From halo to intergalactic medium:

directly constraining the properties of large-scale gas around high-redshift quasars

Some of my collaborators:
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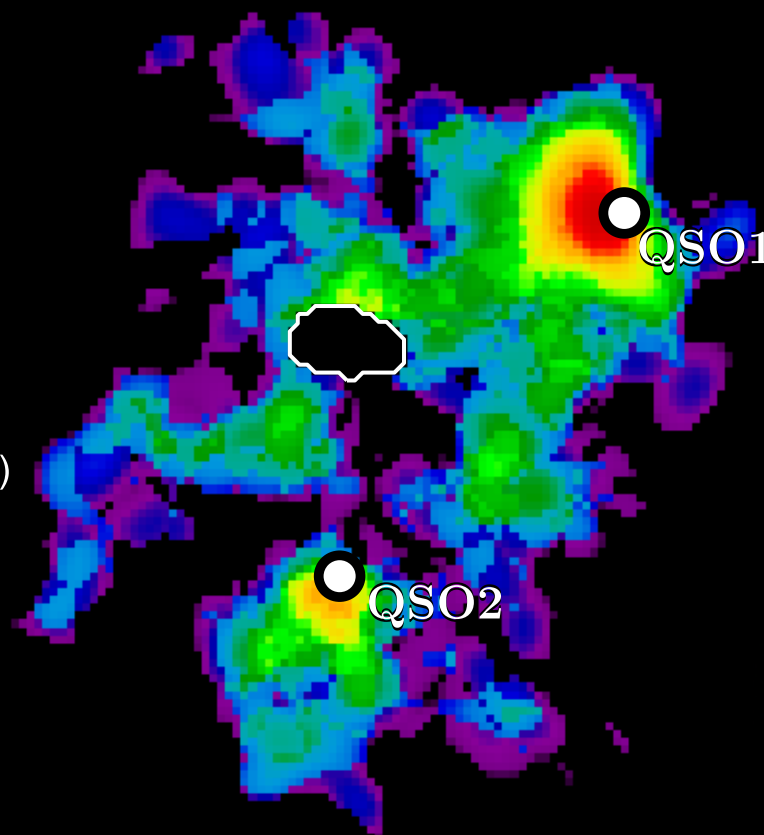
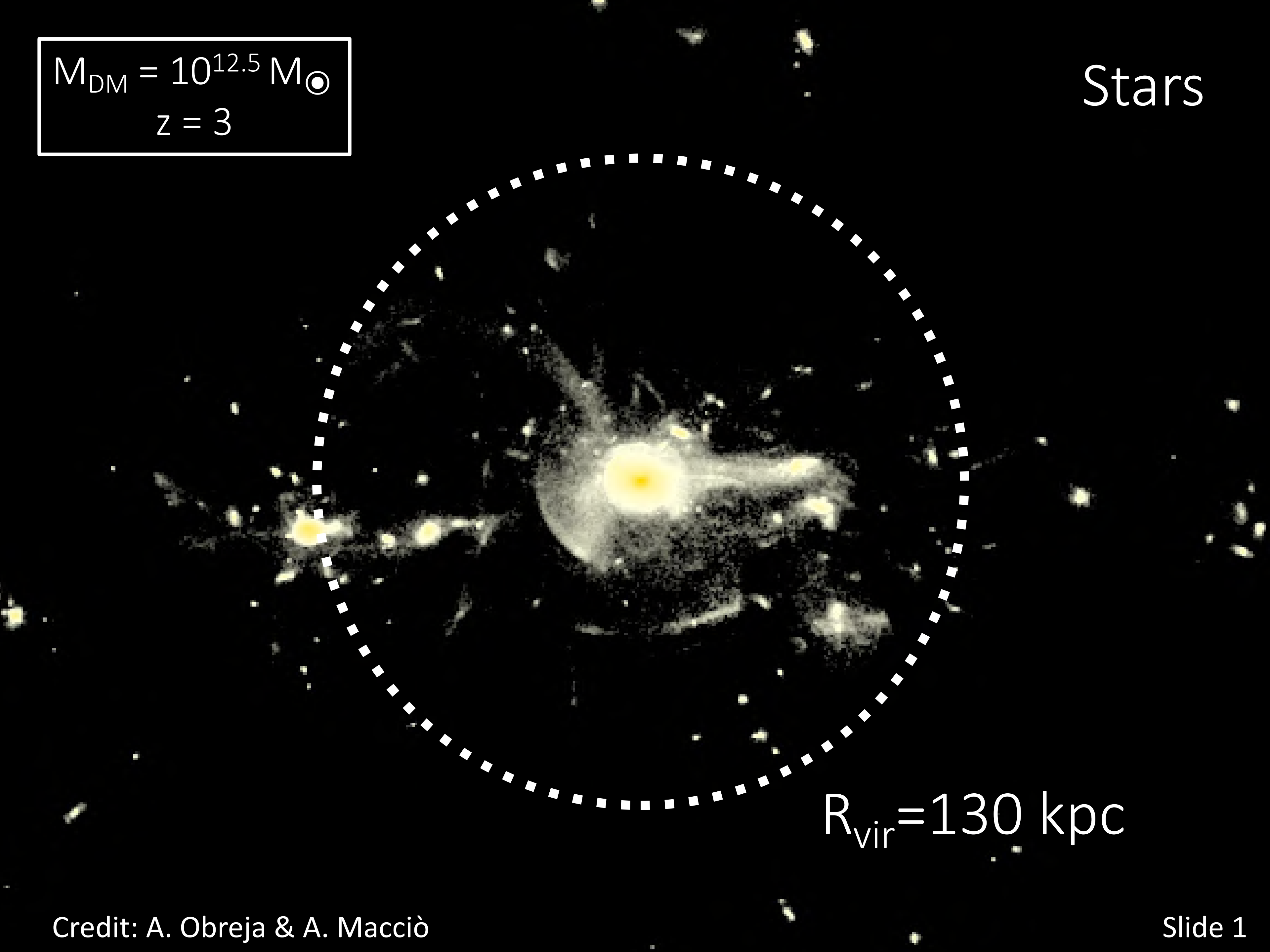
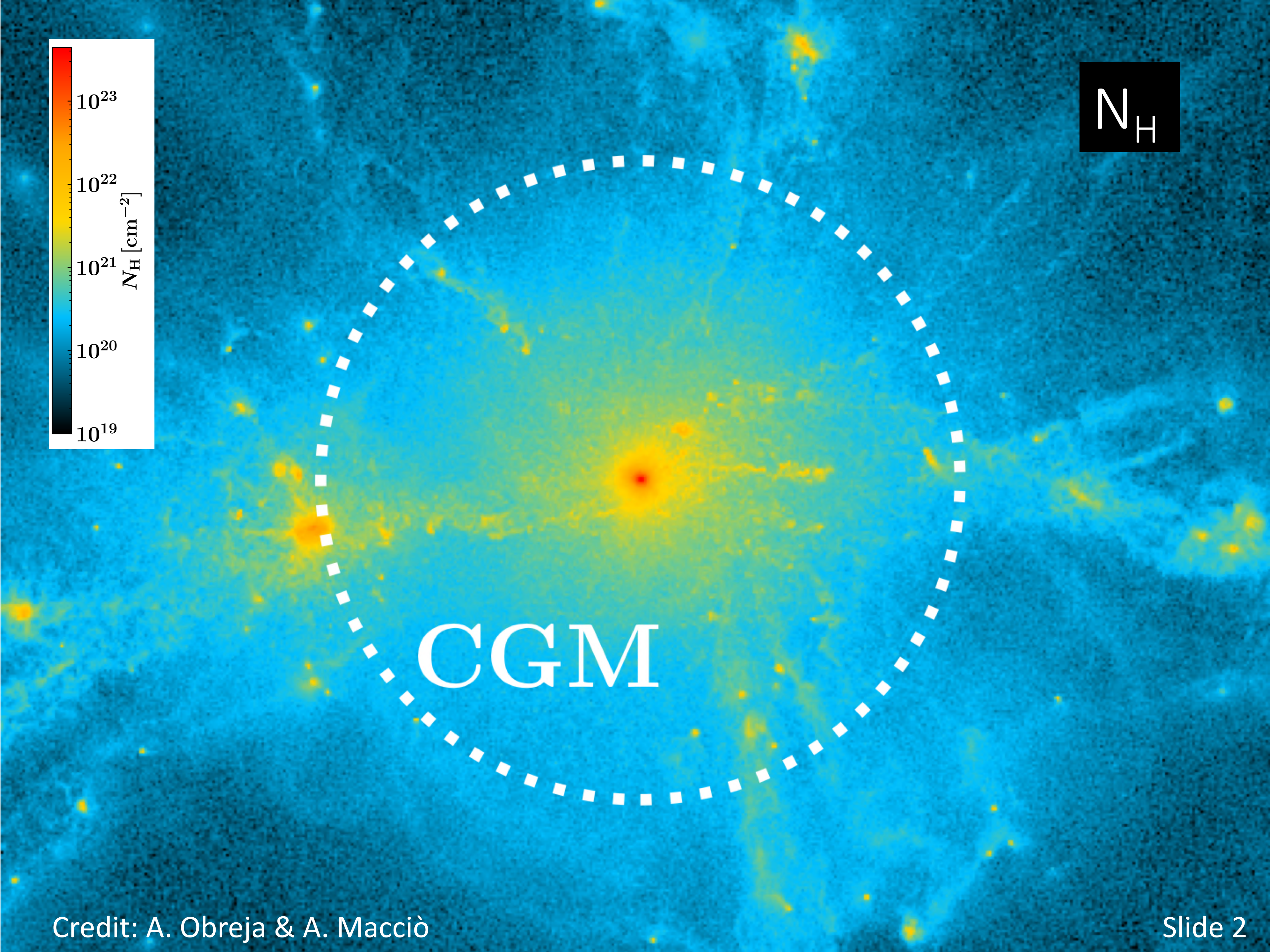


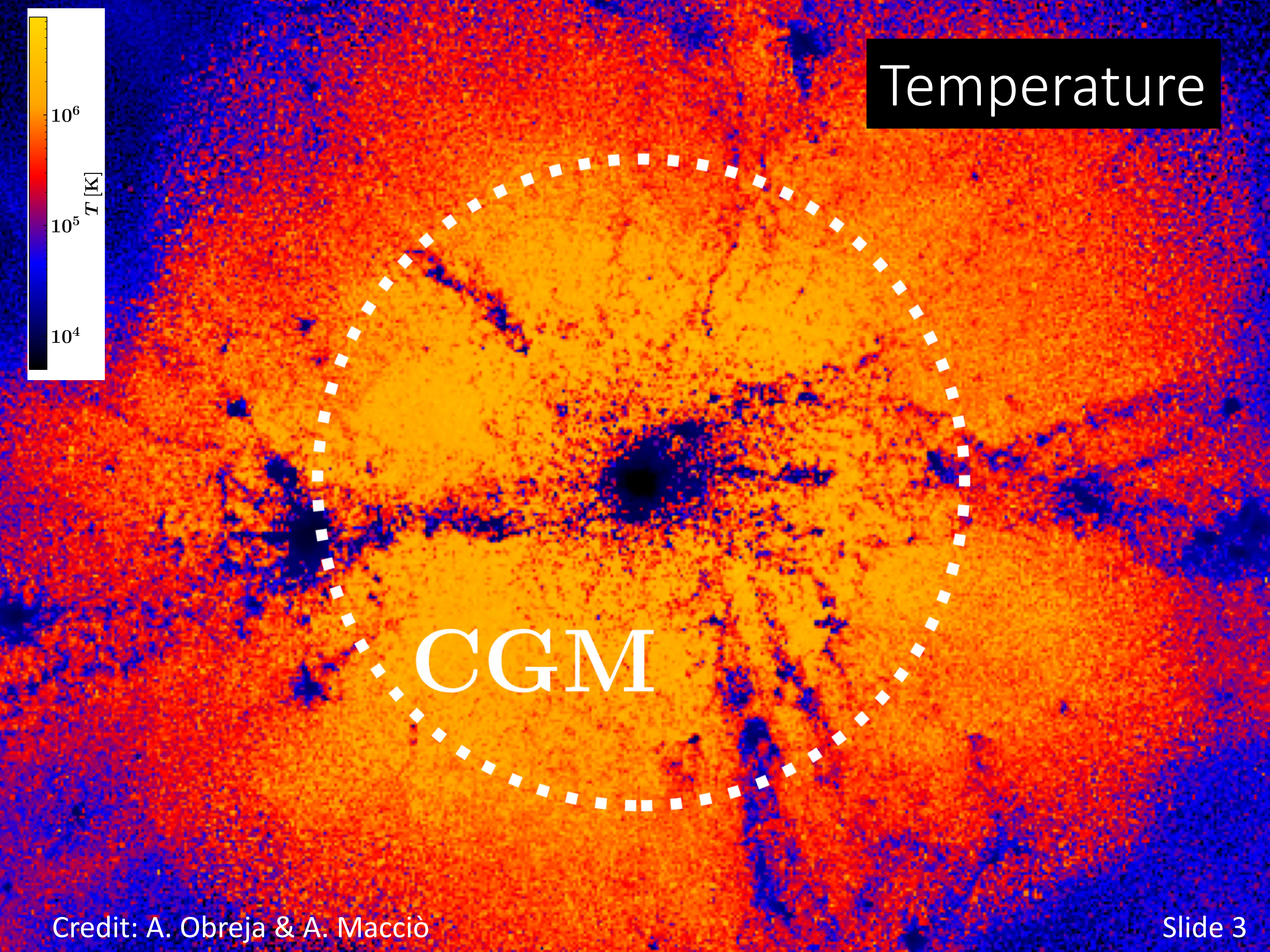
Max-Planck-Institut
für Astrophysik

Fabrizio Arrigoni Battaia or FAB
(MPA)

MAX-PLANCK-GESELLSCHAFT


$M_{DM} = 10^{12.5}\ M_\odot$
$z = 3$
Stars
R_{vir}=130 kpc
Credit: A. Obreja & A. Macciò


10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
$N_H\,[\mathrm{cm}^{-2}]$
N_H
CGM
Credit: A. Obreja & A. Macciò
Slide 2



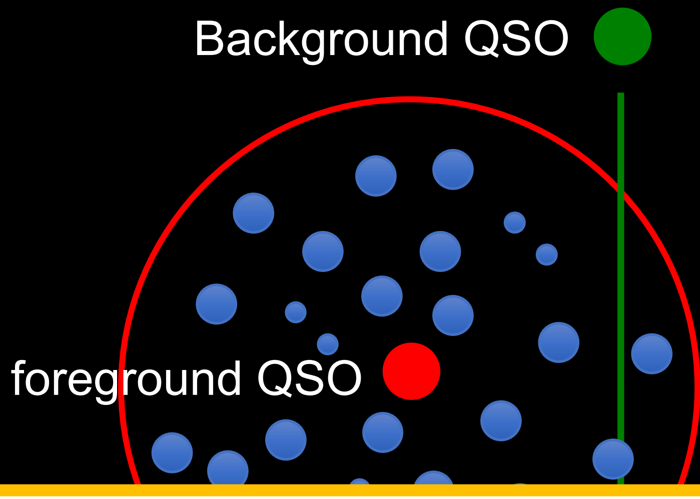
Credit: A. Obreja & A. Macciò

CGM/IGM in emission: a lot of information on galaxy evolution, but is it accessible?

- What are the physical properties of these gas phases?
- What is the spatial distribution of the cool and warm/hot phase in halos?
- How does the IGM funnel into the CGM and onto the central galaxies? What is the role of satellites?
- Can we directly constrain halo dynamics?
- What is the role of AGN in shaping the properties of galactic halos and the surrounding IGM?

Scientific framework before the advent of sensitive integral-field spectrographs

OBSERVATIONS



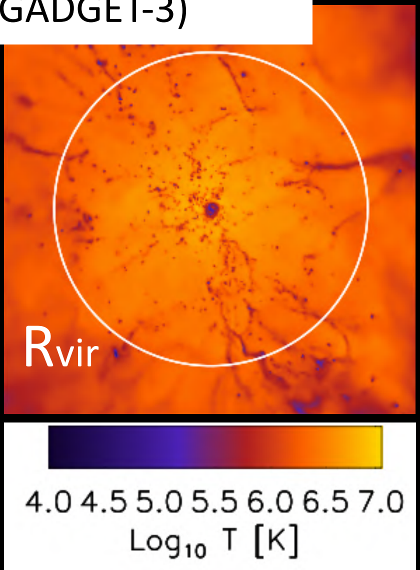
Covering factor of $N_{HI}>10^{19}$ cm^{-2} absorption systems is about 60% for R<150 kpc (Hennawi+2006, Prochaska+2013)

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

R_{vir} = 130 kpc

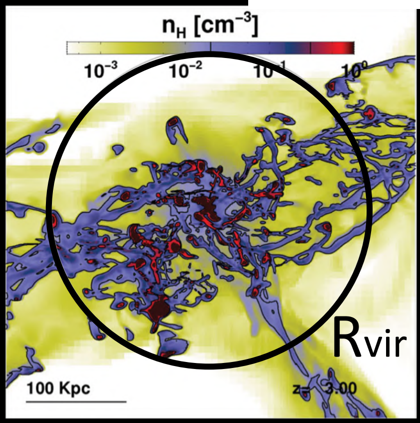
SIMULATIONS

OWLS (modified GADGET-3)



van de Voort+2011

RAMSES



Rosdahl & Blaizot 2012

Diverse results depending on physical models (e.g., feedback prescriptions) and code used.

And many others: Keres+2012, Bertone&Schaye 2012 ....

