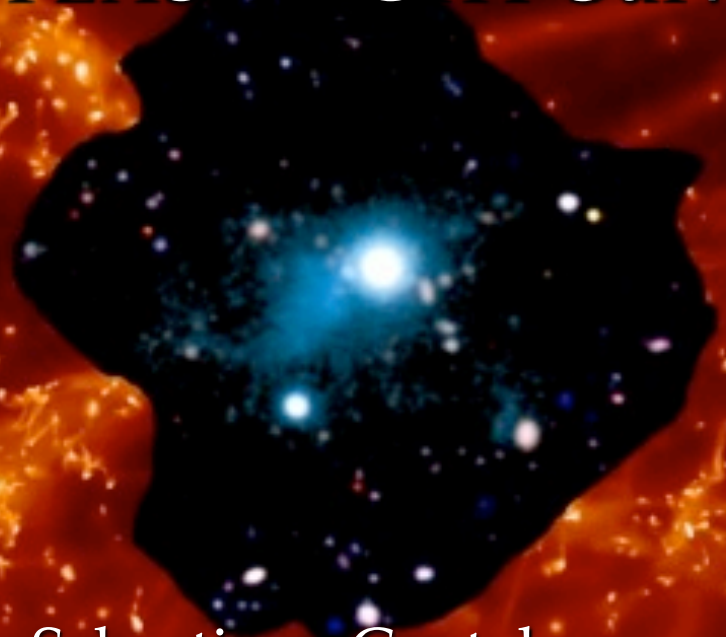
Illuminating the Dark Universe with quasar-induced Lyα emission: the FLASHLIGHT Survey



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Cantalupo et al., *Nature*, 2014

Introduction

the "bright" Universe

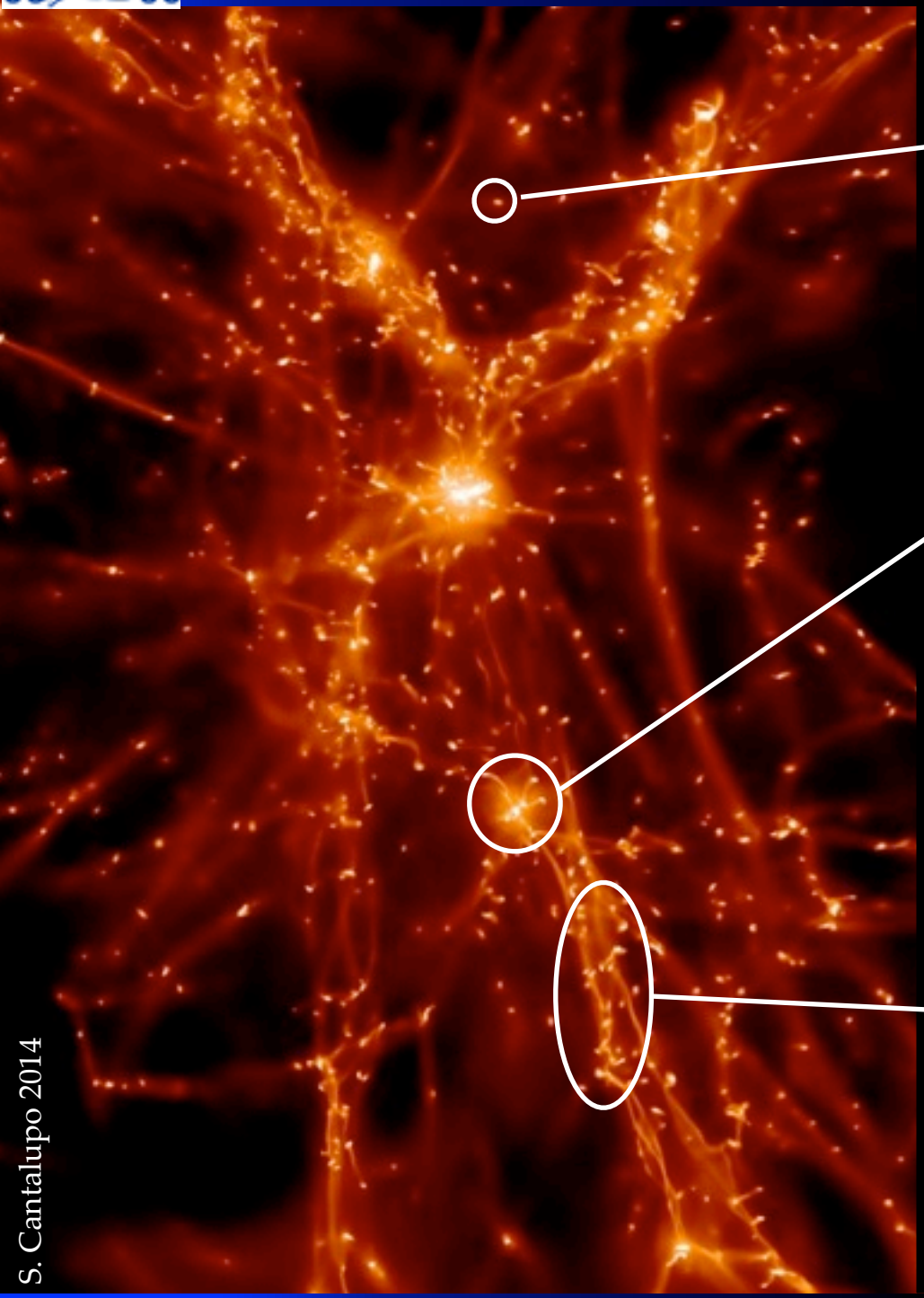
the "dark" Universe

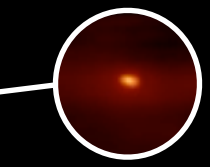
cosmic gas

Hubble eXtreme Deep Field

S. Cantalupo 2014

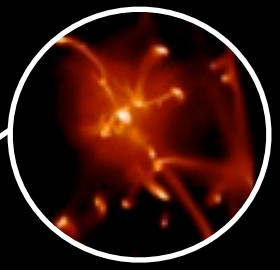
Key Questions & Talk Outline





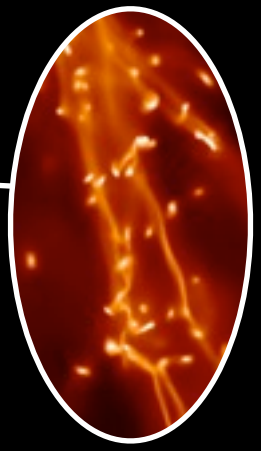
1-10 kpc

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

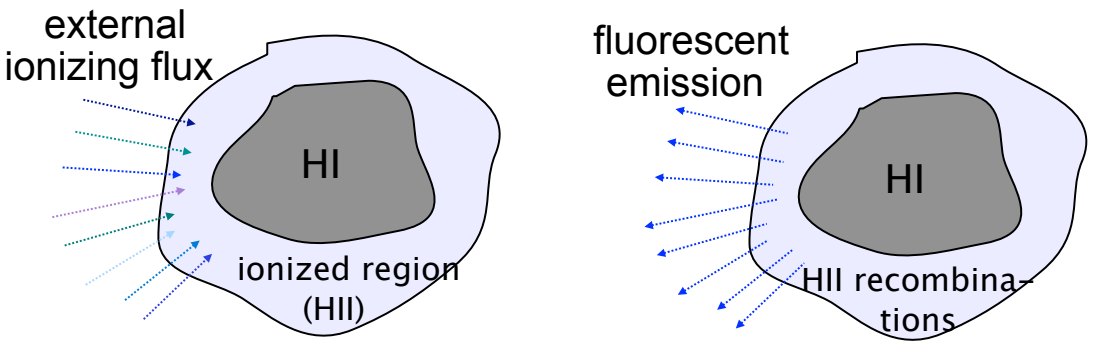
Detecting Cosmic Gas

"Classical" approach: in absorption.

- pro: ability to detect low-density gas including metals.
- con: only 1D information.

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

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

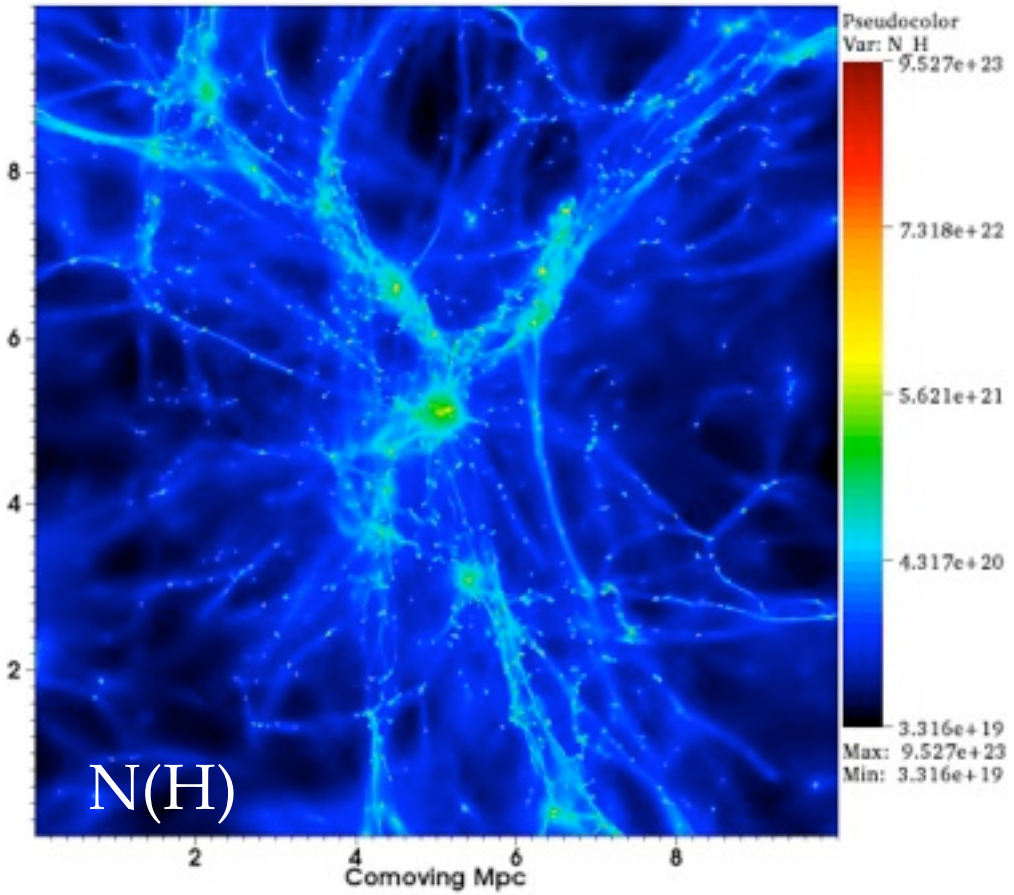


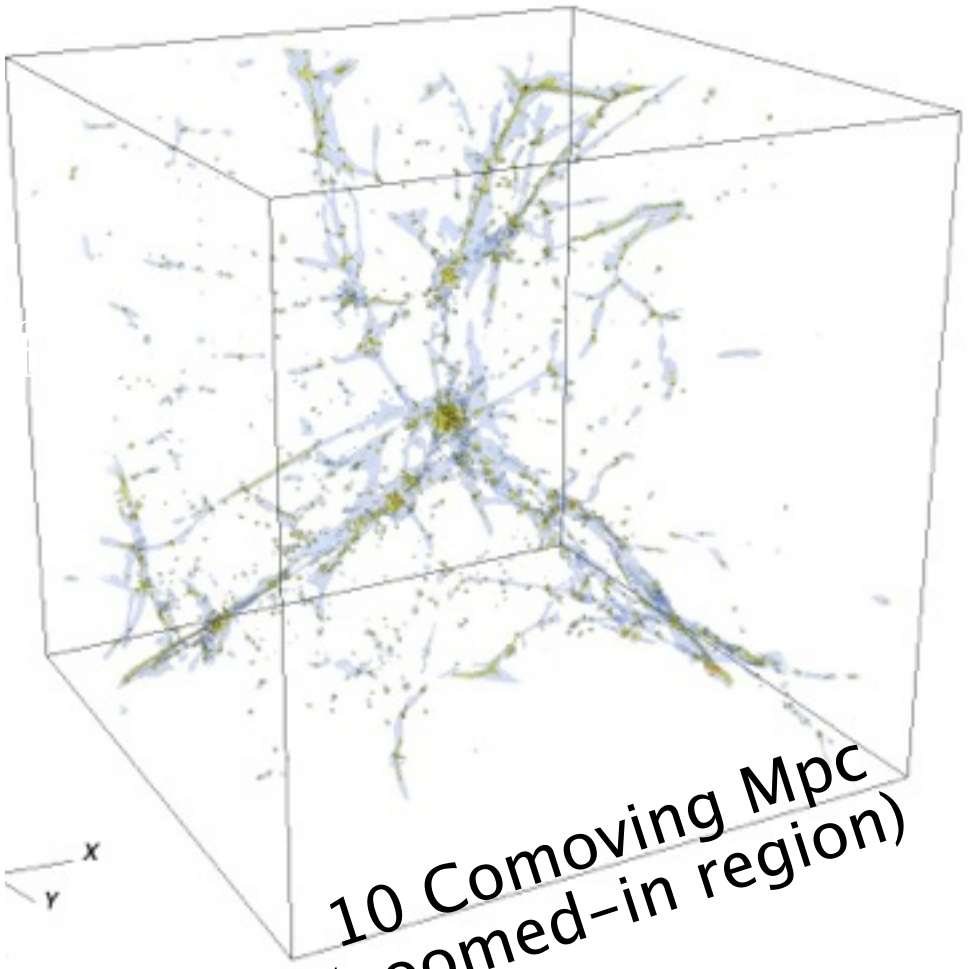
➡ Self-shielded gas (slab): "mirror" emission -> ~60% of incident ionizing radiation "converted" to **Lyα (but see Cantalupo+05).**

➡ Fully ionized gas: proportional to gas density squared.

