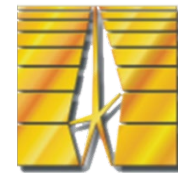




The work is supported by RSF
grant 23-12-00166



The view on quasar nearby environment through the proximate absorption systems

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N. Gupta³, J.-K. Krogager⁴,
F. Combes⁵, S. Lopez⁶, P. Petitjean²,
A. Omont², R. Srianand³, F. Urbina⁶, ...

¹Ioffe Institute, Saint-Petersburg

²Institute d'Astrophysique de Paris, France

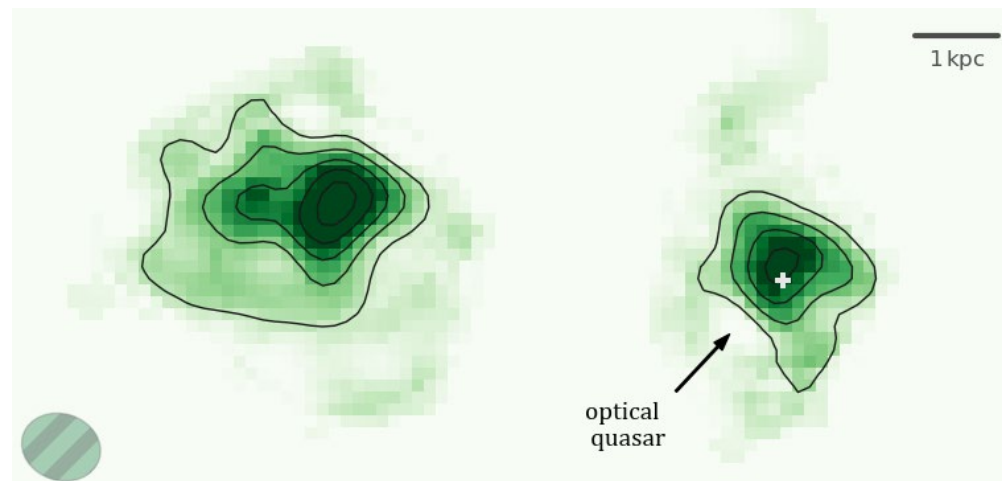
³IUCAA, Pune, India

⁴Universite Lyon I, France

⁵Observatoire de Paris, France

⁶ Universidad de Chile, Chile

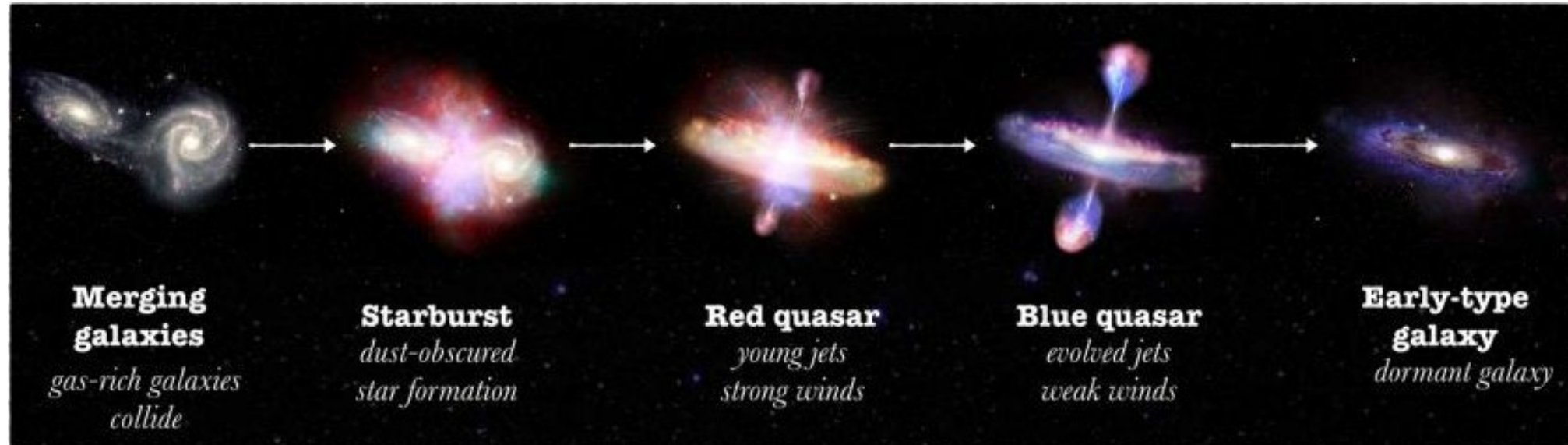
Glazar



16 October 2024

Introduction. Quasars

Quasars are active galactic nuclei at high redshifts. They likely play an important role in galaxy evolution



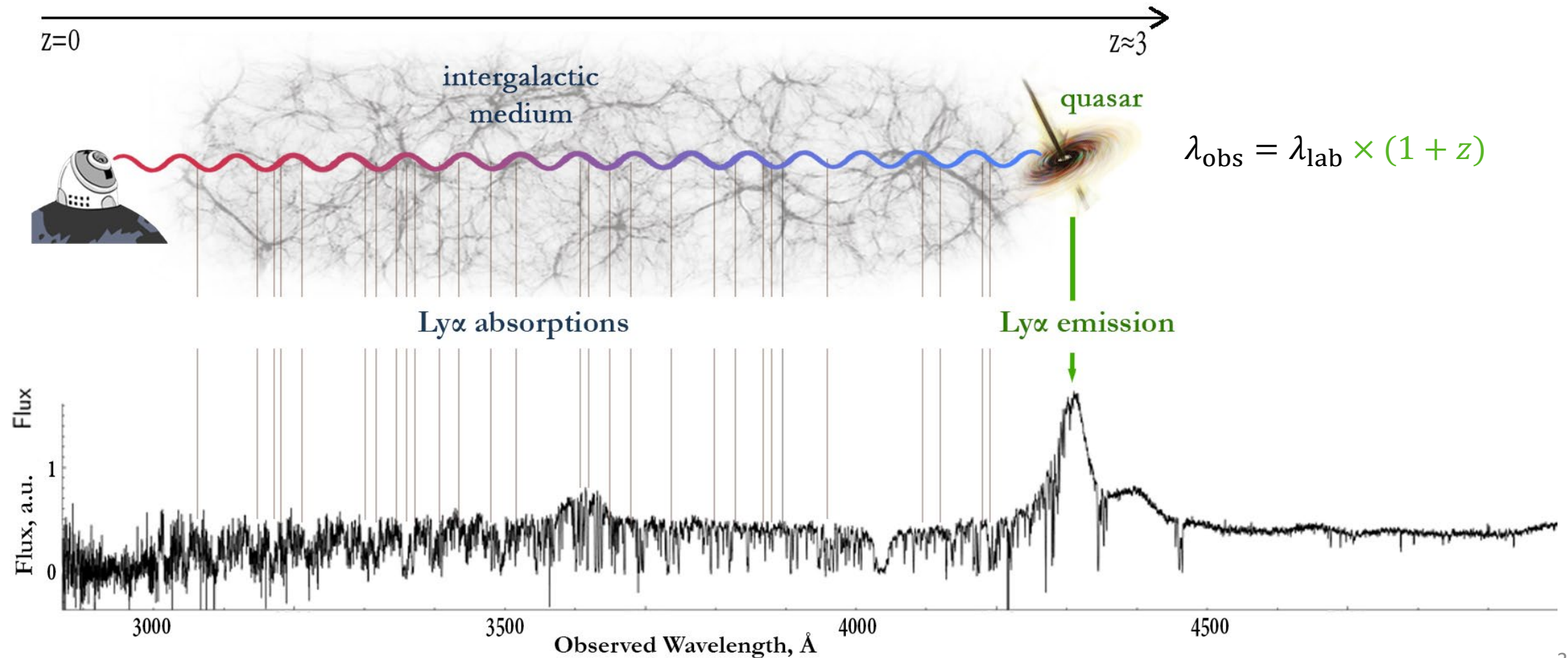
Hypotetical co-evolution path of quasars and galaxies

It is known two types of quasar: obscured – **red (type II)** and unobscured – **blue (type I)**.

The transition **type II** → **type I** is thought to be associated with strong AGN outflows that likely impact of the gas supply, stellar population in the host galaxy (Pontzen+2017) and change in morphology (Dubois+ 2016)

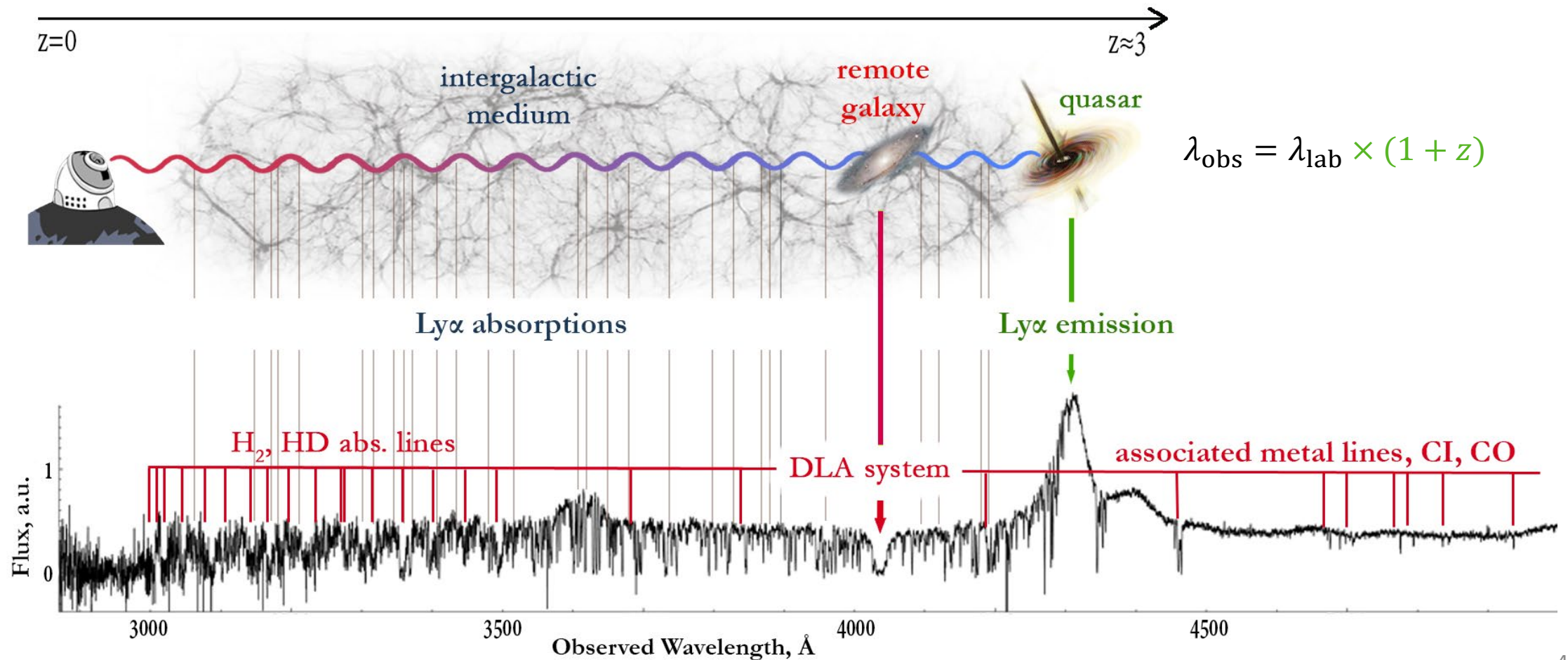
Introduction. Quasar spectroscopy

The absorption lines identified in quasar spectra are the powerful tool to study intergalactic and interstellar medium in the Universe.
Especially at redshifts $\gtrsim 2$, when we can obtain the spectrum at ground optical telescopes...



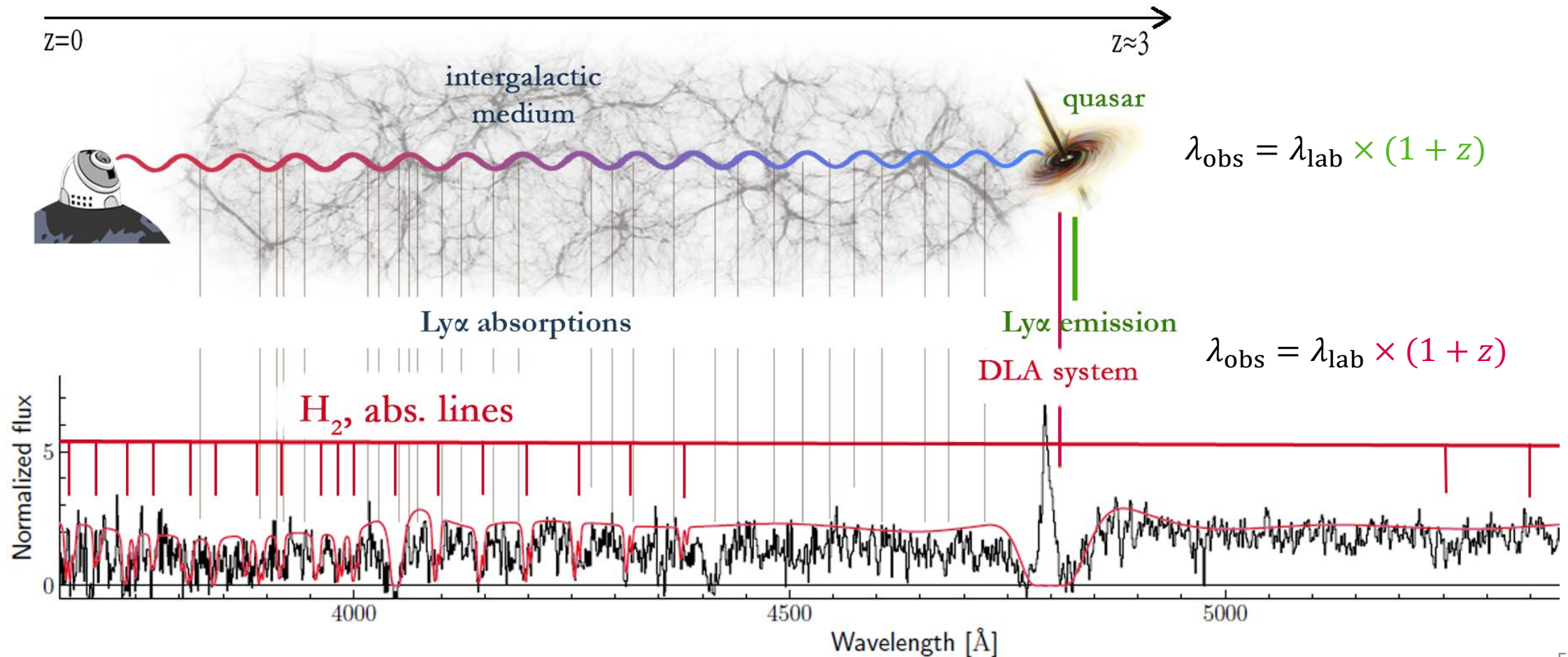
Introduction. Quasar spectroscopy

The absorption lines identified in quasar spectra are the powerful tool to study intergalactic and **interstellar medium** in the Universe.
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Introduction. Proximate absorption systems

