Shedding Light on the Properties of the Circum/Inter-galactic Gas in Emission around Quasars

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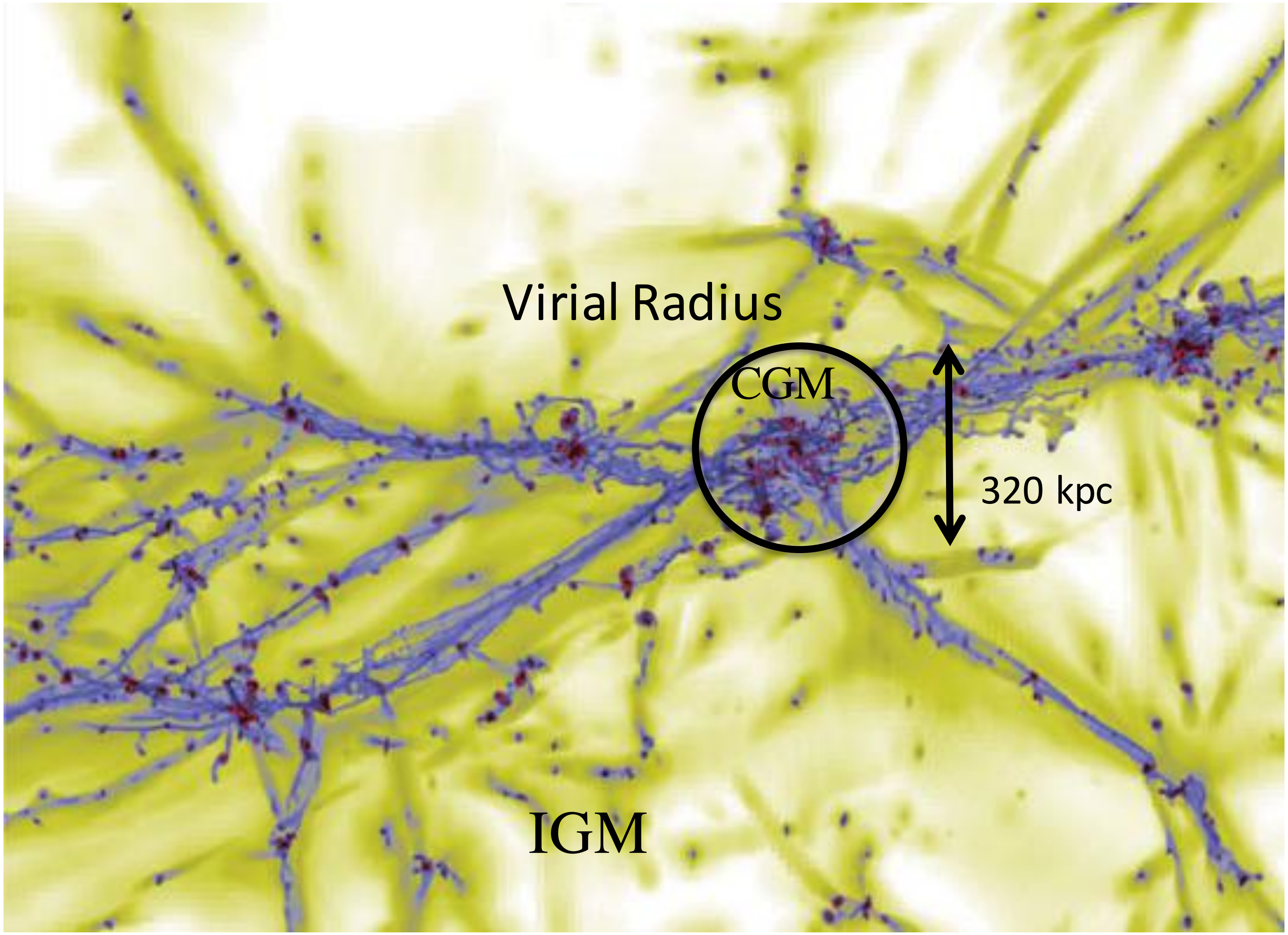
with Joe Hennawi (MPIA), Sebastiano Cantalupo (ETH),
J. Xavier Prochaska (UCSC), Michele Fumagalli (Durham)

Defining the Circum/Inter-Galactic Gas...



Rosdahl & Blaizot 2012

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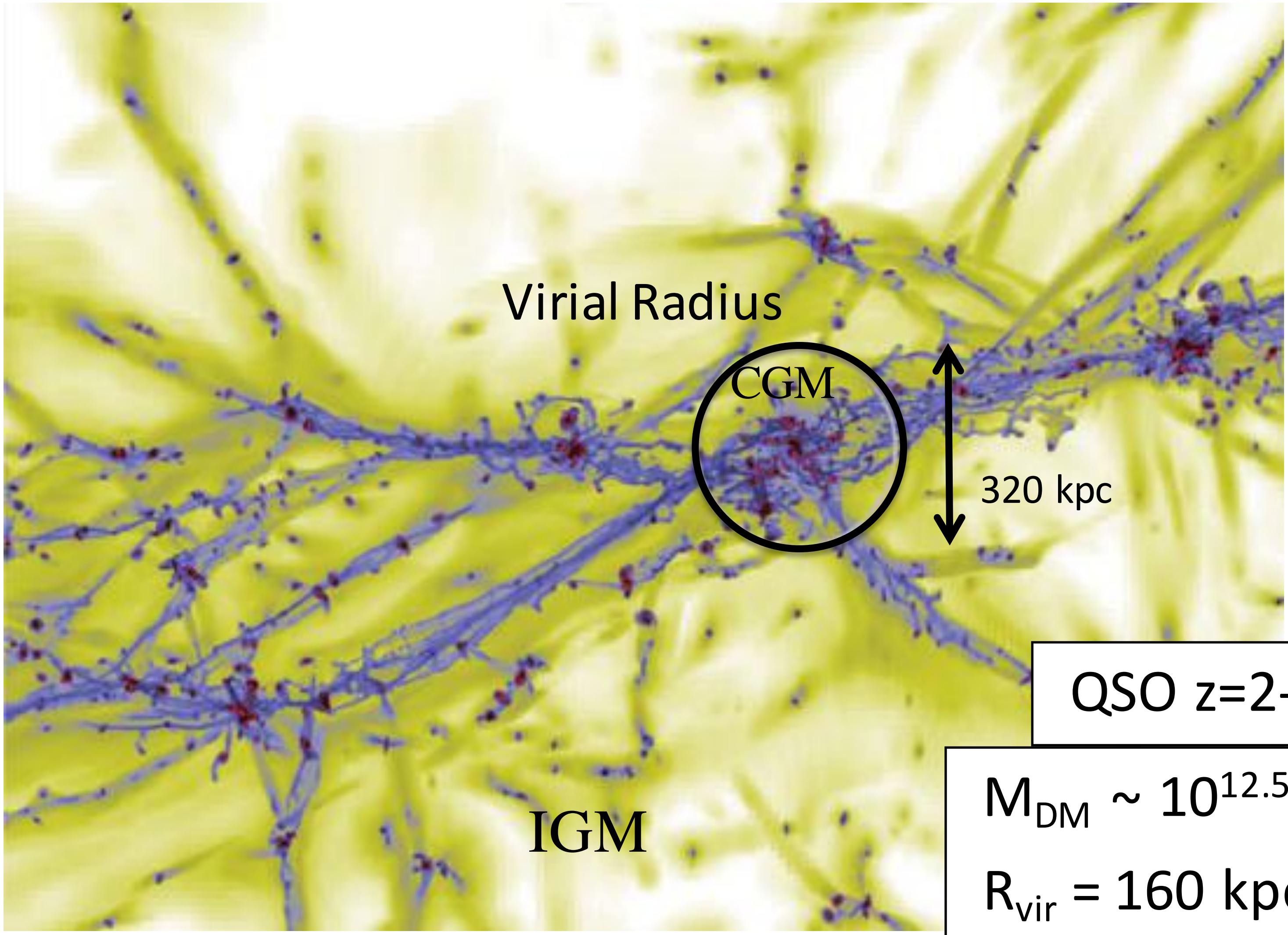


Rosdahl & Blaizot 2012

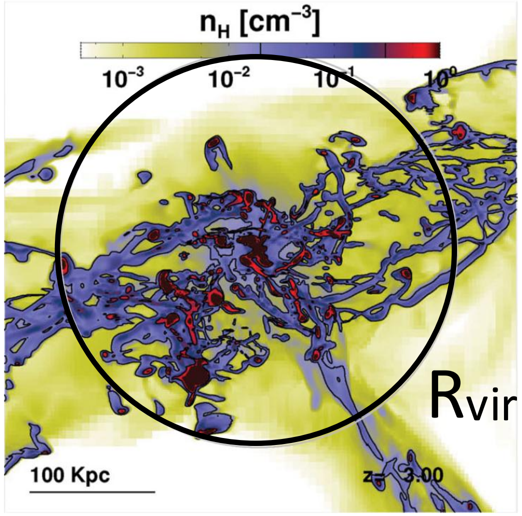
QSO z=2-3

$M_{DM} \sim 10^{12.5}\ M_{\odot}$

$R_{vir} = 160$ kpc

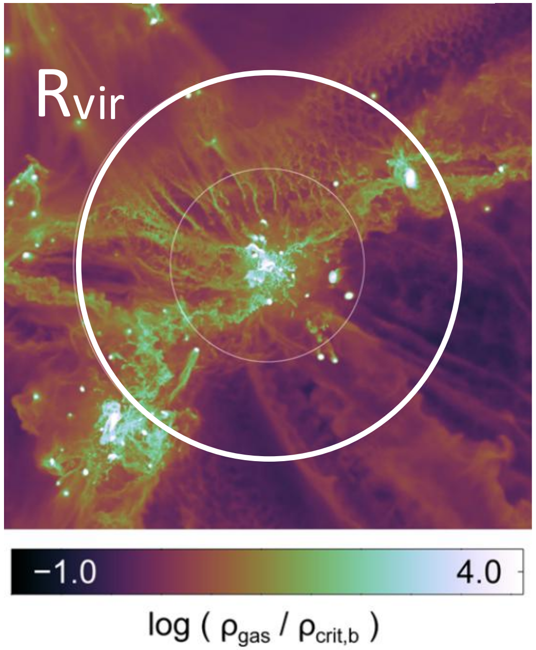
White+2012

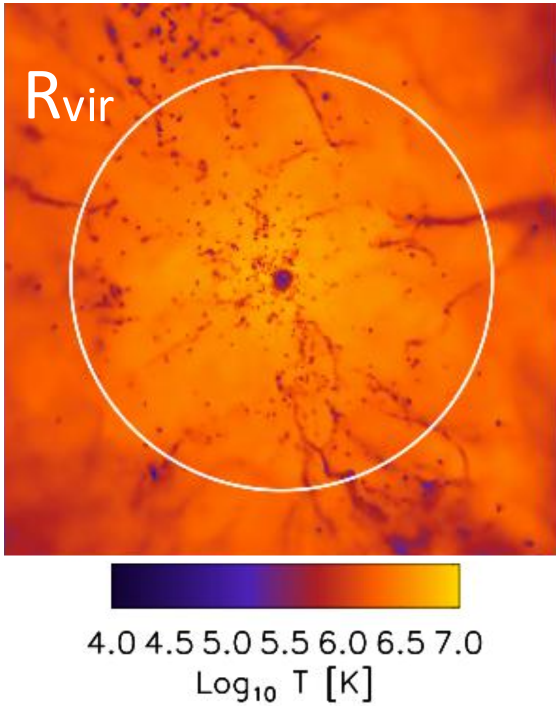
The CGM encodes Precious Information on Structure Formation



Rosdahl & Blaizot 2012

Nelson+2016

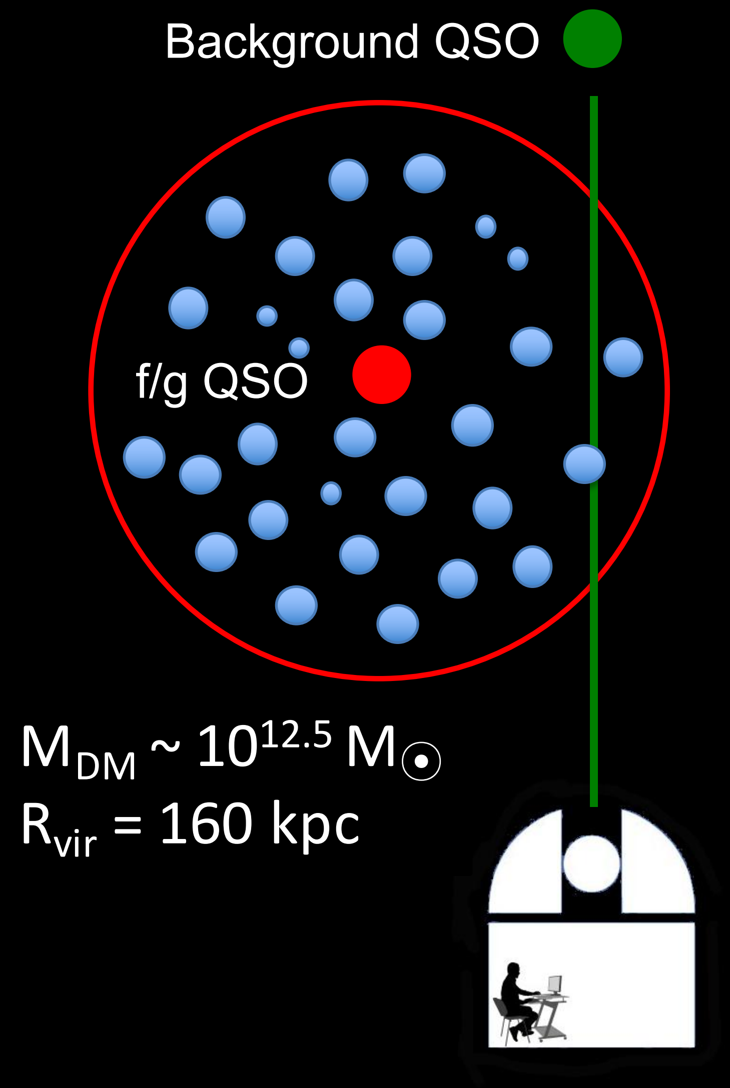




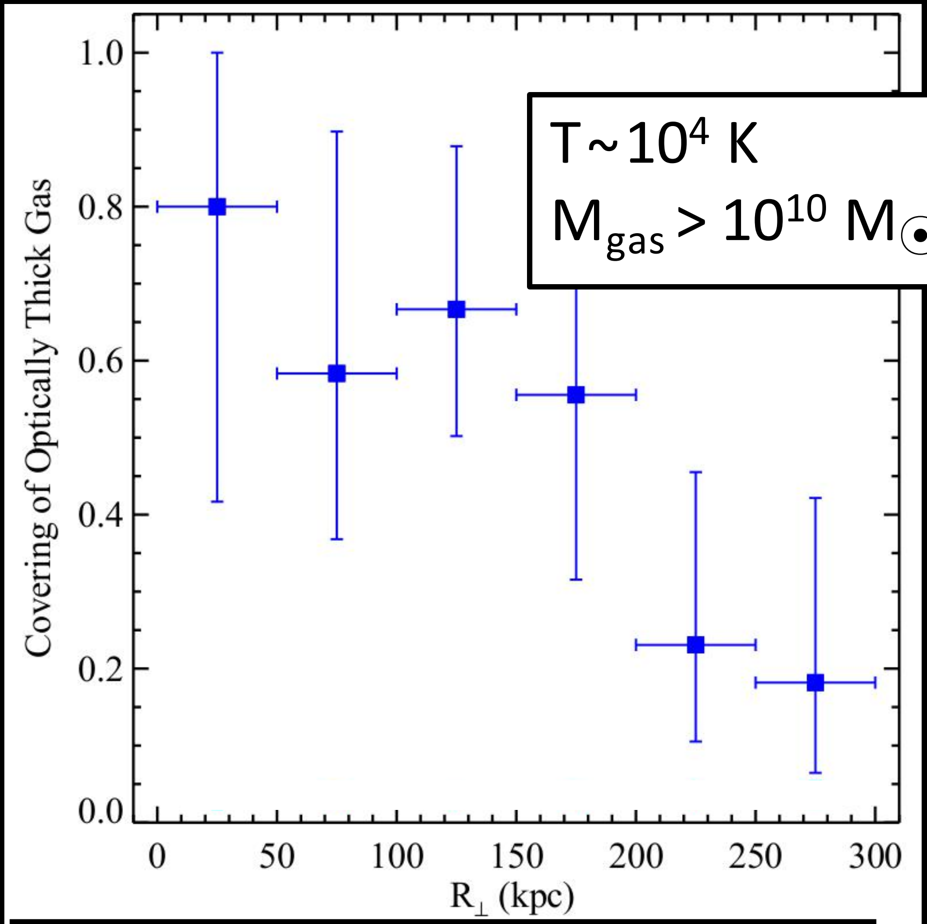
van de Voort+2011

- Feedback?
- Cold flows?
- Amount of cold vs hot gas
- ....

Spectroscopic Absorption Studies @z~ 2

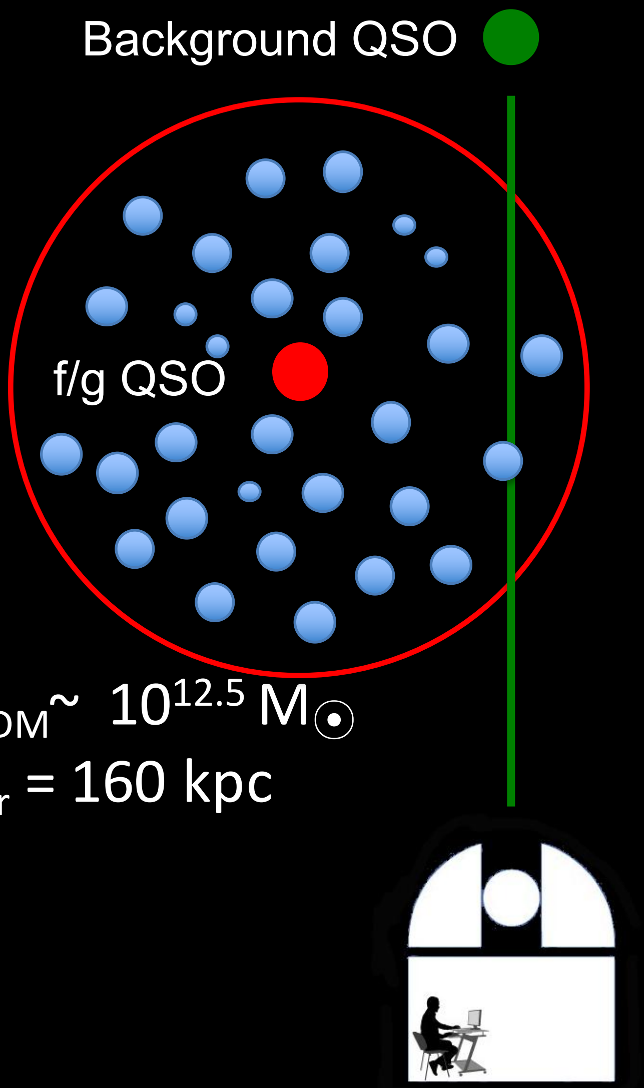


A Large Reservoir of cold $T \sim 10^4$ K gas!



