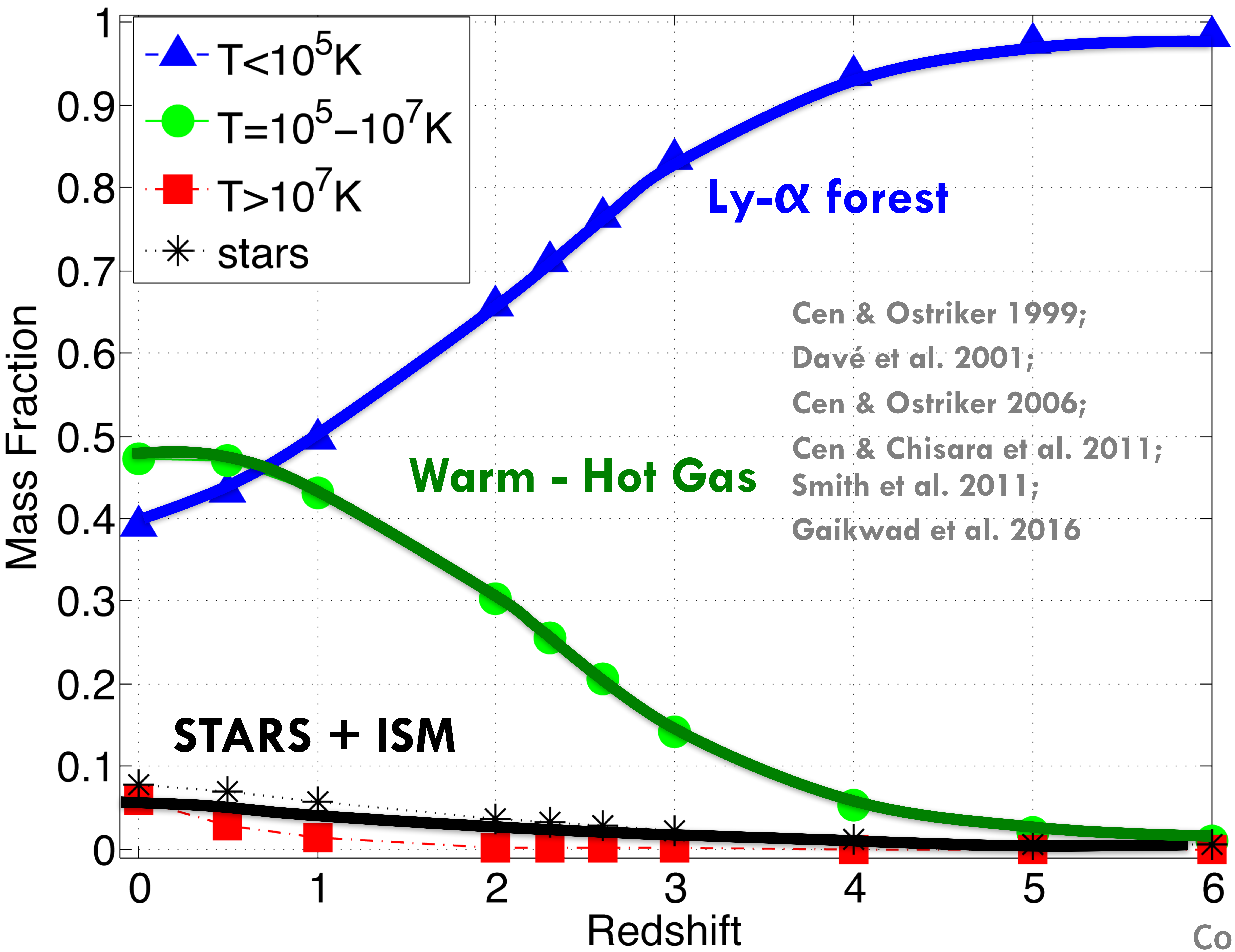
EXPLORING CGM / IGM

moving away from large surveys

anand narayanan

Purvi Udhwani, Aditya Manuwal, Jayadev Pradeep, Sriram Sankar,
Pratyush Anshul, Mathin Yadav, Sachin PC, Dheeraj Kumar Khonde

Raghunathan Srianand (IUCAA), Sowgat Muzahid (IUCAA), Vikram Khaire (IIST), Hum Chand (ARIES),
Jane Charlton (Penn State), Blair Savage (U of Wisconsin), Bart Wakker (U of Wisconsin)



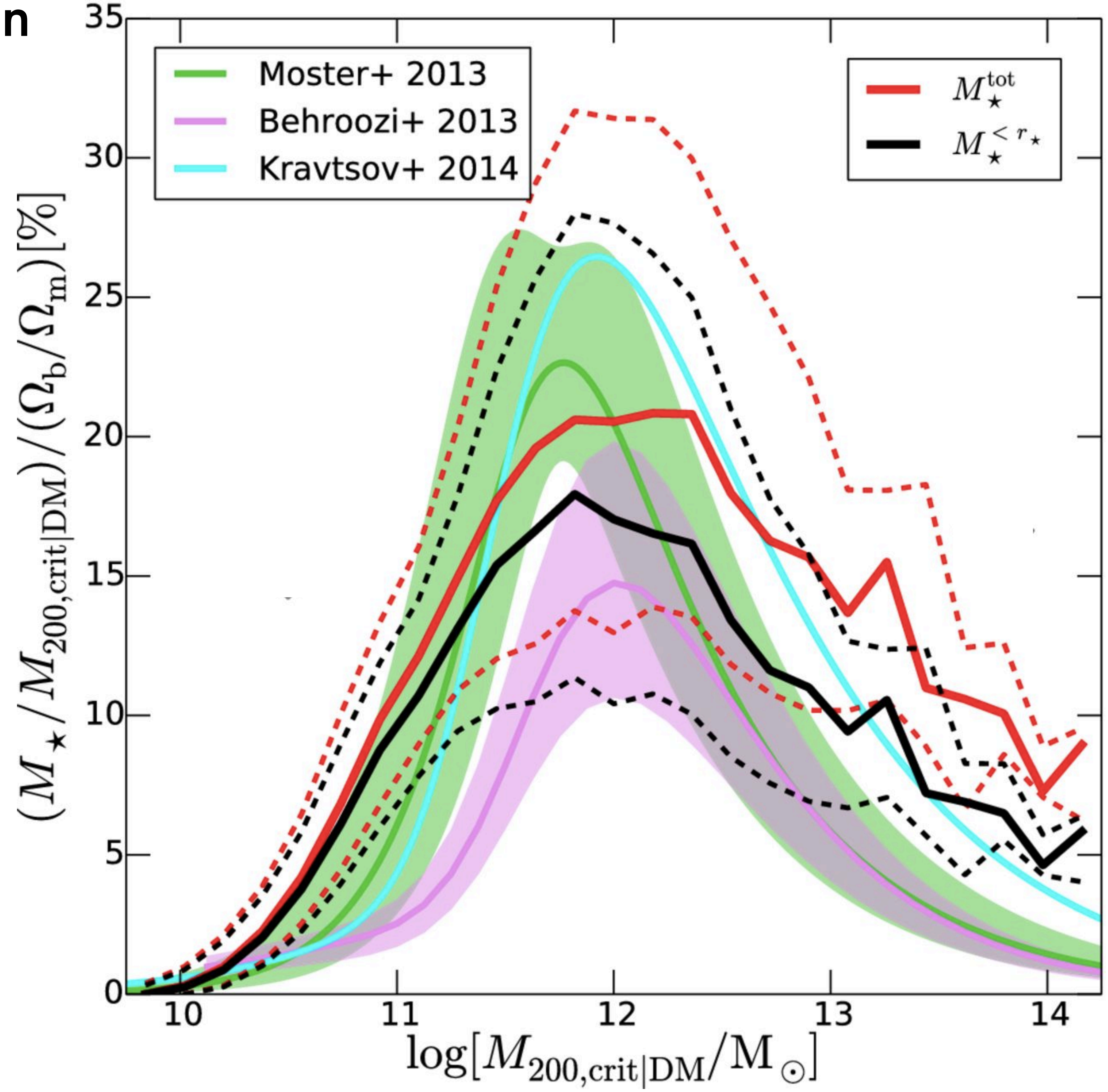
Courtesy: Todd Tripp

cosmic baryon fraction (19% from CMB)

100

if baryons accreted onto the halos all become stars

Feedback processes and accretion rearrange baryons



Vogelsberger et al. (2014)

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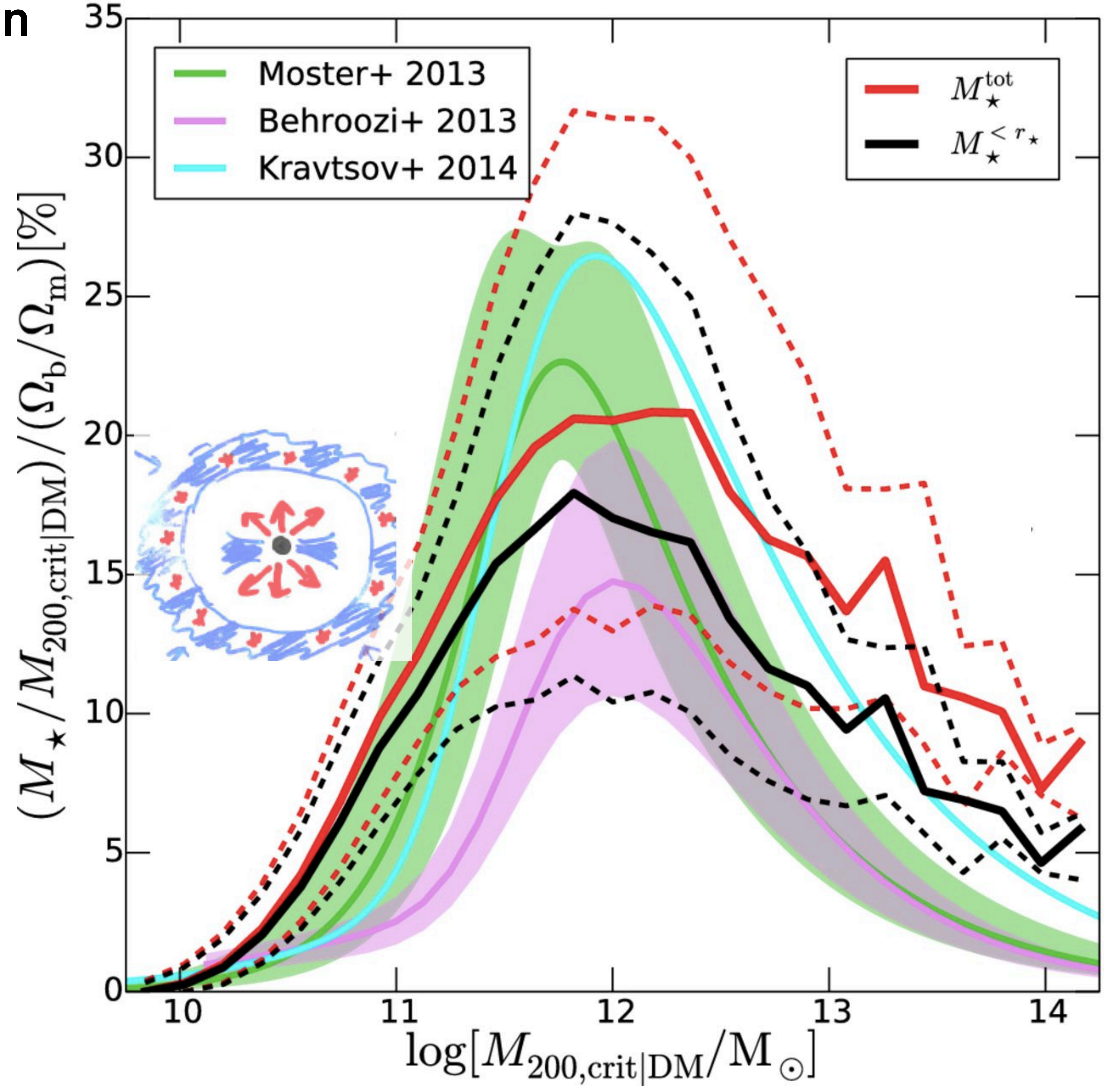

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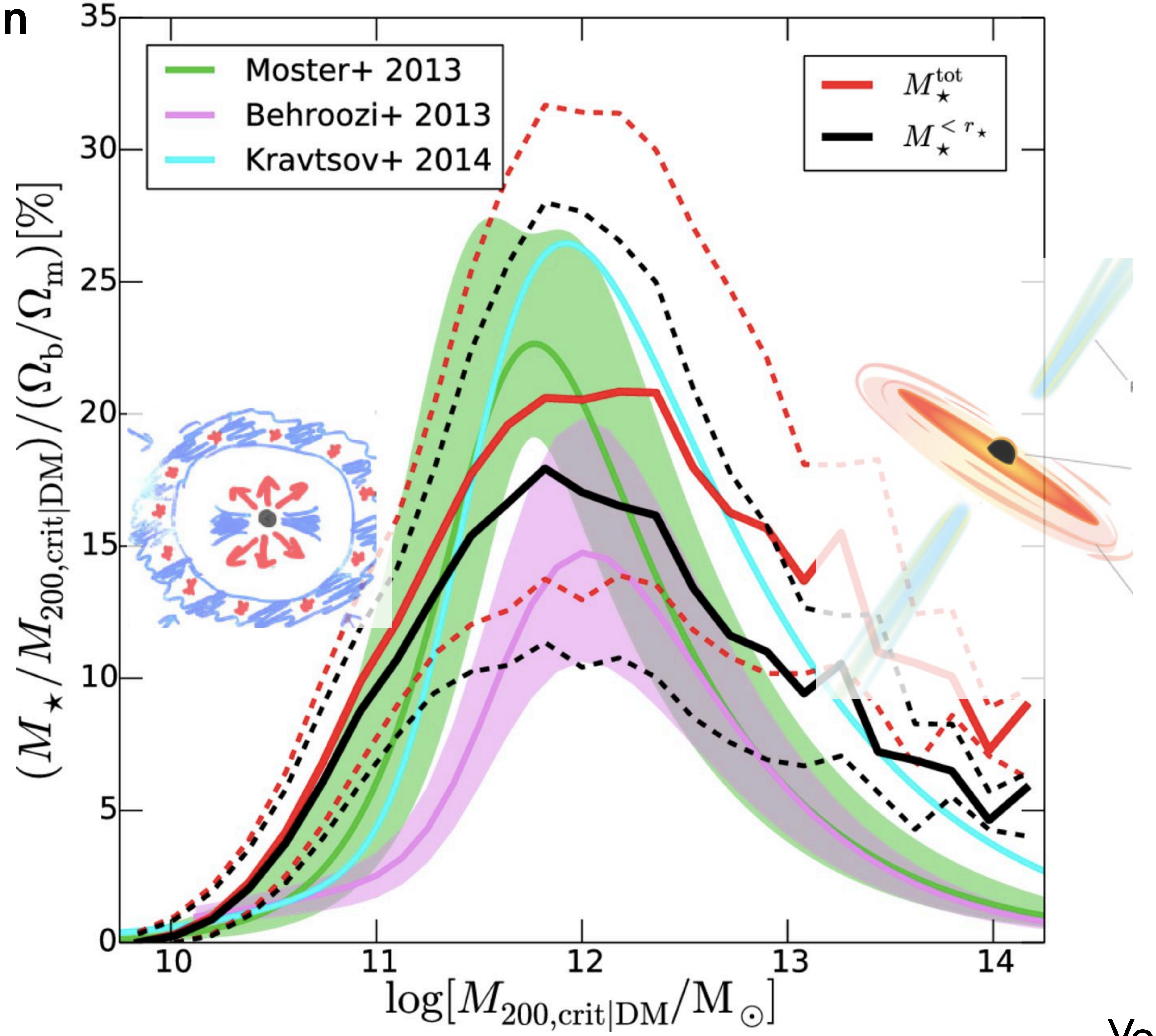

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M81 Galaxy group
Chynoweth et al., NRAO/
(c) APOD / Jordi Gallego


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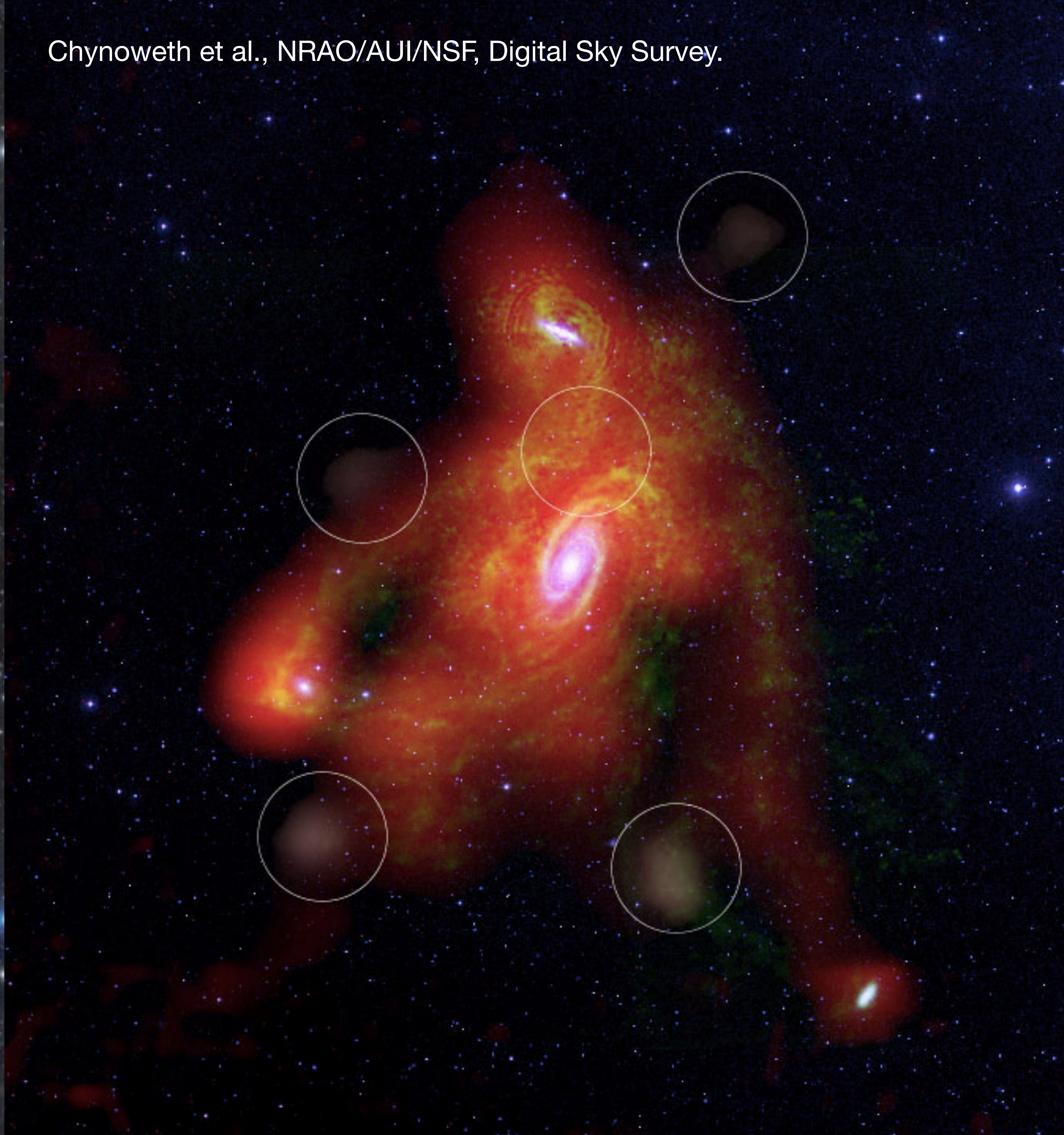
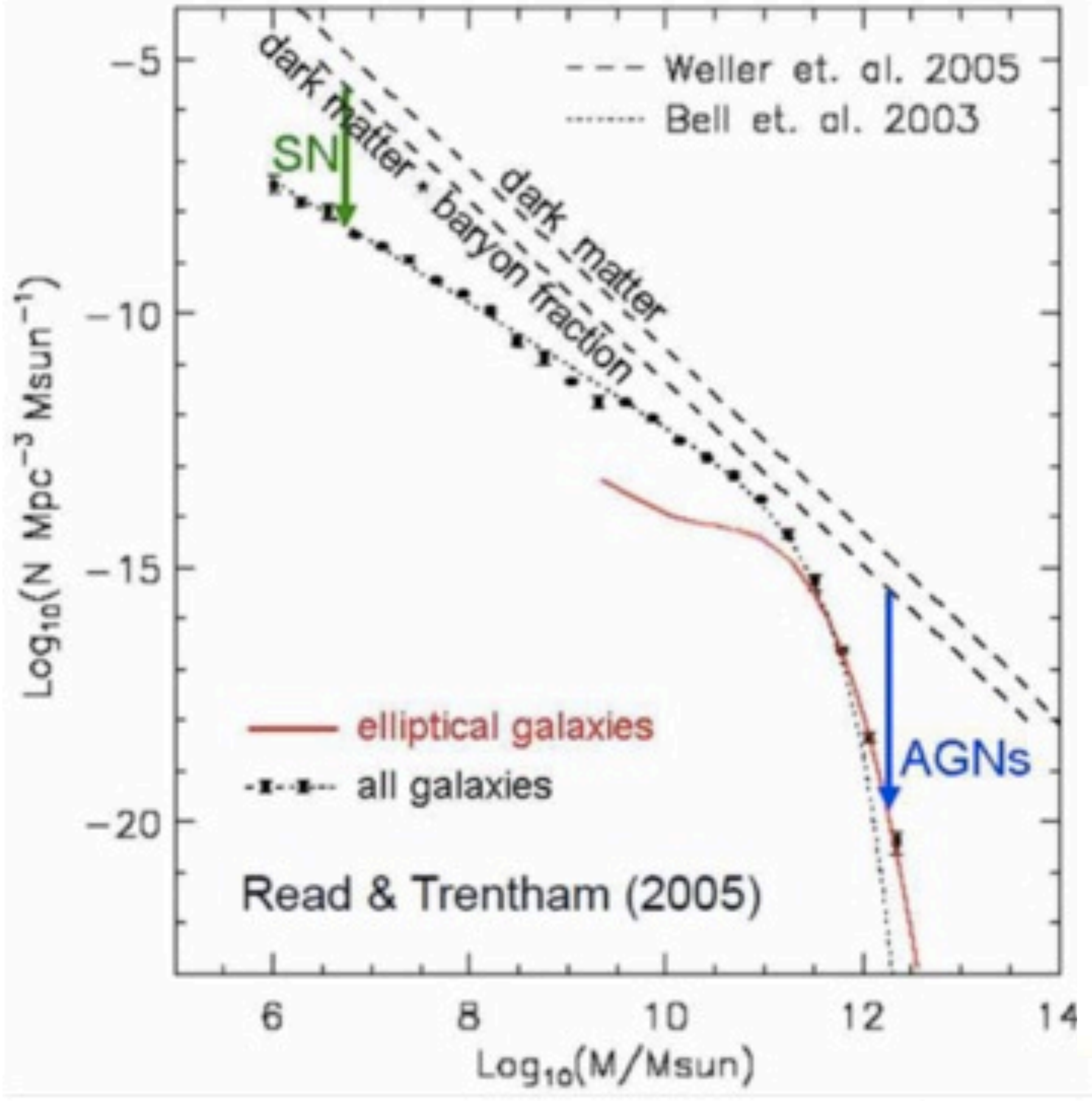
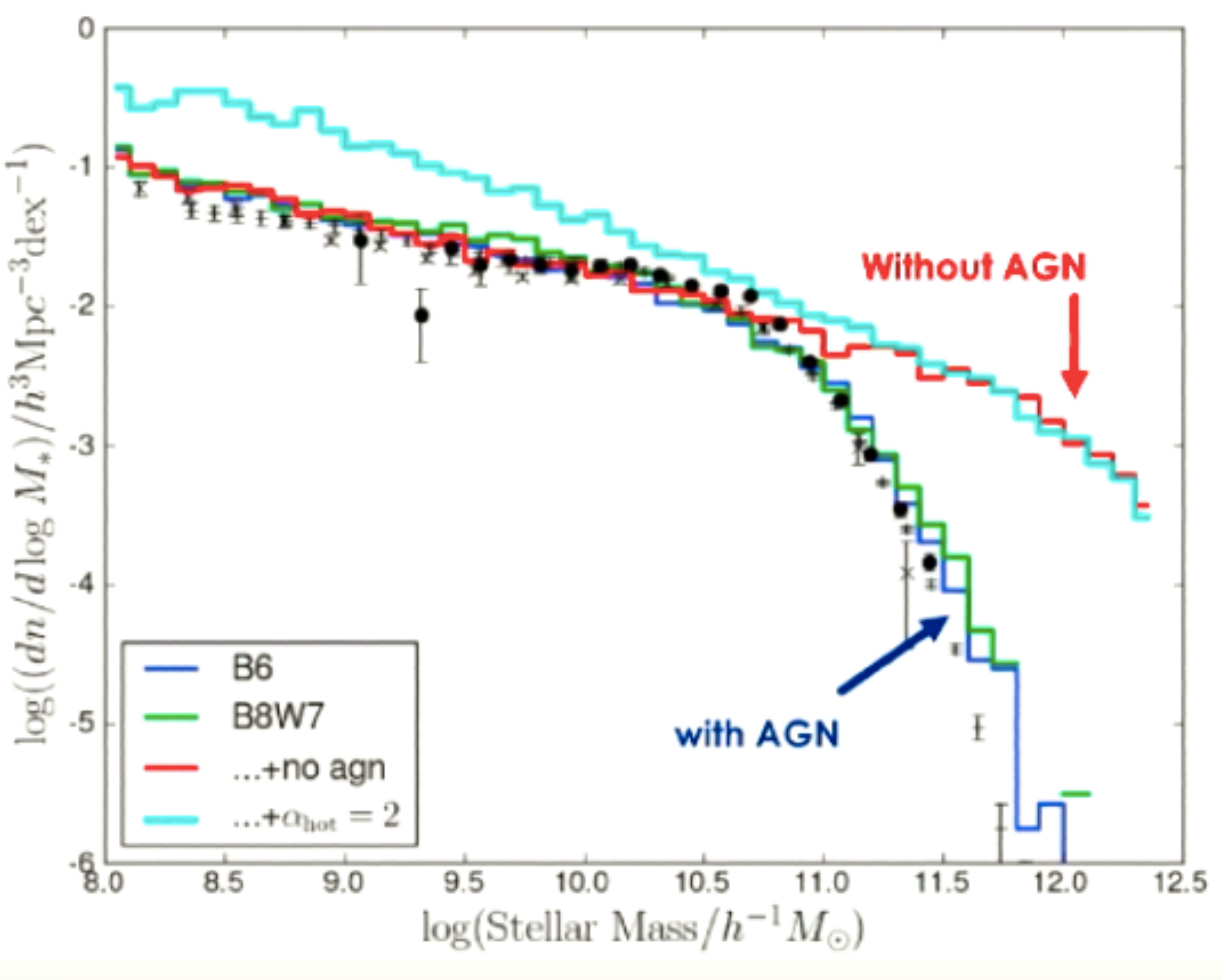

Chynoweth et al., NRAO/AUI/NSF, Digital Sky Survey.

The Role of AGN Feedback



Bower et al. 2011, MNRAS



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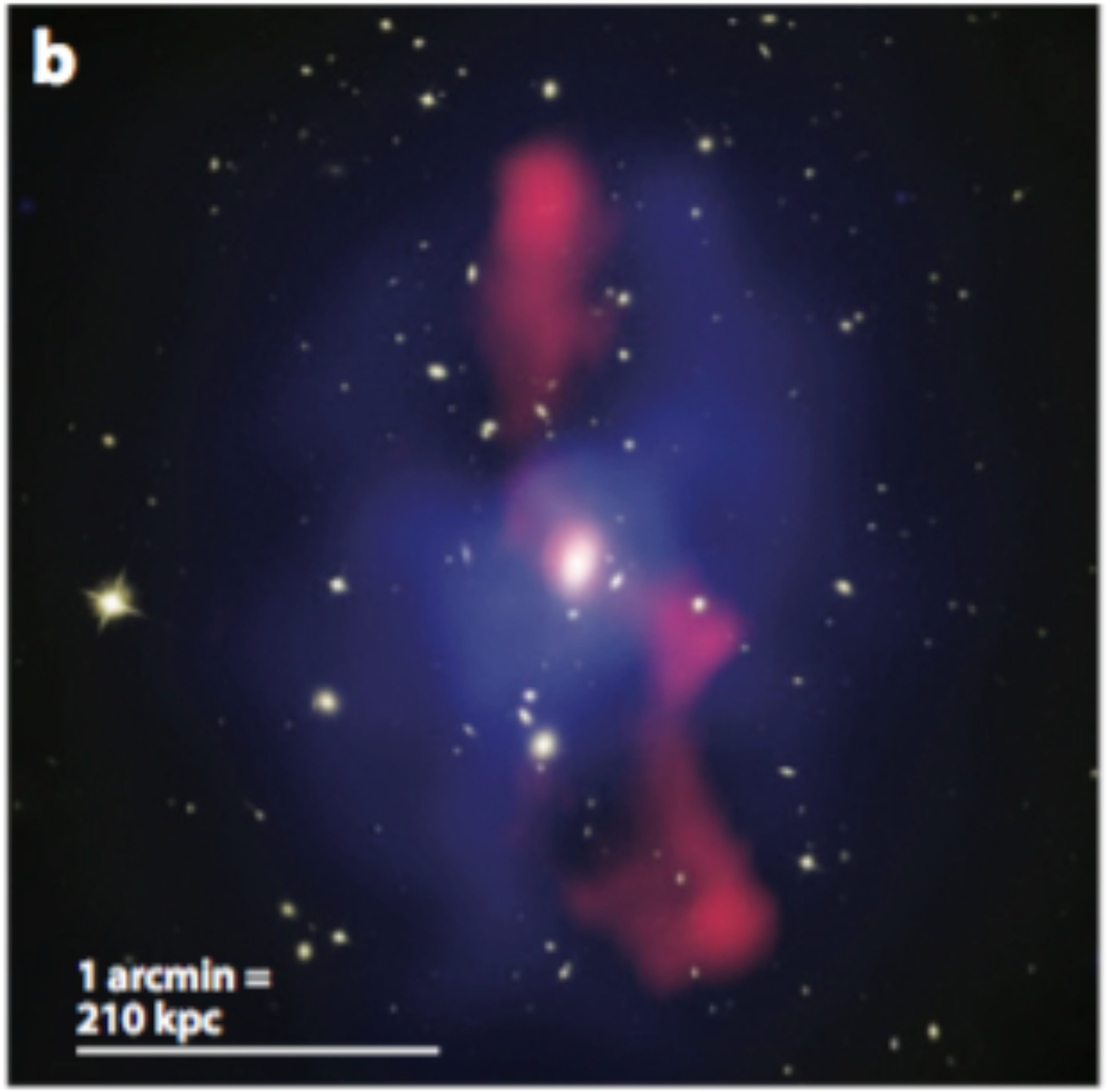

M87 diffuse X-ray (blue) +
radio continuum (red)

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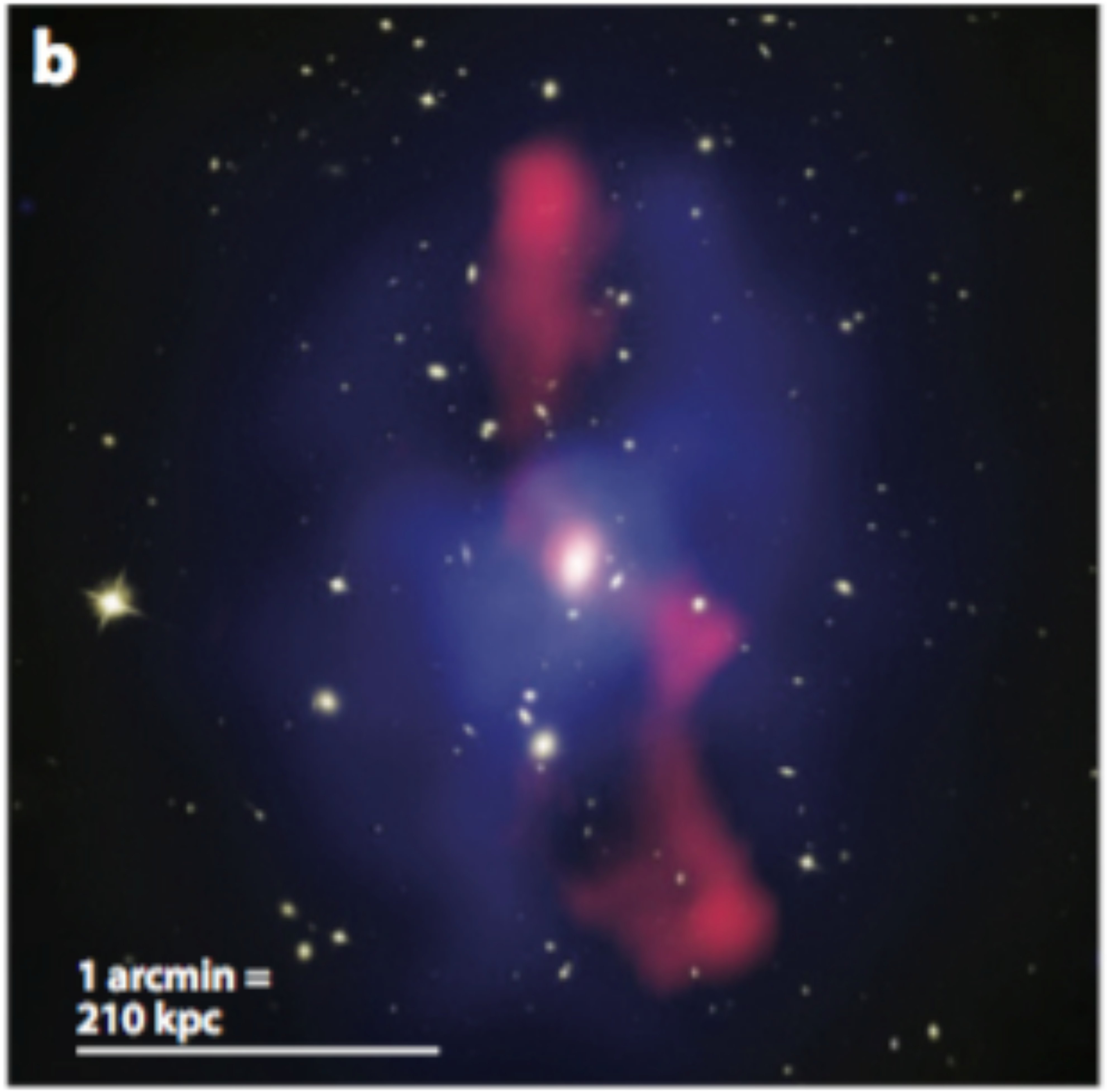

