Illuminating the Dark Universe with quasar-induced Lyα emission

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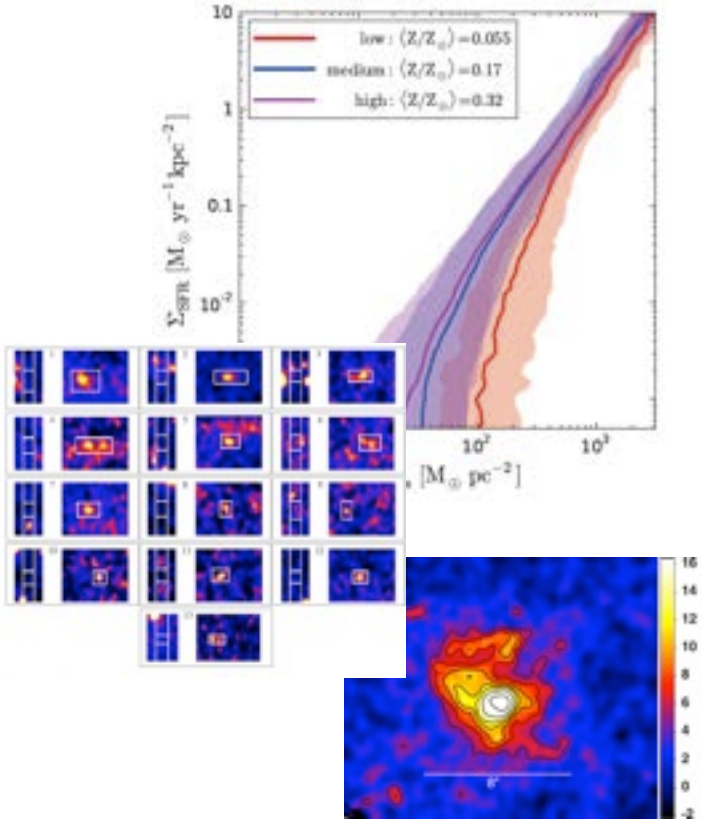
Outline

- Introduction and motivations



- Detecting Dark Galaxies at z~2.4 with fluorescent Lyα emission:
  - pilot VLT/FORS survey
  - dark galaxy fluorescent survey (Keck/LRIS & Gemini/GMOS)

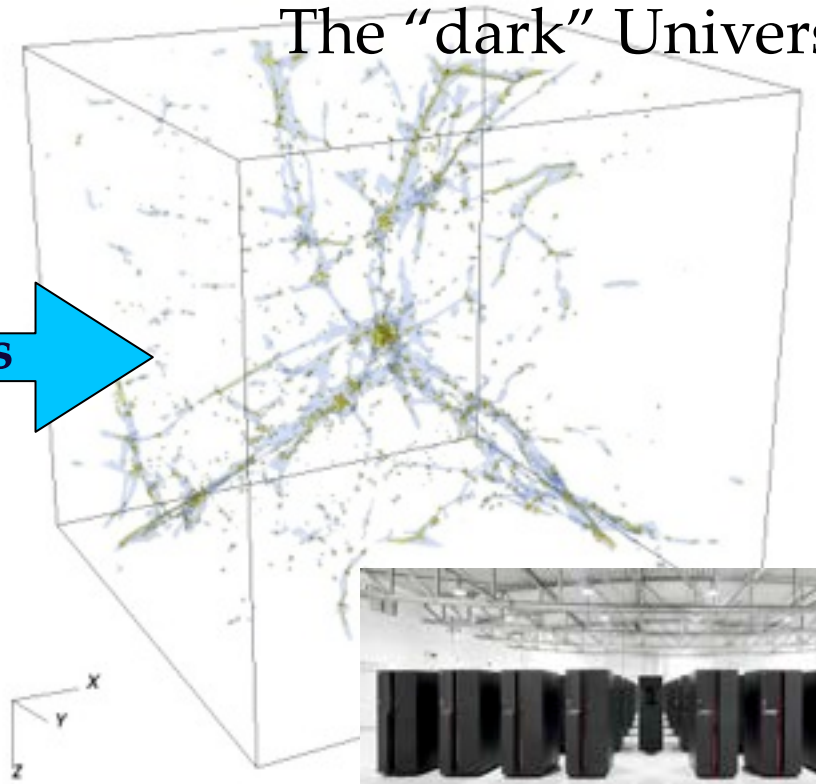
- Detecting the Cosmic Web in fluorescent Lyα Emission

Introduction

The "bright" Universe:

cosmic gas

The "dark" Universe:



scale

"proto -disk"

halo or CGM

IGM

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

How do evolving galaxies get their gas? Cold, hot, lukewarm?

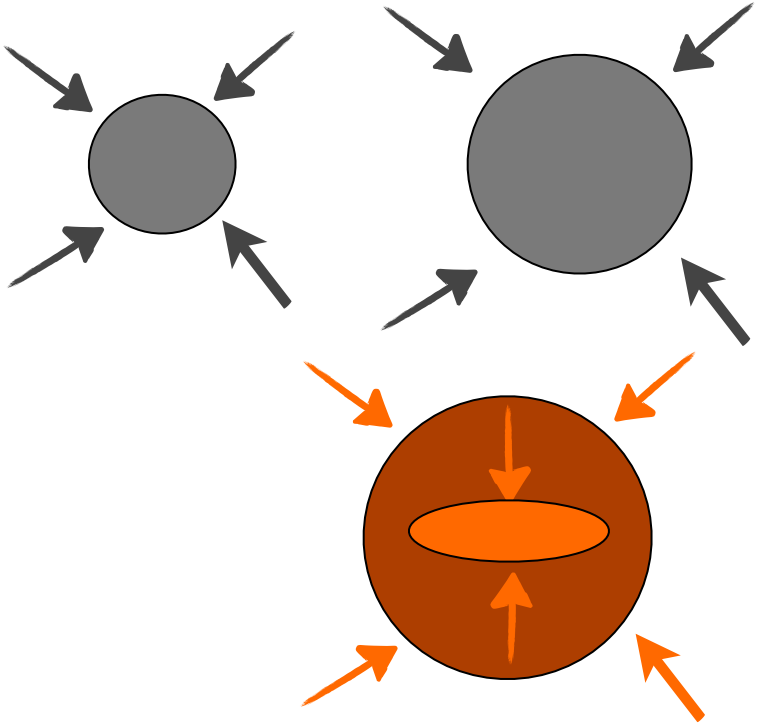
How are galaxies linked to each other? Morphology of "Cosmic" web?

"Dark" galaxy phase?

galaxy formation in a nutshell (for z<6) [e.g. White & Rees 1978]:

Dark Galaxy Phase

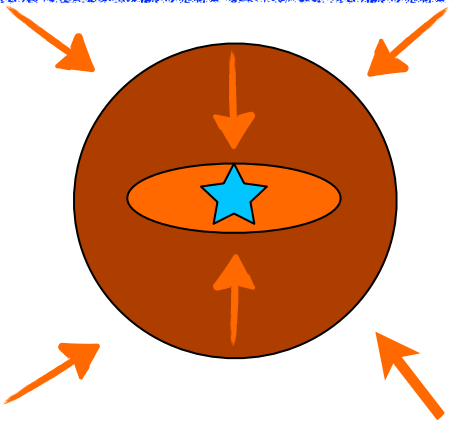
1) Dark Matter collapses into a "halo".
Gravity brings in more Dark Matter.
Pressure prevents gas from "falling" in.



2) With enough Dark Matter (~10^8 M)
the gas collapses into the halo .
It cools down and forms a disk.

Bright Phase

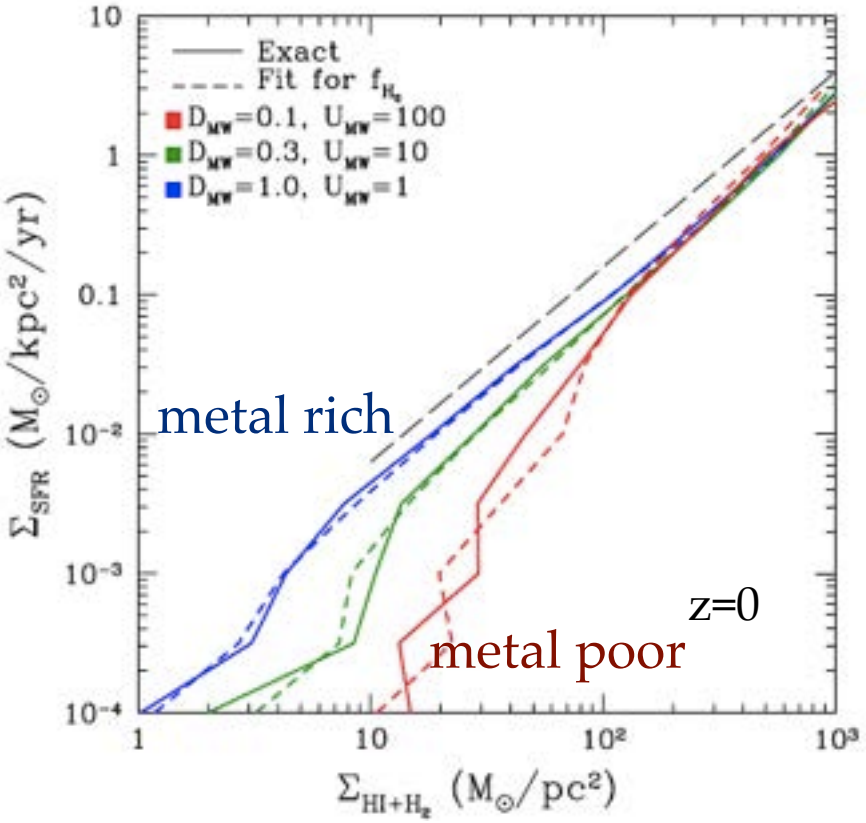
3) The disk accretes gas from the Cosmic Web.
When the gas density is high enough
(e.g., 10 atoms per cm^3) the gas fragments
into stars (?)



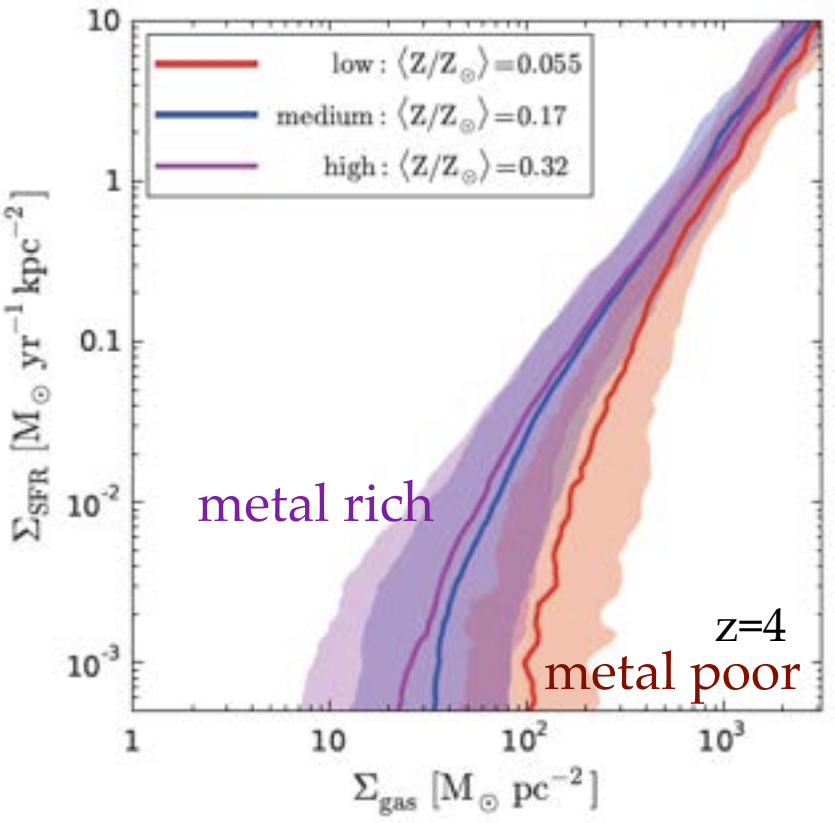
"Dark" galaxy phase?

