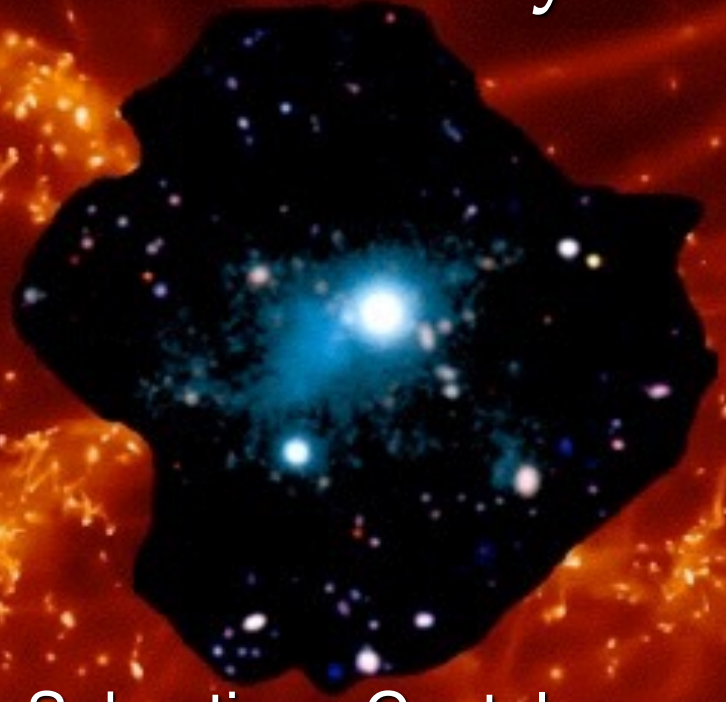
Illuminating the IGM with quasar-induced Lyα emission



Sebastiano Cantalupo
ETH Zurich

In collaboration with:
Simon Lilly (ETH), Elena Borisova (ETH), J. Xavier Prochaska (UCSC), Sammy B. Slug (UCSC), Piero Madau (UCSC),Fabrizio Arrigoni-Battaia (MPIA), Joe Hennawi (MPIA), Martin Haehnelt (IoA)

Cantalupo et al., *Nature*, 2014

Talk Outline

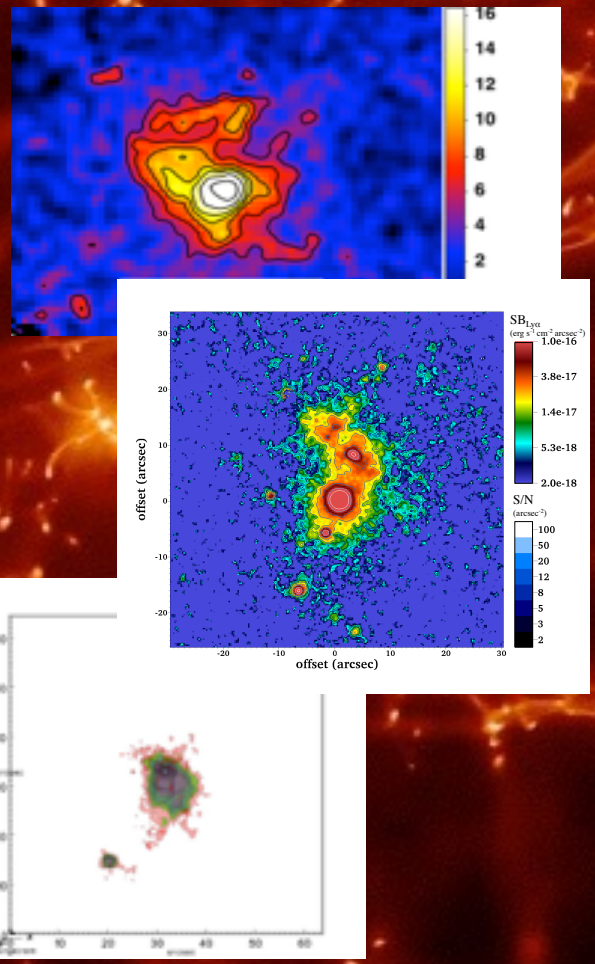
Introduction:
detecting the IGM in Emission

Pilot VLT/FORS Survey

The Keck/Gemini NB
Survey (FLASHLIGHT)

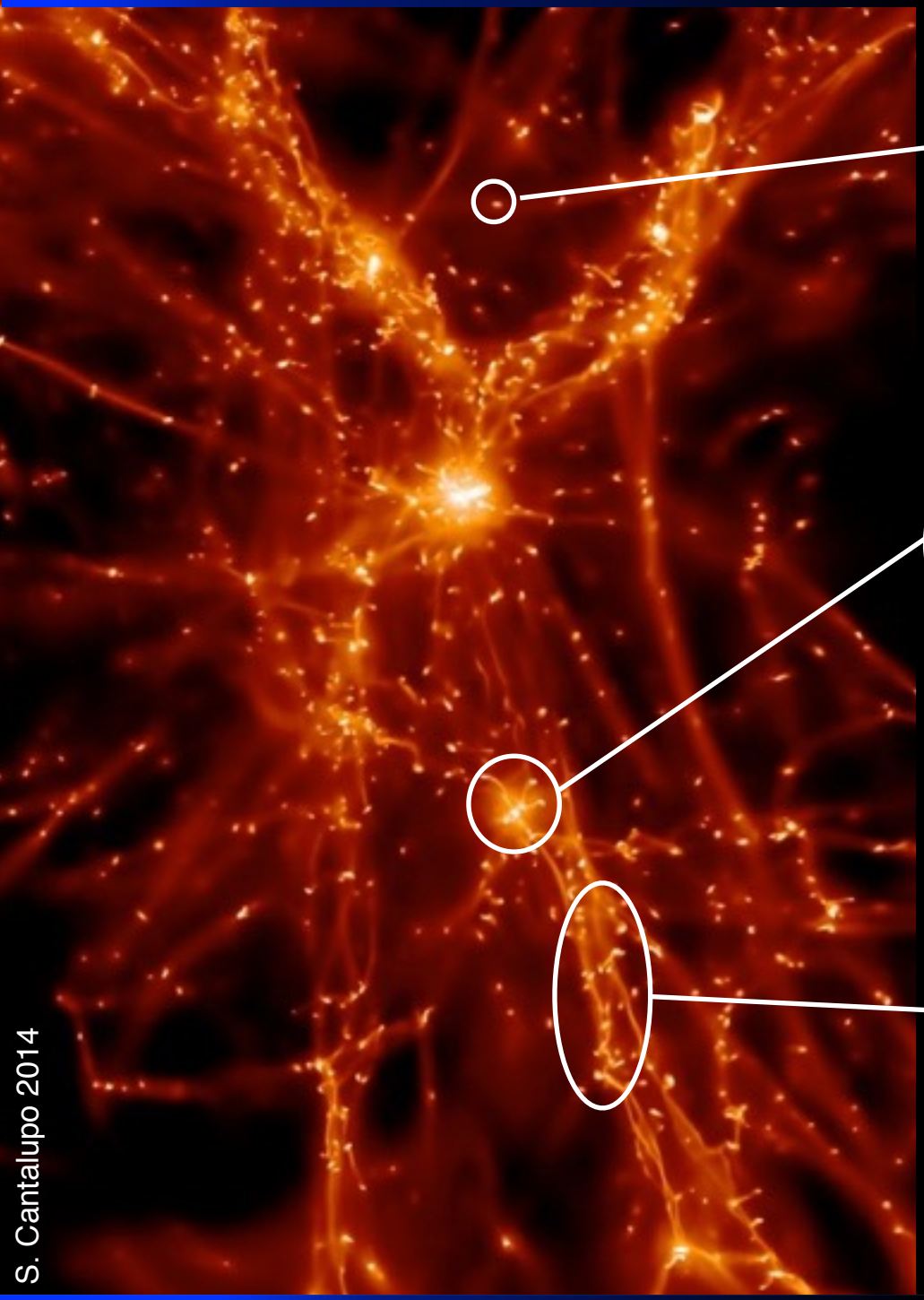
The IGM/CGM in 3D
with MUSE (GTO Survey)

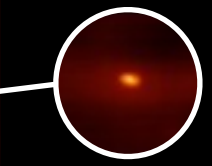
Open questions/Summary



Cantalupo et al., *Nature*, 2014

Key Questions



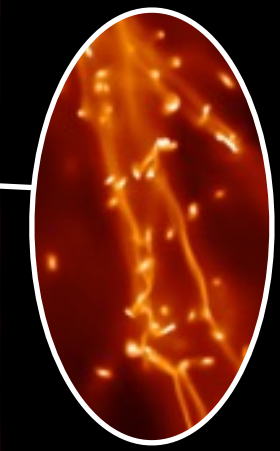


1-10 kpc

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

10-200 kpc

How do galaxies get their gas? Is the CGM cold, hot or lukewarm?



200-1000+ kpc

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

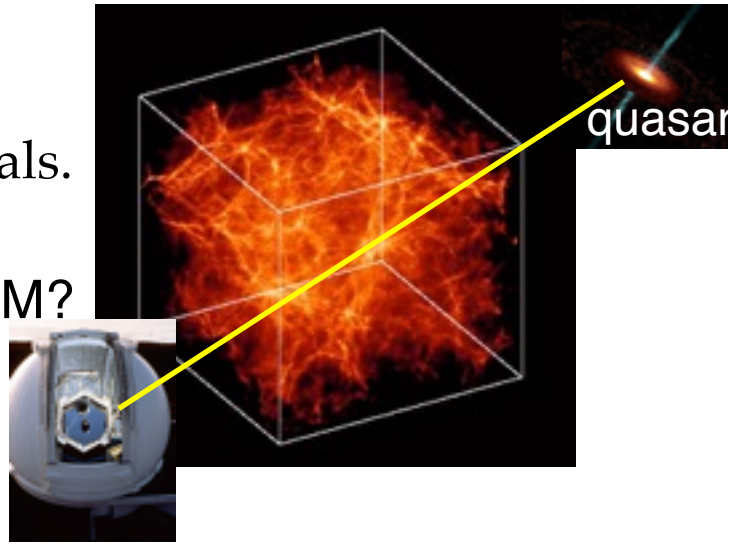
S. Cantalupo 2014

Detecting Cosmic Gas

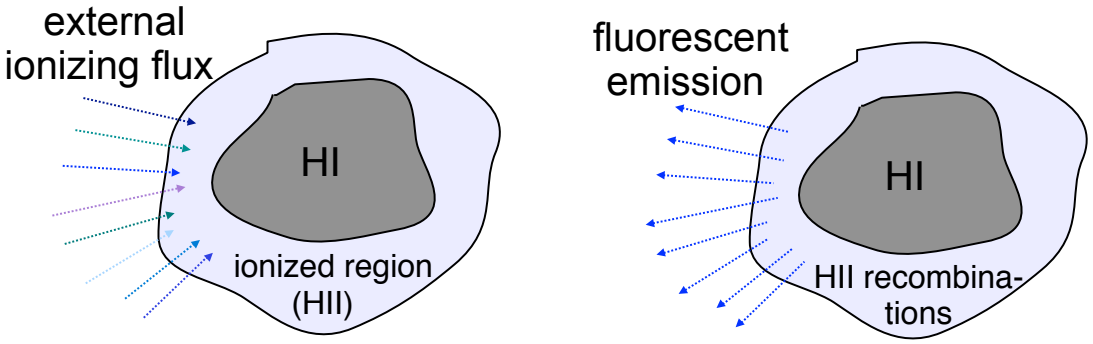
"Classical" approach: in absorption.

- 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 Lyα (*Hogan & Weymann 1987;Gould & Weinberg 1996; Zheng & Miralda-Escude 2005; Cantalupo+05,07; Kollmeier+08, Cantalupo+12*)

