Co-evolution between the first supermassive black holes and their host galaxies

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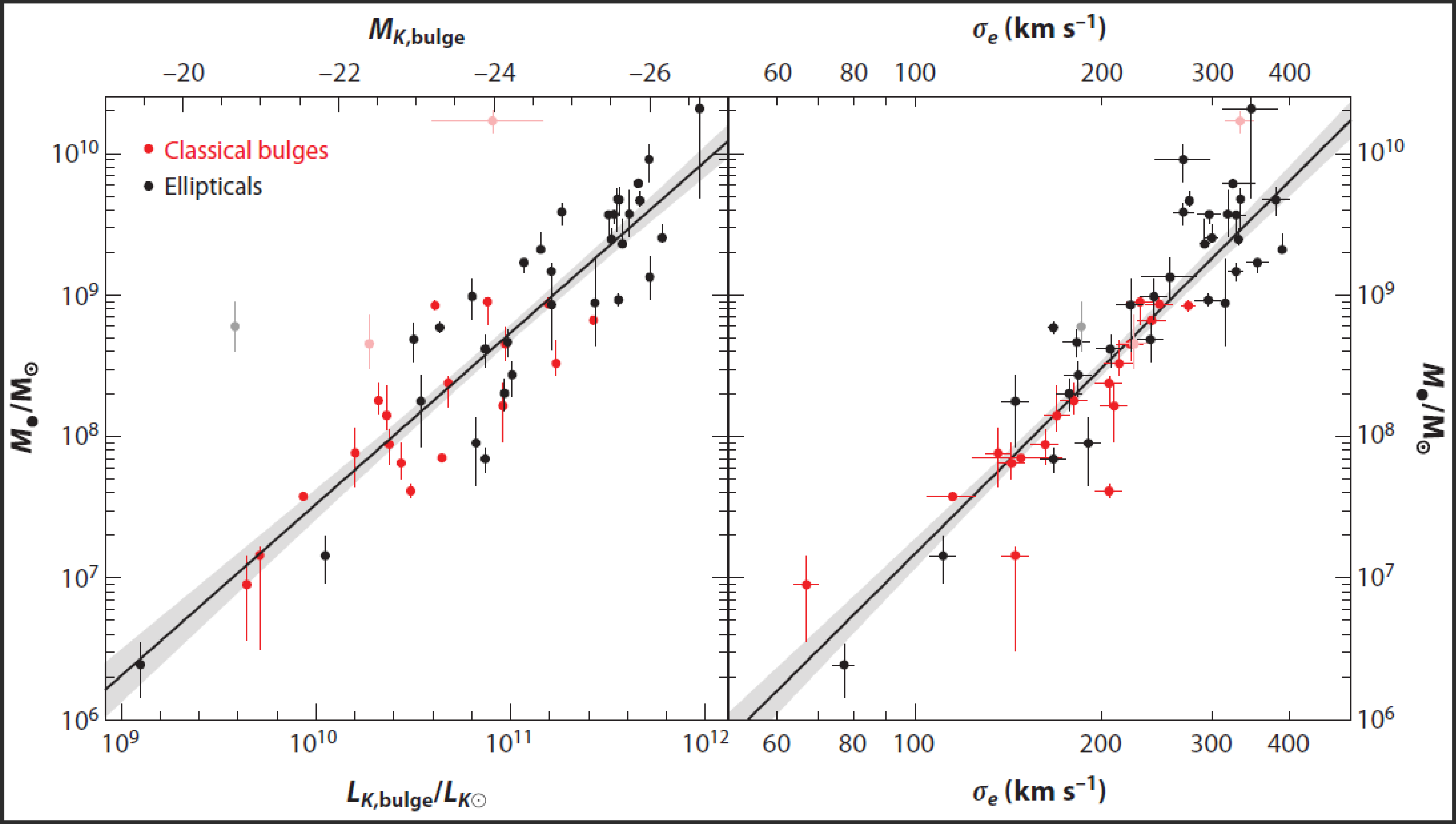
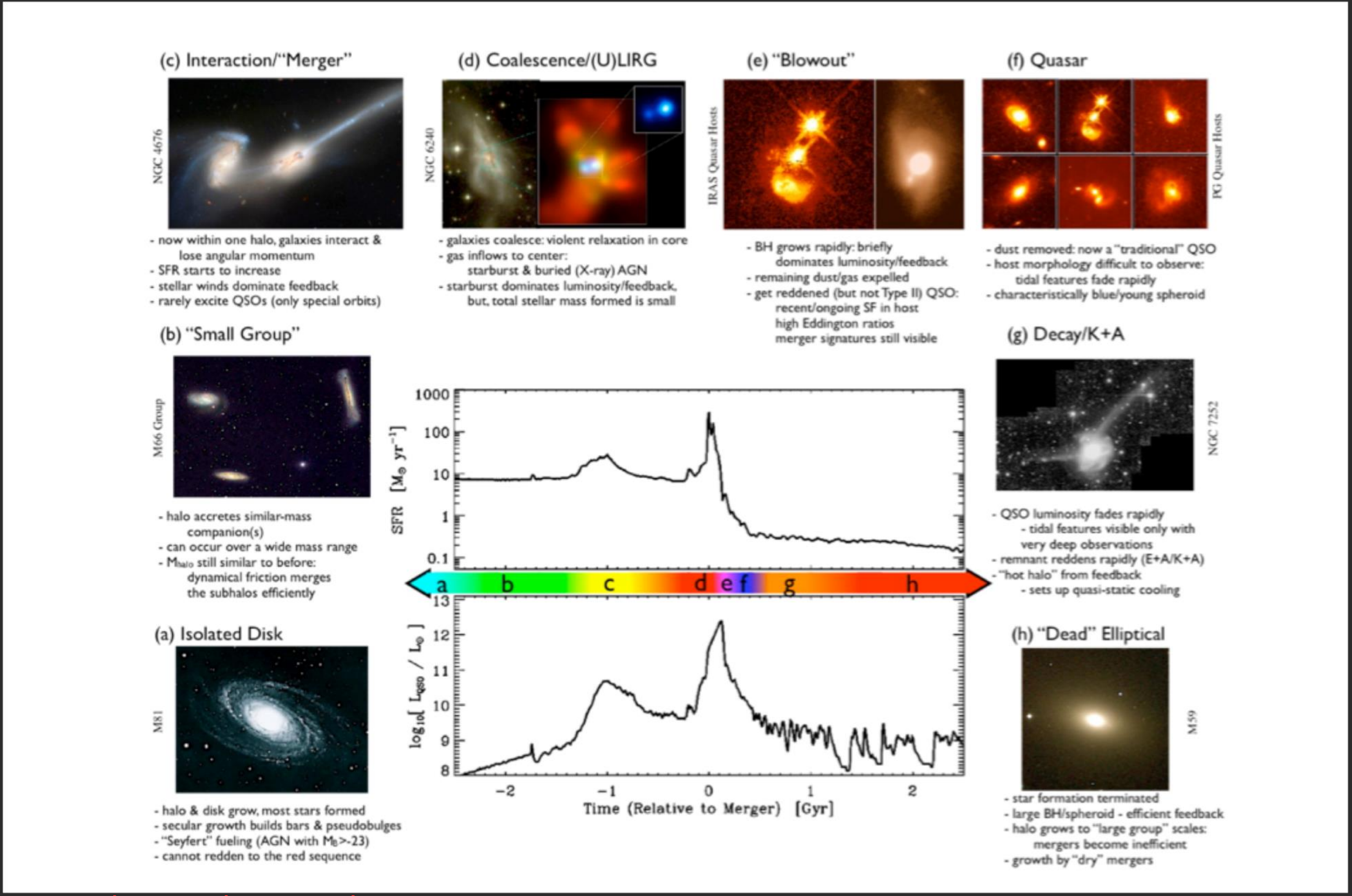
SMBH-galaxy co-evolution