Theoretical/Numerical models:
SF efficiency depends on dust mass/gas metallicity

-> Many low mass haloes especially at high-z may be "dark", e.g.:



Gnedin & Kravtsov 10

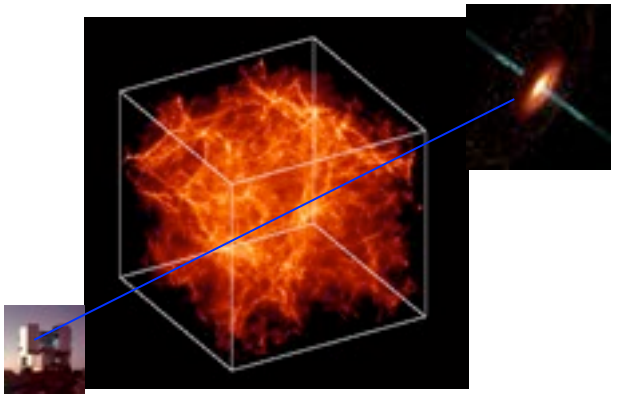


Kuhlen+11

See also: Bouche'+10, Krumholz & Dekel 12, Rafelski+11, Kuhlen+13.

How to observe Cosmic Gas and "dark" galaxies

A) In absorption (the "classical" approach)



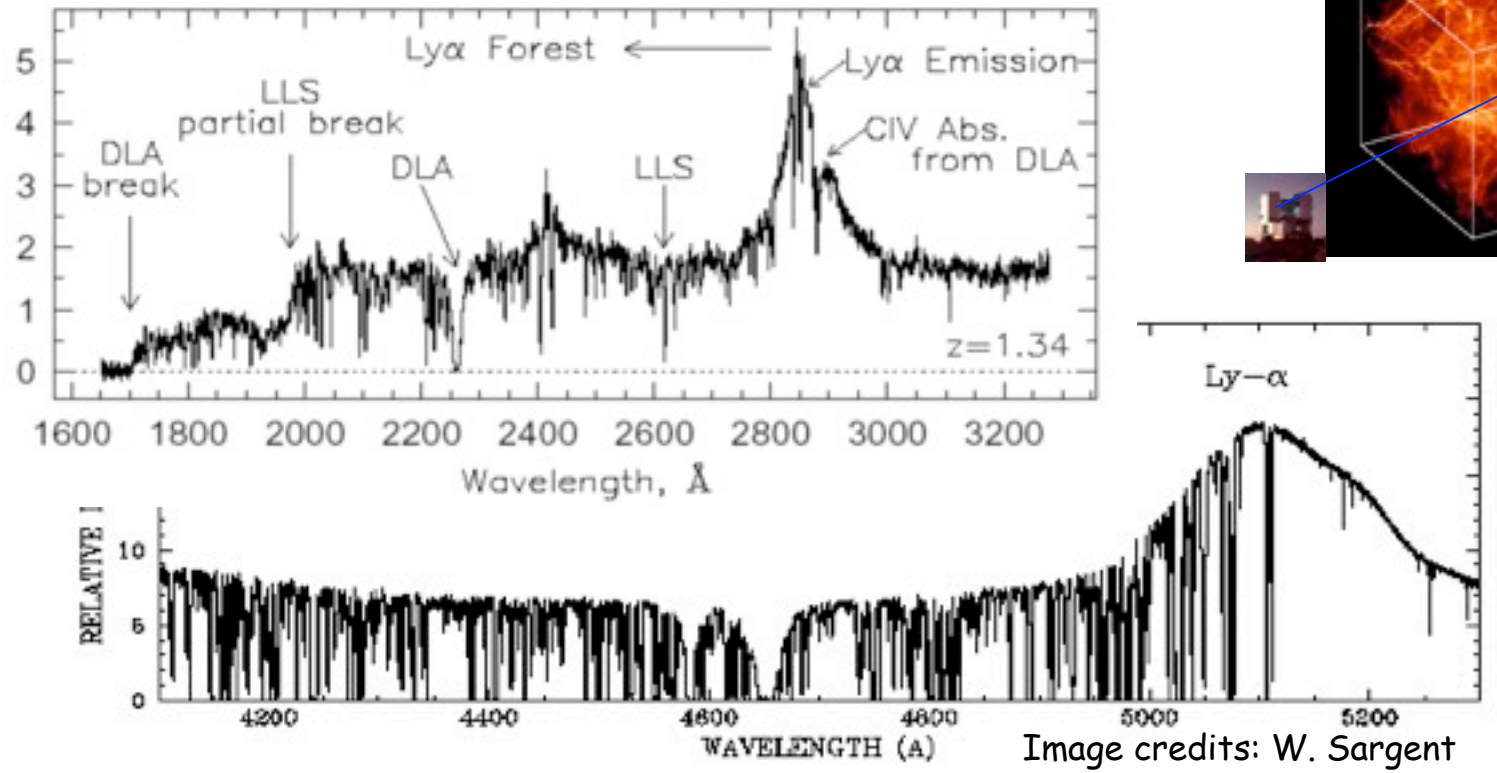


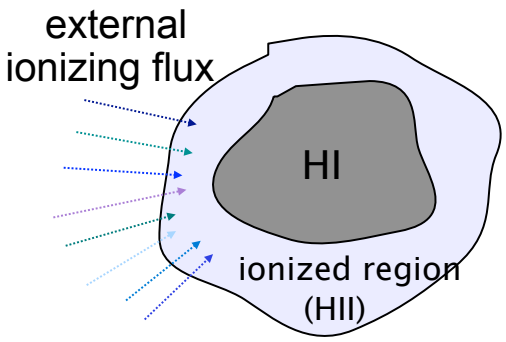
Image credits: W. Sargent

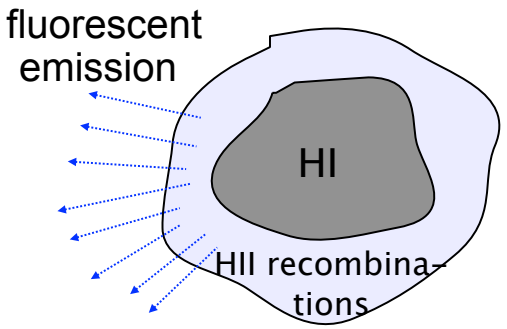
- pro: able to detect low-density gas including metals.
- con: only 1D information.

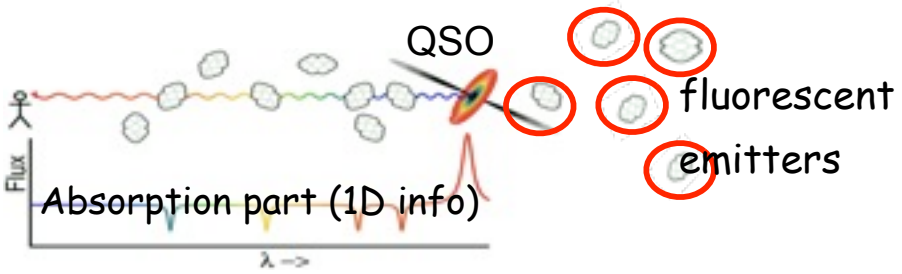
What we would like to have:

- 2D/3D Information
- A mechanism that "illuminates" dense gas independent of internal star formation

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



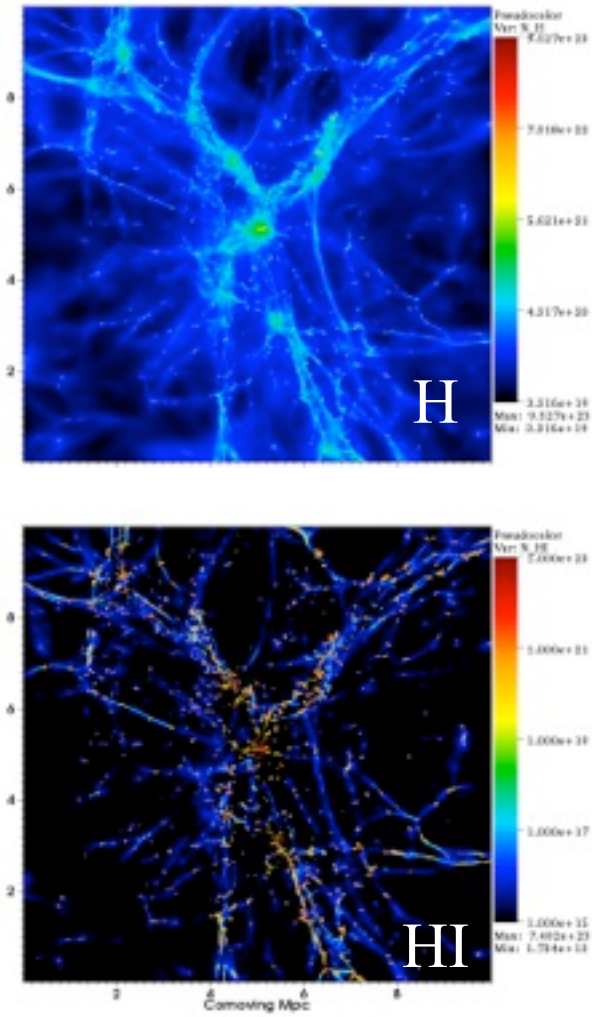


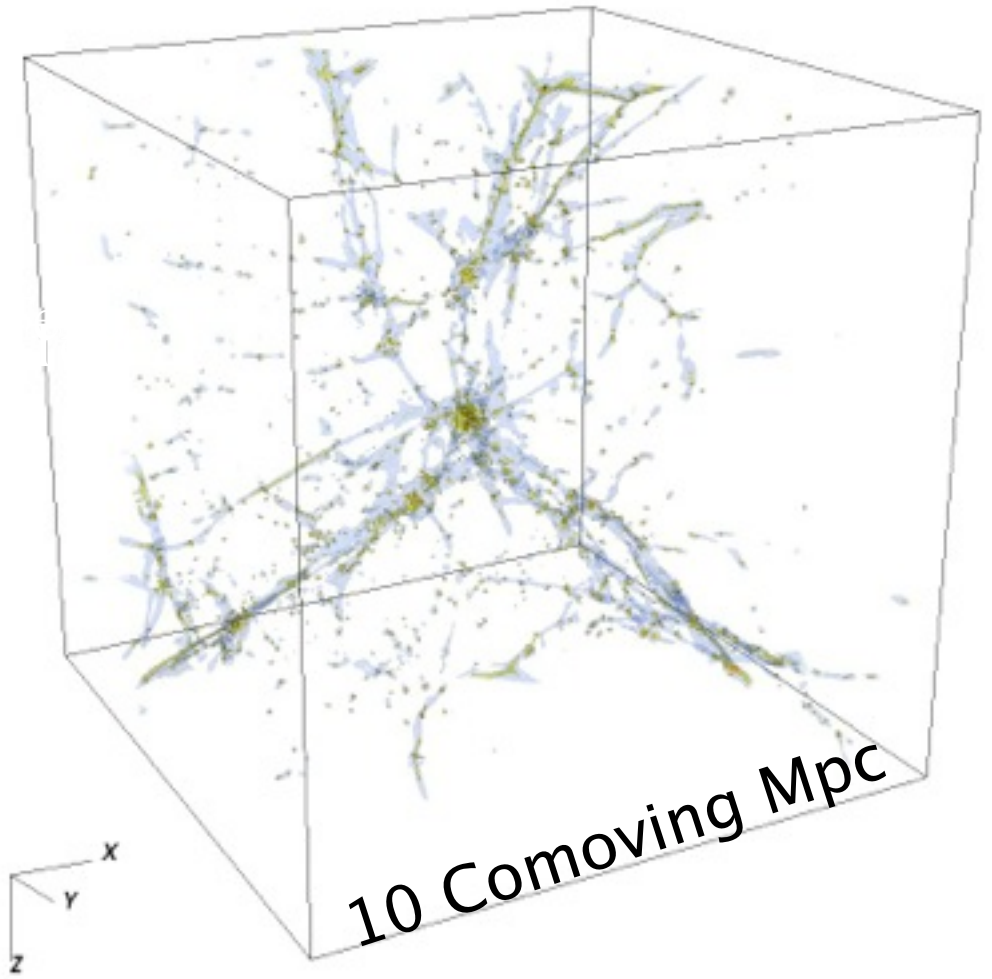


- Self-shielded gas (slab): "mirror" emission -> ~60% of incident ionizing radiation "converted" to **Lyα (but see Cantalupo+05).**
- Fully ionized gas: proportional to gas density squared.

How bright is fluorescent emission: simulations

- 40Mpc^3 (10Mpc^3 high-res) hydro-simulation (RAMSES) around 6x10^{12} M_{sun} halo at z=2.5
- Star formation, SN feedback, on the fly UVB Self-shielding.
- Post-processed with the AMR Radiative Transfer code RADAMESH (Cantalupo & Porciani 2011) for ionizing and Lyα radiation (Cantalupo+05).

