



A 3D View of Gas Emission around High-redshift Galaxies

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In collaboration with:

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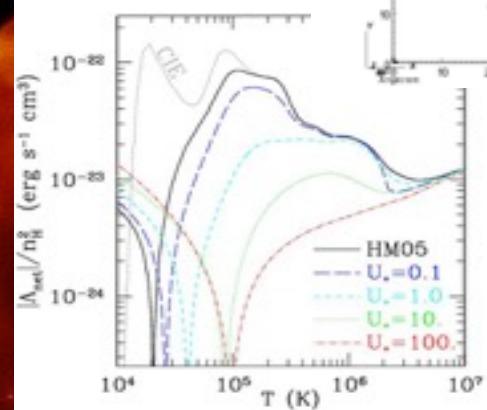
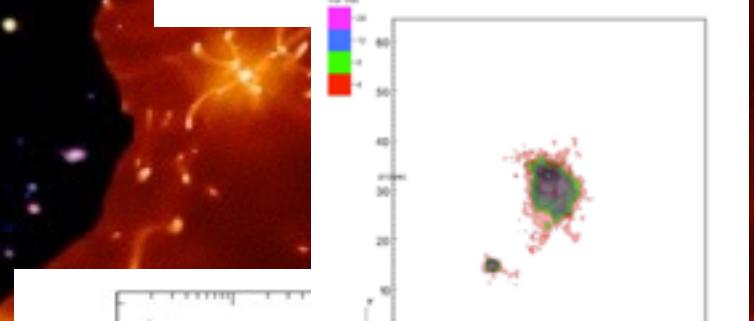
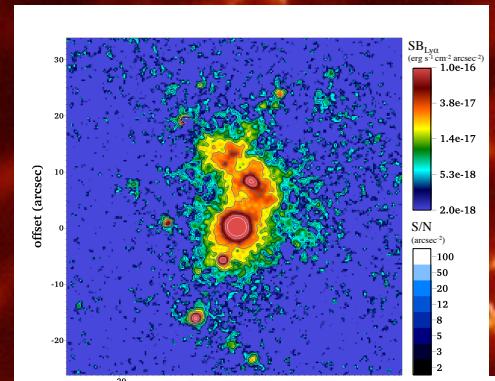
Introduction:
detecting the IGM in Emission

The Keck/Gemini NB
Survey (FLASHLIGHT)

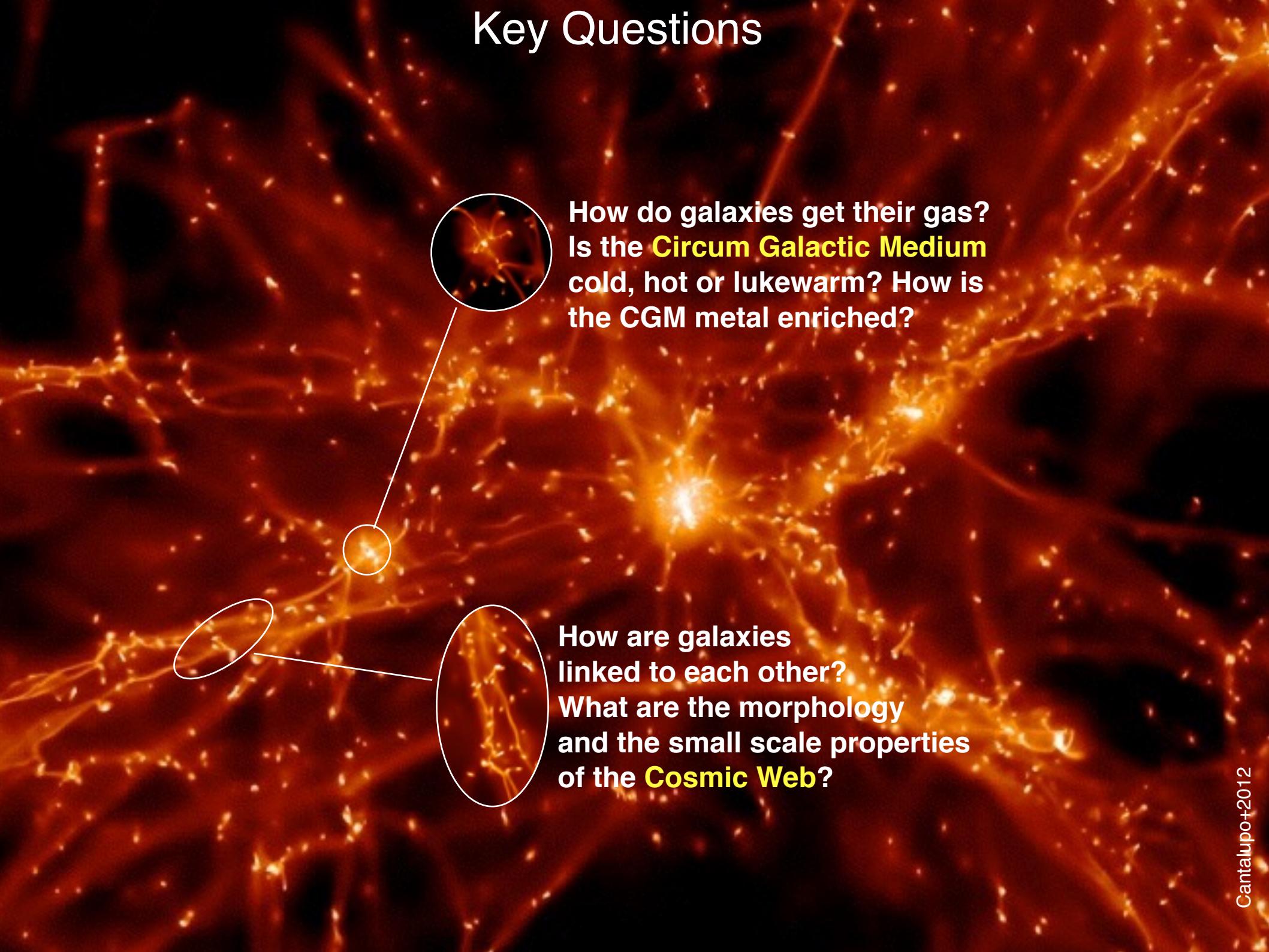
The IGM/CGM in 3D
with MUSE (GTO Survey)

Metals, gas cooling and
galaxy formation

Open questions/Summary



Key Questions



How do galaxies get their gas?
Is the **Circum Galactic Medium**
cold, hot or lukewarm? How is
the CGM metal enriched?

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

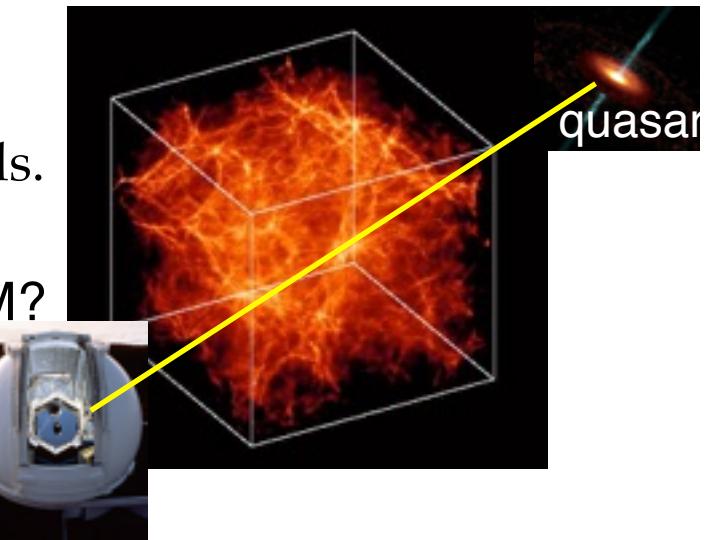
Detecting Cosmic Gas

“Classical” approach: in absorption.

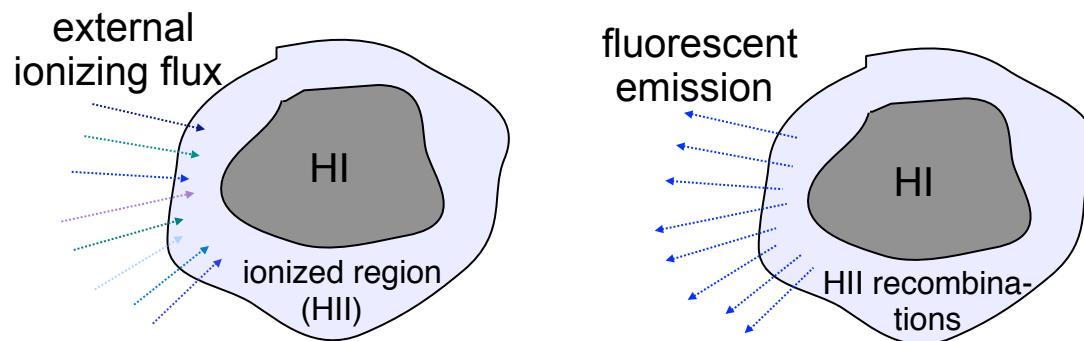
- pro: ability to detect low-density gas including metals.
- con: typically **only 1D** information (or sparse 2D)

LLS/DLAS = “Dark” galaxies? Filaments? IGM? CGM?

... difficult to say without direct detection.



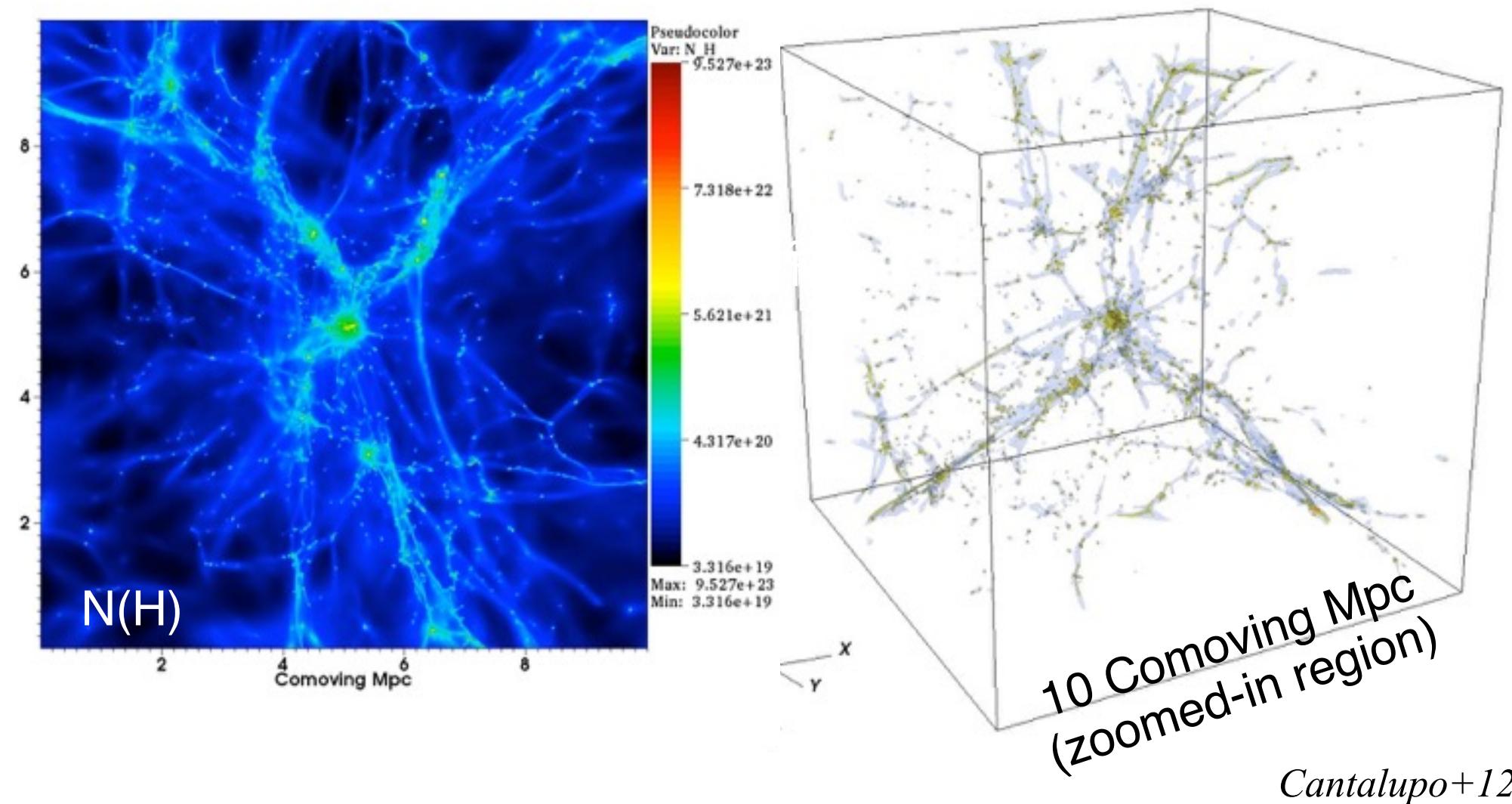
Direct detection in emission: Fluorescent Ly α (Hogan & Weymann 1987; Gould & Weinberg 1996; Zheng & Miralda-Escude 2005; Cantalupo+05,07; Kollmeier+08, Cantalupo+12)



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

How bright is fluorescent emission: simulations

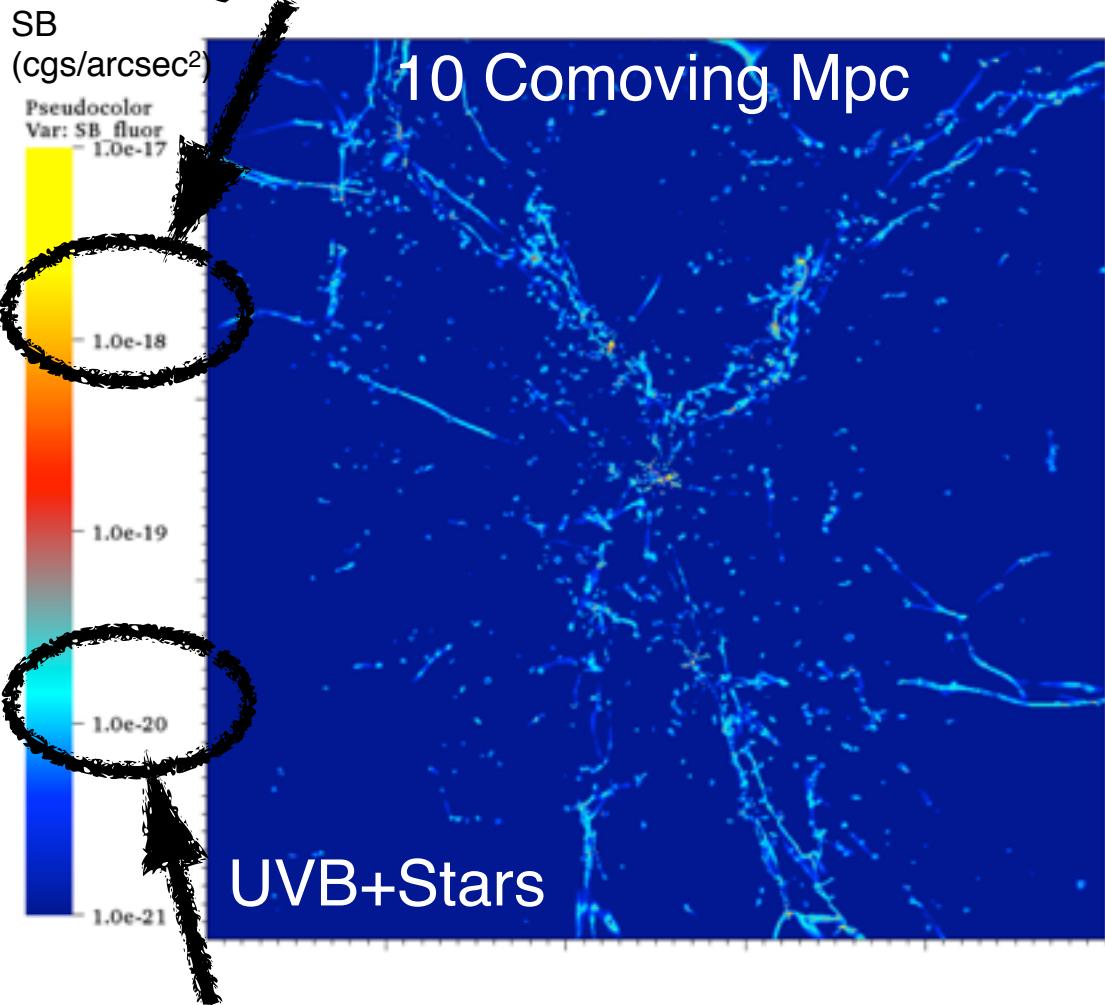
- 40Mpc³ (10Mpc³ high-res) hydro-simulation (RAMSES) around $3 \times 10^{12} M_{\text{sun}}$ halo at z=2.5
- Star formation, SN feedback, on the fly UVB **Self-shielding**.
- Post-processed with 3D Radiative Transfer Code **RADAMESH** (Cantalupo & Porciani 2011) for ionizing and Ly α radiation.



