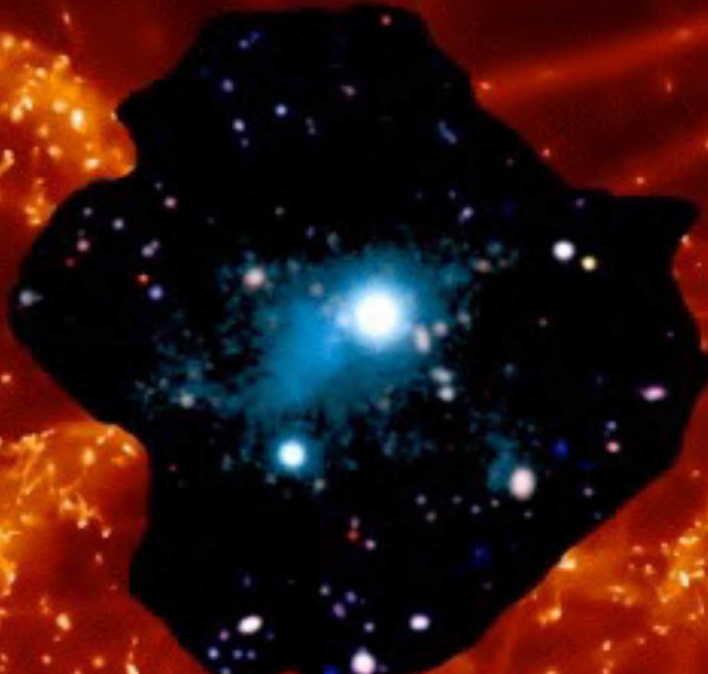
# A 3D view of the Dark Universe: illuminating intergalactic gas with fluorescent Lyman-$\alpha$ emission



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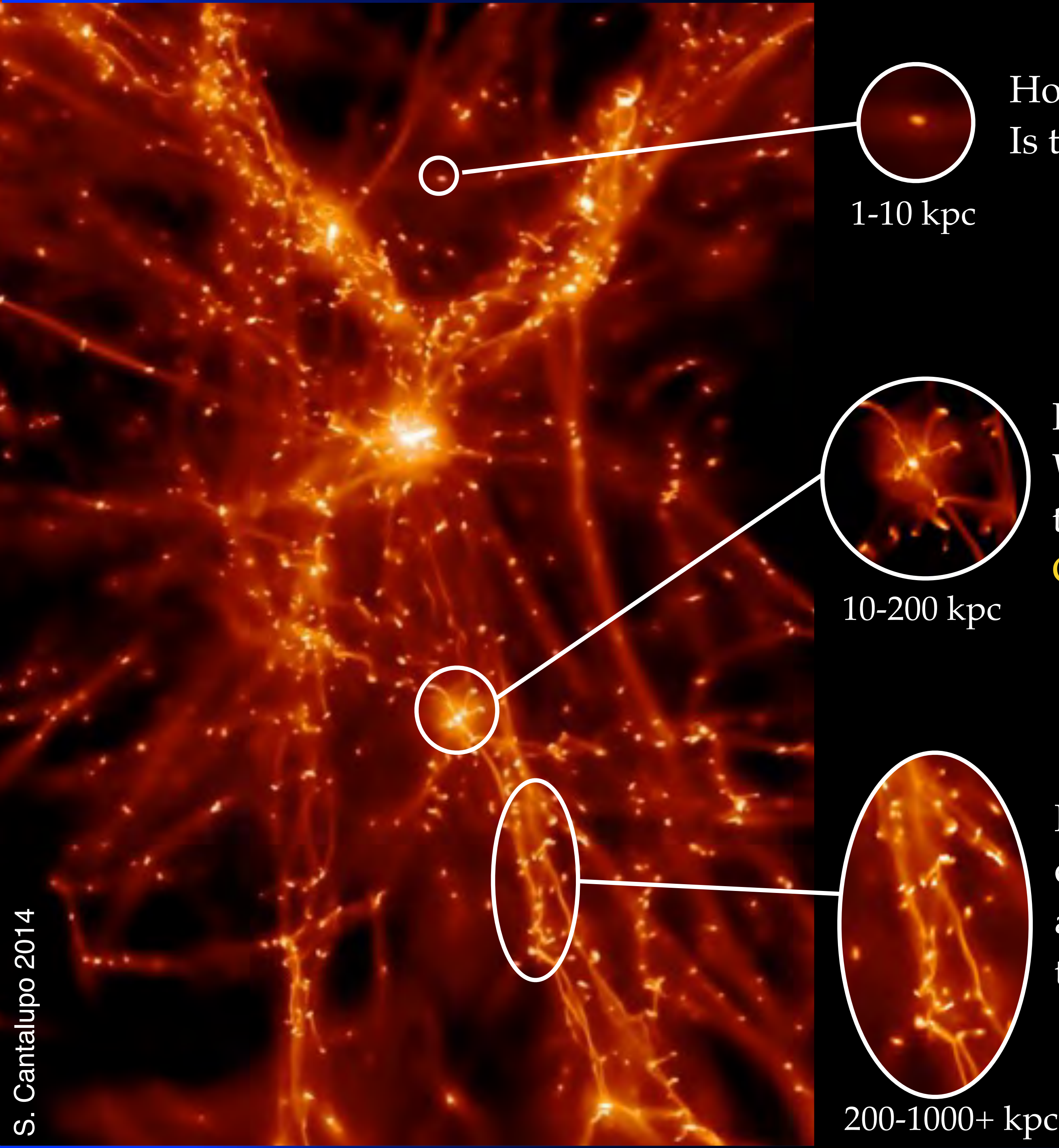
In collaboration with:
**MUSE GTO Team (ETH, CRAL, Leiden, AIP, Toulouse, Gottingen)**, J. Xavier Prochaska (UCSC), Sammy B. Slug (UCSC), Piero Madau (UCSC), Fabrizio Arrigoni-Battaia (ESO), Joe Hennawi (MPIA), Martin Haehnelt (IoA)

Cantalupo et al., *Nature*, 2014

# key questions




How is gas converted into stars? Is there a "dark" galaxy phase?

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

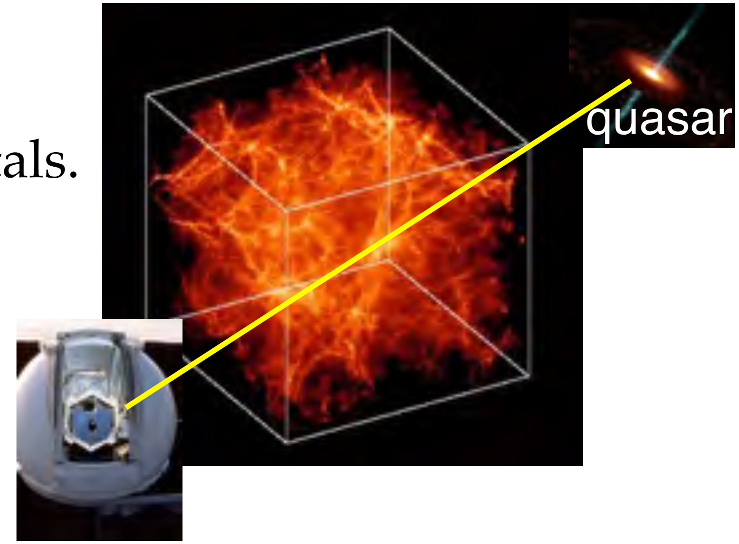
How are galaxies linked to each other? What are the morphology and the small scale properties of the "Cosmic Web"?

# Detecting Cosmic Gas

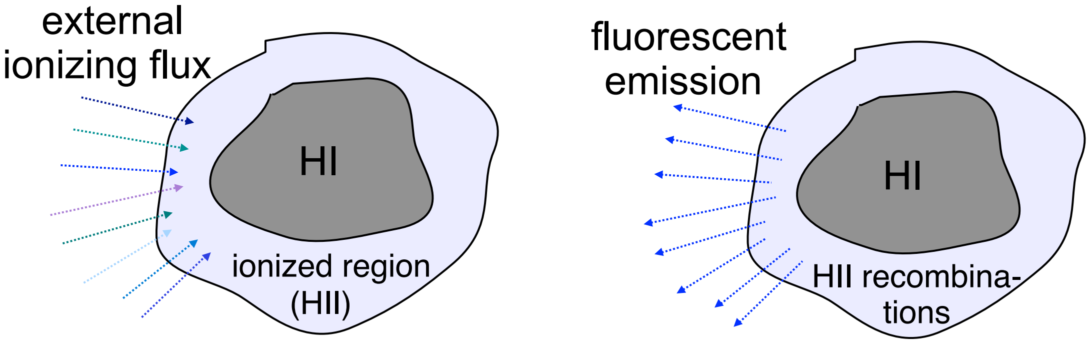
"Classical" approach: in absorption.

- pro: ability to detect low-density gas including metals.
- con: typically only 1D information (or sparse 2D)

LLS/DLAS = "Dark" galaxies? Filaments? IGM? CGM?
... difficult to say without direct detection.



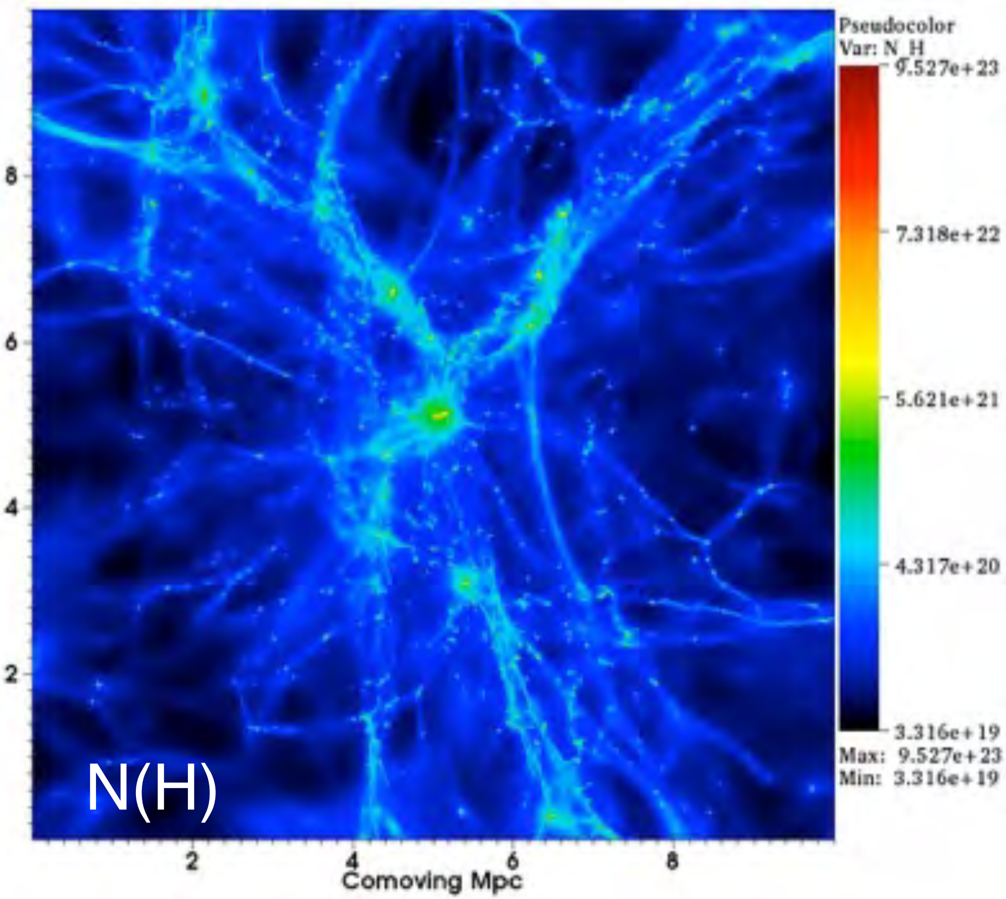

**Direct detection *in emission*: Fluorescent Ly$\alpha$** (*Hogan & Weymann 1987;Gould & Weinberg 1996; Zheng & Miralda-Escude 2005; Cantalupo+05,07; Kollmeier+06,10; Cantalupo+12*)

