Illuminating the Sakura Web with Fluorescent Lyα Emission

Sebastiano Cantalupo

ETH zürich | FNSNF | muse

In collaboration with many people, including: **Cosmic Structure Formation Group at ETH, MUSE GTO Team (ETH, CRAL, Leiden, AIP, IRAP, Gottingen)** J. X. Prochaska, Sakura Slug, P. Madau (UCSC), F. Arrigoni-Battaia (ESO), Joe Hennawi (UCSB), M. Haehnelt (IoA)

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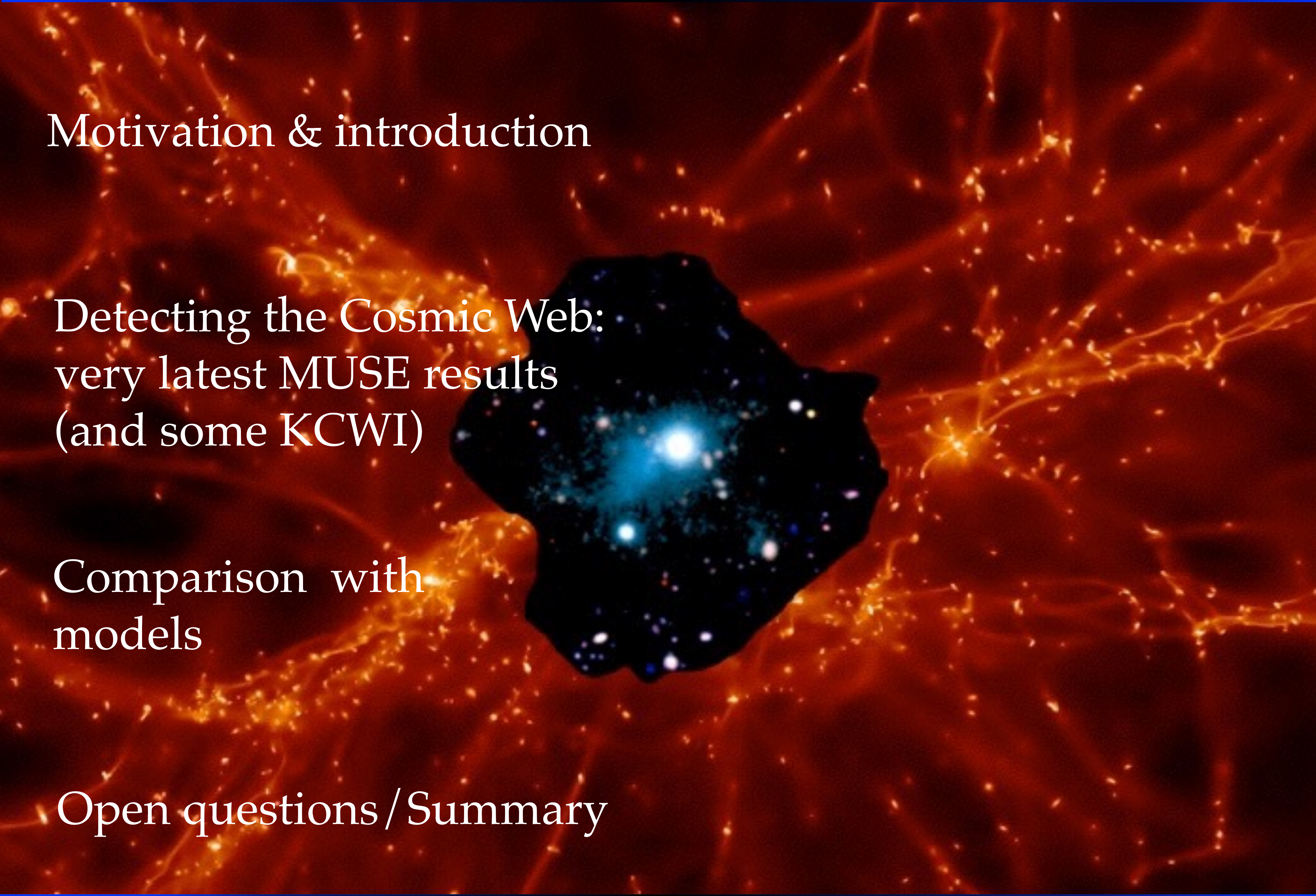
Talk Outline



Motivation & introduction

Detecting the Cosmic Web:
very latest MUSE results
(and some KCWI)

Comparison with
models

Open questions/Summary

We are all *familiar* with the "Cosmic Web"…

… *as seen in hundreds of **simulations**.*

How about the *real universe*?

How are galaxies linked to each other?
What are the morphology and the small scale properties of the "Cosmic Web"?

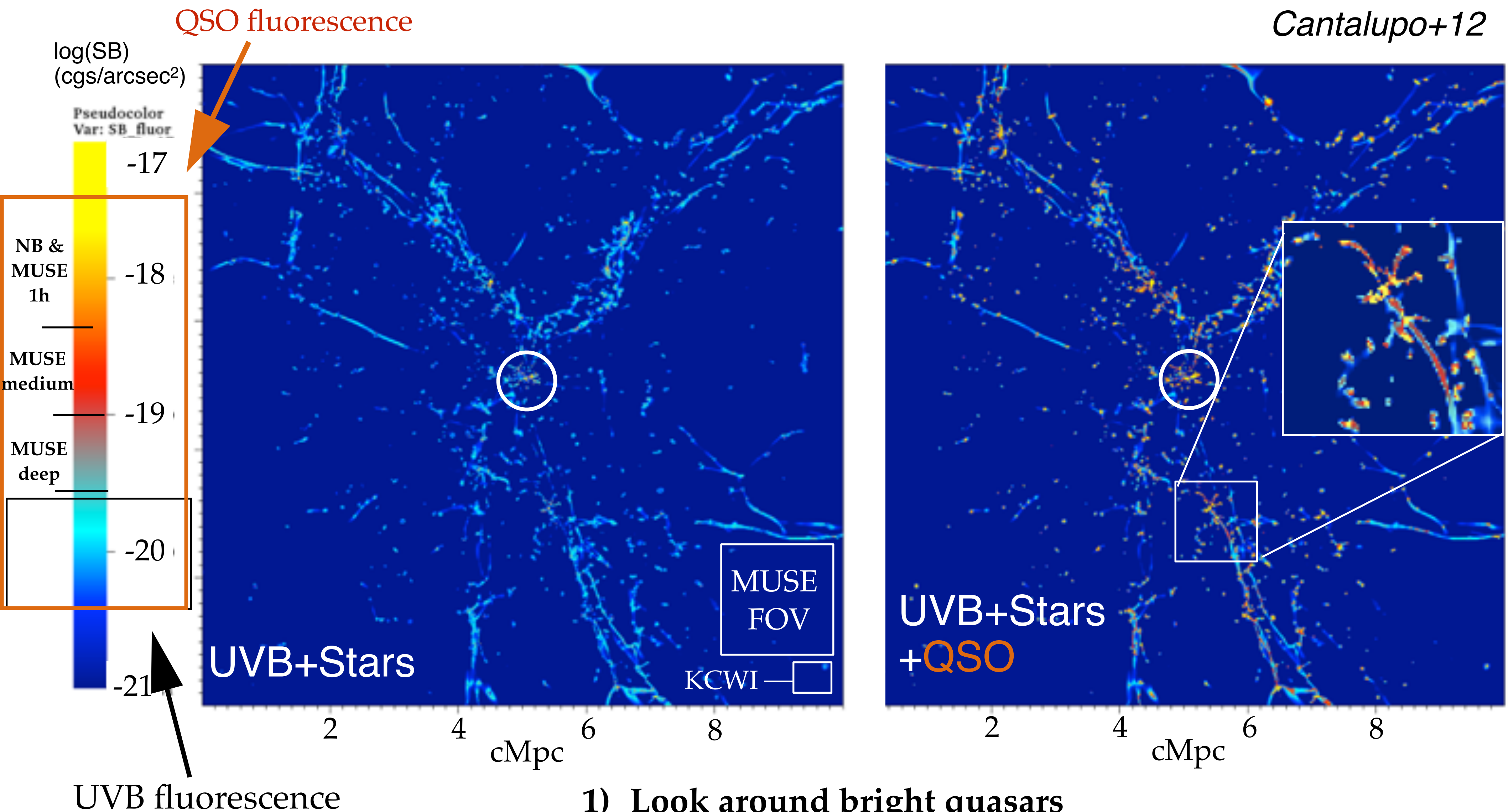
How do galaxies get their gas?
What are the density and temperature of the "Circum Galactic Medium"?

Direct Imaging needed

Movie credits: M. Vogelsberger

The Cosmic Web in fluorescent Lyα emission: expectations

Simulated Lyα images at z~2.5 (20Å NB; no noise/PSF) centred on a ~10^{13} M_{sun} halo
hydro-simulation (`RAMSES`) + Radiative Transfer (`RADAMESH`, SC+12)

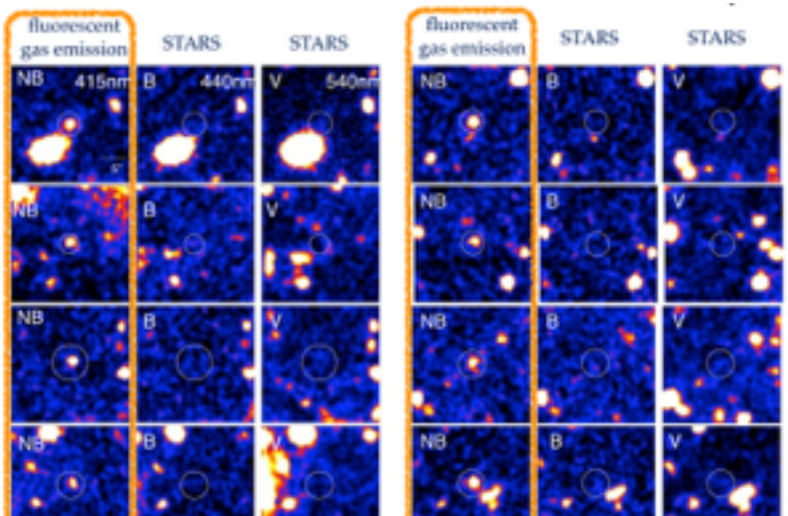


How to detect it?