How bright is fluorescent emission: simulations

- **40Mpc³** (10Mpc³ high-res) hydro-simulation (RAMSES) around 3×10^{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.

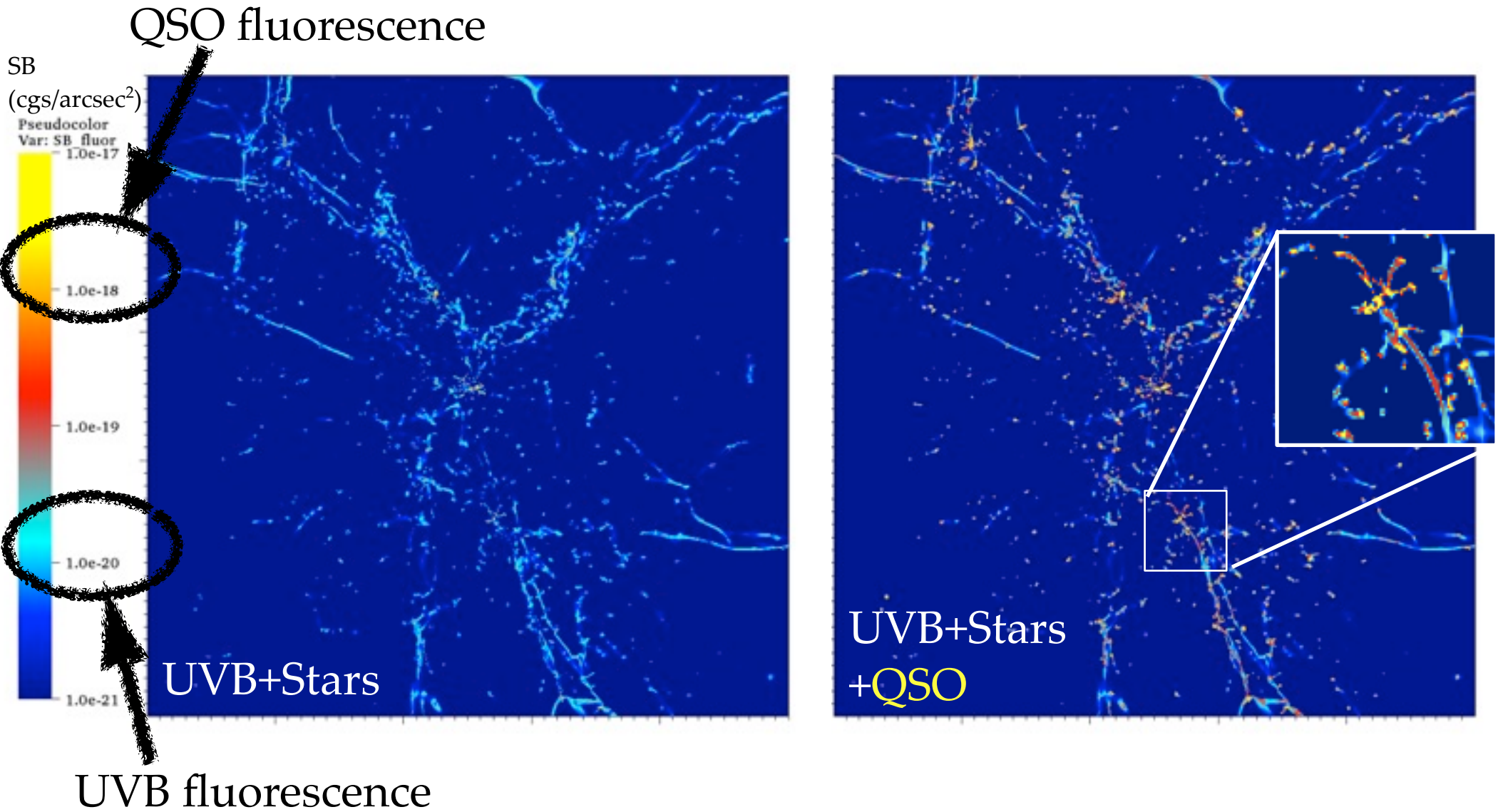




Cantalupo+12

How bright is fluorescent emission: simulations

Simulated Lyα images



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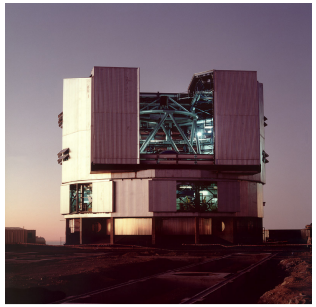
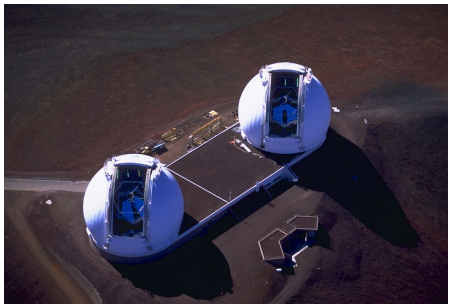
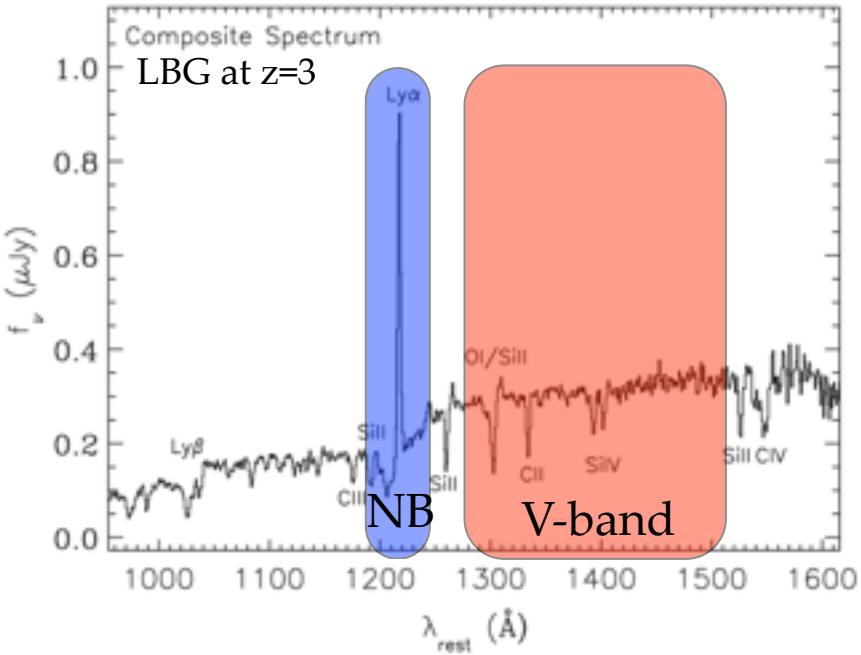
Can we observe it?

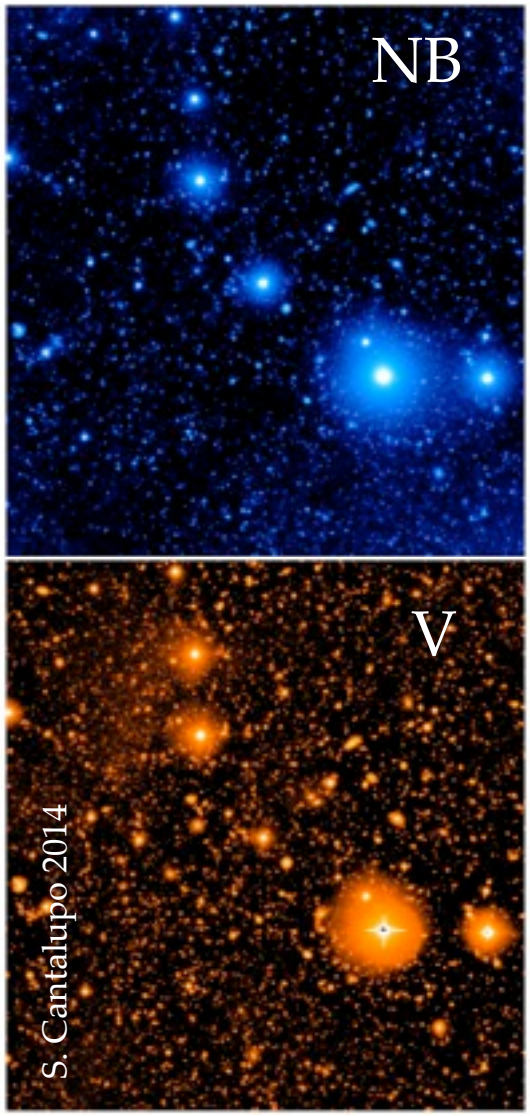
- Look around a bright quasar
- Deep Narrow-Band (NB) and continuum (broad-band) imaging to select Lyα emission and "remove" galaxies from sample

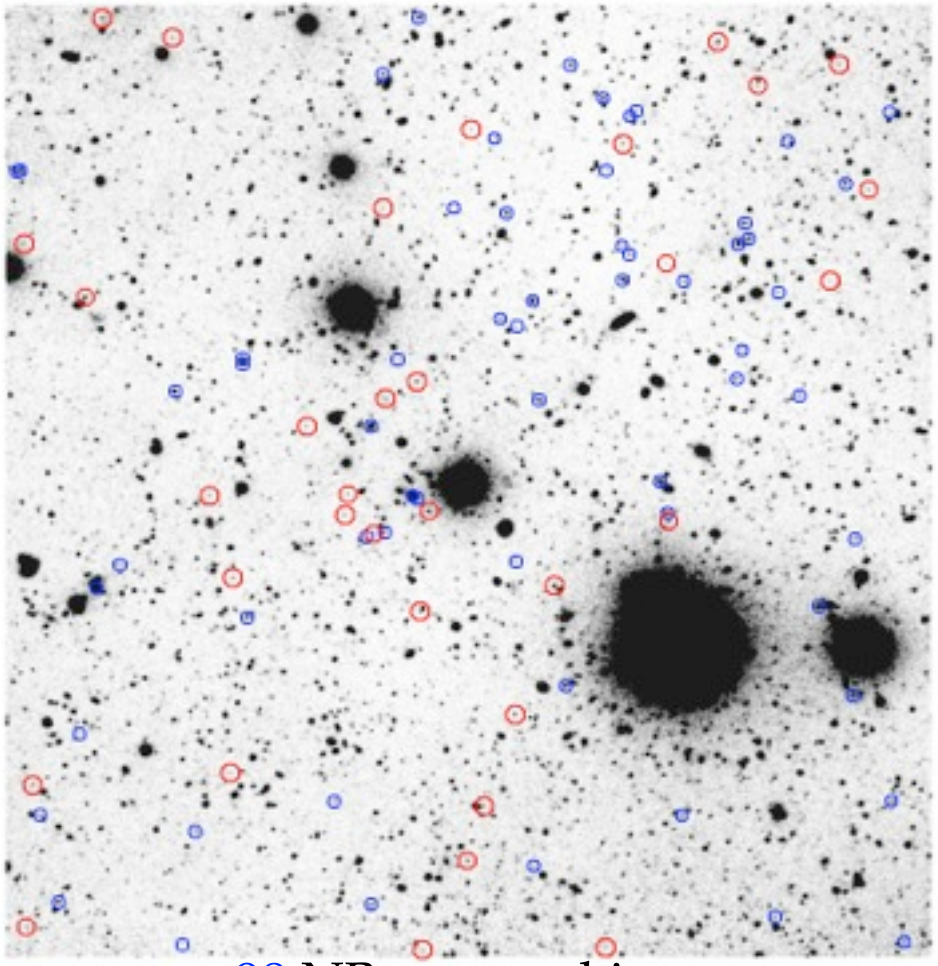


Very Large Telescope (VLT) Pilot Survey

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: ~4x10^{-18} erg/s/cm^2 [5σ for 1 arcsec^2 aperture]





