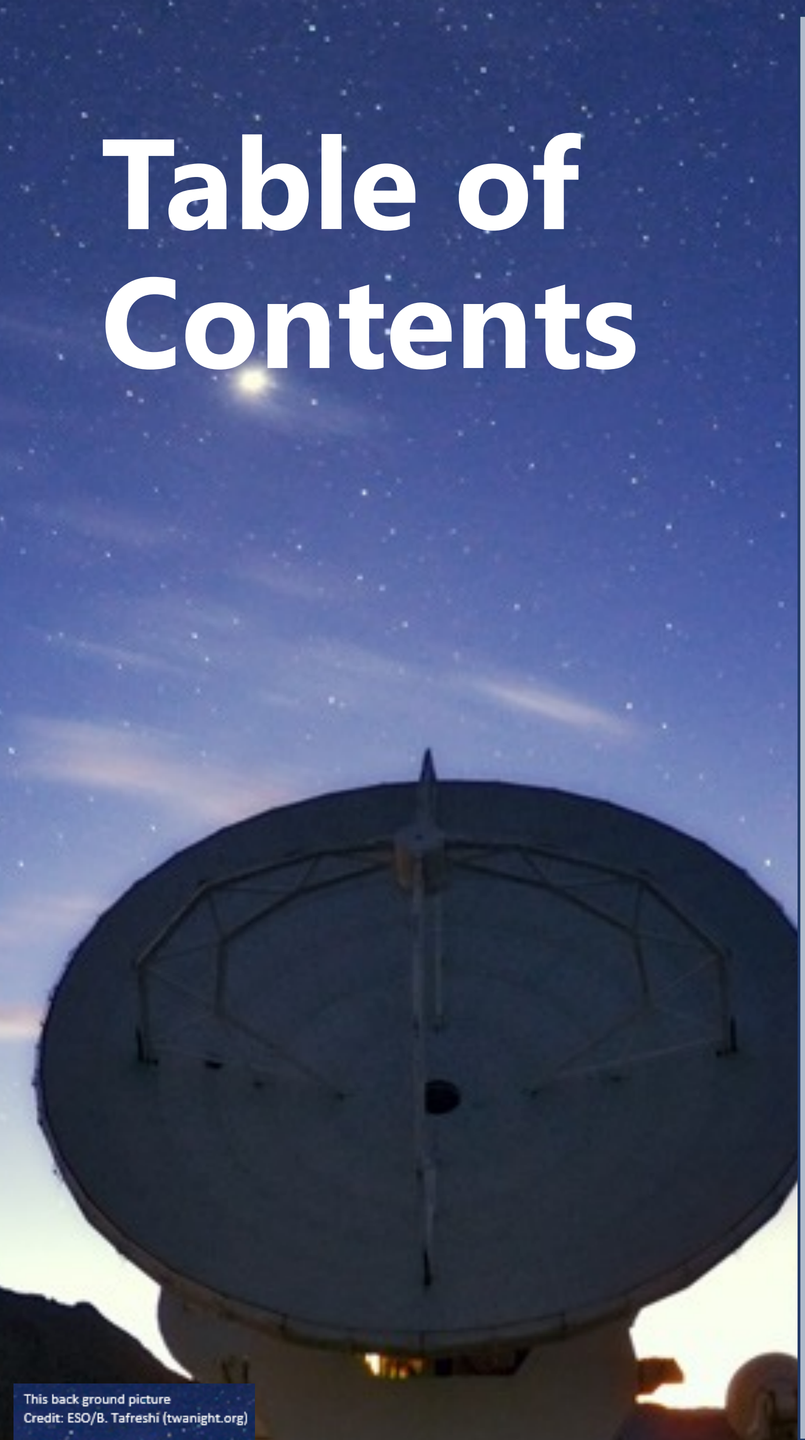
2024/2/28, 29
ブラックホール大研究会
~星質量から超巨大ブラックホールまで~

No galaxy-scale [CII] outflow detected in a z=6.72 red quasar with ALMA

Mahoshi Sawamura
(M1 UTokyo/NAOJ)

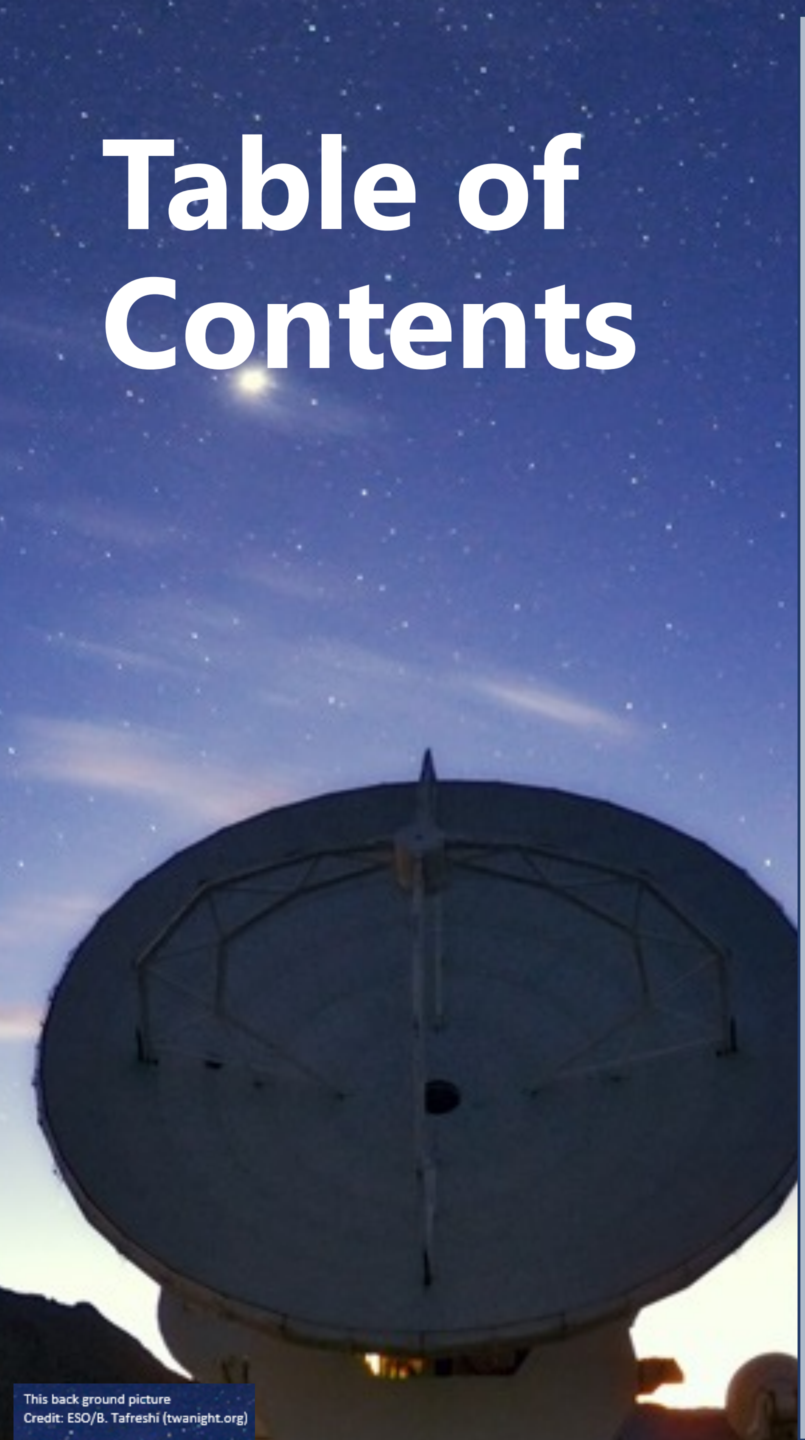
Takuma Izumi(SOKENDAI/NAOJ)
Takeshi Okuda(UTokyo/NAOJ)
Kouichiro Nakanishi(SOKENDAI/NAOJ)
+SHELLQs collaboration

Table of Contents



This back ground picture
Credit: ESO/B. Tafreshi (twanight.org)

Table of Contents



This back ground picture
Credit: ESO/B. Tafreshi (twanight.org)

Co-evolution of galaxies and black holes

- There is a strong correlation between the mass of SMBH and the bulge.

→But… different spatial scales (~6 to 8 orders)

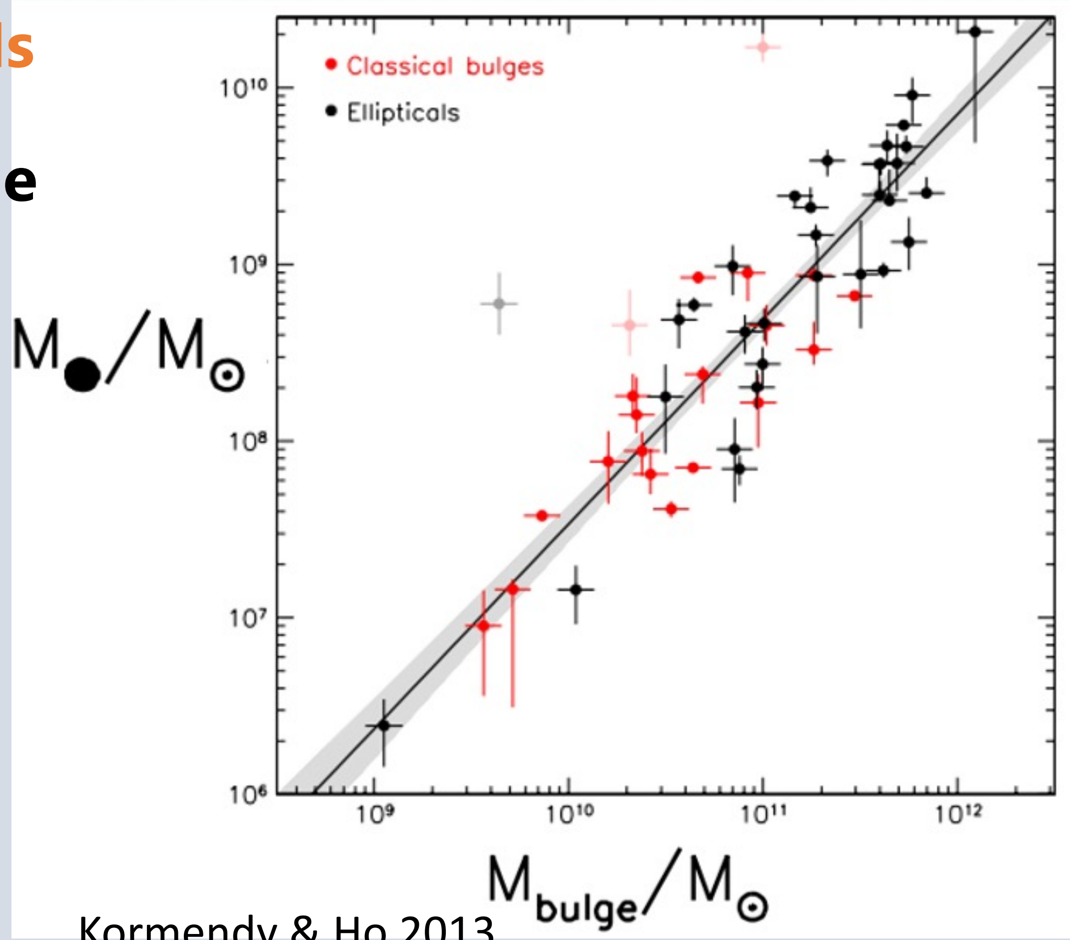
→A complex relationship between the two?

→**Suggesting co-evolution of galaxies and BHs**

- **Understanding this correlation is a challenge**
  - What ties the two together?→**Mechanism**
  - When has this relationship existed?→**Time**

→Necessity to consider the issue from these two perspectives

The importance of investigating both objects from the past to the present.



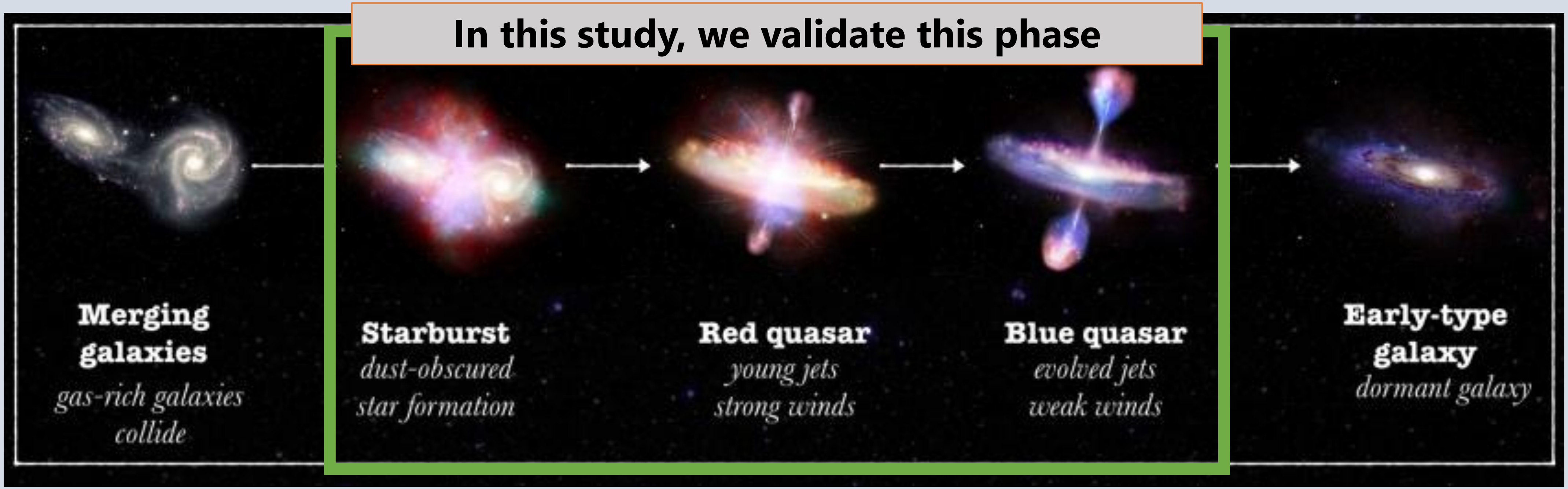
Kormendy & Ho 2013

Negative AGN feedback

- Galaxy evolution through mergers of gas-rich galaxies
- **Negative AGN feedback** (e.g. Hopkins et al. 2006)

Accretion onto SMBH→**AGN driven outflow**→blowing away gas & dust→Quenching SF
(Analytically, determined that outflows suppress star formation.(e.g. Di Matteo et al. 2005))

- **It's crucial to verify whether there is a host scale outflow in the galaxy (quasar)**



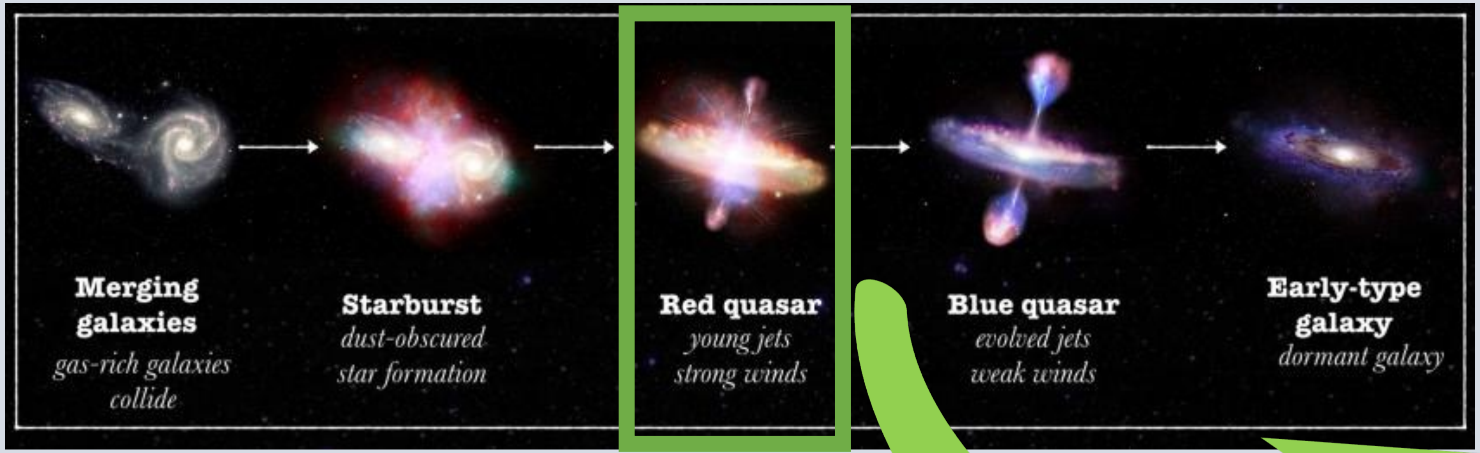
Credits: Gemini Observatory, GMOS-South, NSF/; Adapted by S. Munro.

Red Quasar

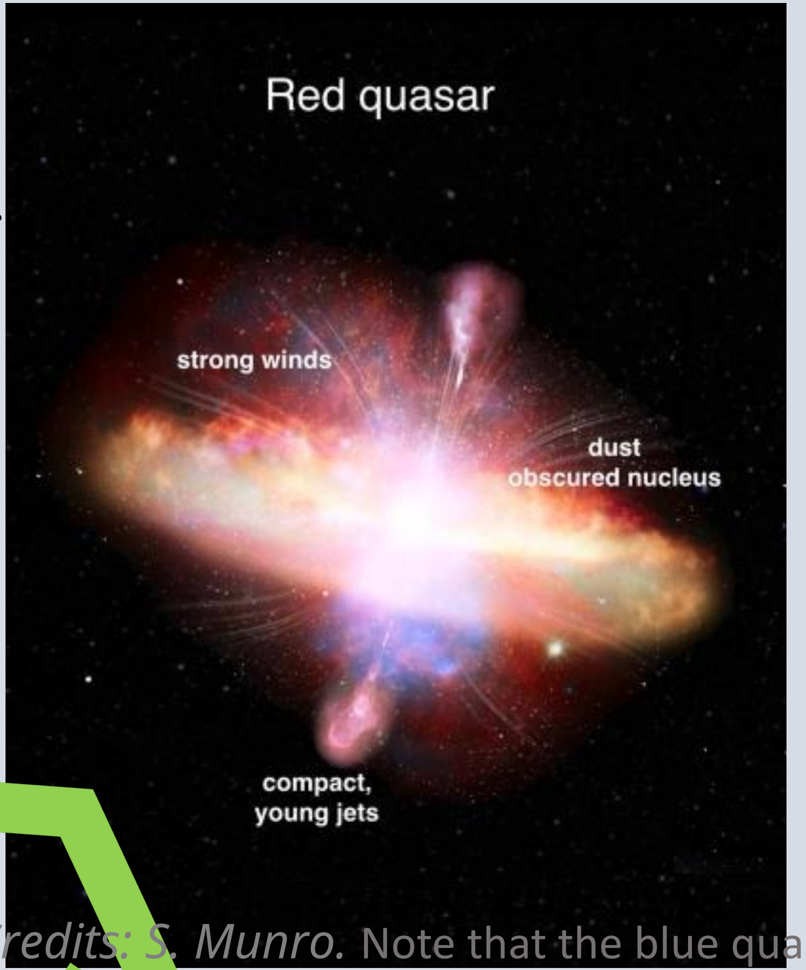
- **Red quasars** are considered as an **intermediate phase** in galaxy evolution.

= The surrounding gas and dust are blown away, exposing the core region slightly.

→Appearing as low-luminosity, but **in reality, luminous**.

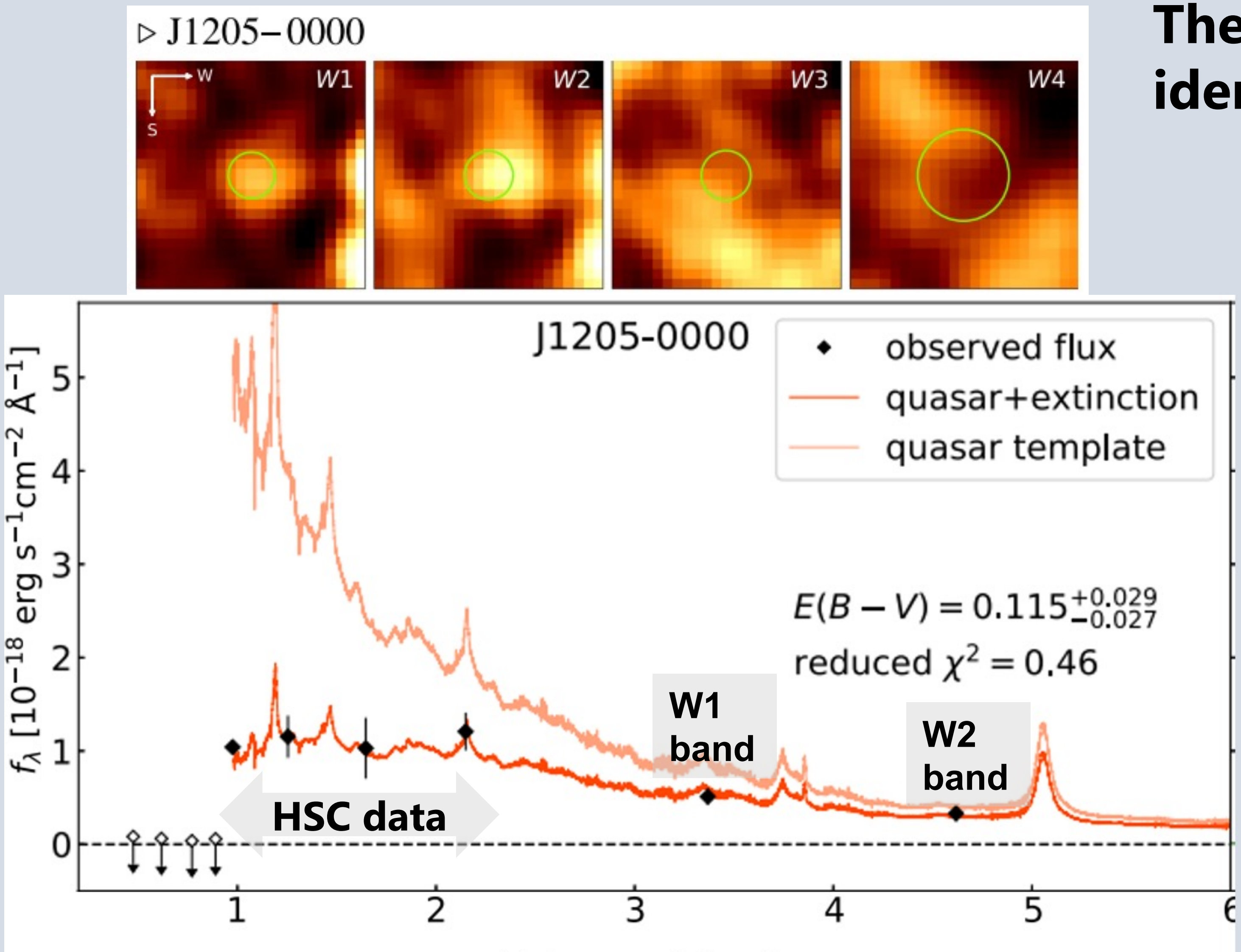


Credits: Gemini Observatory, GMOS-South, NSF/; Adapted by S. Munro.



Credits: S. Munro. Note that the blue quasar portion in this figure has been truncated.