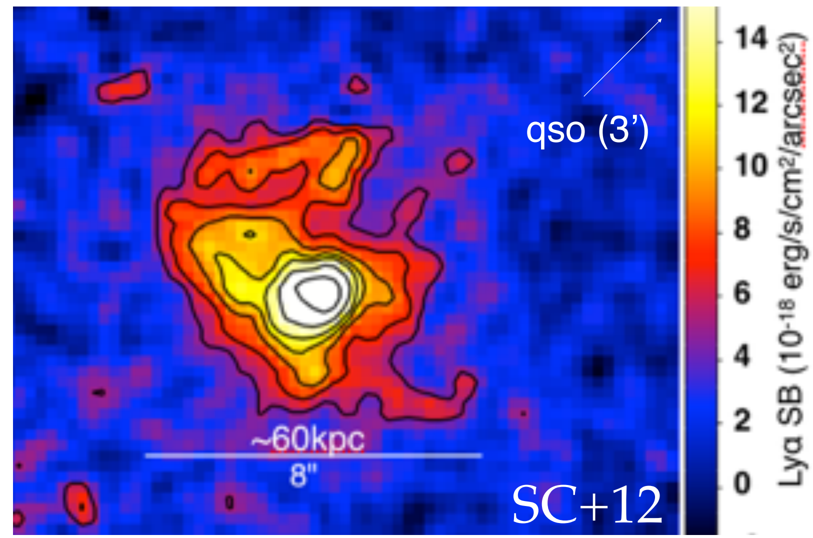
1) **Look around bright quasars**
2) "Stack" for statistical detection (Gallego, SC+2018; see Sofia's poster on 10th floor)
3) Integrate for 100+ hours away from quasars

Highlights from Narrow-Band imaging survey of Quasar fields at z~2.3

Compact fluorescent emitters without stellar counterparts ("Dark galaxies")
SC+12, see also Marino, SC+18



CGM in emission around a bright galaxy



Morphology and SB compatible with "cold filaments"

Giant Quasar Nebulae: the Slug

Cantalupo+14, *Nature*

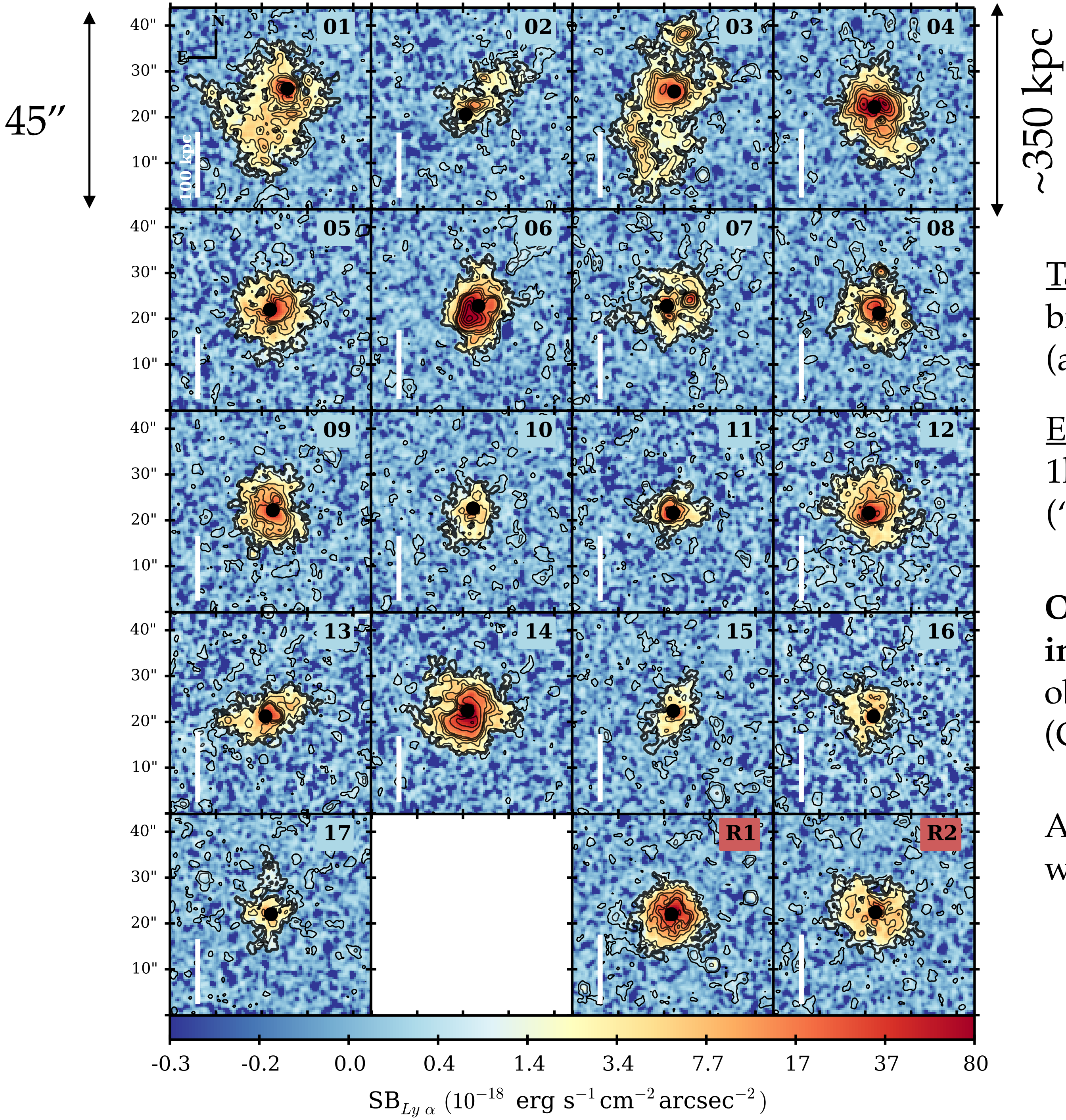
+ other 25 QSOs (FLASHLIGHT Keck+GMOS survey; Cantalupo+, in prep.; Arrigoni-Battaia, SC+, 2016)

main results:

- Giant Nebulae (>100kpc) are **rare** in NB surveys (<10%) at z~2.3, only a few found so far.
- Morphology and "kinematics" compatible with CGM/IGM but **Surface Brightness is too high** for expected gas densities (see later).

…then, finally, came MUSE

MUSE observations of QSOs at z~3.5: 100% detection rate of giant nebulae!



MUSE

Targets:
brightest radio-quiet QSOs at 3<z<4
(and two radio-loud, R1 & R2)

Exposure times:
1h only total integration
("snapshot" survey)

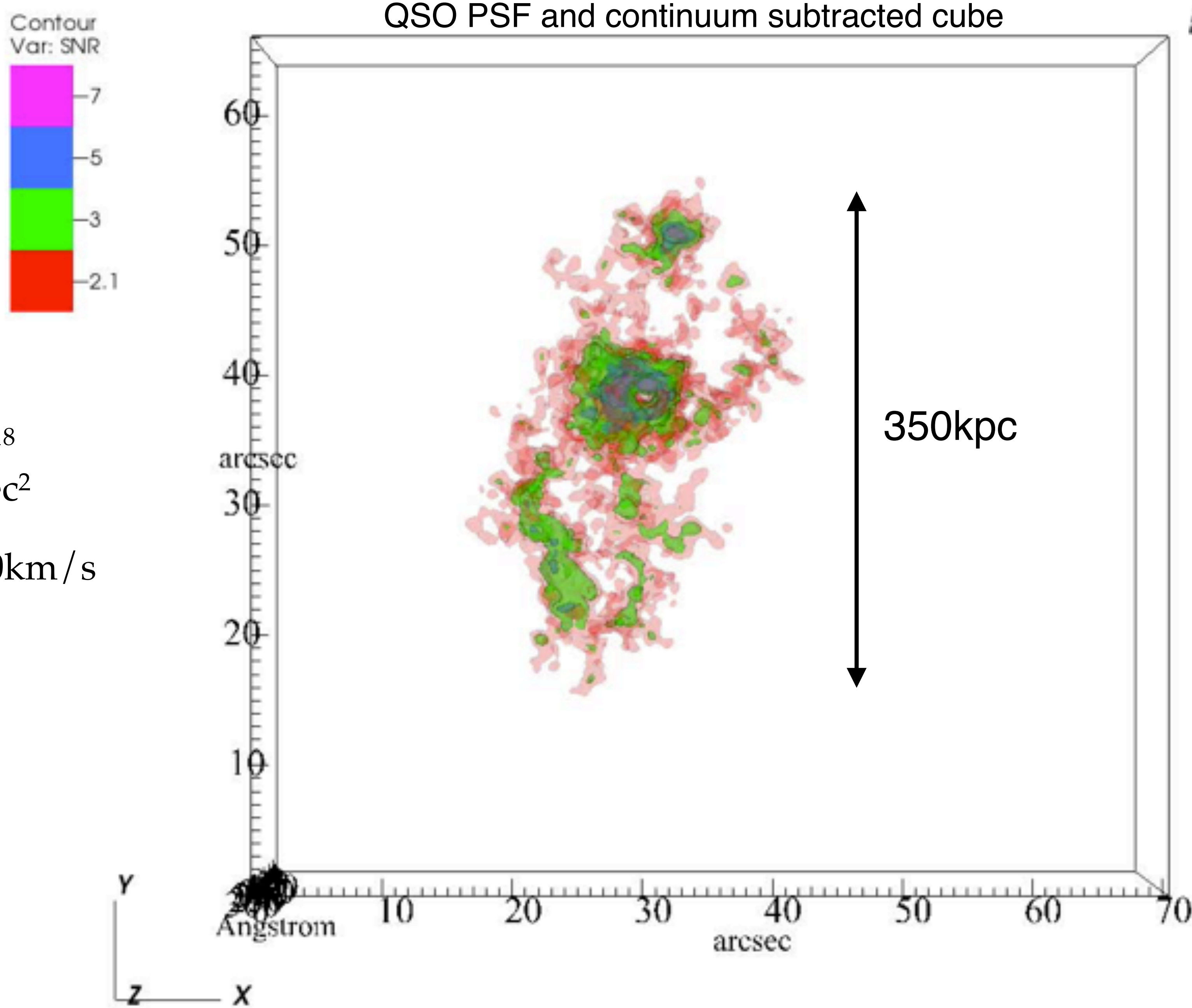
Optimally extracted pseudo-NB images with QSO PSF-subtraction obtained with **CubExactor** (Cantalupo in prep.)