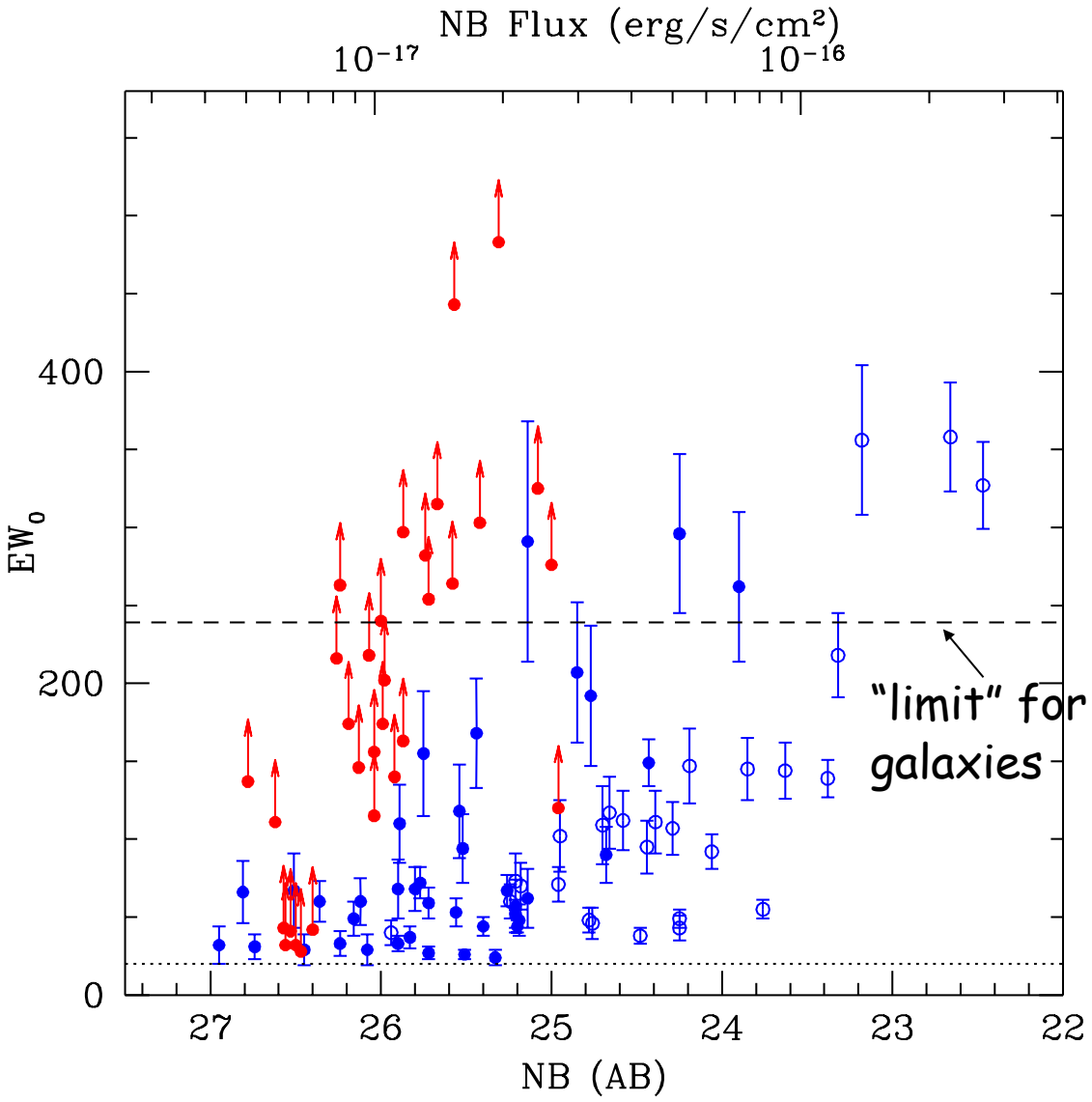
98 NB excess objects

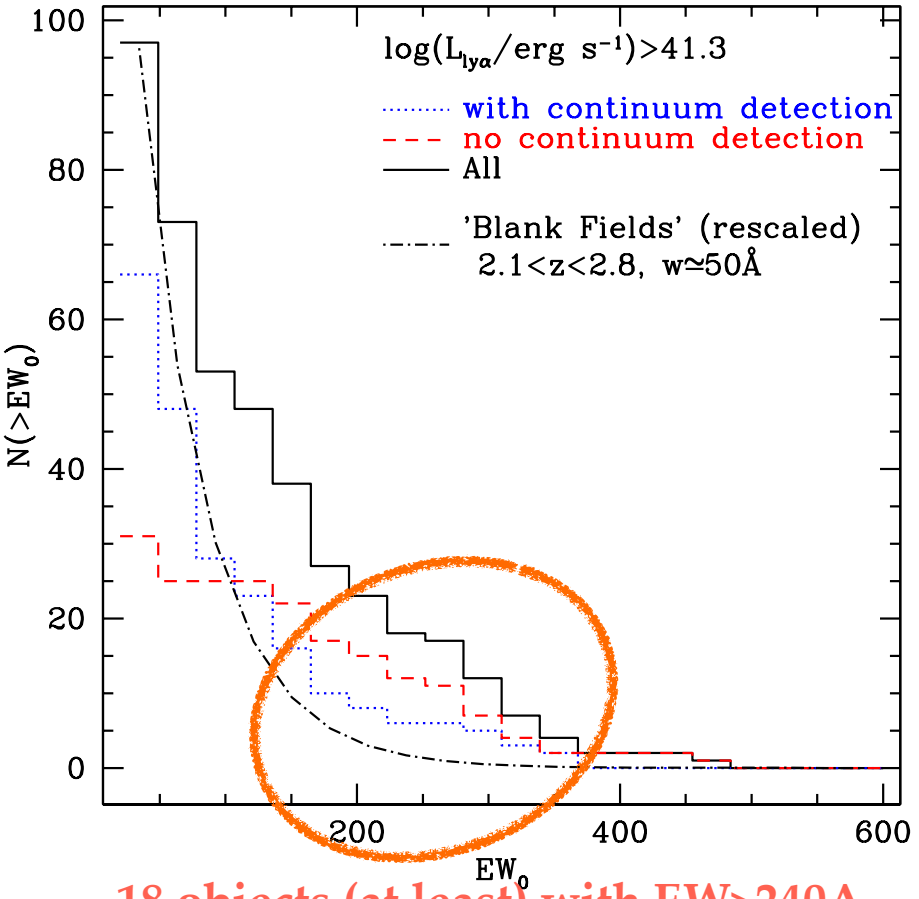
31 without V or B detection (red circles)

Cantalupo, Lilly & Haehnelt 2012

Separating "dark" galaxies from normal population:

EW distribution





18 objects (at least) with EW>240A
12 of these without continuum

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

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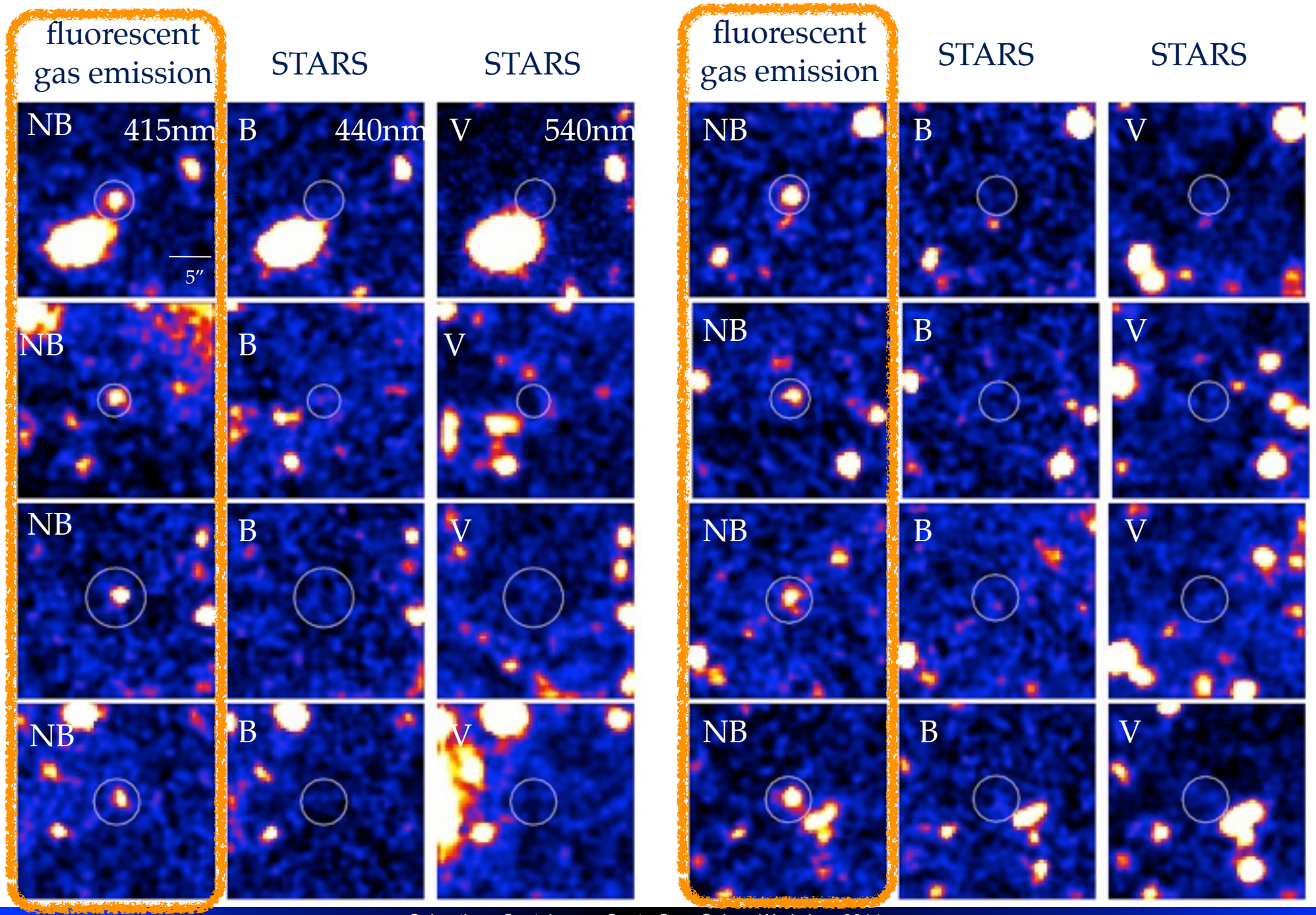
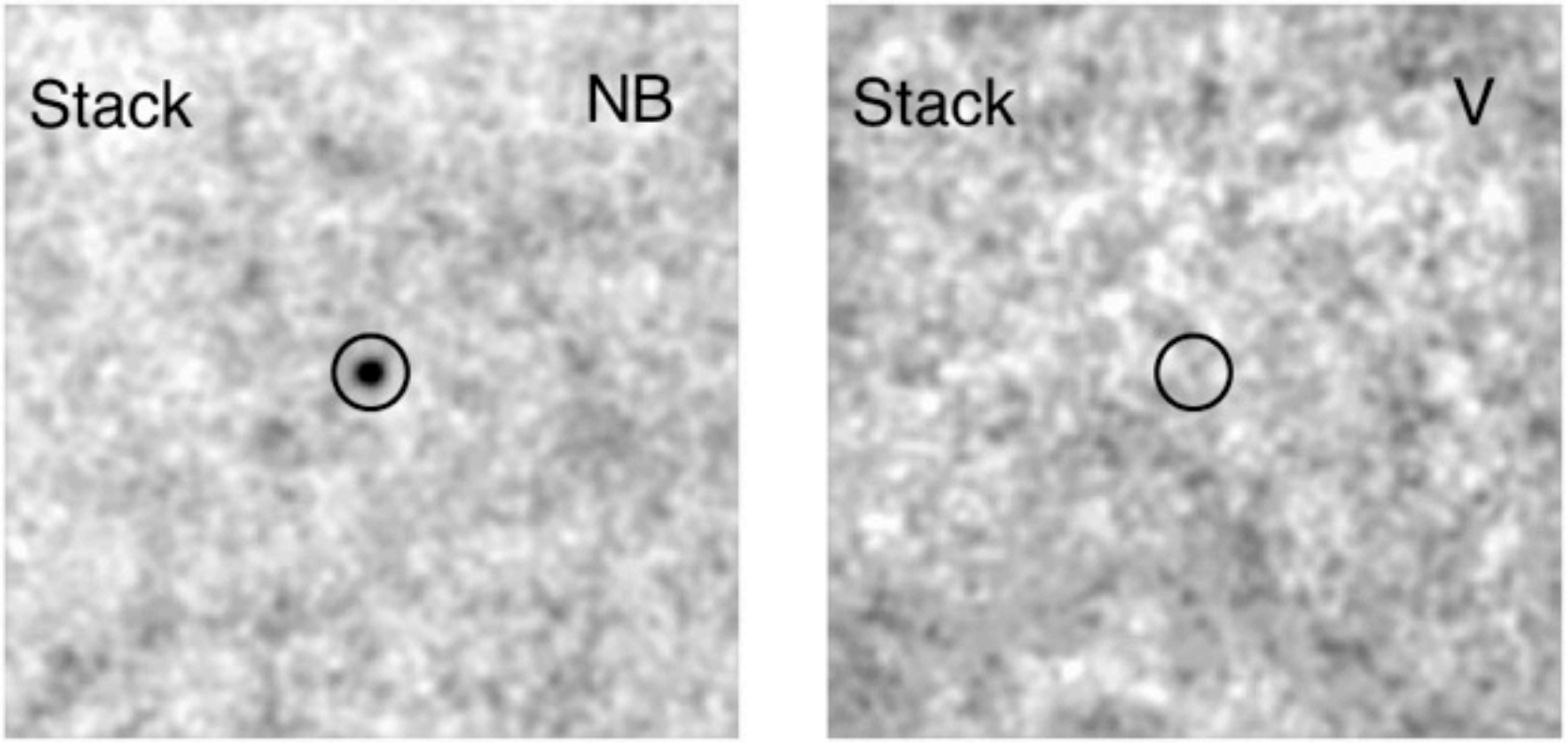


"Dark" Galaxy Stack



Combined constraint: EW>800A (1σ)