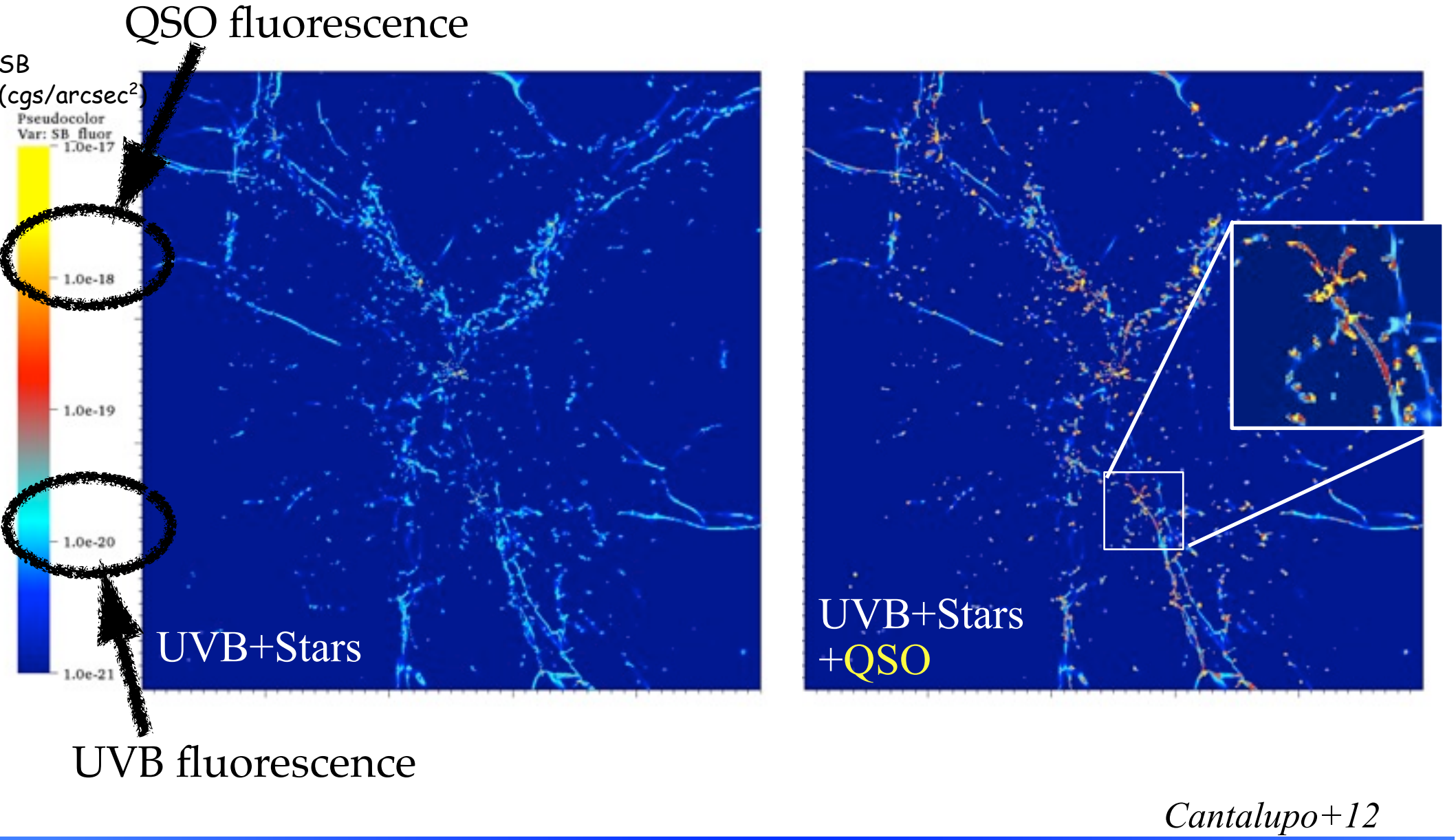




Cantalupo+12

How bright is fluorescent emission: simulations

Simulated Ly-alpha images



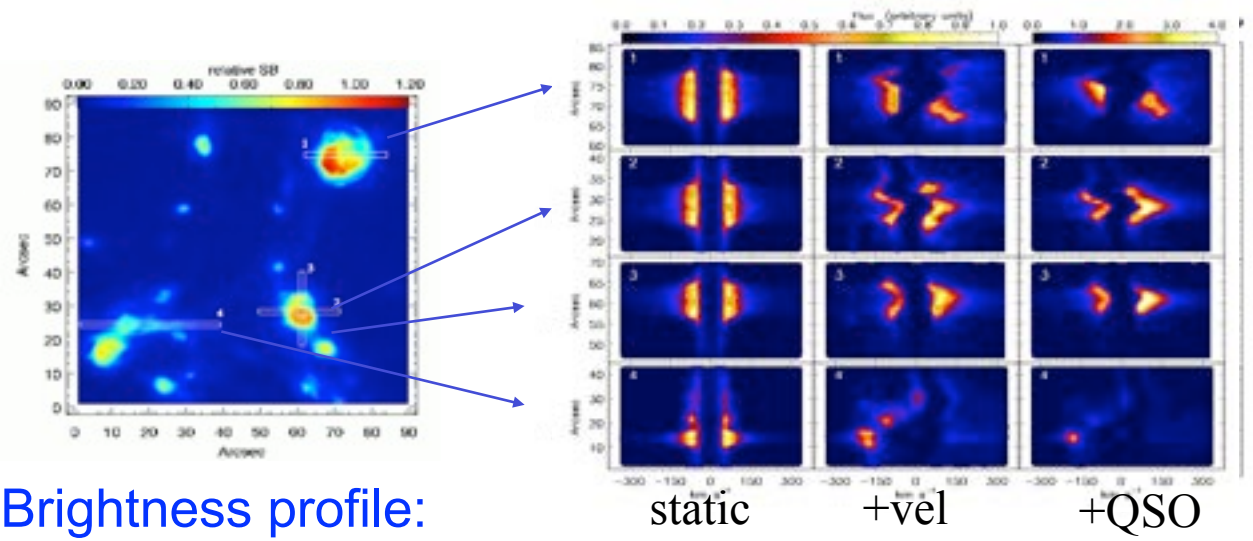
Cantalupo+12

How to distinguish fluorescence from "normal" galaxies?

1) Lyα Emission Shape: Double Peaked Profile (?)

- from Gould & Weinberg 96 "slab" model (see also Zheng & Miralda-Escude' 04)
- Including IGM effects double peaked likely suppressed (Cantalupo+05)
- Also galaxies may have double (triple) peaked profile (e.g., Verhamme+08)!

Simulated Spectra



Cantalupo+05

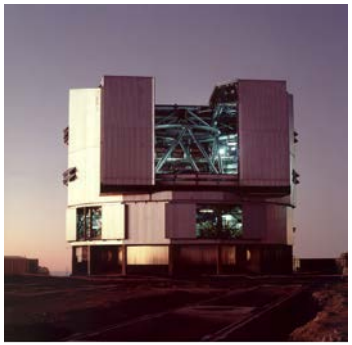
2) Lyα Surface Brightness profile:

- "Flat" SB profile (Cantalupo+05)
- SB proportional to ionizing flux (Gould & Weinberg 1996, but see Cantalupo+05)
- Only works for resolved and optically thick objects!

3) Lyα Equivalent Width (EW) (e.g., Cantalupo+07)

- "Normal" galaxies produce also stellar continuum --> EW<240A (e.g., Schaerer+02)
- Fluorescence only produce line emission and nebular continuum --> EW~10^4 A (!)

Can we observe it?



- Need to look around a bright quasar
- Deep Narrow-Band and continuum (broad-band) imaging to constrain EW

Pilot VLT Fluorescence Survey

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

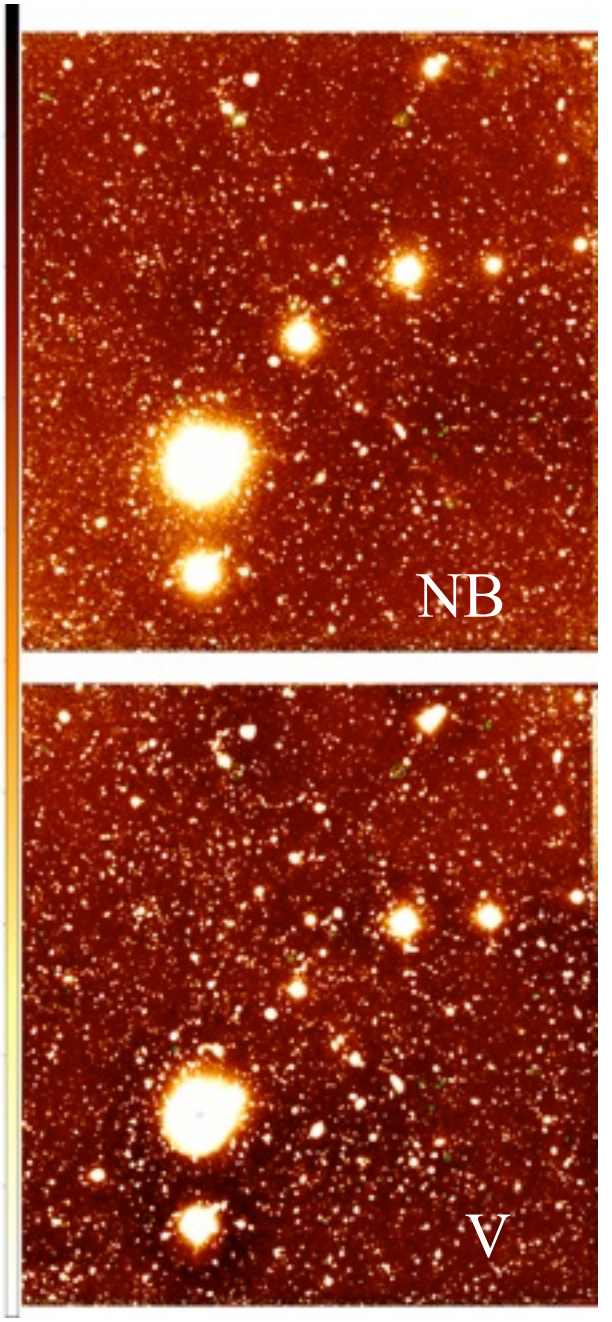
4 Nights @ VLT-FORS

Custom-built filter (FWHM=4nm)

Target: z=2.4 hyper-luminous QSO.
Very accurate systemic redshift (OIII line)

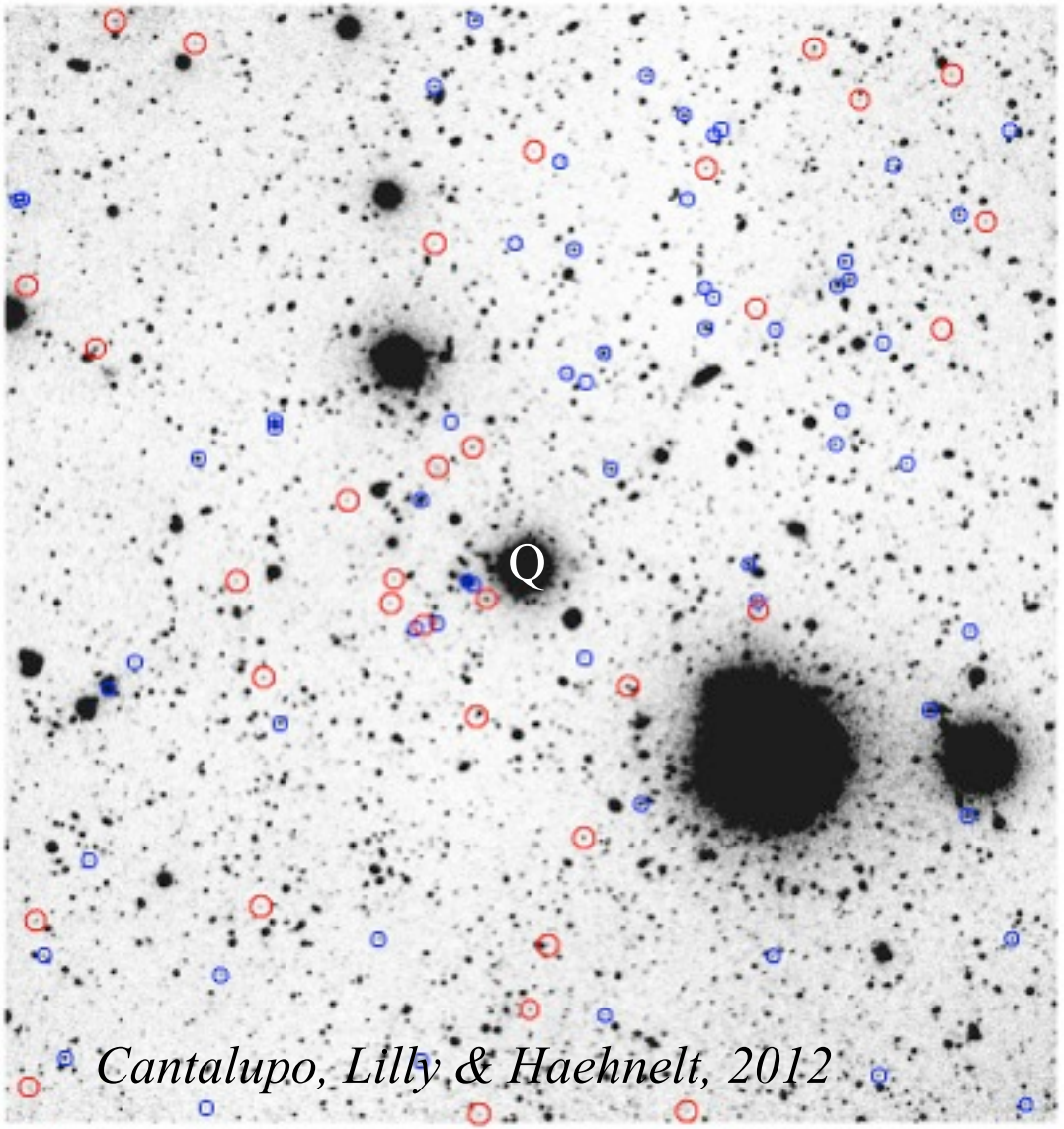
Data collected: ~21 hours NB
~6 hours V-band (1.5h discarded)
~1 hour B-band