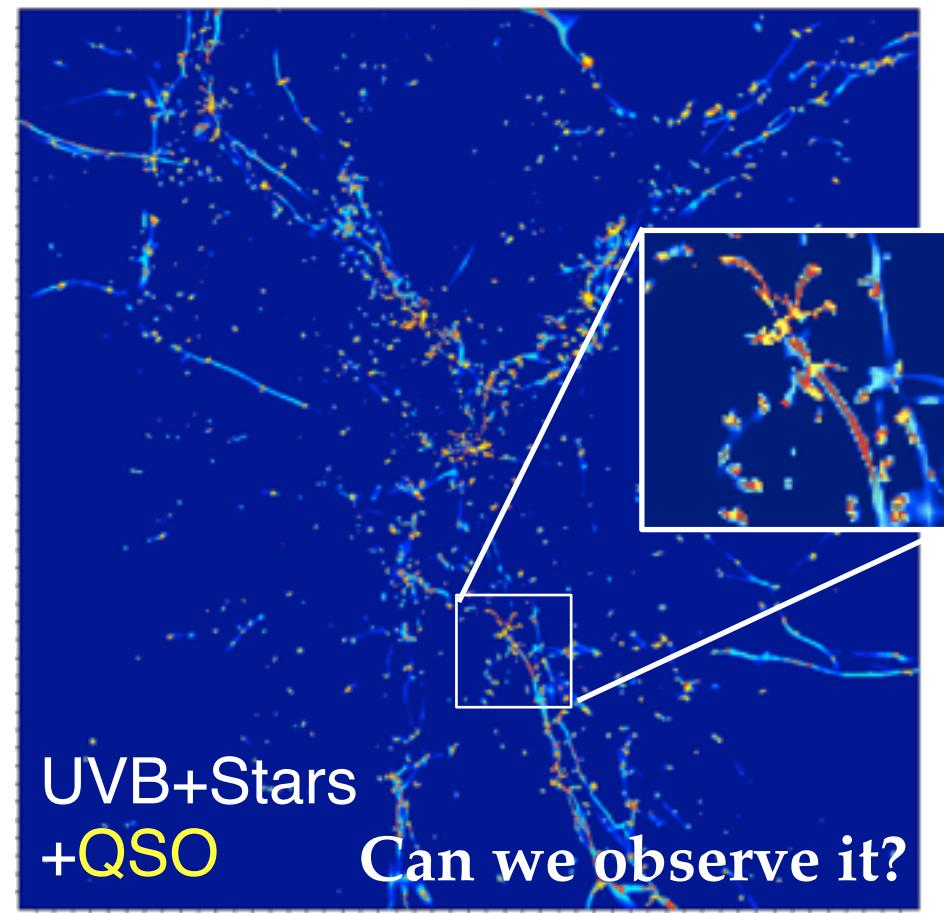
How bright is fluorescent emission: simulations

Simulated Ly α images

QSO fluorescence



UVB fluorescence



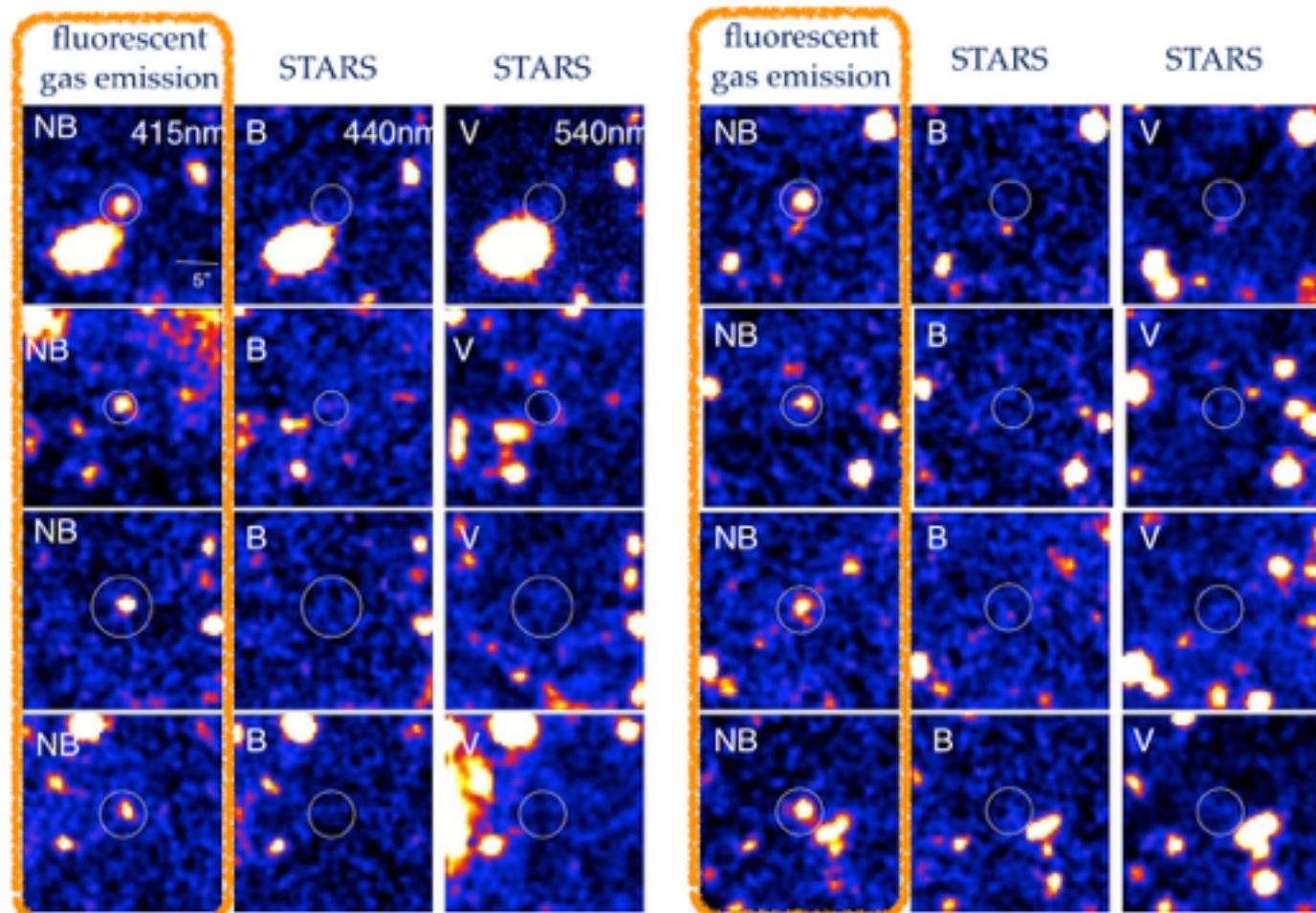
Very Large Telescope (VLT) Pilot Survey

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

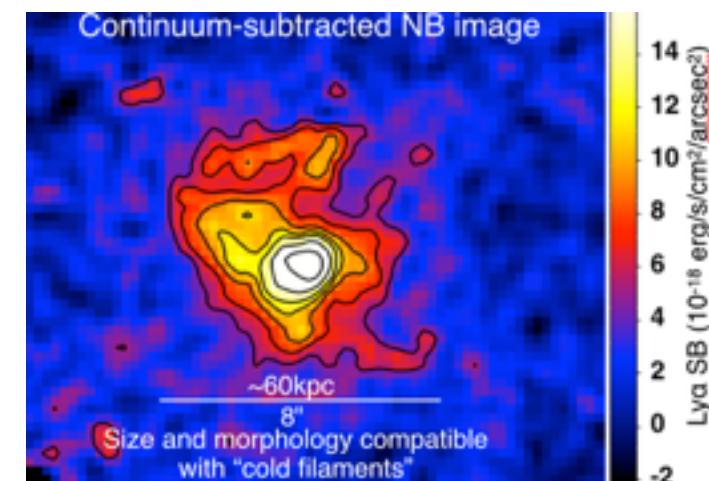
- Custom-built filter (FWHM=4nm) using QSO systemic redshift (OIII line)
- Deepest NB ever taken at VLT: 21 hours (+6h V-band, +1h B-band)
- NB flux limit: $\sim 4 \times 10^{-18}$ erg/s/cm² [5 σ for 1 arcsec² aperture]



Results: “Dark Galaxies”

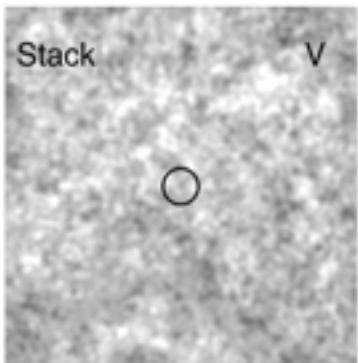
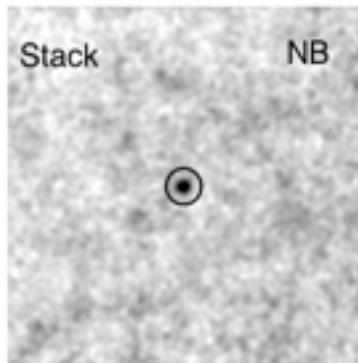


CGM in emission



Cantalupo, Lilly & Haehnelt 2012

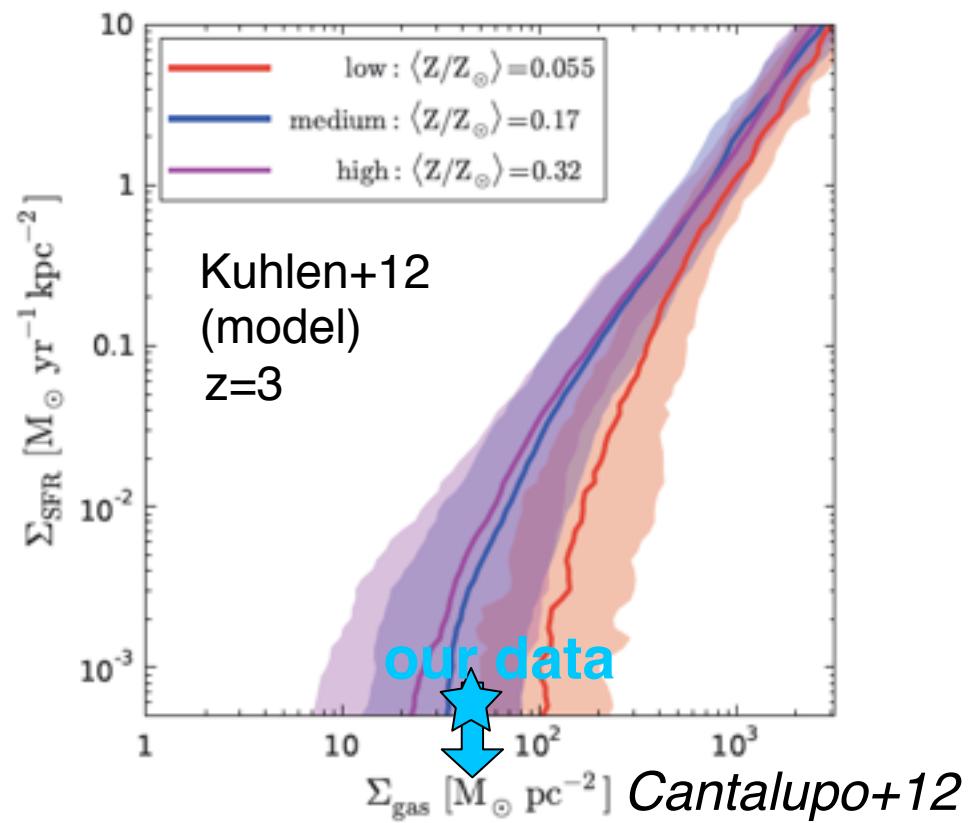
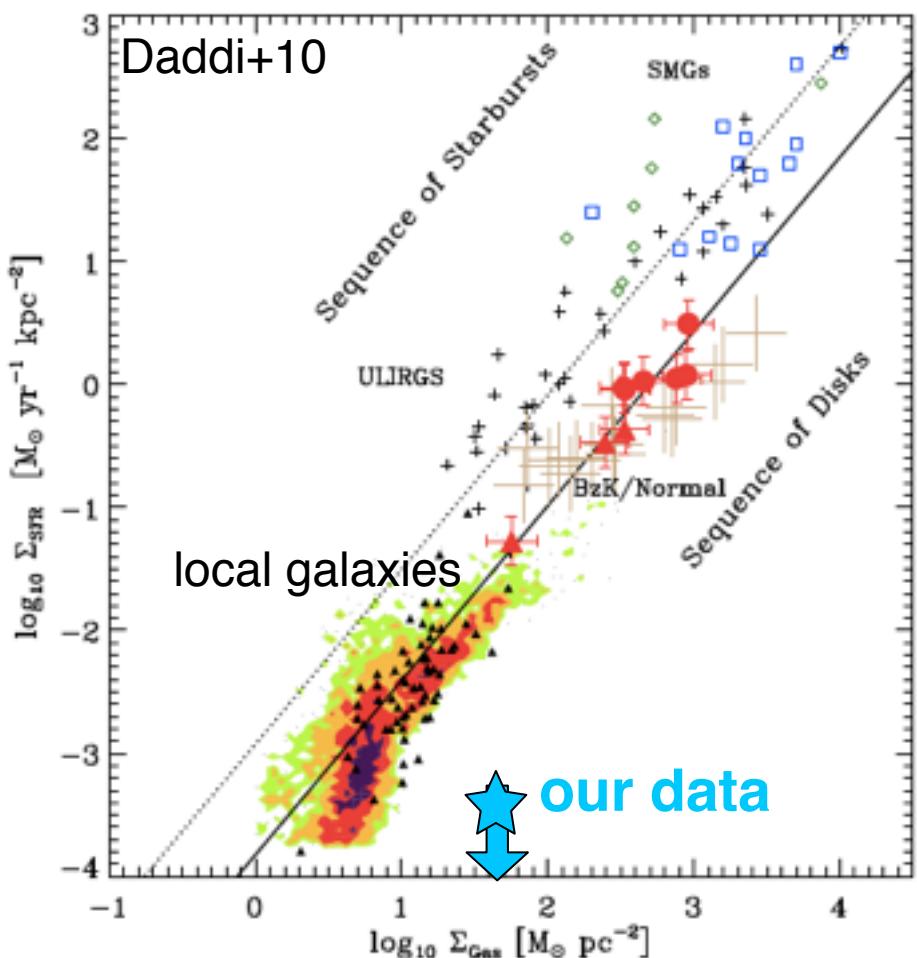
Dark Galaxies: Gas Mass and Star Formation Efficiency



from NB: Inferred (cold) **Gas Mass: $\sim 10^9 M_{\odot}$**
from V-band Stack: **SFR < $0.01 M_{\odot}/\text{yr}$**

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

Where are they on the
Kennicutt-Schmidt relation?



Ongoing Fluorescence Surveys [~200h + MUSE GTO]

FLASHLIGHT: Keck ang Gemini NB survey [at $z \sim 2$] for Ly-alpha
(Cantalupo, Prochaska, Arrigoni-Battaia, Hennawi, Madau)

- targets: 26 bright SDSS QSOs at $z \sim 2$, 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



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

MILES3D: MUSE Intergalactic Line Emission Survey in 3D at [$z \sim 3$] (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
8 QSO snapshot fields (1h)

IFU survey: Ly-alpha + metal emission



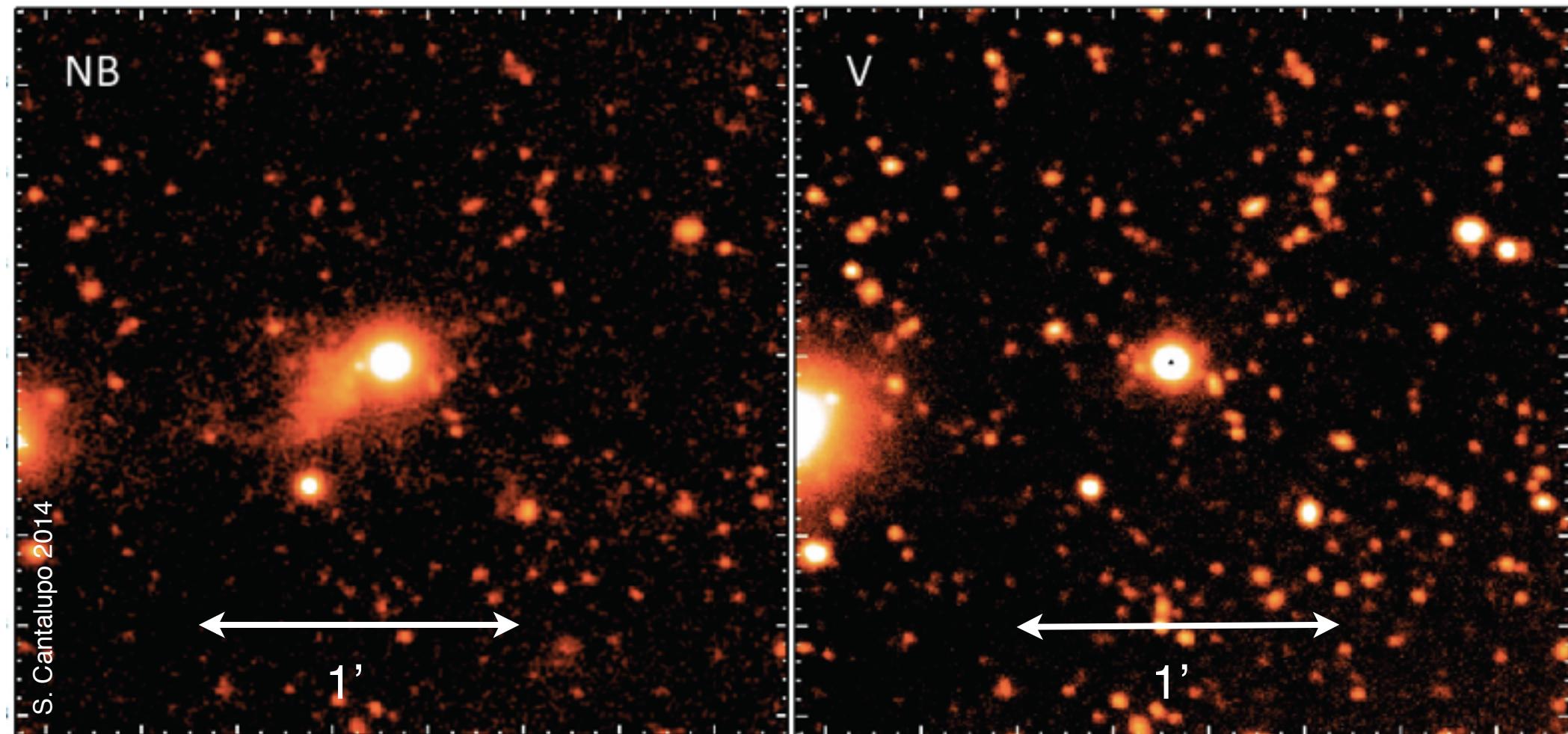
$$1\sigma \sim 1-3 \times 10^{-19} \text{ cgs/arcsec}^2 \text{ (deep)}$$