All nebulae larger than 100 kpc with **various morphologies.**

Borisova, Cantalupo+ 2016

A 3D view of the Muse Quasar Nebula 3 (MQN03), 350kpc in size:

CubExtractor (Cantalupo, in prep.) + VisIt
QSO PSF and continuum subtracted cube



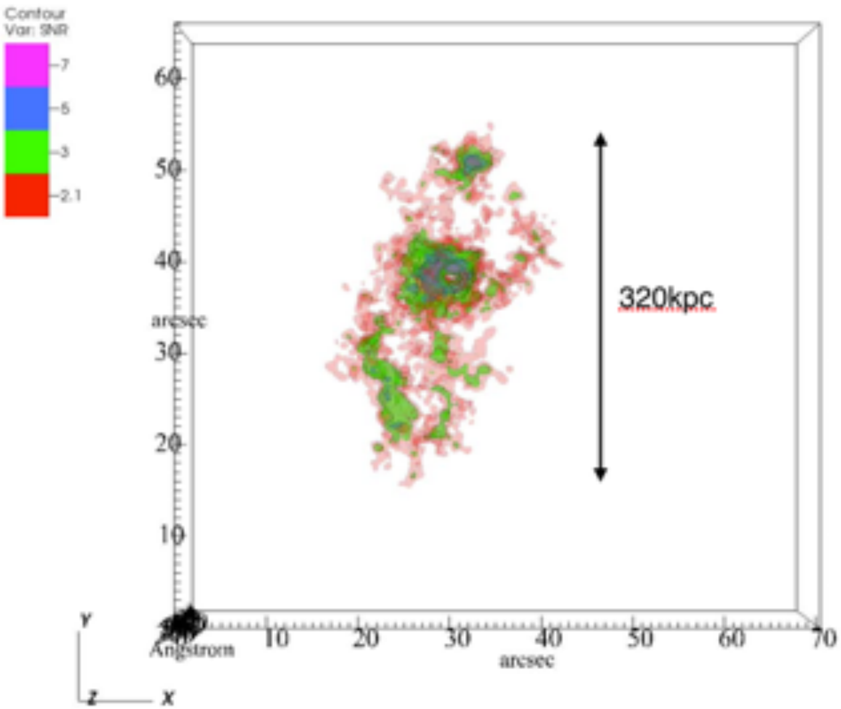
$2\sigma \sim 1\times10^{-18}$ cgs/arcsec^2

10A ~ 600km/s

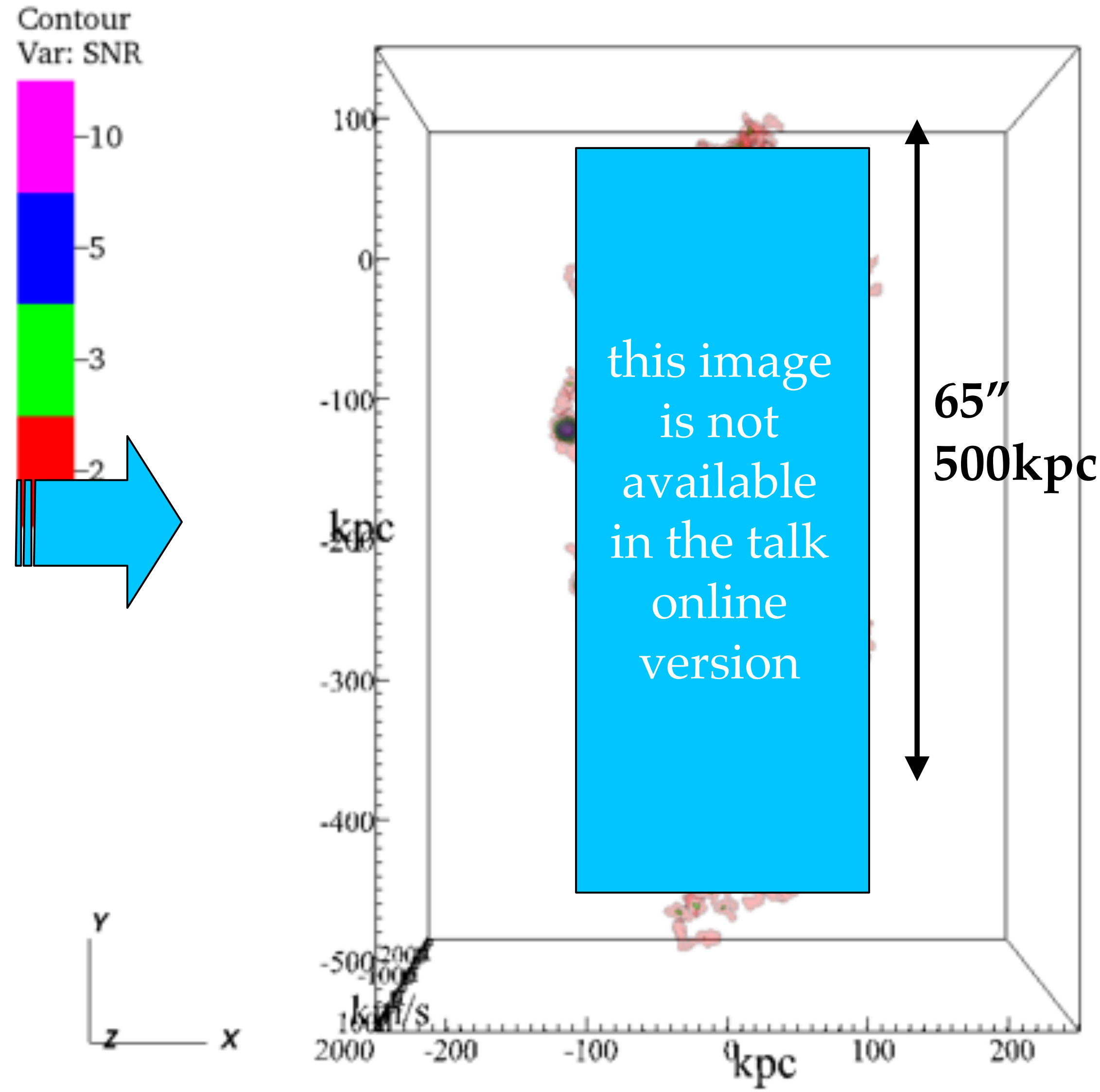
Borisova, Cantalupo+, 2016

Latest results: hunting for the "Cosmic Web" around MQN03

data collected during 2016-2017 (1x2 mosaic, ~15h in deepest part):