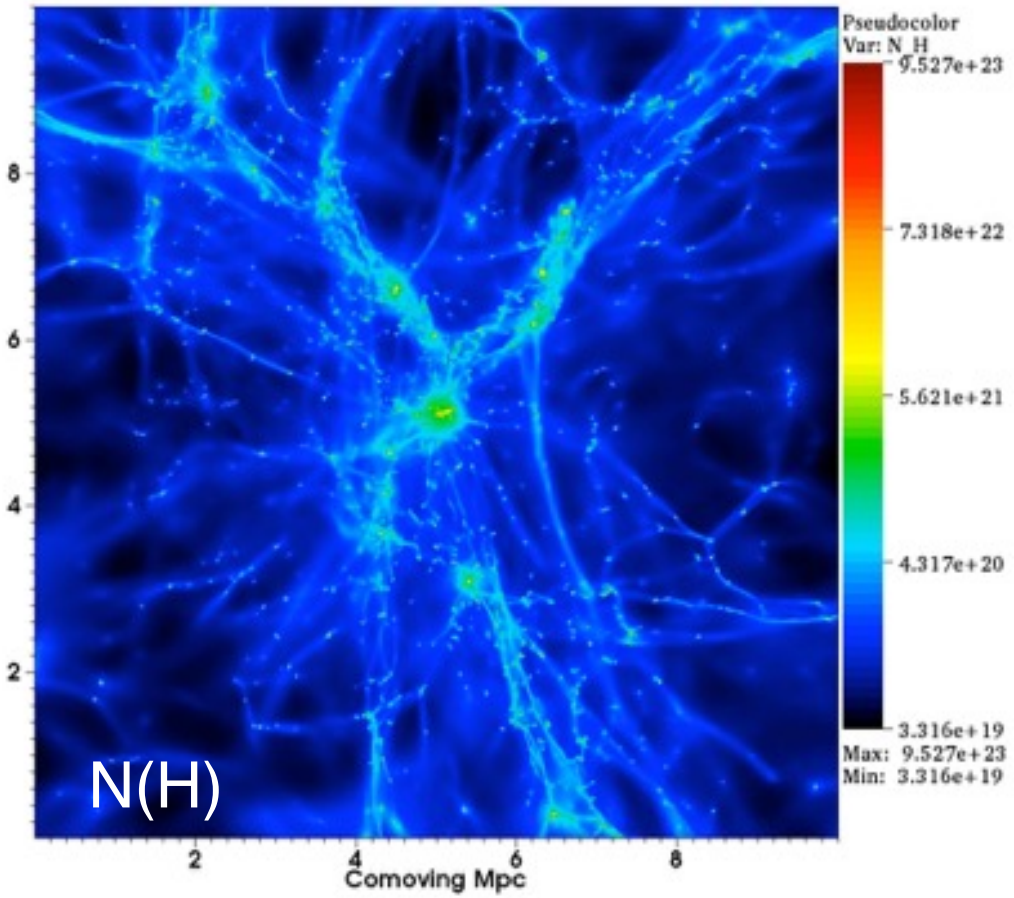


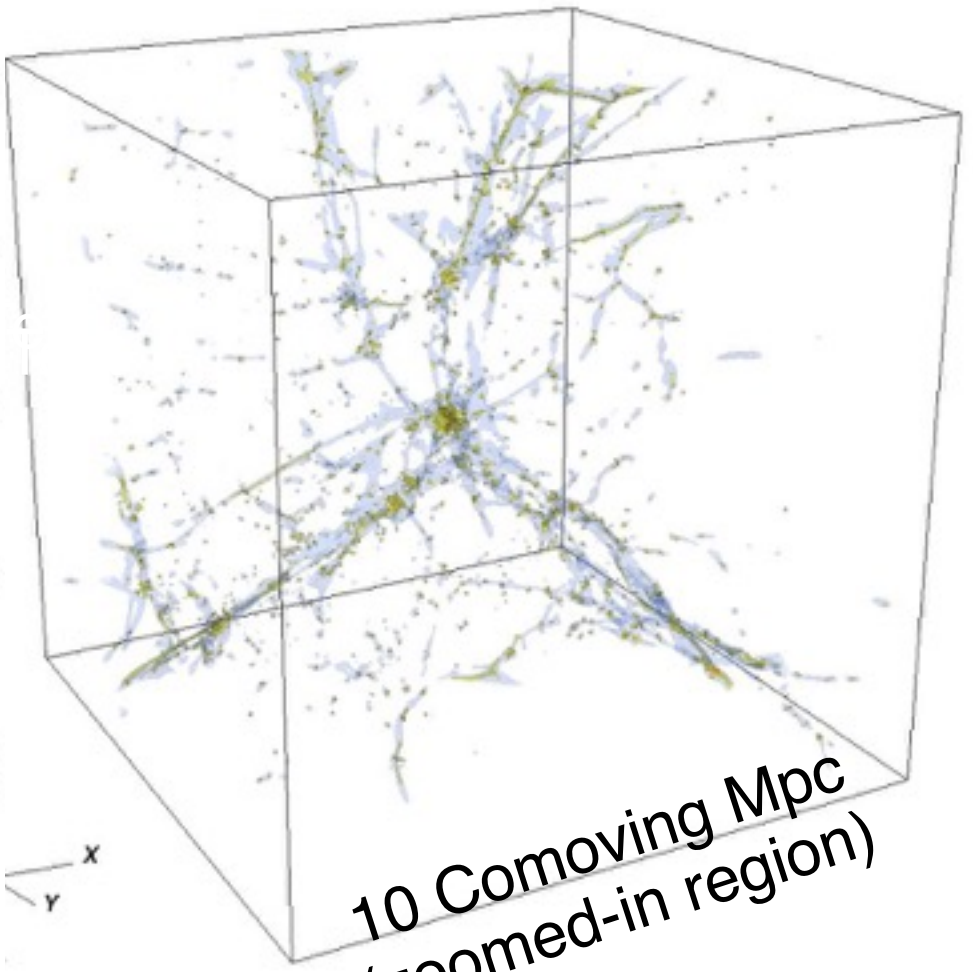
➡ Self-shielded gas (slab): "mirror" emission -> ~60% of incident ionizing radiation "converted" to **Lyα (but see Cantalupo+05).**

➡ Fully ionized gas: proportional to gas density squared.

How bright is fluorescent emission: simulations

- **40Mpc^3** (10Mpc^3 high-res) hydro-simulation (RAMSES) around 3x10^{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 Lyα radiation.

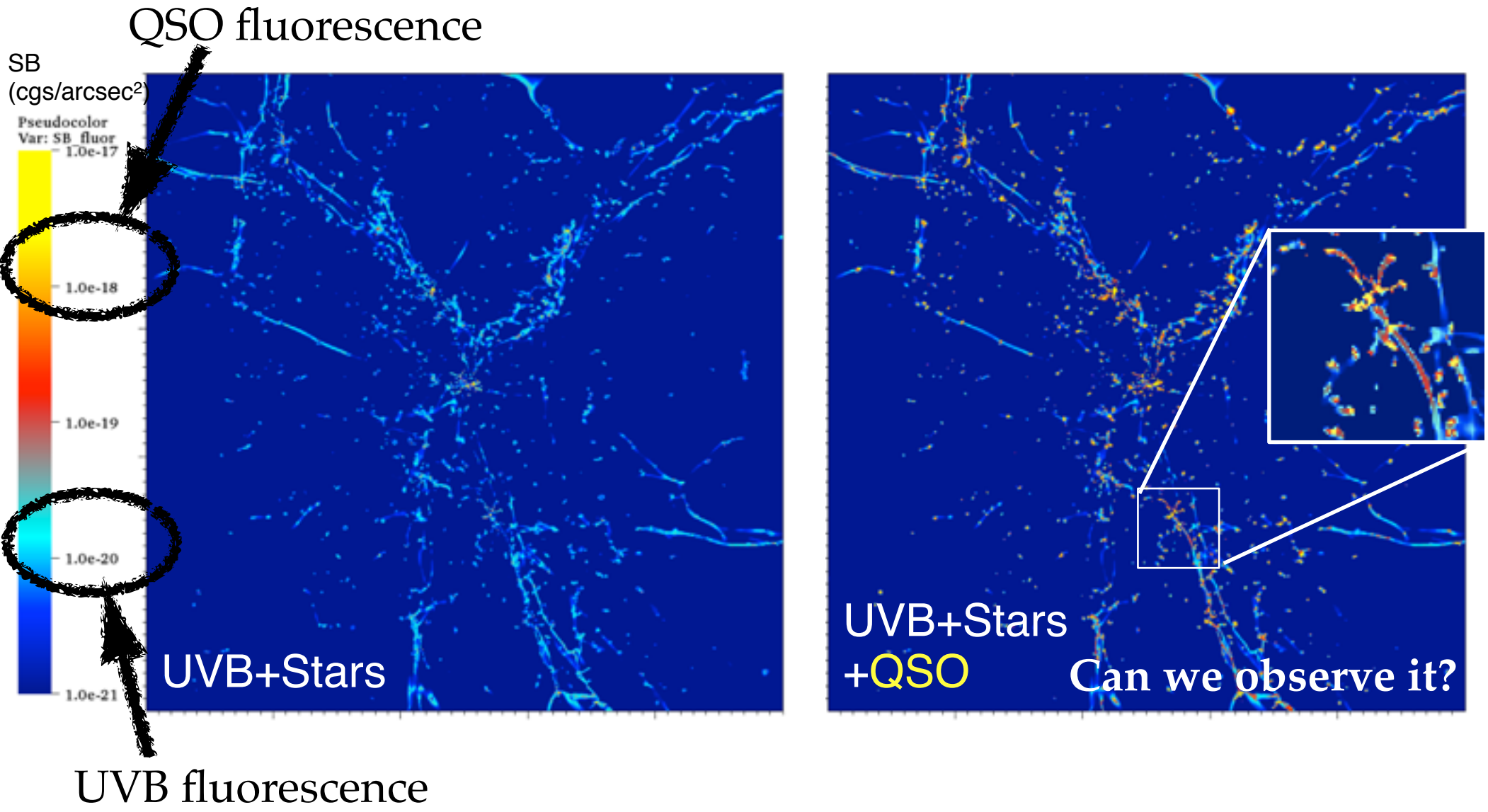




Cantalupo+12

How bright is fluorescent emission: simulations

Simulated Lyα images

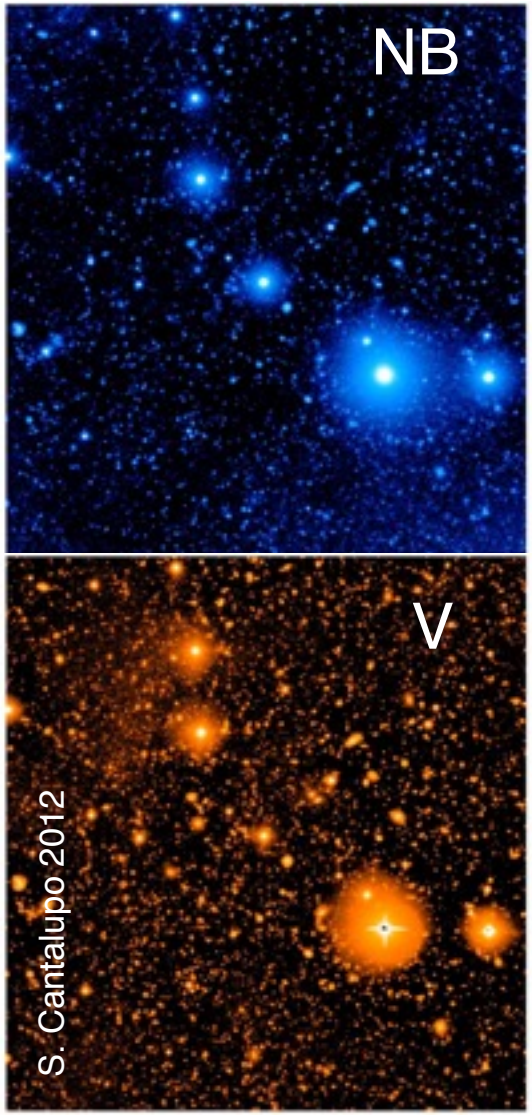


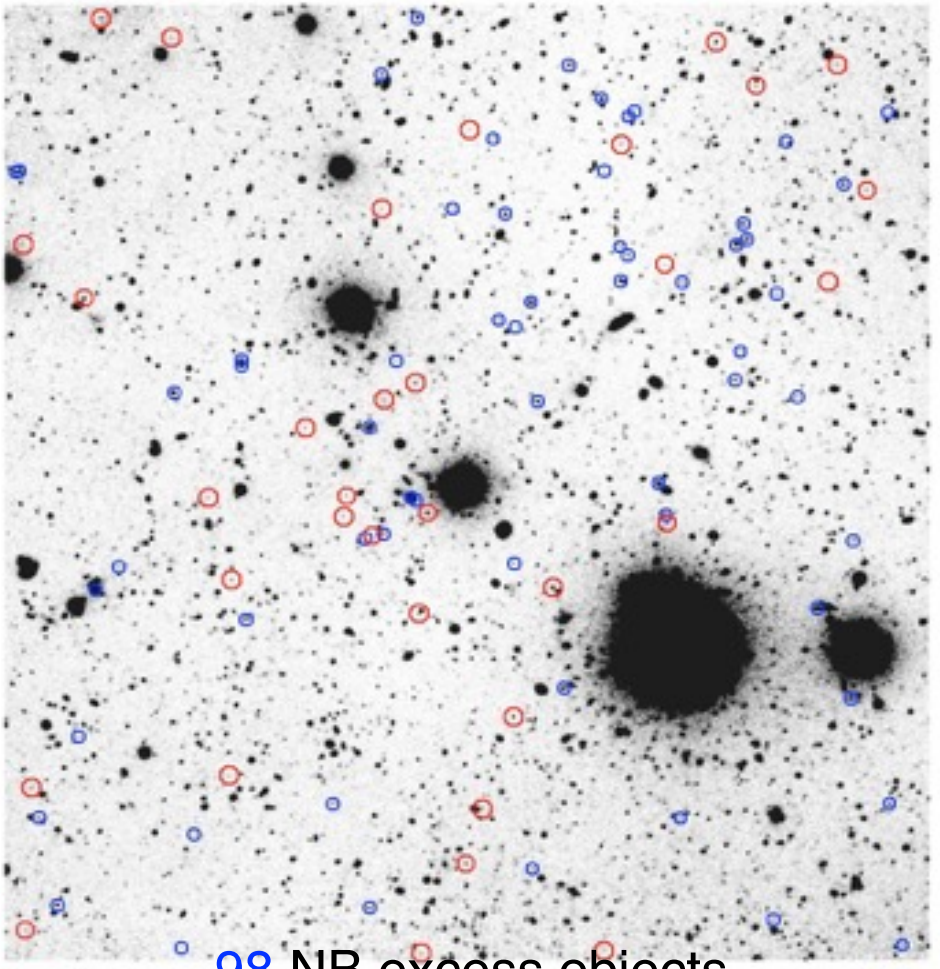
Cantalupo+12

Very Large Telescope (VLT) Pilot Survey

Deep Narrow-Band (NB) and continuum imaging around a QSO @ z=2.4

- Custom-built filter (FWHM=4nm) using QSO systemic redshift (OIII line)
- Deepest NB ever taken at VLT: 21 hours (+6h V-band, +1h B-band)
- NB flux limit: ~4×10^{-18} erg/s/cm^2 [5σ for 1 arcsec^2 aperture]