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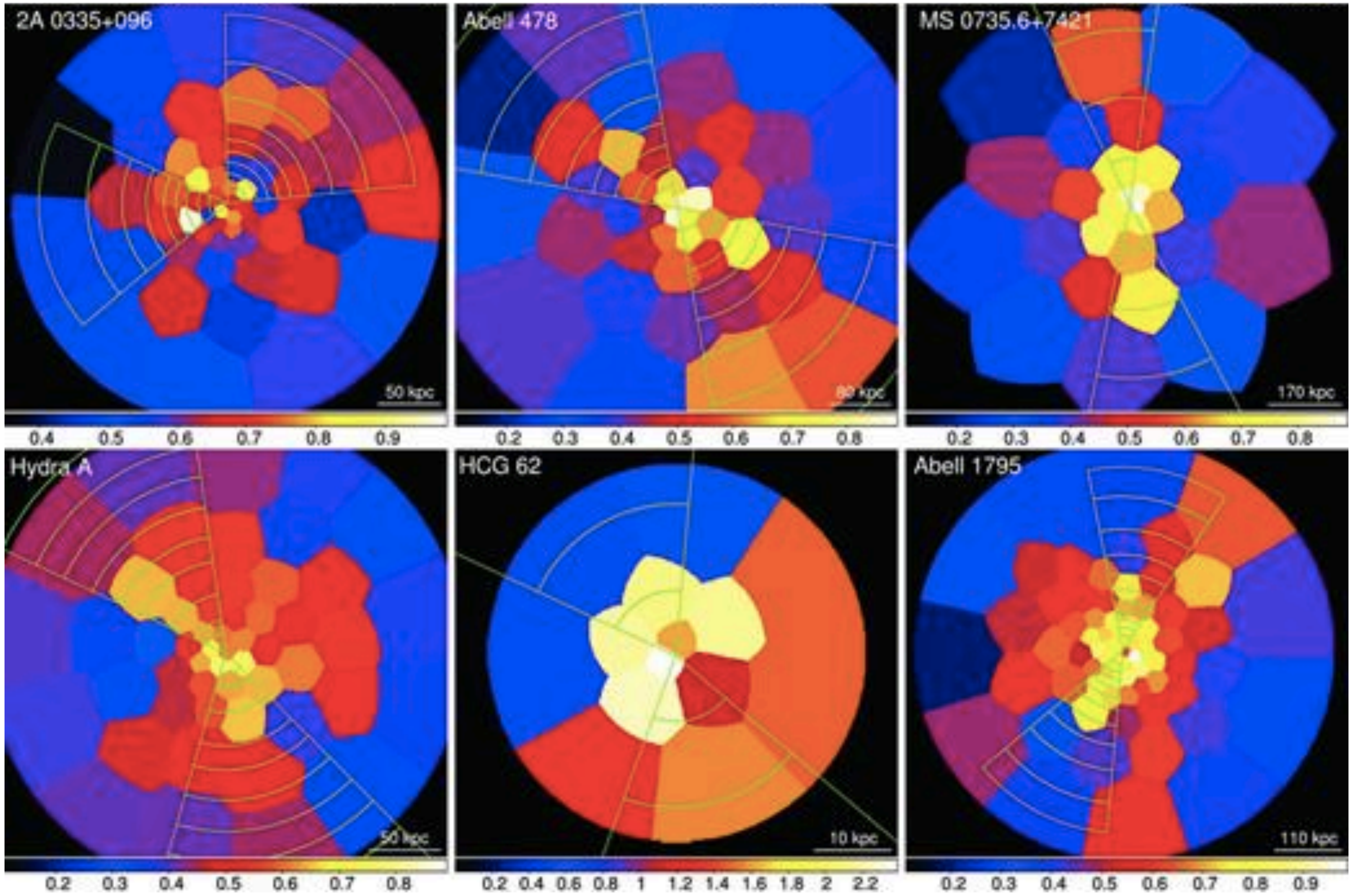
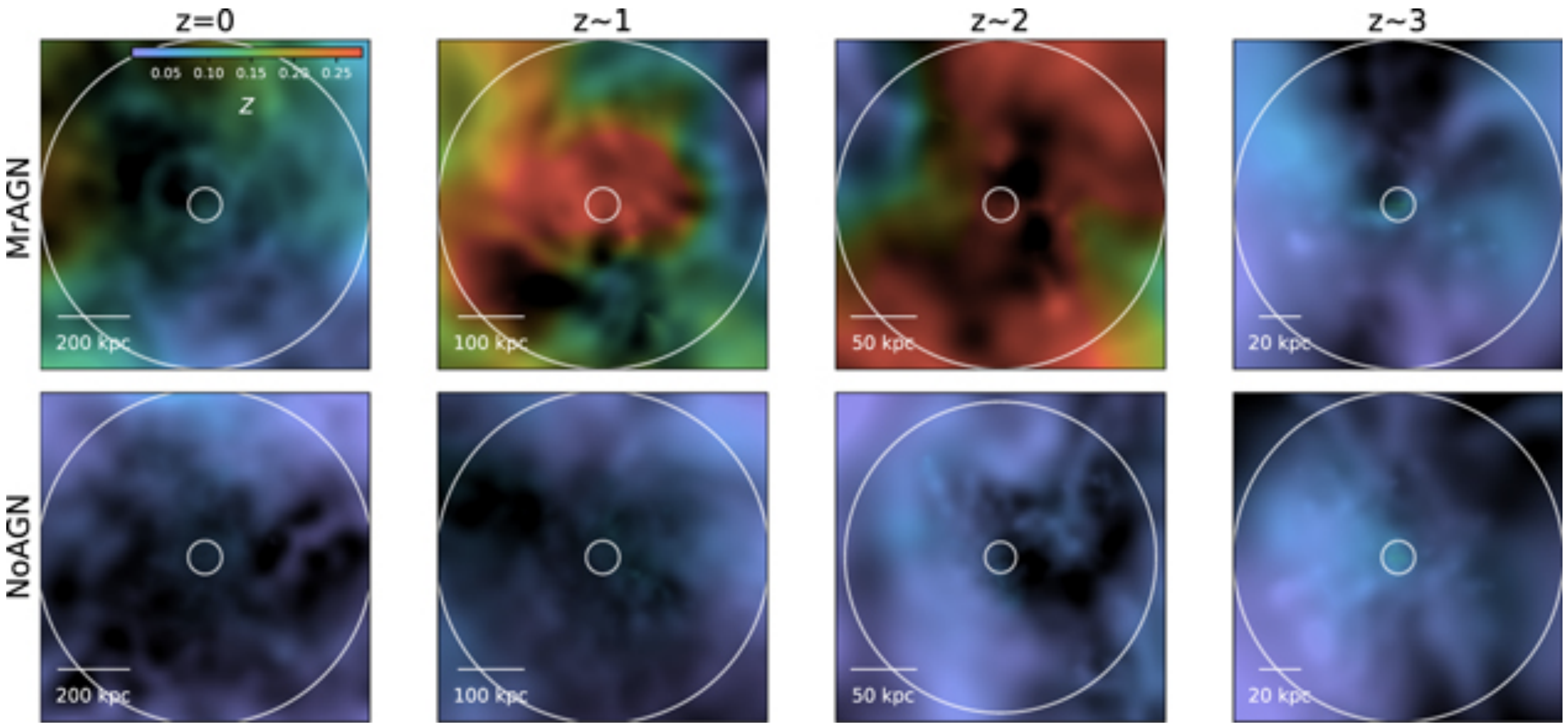


C. C. Kirkpatrick, B. R. McNamara, 2015, MNRAS

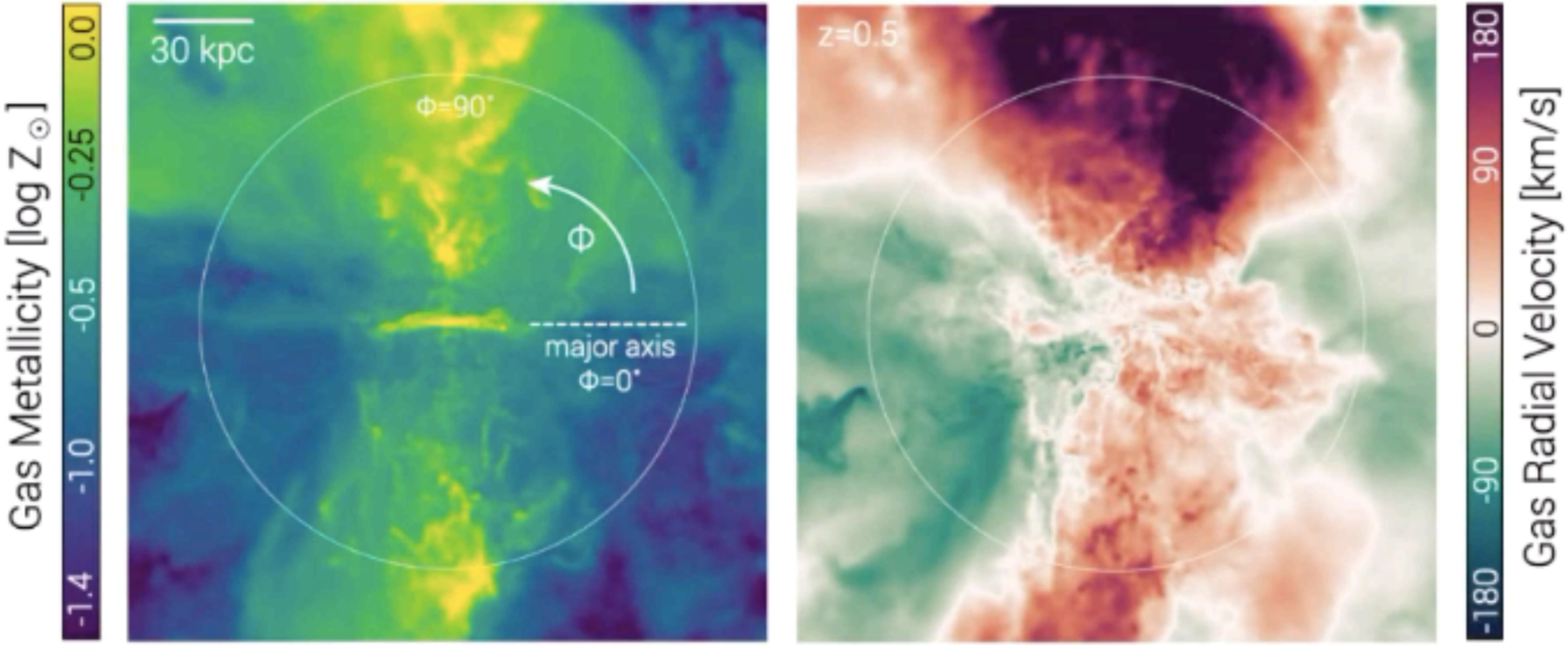
The Role of AGN Feedback

Choi, Ena et al. 2020, ApJ



Two matched sets of simulations of massive halos ($10^{10} < M^*/M_{solar} < 10^{12}$) with and without AGN feedback

Feedback from Star Formation

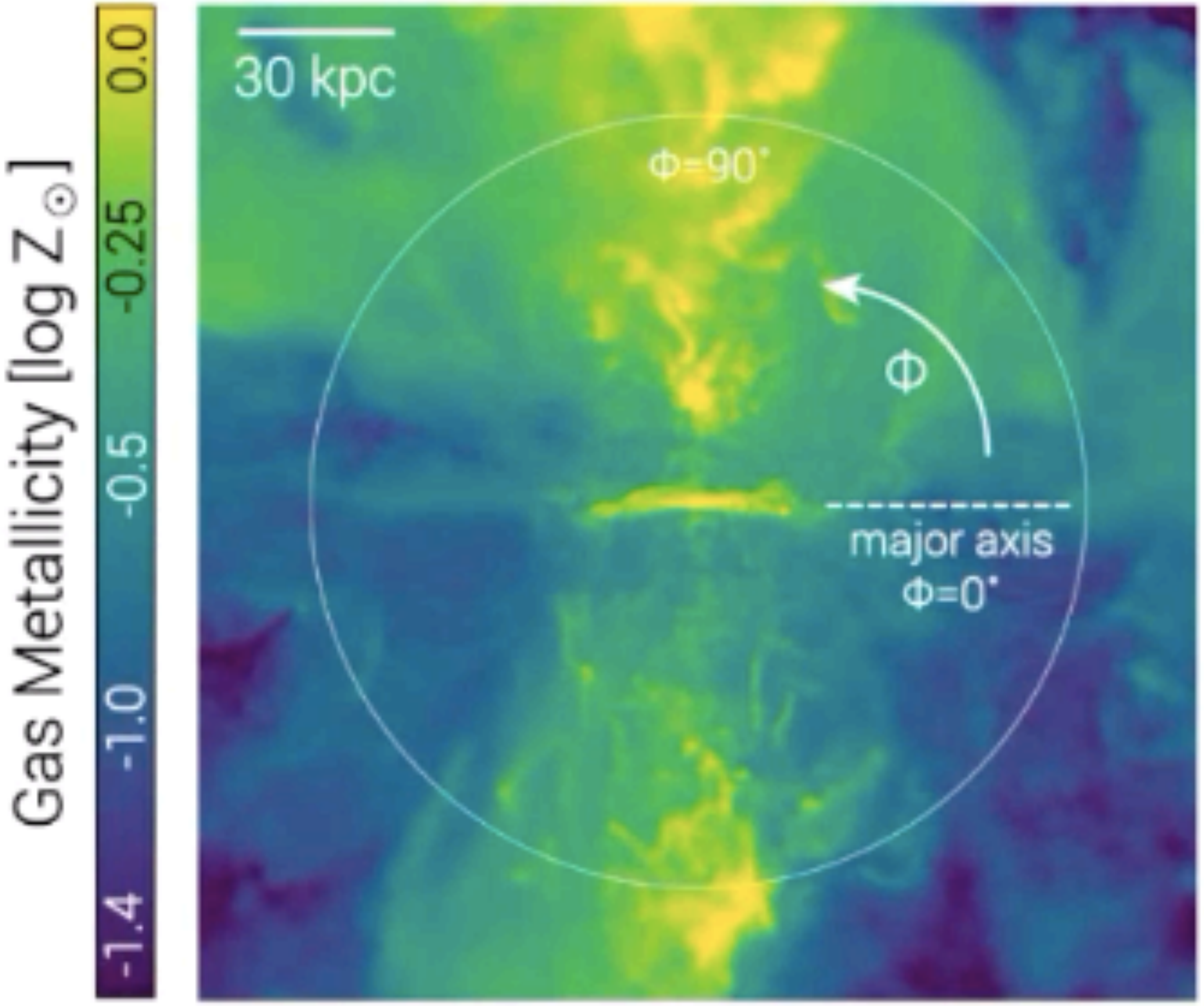


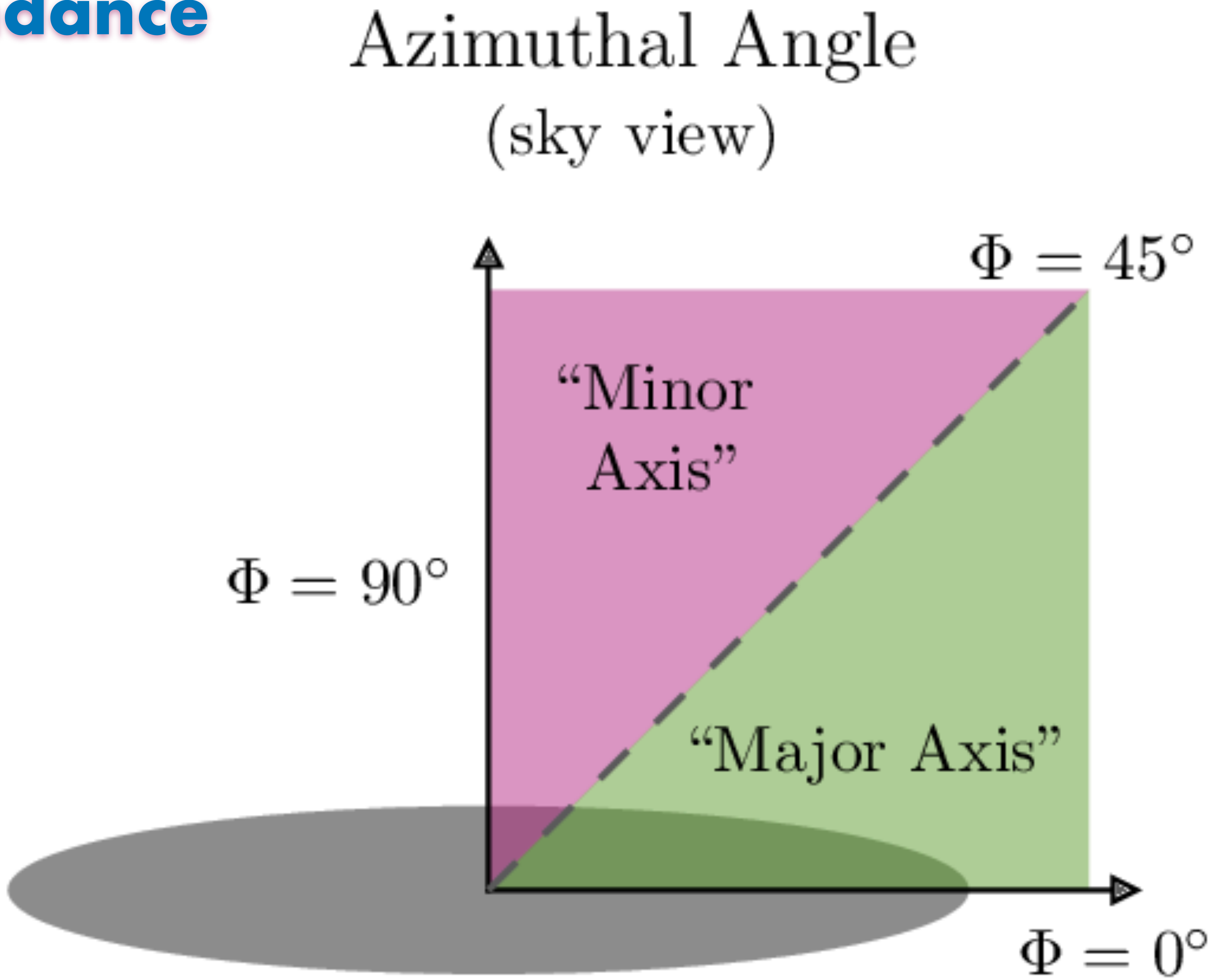
https://www.tng-project.org/media/

IllustrisTNG50

Tumlinson et al. 2011

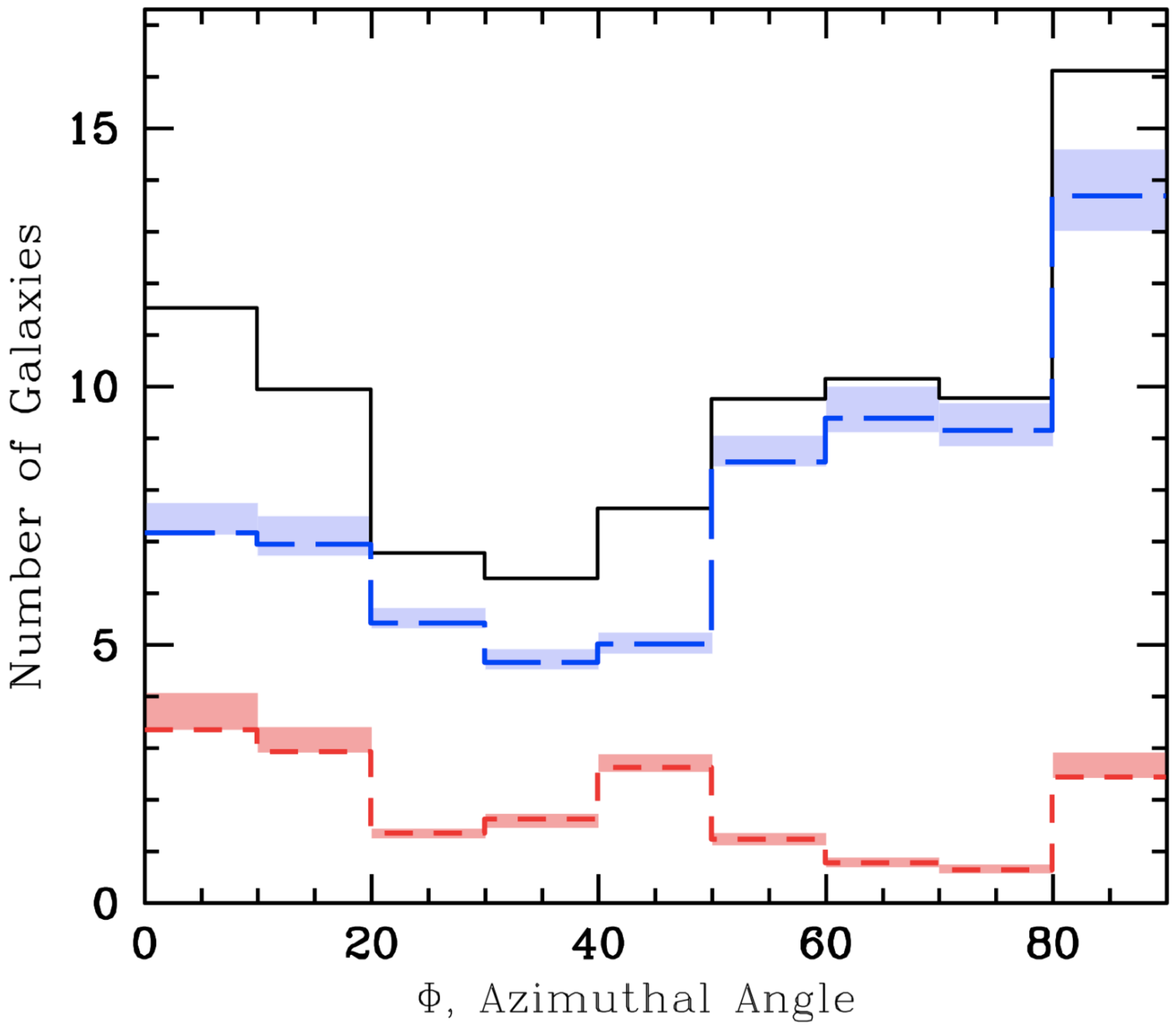
Feedback from Star Formation & Accretion
Azimuthal Angle Dependance





Nielsen et al. 2015

Outflows & Accretion
Azimuthal Angle Dependance



Azimuthal angle dependence of Mg II

Kacprzak et al. 2012

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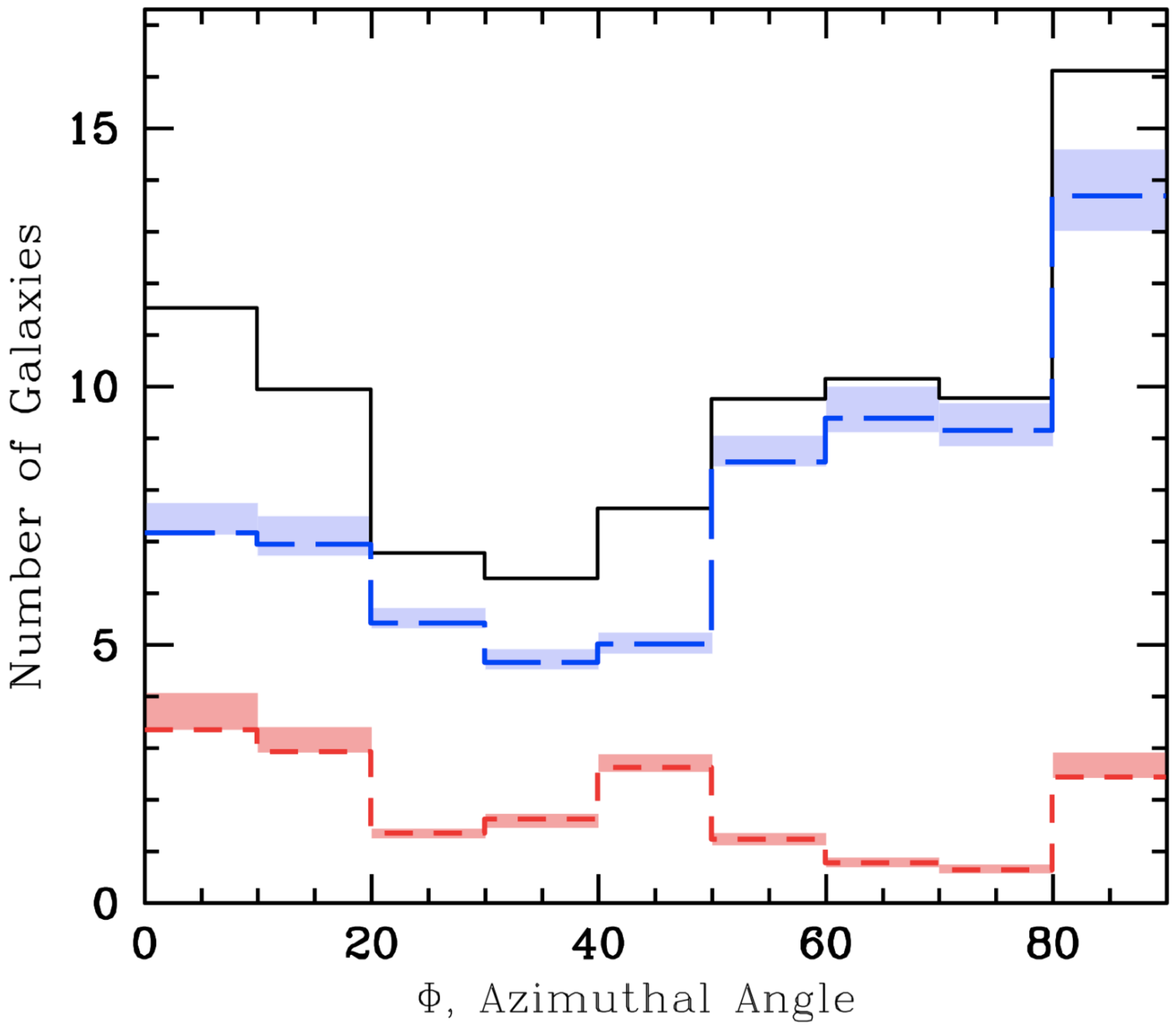

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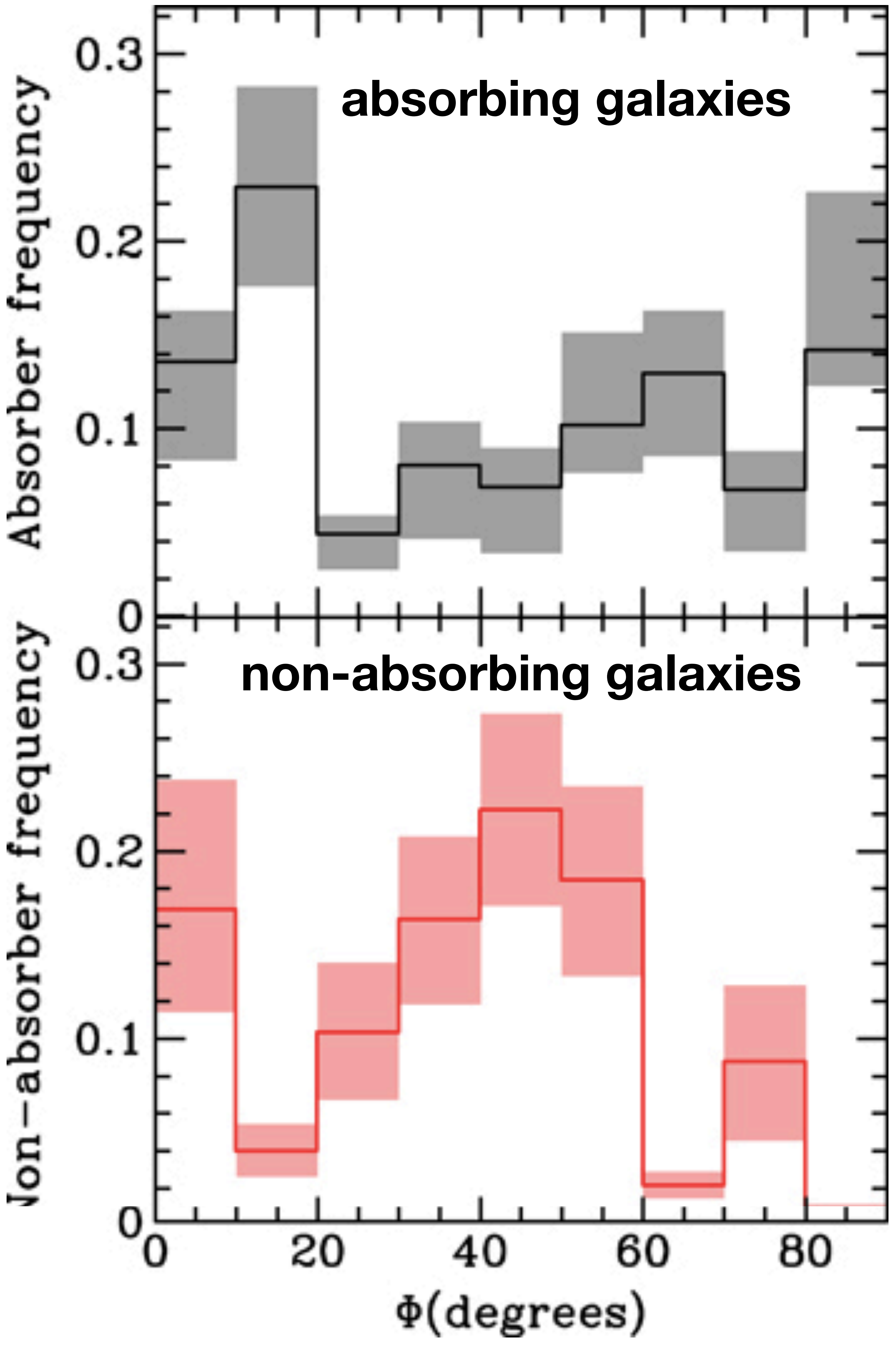

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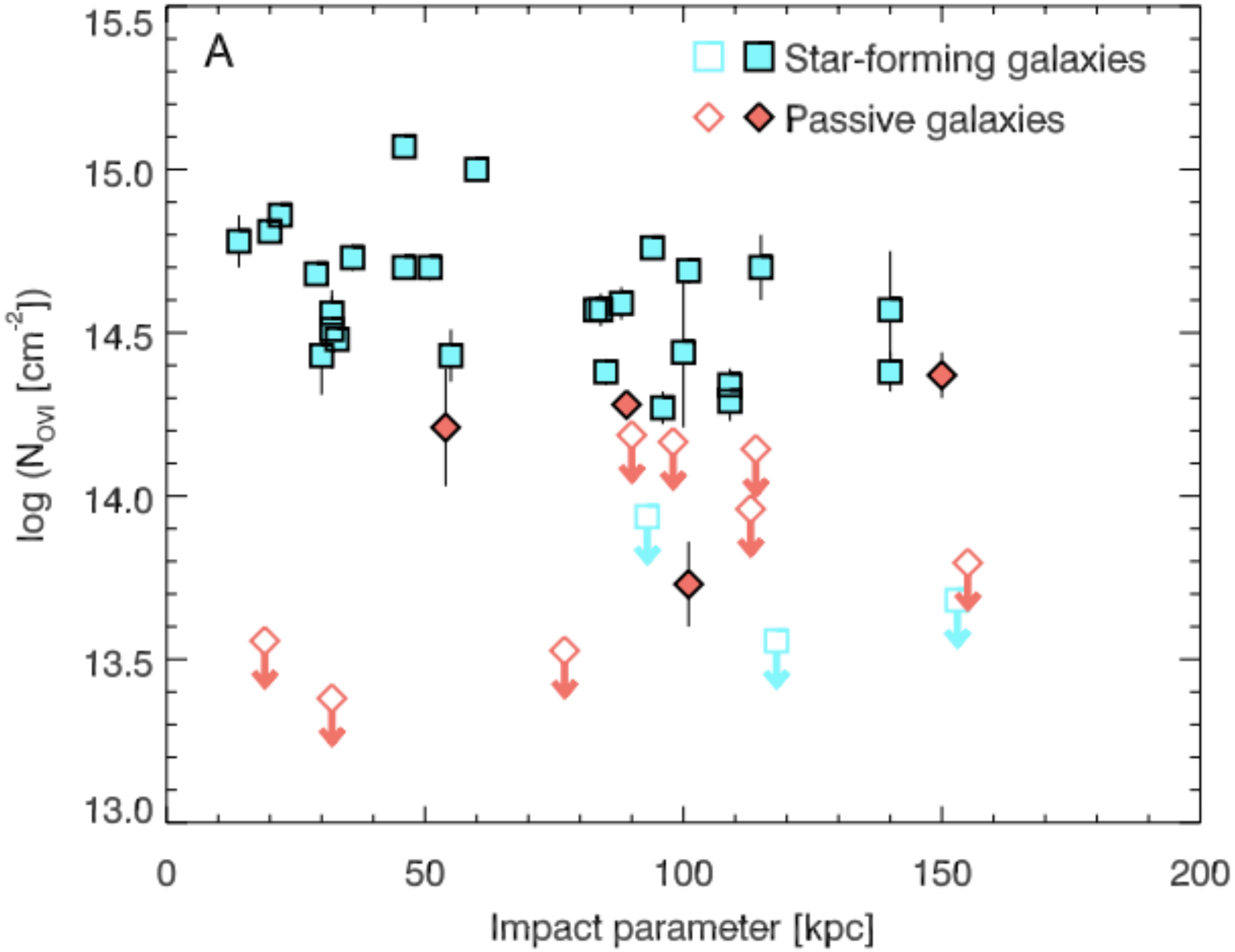
High SFR -> enriched winds -> large covering fraction of warm absorbers



