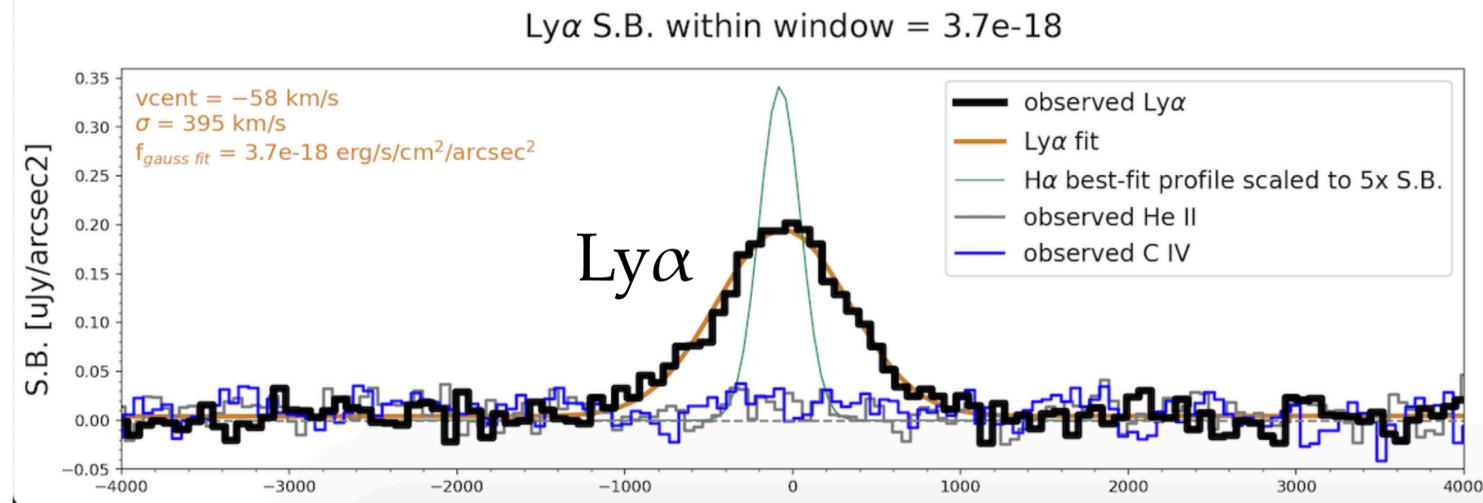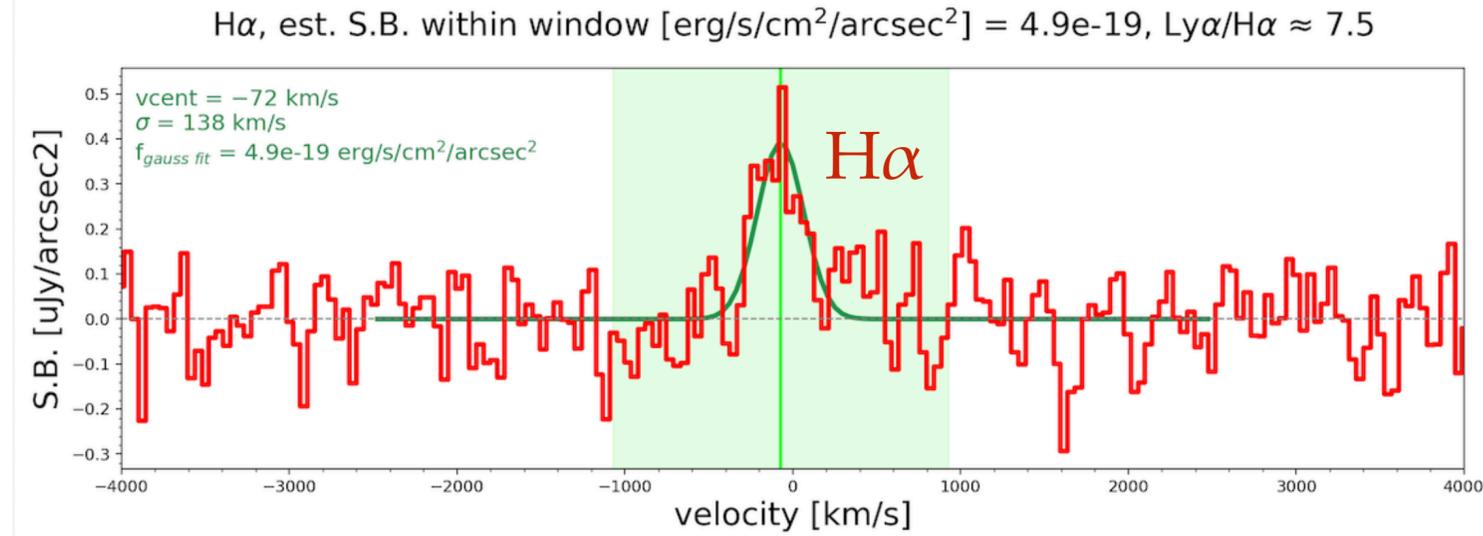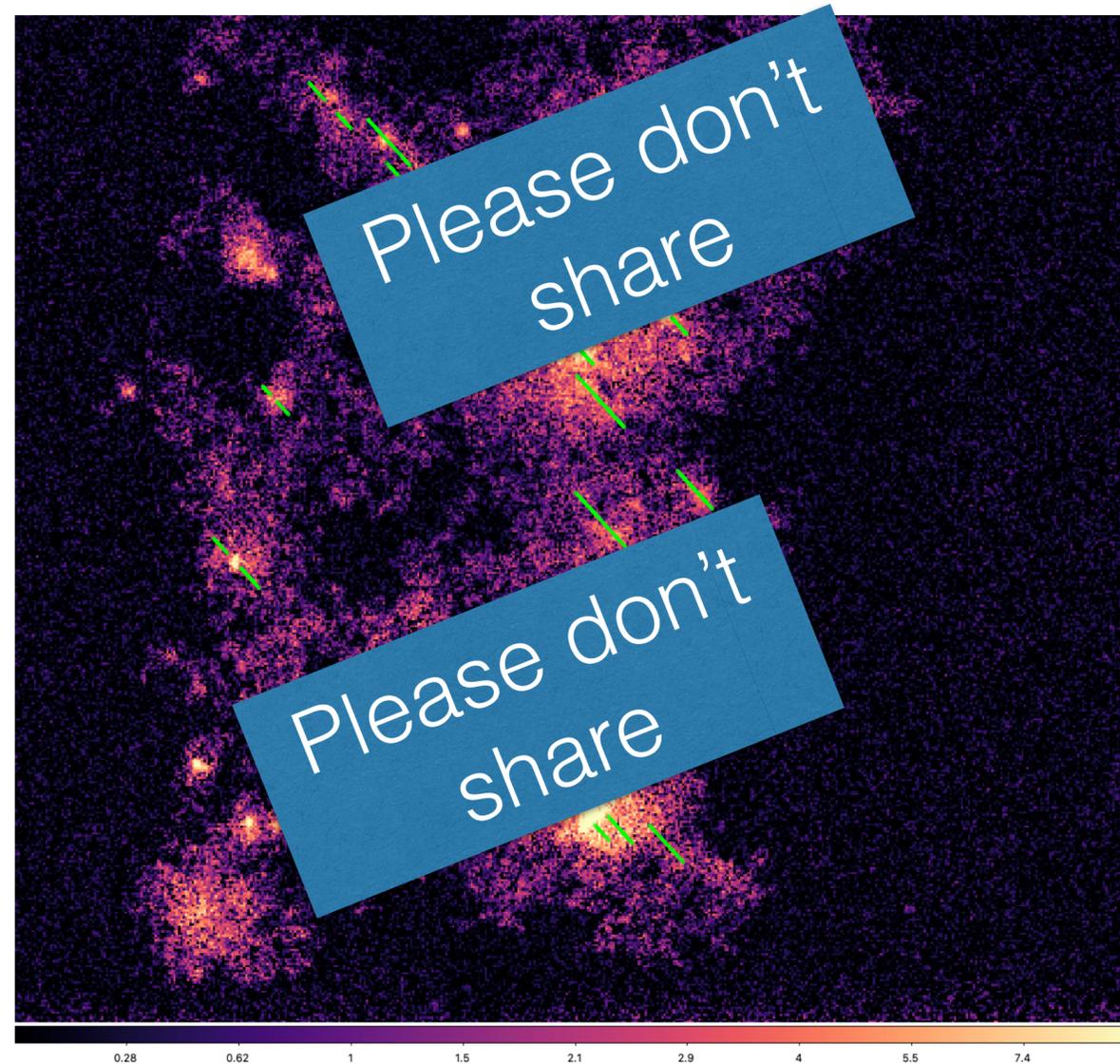80+ hours of MUSE obtained to map full structure in Lyα emission (observations recently completed).