$T \sim 10^4$ K
$M_{gas} > 10^{10} M_\odot$

Prochaska, Hennawi, Simcoe, 2013



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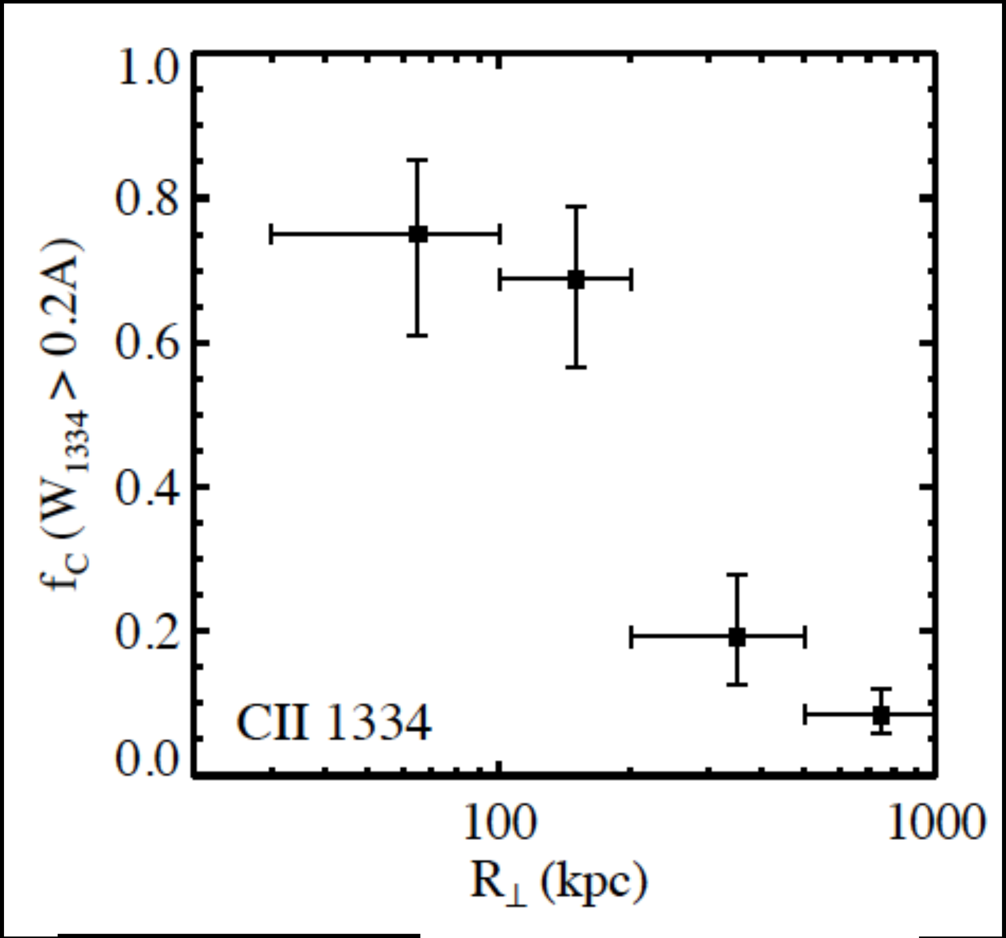
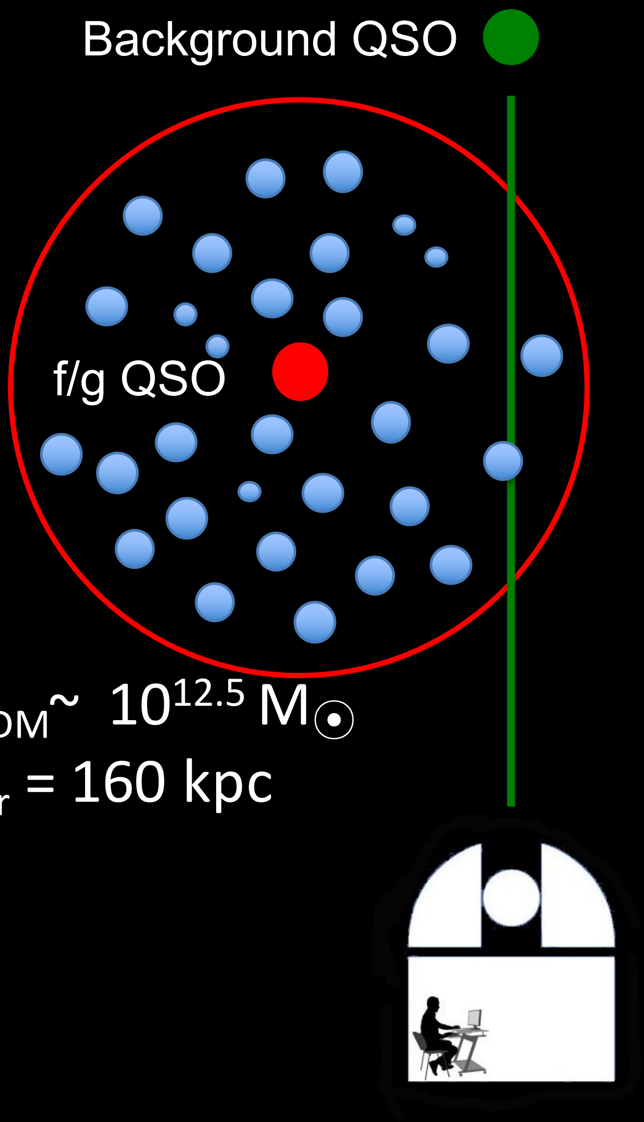


Prochaska+2014



M_{DM}~ $10^{12.5}$ $M_\odot$

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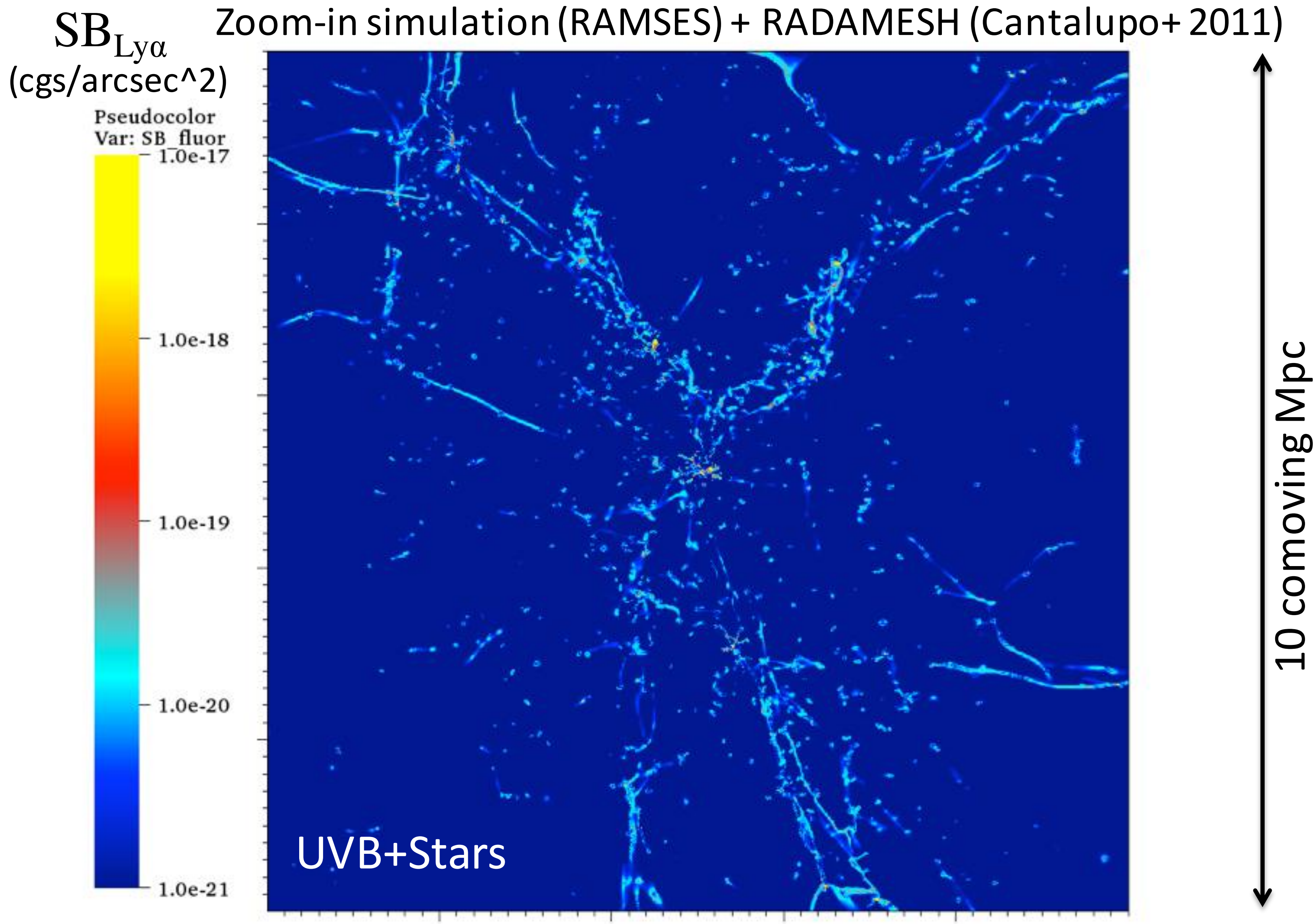
Fluorescent Lyα Emission



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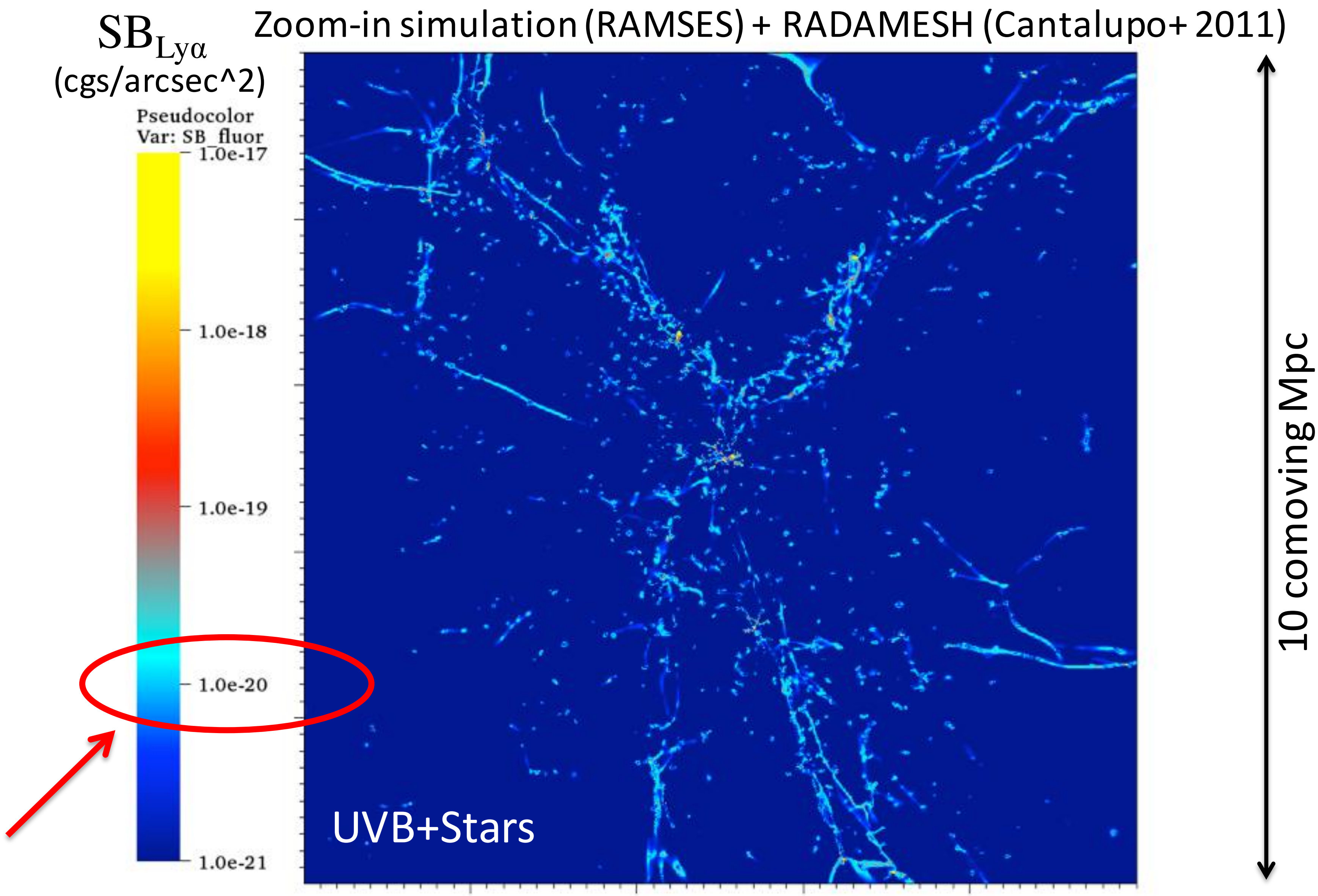

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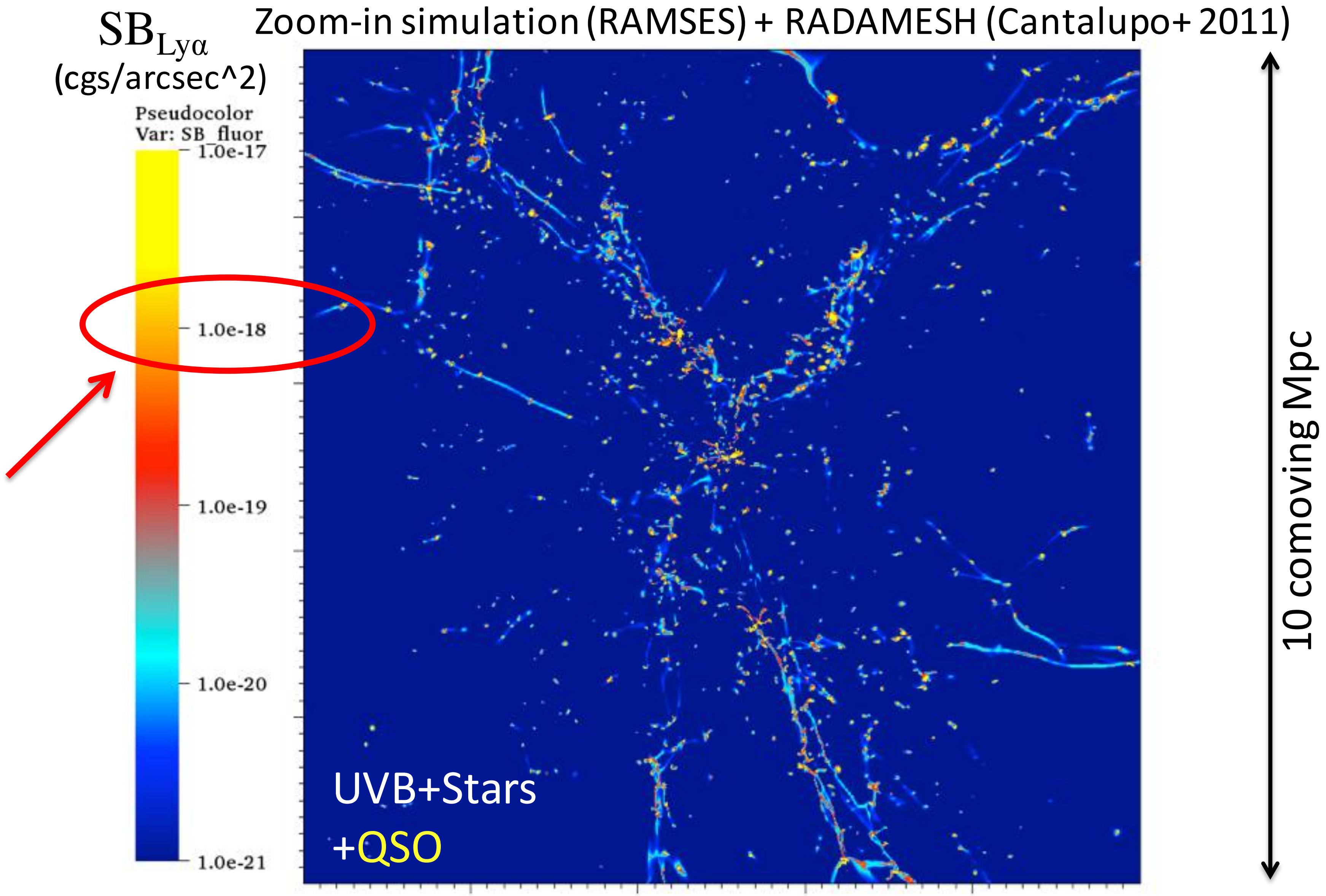

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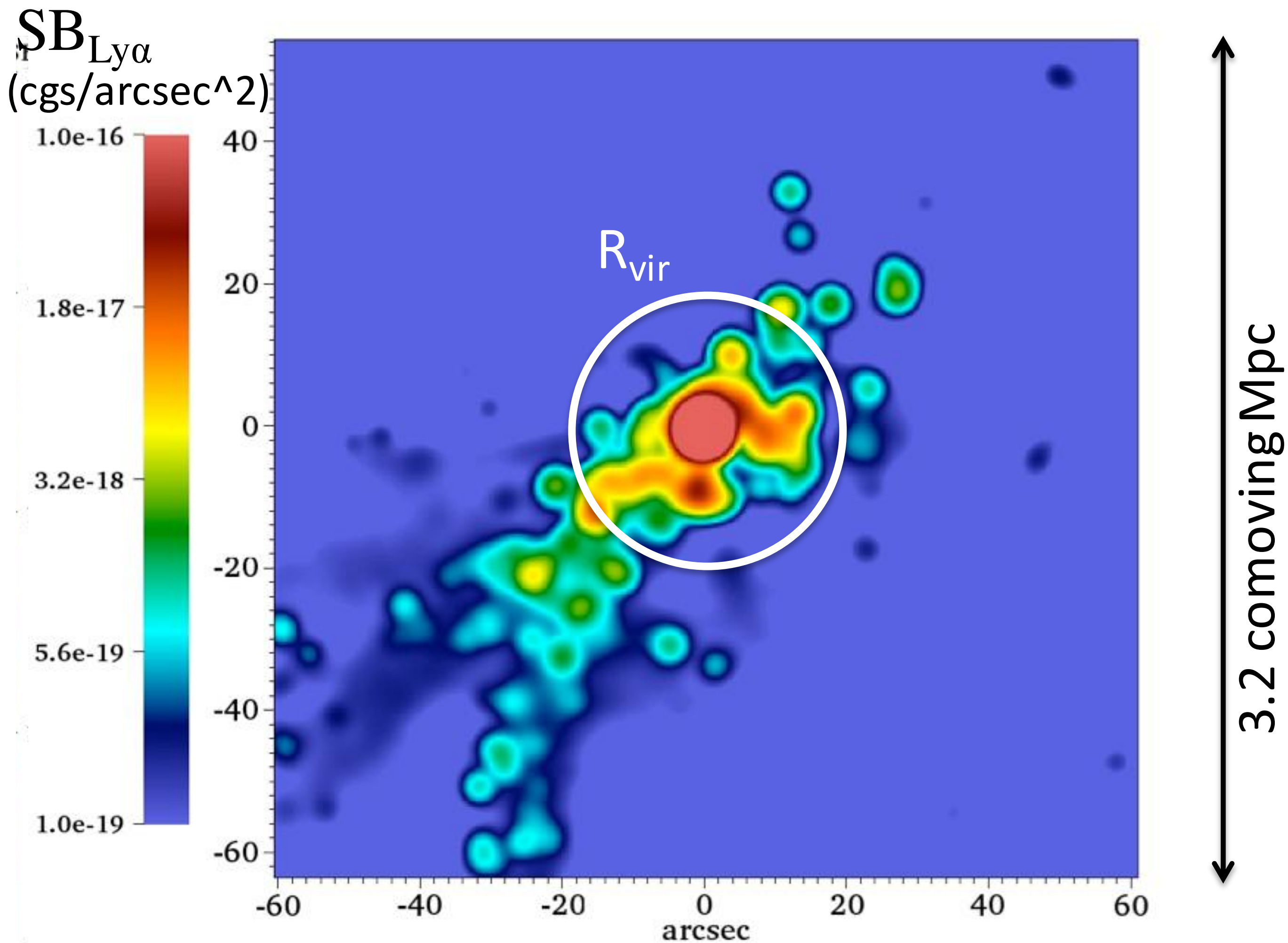
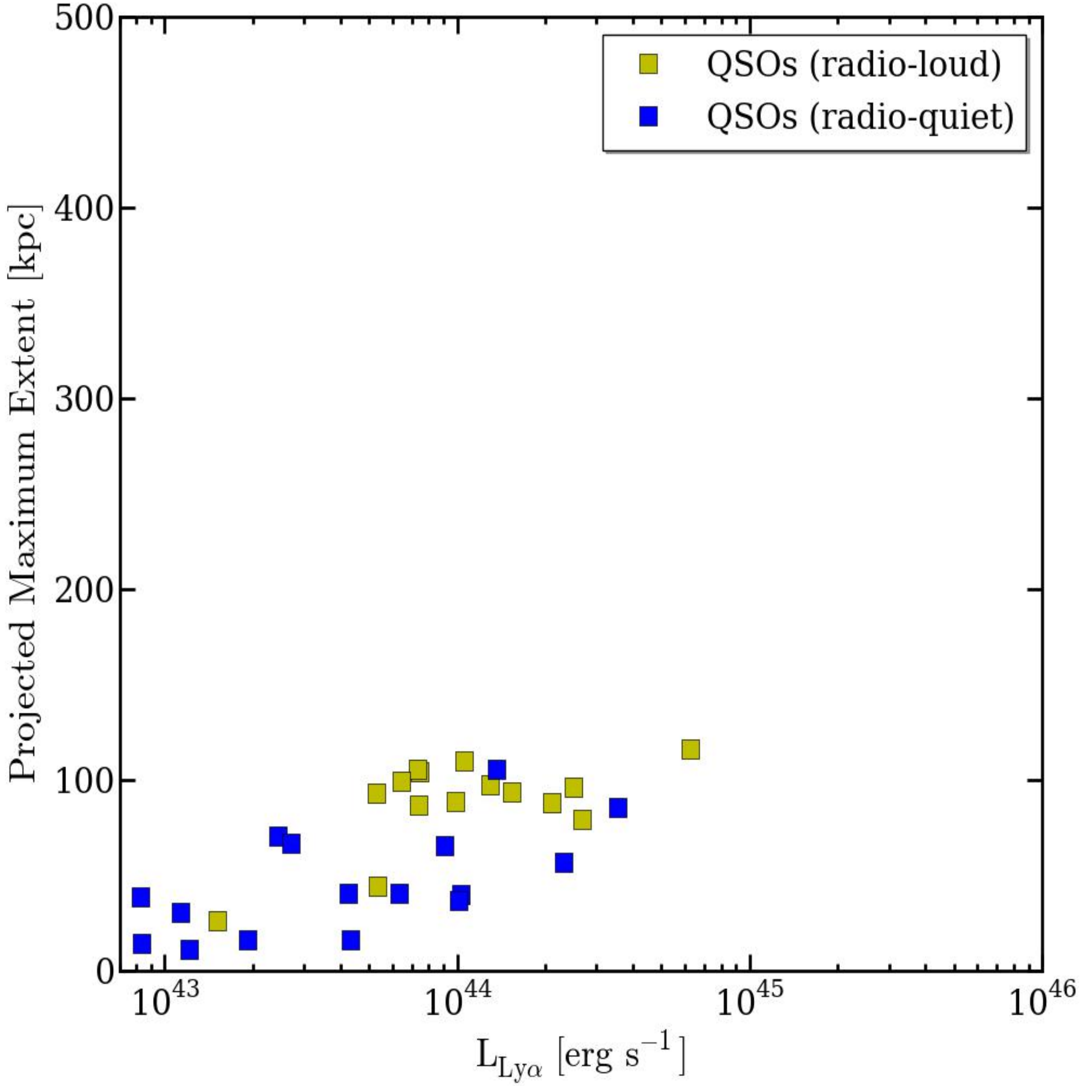
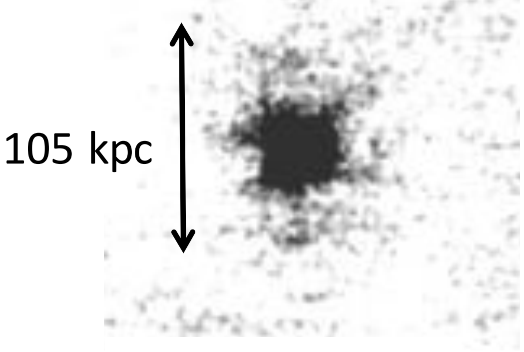