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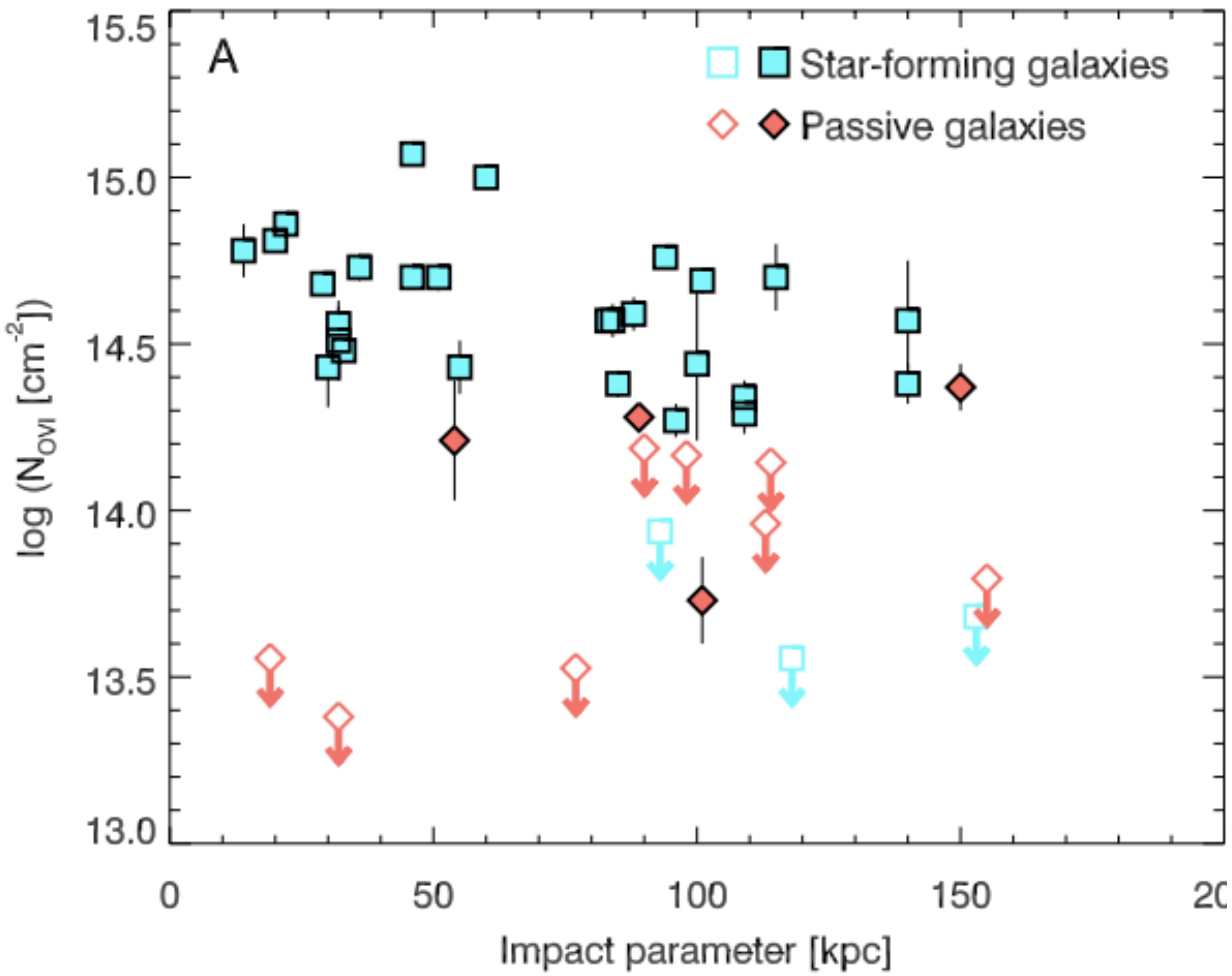

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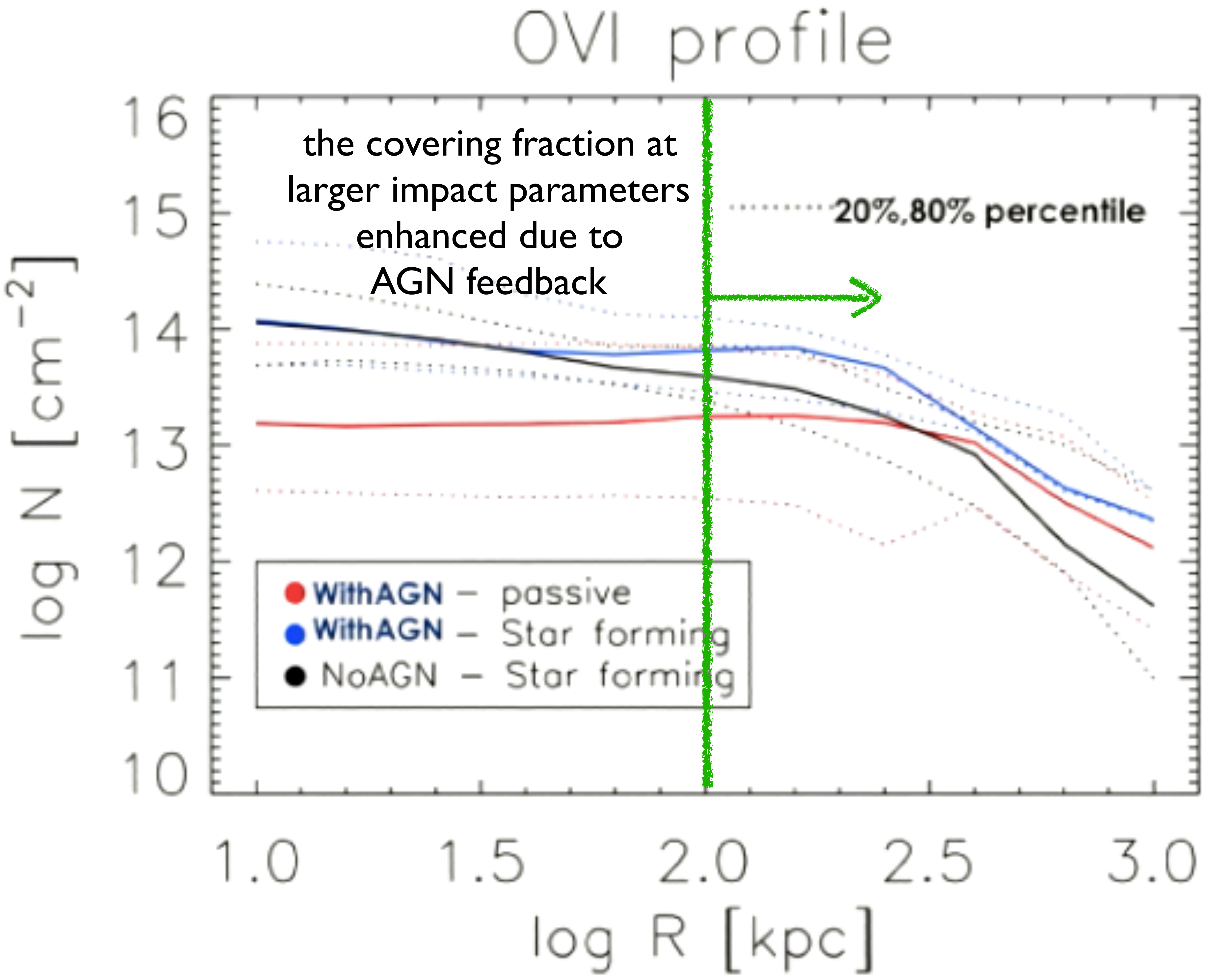

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AGN radiation impacts the CGM anisotropically —> asymmetry in metal ion absorption ?

Spatial sampling at high spectral resolutions as it has been done for some normal galaxy CGMs

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For galaxies of similar mass, to what extent does AGN lower the fraction of halo gas that is cooling?
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Do all AGN host galaxy CGM have enhanced metal abundances and higher covering fraction of O VI?

AGN activity picks up –> outflows and jets push CGM gas away –> strong AGN feedback quenches SF –> lowers the covering fraction of OVI in the CGM.

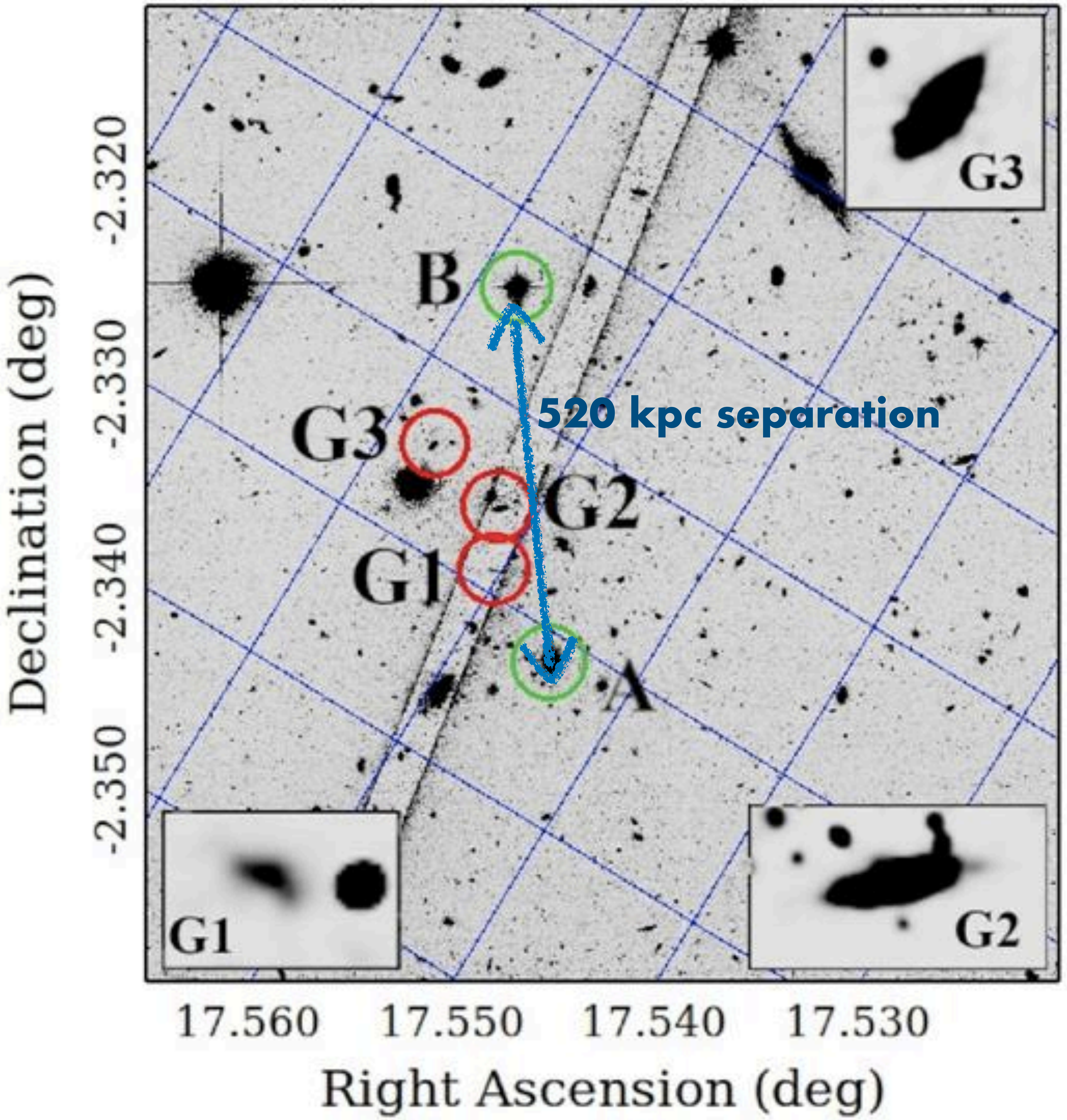
enhanced covering fraction of metals around AGNs a temporary phenomenon? (simulations and observations)

PAIR QUASAR SIGHTLINES PROBING
MULTIPHASE GAS ASSOCIATED WITH CGM AND GALAXY GROUP ENVIRONMENT

Anshul et al. 2021

Q0107–025A & B : pair quasar sightline

absorber z ˜ 0.4



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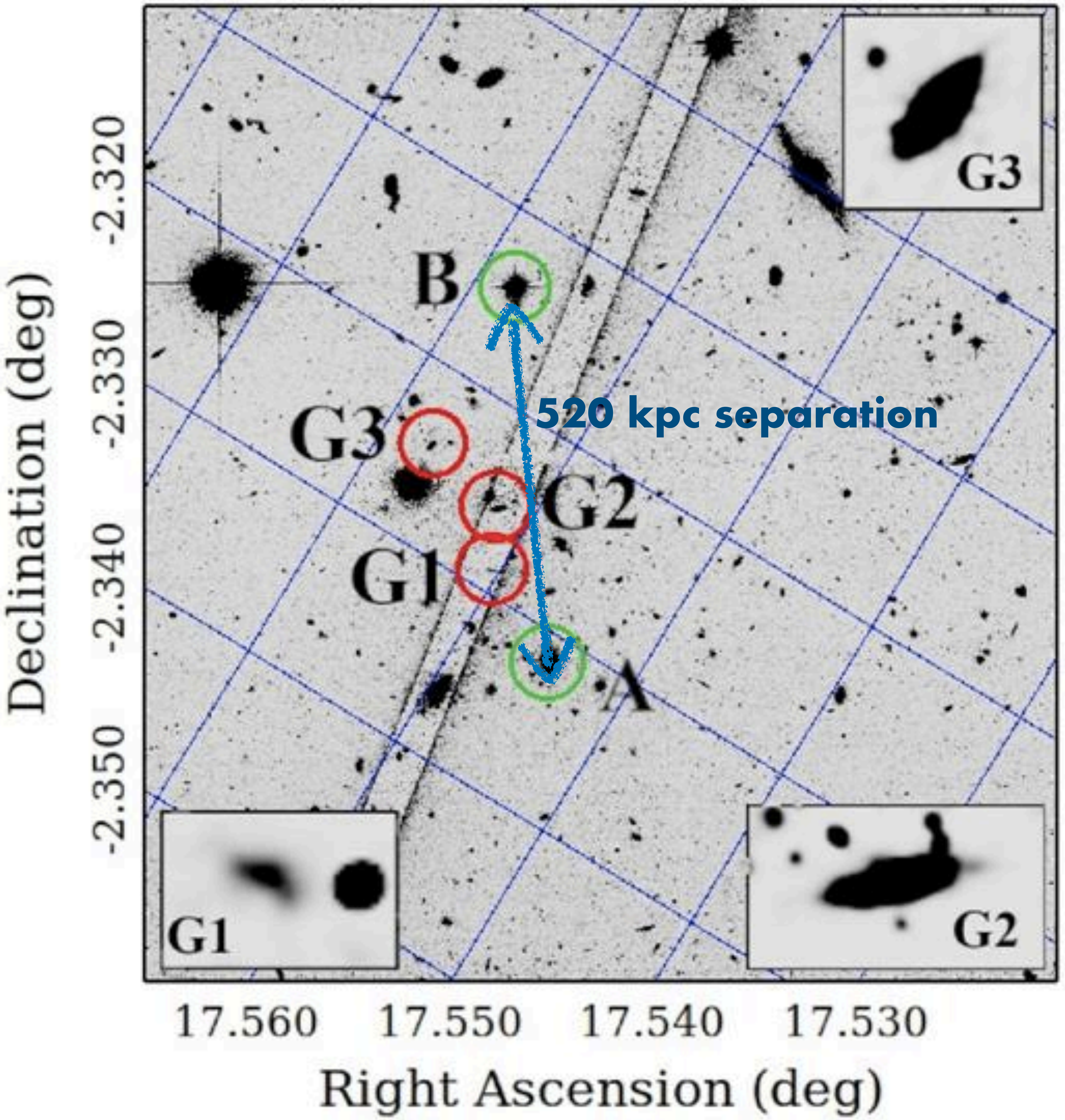

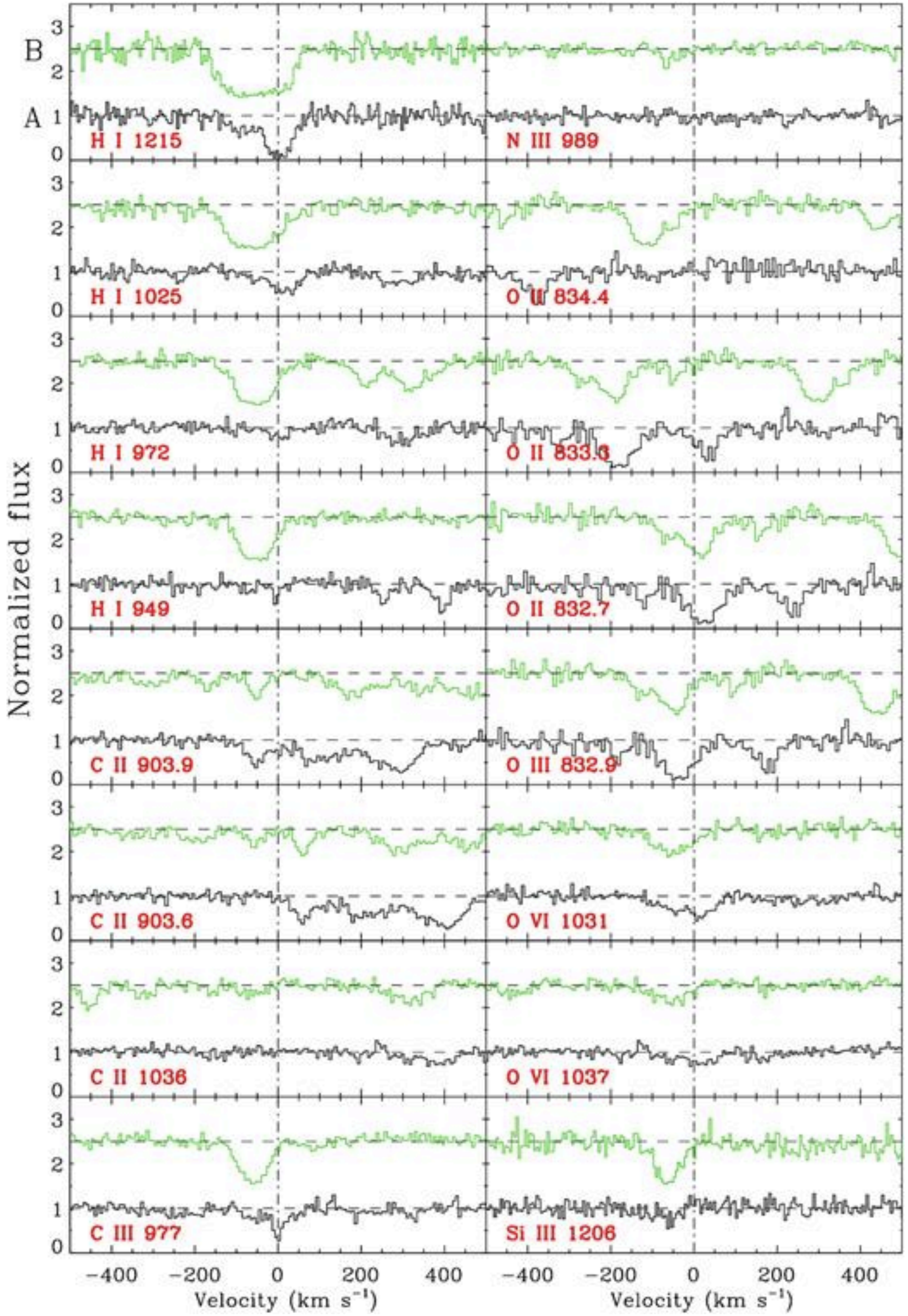

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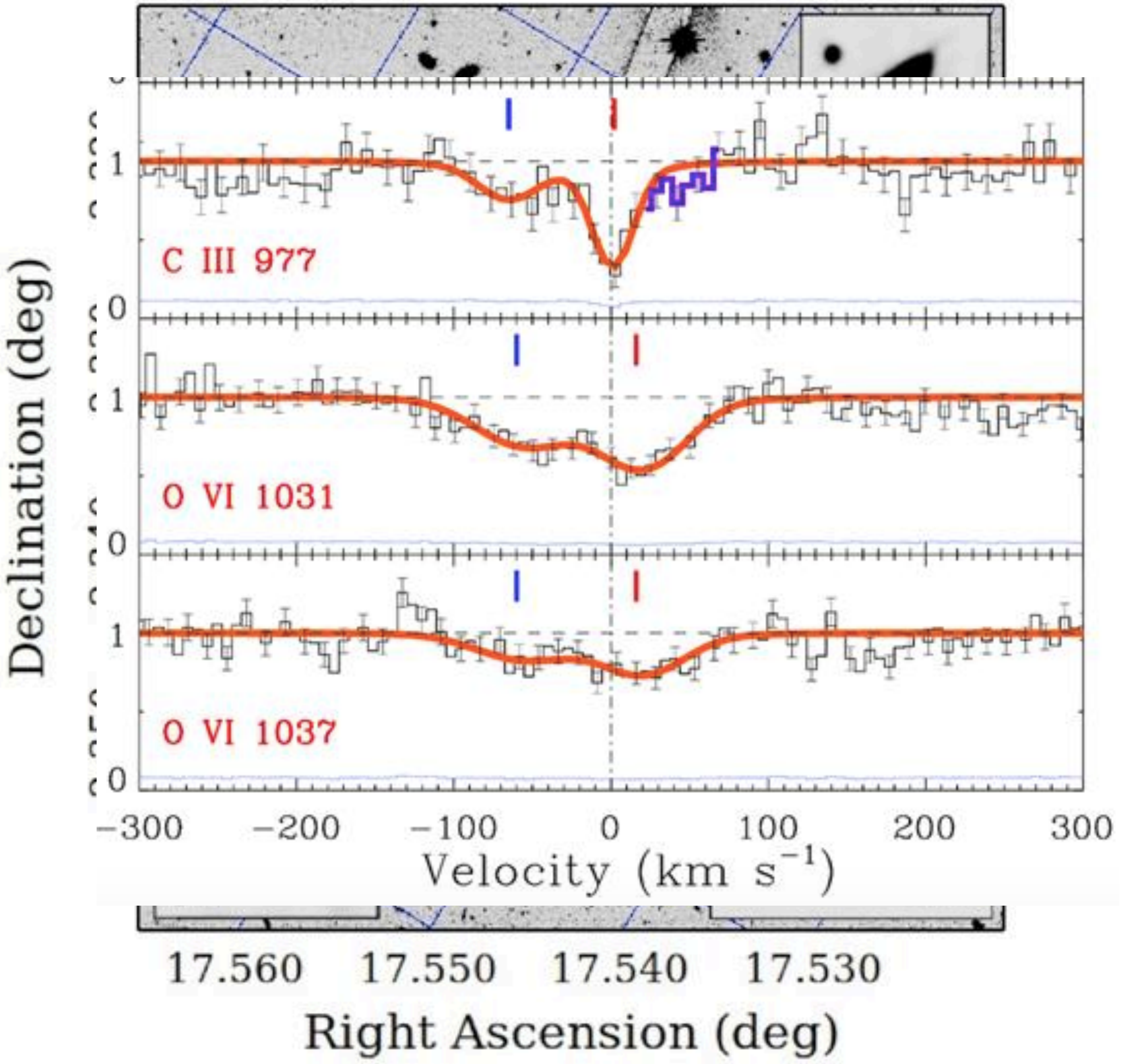

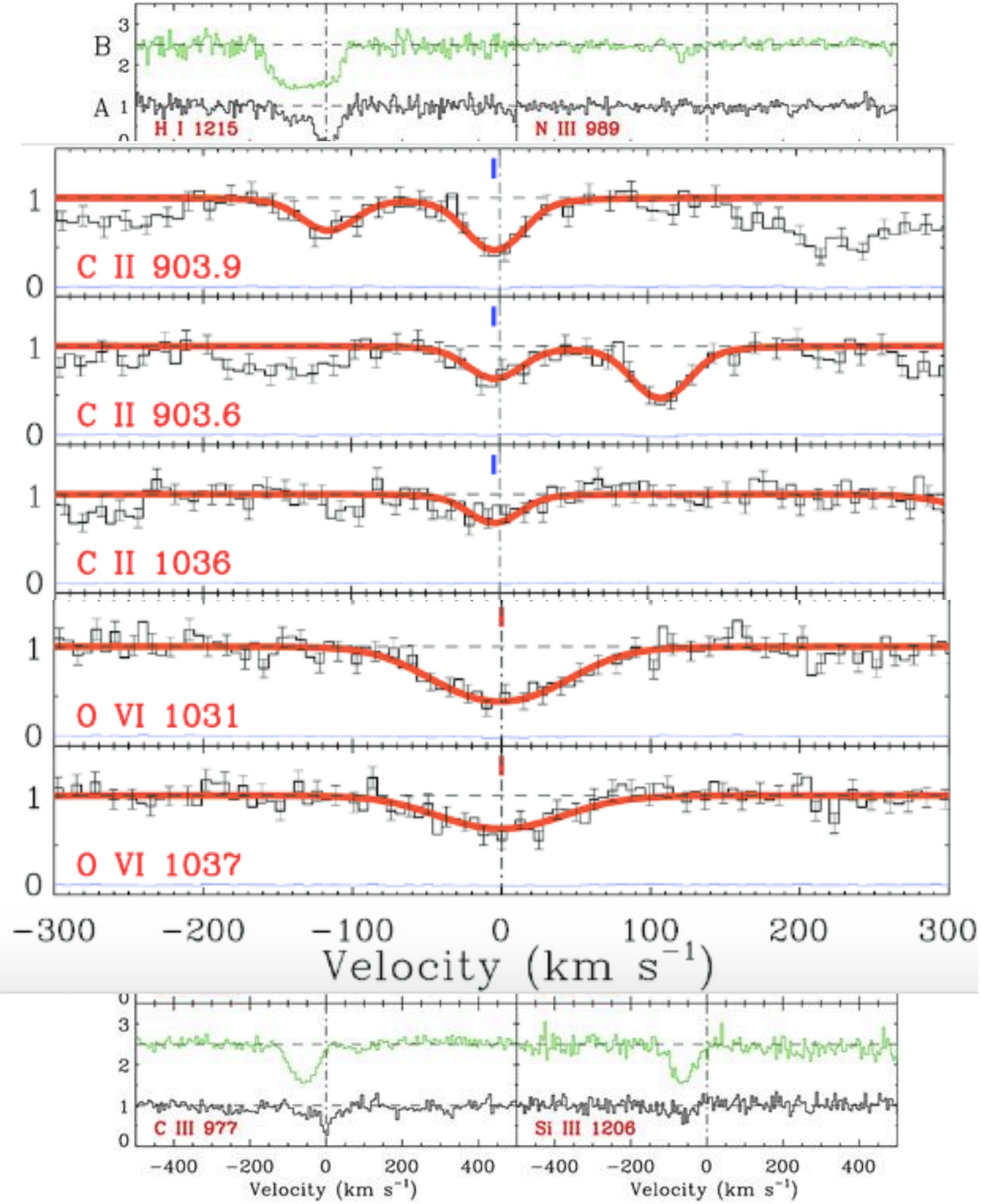

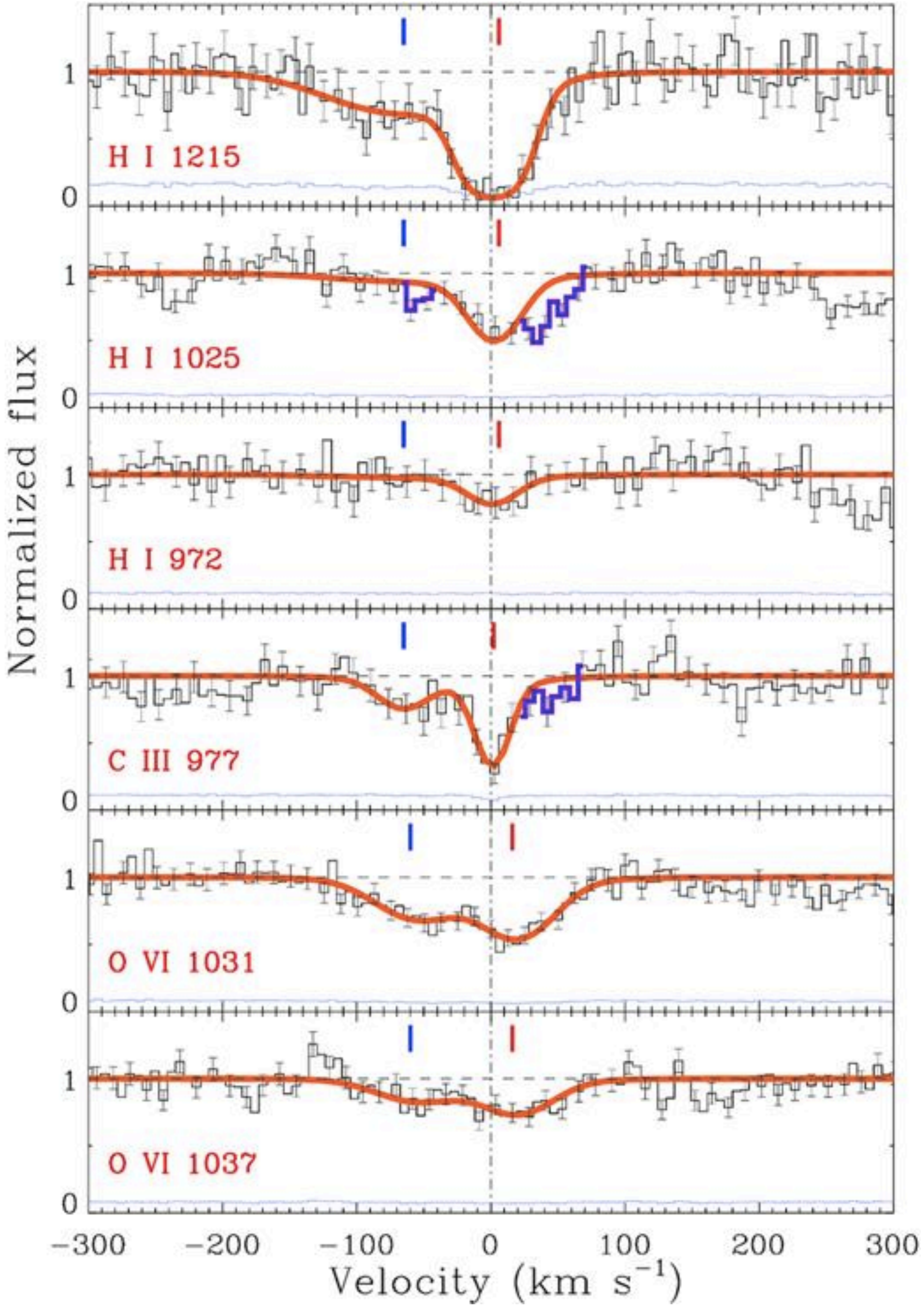

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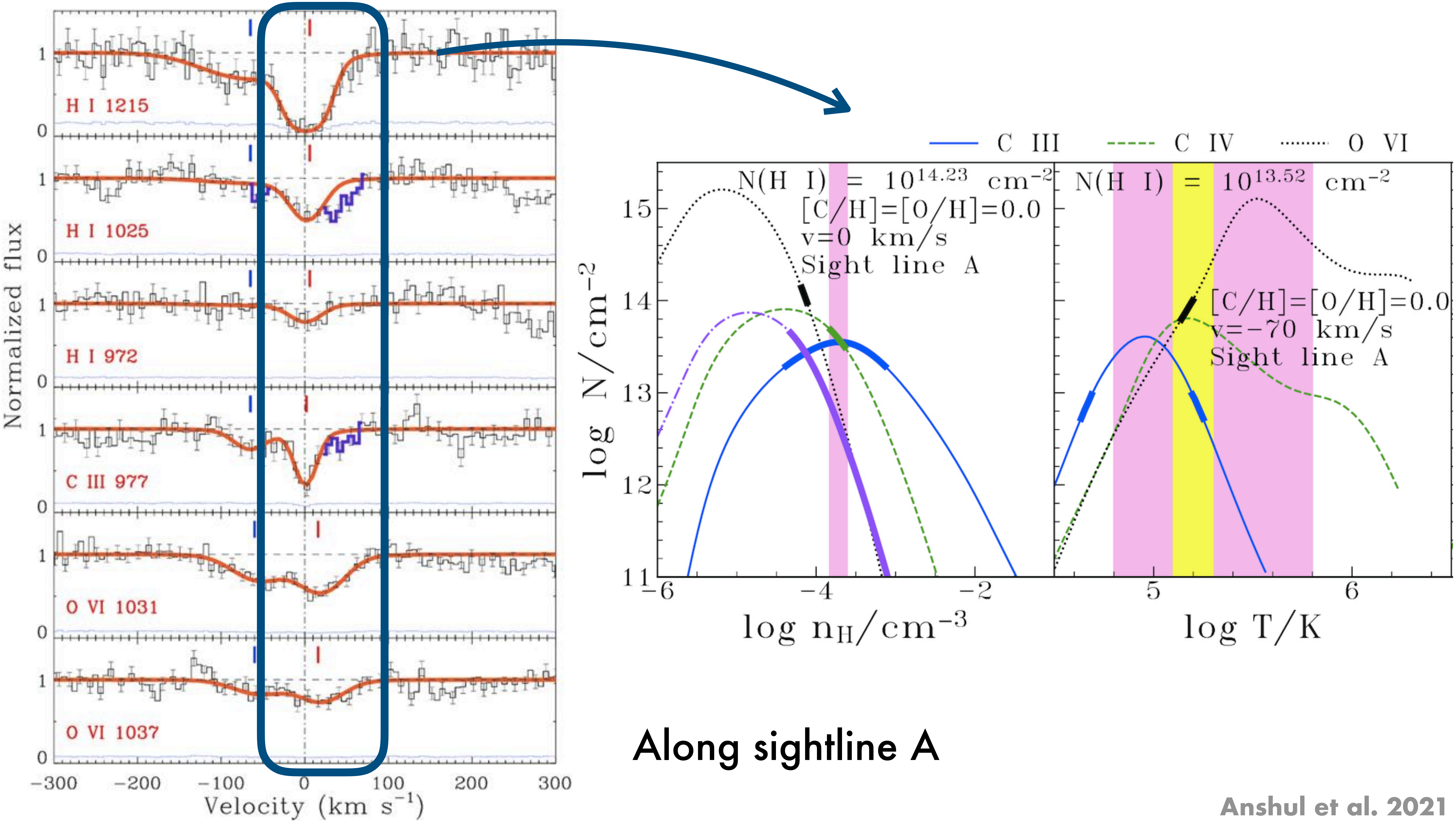
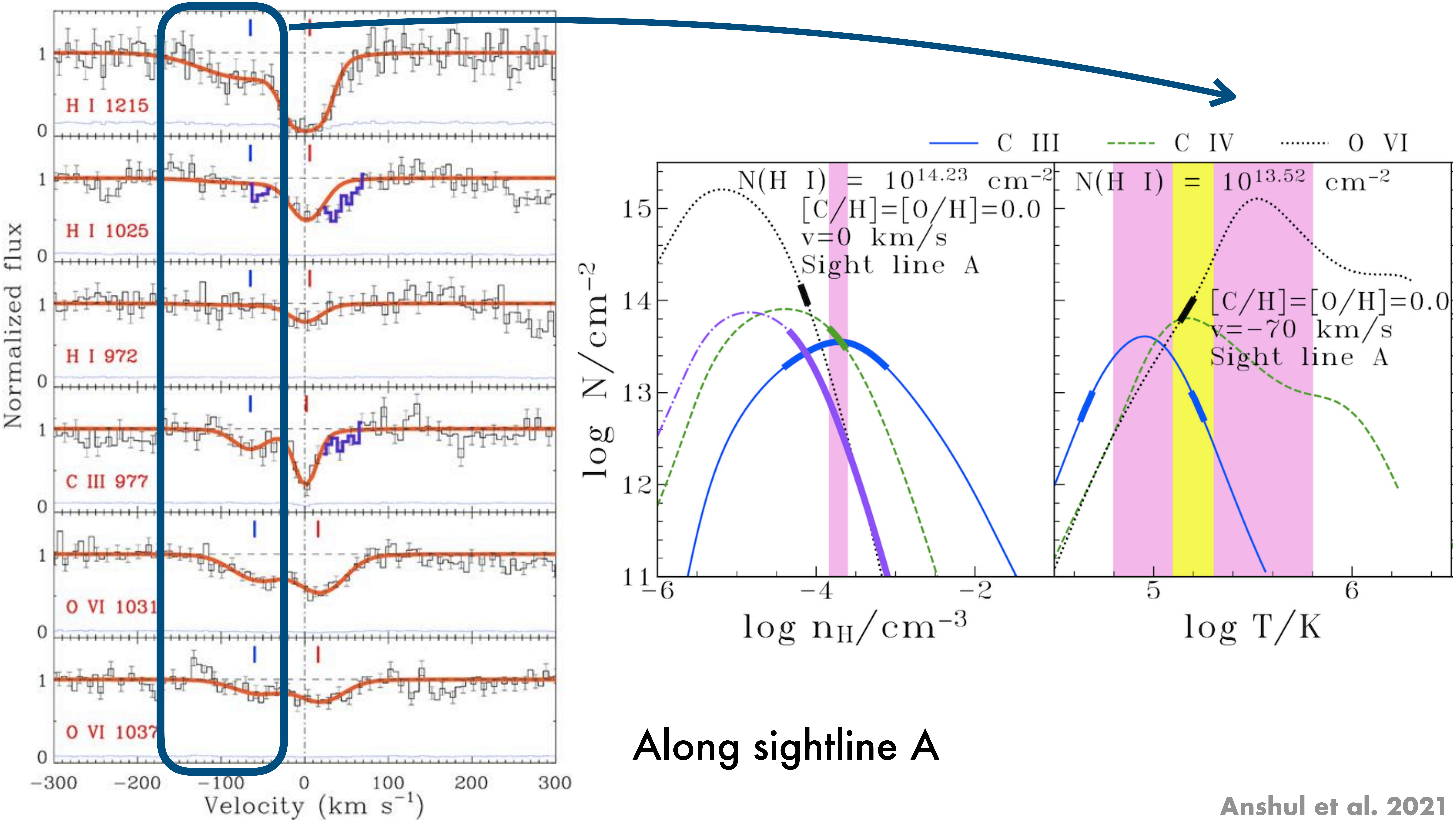