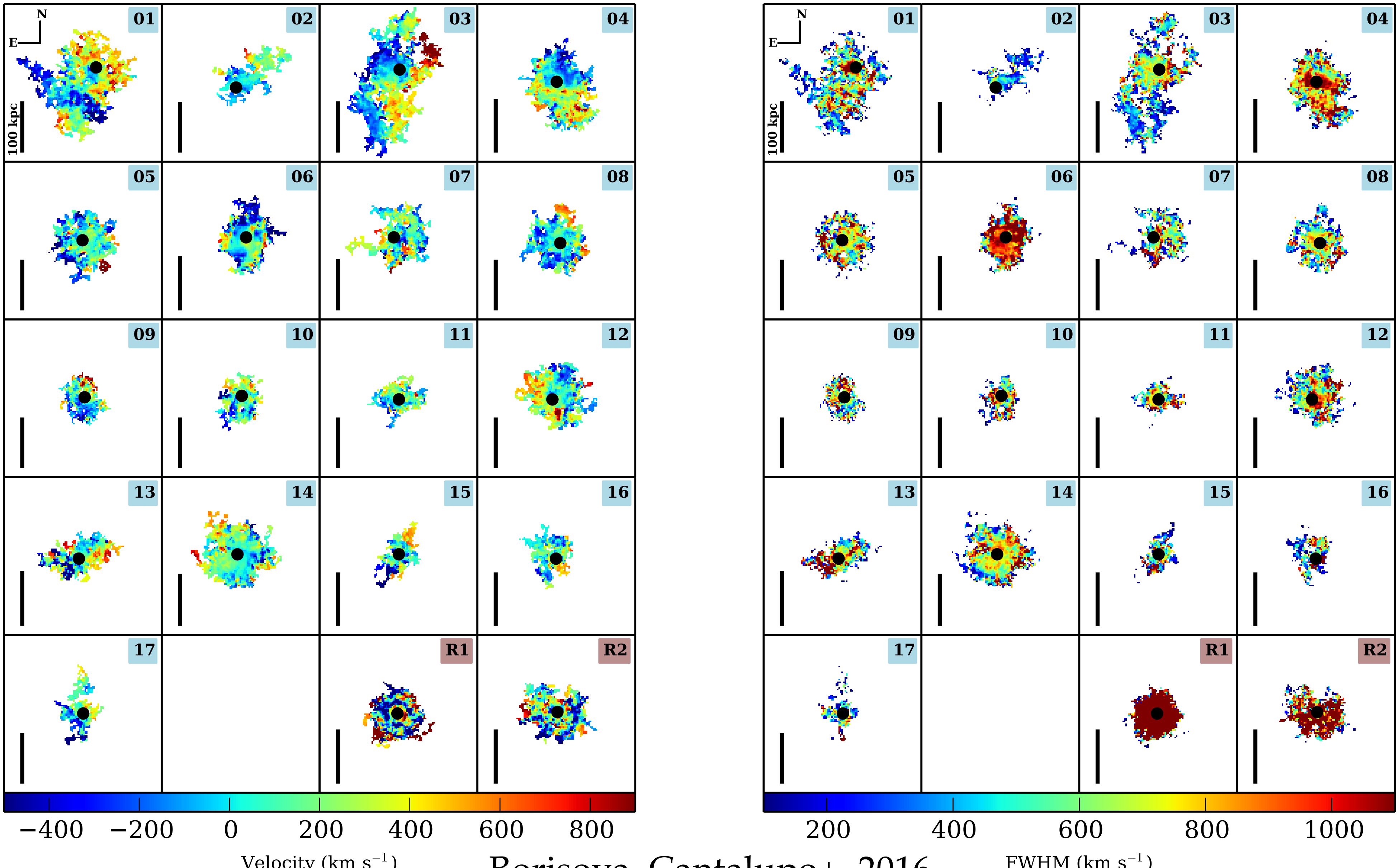
previous 1h-deep snapshot
(single pointing)



Sakura Nebula?

A statistical view: 2D Velocity maps of the Muse Quasar Nebulae

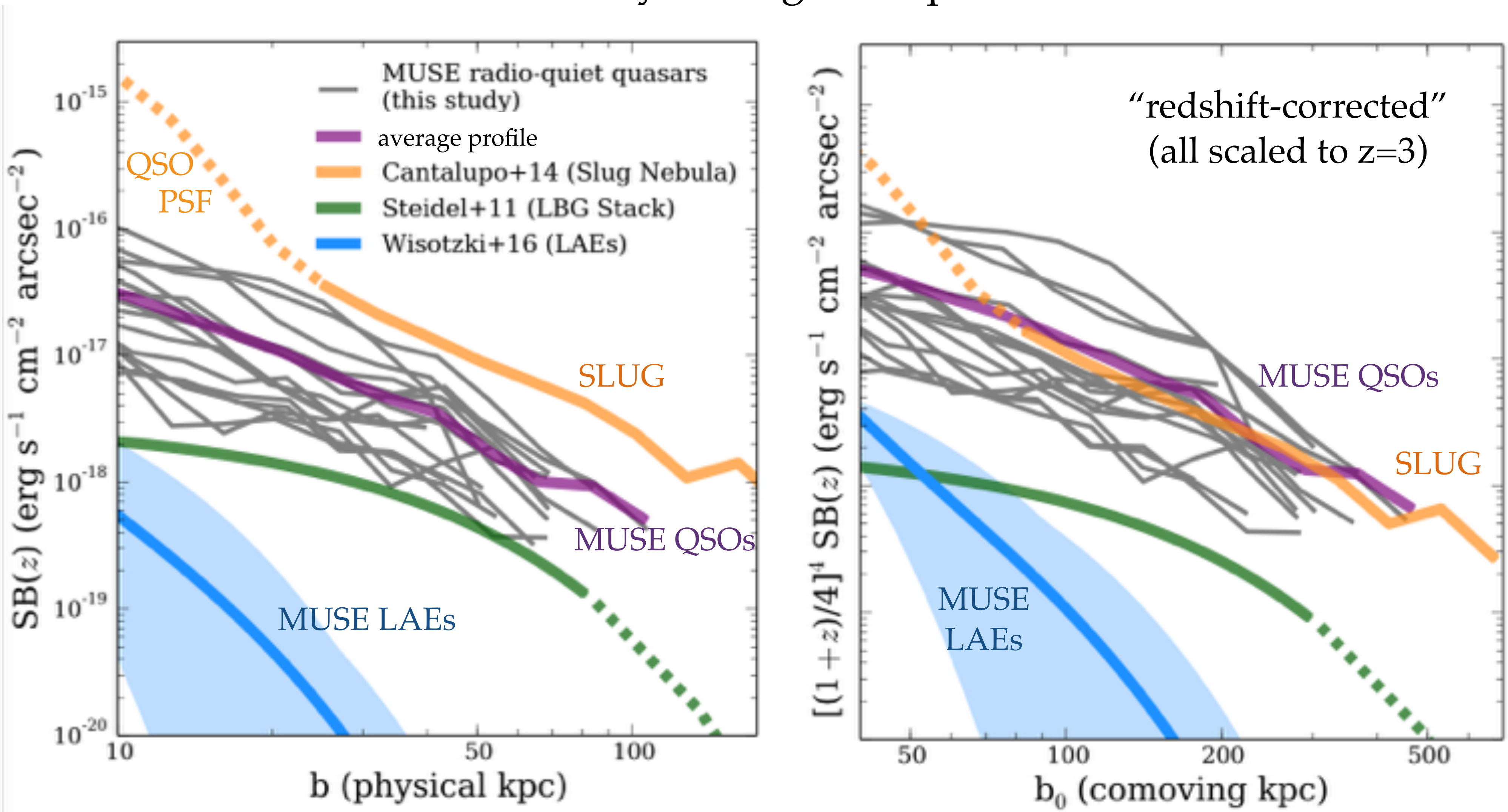
- no clear signs of "rotation" (with some exceptions);
- radio-quiet nebulae (1-17) are kinematically "narrow".



Borisova, Cantalupo+, 2016

How do they compare with other Lyα Nebulae and "haloes"?

Circularly averaged SB profile



All giant **quasar** nebulae have similar SB profiles both at z~2 and z~3 once "redshift-corrected"