Image credit: S. Cantalupo

Giant Lyα Nebulae

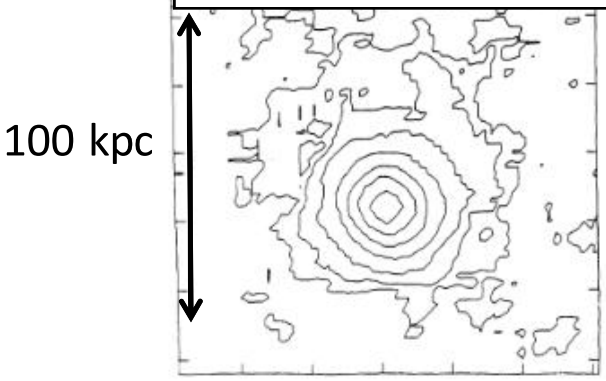


J2233-606 z=2.238



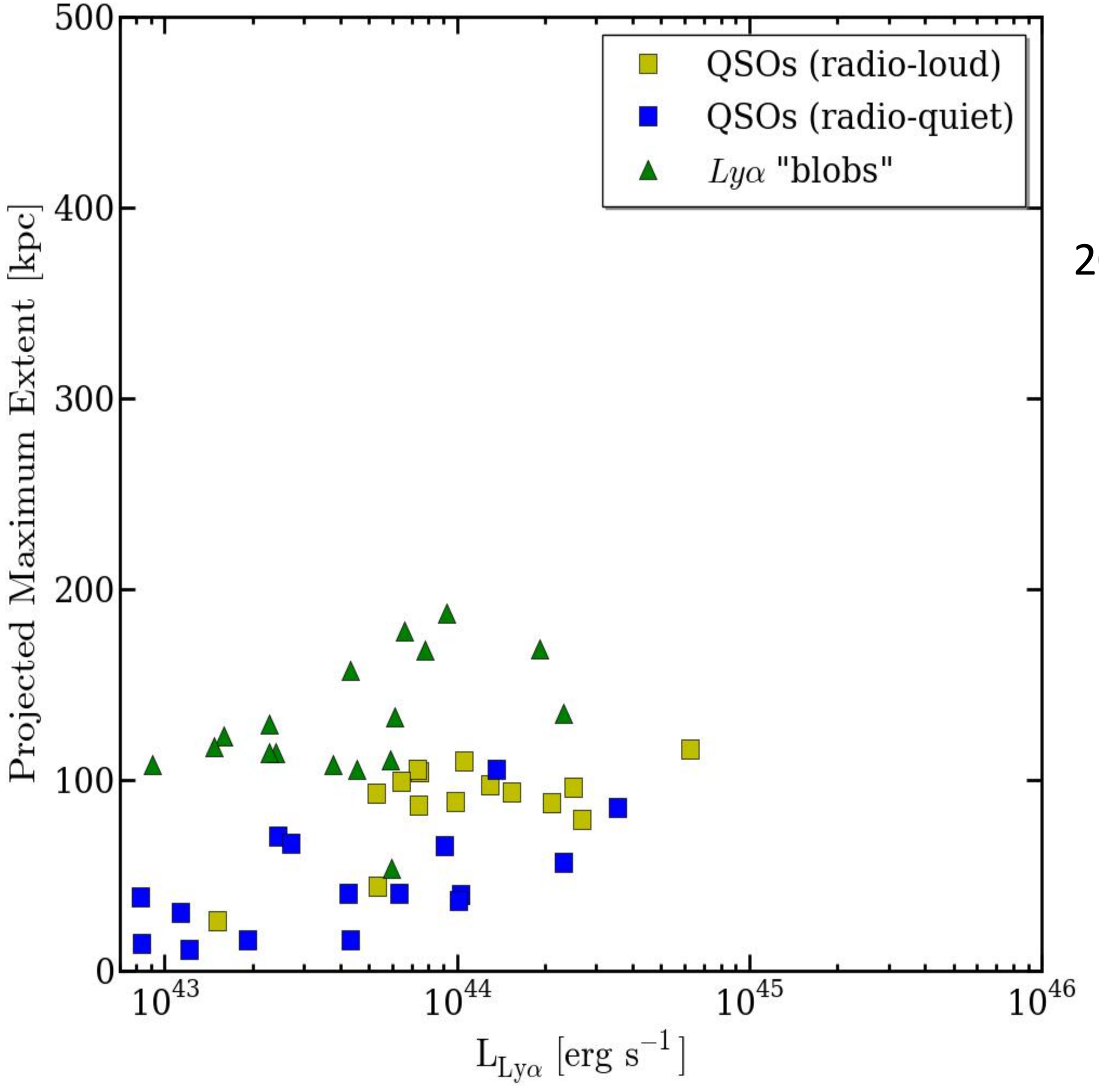
Bergeron+1999

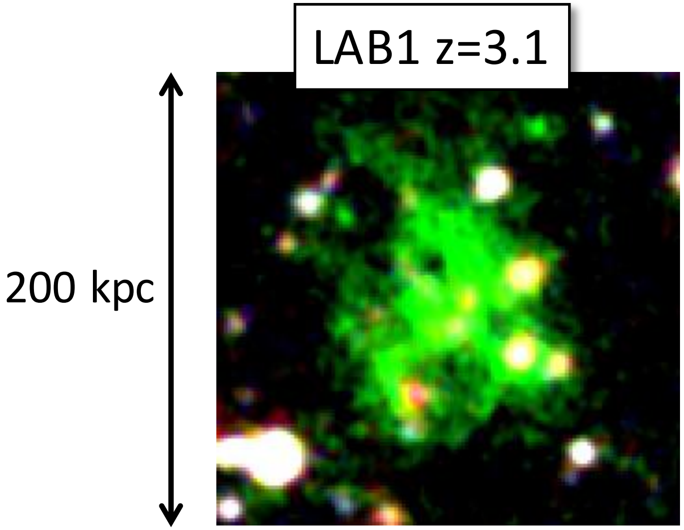
Q0730+257 z=2.686



Heckman+1991

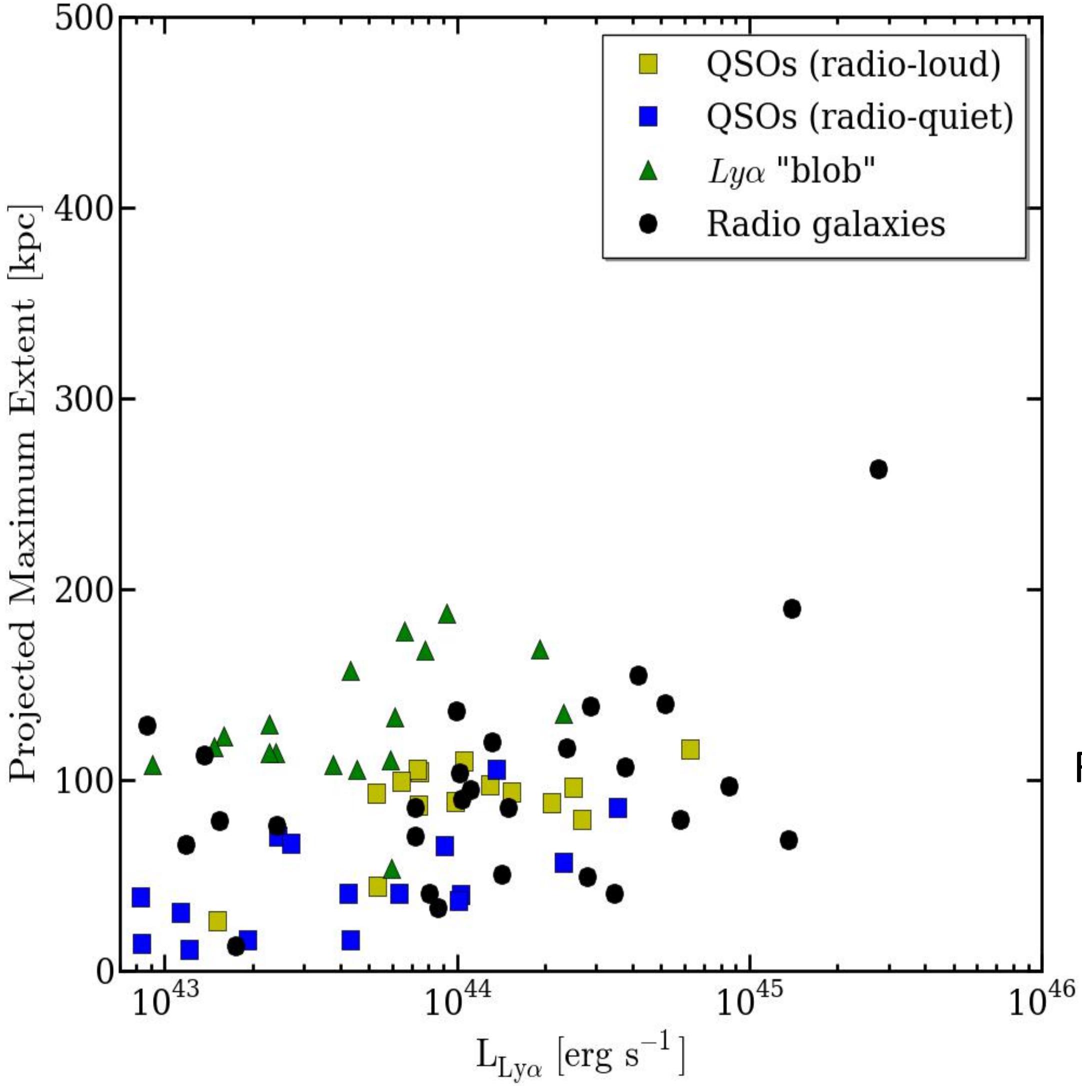
Giant Lyα Nebulae



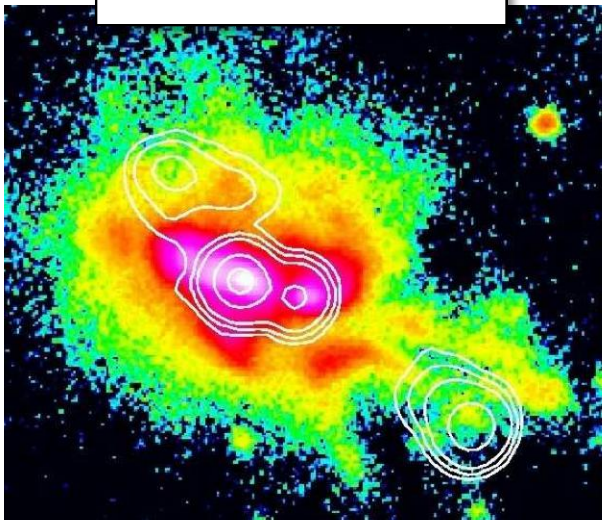


Steidel+2000, Matsuda+2004

Giant Lyα Nebulae



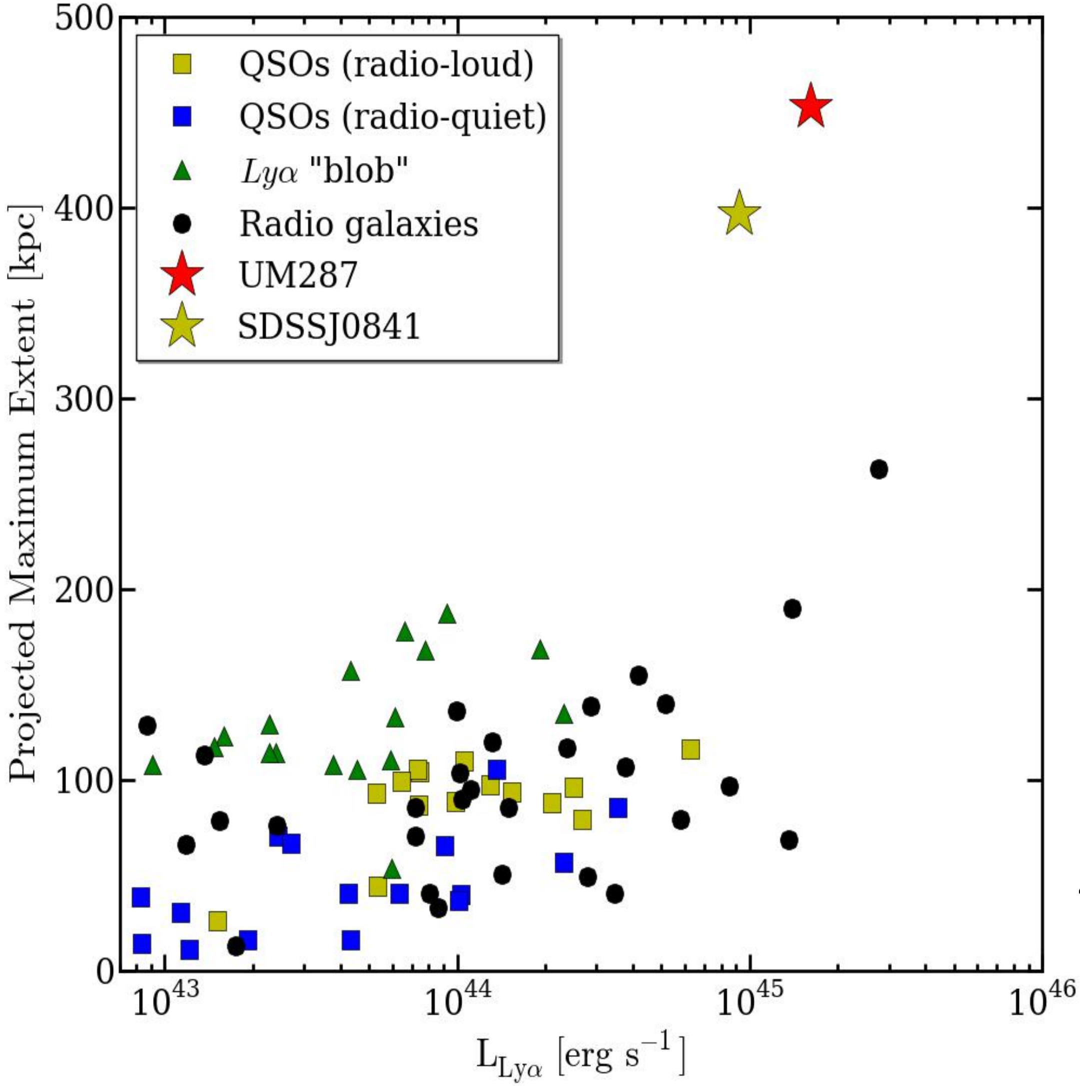
4C 41.17 z=3.8

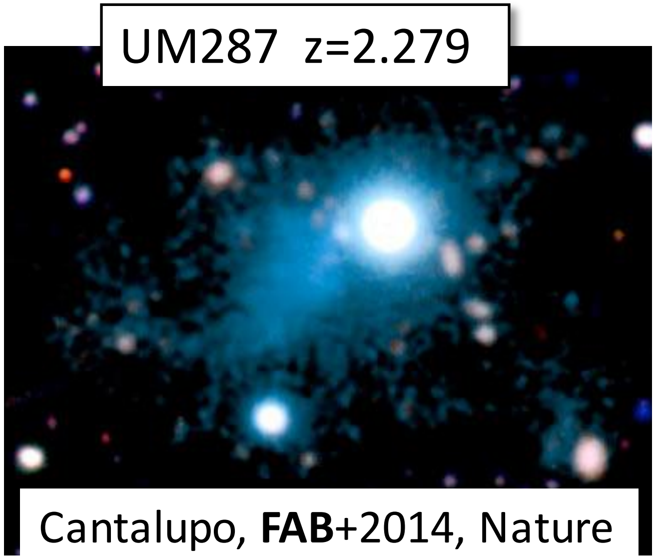


150 kpc

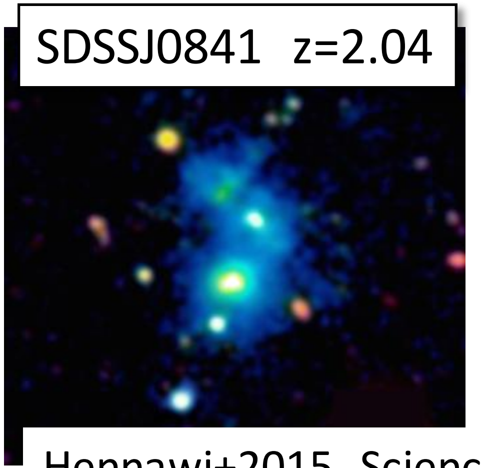
Reuland+2003, Miley&De Breuck2008

Giant Lyα Nebulae





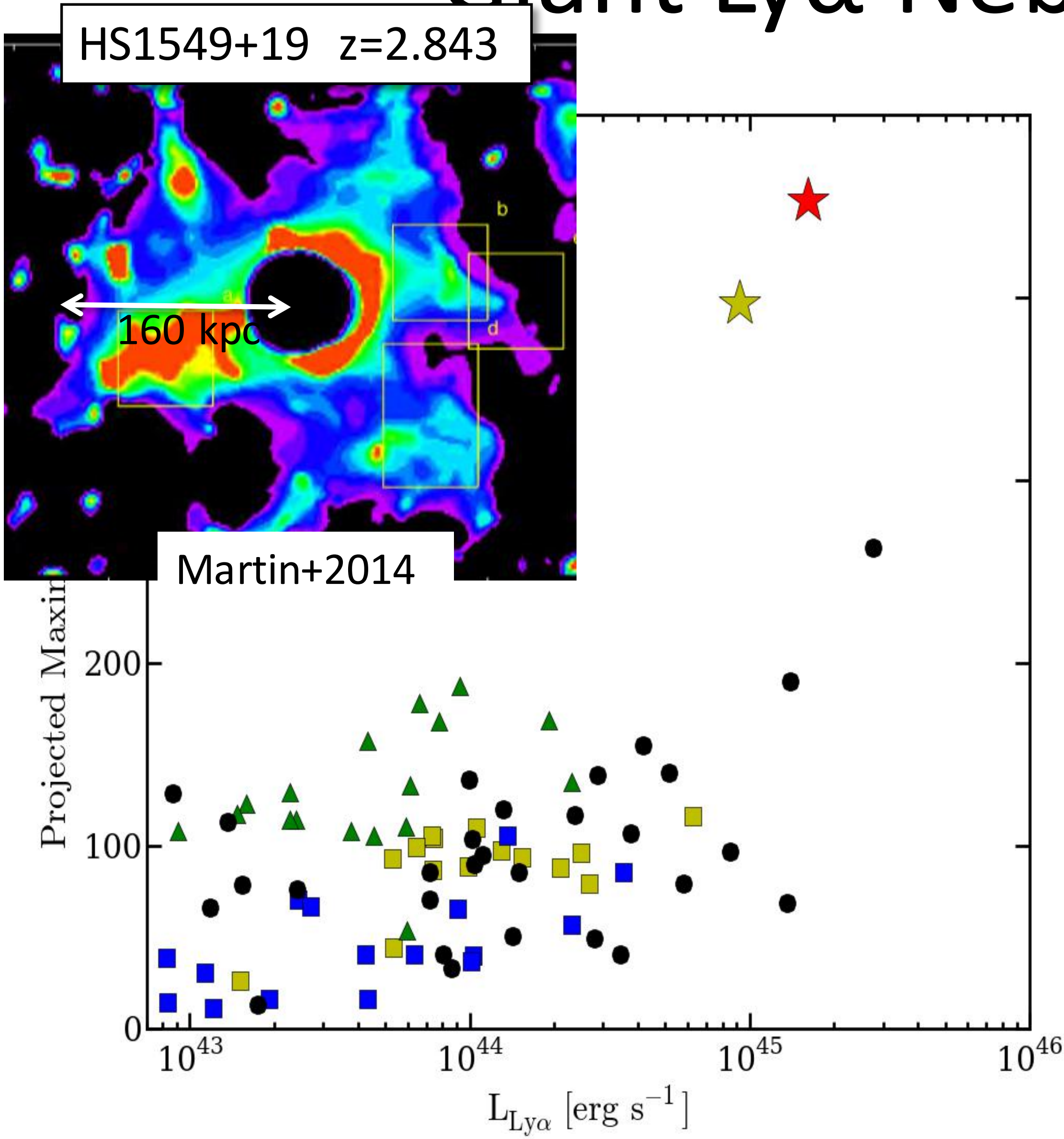
630 kpc

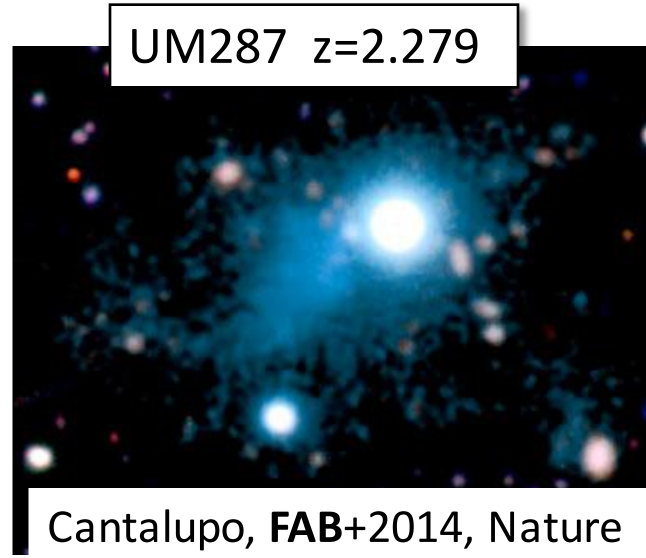


460 kpc

Hennawi+2015, Science

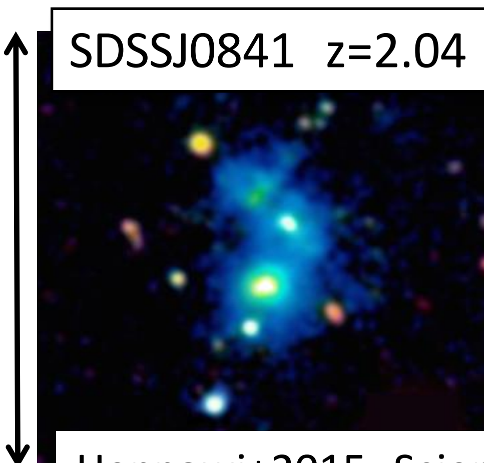
Giant Lyα Nebulae





Cantalupo, **FAB**+2014, Nature

630 kpc



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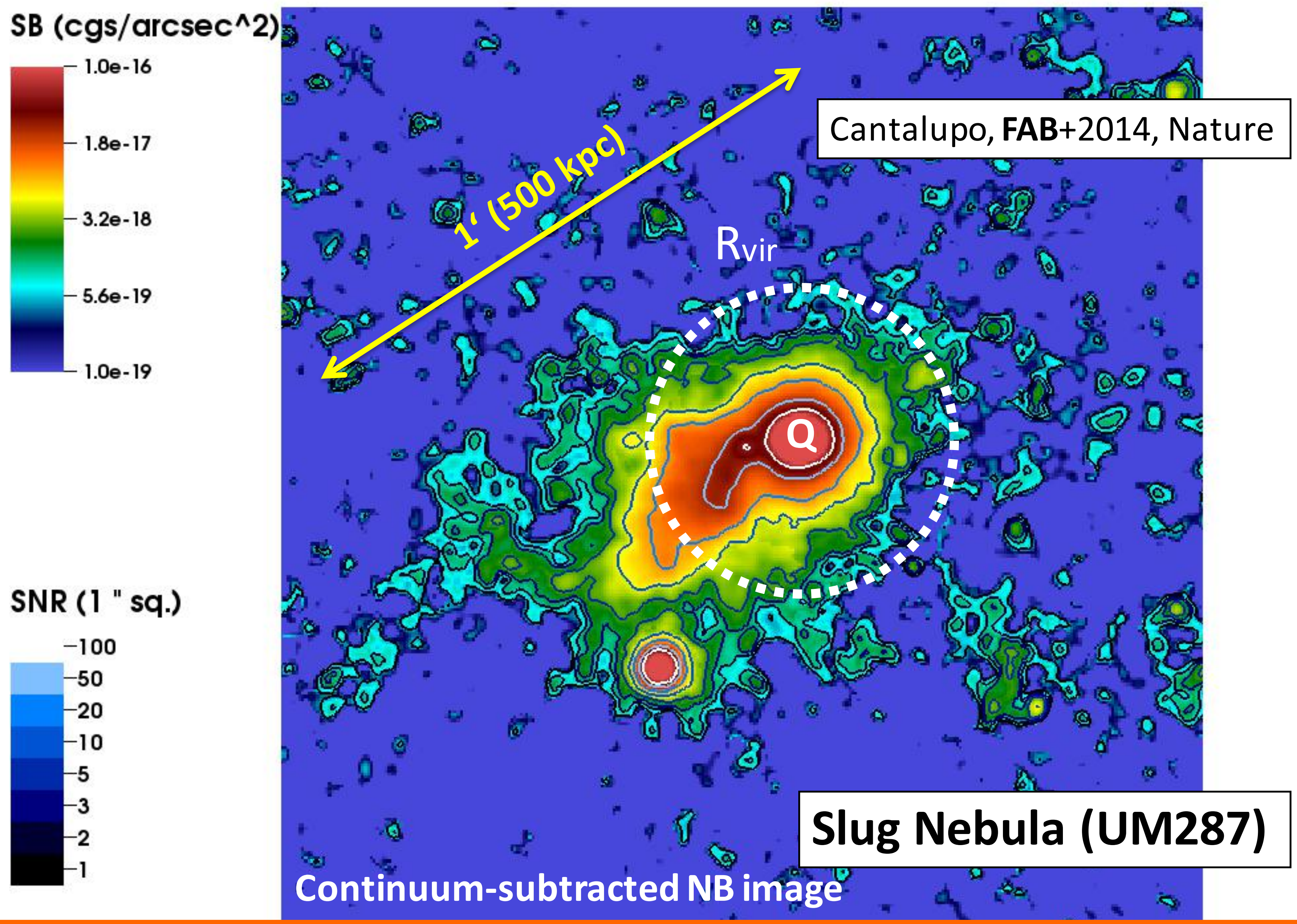
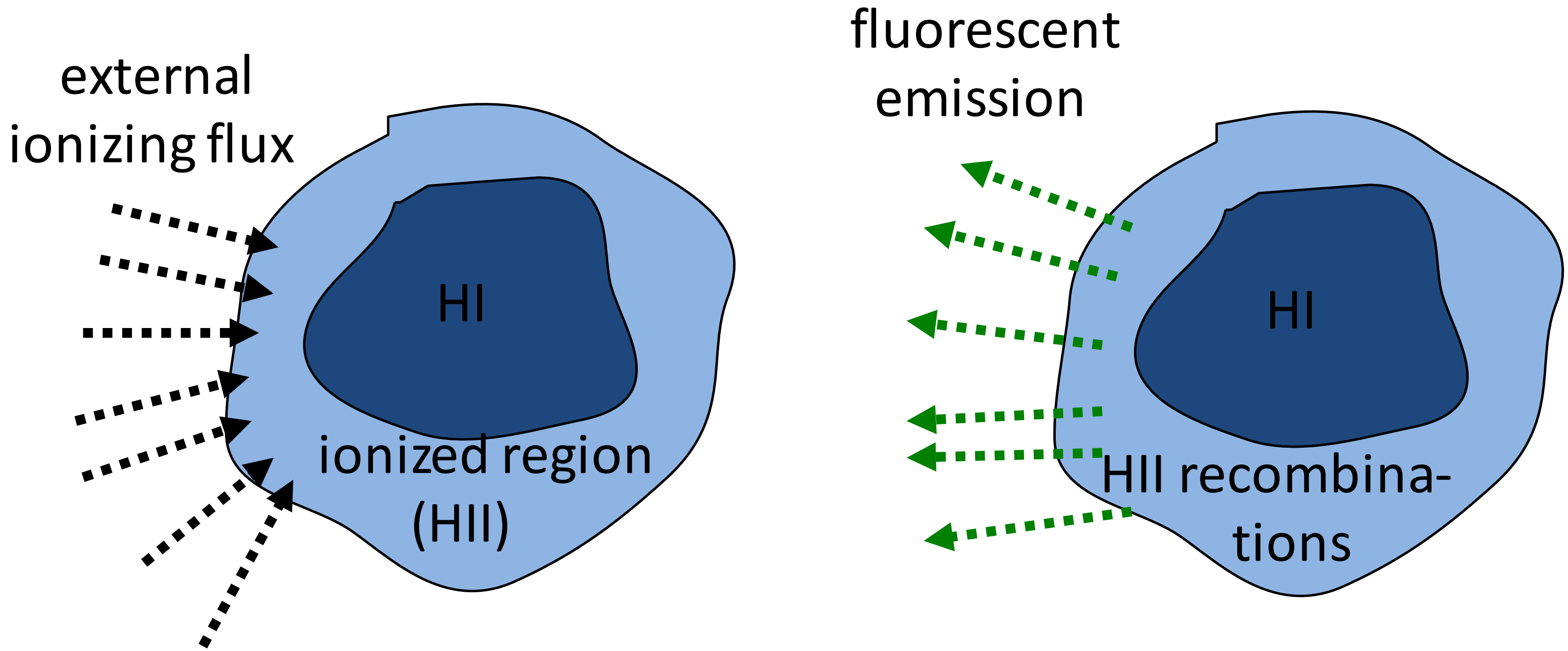
Hennawi+2015, Science


SB (cgs/arcsec^2)
1.0e-16
1.8e-17
3.2e-18
5.6e-19
1.0e-19
SNR (1 " sq.)
100
50
20
10
5
3
2
1
1′ (500 kpc)
Cantalupo, **FAB**+2014, Nature
Rvir
Q
Slug Nebula (UM287)
Continuum-subtracted NB image

Fluorescent Lyα Emission: 2 cases

(*Hogan & Weymann 1987;Gould & Weinberg 1996; Cantalupo+2005*)