Along sightline A

Anshul et al. 2021



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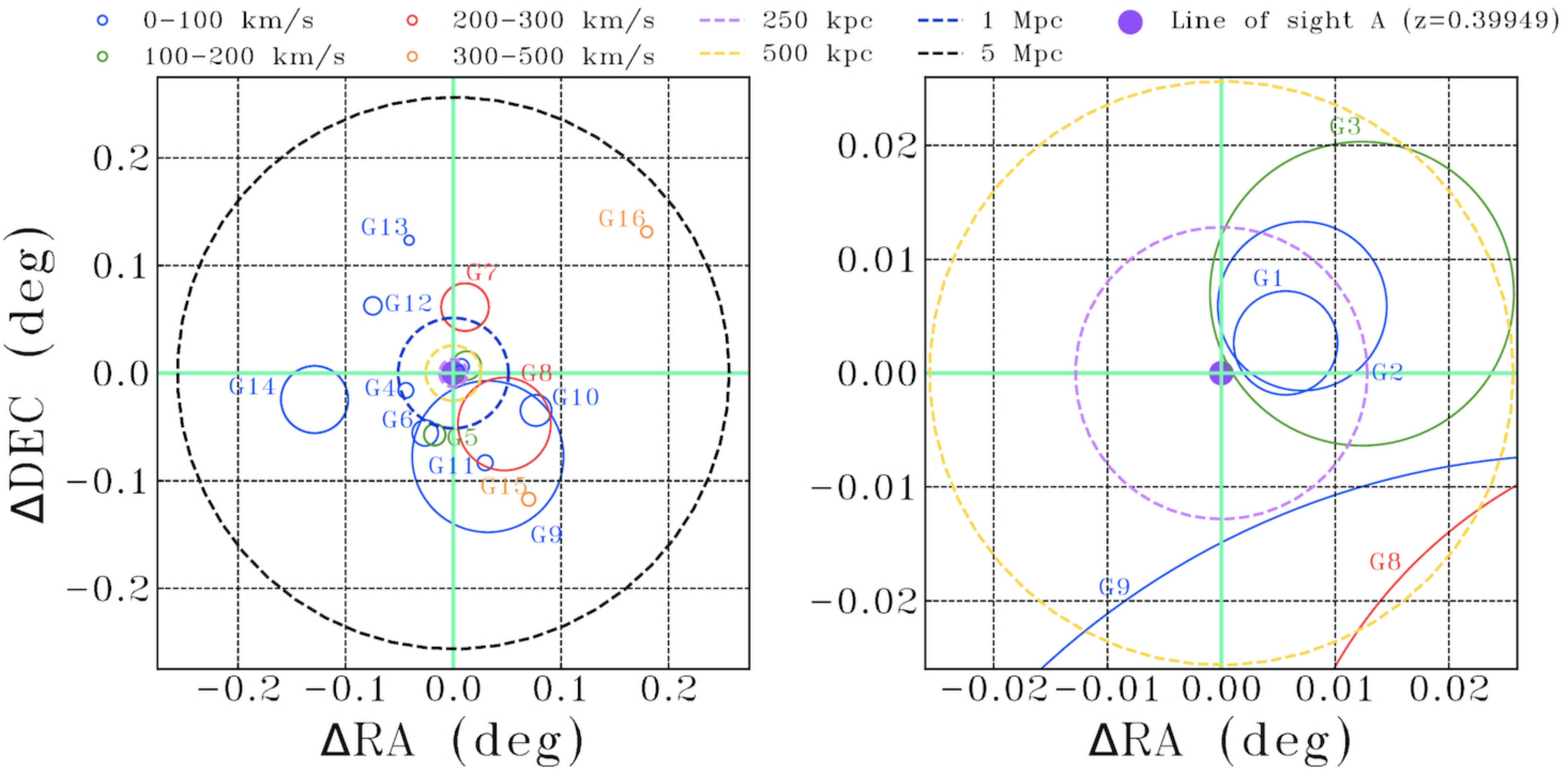


12 galaxies within ± 250 km/s and 2 Mpc of projected distance from the sightlines of which five are within 500 kpc. Stellar masses range from $M_* \sim 10^{8.7} - 10^{11.5}$ Msun

Anshul et al. 2021

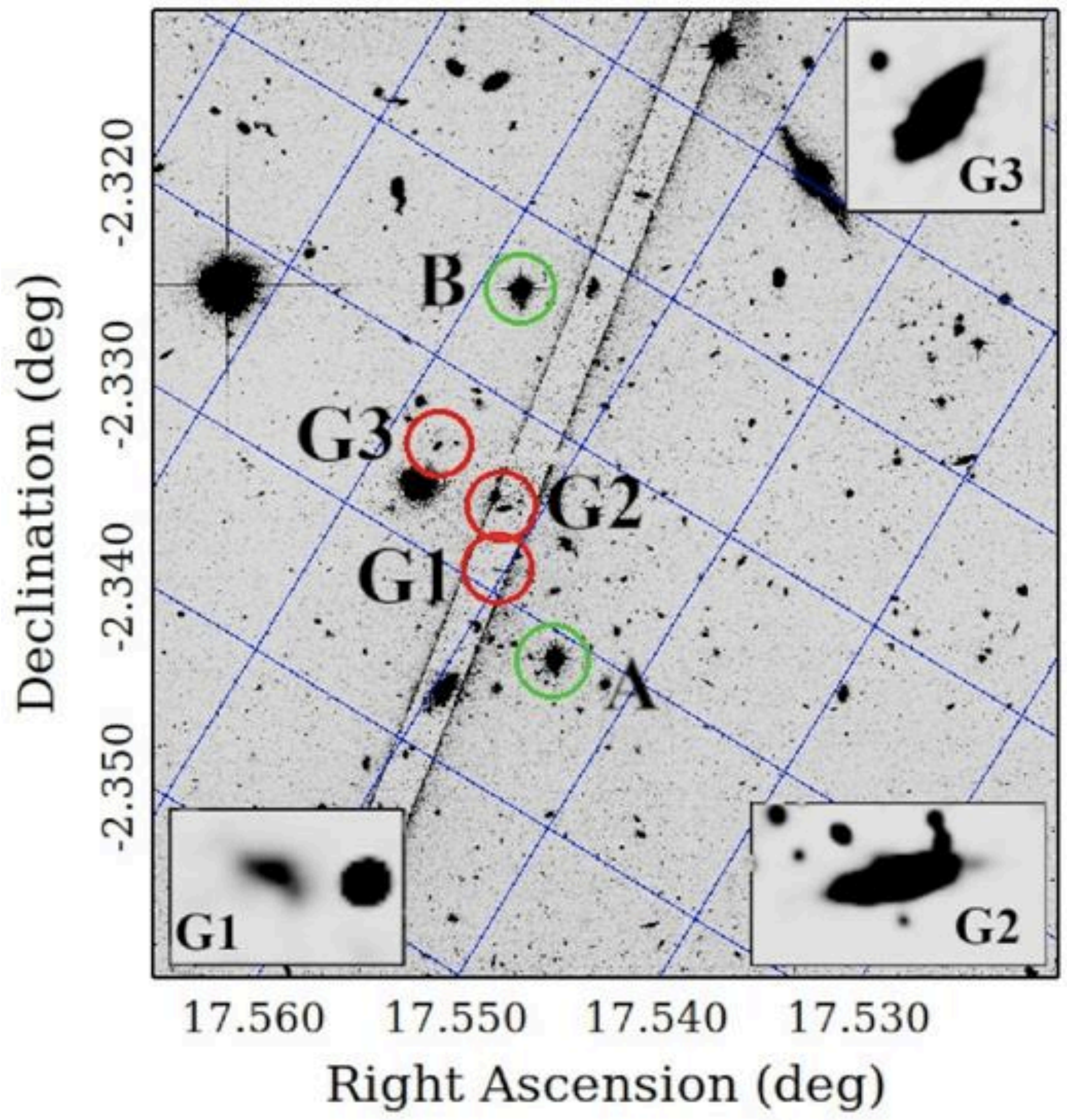
Galaxies in the Group Environment

Label	RA (deg)	Dec. (deg)	m_R	z_{gal}	ρ (Mpc) A	ρ (Mpc) B	Δv (km s^{-1}) A	Δv (km s^{-1}) B	M_R	log(L/L*)	log($M_*/M_\odot$)	R_{vir} (kpc)	ρ_A/R_{vir}	ρ_B/R_{vir}	log($M_h/M_\odot$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
G1	17.560 48	−2.328 71	25.1	0.399 54	0.121	0.318	−12	−83	−16.5	−2.6	8.7	87.9	1.3	3.5	11.0
G2	17.561 94	−2.325 47	22.0	0.399 35	0.179	0.249	28	−42	−19.6	−1.4	10.0	143.2	1.2	1.7	11.6
G3	17.567 18	−2.324 38	21.3	0.398 82	0.276	0.200	142	71	−20.3	−1.1	10.6	257.2	1.0	0.7	12.4
G4	17.510 73	−2.347 42	21.3	0.399 92	0.915	1.288	−92	−163	−20.3	−1.1	9.9	136.3	6.6	9.3	11.6
G5	17.537 55	−2.388 53	21.3	0.398 82	1.164	1.566	143	73	−20.3	−1.1	10.4	193.2	5.9	8.0	12.0
G6	17.528 69	−2.386 92	20.8	0.399 30	1.197	1.611	40	−31	−20.8	−0.9	10.6	232.2	5.0	6.8	12.3
G7	17.565 68	−2.270 01	20.1	0.400 54	1.214	0.861	−226	−296	−21.5	−0.6	11.0	428.5	2.8	1.9	13.1
G8	17.602 23	−2.378 62	19.8	0.400 53	1.305	1.425	−223	−294	−21.9	−0.4	11.2	834.3	1.5	1.6	13.9
G9	17.586 91	−2.408 84	19.7	0.399 12	1.635	1.884	79	8	−21.9	−0.4	11.4	1357.3	1.1	1.3	14.6
G10	17.631 62	−2.366 04	21.6	0.399 22	1.643	1.604	57	−13	−20.0	−1.2	10.7	279.9	5.8	5.6	12.5
G11	17.584 39	−2.414 57	21.4	0.399 93	1.722	1.985	−96	−167	−20.2	−1.1	9.9	138.1	12.3	14.2	11.6
G12	17.480 10	−2.268 85	23.9	0.399 50	1.900	1.924	−4	−74	−17.7	−2.1	10.1	160.2	11.7	11.8	11.8
G13	17.513 76	−2.207 93	22.3	0.399 78	2.536	2.323	−63	−134	−19.3	−1.5	8.6	86.5	29.0	26.5	11.0
G14	17.425 89	−2.355 86	20.3	0.399 45	2.559	2.884	7	−64	−21.3	−0.7	11.1	602.1	4.2	4.7	13.5
G15	17.624 84	−2.448 52	22.1	0.401 78	2.661	2.847	−491	−562	−19.5	−1.4	9.6	120.1	21.9	23.4	11.4
G16	17.734 52	−2.200 09	21.7	0.401 80	4.339	3.939	−496	−567	−20.0	−1.2	9.2	102.5	41.8	38.0	11.2

Data from VLT/VIMOS, Keck/DEIMOS, and Gemini/GMOS and Tejos et al. (2014)

stellar masses from M*/L ratio as a function of color tables
halo masses estimated using the stellar-to-halo-mass relation
SFR using H-alpha or [O II]

Anshul et al. 2021



gas detected at z ~ 0.4 along sightline B
is a partial Lyman limit system

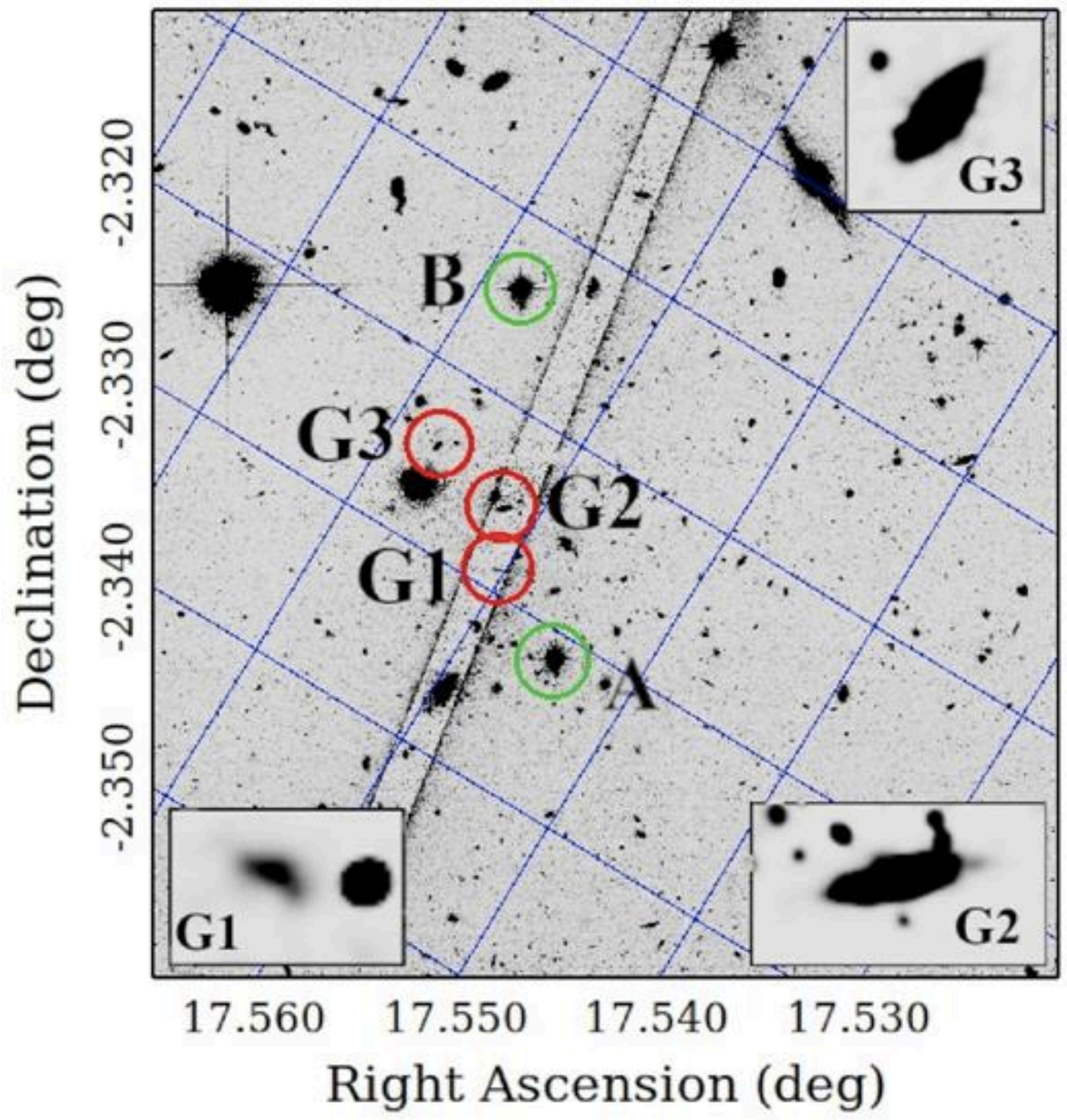
multiple photoionised gas phases with metallicities of 1/10 solar

O VI tracing collisionally ionized gas of higher temperature

absorber along the projected major axis of the nearest galaxy (G3)

$$\Phi \approx 3^0, \;\; d/R_{vir} \approx 0.7, \;\; \mathrm{SFR} < 0.1 \; \mathrm{M}_\odot \; \mathrm{yr}^{-1}$$

Anshul et al. 2021



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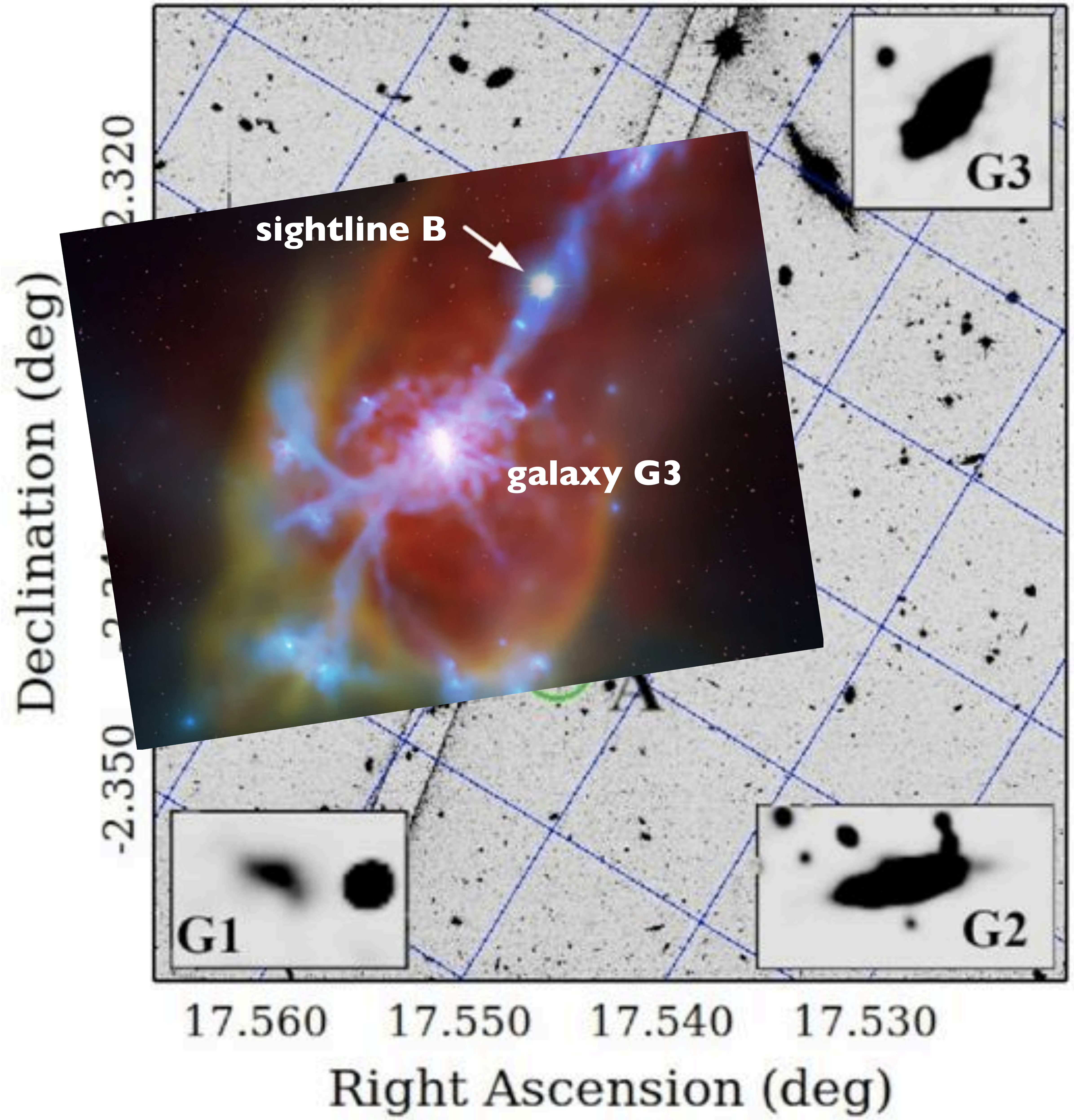
cold accretion stream from the group environment ?

Group environments have plenty of cool gas away from galaxies mixed with metals from past outflows and tidal streams. Accreting gas need not be pristine.

Anshul et al. 2021



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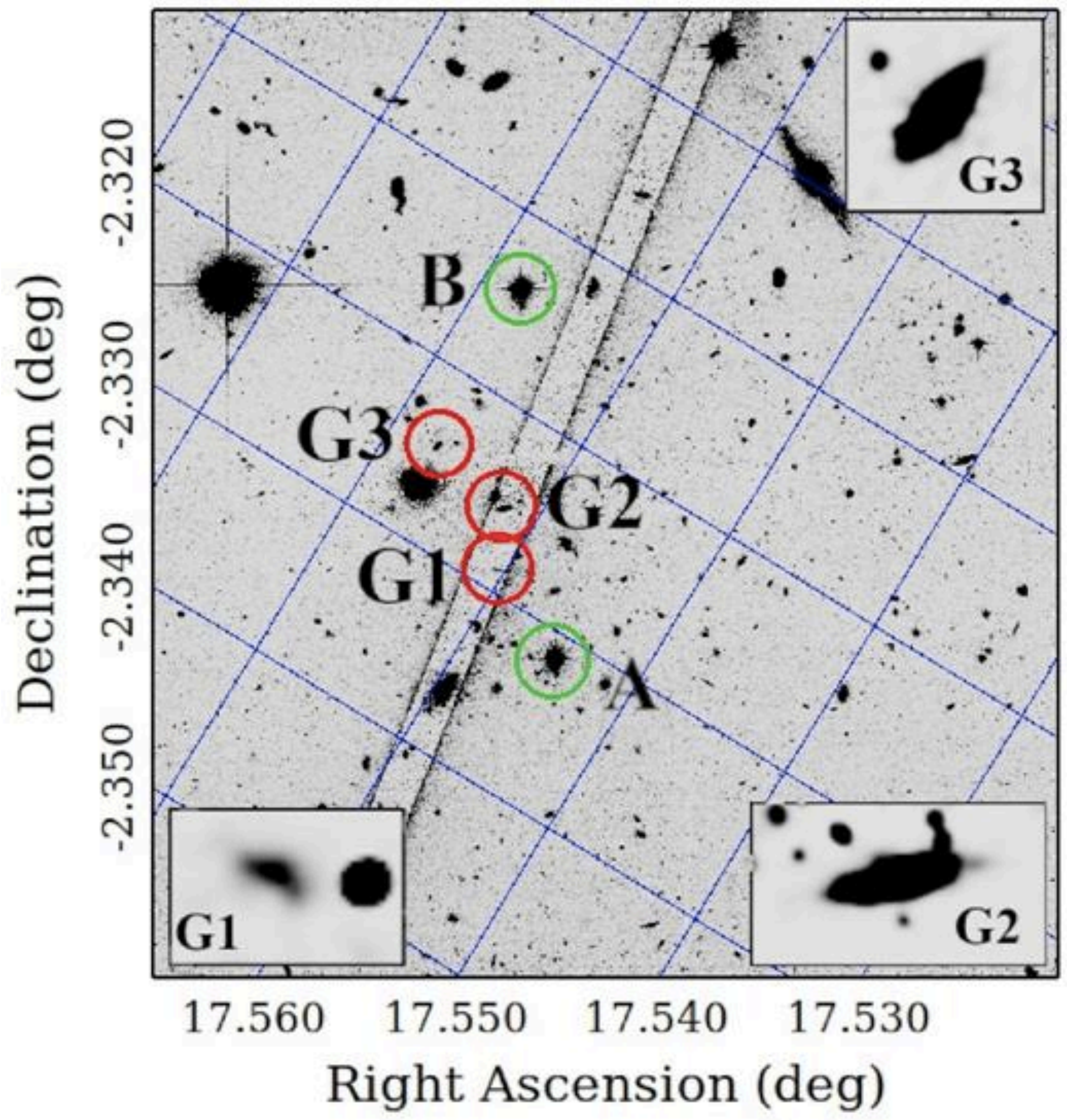

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has a lower column density in cold gas

O VI and HI line broadening suggests $T \gtrsim 10^5$ K

absorption from both photoionised and collisionally ionised phases of gas

metal abundances of solar

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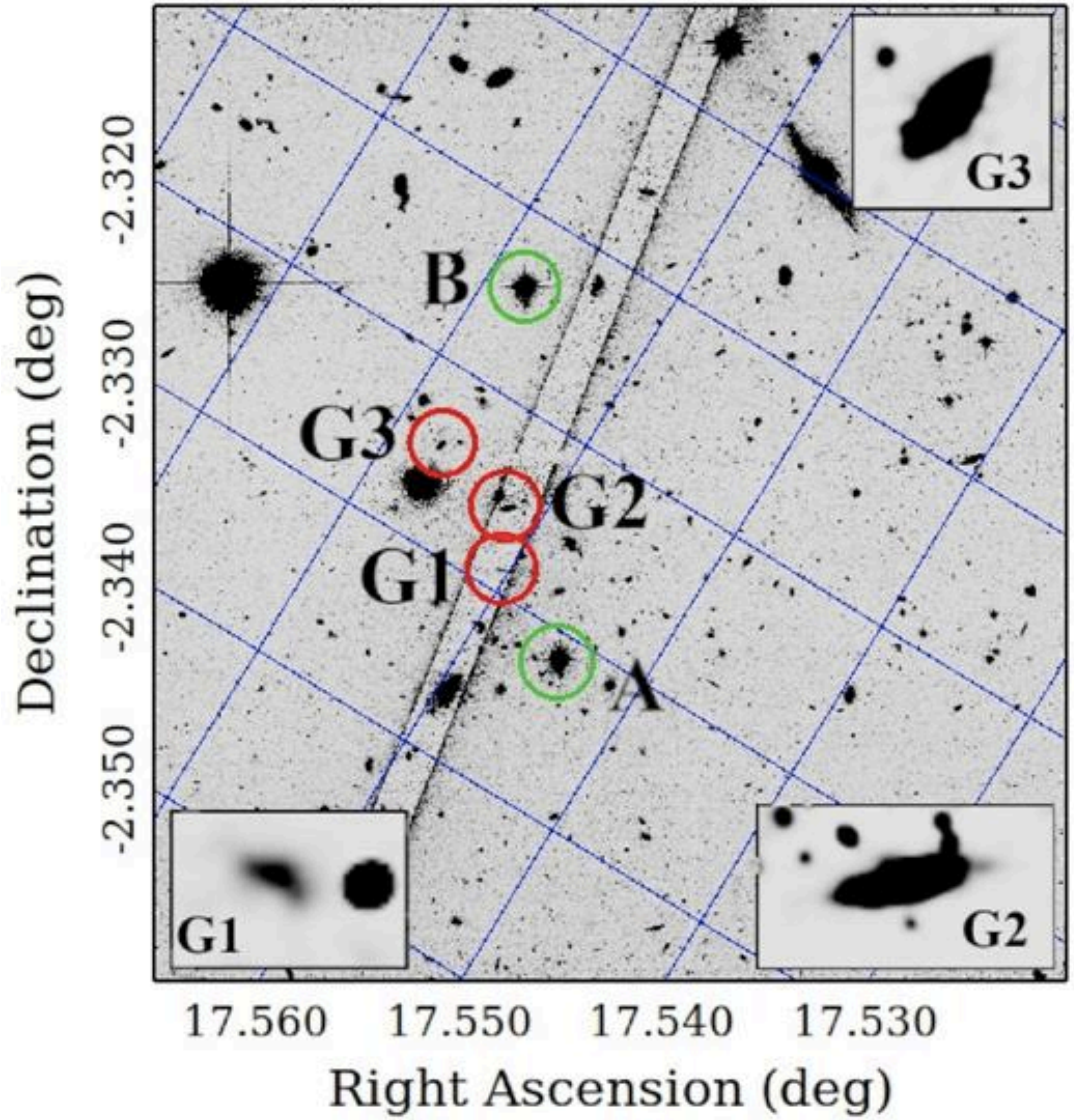
$\Phi \approx 86^0, \;\; d/R_{vir} \approx 1.1, \;\; \mathrm{SFR} \approx 3 \; \mathrm{M}_\odot \; \mathrm{yr}^{-1}$

Anshul et al. 2021



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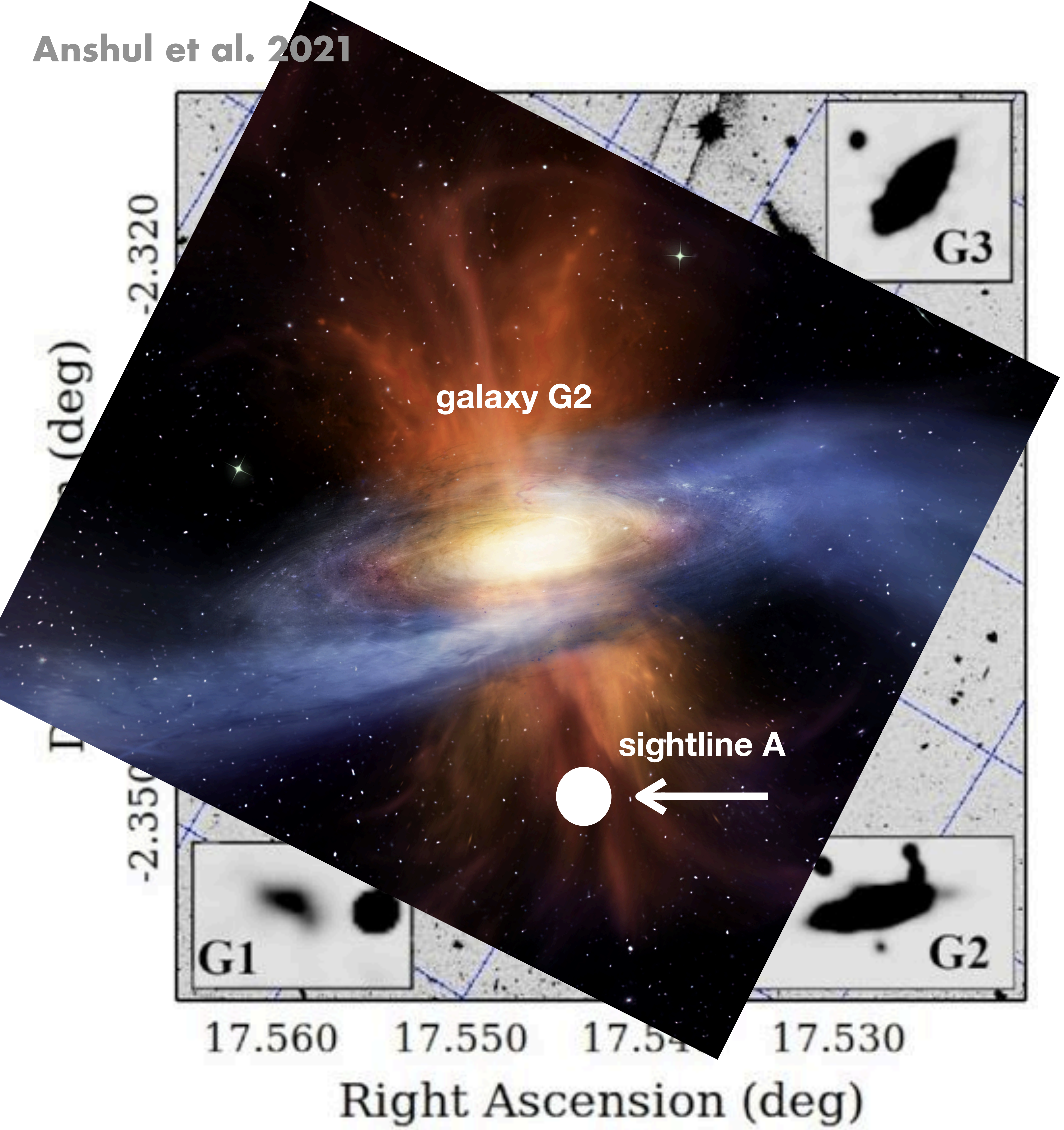