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

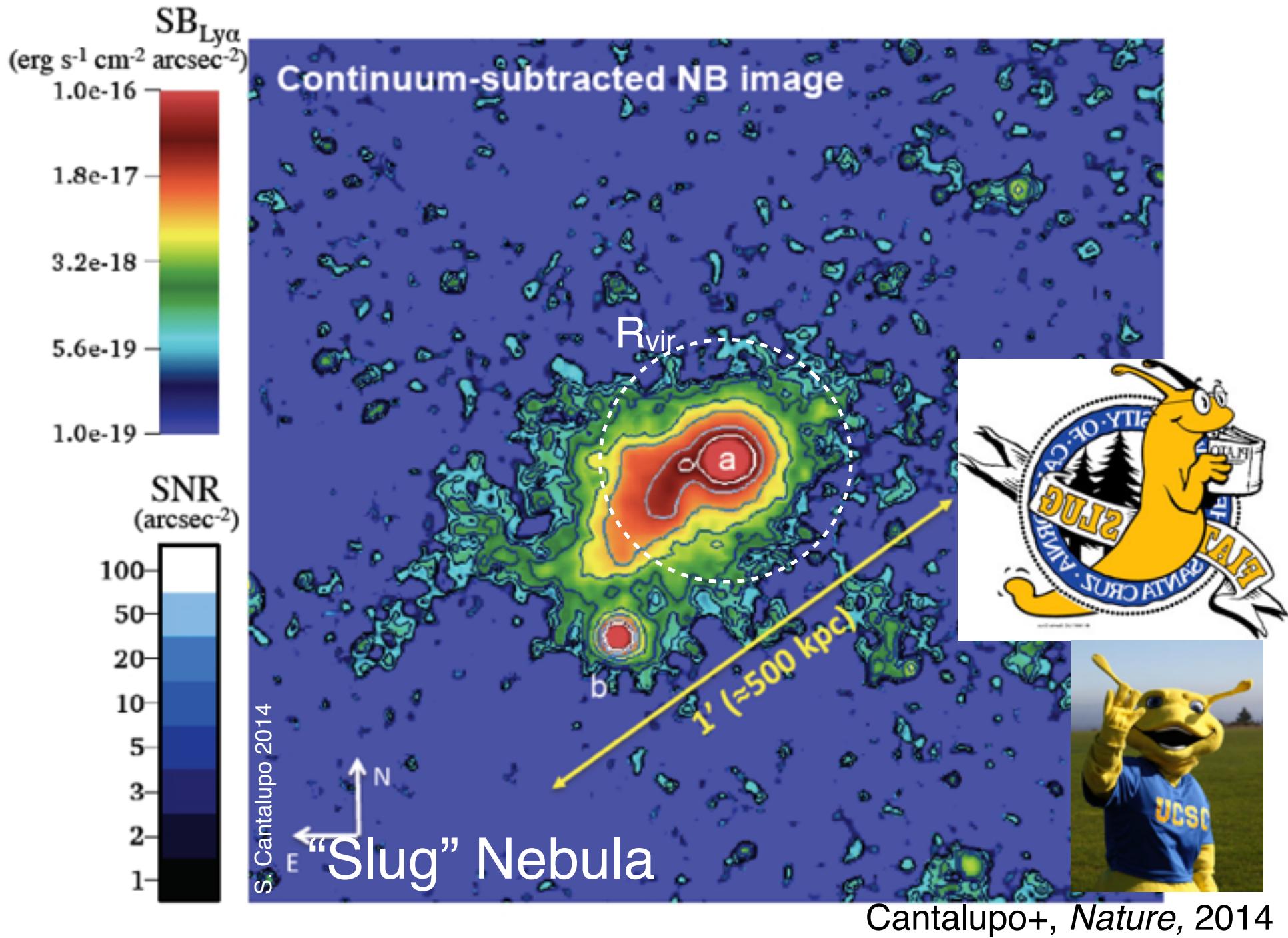
FLASHLIGHT: First Keck/LRIS results

- 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

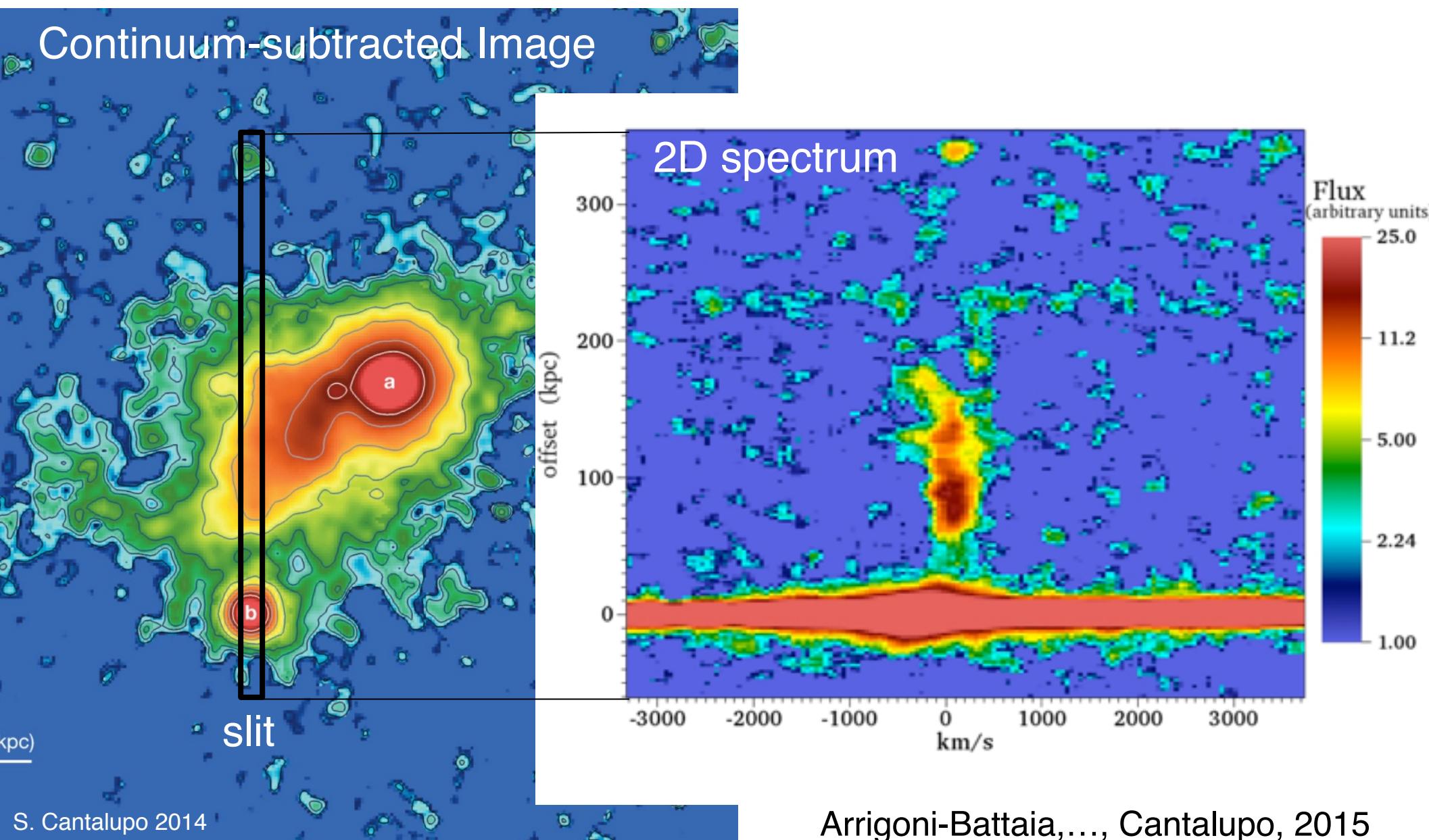


FLASHLIGHT: First Keck/LRIS results



Keck/LRIS Low-Resolution Spectroscopic Follow-up

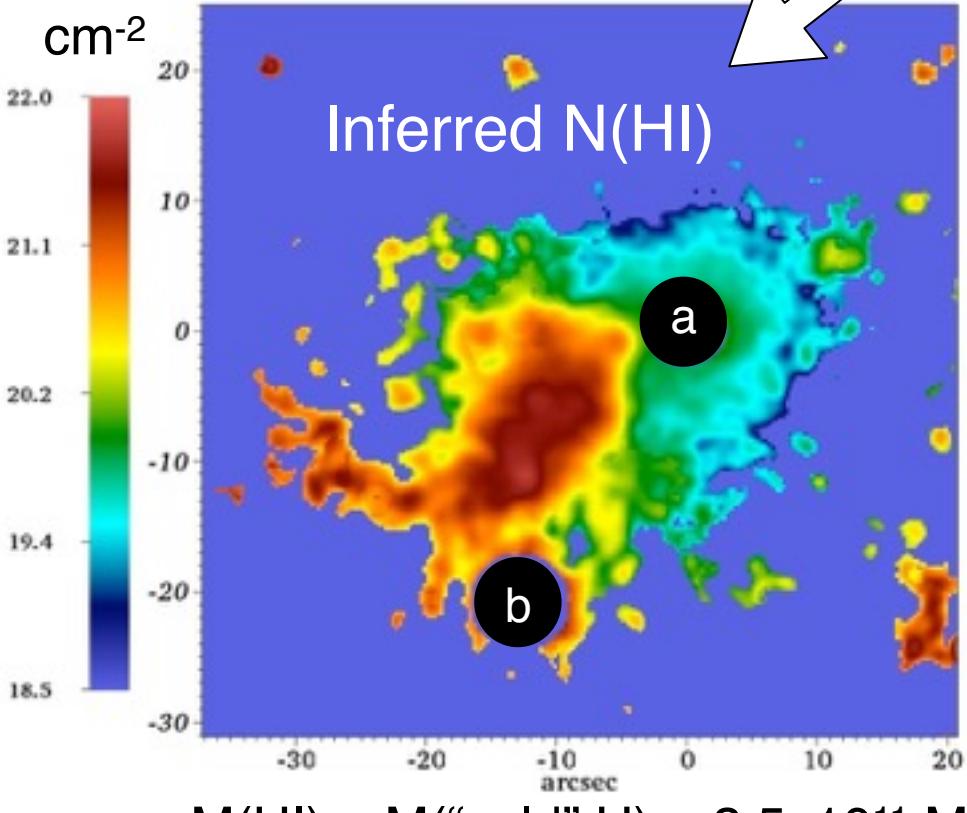
- kinematically “quiet”: FWHM<500km/s (vs. >1000km/s of RadioGalaxies!)



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

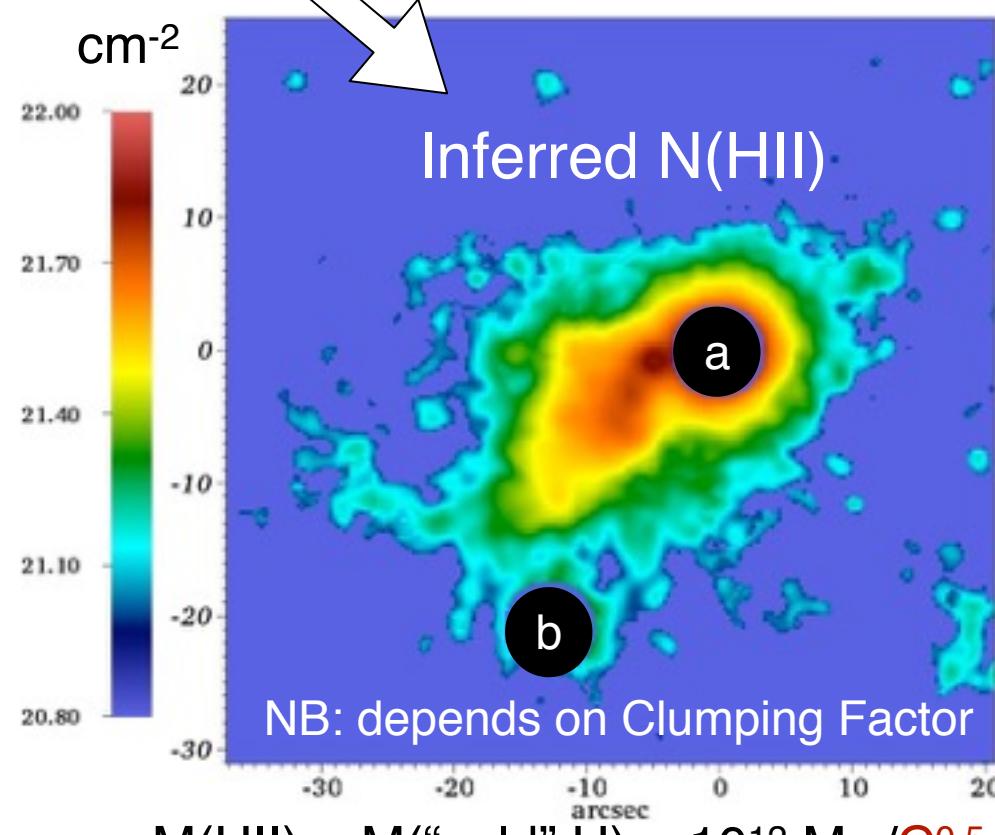
Cantalupo+, *Nature*, 2014

“Photon-pumping” case
(gas mostly neutral)