a) Optically thin gas (fully ionized): emission proportional to gas density squared

a) Optically thick gas: behaves like a mirror, about 60% of incident ionizing radiation is converted in Lyα

Fluorescent Lyα Emission

Given the luminosity of the QSO, the nebula cannot be optically thick.

Optically thin ($\log N_{HI} << 17.2$)

$$SB_{Ly\alpha} \propto f_c n_H N_H$$

$$M_c = \pi R^2 f_C N_H \frac{m_p}{X}$$

Optically thick ($\log N_{HI} >> 17.2$)

$$SB_{Ly\alpha} \propto f_c L_{\nu_{LL}}$$

The Lyα emission would have been much brighter than observed.

FAB+2015b**;** Hennawi+2015**; FAB**+2016

Why CIV (1549 Å) and HeII (1640 Å)?

- If present, should be the strongest lines after Lyα (redshifted into the optical)

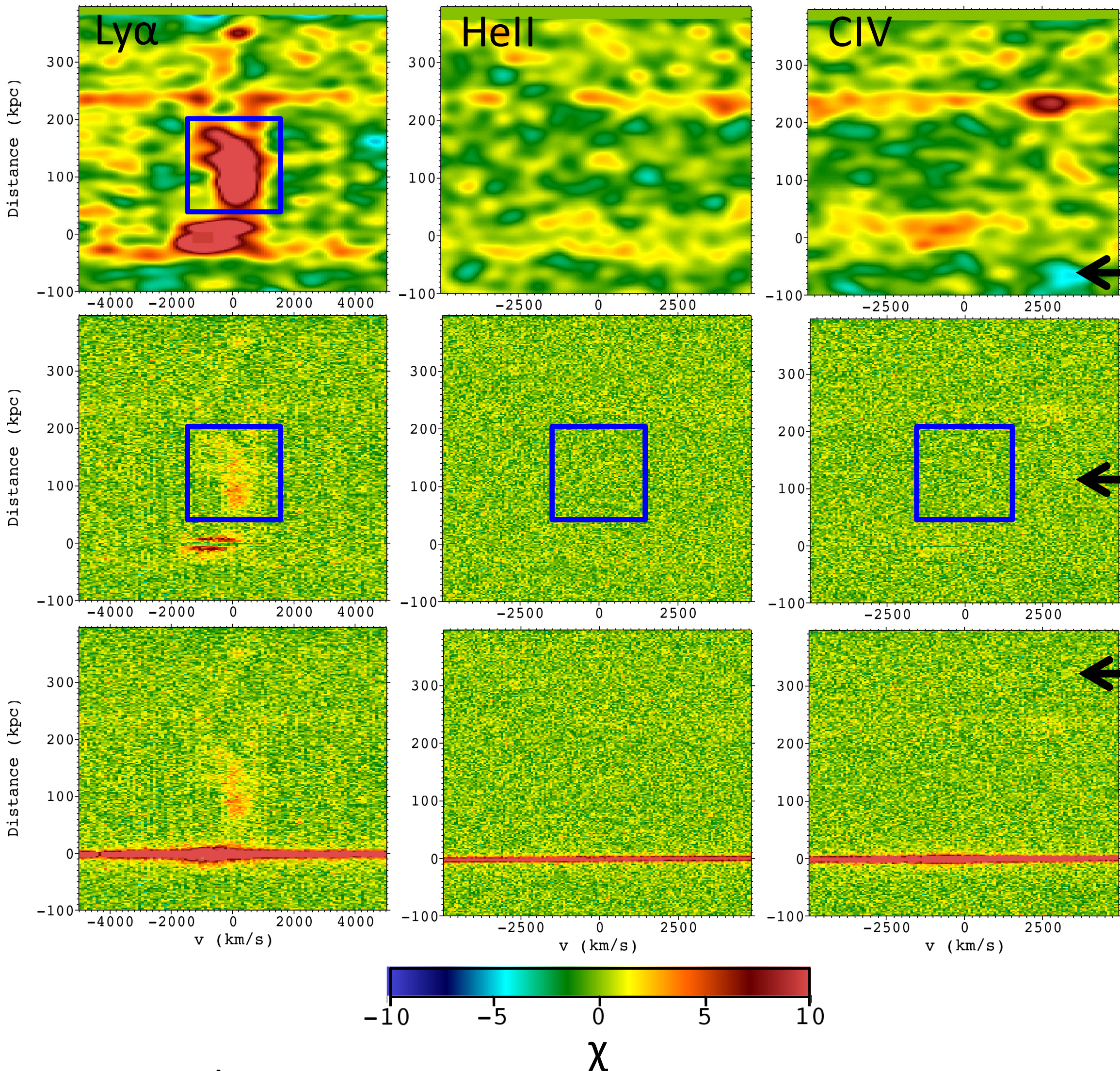
- Extent of HeII ⟶ probe radiative transfer of Lyα

- HeII/Lyα : - hardness of the ionizing sources
  - density indicator
  - speed of shocks

- CIV/HeII : - hardness of the ionizing sources
  - speed of shocks
  - metallicity indicator
- Extent of CIV : metal enrichment + outflows scale

Slug Nebula(UM287)

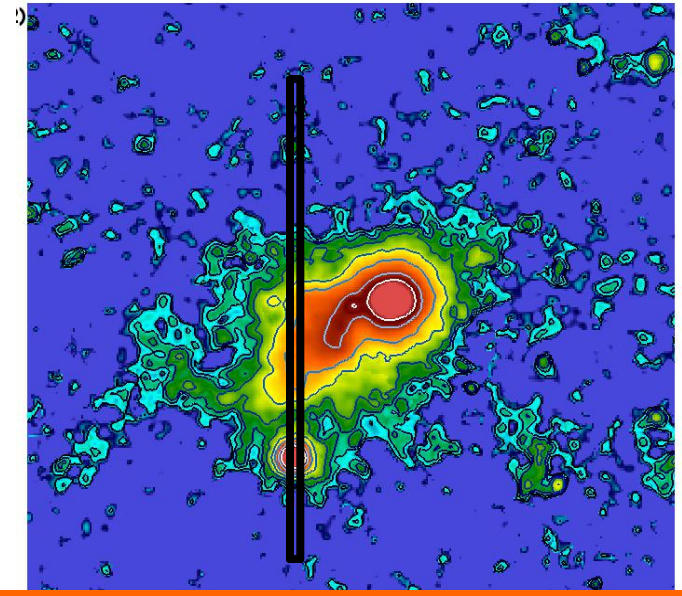
2 hours on LRIS/Keck



smoothed

psf subtracted

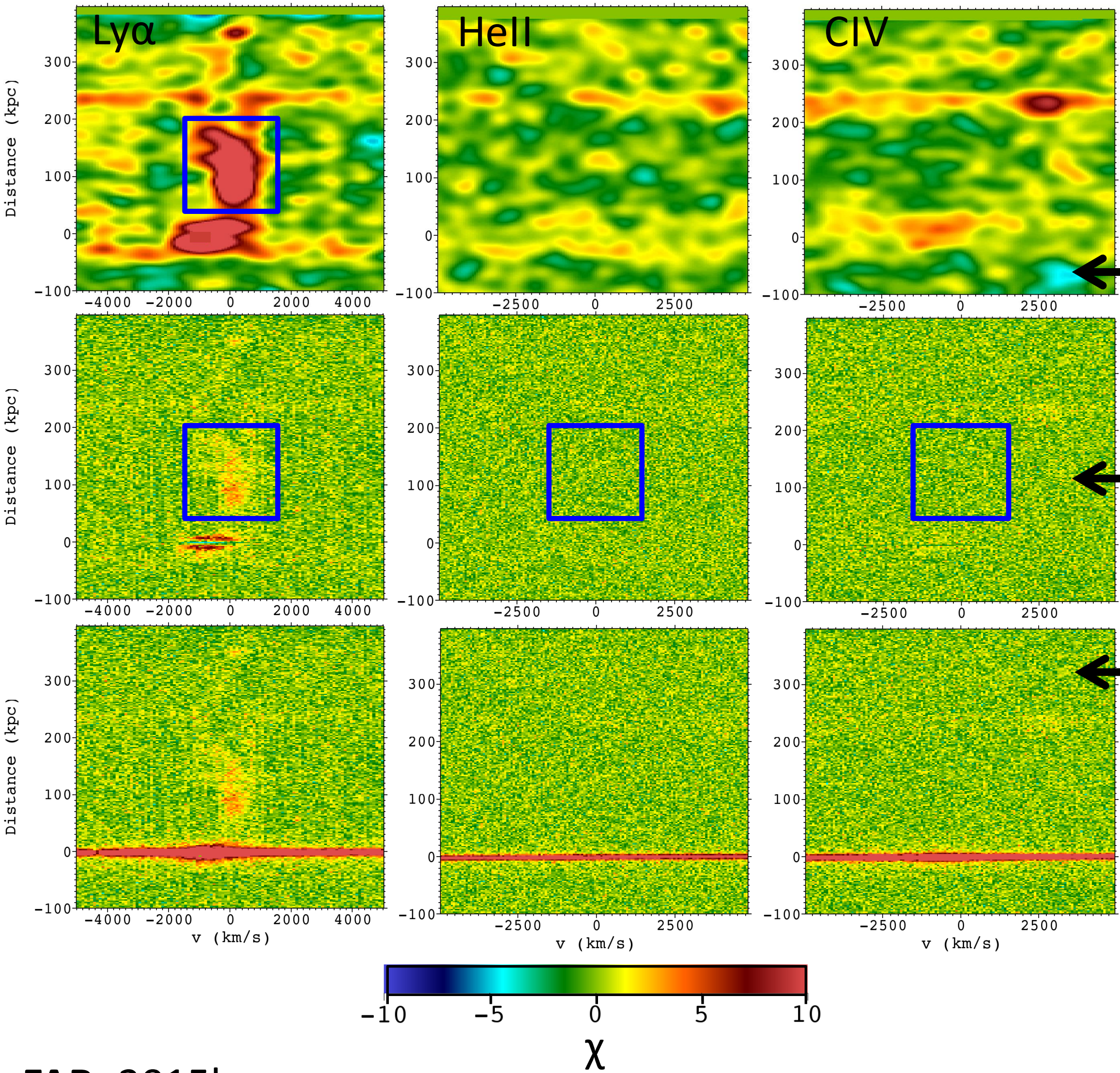
2d spectrum



FAB+2015b

SB_{Lya} = 7.04 x 10^{-18} cgs/arcsec^2

(In agreement with NB imaging)