Constraining dark matter properties using clumpiness and morphology of filaments (Lazeyras, SC+, in prep.)
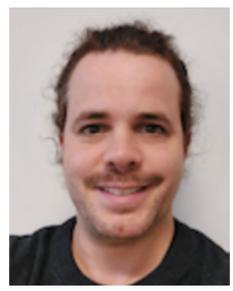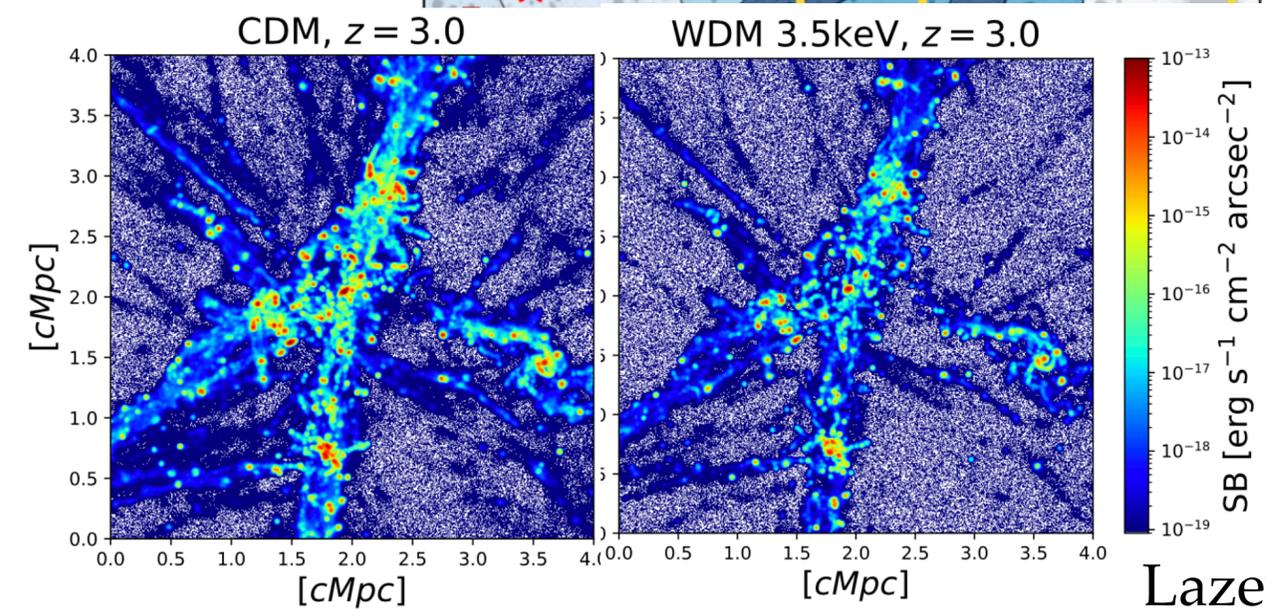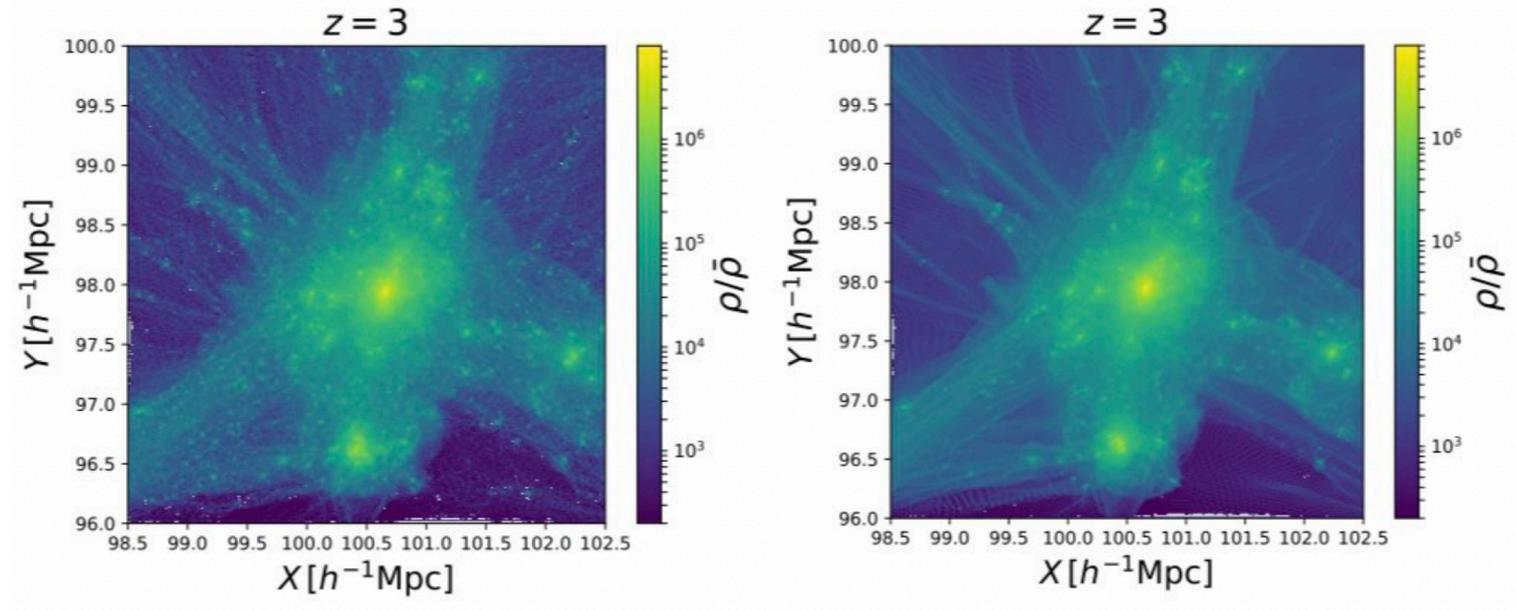