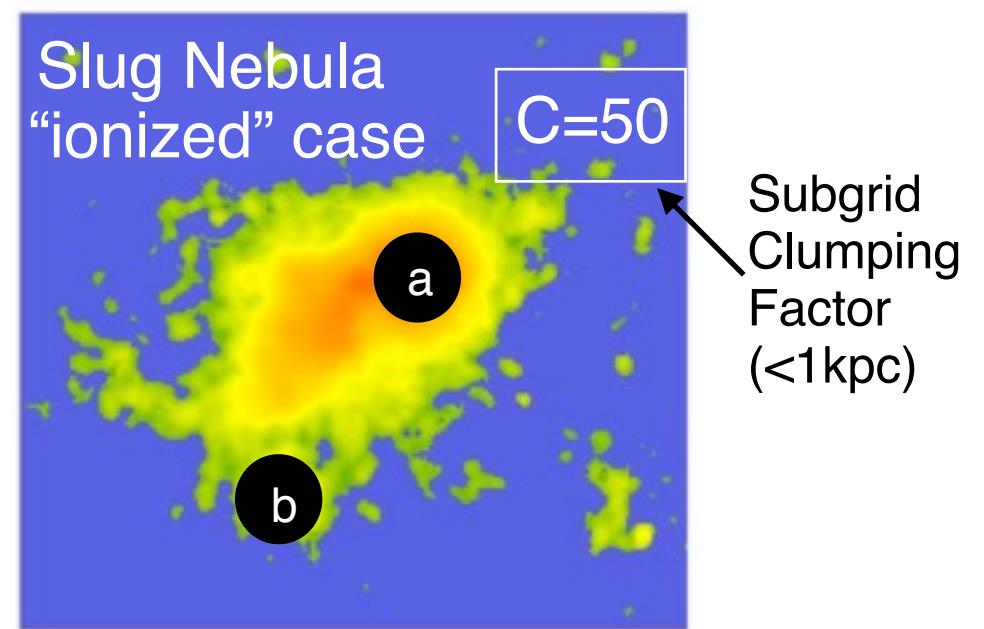
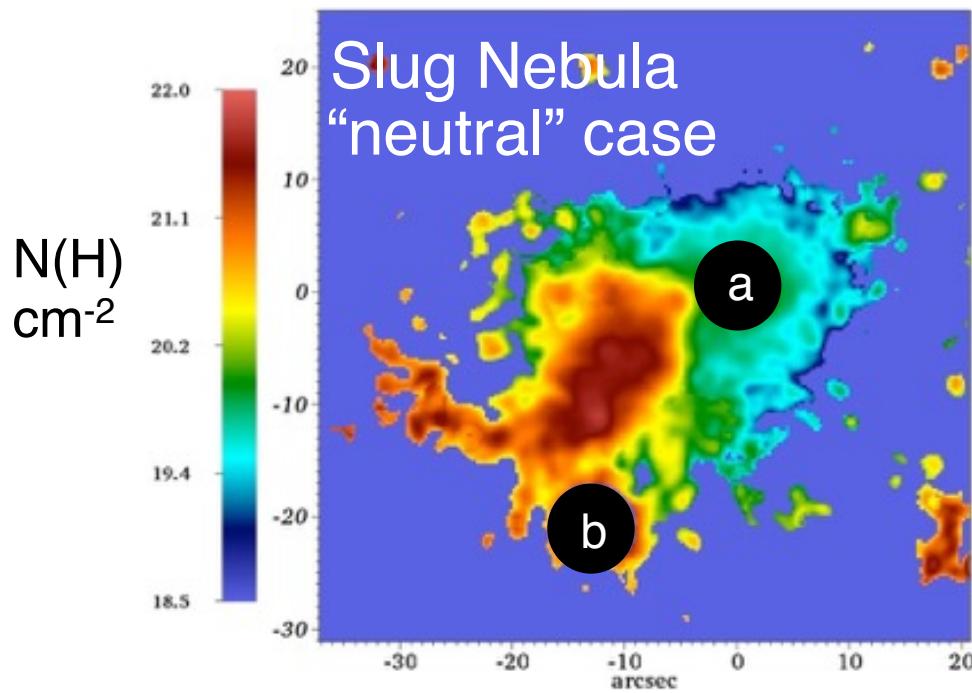
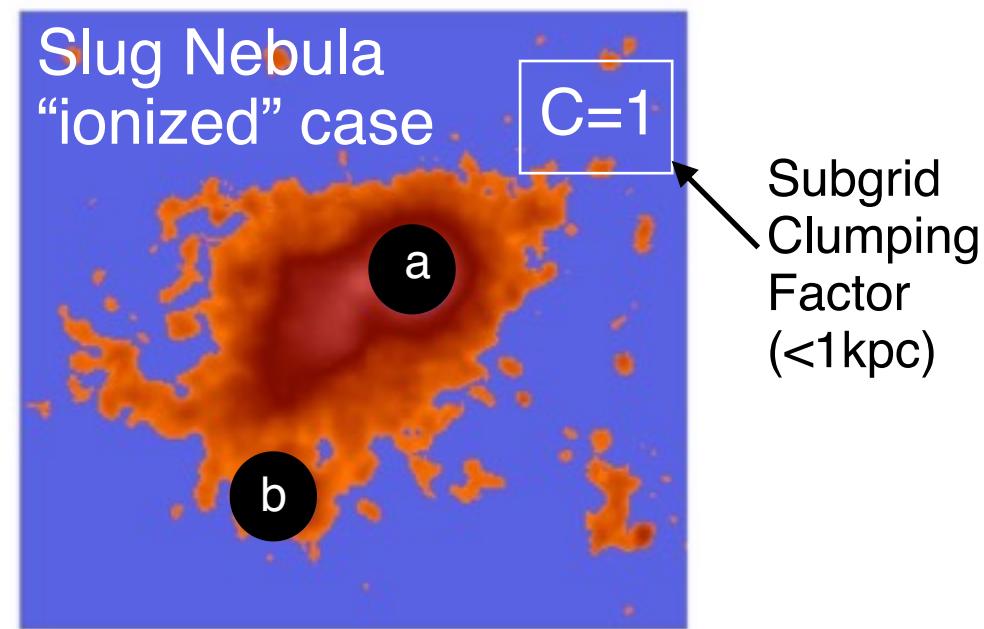
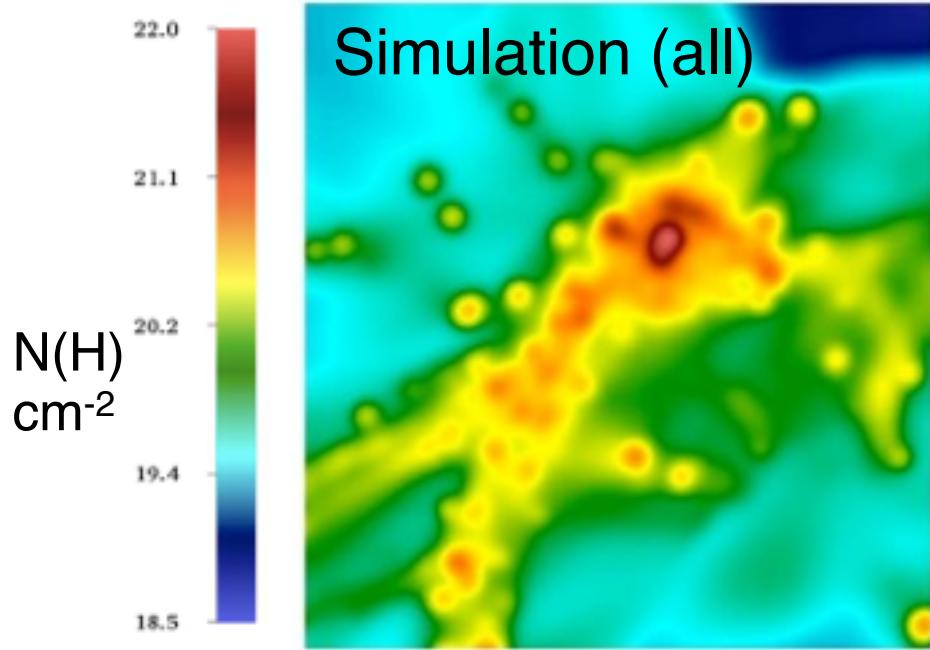
$$M(\text{HI}) \sim M(\text{“cold” H}) \sim 2.5 \times 10^{11} M_{\odot}$$

“Recombination” case
(gas mostly ionized)



$$M(\text{HII}) \sim M(\text{“cold” H}) \sim 10^{12} M_{\odot}/C^{0.5}$$

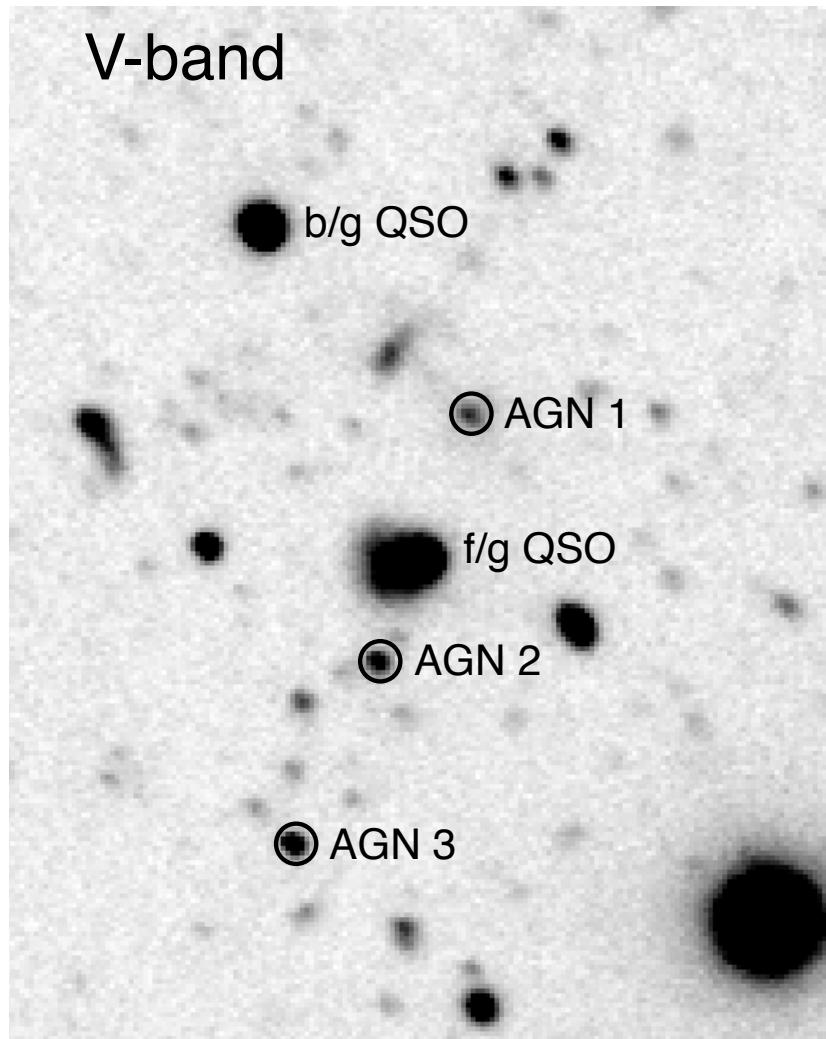
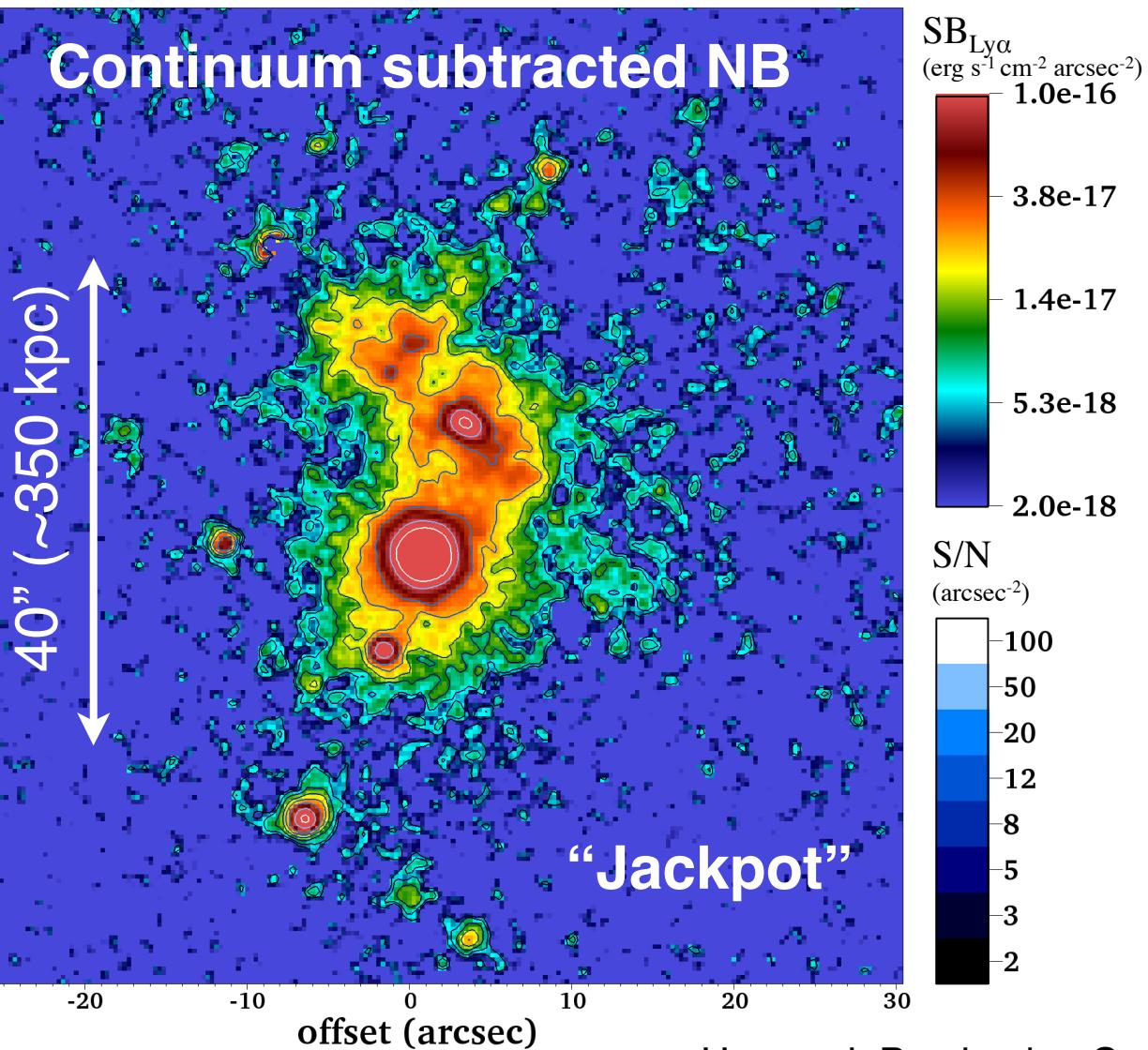
Comparison with simulations: more IGM “clumps” needed!



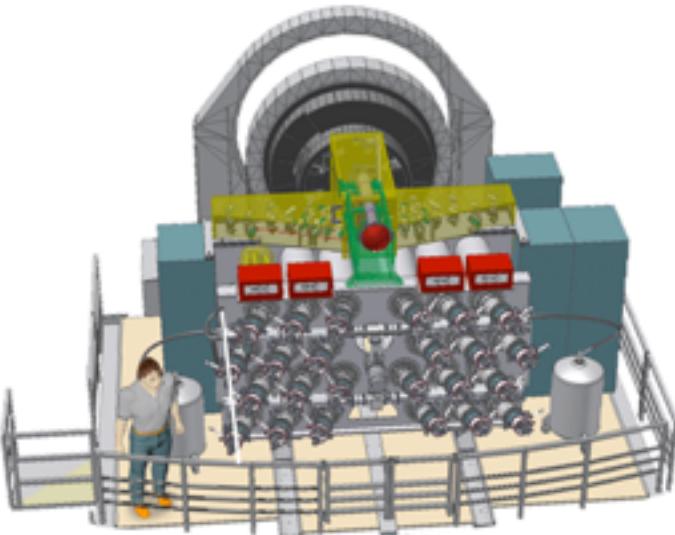
Cantalupo+, *Nature*, 2014

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

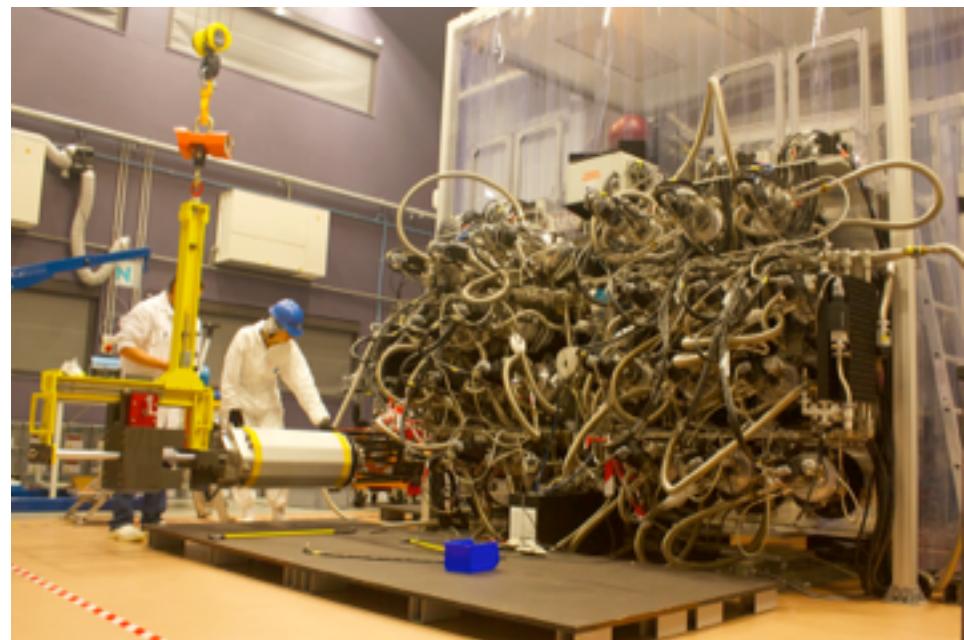


MUSE-VLT: Concept

- 1'x1' Integral Field Unit (image slicer)
- 24 Spectrographs
- 370 million pixels per exposure!
- 480nm-950nm range ($3 < z < 6.5$ for Ly-alpha)
- $1.25\text{\AA} \times 0.2'' \times 0.2''$ voxels
- high efficiency (58% peak)

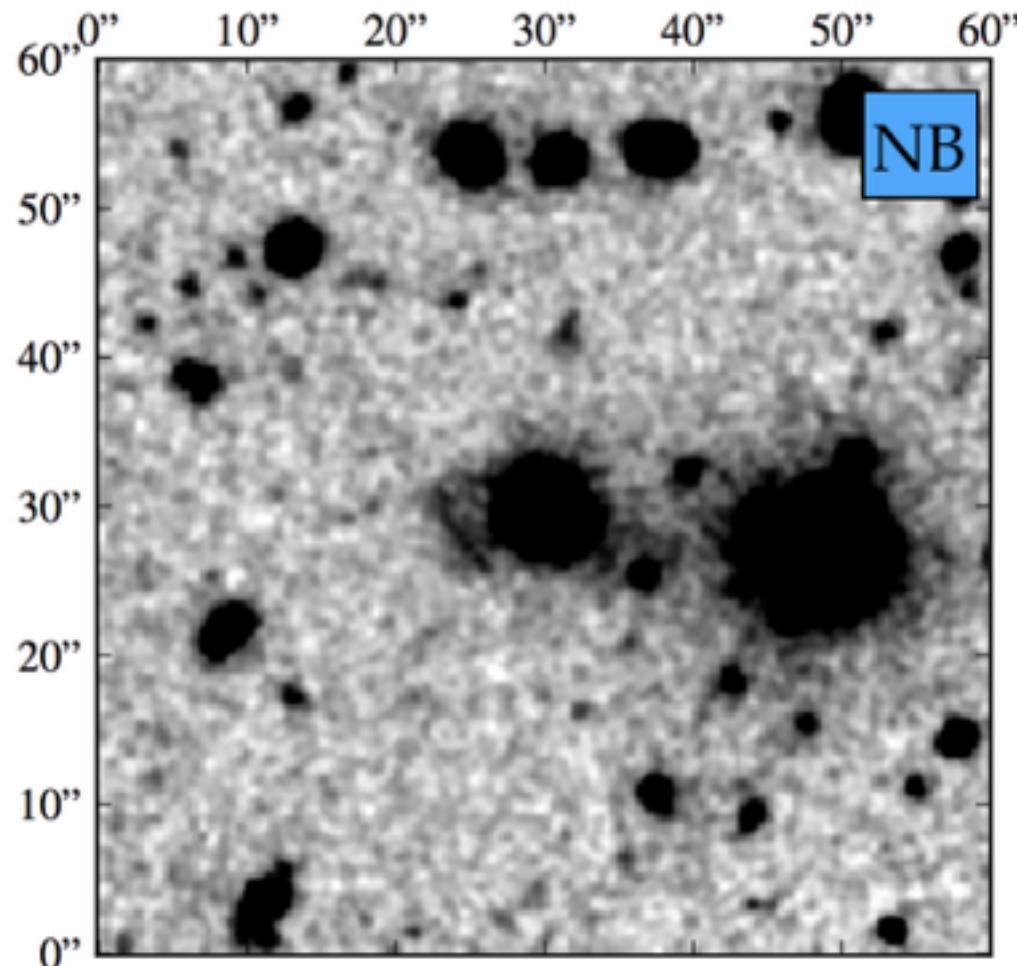
MUSE-VLT: “Reality”