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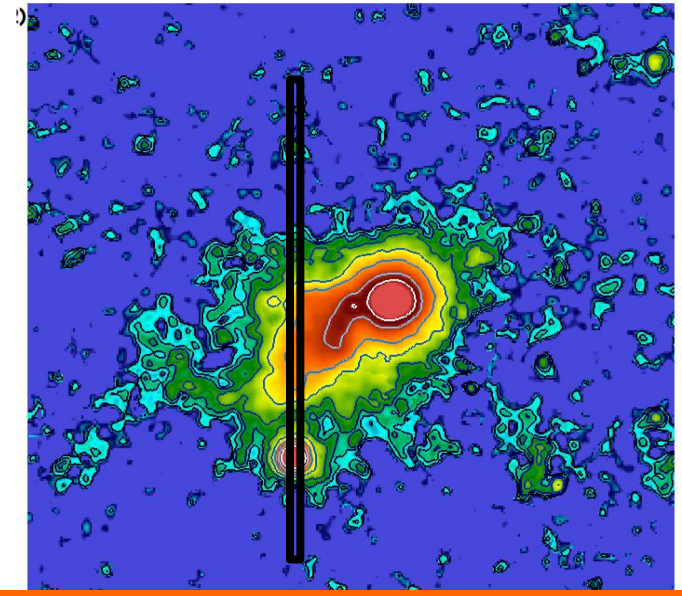
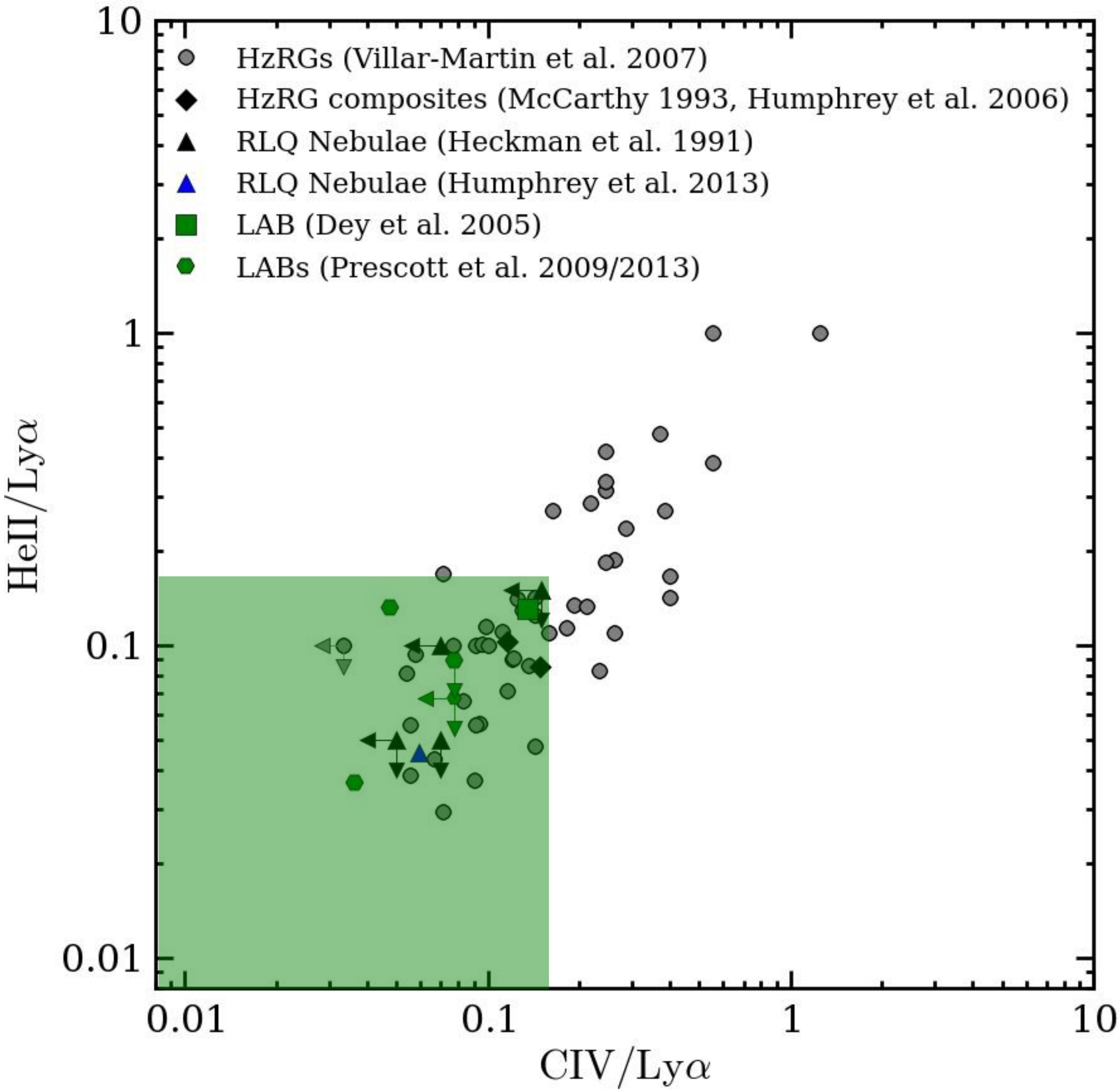


FAB+2015b

HeII/Lyα < 0.18 and CIV/Lyα < 0.16

(3σ limits)

Comparison with other Lyα Nebulae



FAB+2015b

HzRG = High-z Radio Galaxies

RLQ = Radio-Loud Quasar

Photoionization Modeling of Extended Emission

$R \sim 160$ kpc

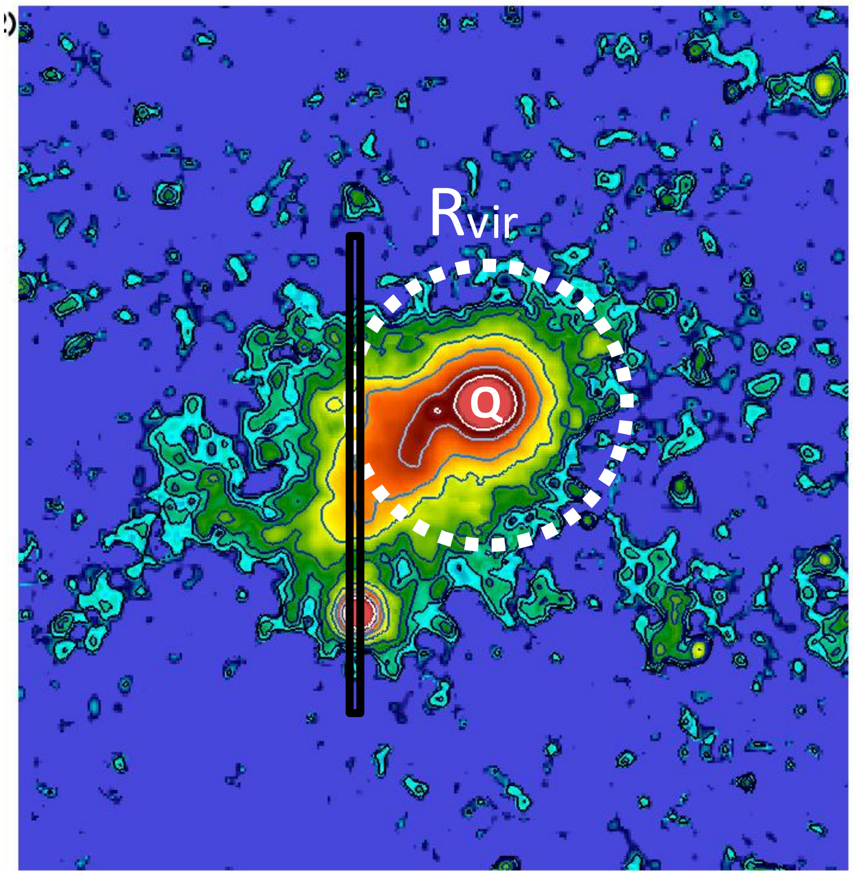
n_H

N_H

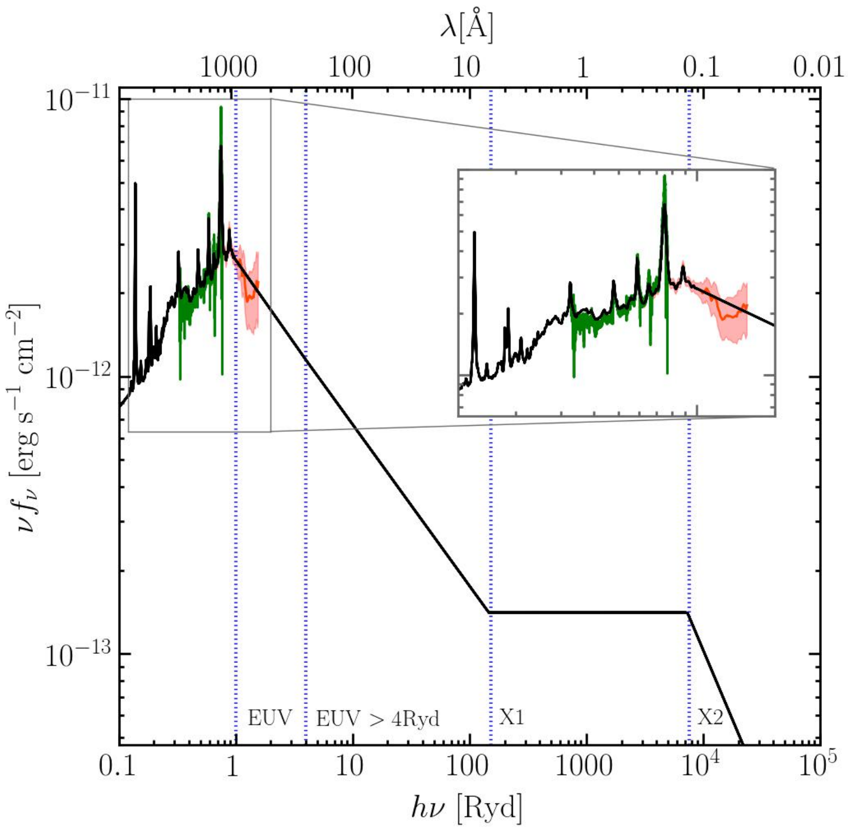
f_C

L_ν (or $i_{QSO} = 17.28$)

$$U = \frac{\Phi}{c n_{\rm H}} \propto \frac{L_\nu}{n_{\rm H}}$$

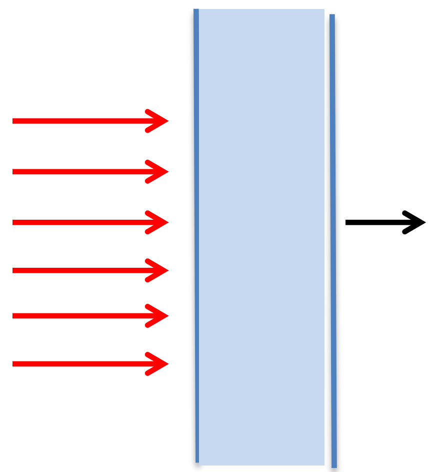


Photoionization Modeling of Extended Emission: Cloudy (Ferland+2013)

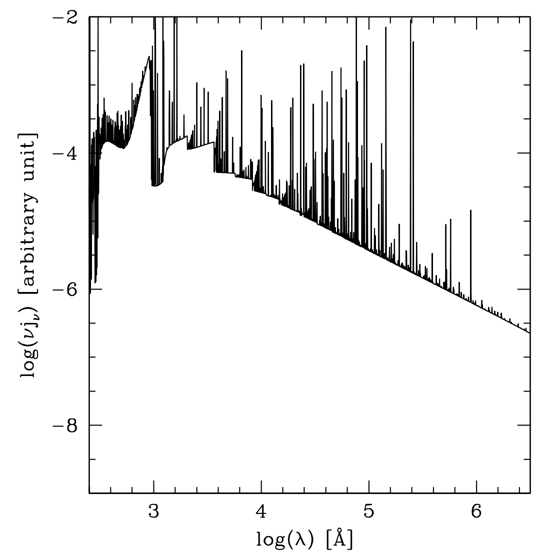


α_{EUV}=-1.7

Lusso+2016



Slab – plane parallel geometry



Photoionization Modeling: Optically Thin Models

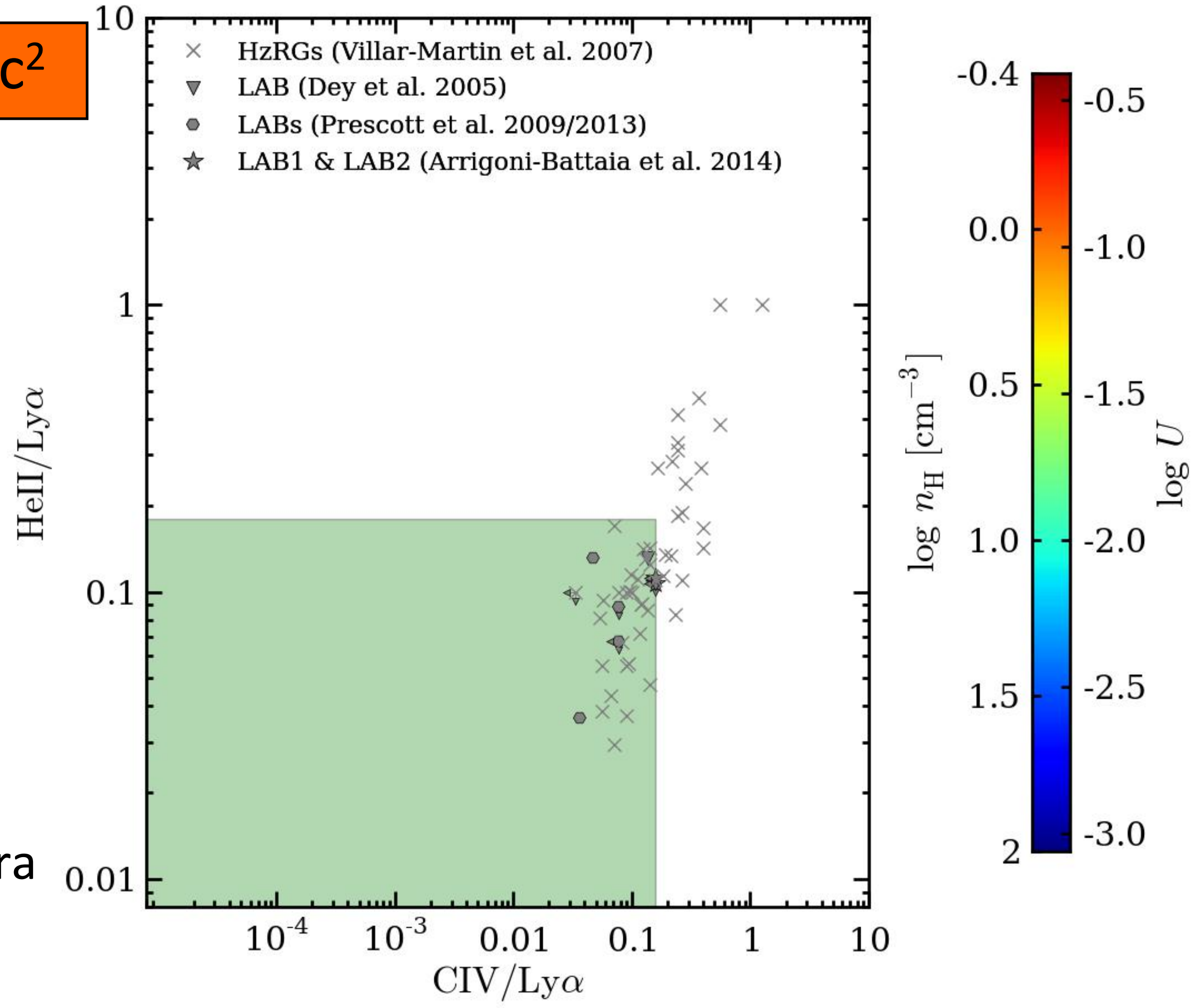
FAB+2015b

SB$_{Ly\alpha}$~ 7 x 10^{-18} cgs/arcsec^2

$$\mathrm{SB}_{Ly\alpha} \propto f_c n_H N_H$$

Model parameters:

- logN_H= 18 to 22
- nH = 0.01 to 100 cm^{-3}
- f_C = 1.0
- Z = 0.001, 0.01, 0.1, 1 $Z_\odot$
- Three different input spectra



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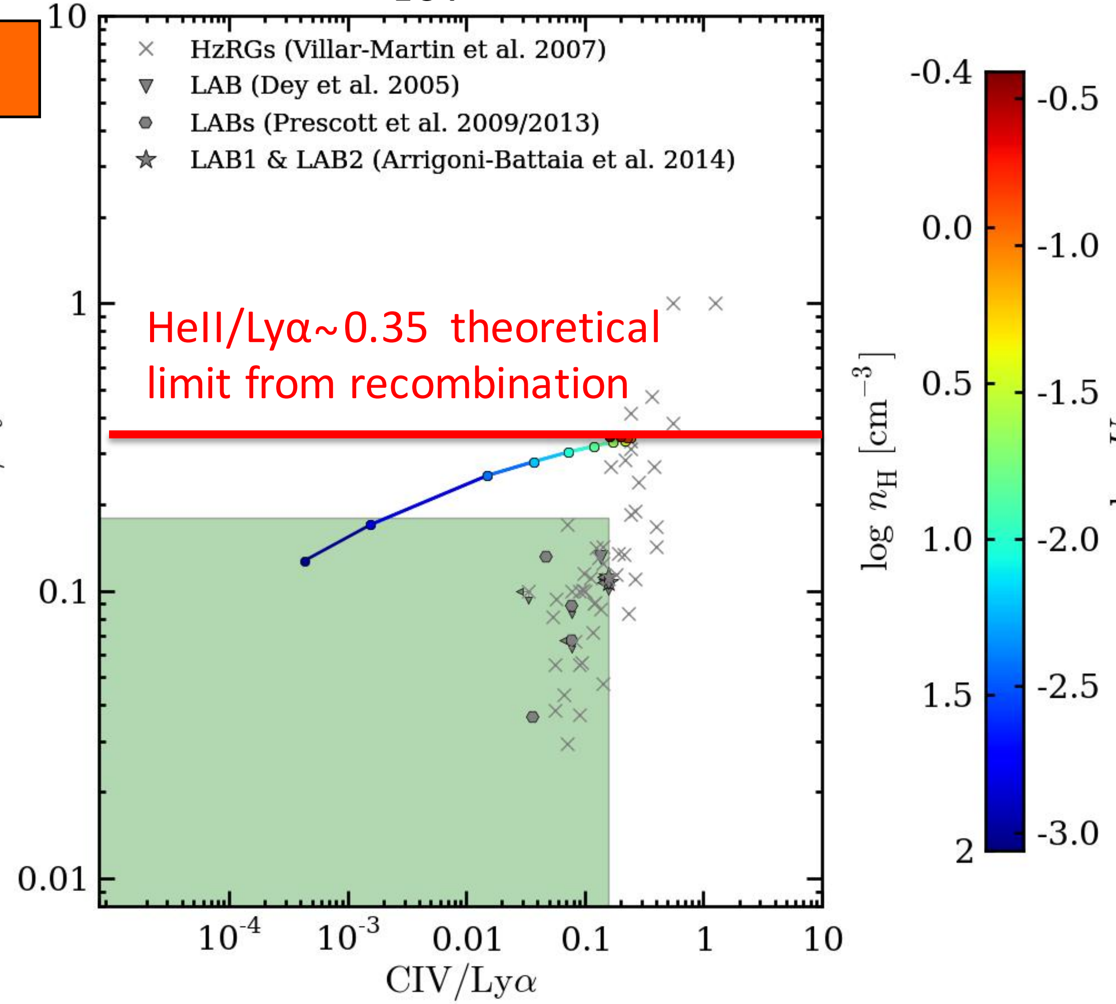