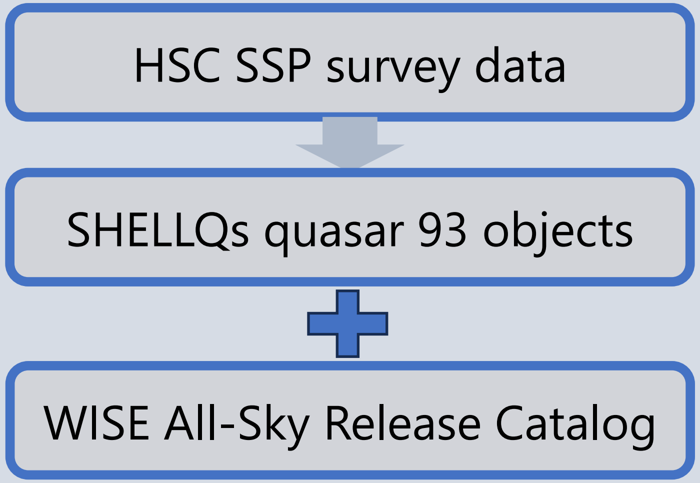
High-z red quasars



Kato et al. 2020

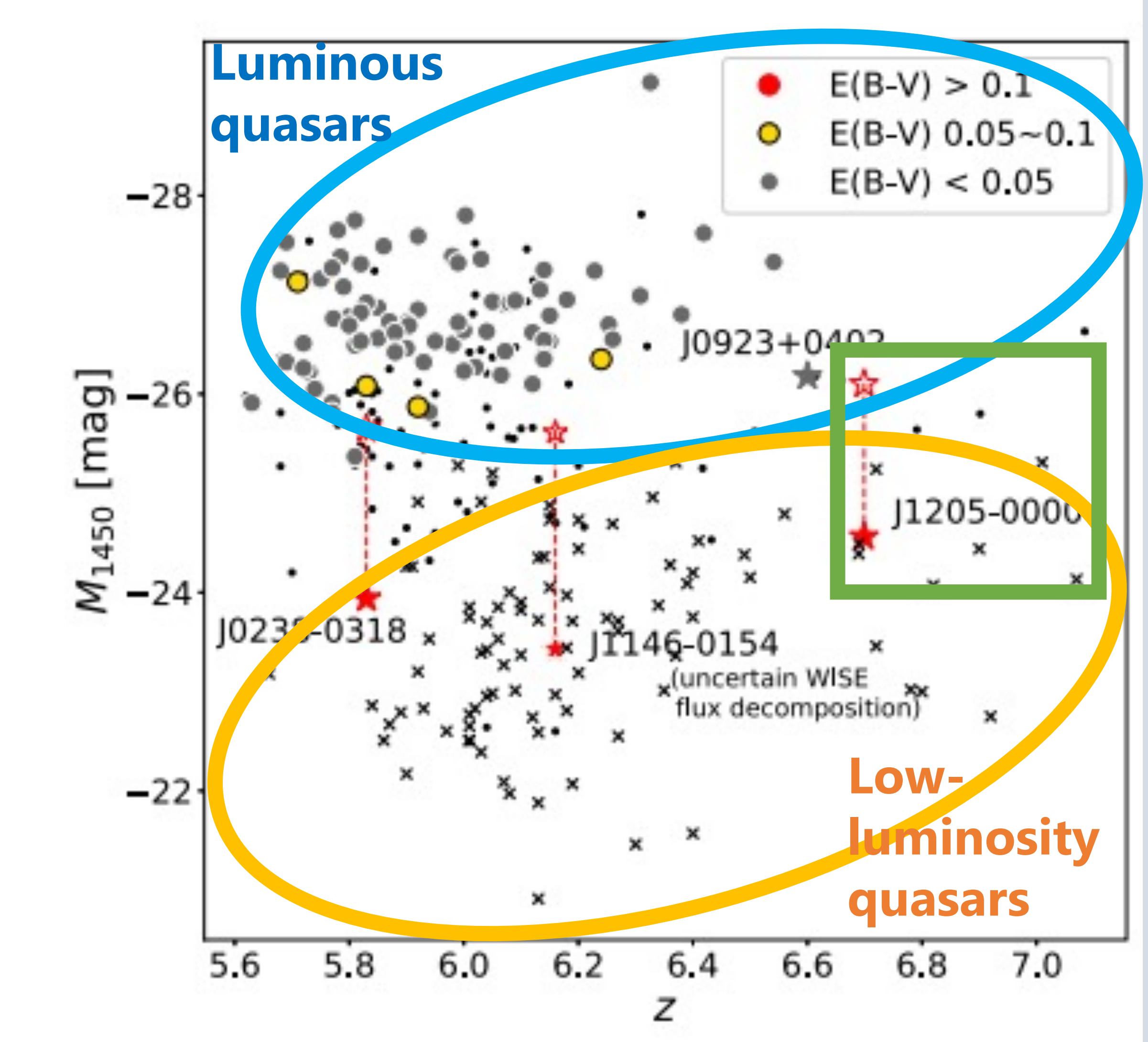
The selection process for identifying red quasars at high z

- Narrowing down red quasar candidate objects to 4 based on



- Selecting the two objects as red quasar with SED fitting (E(B − V) > 0.1) (**J1205-0000**, J0238−0318)

Our target J1205-0000 @ $z_{MgII} = 6.699^{+0.007}_{-0.001}$



Kato et al. 2020

- Considering the dust attenuation, J1205-0000 is positioned within the luminous quasar regime.

- Dust attenuation correction (E(B-V) = 0.12)

J1205-0000	No Correction	After Correction
M_{1450} (mag)	-24.5	-26.1
M_{BH} (MgII) (10^9 Msun)	2.2	2.9
L_{bol} / L_{Edd}	0.16	0.22

Our target J1205-0000 @ $z_{MgII} = 6.699^{+0.007}_{-0.001}$

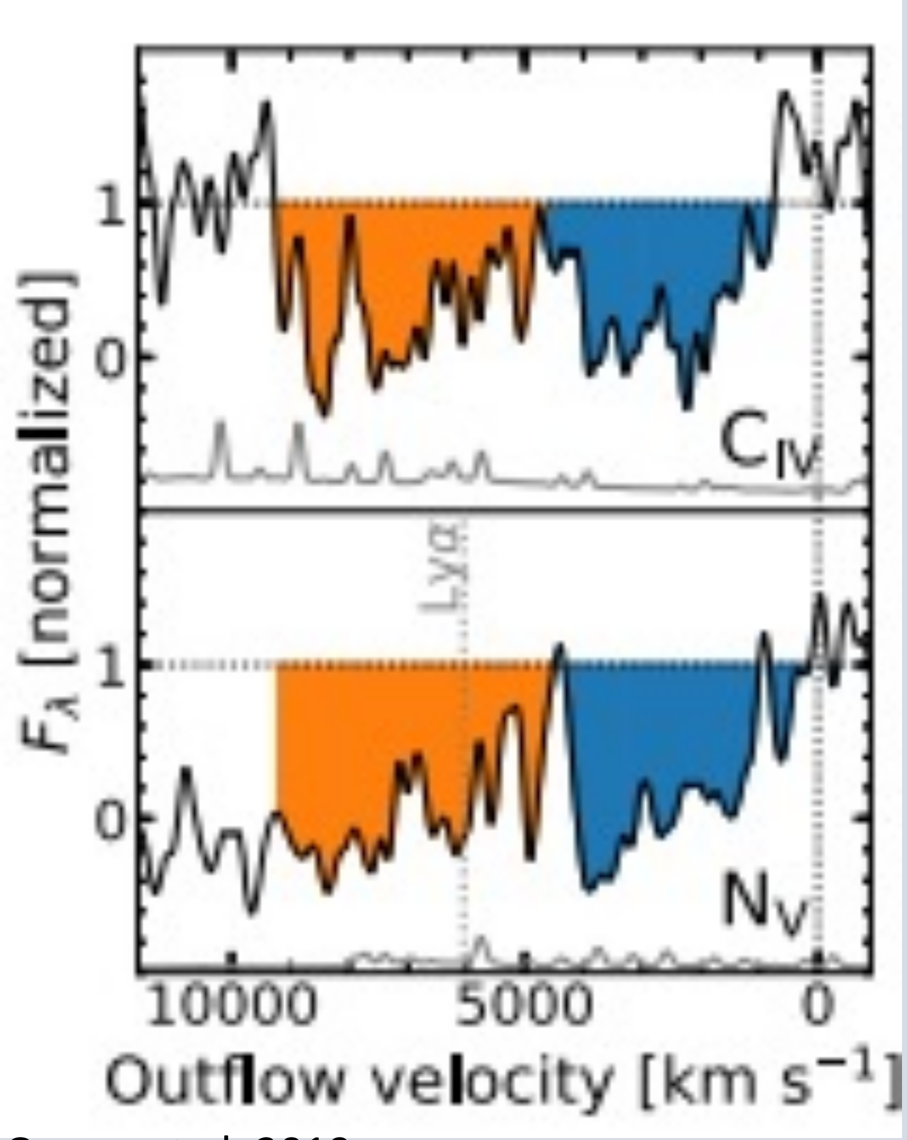
- J1205-0000 hosts N V, C IV BALs (Broad Absorption Lines)

→**nuclear outflow exist**
(Outflows are blowing near the center of the galaxy)

- Observing [CII] 158 μm to confirm outflows at the scale of the host galaxy

→**Validating the merger driven evolutionary process**

- Checking SF activity



Onoue et al. 2019

Table of Contents

This back ground picture
Credit: ESO/B. Tafreshi (twanight.org)

ALMA observation

- ALMA cycle 7 Band 6 (211 – 275 GHz) Observing **[CII] 158 μm and rest-FIR continuu**
  (ID : 2019.1.00074.S, PI : T.Izumi)

- Using 41 12m antennas with a field of view of 24″, a total ovservational time of 71 minutes

- Data analysis with CASA version 5.6

- Beam size = 4.2 kpc × 2.6 kpc ($0''.79 \times 0''.49$)、

- 1σ = 0.28 mJy/beam (Velocity resolution = 75 km/s)

Credit: ALMA (ESO/NAOJ/NRAO)

Imaging ：FIR continuum map

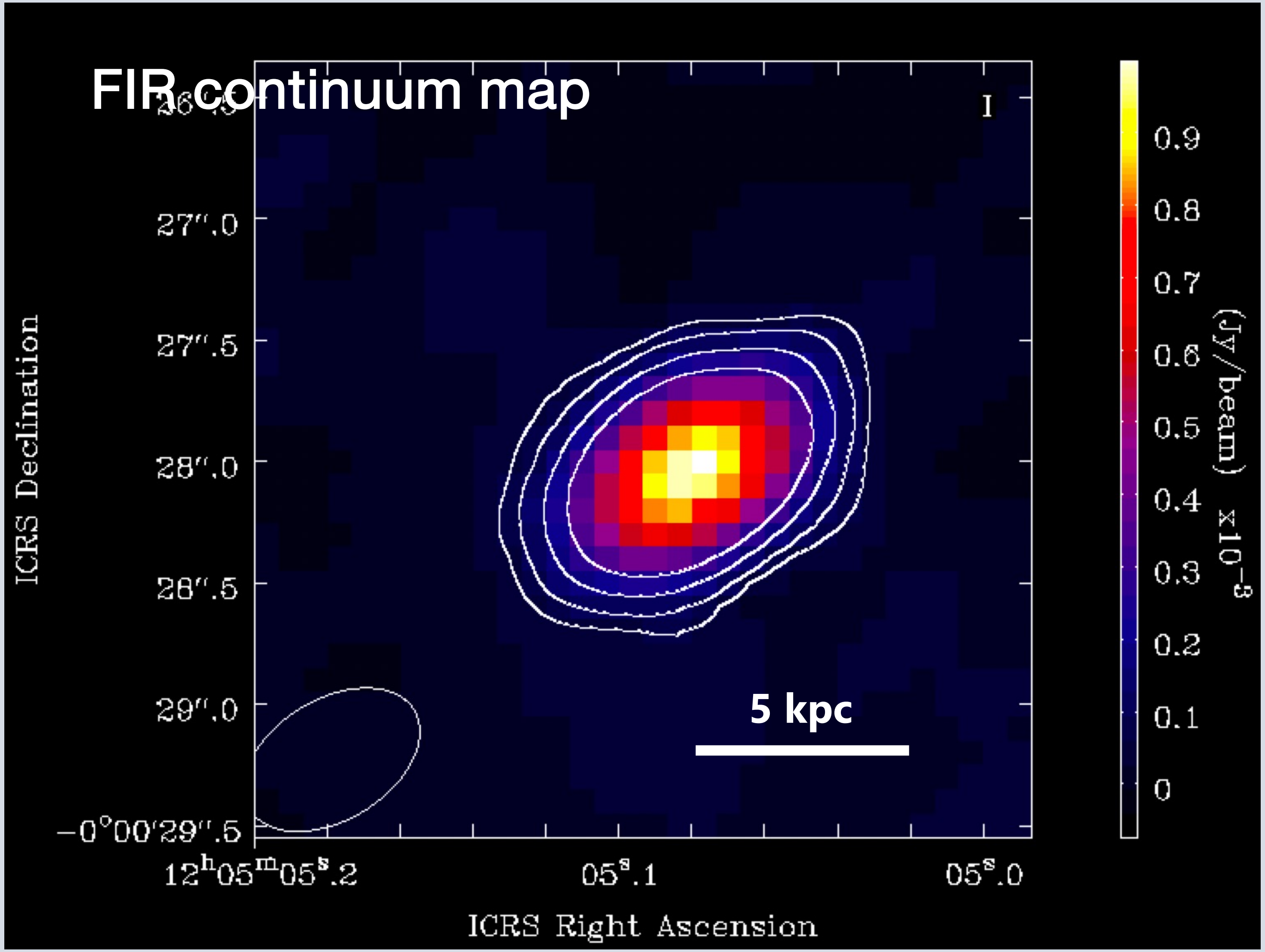
- FIR continuum luminosity

- $L_{\mathrm{FIR}} = (2.3 \pm 0.2) \times 10^{12}\ L_{\odot}$

- $L_{\mathrm{IR}} = (3.3 \pm 0.3) \times 10^{12}\ L_{\odot}$

  Deriving with assumption of optically thin modified black body
  - dust temperature $T_b = 47$ K
  - emissivity index $\beta = 1.6$

- D = 1.44 ± 0.32 kpc
(beam deconvolved major axis of 2D Gaussian fit)



contours overlaid at 3σ, 5σ, 9σ, 15σ, and 23σ (1σ = 0.19 μJy beam⁻1)

Star Formation Activity

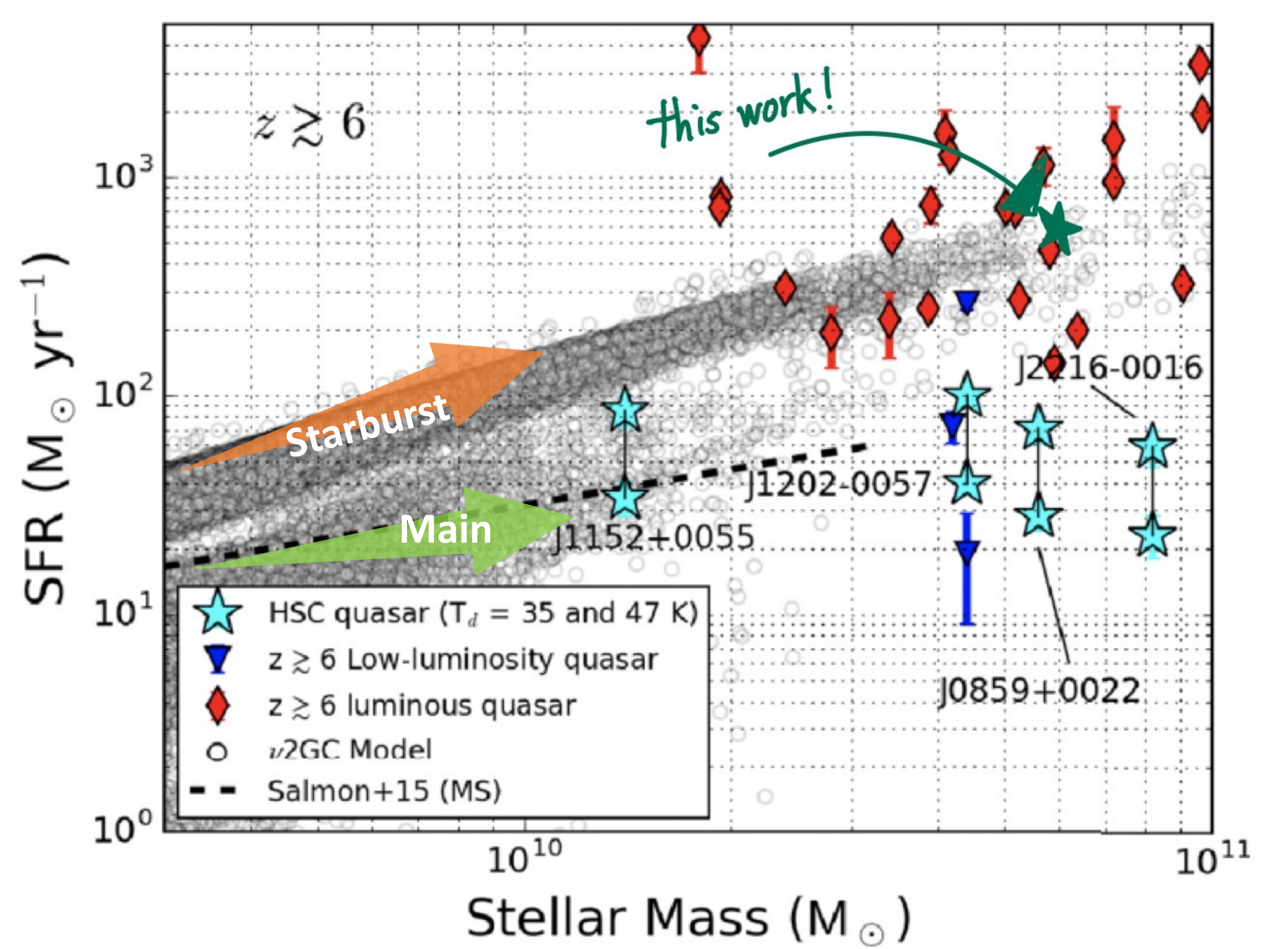
- Assuming that all of the IR continuum comes from SF activities.

- SFR= 486 Msun/yr

J1205-0000 positions at Starburst Sequence

→my target has the active star forming

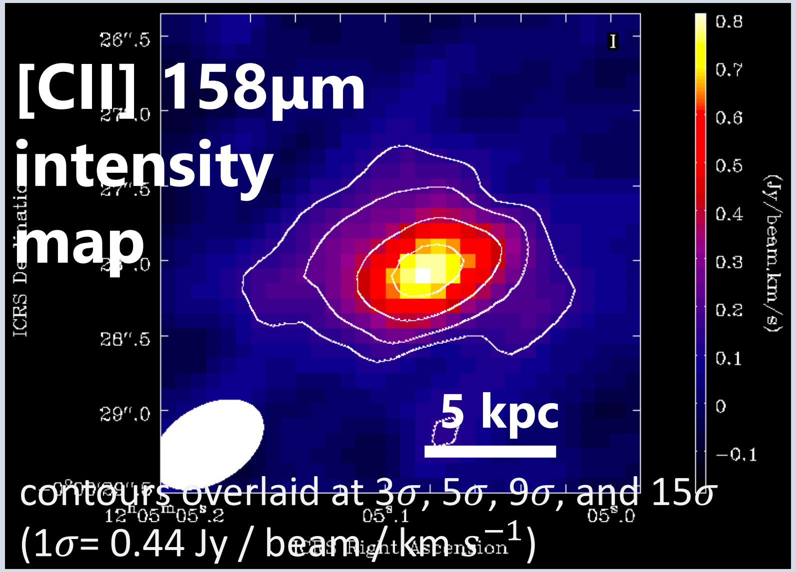
→suggesting that AGN feedback is not affecting SF in my target as long as we assume that all the FIR flux originates from star-forming activities.

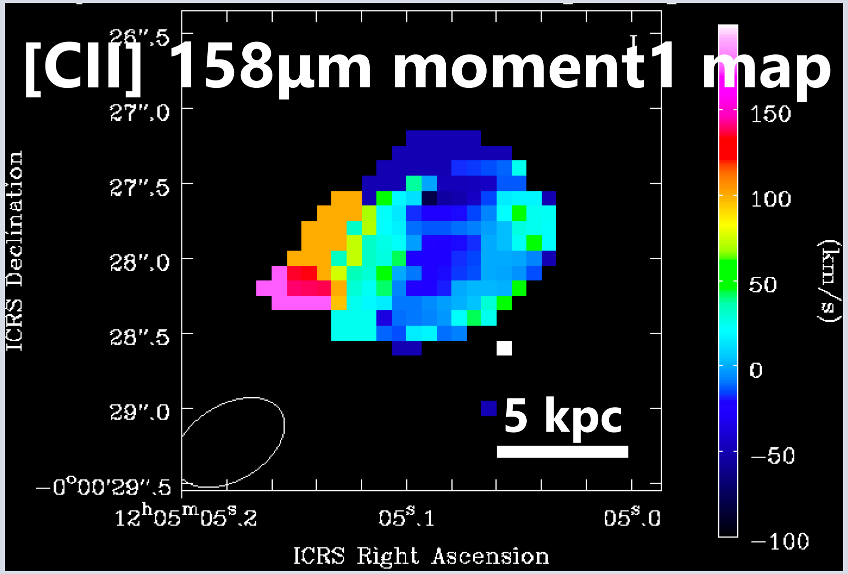


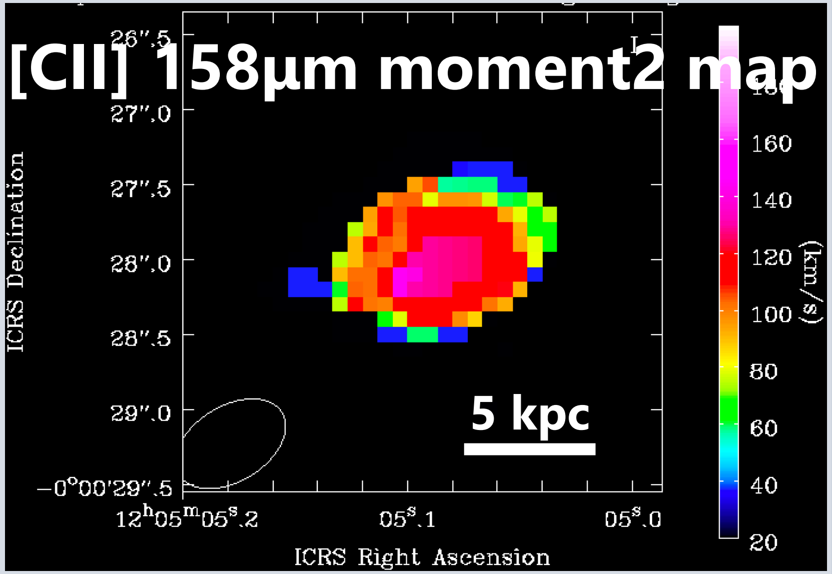
※ I overlaid my results onto Izumi et al. 2018

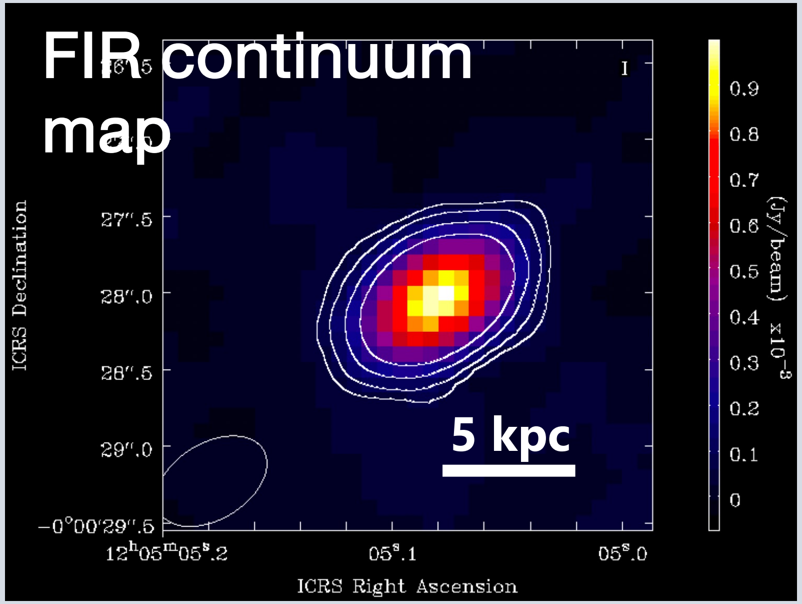
※ **Dynamical mass is used as Stellar mass**