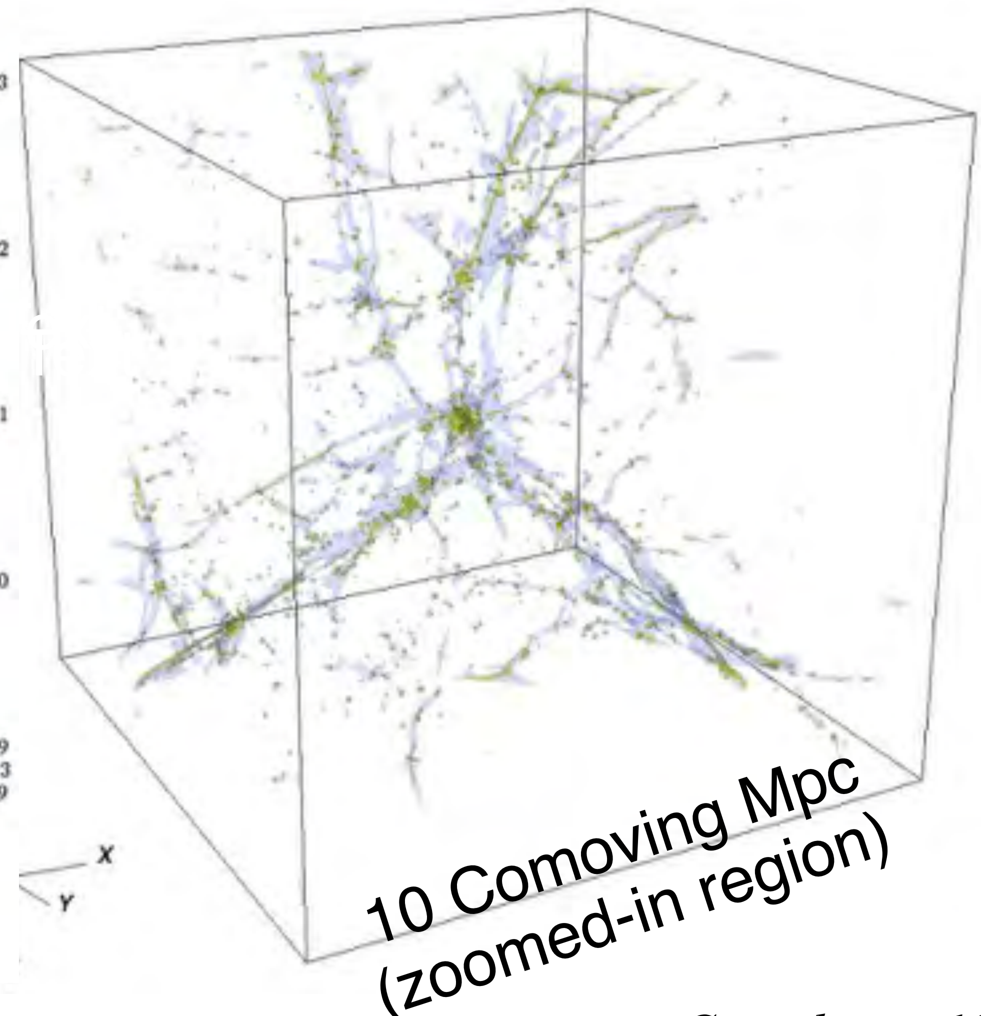



- Self-shielded gas (slab): "mirror" emission -> ~60% of incident ionizing radiation "converted" to **Ly$\alpha$ (but see Cantalupo+05).**
- Fully ionized gas: proportional to gas density squared.

# How bright is fluorescent emission: simulations

- **40Mpc³** (10Mpc³ high-res) hydro-simulation (RAMSES) around $3\times10^{12}\ M_{sun}$ halo at $z=2.5$
- Star formation, SN feedback, on the fly UVB Self-shielding.
- Post-processed with 3D Radiative Transfer Code RADAMESH (Cantalupo & Porciani 2011) for ionizing and Ly$\alpha$ radiation.



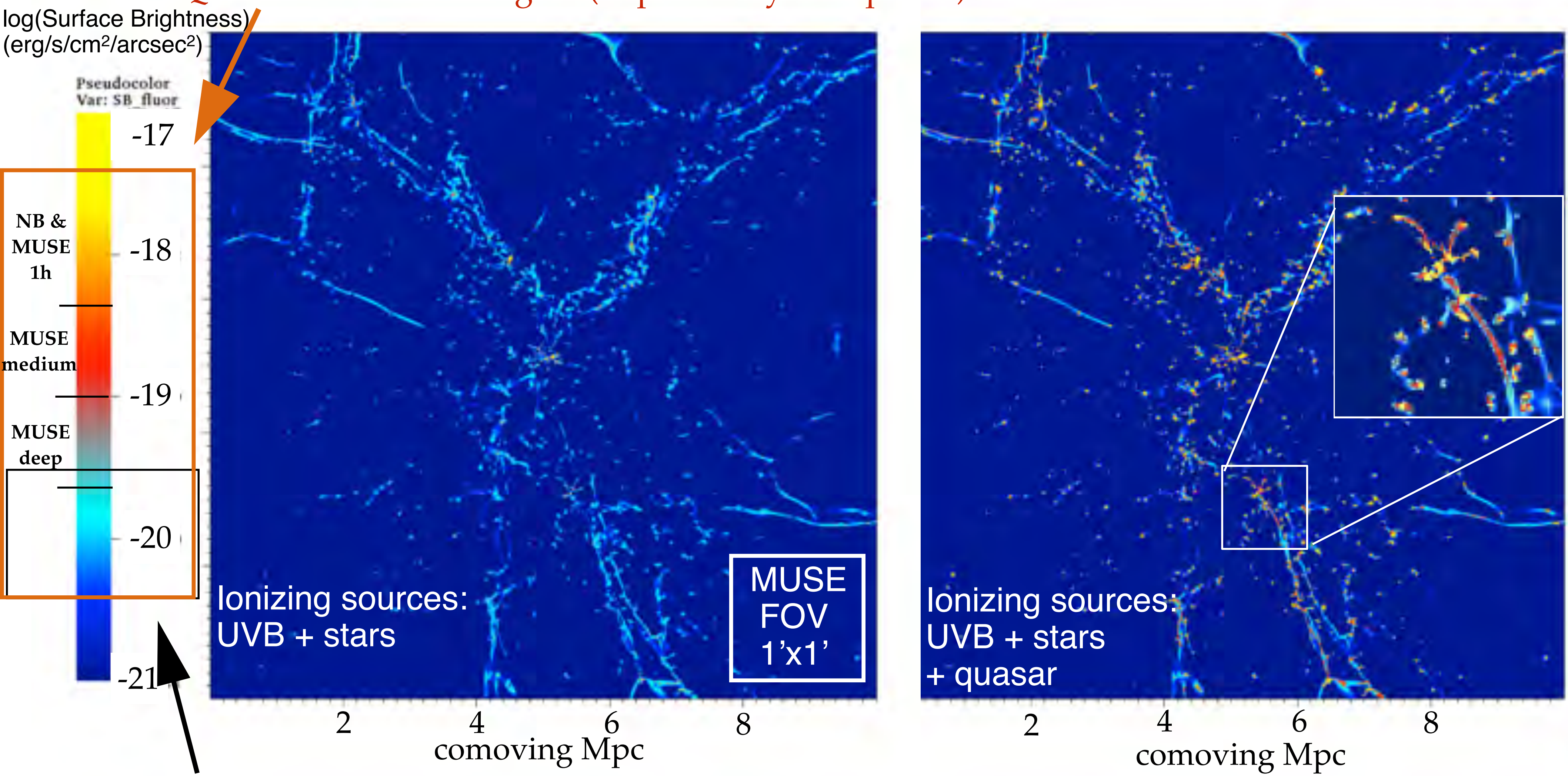

*Cantalupo+12*

# How bright is fluorescent emission: simulations

Simulated Ly$\alpha$ images at redshift 3

cosmological simulation (`RAMSES`) + Radiative Transfer (`RADAMESH`): Cantalupo+12

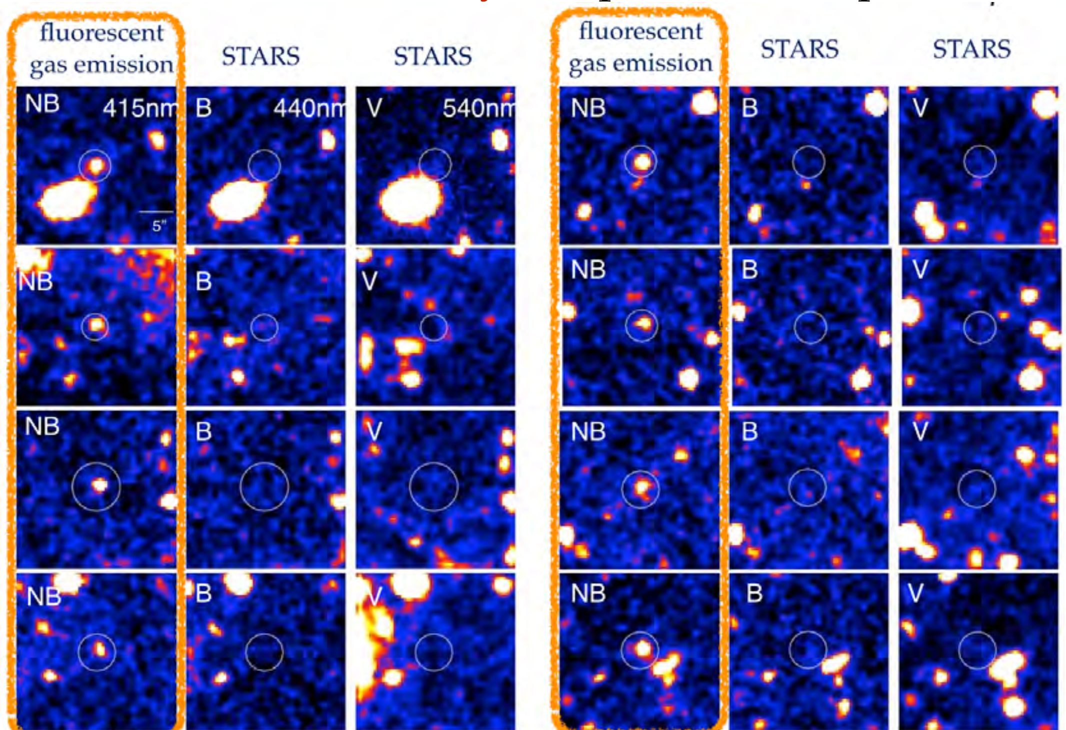
Quasar fluorescence signal (in proximity of a quasar)