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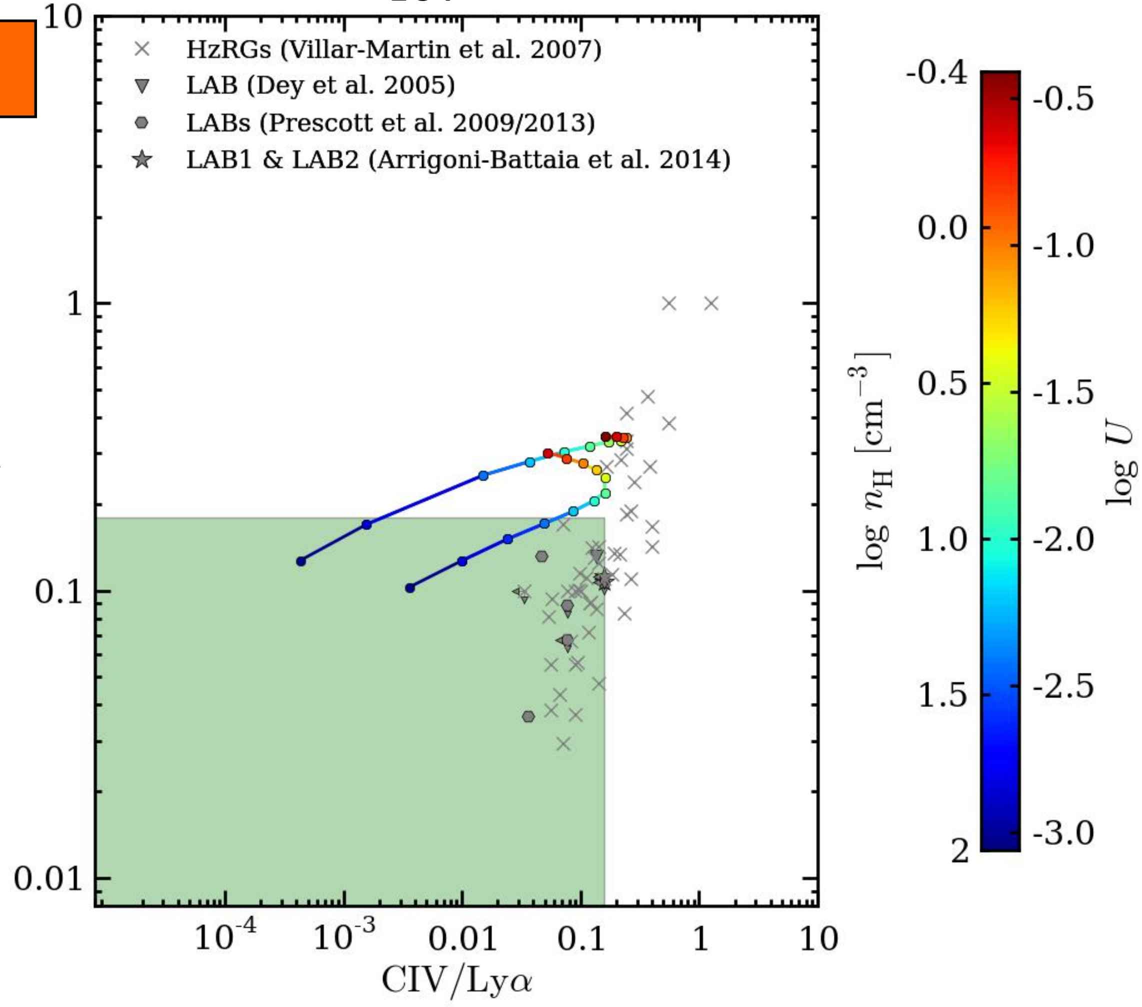

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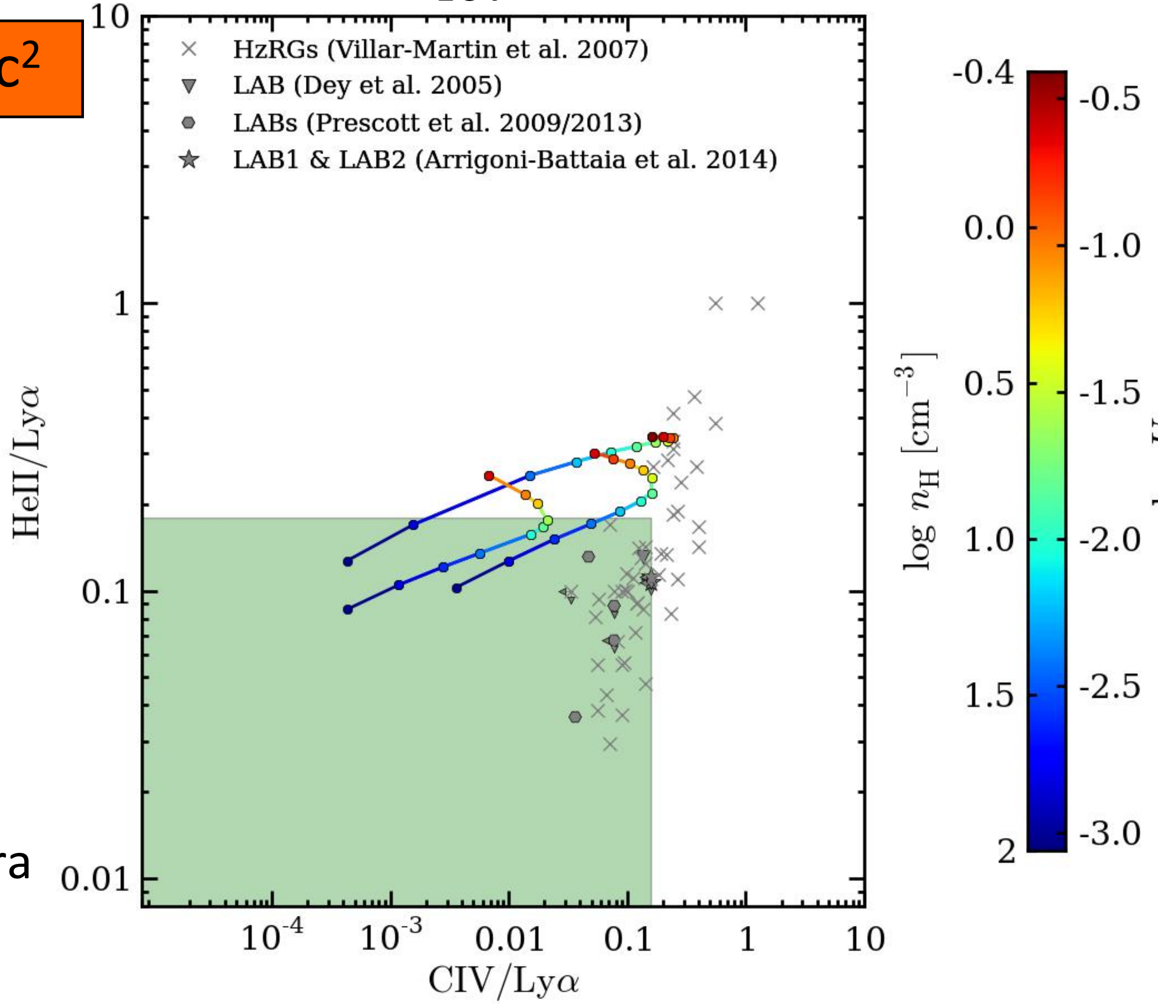

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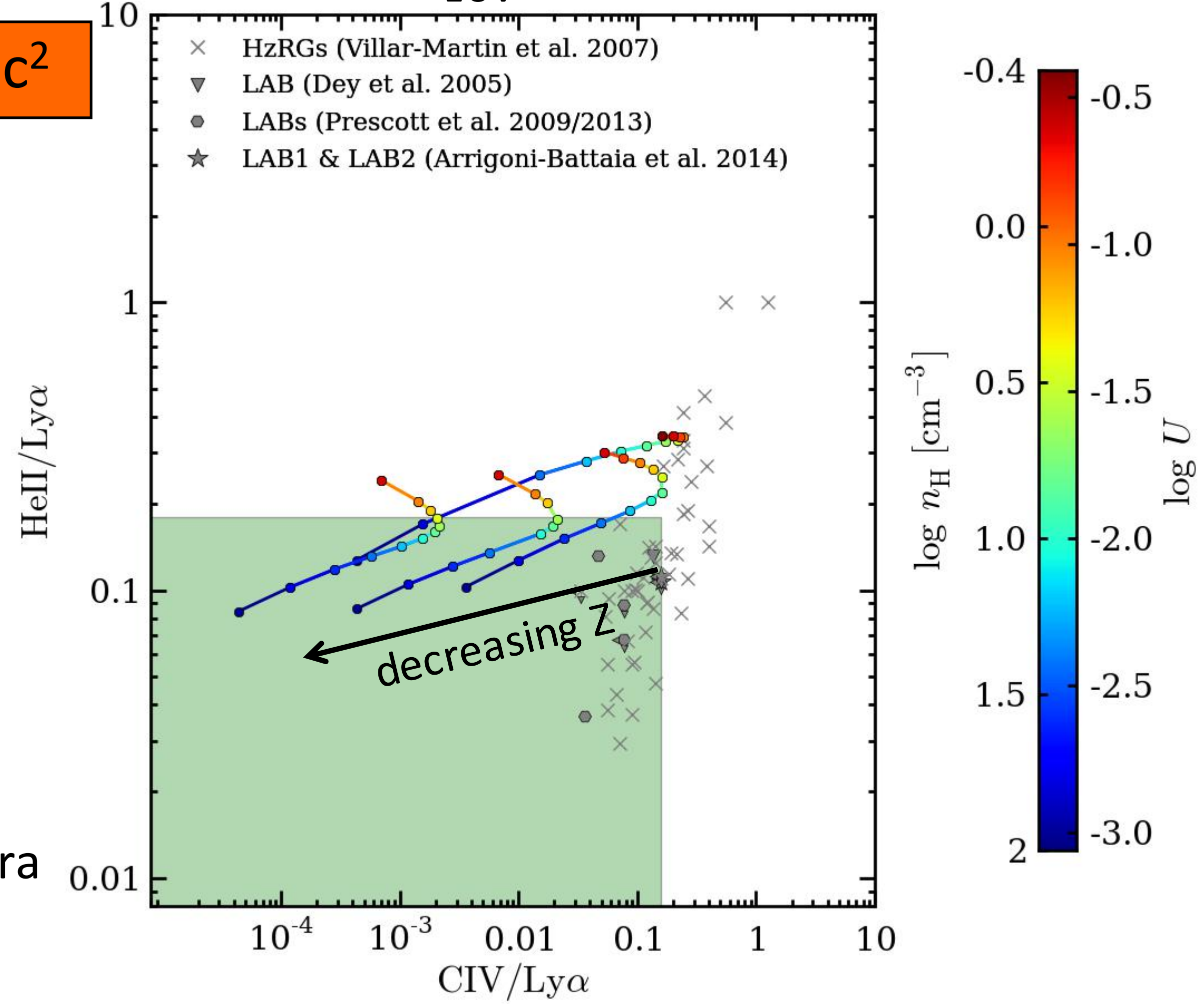
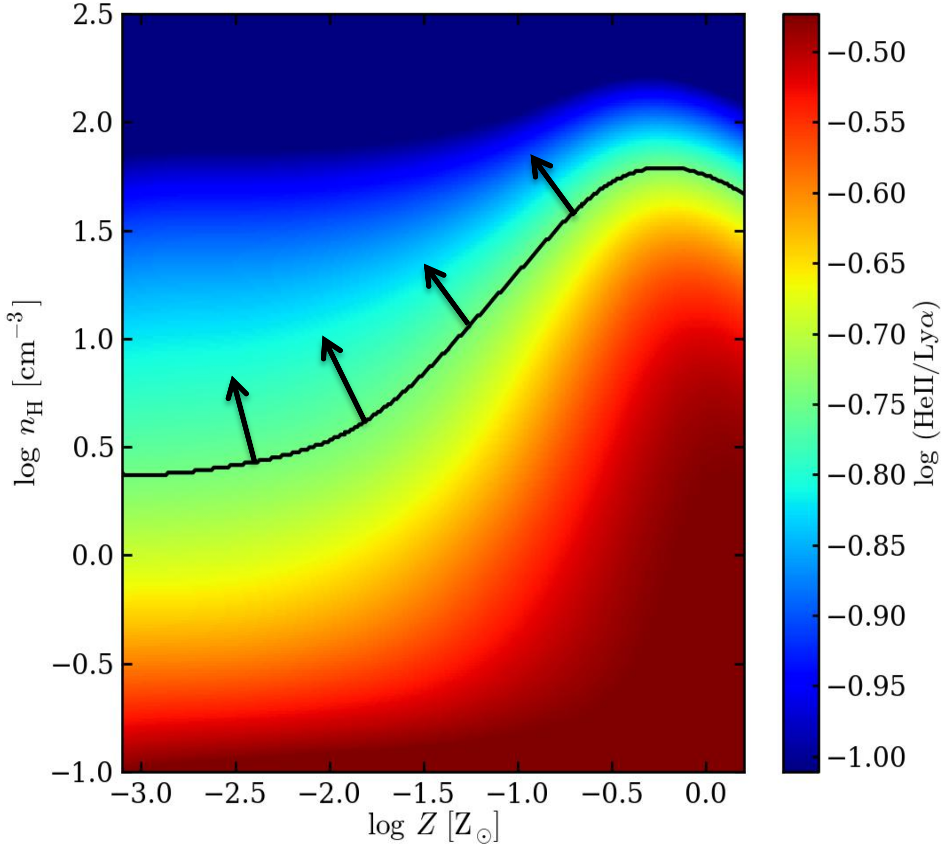


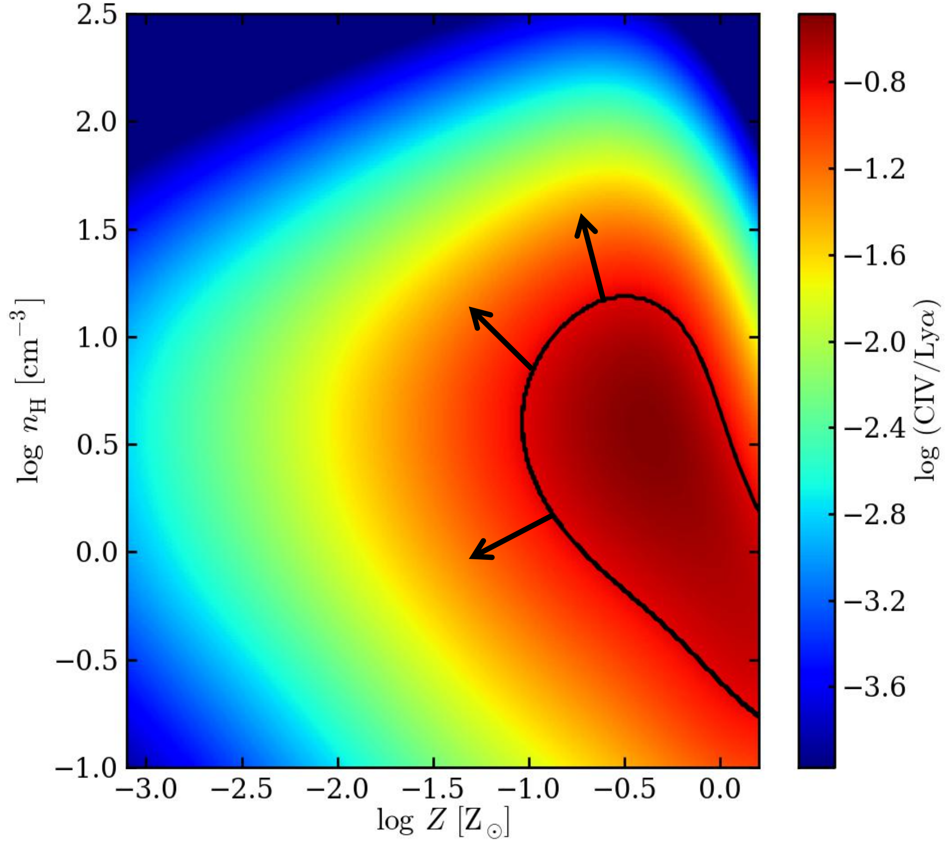
Models require high gas densities

$SB_{Ly\alpha} \sim 7 \times 10^{-18}$ cgs/arcsec^2

HeII/Lyα < 0.18

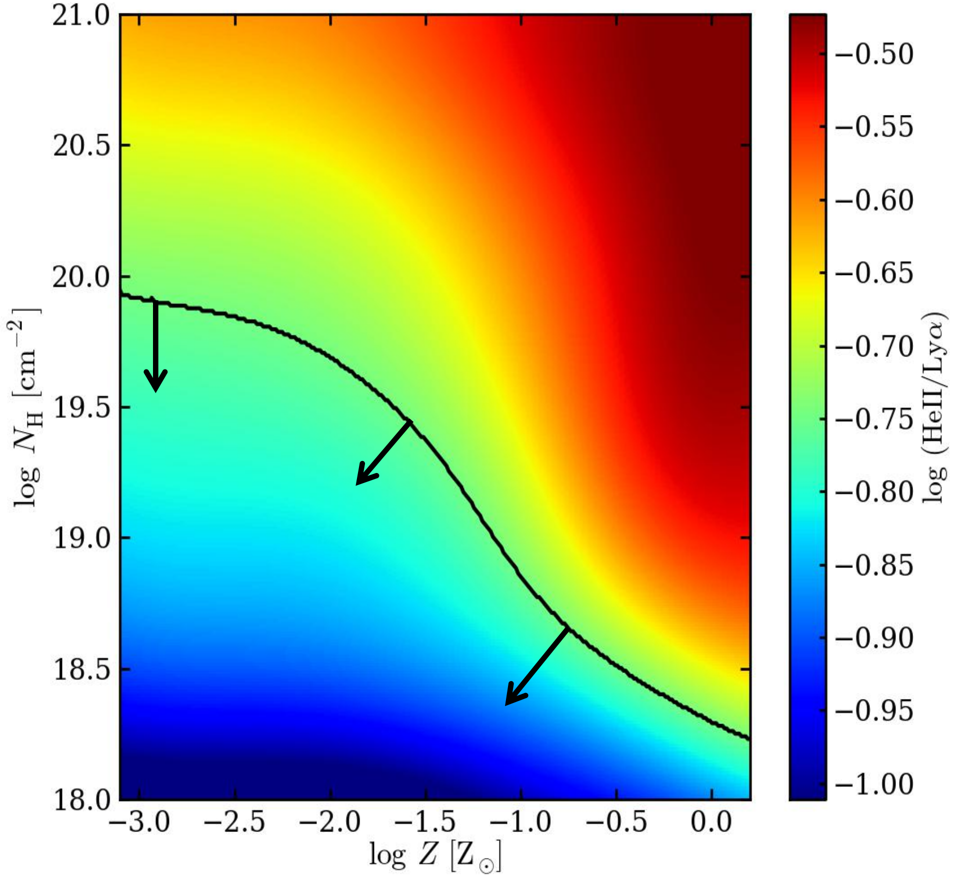


CIV/Lyα < 0.16



Large Reservoir of Cool (10^4 K) Gas

HeII/Lyα < 0.18



$N_H < 10^{20}$ cm^{-2}

$M_{cool} < 6.4 \times 10^{10}\ M_\odot$

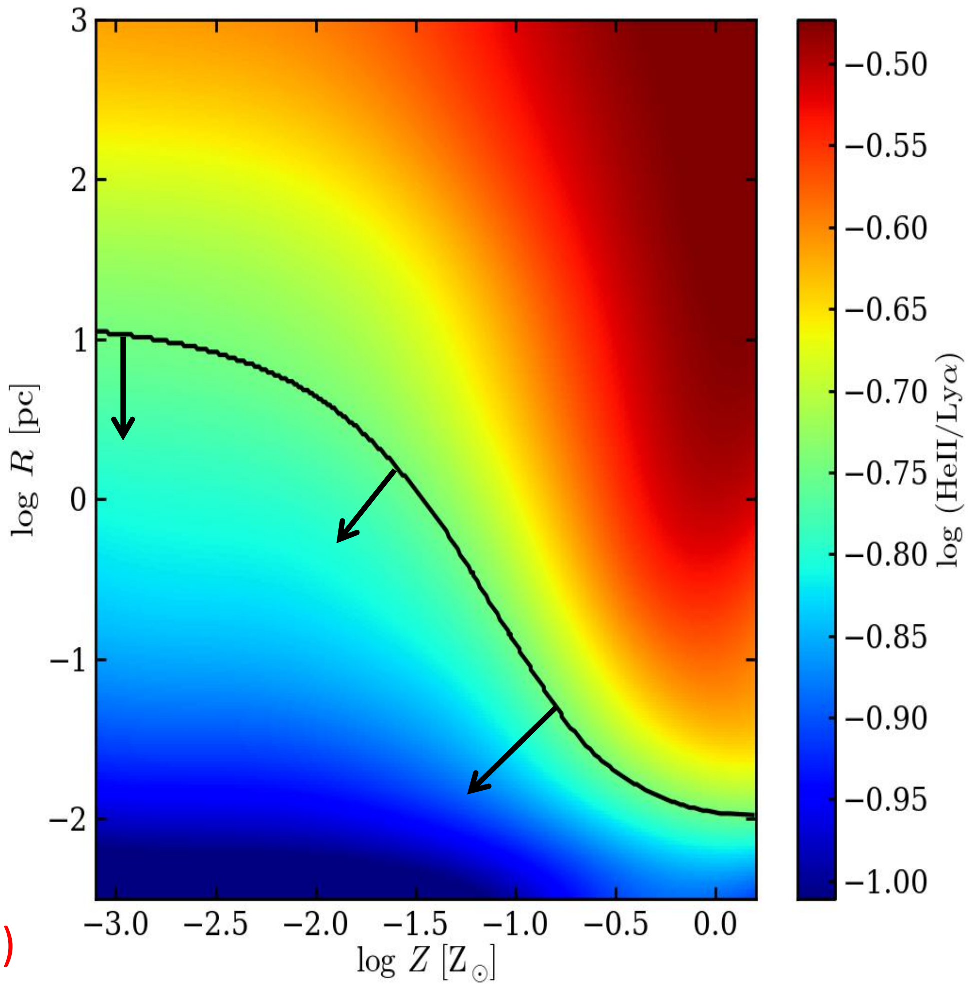
(rough estimate for the whole nebula)

Models require clouds with parsec size

$SB_{Ly\alpha} \sim 7 \times 10^{-18}$ cgs/arcsec^2

$$R \approx \frac{N_H}{n_H} \ll 1 \text{ kpc}$$

HeII/Lyα < 0.18



Cosmological simulations miss subkiloparsec gas-clumps...