- @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.) + Vislt
QSO PSF and continuum subtracted cube

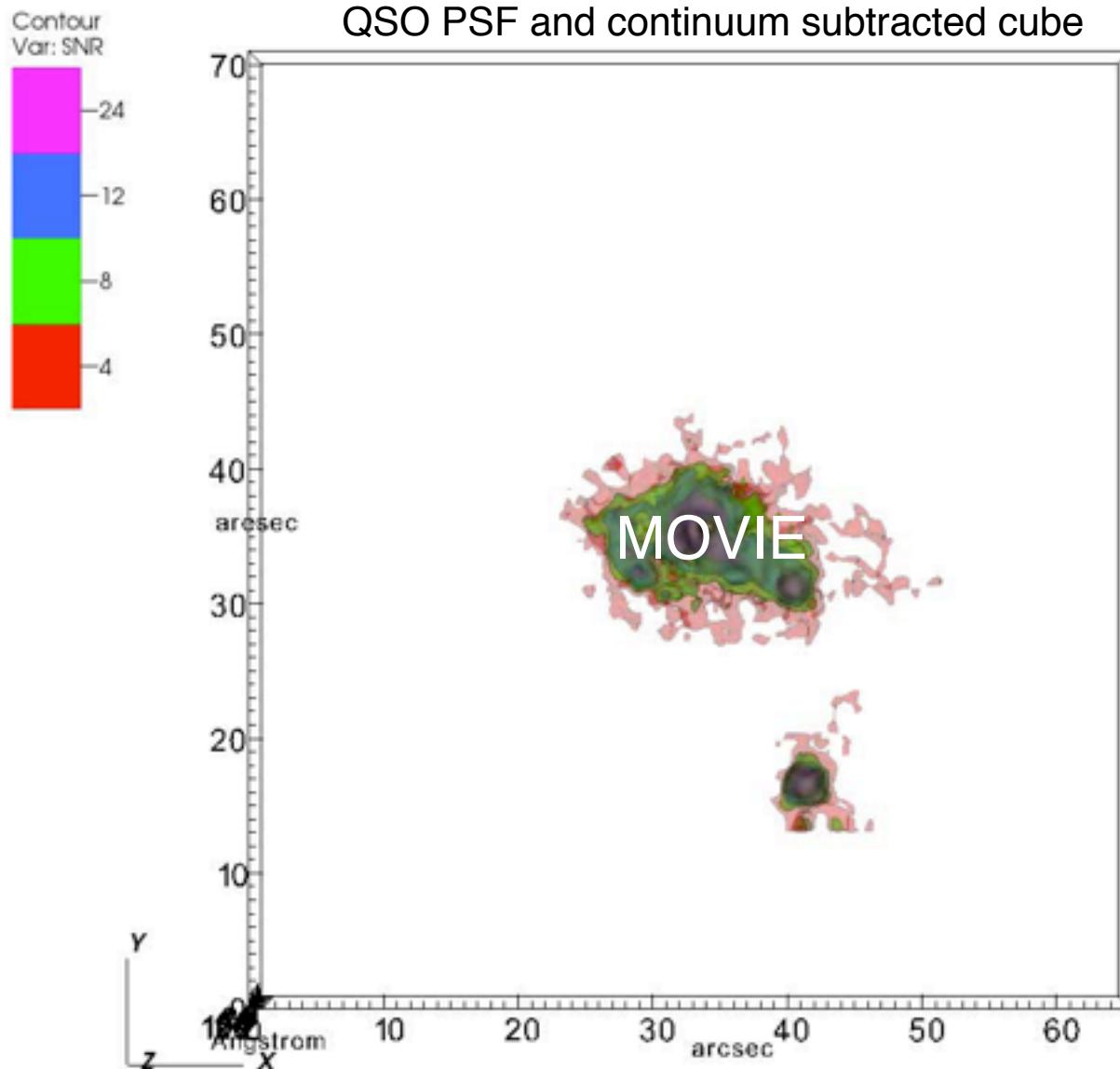


Cantalupo+, in prep.

MILES3D Deep Fields: the Hammerhead Nebula



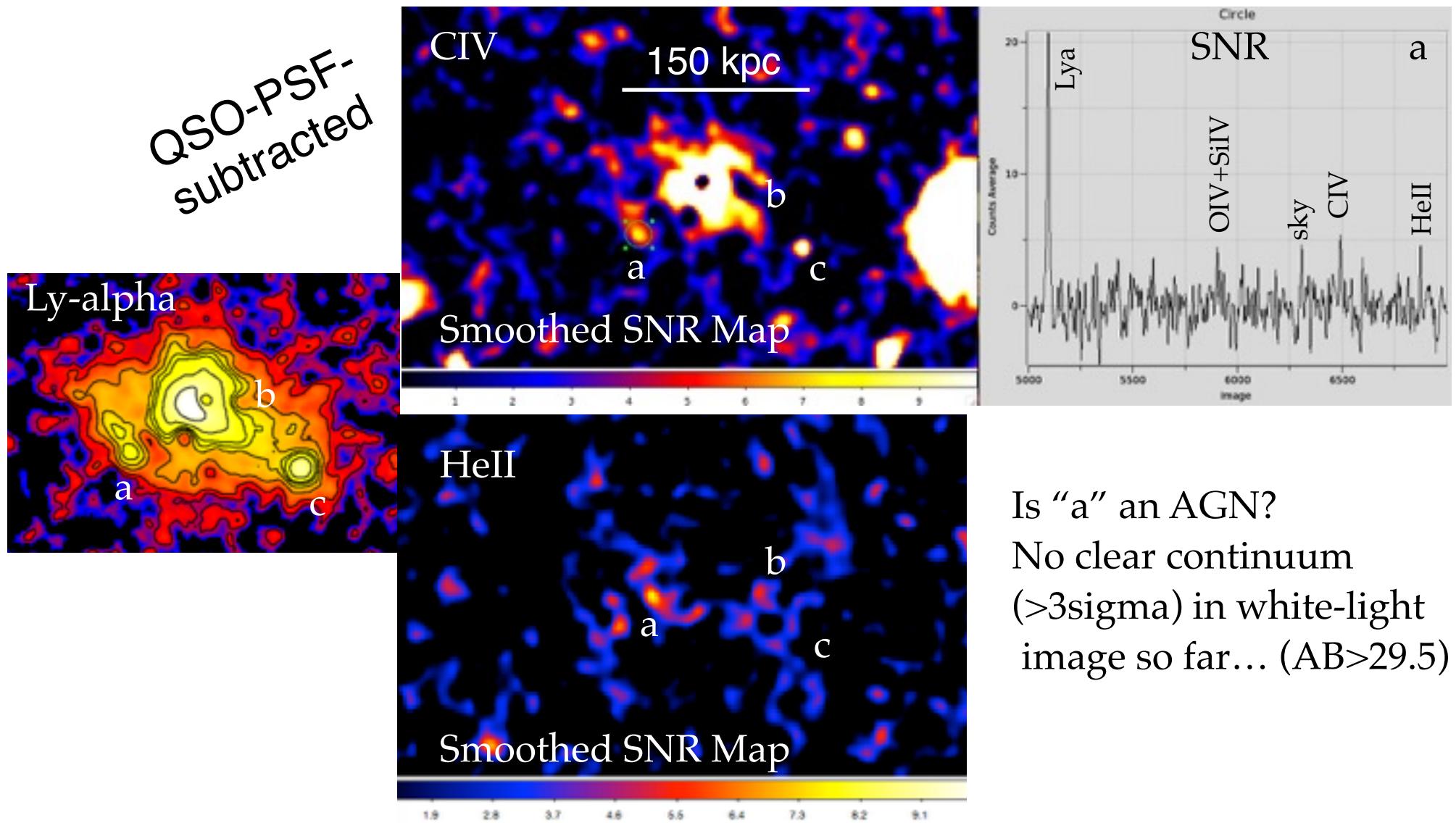
CubExtractor (Cantalupo, in prep.) + Vislt
QSO PSF and continuum subtracted cube



Cantalupo+, in prep.

MILES3D Deep Fields: the Hammerhead Nebula

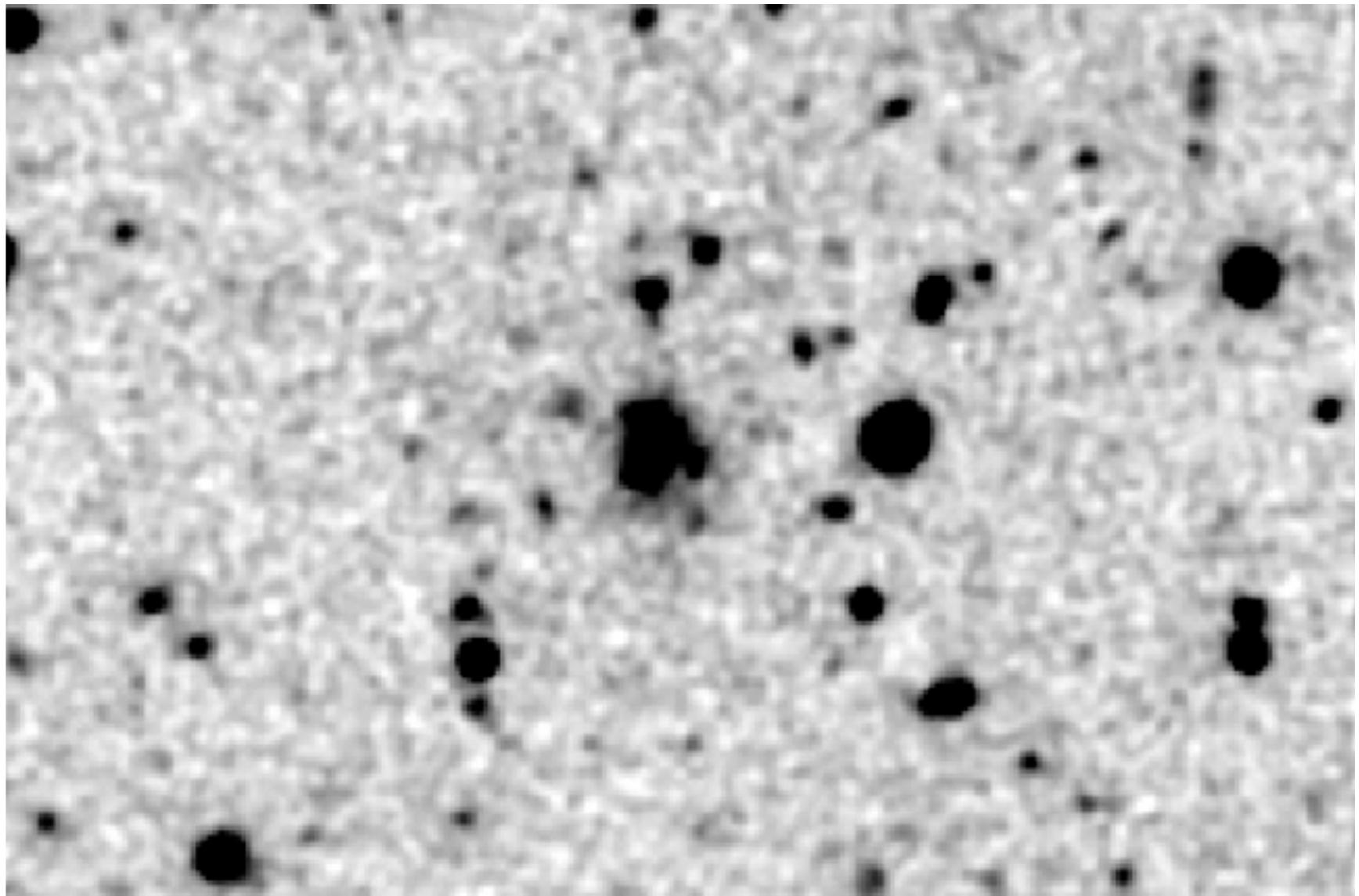
CIV and HeII detected from parts of the Nebula



Is “a” an AGN?
No clear continuum
($>3\sigma$) in white-light
image so far... (AB>29.5)

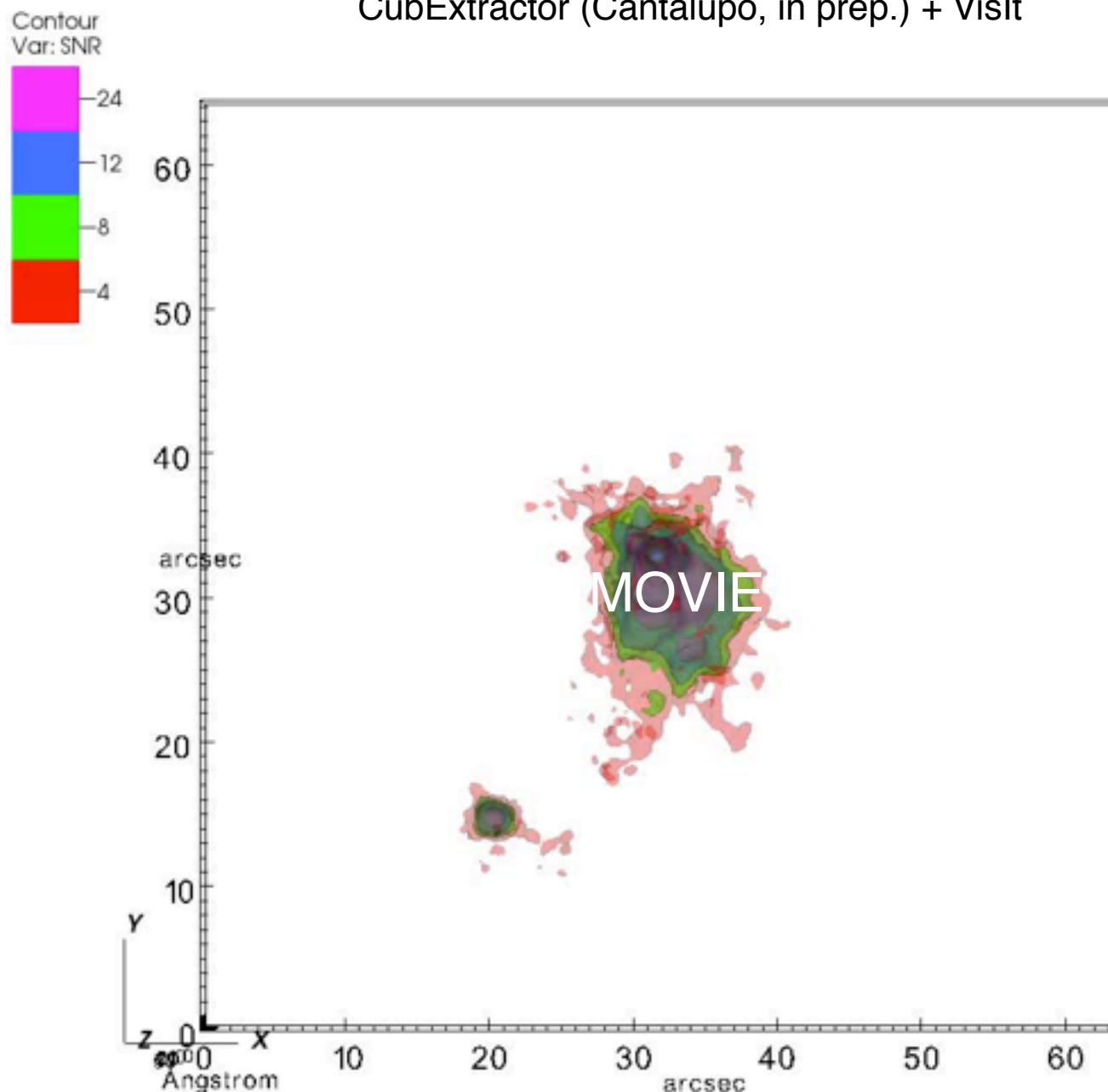
Cantalupo+, in prep.