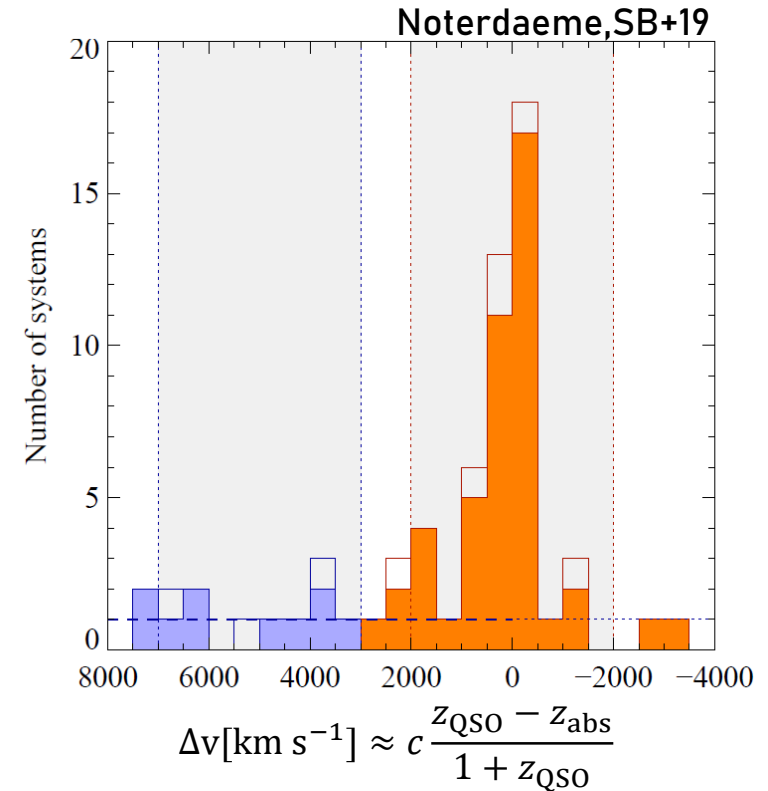
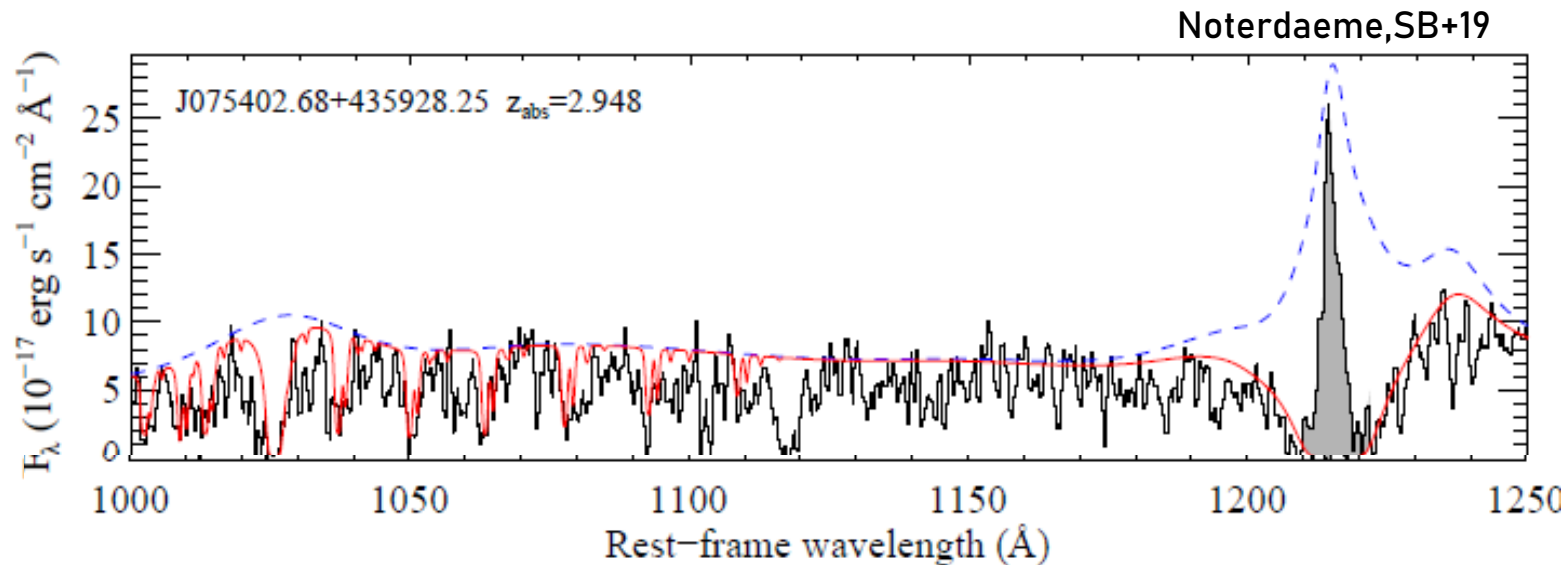
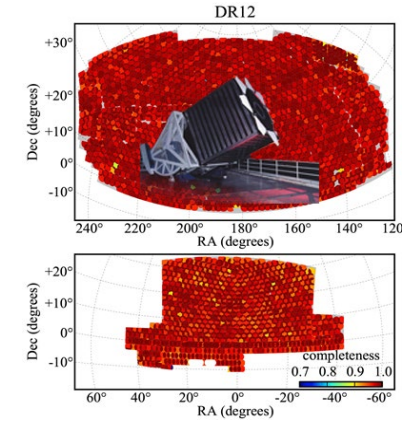
The gas around the quasar may manifest itself as an **proximate absorption systems** with similar redshift. The peculiar motions do not allow us to easily infer the distance between AGN and gas.



Introduction. Proximate H₂ absorption system

Using SDSS we found a population ($\gtrsim 100$) of H₂-bearing proximate DLAs with $z > 2.5$:

- Incidence rate of H₂ >5 times higher in comparison with intervening ones
- In ~ 50 % systems we detect extended Ly α emission seen as a narrow emission in the core of Ly α damped absorption



Proximate H₂. Follow-up studies

VLT/X-shooter (2018-2022)	→	11 objects (32 hrs)	}	Noterdaeme,SB+2021ab,2023; Urbina+2024 In prep: Balashev+, Cuellar+,
NOEMA (2020-2021)	→	10 objects (80 hrs)		
ALMA (2022)	→	4 objects (16 hrs)		
VLT/MUSE (2023)	→	1 object (3 hrs)		
MEGARA/GTC (2024)	→	1 object (3 hrs, planned)		

Quasar	Z	Xshooter	Extended	NOEMA	CO 3-2	ALMA	comment
J0015 + 1842	2.63	+	Y. red	+	Y	-	Noterdaeme, SB+2021
J0019 – 0137	2.53	+					
J0059 + 1124	3.03	+	Y. red	+	Y	-	
J0125 – 0129	2.67	+	Y. blue	+	Y	+	Balashev+2024 submitted
J0126 + 1138	2.60			+	Y		
J0216 + 0413	2.66			+			
J0223 – 0307	2.58			+	Y		
J1242 + 2006	3.39			+			
J1236 + 0010	3.03	+					
J1248 + 0639	2.53	+					
J1259 + 0309	3.25	+	Y. blue	+	Y		Urbina+2024
J1331 + 0206	2.92	+	Y. blue	+	Y		
J1358 + 1410	2.89	+					
J2228 – 0221	2.77	+	Y. red	+	Y	-	
J2325 + 1539	2.62	+					
Total:		11	6/11	10	8/10	1/4	

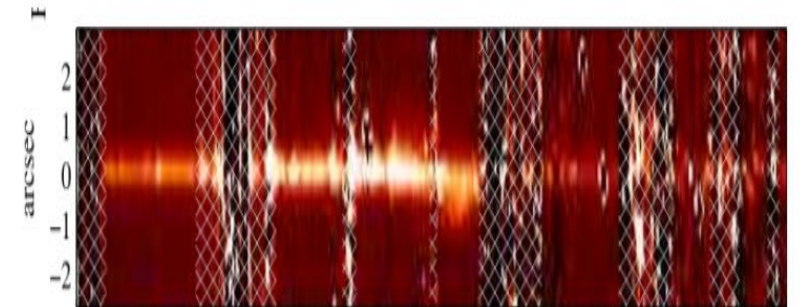
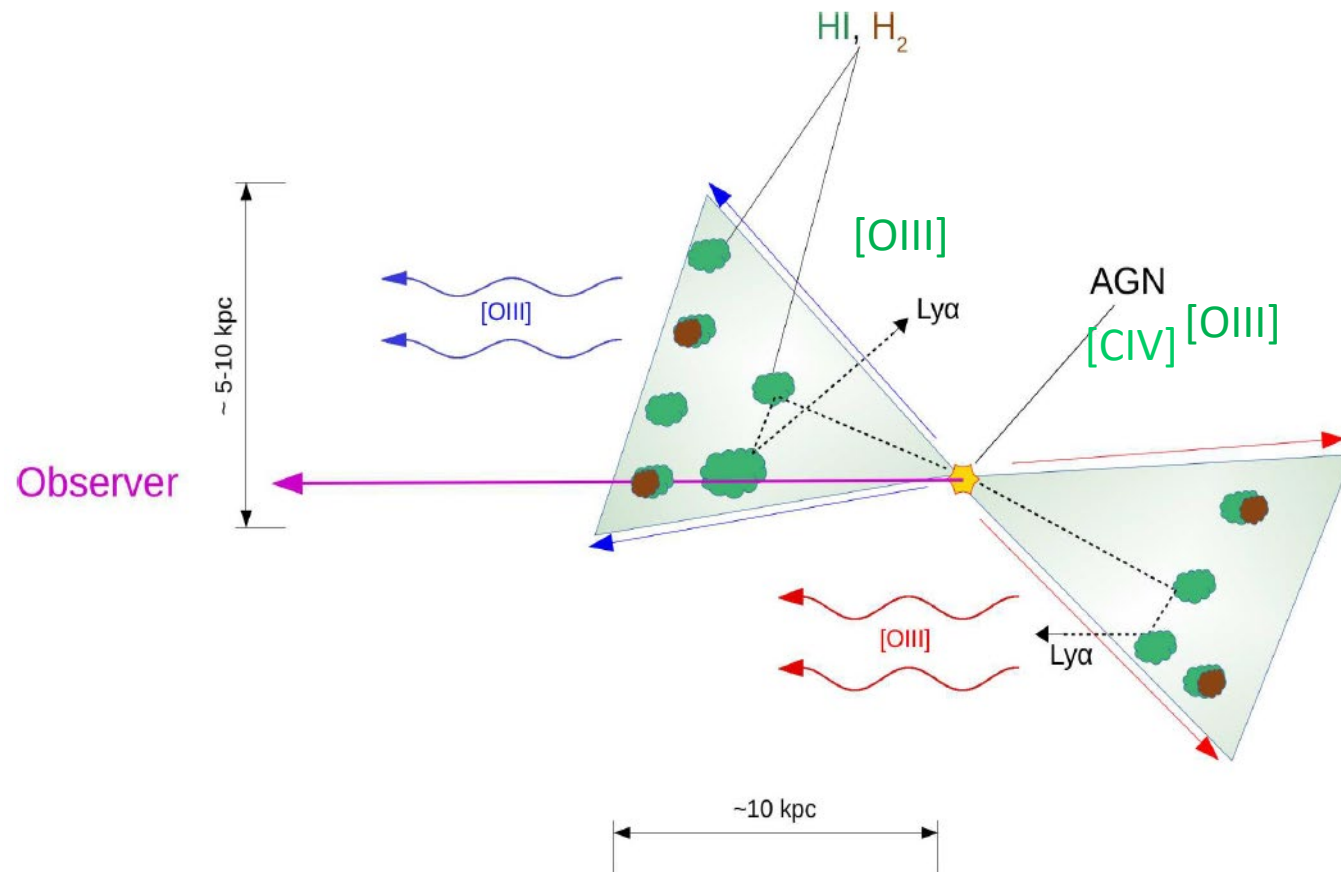
Proximate H₂. Follow-up studies