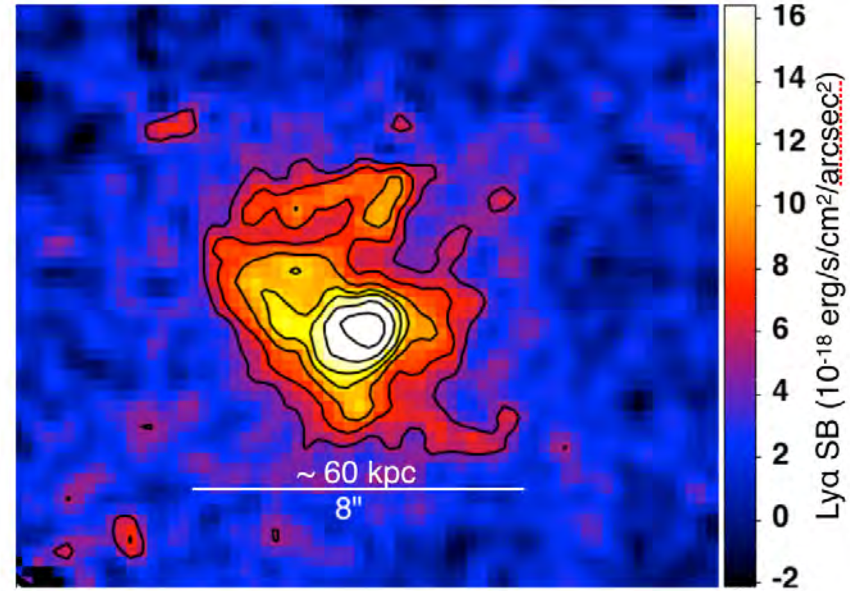



average fluorescence signal in random locations

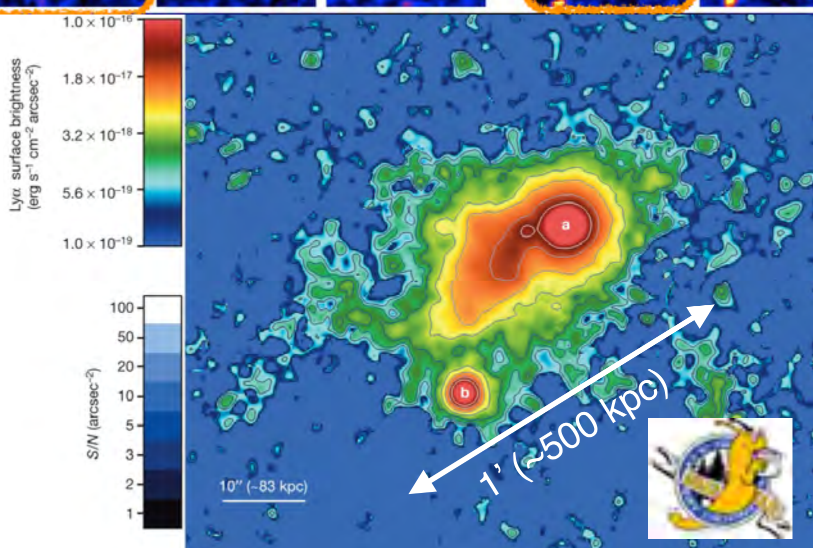
# Pilot Observations with Narrow Band filters in Quasar fields at z~2.3

First Dark Galaxy sample (Cantalupo+12)




Circumgalactic gas in emission
(Cantalupo+12)




The Slug Nebula - a filament of the Cosmic Web
(Cantalupo+, Nature, 2014)

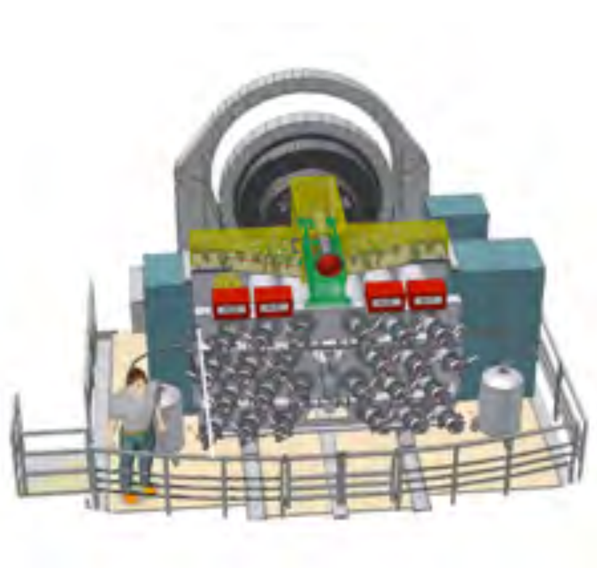
\+ other 25 QSOs (FLASHLIGHT Keck+GMOS survey; Cantalupo+, in prep.; Arrigoni-Battaia+; see next talk)

main results:

—> Giant QSO Nebulae are **rare** in NB surveys (<10%)

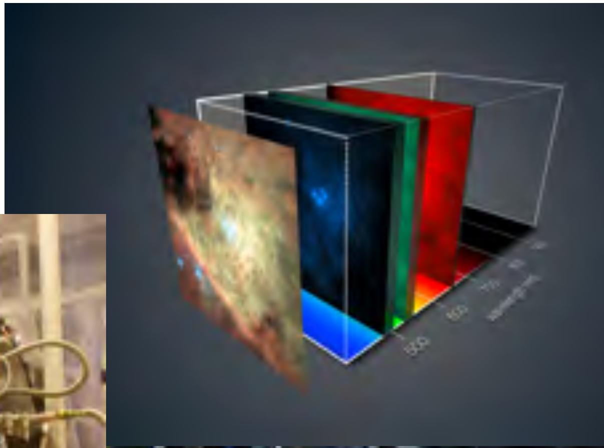
—> Morphology and "kinematics" compatible with Cosmic Web filaments, but SB is too high for average IGM densities —> **dense clumps required**.

# 3D! with MUSE



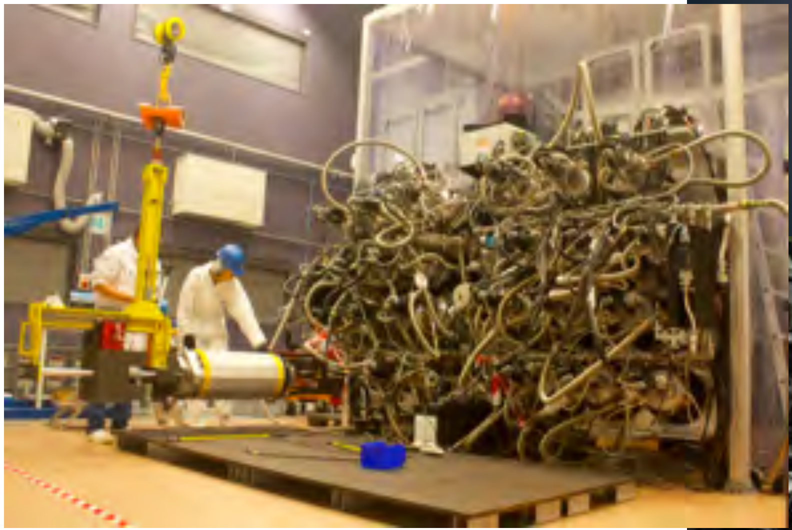
## MUSE-VLT: Concept

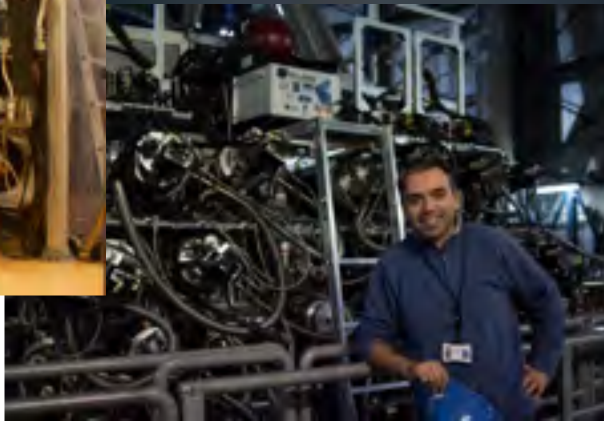
- 1′x1′ Integral Field Unit (image slicer)
- 24 Spectrographs: 370 million pixels per exposure!
- 480nm-950nm range (3<z<6.5 for Ly$\alpha$)
- 1.25Å x 0.2″ x 0.2″ voxels
- high efficiency (58% peak)

## MUSE-VLT: "Reality"

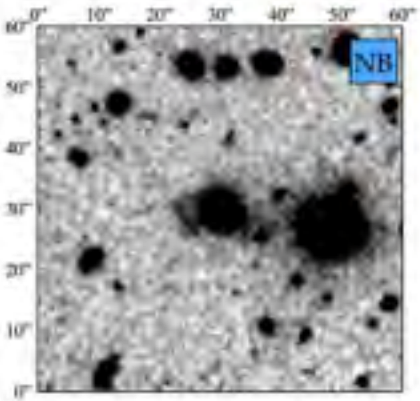
- @Paranal Since 2014
- Commissioning Feb-Jun 2014
- 5yr Guaranteed Time Obs. (~250 nights) started in Sep 2014.