Imaging : [CII] 158μm



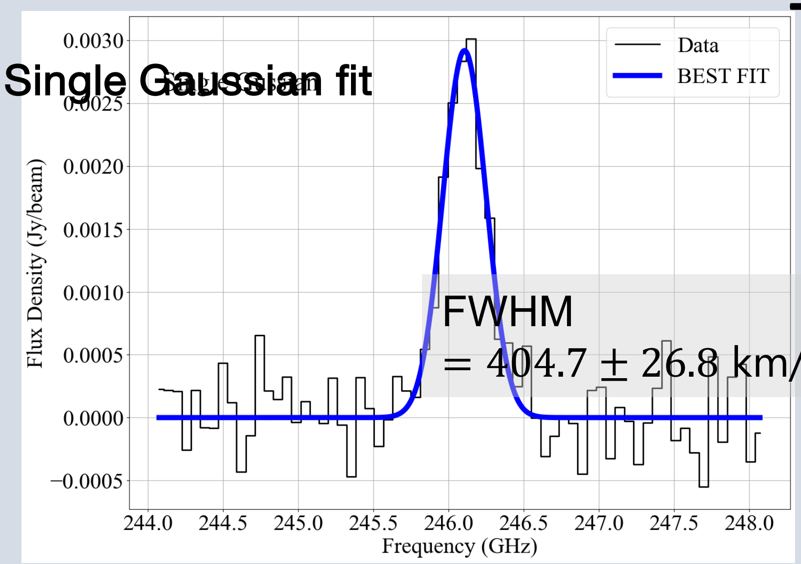


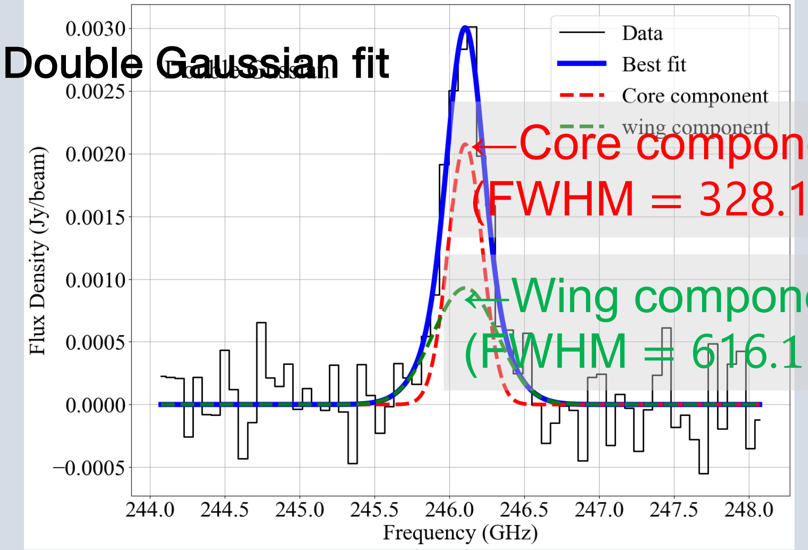




- $L_{[\mathrm{CII}]} = (1.5 \pm 0.2) \times 10^{9}\, L_{\odot}$
- D = 5.46 ± 0.64 kpc
(beam deconvolved major axis of 2D Gaussian fit)
- Integration over a velocity range of ±750 km/s

Whether there is an outflow or not





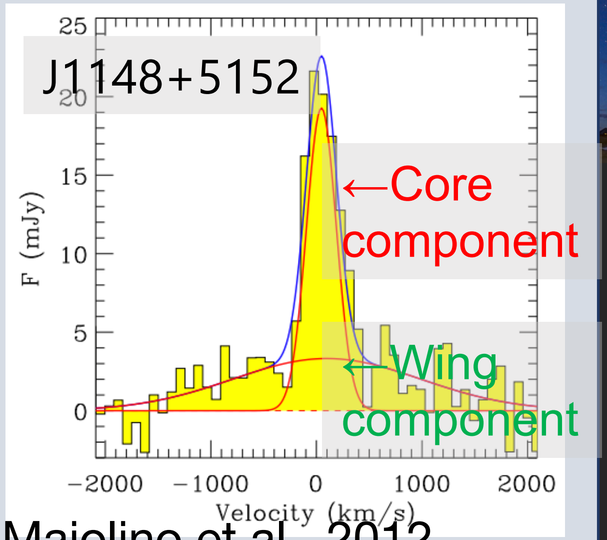
The results of the Single and Double Gaussian fits to the [CII] line

- $z_{[CII]} = 6.7224 \pm 0.0003$

  ($z_{MgII} = 6.699^{+0.007}_{-0.001}$ (Onoue et al. 2019))

- Reduced chi square

J1205-0000	Single Gaussian	Double Gaussian
χ^2/ d.o.f	0.918	0.917

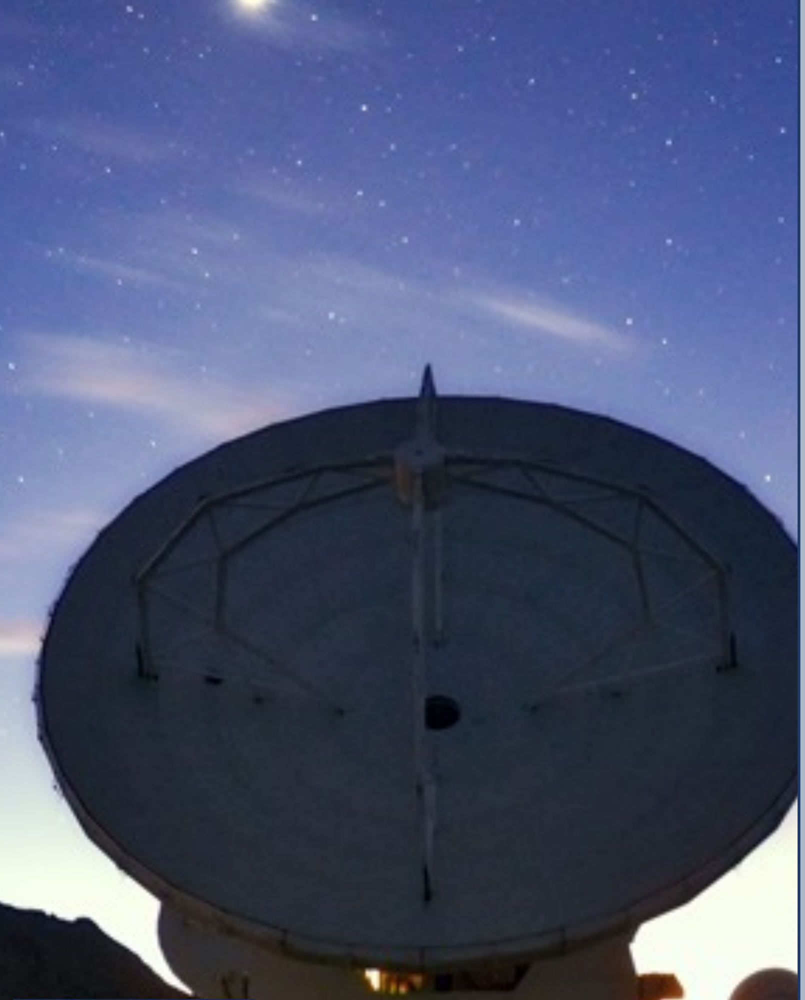


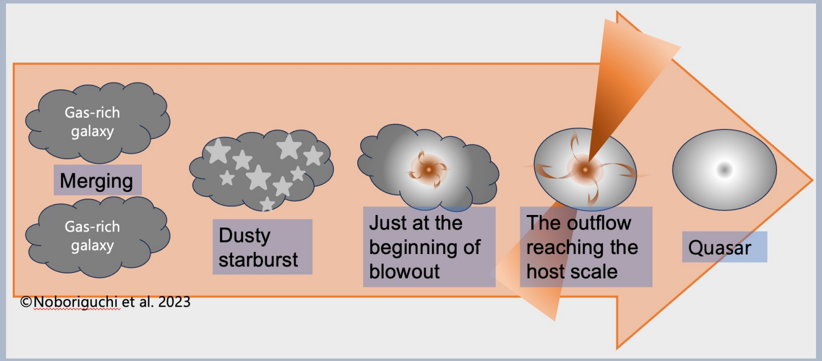
Maiolino et al. 2012

While the Double Gaussian fit allowed us to **separate the core and wing components**, a comparison of the reduced chi-square **did not reveal any significant difference.**

→ **We can't statistically conclude that there is an outflow.**

Table of Contents



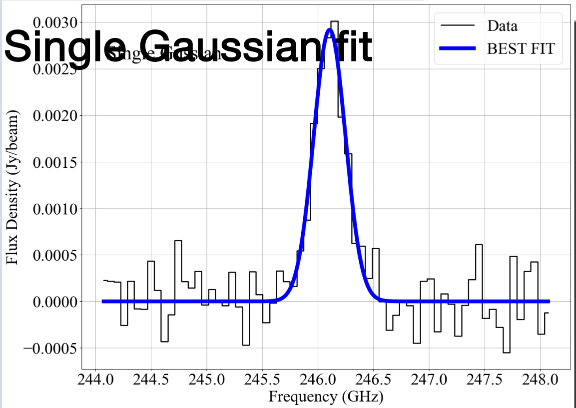


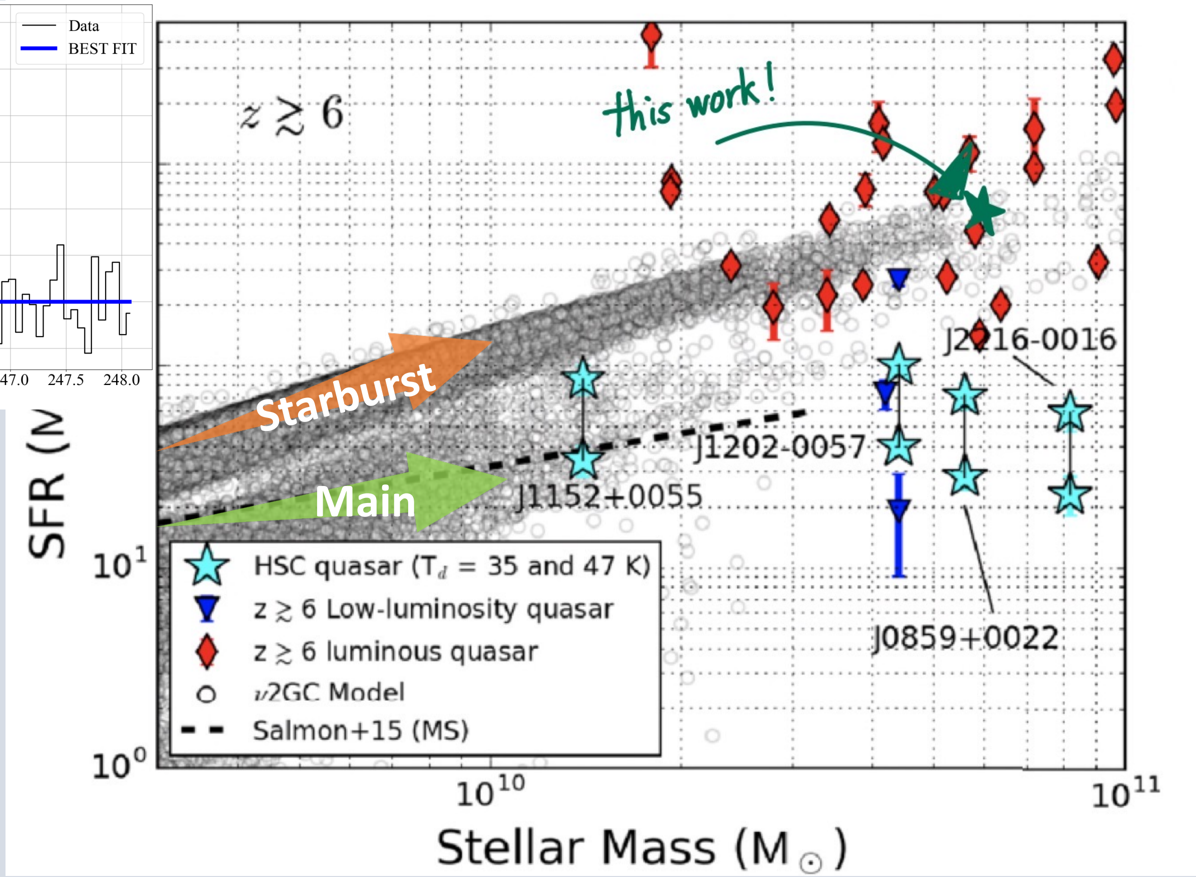
This back ground picture
Credit: ESO/B. Tafreshi (twanight.org)

Interpretation A : Too young outflow

・Starforming activity of J1205 is not quenched.

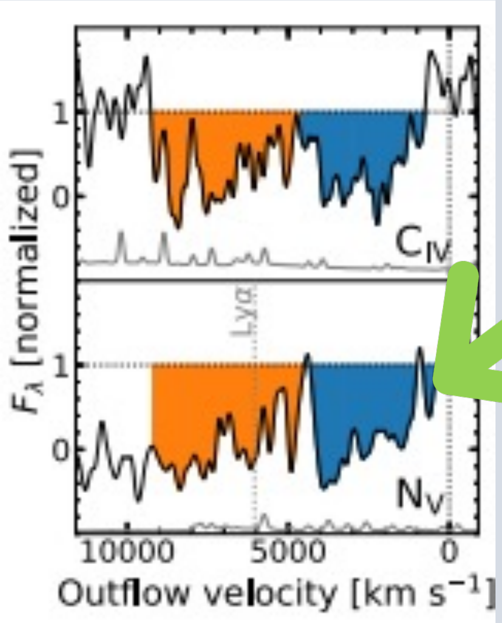
・Taking the [CII] spectrum into consideration, no host galaxy scale outflow is identified.





※ I overlaid my results onto Izumi et al. 2018

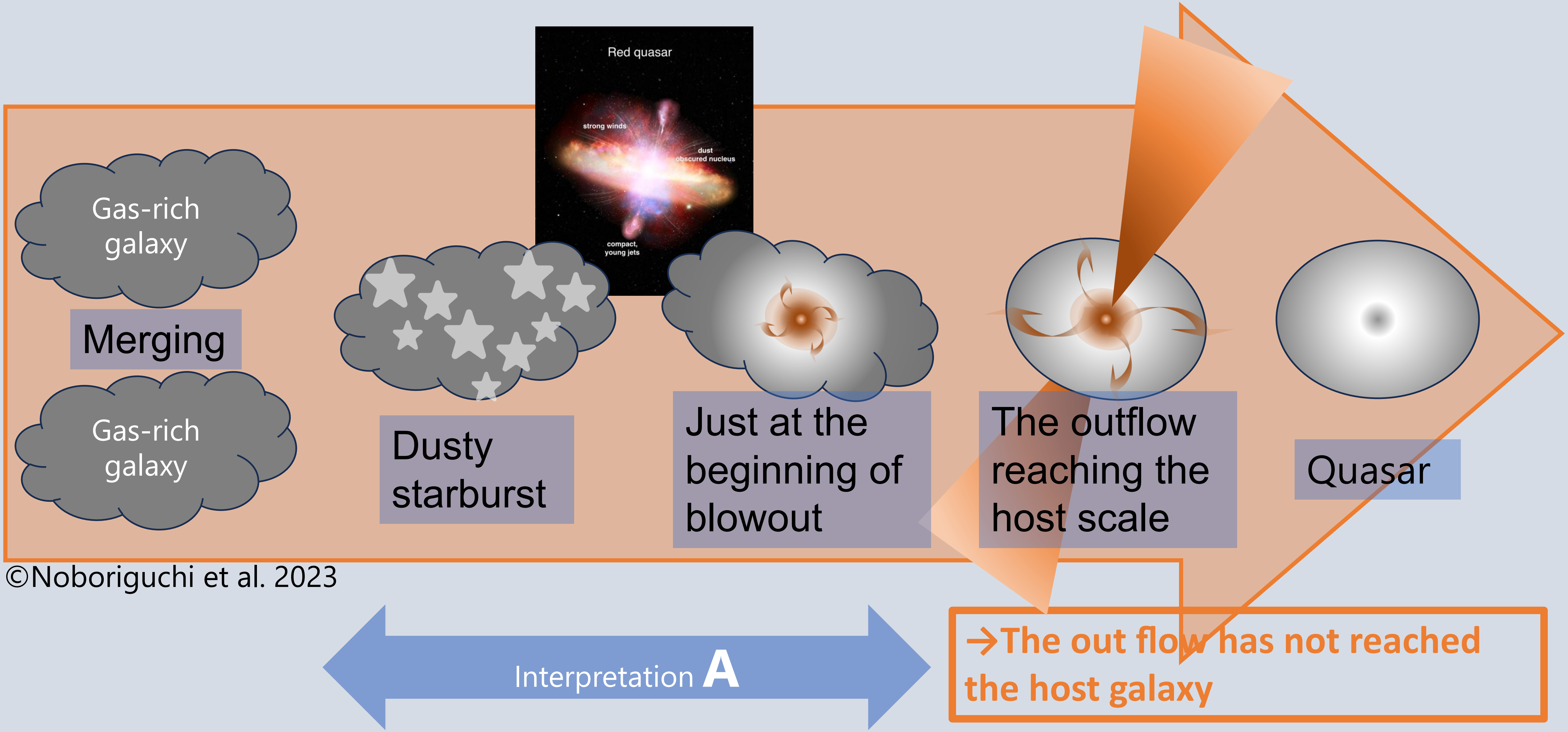
・Outflows from near the core have been confirmed.



Onoue et al. 2019

→The outflow has not reached the host galaxy

Interpretation A : Too young outflow

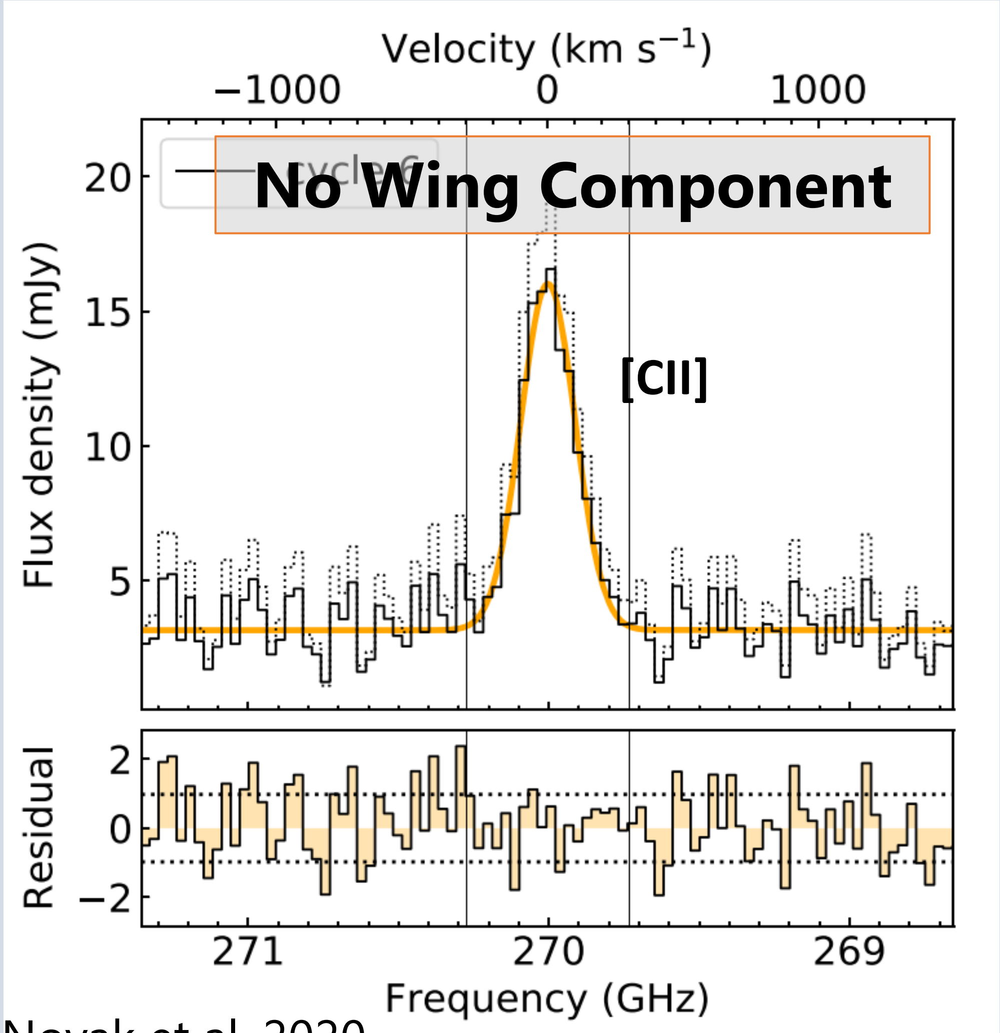


©Noboriguchi et al. 2023

→The out flow has not reached the host galaxy

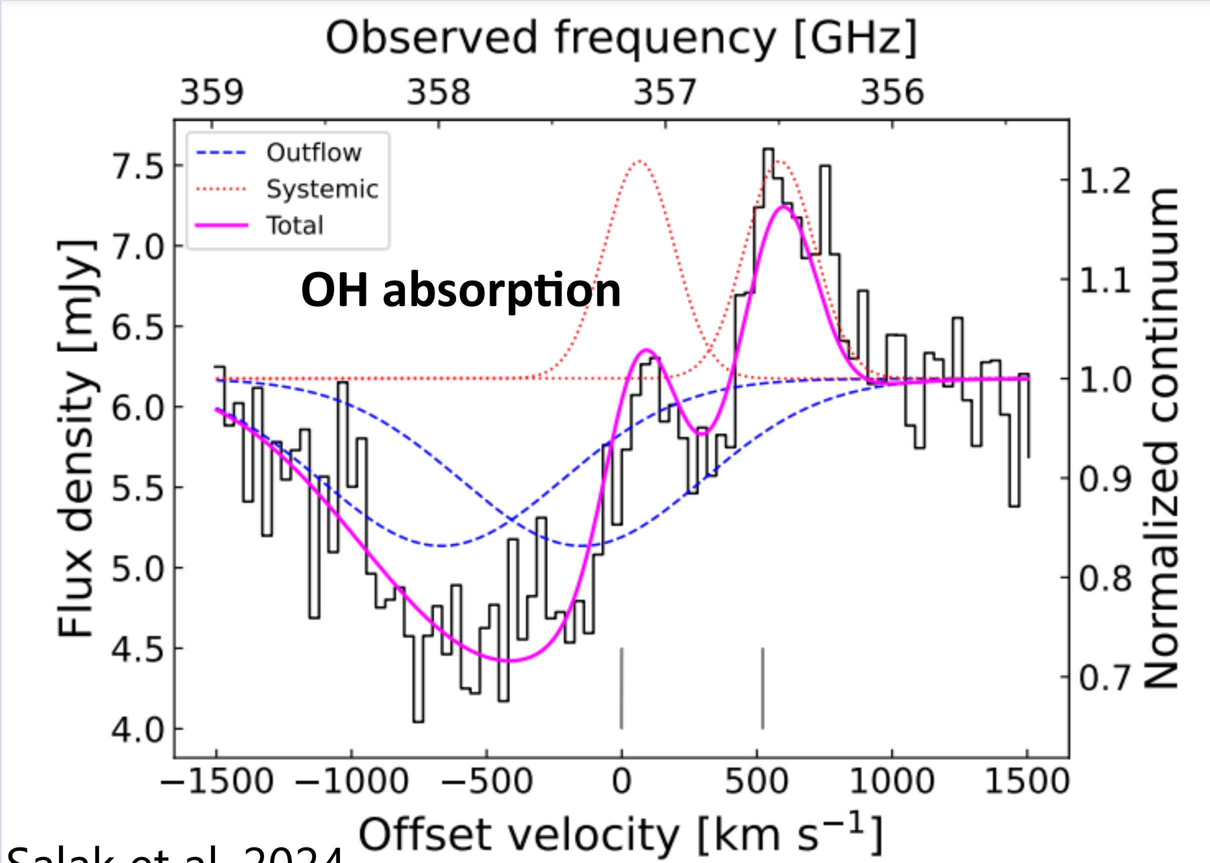
Interpretation B : [CII] is not a good tracer of outflows

- **J2054-0005** : While not visible in [CII], this shows outflows as OH absorption.