VLT/X-shooter (2018-2022)	→	11 objects (32 hrs)	}	Noterdaeme, SB+2021ab, 2023; Urbina+2024 In prep: Balashev+, Cuellar+,
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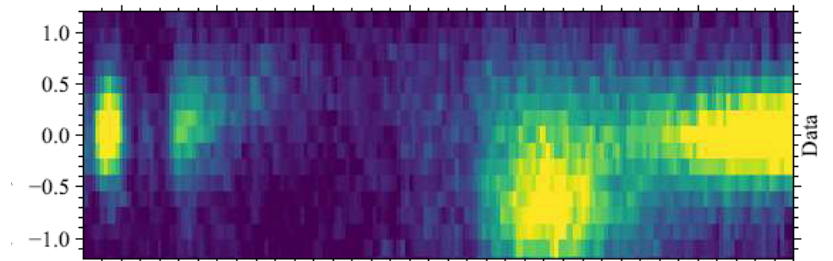
Quasar	Z	X-shooter	Extended	NOEMA	CO 3-2	ALMA	comment	
J0015 + 1842	2.63	+	Y. red	+	Y	-	Noterdaeme, SB+2021	→ Outflow
J0019 – 0137	2.53	+						
J0059 + 1124	3.03	+	Y. red	+	Y	-		
J0125 – 0129	2.67	+	Y. blue	+	Y	+	Balashev+2024 submitted	→ Major merger
J0126 + 1138	2.60			+	Y			
J0216 + 0413	2.66			+				
J0223 – 0307	2.58			+	Y			
J1242 + 2006	3.39			+				
J1236 + 0010	3.03	+						
J1248 + 0639	2.53	+						
J1259 + 0309	3.25	+	Y. blue	+	Y		Urbina+2024	→ Environment
J1331 + 0206	2.92	+	Y. blue	+	Y			
J1358 + 1410	2.89	+						
J2228 – 0221	2.77	+	Y. red	+	Y	-		
J2325 + 1539	2.62	+						
Total:		11	6/11	10	8/10	1/4		

Proximate H₂. Outflow in J0015-1842

Proximate H₂ towards J0015-1842 are produced in AGN outflow:



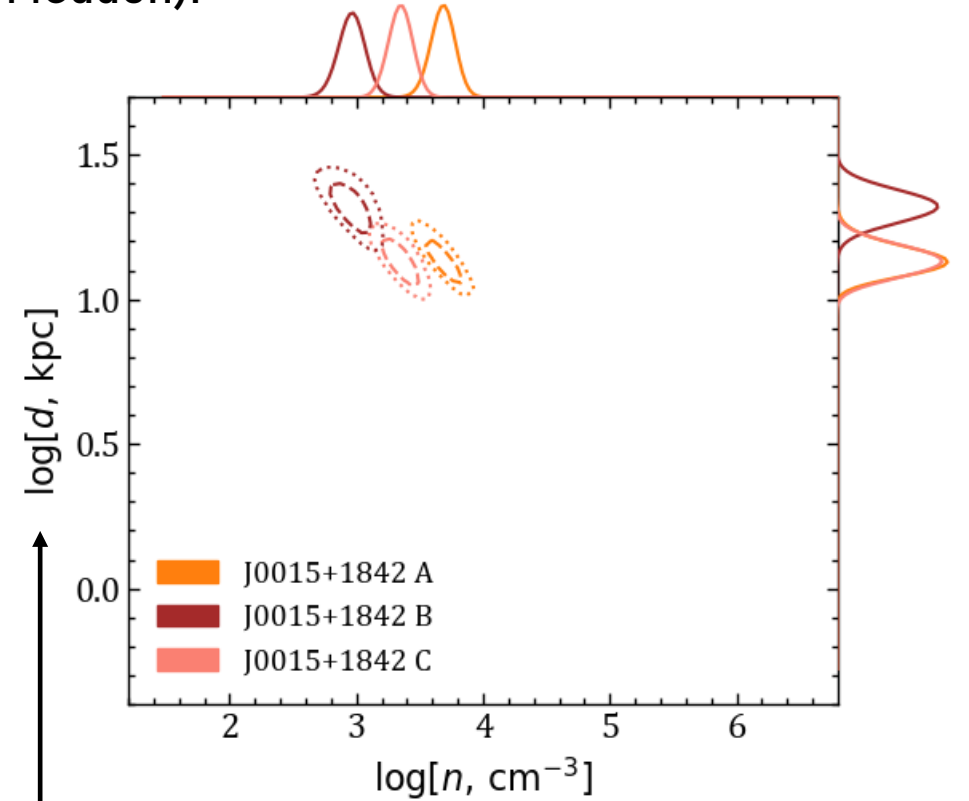
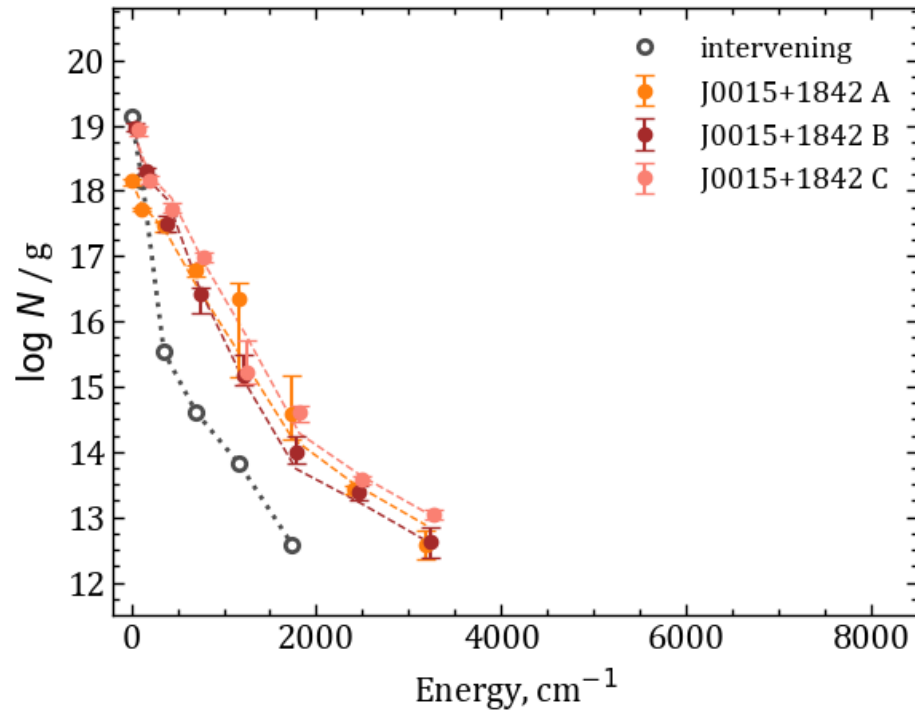
A region around [OIII]5008 line towards J0015-1842, z=2.628



A region around Ly α line towards J0015-1842, z=2.628

Proximate H₂ Outflow in J0015-1842

Modelling the observed population of H₂ rotational levels (PDR Meudon):



(UV flux is converted to the distance to AGN)

Results:

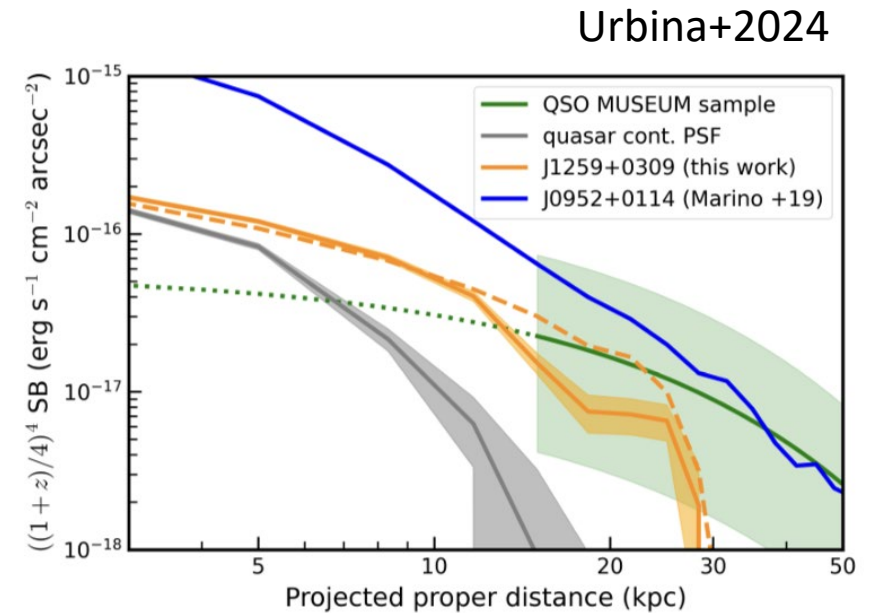
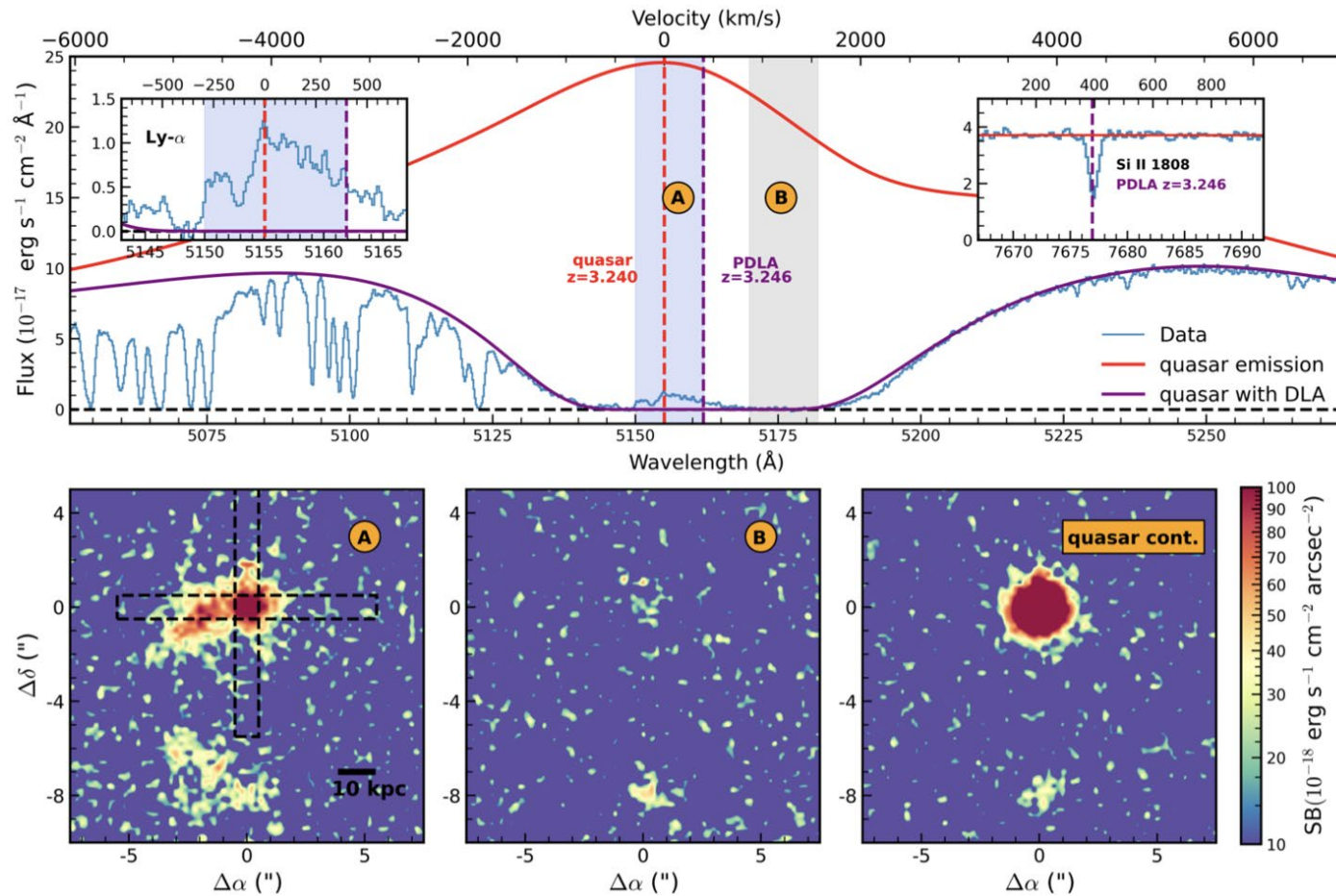
UV $\sim 10^{2-3}$ Mathis field ($\rightarrow 10 - 20$ kpc)
 $T \sim 100 - 200$ K
 $n \sim 10^{3-4} \text{ cm}^{-3}$



Typical conditions in photodissociation regions (PDR)

Proximate H₂. Extended Ly α emission in J1259+0309

Proximate DLA system is a natural coronagraph that makes a perfect PSF subtraction by blocking quasar Ly α emission (+continuum) and allow to study the extended Ly α emission in the close vicinity (< several kpc)



The profile of the surface brightness in Ly α line of J1259+0309, $z=3.24$

Proximate H₂. Major merger in J0125-0129

This quasar was found only recent:

$$z_q = 2.659$$

1. SDSS:

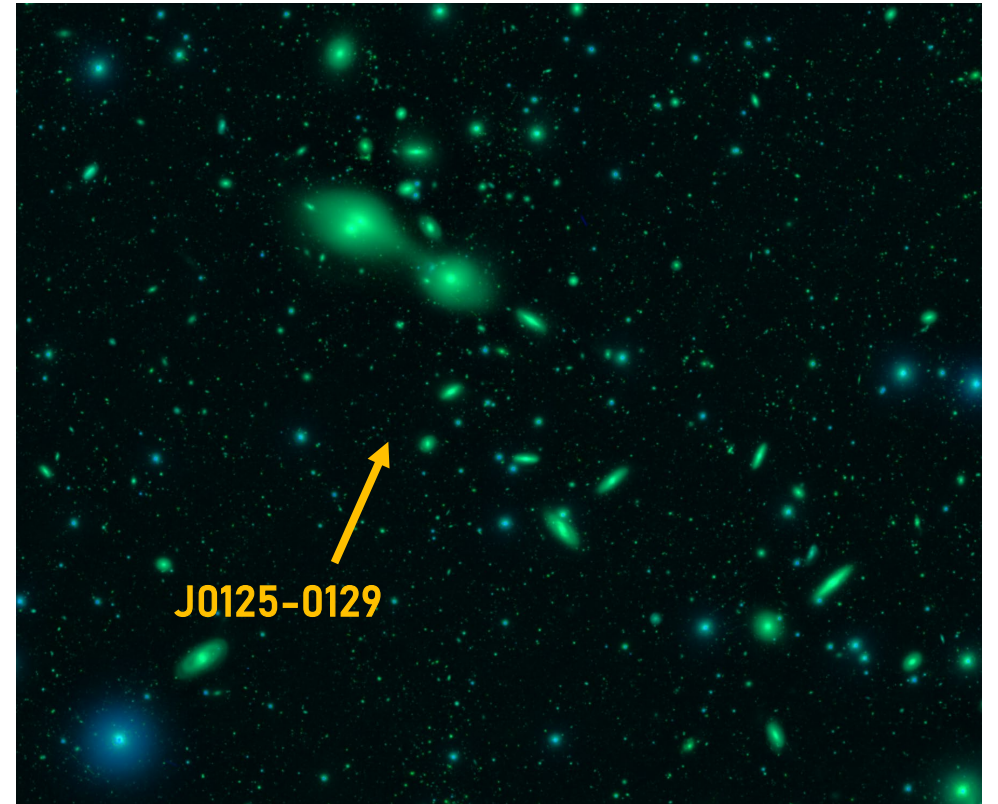
$$u=25.6, g=21.61, r=20.92, i=20.71, z=20.22$$