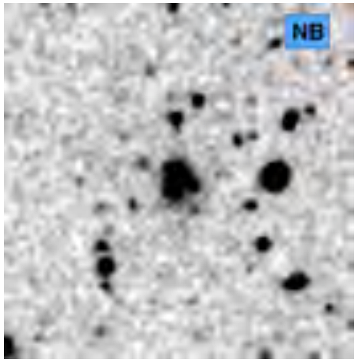


# 3D! with MUSE: MILES3D first year survey strategy

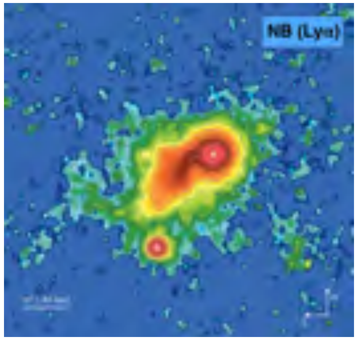
1) Medium-deep exposures (9h-20h) on “pre-imaged” fields:




QSO Nebula at z~3, VLT/FORS

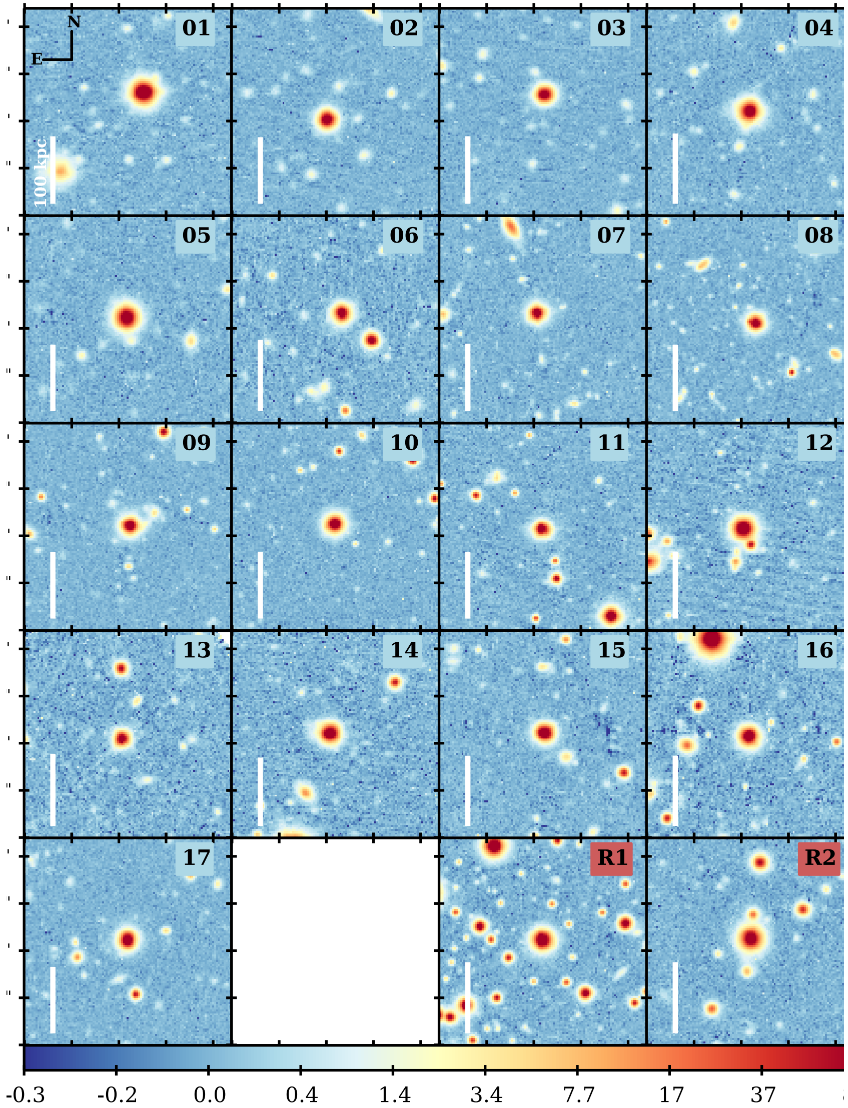



“galaxy” Nebula in z=3 QSO field, CTIO




Slug Nebula (z~2.3), HeII and CIV search

2) Snapshot blind survey (1h) on brightest radio-quiet (17) quasars at z>3 (+2 radio-loud quasars, R1, R2):



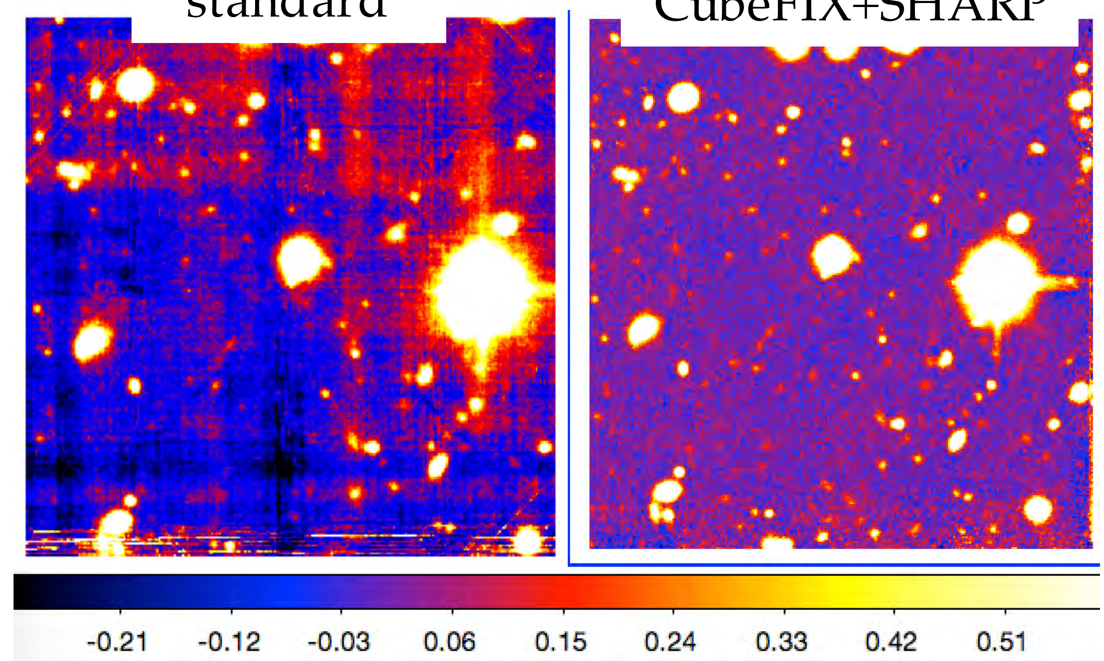

Broad-band images (1′x1′)

# **CubExtractor:** data reduction and analysis package for MUSE cubes

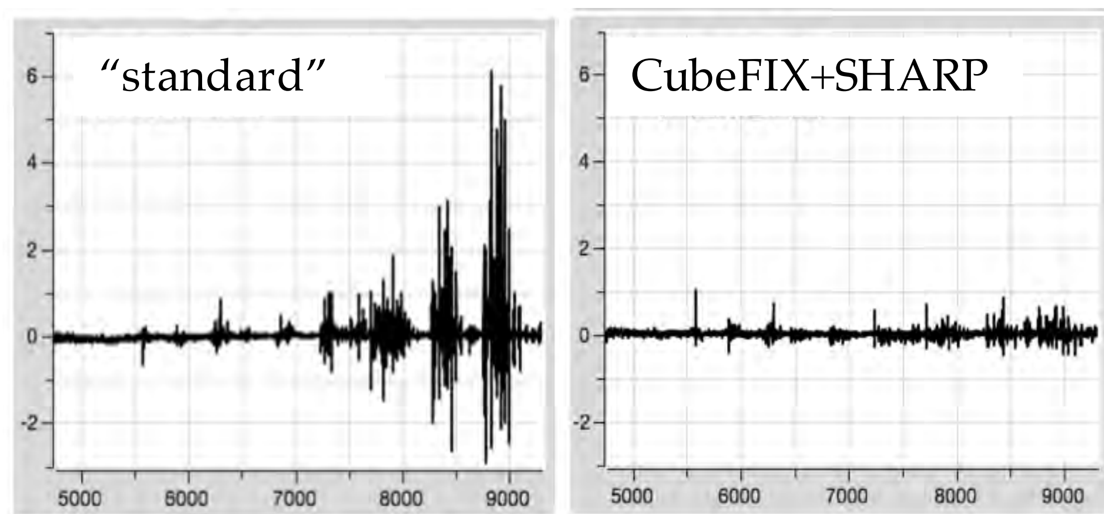
Including:

- Self-calibration Flat-fielding (**CubeFIX**)
- Flux-conserving Sky-subtraction (**CubeSHARP**; empirical LSF correction)

36 combined exposures (9h; **Hammerhead QSO** GTO field):




white-light images



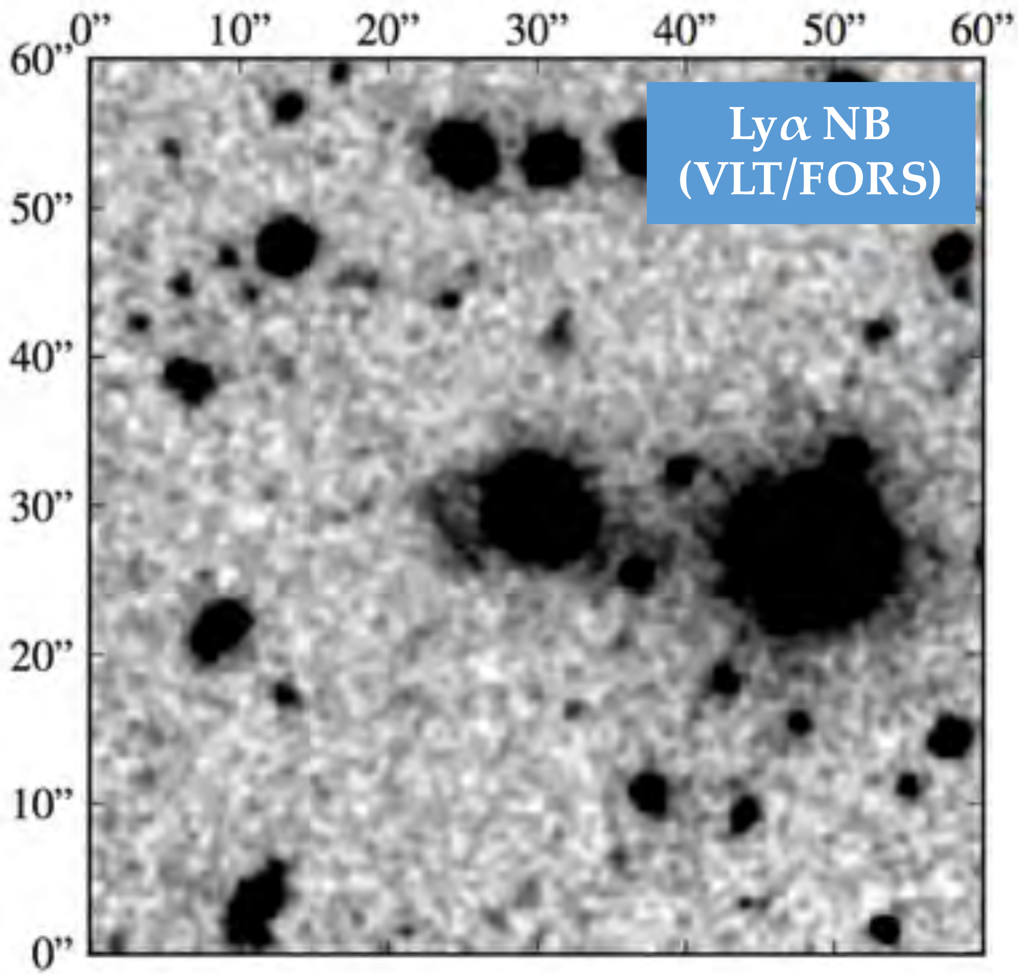

Sky residuals

Cantalupo, in prep.