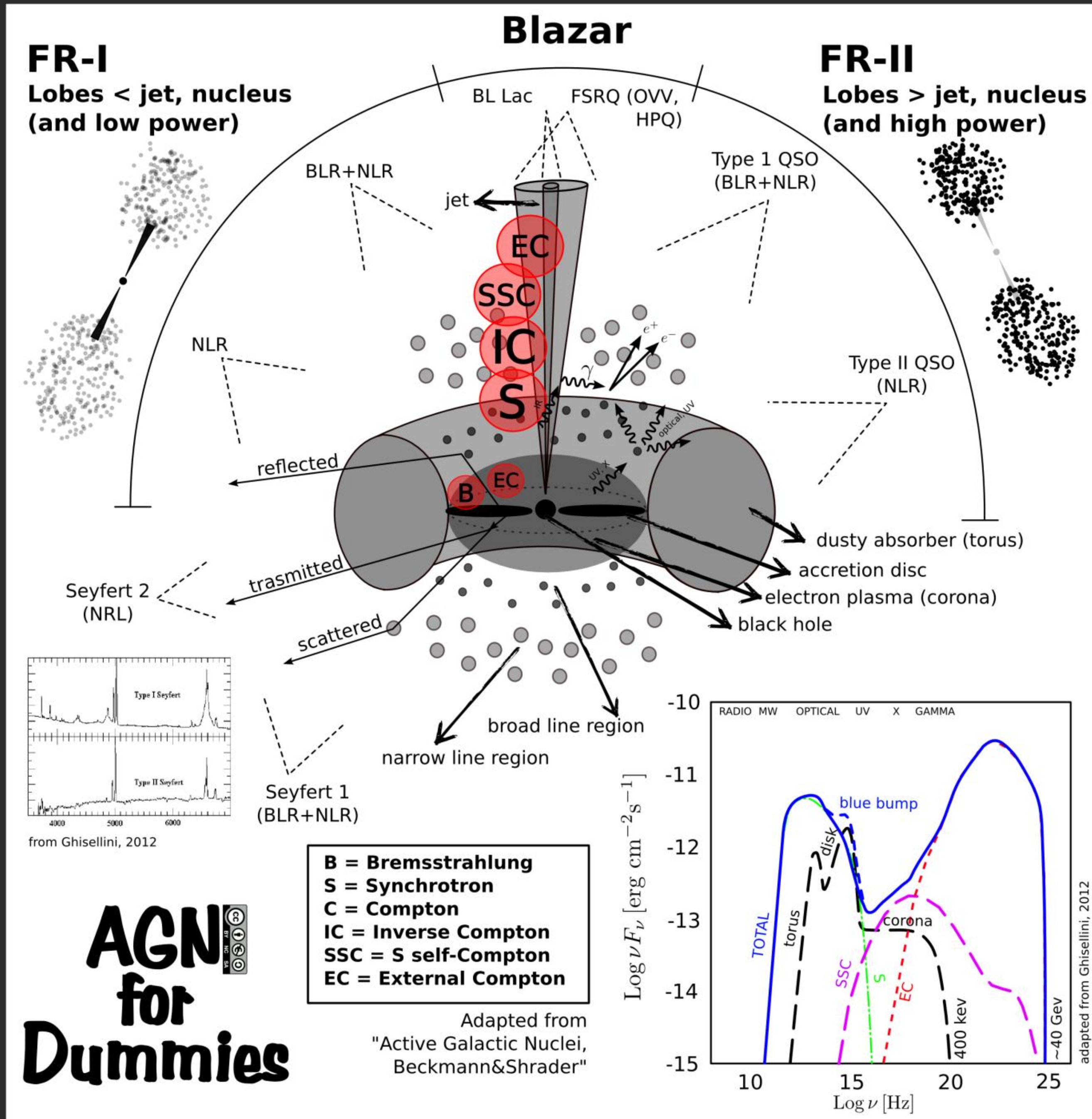
Kormendy & Ho 2013

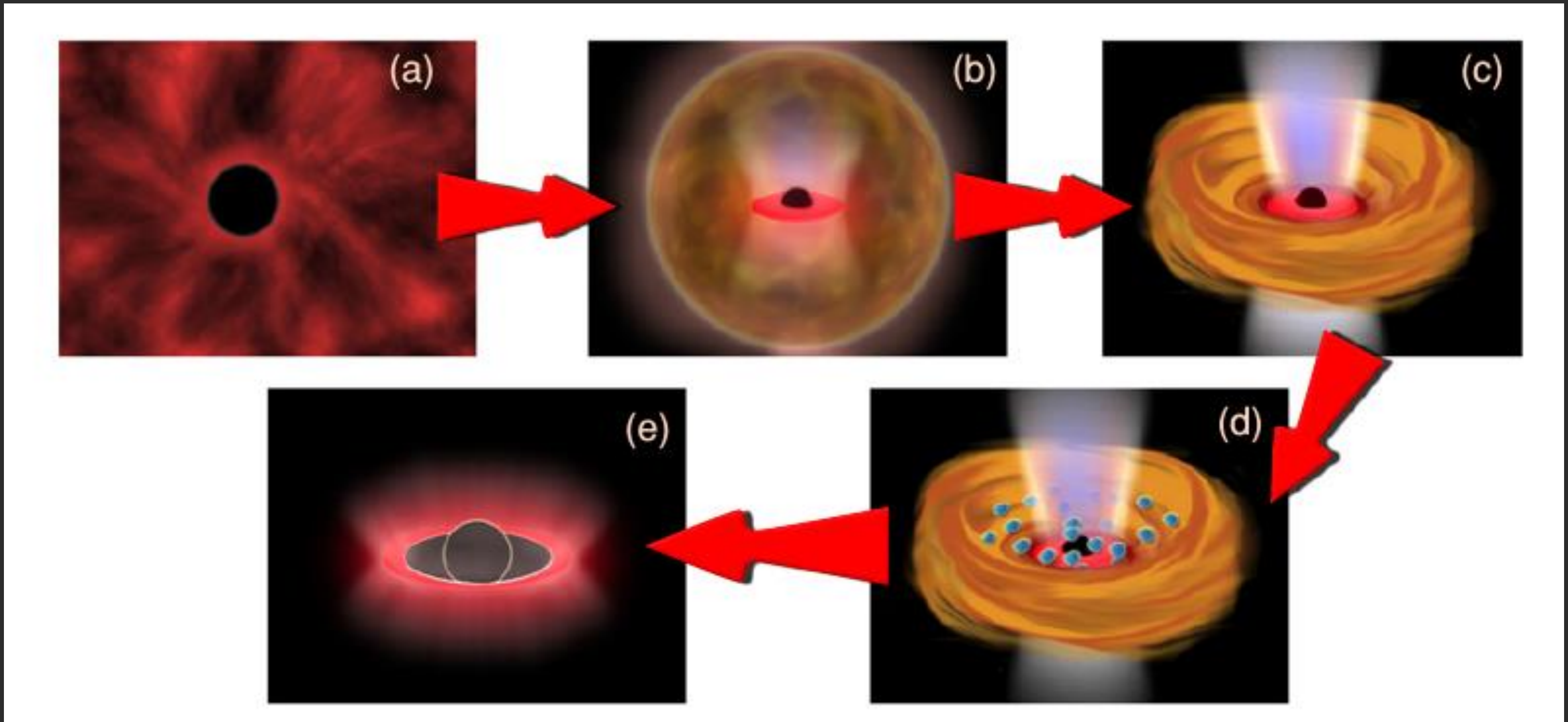
$$\frac{M_\bullet}{10^9\ M_\odot} = \left(0.49^{+0.06}_{-0.05}\right)\left(\frac{M_{\text{bulge}}}{10^{11}\ M_\odot}\right)^{1.17\pm0.08}; \quad \text{intrinsic scatter} = 0.28\ \text{dex.}$$

SMBH-galaxy co-evolution



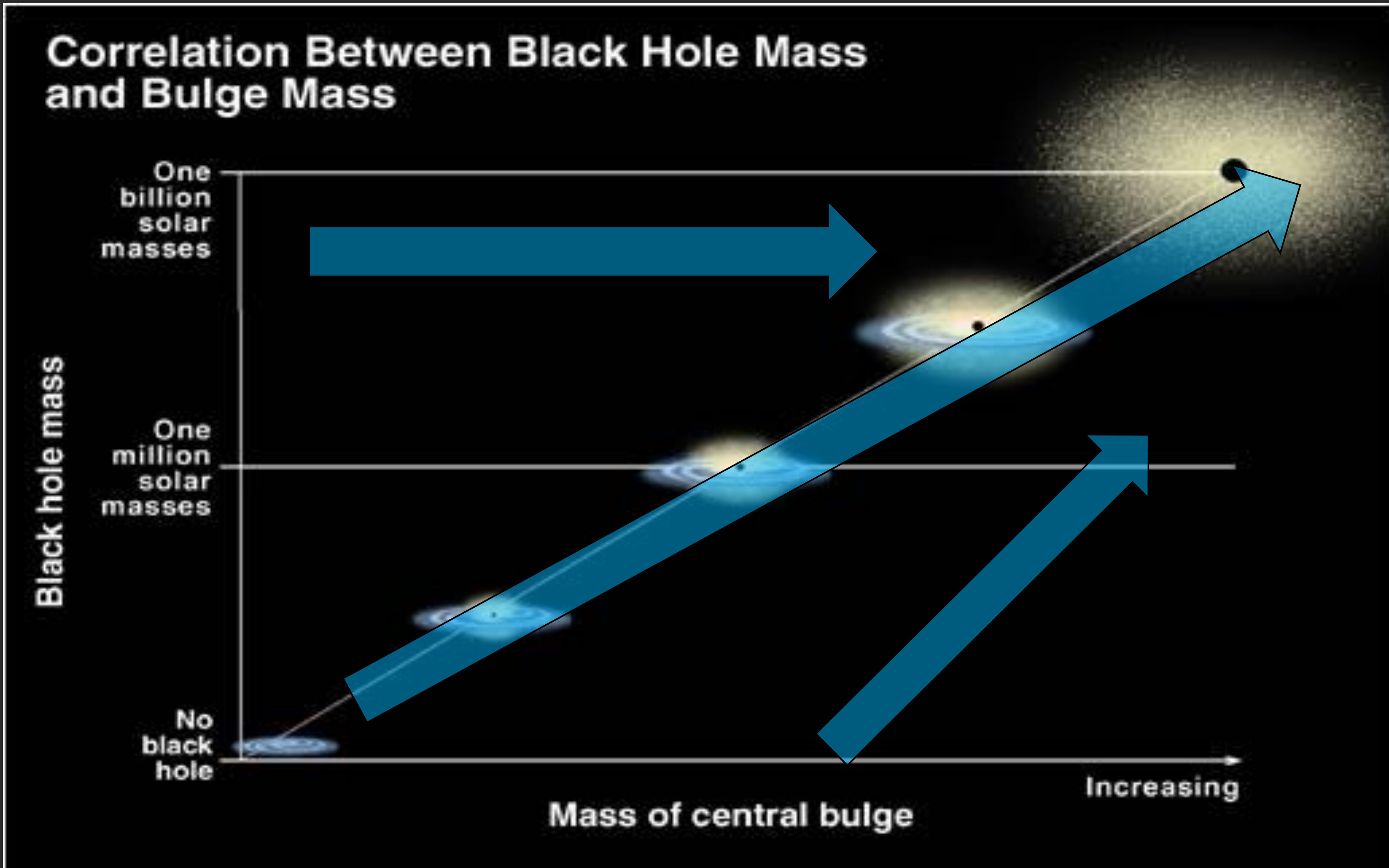
Credit: Hopkins et al. NSF


Blazar
FR-I
Lobes < jet, nucleus
(and low power)
FR-II
Lobes > jet, nucleus
(and high power)
BL Lac
FSRQ (OVV, HPQ)
BLR+NLR
jet
Type 1 QSO
(BLR+NLR)
EC
SSC
IC
S
NLR
Type II QSO
(NLR)
reflected
B
EC
dusty absorber (torus)
accretion disc
electron plasma (corona)
black hole
Seyfert 2
(NRL)
trasmitted
scattered
broad line region
narrow line region
Seyfert 1
(BLR+NLR)
from Ghisellini, 2012
B = Bremsstrahlung
S = Synchrotron
C = Compton
IC = Inverse Compton
SSC = S self-Compton
EC = External Compton
AGN for Dummies
Adapted from
"Active Galactic Nuclei,
Beckmann&Shrader"
RADIO MW OPTICAL UV X GAMMA
blue bump
disk
torus
corona
TOTAL
SSC
S
EC
400 kev
~40 Gev
$\mathrm{Log}\,\nu F_\nu\,[\mathrm{erg\,cm^{-2}s^{-1}}]$
$\mathrm{Log}\,\nu\,[\mathrm{Hz}]$
adapted from Ghisellini, 2012