Dark galaxies are spatially unresolved: d<0.7" (~5 pKpc at z=2.4)
(22 orbits of HST awarded this cycle to constrain their sizes)

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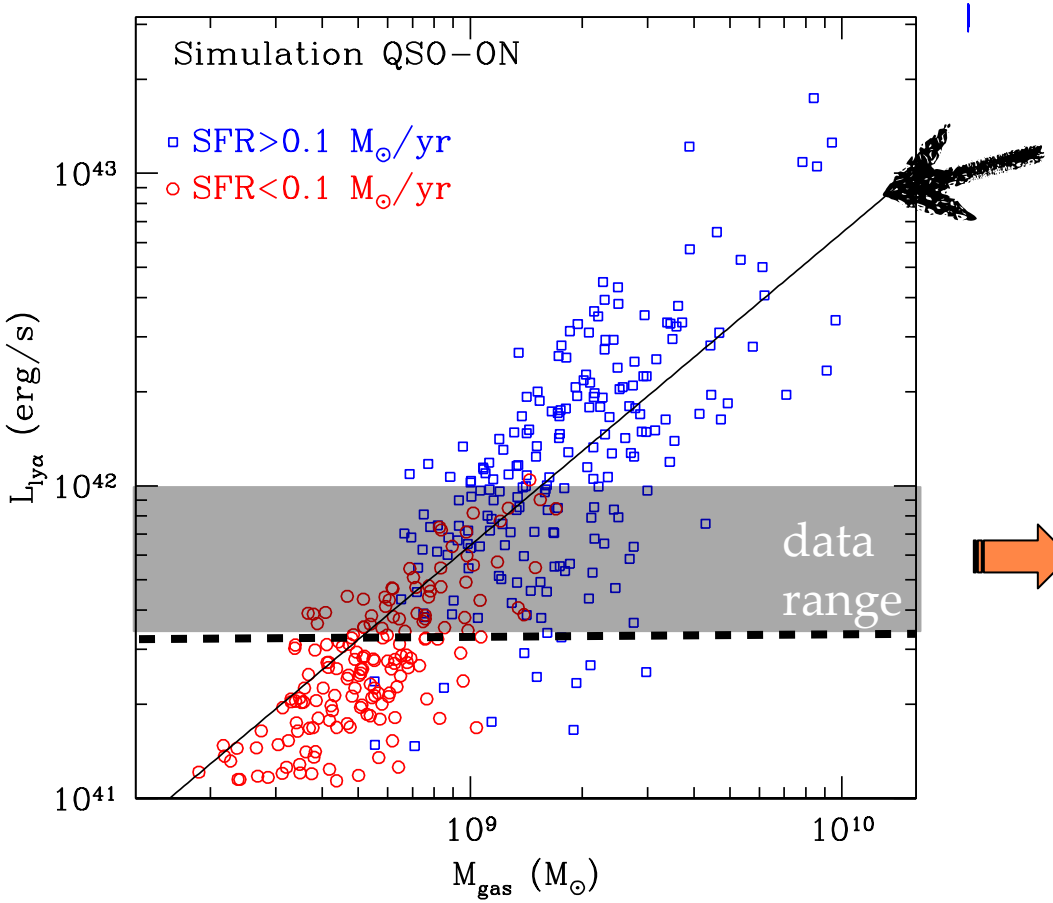
Inferring the Mass and Star Formation Efficiency (1)

$$L_{\rm ly\alpha} = \chi_e \alpha^{\rm eff}_{\rm ly\alpha}(T) h\nu_{\rm ly\alpha} \int_V n^2_{\rm HII} dV$$

(HII recombinations only and no star formation)

➡ for a fully ionized cloud: $M_{\rm gas} \sim 1.4 \times 10^9 M_\odot \left[\frac{L_{\rm ly\alpha}}{10^{42} {\rm erg\ s^{-1}}}\right] \left[\frac{T}{2 \times 10^4 K}\right] \cdot C^{-1}$

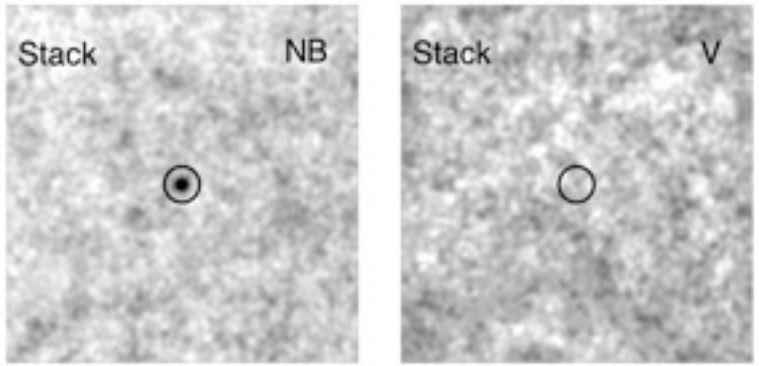


Consistent with hydro + RT simulation (RADAMESH) with variable temperature, "clumping factor", cloud shape, etc.

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

Cantalupo+12

Inferring the Mass and Star Formation Efficiency (2)



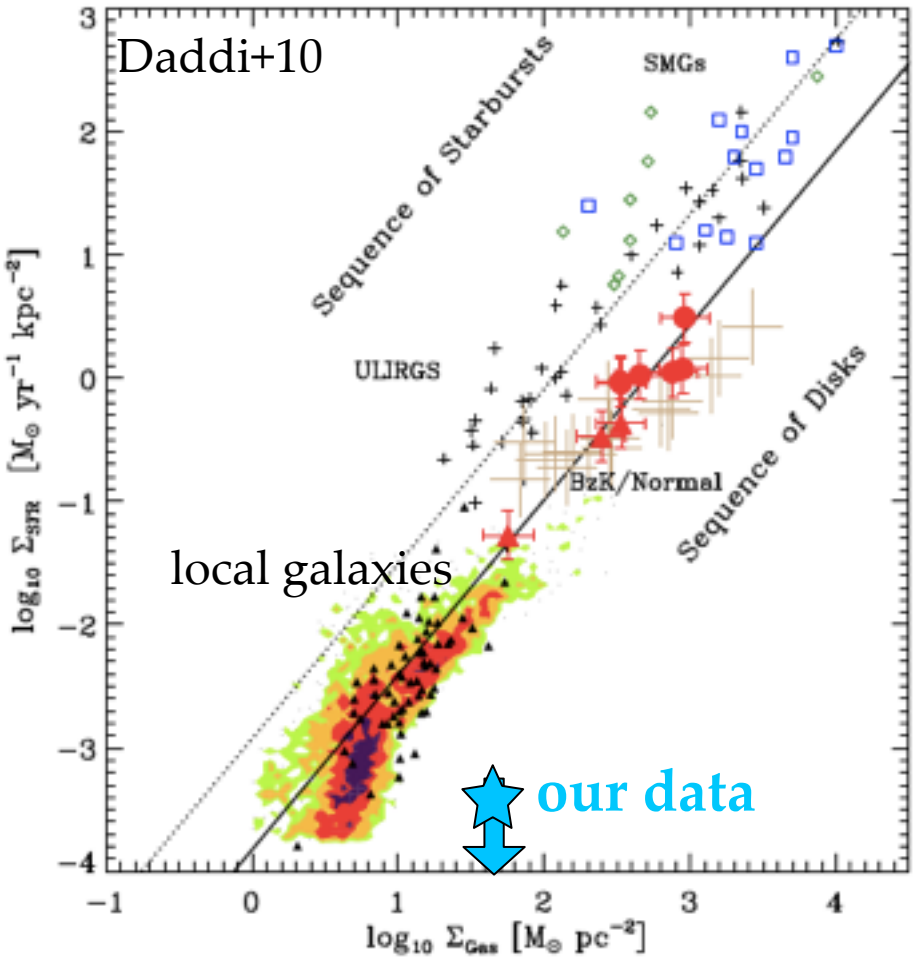
from V-band Stack:

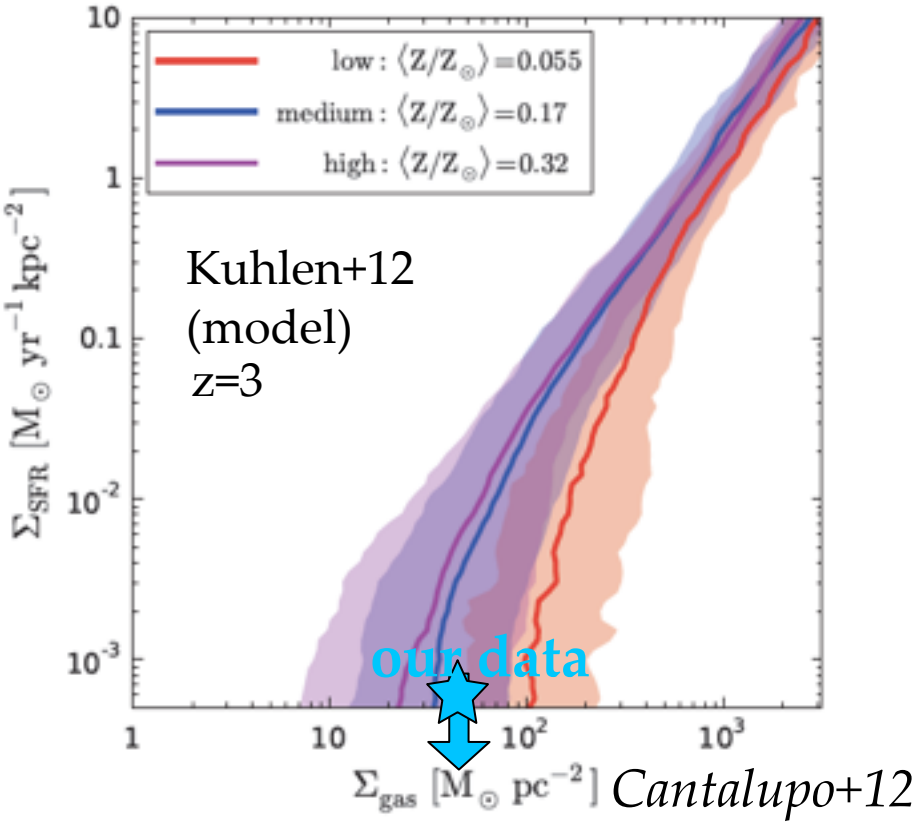
SFR<0.01 M_{sun}/yr (Salpeter IMF, 200 Myr burst)

⇒ SF Efficiency: $<10^{-11}$ yr^{-1}

(gas consumption time >100 Gyr)

Where are they on the Kennicutt-Schmidt relation?