# **CubExtractor**: data reduction and analysis package for MUSE cubes

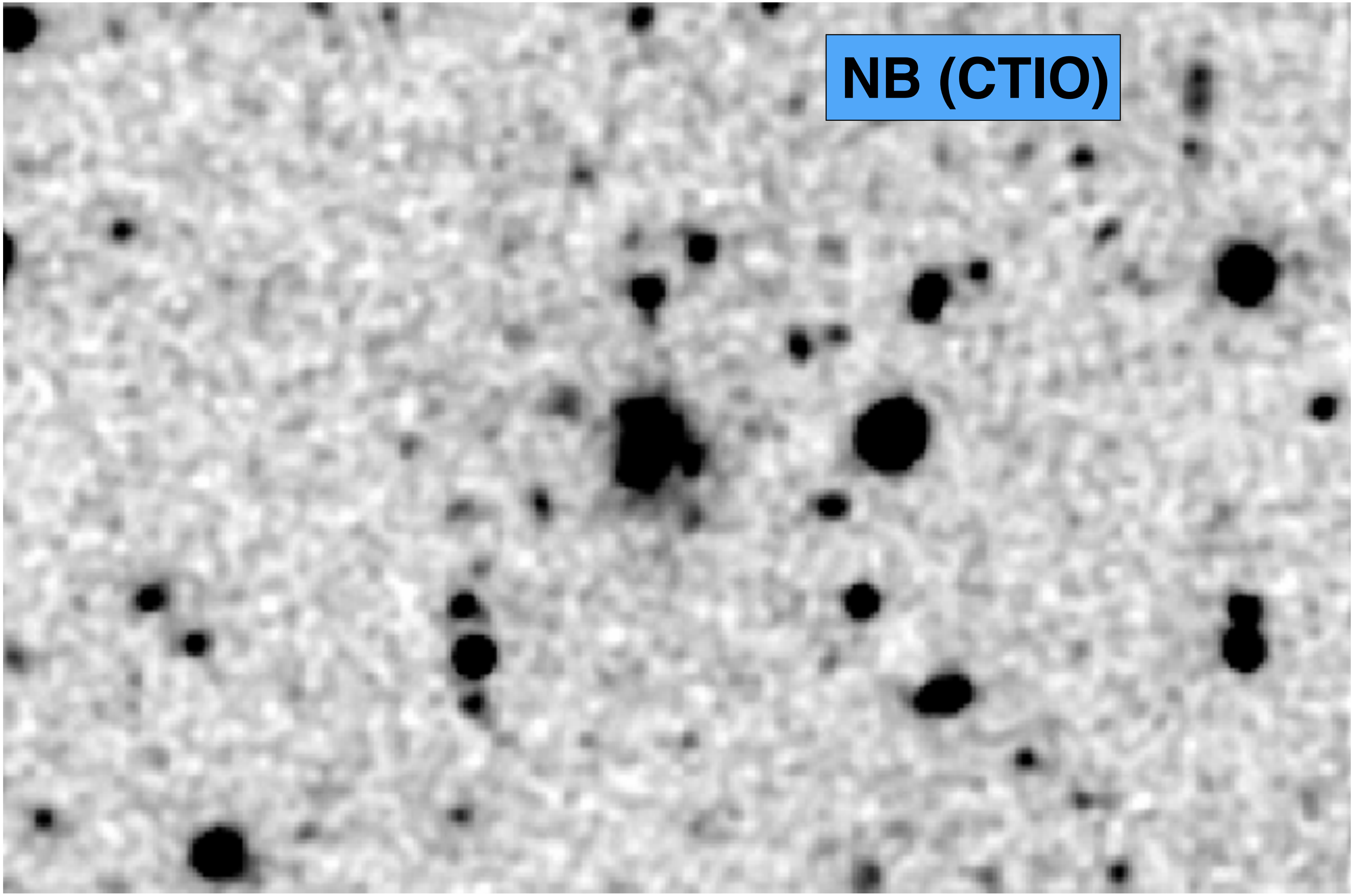
Including:

- 3D detection and extraction (including QSO PSF and continuum subtraction)

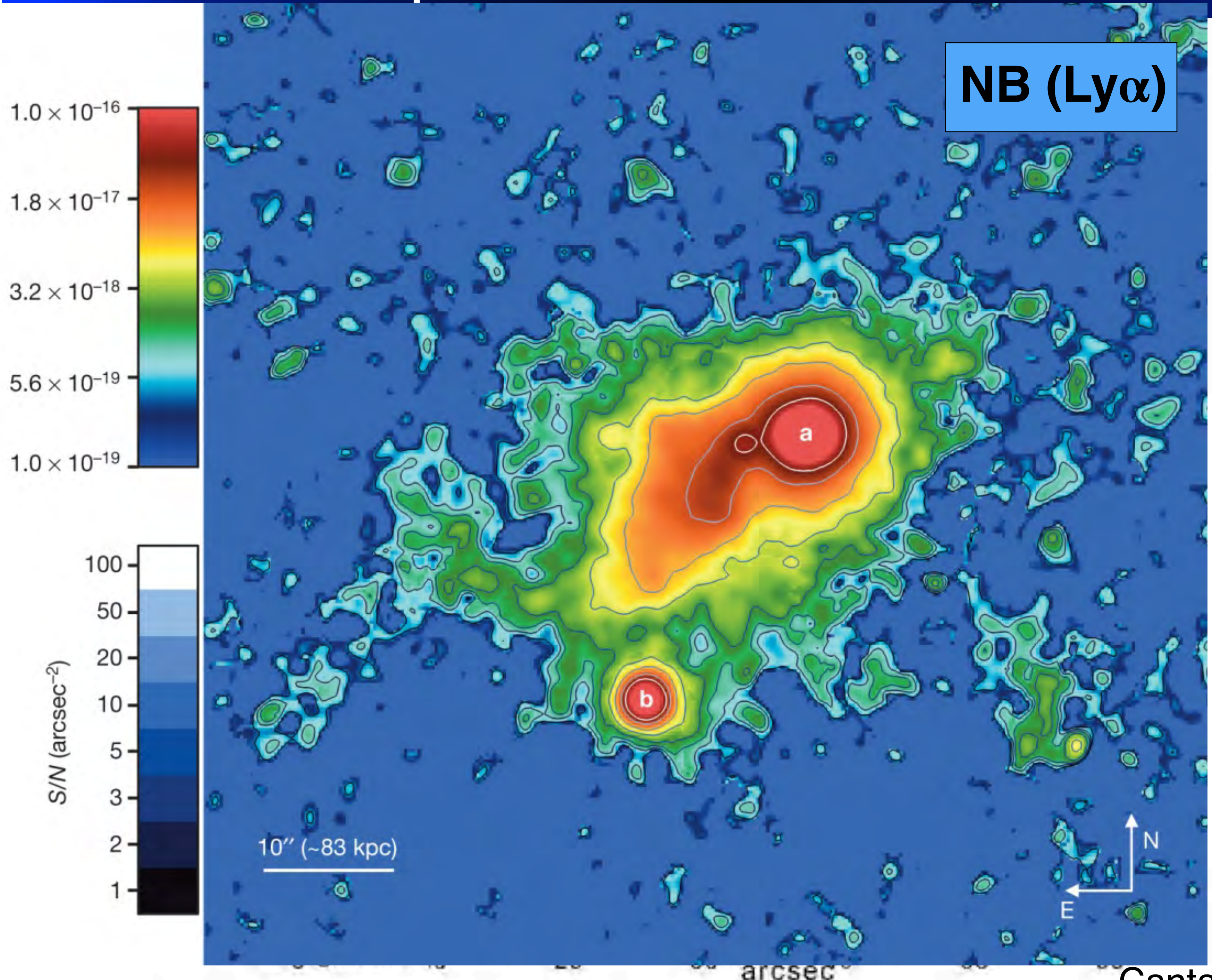



Cantalupo+, in prep.