Rees 1988

epochs corresponding to redshifts $z \lesssim 3$. This gas, expected to have a two-phase structure, could be highly luminous if it were irradiated by a central quasar. Evidence for extended emission-line 'fuzz' around high-z quasars (or even upper limits to the surface brightness of any such reprocessed radiation) can yield surprisingly strong clues to the nature and formation mechanism of their host galaxies. In the absence of a central quasar, infalling gas that cooled from the

Haiman & Rees 2001

EXTENDED Lyα EMISSION AROUND YOUNG QUASARS: A CONSTRAINT ON GALAXY FORMATION

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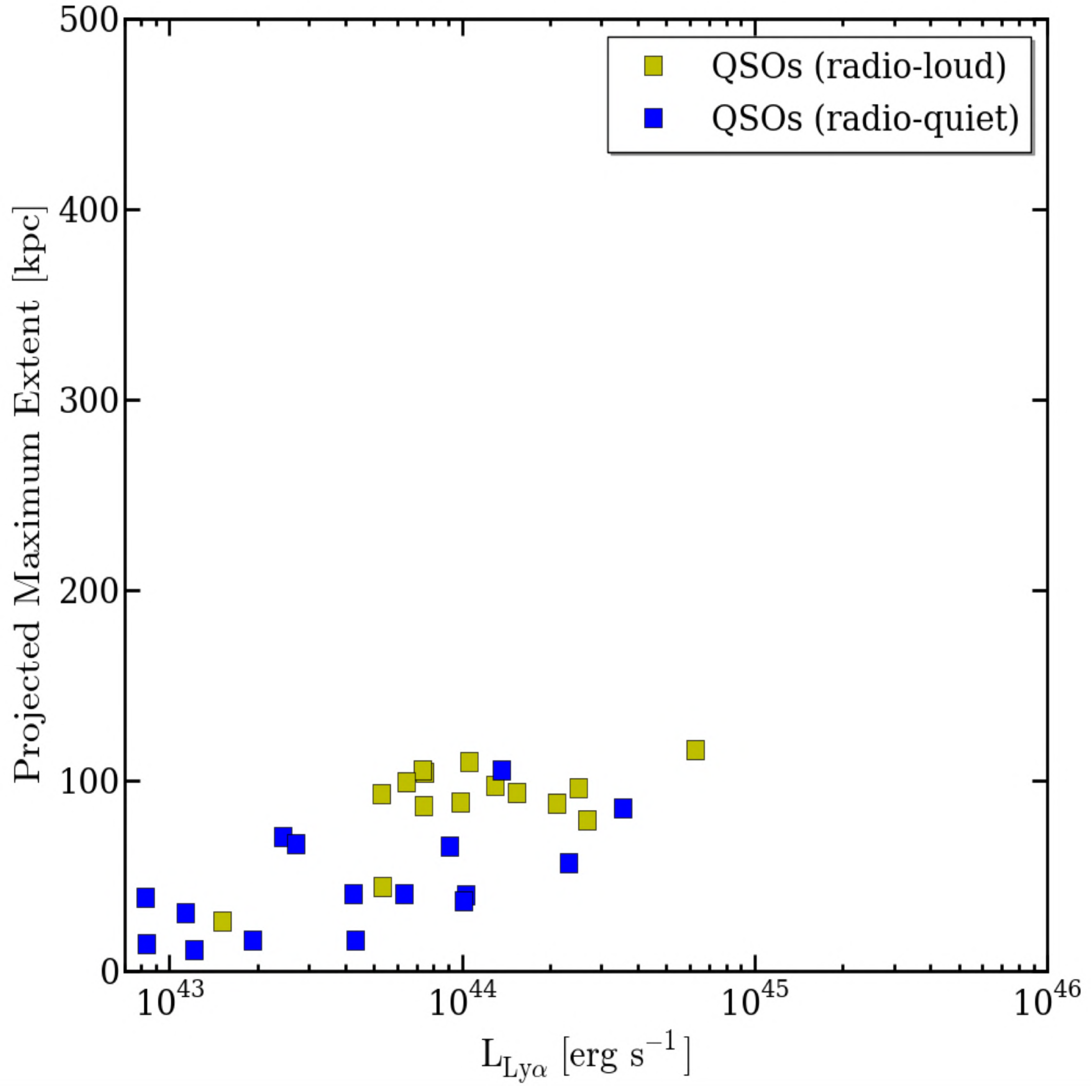
ABSTRACT

The early stage in the formation of a galaxy inevitably involves a spatially extended distribution of infalling, cold gas. If a central luminous quasar turned on during this phase, it would result in significant extended Lyα emission, possibly accompanied by other lines. For halos condensing at redshifts $3 \lesssim z \lesssim 8$ and having virial temperatures 2×10^5 K $\lesssim T_{\rm vir} \lesssim 2 \times 10^6$ K, this emission results in a "fuzz" of characteristic angular diameter of a few arcseconds and surface brightness $\sim 10^{-18}$ to 10^{-16} ergs s^{-1} cm^{-2} $arcsec^{-2}$. The fuzz around bright, high-redshift quasars could be detected in deep narrowband imaging with current telescopes, providing a direct constraint on galaxy formation models. The absence of detectable fuzz might suggest that most of the protogalaxy's gas settles to a self-gravitating disk before a quasar turns on. However, continued gas infall from large radii, or an on-going merger spreading cold gas over a large solid angle, during the luminous quasar phase could also result in extended Lyα emission, and can be constrained by deep narrowband imaging.

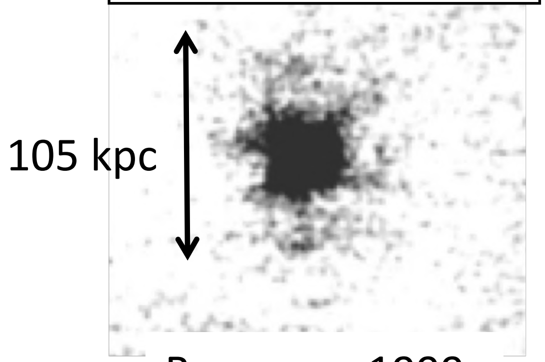
and out to the IGM (e.g., Hogan & Weymann 1987, Gould & Weinberg 1996, Cantalupo+2005, Kollmeier+2010)

Scientific framework before the advent of sensitive integral-field spectrographs: Lyα nebulae around quasars



Weidinger+2004/2005, Christensen+2006, …

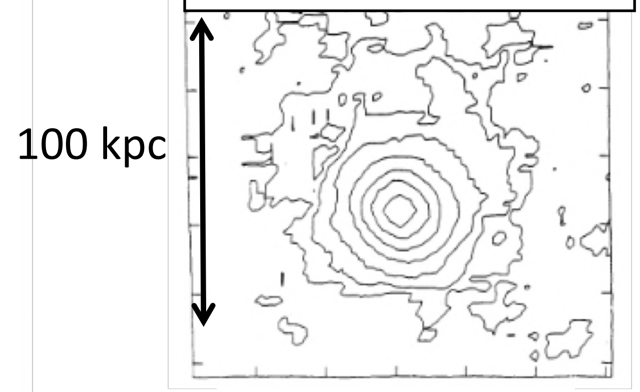
J2233-606 z=2.238



Bergeron+1999

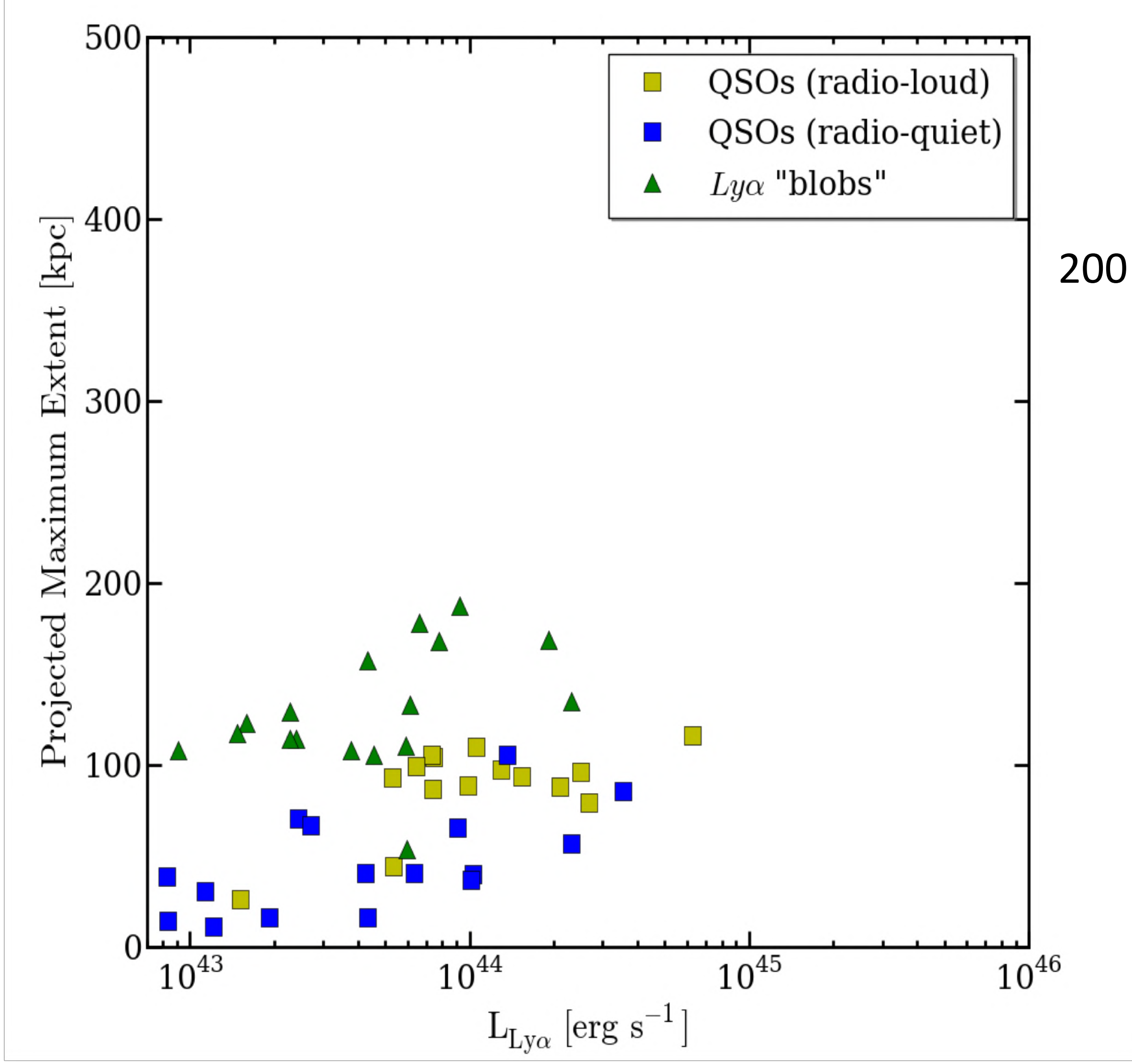
$\mathrm{SB_{Ly\alpha}} > 10^{-17}\mathrm{erg\ s^{-1}\ cm^{-2}\ arcsec^{-2}}$

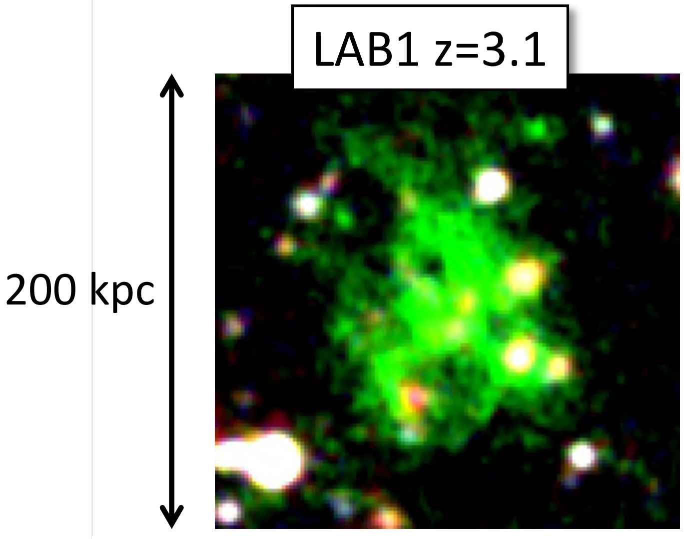
Q0730+257 z=2.686



Heckman+1991

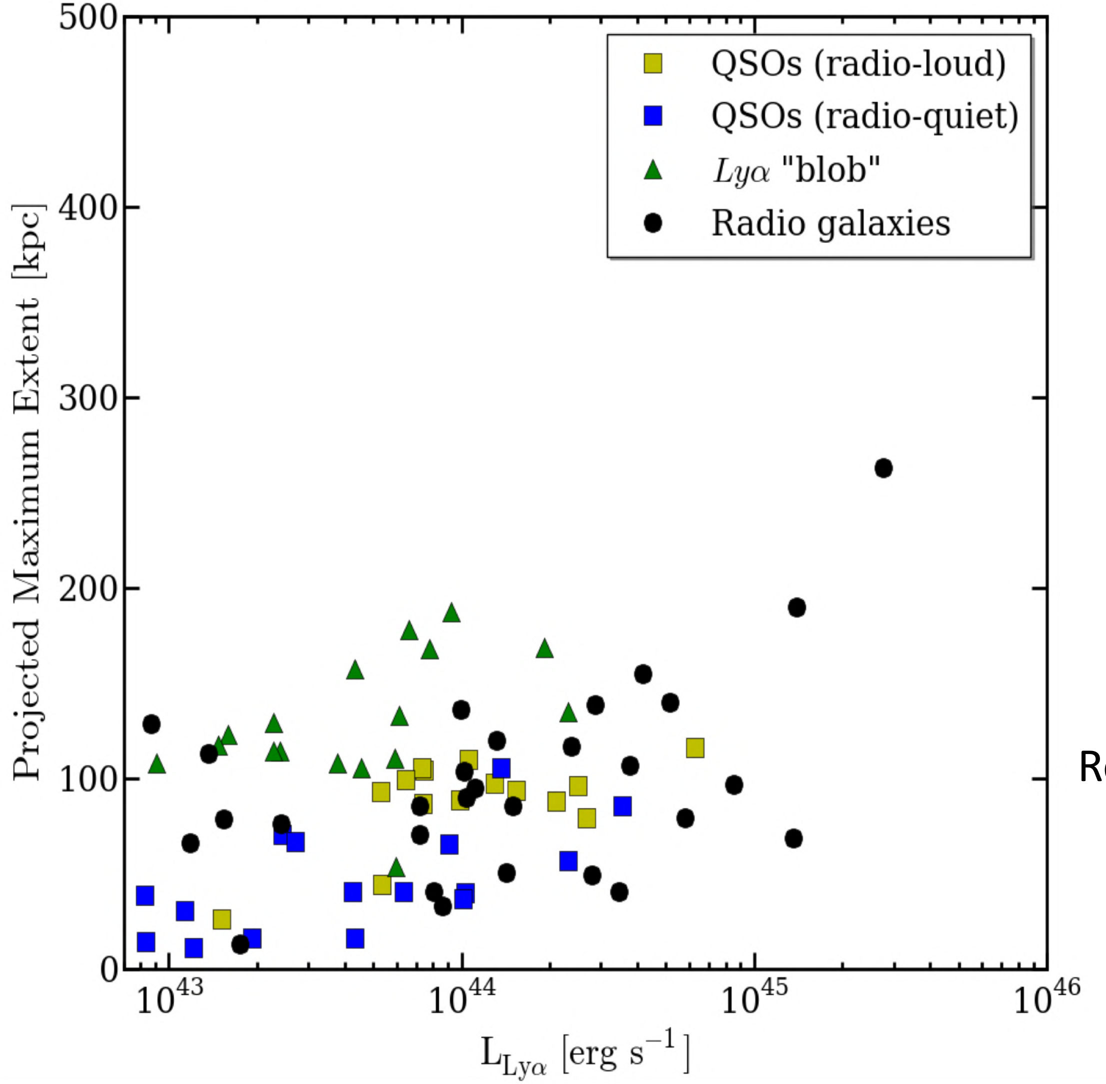
Scientific framework before the advent of sensitive integral-field spectrographs: Lyα blobs

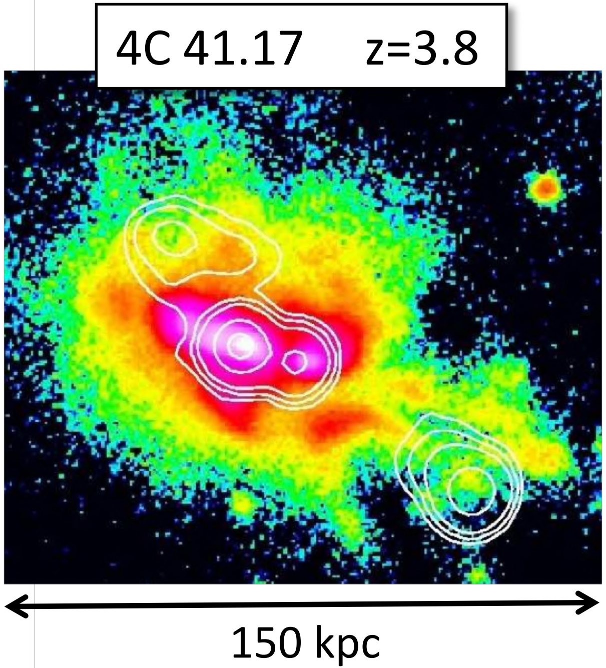




Steidel+2000, Matsuda+2004

Scientific framework before the advent of sensitive integral-field spectrographs: High-z radio galaxies