2. Quasar field is seen in some deep surveys:
Subaru/HSC, SCUBA2, ...

3. VLT/X-shooter: 5 hours (5 exposures)

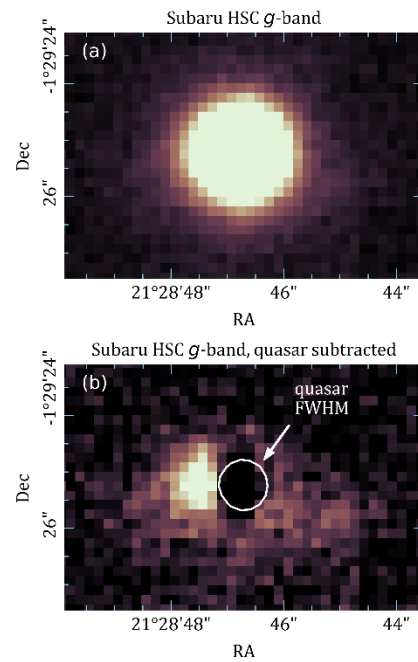
4. NOEMA: \approx 6 hours (3 mm, CO 3-2)

5. ALMA: \approx 4 hours (Band 3 и 6)



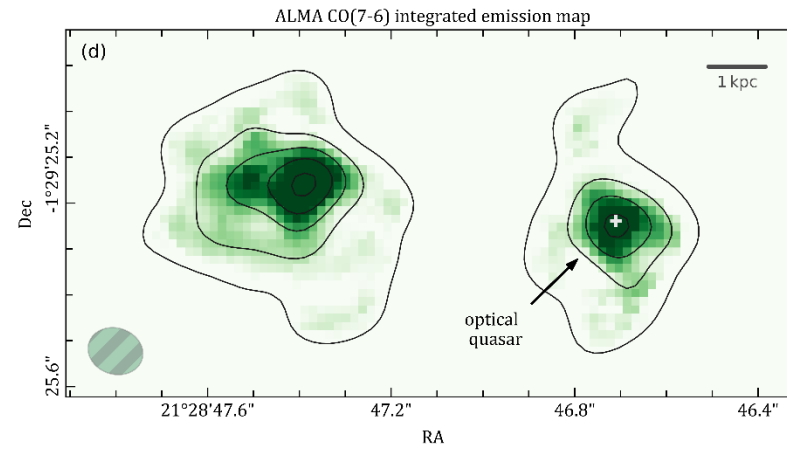
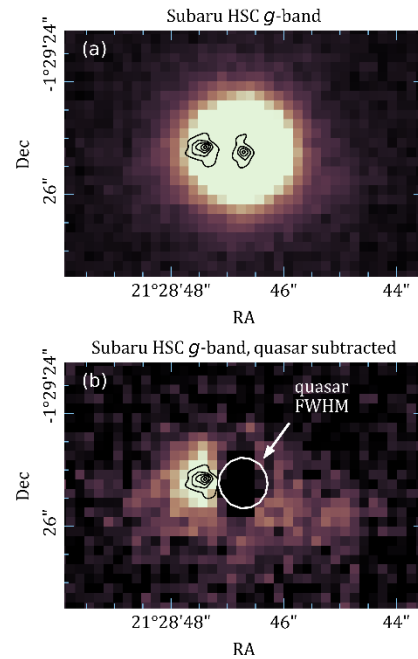
Galaxy cluster Abell 0194 ($z \approx 0.0178$)

Major merger in J0125-0129



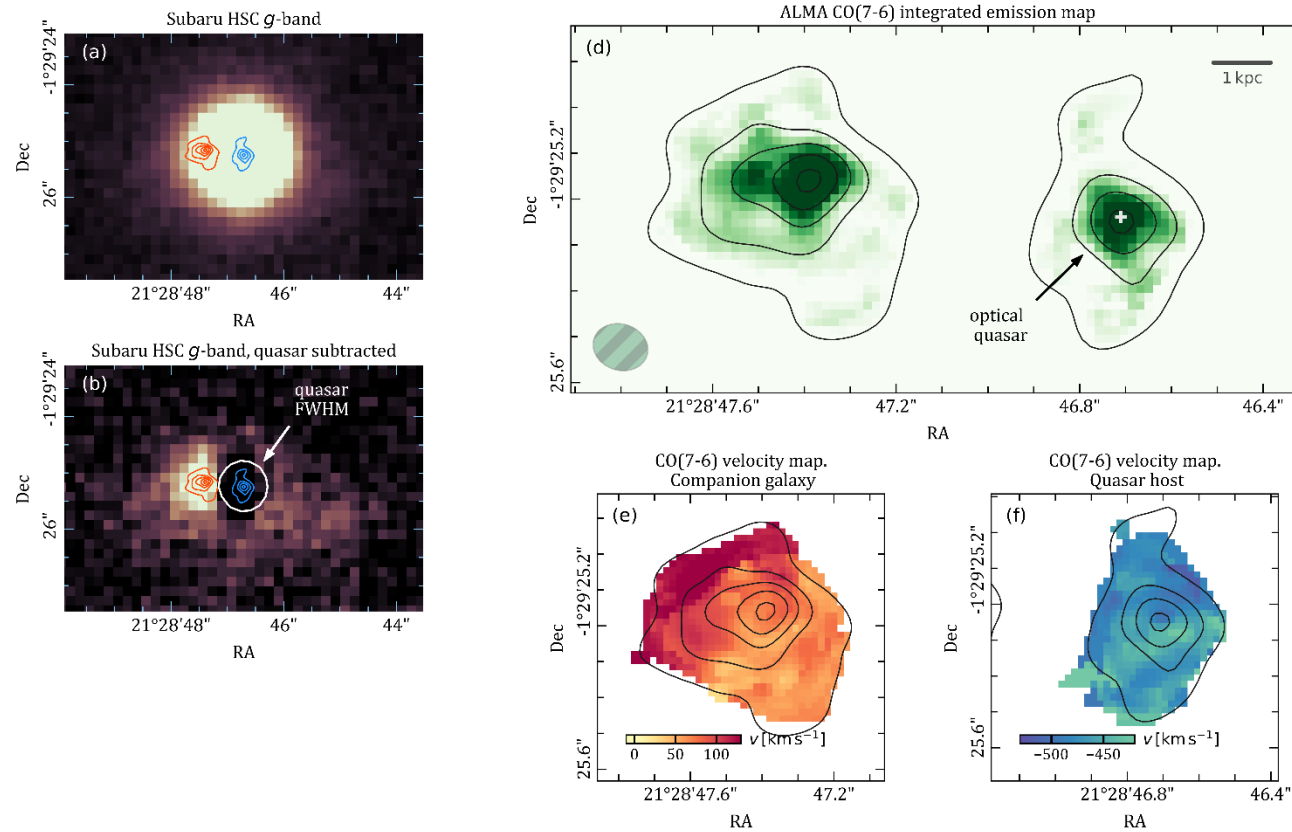
1. Optical image in Subaru HSC indicate some asymmetry.

Major merger in J0125-0129



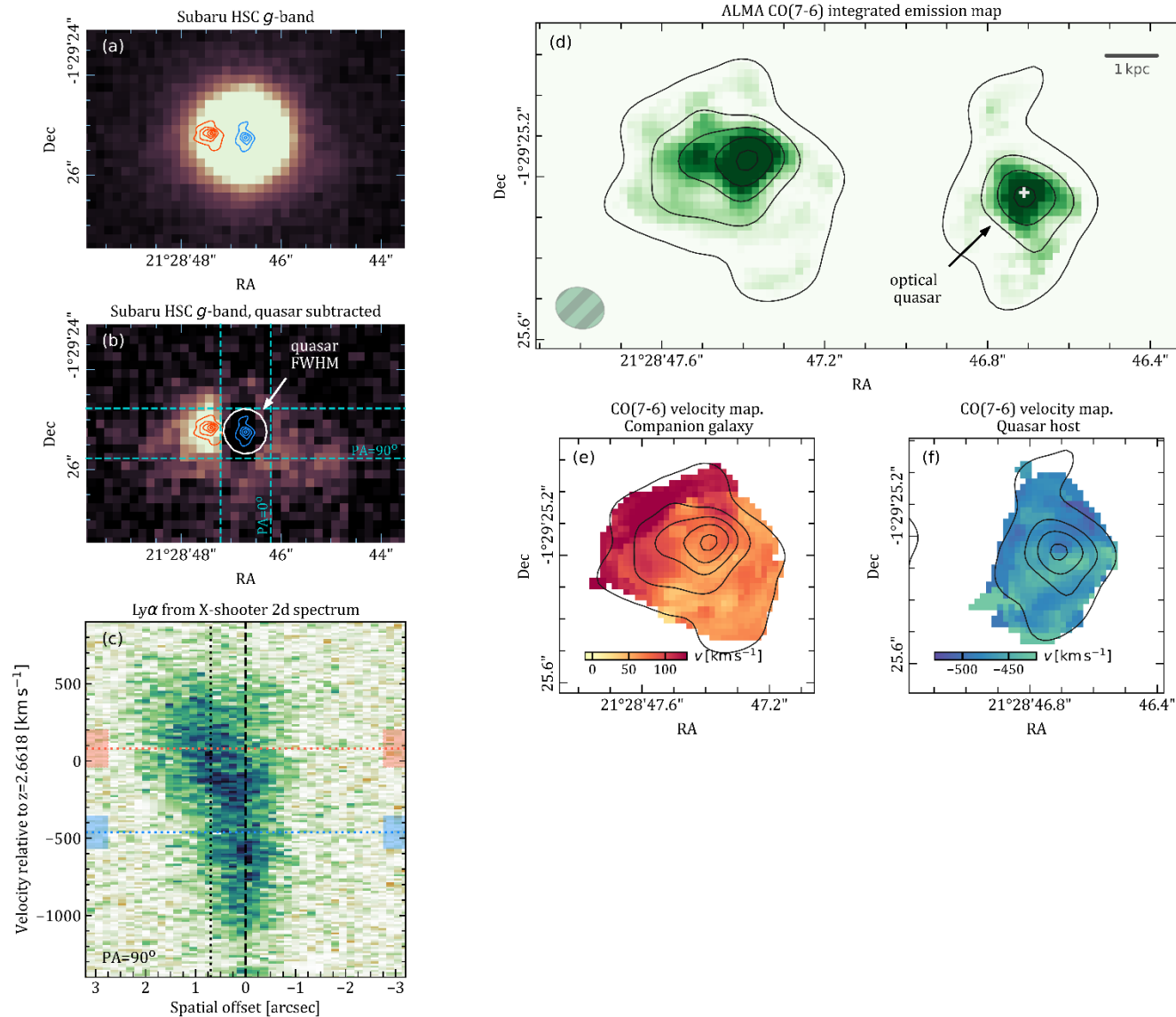
1. Optical image in Subaru HSC indicate some asymmetry.
2. We identified two sources (galaxies) in CO(7-6) line using ALMA Band 6, that coincides with optical sources