Novak et al. 2020

→The possibility that [CII] is unsuitable as an outflow tracer

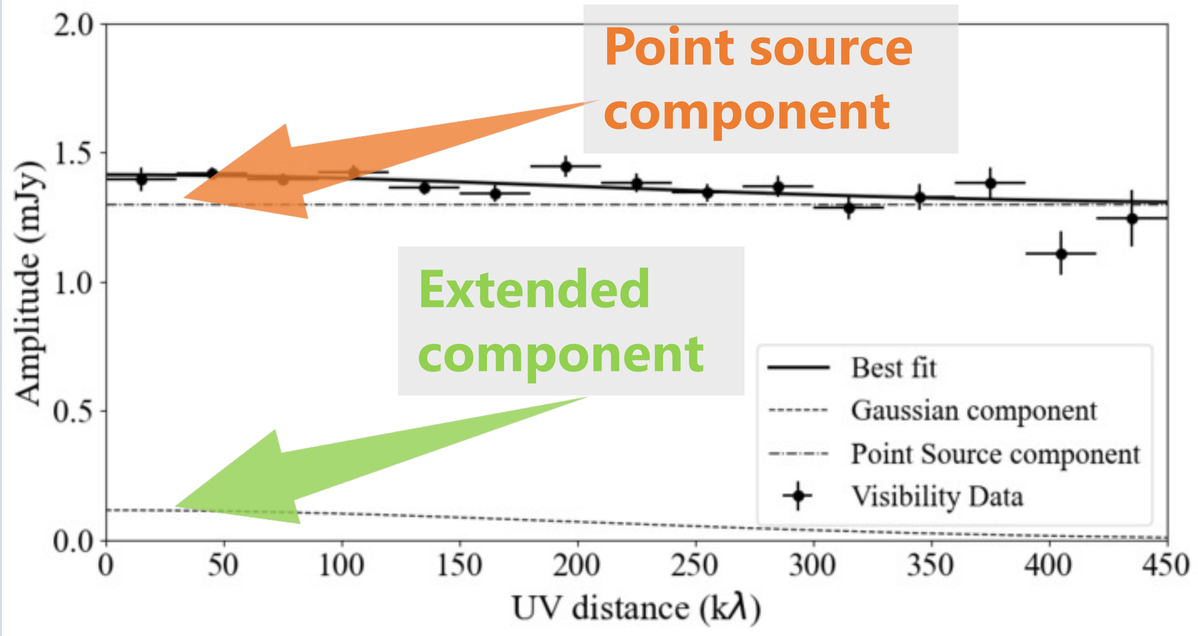


Salak et al. 2024

Supportive evidence : IR is mainly from AGN

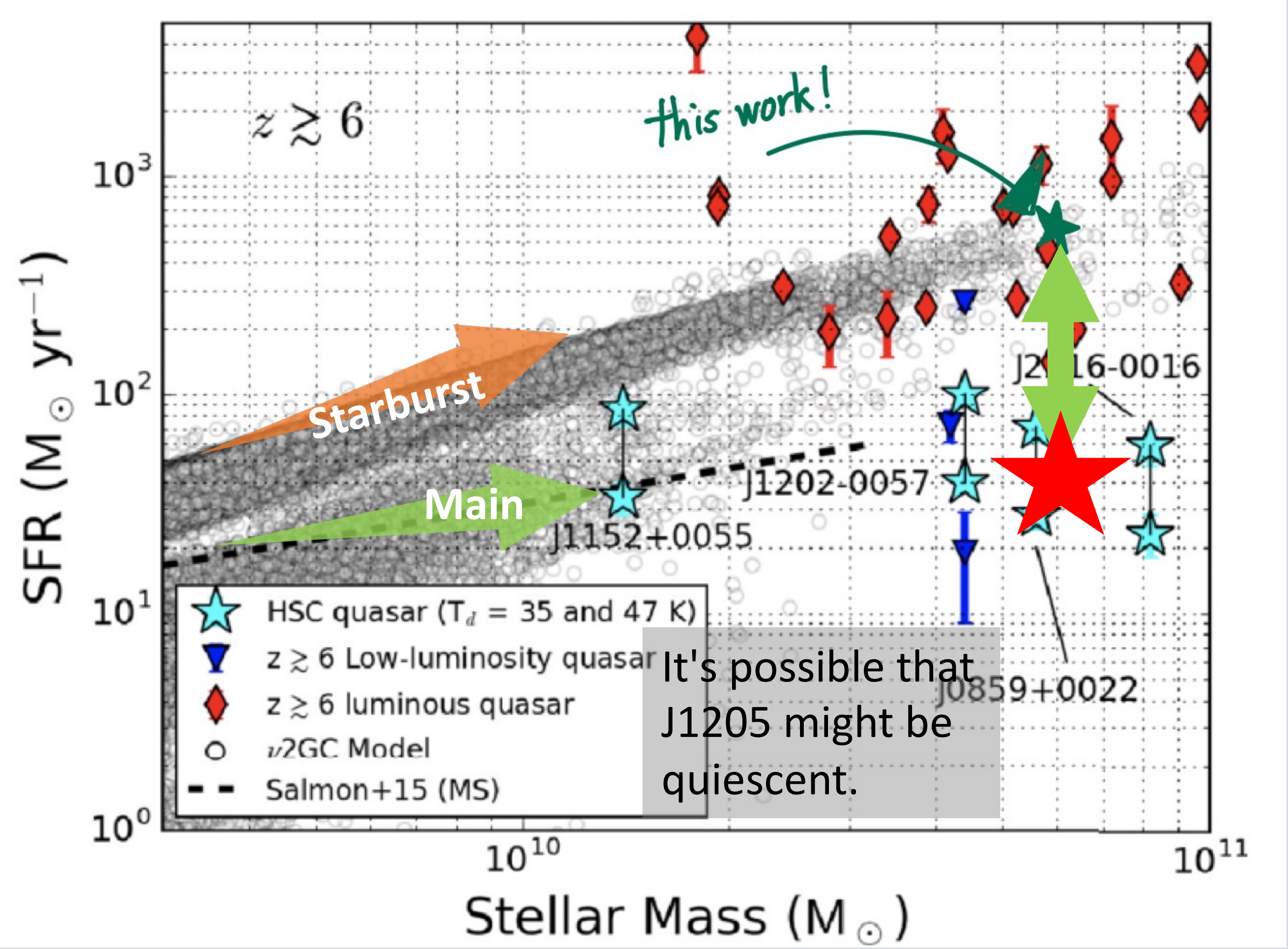
J1205 has almost point source nature, and can't extract the extended structure

Since only the IR from the AGN is visible, the SFR could be much smaller



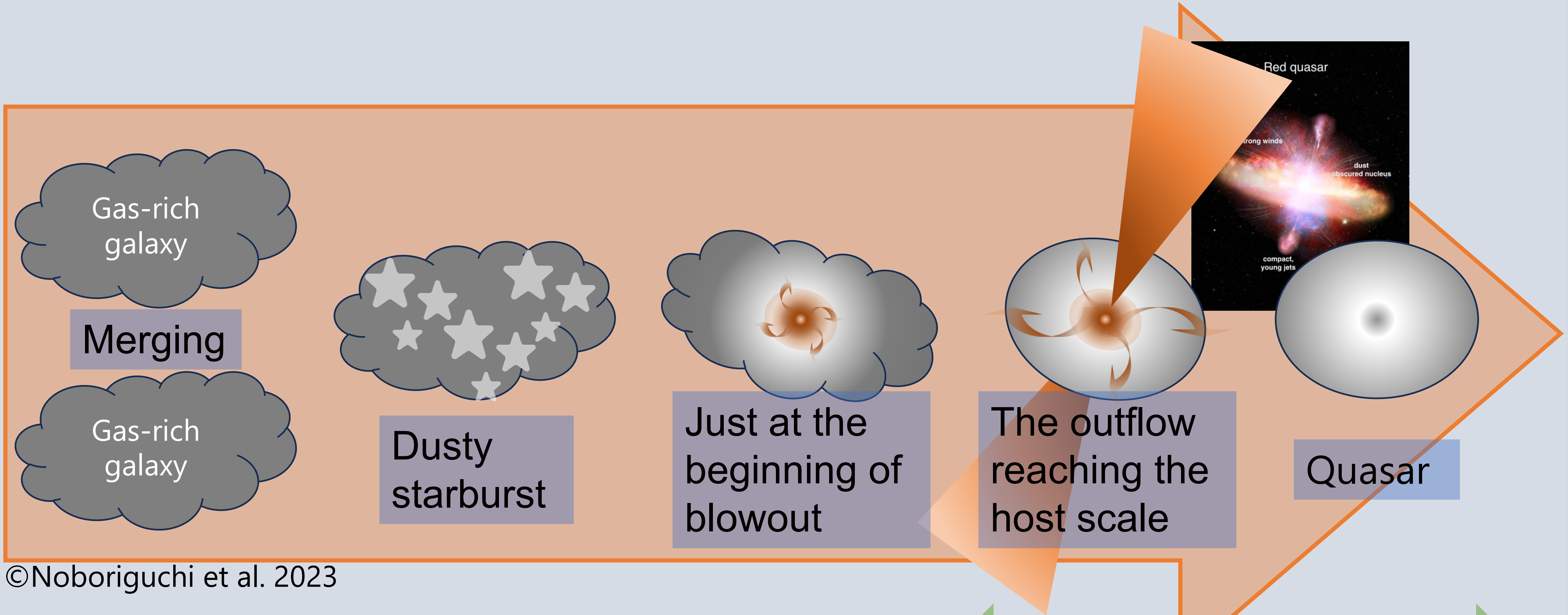
Short Base Line

Long Base Line

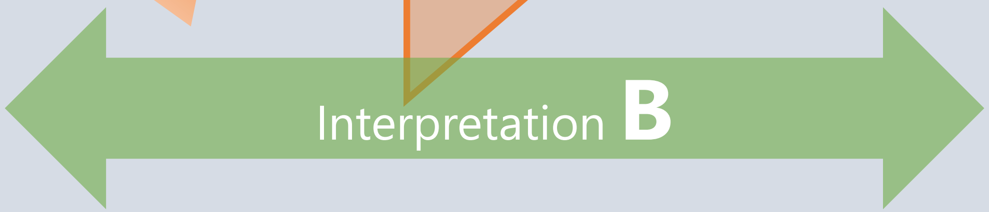


※ I overlaid my results onto Izumi et al. 2018

Interpretation B : [CII] is not a good tracer of outflows



Therefore, J1205 might be a system where SF is not active due to AGN feedback



Future Work

We will **observe another line emission** (e.g. OH, [OI]), we can validate the Interpretation B.

- OH absorption line

As Salak et al. 2024, there is a possibility that it is seen in OH absorption line rather than in [CII] 158 um.

- [OI] 63, 145 um line

	[CII] 158 um	[OI] 63 um	[OI] 145 um
Critical Density (cm^{-3})	2.8×10^{3}	4.7×10^{5}	9.4×10^{4}

If the outflow is dense and collisional de-excitation dominates, resulting in no appearance of the [CII] wing component, there is a possibility of tracing dense outflows by observing the line with higher critical densities.

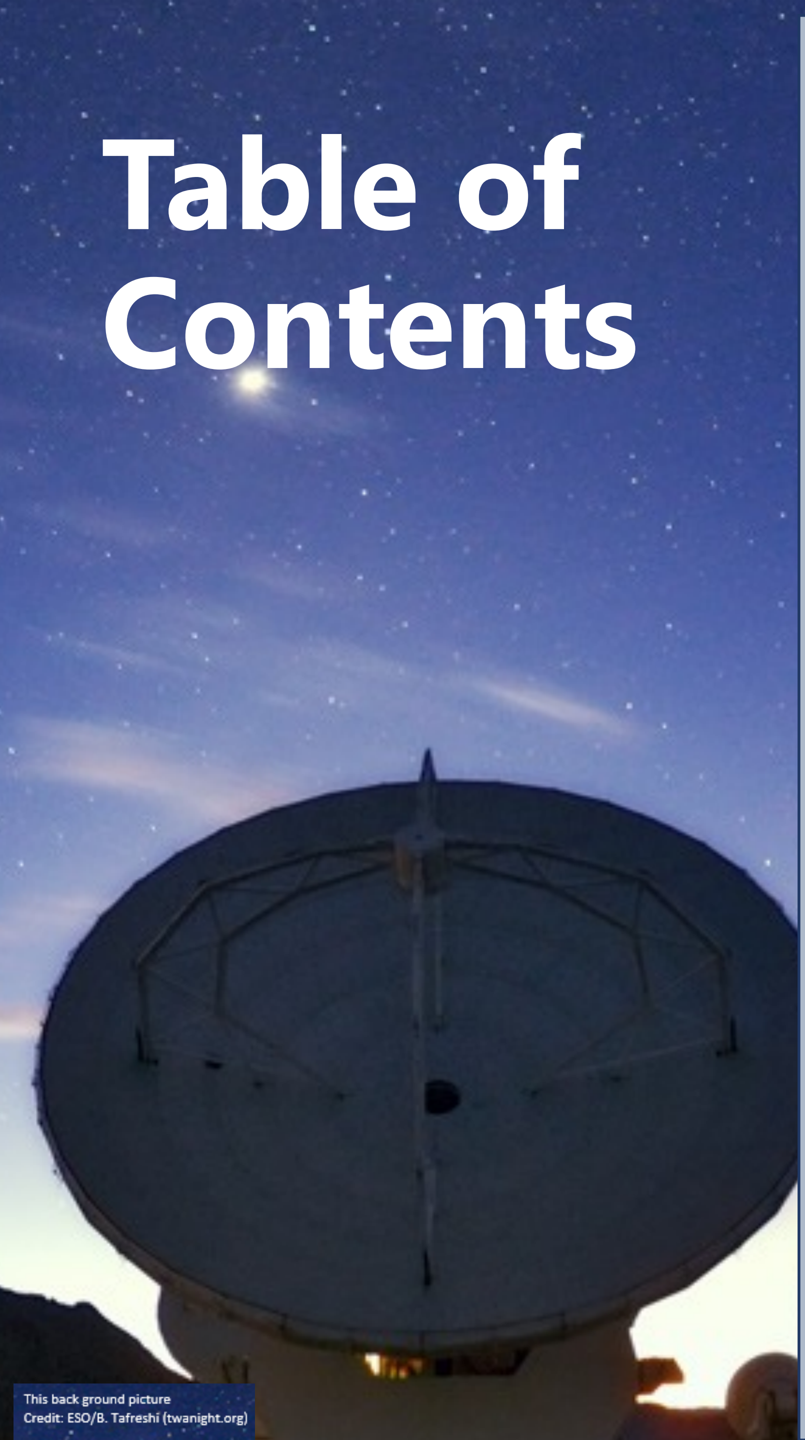


Table of Contents

This back ground picture
Credit: ESO/B. Tafreshi (twanight.org)

Summery

- We successed to observe FIR continuum and [CII] 158μm

- J1205-0000, positioned in a starburst sequence, suggests an intermediate phase of evolution as long as we assume that all the FIR flux originates from star-forming activities.

- $\boldsymbol{z_{[CII]} = 6.72}$ was determined from the [CII] spectrum. Furthermore, these results don't strongly support the presence of an AGN-driven outflow at the scale of the host galaxy.

- From these results, There could be the two interpretations.
  - ➢ **Interpretation A** : Nuclear outflow and active starforming indicate that this galaxy is in the early stages of being blown away.
  - ➢ **Interpretation B** : The possibility that [CII] 158μm is unsuitable as an outflow tracer（Salak et al. 2024). And my uv-amplitude analysis reveals that IR from my target is observed as a point source.→My target might have started to cease SF due to AGN feedback.

- To validate these interpretations
  - **Observing another line emission** (e.g. OH, [OI]), we can validate the Interpretation B.

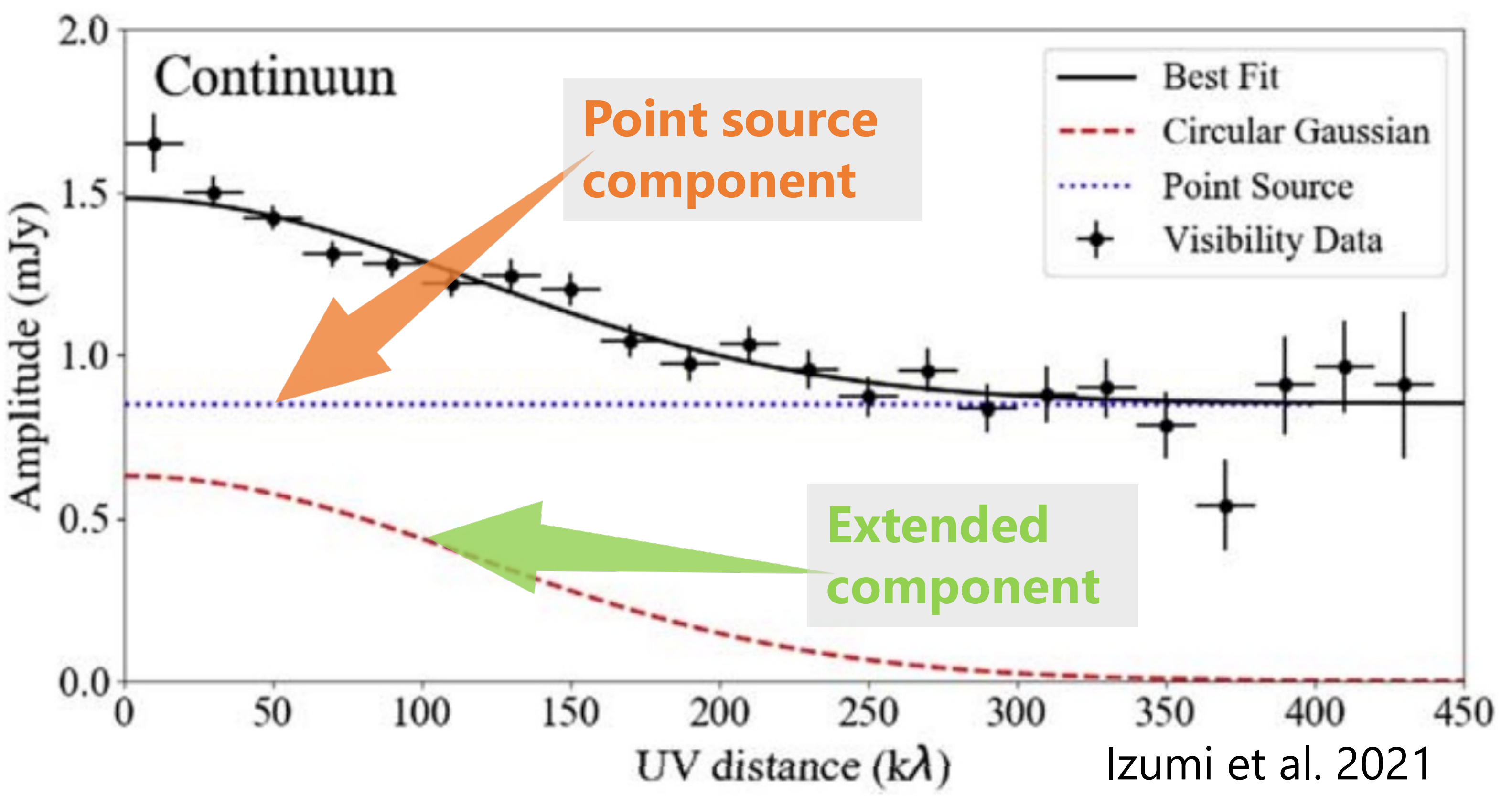
Backup slides

Supportive evidence : IR is mainly from AGN

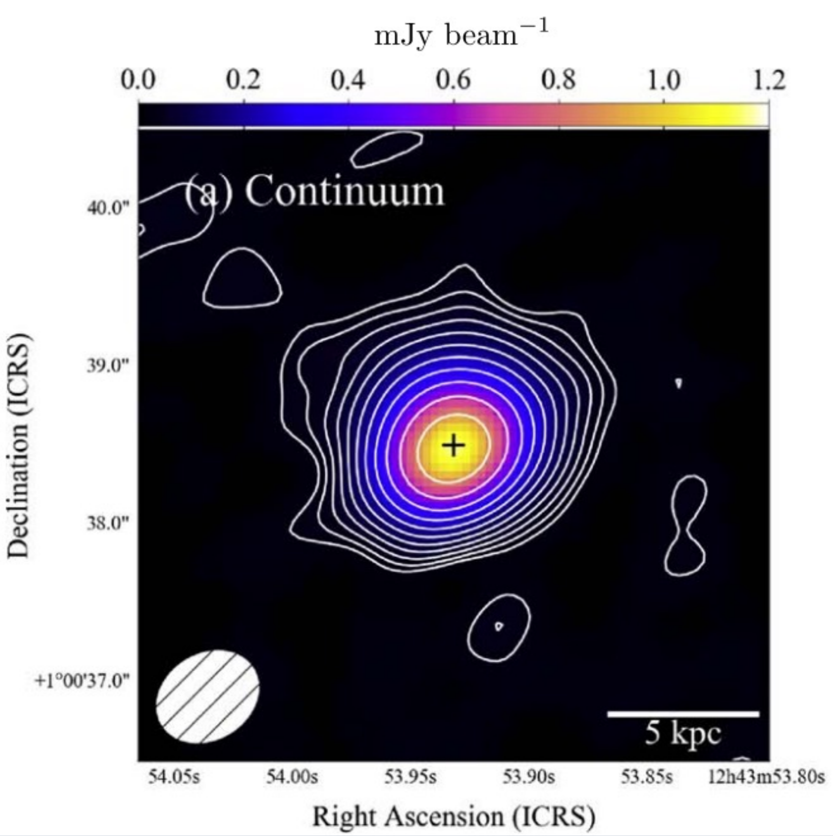
Case study
J1243+0100

- Point source components are brighter than extended components.

- For a conservative estimate of SFR, it's necessary to adopt the flux obtained from the extended component.