NB Flux limit: ~4×10^{-18} erg/s/cm^2 ($L_{ly\alpha} \sim 2 \times 10^{41}$ erg/s)
[5σ for 1 arcsec^2 aperture]



Cantalupo, Lilly & Haehnelt 2012

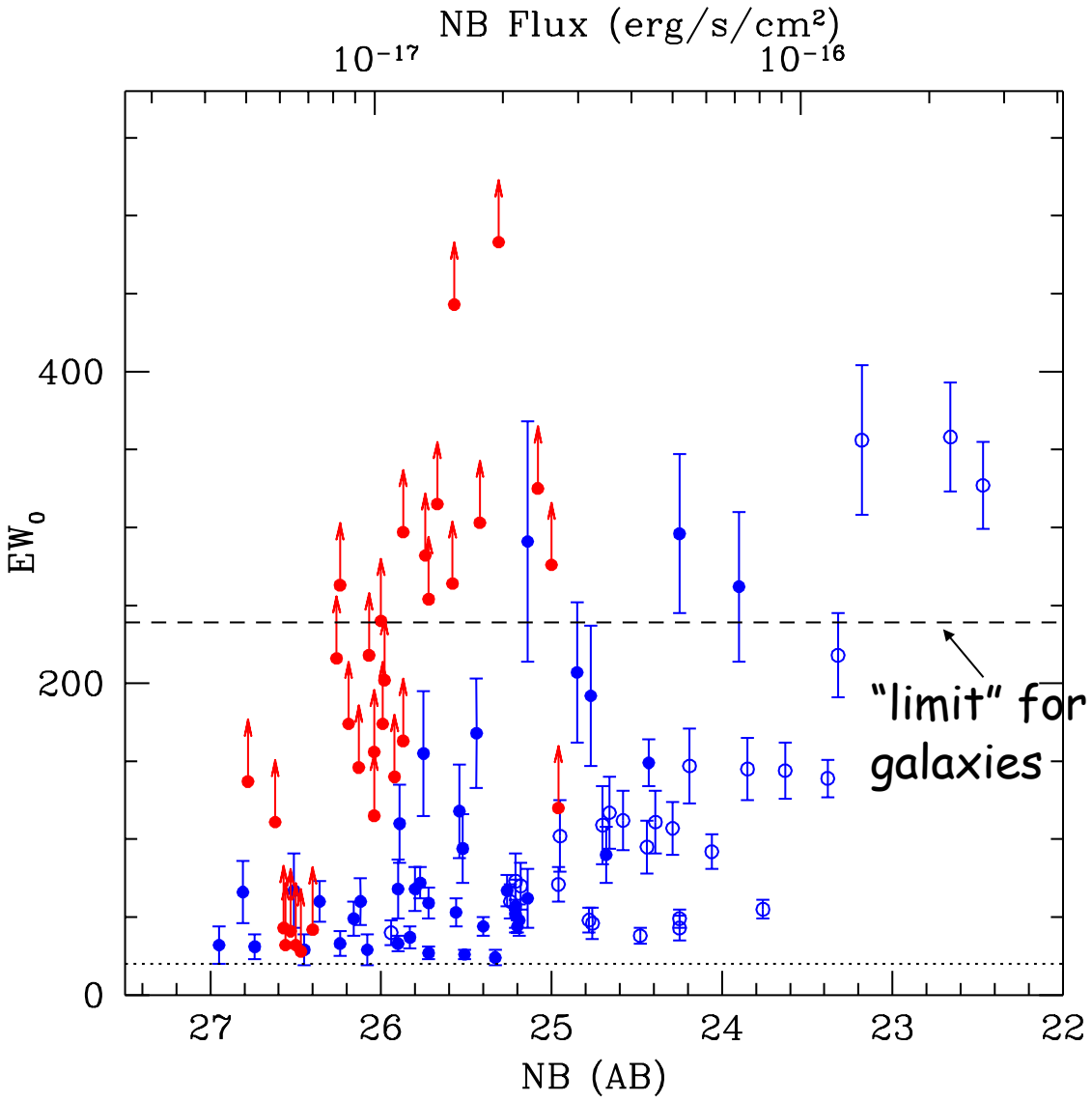
Results

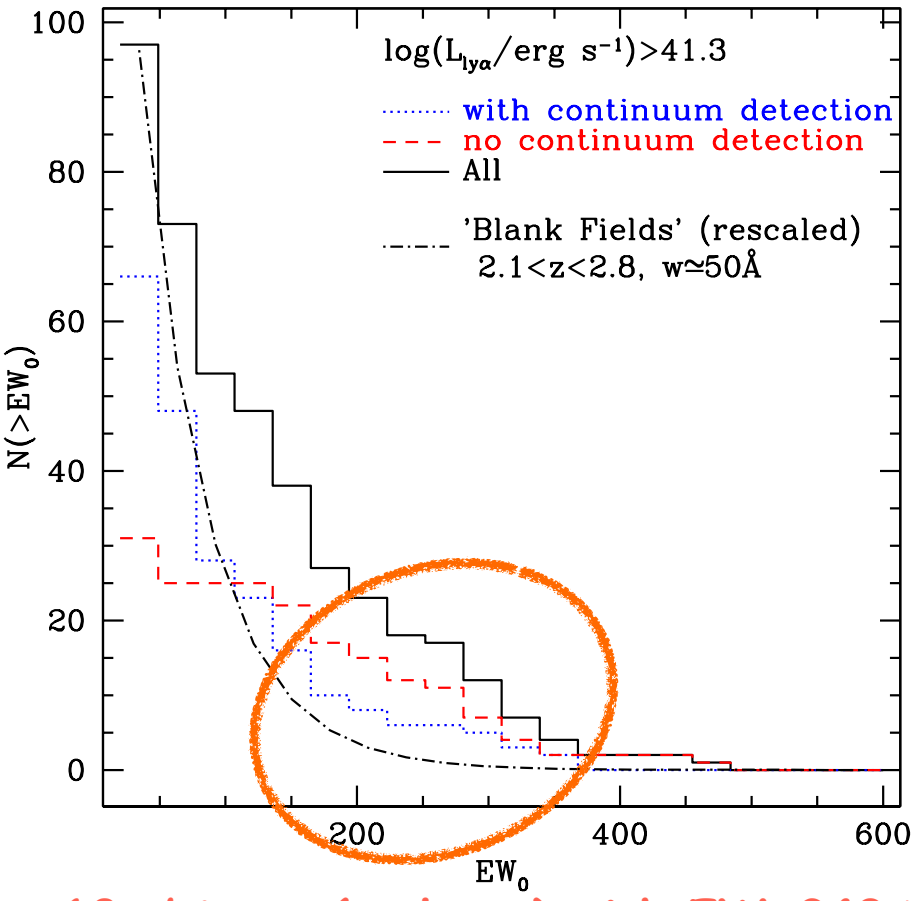


98 NB excess objects
31 without V or B detection (red circles)

Separating "dark" galaxies from "normal" LAE population:

- "Normal" galaxies produce also stellar continuum --> EW<240A (e.g., Schaerer+02)
- Fluorescence only produce line emission and nebular continuum --> EW~10^4 A (!)