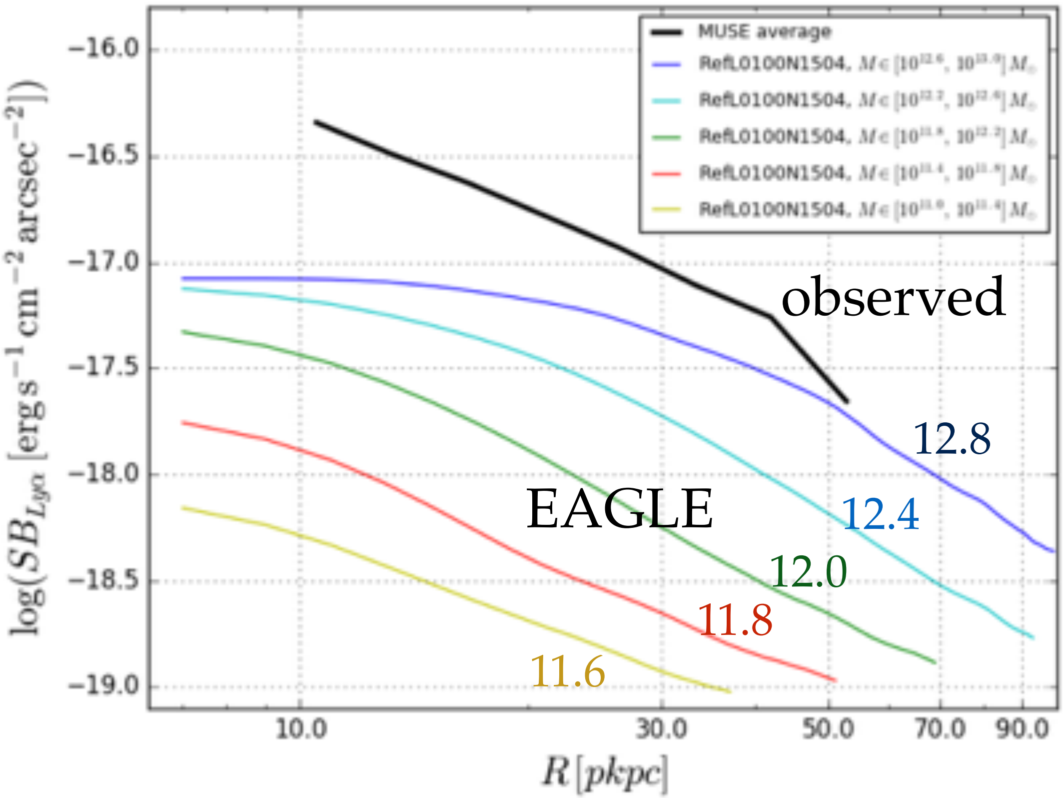
Borisova, Cantalupo+, 2016

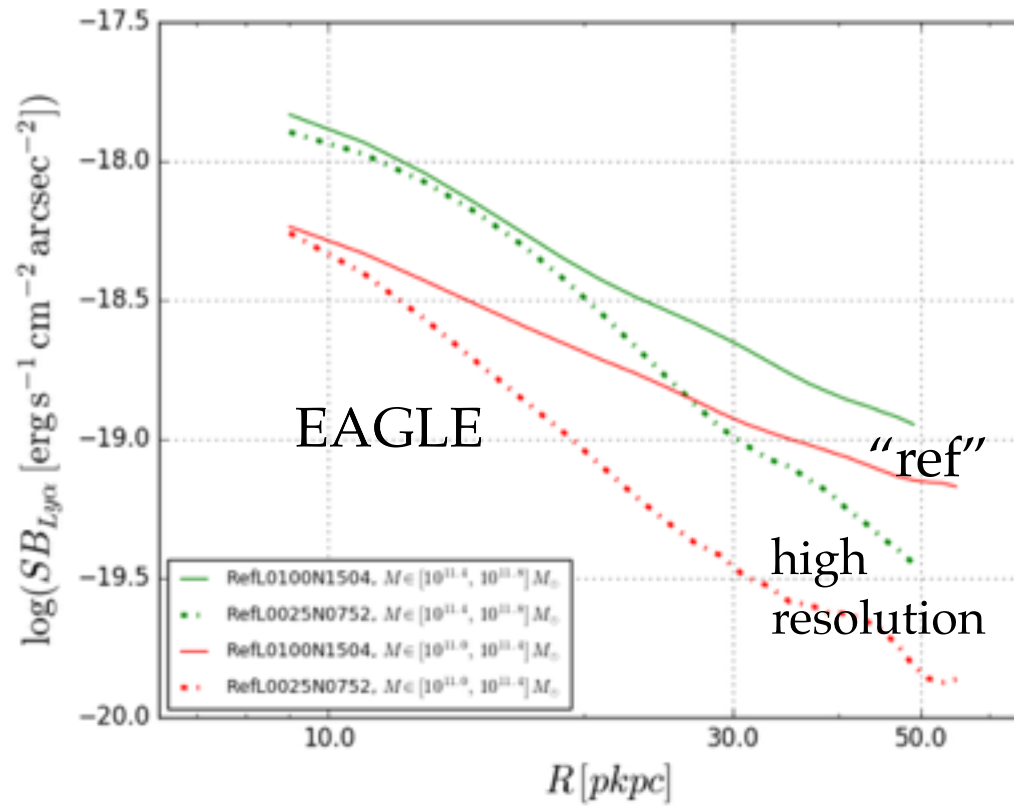
How do they compare with expectations from cosmo-simulations?

- RAMSES (AMR) simulation of SC+14 including Lyα RT : **simulated SB** (a few haloes at $10^{12.5\text{-}13}\,M_{sun}$) is **~10-100 fainter** than observed for both recombination and “photon-pumping” (scattering from QSO BLR)

- Same discrepancy in EAGLE (SPH) for maximal fluorescent emission:

Tresoldi, SC & Pezzulli, in prep.

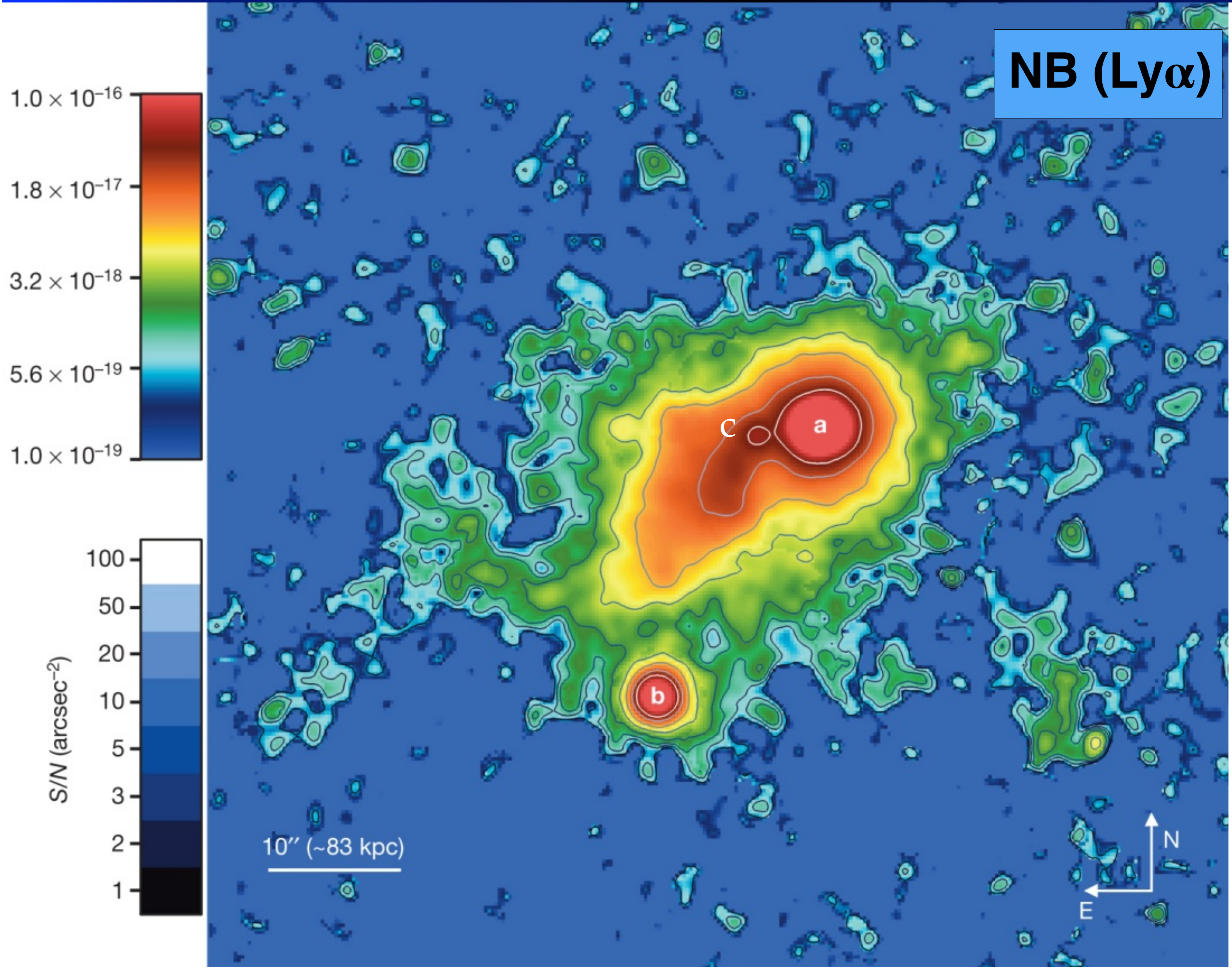




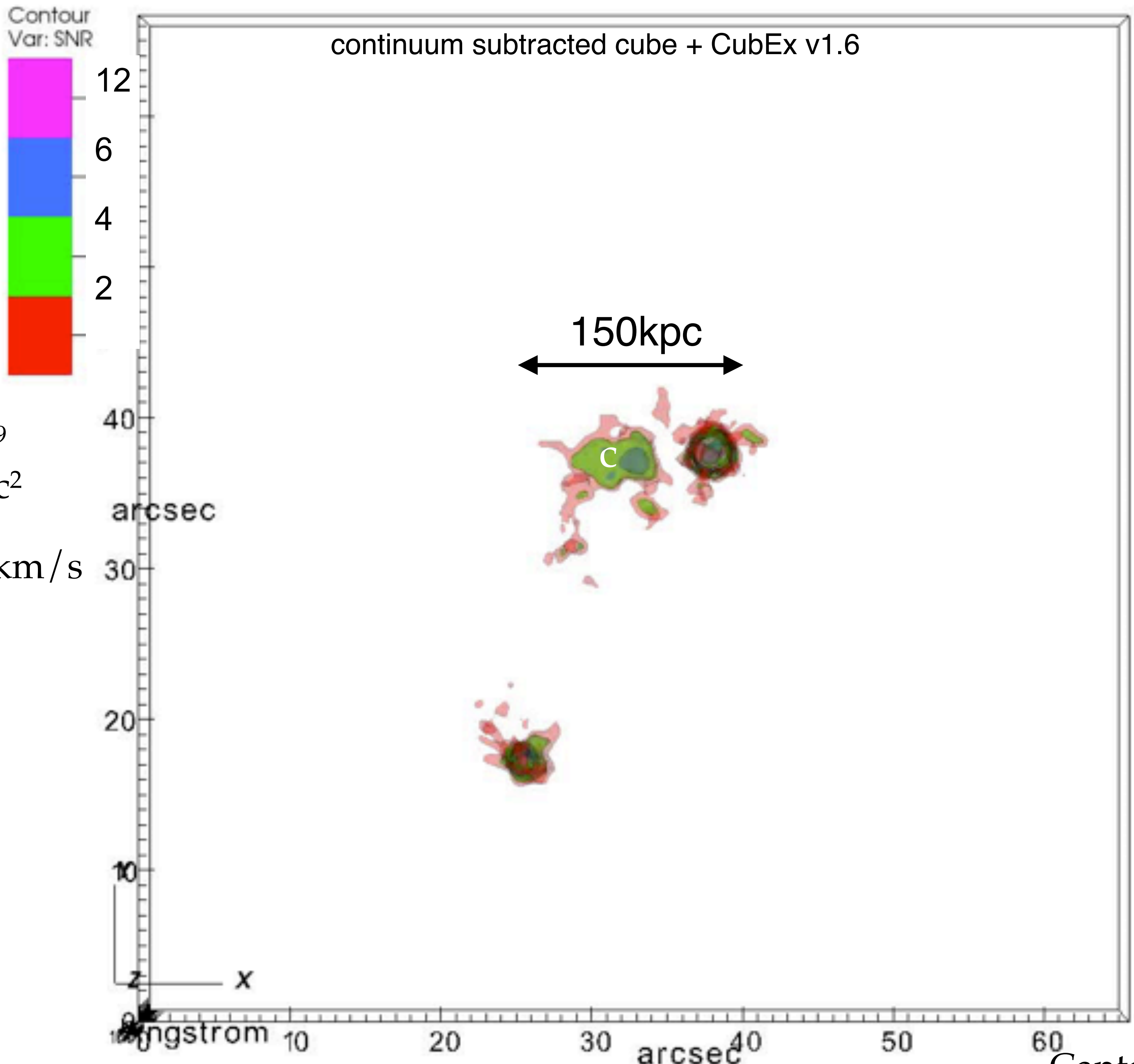
- Comparison with FIRE, ILLUSTRIS-TNG and reassessment of ILLUSTRIS (see Gronke & Bird 2017) in progress.