MILES3D Deep Fields: the “Bulb” Nebula



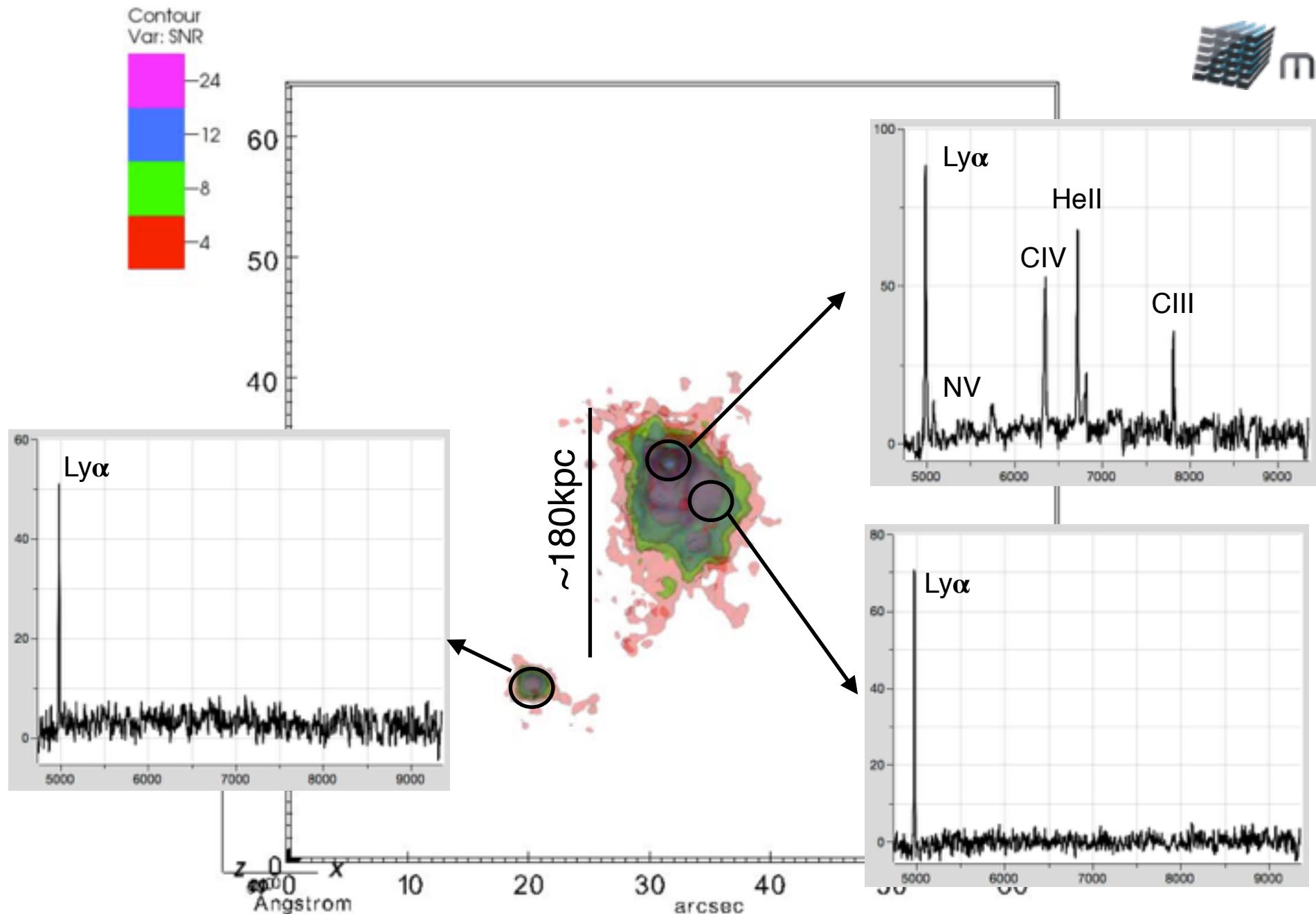
MILES3D Deep Fields: the “Bulb” Nebula

CubExtractor (Cantalupo, in prep.) + Vislt



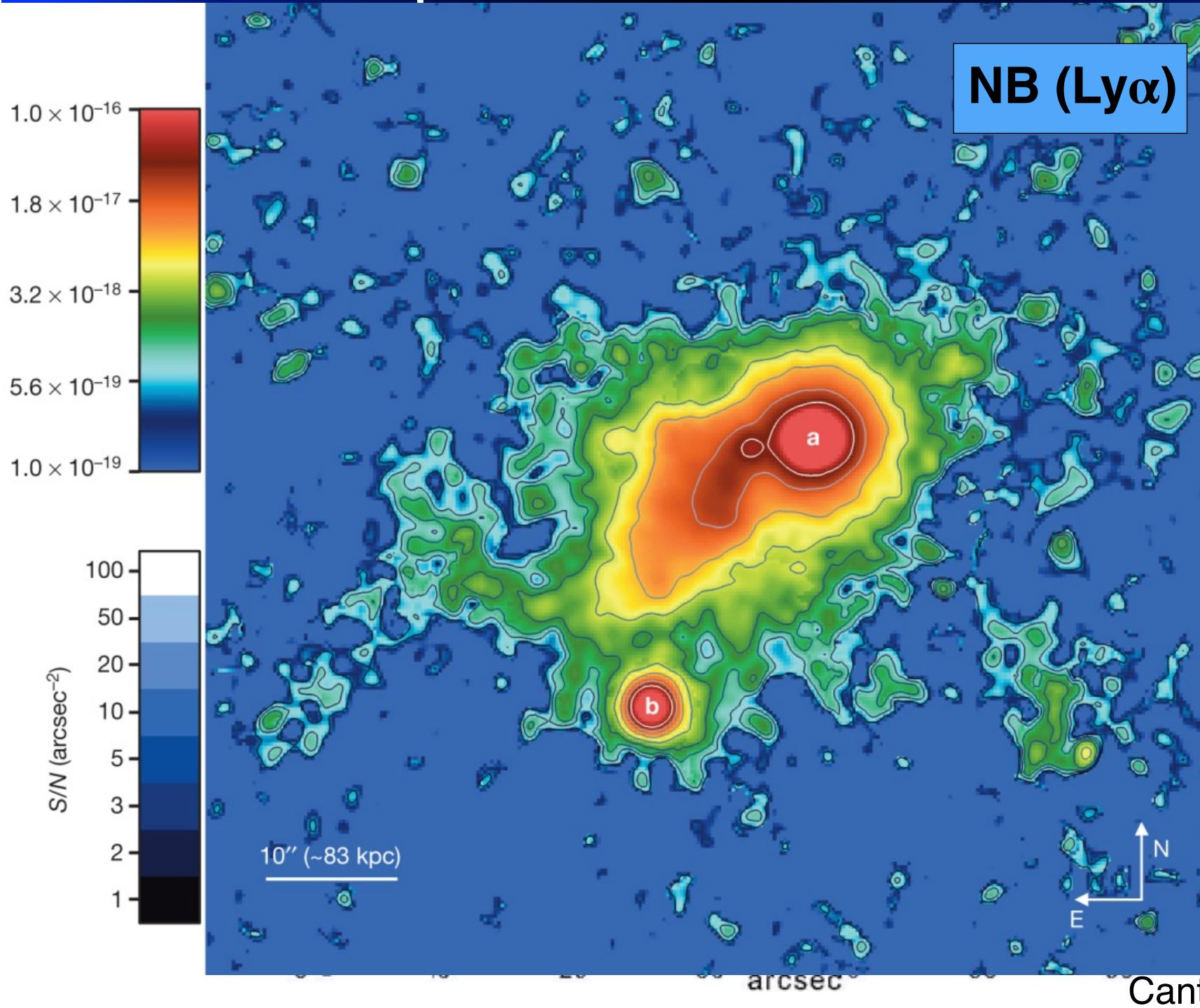
Cantalupo+, in prep.

MILES3D Deep Fields: the Bulb Nebula

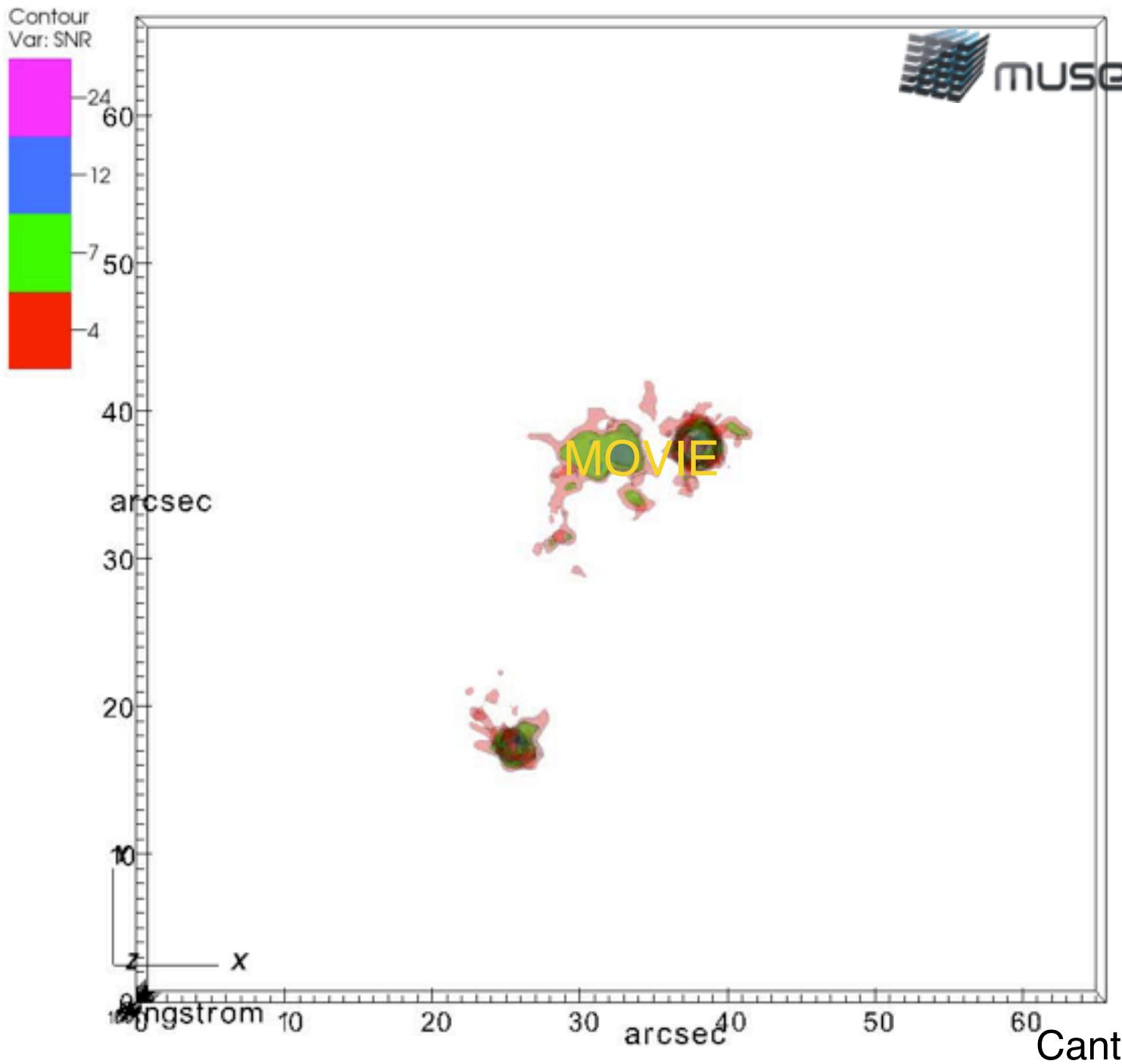


Cantalupo+, in prep.

MILES3D Deep Fields: Extended Hell emission from the Slug

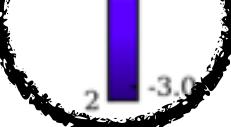
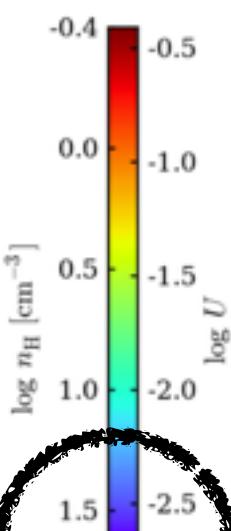
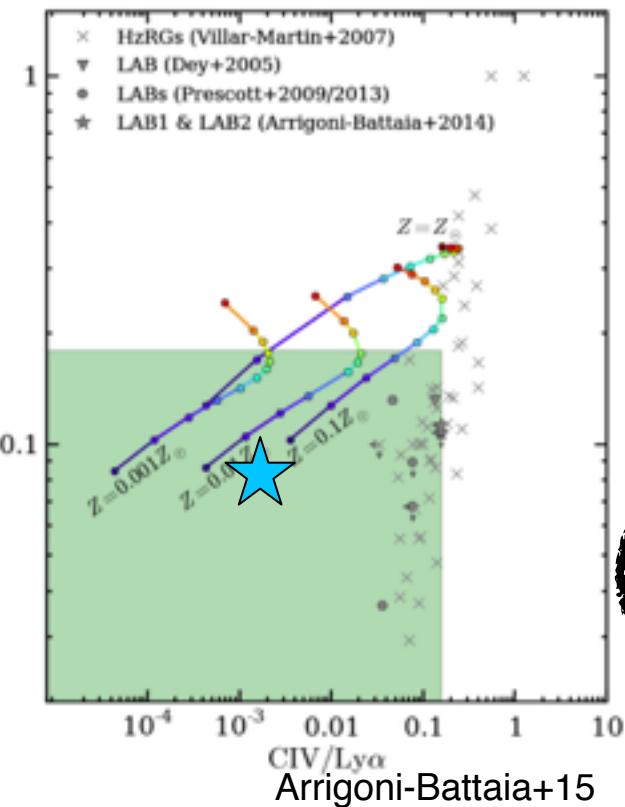
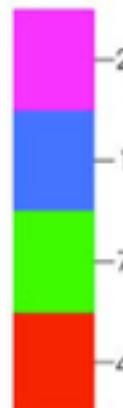


MILES3D Deep Fields: Extended Hell emission from the Slug



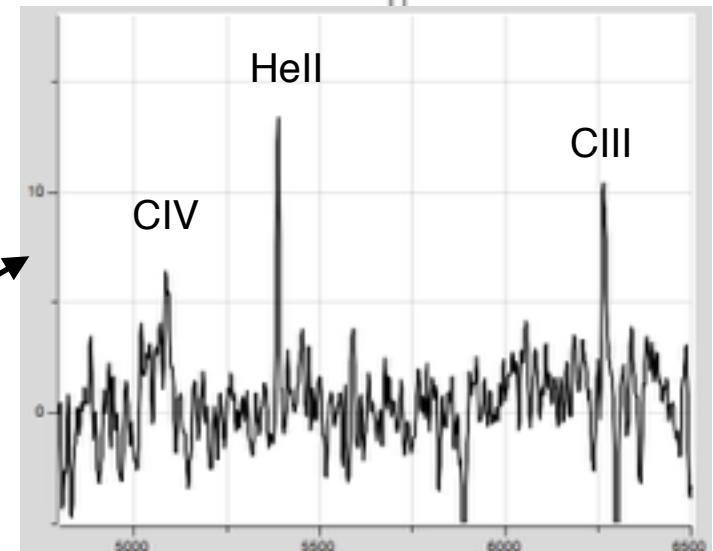
MILES3D Deep Fields: Extended Hell emission from the Slug

Contour
Var: SNR



30 arcsec

40



$$\begin{aligned} z(C) &= 2.286 \\ z(\text{QSO,NIR}) &= 2.279 \\ z(\text{QSO,CO}) &= 2.283 \end{aligned}$$

(+600km/s)
(+270km/s)

High densities (clumps),
 $n > 10 \text{ cc}$, $R < 20 \text{ pc}$!

Cantalupo+, in prep.

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 a clumpy IGM/CGM affects galaxy and QSO formation?
(fast gas accretion, violent disk instability,...)

More than one component in the Slug Nebula?
HeII+H α +metal emission suggests a large structure in projection (>3Mpc).

Part III: What happens when you “illuminate” the CGM

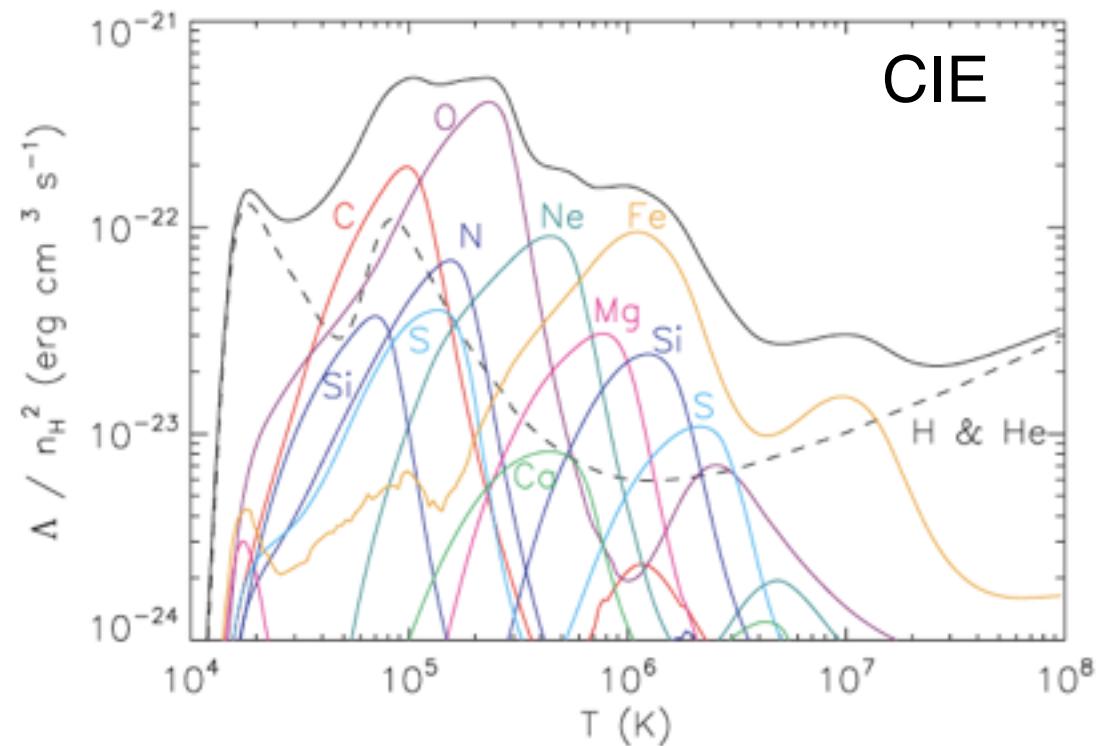
“We understand everything about gas cooling thanks to our hydrodynamical simulations, so we only need to focus on SN and AGN feedback.”