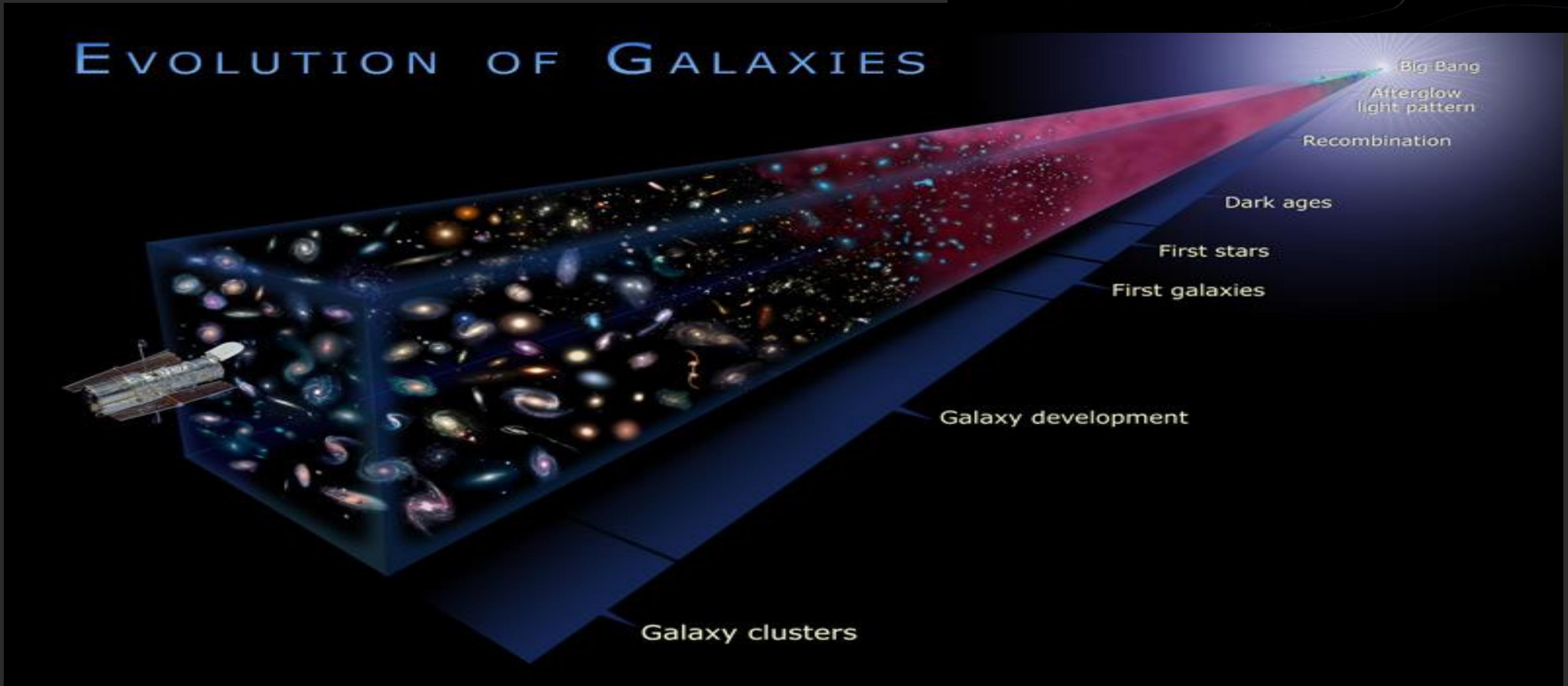


Liu & Zhang 2011

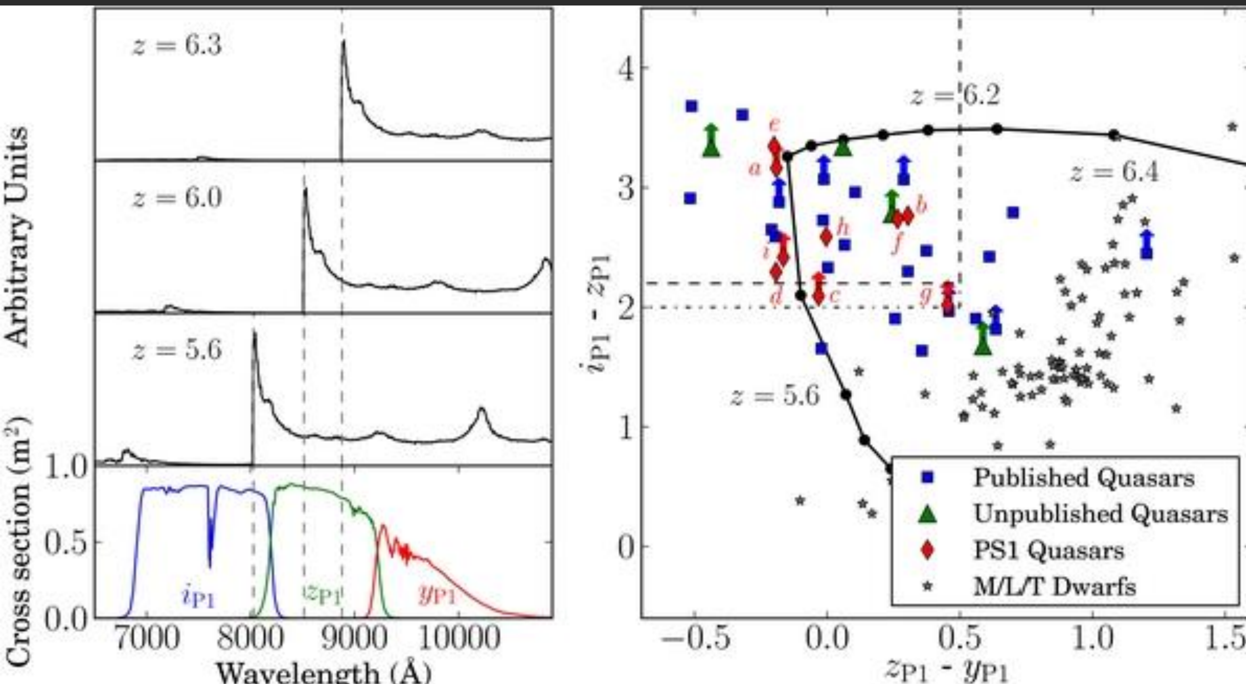
SMBH-galaxy co-evolution



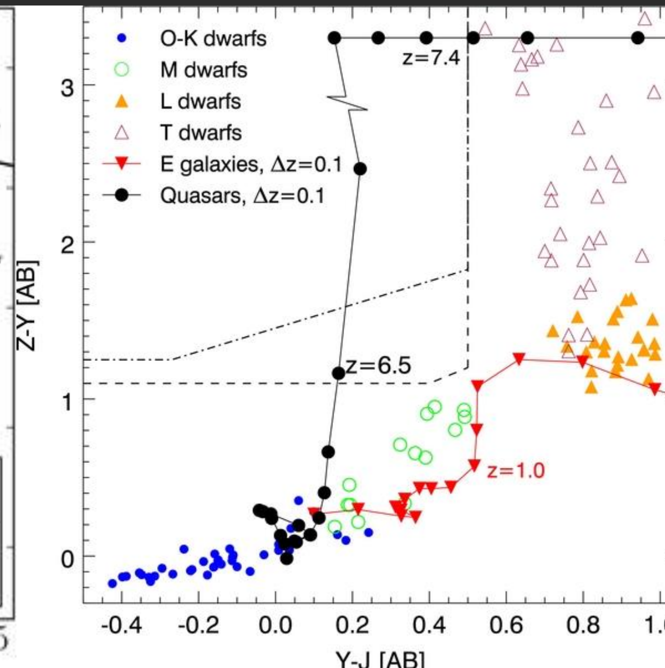
Quasars discovered at the highest redshift



Quasars discovered at the highest redshift



Banados et al. 2014 : PAN-STARRS1



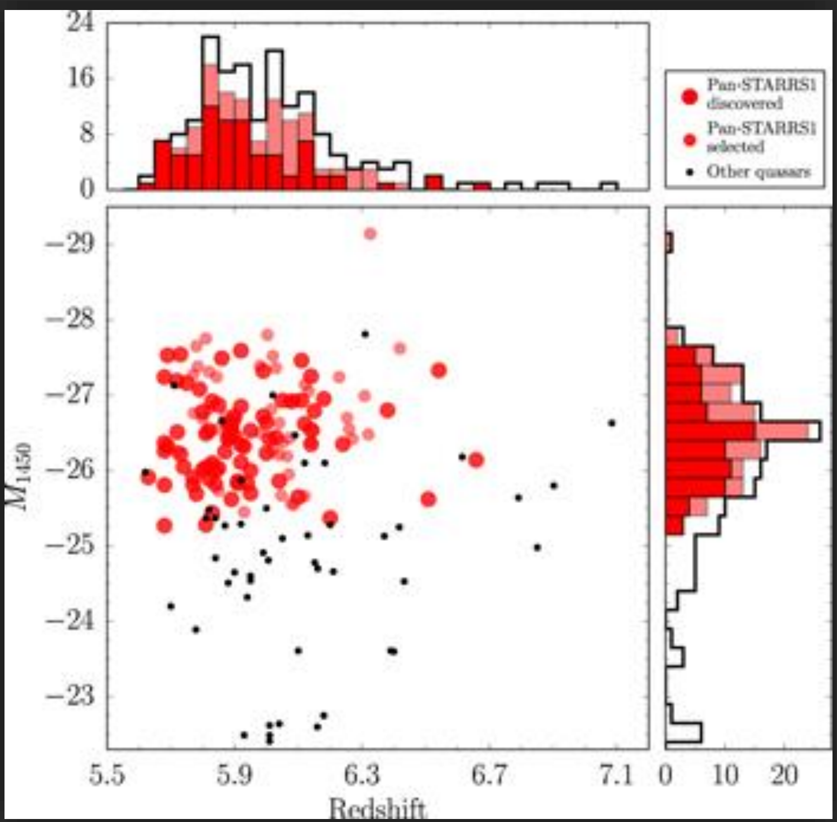
Venemans et al. 2013: VISTA

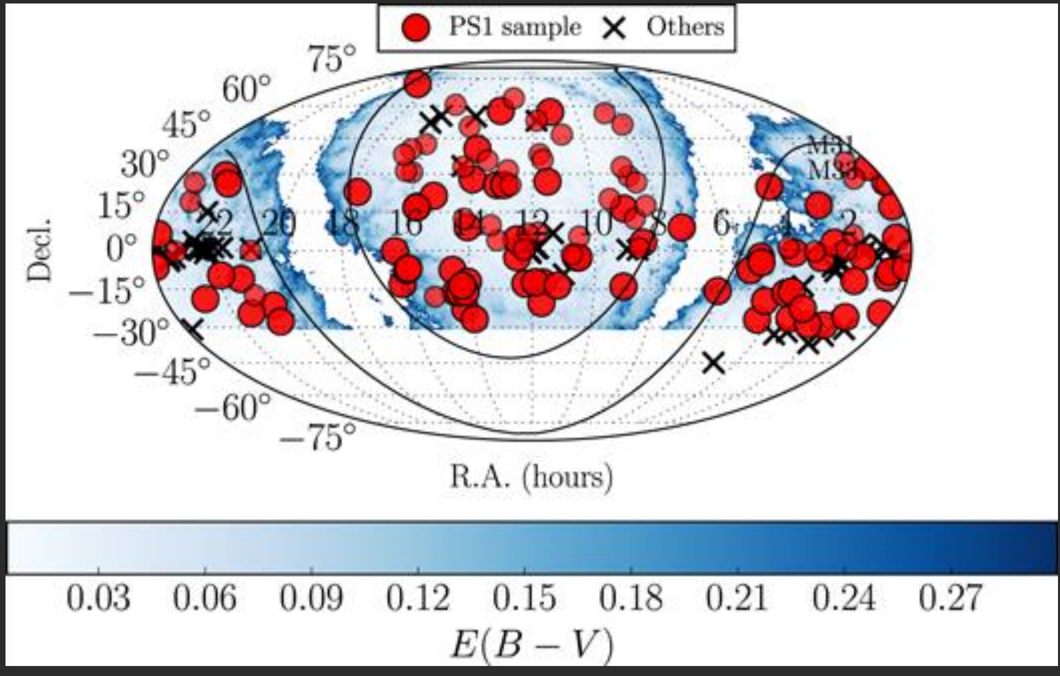
- More than 180 quasars at z>5.7 discovered from the large optical/near-IR surveys:
- SDSS main survey, mag_z<20.2, Fan et al. 2000~2006
- SDSS stripe 82, Jiang et al. 2008, 2009; CFHQS, Willott et al. 2007-2010; UKIDSS, Mortlock et al. 2011; VISTA, Venemans et al. 2013; PAN-STARRS1, Banados et al. 2014; Venemans et al. 2013, 2015, Banados et al. 2016; Subaru: Matsuoka et al. 2017

Introduction: Discovery of highest-z quasars

- More than 180 quasars at z>5.6 discovered from the large optical/near-IR surveys: SDSS, Pan-STARRS1, CFHQS, etc.