Reuland+2003, Miley&De Breuck2008

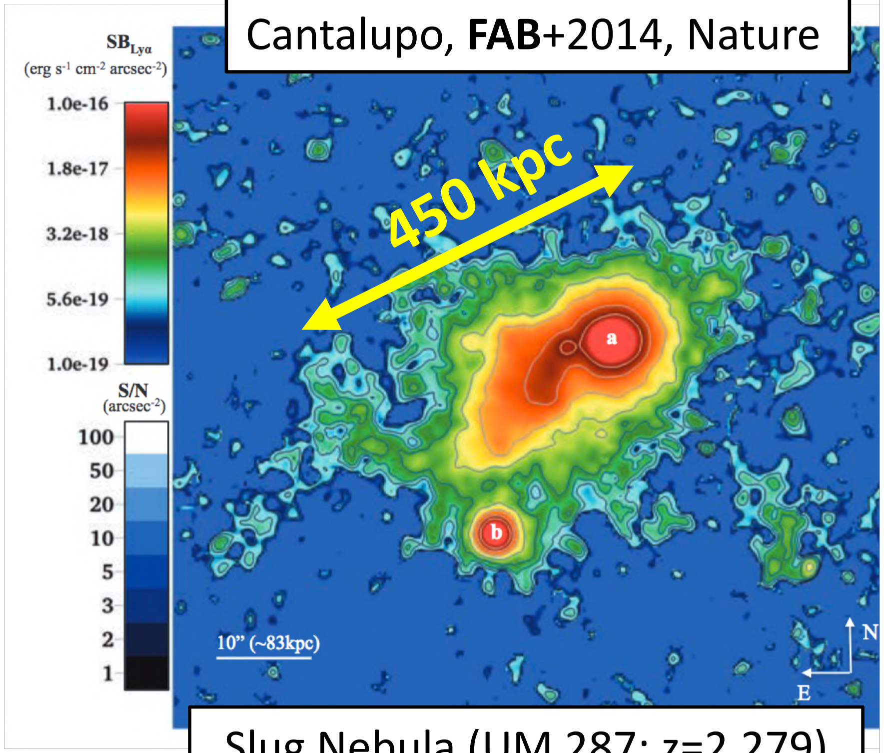
FLASHLIGHT survey: deep narrow-band imaging of z ~2 radio-quiet quasars

FAB+2014

Survey carried out with the LRIS/Keck and GMOS/Gemini-South instruments:
- 11 quasars (Keck)
- 15 quasars (Gemini)

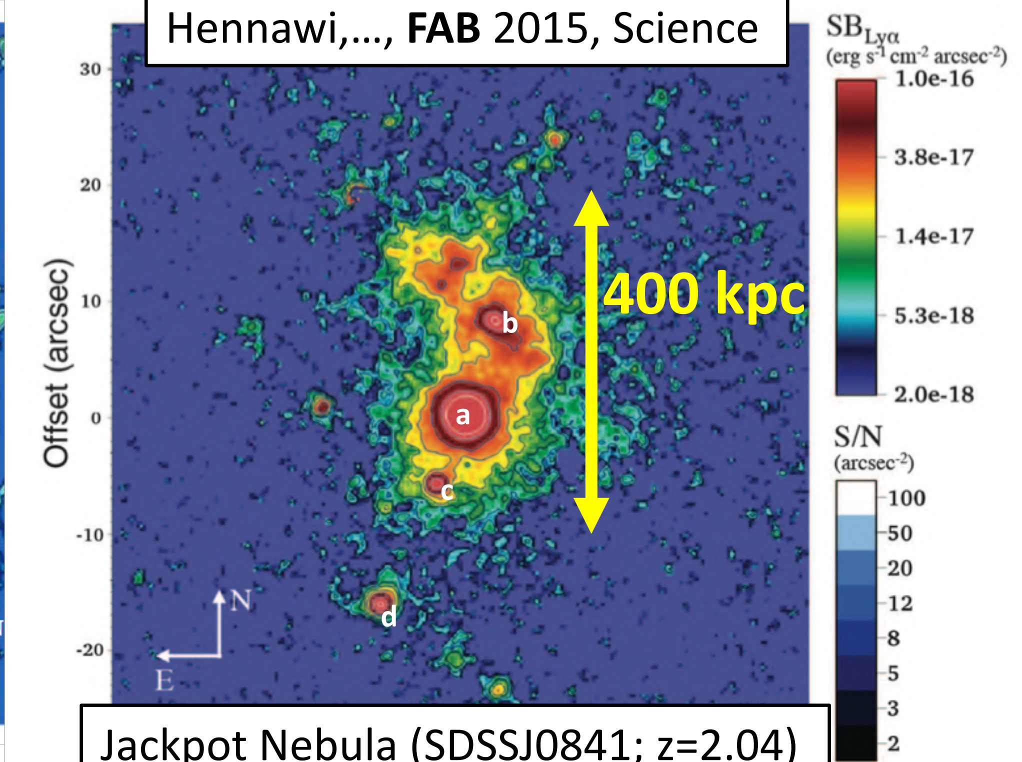
$\mathrm{SB_{Ly\alpha}} \sim 1 - 4 \times 10^{-18}\,\mathrm{erg\ s^{-1}\ cm^{-2}\ arcsec^{-2}}$

Cantalupo, **FAB**+2014, Nature



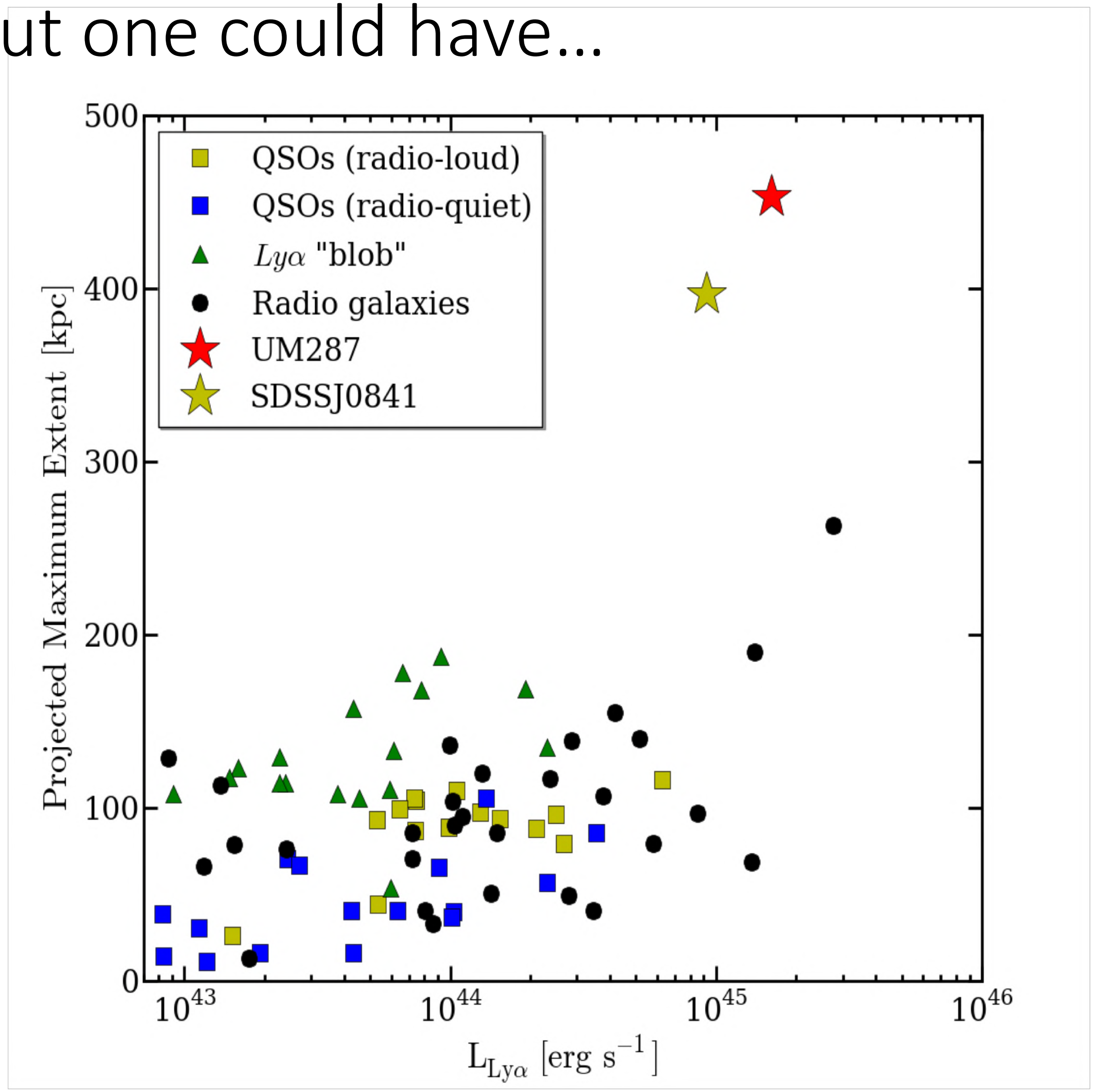
Slug Nebula (UM 287; z=2.279)

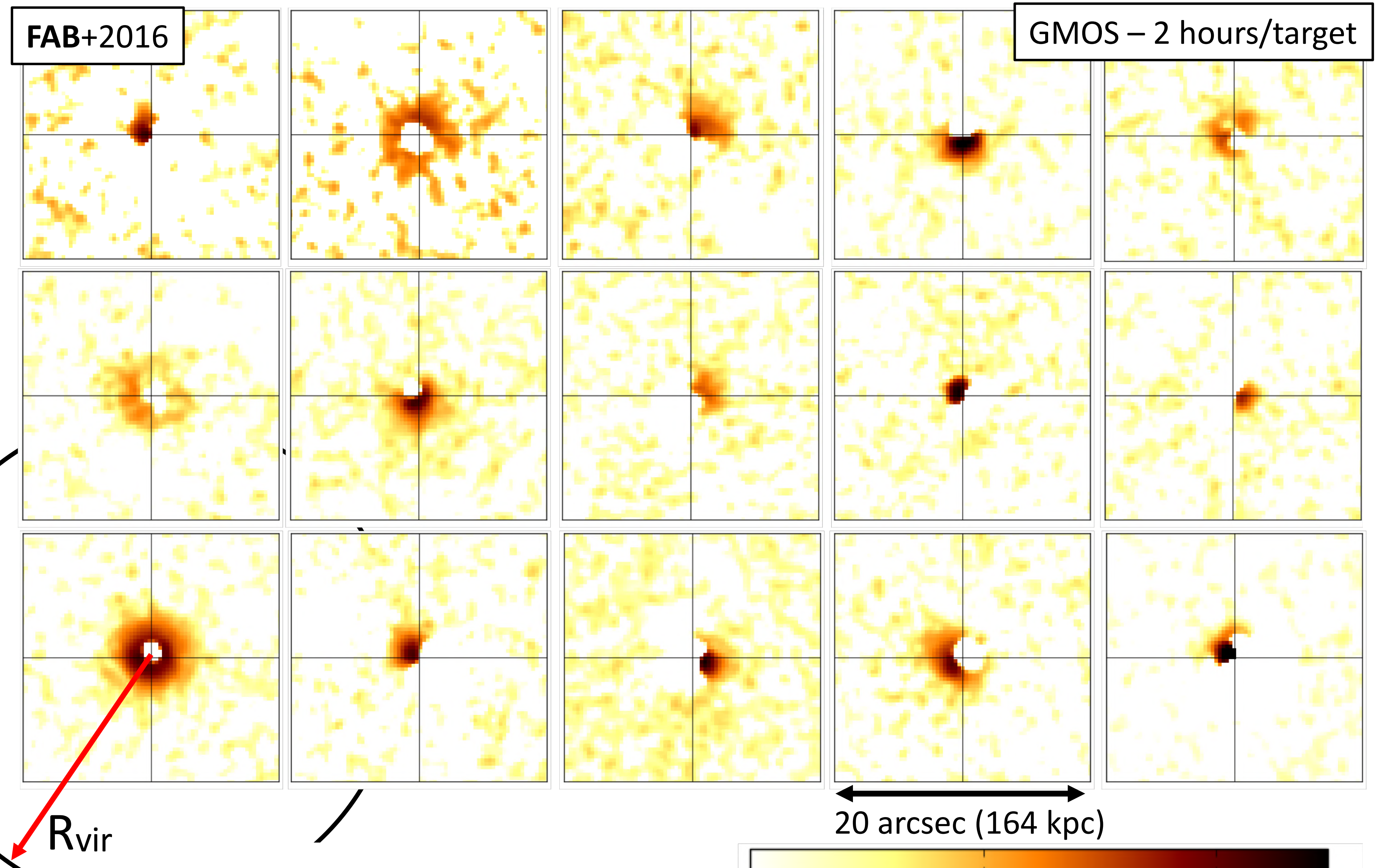
Hennawi,…, **FAB** 2015, Science



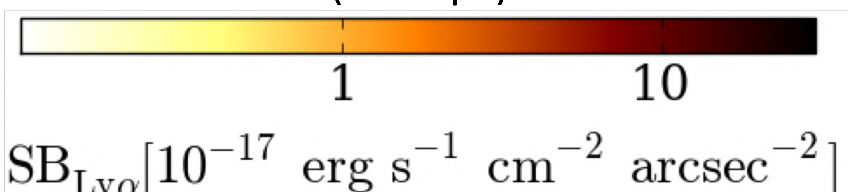
Jackpot Nebula (SDSSJ0841; z=2.04)