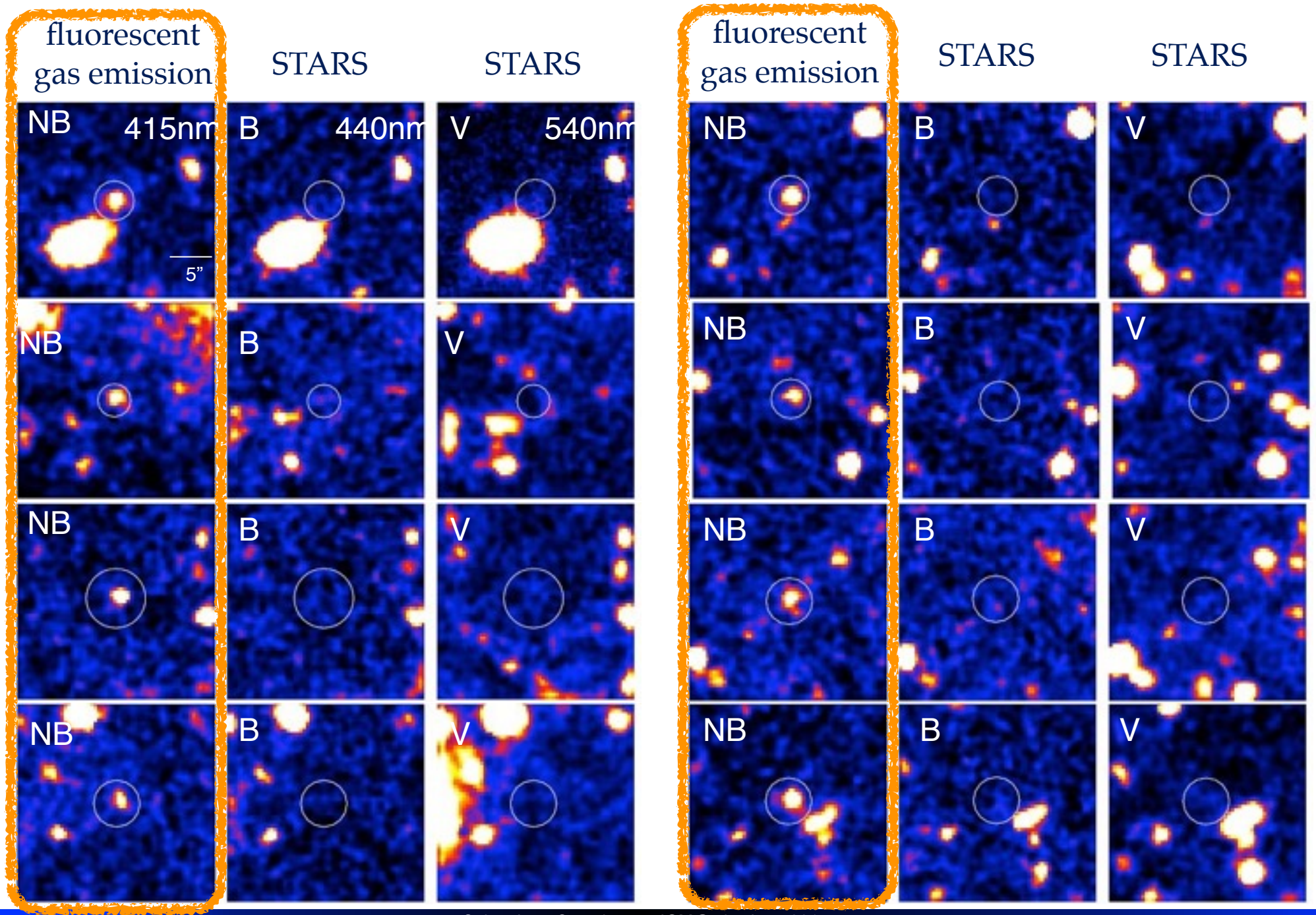


98 NB excess objects
31 without V or B detection (red circles)

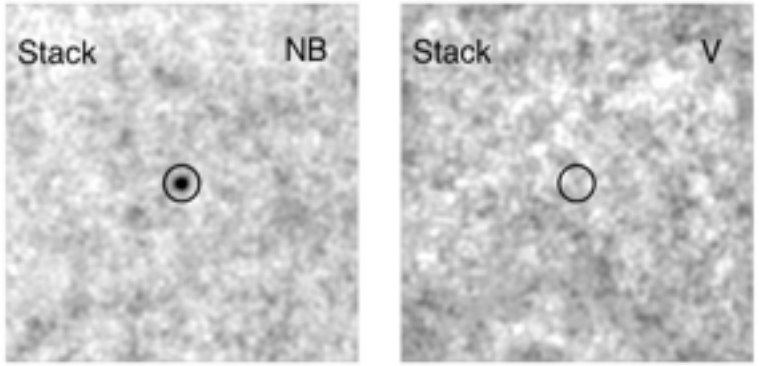
Cantalupo, Lilly & Haehnelt 2012

"Dark" Galaxies - a selection (EW>240A, no continuum)

Cantalupo+12



Dark Galaxies: Gas Mass and Star Formation Efficiency

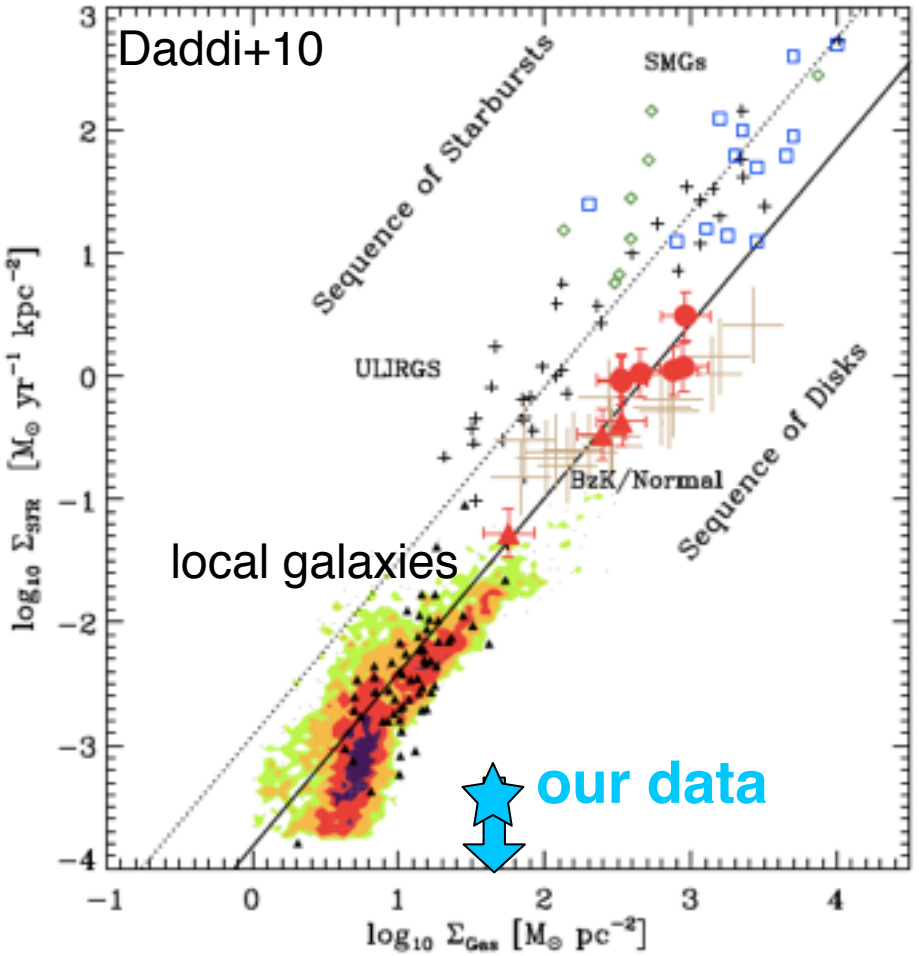


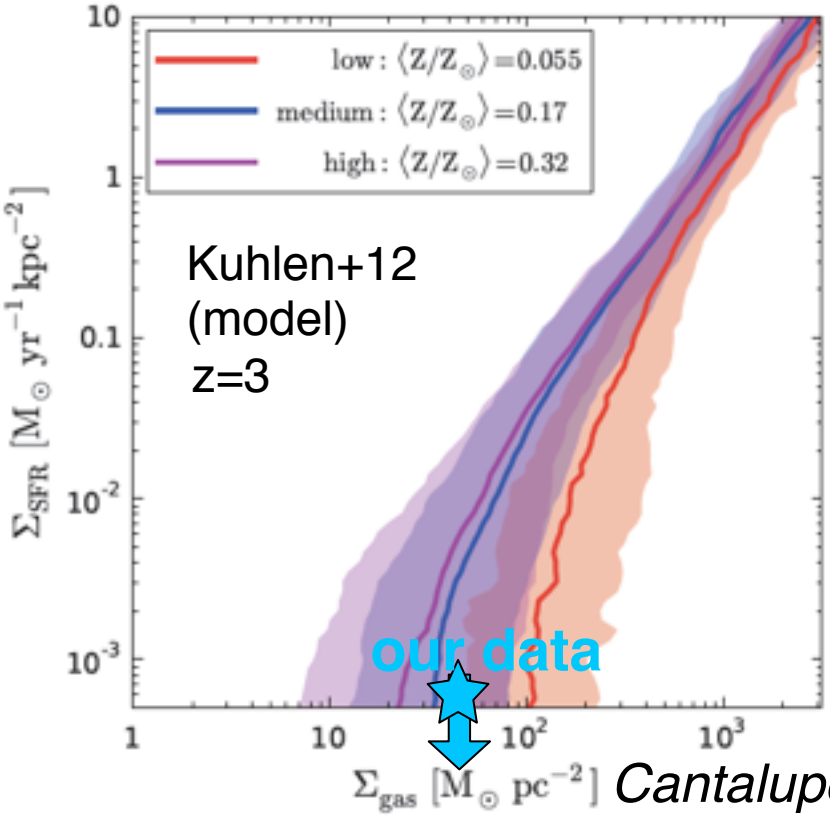
from NB: Inferred (cold) Gas Mass: ~10^9 M_{sun}

from V-band Stack: SFR<0.01 M_{sun}/yr

SF Efficiency: <10^{-11} yr^{-1}
(gas consumption time >100 Gyr)

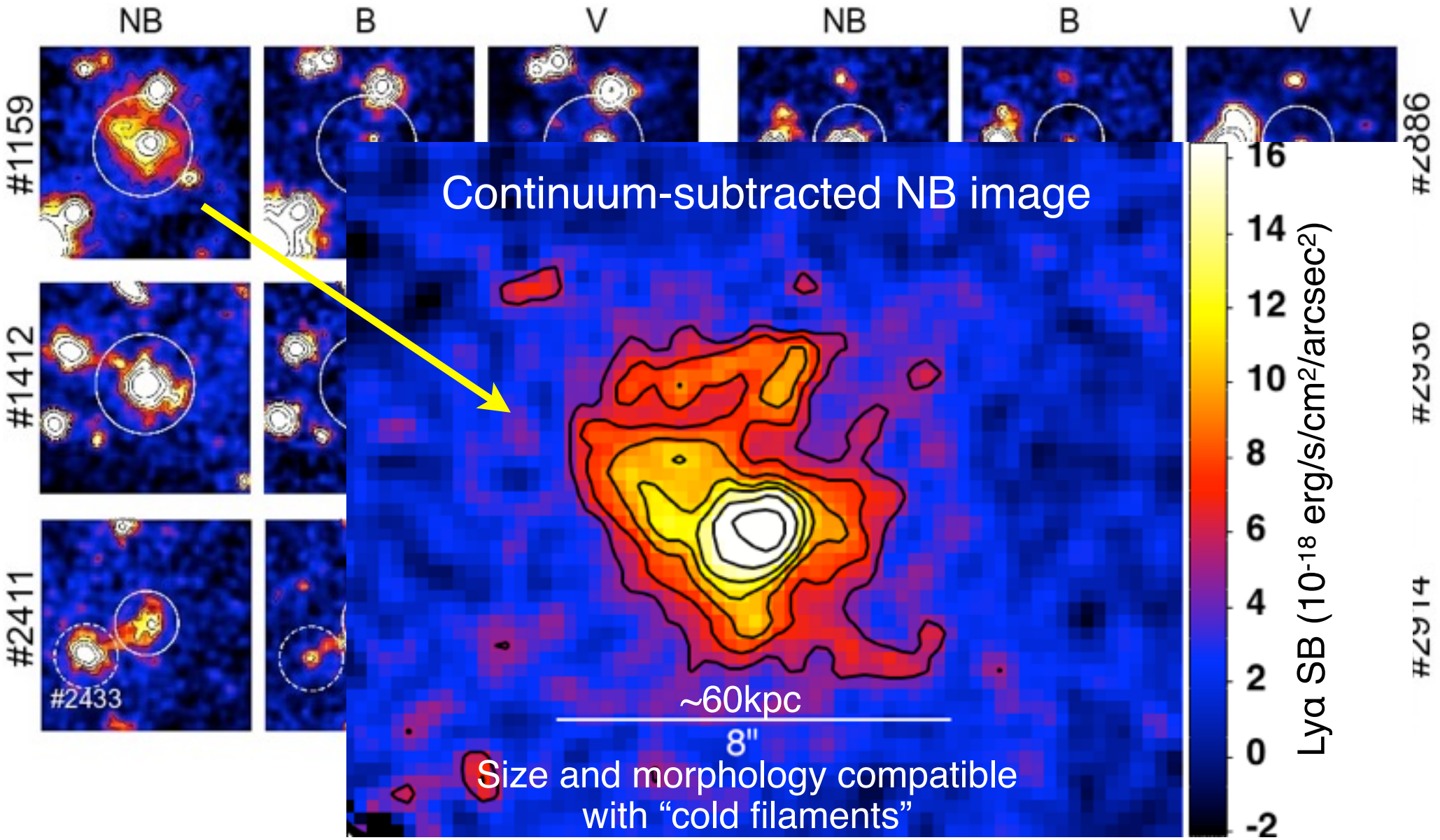
Where are they on the Kennicutt-Schmidt relation?