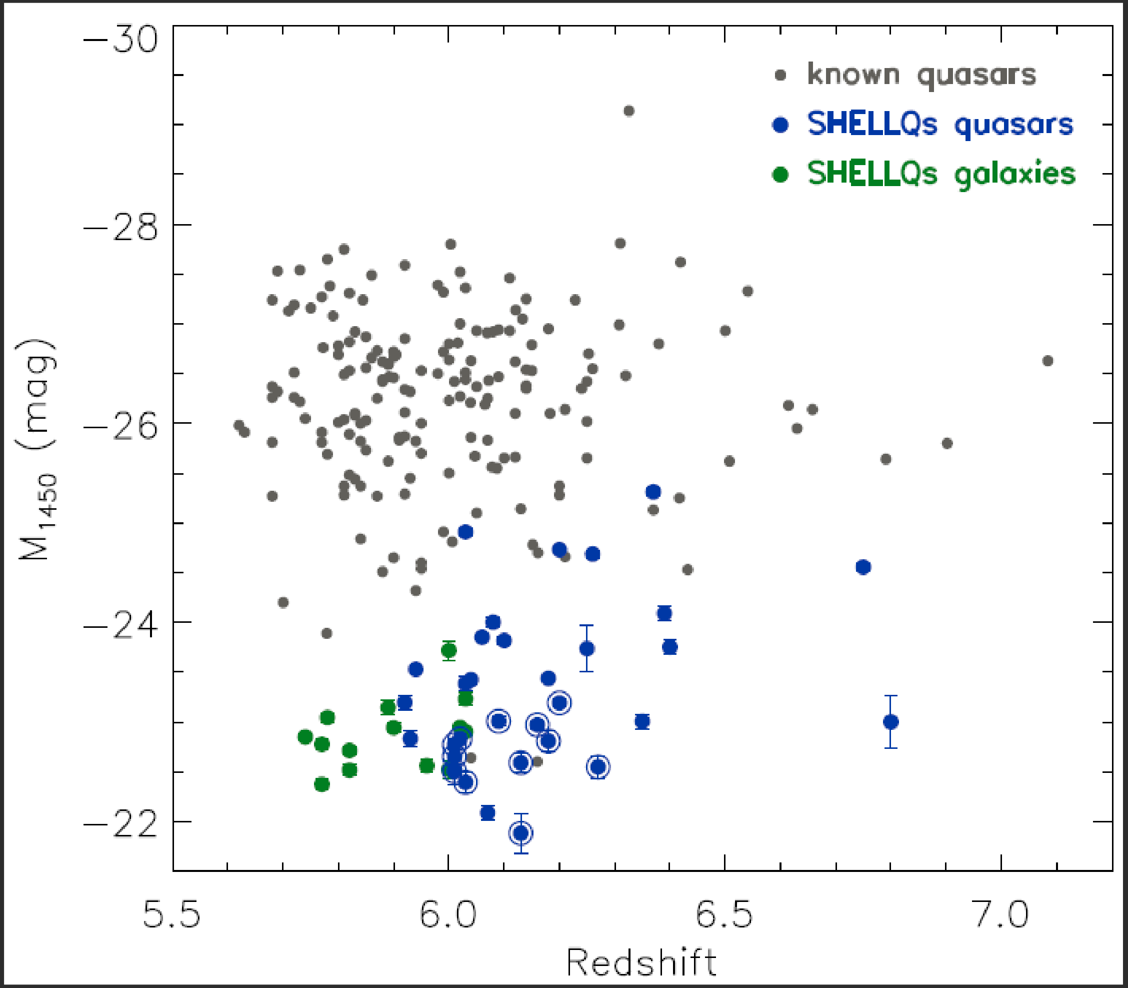
recent summary from Banados et al. 2016, ApJS, 227, 11





Introduction: Discovery of highest-z quasars

- Fainter objects, less luminous and more common population at the highest redshift : Subaru SHELLQs, etc.   (Matsuoka et al. 2017, PASJ)



Quasars discovered at the highest redshift

•More than 200 quasars at z>5.7 discovered from the large optical/near-IR surveys:

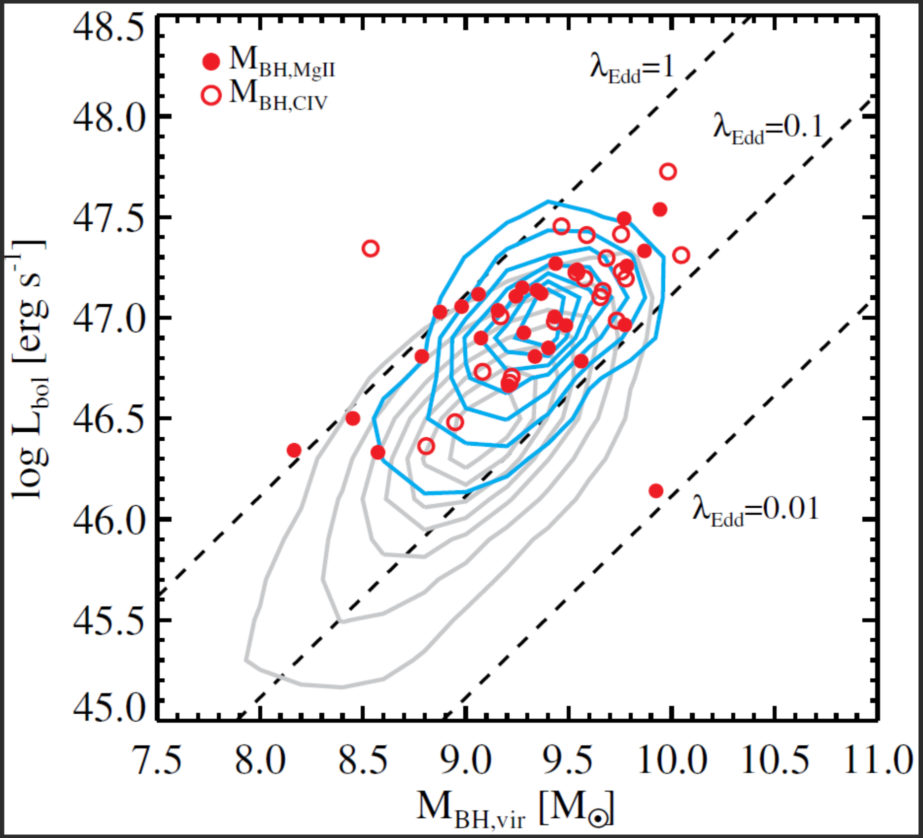
•SDSS main survey, mag_z<20.2, Fan et al. 2000~2006

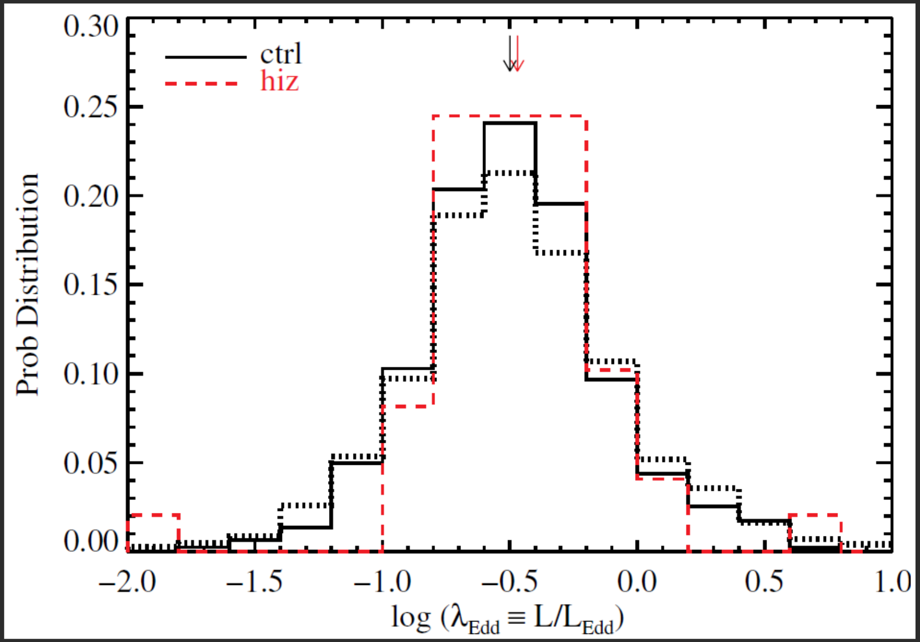
•SDSS stripe 82, Jiang et al. 2008, 2009; CFHQS, Willott et al. 2007-2010; UKIDSS, Mortlock et al. 2011; VISTA, Venemans et al. 2013; PAN-STARRS1, Banados et al. 2014; Venemans et al. 2013, 2015, Banados et al. 2016; Subaru: Matsuoka et al. 2017, 2019;

•Fainter objects, less luminous and more common population at the highest redshift : Subaru SHELLQs, etc. (Matsuoka et al. 2017, 2019, PASJ)

Quasars discovered at the highest redshift

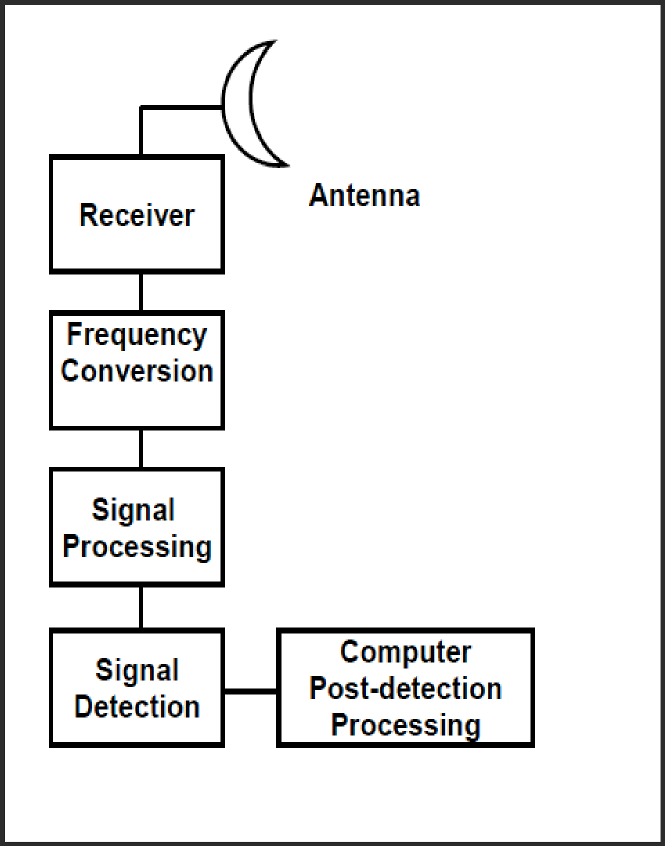
- Quasar activities : similar to the low-z quasars in similar luminosity range (Shen et al. 2019).