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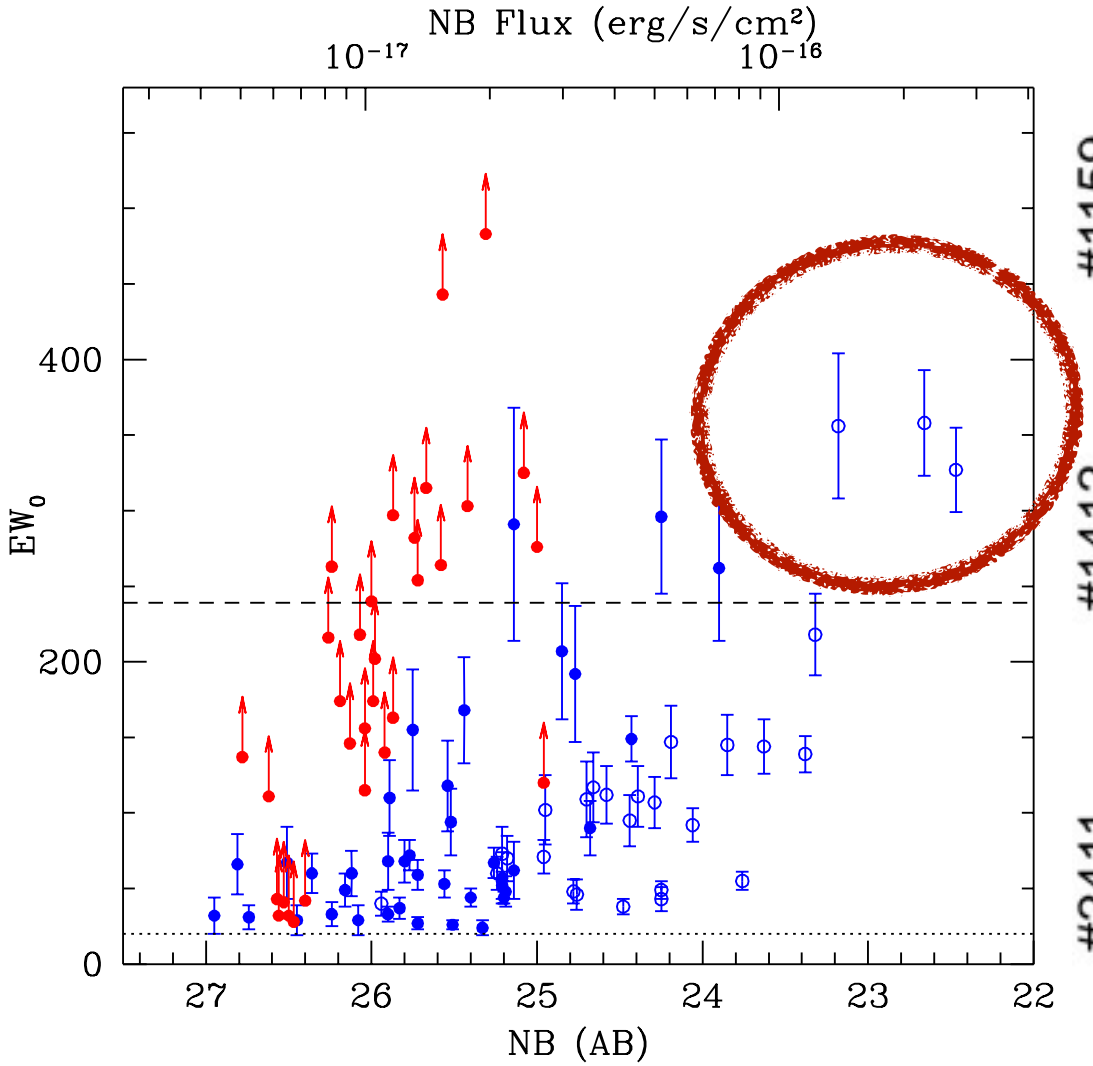
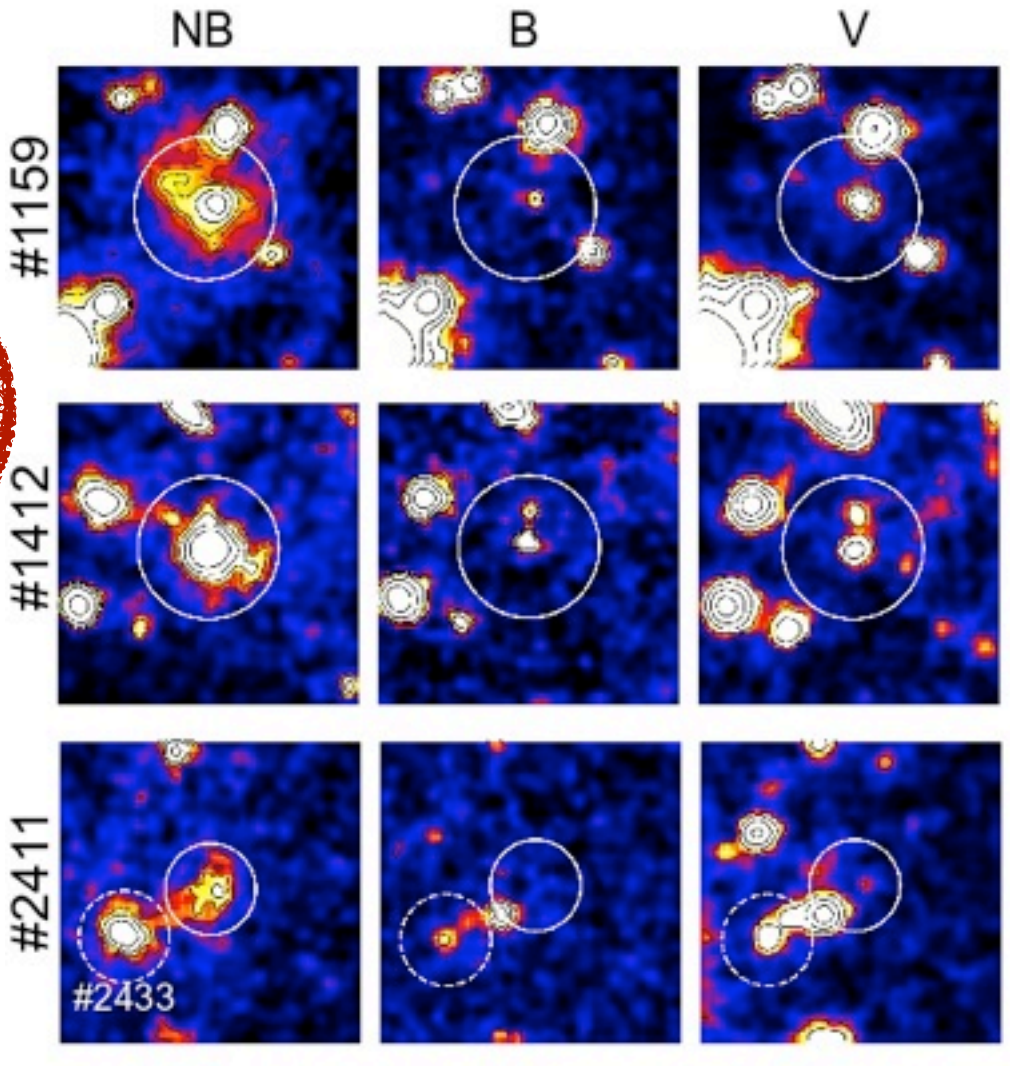
Extended objects with EW>240 and continuum





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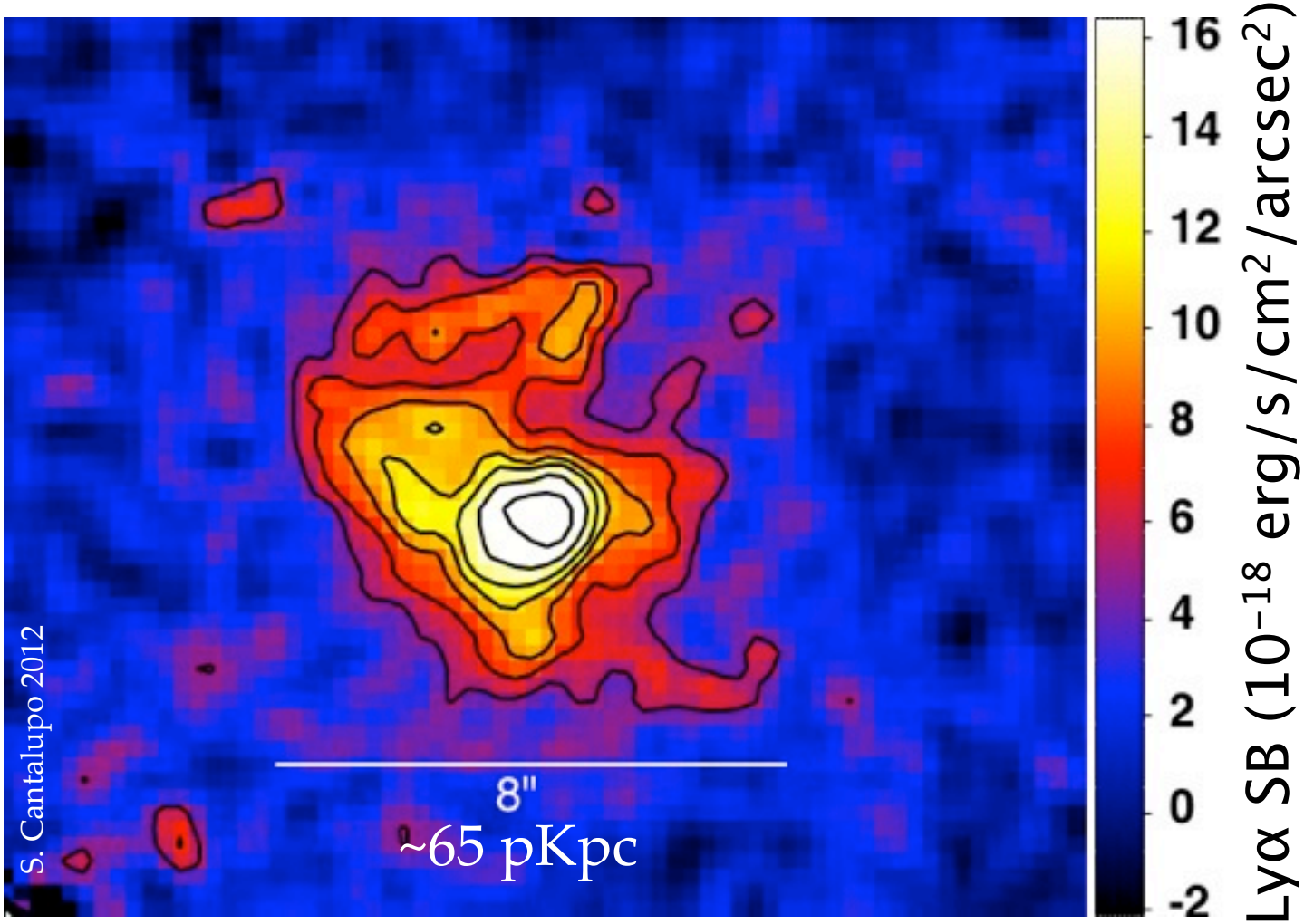
"Cold streams" around #1159?



Continuum-subtracted NB image

(QSO is 3' away)

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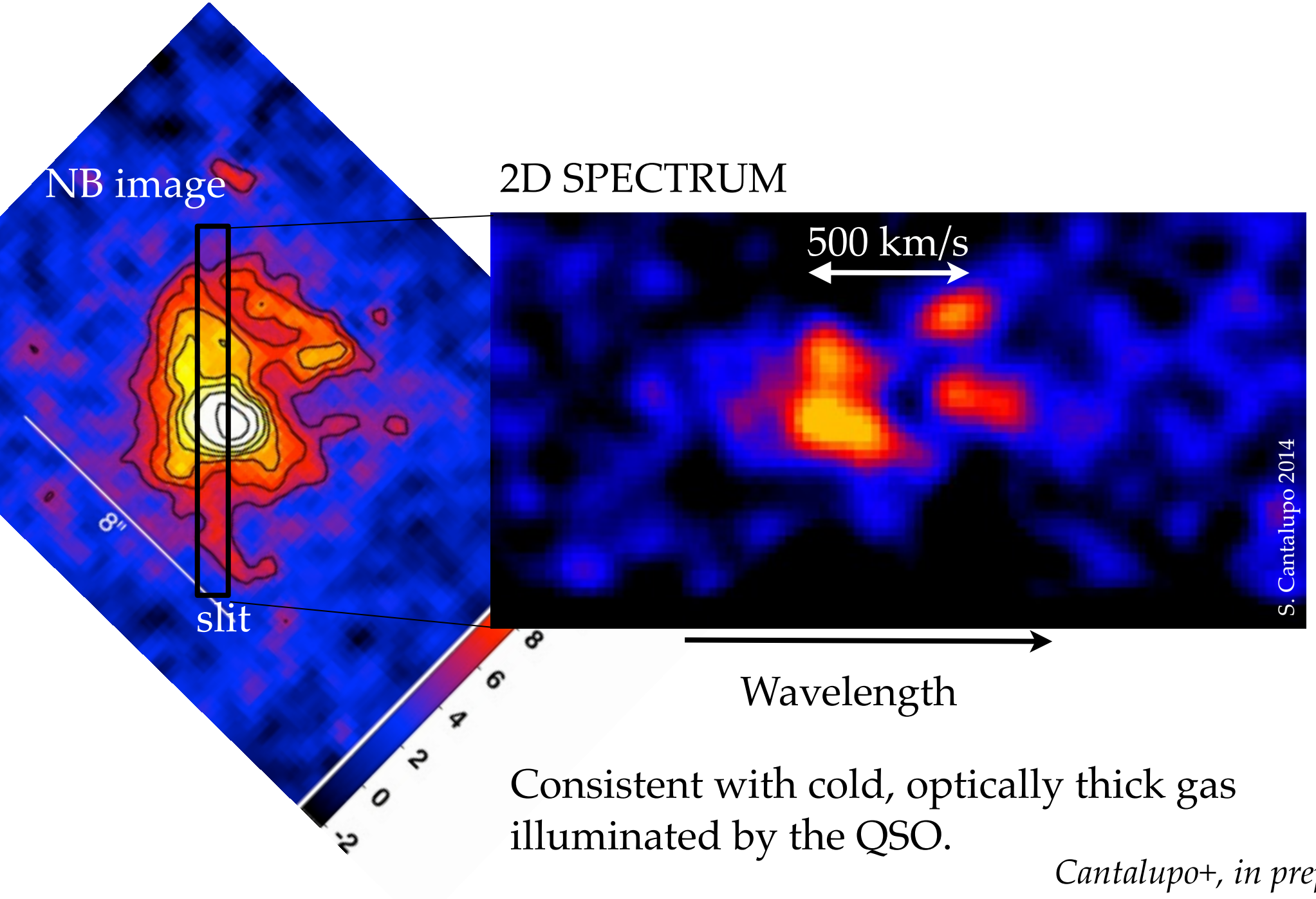
Spectroscopic follow-up @ VLT-FORS (preliminary)



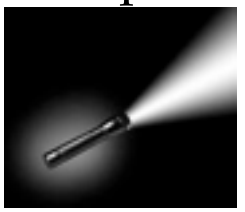
Consistent with cold, optically thick gas illuminated by the QSO.

Cantalupo+, in prep

Ongoing: Keck/GEMINI Survey [~200h]

FLASHLIGHT:

Fluorescent Ly-Alpha Survey for Hydrogen iLuminated by hIGH-redshifT quasars.