Cantalupo+12

Extended objects: CircumGalactic Medium in emission



Cantalupo+12

Ongoing Fluorescence Surveys [~200h + MUSE GTO]

FLASHLIGHT: Keck ang Gemini NB survey [at z~2]

(Cantalupo, Prochaska, Arrigoni-Battaia, Hennawi, Madau)

- targets: 26 bright SDSS QSOs at z~2, custom-built NB filters (4)
- Data collected so far: 3 QSOs (deep) + 5 (medium-deep) on Keck/LRIS
  3 QSOs (deep) + 15 QSOs (shallow) on GMOS

$1\sigma \sim 5\text{-}8 \times 10^{-19}$ cgs/arcsec^2 (deep)

MILES3D: MUSE Intergalactic Line Emission Survey in 3D at [z~3] (GTO)

(Cantalupo, Lilly, Borisova, Marino, Gallego + MUSE GTO Team)

- targets: "pre-imaged" QSO fields + brightest QSOs at z>3
- Data collected so far: 3 deep exposures (9h) on "pre-imaged" fields
  15 QSO snapshot fields (1h)

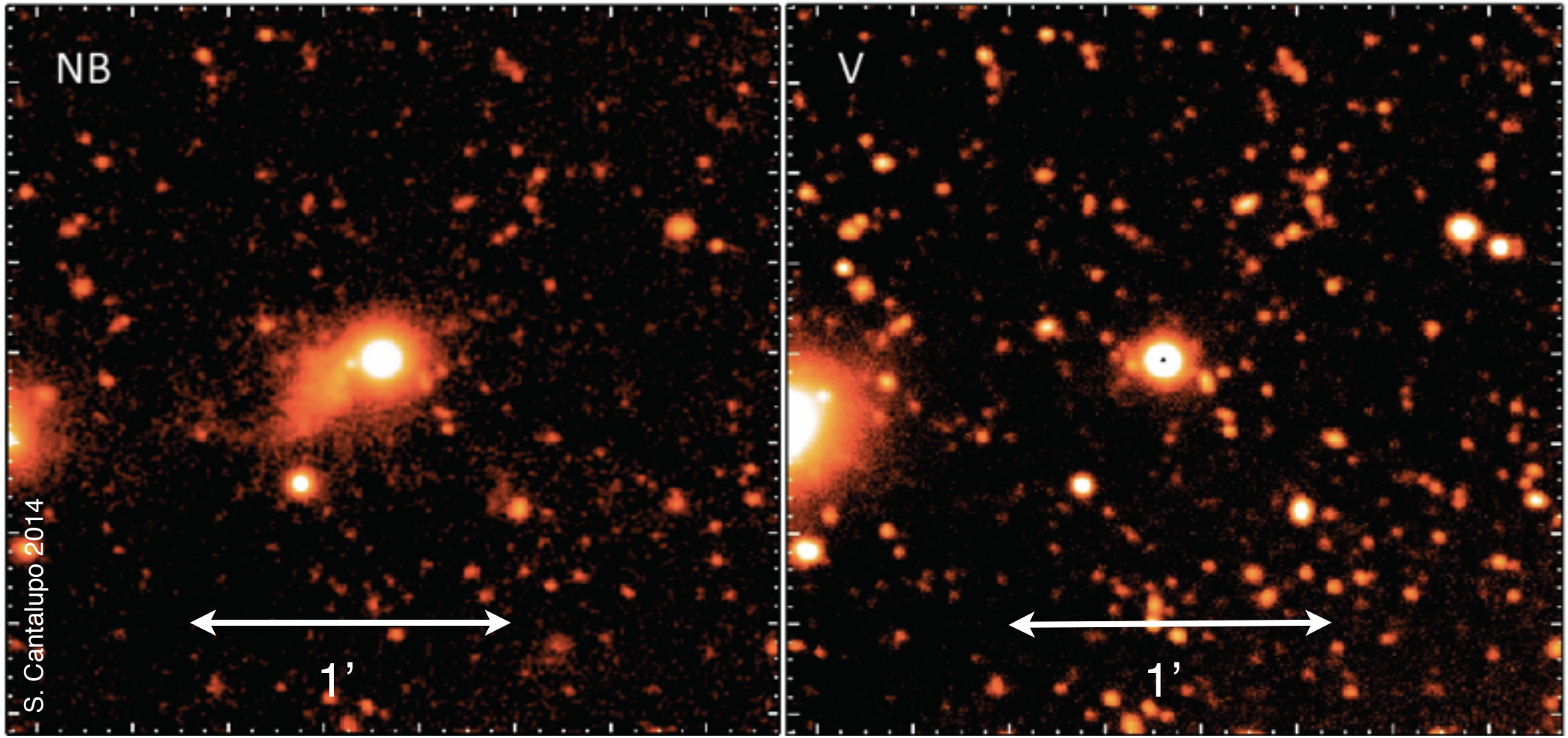
$1\sigma \sim 1\text{-}3 \times 10^{-19}$ cgs/arcsec^2 (deep)

long term goal: 80h on Quasar Field reaching $1\sigma \sim 3\text{-}5 \times 10^{-20}$ cgs/arcsec^2

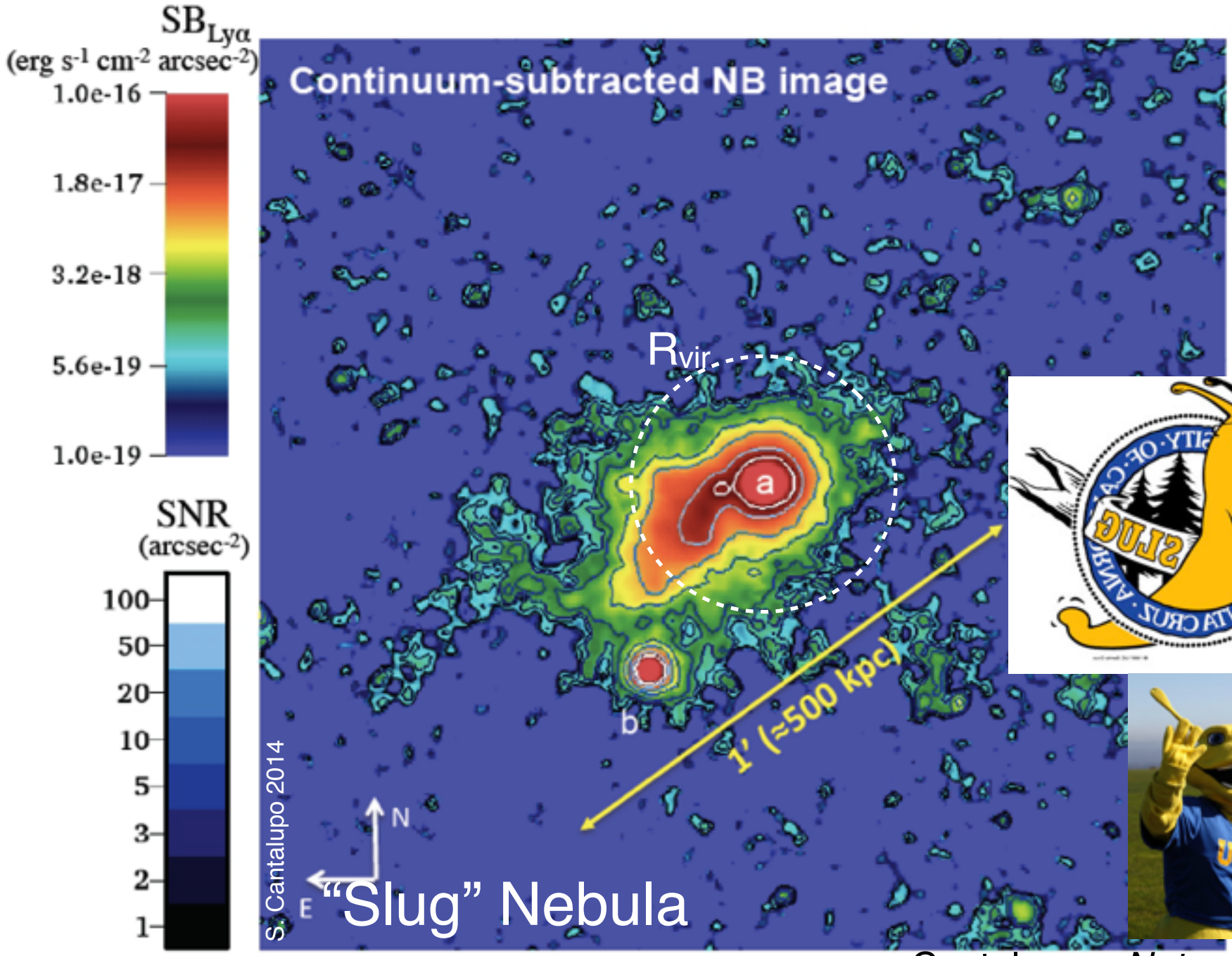
FLASHLIGHT: First Keck/LRIS results

1) NB imaging of a bright, radio-quiet quasar @ z=2.27
   10h NB, 10h V-band (parallel)
   1h B, 1h R (parallel)