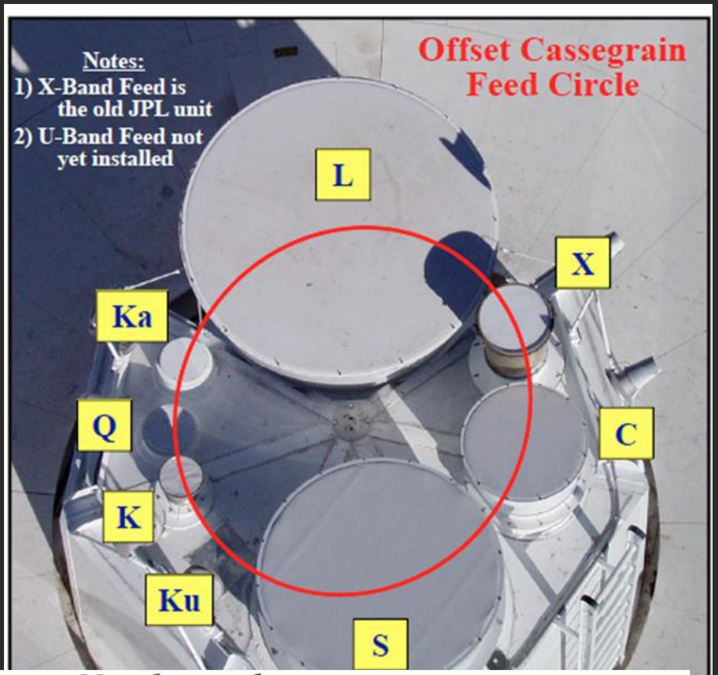


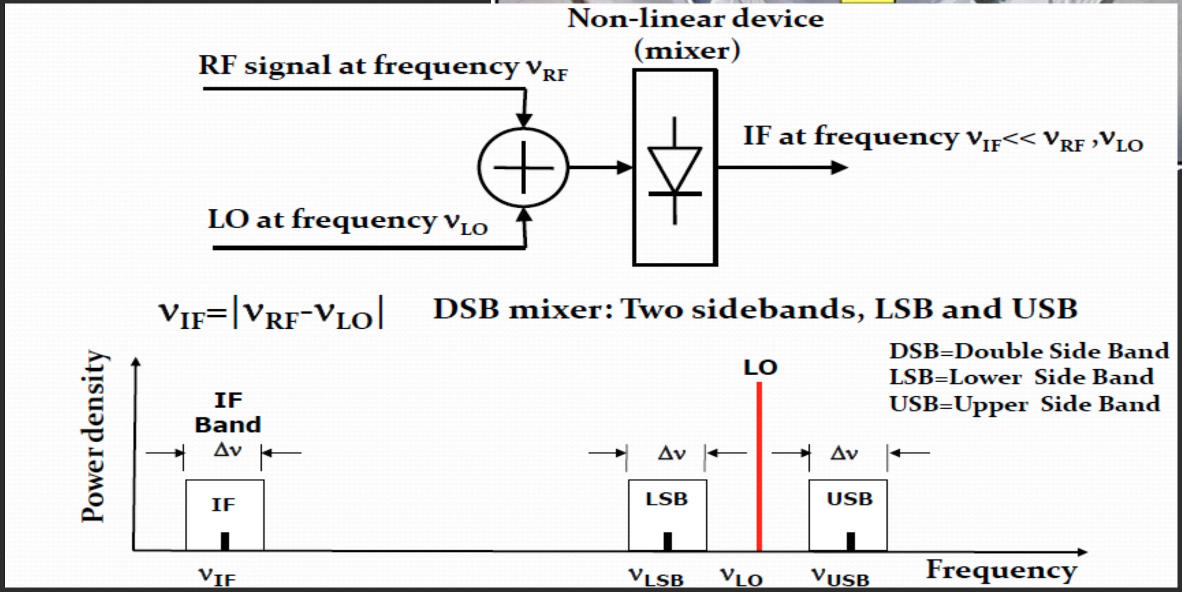


The millimeter and radio telescopes

Heterodyne receivers

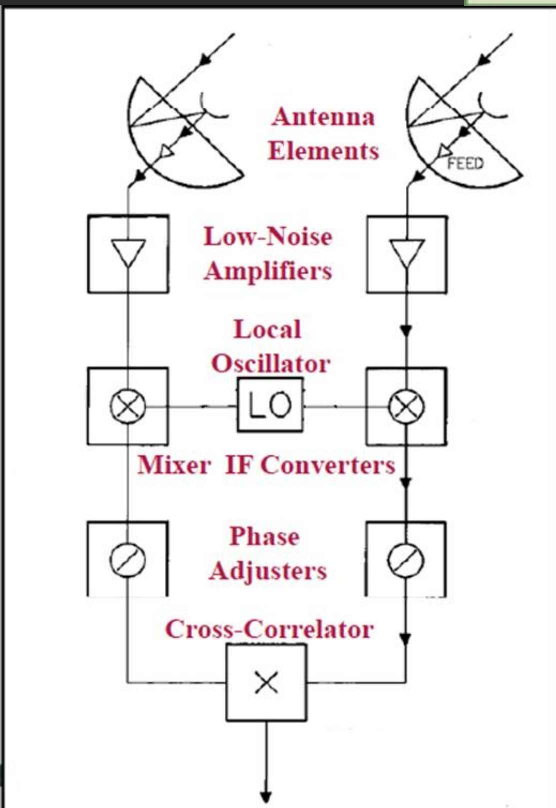






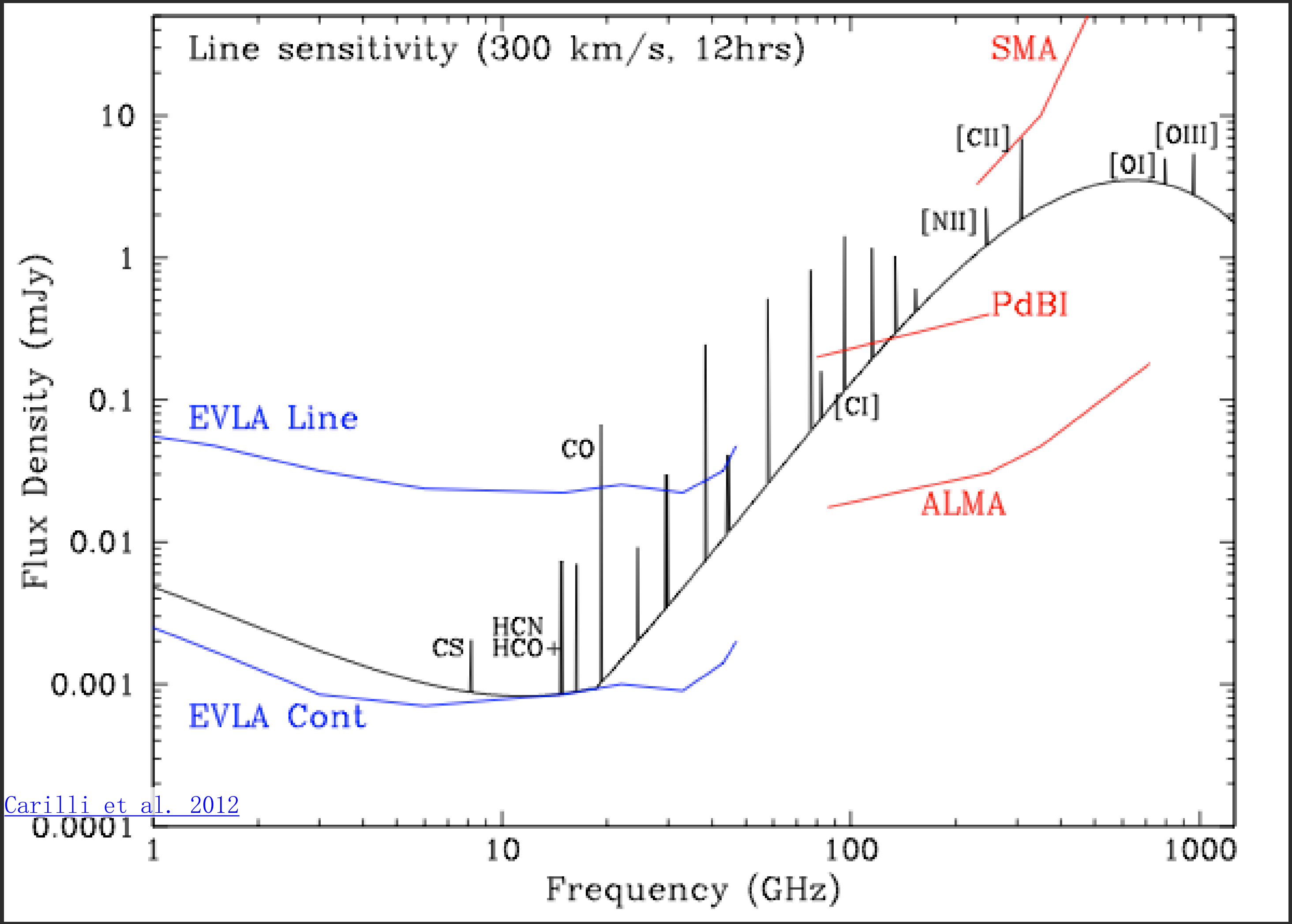
ALMA: Best sensitivity; Spatial resolution.

	Specification
Number of Antennas	*At least 50×12-m (12-m Array), plus 12×7-m & 4×12-m (ACA)*
Maximum Baseline Lengths	*0.15 - 16 km*
Angular Resolution (")	*~0.2" × (300/ν GHz) × (1 km / max. baseline)*
12-m Primary beam (")	*~20.6" × (300/ν GHz)*
7-m Primary beam (")	*~35" × (300/ν GHz)*
Number of Baselines	*Up to 1225 (ALMA correlator can handle up to 64 antennas)*
Total Bandwidth	*16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)*
Velocity Resolution	*As narrow as 0.008 × (ν/300 GHz) km/s*
Polarimetry	*Full Stokes parameters*