FLASHLIGHT survey: never seen such large nebulae before, but one could have…

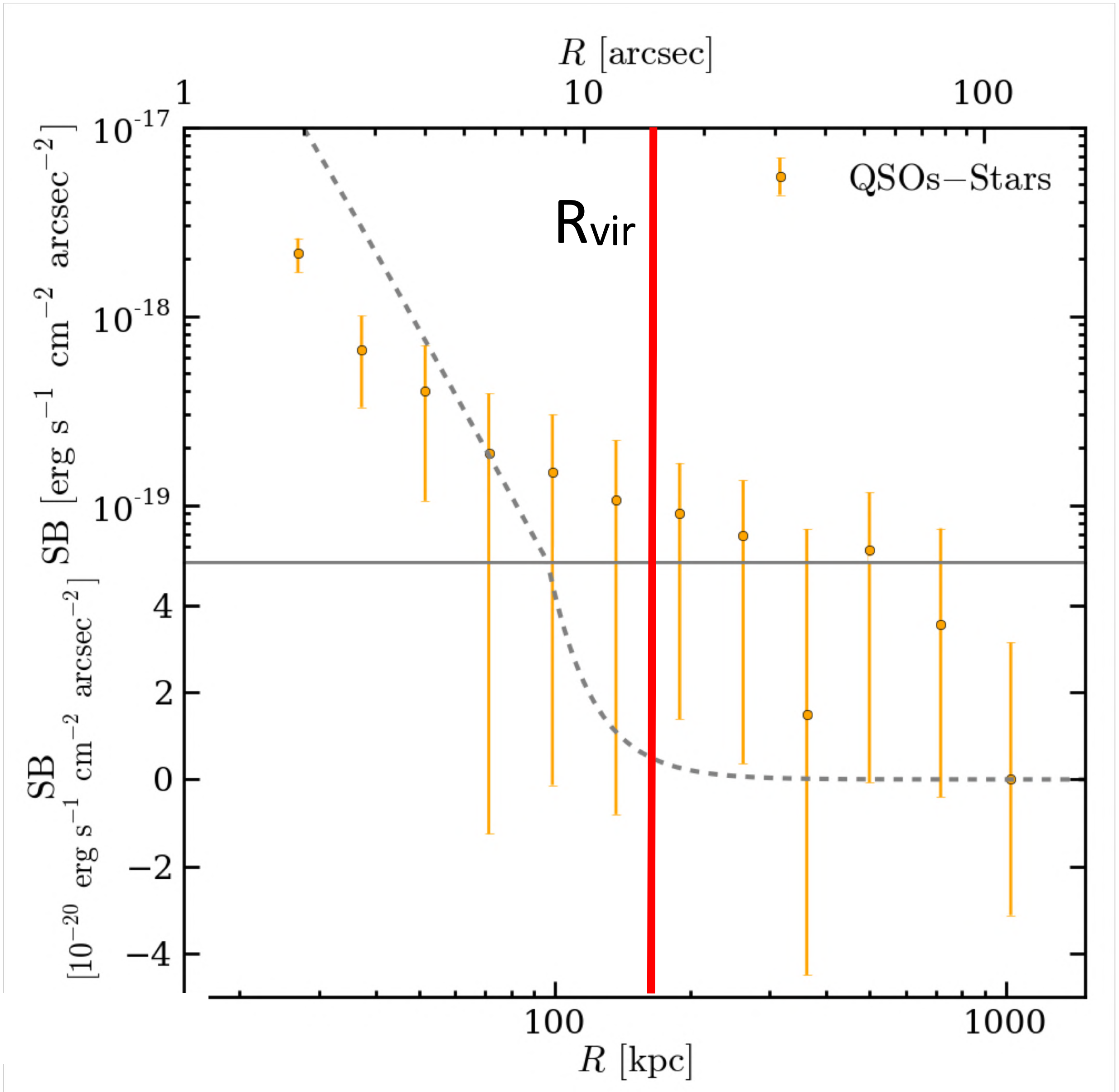




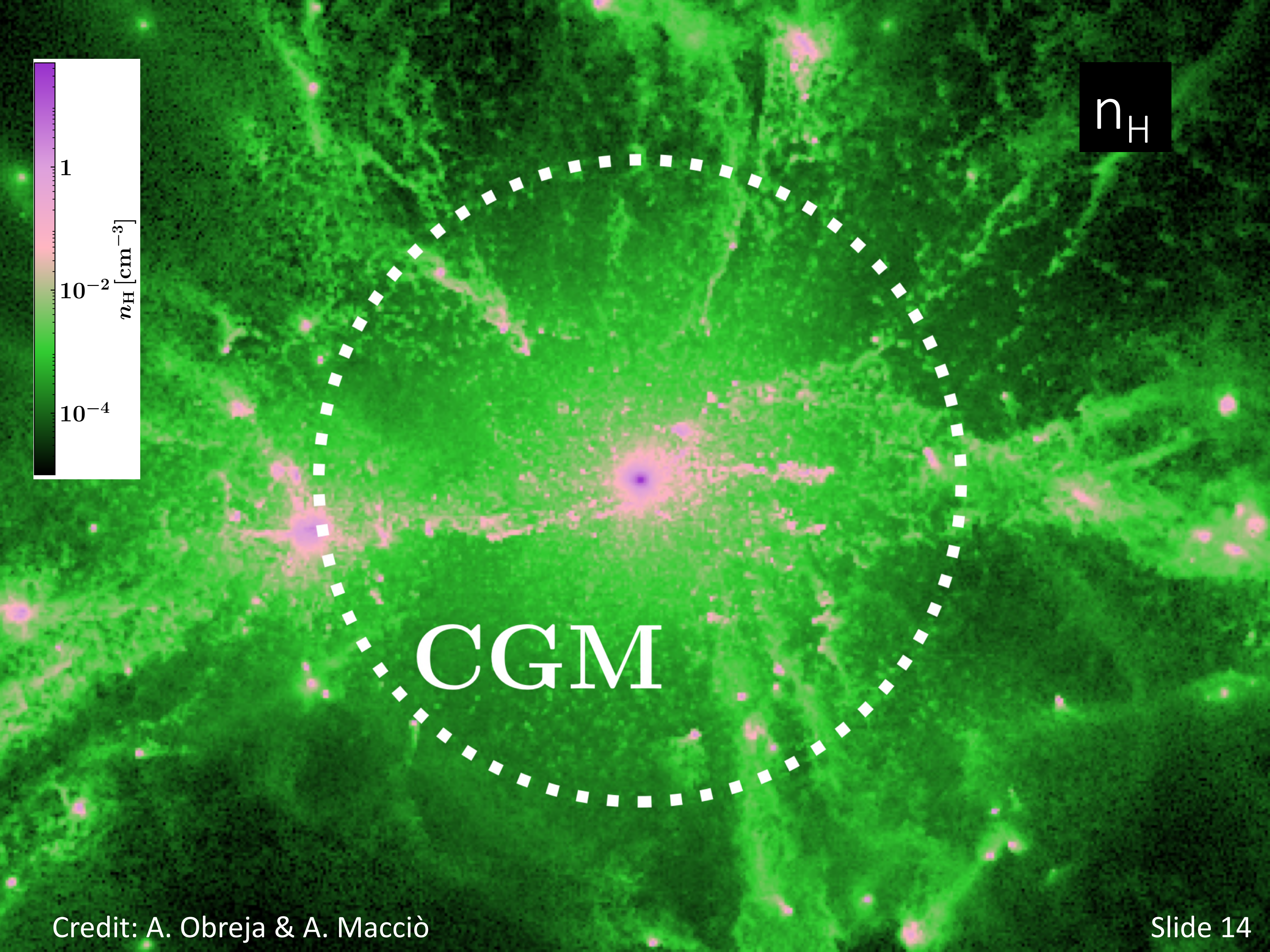
PSF and continuum subtracted
Lyα maps of 15 QSOs @z=2.25



First average Lyα profile around high-z quasars



FAB+2016



Credit: A. Obreja & A. Macciò

The importance of a constraint on HeII (1640Å) emission

FAB+2015

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

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

HeII

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

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

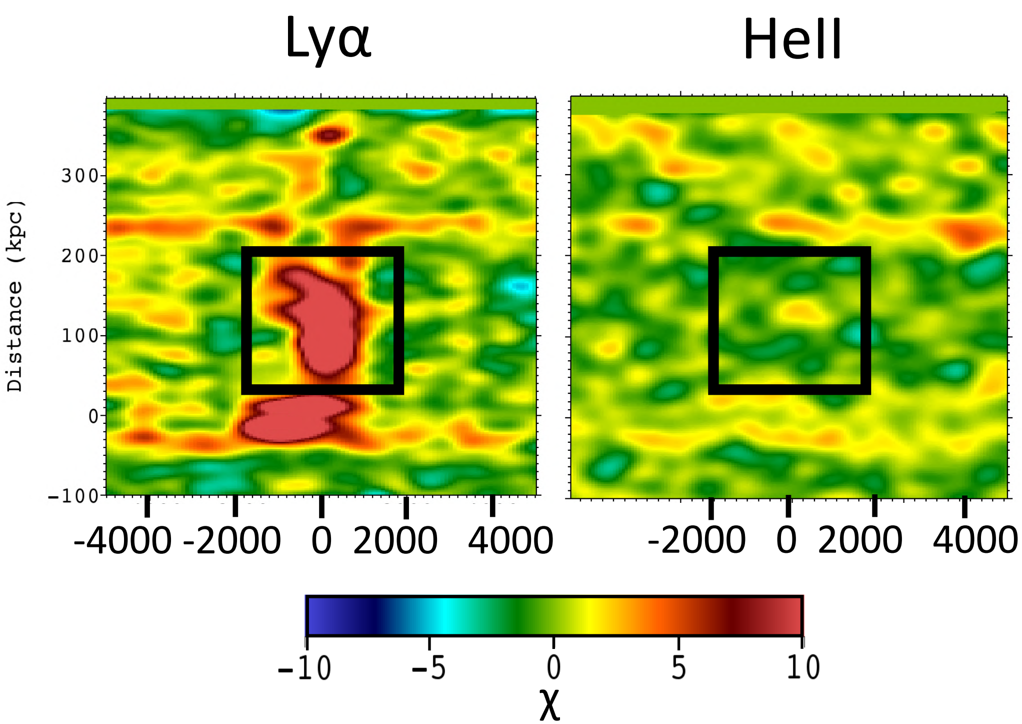
$$\mathrm{SB}_{Ly\alpha} \propto f_c L_{\nu_{LL}}$$

The Lyα emission would have been much brighter than observed.

Hennawi & Prochaska 2013

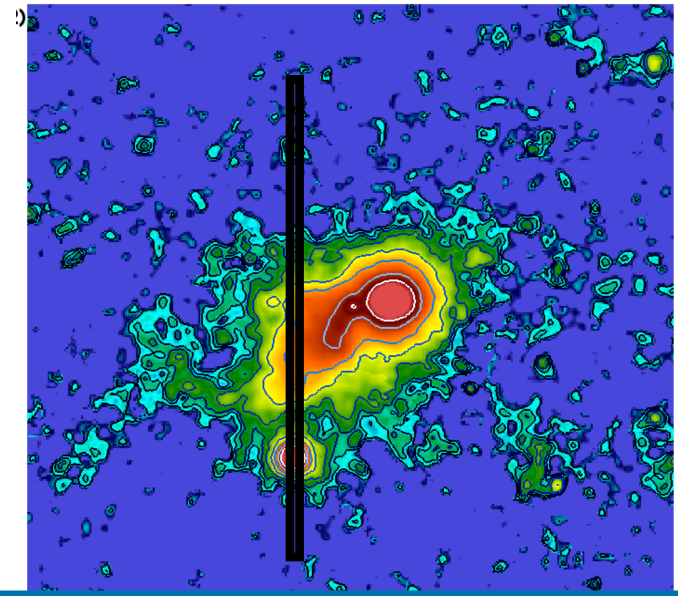
Constraining the gas densities on CGM scales: Slug Nebula (UM287)

FAB+2015b



2 hours on LRIS/Keck

psf subtracted, smoothed 2D spectrum

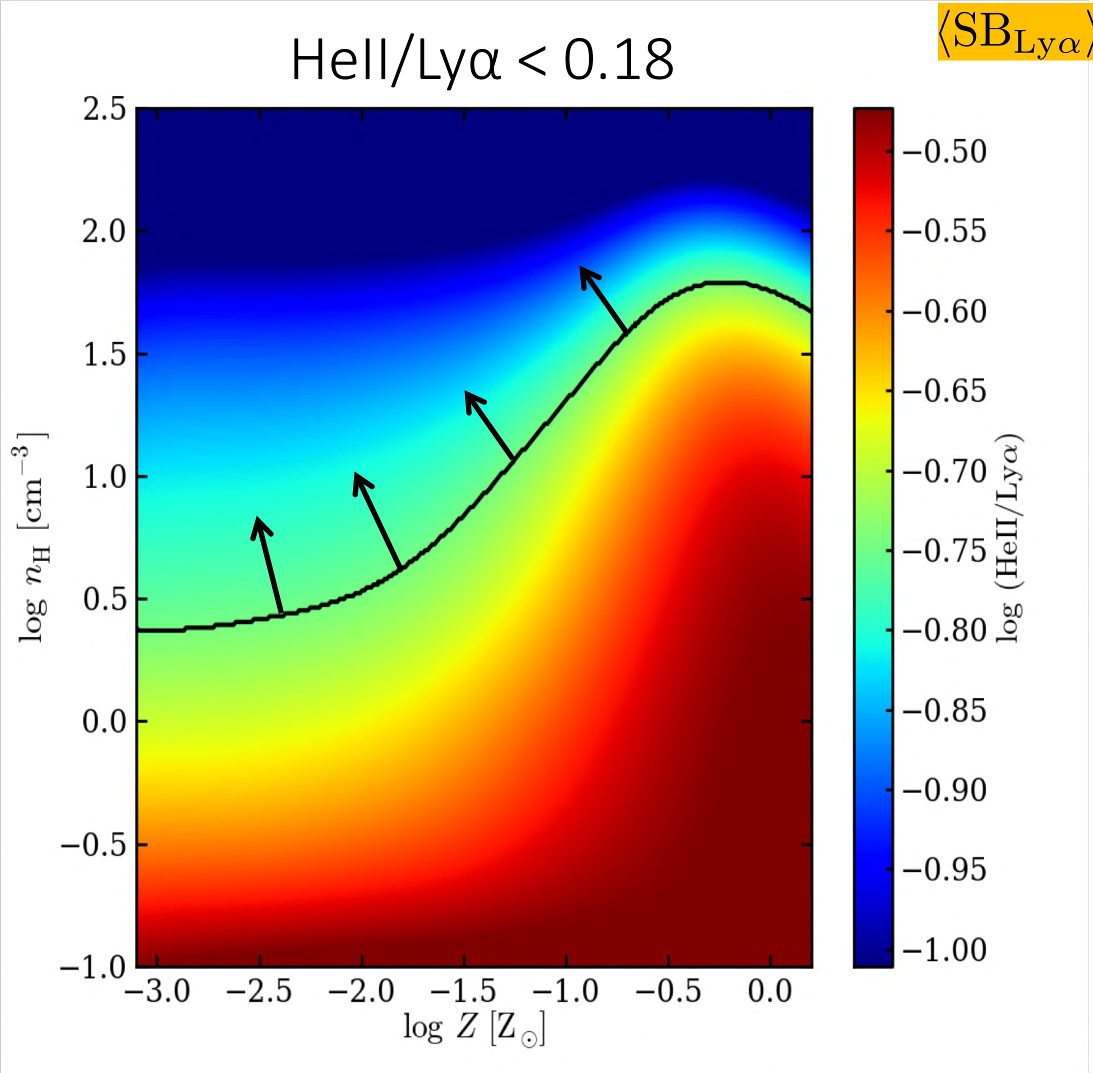


HeII/Lyα < 0.18 (3σ limit)

Photoionization models require high densities: ISM densities on 100 kpc scales?

FAB+2015

$$\langle \mathrm{SB}_{\mathrm{Ly}\alpha} \rangle = 7 \times 10^{-18}\ \mathrm{erg\ s^{-1}\ cm^{-2} arcsec^{-2}}$$



$$n_{\rm H} \gtrsim 3\ \mathrm{cm^{-3}}$$

(for any metallicity)

Photoionization models require clouds with parsec sizes!

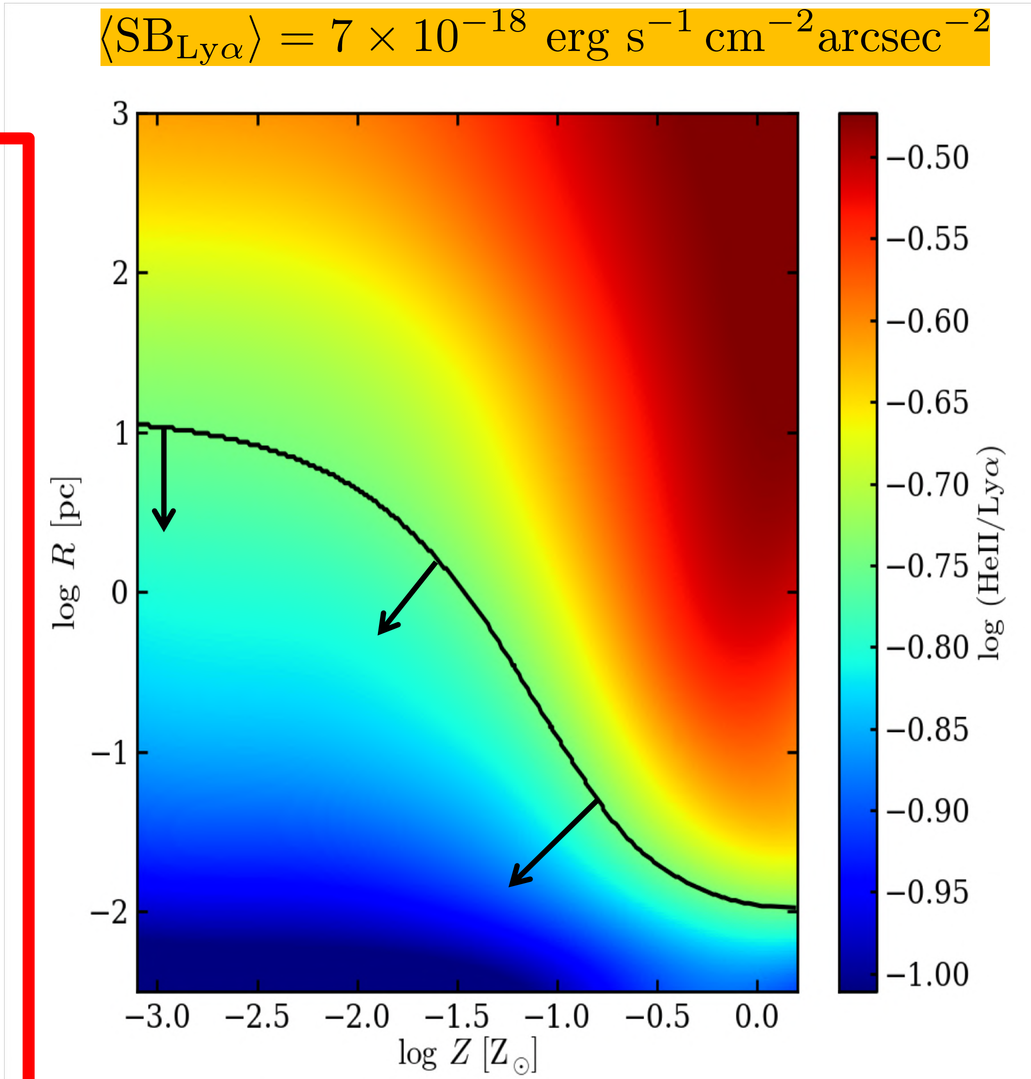
FAB+2015

$$R \approx \frac{N_{\rm H}}{n_{\rm H}} \ll 1\ {\rm kpc}$$

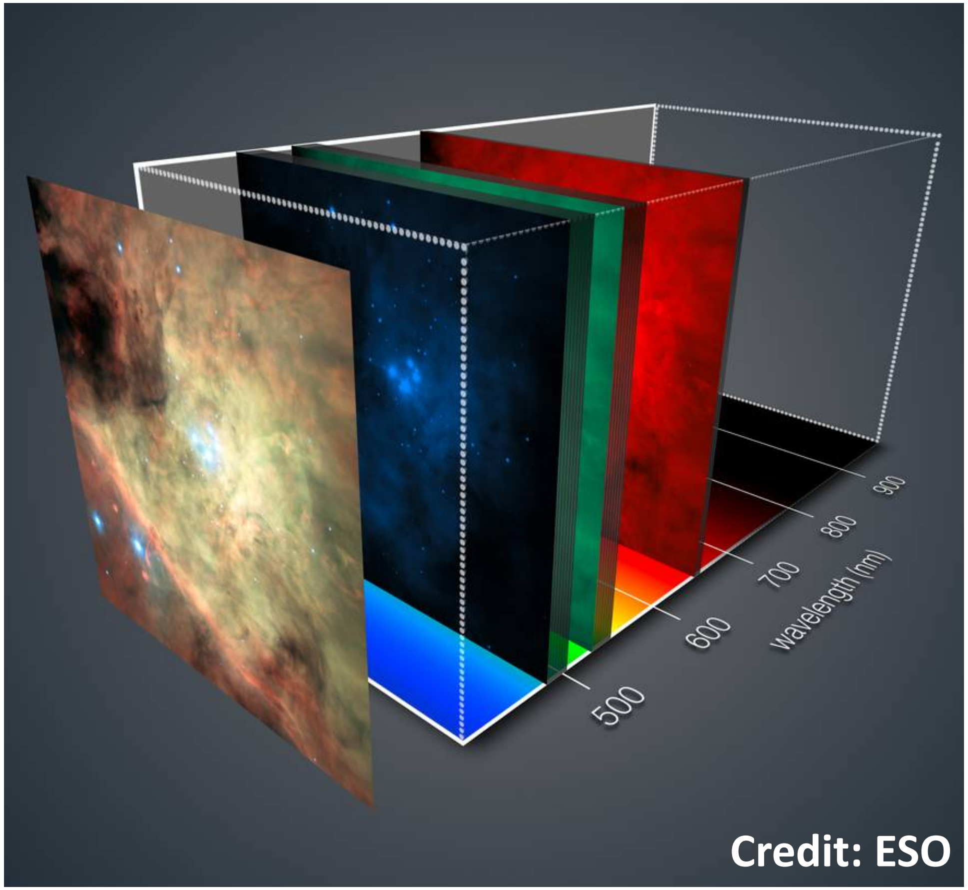
Most of current cosmological simulations cannot resolve subkiloparsec gas-clumps on large scales (e.g., CGM)...