- High densities in CGM/IGM are needed and unresolved by cosmo-sims.

Constraining the densities and emission mechanism with HeII 1640:



Extended HeII emission from the Slug Nebula



$2\sigma \sim 3 \times 10^{-19}$ cgs/arcsec^2

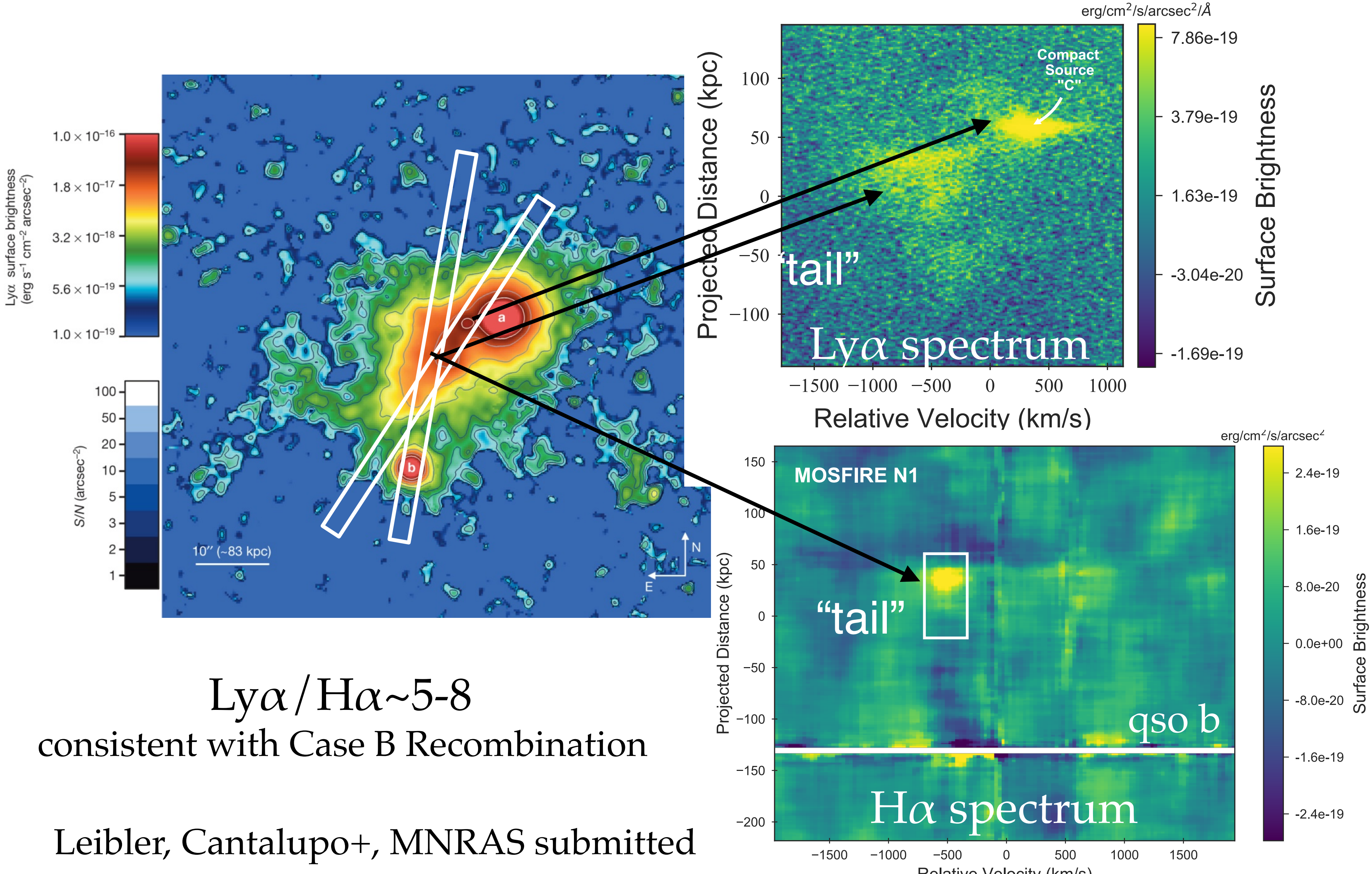
10A ~ 600km/s

Cantalupo+, in prep.

Why is HeII "missing" from the Slug "tail"?

1) "Tail" Lyα emission due to "photon-pumping / scattering"

➡ ruled out by MOSFIRE Hα (and preliminary MUSE CIII) detection



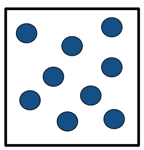
Lyα/Hα~5-8
consistent with Case B Recombination

Leibler, Cantalupo+, MNRAS submitted

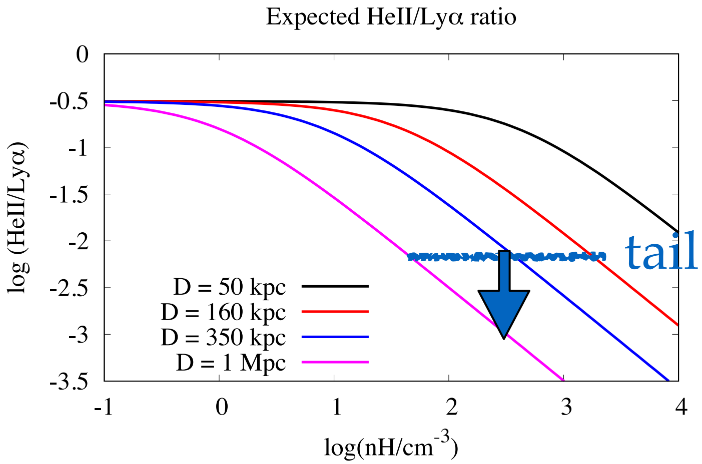
Why is HeII “missing” from the Slug “tail”? High densities required

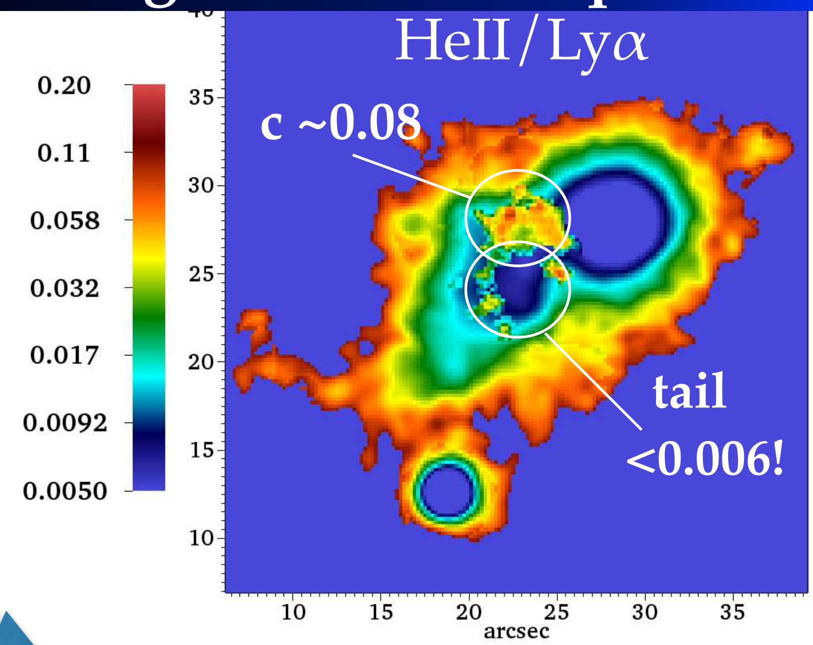
2) High densities and larger distances

(a)

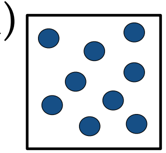


“single-density” clump scenario



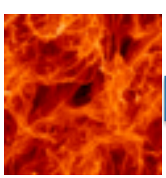


(a)