Cantalupo+, *Nature*, 2014



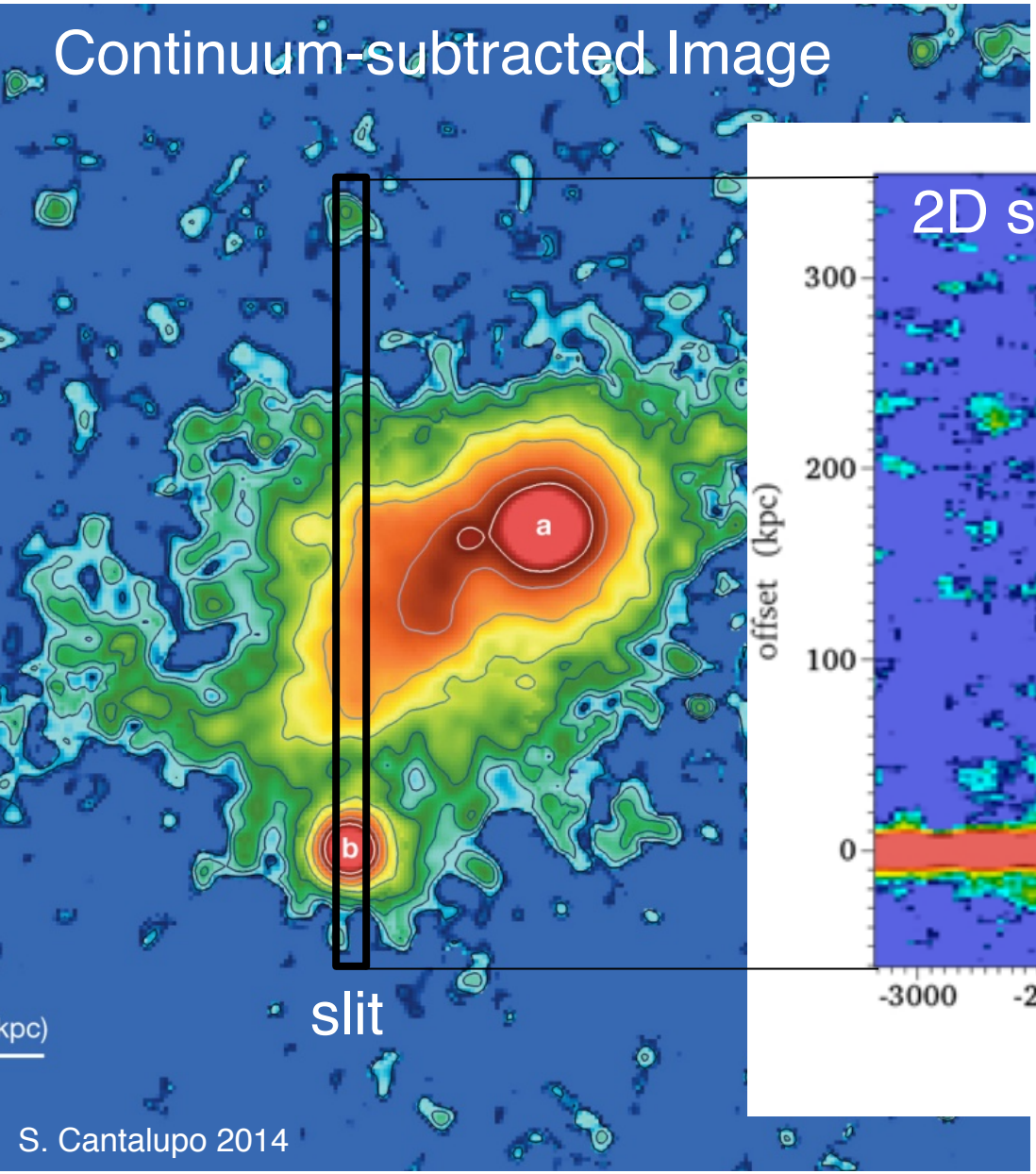
FLASHLIGHT: First Keck/LRIS results

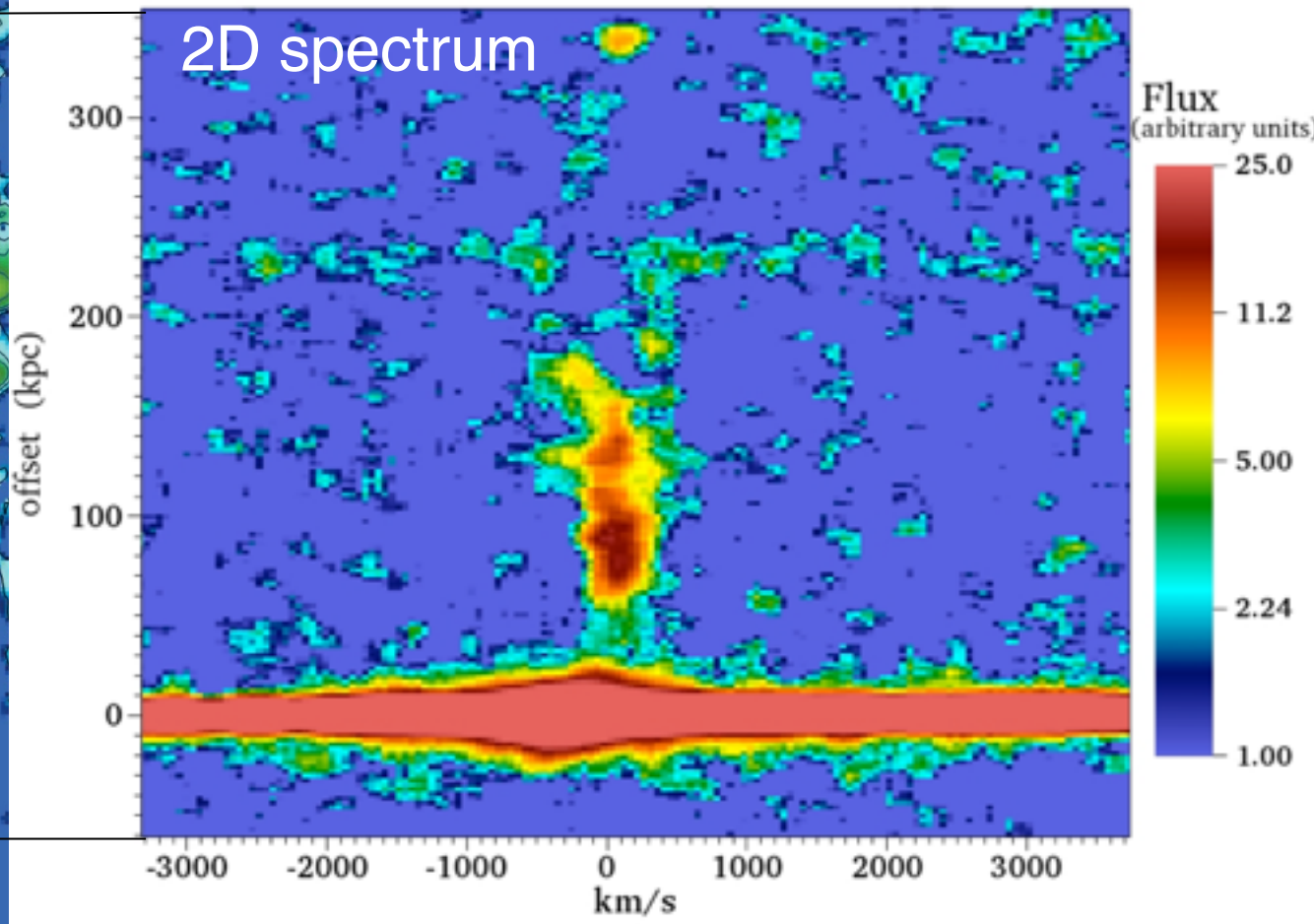


Cantalupo+, *Nature,* 2014

Keck/LRIS Low-Resolution Spectroscopic Follow-up

- kinematically “quiet”: FWHM<500km/s (vs. >1000km/s of RadioGalaxies!)

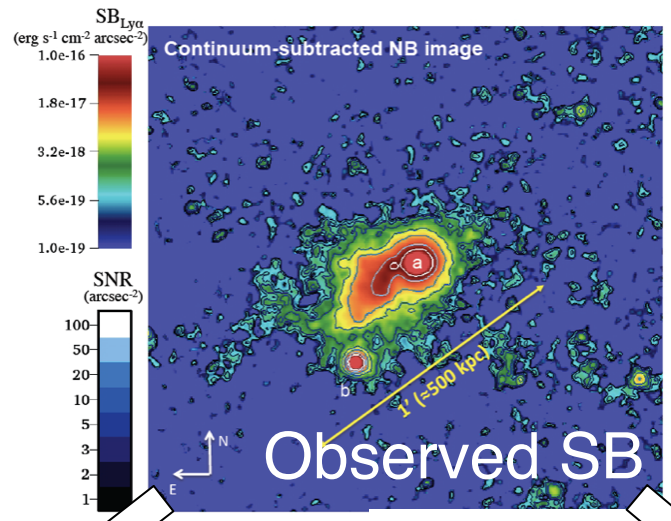




Arrigoni-Battaia,…, Cantalupo, 2015

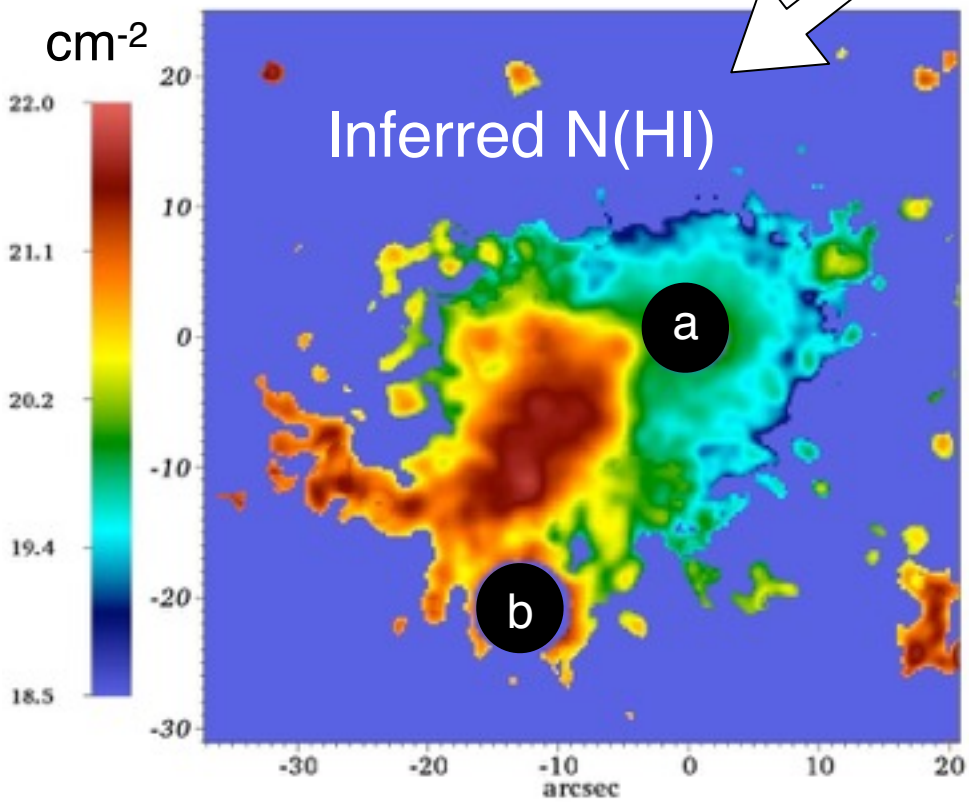
Inferring the cold gas content of the Slug Nebula: 2 cases

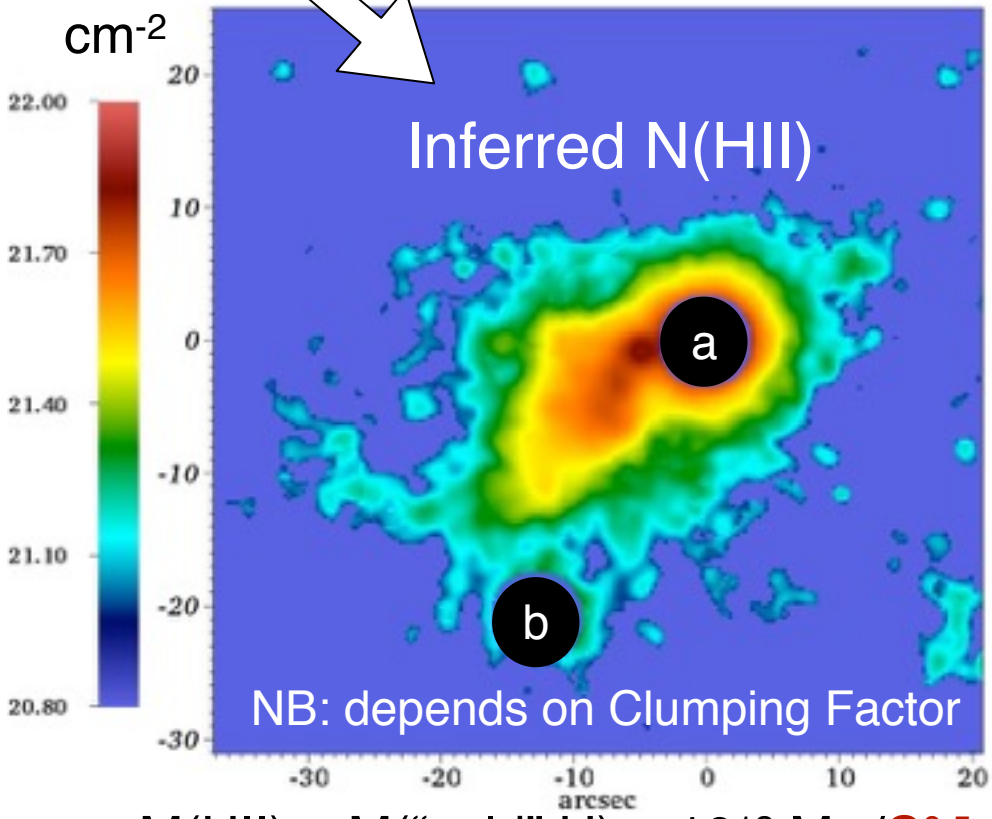
Cantalupo+, *Nature*, 2014



"Photon-pumping" case
(gas mostly neutral)

"Recombination" case
(gas mostly ionized)