A Colloquium Speaker, IoA, 2009

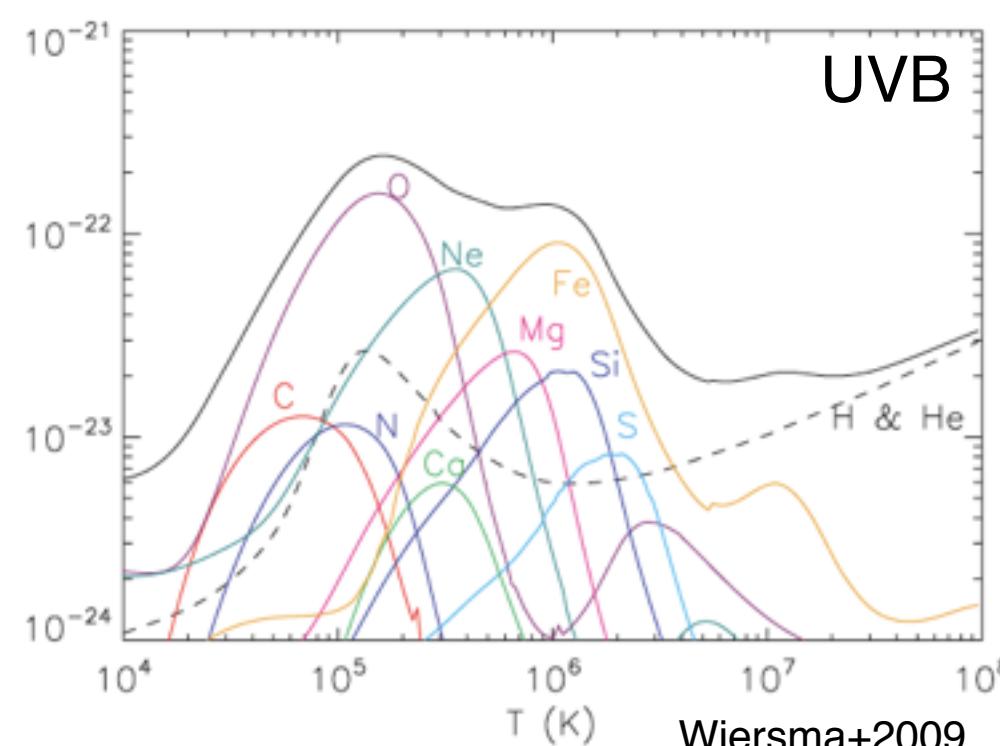
How to “regulate” the SFR of galaxies?

- 1) removing the gas from the galaxy (e.g., SN feedback, “ejective feedback”).
- 2) reducing/stopping cooling gas accretion from halo (“preventive feedback”).

Cooling Function: the basics



CIE



UVB

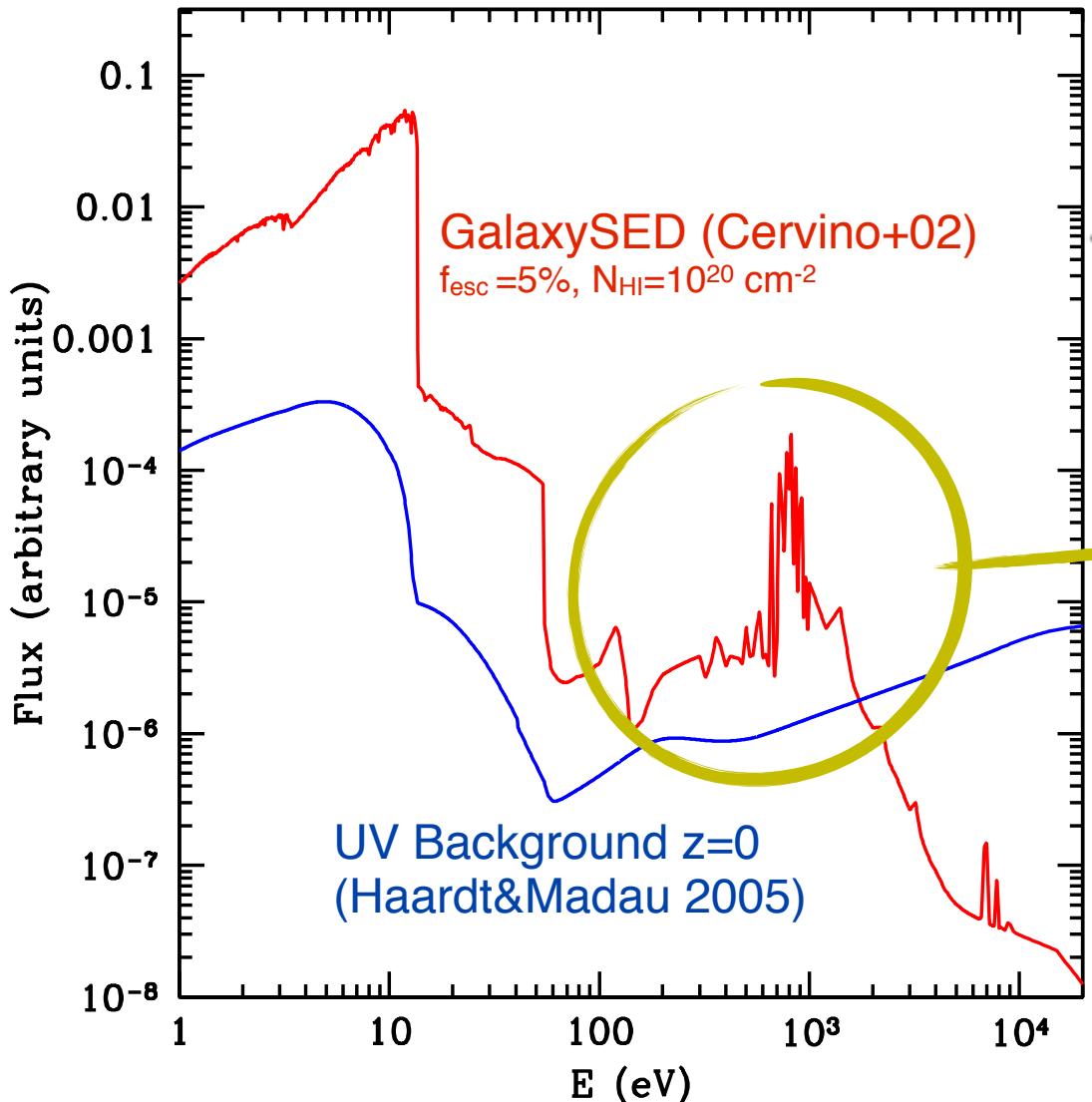
Wiersma+2009

Main coolants:

<i>ion</i>	<i>line</i>	<i>Ion.Potential</i>
O^{4+}	OV[630A]	113.9 eV
Ne^{5+}	NeVI[400A]	157.9 eV
Fe^{8+}	FeIX[169A]	233.6 eV

In order to “kill” the cooling at the peak of the cooling function we need to “illuminate” the gas with soft X-ray photons

Soft X-ray emission from GALAXIES: linear relation with SFR



Strickland+04

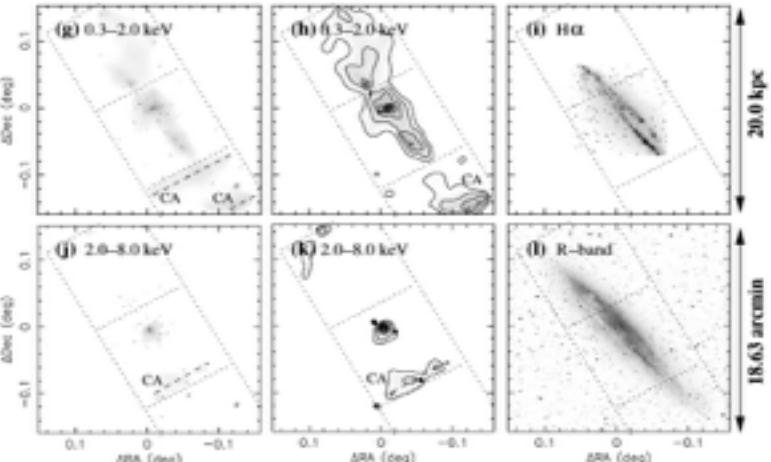


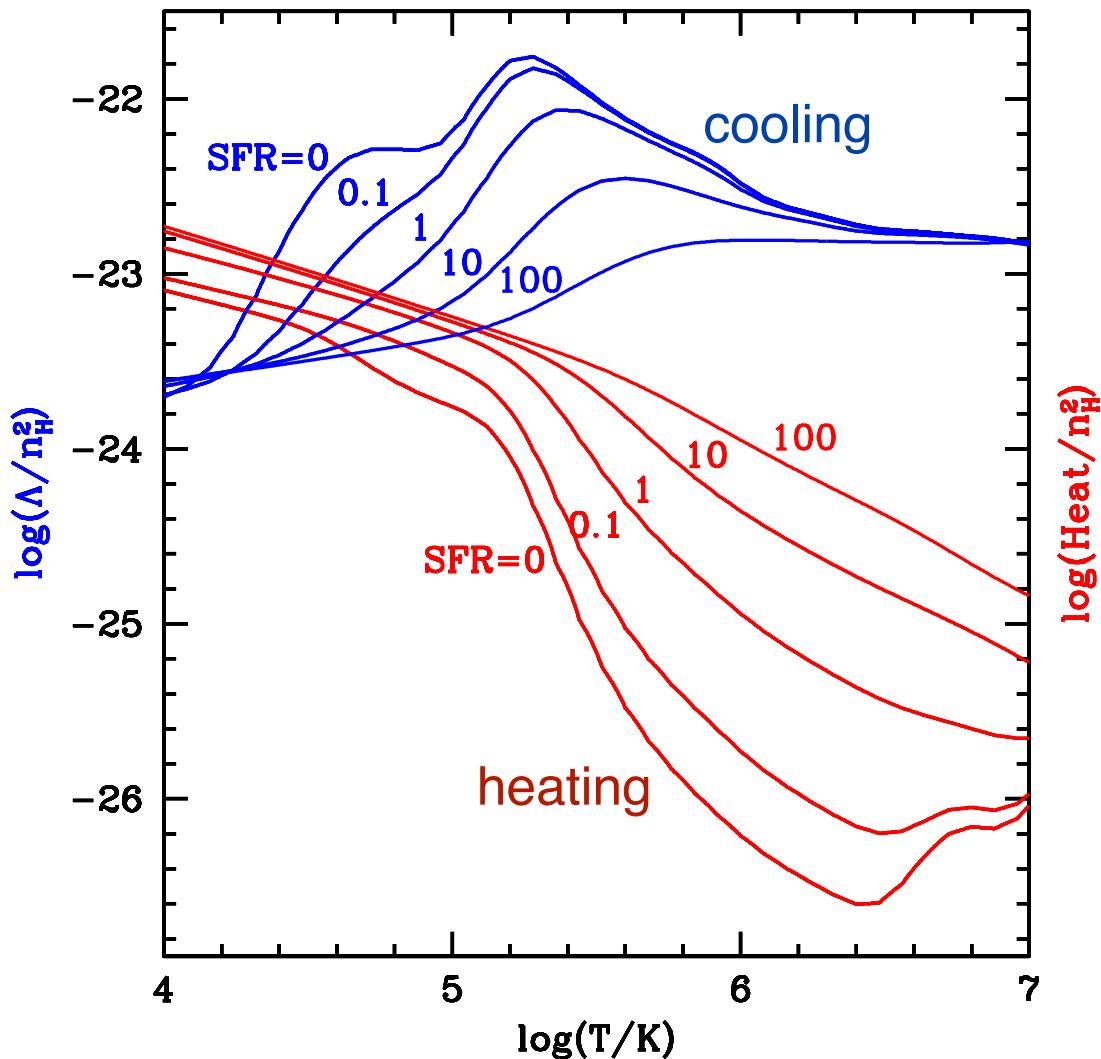
Fig. 9.—Chandra X-ray and optical images of NGC 4945. The meaning of each panel, and the intensity scales and contour levels used, are the same as described in Fig. 2.

Soft X-ray (model) produced
by SN bubbles, calibrated
to reproduce observed
SFR - Soft Xray relation.

NB: X-ray binaries not included.

Cantalupo 2010

Effect on gas cooling: Cloudy modeling for “typical” CGM



$n_H = 10^{-3} \text{ cm}^{-3}$ ($\delta \sim 5 \times 10^3$ @ $z=0$)
 $(\delta \sim 6 \times 10^2$ @ $z=1$)

$d = 5 \text{ kpc}$ from galaxy

$Z = 0.03 Z_\odot$

$$\Lambda(n, T, Z, U^* + U_{\text{UVB}})$$

$$U^* \propto SFR \times d^{-2} \times n_H^{-1}$$

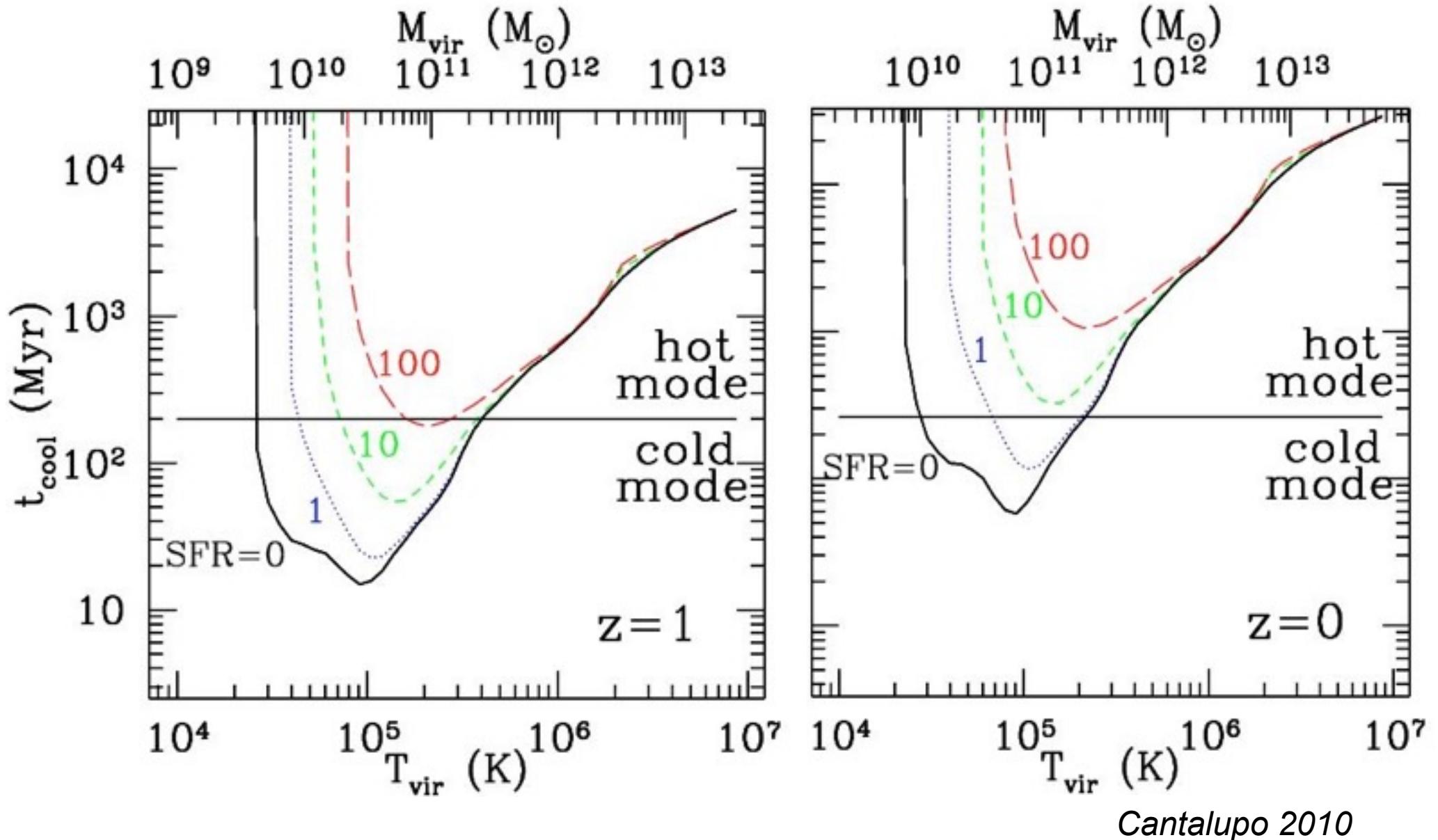
NB: for isothermal halo profile:
 $U^* \propto SFR \times M_{\text{vir}}^{-2/3} \times (1+z)^{-1}$

→ dramatic effect of local sources on **cooling rates** of CGM gas (+ some extra heating).

Cantalupo 2010

The hot-mode/cold-mode transition (Dekel & Birnboim 2006) revisited

Result: transition depends on SFR.
For high SFR there is no “critical halo mass”.