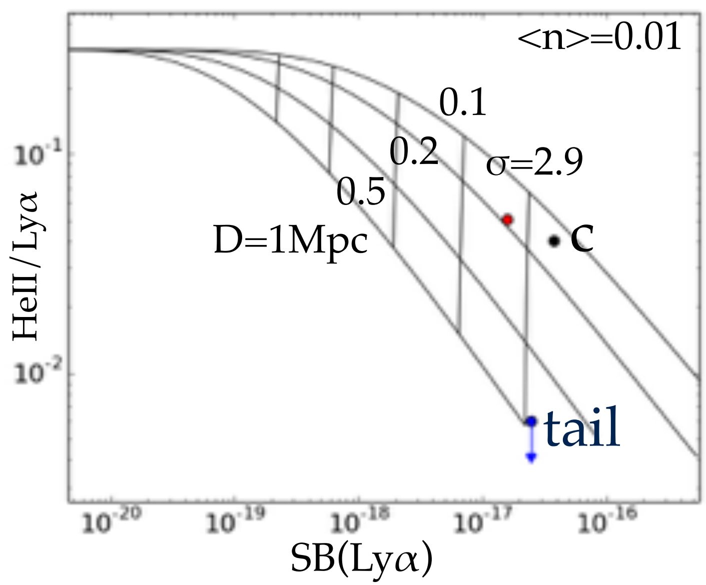


n_{clump}~10^2-10^4 cc ! (depending on actual distance)

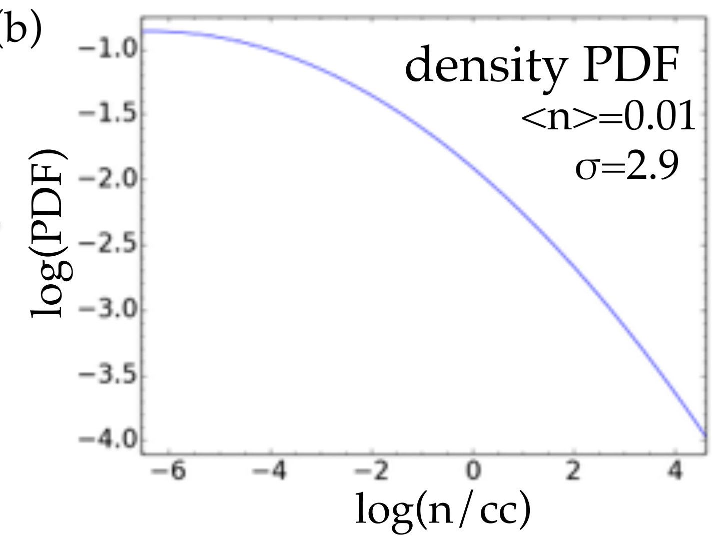
(b)



“turbulent/lognormal density distribution” scenario



(b)



Cantalupo+, in prep.

Open Questions and (some) Future Directions

*What sets the **frequency**, **size** and **luminosity** of the giant quasar Nebulae?*
(quasar lifetime, opening angle, halo mass, redshift, quasar luminosity,…)

*What is the origin of the IGM/CGM **clumps** traced by the Nebulae?*
(thermal/gravitational instabilities, quasar radiation effects,…)

*How this **affects** galaxy and QSO formation?*
(fast gas accretion, violent disk instability,…)

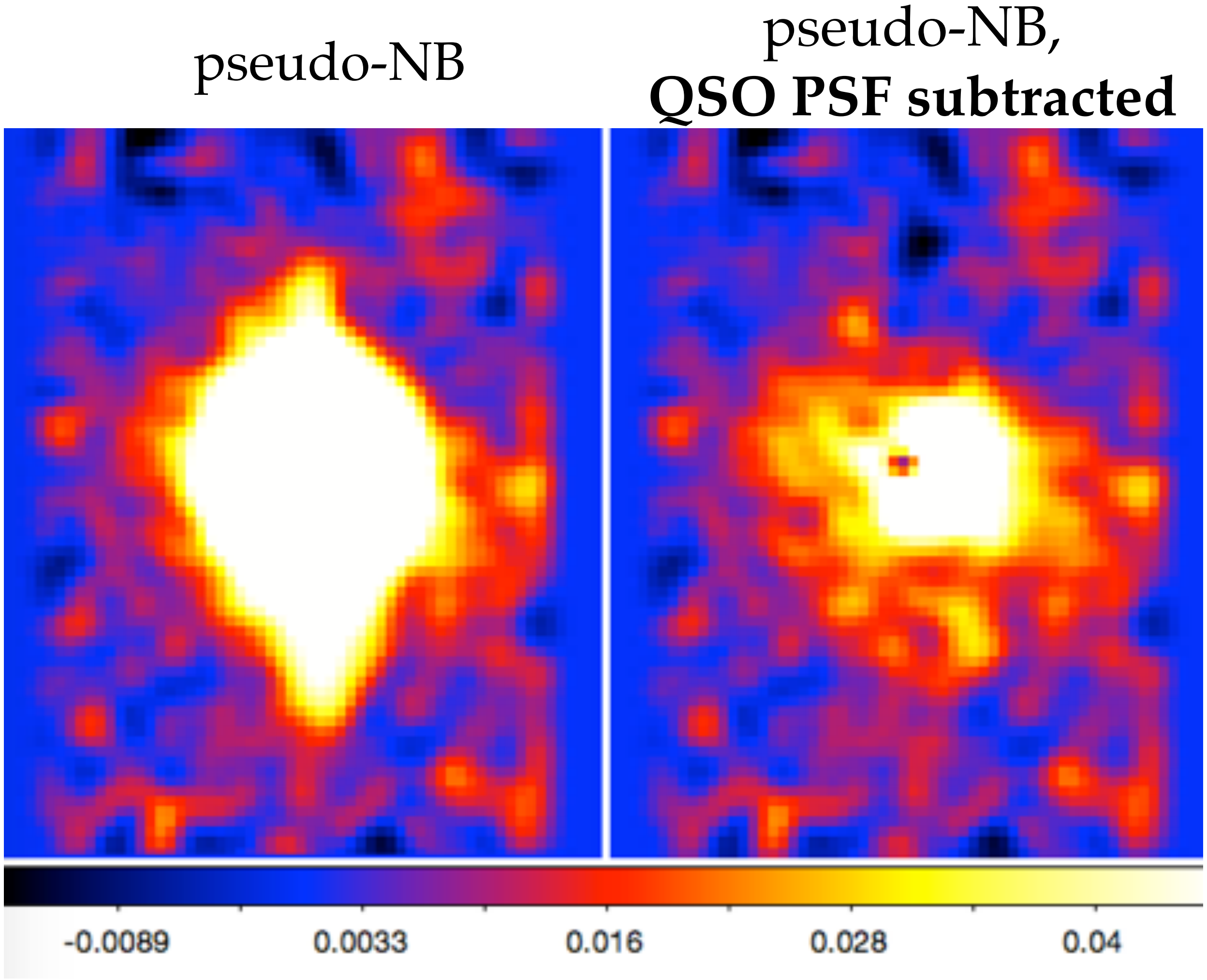
Exploring a larger parameter space:
- include lower luminosity quasars;
- extend the redshift range to $2<z<3$ (not possible with MUSE, KCWI required)
- Hα followup to constrain emission mechanism and “spatially resolve” clumps.

Improving our theoretical understanding of IGM “clump-formation”:
- hydrodynamical and thermal stability analysis;
- detailed comparison with observational data.

Moving “away” from quasars:
- detect “average” Cosmic Web filaments connecting galaxies and illuminated by the cosmic UVB (>100h-deep exposure with MUSE and/or KCWI).

KCWI (ongoing) snapshot survey of bright quasars at z~2.3

- Targets: >10 of the brightest quasars at z~2.3 (including QSOs previously observ with NB imaging with no detectable nebulae)
- Preliminary results: ~100% detection rate *under QSO PSF* but lower SB than z~3 MUSE Quasar Nebulae (to be confirmed) —> possible redshift evolution

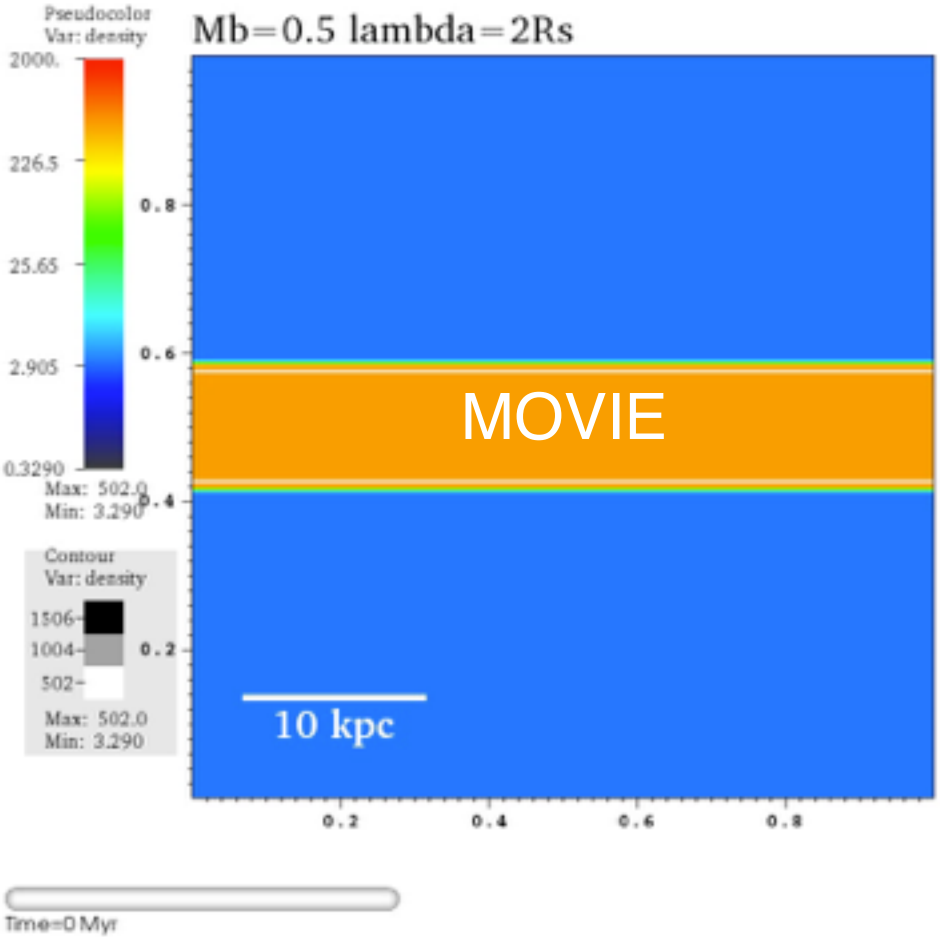


Cantalupo+, in prep.