Major merger in J0125-0129



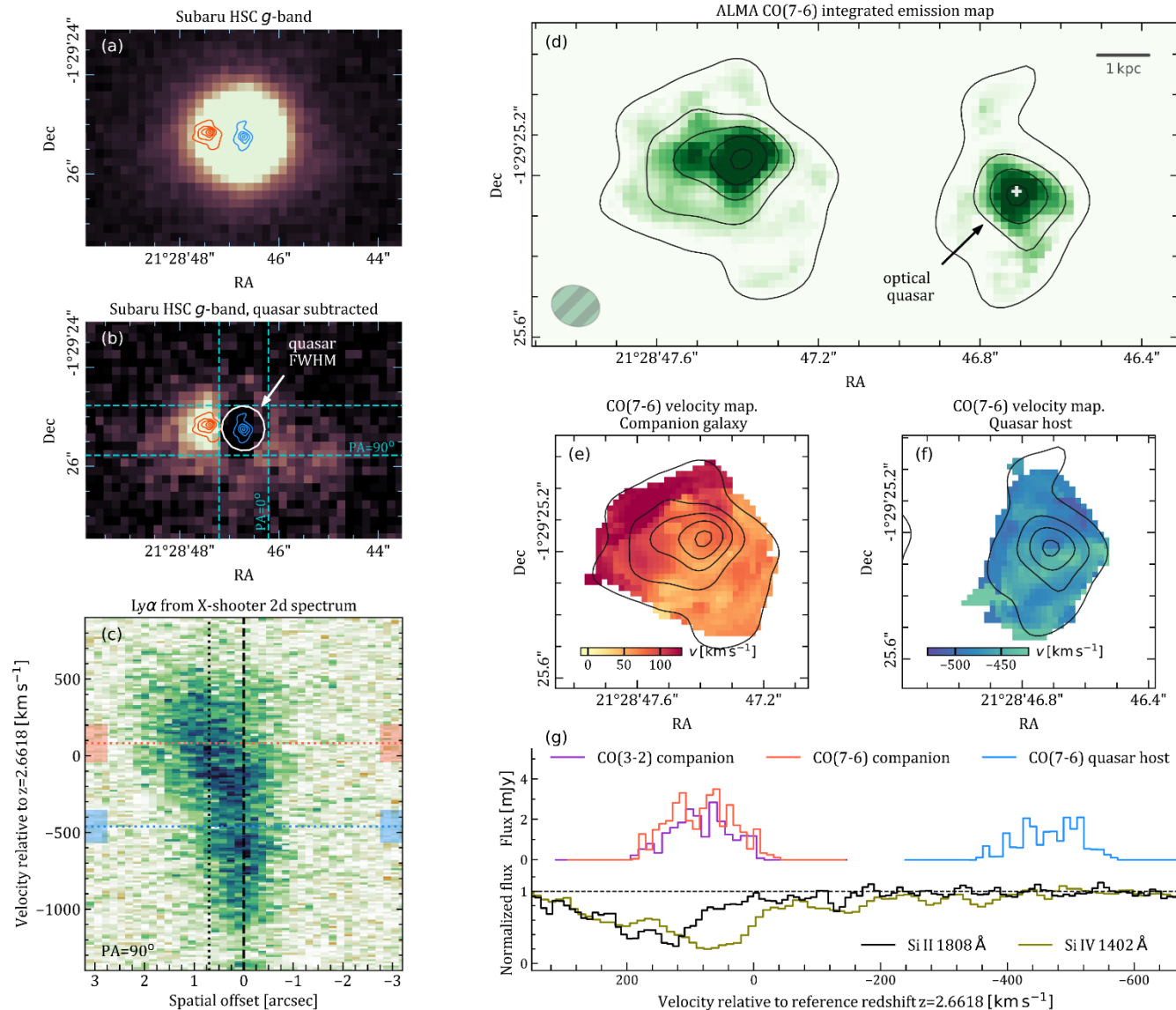
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3. The relative velocity of sources ≈ 500 km/s

Major merger in J0125-0129



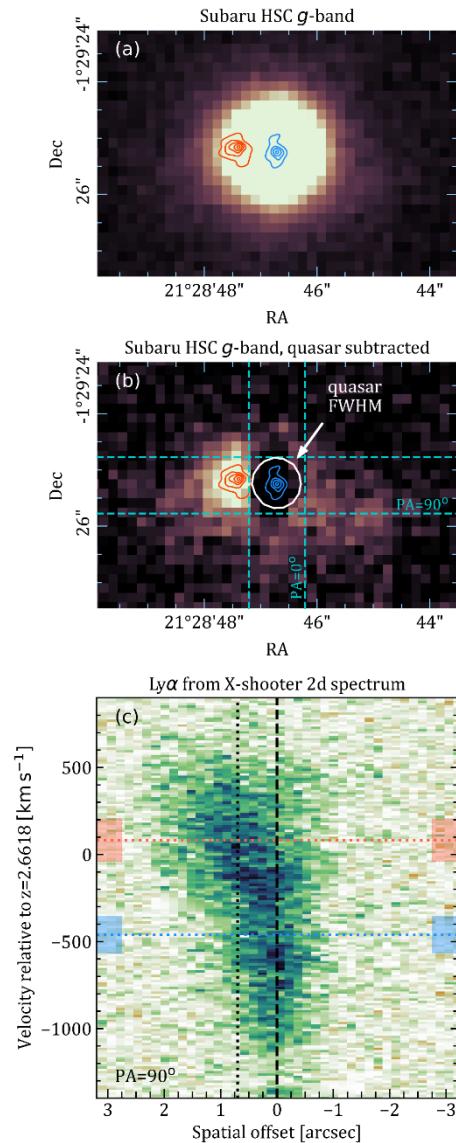
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4. In X-shooter (PA = 90°) 2d spectrum extended Ly α emission coincides kinematically and spatially with ALMA

Major merger in J0125-0129

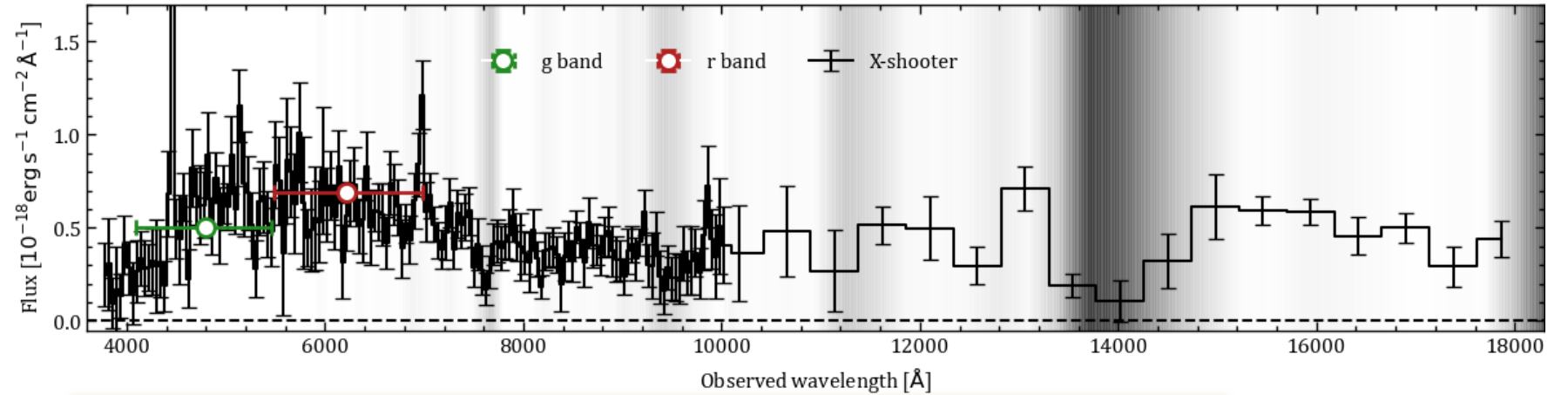


1. Optical image in Subaru HSC indicate some asymmetry.
2. We identified two sources (galaxies) in CO(7-6) line using ALMA Band 6, that coincides with optical sources
3. The relative velocity of sources $\approx 500 \text{ km/s}$
4. In X-shooter ($\text{PA} = 90^{\circ}$) 2d spectrum extended $\text{Ly}\alpha$ emission coincides kinematically and spatially with ALMA
5. Strong H_2 -bearing proximate DLA is at the velocity of companion source.

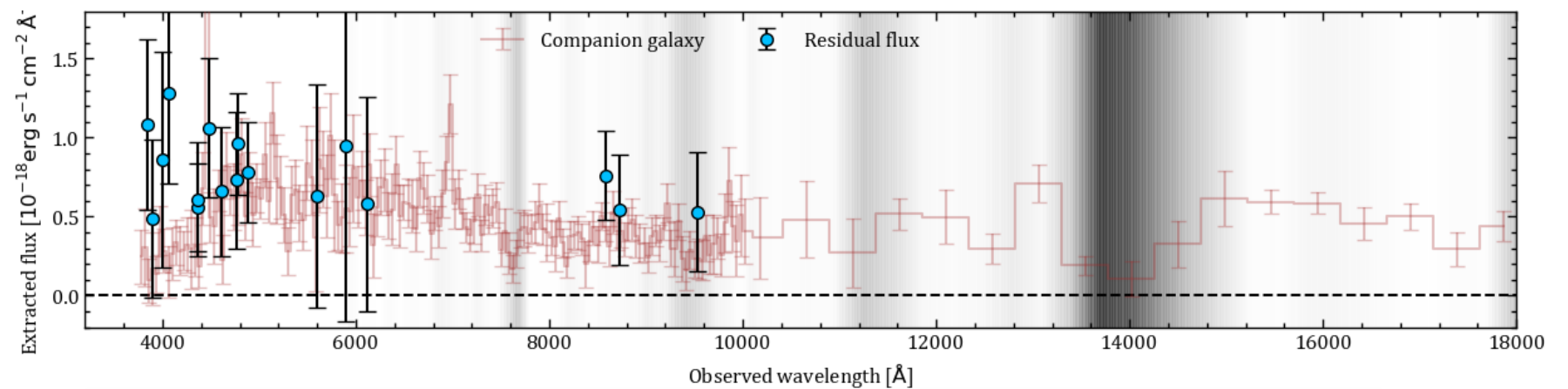
Major merger in J0125-0129. Companion galaxy spectrum



We extracted companion and host galaxy spectra using X-shooter spectrum:

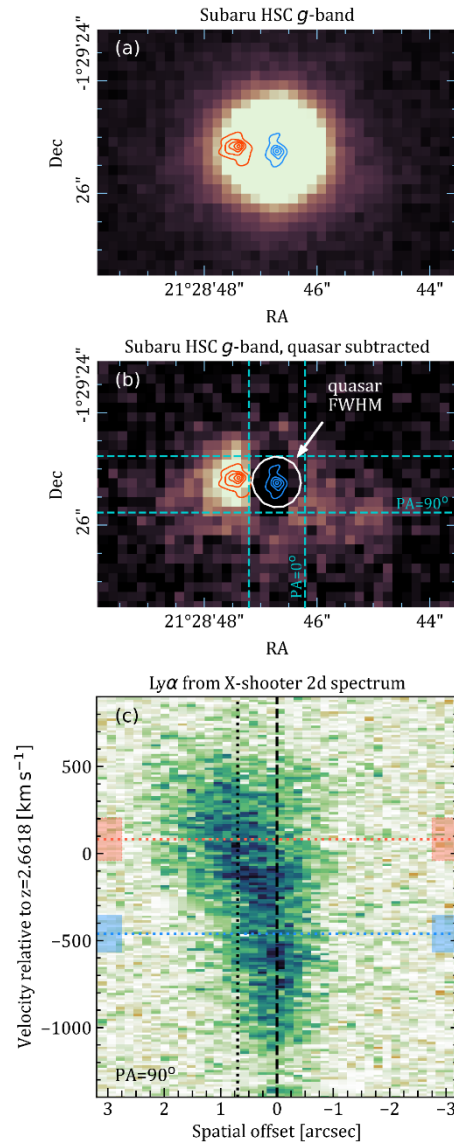


Companion galaxy spectra, extracted from 2d X-shooter spectrum

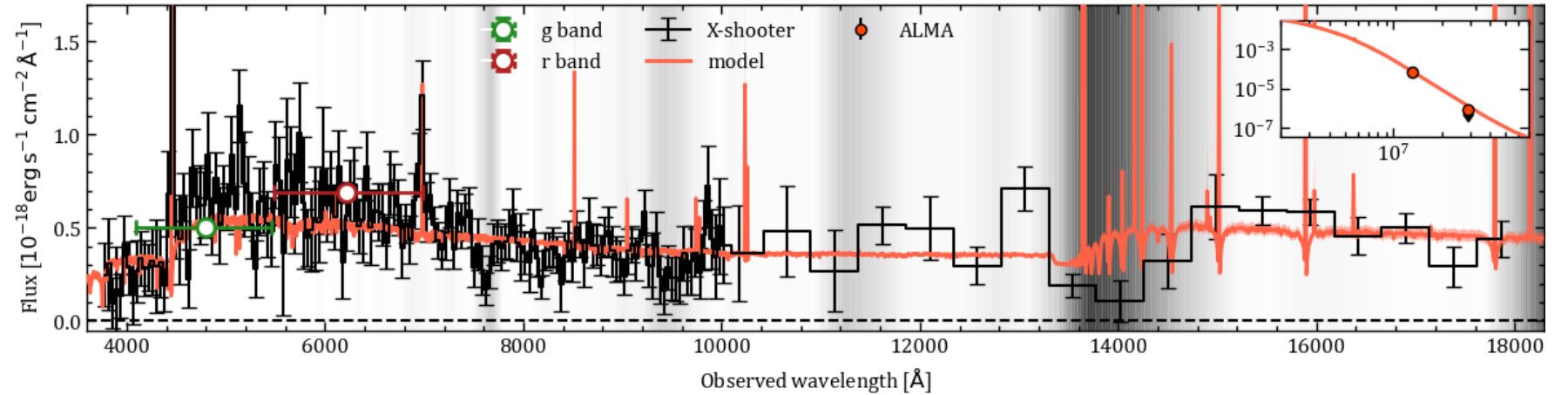


The flux of the host galaxy spectra, extracted using 1d X-shooter spectrum

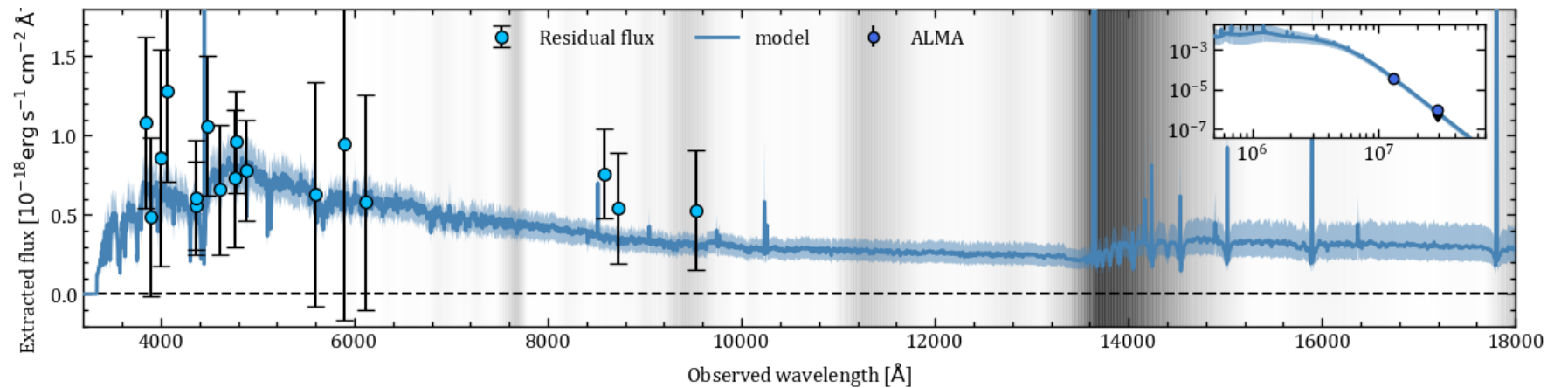
Major merger in J0125-0129. Companion galaxy spectrum