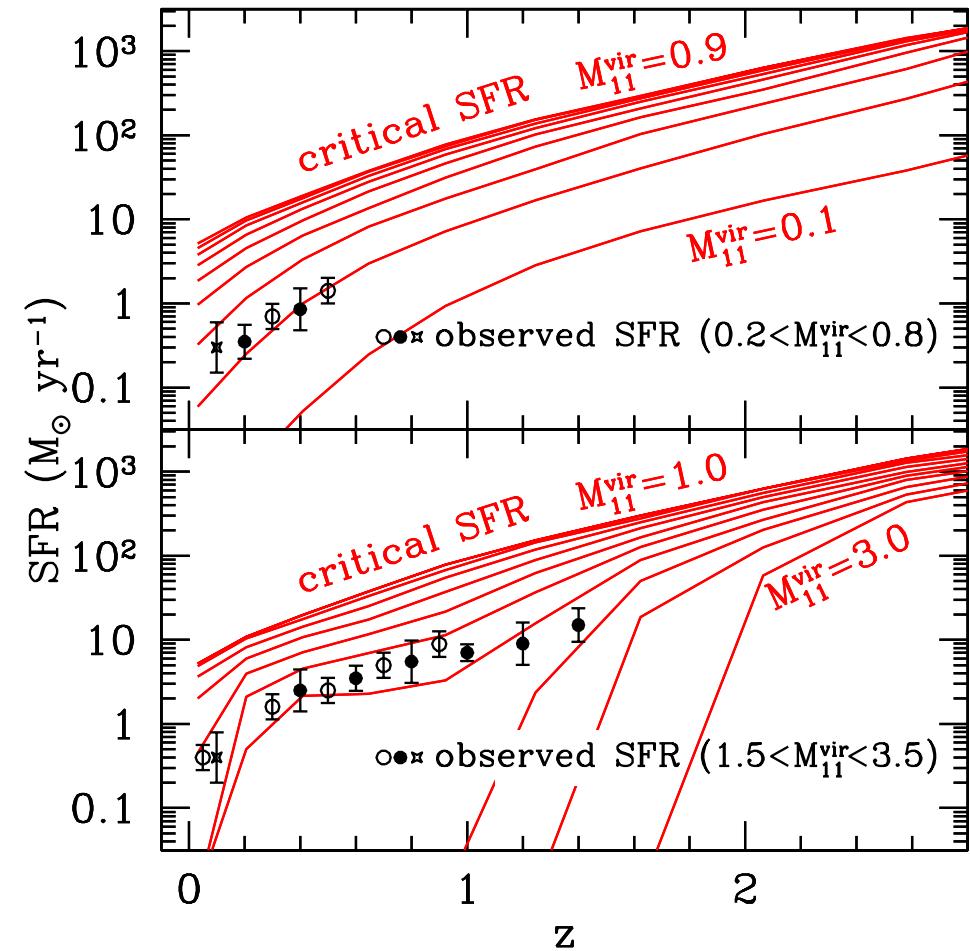
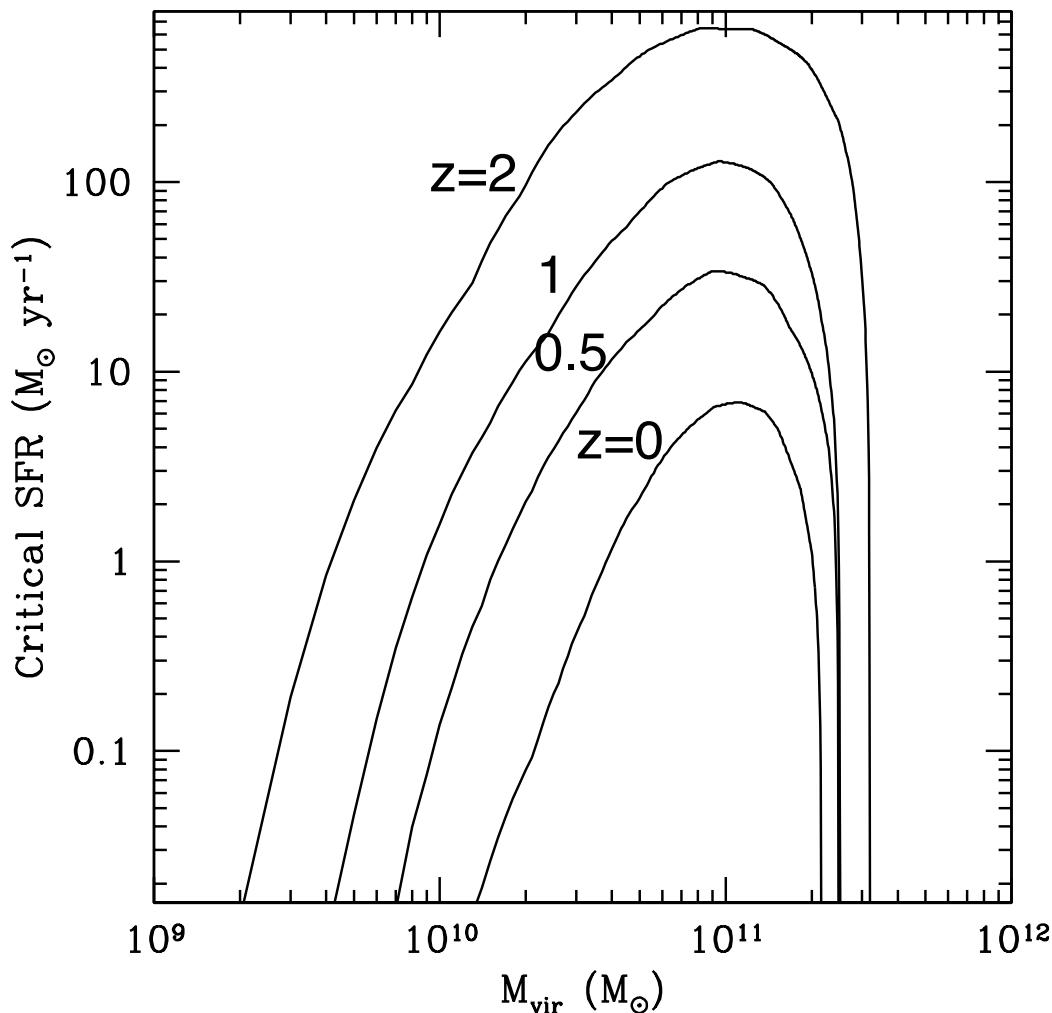
Cantalupo 2010

Implications for Galaxy Formation: the Critical SFR

Critical SFR(M_{vir}, Z, z) := SFR where $t_{\text{cool}}=t_{\text{comp}}$

SFR > Critical SFR \rightarrow “hot-mode”

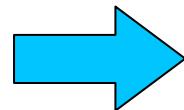
SFR < Critical SFR \rightarrow “cold-mode”



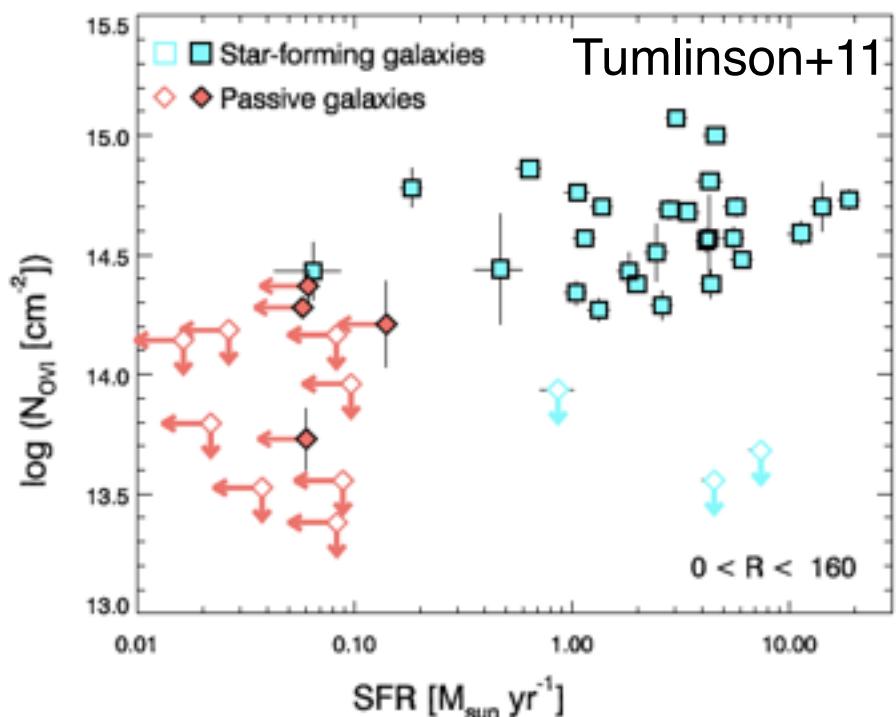
Same steep redshift evolution
as observed SFR!

Observational evidence for local source effect on cooling?

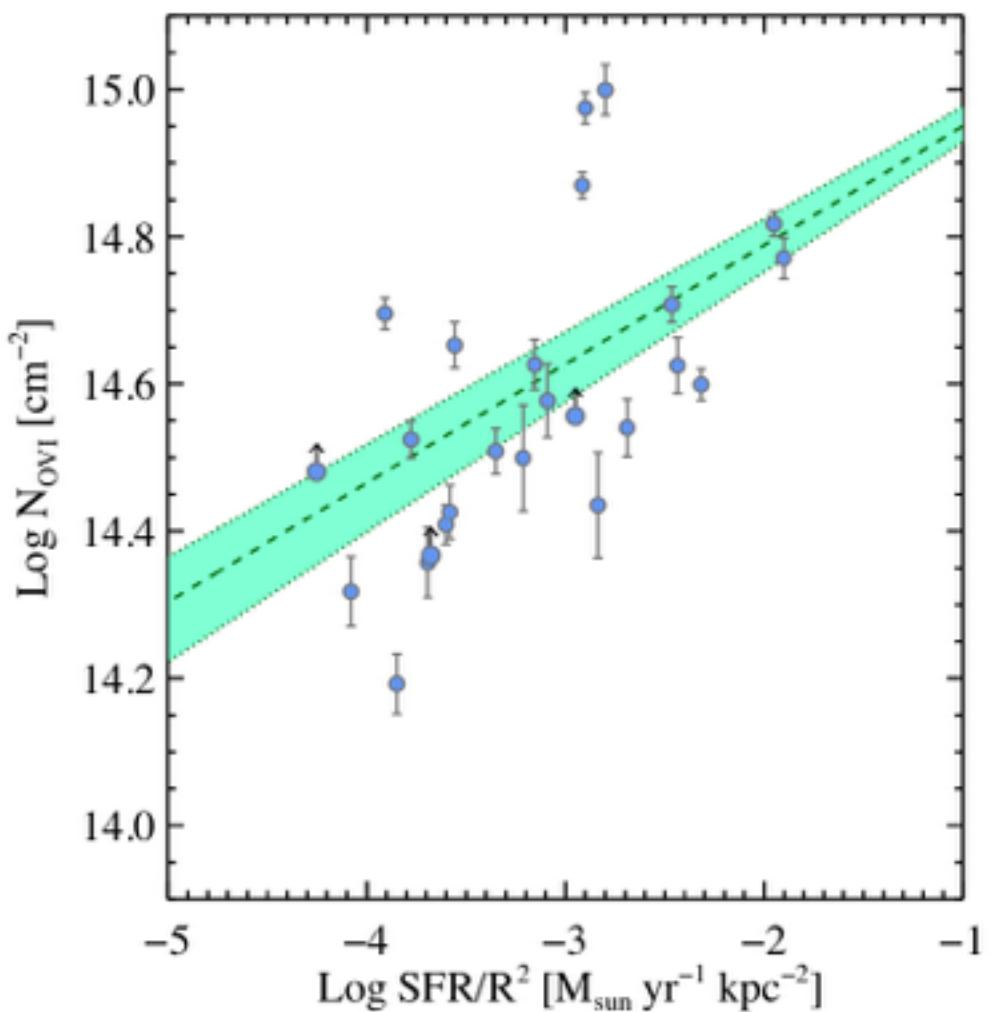
- “absence” of the main cooling line (OV630A) is difficult to probe directly.
- indirect evidence: excess of O⁵⁺ (OVI) or higher potential ions.



COS-Halo Survey

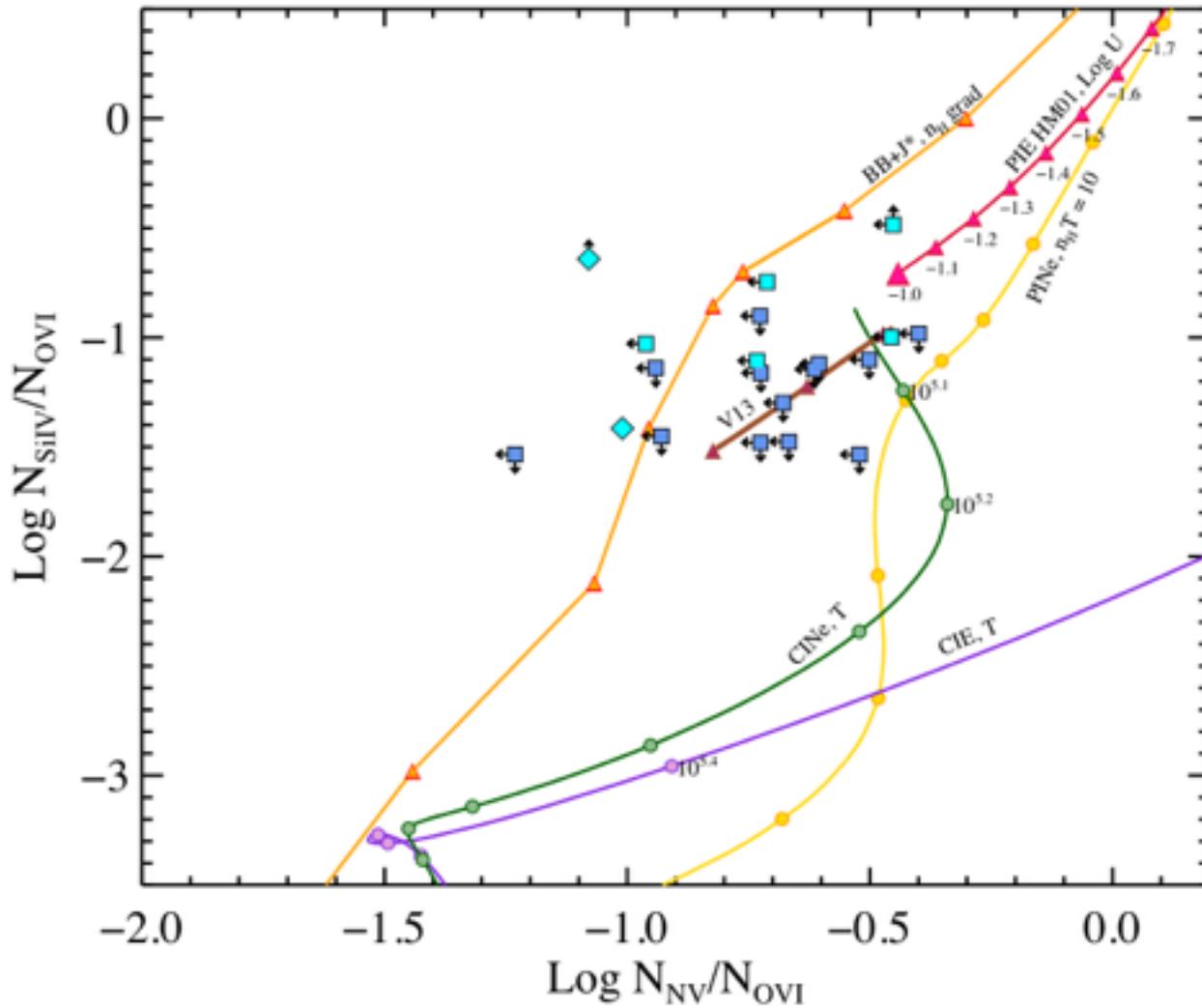


Enhancement of OVI around
“critical SFR” consistent with
local soft-Xray effect.



Constraining local source SED with COS-Halo ion ratios

Ion ratios



Werk, Prochaska, Cantalupo+, submitted

Ion ratios require local source effect.

Collisional ionization (non-)equilibrium ruled out

X-ray binary (Black body) + ISM absorption and clumpy CGM works well.

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 ($\sim 10^9 M_{\text{sun}}$) with extremely low SF efficiency: $< 10^{-11} \text{ yr}^{-1}$ (gas consumption rate $> 100 \text{ Gyr}$).
 - **Circum-Galactic filaments in emission**
Morphology and size compatible with “cold streams”.
 - **Intergalactic Filaments $\sim 200\text{-}500 \text{ kpc}$ size**
Morphology compatible with “Cosmic Web”. More cold/neutral gas than expected: $\sim 10^{12} M_{\text{sun}}$ or dense clumps needed. Low metallicity.
Tension with models - missing physics?
- Local EUV and Soft-X-ray radiation reduce CGM cooling by orders of magnitude → **Critical SFR for cold/hot-mode accretion**. Additional observational evidence from COS-Halo survey (Werk, Prochaska, Cantalupo+, submitted.)
- Next Future:
 - **Ultradeep MUSE fields (GTO) at $z > 3$**
 - **Lya + Ha high-resolution spectroscopy of the $z \sim 2$ Keck fields (LRIS + KCWI + MOSFIRE)**.

Stay tuned!