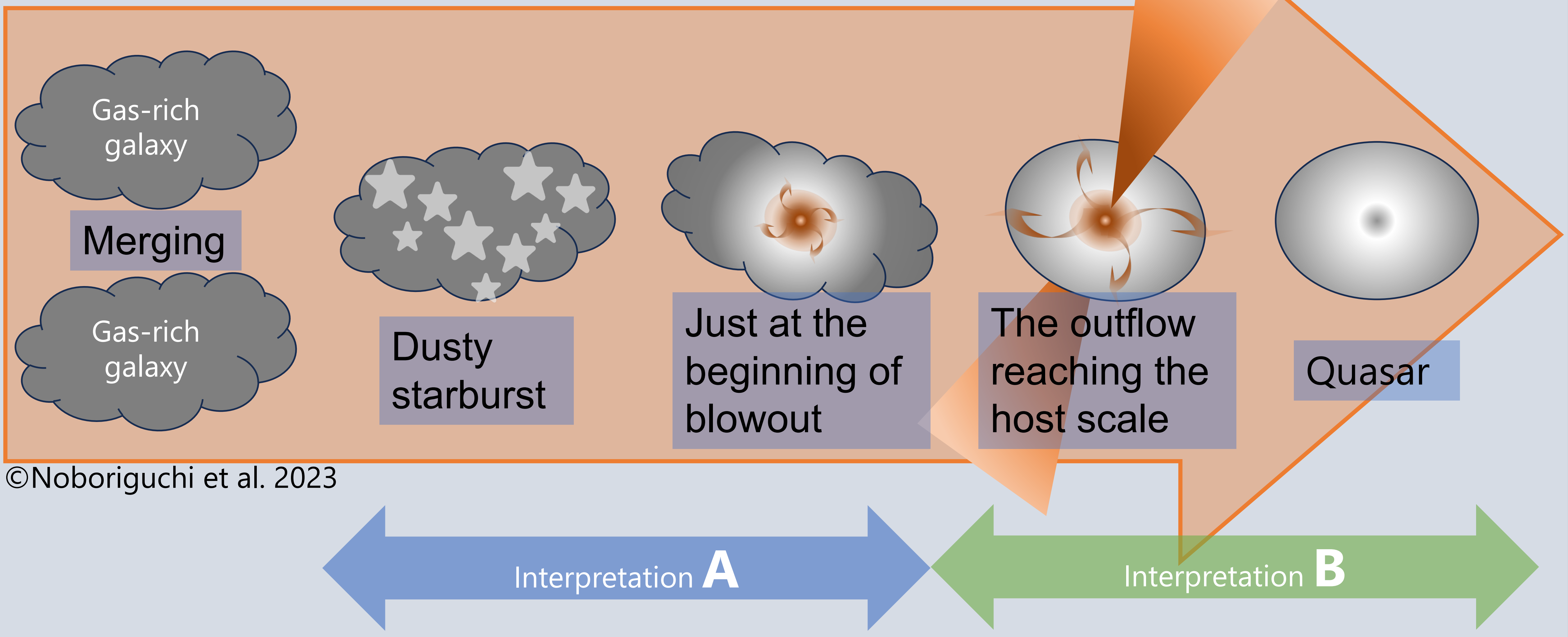


Izumi et al. 2021



Two interpretations of my results

From these results, two interpretations can be made based on the difference in phases of this evolutional proses



Deriving SFR

Star forming activity

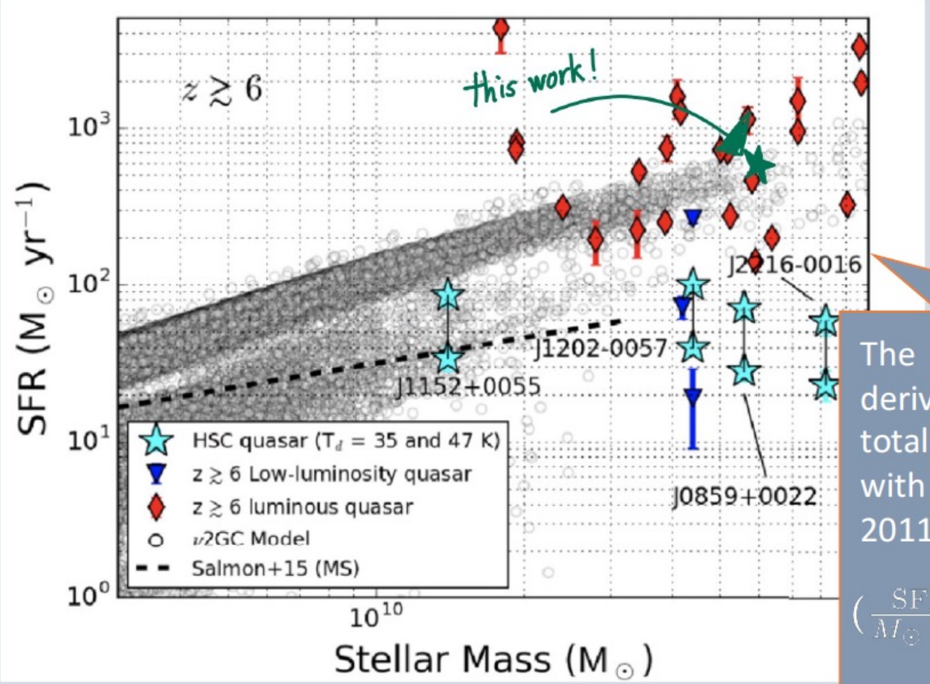


Fig.7
the M_* -SFR relationship for z ≥ 6.
※ I overlaid my results onto Izumi et al. 2018

The following equation is used to derive the SFR from the obtained total IR luminosity, in accordance with the calibration by Murphy et al. 2011.

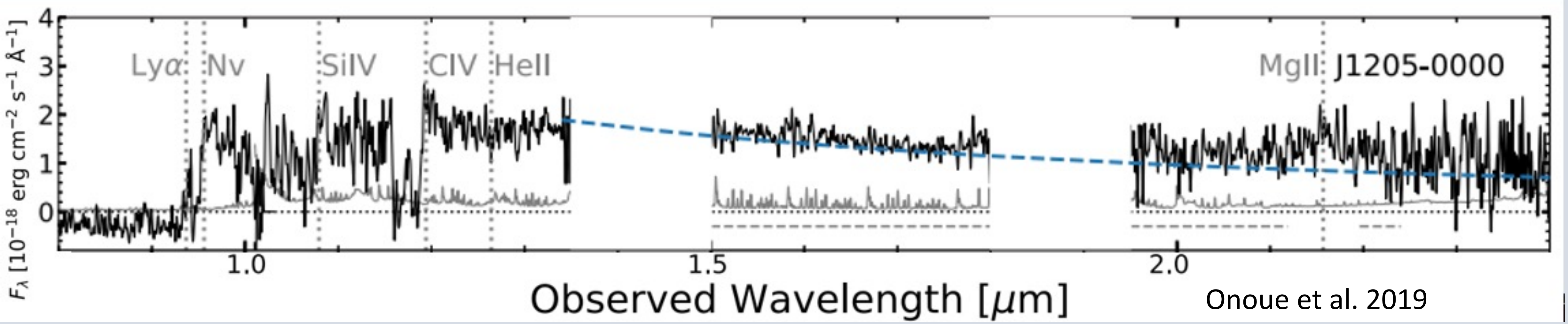
$$\left(\frac{\mathrm{SFR_{IR}}}{M_\odot\ \mathrm{yr}^{-1}}\right) = 3.88 \times 10^{-44}\left(\frac{L_{\mathrm{IR}}}{\mathrm{erg\ s^{-1}}}\right)$$

The dynamical mass (M_{dyn}) of the host galaxy is derived using the following equation, which assumes [CII] emission from a geometrically thin disk.

$$M_{\mathrm{dyn}}\ \sin^2 i/M_\odot = 1.16 \times 10^5 \left(\frac{0.75\mathrm{FWHM_{[CII]}}}{\mathrm{km\ s^{-1}}}\right)^2 \left(\frac{D}{\mathrm{kpc}}\right)$$

M_{dyn} is regarded as stellar mass (M_*) in this work for simplicity.

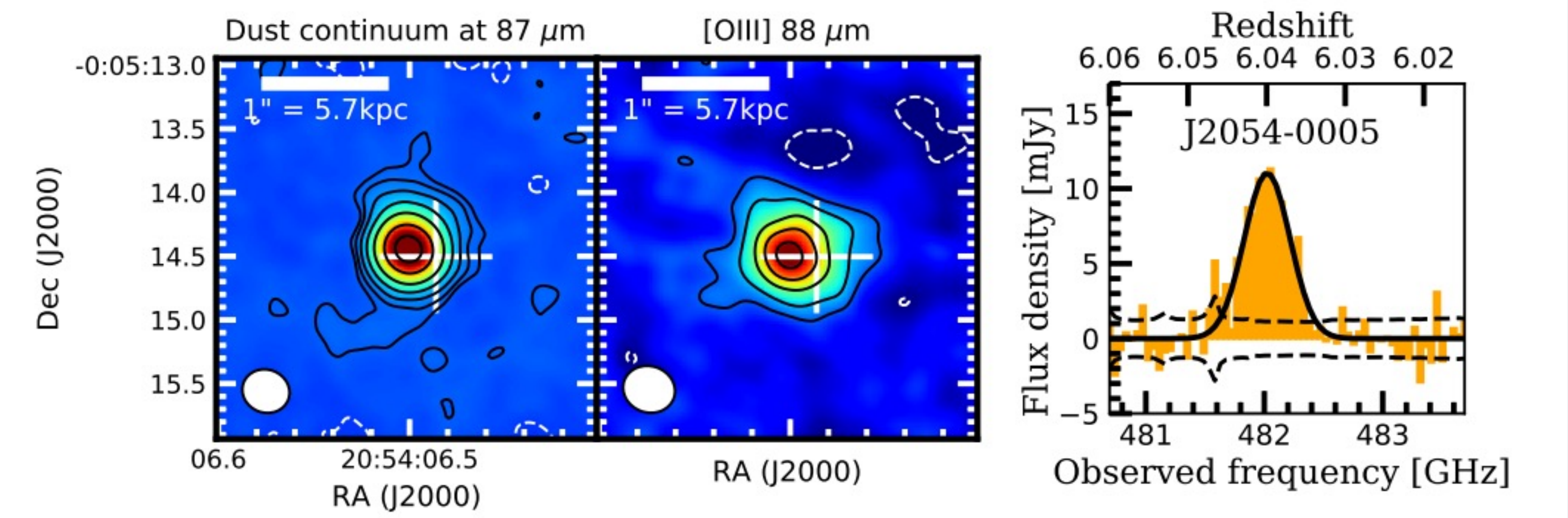
J1205-0000 : Spectra



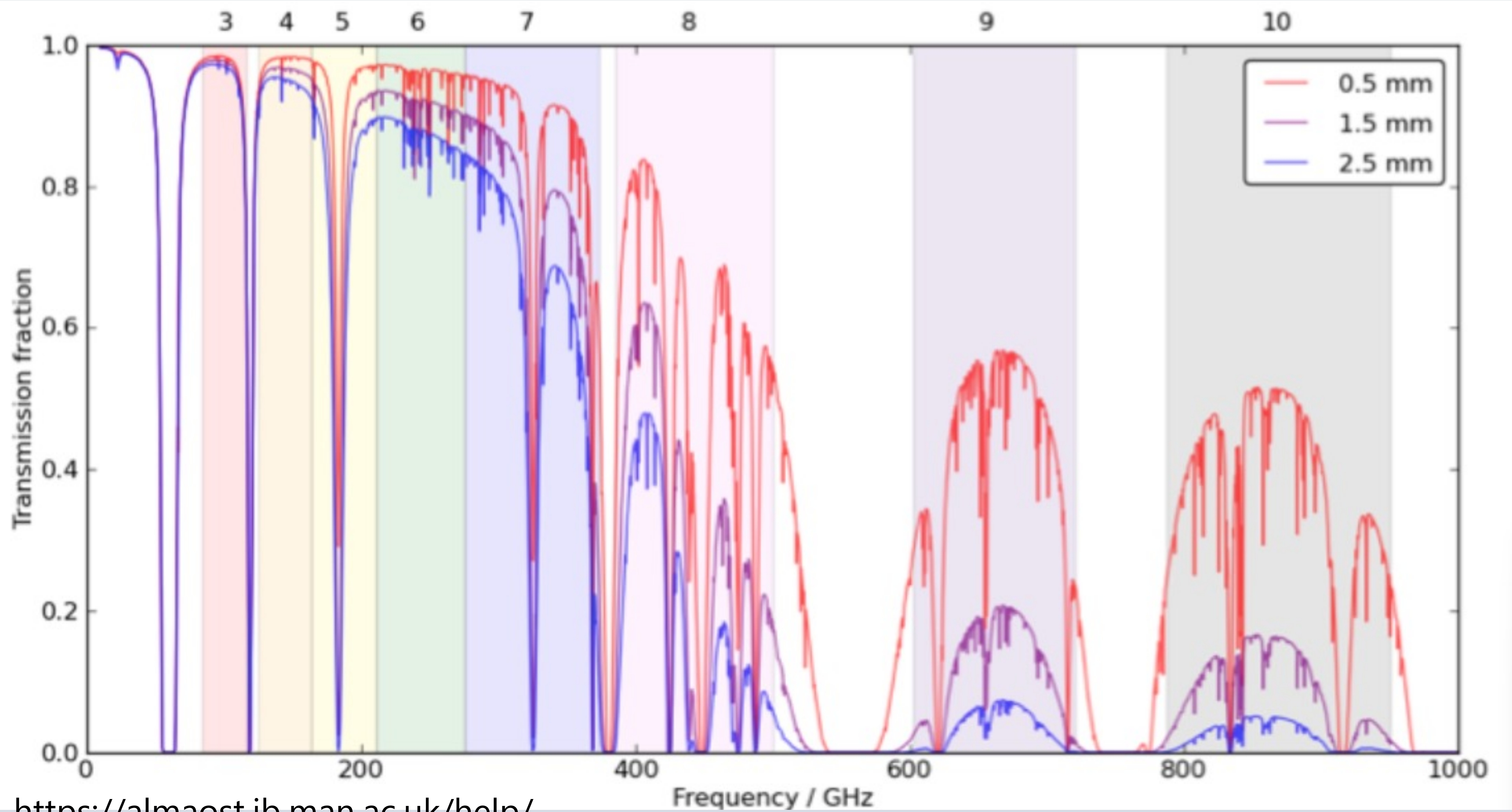
Onoue et al. 2019

J2054-0005 [OIII]

[OIII]



Atmospheric transmission fraction at the ALMA site



https://almaost.jb.man.ac.uk/help/

Critical density for fine structure line

輝線	遷移	励起温度 (K)	臨界密度 (cm^{-3})	静止波長 (μm)
[C I]	$^3P_2 \to {}^3P_1$	63	1.2×10^3	370.42
[C I]	$^3P_1 \to {}^3P_0$	24	4.7×10^2	609.14
[C II]	$^2P_{3/2} \to {}^2P_{1/2}$	91	2.8×10^3	157.74
[O I]	$^3P_1 \to {}^3P_2$	228	4.7×10^5	63.18
[O I]	$^3P_0 \to {}^3P_1$	329	9.4×10^4	145.53
[O III]	$^3P_2 \to {}^3P_1$	440	3.6×10^3	51.82
[O III]	$^3P_1 \to {}^3P_0$	163	5.1×10^2	88.36
[N II]	$^3P_1 \to {}^3P_2$	188	3.1×10^2	121.90
[N II]	$^3P_1 \to {}^3P_0$	70	4.8×10^1	205.18

https://www.asj.or.jp/geppou/archive_open/2017_110_03/110_185.pdf

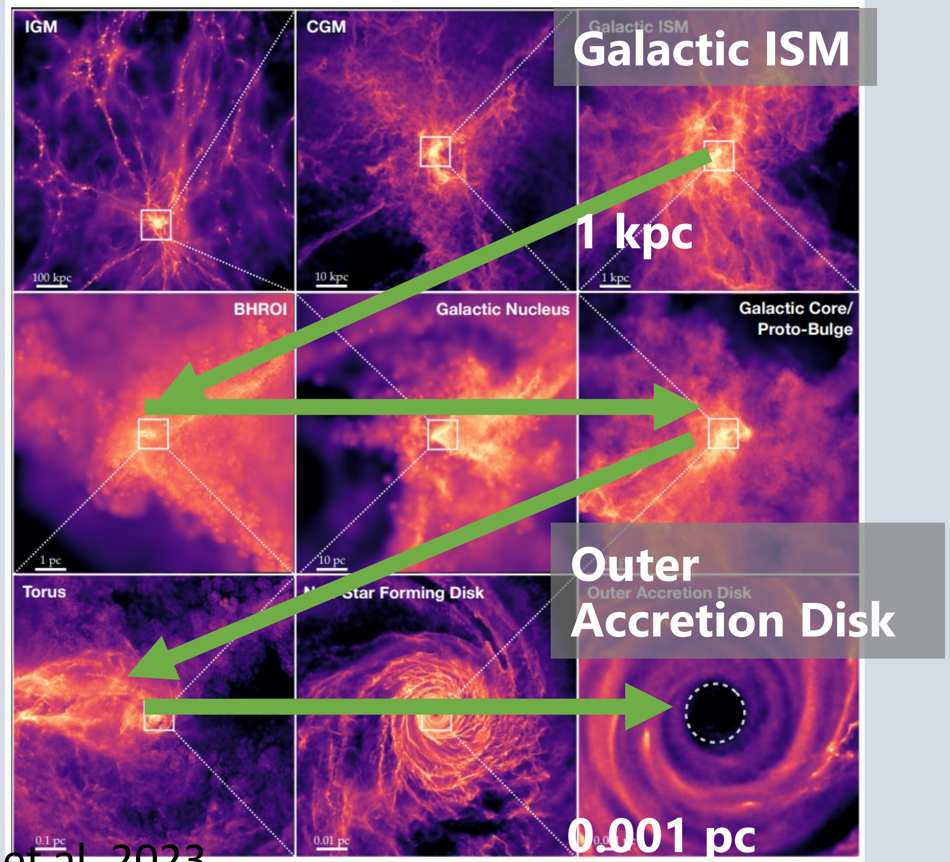
Co-evolution of galaxies and black holes

- There is a strong correlation between the mass of SMBH and the bulge.

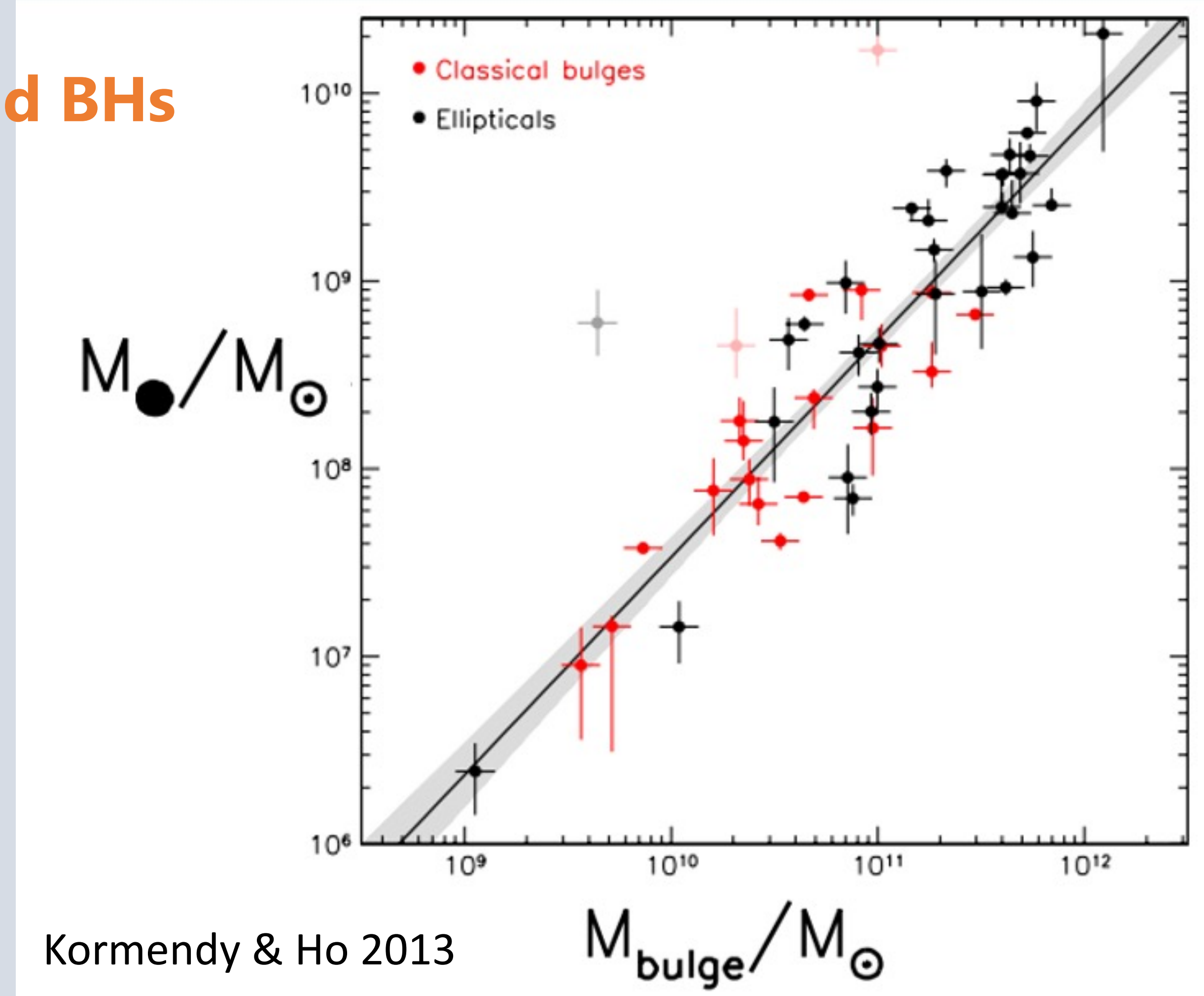
→However, both objects operate on different spatial scales (3 to 6 orders)

→A complex relationship between the two?

→**Suggesting co-evolution of galaxies and BHs**



Hopkins et al. 2023



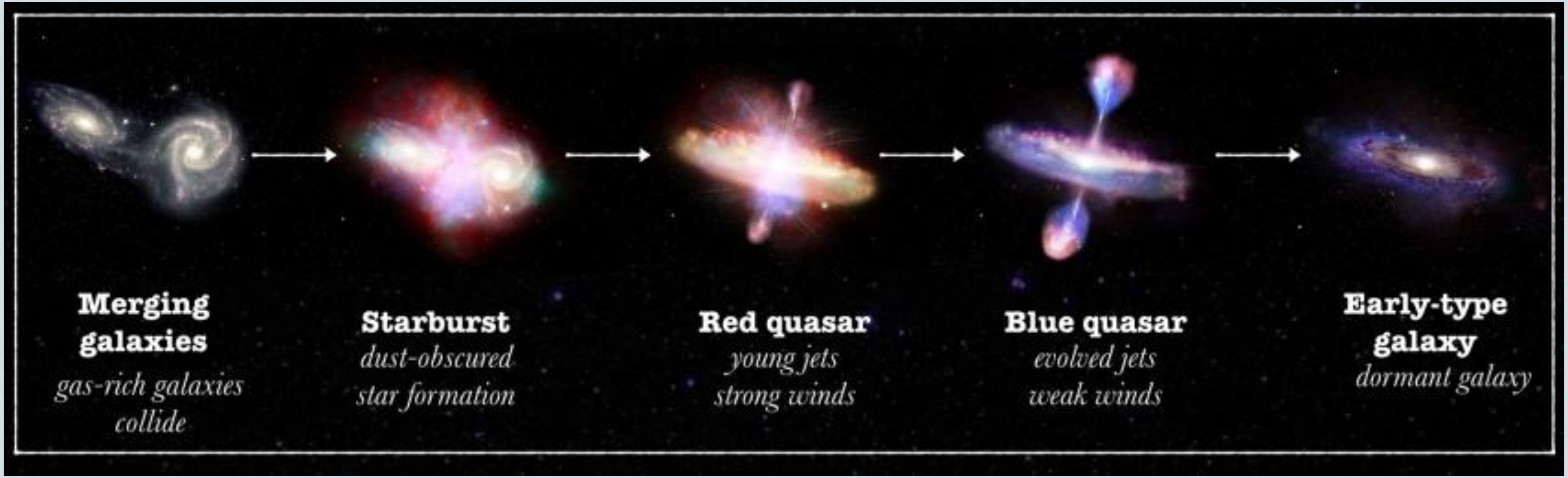
Kormendy & Ho 2013

Negative AGN feedback

- Galaxy evolution through mergers of gas-rich galaxies
- **Negative AGN feedback** (e.g. Hopkins et al. 2006)

Accretion onto SMBH→**AGN driven outflow**→blowing away gas & dust→Quenching SF
(Analytically, determined that outflows suppress star formation.(e.g. Di Matteo et al. 2005))

- **It's crucial to verify whether there is a host scale outflow in the galaxy (quasar)**

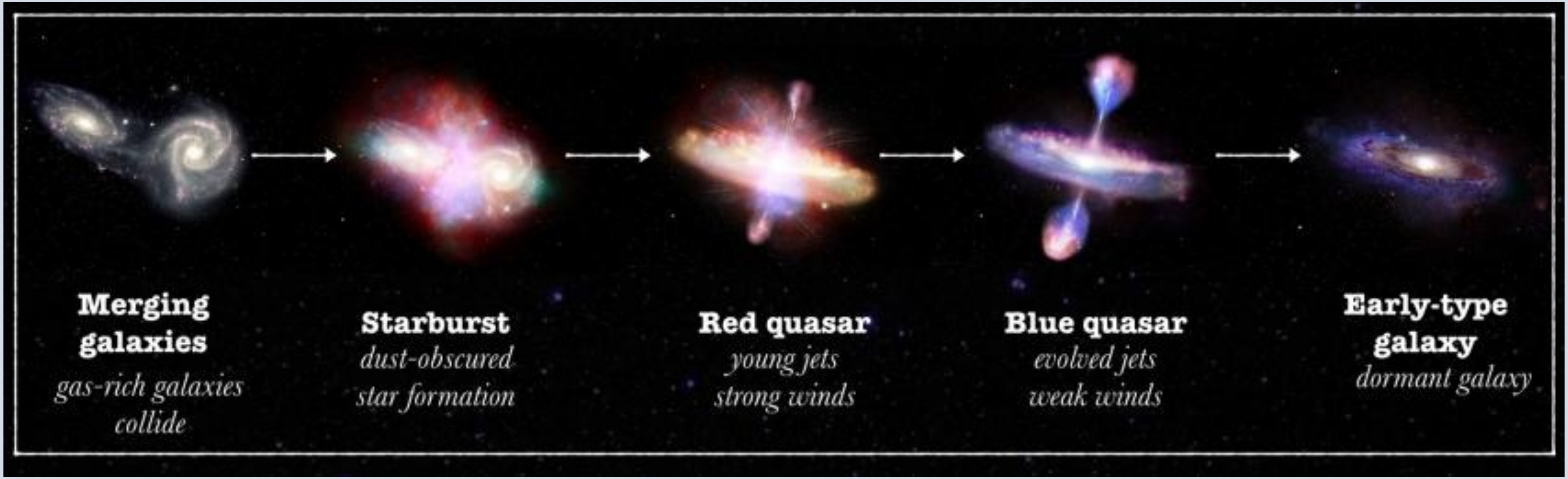


Credits: Gemini Observatory, GMOS-South, NSF/; Adapted by S. Munro.