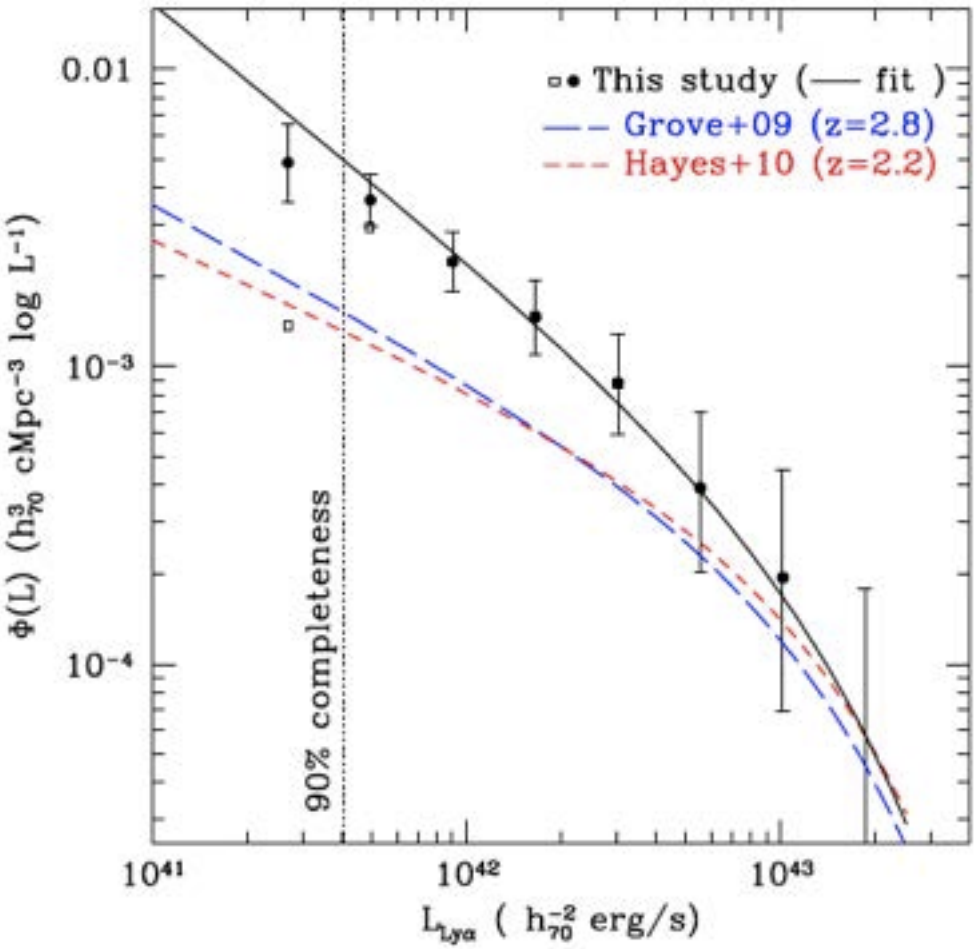


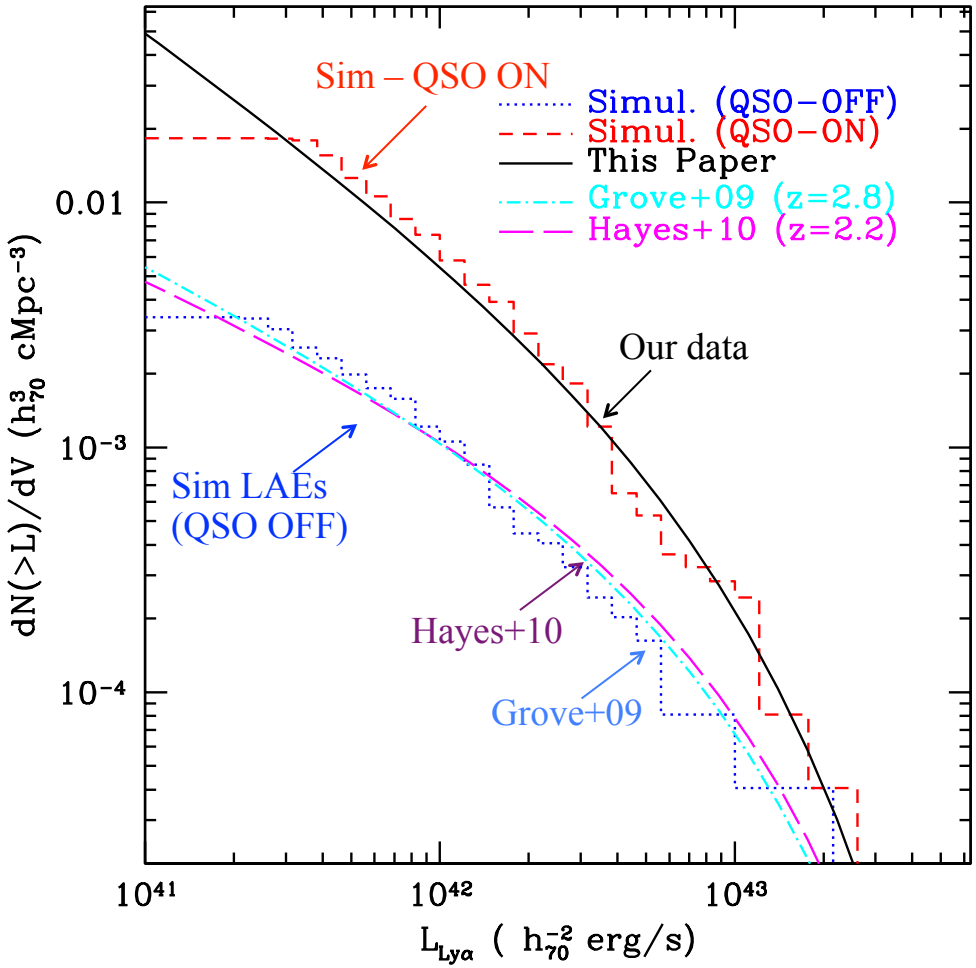


18 objects (at least) with EW>240A

Cantalupo+12

Additional evidence for Fluorescence (1): LF





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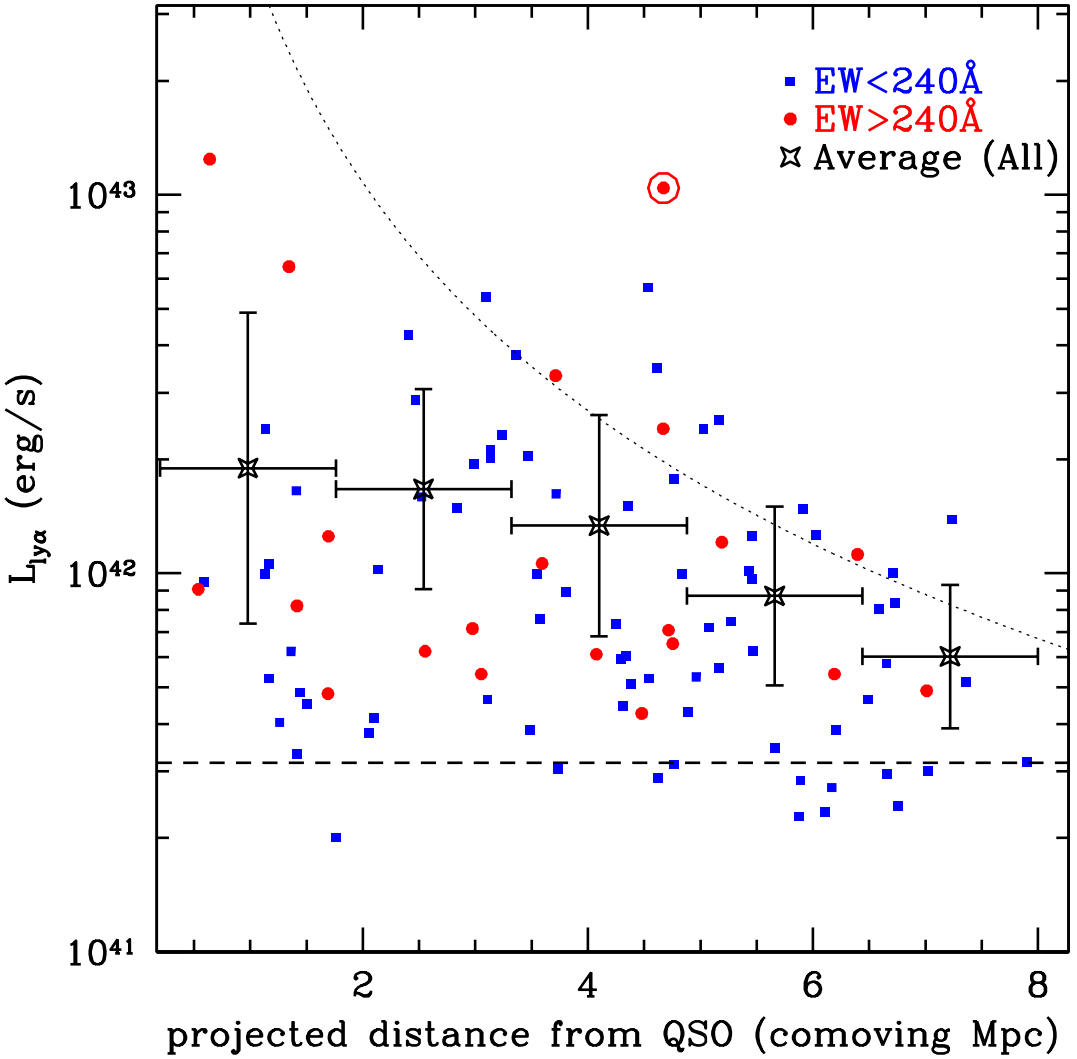
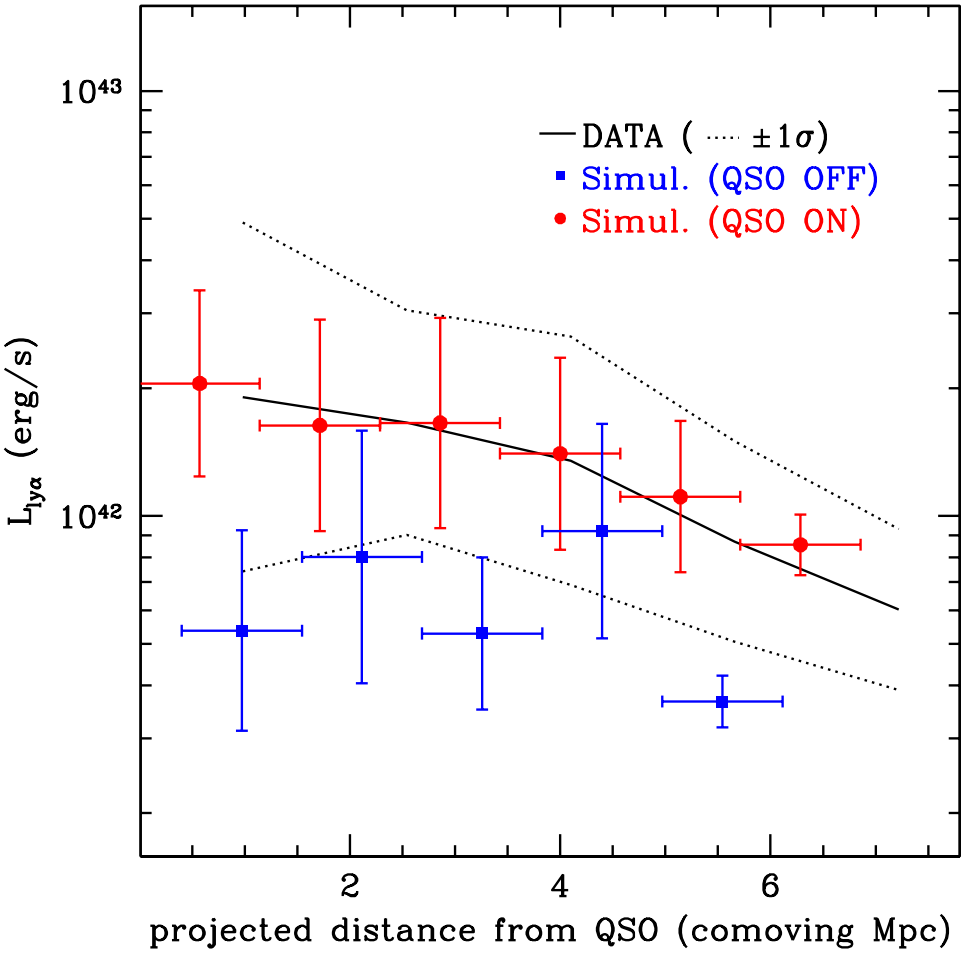
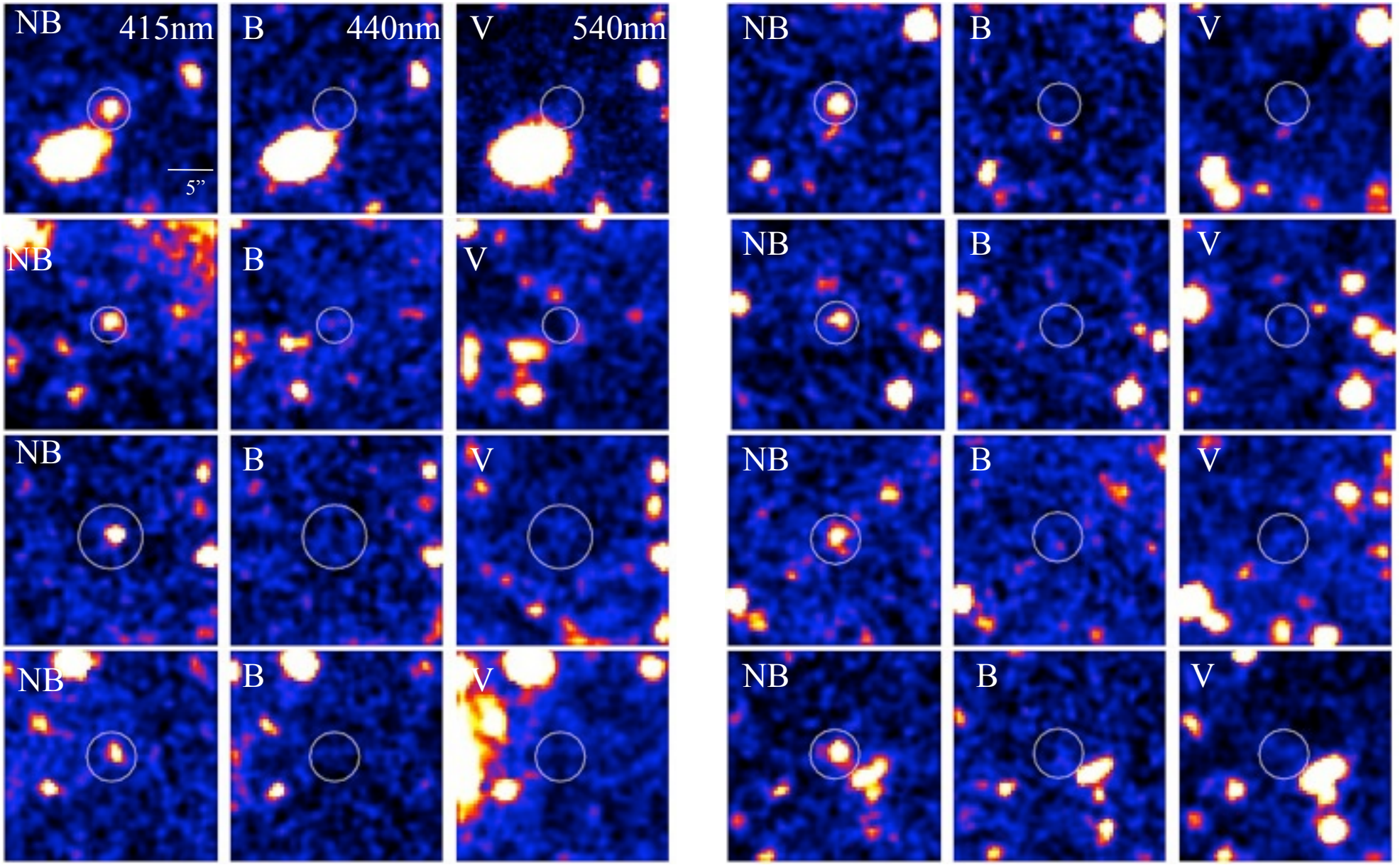
Additional evidence for Fluorescence (2): Luminosity vs distance from QSO