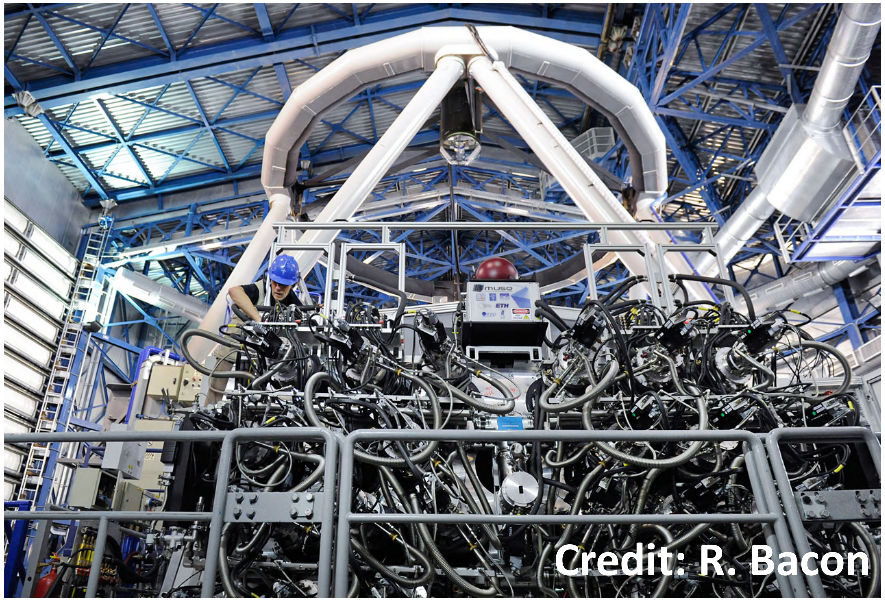
This, together with other results (HVCs, galactic winds, ...) motivated new theoretical research:

- High-resolution simulations of multiphase gas (e.g., McCourt+2018, Gronke&Oh 2018-2019-2020, Mandelker+2018, Vossberg+2019);
- Cosmological simulations with higher refinement schemes for CGM (e.g., Hummels+2018, Suresh+2018);
- Lognormal distribution for gas densities (e.g., Cantalupo+2019)



A game changer: MUSE (the Multi-Unit Spectroscopic Explorer) on VLT/ESO





QSO MUSEUM:
Quasar's **S**napshot **O**bservations with **MU**se: **S**earch for **E**xtended **U**ltraviolet e**M**ission

FAB+2019a

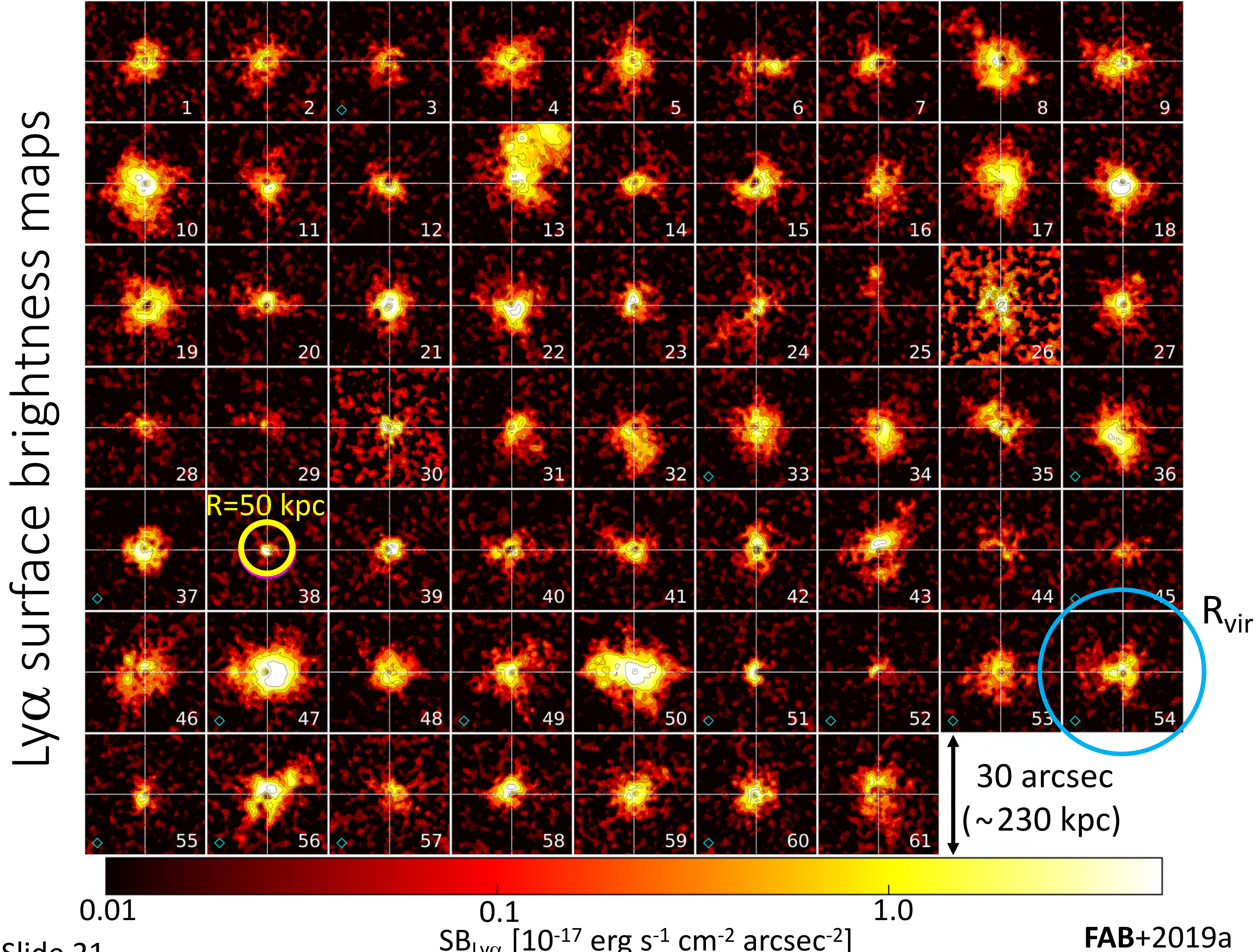
- **"Service mode" with MUSE/VLT** (142 hours awarded so far)

- **Targeted so far:** 61 z ~3.2 quasars (15 radio-loud);
  average i_mag (AB) = 18.13 (GTO sample is 17.5 @z~ 3.4)

- **Exposure time:** average 45 minutes/source (some longer, up to 4.5 hours/source);

- **SB limit @Lya line:** 1σ ~ 2 x 10^{-18} erg s^{-1} cm^{-2} $arcsec^{-2}$ (30Å NB); 1σ ~ 8.8 x 10^{-19} erg s^{-1} cm^{-2} $arcsec^{-2}$ (1.25Å layer)

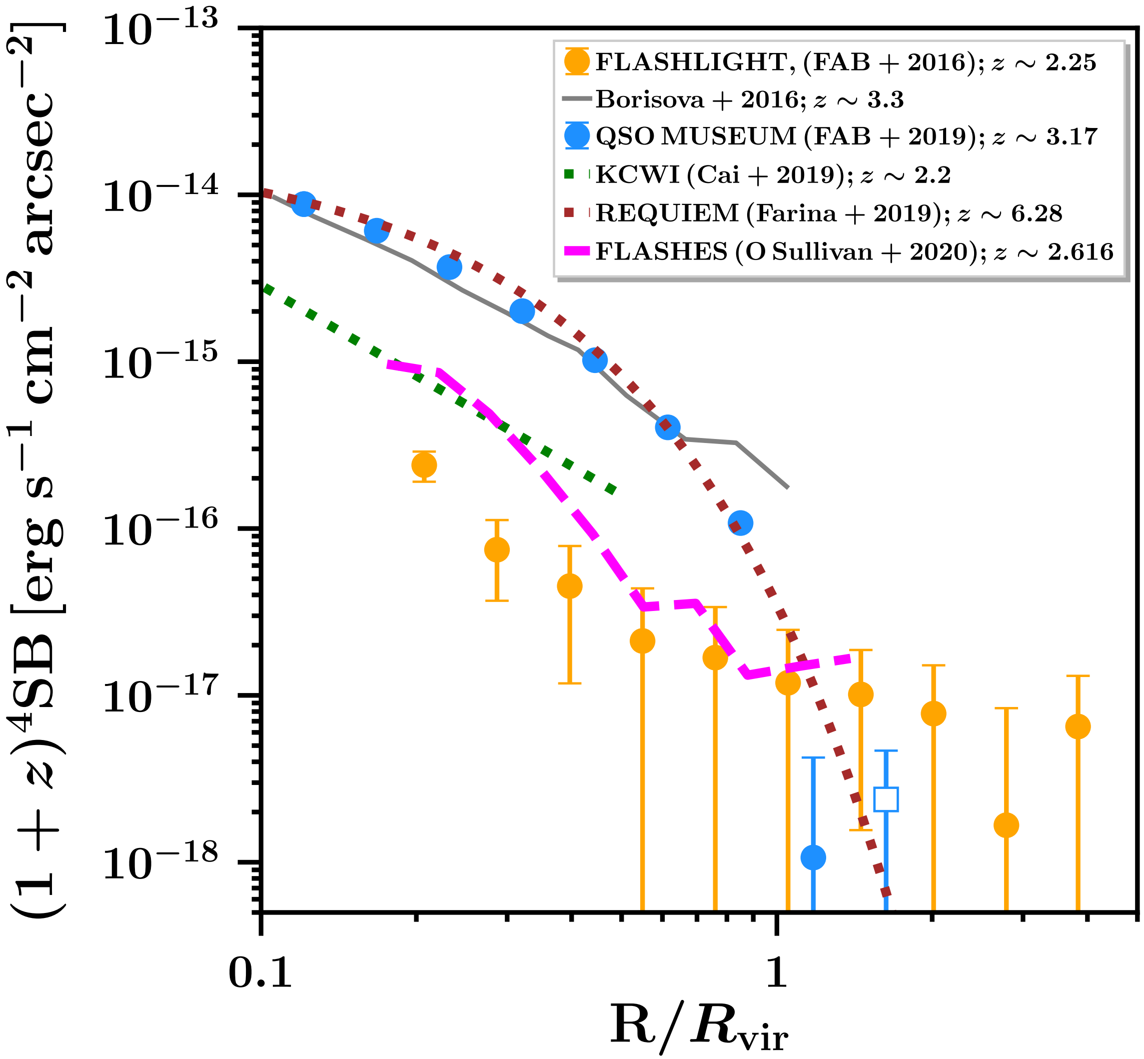
- **Seeing:** average 1" (0.6"-1.8") **Weather:** clear or photometric


Lyα surface brightness maps
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61
R=50 kpc
R_vir
30 arcsec
(~230 kpc)
0.01
0.1
1.0
SB_Lyα [10^-17 erg s^-1 cm^-2 arcsec^-2]
FAB+2019a

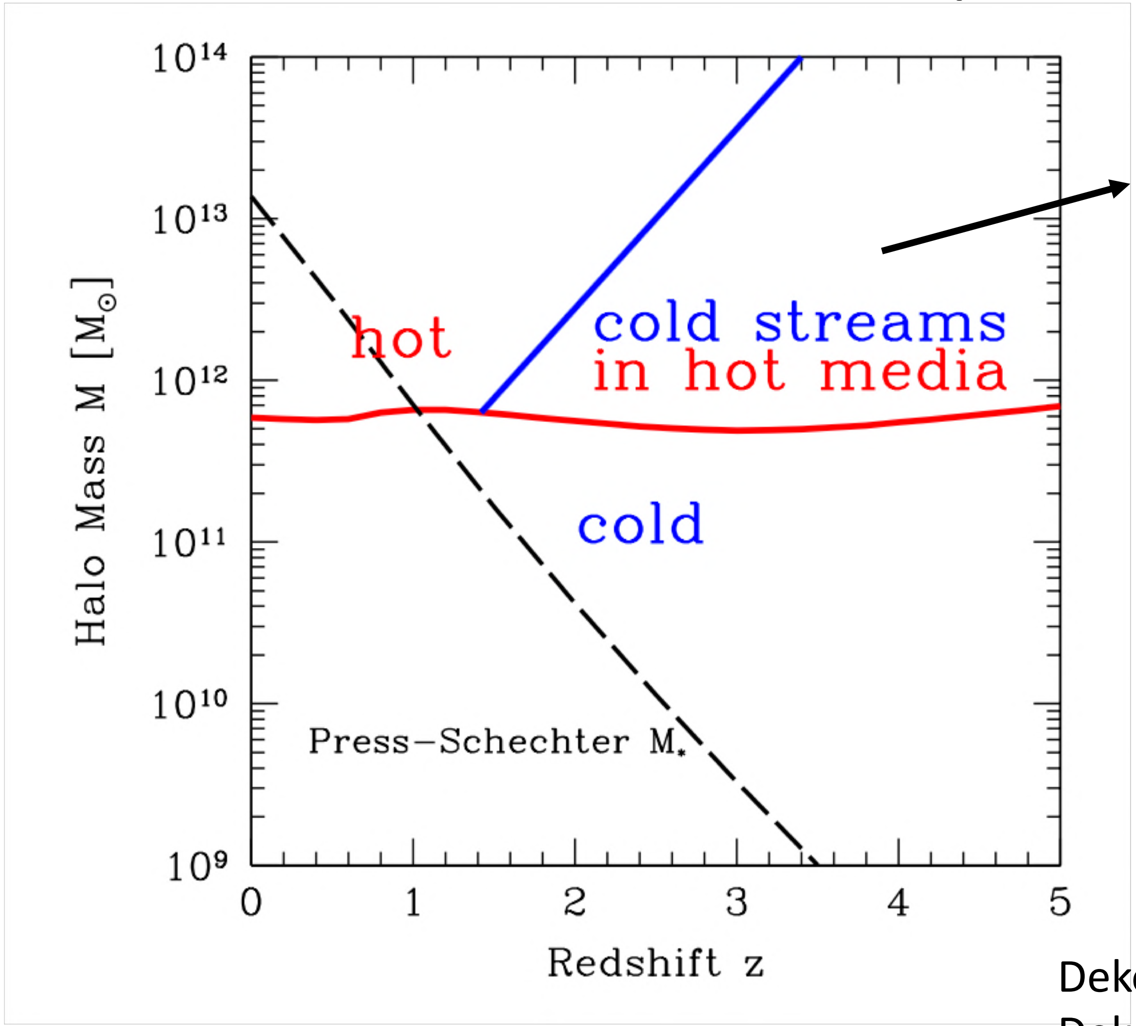
Slide 21

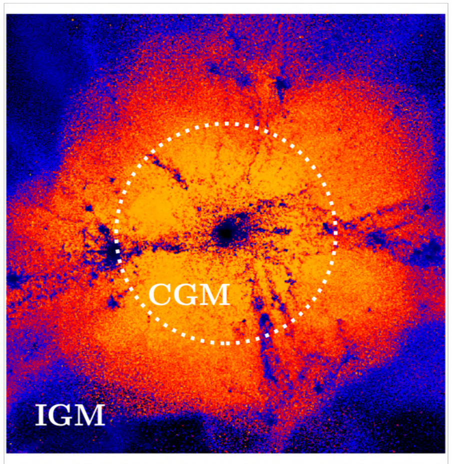
Is there a redshift evolution?

FAB+2019a



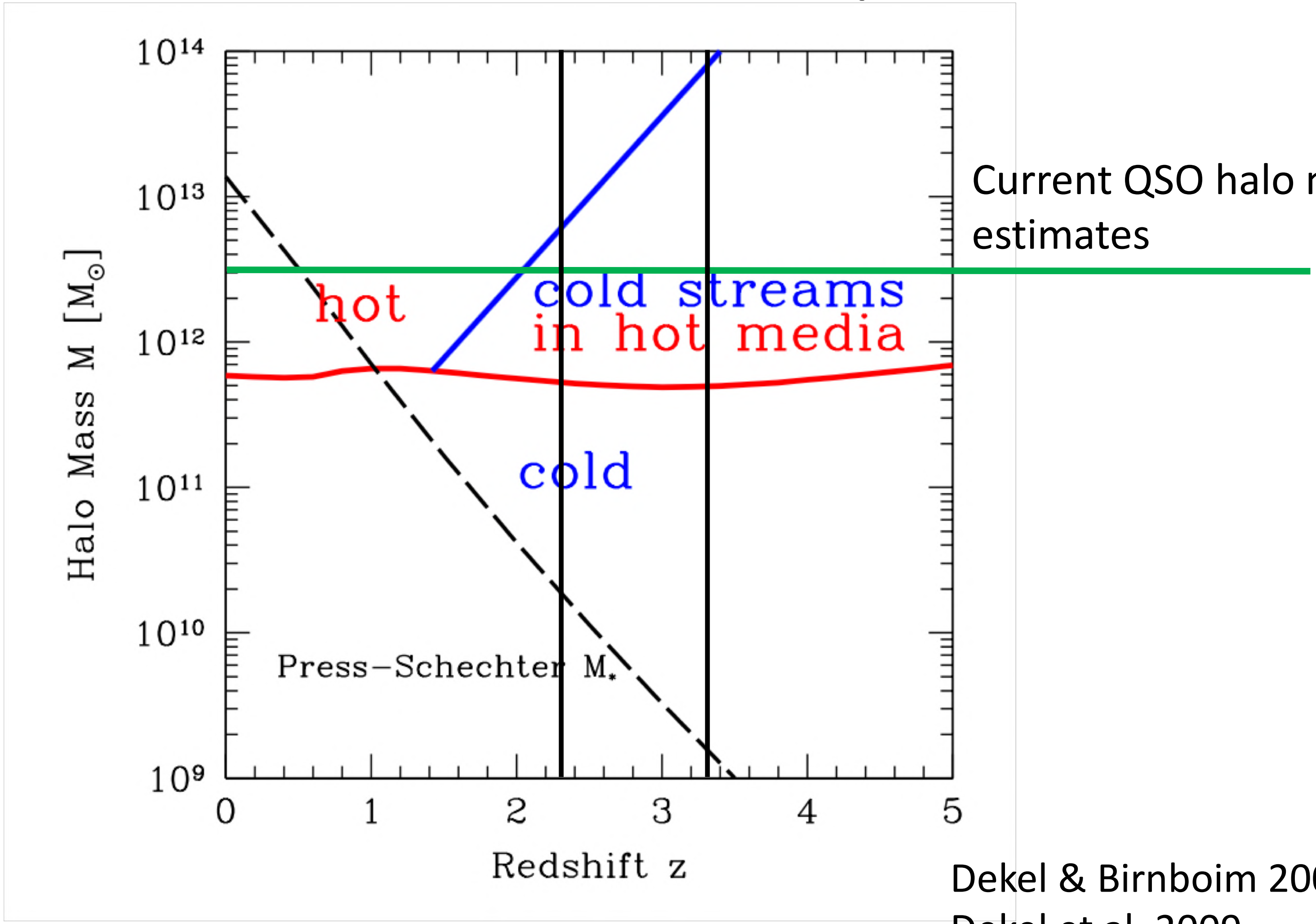
Witnessing the transition between cold vs hot mode accretion for quasar hosts?