Co-evolution of galaxies and black holes

The importance of investigating both objects from the past to the present.

- The evolution through mergers of gas-rich galaxies is considered a plausible scenario



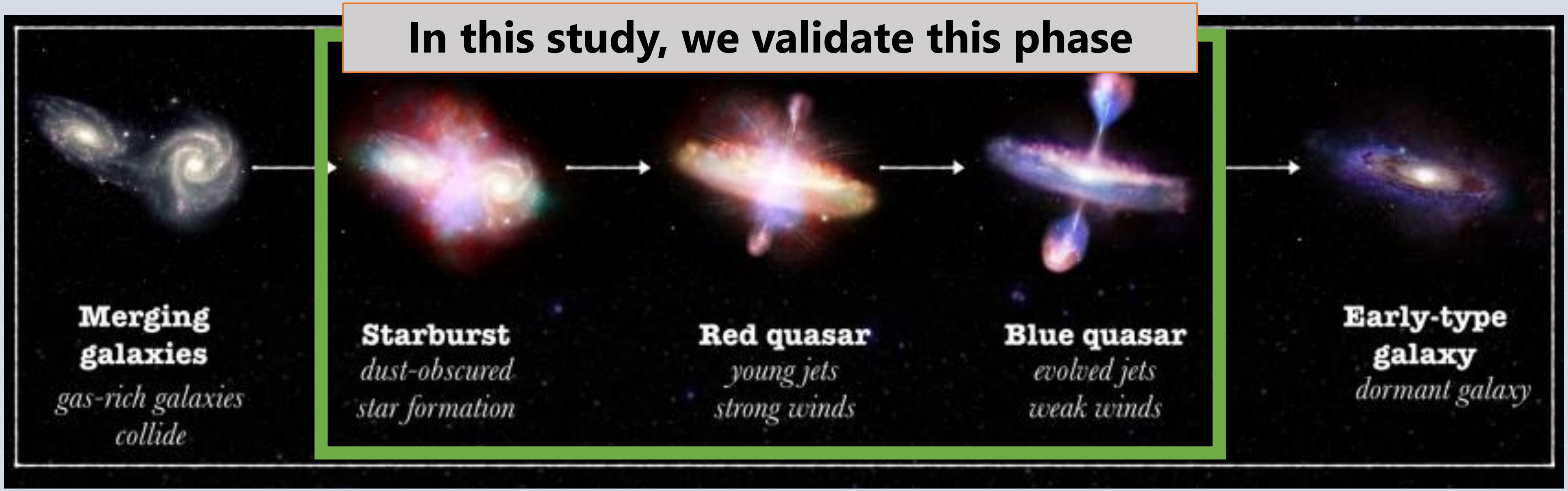
Credits: Gemini Observatory, GMOS-South, NSF/; Adapted by S. Munro.

Negative AGN feedback

- Galaxy evolution through mergers of gas-rich galaxies
- **Negative feedback** (e.g, Hopkins et al. 2006)

Accretion onto SMBH→**AGN driven outflow**→blowing away gas & dust→Quenching SF
(Analytically, determined that outflows suppress star formation.(e.g. Di Matteo et al. 2005))

- **It's crucial to verify whether there is an host scale outflow in the galaxy (quasar)**



Credits: Gemini Observatory, GMOS-South, NSF/; Adapted by S. Munro.

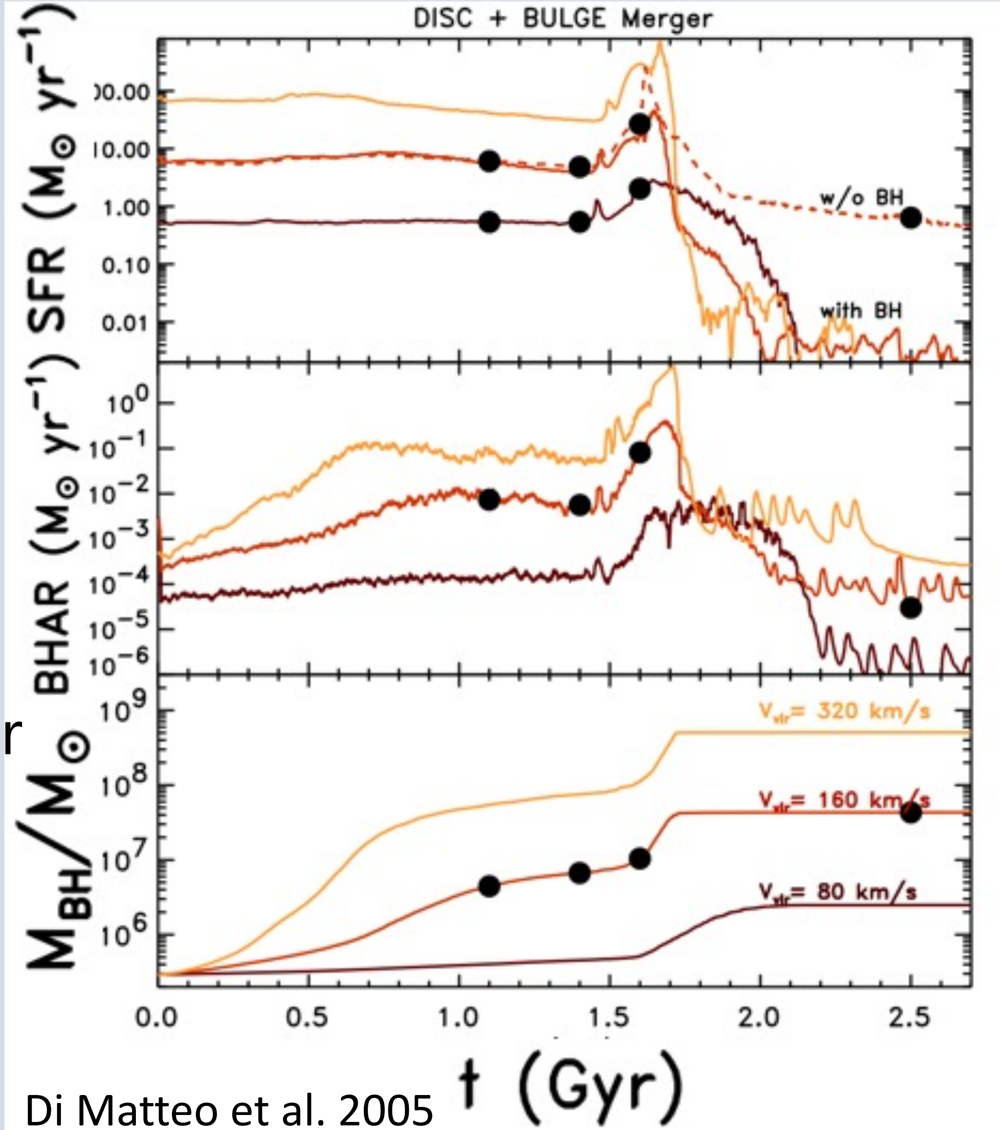
Negative feedback

- Galaxy evolution through mergers of gas-rich galaxies

- **Negative feedback** (e.g, Hopkins et al. 2006)

Accretion onto SMBH
→**AGN driven outflow**
→blowing away gas & dust
→Quenching SF

Analytically, determined that outflows suppress star formation (e.g. Di Matteo et al. 2005)

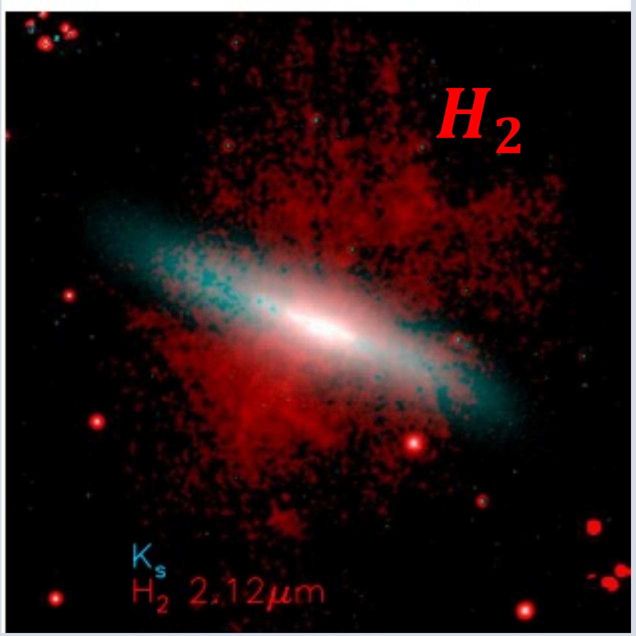


Di Matteo et al. 2005

Outflows

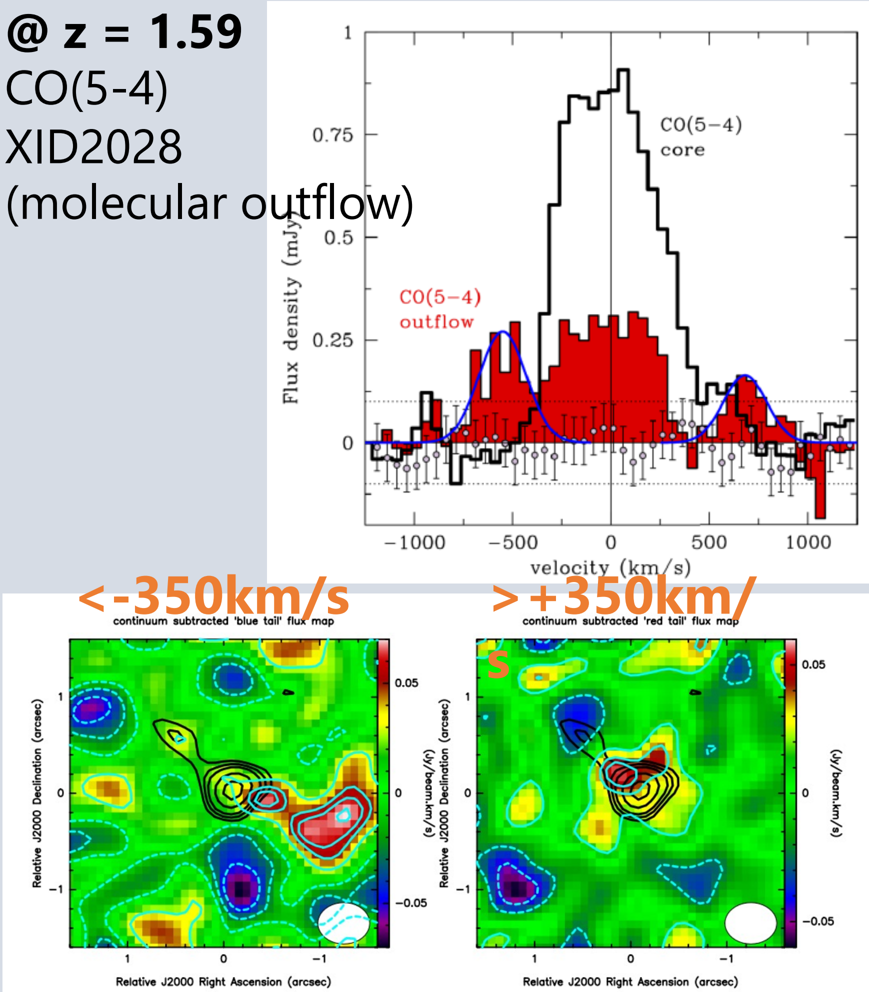
- **Outflows have been observed from the present into the past.**

@ Nearby
H_2
M82
(molecular outflow)



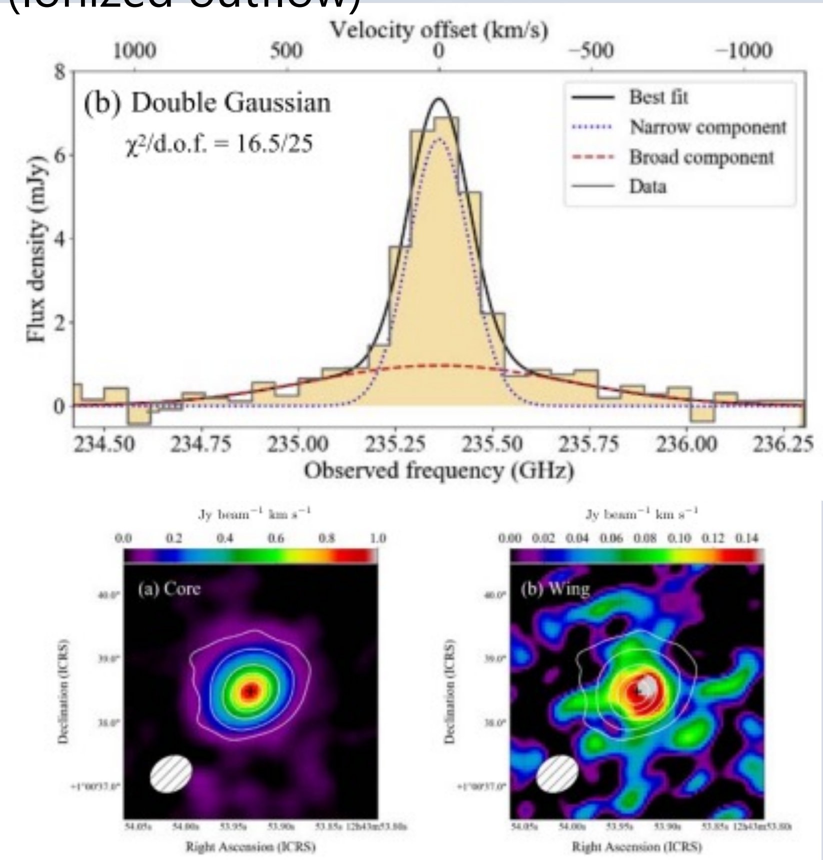
Veilleux et al. 2009b

@ z = 1.59
CO(5-4)
XID2028
(molecular outflow)



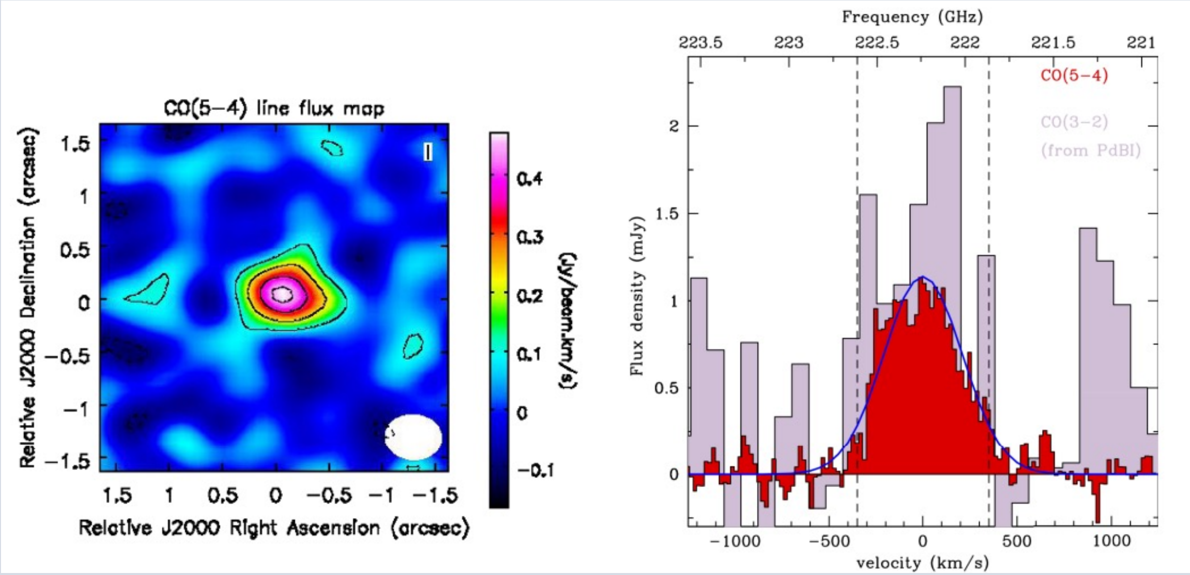
Brusa et al. 2018

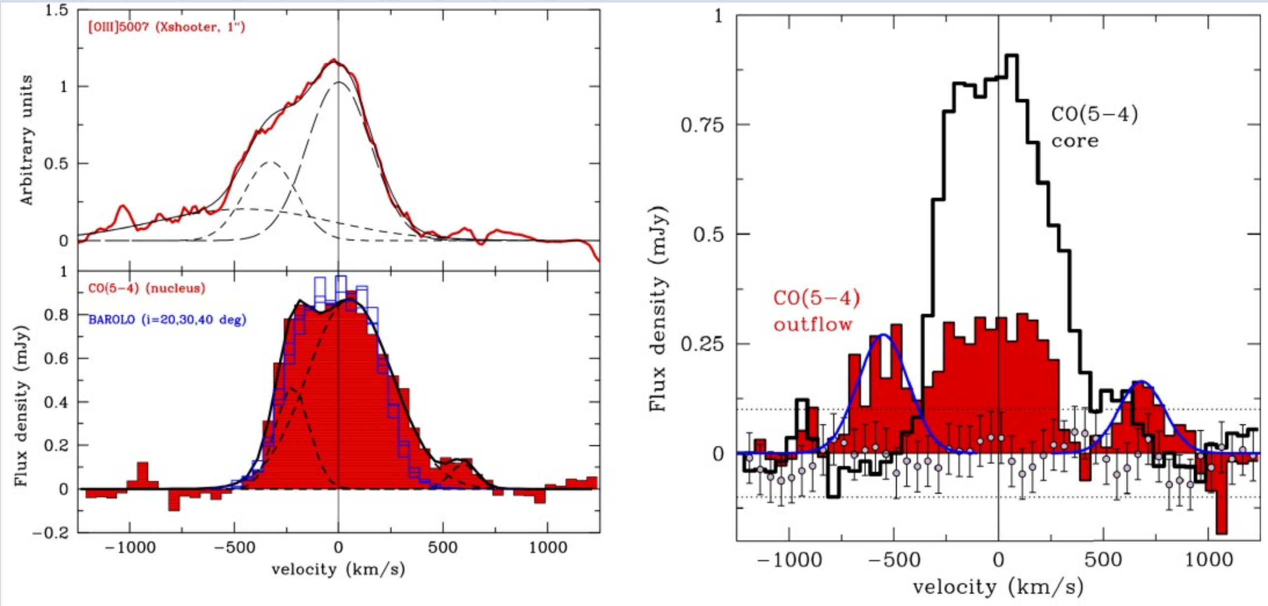
@ z = 7.07
[CII] 158μm J1243+0100
(Ionized outflow)

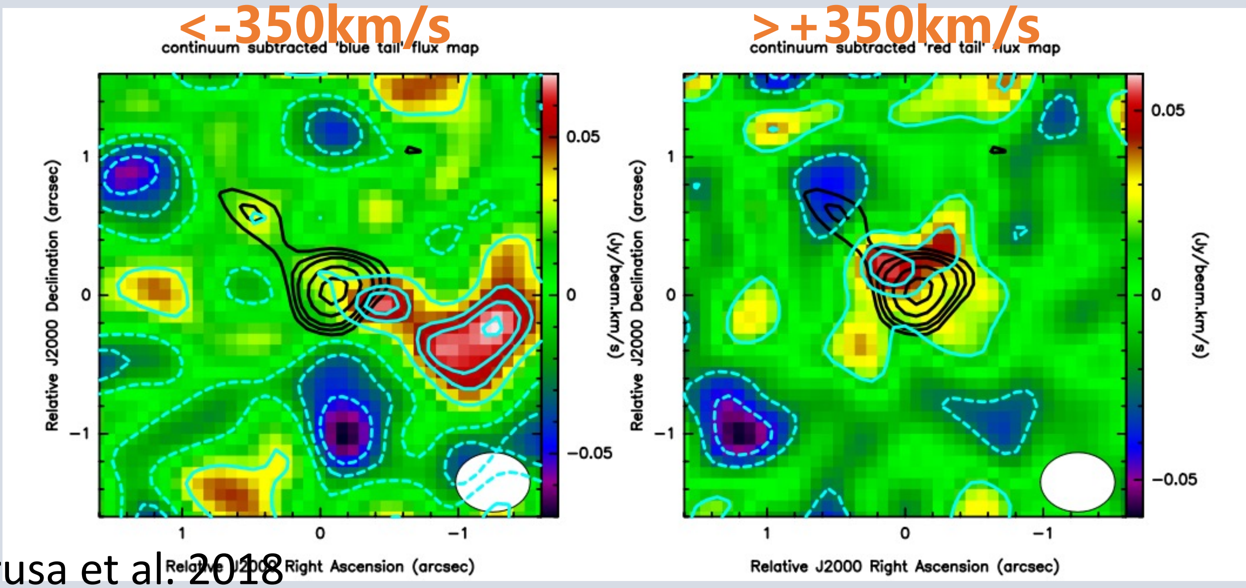


Izumi et al. 2021

Brusa et al. 2018







Brusa et al. 2018

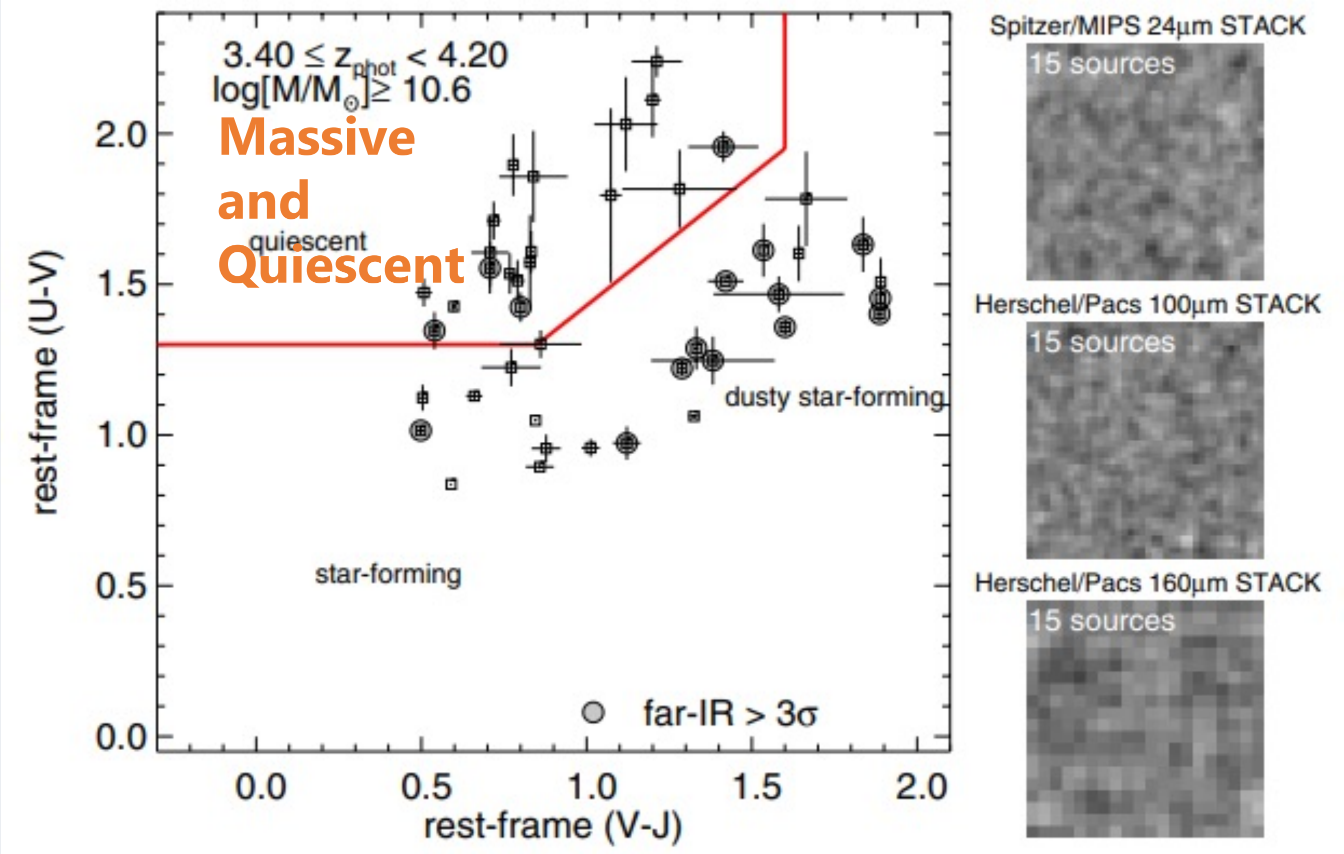
The importance of the High z Quasar observation

- It's known that the massive and quiescent galaxies already existed at z = 3~4.