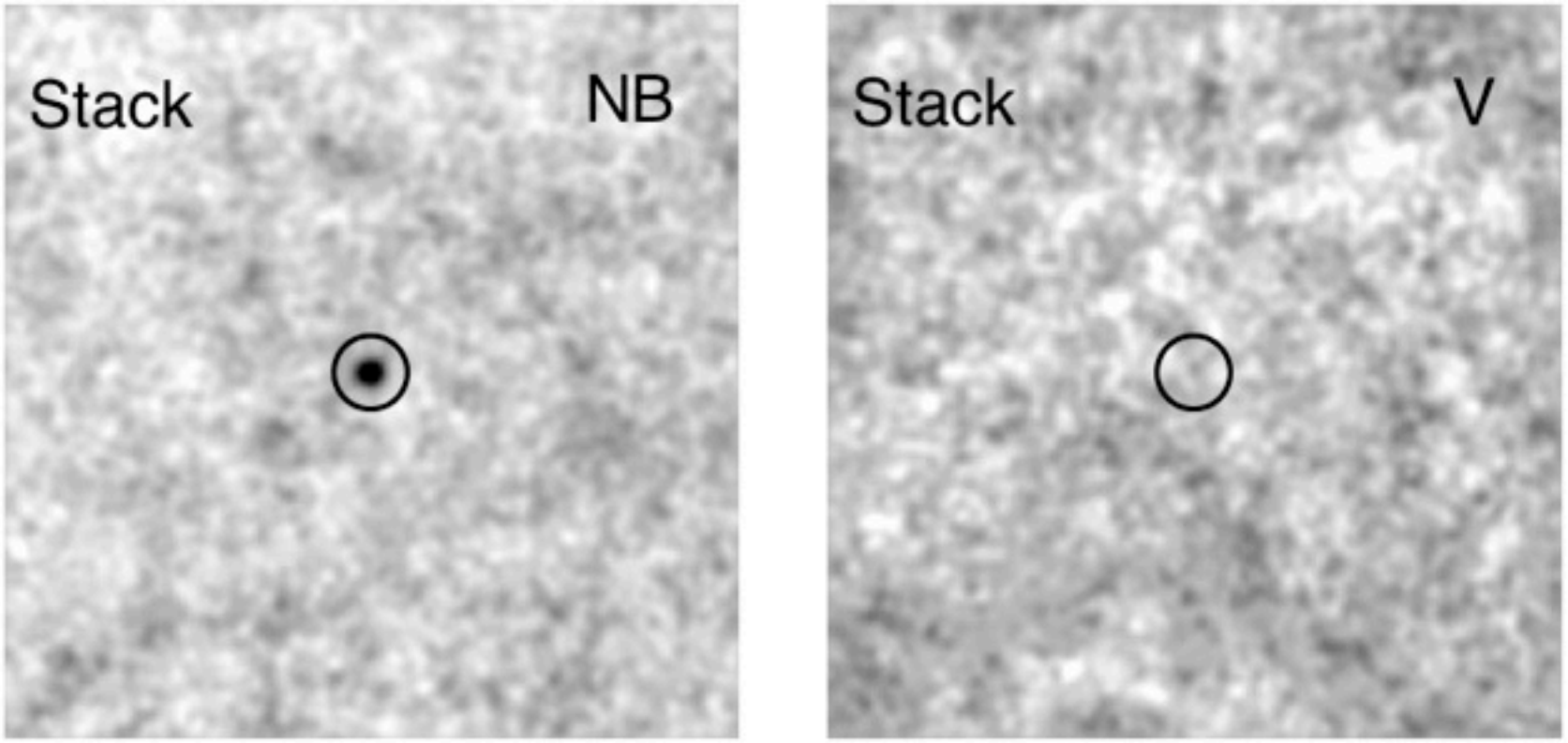


A selection of candidates for Dark Galaxies (EW>>240A and no continuum)

Cantalupo+12



Stack of the high EW objects (EW>240A)



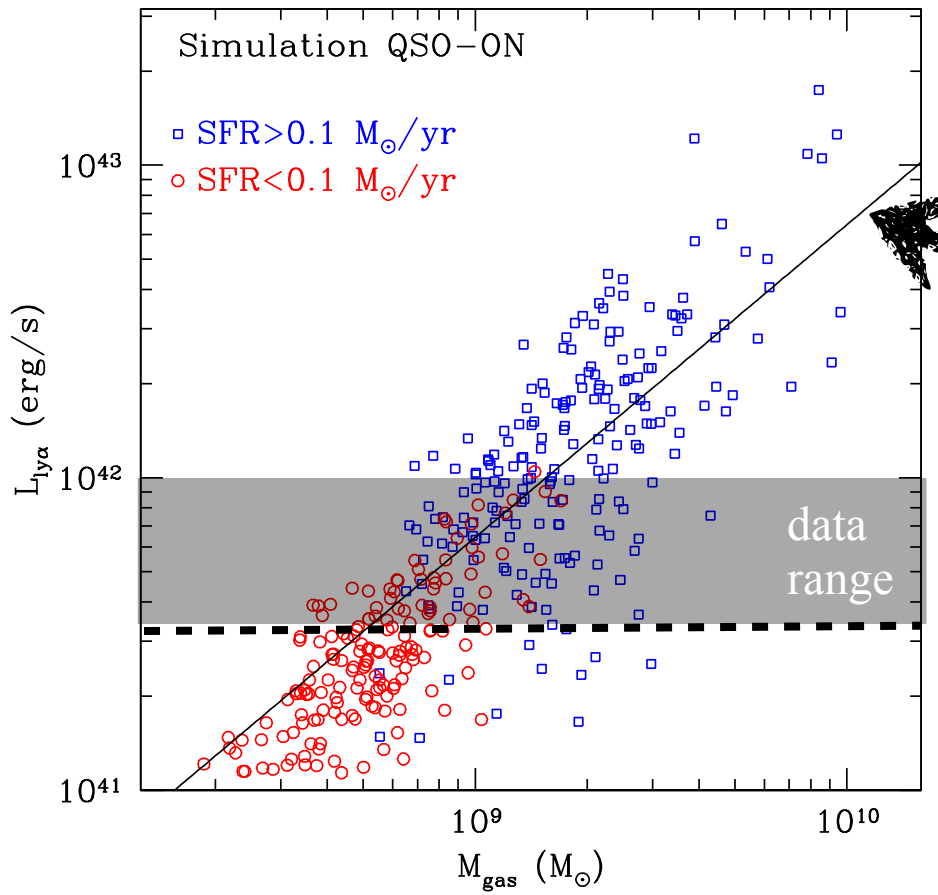
Combined constraint: EW>800A (1σ)

Note: sources are spatially unresolved: d<0.7" (~5 pKpc at z=2.4)

Cantalupo+12

Inferring the Mass and Star Formation Efficiency (1)

Since $L_{\rm lya} = \chi_e \alpha^{\rm eff}_{\rm lya}(T) h\nu_{\rm lya} \int_V n^2_{\rm HII} dV$ (HII recombinations only and no star formation)

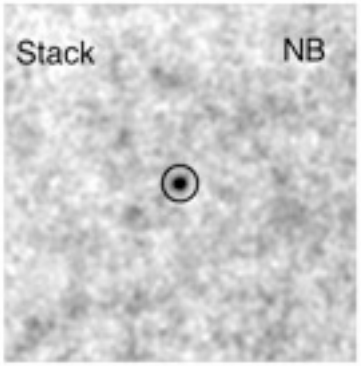


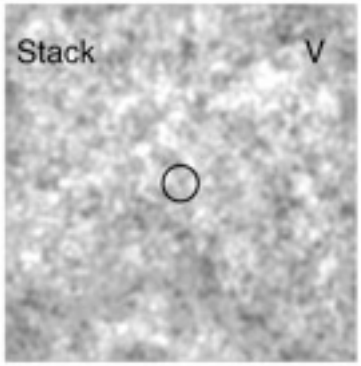
then for a fully ionized cloud:

$$M_{\rm gas} \sim 1.4 \times 10^9 M_\odot \left[\frac{L_{\rm lya}}{10^{42} {\rm erg\ s^{-1}}}\right] \left[\frac{T}{2 \times 10^4 K}\right] \cdot C^{-1}$$

Consistently with hydro + full RT simulation.

➡ Inferred (cold) Gas Mass: ~10^9 M_{sun}
(or larger if clouds are partially ionized)





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!**)