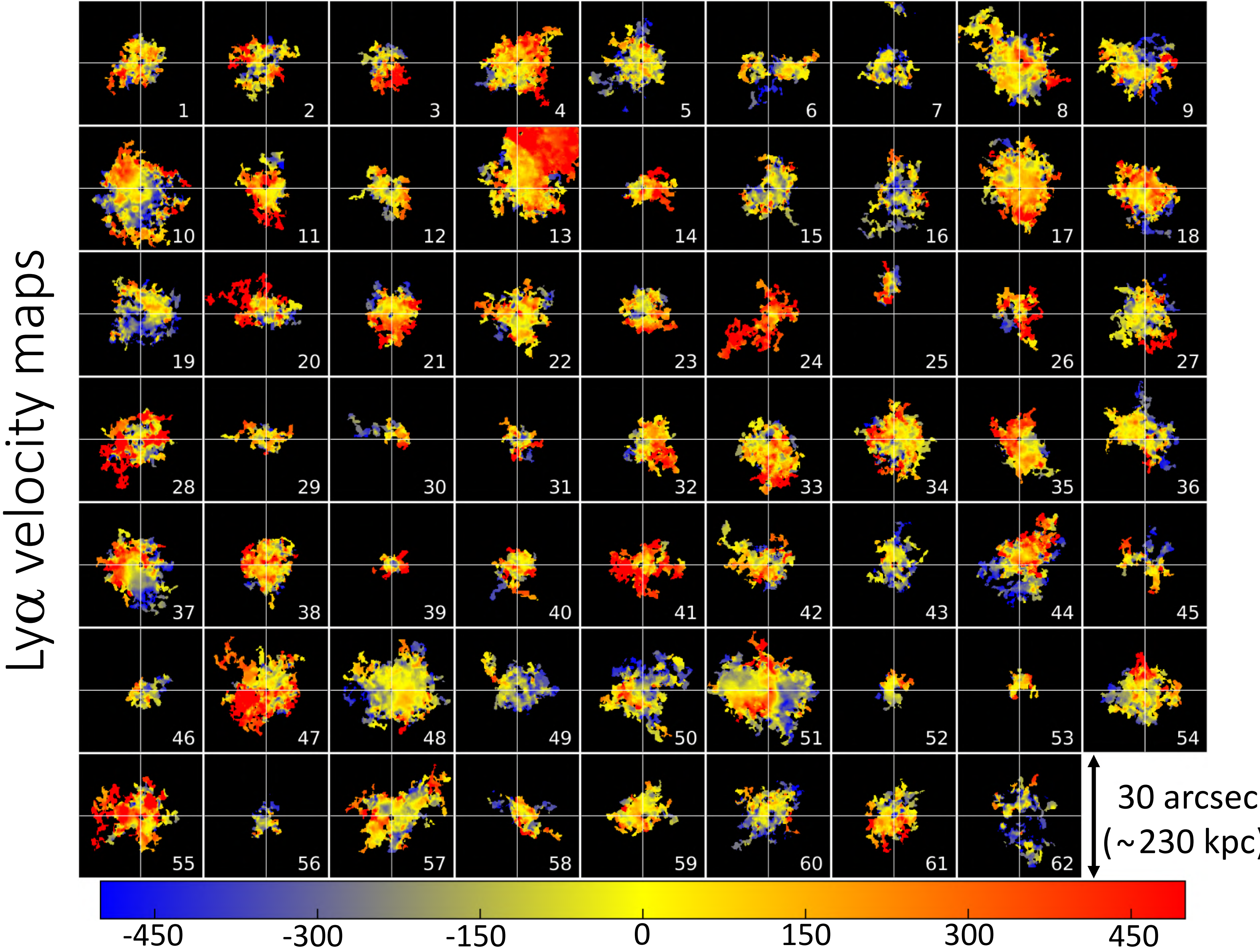


Dekel & Birnboim 2006
Dekel et al. 2009

Witnessing the transition between cold vs hot mode accretion for quasar hosts?



Dekel & Birnboim 2006
Dekel et al. 2009


Lyα velocity maps
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44
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46
47
48
49
50
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55
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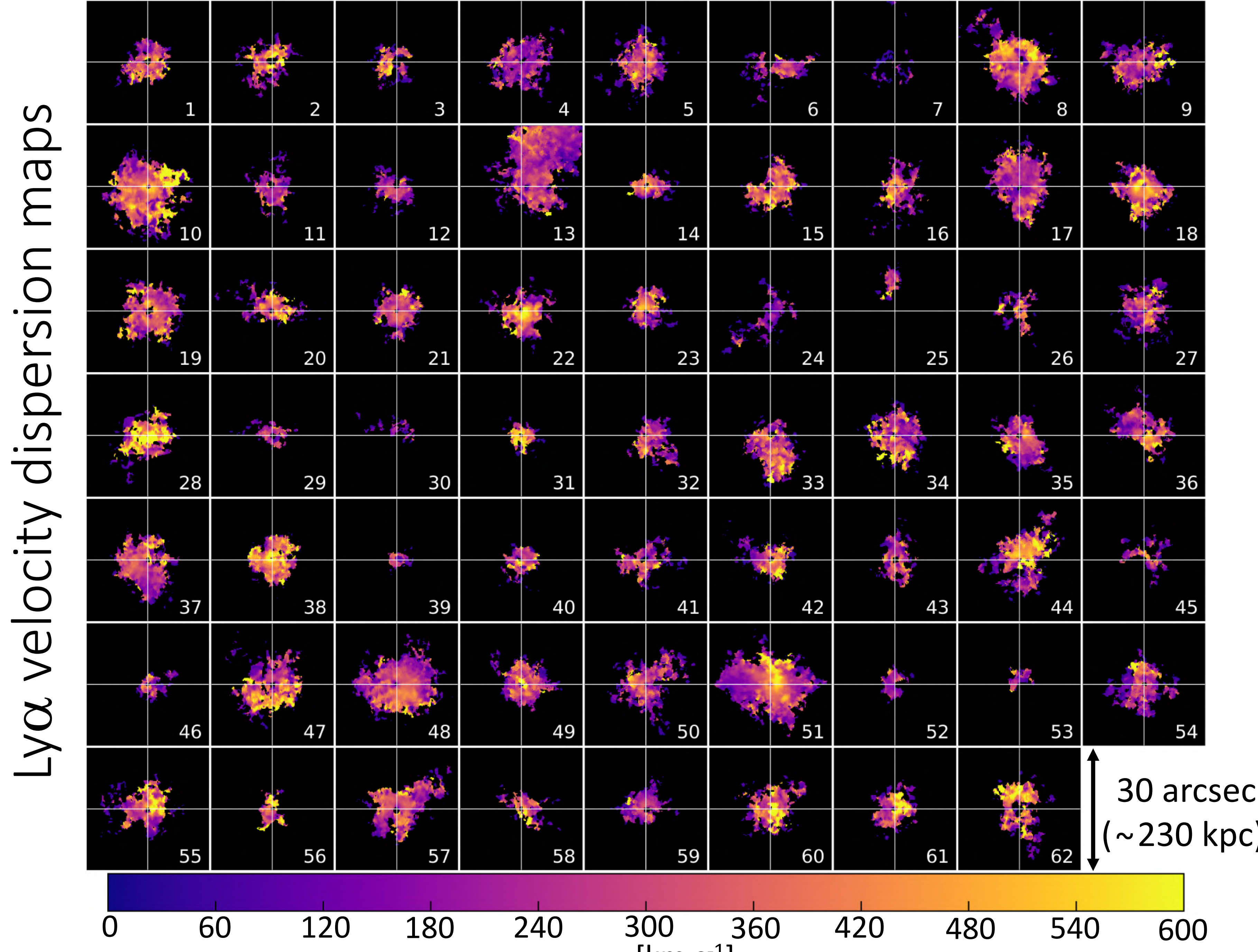
57
58
59
60
61
62
30 arcsec
(~230 kpc)
-450
-300
-150
0
150
300
450
$\Delta v_{Ly\alpha}$ [km s^{-1}]

FAB+2019a



Lyα velocity dispersion maps
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53
54
55
56
57
58
59
60
61
62
30 arcsec
(~230 kpc)
0
60
120
180
240
300
360
420
480
540
600
σLyα [km s-1]

FAB+2019a

$$M_{\rm DM} \approx 10^{12.5}\ M_\odot;\ \text{NFW profile at } z \sim 3$$

$$V_{\rm circ}^{\rm max} \approx 360\ {\rm km/s}$$

$$\sigma_{\rm 1D} = V_{\rm circ}^{\rm max}/\sqrt{2} \approx 250\ {\rm km/s}$$

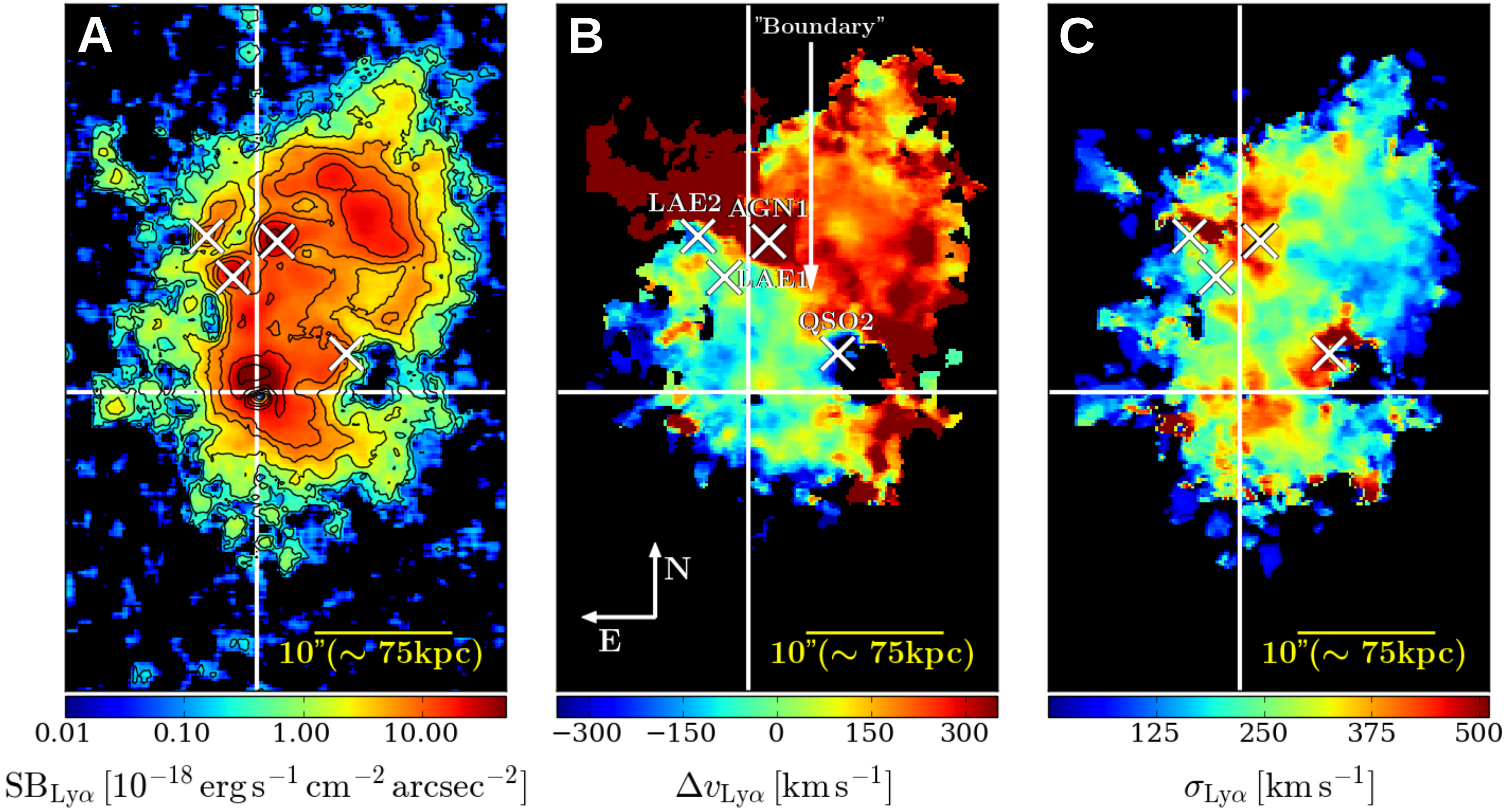
⇩

The kinematics are consistent with gravitational motions

(even more when considering Lyman-alpha resonant scattering and MUSE spectral resolution)

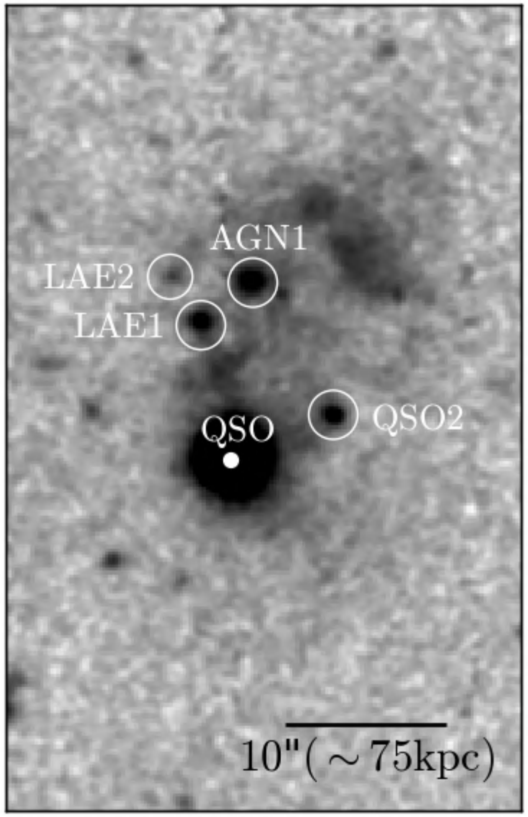
FAB+2019a

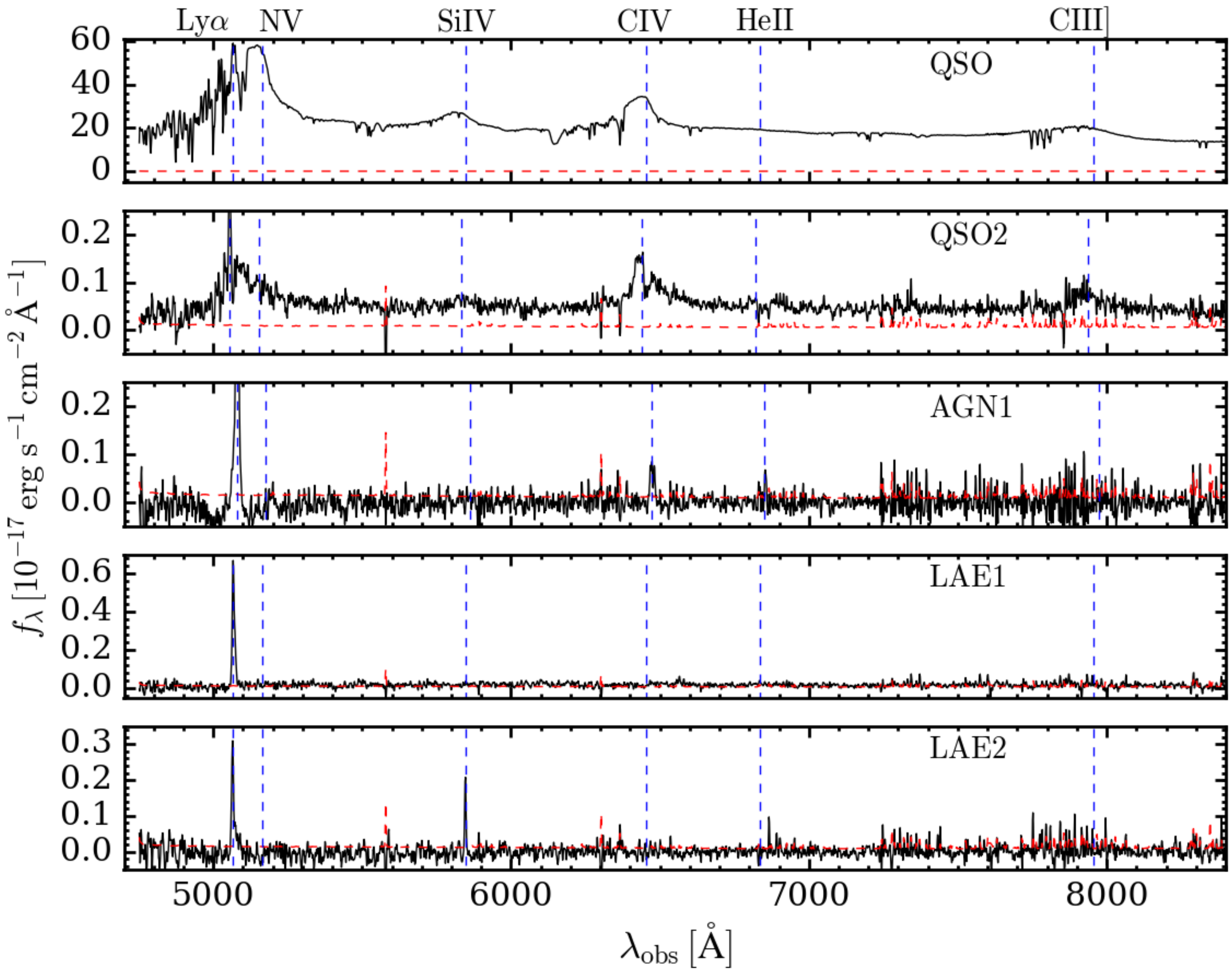
A coherent velocity pattern over > 100 kpc