(e.g. Straatman et al. 2014)

→In an era preceding this, there were significant SF, and the quenching within the process

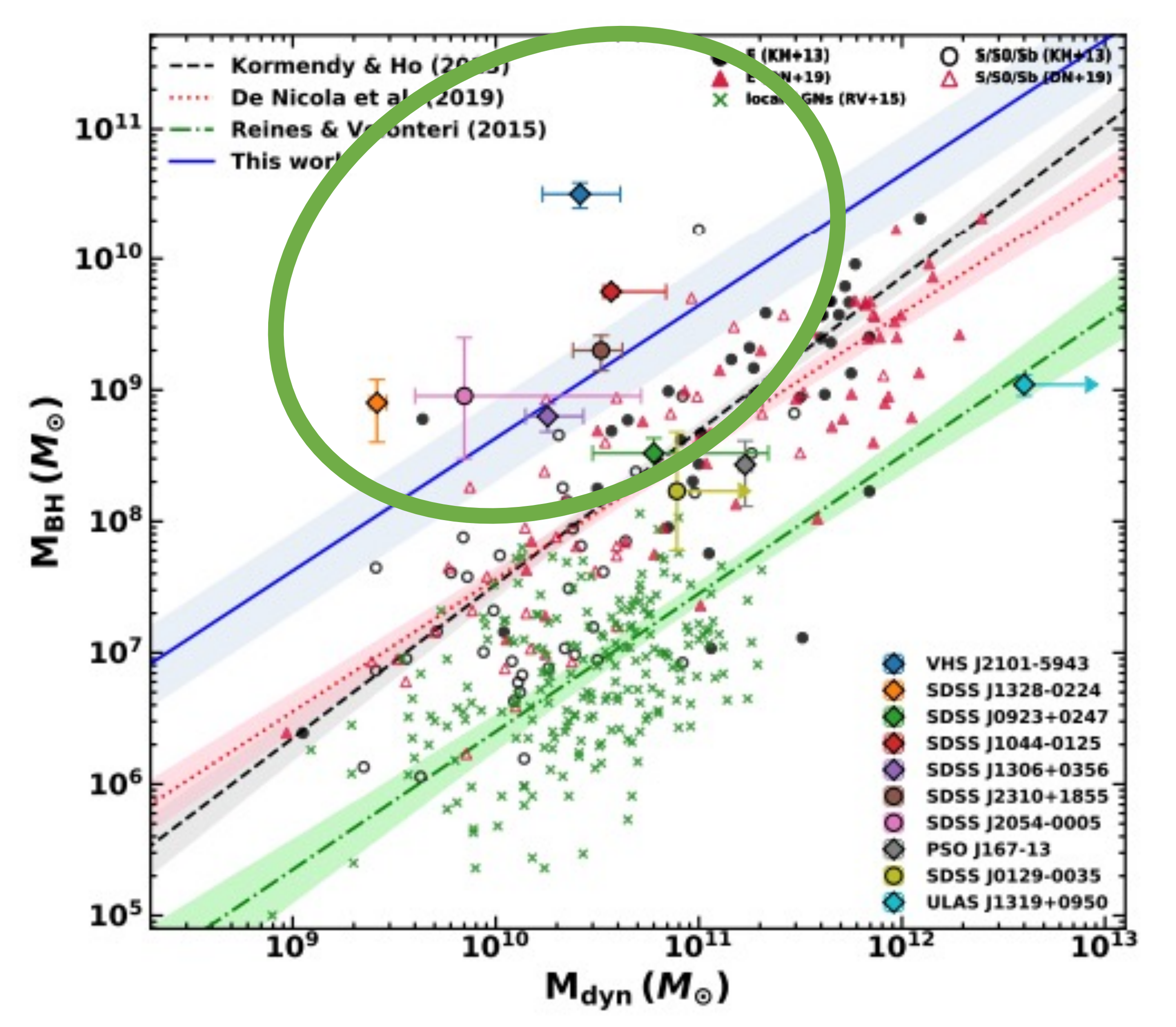
→**More observations in more distant regions of the universe are essential to validate the evolution process**



Straatman et al. 2014

High z Quasar (時間)

- BH is over massive (~10 times) in the relation between dynamical mass and BH mass
 (e.g. Pensabene et al. 2020, Lamastra et al. 2010)
- However, this presents a biased representation, with a majority of luminous quasars dominating the image.



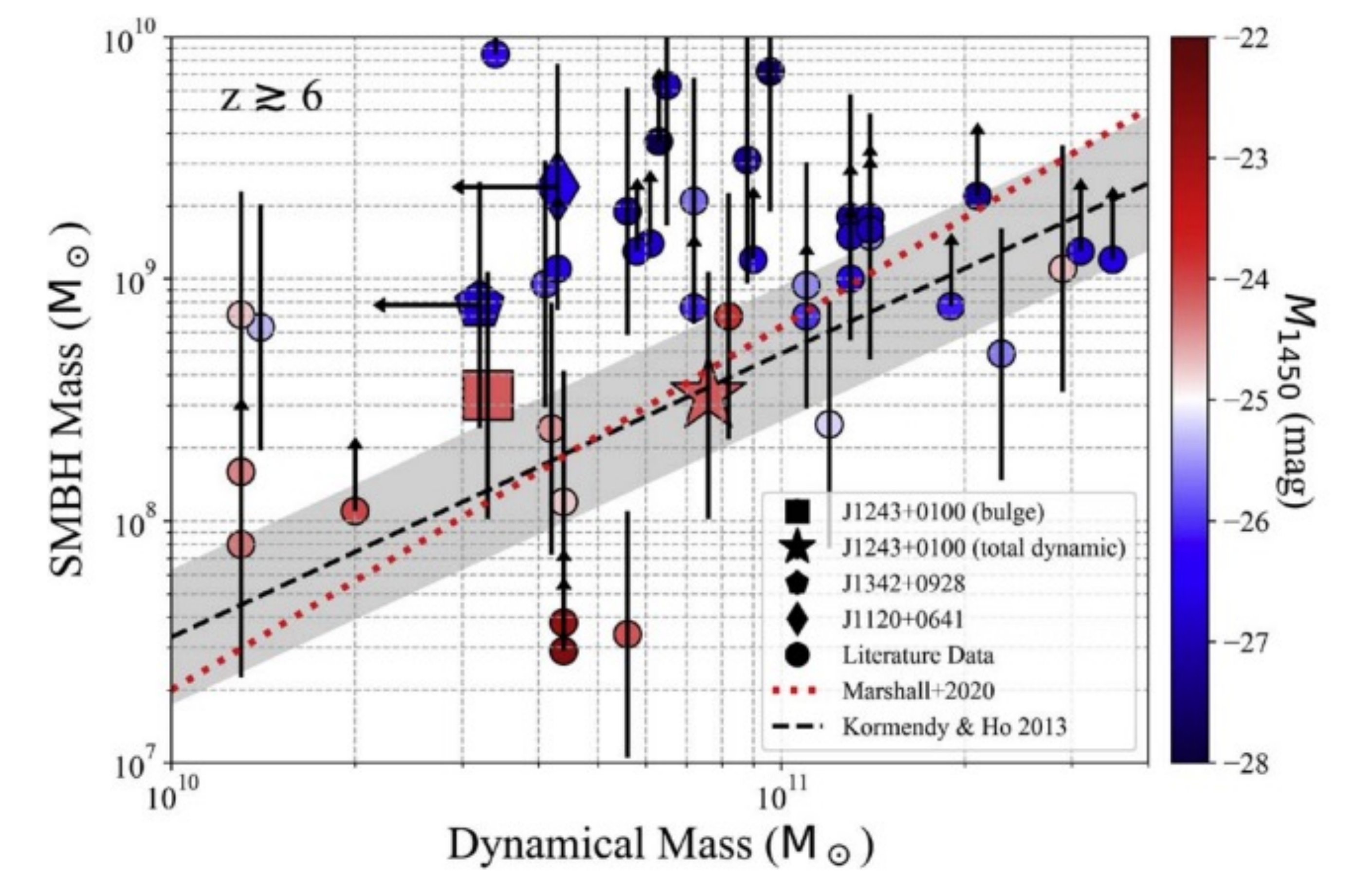
Pensabene et al. 2020

Low luminosity Quasar at high redshift (時間)

- Another tendency between Low luminosity quasar and luminous quasar

Luminous quasar → BH mass is over massive

Low-luminosity quasar → Similar to the local

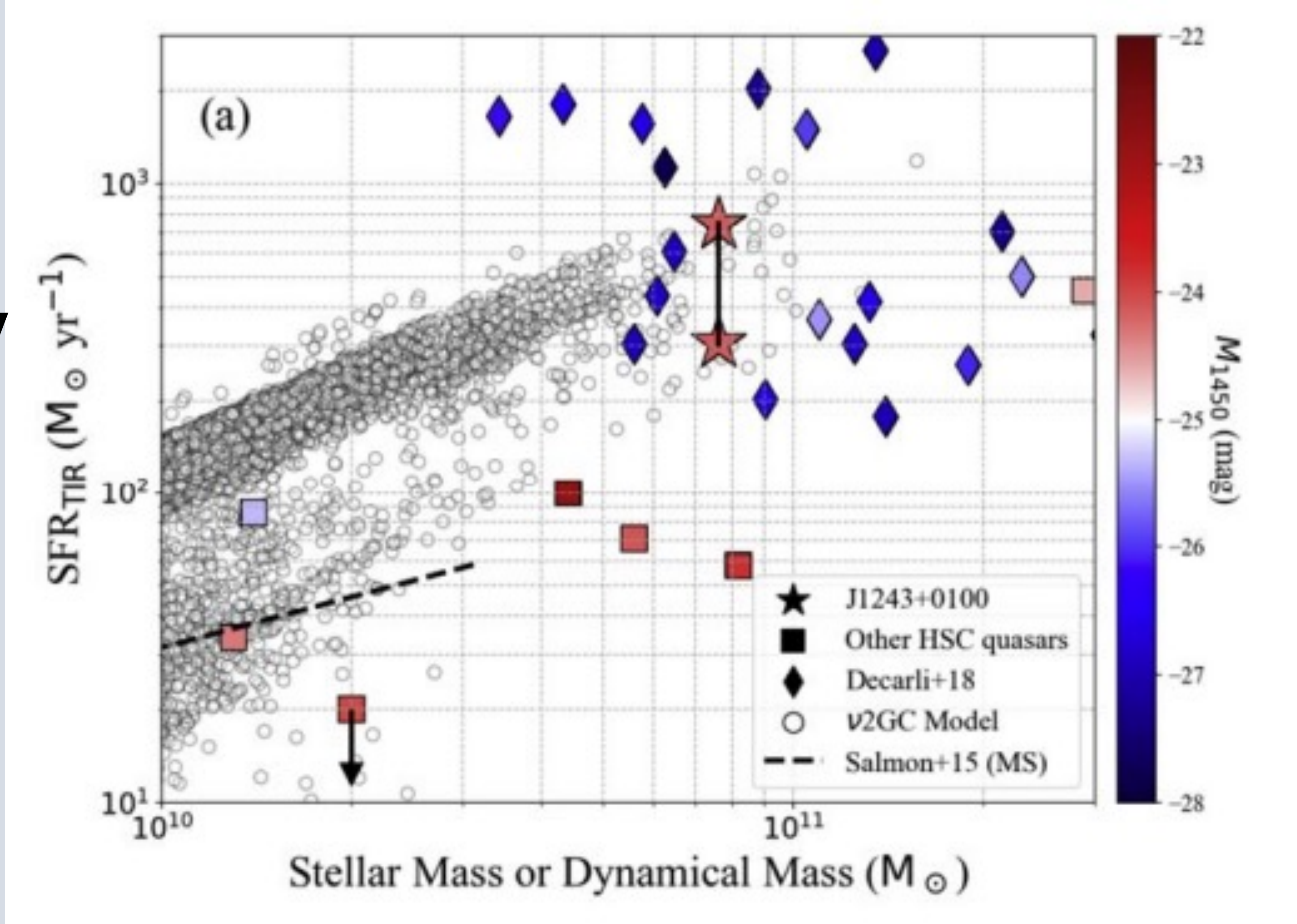


Izumi et al. 2021

Low luminosity Quasar at high redshift (時間)

- Even in SF activities, differences in luminosity lead to variations in trends.

→Observations of low-luminosity quasars are crucial for obtaining unbiased insights



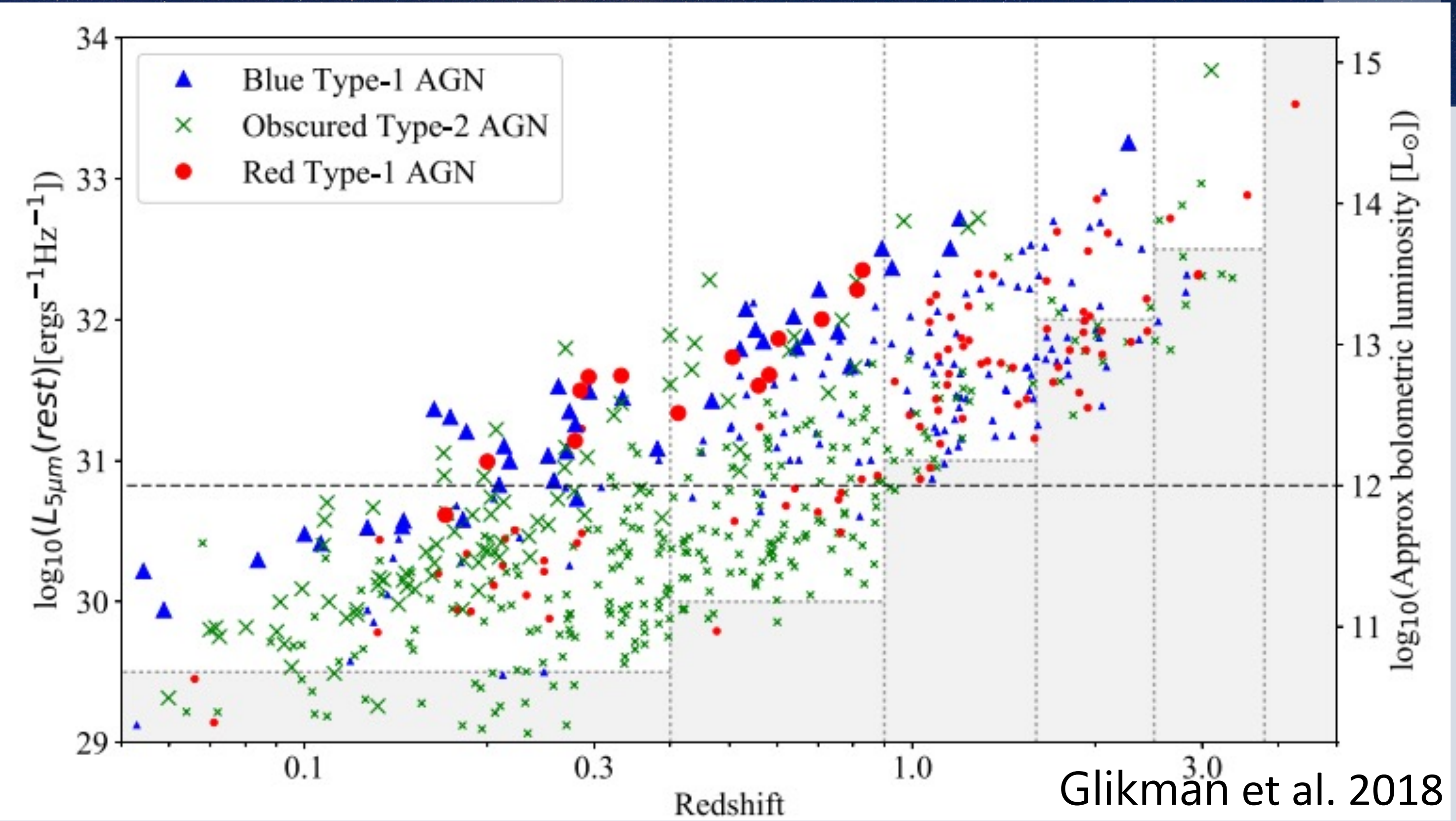
Izumi et al. 2021

Red Quasar : low-z

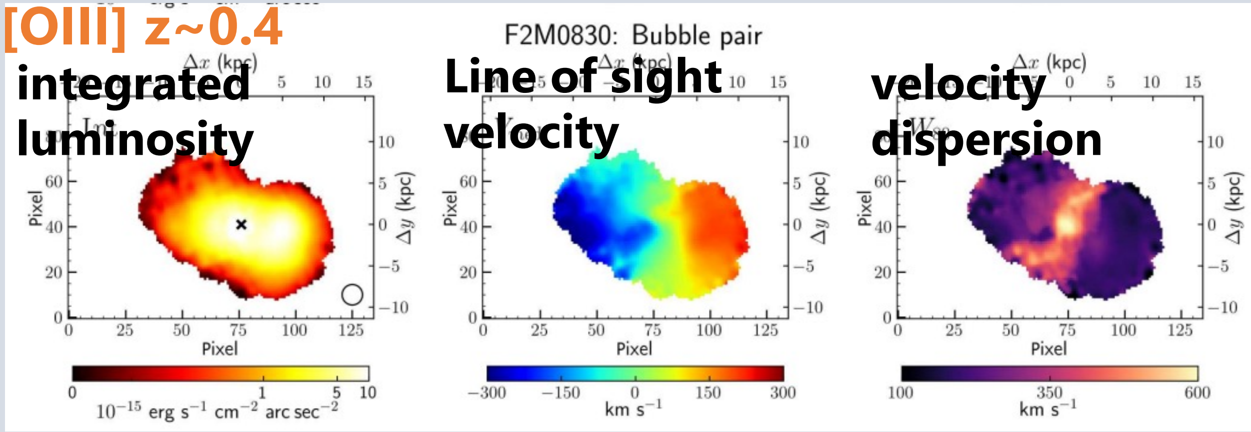
Low redshift

- Many Red Quasar is selected
→be able to discuss analytically

- The observation also confirms the presence of outflows



Glikman et al. 2018



Shen et al. 2023

Red Quasar : high-z

High redshift

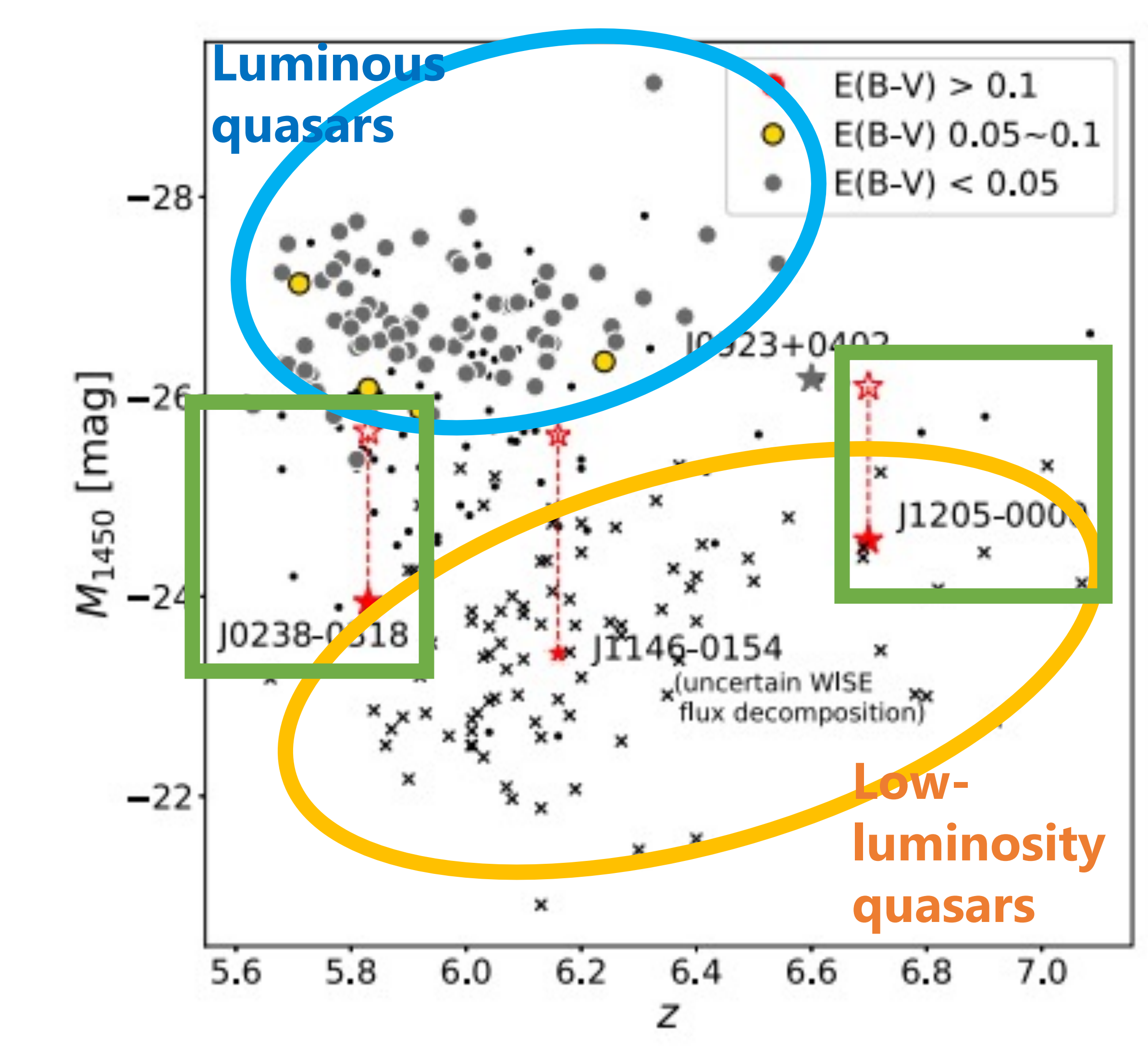
- Only two red quasars have been found
  (J1205-0000, J0238-0318)

→insufficient for statistical discussions

- Intrinsically luminous

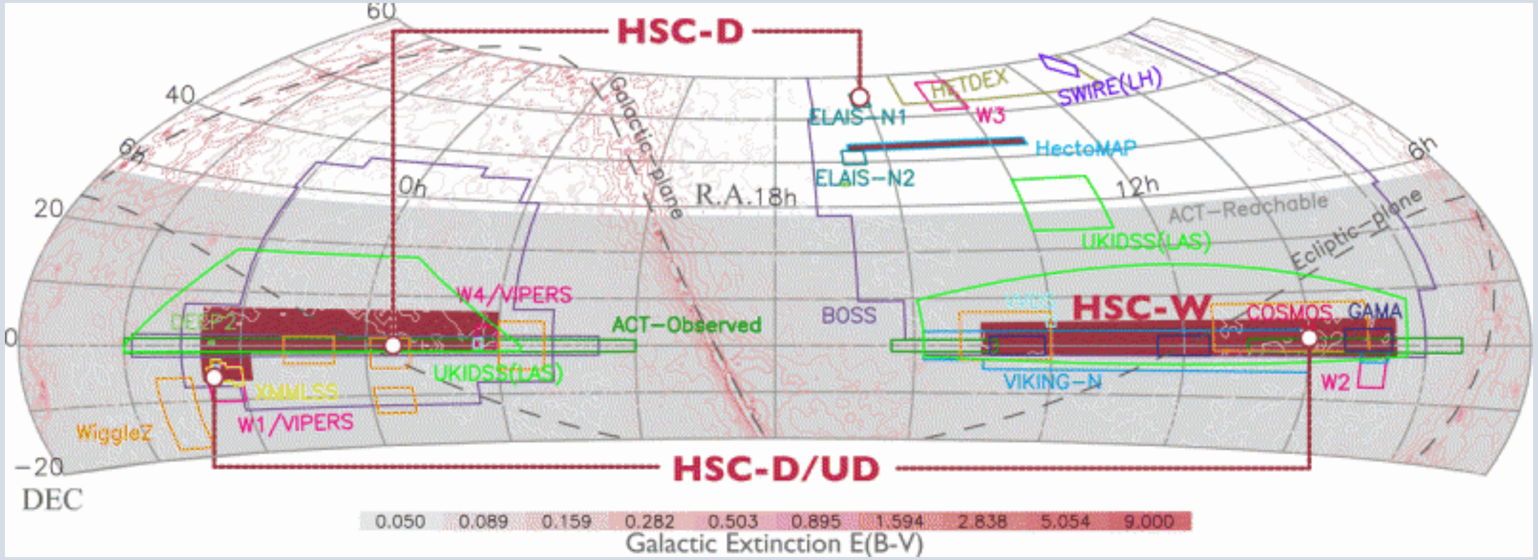
- Outflows have not been observed

→Observations of **low-luminosity** **red quasars** at **high z** are essential.