We performed SED fitting of the galaxy spectra using bagpipes code (Carnall+2018):



Companion galaxy spectra, extracted from 2d X-shooter spectrum

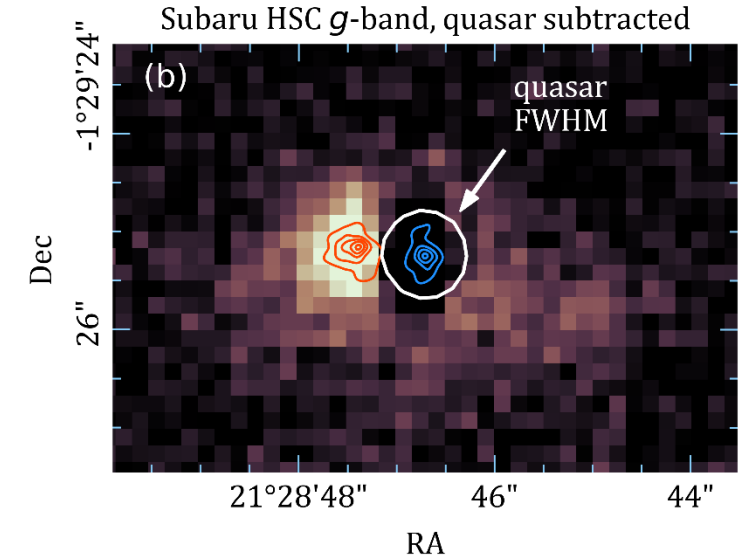


The flux of the host galaxy spectra, extracted using 1d X-shooter spectrum

Major merger in J0125-0129. Properties of the galaxies

Table 1 Main properties of two merging galaxies. For derivation of SMBH, M_{SMBH} , stellar, M_* , molecular, M_{H_2} , and dust, M_{dust} mass see Sections 2.2.5 and 2.2.6.

Quantity	Companion galaxy	Quasar host
redshift	2.663 ± 0.001	2.659 ± 0.001
approaching velocity	$\sim 550 \text{ km s}^{-1}$	
projected distance	$\sim 6 \text{ kpc}$	
$\log M_{\text{SMBH}}/M_{\odot}$	–	8.3 ± 0.4
$\log M_*/M_{\odot}$	$10.96^{+0.12}_{-0.10}$	$10.9^{+0.3}_{-0.3}$
$\log M_{\text{H}_2}/M_{\odot}$	$10.89^{+0.05}_{-0.05}$	9.10
$\log M_{\text{dust}}/M_{\odot}$	$8.5^{+0.3}_{-0.5}$	$8.3^{+0.3}_{-0.6}$
SFR [$M_{\odot} \text{ yr}^{-1}$]	200^{+50}_{-30}	40^{+32}_{-16}



Observations indicate that we see a **major merger** of galaxies at $z = 2.7$, at transverse distance $\approx 6 \text{ kpc}$ and approaching at $\approx 550 \text{ km/s}$. An evidence of the asymmetric extended emission seen in HSC likely indicate already merging phase

And what about the longitudinal distance?

Major merger in J0125-0129. Properties of the galaxies

Table 1 Main properties of two merging galaxies. For

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Merging galaxies Arp 107 (HST image)

kpc

/

Major merger in J0125-0129. Properties of the galaxies

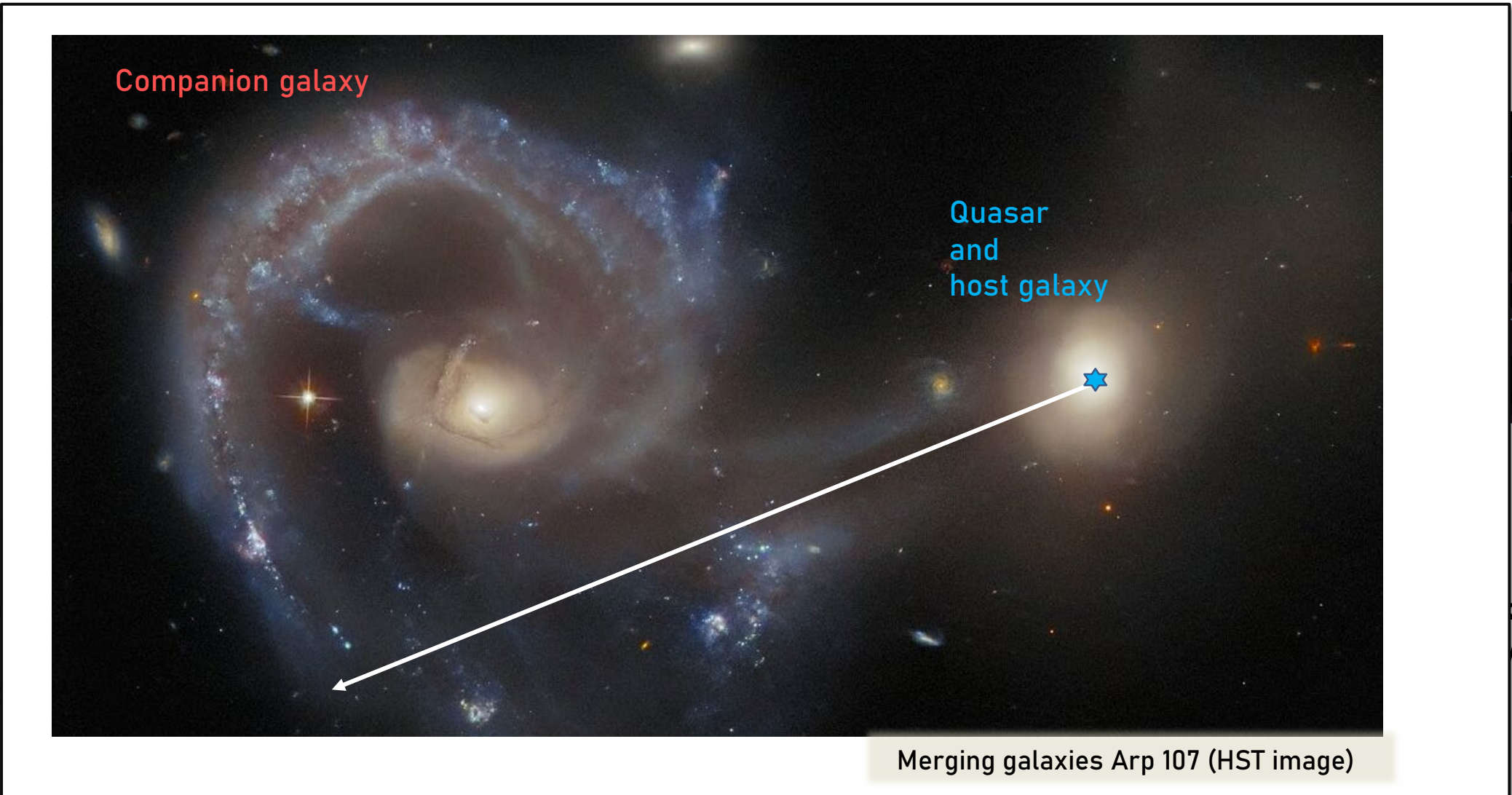
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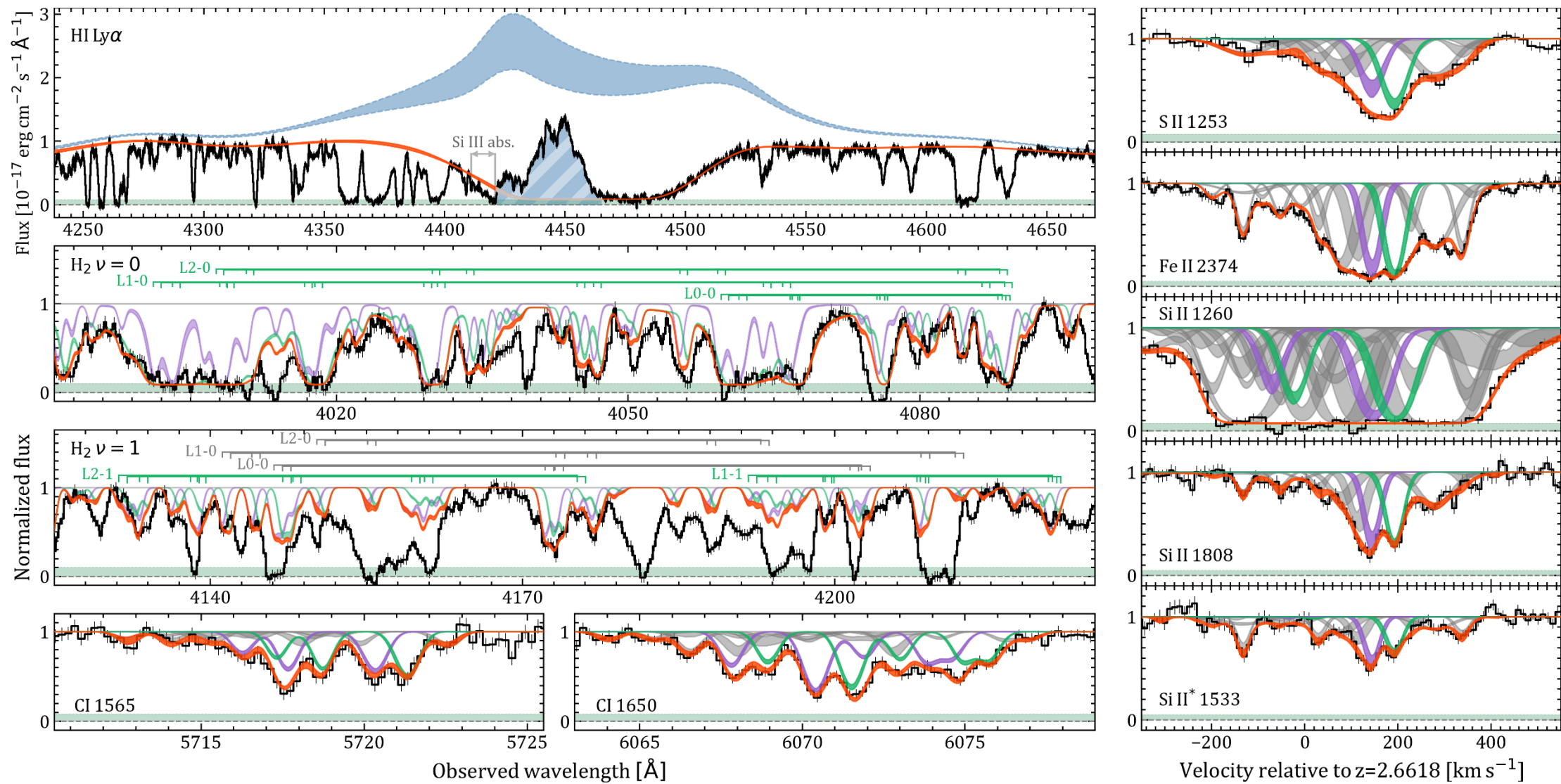
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and
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And



kpc

Major merger in J0125-0129. DLA absorption system



Major merger in J0125-0129. DLA absorption system

We identified extremely strong (ES)DLA system at J0125-0129 :

$$\log N(\text{HI}) = 21.91 \pm 0.02, \quad z = 2.66347(25)$$

with metal lines gives:

$$\log Z = -0.92 \pm 0.03 \text{ (resp. Solar)} \quad z_{\text{main}} = 2.66355 \quad \Delta v_{90} \approx 400 \text{ km/c}$$

and molecular hydrogen lines:

$$\log N(\text{H}_2) = 21.19 \pm 0.02, \quad \text{in two components: } z_1 = 2.663447(6), \quad z_2 = 2.664159(4), \quad \Delta v \approx 60 \text{ km/s}$$

with extreme excitation of the levels:

for the first time (at $z > 0$) lines from first vibrational levels.

and fine structure lines:

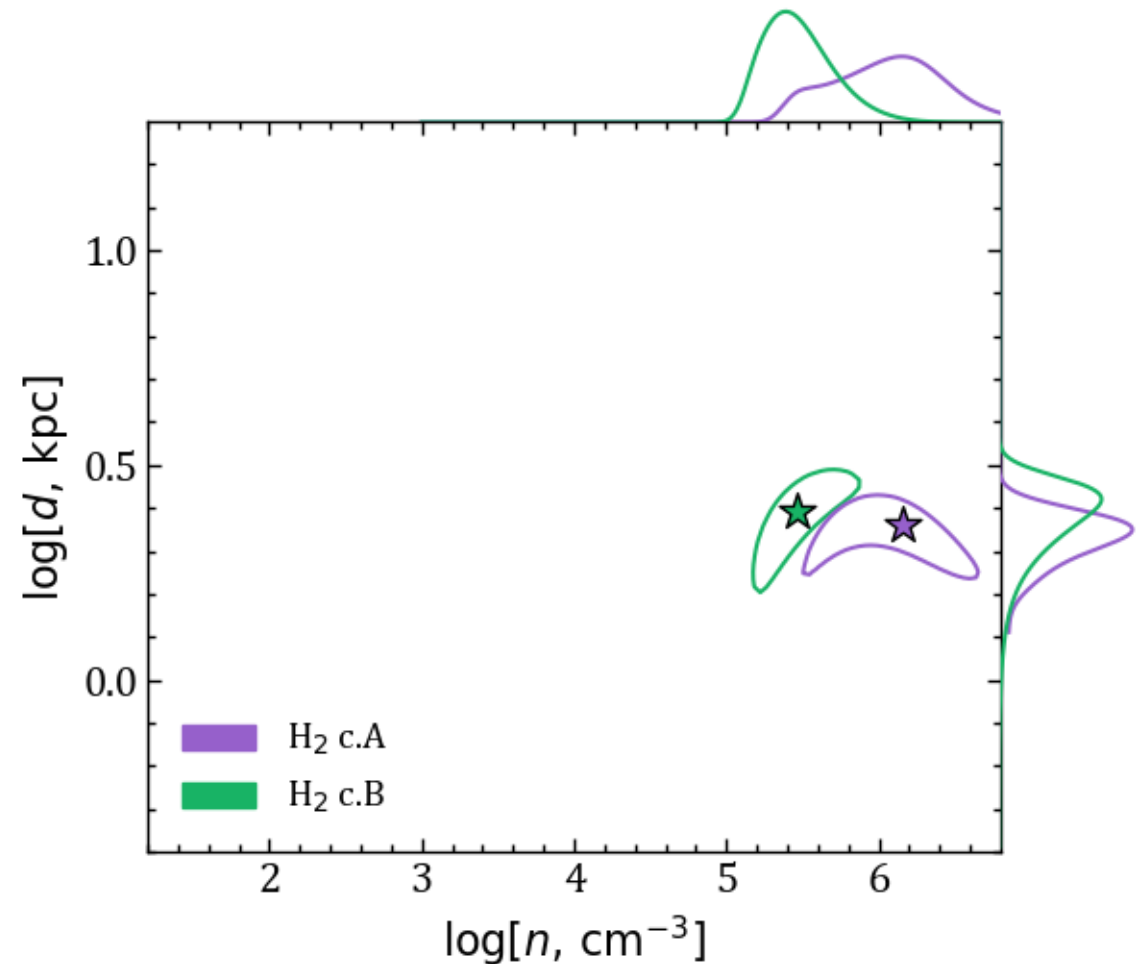
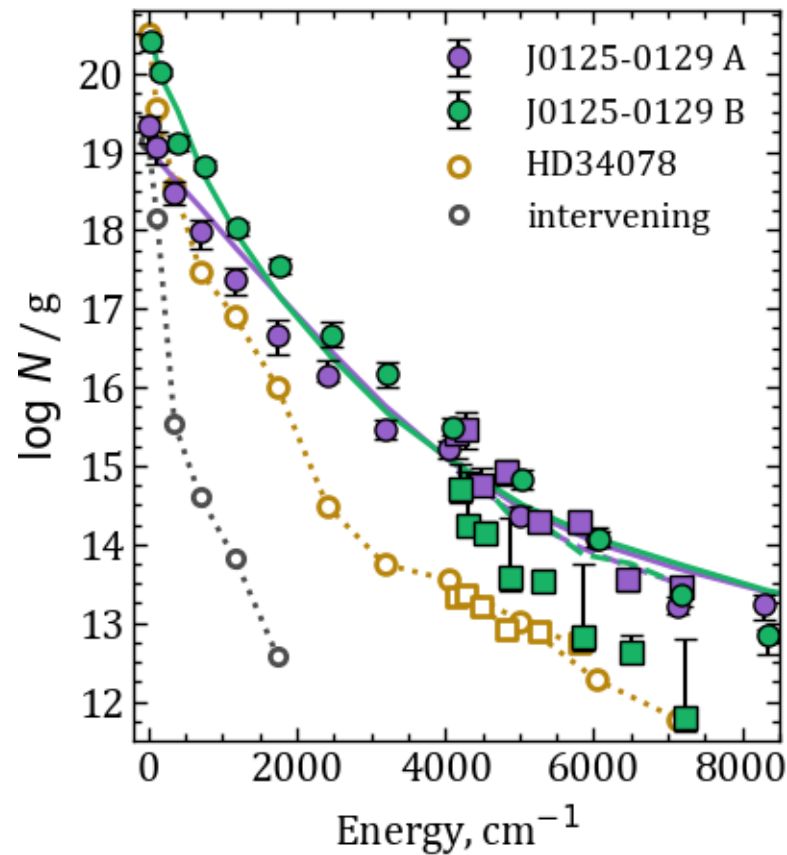
$$\log N(\text{CI}) = 15.09_{-0.08}^{+0.13} \quad \text{SiII}^* (\text{SiII}^*/\text{SiII} \approx -1..-2), \quad \text{OI}^{**}$$

and tentative detection of CO:

$$\log N(\text{CO}) = 14.0 \pm 0.1 \text{ (for the first time in proximate absorption system)} \quad + \text{H}_2\text{O? CH?}$$

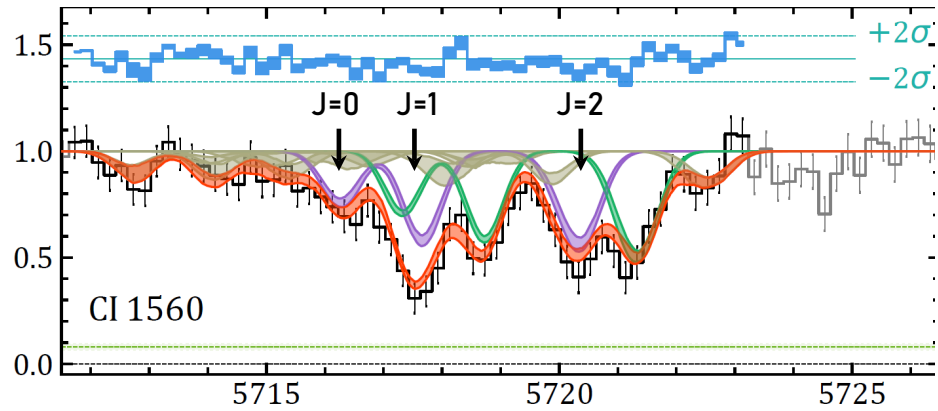
Major merger in J0125-0129. Physical conditions.H2

Population of H2 levels allow us to constrain physical conditions (number density and UV field) at the medium associated with the H2 absorption lines:



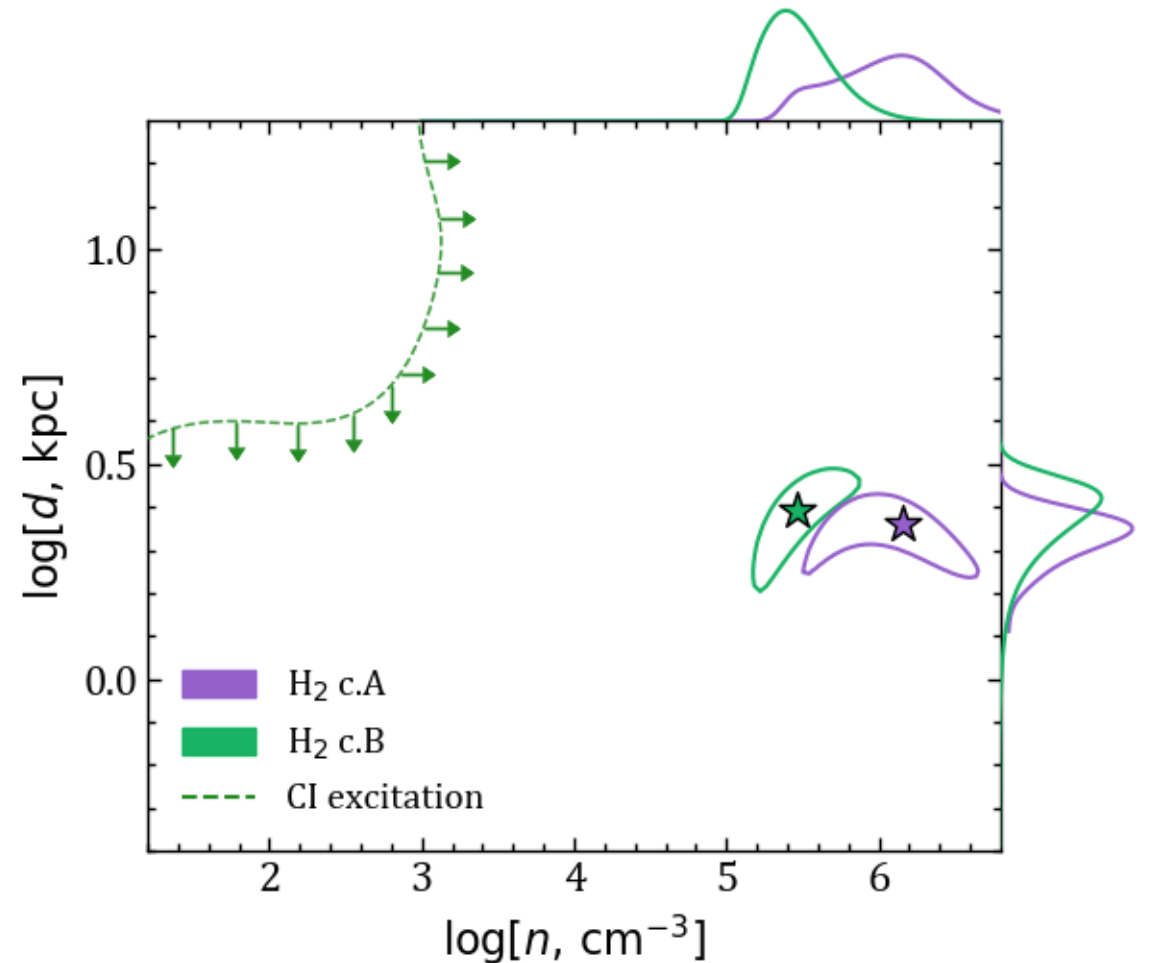
Major merger in J0125-0129. Physical conditions. CI

Population of CI fine-structure levels also allow us to constrain these parameters:



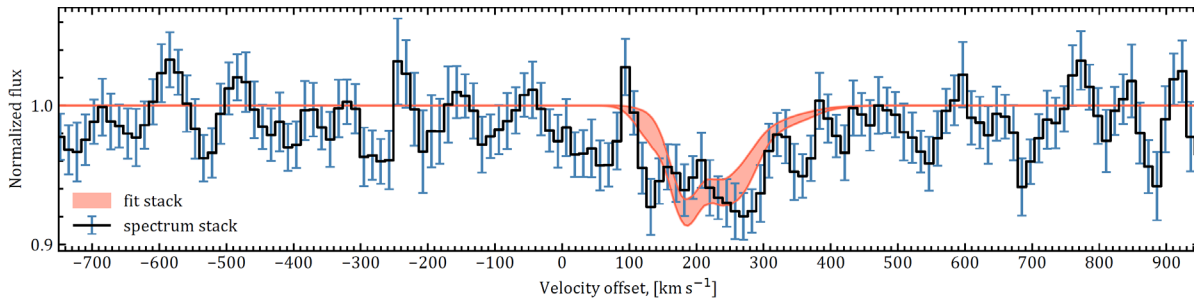
$$\log \frac{N(\text{CI}_{J=1})}{N(\text{CI}_{J=0})} \approx 3 \quad \log \frac{N(\text{CI}_{J=2})}{N(\text{CI}_{J=0})} \approx 3$$

That is close to the statistical weight ($g_J = 2J + 1$) ratio: 3 and 5



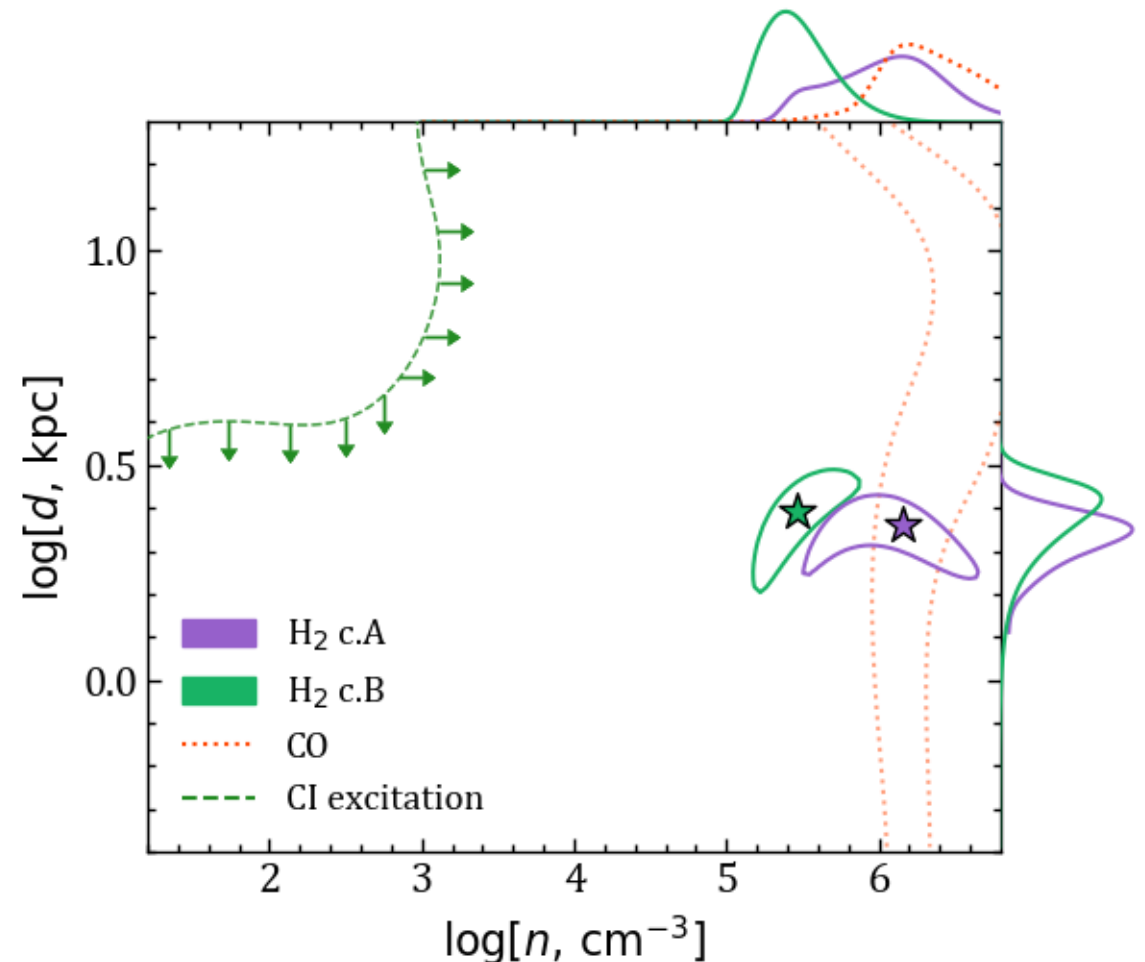
Major merger in J0125-0129. Physical conditions. CO