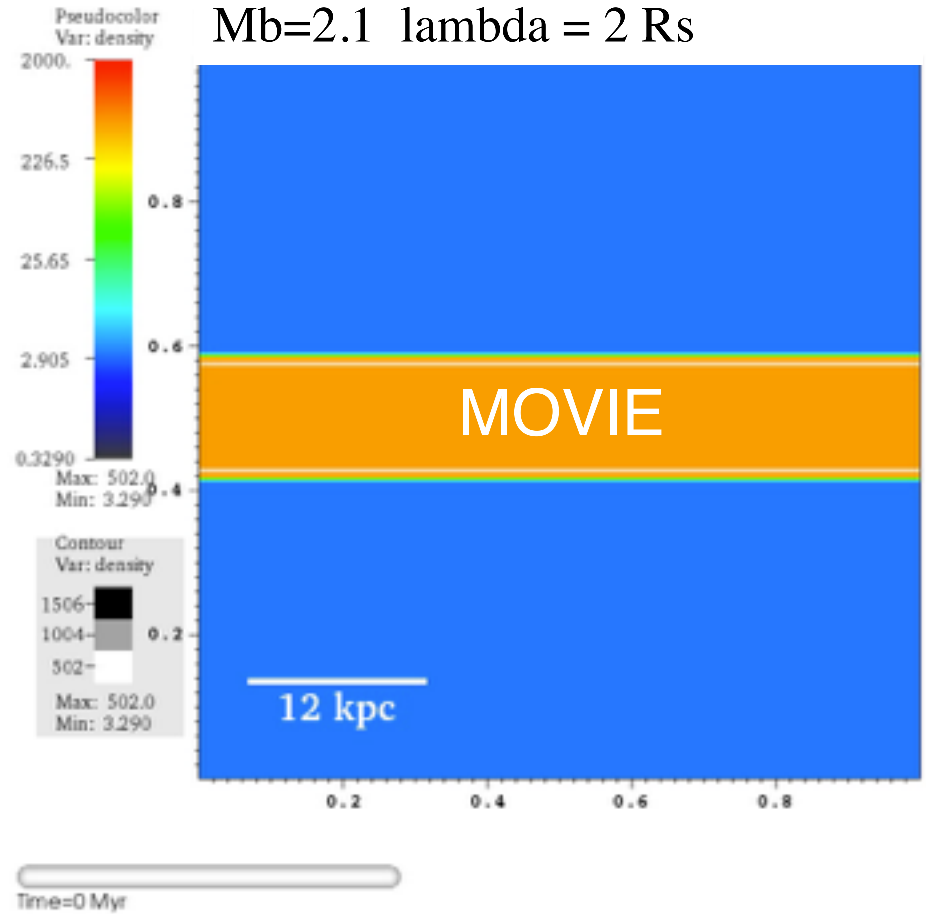
Where are the "clumps" coming from? Instabilities from filament accretion:

- RAMSES 2D simulation (resolution ~5pc) of "cold" filaments flowing through hot gas and initially small (5%) pressure perturbation at the interface.

subsonic case, adiabatic



supersonic case, adiabatic



Vossberg, Cantalupo & Pezzulli, in prep.
(see also Mandelker et al. 2016)

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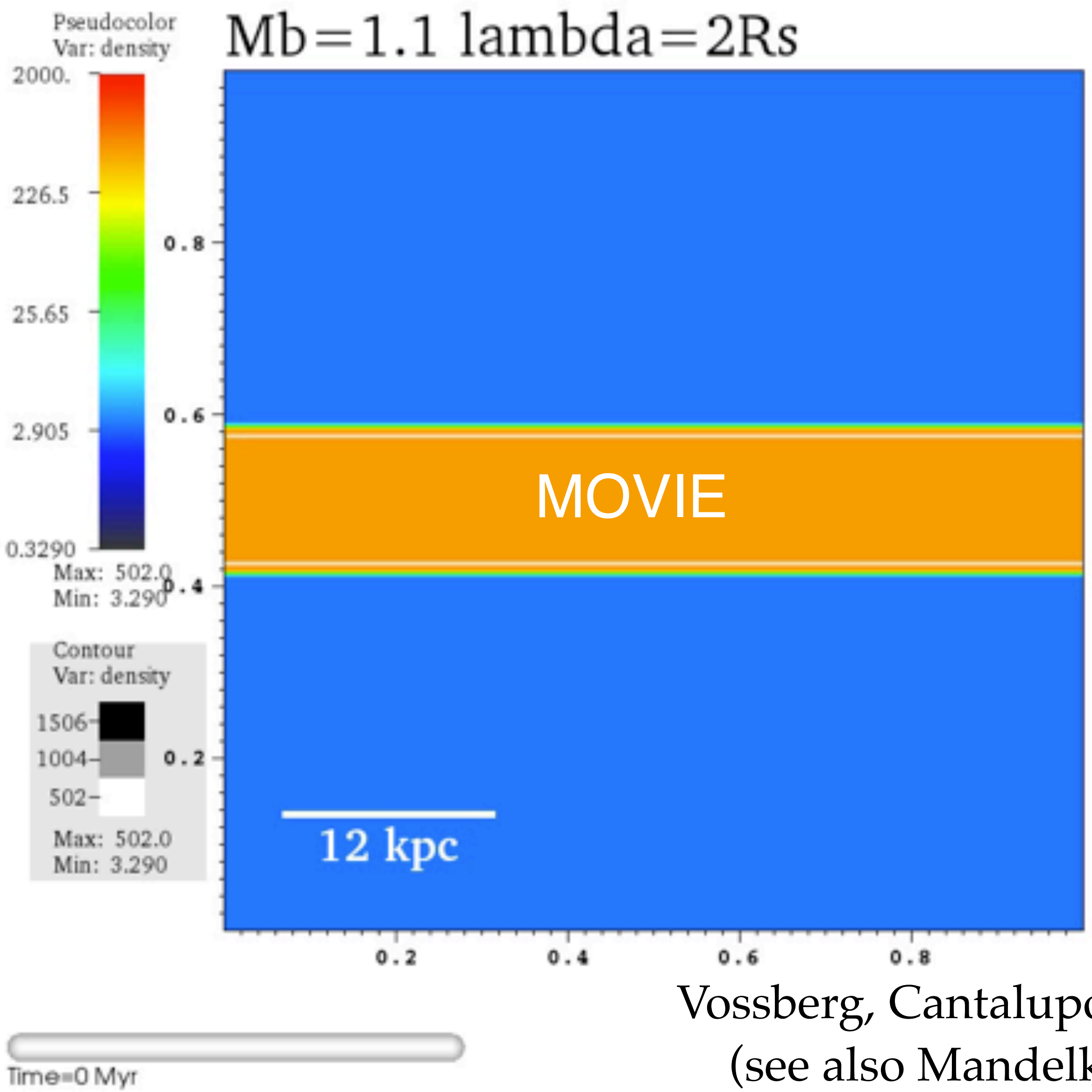

Vossberg, Cantalupo & Pezzulli, in prep.
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Summary, *some open questions* and future steps

- We can finally directly detect the "Cosmic Web" on >500kpc scales with the help of quasar fluorescent emission and MUSE.

- Giant Lyα Nebulae are ubiquitous around bright QSOs at z~3.5 (MUSE) and apparently less frequent in NB surveys at z~2 (or just less luminous, from our KCWI preliminary data).
Is this a real redshift evolution in the quasar and/or their CGM properties or due to different observational techniques?

- Observations of H-Lyα, H-Hα, HeII emission suggest that clumps with large densities ($n \gg 10\ cm^{-3}$) and small sizes (~pc) or log-normal/turbulent density distributions with large σ should be present on intergalactic scales around quasars.
What is the origin of the "clumps" and their effect on galaxy formation and evolution?

- Next Future:
  - Finding new "Cosmic Web" filaments with deep MUSE observations and enlarge the parameter space for statistical studies ("snapshots").
  - Hα followup of MUSE nebulae (with JWST) and/or KCWI nebulae (from the ground).
  - New theoretical/numerical simulations to "resolve" circumgalactic gas physics.
  - Moving away from quasars (new instruments/idea required!).

Stay tuned!