Kato et al. 2020

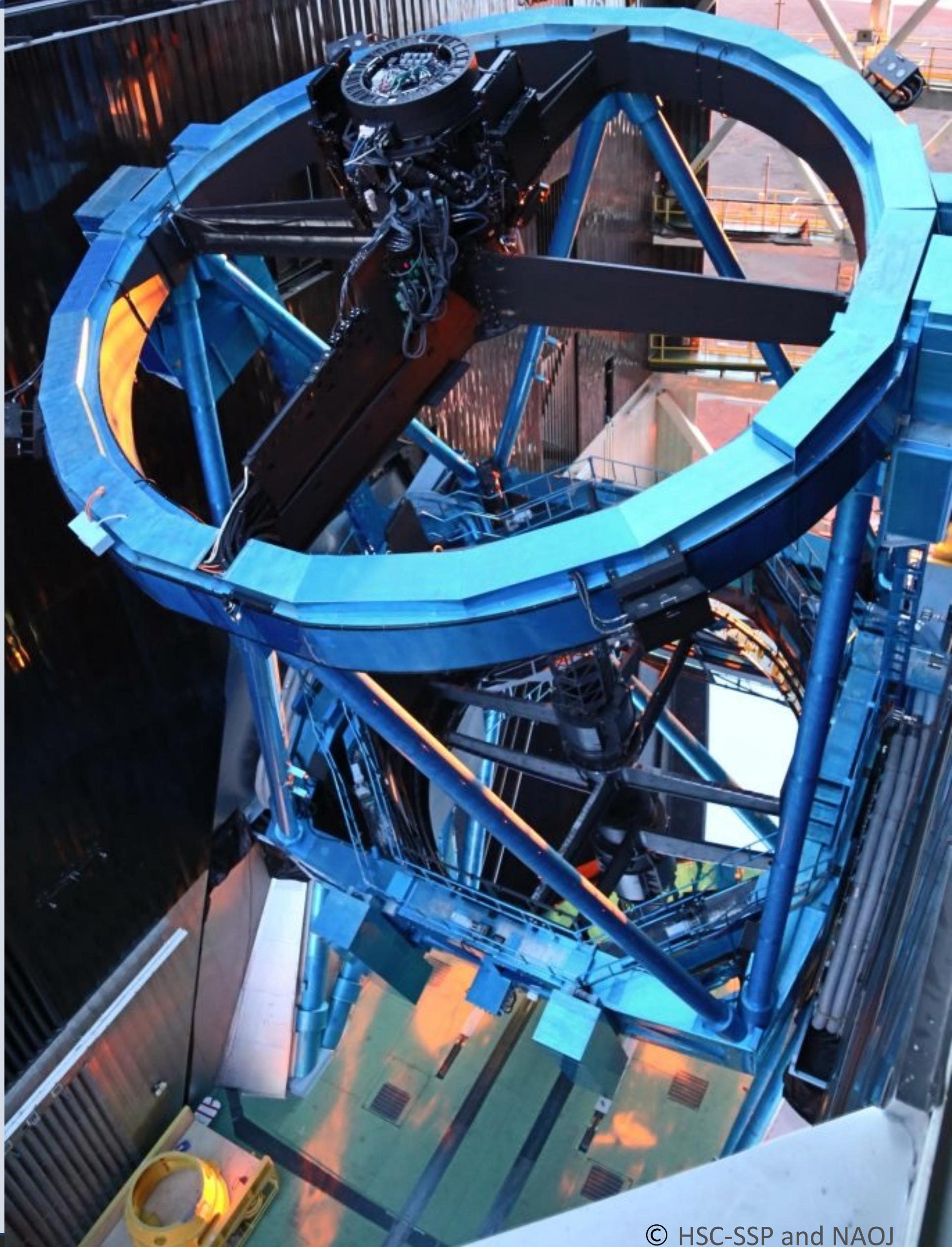
The HSC Subaru Strategic Program (SSP) survey



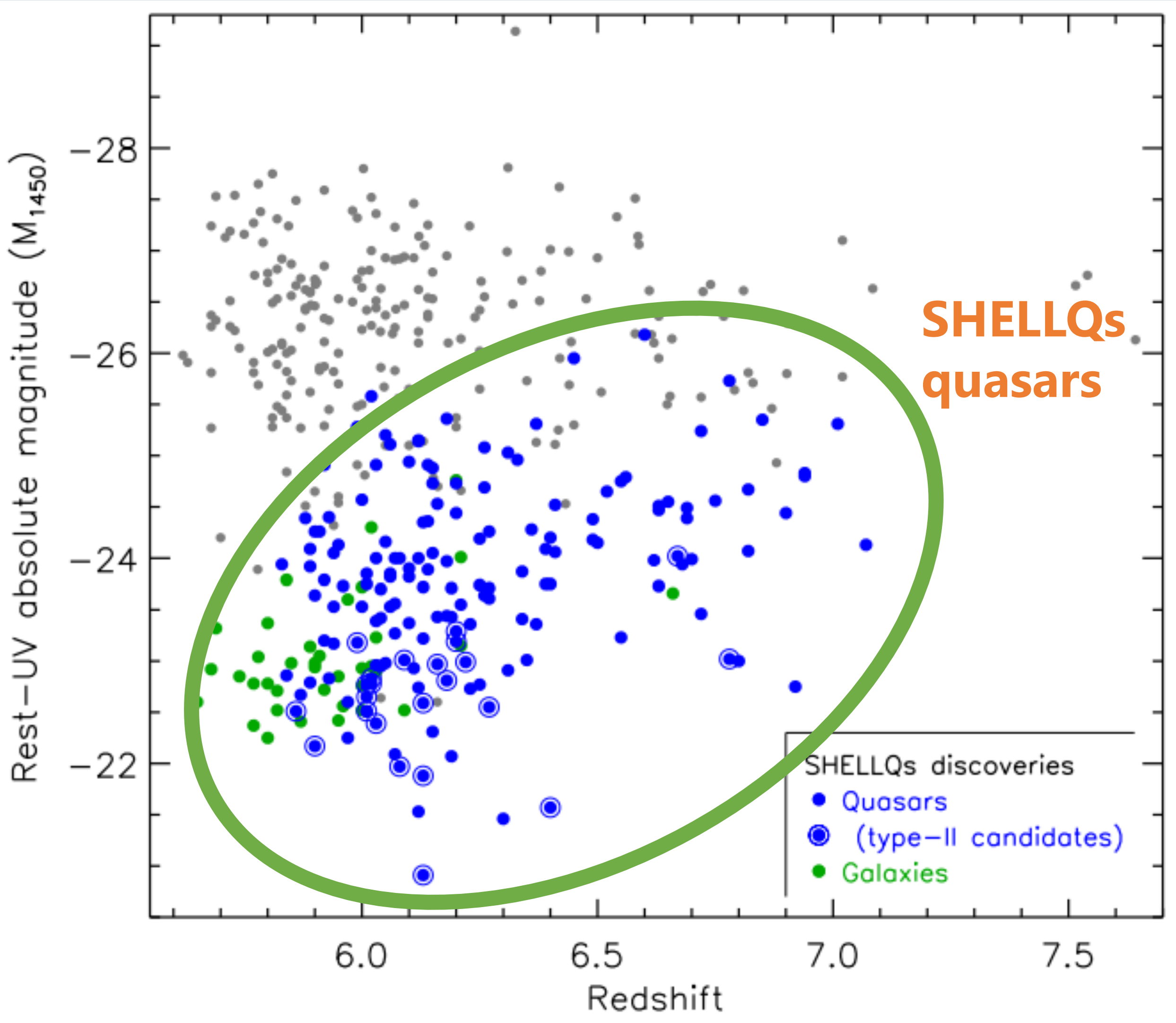
- 330 nights (Feb. 2014 ~ 2021)
- 5 broad band(g, r, i , z, y), some narrow bands
- 3 layers (2, 3 magnitude deeper than SDSS)

Layers	Area [deg^2]	Depth for a point source
Wide	1400	$r_{5\sigma}$ ~26 mag
Deep	26	$r_{5\sigma}$ ~27 mag
UltraDeep	3.5	$r_{5\sigma}$ ~28 mag

Aihara et al. 2014

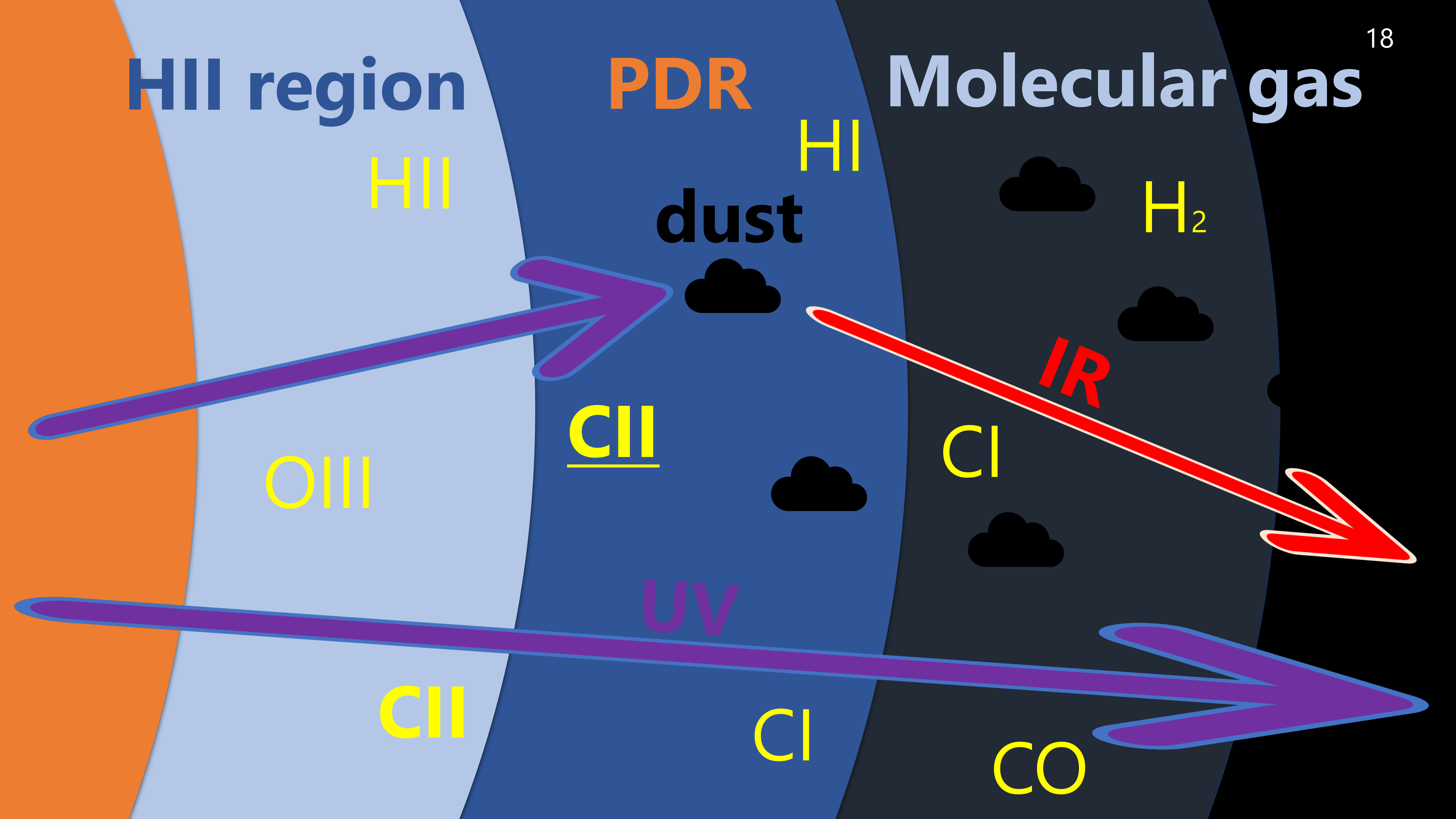


SHELLQs quasar selection



Matsuoka et al. 2022

- SHELLQs (Matsuoka et al. 2016) : Subaru High-z Exploration of Low-Luminosity Quasars
- With HSC data, selecting z > 5.6 quasar (Bayesian-based probabilistic selection method)
- **A total 154** high z and low-luminosity quasars were identified through this project.


HII region
PDR
Molecular gas
HII
HI
dust
H_2
IR
CII
CI
OIII
UV
CII
CI
CO

The definition of Red Quasar?

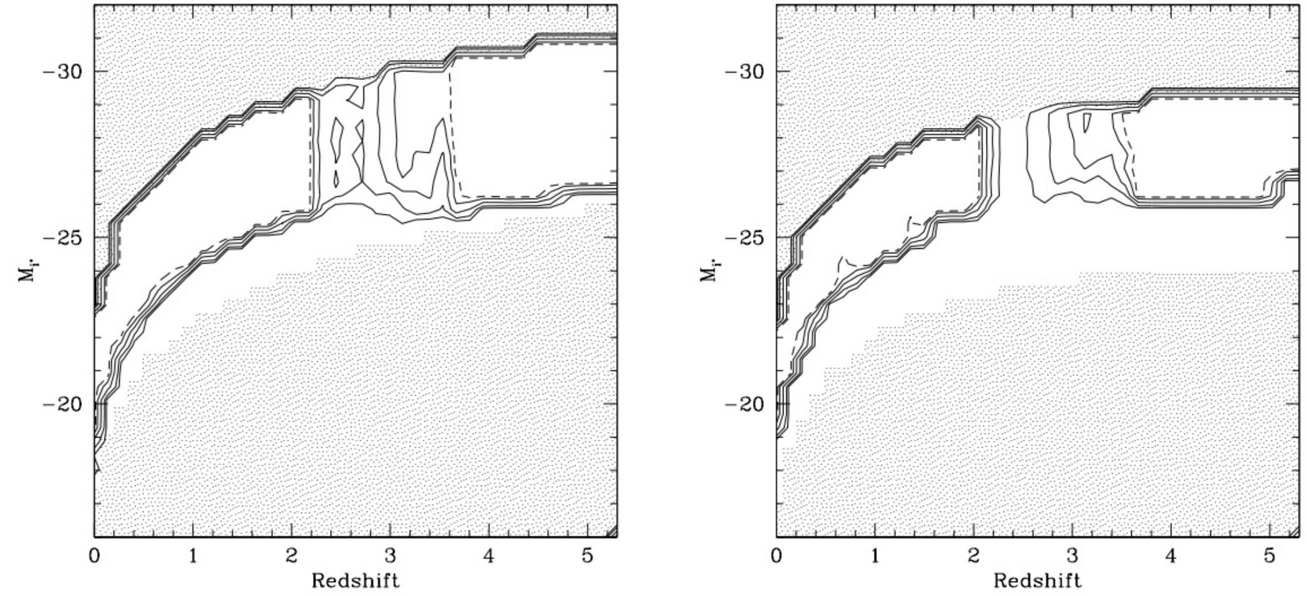


Fig. 1.— *Left:* Completeness for simulated red (optically steep) but unextincted quasars with $\alpha_\nu = -1.5 \pm 0.3$. *Right:* Completeness for simulated dust reddened and extincted quasars with $E(B-V) = 0.1$ (assuming SMC dust extinction). In both panels, contours are drawn at 10, 25, 50, 75 and 90% completeness, with the 90% completeness contour shown as a dashed line. The shaded region is where there are no objects in the simulations; quasars more luminous than the most luminous of our simulated quasars are clearly even more likely to be detected.

Richards et al. 2003

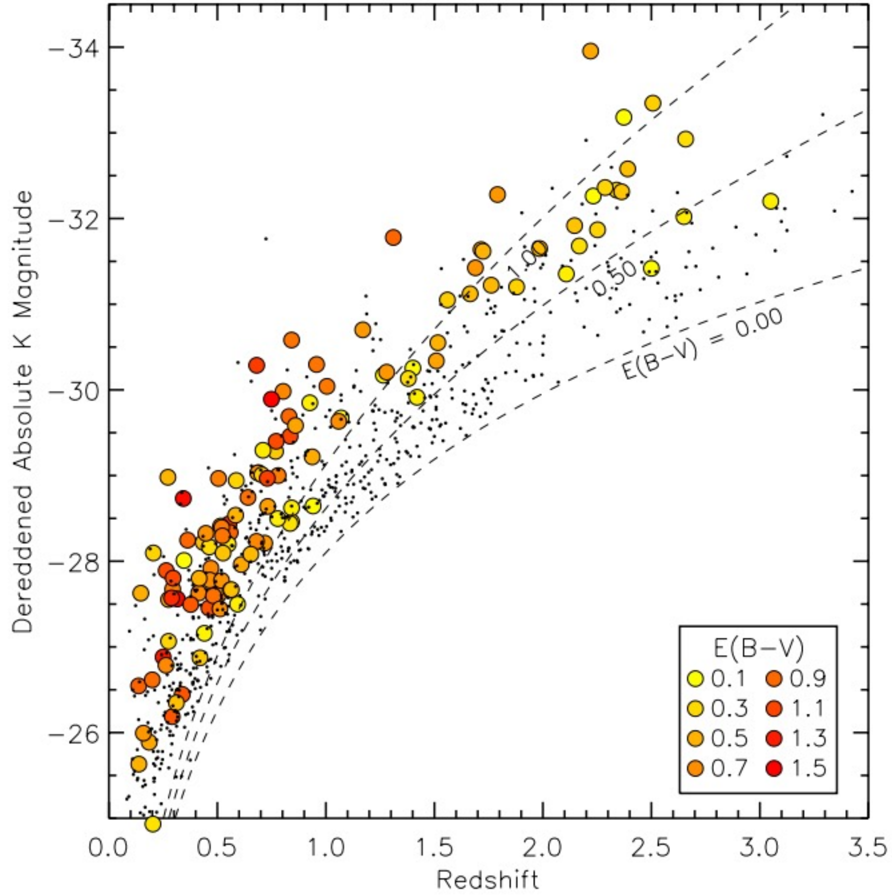
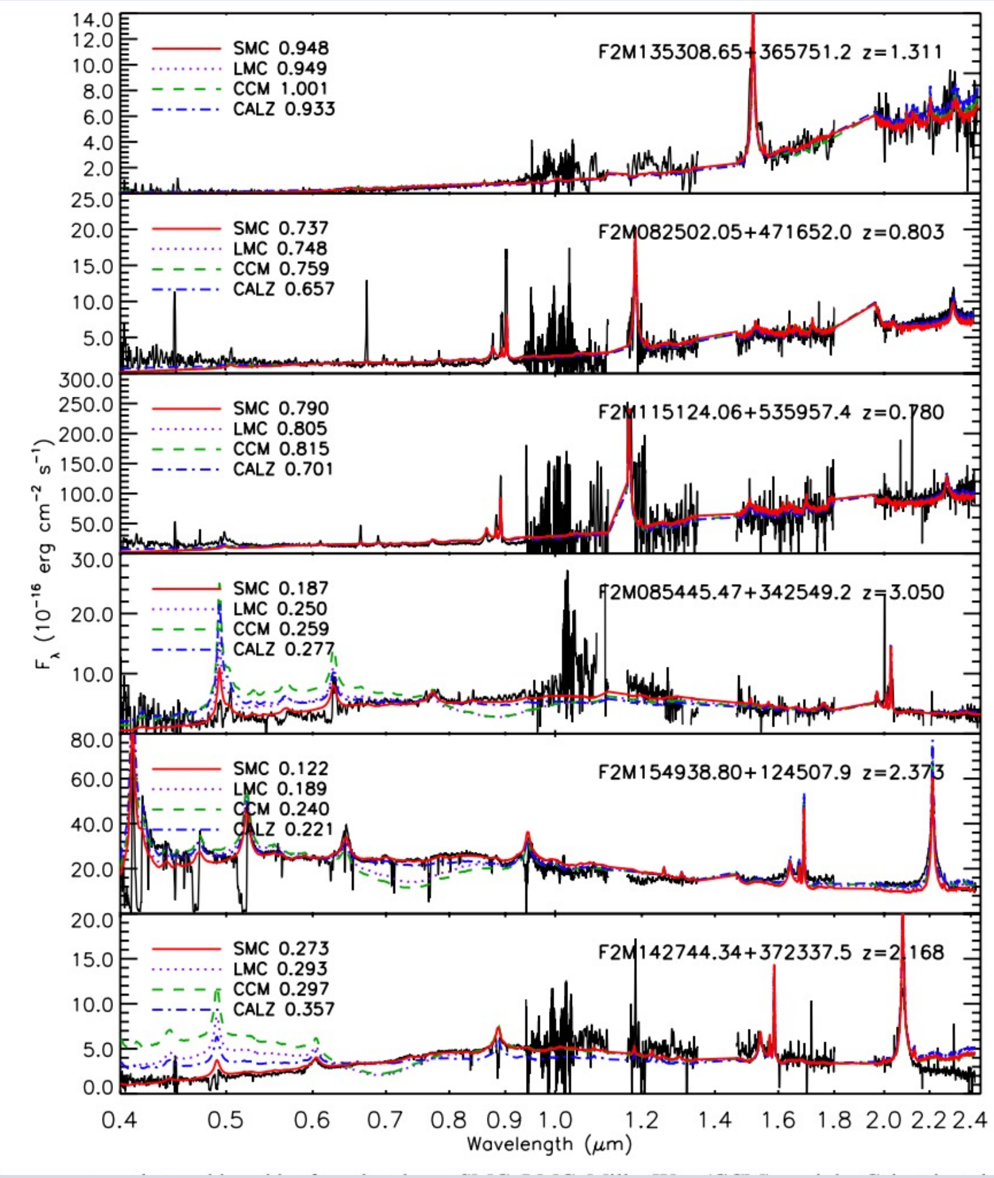


Figure 15. Dereddened *K*-band absolute magnitude as a function of redshift. The colors of the circles correspond to the amount of extinction, ranging from low extinction (yellow) to heavily reddened (red). The dotted lines indicate the survey limit ($K < 16$) for increasing amounts of extinction. The small dots are FBQS-II and FBQS-III quasars, which we assume are unabsorbed. At every redshift, red quasars are the most luminous.

Glikman et al. 2012

Four dust low



HSC SSP survey data

Select Low luminosity and High-z quasar 157 objects

SHELLQs quasar 93 objects

+

WISE All-Sky Release Catalog

=

Select 4 Red quasar candidates

WISE detection and SED fit to derive E(B-V)>0.1

Determine 2 objects as the red quasar

→

HSC SSP survey data

Machine Learning method like Random Forest

+

WISE All-Sky Release Catalog

=

Select 4 Red quasar candidates

WISE detection and SED fit to derive E(B-V)>0.1

Determine 2 objects as the red quasar