- targets: ~20 bright SDSS QSOs at z~2, custom-built NB filters (4)

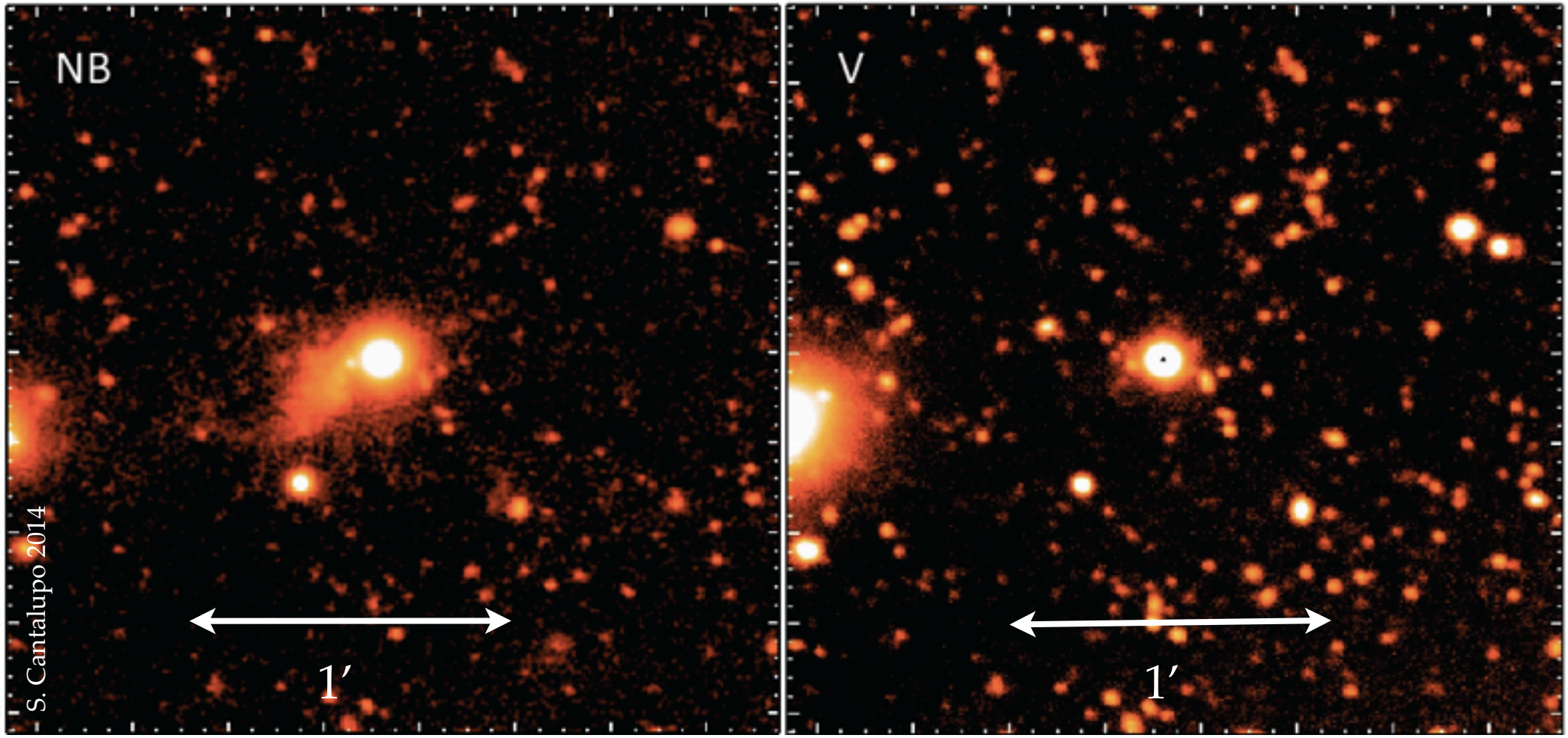
- Data collected so far: 6 QSOs on Keck/LRIS
  3 QSOs (deep) + 10 QSOs (shallow) on GMOS

$1\sigma \sim 5\text{-}8 \times 10^{-19}$ erg/s/cm^2/arcsec^2 (1 arcsec^2 aperture) for deep survey

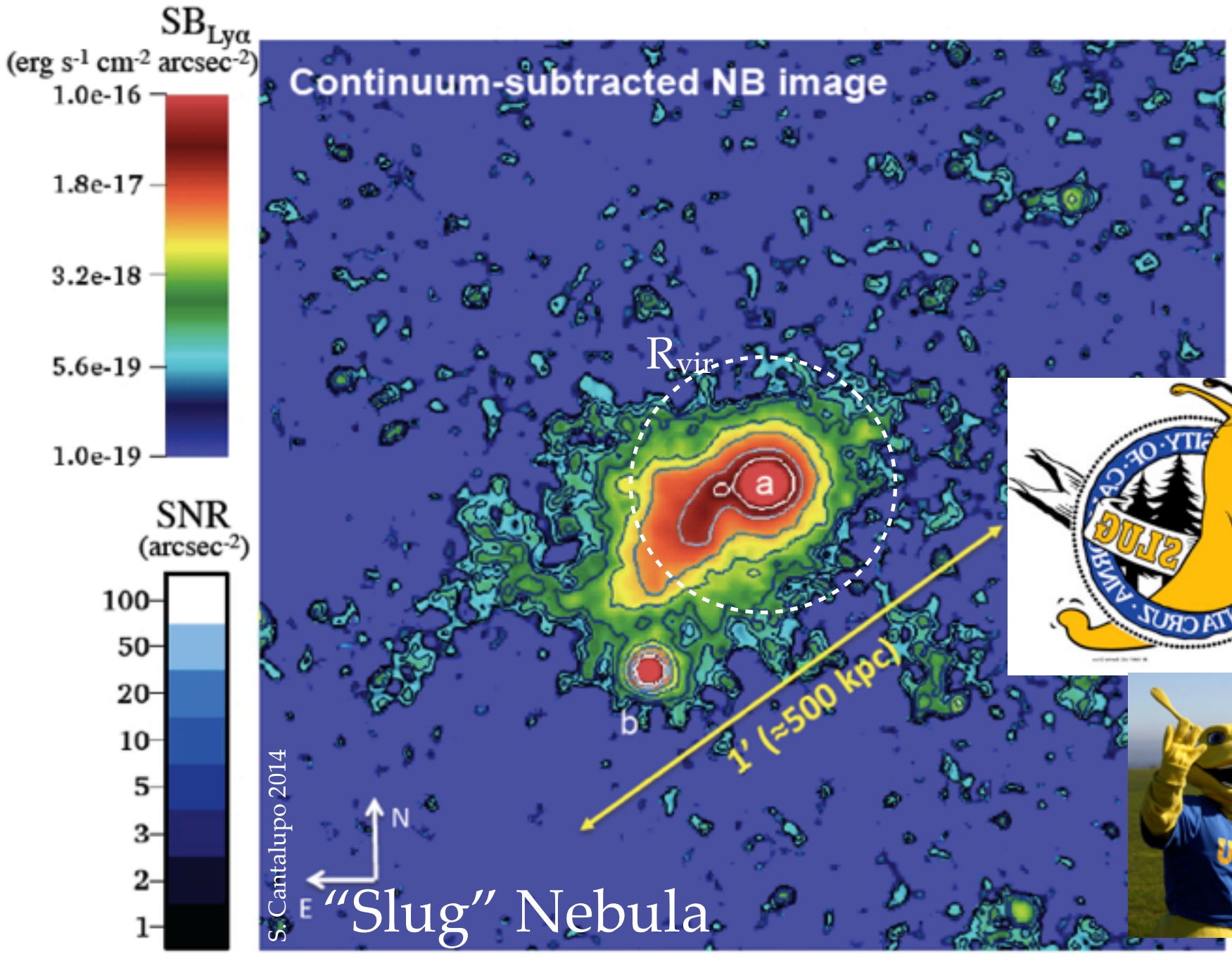
FLASHLIGHT: First Keck/LRIS results

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



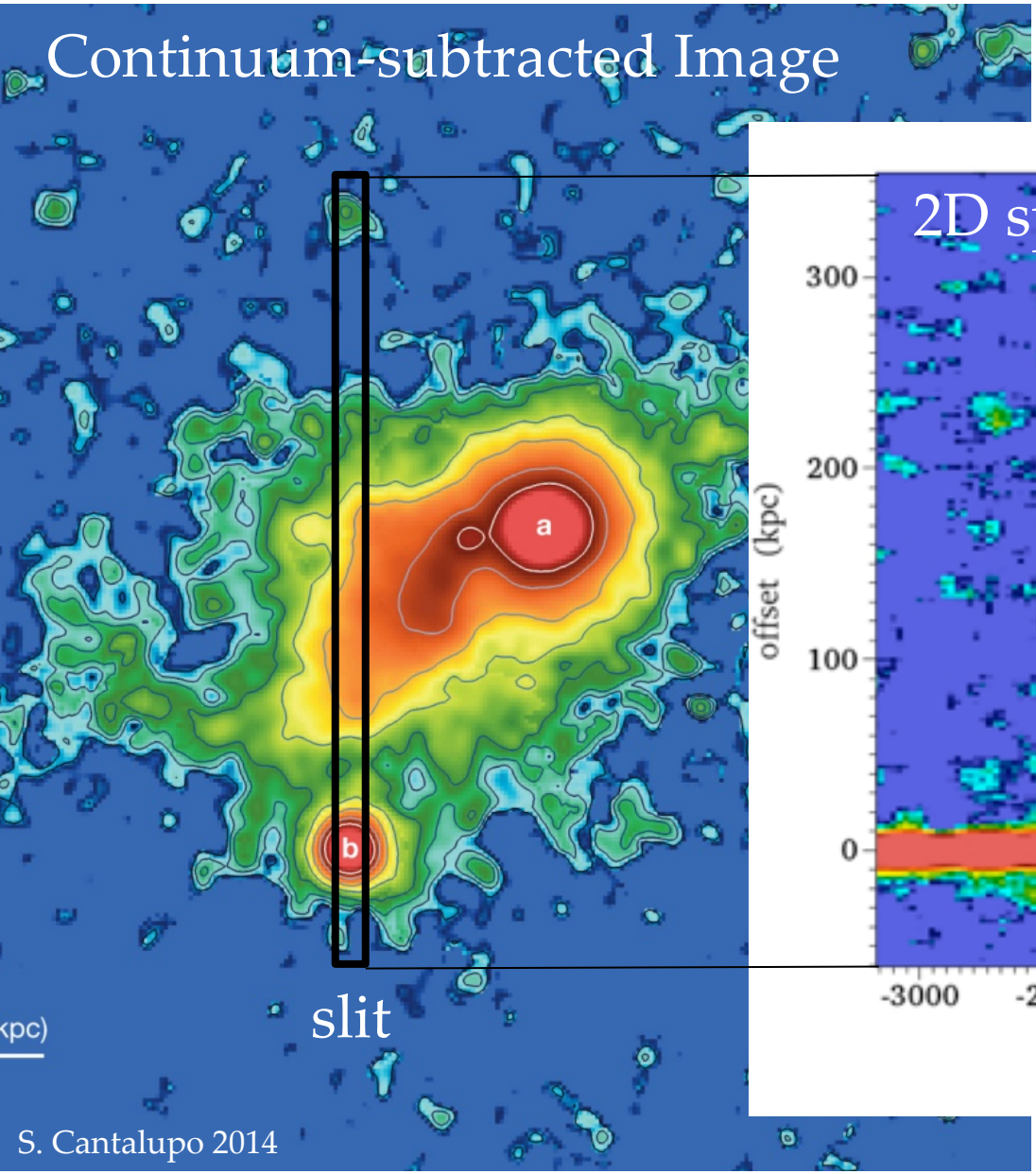
FLASHLIGHT: First Keck/LRIS results

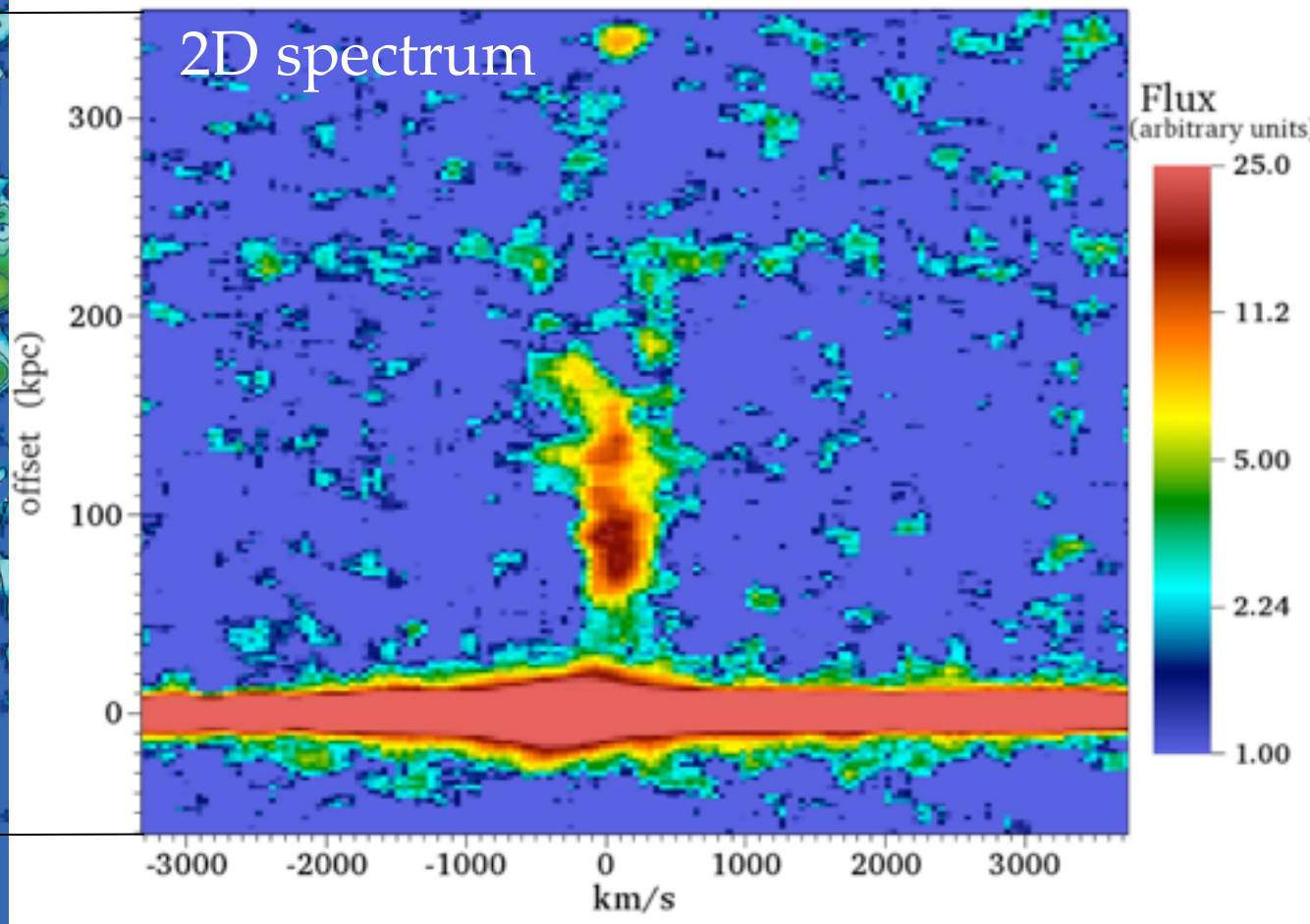


Cantalupo+, 2014

Low-Resolution Spectroscopic Follow-up

- kinematically “quiet”: FWHM<350km/s (vs. >1000km/s of RadioGalaxies!)