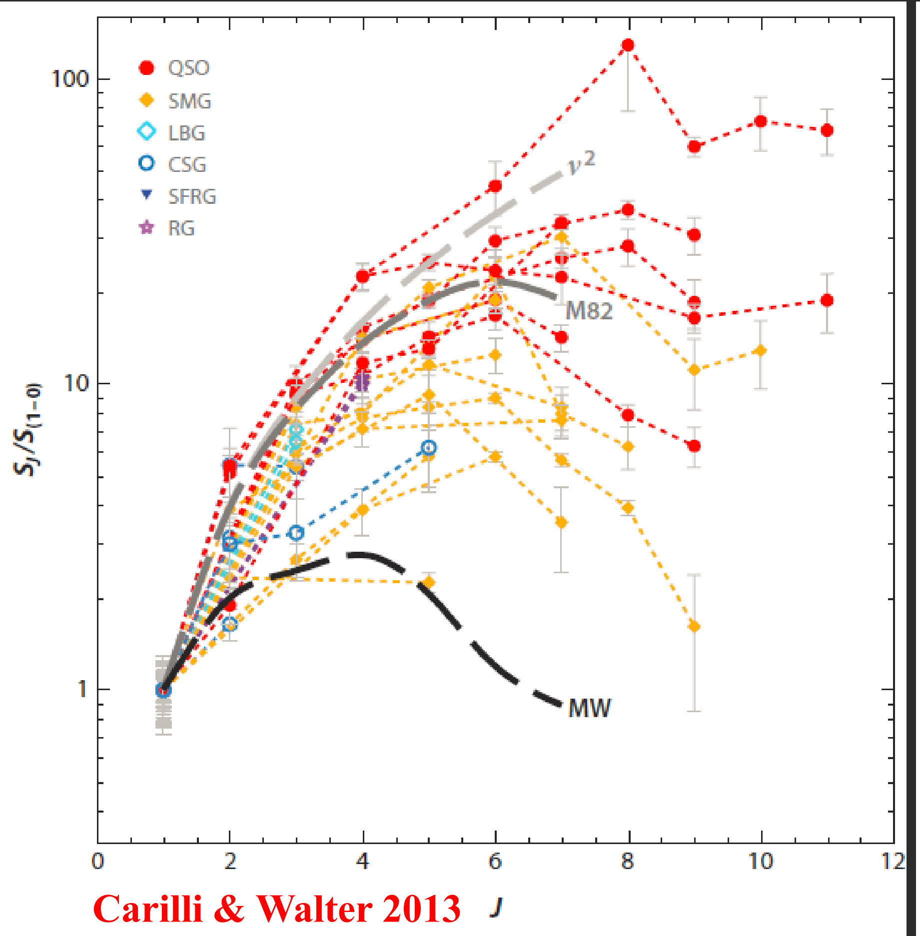
Full Science Capabilities						Most Compact		Most Extended	
Band	Frequency (GHz)	Wave-length (mm)	Primary Beam (FOV; ")	Ap-prox. Max. Scale (")	Contin-uum Sen-sitivity (mJy/beam)	Angular Resolu-tion (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
1‡	31.3-45	6.7-9.5	145-135	93	‡	13-9	‡	0.14-0.1	‡
2‡	67-90	3.3-4.5	91-68	53	‡	6-4.5	‡	0.07-0.05	‡
3	84-116	2.6-3.6	72-52	37	0.07	4.9-3.6	0.04	0.05-0.038	430
4	125-163	1.8-2.4	49-37	32	0.06	3.3-2.5	0.048	0.035-0.027	330
5	163-211	1.4-1.8	37-29	23	*	*	*	*	*
6	211-275	1.1-1.4	29-22	18	0.09	2.0-1.5	0.05	0.021-0.016	490
7	275-373	0.8-1.1	22-16	12	0.15	1.5-1.1	0.08	0.016-0.012	814
8	385-500	0.6-0.8	16-12	9	0.40	1.07-0.82	0.28	0.011-0.009	1900
9	602-720	0.4-0.5	10-8.5	6	1.4	0.68-0.57	0.9	0.007-0.006	8900
10	787-950	0.3-0.4	7.7-6.4	5	1.2	0.52-0.43	1.6	0.006-0.005	—

Star forming galaxies at high redshift

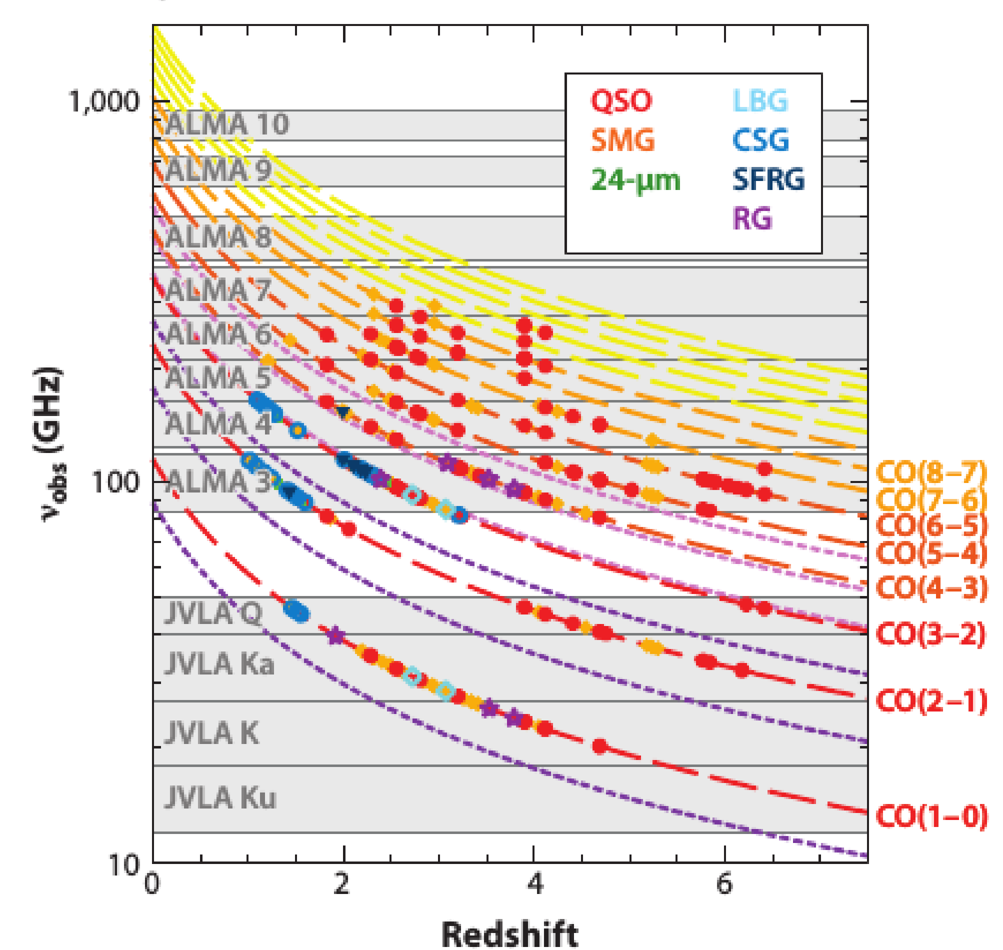
- 

Carilli et al. 2012

- Quasar host galaxies at the very high redshift, Molecular CO lines :



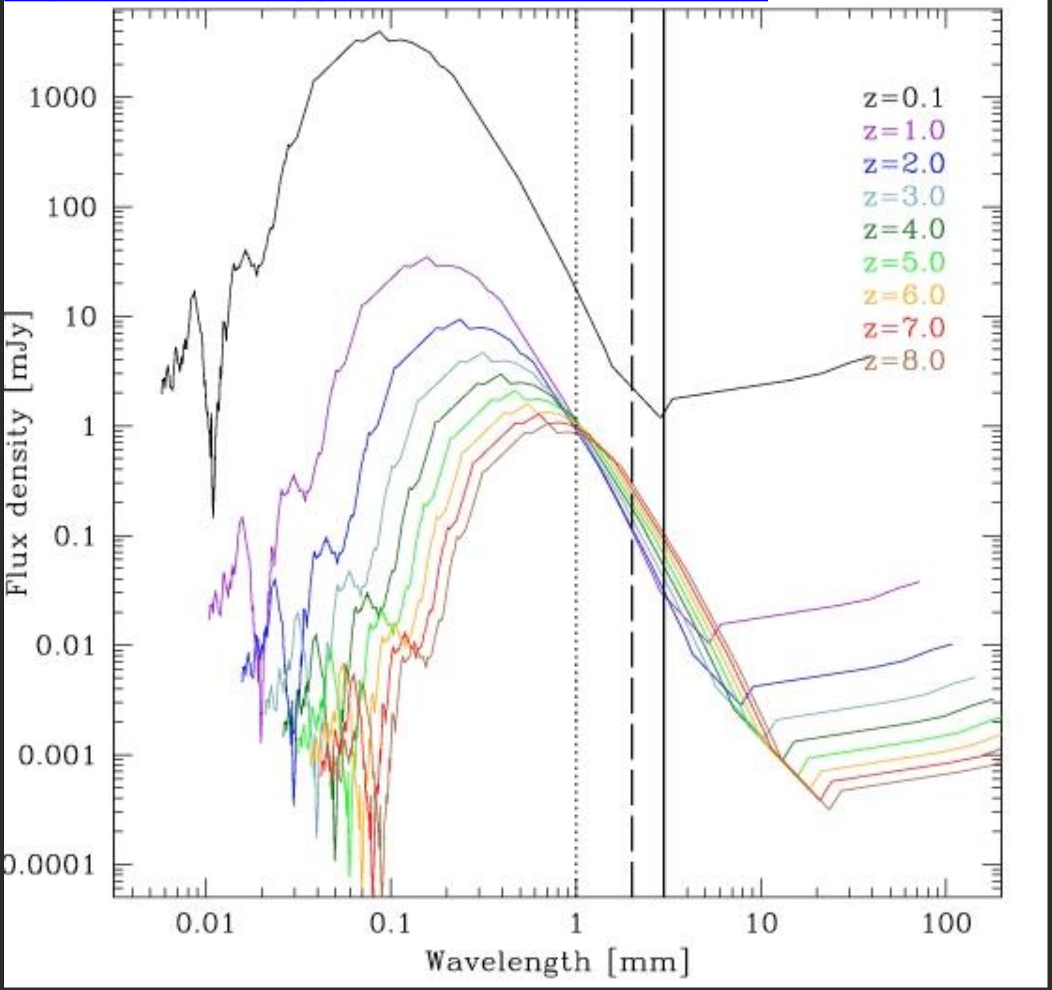
Carilli & Walter 2013



The negative K-correction and dust emission at high-z

- $L_{fir} \sim 4.7 \times 10^{12} (S_{250GHz}/mJy)$ L_{sun} at z~2;
- $L_{fir} \sim 3.6 \times 10^{12} (S_{250GHz}/mJy)$ L_{sun} at z~4;
- $L_{fir} \sim 2.34 \times 10^{12} (S_{250GHz}/mJy)$ L_{sun} at z~6;

http://www.mpia-hd.mpg.de/homes/decarli/science.html



Millimeter and radio observations of the earliest quasar host galaxies

- Submm/mm continuum : redshifted FIR thermal dust continuum emission, 40~60 K, usually heated by nearby star formation;
- Molecular CO : direct tracer of the molecular gas;
- [C II] fine structure line : tracer of star formation, atomic and ionized gas;
- Interferometer observations :
  - Resolve the distributions of the dust, gas components and star formation activity;
  - Spectral lines : resolve the velocity field of the gas.