How important is the physics on these scales for simulations?
(see also Chrighton+2015 and Hennawi+2015)

Take-Home Messages:

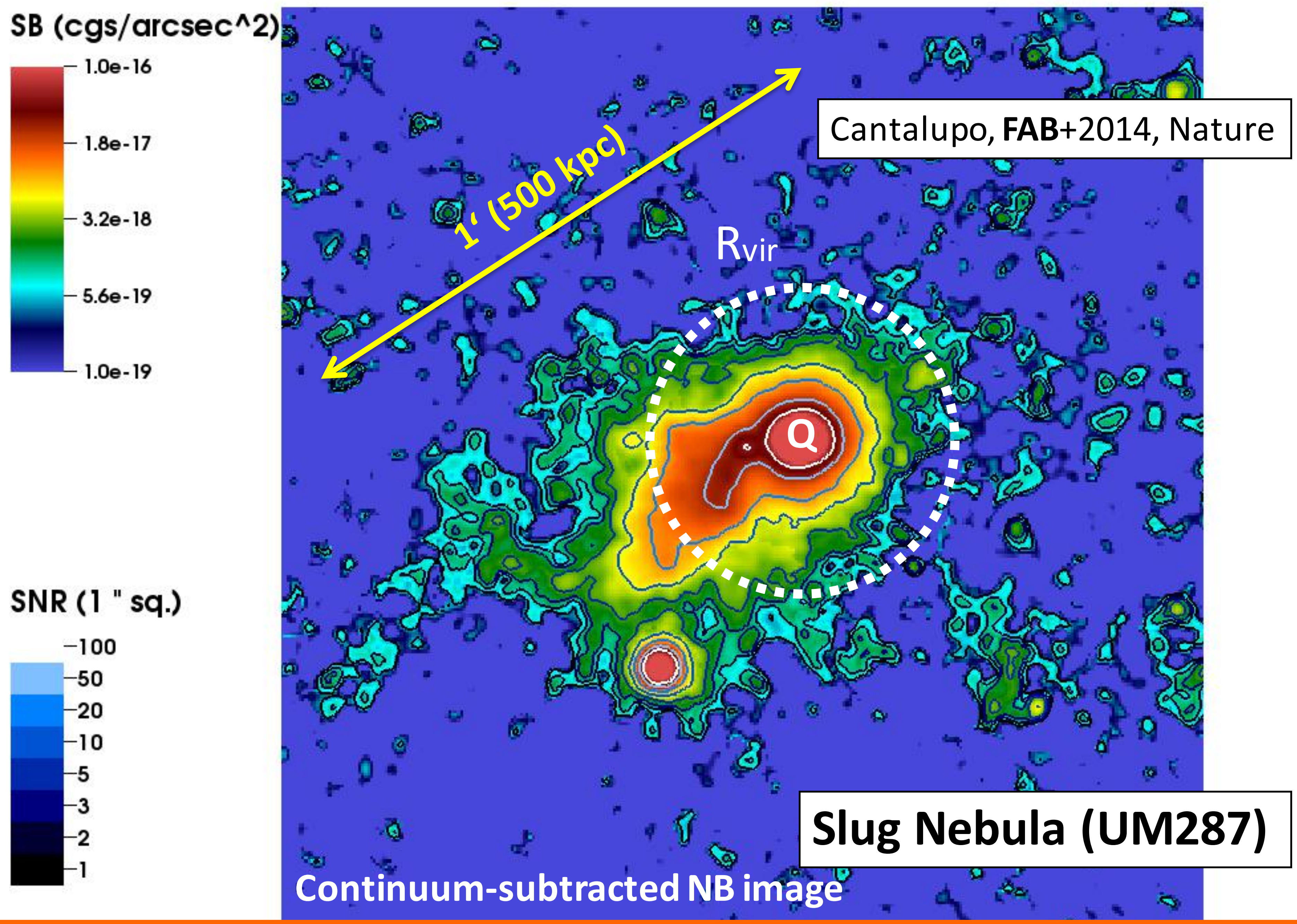
- The nebula should be illuminated by the QSO

⬇

The nebula is optically thin

- Optically-thin models suggest:

1. $n_H > 3\ cm^{-3}$
2. $N_H < 10^{20}\ cm^{-2}$
3. $R < 20\ pc$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2
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1' (500 kpc)
Cantalupo, FAB+2014, Nature
Rvir
Q
Slug Nebula (UM287)
Continuum-subtracted NB image

FLASHLIGHT-GMOS: a Narrow-band Survey

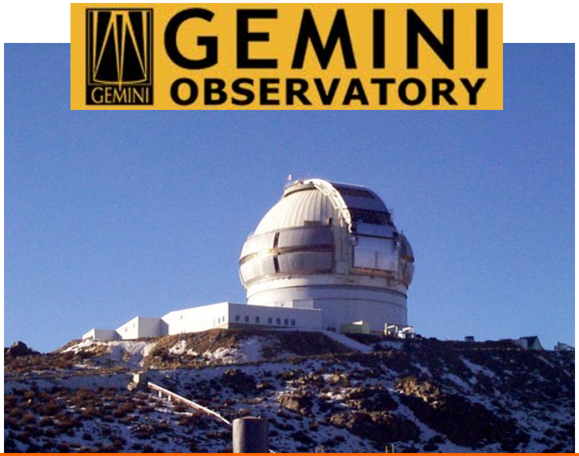
FAB+2016

Targets: brightest SDSS QSOs at z = 2.253 → Radio-quiet Accurate z (Mg, NIR)

Sample: 15 QSOs on GMOS-S

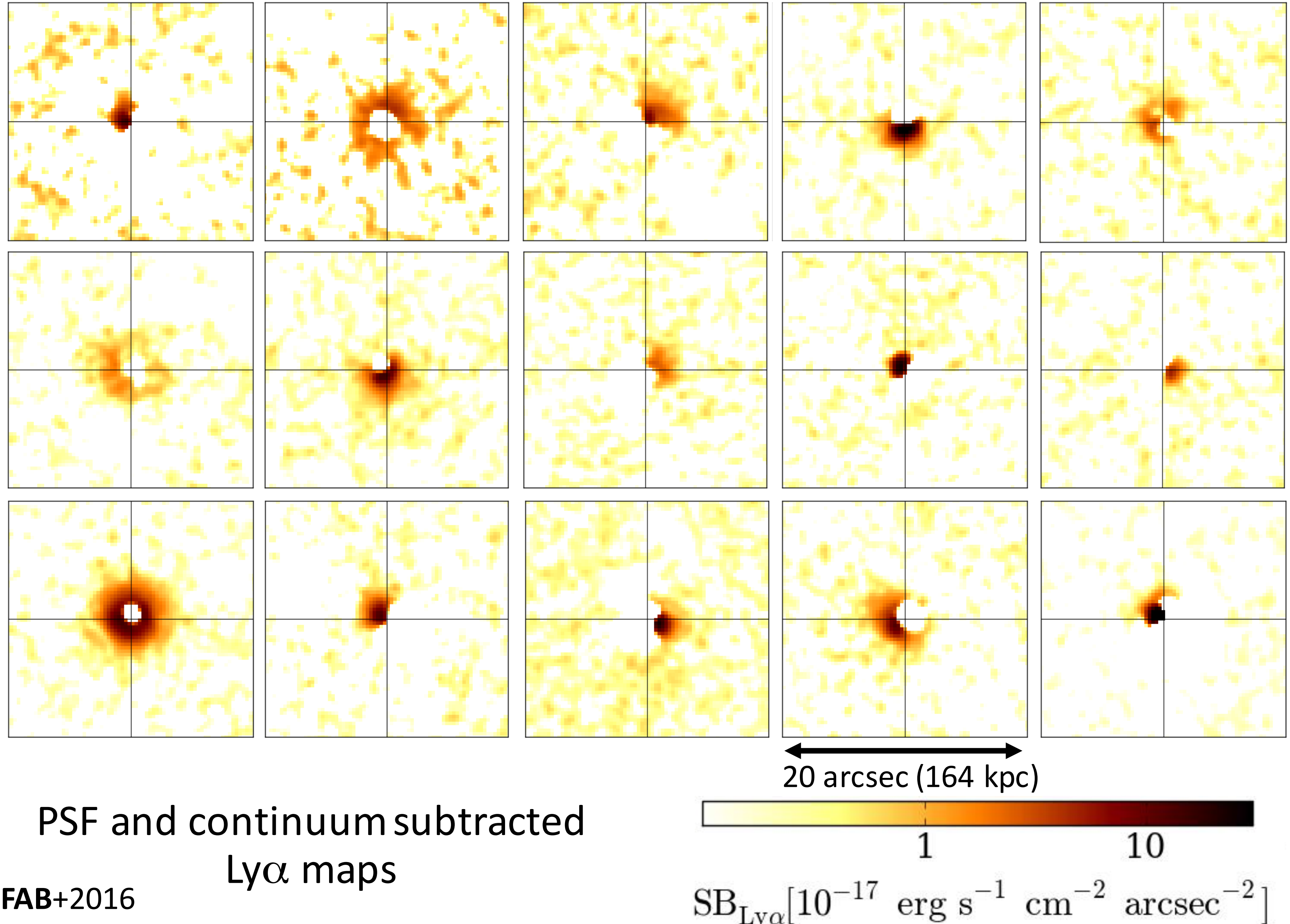
How: custom-built narrow-band filter (λ = 3955Å; FWHM = 32.7 Å)

$1\sigma \sim 2\text{-}4.5 \times 10^{-18}$ erg/s/cm^2/arcsec^2
(1 arcsec^2 aperture)