Tentative identification of CO indicate a very dense gas:



$$\log \frac{N(\text{CO})}{N(\text{H}_2)} \approx \log \frac{10^{14.0 \pm 0.1}}{10^{21.19 \pm 0.02}} \approx -7.2 \pm 0.1 \quad \Rightarrow$$

Since the extinction is low ($A_V \sim 0.2$), the presence of CO indicate a dense gas, since residual fraction of CO can be formed by the O-bearing chemistry network:



Major merger in J0125-0129. Physical conditions. HI/H2

The abundance of H₂/HI also provide constrains on these parameters:

Следуя Sternberg+2014, Bialy+2016:

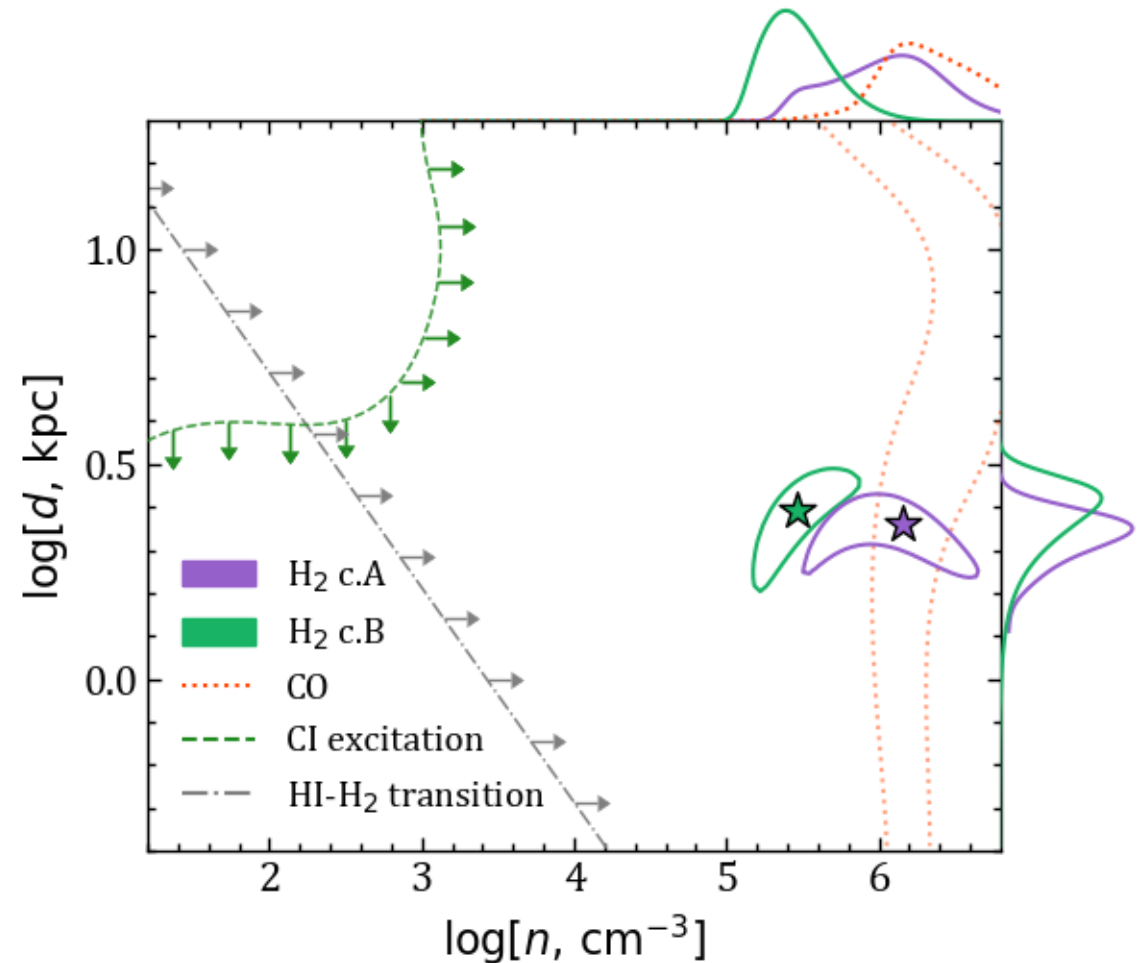
$$N_{\text{HI}}(N_{\text{H}_2}) = \frac{1}{\sigma_g} \ln \left(\frac{\alpha G}{2} w(N_{\text{H}_2}, \sigma_g) + 1 \right)$$

$$\alpha G = 1.8 I_{\text{UV}} \tilde{\sigma}_g \left(\frac{10^{-17} \text{ cm}^3 \text{ s}^{-1}}{R} \right) \times \left(\frac{100 \text{ cm}^3}{n} \right) \left(\frac{9.9}{1 + 8.9 \tilde{\sigma}_g} \right)^{0.37}$$

σ_g – LW photons cross-section by dust ($\propto Z$)

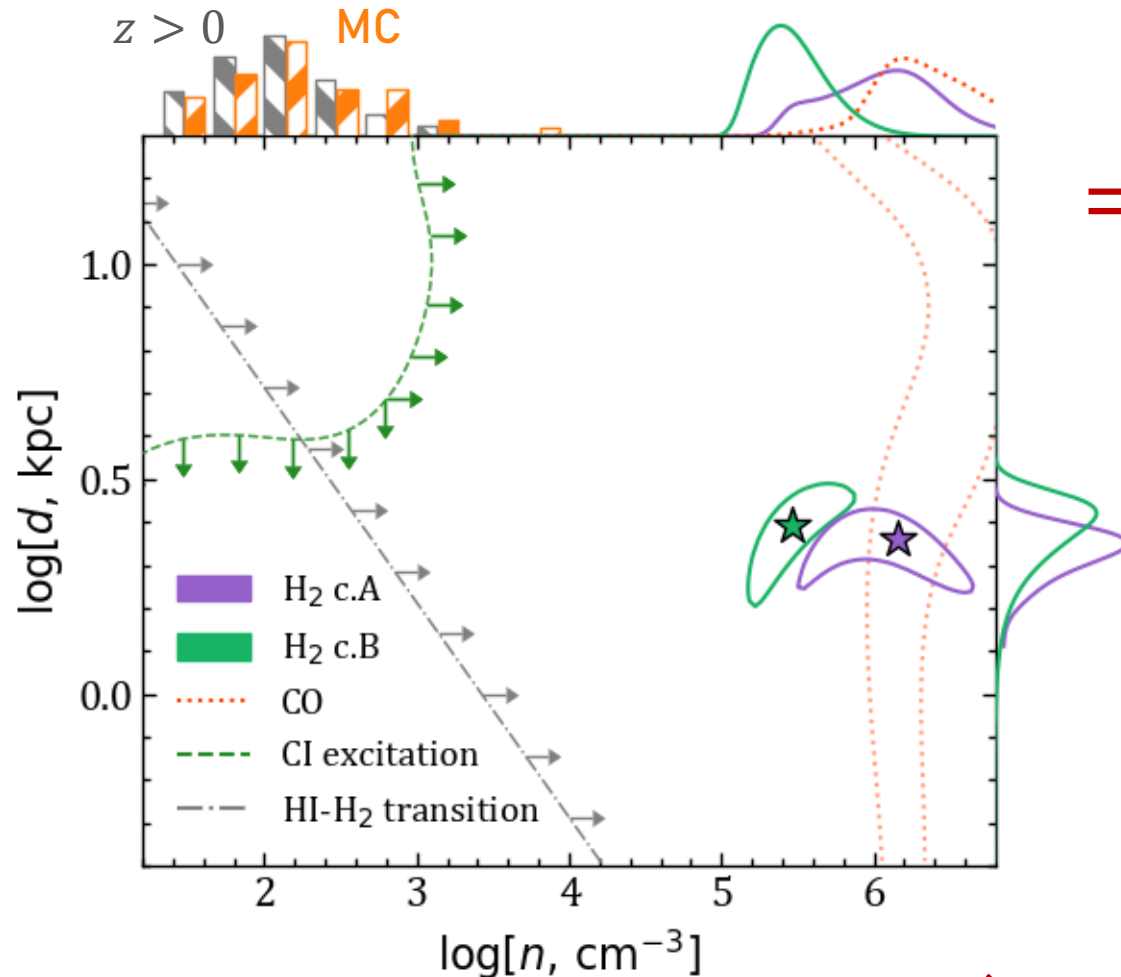
$w(N_{\text{H}_2}, \sigma_g)$ – some function that describe the H2 shielding f_{shield}

Taken $\left\{ \begin{array}{l} \log N_{\text{HI}} < 21.93 \\ \log N_{\text{H}_2} = 21.19 \end{array} \right.$



Major merger in J0125-0129. Physical conditions. HI/H2

If we compare the derived properties with other absorption line measurements ($z > 0$ и **Magellanic clouds**):



$$\begin{cases} T_{01} \approx 300 \pm 20 \text{ K} \\ n \approx 10^{5-6} \text{ cm}^{-3} \\ UV \approx 10^{3.5 \pm 0.1} \text{ Draine} \\ d \approx 2 - 3 \text{ kpc} \end{cases}$$

$$l = 10^{14} - 10^{16} \text{ cm} \ll \text{pc}$$

Can not form stars?

$$M_{\text{clump}} = \mu m_p \frac{\pi l^3}{6} n < 0.02 M_{\odot}$$

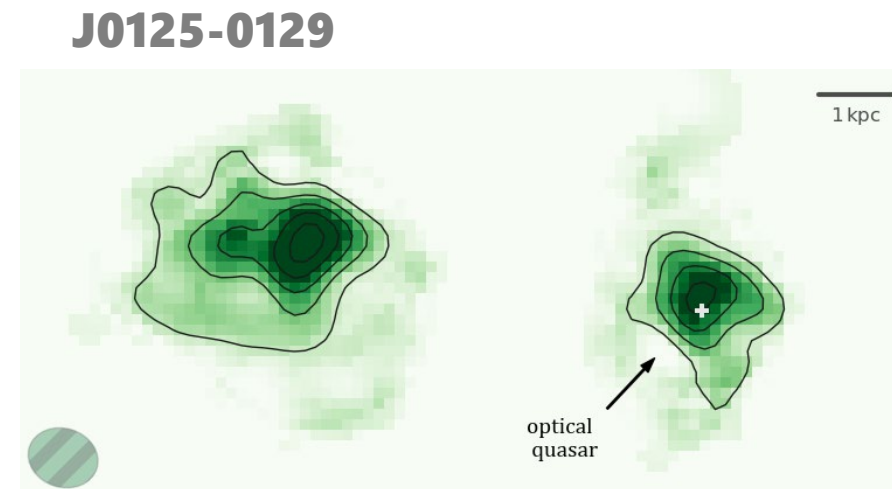
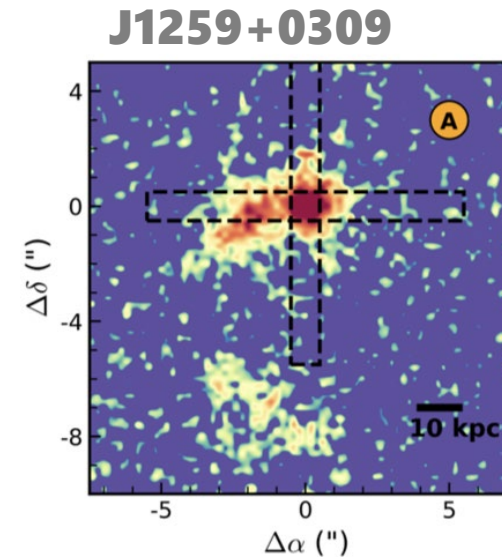
+ diffuse gas ($n \approx 10^2 \text{ cm}^{-3}$) have to dissociate on the timescales:

$$t_{\text{diss}} \sim \frac{1}{D_0} = \frac{550}{I_{UV}} < 0.1 \text{ yr}$$

⇒ **Direct evidence of the negative AGN feedback**

Summary

1. We found a distinct population of proximate H₂ absorption systems at $z > 2.5$ in quasar spectra using SDSS catalog. ...and started the follow-up campaign to derive its origin.
2. The first results of the follow-up observations indicate that these absorption systems may have different origin including: galaxies in quasar environment, outflowing gas and merging galaxies.
3. DLA provide a natural coronagraph that make a perfect PSF subtraction and allow to get insights on the extended Ly α emission of quasar at small projected distances.
4. H₂ molecular hydrogen (and some other associated lines) are powerful diagnostic tool to measure a physical conditions in the associated medium and constrain the distance to the AGN.
5. A major merger identified in J0125-0129 provide an example of the negative AGN feedback on the ISM of the companion galaxy.



Summary

1. We found a distinct population of proximate H₂ absorption systems at $z > 2.5$ in quasar spectra using SDSS catalog. ...and started the follow-up campaign to derive its origin.
2. The first results of the follow-up observations indicate that these absorption systems may have different origin including: galaxies in quasar environment, outflowing gas and merging galaxies.
3. DLA provide a natural coronagraph that make a perfect PSF subtraction and allow to get insights on the extended Ly α emission of quasar at small projected distances.
4. H₂ molecular hydrogen (and some other associated lines) are powerful diagnostic tool to measure a physical conditions in the associated medium and constrain the distance to the AGN.
5. A major merger identified in J0125-0129 provide an example of the negative AGN feedback on the ISM of the companion galaxy.