# MILES3D Deep Fields: the Bulb Nebula

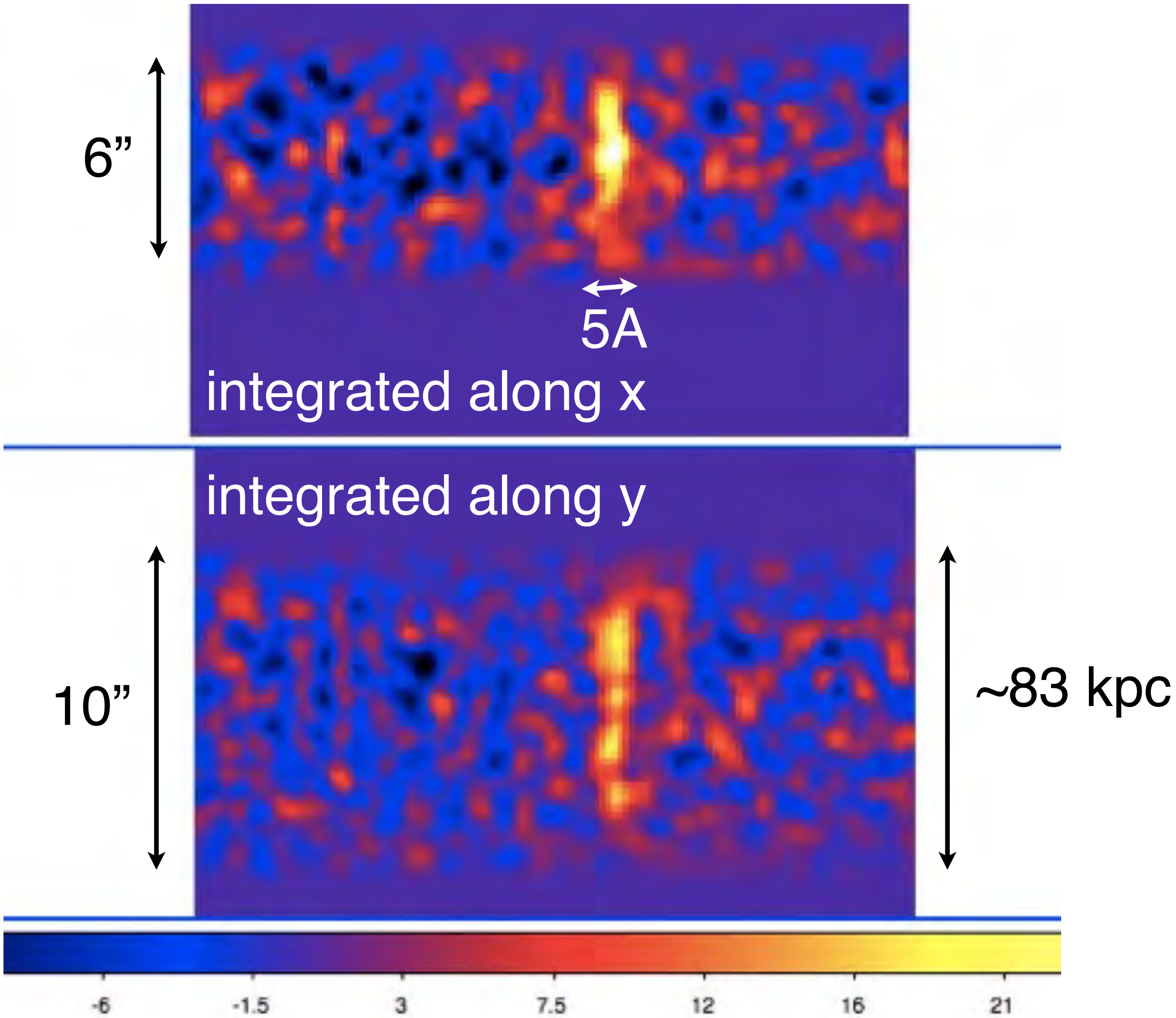


# MILES3D Deep Fields: Extended HeII emission from the Slug




Cantalupo+, in prep.

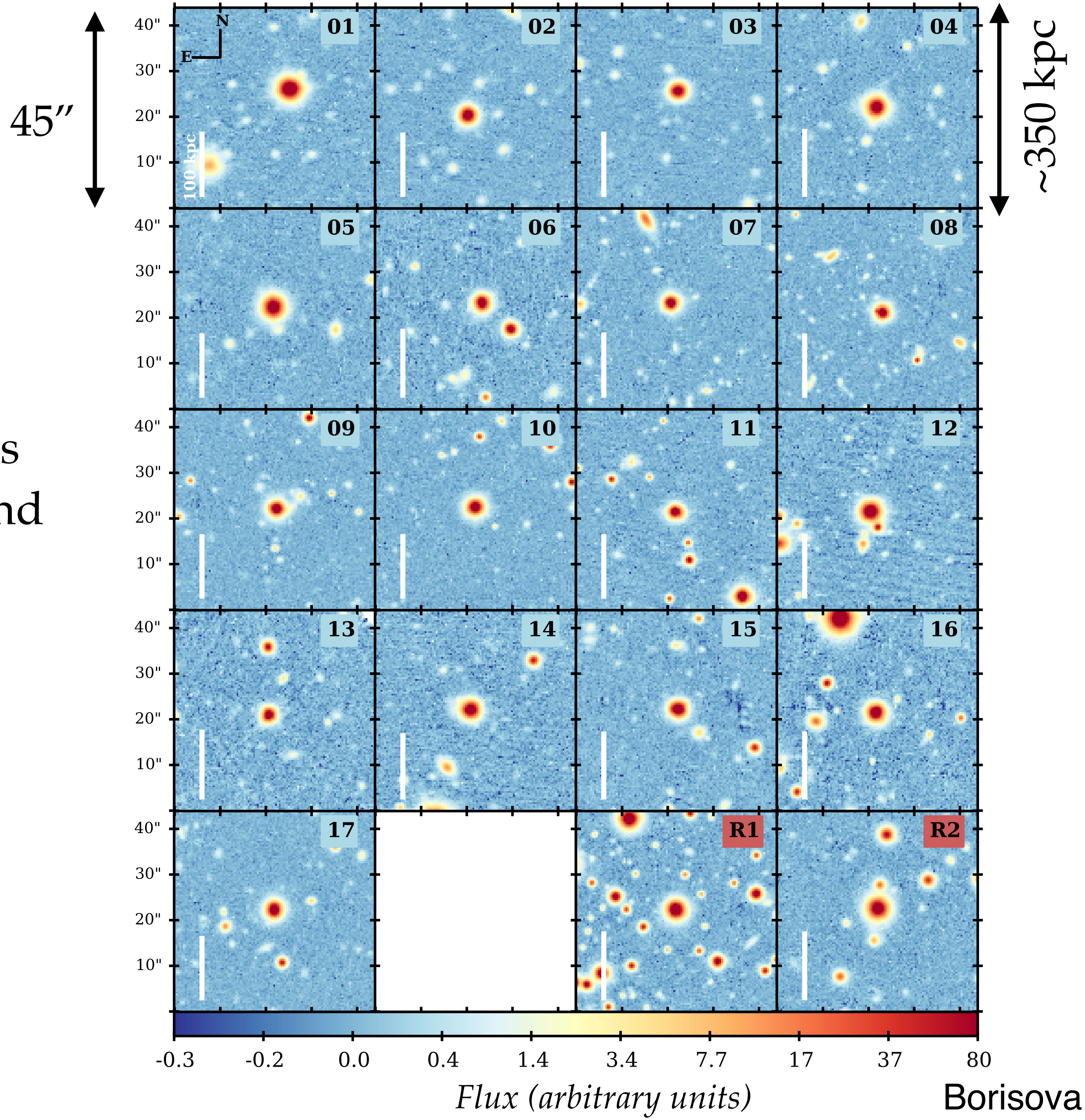
# “Optimally-extracted” HeII 2D Spectra: coherent velocity over >80kpc!




FWHM<5A, Size~40 arcsec$^2$
average SB~8x10$^{-19}$ cgs/arcsec$^2$

# QSO snapshot survey for giant Nebulae:

QSO fields
Broad-Band
Images




muse

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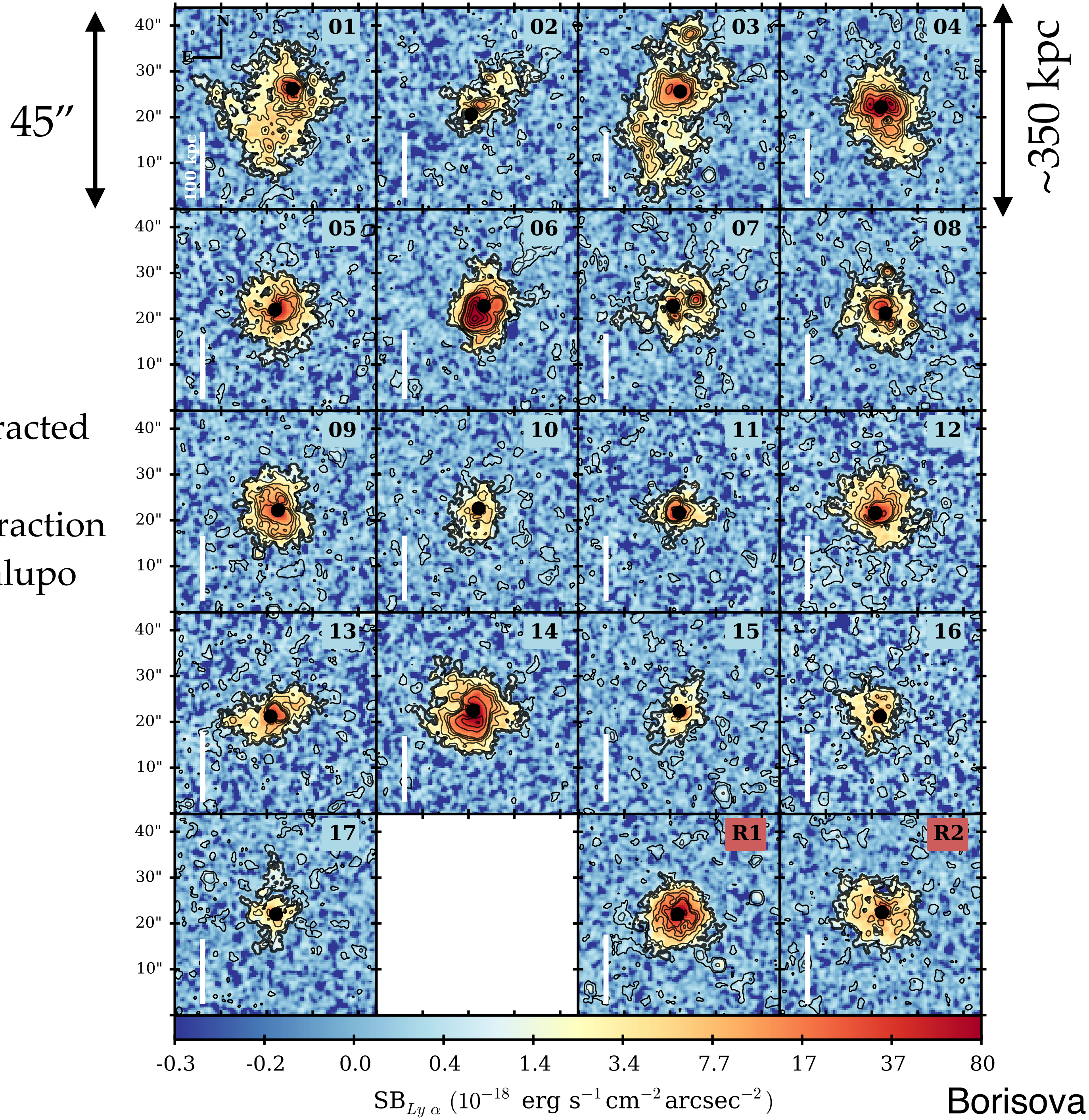
# QSO snapshot survey for giant Nebulae: 100% detection rate!




Optimally extracted pseudo-NB with PSF-subtraction (CubEx, Cantalupo in prep.)