Questions on SMBH-galaxy formation

- Star formation co-eval with SMBH accretion ?
  - Searching for 40~60 K warm dust, [C II], molecular CO in the quasar host galaxies;
- Size, distribution of star formation ?
  - Mapping of the tracers of star formation, e.g., [C II];
  - Resolving the intense star formation in the nuclear region of a few kpc scale.
- Star formation rate ?
  - Questions of dust SED decomposition, IMF, etc.
- AGN feedback ?
  - Gas kinematics, outflows;
  - ISM excitation ;
- Masses of dust, gas, and stellar components, SMBH-host relations

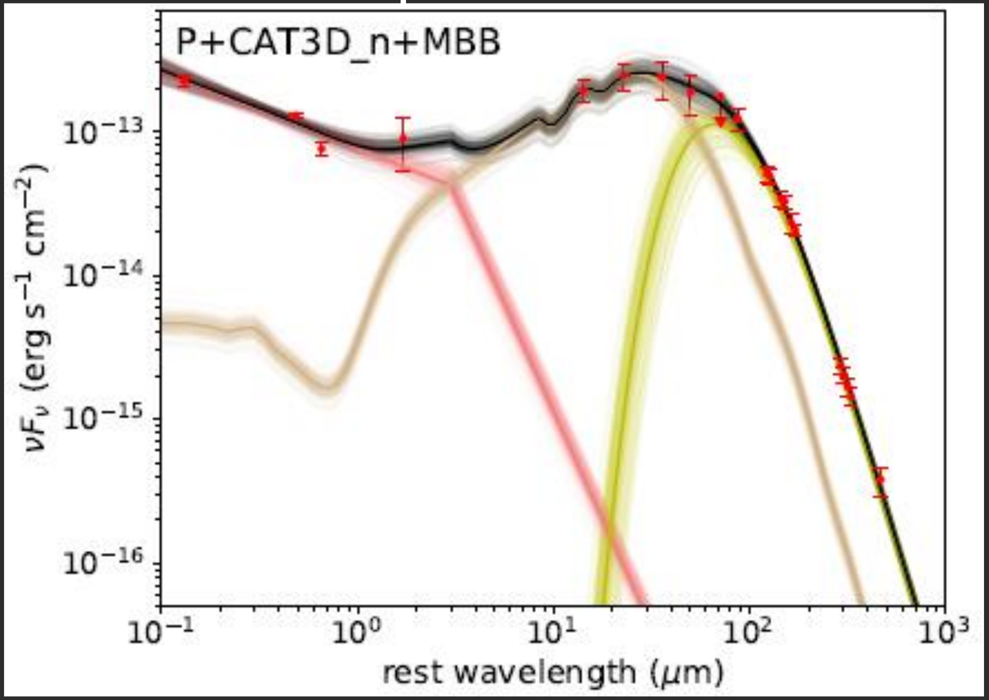
Star formation: Dust and [C II] surveys

- Bright FIR dust continuum was first detected in ~30% of the optically luminous quasars at z~6 using the JCMT, IRAM-30m;
- Combine of Herschel, IRAM, JCMT data: FIR emission powered by massive star formation in quasar hosts.
- FIR luminosities and

Star formation rates comparable to ULIRGs or HLIRGs.

Right : the SED of a z=6 Quasar J2310 with

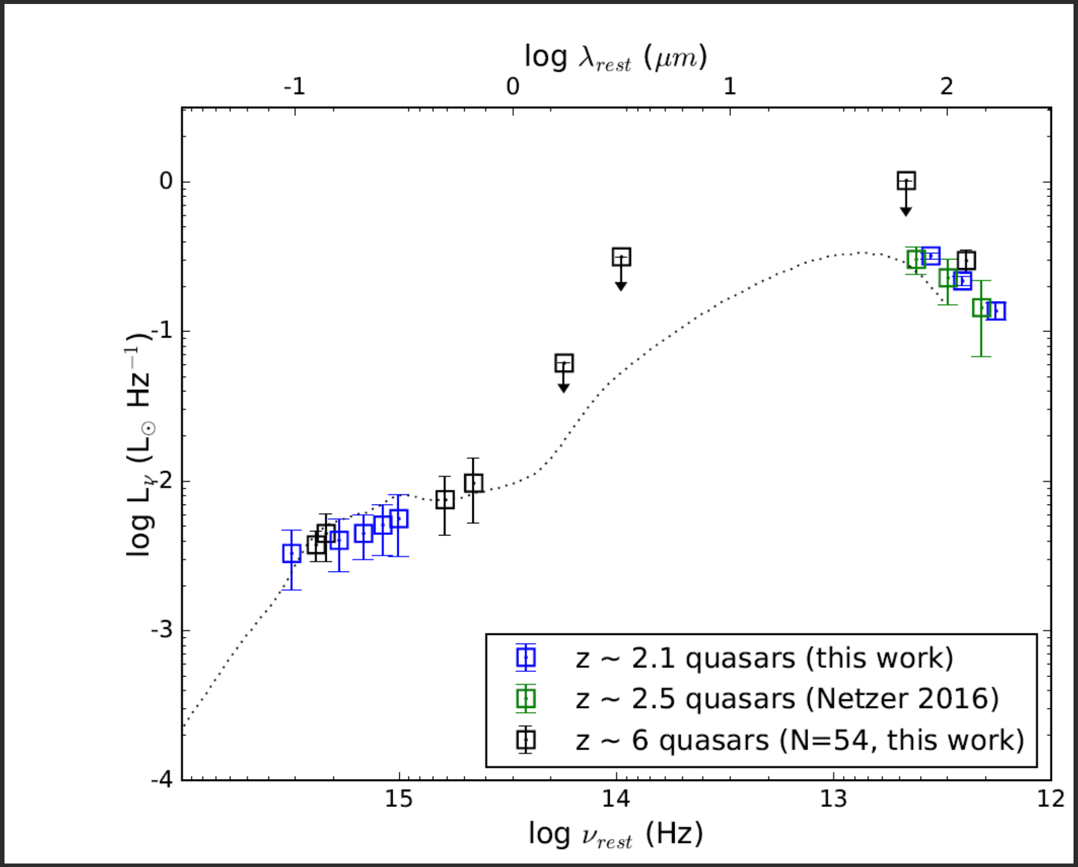
T_{dust}~40 K



Shao et al. 2018, submitted

Star formation: Dust and [C II] surveys

- No clear evolution on the average optical to FIR SED of quasars from low-z to z~6.
- JCMT SCUBA-2 survey of 54 z~6 quasars by Qiong Li et al. 2019, in prep.



Recent ALMA programs of z>=6 quasars by our and other groups

- The ALMA observations mainly focus on the [C II] 158 micron fine structure line and dust continuum:
  - Surveys of optically/mm-selected sample: sub-arcsec resolution, to constrain the source size and total fluxes;
    - [C II] emission from the sources that are bright in dust continuum from previous mm surveys, e.g., ALMA Cycle 0 Wang et al. (2013);
    - ALMA survey of optically selected z>6 quasars with M_{1450} < -25.25, Decarli et al. 2018:

    27 objects at z>6, 100% detected in continuum and 85% in [C II];
    - ALMA observations of the optically fainter quaars discovered from HSC (Izumi et al. 2018, 2019)

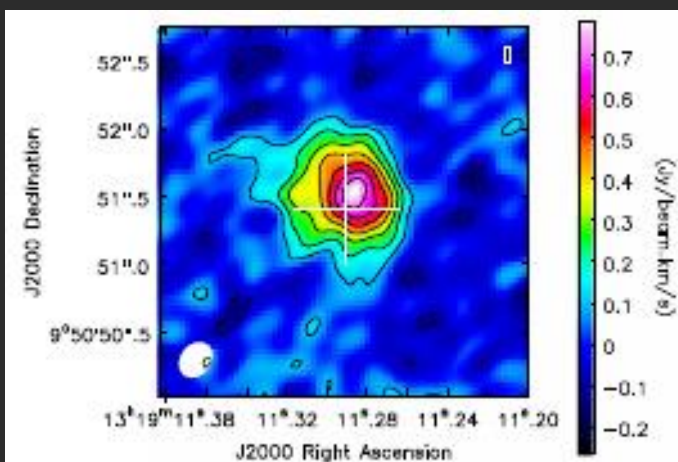
Recent ALMA programs of z>=6 quasars by our and other groups

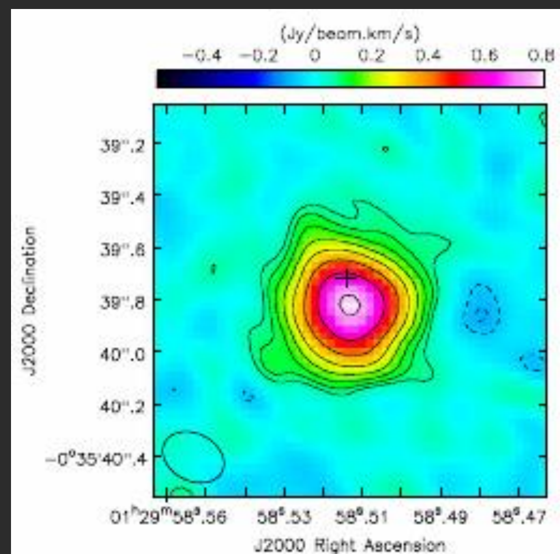
- Continuum sensitivity 5~10 times deeper than previous single dish surveys;
- FIR luminosities 3×10^{11} $L_\odot$ ~ 10^{13} $L_\odot$;
- Dust mass from 2×10^7 ~ 10^9 $M_\odot$.

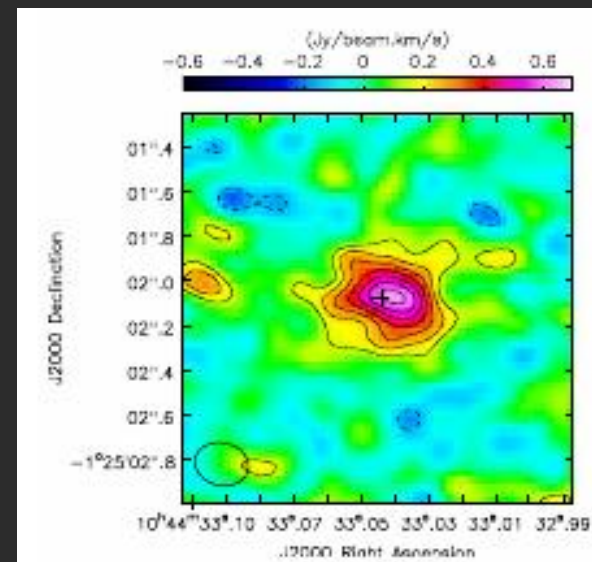
- Detailed studies of the most [C II] luminous objects;
  - 0.1”~0.3” resolution imaging (e.g. Shao et al. 2017, Wang et al. 2019);
  - Observations of CO and other fine structure lines (e.g., Venemans et al. 2017; Carniani et al. 2019);

Dust and [C II] mapping on kpc scale

- ALMA observation of three z~6 quasars at 0.2” resolution; Wang et al. 2019
- FWHM Source sizes : [C II] 0.3”~0.6” or 1.8 kpc ~ 3.6 kpc;
- The continuum emission is usually more compact;