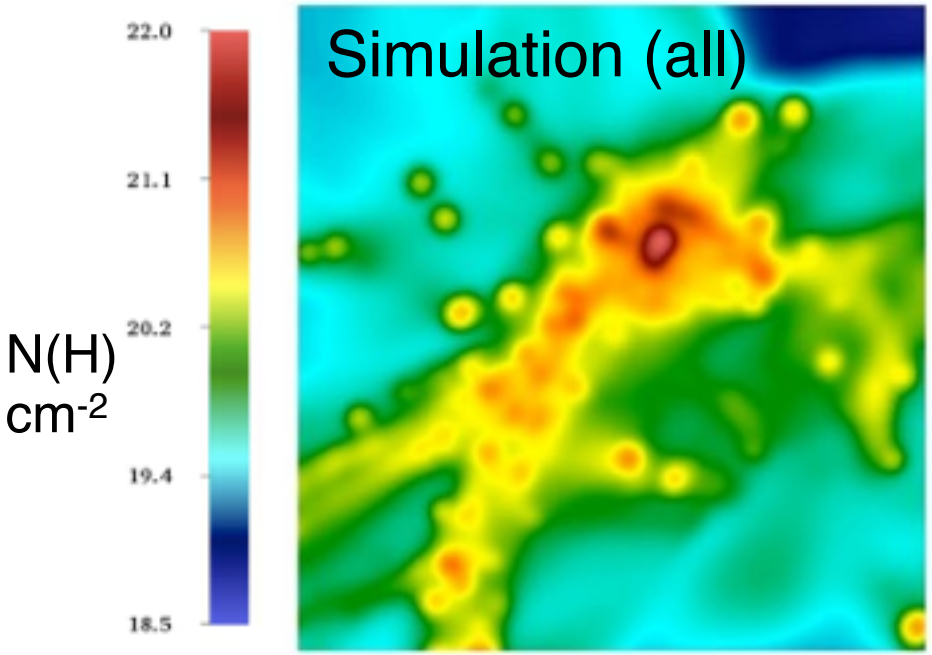


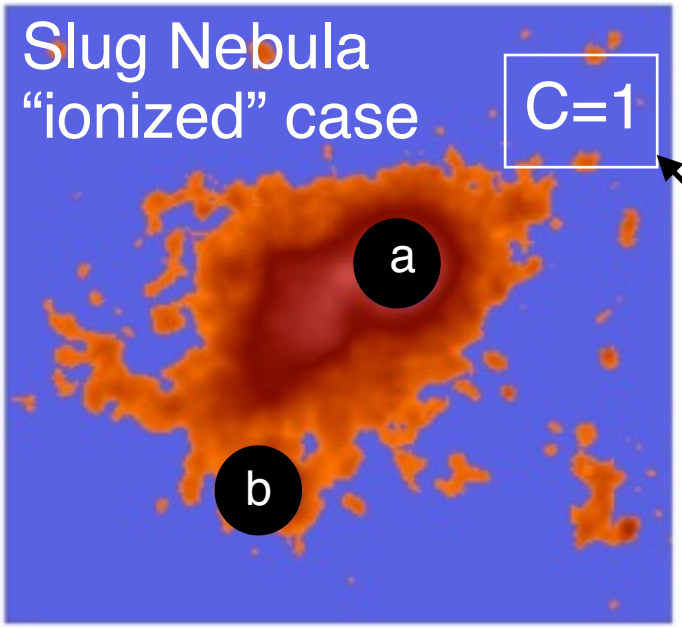


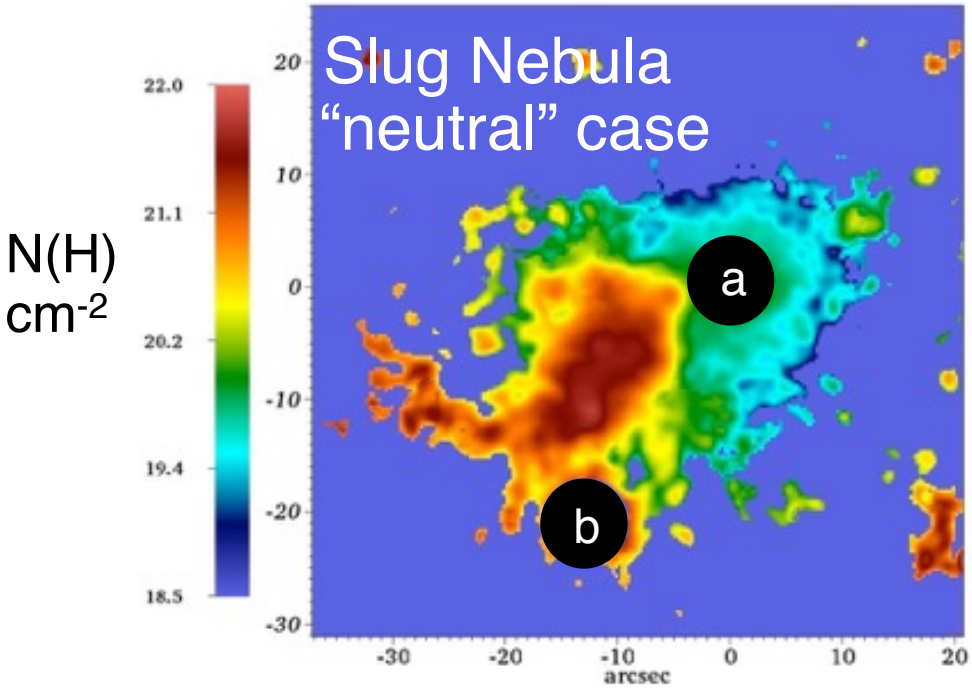
M(HI) ~ M("cold" H) ~ 2.5x10^{11} M$_\odot$

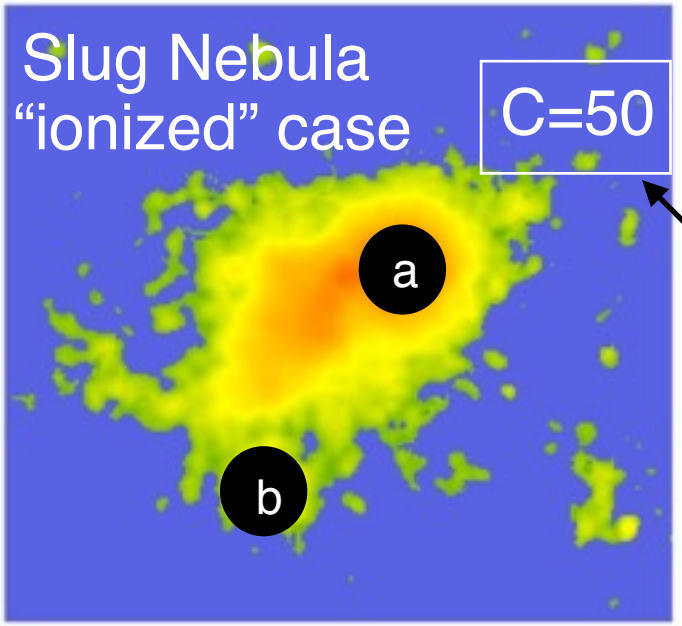
M(HII) ~ M("cold" H) ~ 10^{12} M$_\odot$/C$^{0.5}$

Comparison with simulations: more IGM "clumps" needed!





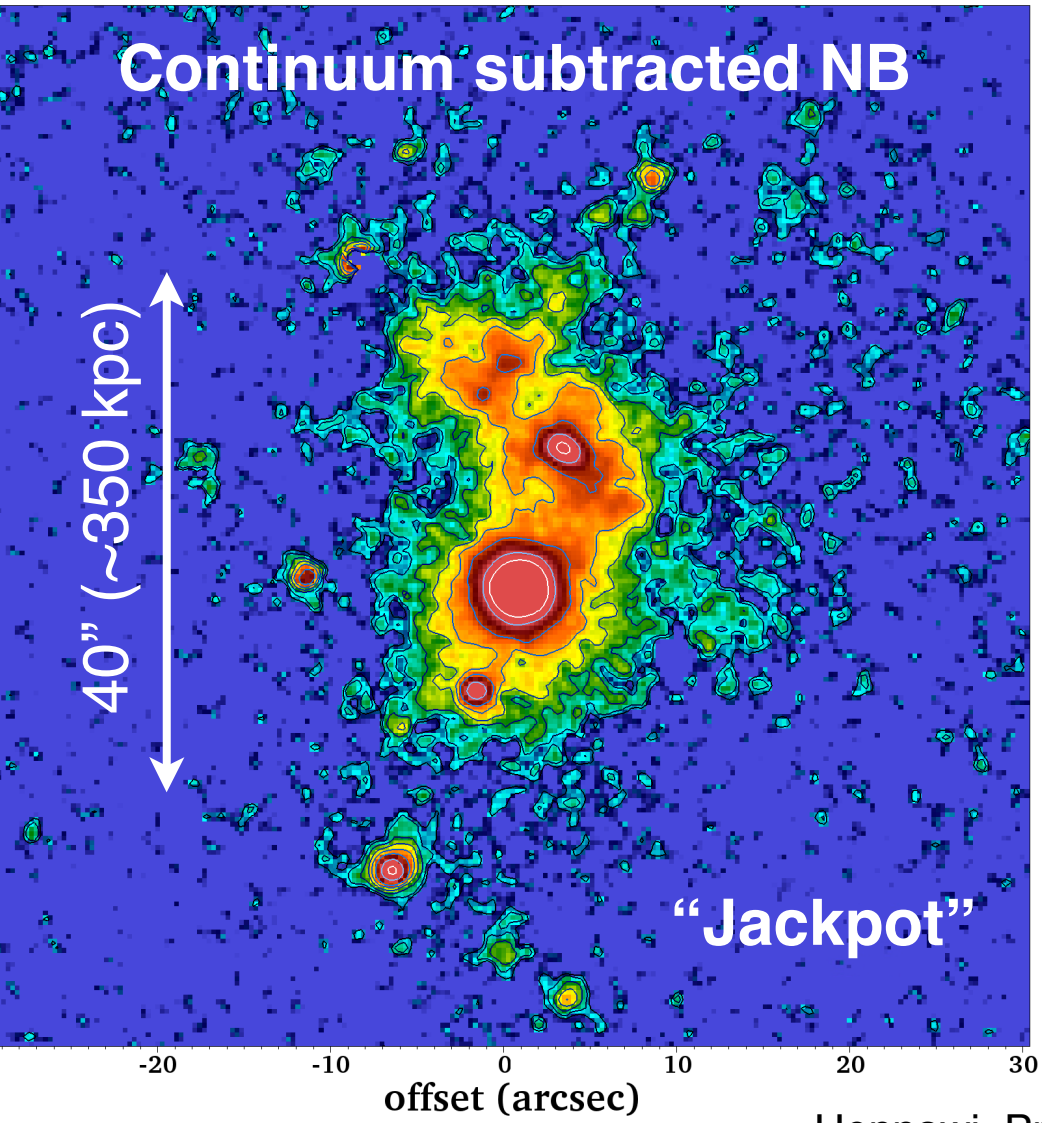


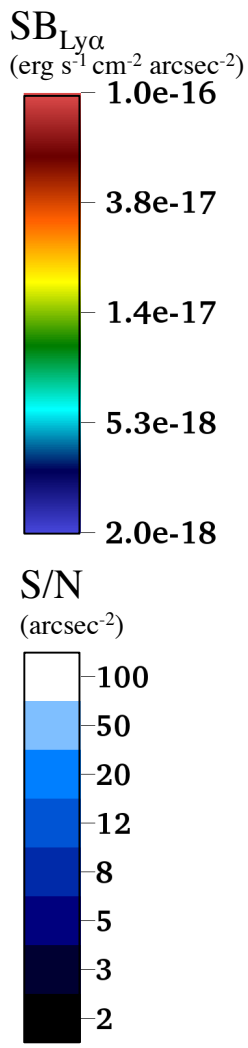


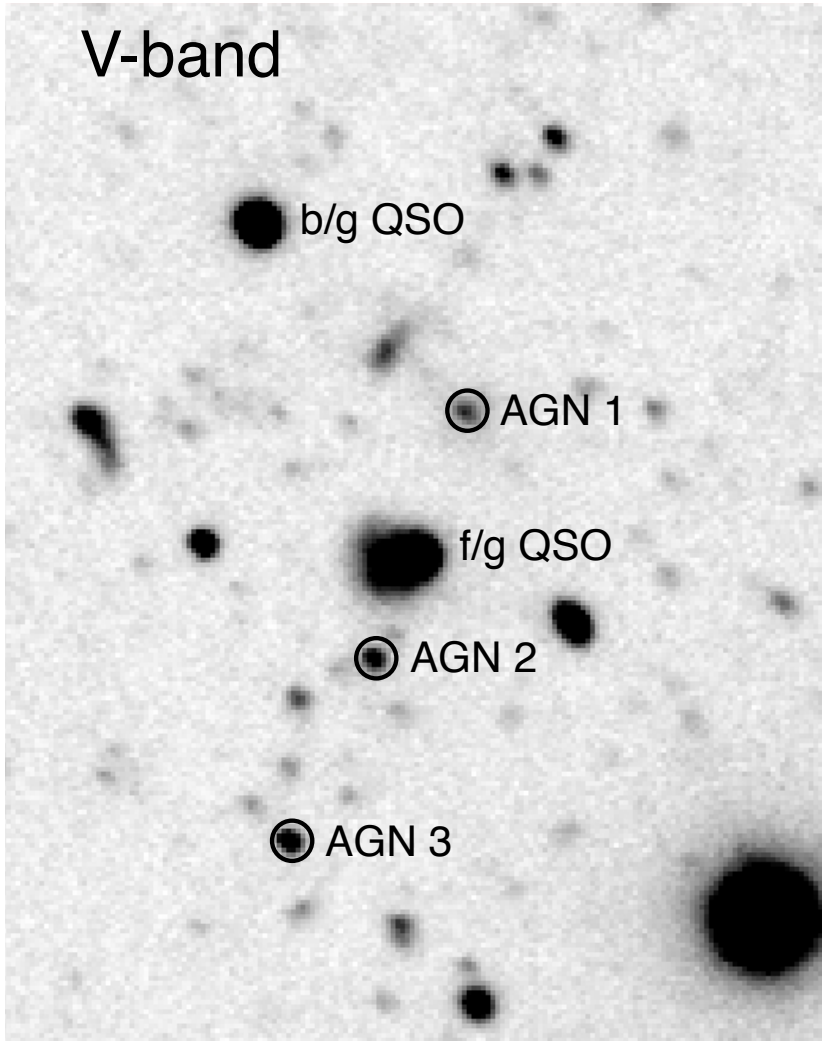
Cantalupo+, *Nature,* 2014

FLASHLIGHT: First Keck/LRIS results

2) NB imaging of a “quasar pair” field at z=2.0 from Hennawi+13
3h NB, 3h V-band (parallel)