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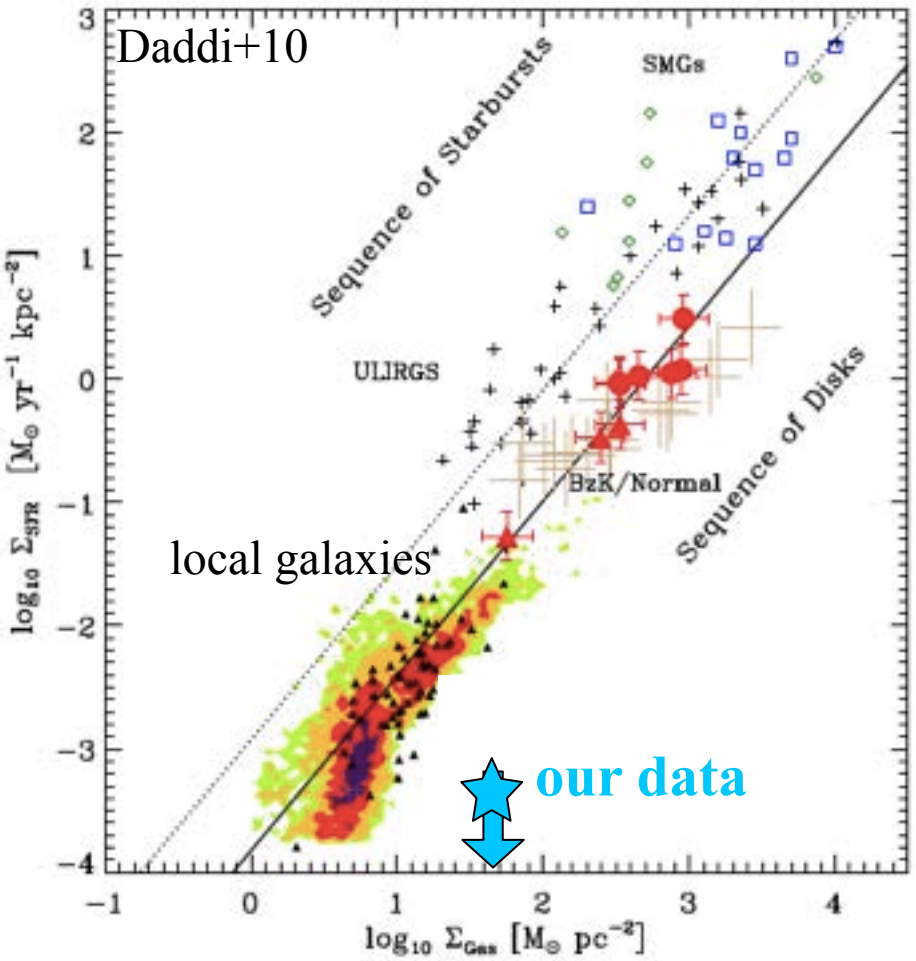
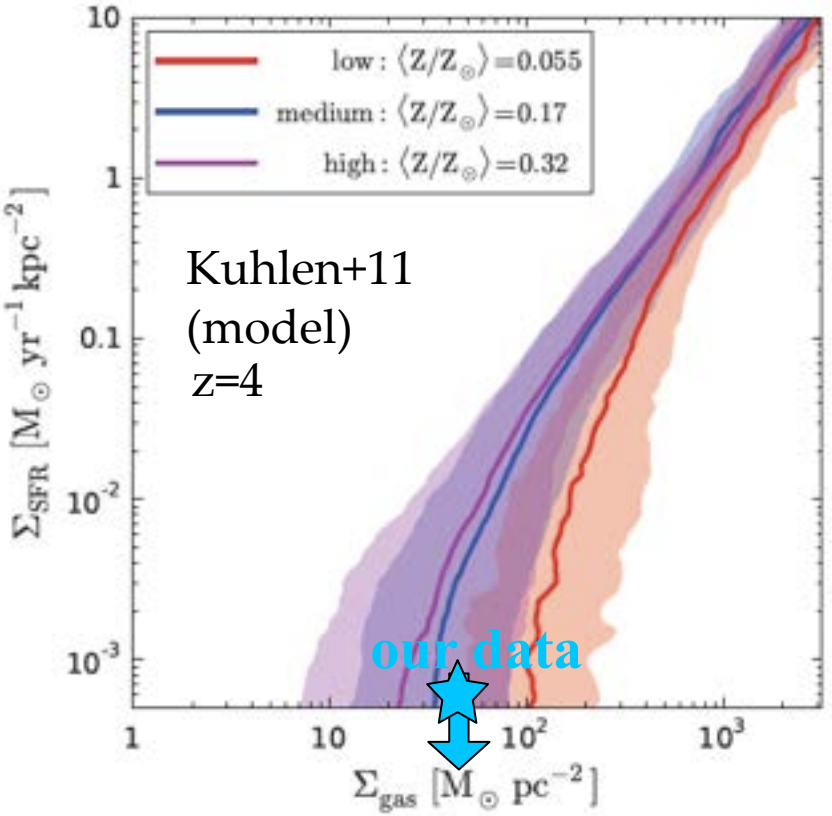
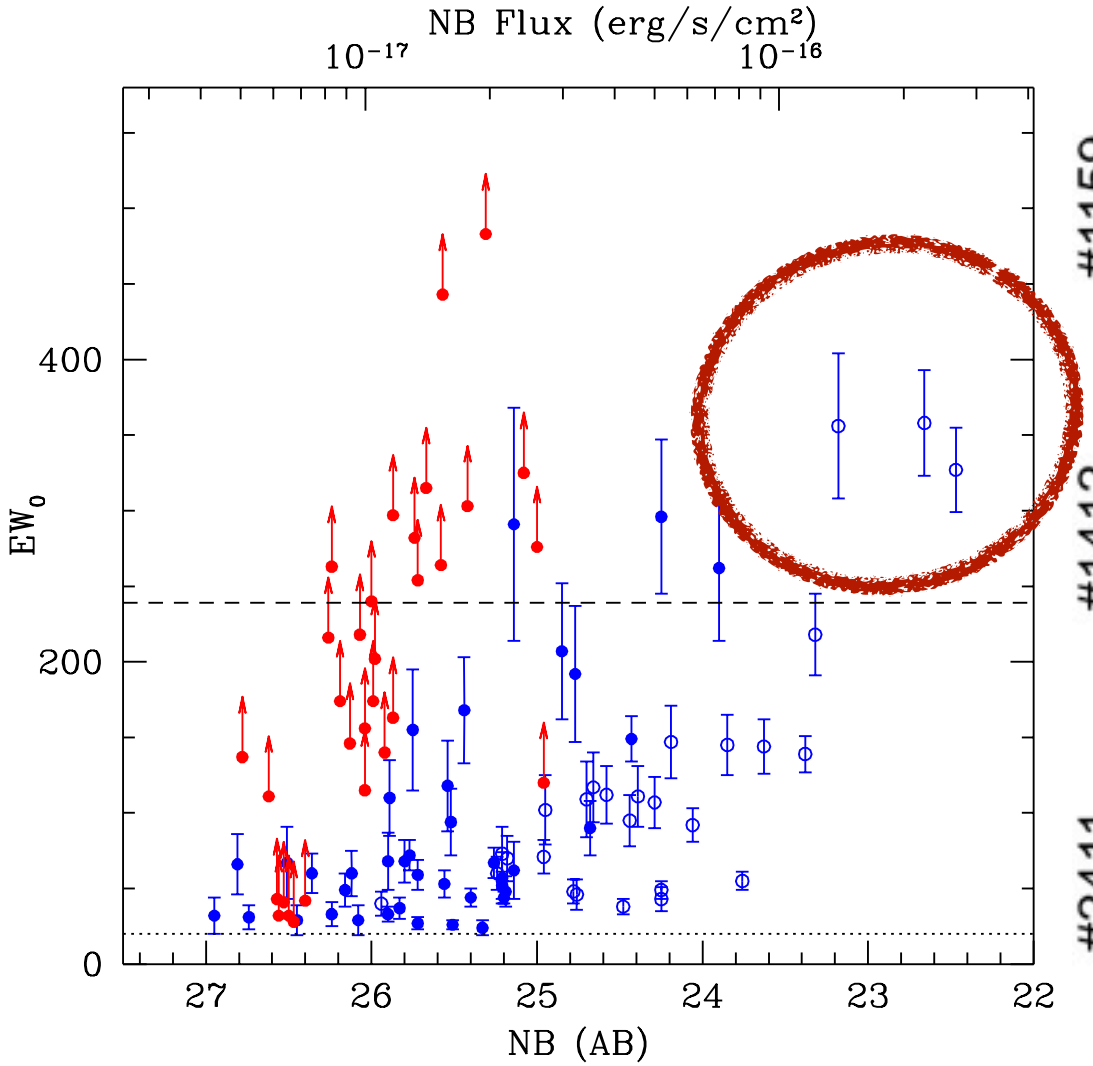
Where are they on the Kennicutt-Schmidt relation?

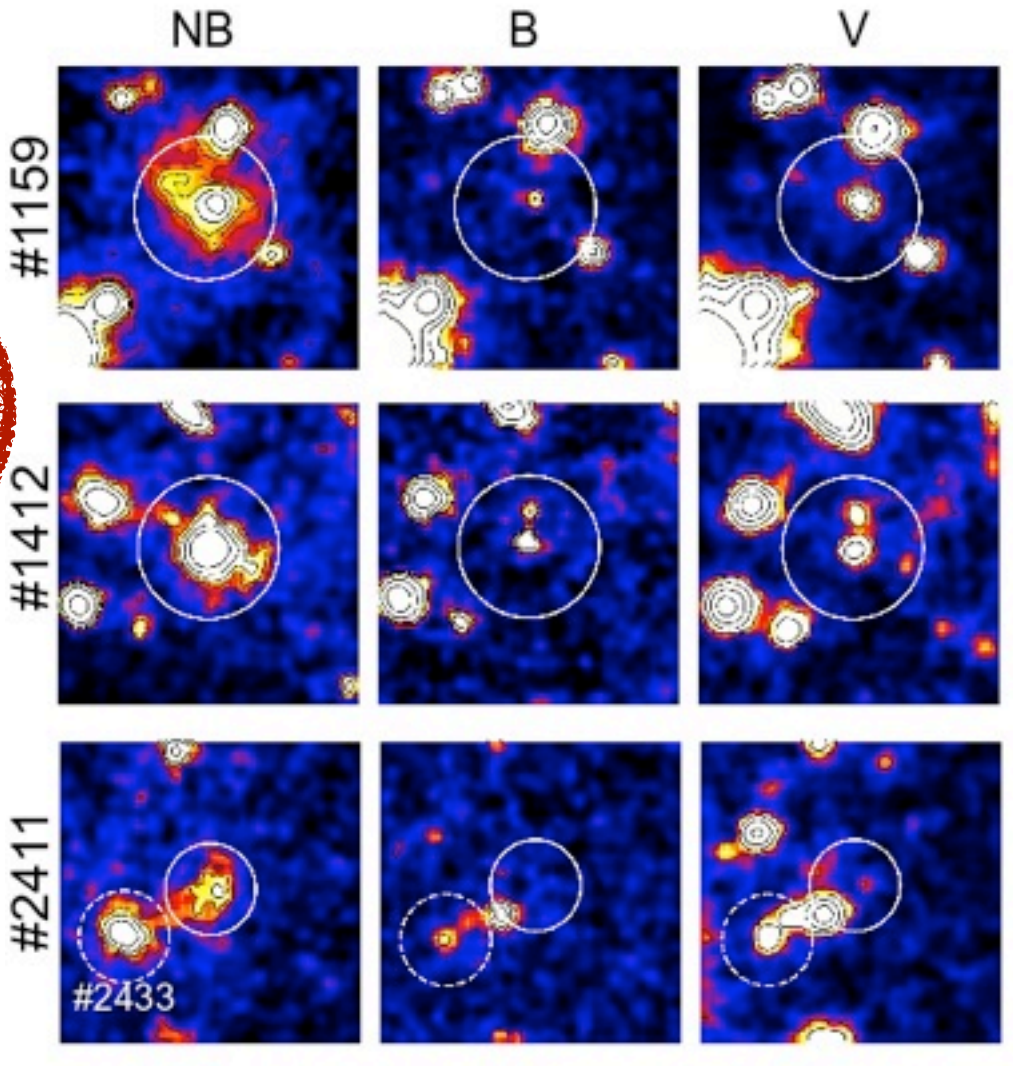




Cantalupo+12

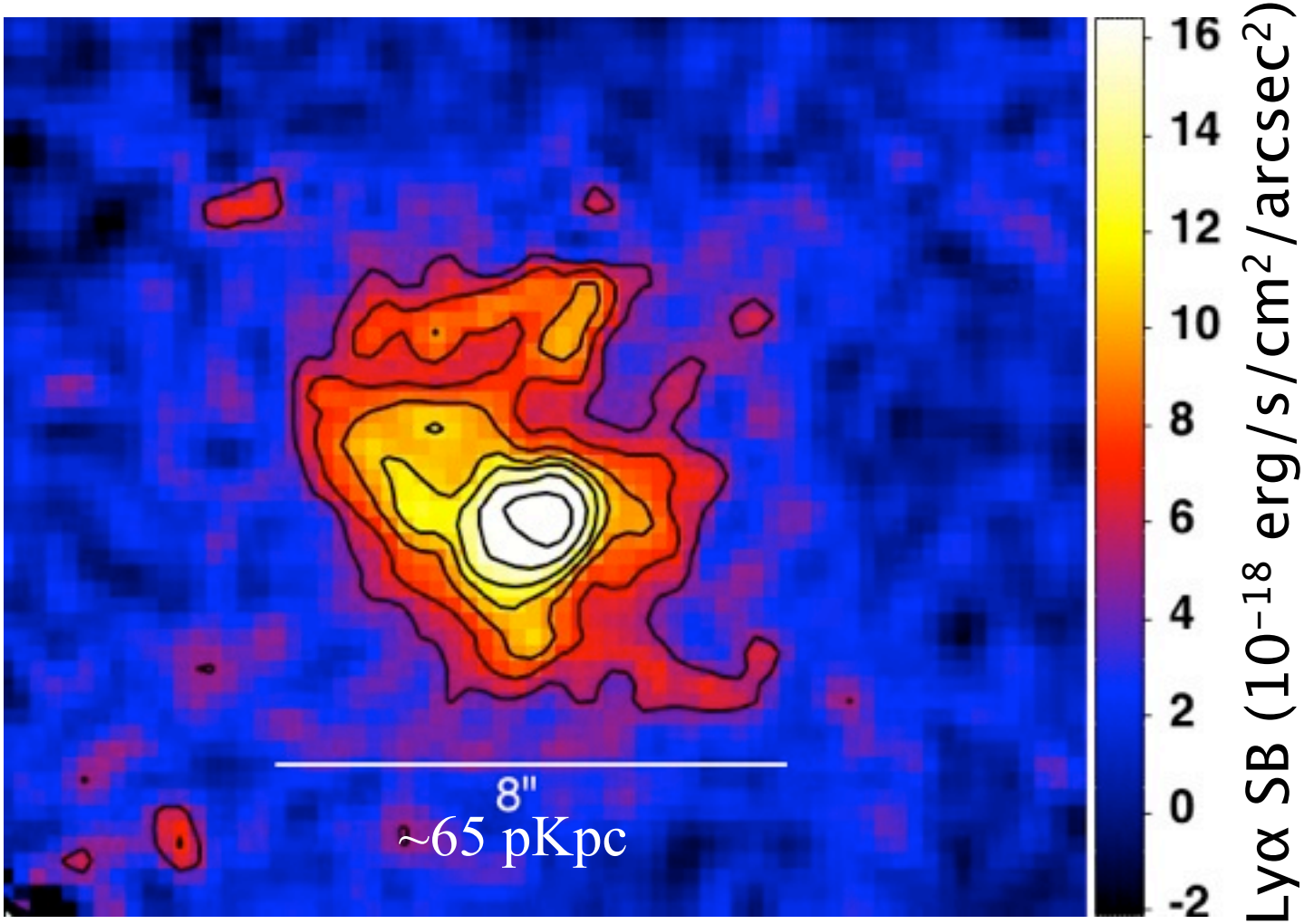
Extended objects with EW>240 and continuum





Cantalupo+12

The CGM in Ly-alpha emission: "streams" around #1159?