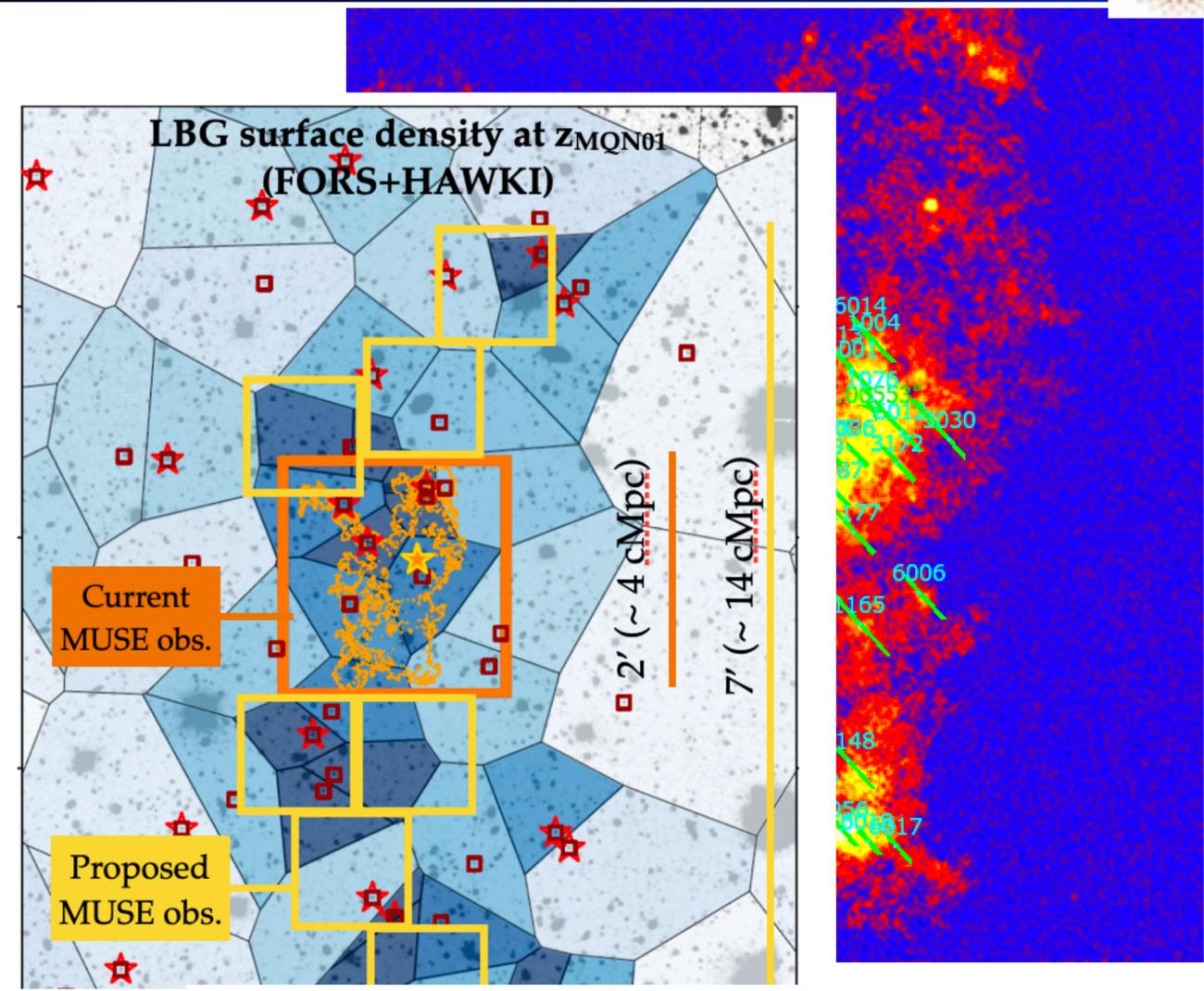
LBG surface density at z_{MQN01} (FORS+HAWKI)