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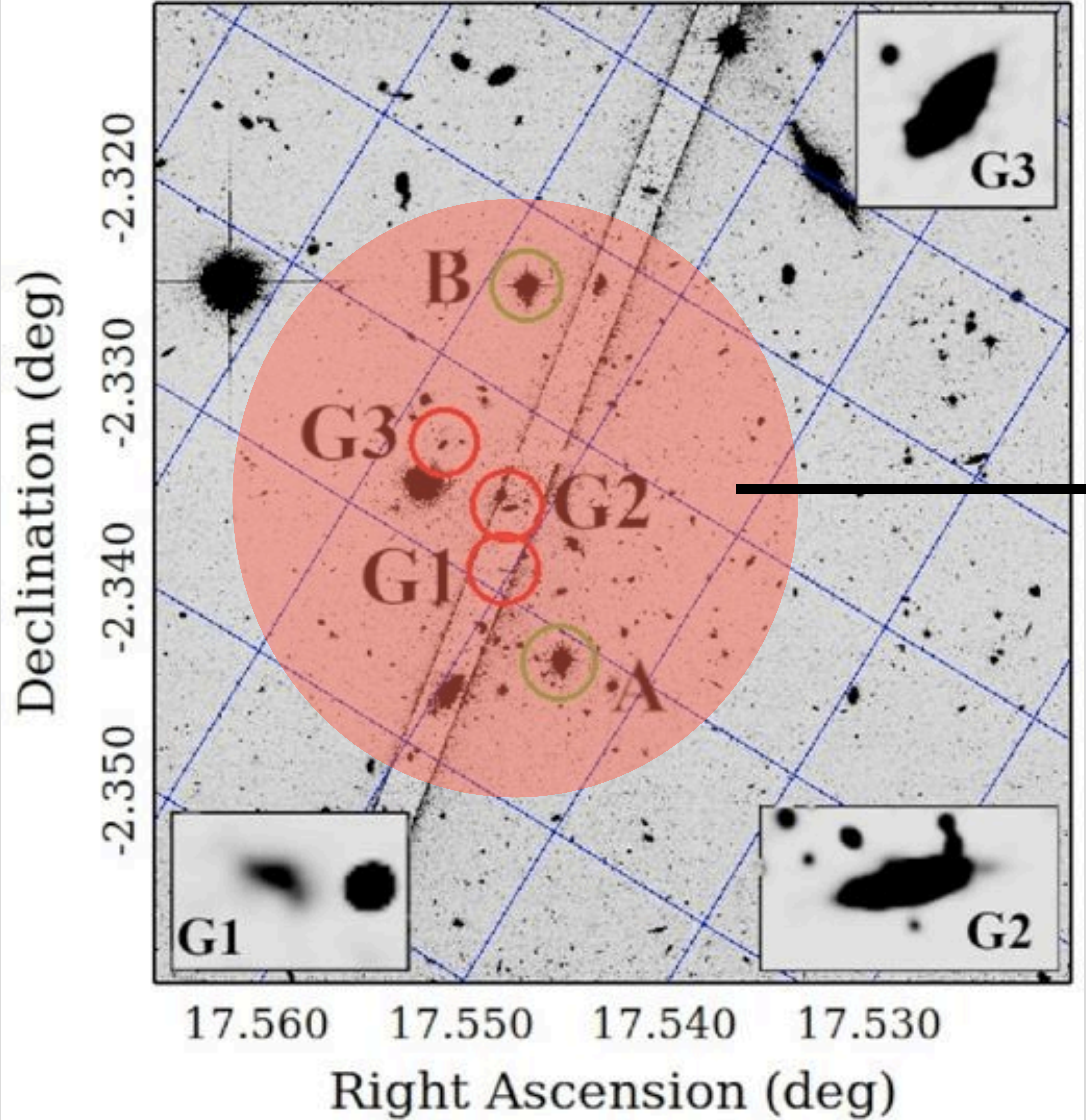

O VI similar absorption along both lines of sight broader than other metals

Galaxy groups contain warm gas

O VI part of the warm phase of the intragroup medium

Stocke et al. 2014

Anshul et al. 2021

Lyman Limit System - BLA - OVI Tracing (Possible) Gas Accretion onto CGM

Khonde et al. 2024, submitted

HST/COS + VLT/MUSE Observations of a LLS with BLA - O VI at z ~ 0.4

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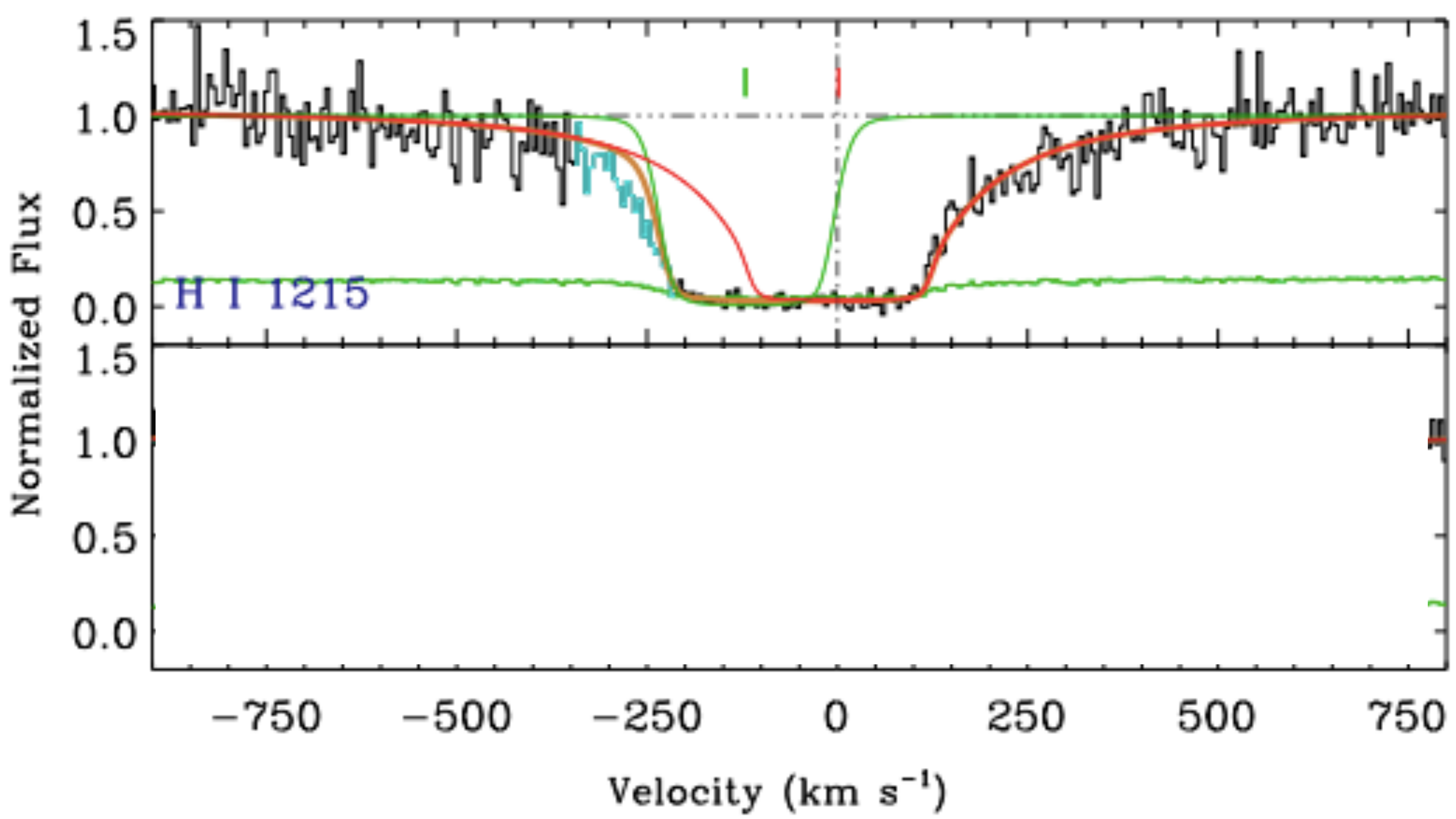

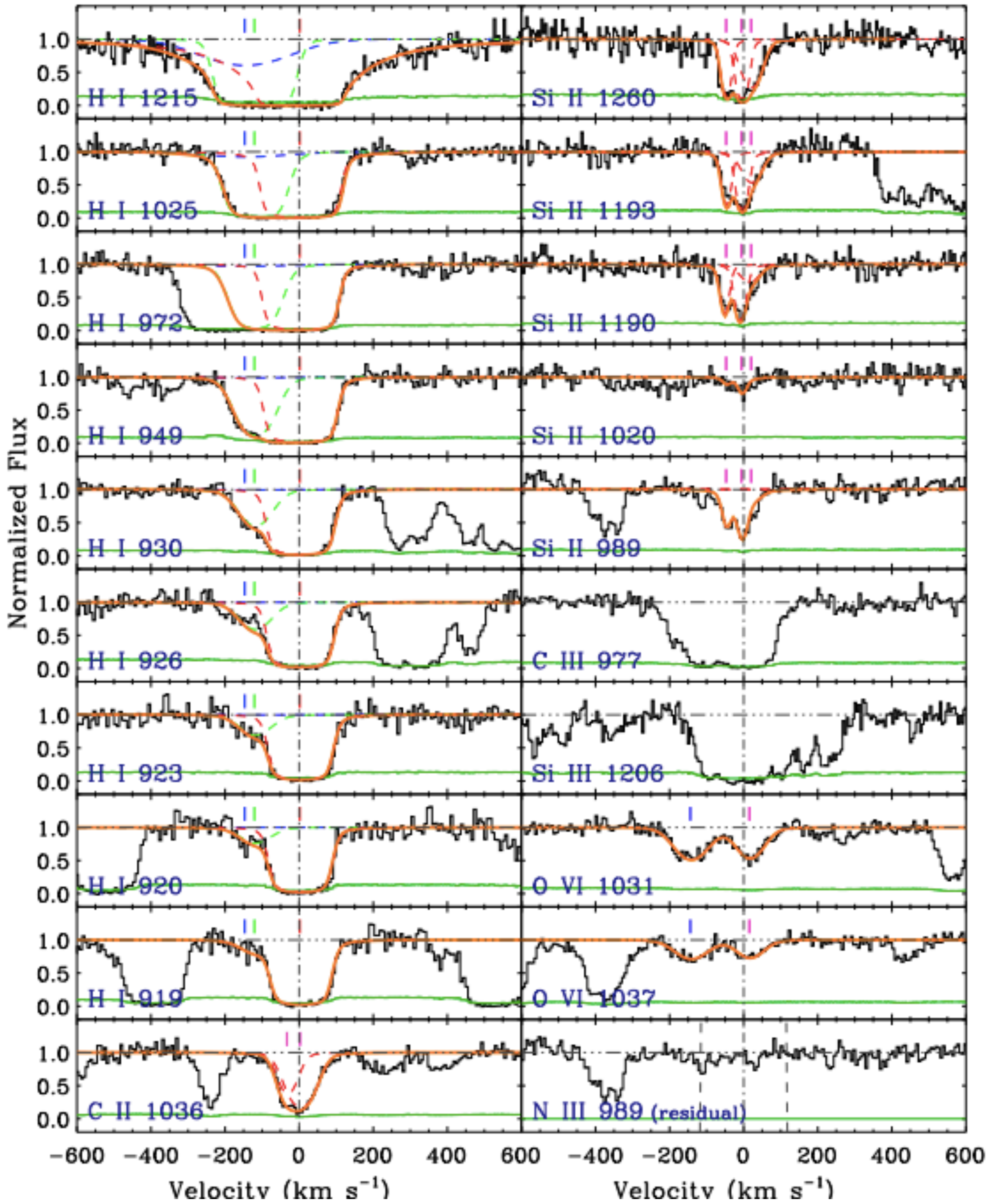

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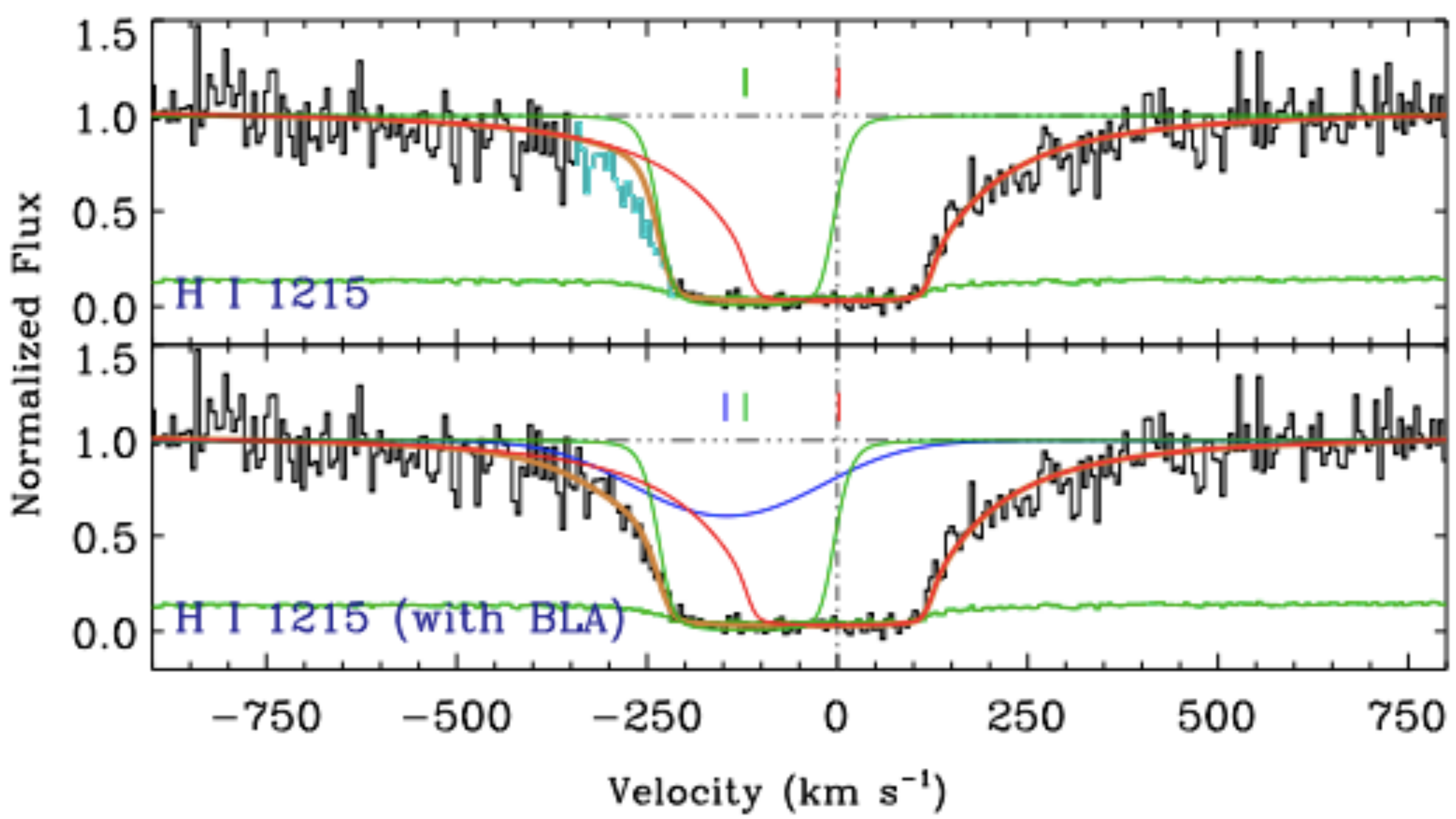

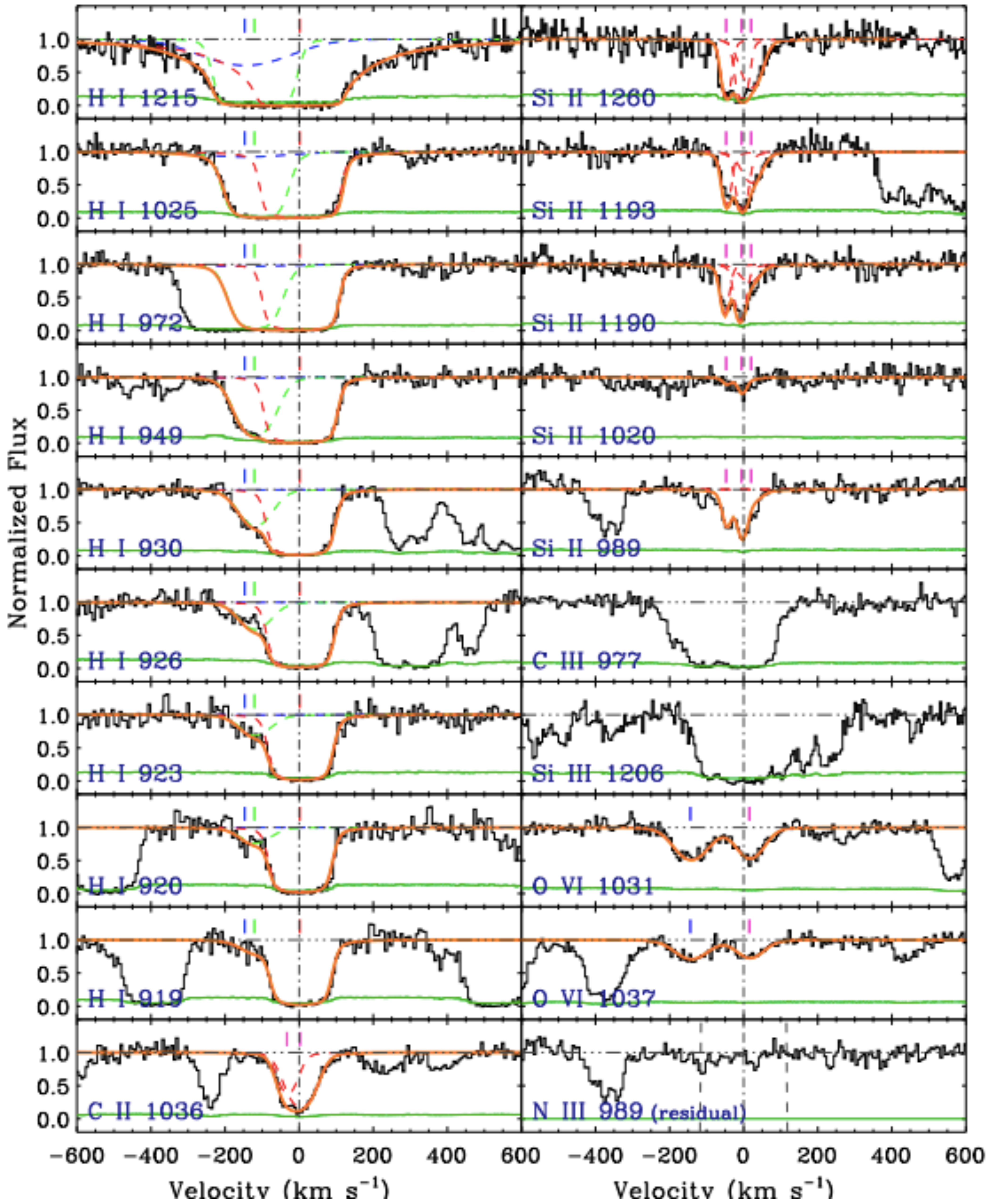

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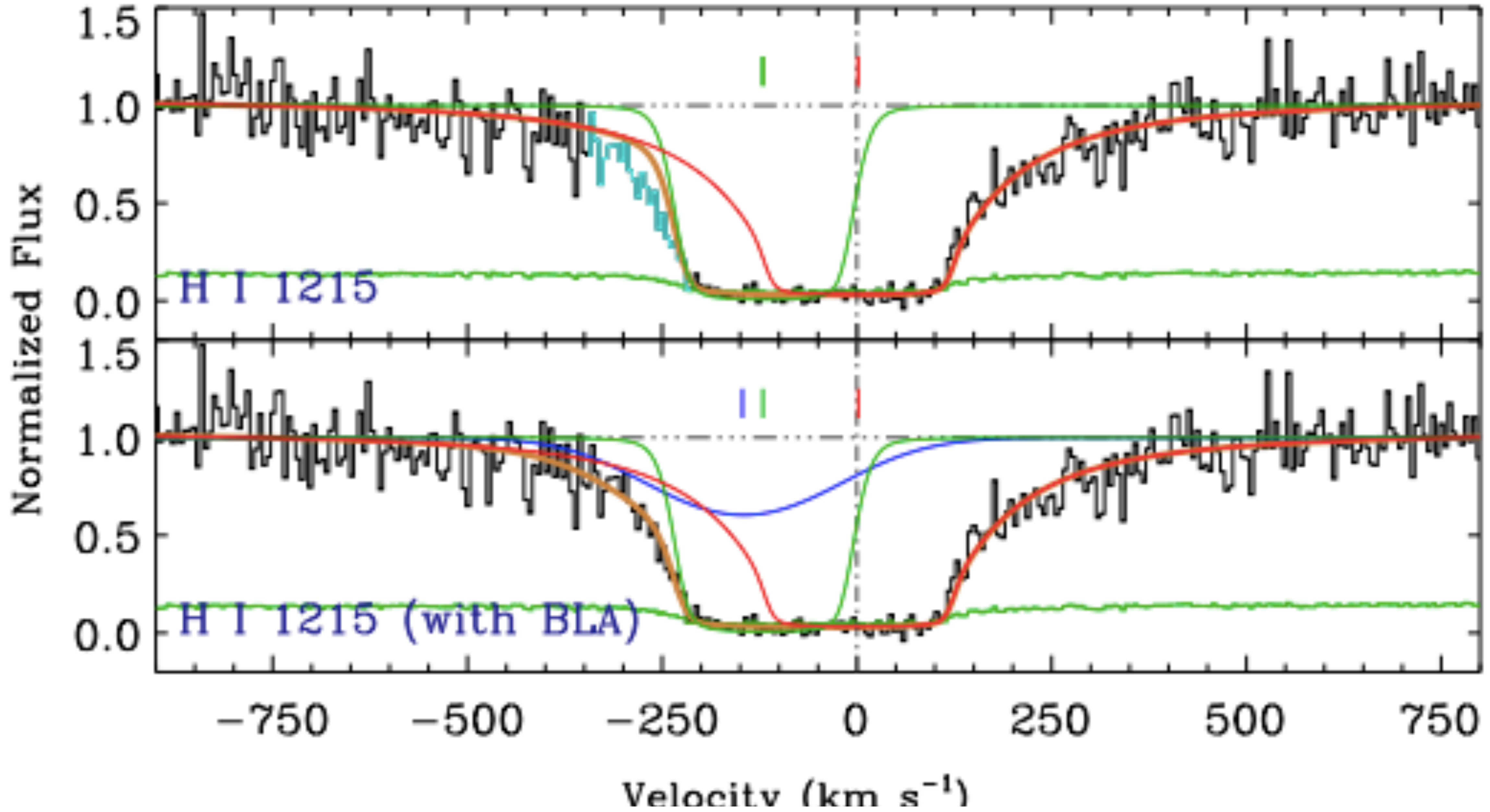
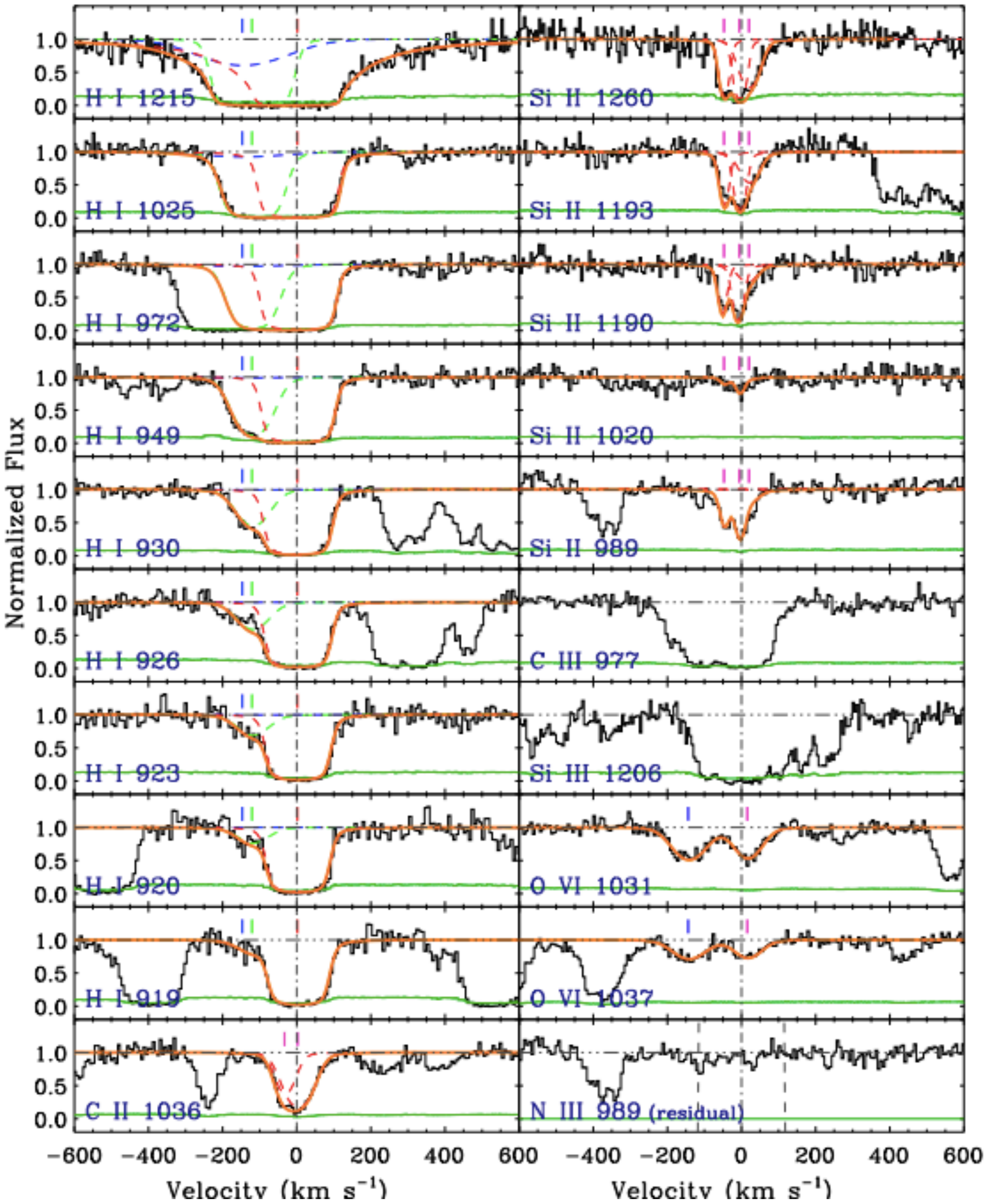
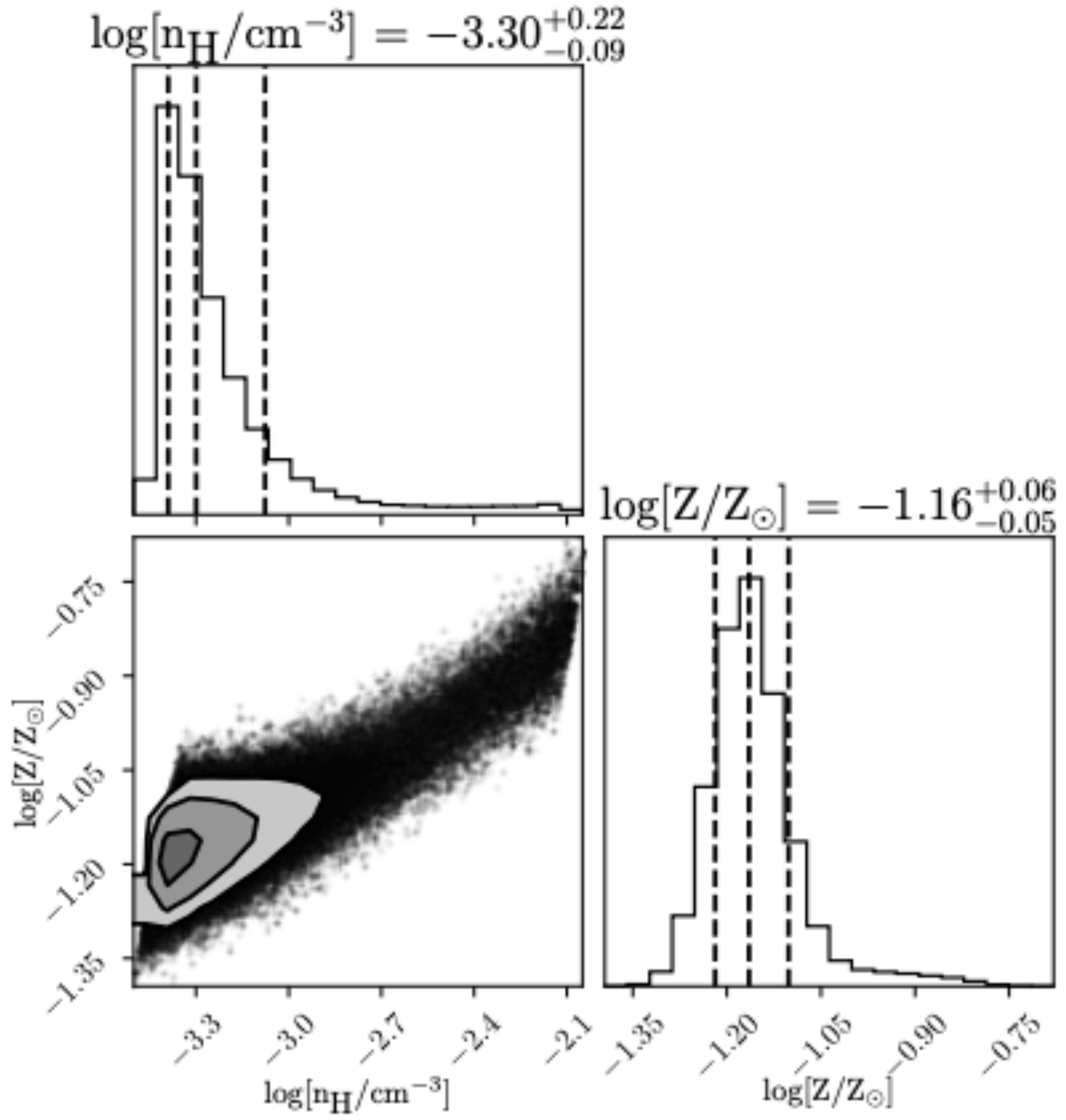
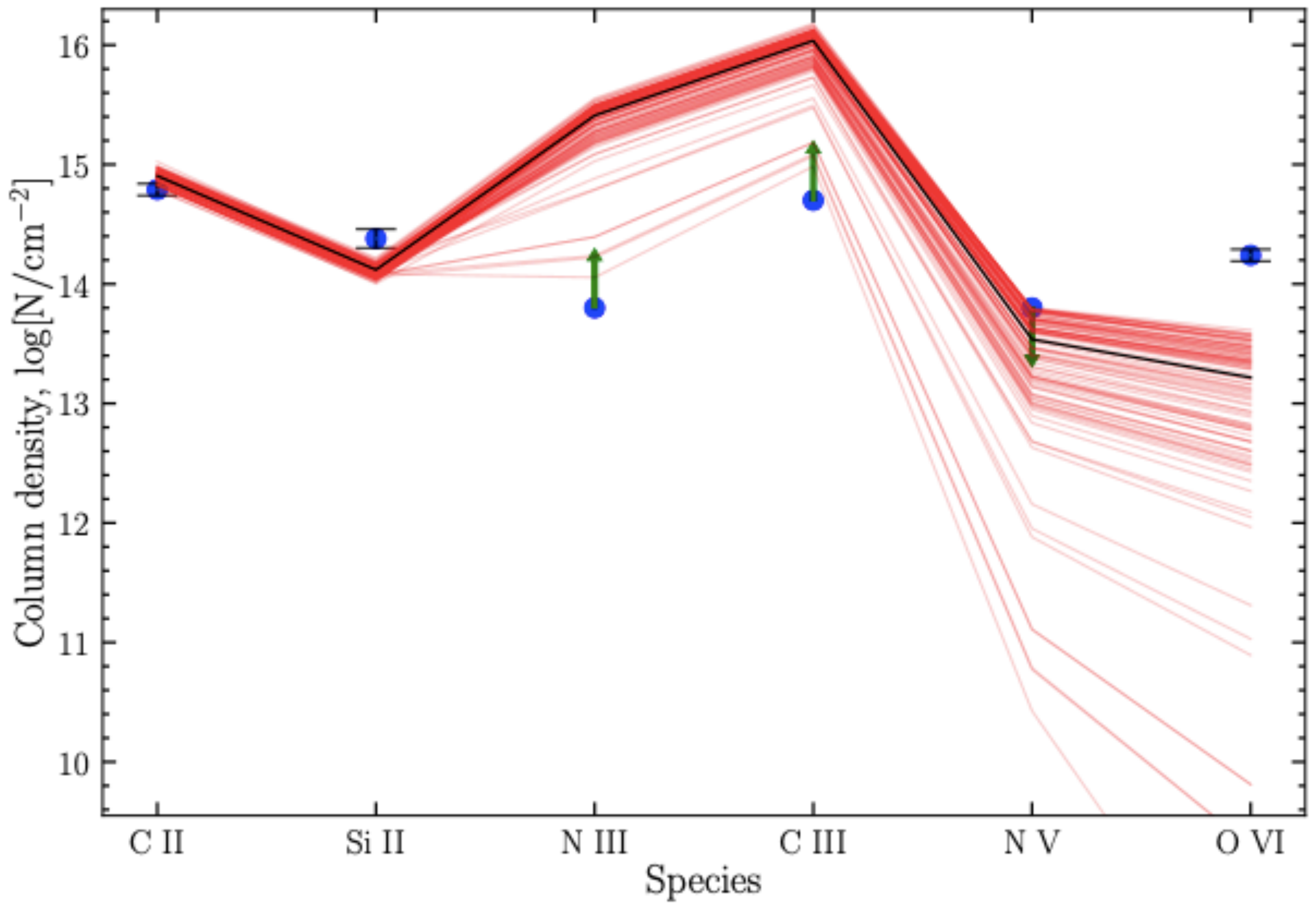