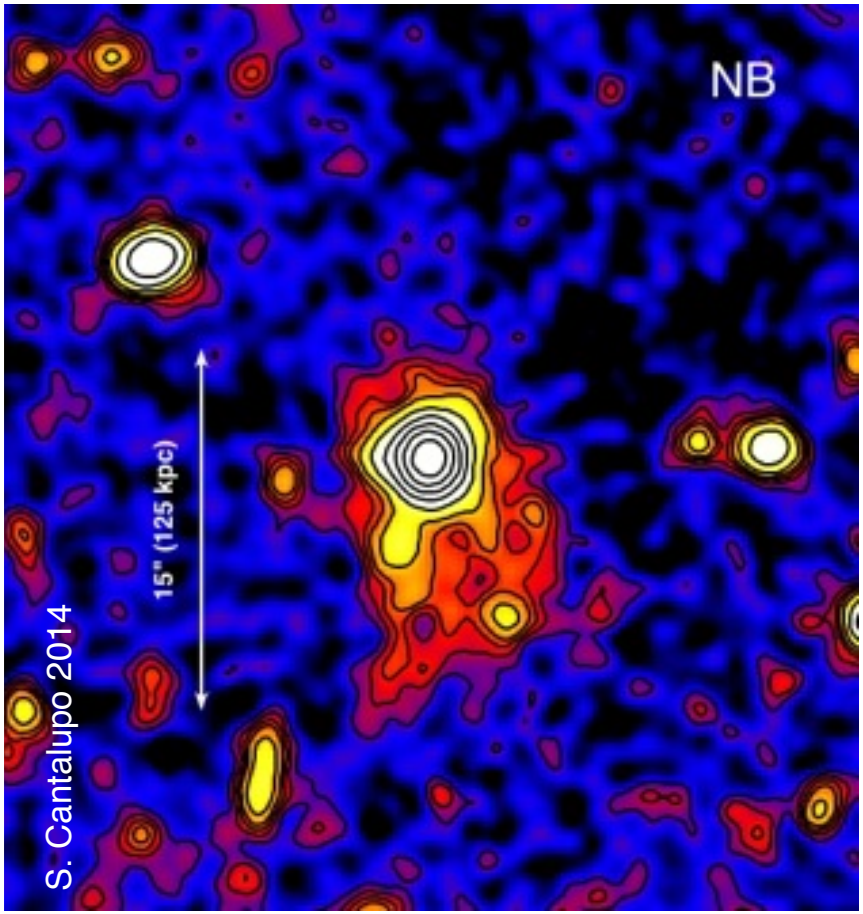


Hennawi, Prochaska, Cantalupo, & Arrigoni-Battaia, *Science*, 2015

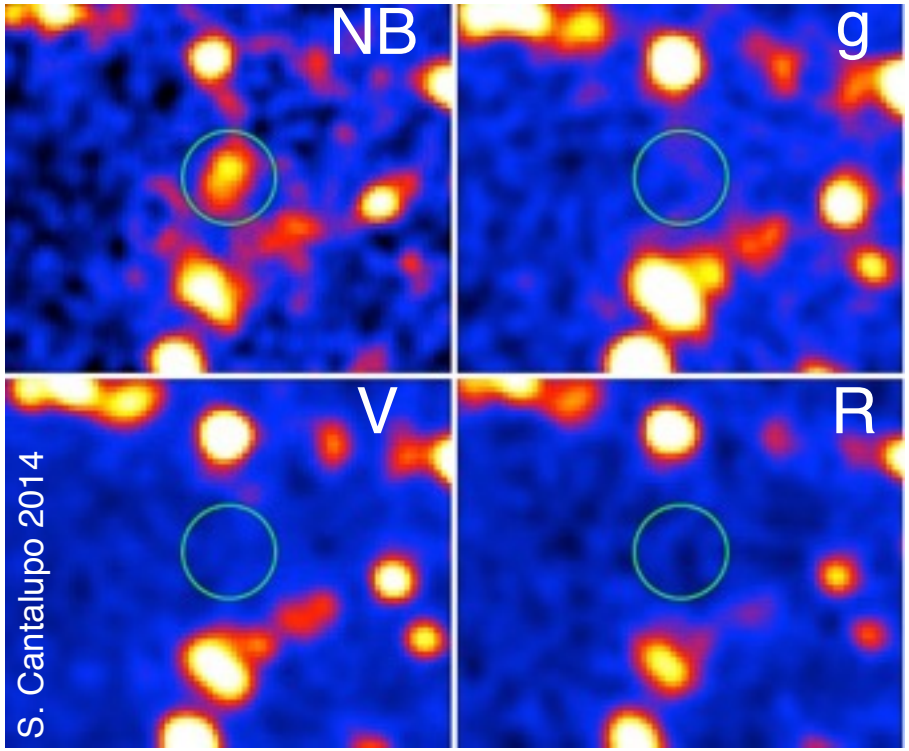
FLASHLIGHT/Keck: other preliminary results

Other observed fields so far are also rich in Lyα-Slugs (but not around target QSOs) and Dark Galaxies.

Some interesting examples:

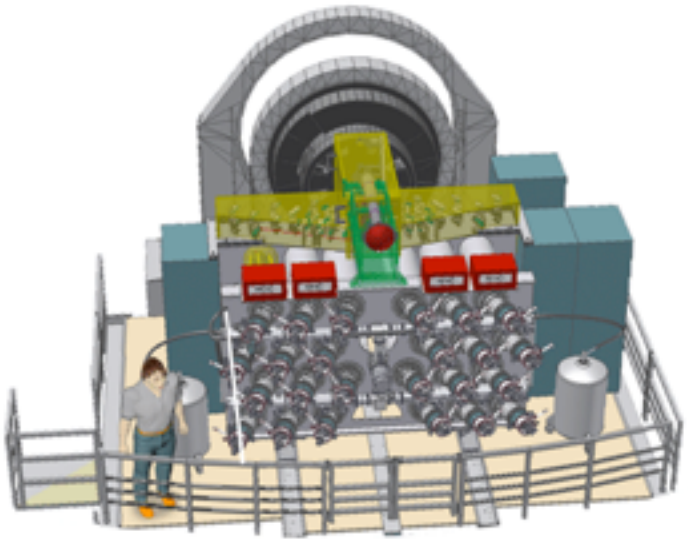


>120kpc Lyα-Slug around g~21 source at 1' from QSO with possible outflow signatures (AGN?)



Spatially resolved Dark Galaxy with EW>300A

Cantalupo+, in prep

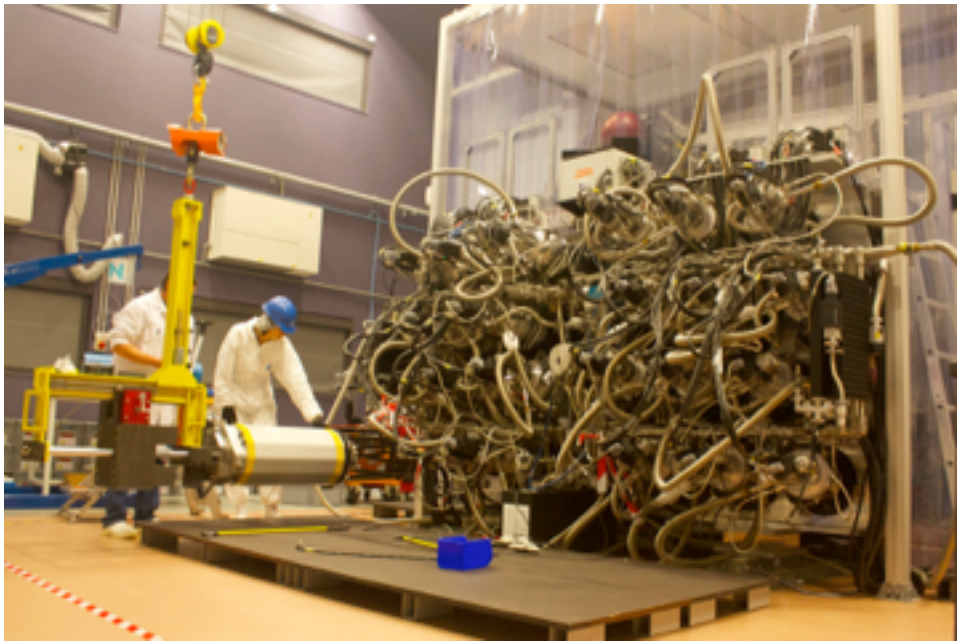


MUSE-VLT: Concept

- 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)

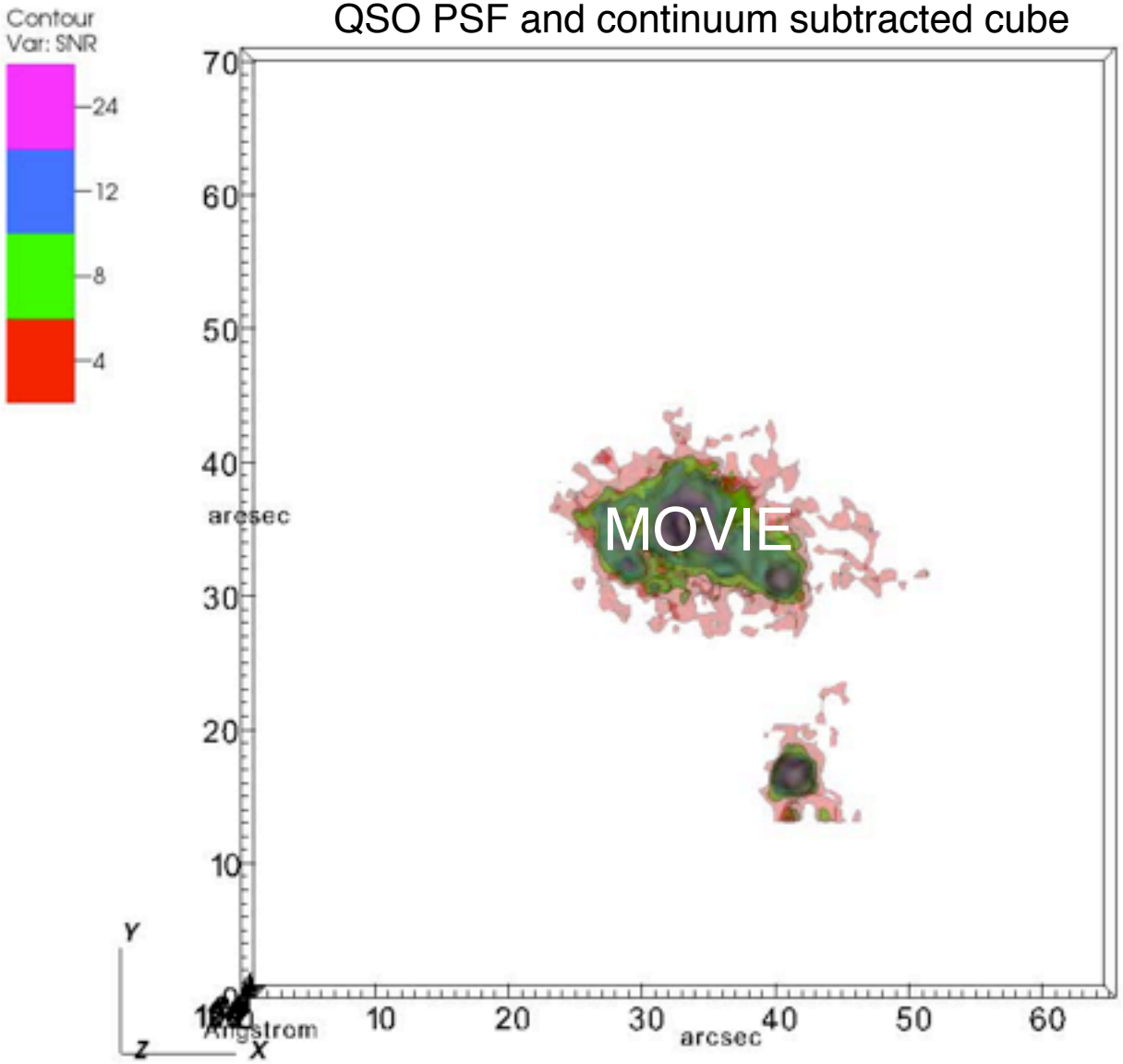
MUSE-VLT: "Reality"

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



MILES3D Deep Fields: the Hammerhead Nebula

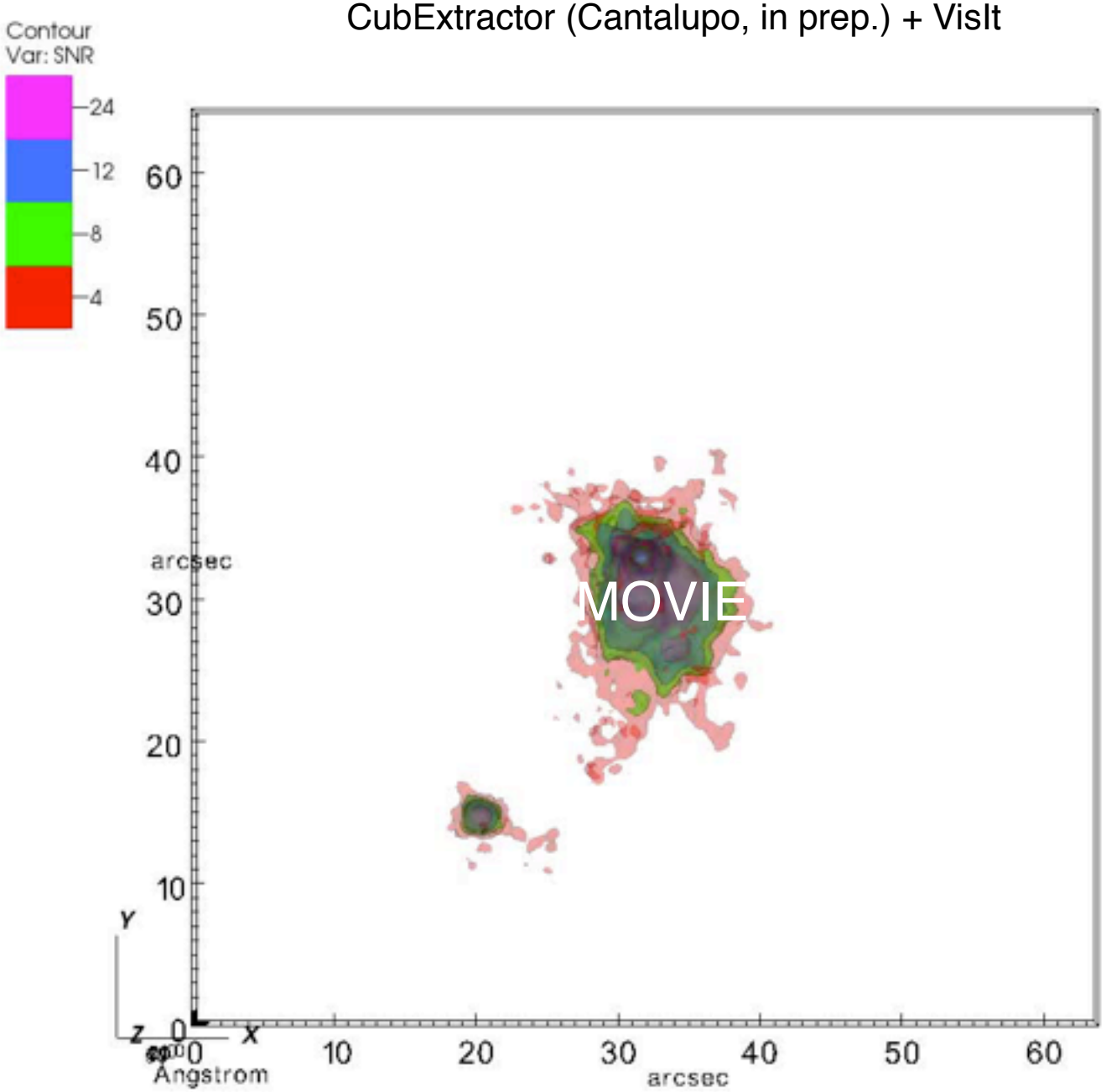
CubExtractor (Cantalupo, in prep.) + VisIt
QSO PSF and continuum subtracted cube



Cantalupo+, in prep.