FAB+2018a

…and at least 4 companions (2 AGN)

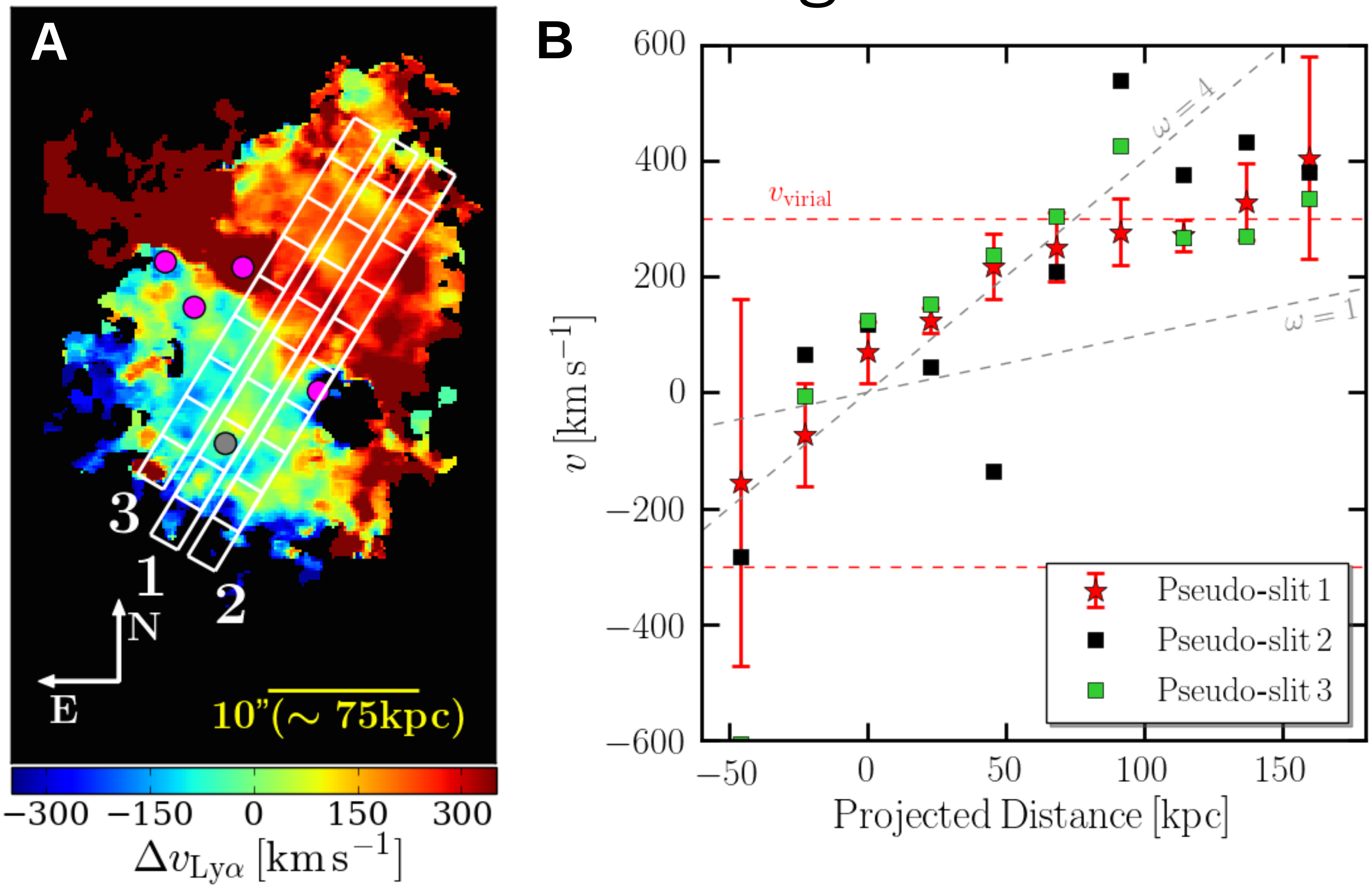




FAB+2018

i_mag ~ 25 for the companions AGN → How well do we know 'faint AGN' clustering?

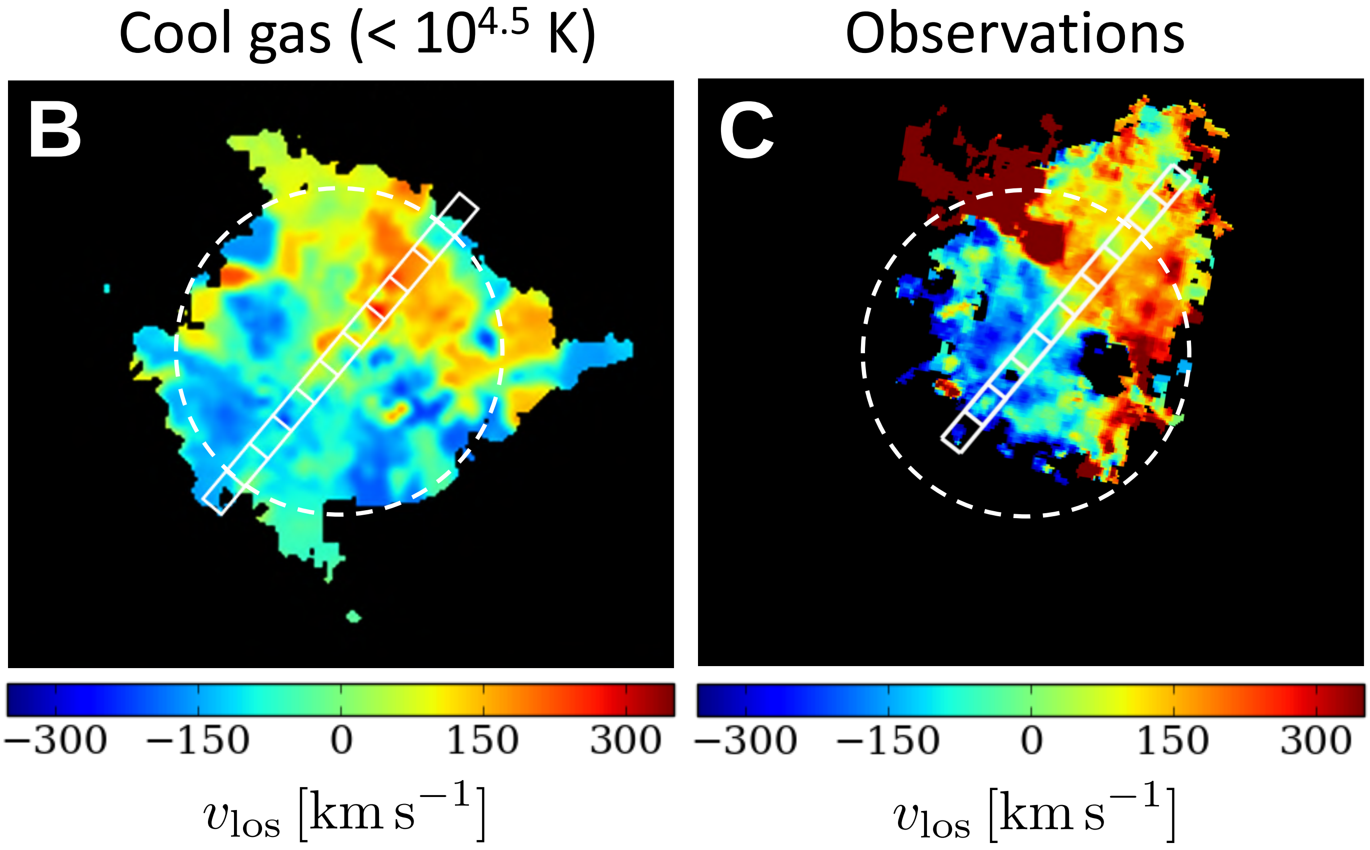
A coherent velocity pattern over > 100 kpc: rotation-like signature



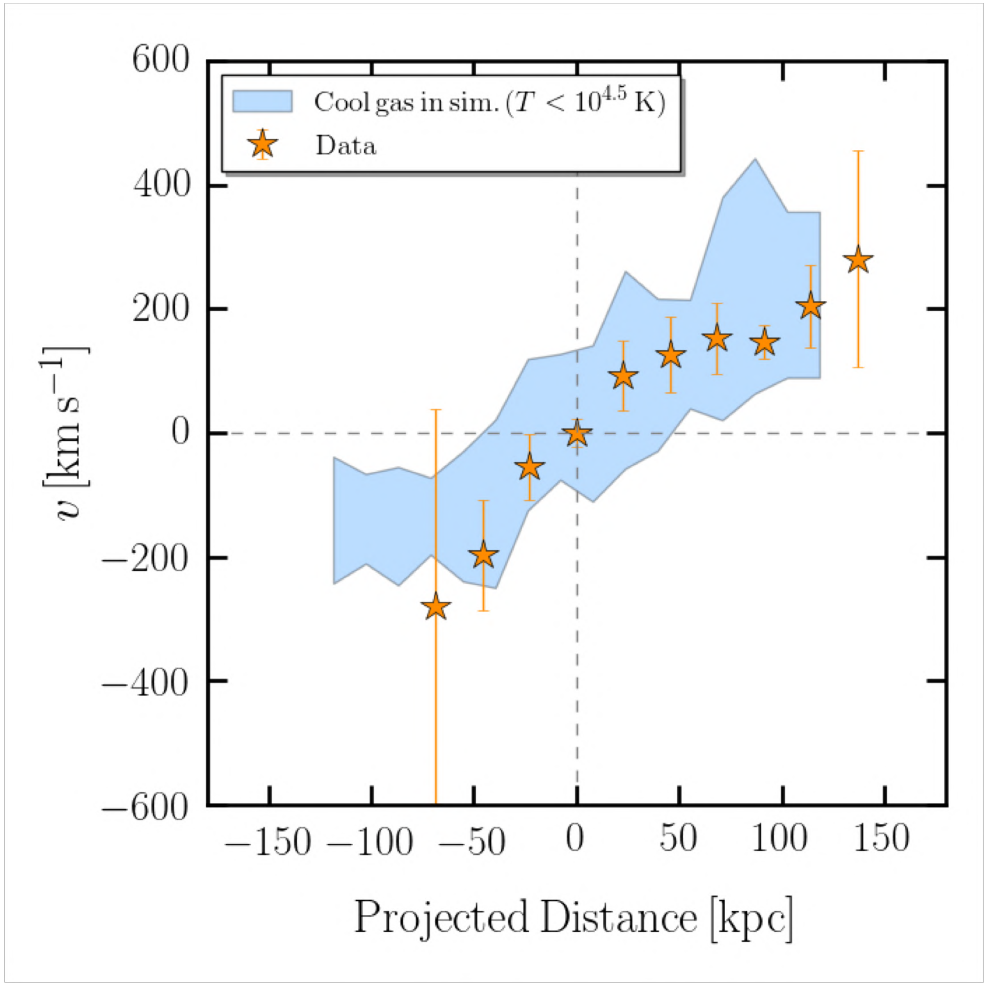
FAB+2018a

Comparison with cosmological simulations: witnessing the build up of a massive system

FAB+2018a

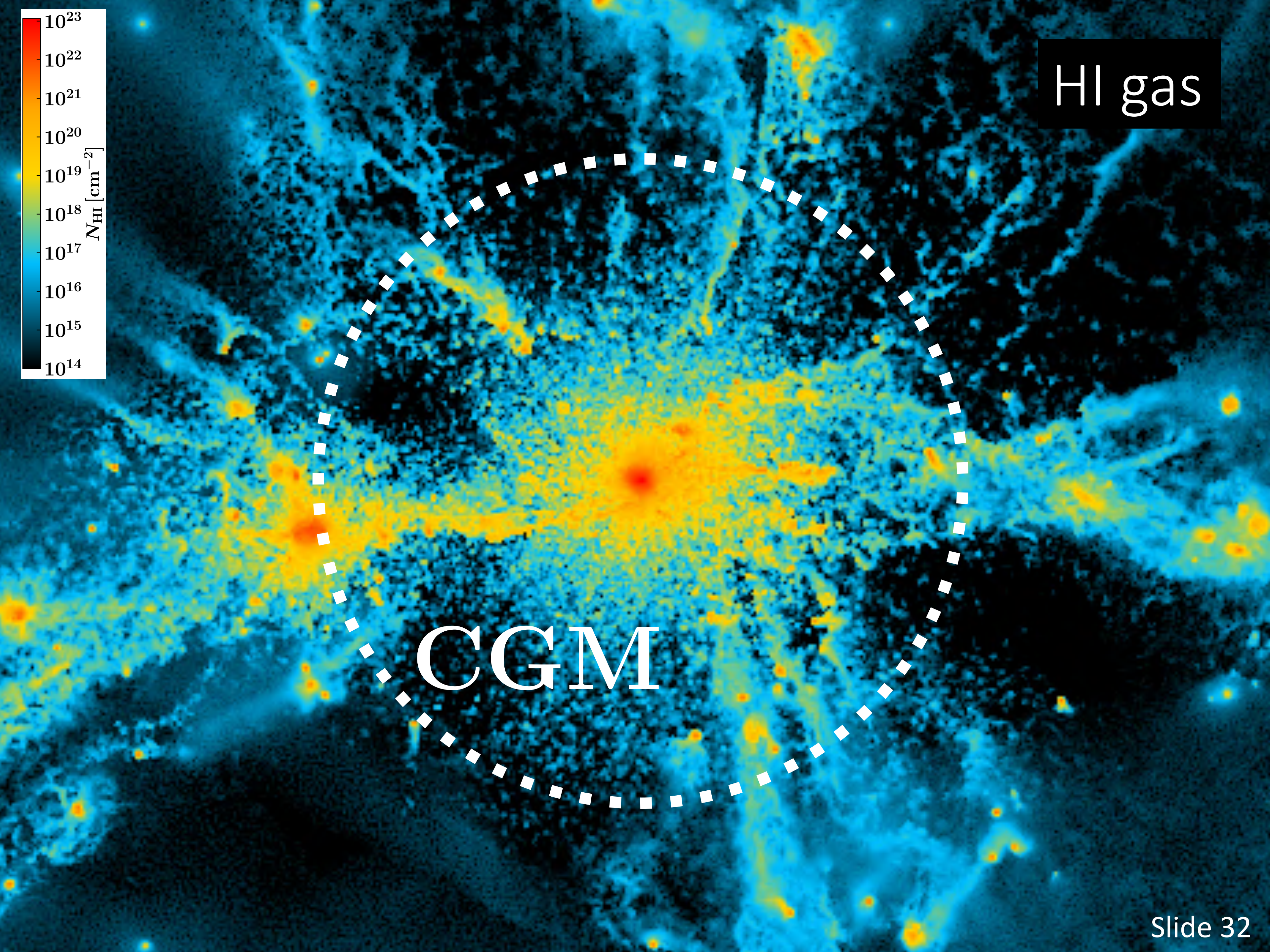


The observed velocity gradient could trace the inspiraling of substructures within a massive halo



≈20 % of projections

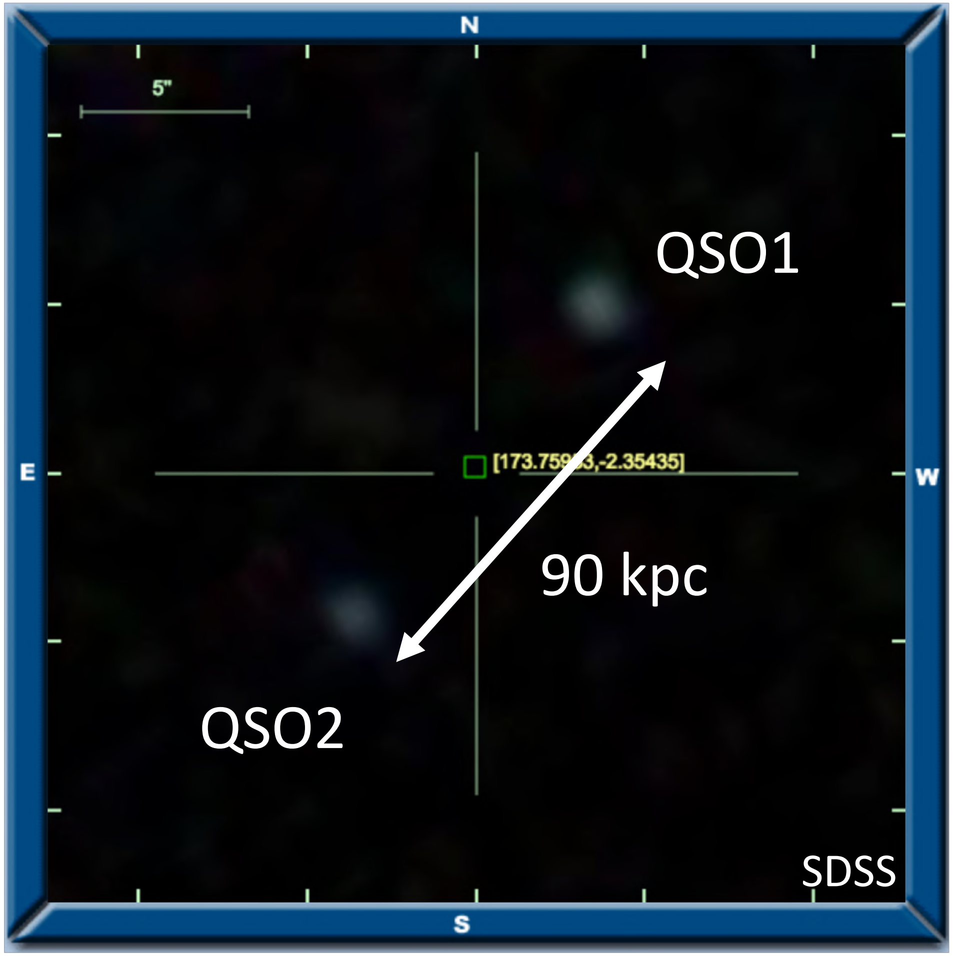
FAB+2018a


HI gas
CGM
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
$N_{\rm HI}$ [cm^{-2}]