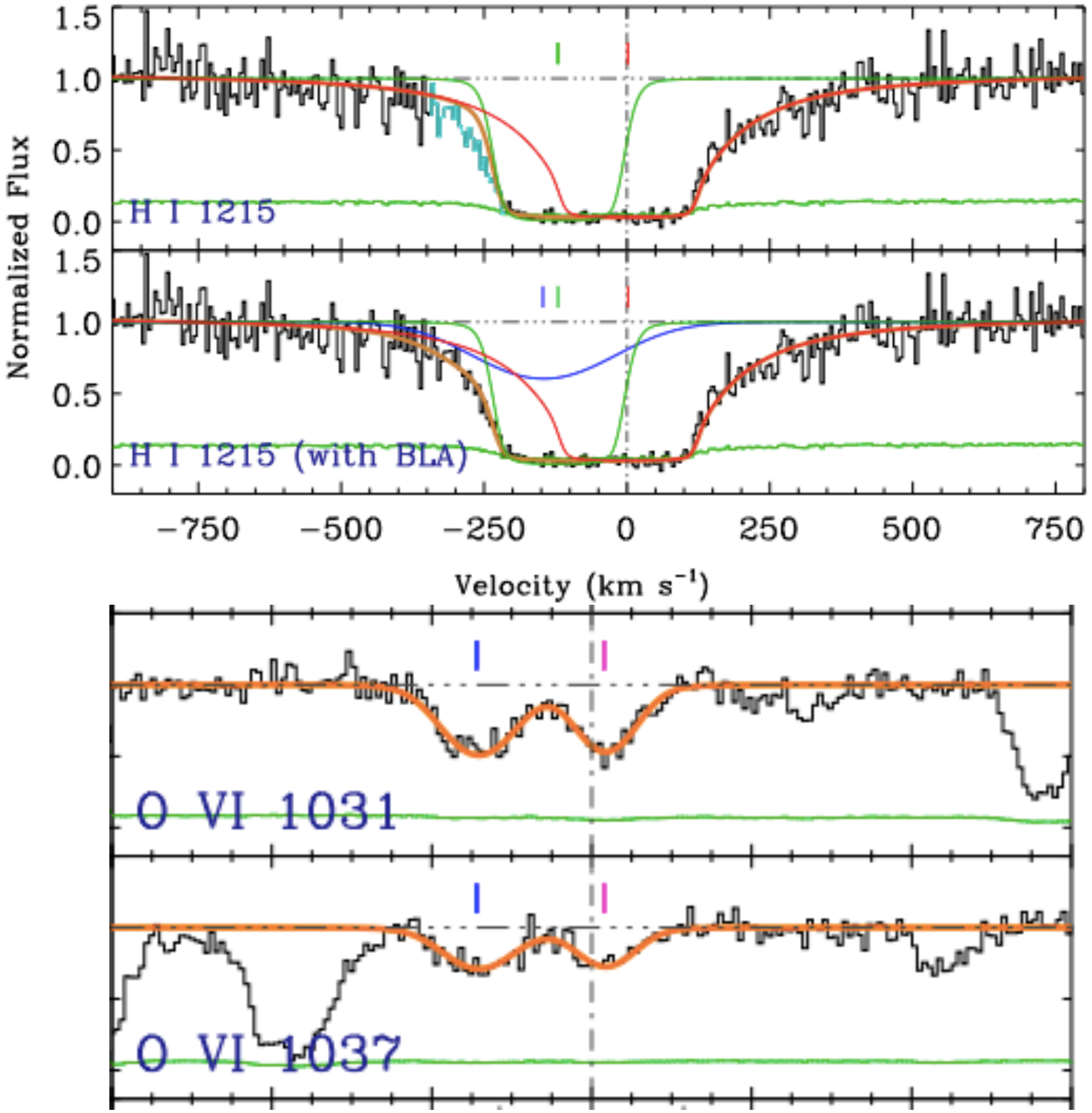






HST/COS + VLT/MUSE Observations of a LLS with BLA - O VI at z ~ 0.4

Khonde et al. 2024, submitted



Lyman limit component + low ionization metals trace gas with T ~ 10^4 K

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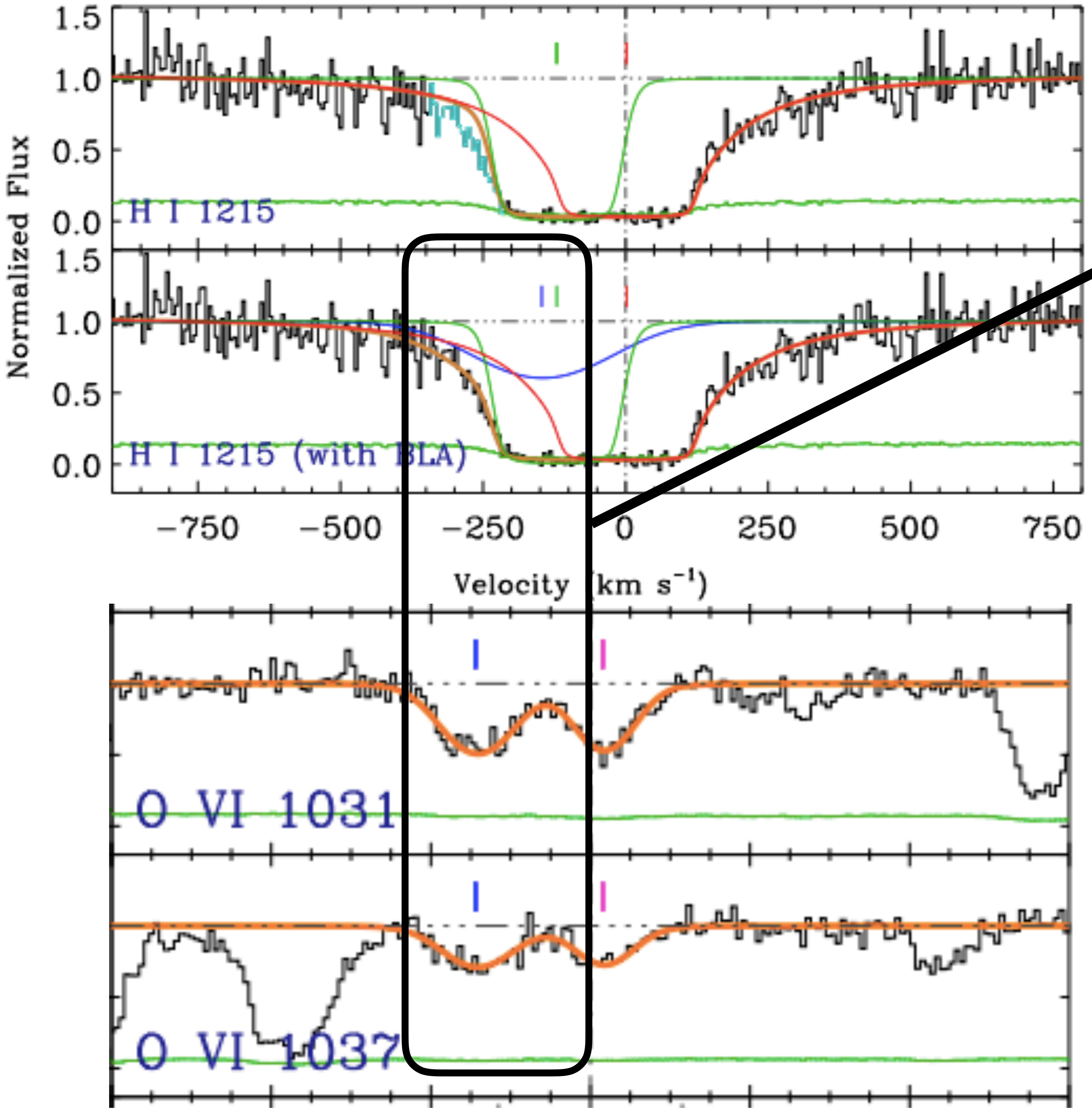


Lyman limit component + low ionization metals trace gas with T ~ 10^4 K

O VI + BLA traces gas with T ~ 10^6 K

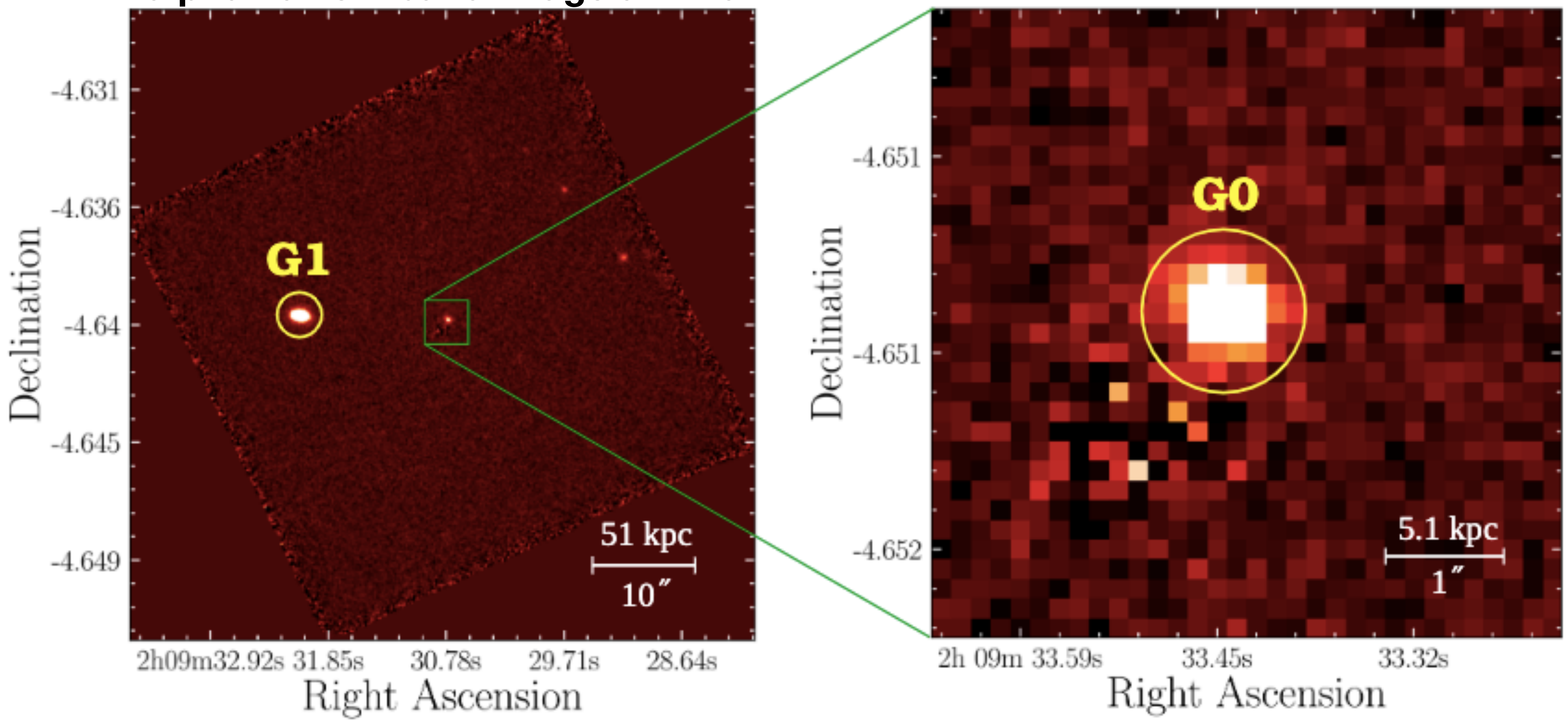
The baryonic column density in the cold and hot phases are comparable

N(H) = N(H I) + N(H II) ~ 10^{20} cm^{-2}

HST/COS + VLT/MUSE Observations of a LLS with BLA - O VI at z ~ 0.4

Khonde et al. 2024, submitted

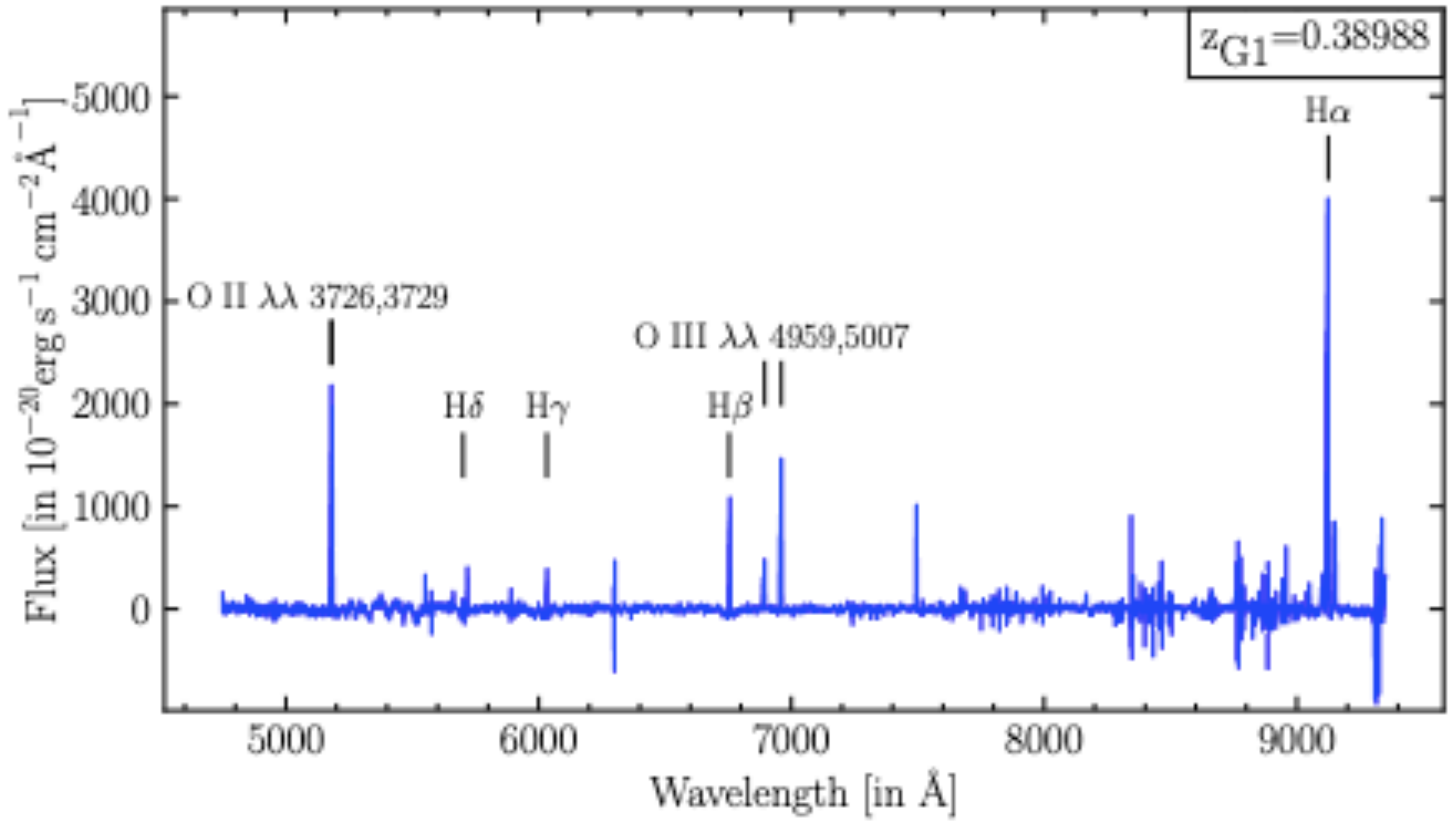
H-alpha narrow band image at z ~0.4

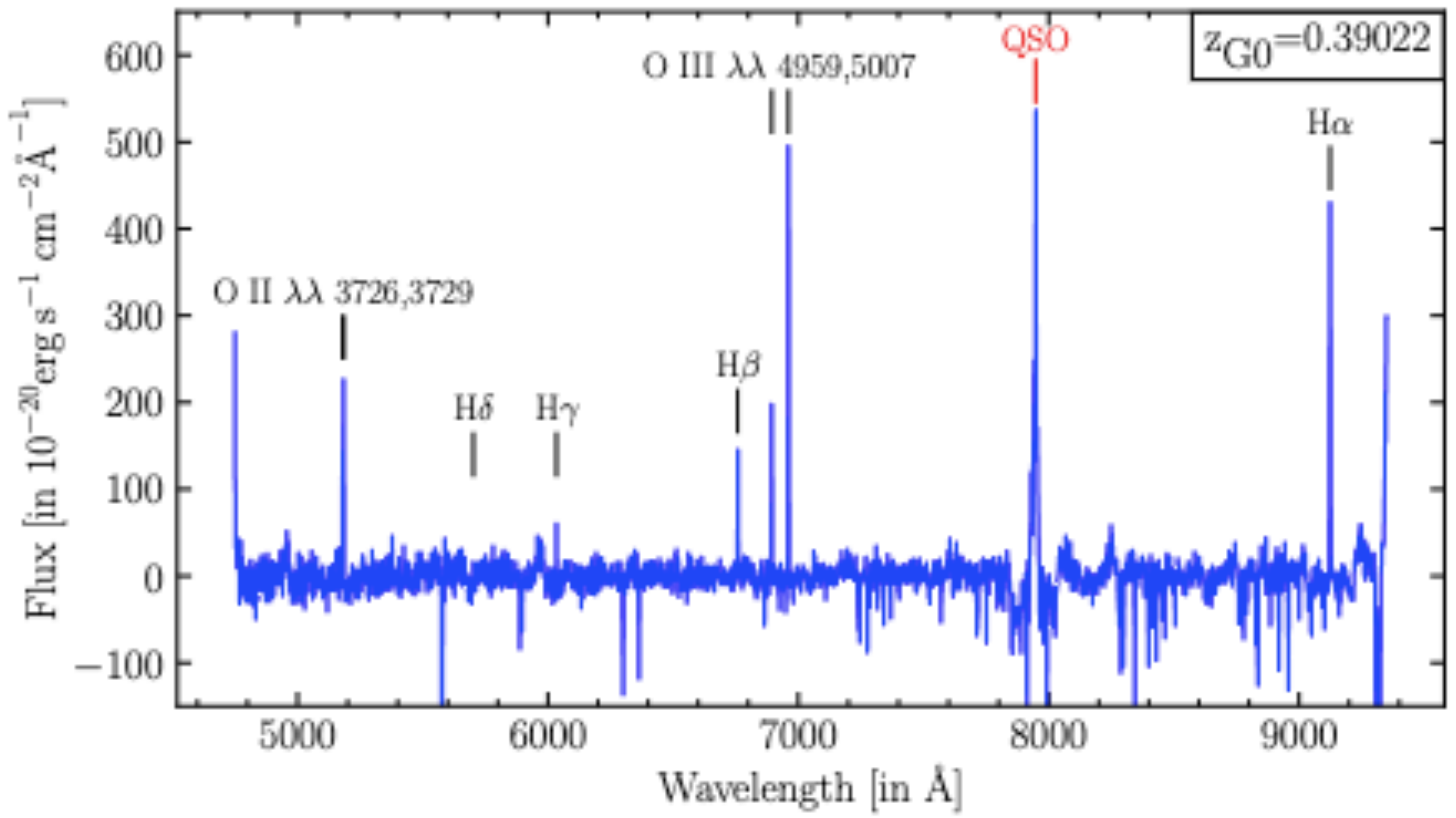


G0 : $\rho = 12$ kpc, $|\Delta v| = 54$ km/s

G1 : $\rho = 104$ kpc, $|\Delta v| = 127$ km/s

Parameter	G0	G1
z	0.39022	0.38988
M_* ($M_\odot$)	$\approx 10^6$	$\approx 10^{10}$
SFR ($M_\odot$ yr^{-1})	0.01	1.78
R_{vir} (kpc)	31.53	138.93
[O/H]	−0.058	0.218





G0 is probably a dwarf satellite of G1

$\rho/R_{vir} \approx 0.7$

The [O/H] for the galaxies is much higher than the metallicity inferred from ionization models for the cold and warm gas phases

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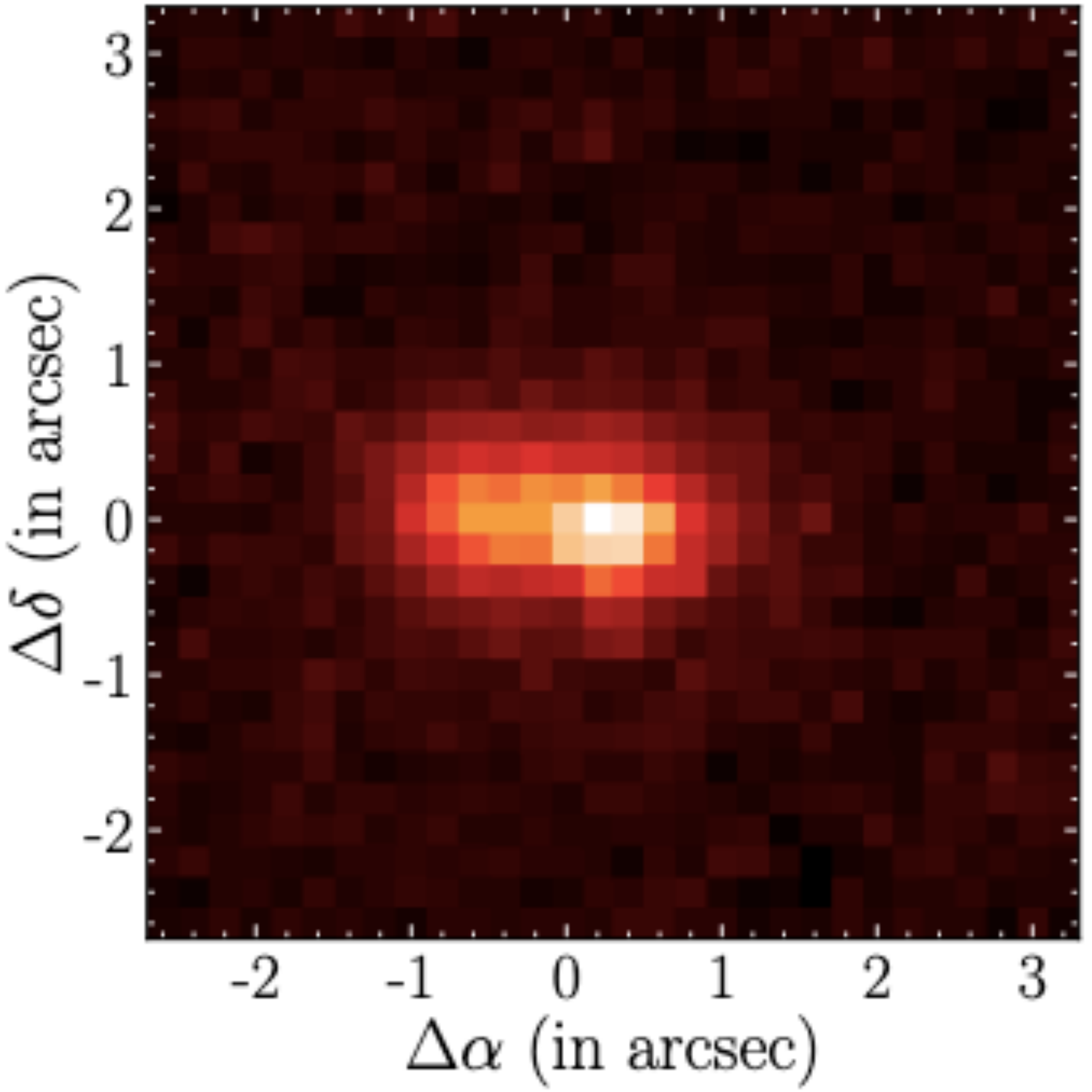

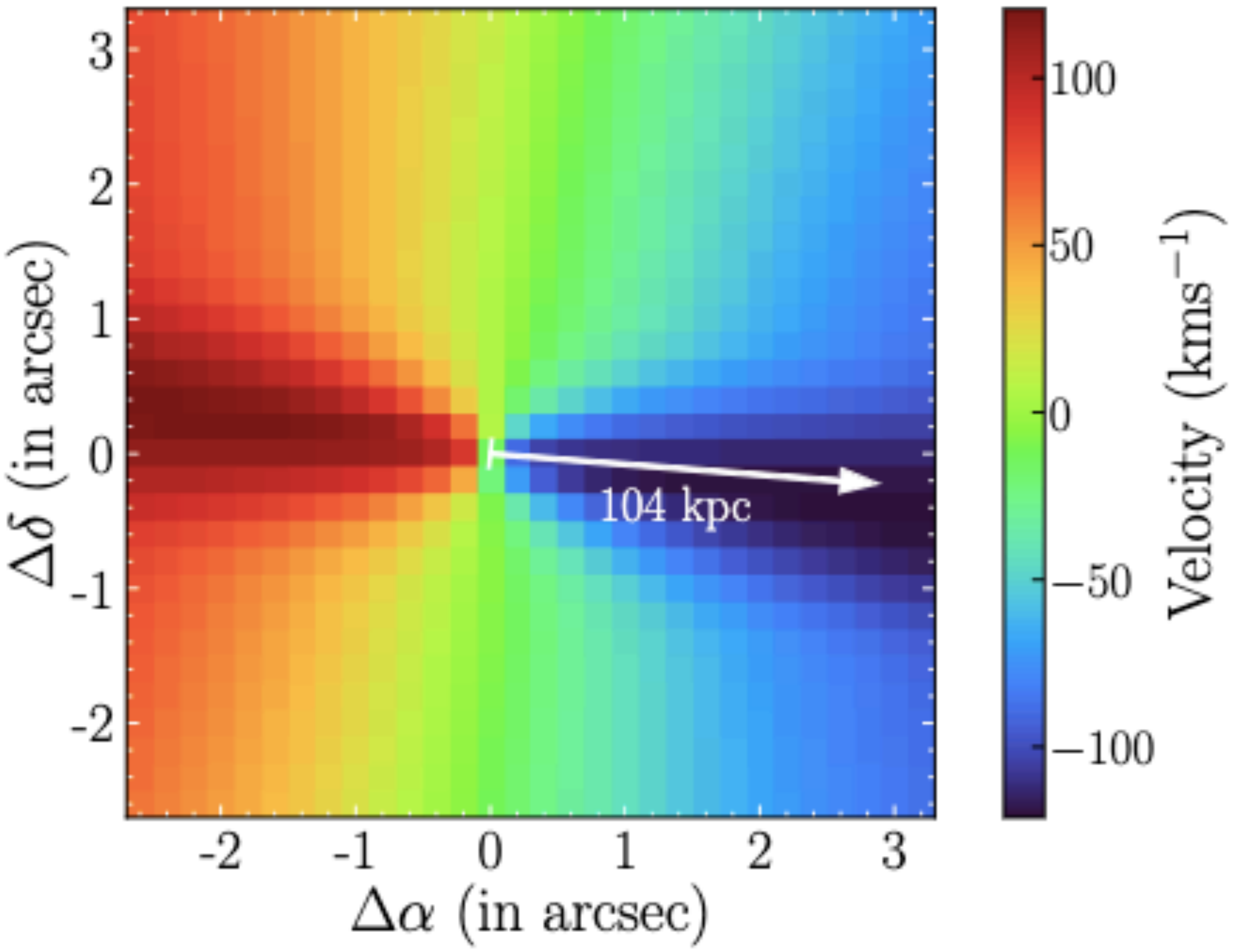

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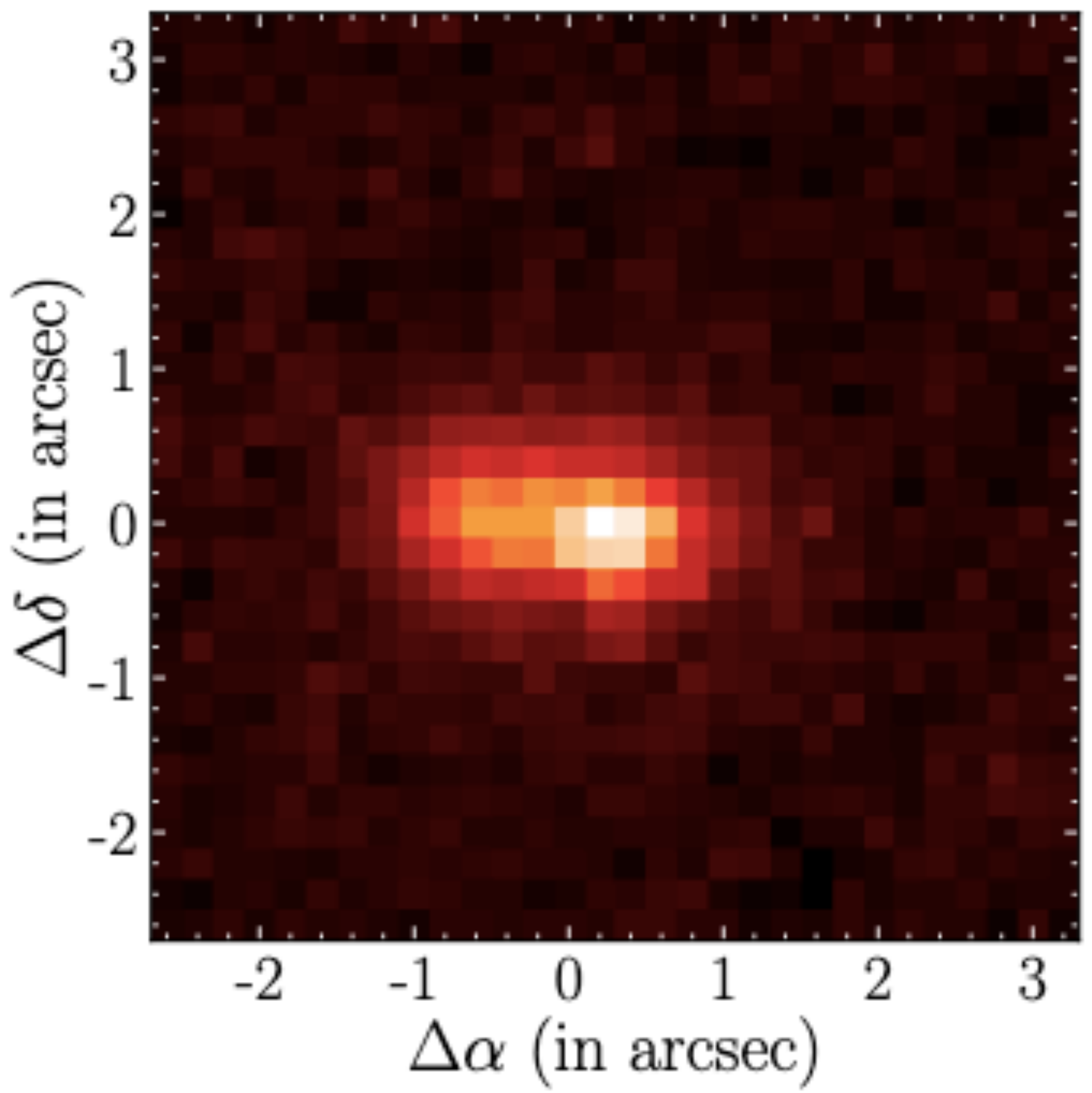
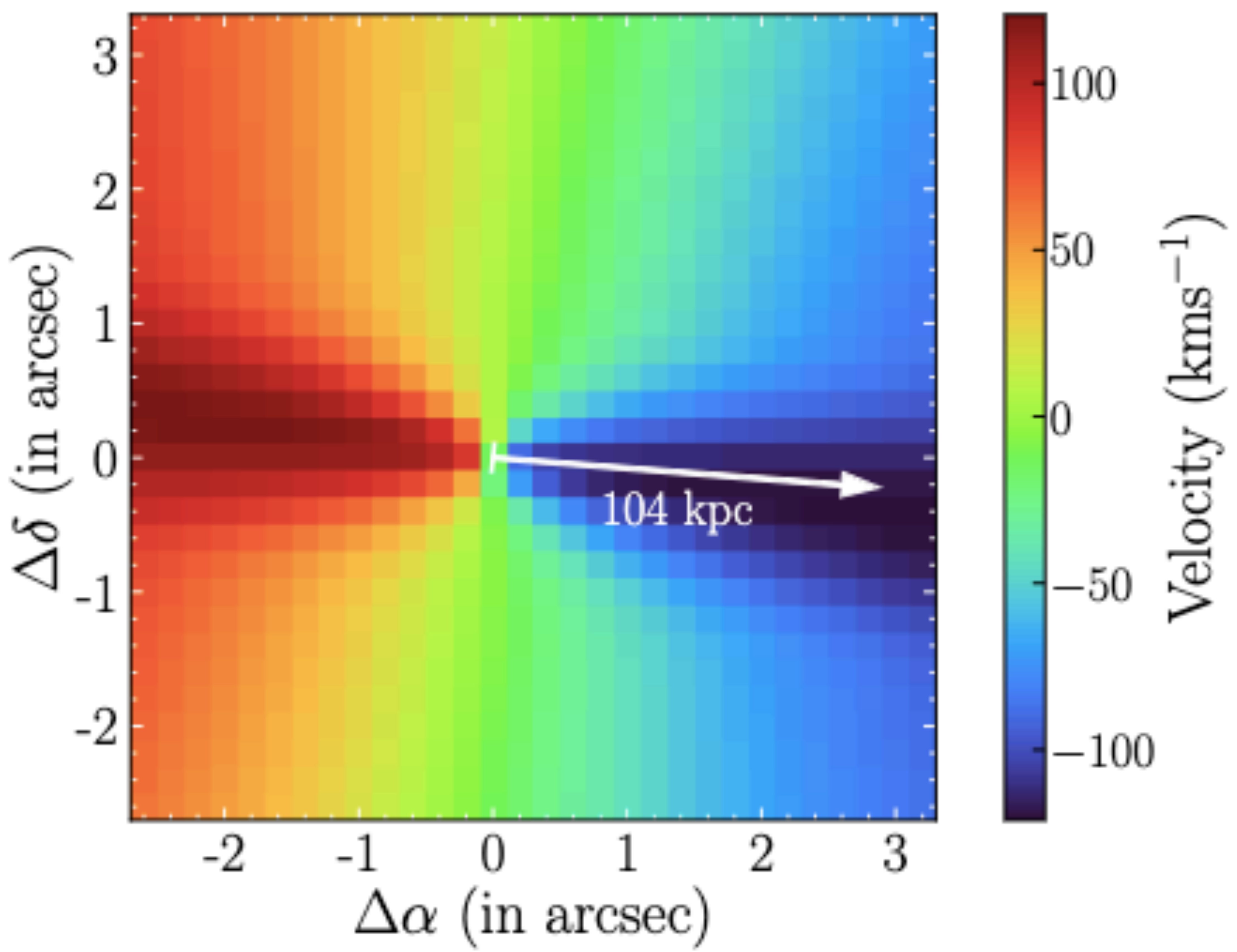
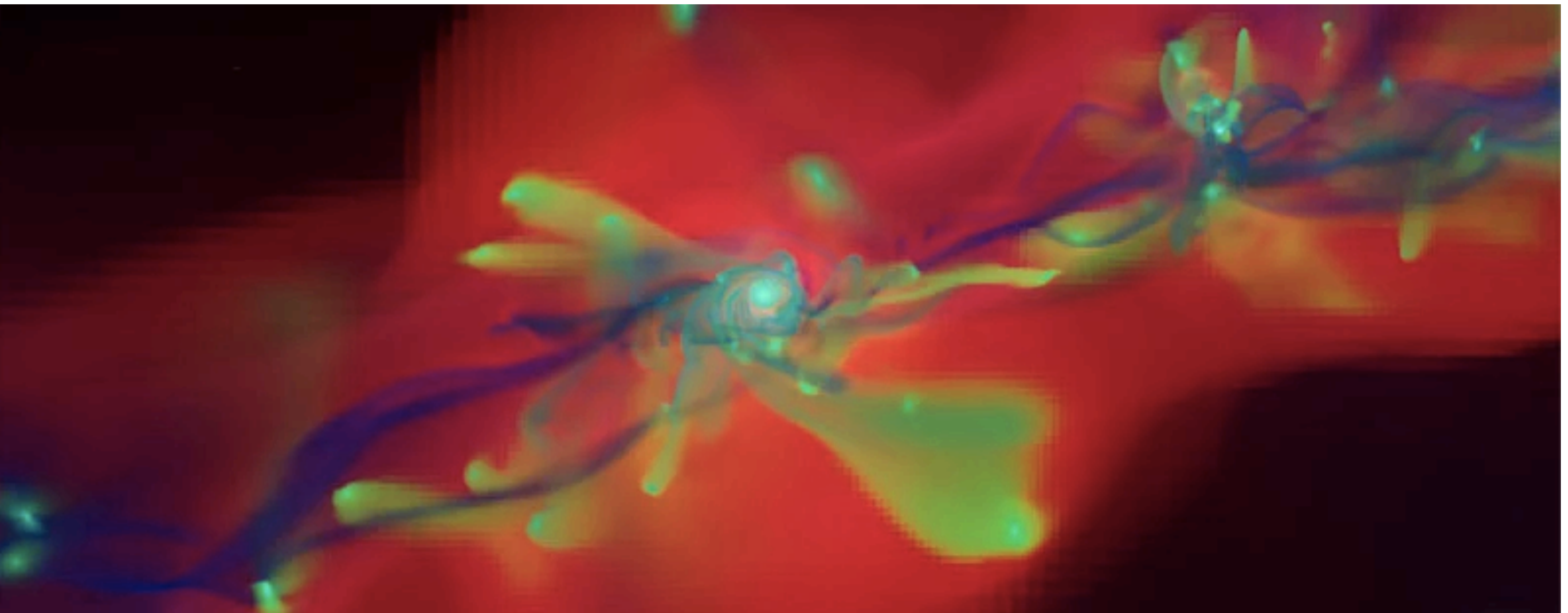