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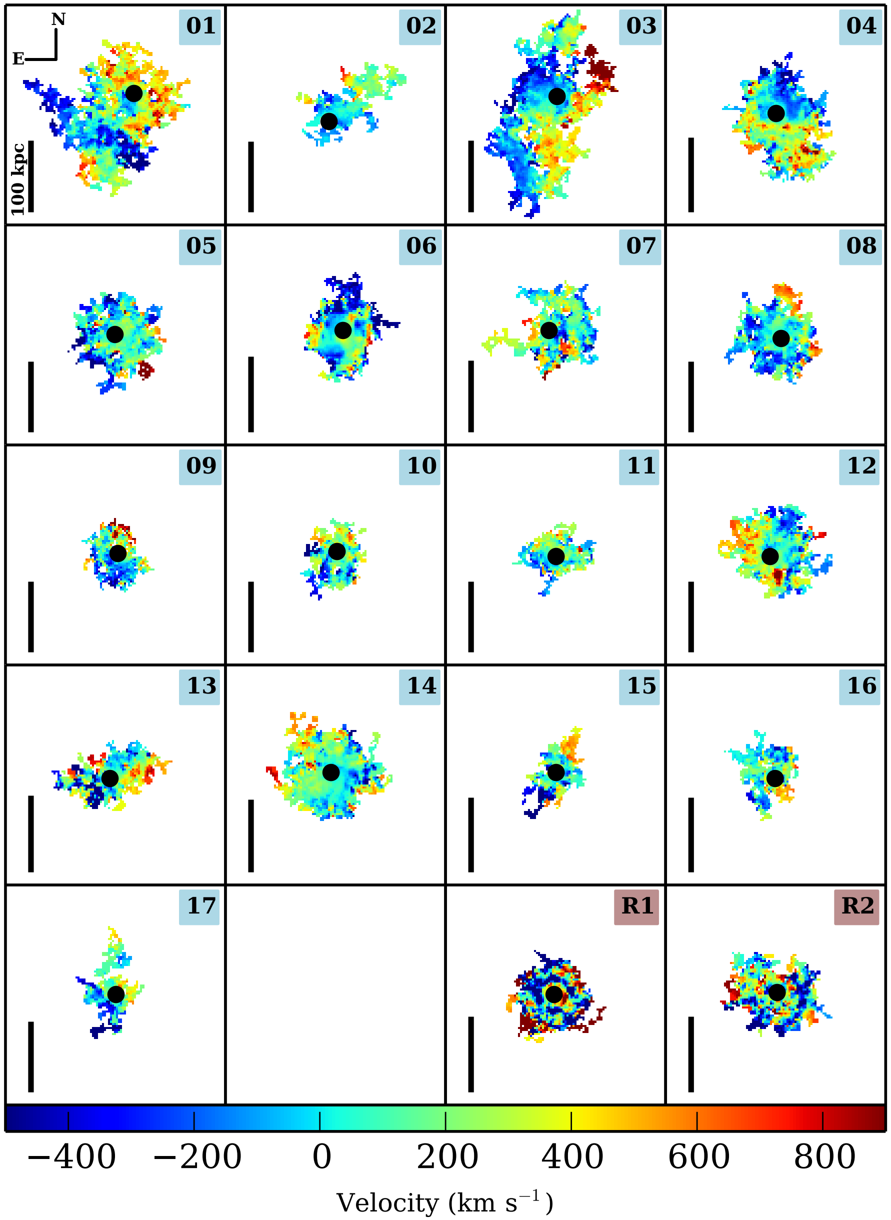
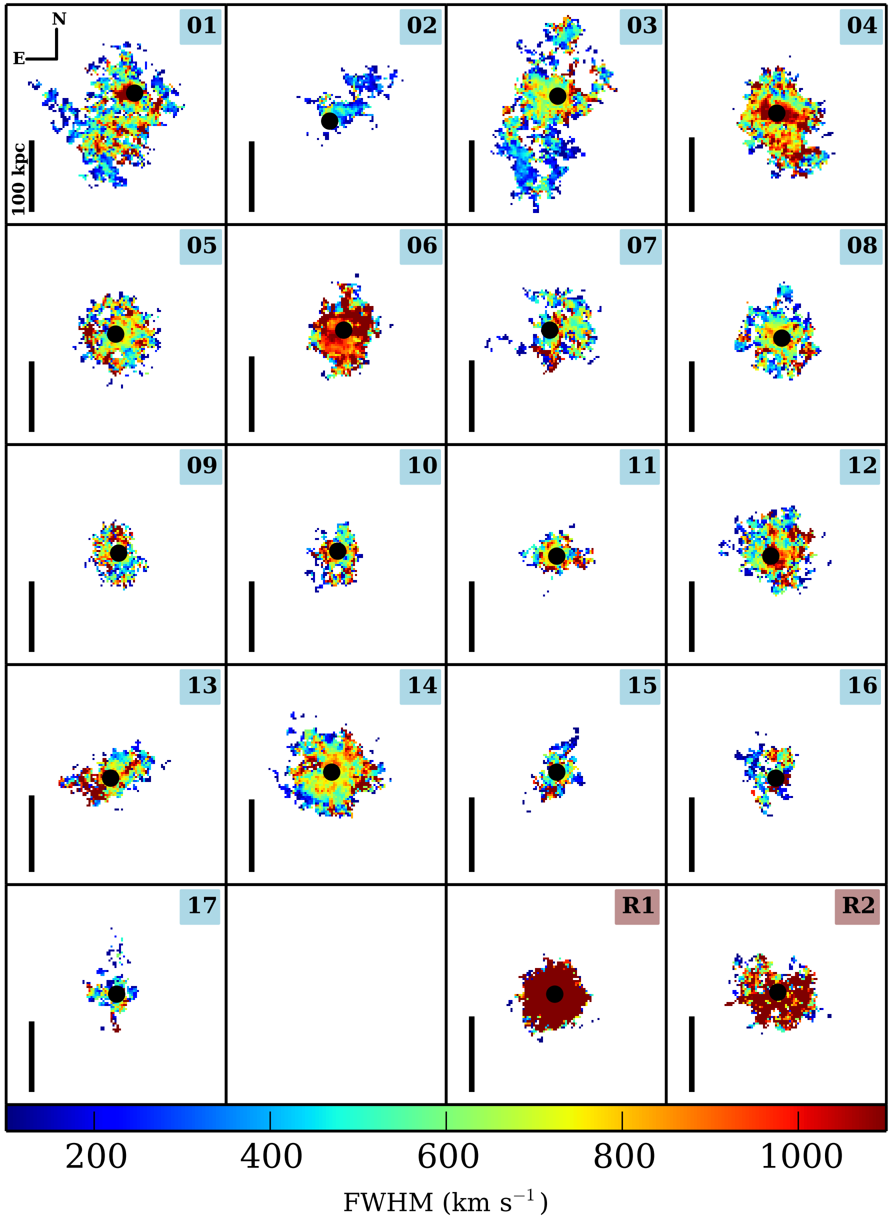
# 2D Velocity maps:

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

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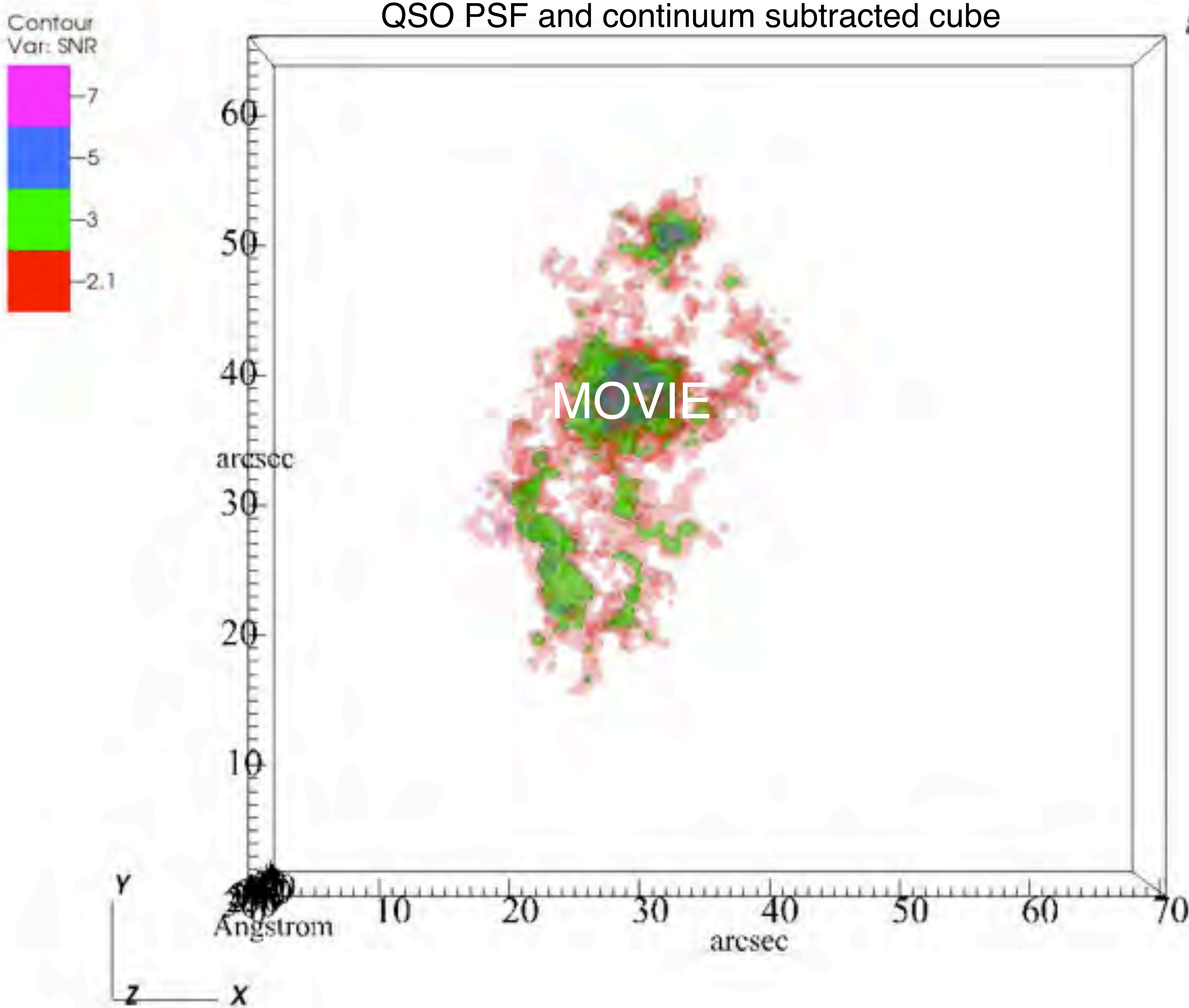
# A 3D view of the Muse Quasar Nebula 3 (MQN03), 350kpc in size:

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

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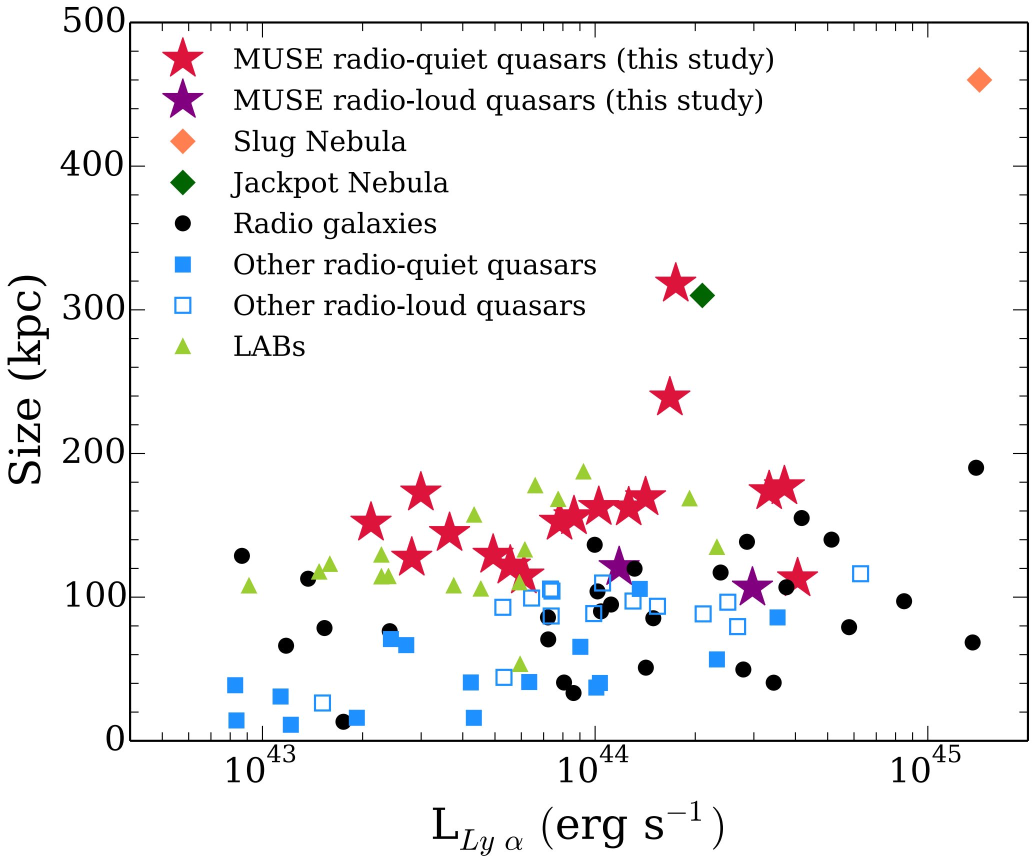
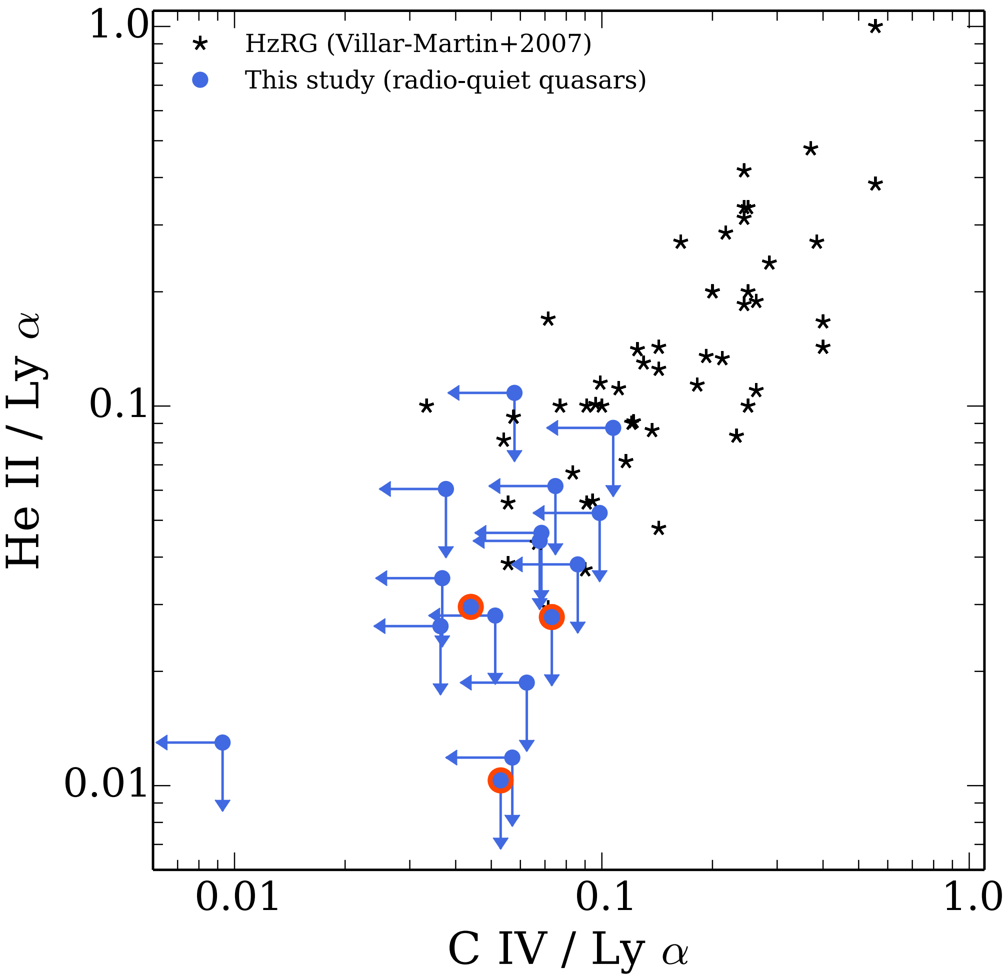
# How do they compare with other Lyα Nebulae and "haloes"?

## Size and Luminosity




## Line Ratios




➡ Qualitatively similar to LABs, clearly distinct from radio-loud sources (kinematically and in terms of line ratios).

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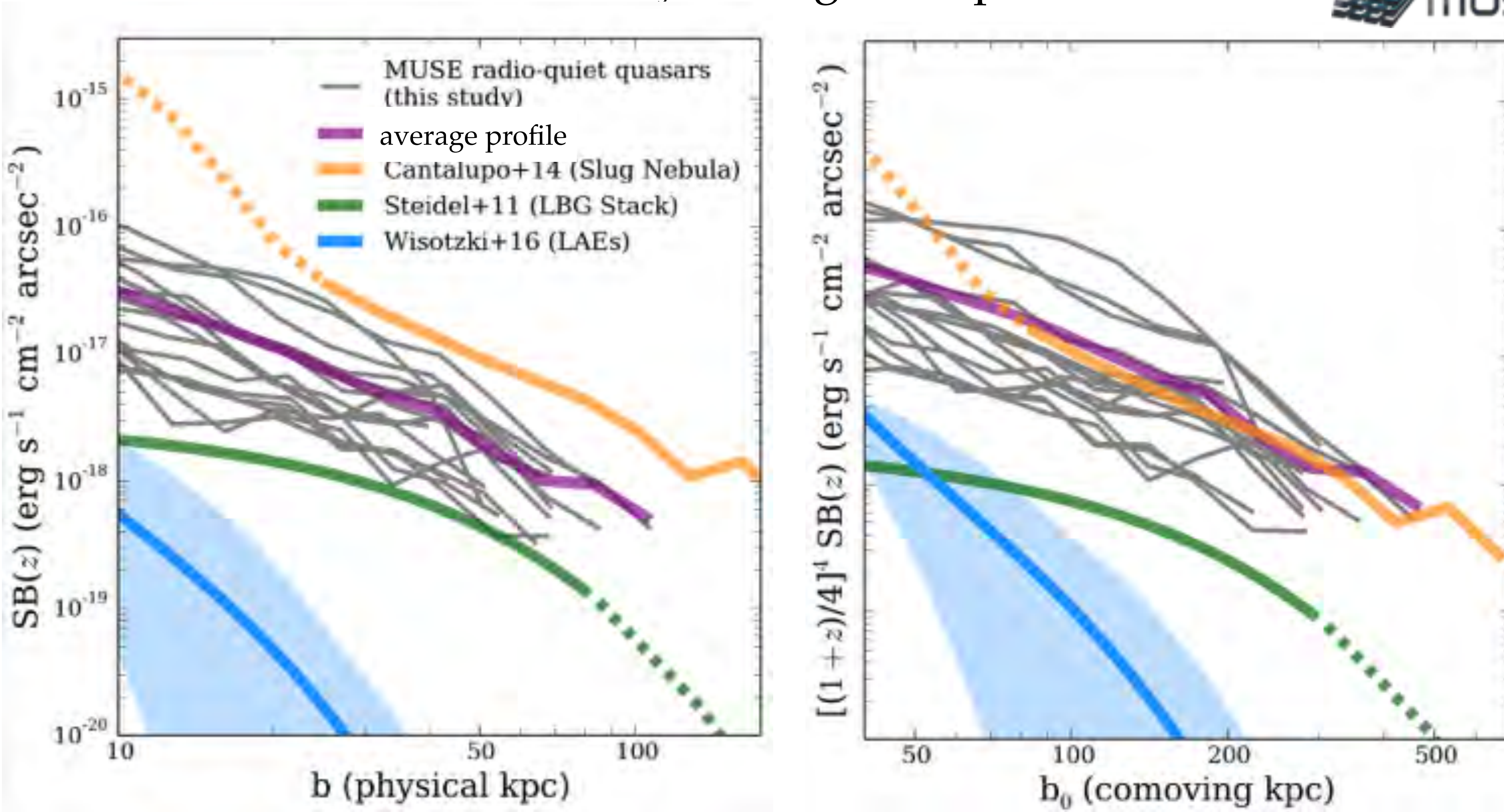
# How do they compare with other Lyα Nebulae and "haloes"?

## Circularly averaged SB profile




➡ All giant quasar nebulae have similar SB profile and are consistent with fluorescence (including Steidel LBG-stack "halo"!)

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# Open Questions and 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, KWCI required)

**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 (>50h-deep exposure with MUSE and/or KWCI required).

# Summary and open questions

**New technique to "illuminate" cosmic gas at high-z with the help of QSOs.**
Pilot NB surveys revealed "dark-galaxies" and intergalactic filaments around QSOs up to 500kpc size (with detection rate <10%).

**Large MUSE survey for intergalactic gas around QSOs (GTO):**

→ New data reduction and analysis tool for MUSE datacubes: CubExtractor, including optimized Flat-fielding, Sky-subtraction and 3D extraction/detection.

→ Giant nebulae are ubiquitous around MUSE QSOs at z~3.5. Tension with NB observations at z~2. Redshift/Luminosity evolution?

→ MUSE observations of Ly$\alpha$, HeII and metal emission lines suggest large gas densities (clumps). Tension with numerical models, missing physics?

**Next Future:**

→ Ultradeep MUSE fields (GTO) for Cosmic Web detection around QSOs and in blank fields.

→ Extending luminosity and redshift range for Quasar giant nebulae "snapshot" surveys.

→ New theoretical/numerical models for IGM emission studies.

Stay tuned!