Towards a clear IGM detection: from individual quasars to quasar pairs

FAB+2019b

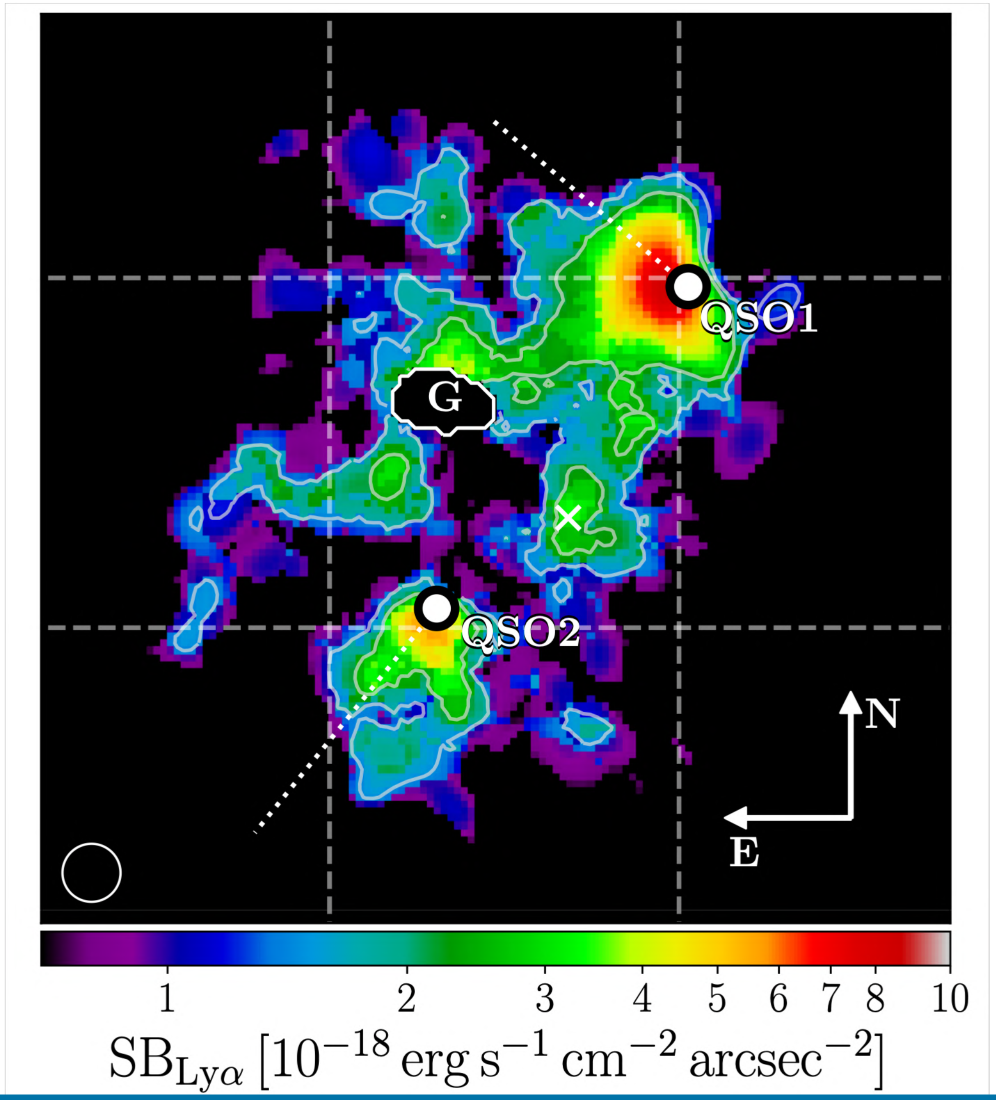
$z_{QSO1} = 3.020$
$z_{QSO2} = 3.008$
$M_{1450}^{QSO1} = -23.44$
$M_{1450}^{QSO2} = -23.12$



From a survey of 11 z~3 quasar pairs

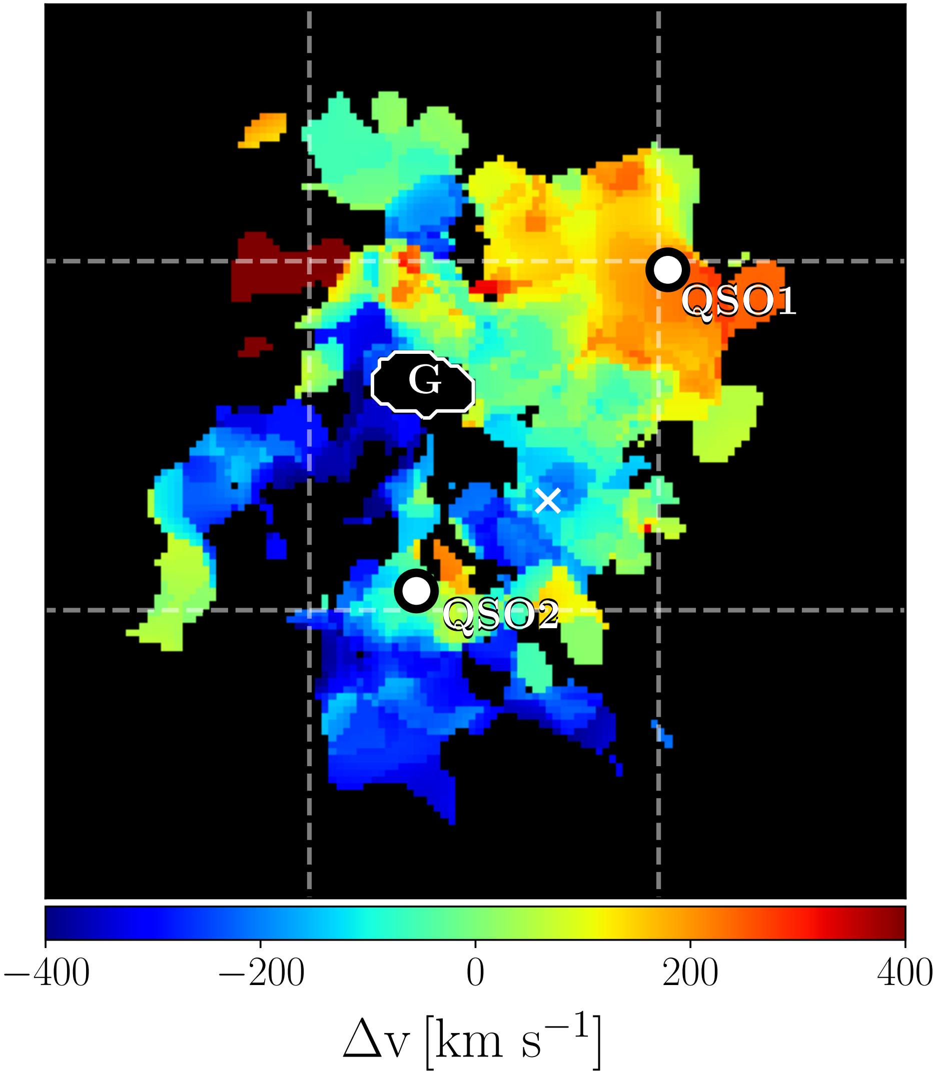
Discovery of intergalactic Lyα bridges

FAB+2019b



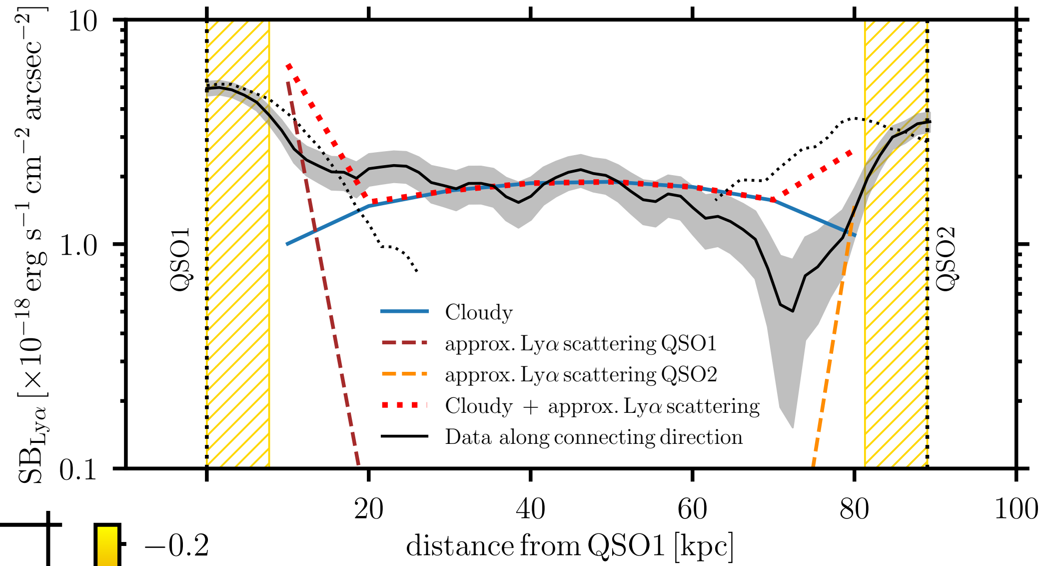
Discovery of intergalactic Lyα bridges

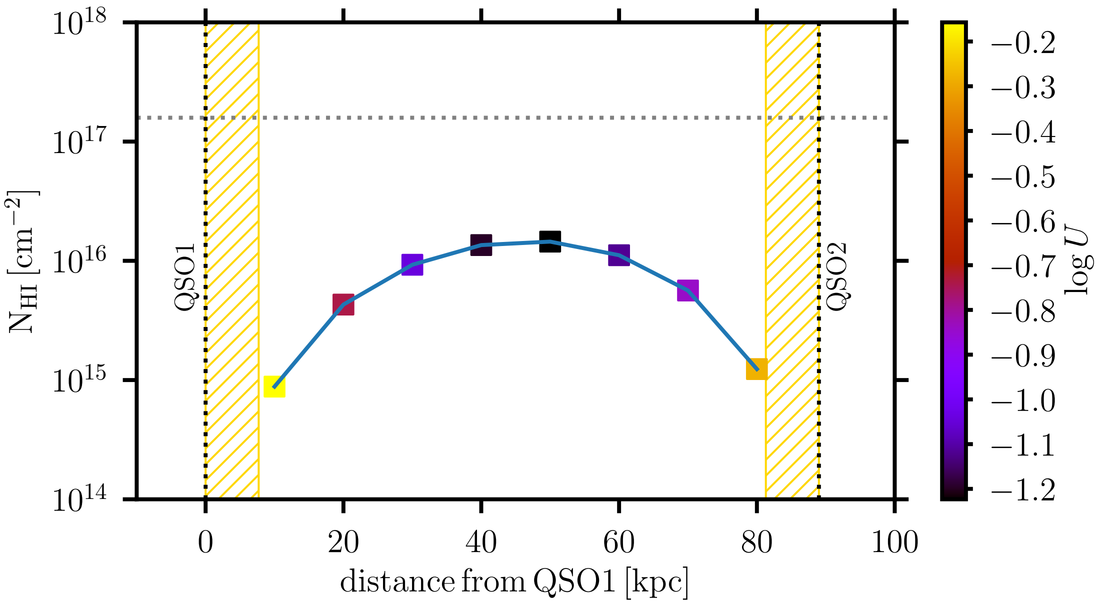
FAB+2019b



Photoionization modeling: constraining the physical properties and geometry of the system

1) Assuming the quasar pair at projected distance





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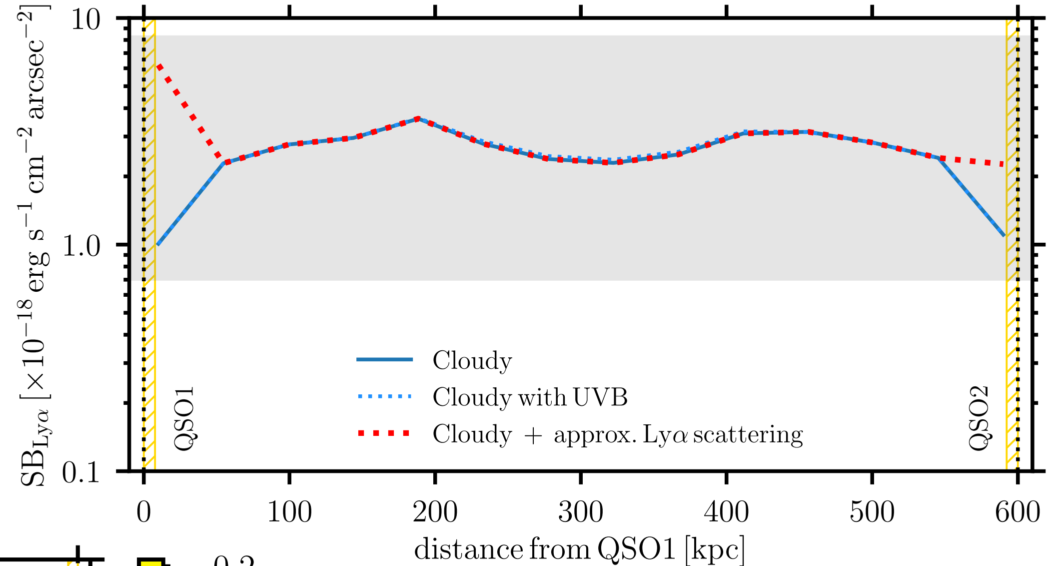
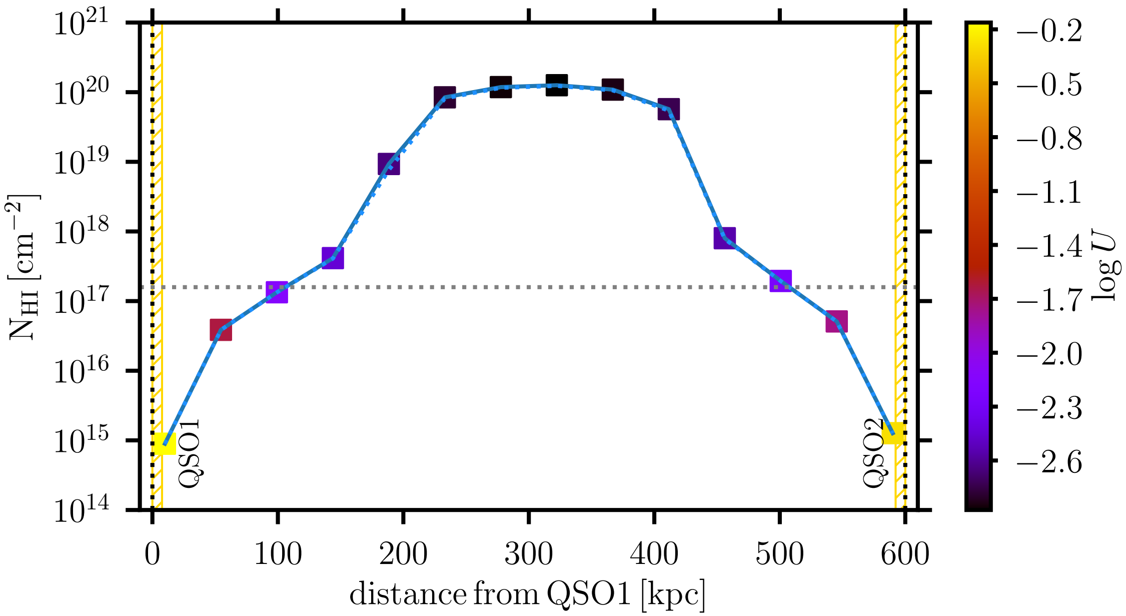
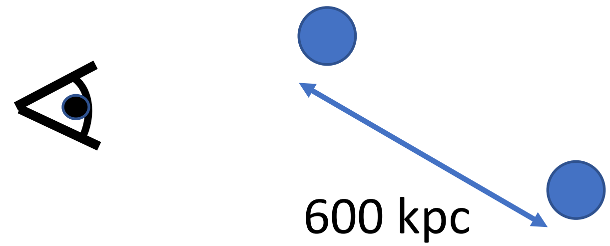


2) Assuming the quasar pair at 600 kpc distance





CGM/IGM in emission: a new field, still a lot to explore and learn…

Statistical observations of CGM of massive systems; IGM seen only in peculiar systems/fields

- What are the physical properties of these gas phases?

Hints for cool gas made up of dense structures

- What is the spatial distribution of the cool and warm/hot phase in halos? molecular phase?

Cool gas is routinely observed! diverse morphologies

- How does the IGM funnel into the CGM and onto the central galaxies? What is the role of satellites?

In a cool phase dominated by gravitational motions? Redshift evolution?

- Can we directly constrain halo dynamics?

Possibly

- What is the role of AGN in shaping the properties of galactic halos and the surrounding IGM?

No violent AGN winds/outflows detected in the cool CGM