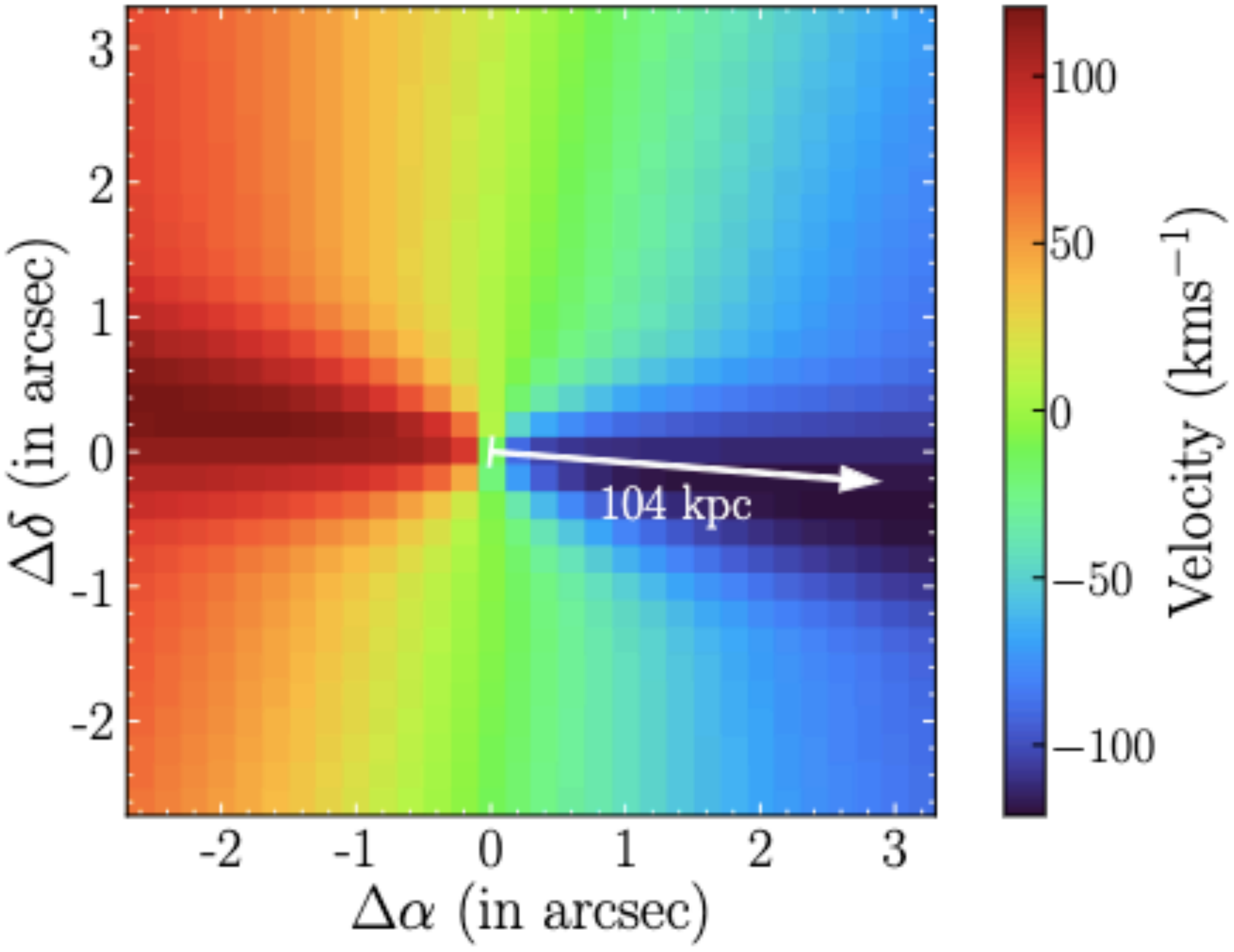


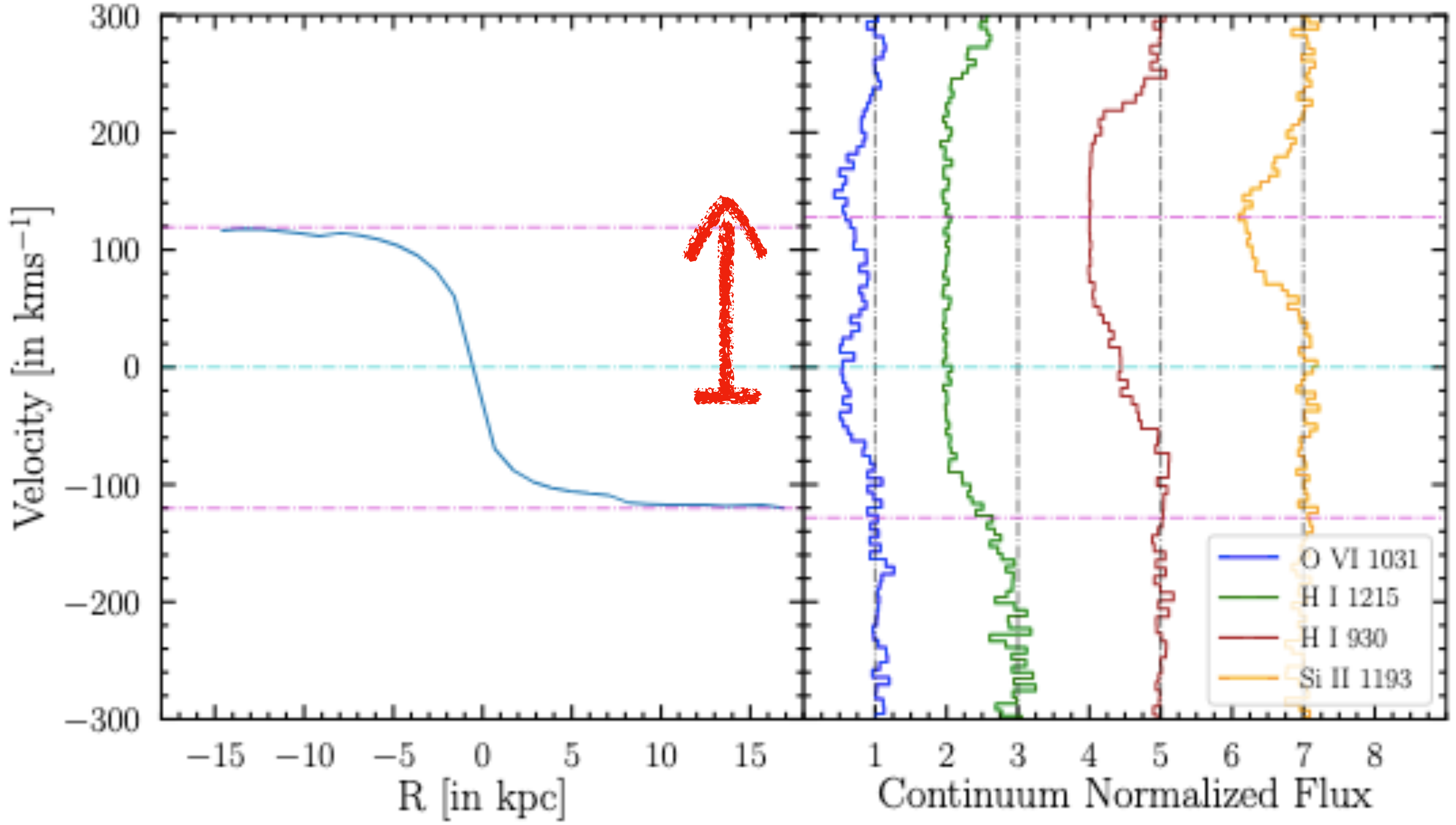


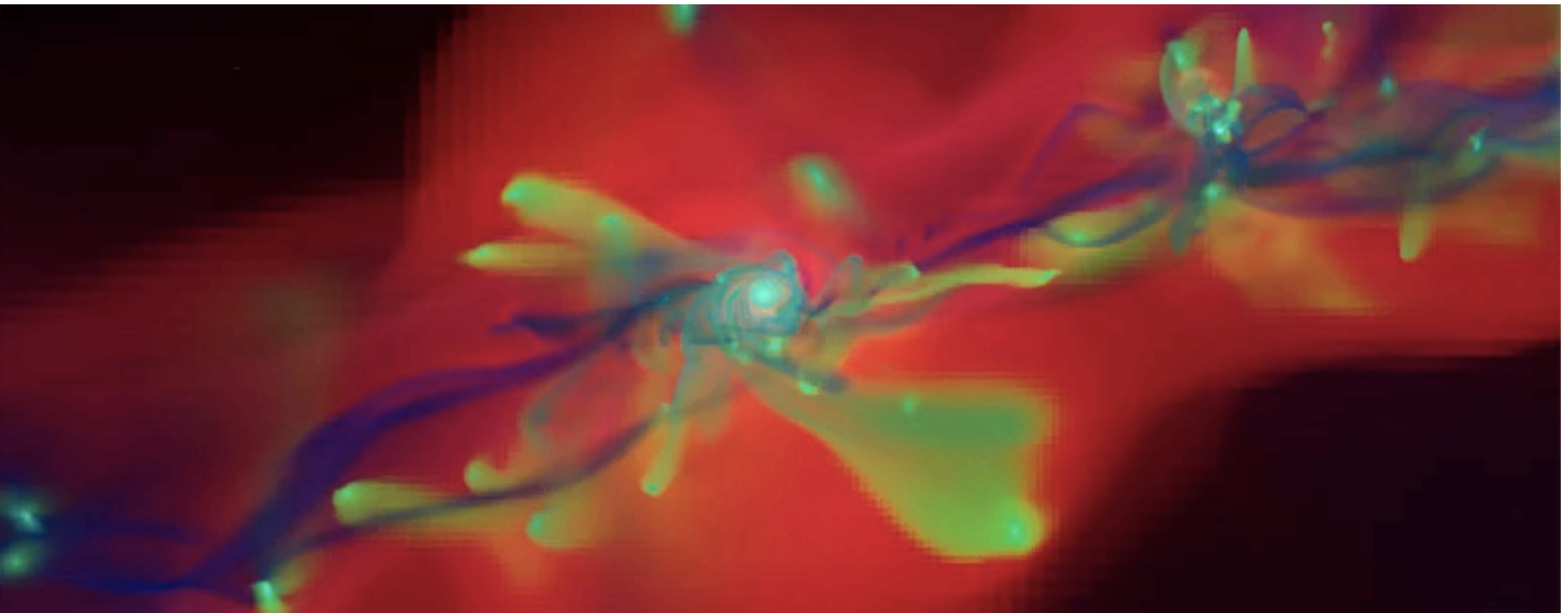
Accreting streams from the cosmic web (blue) typically starts corotating with the disk in the final stages of its accretion.

HST/COS + VLT/MUSE Observations of a LLS with BLA - O VI at z ~ 0.4

Khonde et al. 2024, submitted



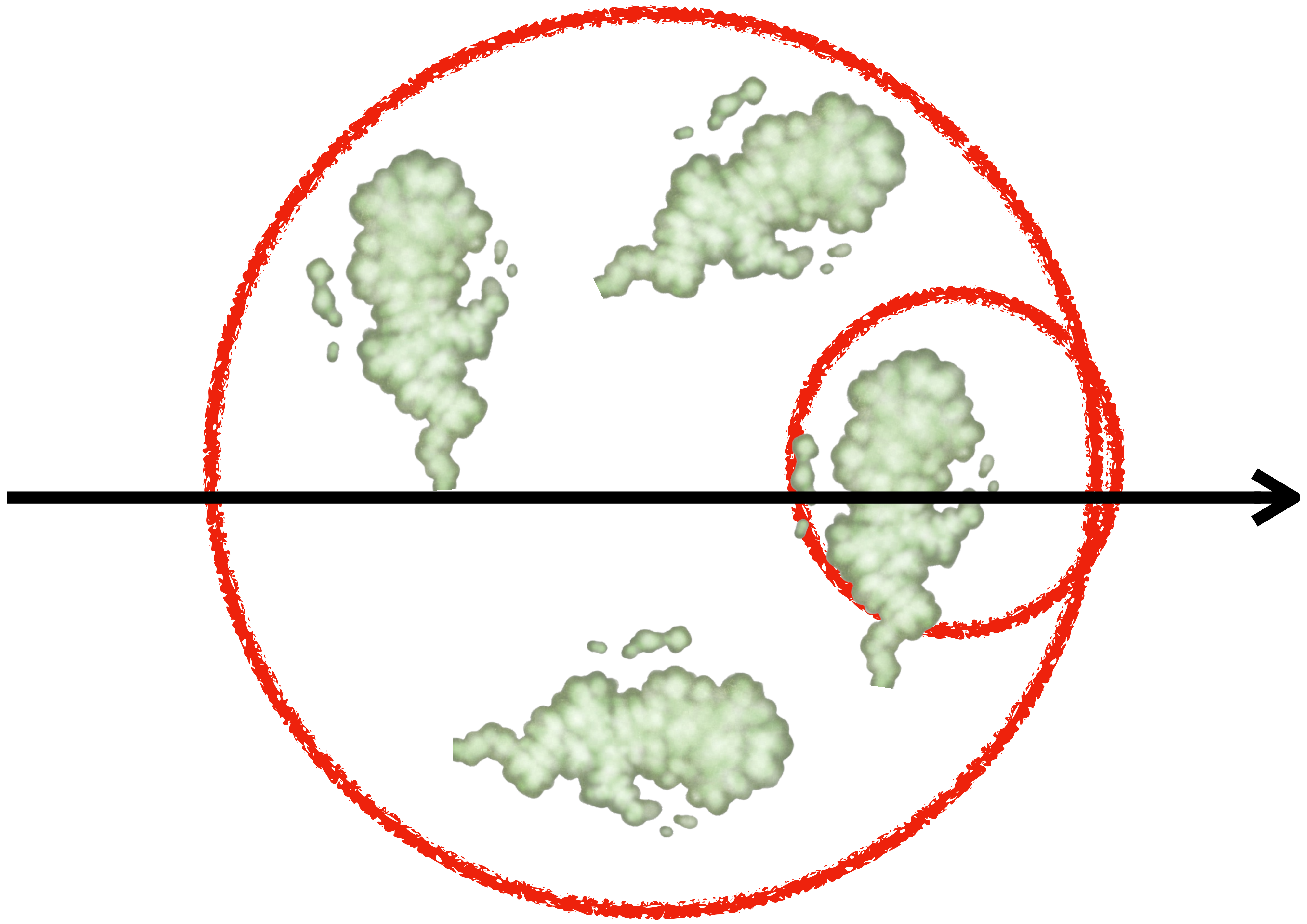




Accreting streams from the cosmic web (blue) typically starts corotating with the disk in the final stages of its accretion. Here it is counter rotating

HST/COS + VLT/MUSE Observations of a LLS with BLA - O VI at $z \sim 0.4$

Khonde et al. 2024, submitted

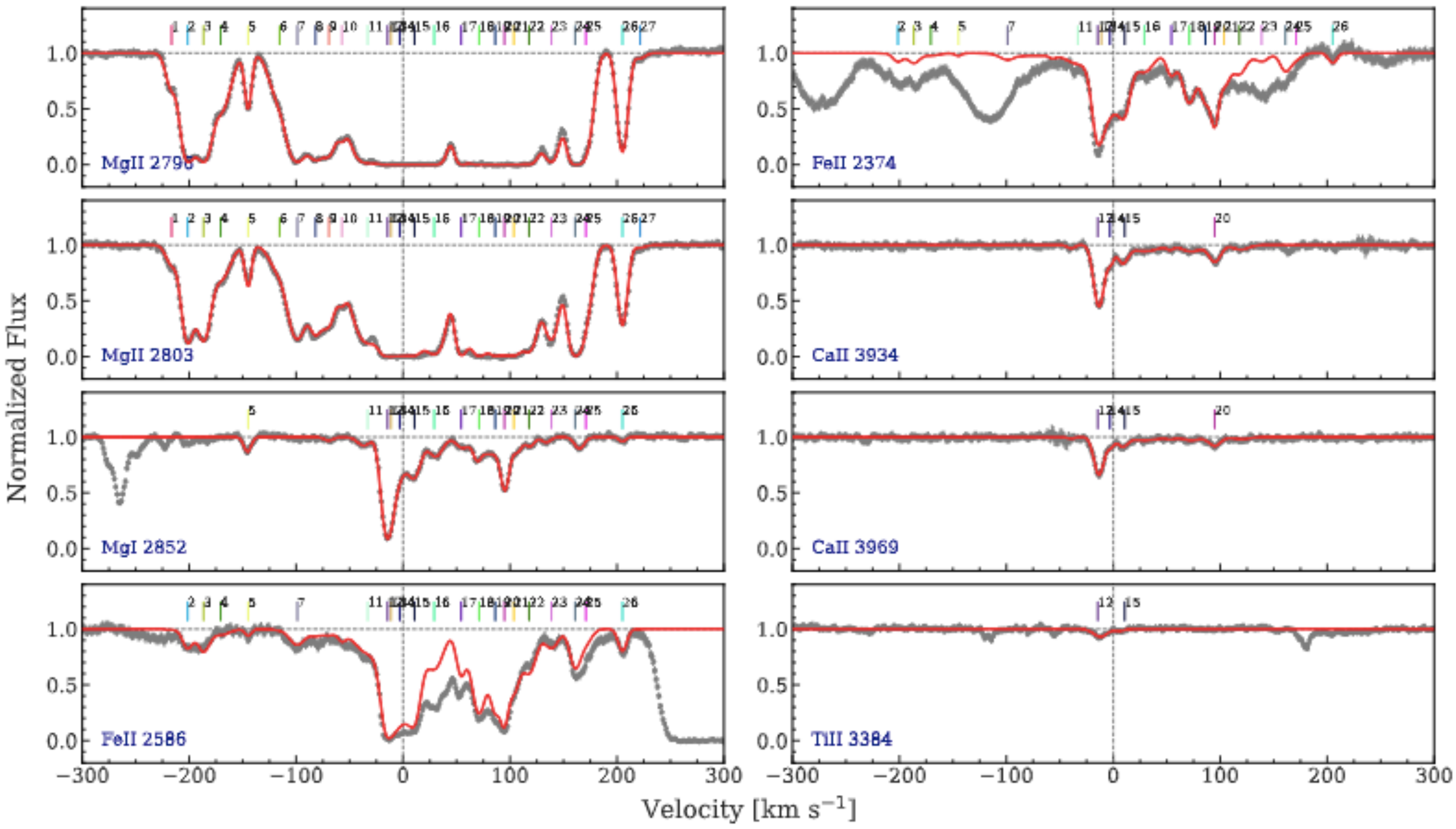


The metallicity 1/10th solar for the LLS compares well with median metallicity of such absorbers in simulations where they trace past outflows or tidally stripped material

LLS tracing high velocity gas
O VI transition temperature gas

Ultra-Strong Mg II at z ~1.13 tracing gas accretion from the CGM?

Udhwani et al. in prep



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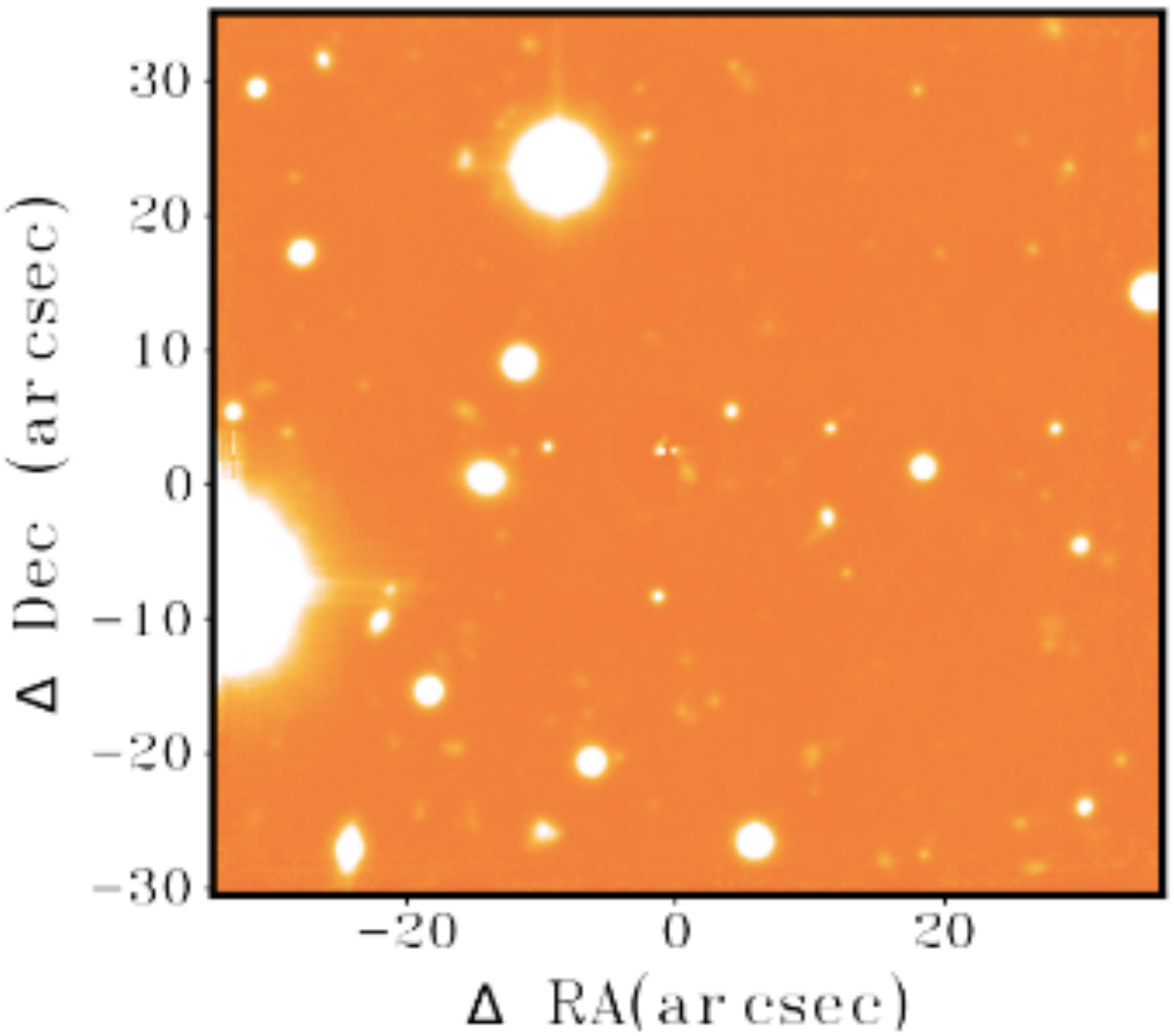
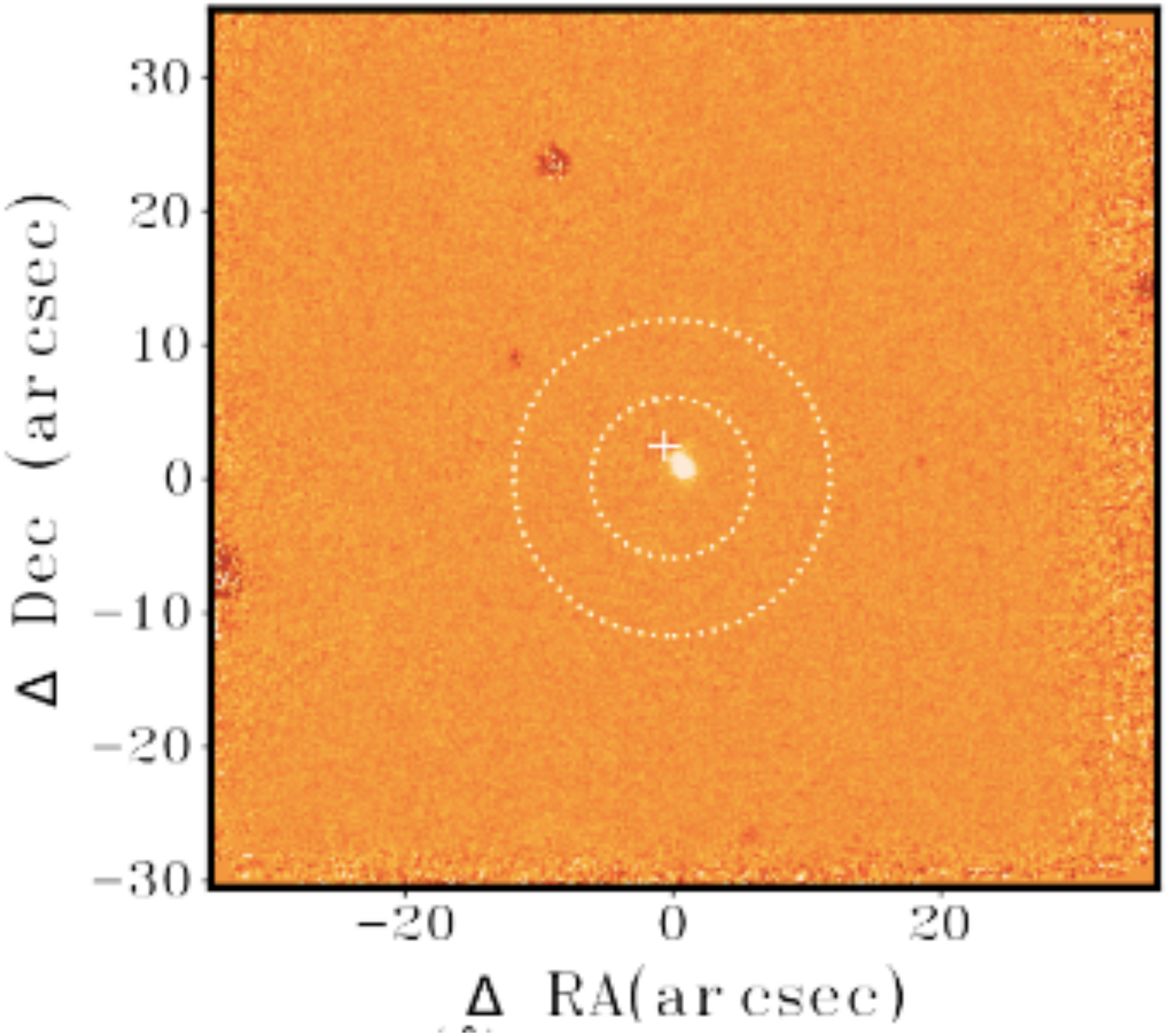




$M_* \approx 5 \times 10^{10}\ M_\odot$, $\mathrm{SFR} \approx 8\ \mathrm{M_\odot\ yr^{-1}}$

$\rho / R_{vir} \approx 0.12$, $z_{abs} \approx z_{gal}$

no bright companion to the GOTOQ within 500 kpc

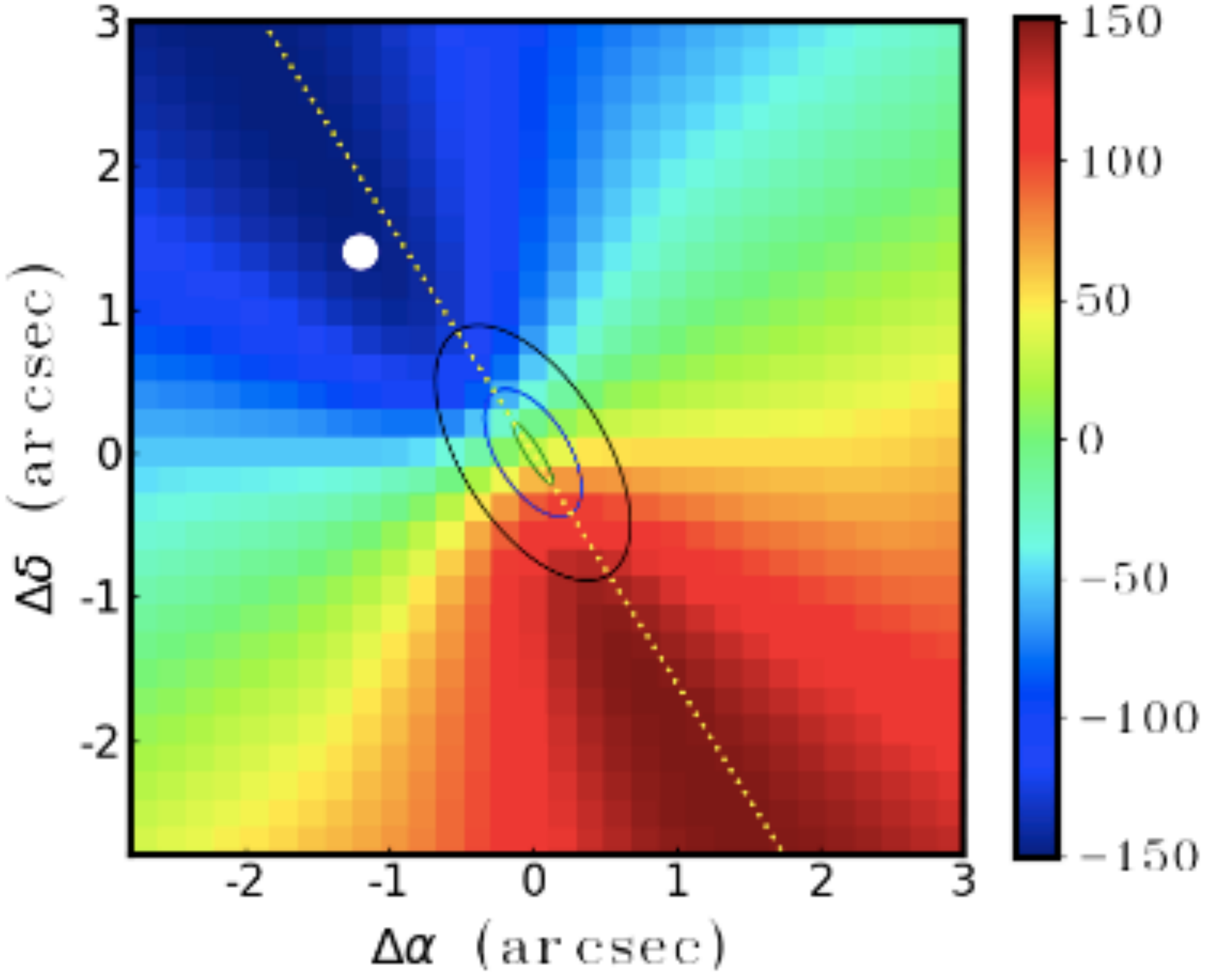
Ultra-Strong Mg II at z ~1.13 tracing gas accretion from the CGM?