Current MUSE obs.

Proposed MUSE obs.

$2'\ (\sim 4\ cMpc)$

$7'\ (\sim 14\ cMpc)$

$z = 3$

$z = 3$

CDM, $z = 3.0$

WDM 3.5keV, $z = 3.0$

SB [erg s^{-1} cm^{-2} arcsec^{-2}]

Lazeyras, SC+, in prep.

Lyα (gas)

Lyα (gas)

Cantalupo+, to be submitted

4' (8 cMpc)

Please don't share

Please don't share

Please don't share

Please don't share

Cantalupo+, to be submitted

SF Galaxies overdensity

Original mosaic: 4' cMpc

SF node

QG node
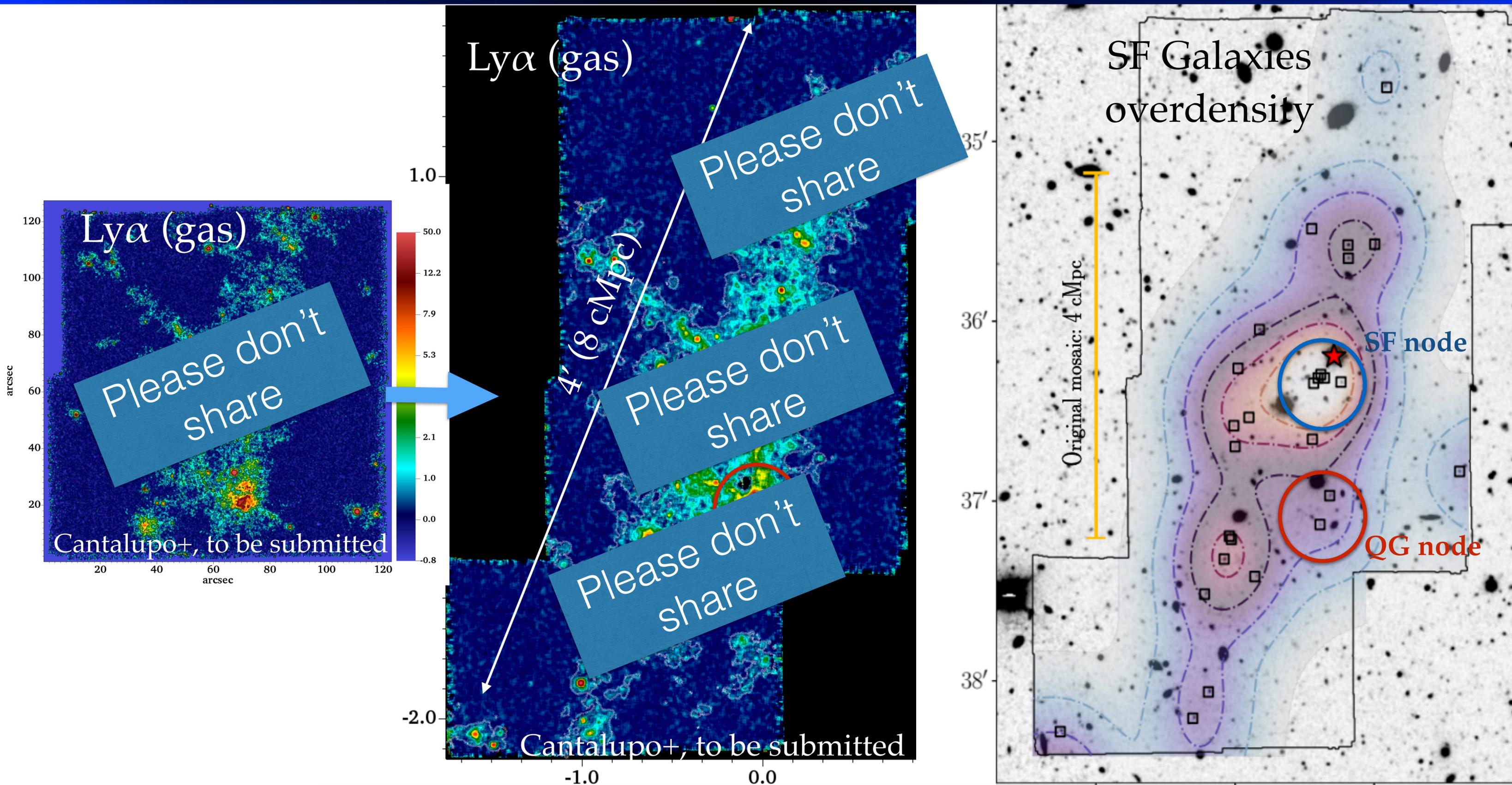
Summary, some open questions and future outlook

We can finally study Cosmic gas in emission and related it to galaxy properties across different environments on both small (<kpc) and large (>Mpc) scales thanks to Quasars and new instruments such as MUSE/VLT

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?

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!