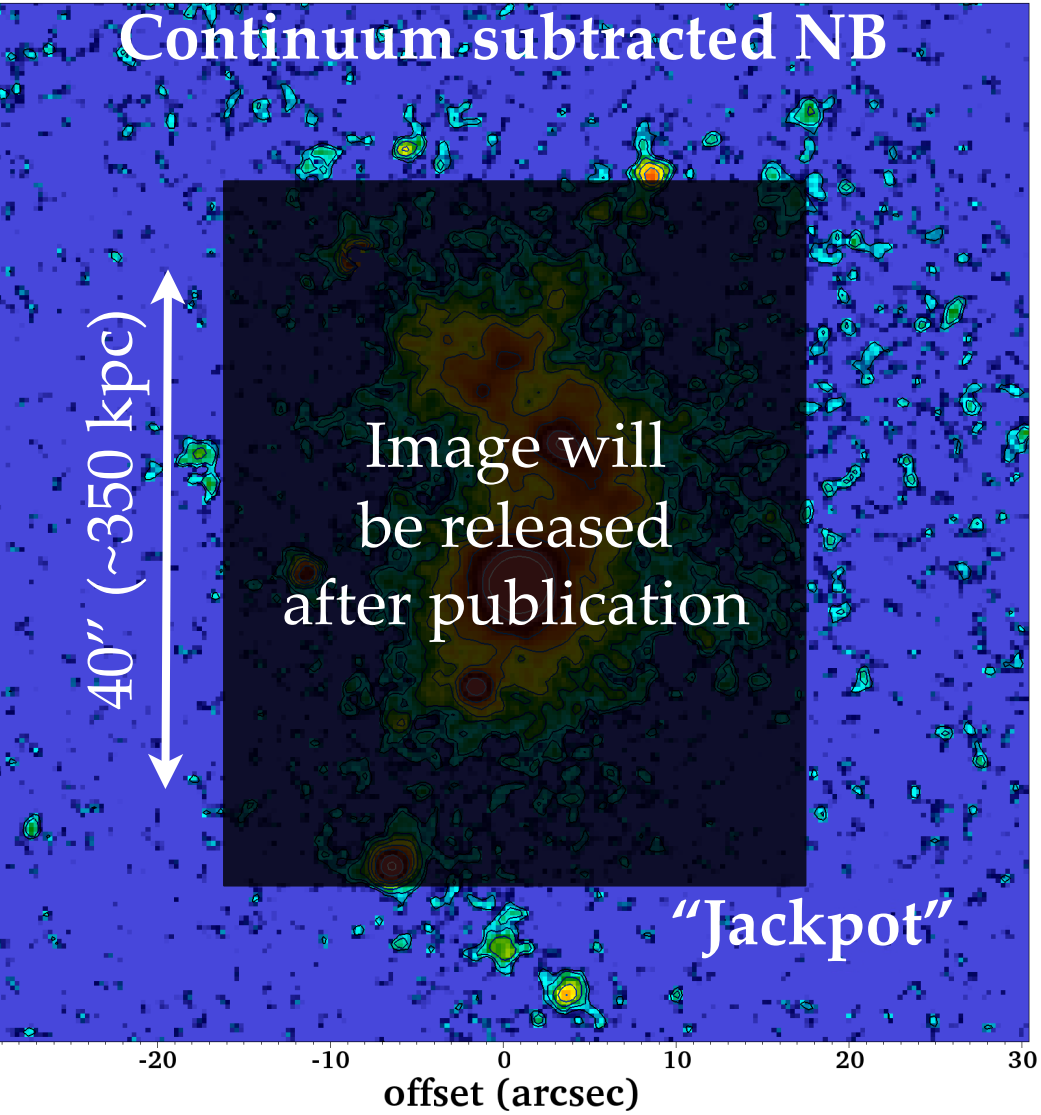


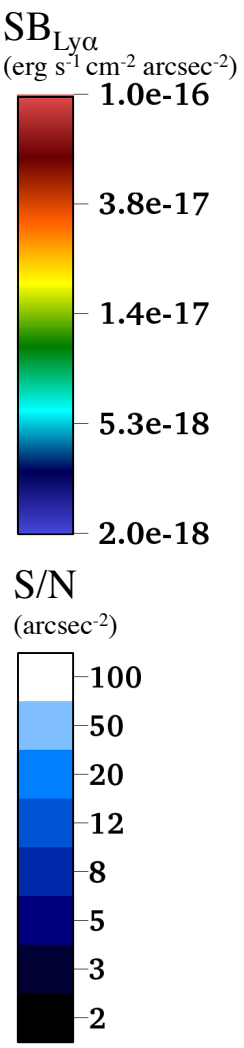


Cantalupo+, in prep

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)

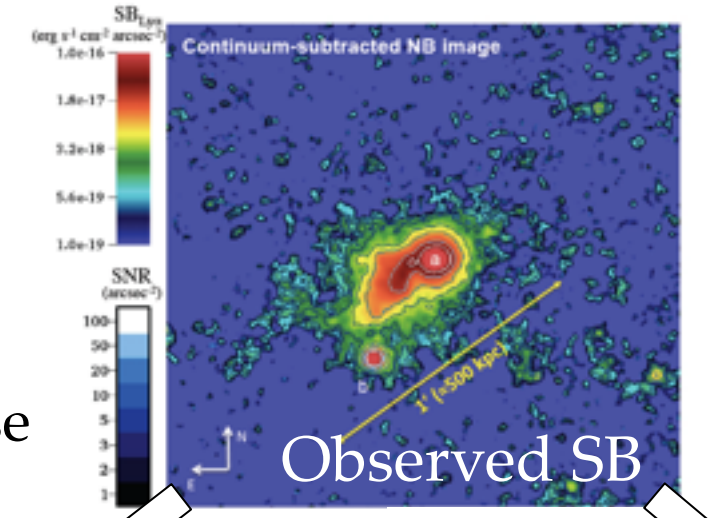




Hennawi, Cantalupo+, TBS

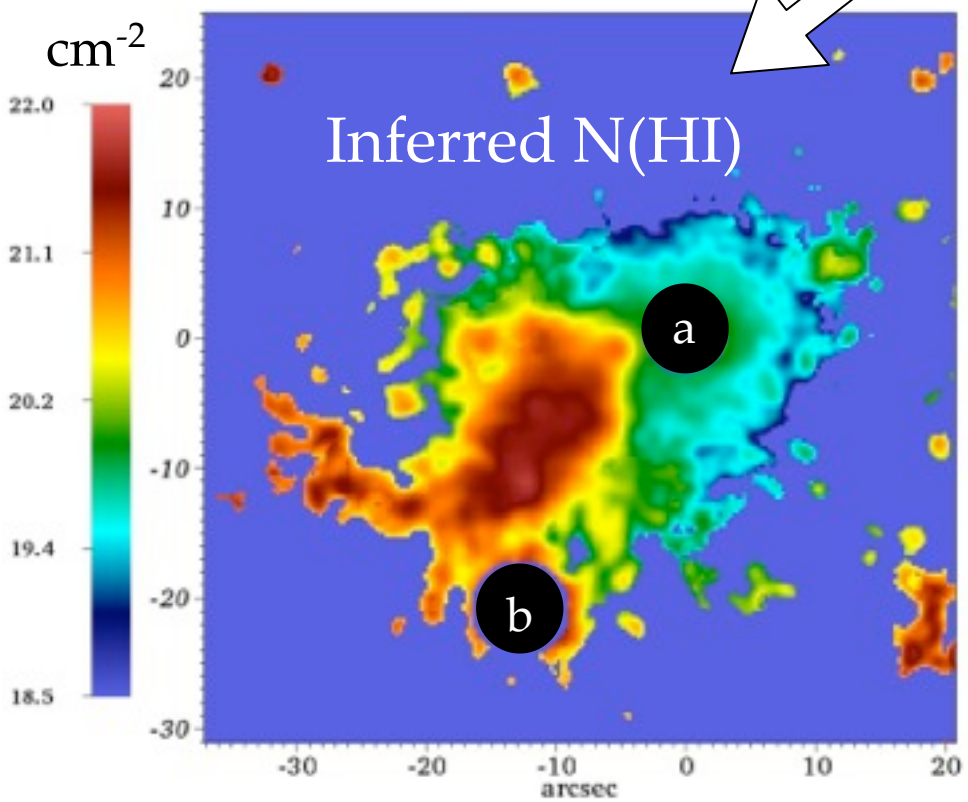
Inferring the cold gas content of the Slug Nebula: 2 cases

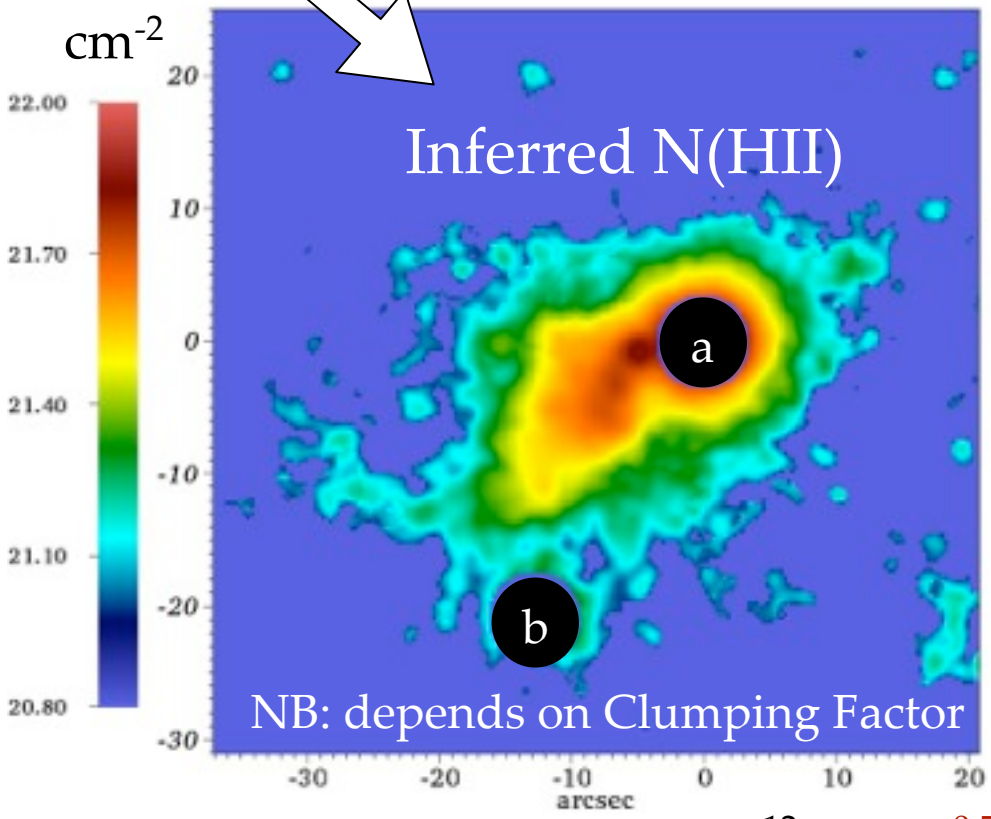
Cantalupo+ 2014



"Photon-pumping" case
(gas mostly neutral)

"Recombination" case
(gas mostly ionized)