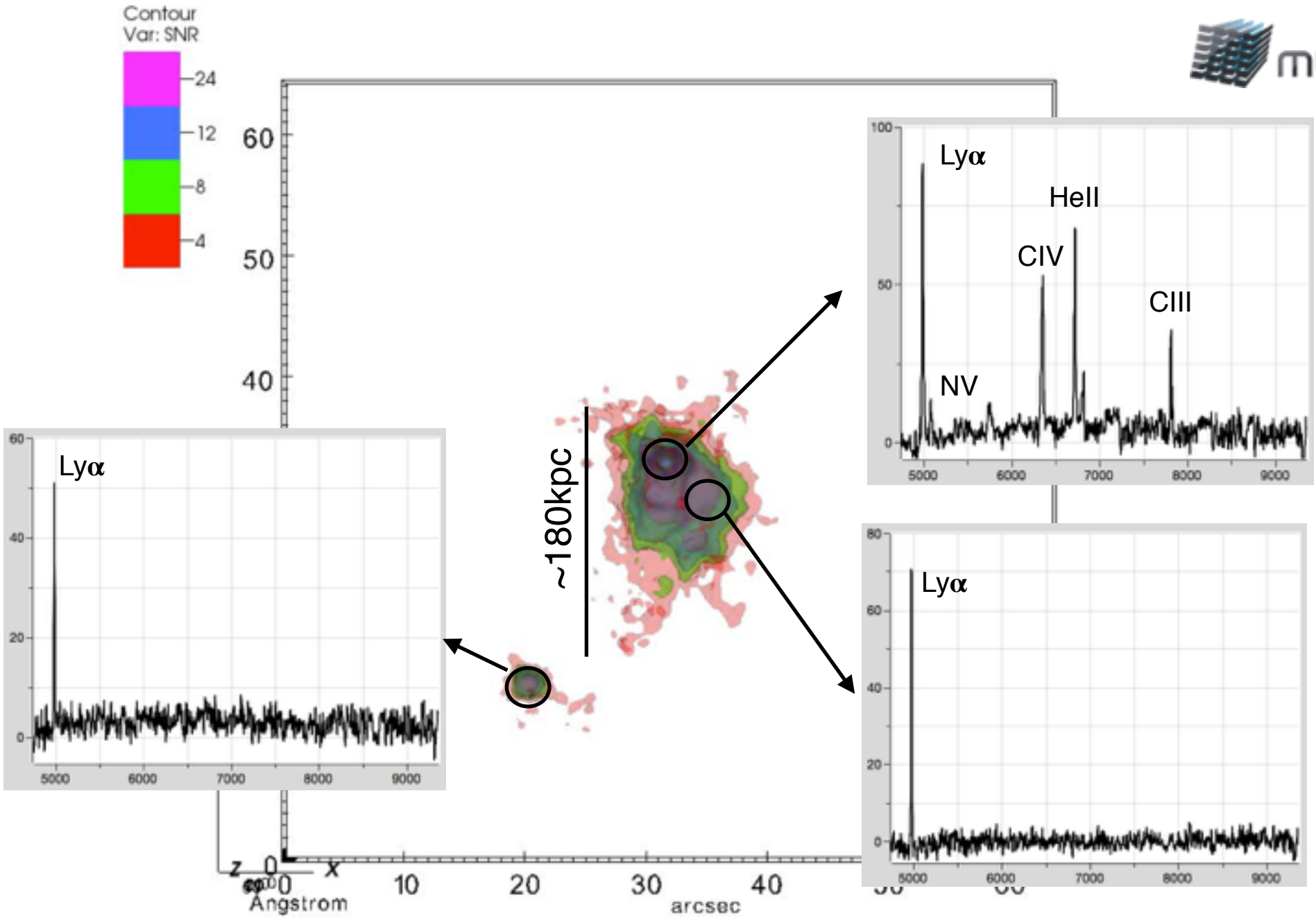
MILES3D Deep Fields: the Bulb Nebula

CubExtractor (Cantalupo, in prep.) + VisIt



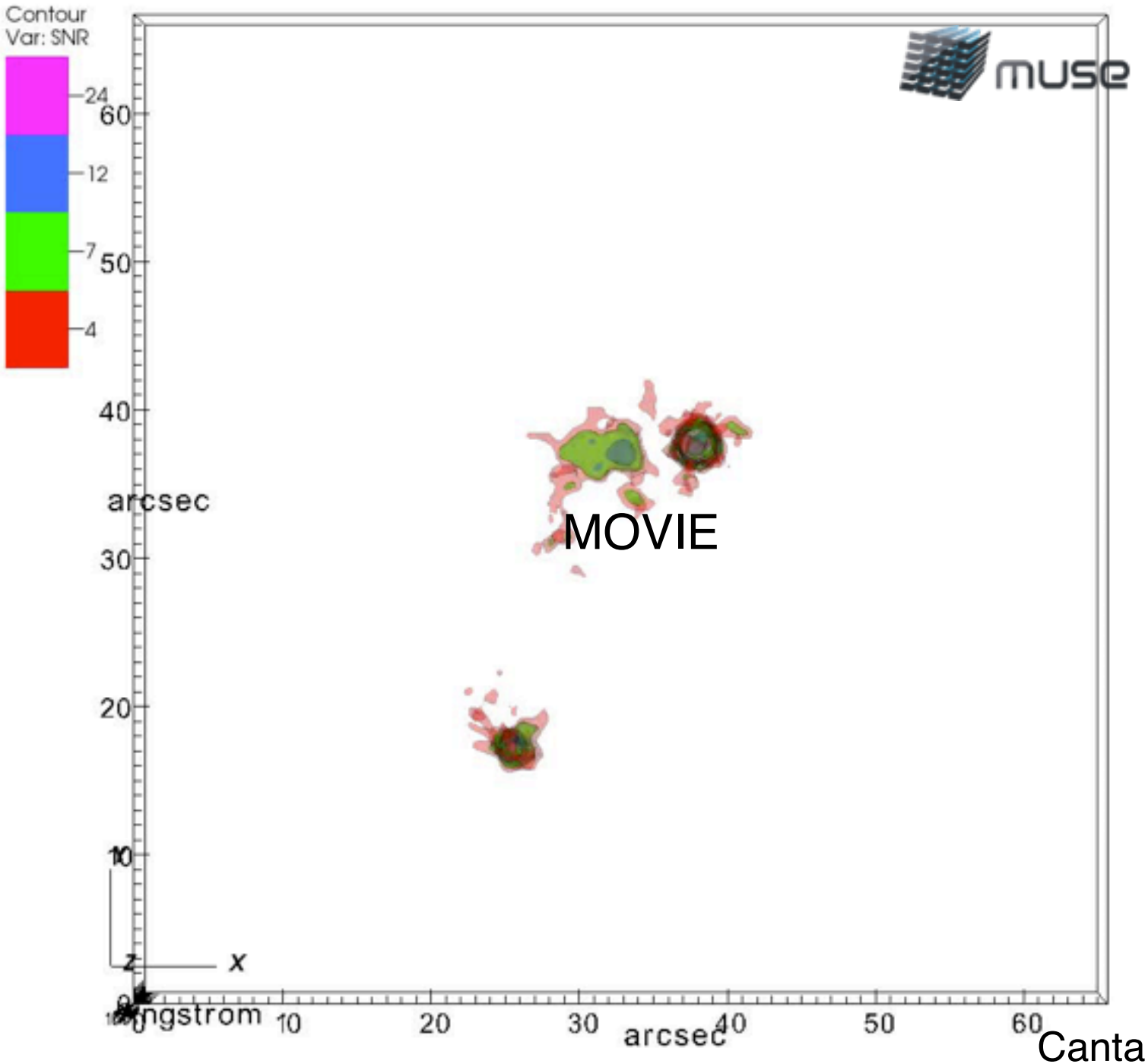
Borisova, Cantalupo+, in prep.

MILES3D Deep Fields: the Bulb Nebula



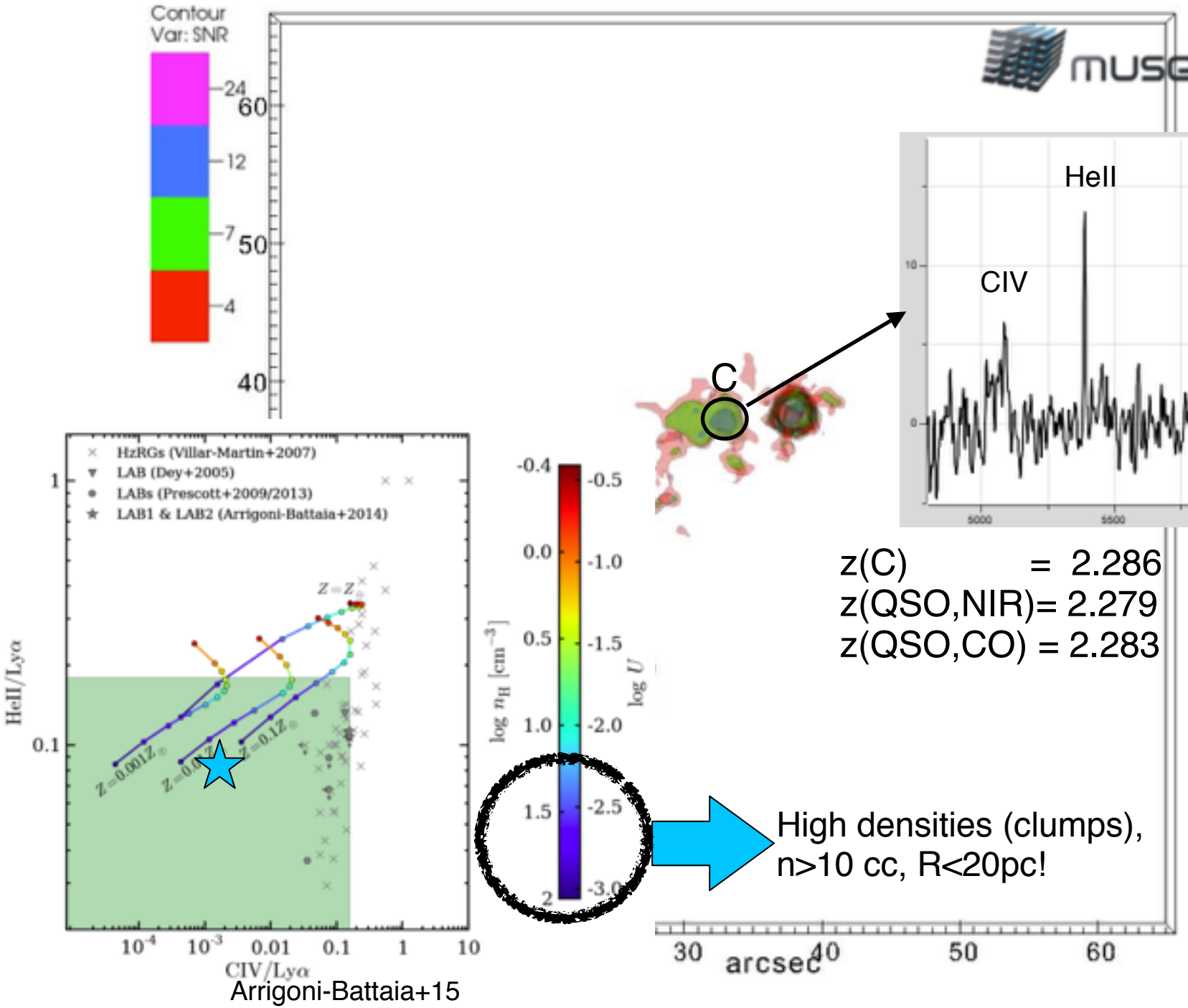
Borisova, Cantalupo+, in prep.

MILES3D Deep Fields: Extended HeII emission from the Slug



Cantalupo+, in prep.

MILES3D Deep Fields: Extended HeII emission from the Slug



Arrigoni-Battaia+15

Open Questions

What sets the frequency of giant bright Nebulae around quasars?
(Lifetime, opening angle, quasar multiplicity,…)

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

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

More than one component in the Slug Nebula?
HeII+Hα+metal emission suggests a large structure in projection (>3Mpc).
(See C.Martin talk for another possibility)

Summary

➡ New technique to “illuminate” cosmic gas at high-z with the help of QSOs.

➡ NB and IFU surveys ongoing on Keck/Gemini and with MUSE:

- Dark Galaxy candidates
  Compact and dense gas clouds (~10^9 M_{sun}) with extremely low SF efficiency: <10^{-11} yr^{-1} (gas consumption rate >100 Gyr).
- Circum-Galactic filaments in emission
  Morphology and size compatible with “cold streams”.
- Intergalactic Filaments ~200-500 kpc size
  Morphology compatible with “Cosmic Web”. More cold/neutral gas than expected: ~10^{12} M_{sun} or dense clumps needed. Tension with models - missing physics?

➡ Next Future:

- Ultradeep MUSE fields (GTO) at z>3
- Lyα + Hα high-resolution spectroscopy of the z~2 Keck fields (LRIS + KCWI + MOSFIRE).

Stay tuned!