Continuum-subtracted NB image

(QSO is 3' away)

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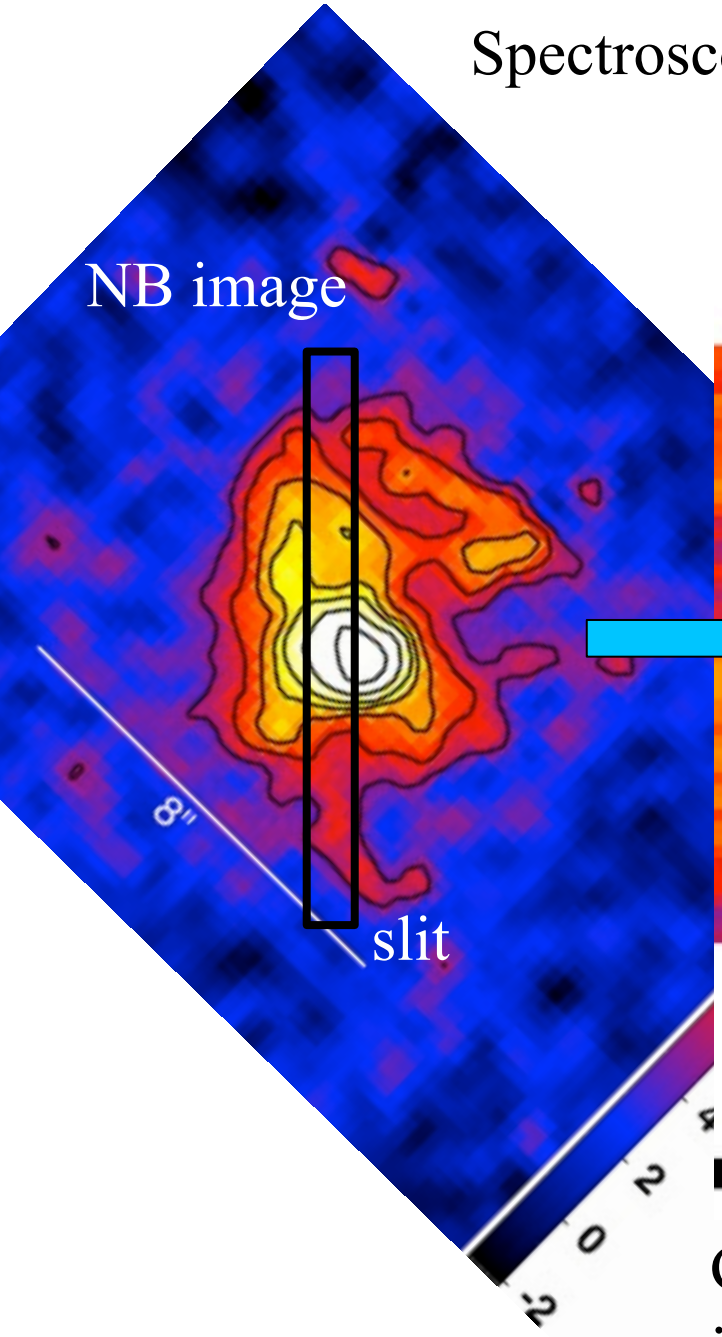
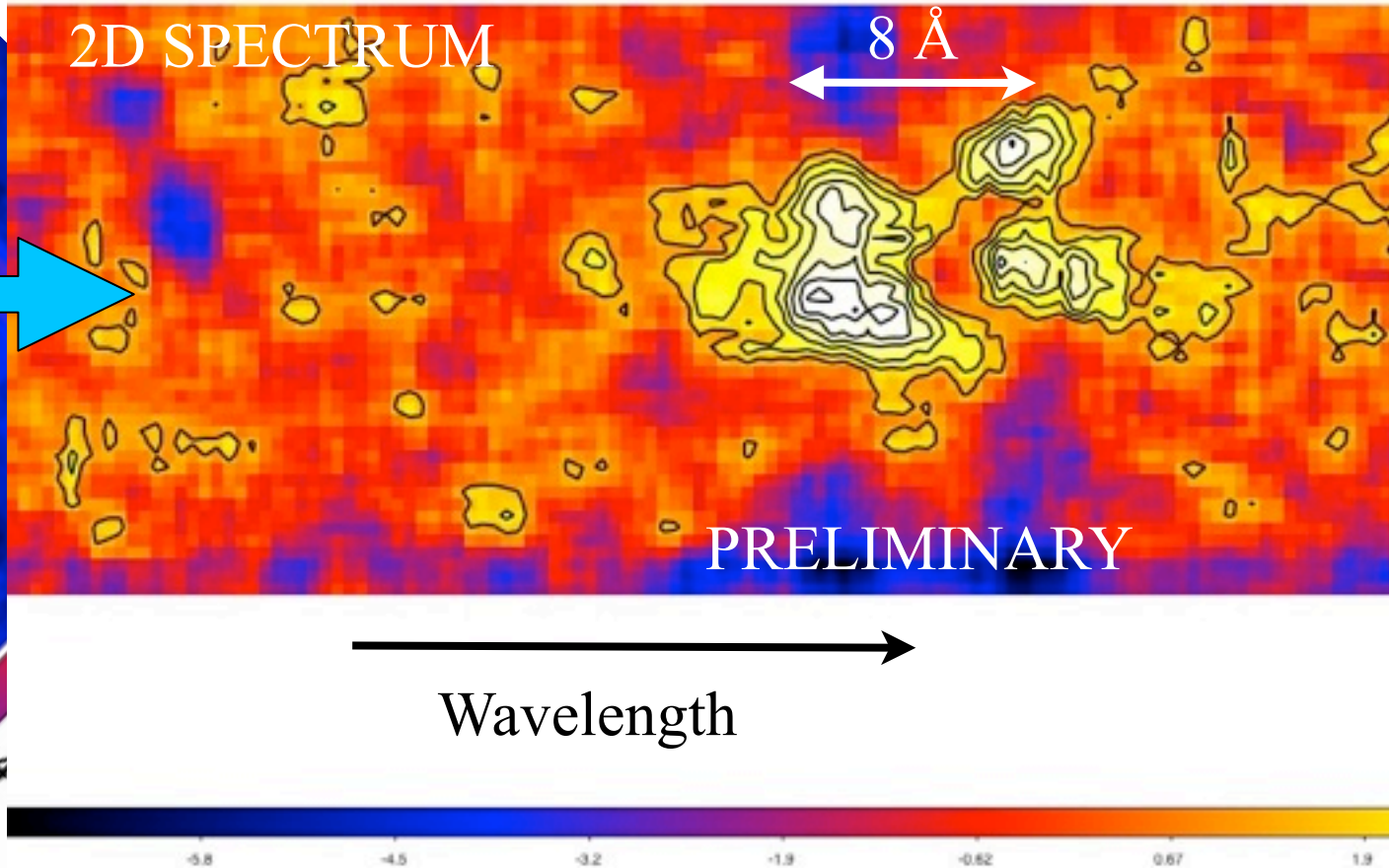
Spectroscopic follow-up @ VLT-FORS (Oct 2012)





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

Cantalupo+, in prep

Ongoing: Keck/GEMINI Fluorescence Survey [~150h]

- targets: ~15 bright SDSS QSOs at z~2, custom-built NB filters (4)

- Data collected so far: 5 QSOs on Keck/LRIS
  1/5 QSOs on GMOS

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

First Keck/LRIS results (Nov 2012)

1) NB imaging of a bright, radio-quiet quasar @ z=2.3
   10h NB, 10h V-band (parallel)
   1h B, 1h R (parallel)

Cantalupo+, submitted

"Slug" Nebula

IMAGES EMBARGOED

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

"Calibration" from RT simulations:

"Scattering" case
(gas mostly neutral)

"Fluorescence" case
(gas mostly ionized)

"Slug" Nebula

$N(HI) \propto (SB/b^2)^2$

$N(HII) \propto (SB/C)^{0.5}$

IMAGES EMBARGOED

b=impact parameter, C=clumping factor

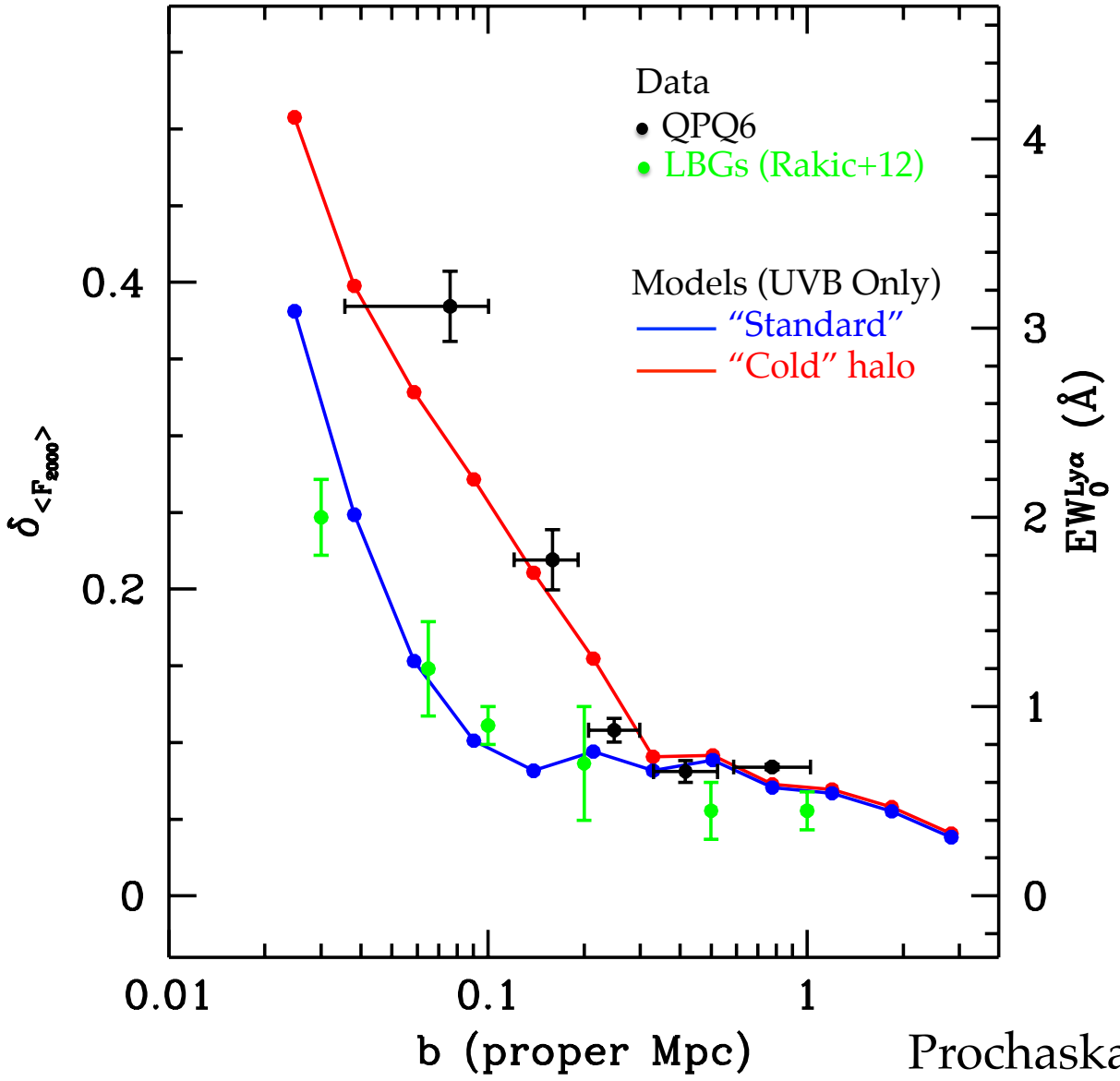
Is there “enough” gas in the simulation?

“Slug” Nebula

IMAGES EMBARGOED

Is there "enough" gas in the simulation?

Similar problem to reproduce gas absorption around quasars (with the same simulation).



Prochaska,...,SC+, ApJ in press

Summary

- New technique to "illuminate" dense gas at high-z with the help of QSOs from kpc to Mpc scales.

- "Fluorescent" dataset with:
  - Dark Galaxy candidates (12)
    Inferred Gas Mass: ~10^9 M_{sun} (if mostly ionized by the QSO).
    SF efficiency: <10^{-11} yr^{-1} (gas consumption rate >100 Gyr)
  - Cold, dense Circum-Galactic Medium in emission
    morphology and size compatible with "cold filaments"

- Ongoing deep survey around several QSOs (Keck & Gemini; goal:~15 QSOs)

- First possible image of the "Cosmic Web": Slug Nebula. Largest (500-kpc) Ly-alpha nebula ever seen discovered around z=2.3 radio-quiet QSO.

- Extended emission is rare: 1 over 6 QSOs + 1 preselected from spectroscopy [so far]. Orientation/illumination effect?

- Comparison with "Cosmic Web" simulations: more cold/neutral gas than expected. Tension with models? Missing physics?