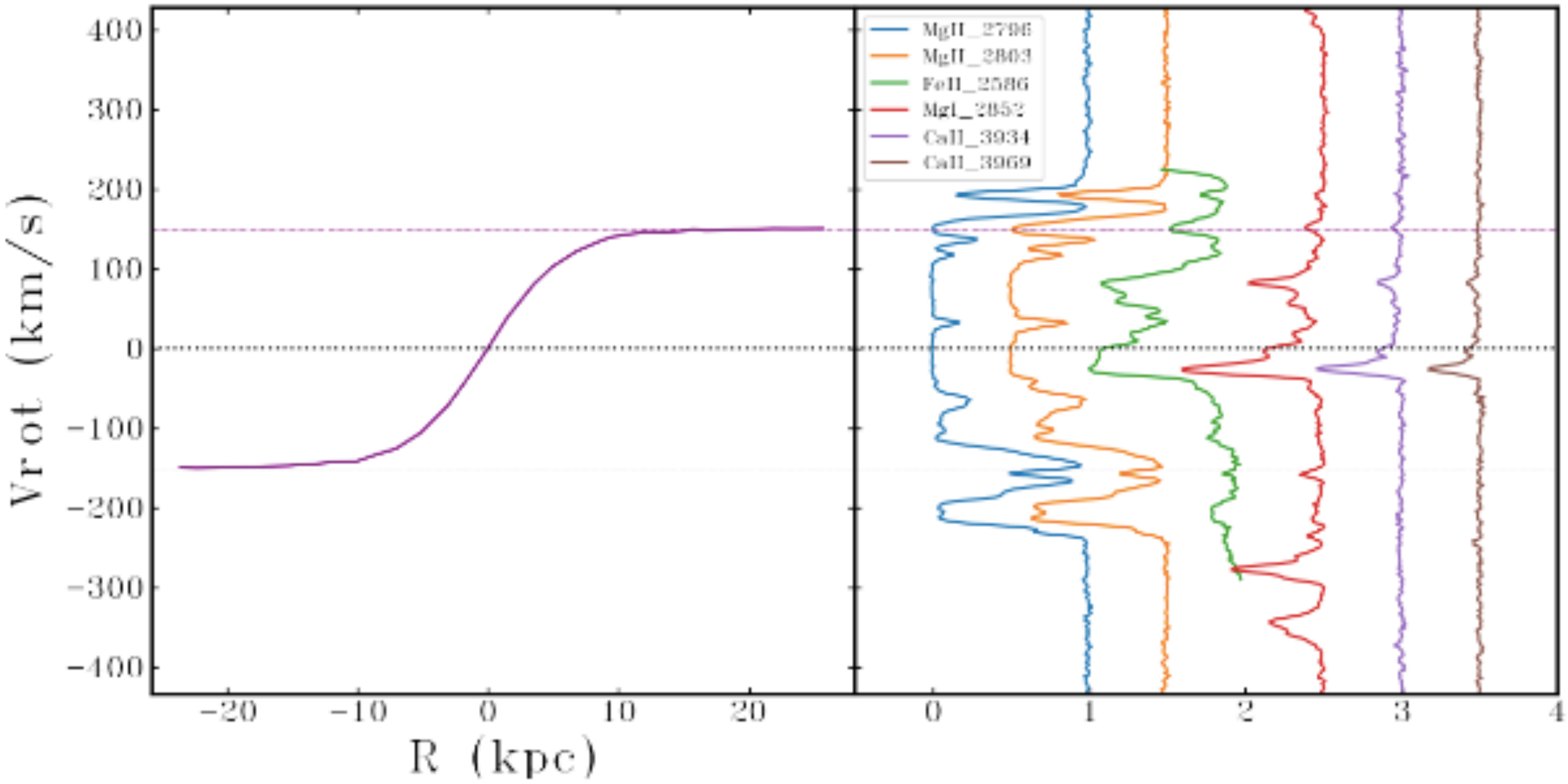
Udhwani et al. in prep

The absorber is nearly co-planar with the projected major axis of the galaxy

Ultra-Strong Mg II at z ~1.13 tracing gas accretion from the CGM?

Udhwani et al. in prep





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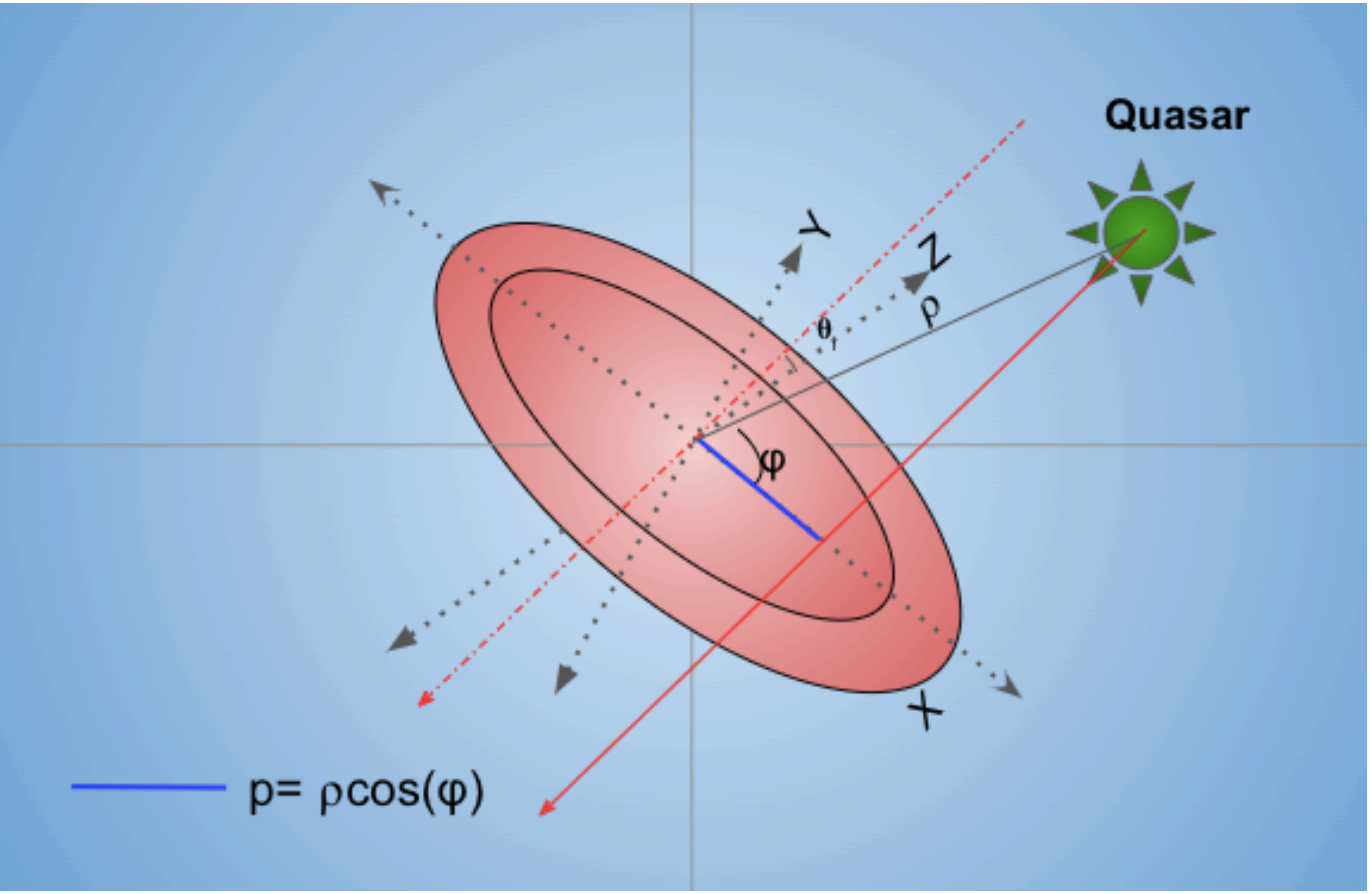
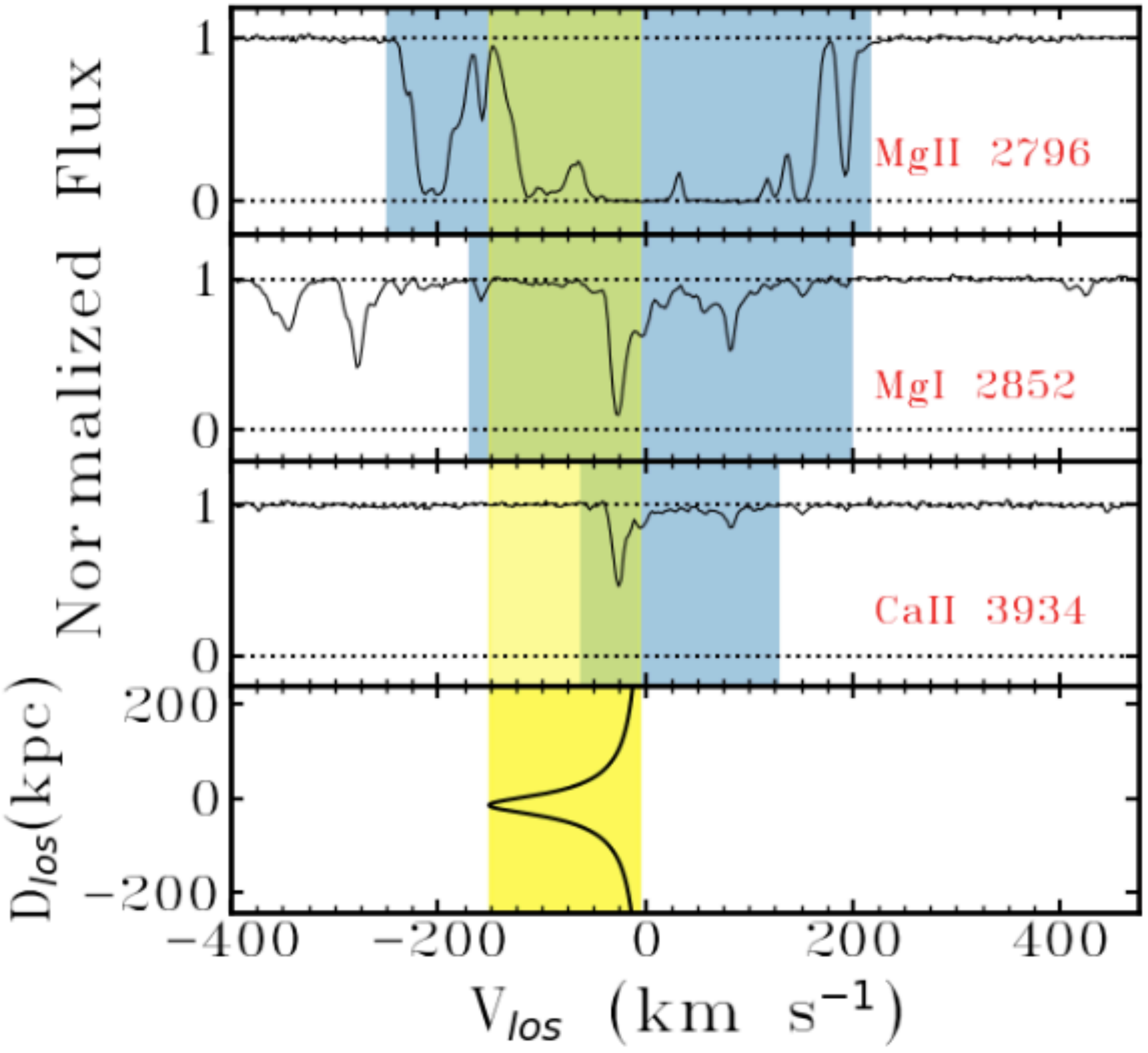




Even very large disk thickness of 100 kpc does not reproduce the full velocity range of absorption

Extraplanar gas with random velocities have to be contributing to the absorption

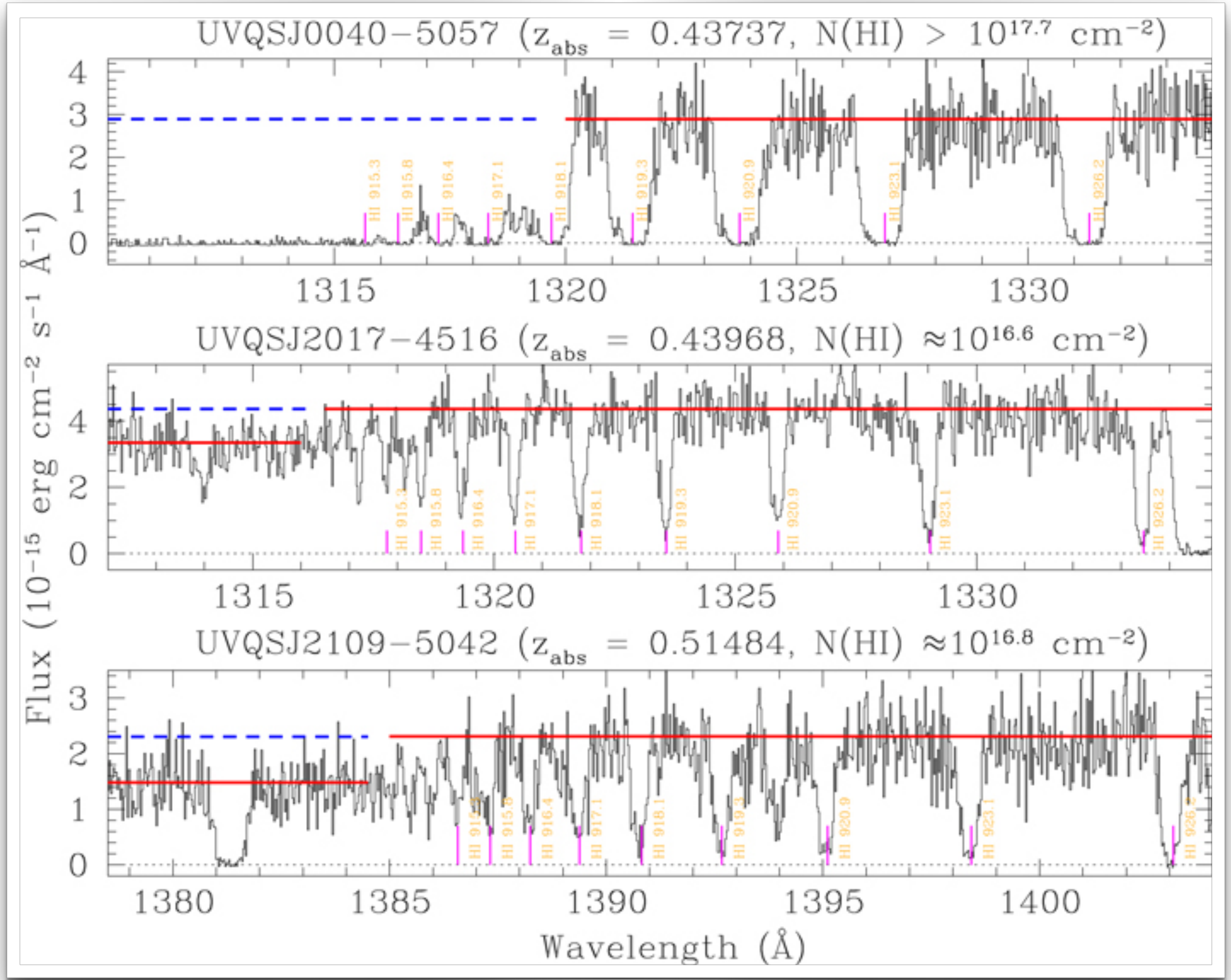
Possibly metal enriched CGM getting accreted : co-rotating + infalling

Metals in Circum-Cluster Medium at z ~ 0.4

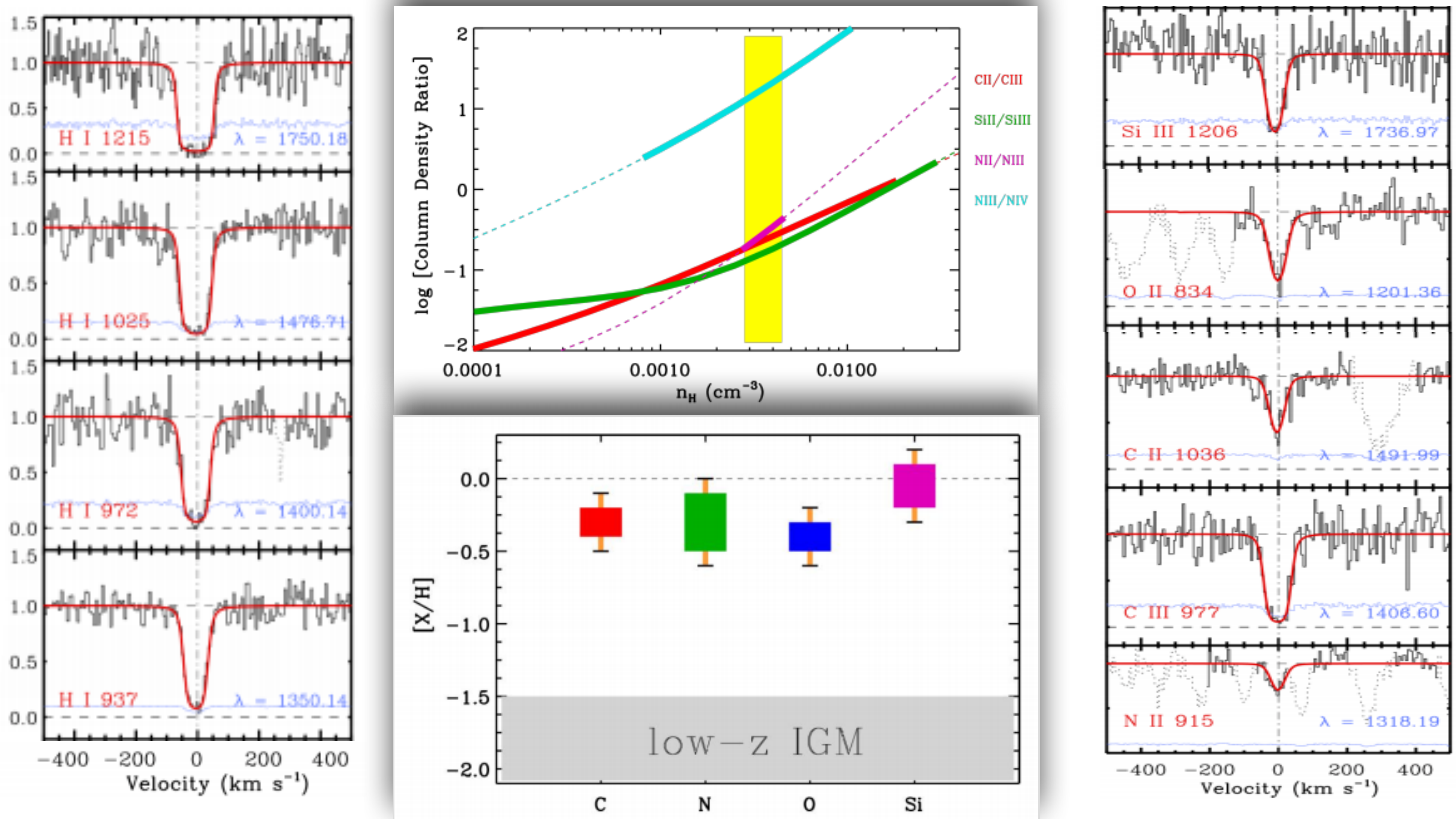
Cluster	z_{cl}	M_{500} (10^{14} $M_\odot$)	r_{500} Mpc	QSO	z_{QSO} Mpc	ρ_{cl}/r_{500}	z_{abs}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
J0041-5107	0.45± 0.04	3.04 ± 0.87	0.87	J0040-5057	0.608	4.4	0.43737
J2016-4517	0.45 ± 0.03	3.19 ± 0.89	0.89	J2017-4516	0.692	4.7	0.43968
J2109-5040	0.47 ± 0.04	3.81 ± 0.87	0.93	J2109-5042	1.262	1.6	0.51484

Table 1. Information about the QSO-cluster pairs. Cluster names (1), photometric redshifts (2), and masses (3) are from Bleem *et al.* (2015). QSO names (5) and redshifts (6) are from Monroe *et al.* (2016). The r_{500} values (4), normalized clustocentric impact parameters of the QSO sightlines (7) and absorber redshifts (8) are from Muzahid *et al.* (2018).

Muzahid et al. 2017
Pradeep et al. 2019



Muzahid et al. 2017



H I 1215
λ = 1750.18
H I 1025
λ = 1476.71
H I 972
λ = 1400.14
H I 937
λ = 1350.14
Velocity (km s⁻¹)
log [Column Density Ratio]
n_H (cm⁻³)
CII/CIII
SiII/SiIII
NII/NIII
NIII/NIV
[X/H]
low−z IGM
C
N
O
Si
Si III 1206
λ = 1736.97
O II 834
λ = 1201.36
C II 1036
λ = 1491.99
C III 977
λ = 1406.60
N II 915
λ = 1318.19
Velocity (km s⁻¹)

QSO	z_{abs}	log N(HI)	n_H (cm^{-3})	log N_H	p/k ($K\,cm^{-3}$)	T (K)	L (kpc)	[C/H]
UVQS J0040-5057	0.43737	18.63 ± 0.07	$\gtrsim 5 \times 10^{-4}$	$\lesssim 20.9$	$\gtrsim 8.6$	$\lesssim 1.7 \times 10^4$	$\lesssim 492.8$	≥ -0.9
UVQS J2017-4516	0.43968	16.55 ± 0.02	$\sim 3 \times 10^{-3}$	~ 18.8	~ 43.7	$\sim 1.5 \times 10^4$	~ 0.9	−0.35 ± 0.10
UVQS J2109-5042	0.51484	16.72 ± 0.05	$\sim (0.9 - 3.9) \times 10^{-3}$	~ [19.0, 19.7]	~ [18.0, 60.9]	$\sim 1.7 \times 10^4$	~ [0.9,18.4]	[-1.0,-0.6]

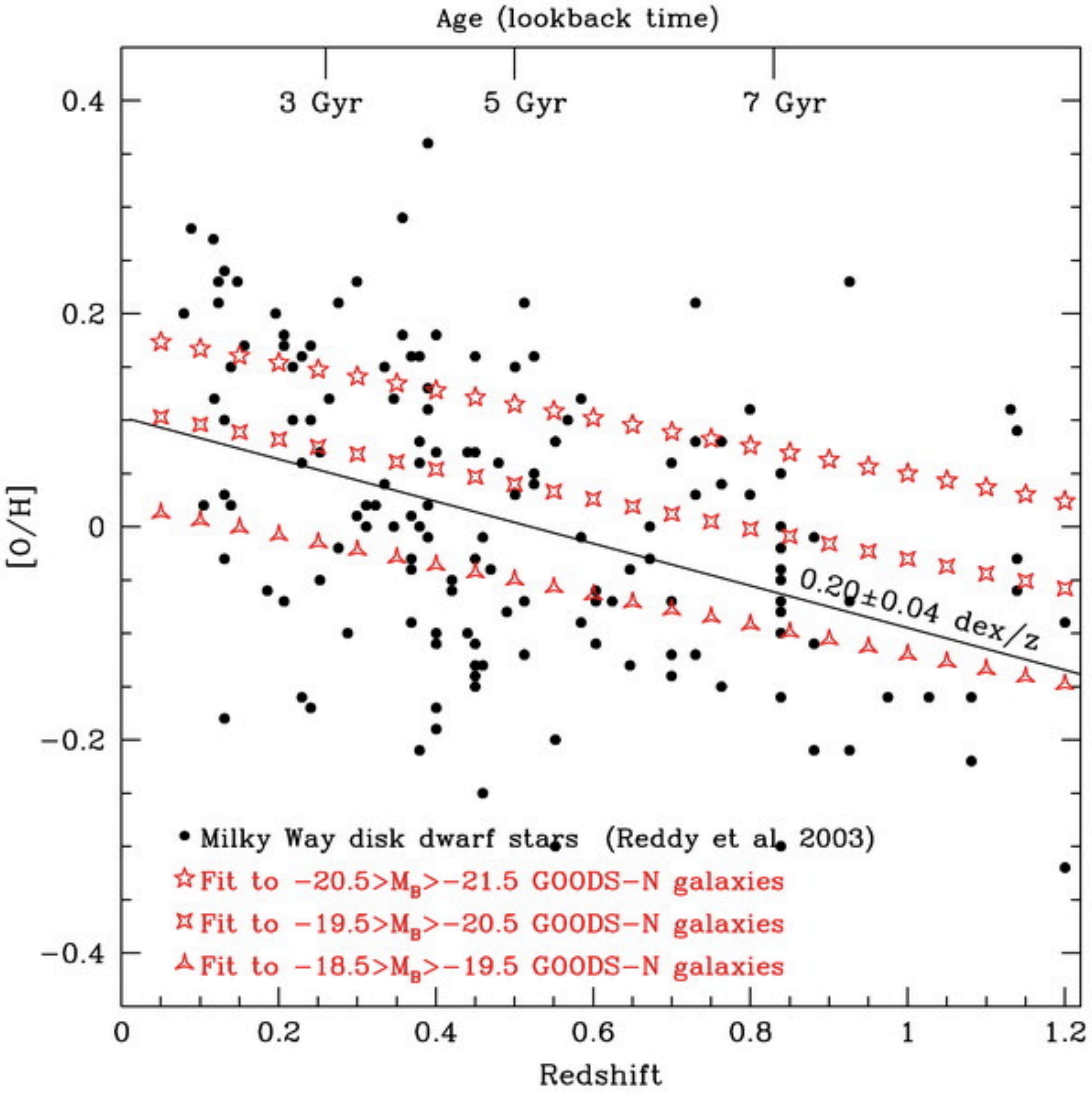
High HI column densities in clusters

100 times more baryons

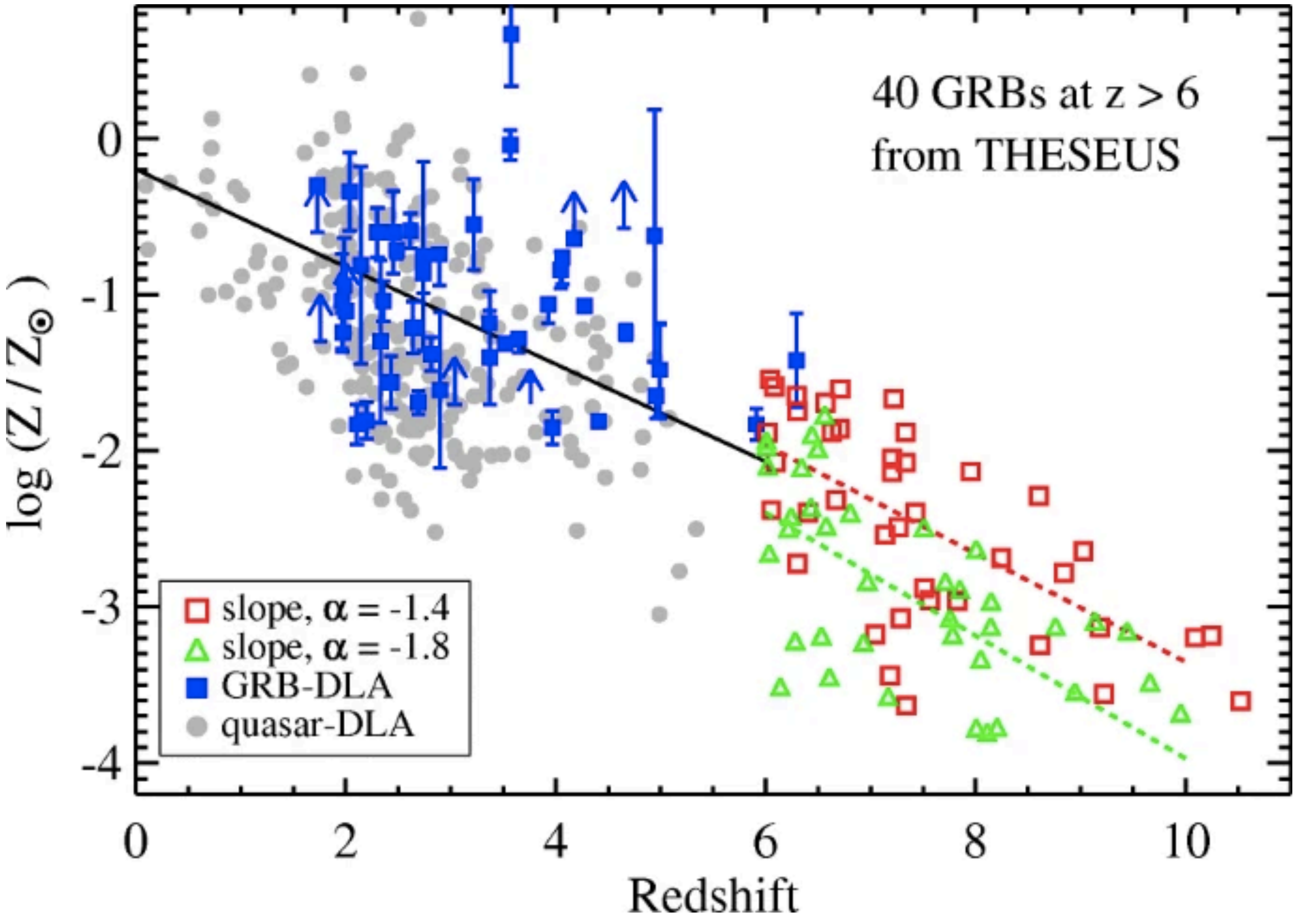
ICM enriched by feedback from star formation, AGN activity and/or ram pressure or tidal stripping

Pradeep et al. 2019

Slow build up of metals



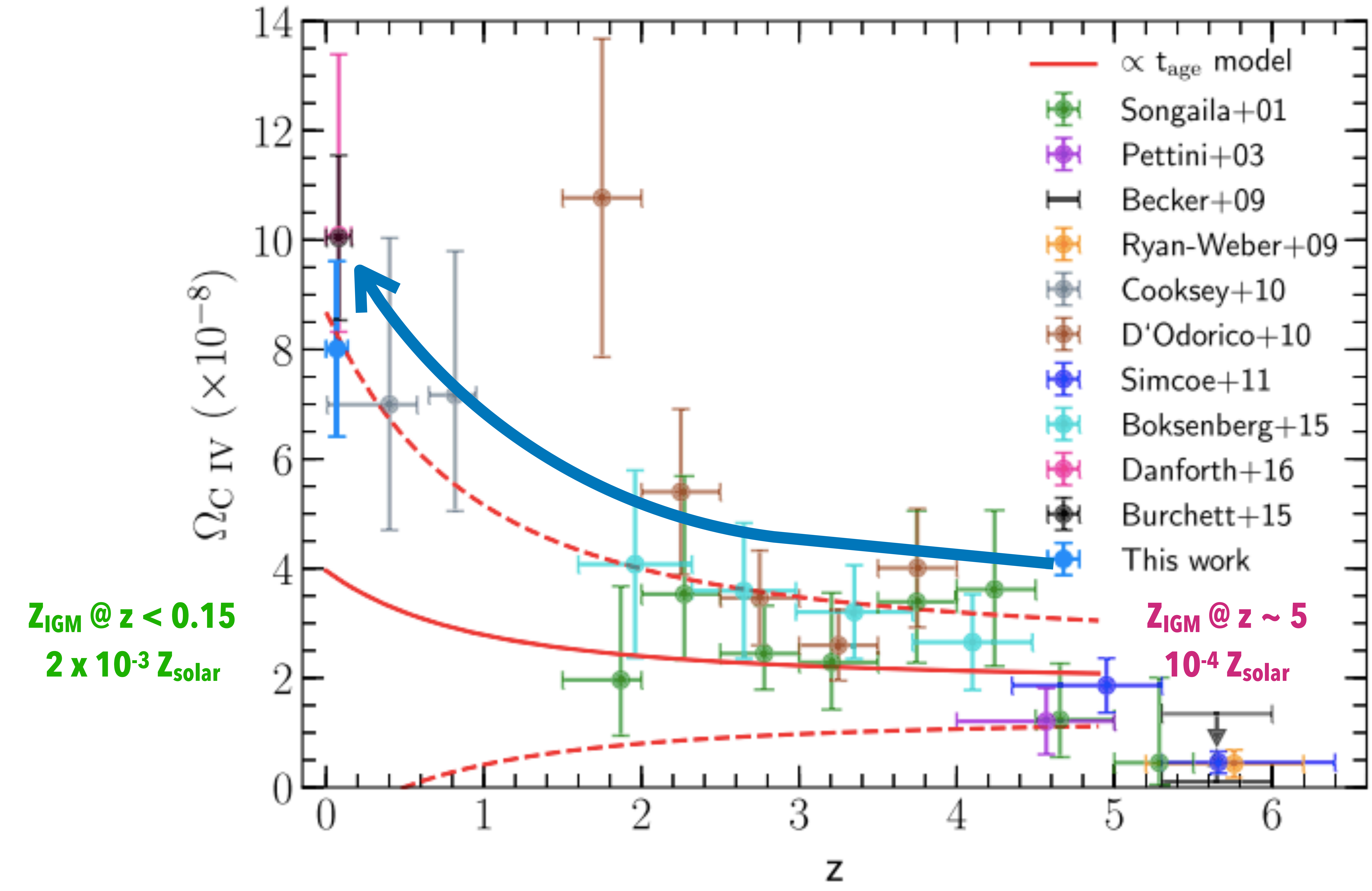
Kobulnicky & Kewley 2004



Tanvir et al. 2021

COS Legacy Survey of C IV

Manuwal et al. (2021)



Mass density of baryons in metals in the CGM / IGM environment show a gradual increase in the last 12 Gyrs

Feedback from SNe and AGN