Exp. Time (narrow-band) = 2-5 hrs

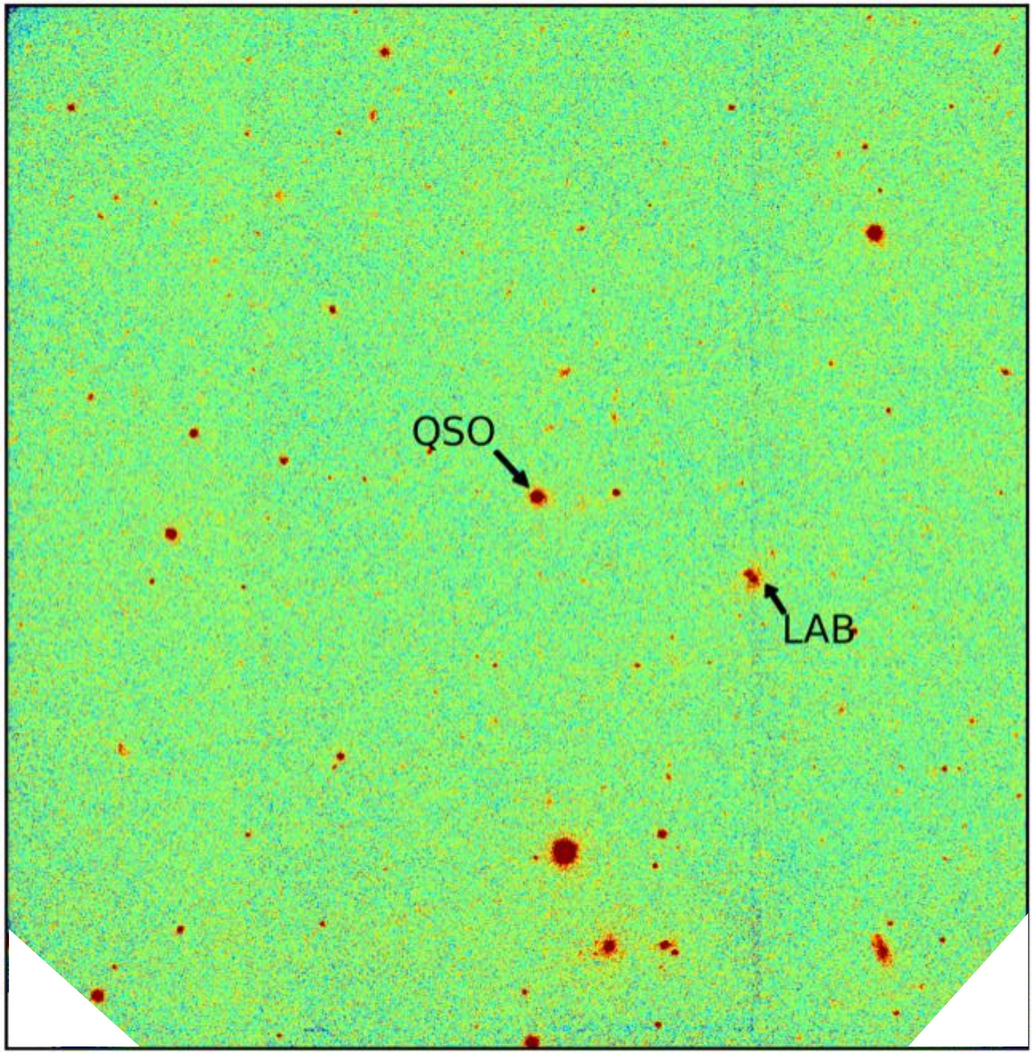
Exp. Time (g-band) = 0.7-3 hrs



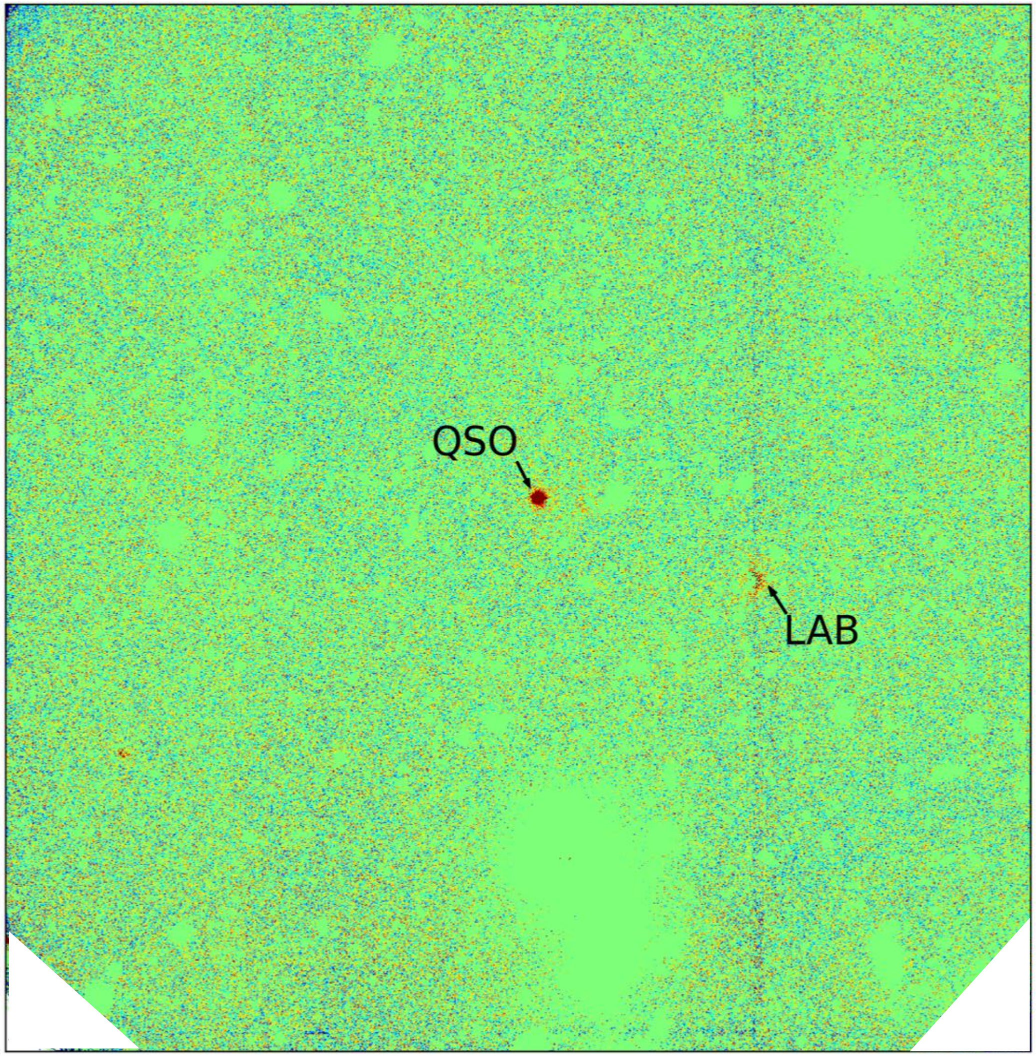
PSF and continuum subtracted Lyα maps

FAB+2016

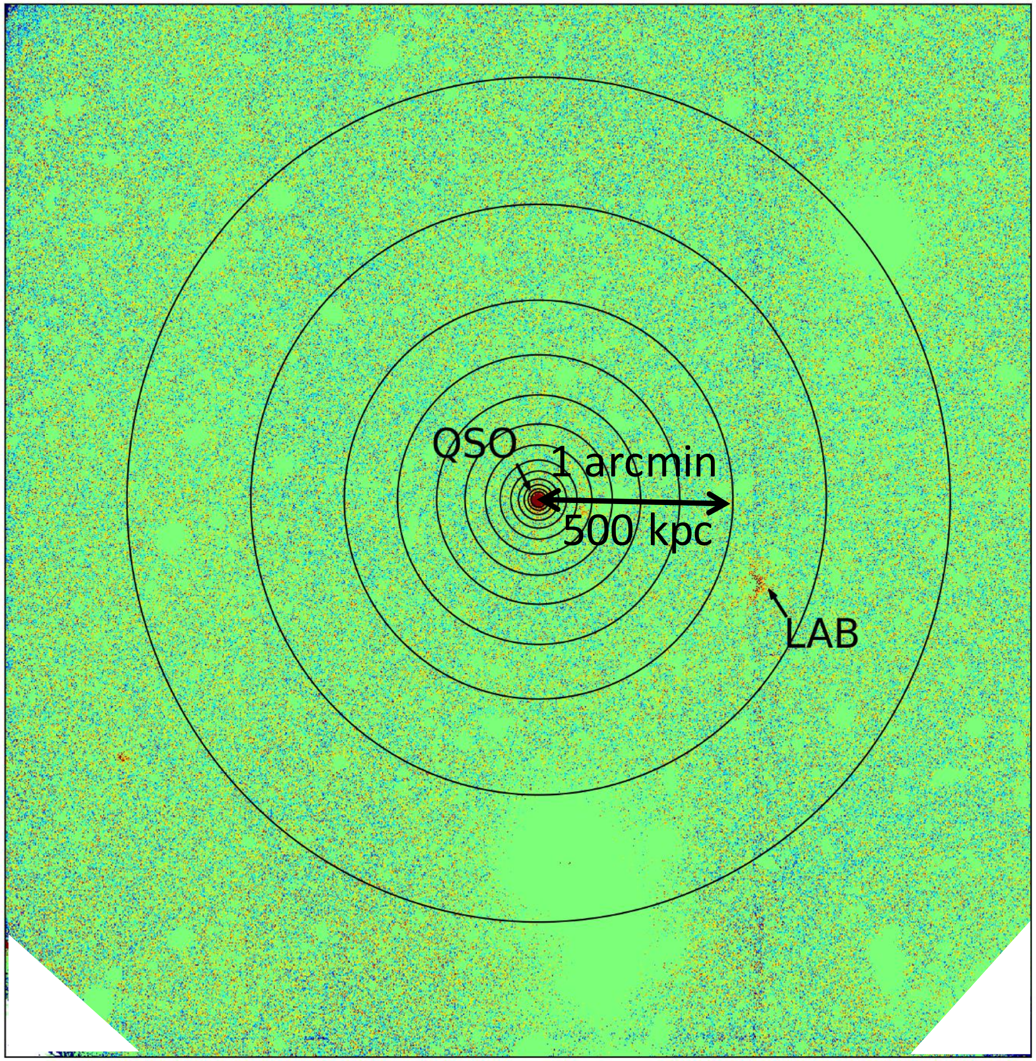
Example of a masked NB image



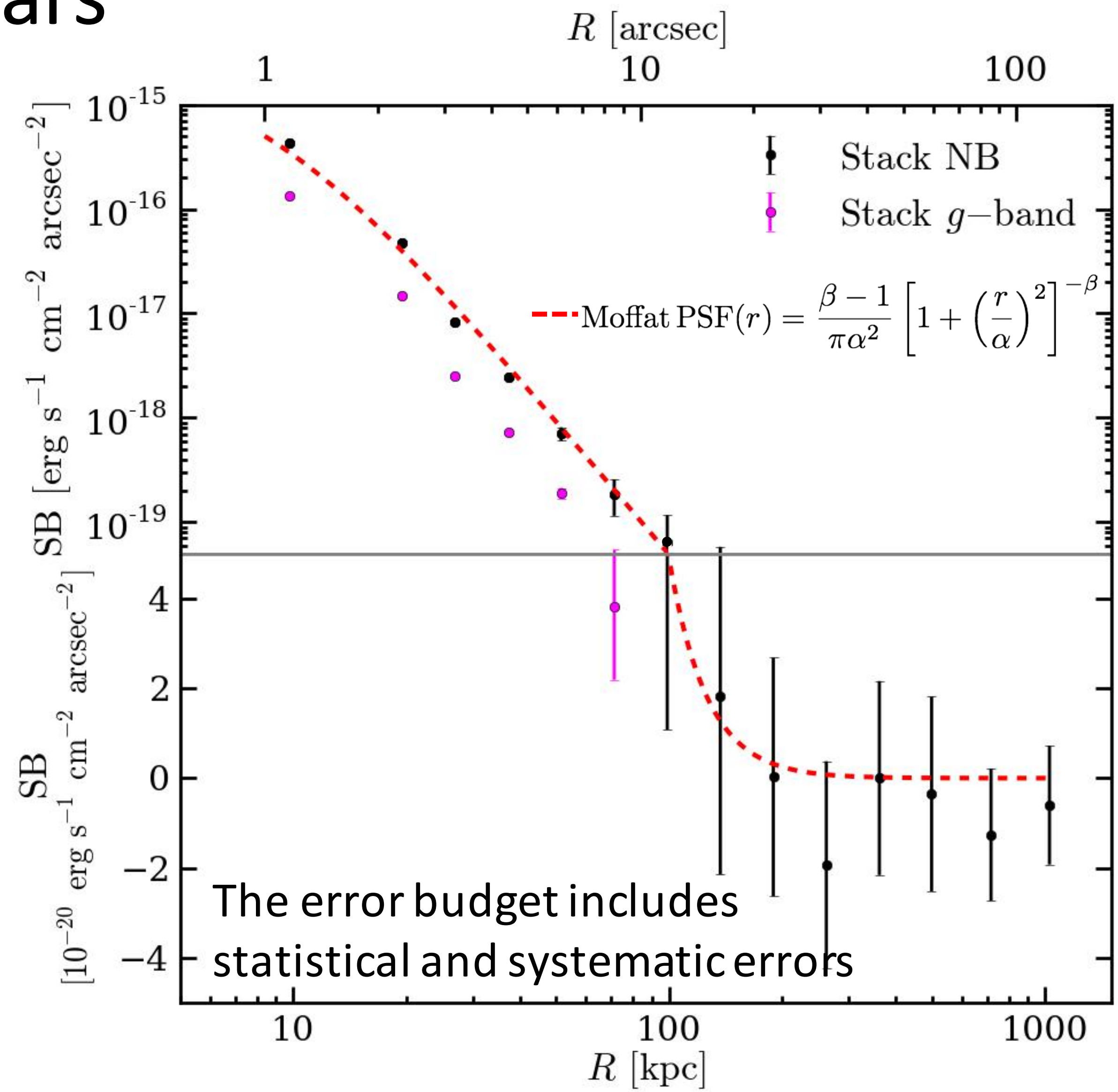
Example of a masked NB image



We extract the radial profile of 15 QSOs



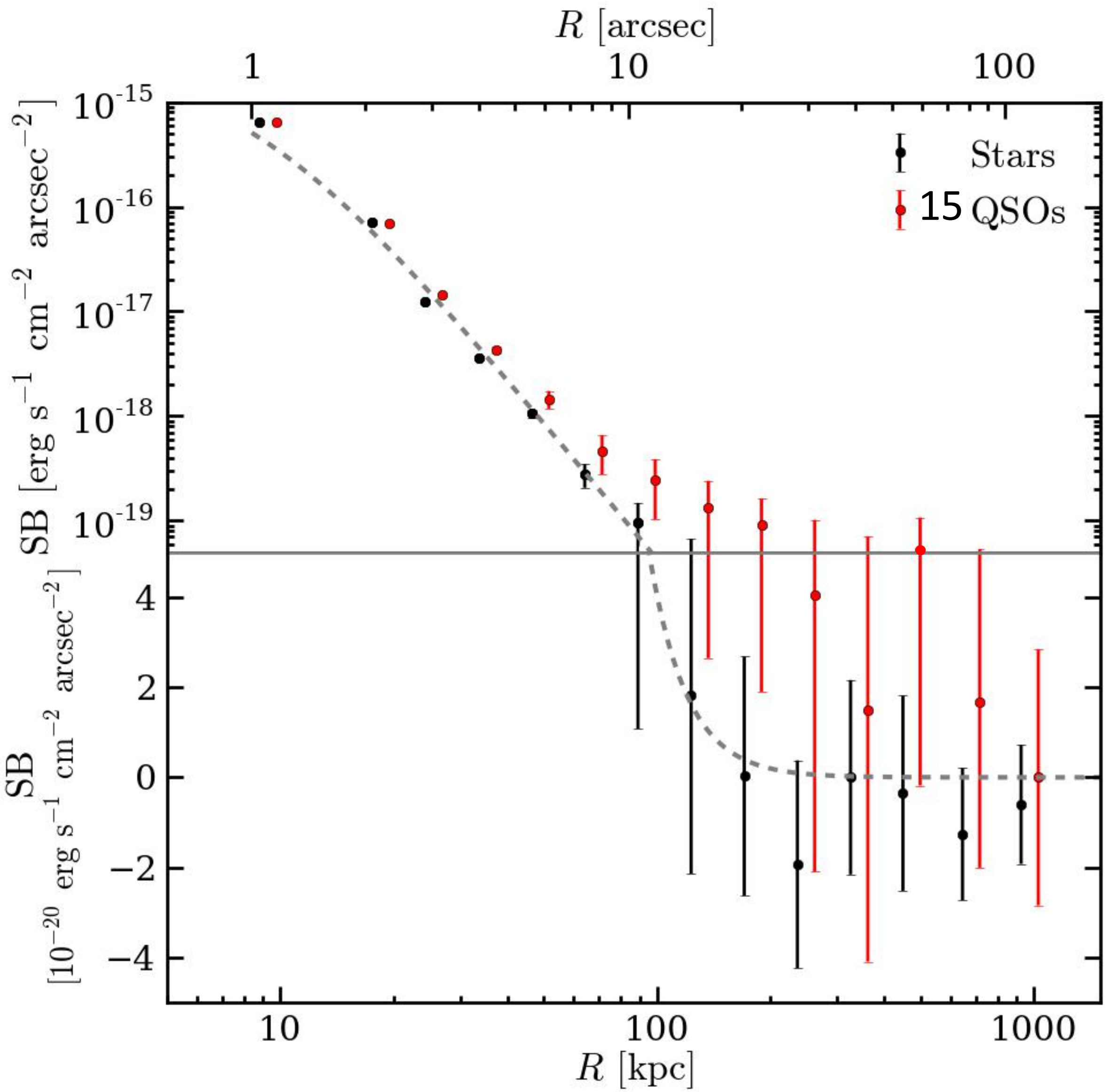
Determining the Point Spread Function (PSF) from Stars



For the NB, about 100 stars are used.

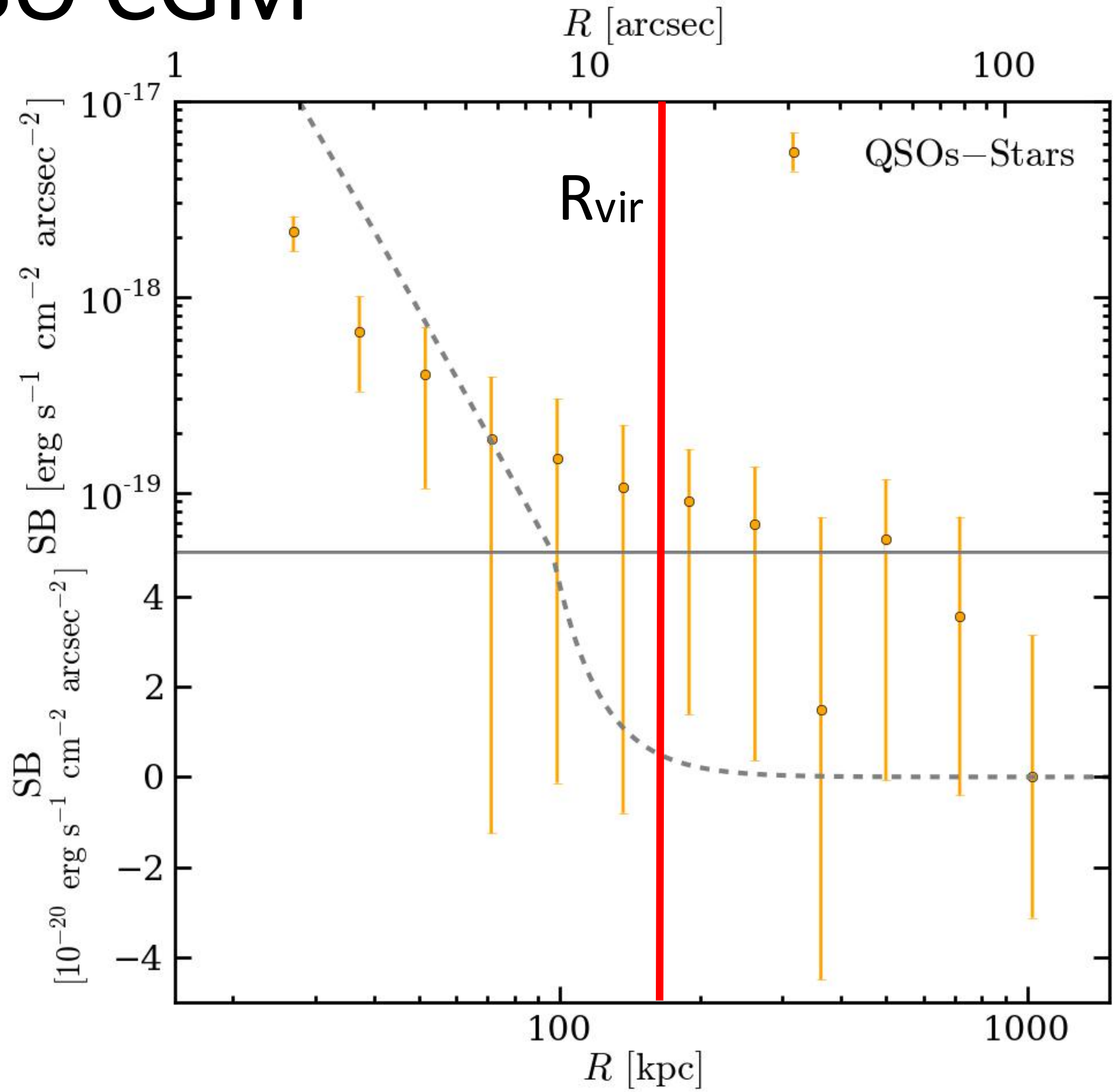
FAB+2016

The average QSO profile differs from the PSF

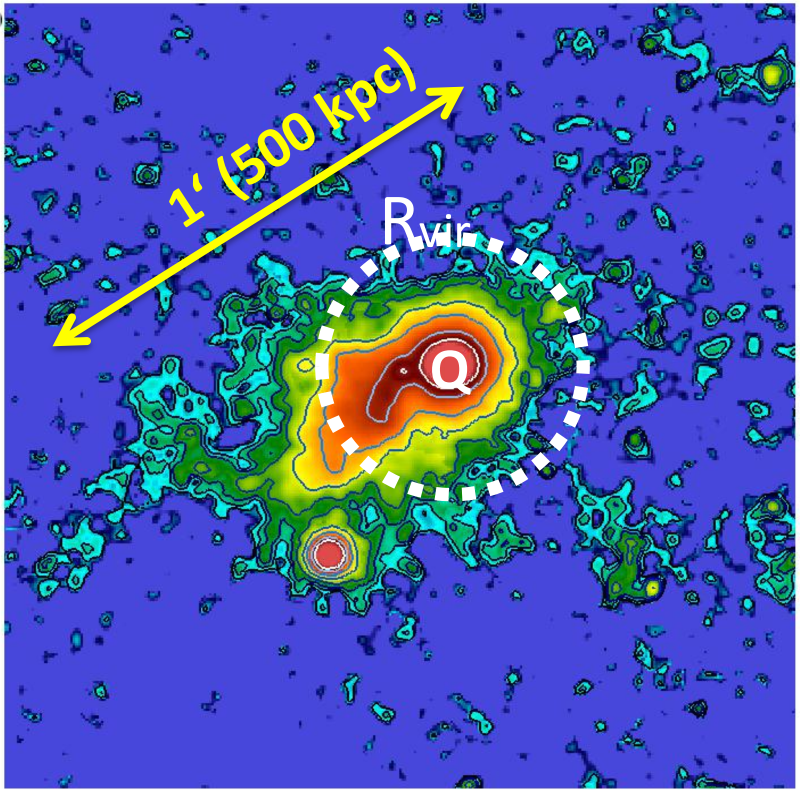


FAB+2016

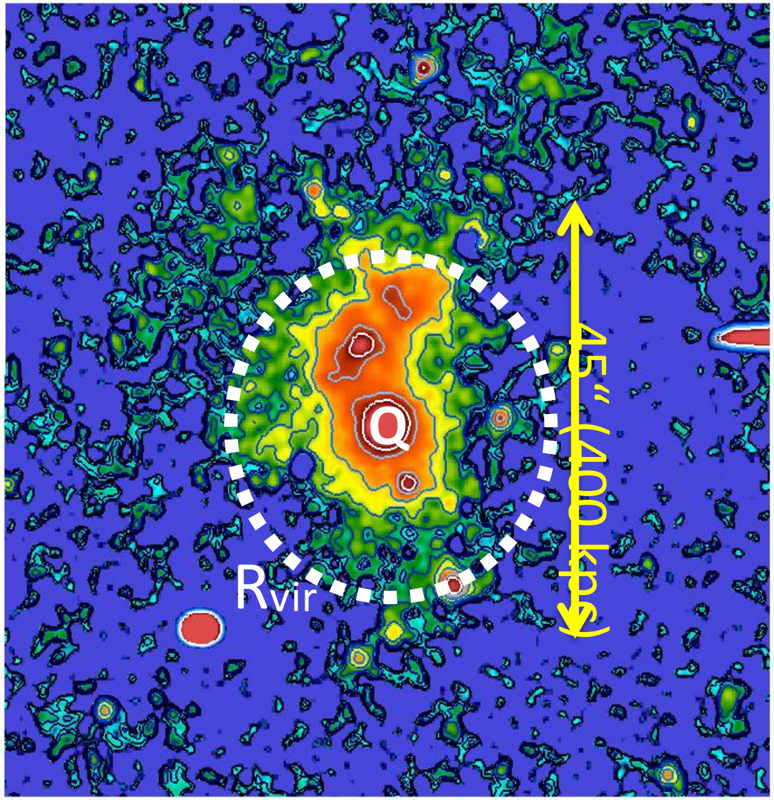
The Average Radial Emission Profile of the z~2 QSO CGM



FAB+2016

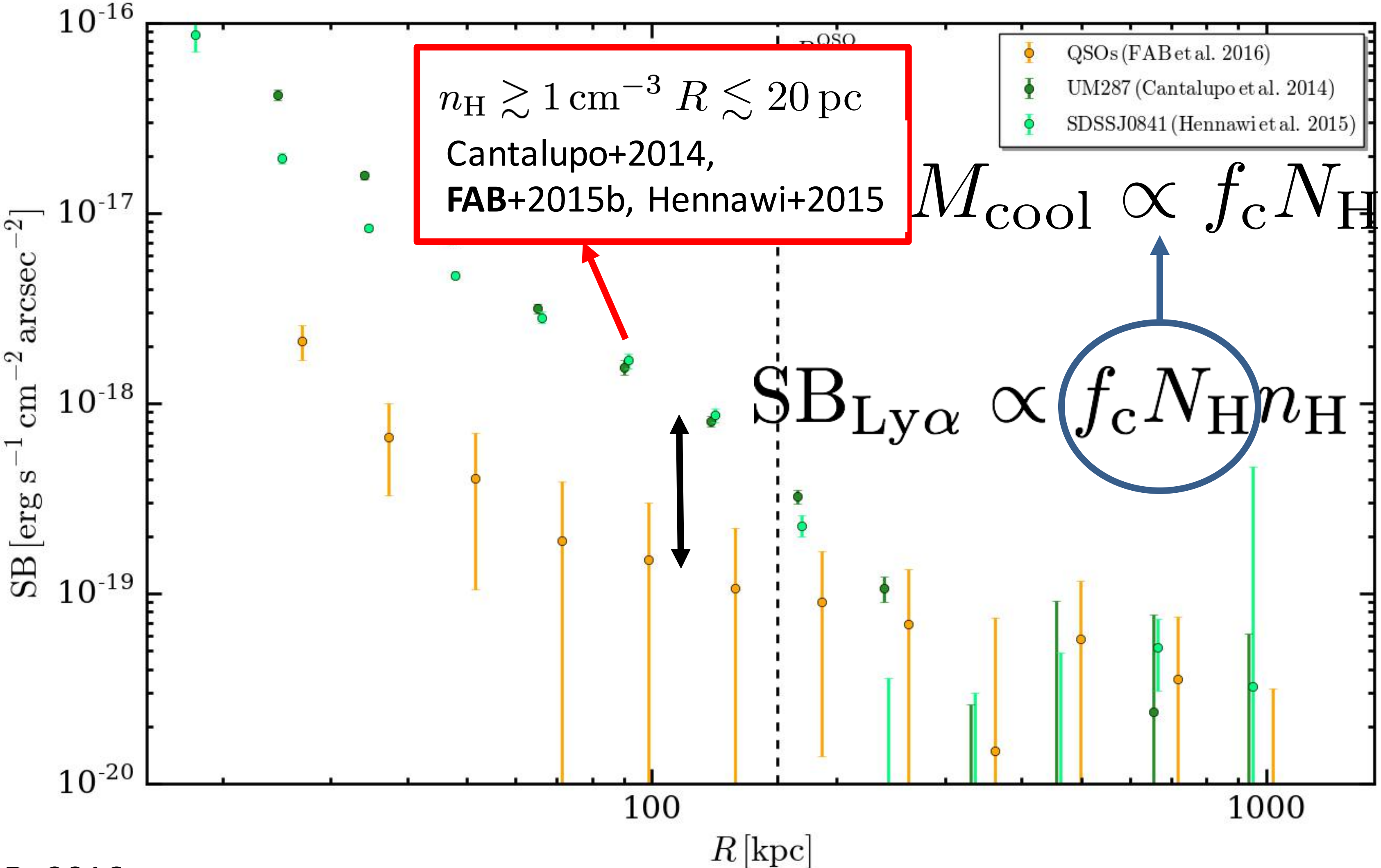


Cantalupo, **FAB**+2014, Nature



Hennawi, +**FAB**,Science,2015

Different densities in the cool CGM?



FAB+2016

Summary

- No extended Lyα emission (>50 kpc) around 15 QSOs
- We compute the average radial emission profile of the typical QSO CGM.
- $n_H < 0.1$ cm^{-3} within diffuse gas on large scales.
- The CGM of typical QSOs seems to show densities lower than those in giant Lyman-alpha nebulae around QSOs. Comparisons with simulations are needed...
- Large surveys are needed to uncover the brightest nebulae on the sky.

QSO MUSEUM

FAB+, in prep.

Quasars **S**peedy **O**bservations with **MU**se: **S**earch for **E**xtended **U**ltraviolet e**M**ission-lines

Targets: QSOs at z~3

So far: ~ 59 QSOs (11 radio-loud)

1σ ~ 3 x 10^{-18} erg/s/cm^2/arcsec^2
(1 arcsec^2 aperture in 30A band)

Exp. Time = 45 mins