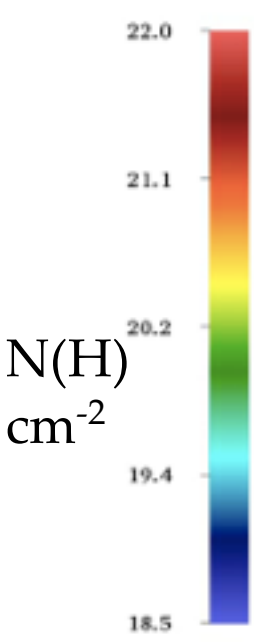


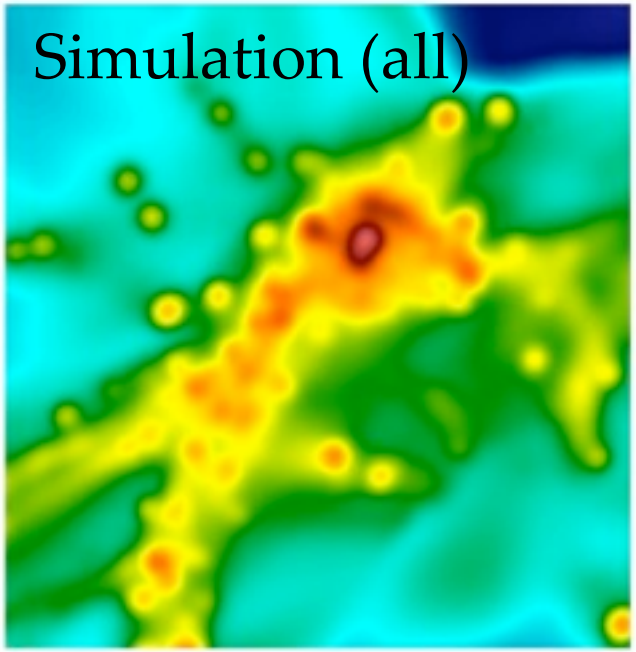


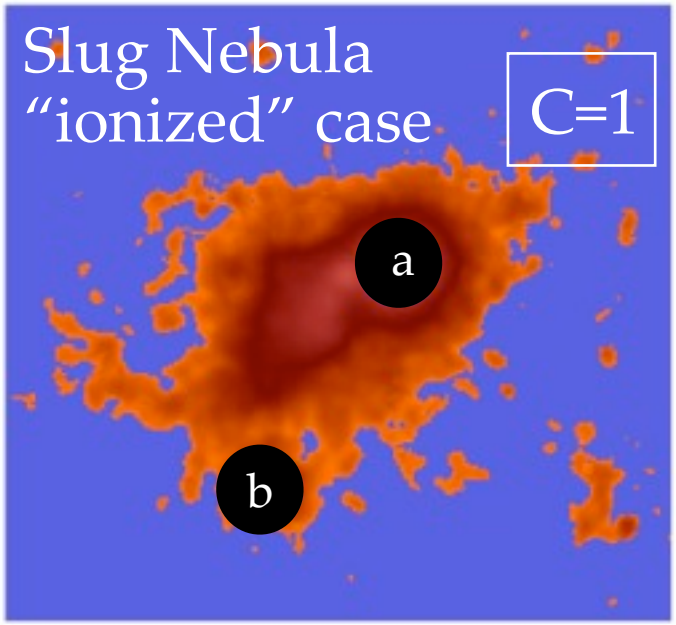
M(HI) ~ M("cold" H) ~ 2.5×10^{11} $M_\odot$

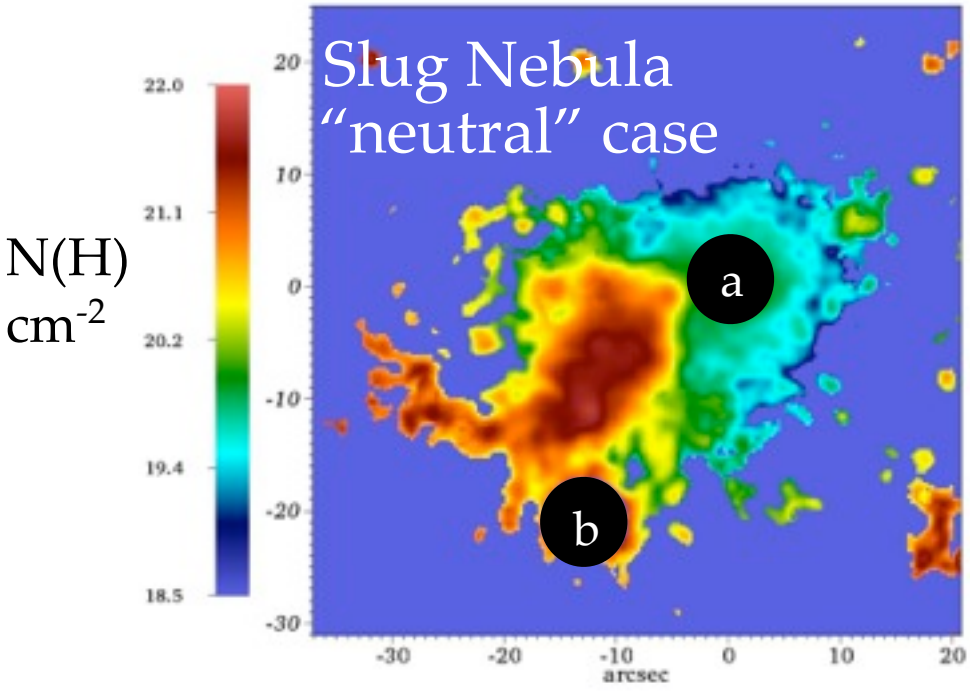
M(HII) ~ M("cold" H) ~ 10^{12} $M_\odot / C^{0.5}$

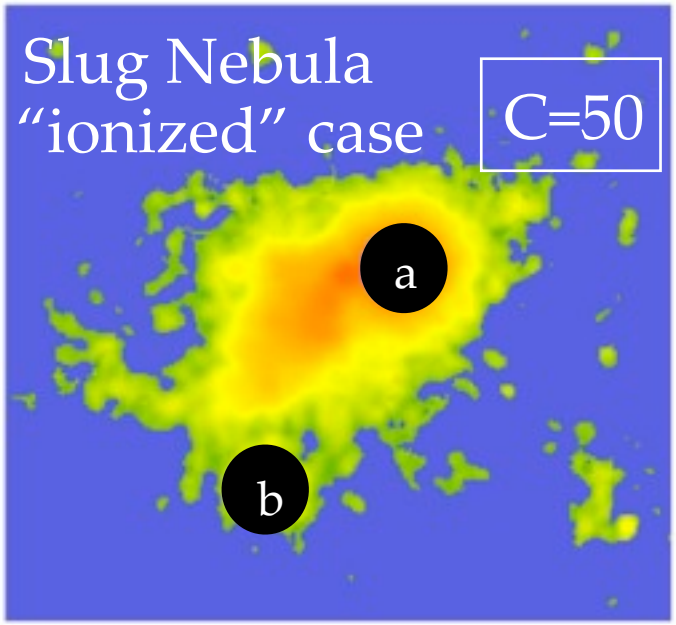
Comparison with simulations: more IGM "clumps" needed







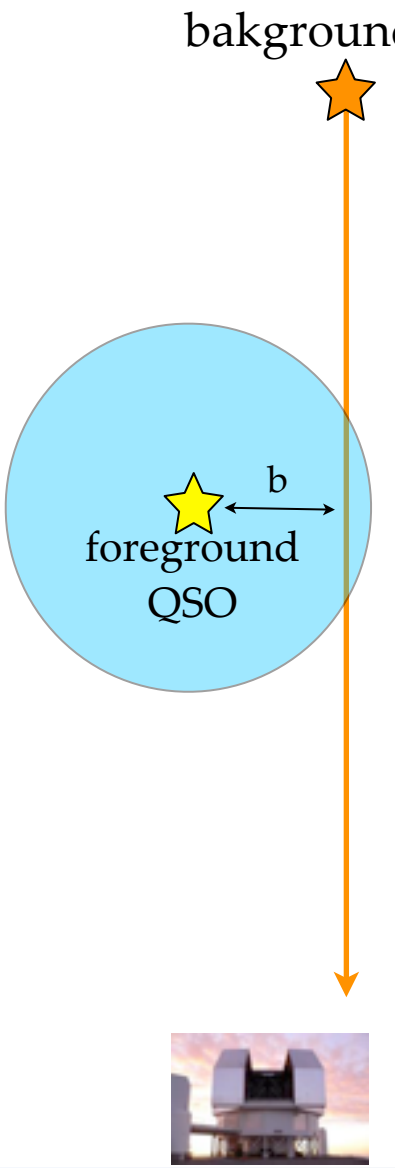


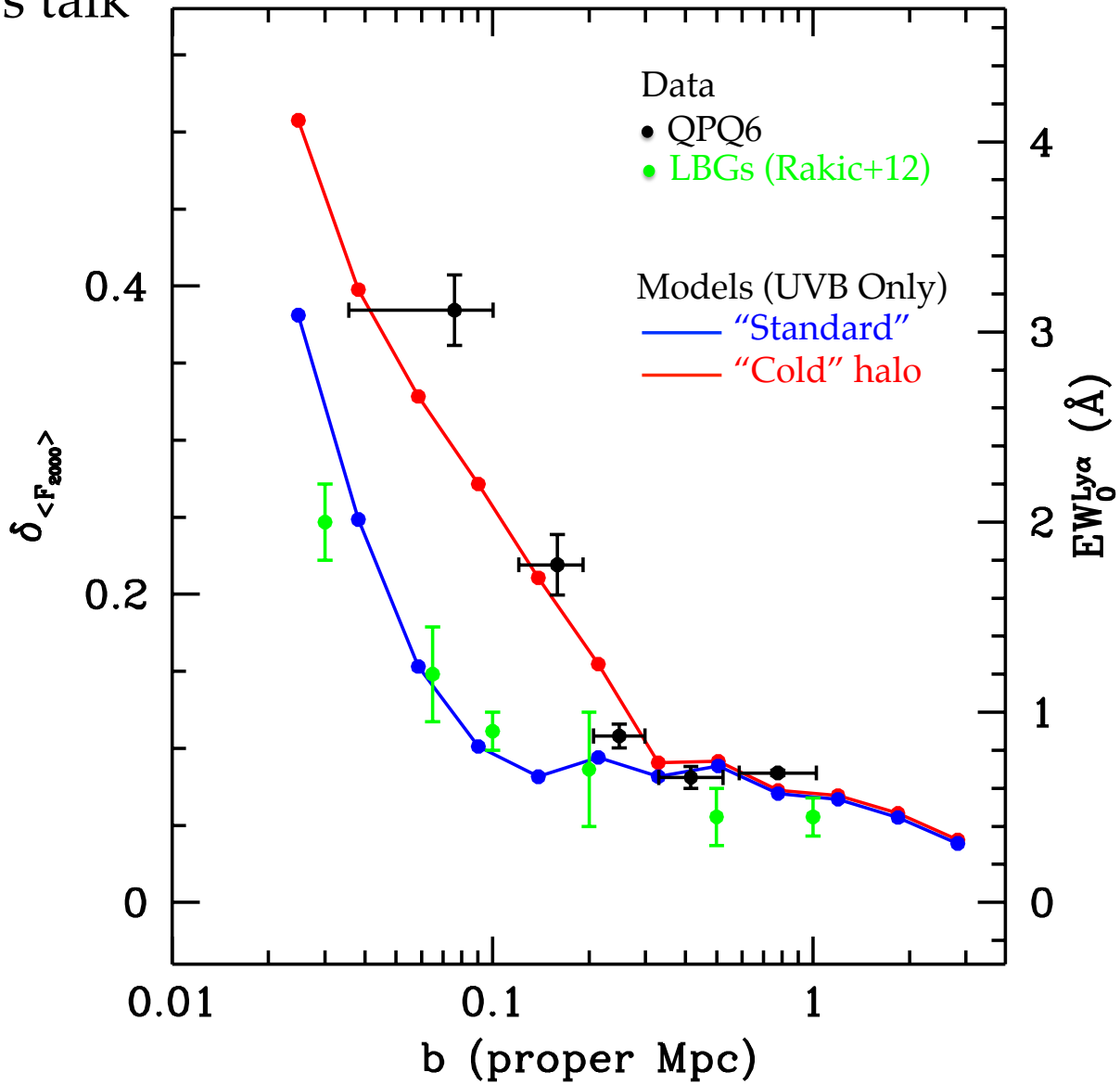


Cantalupo+ 2014

Comparison with simulations: more IGM "clumps" needed

Similar problem to reproduce gas absorption around quasars (QPQ) in transverse direction see Marie's talk





Prochaska,...,Cantalupo+,2013

Summary

- New technique to "illuminate" cosmic gas at high-z with the help of QSOs.
  Key components are:
  - cosmological radiative transfer RADAMESH for ionizing and Lyα emission.
  - specifically designed surveys with custom-built NB filters.

- FLASHLIGHT: first results at z~2.3 (including VLT Survey)
  - Dark Galaxy candidates (>20 so far).
    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 (Slug & Jackpot), ~500 kpc size.
    Morphology compatible with "Cosmic Web". More cold/neutral gas than expected: ~10^{12} M_{sun}. Tension with models - missing physics?

- Next Future:
  - Large MUSE Survey for quasar-induced IGM Lyα and metal emission at z>3 From September + 5yr.
  - Lyα + Hα high-resolution spectroscopy of the Slug (2.5n LRIS + MOSFIRE in Sep/Oct).

Stay tuned!