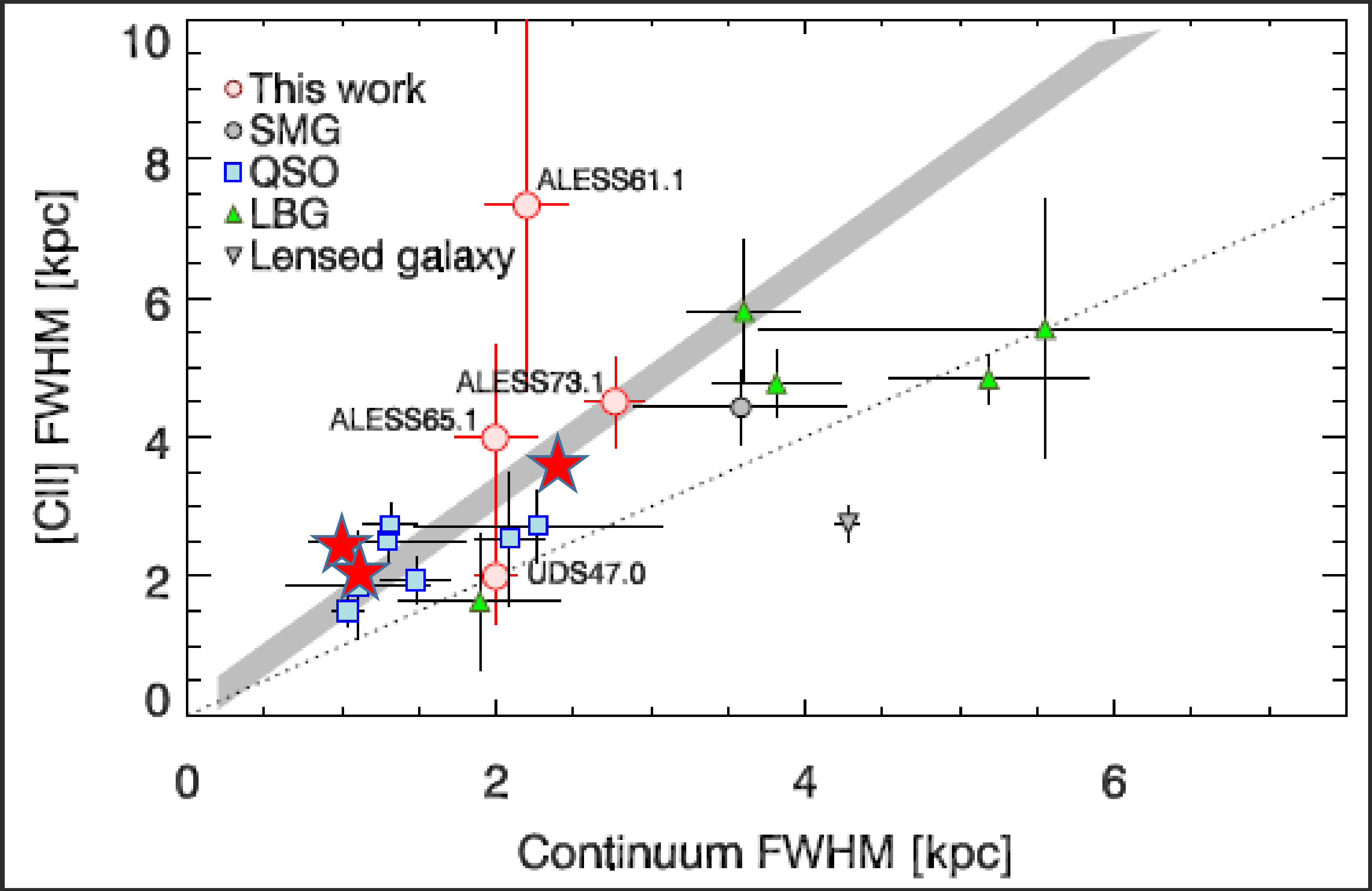






Shao et al. 2017; Wang et al. 2019)

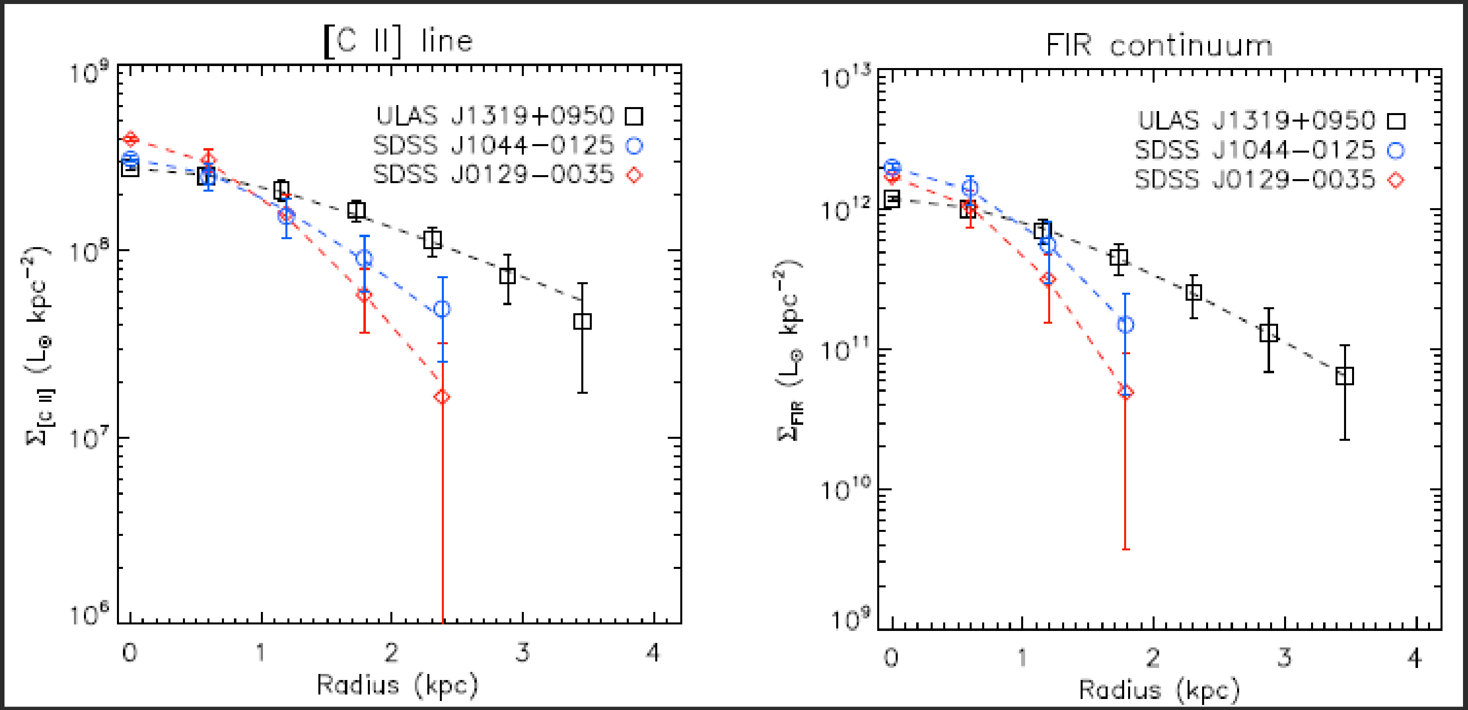
- Following the trend defined by other SMGs and quasars at lower redshift (Gullberg et al. 2018).



Adopted from Gullberg et al. 2018

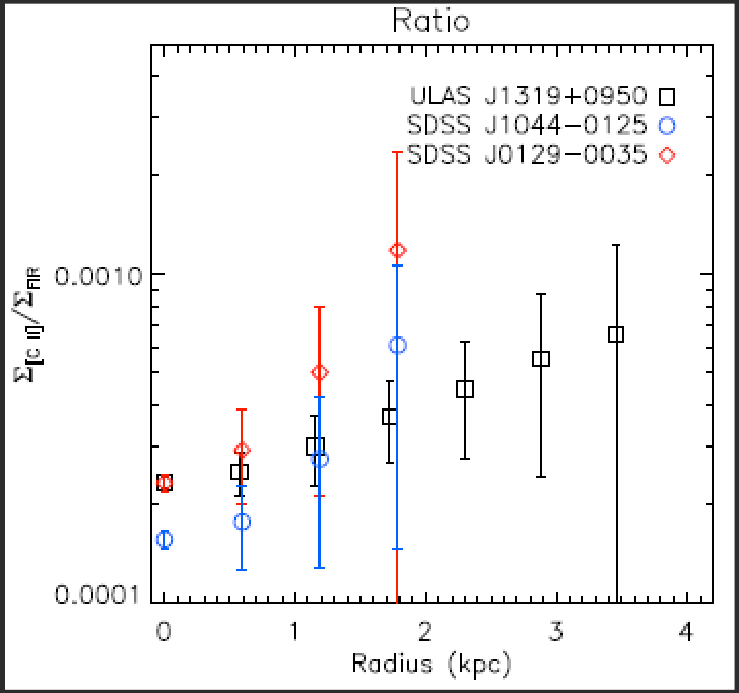
- Surface brightness vs. radius of [C II] and dust continuum: consistent with exponential light profiles;

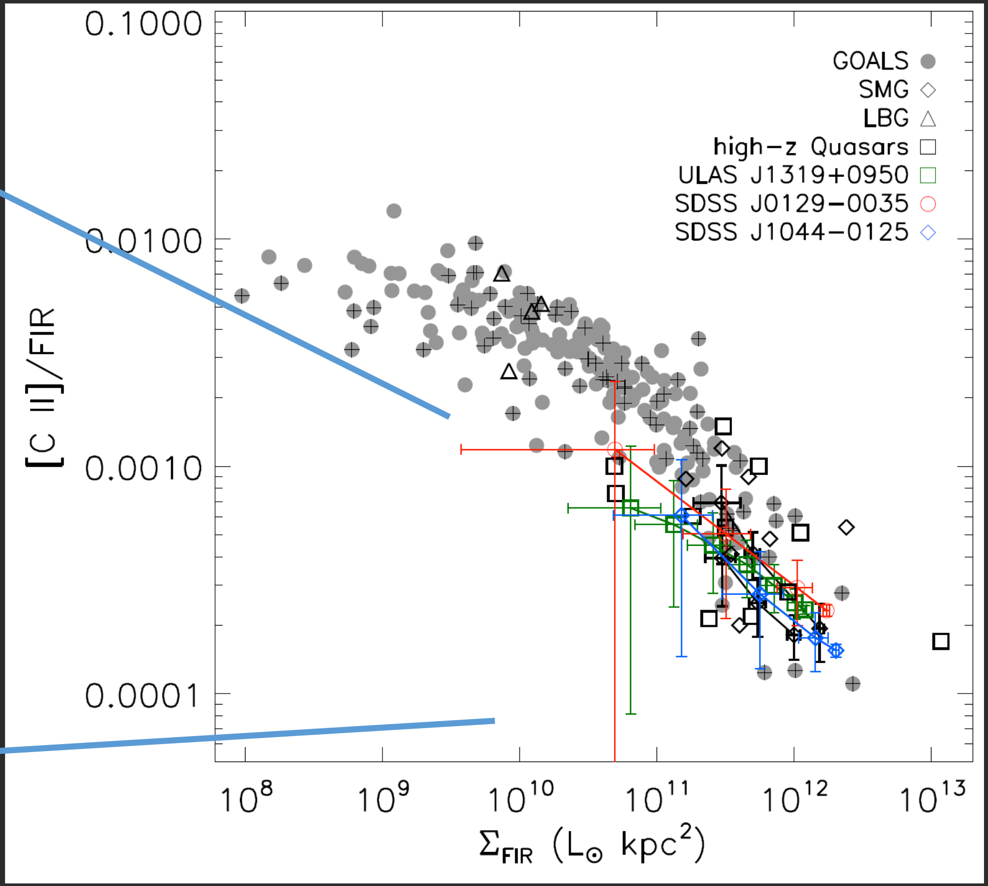
Wang et al. 2019



[CII] to FIR intensity ratio over the disk

- The FIR surface brightnesses in the nuclear region of all three objects are in the range between a few 10^{10} to 2×10^{12} $L_\odot$ kpc^{-1}, indicating a high density and dusty ISM with strong radiation field which could result in the low [C II]-to-FIR ratios

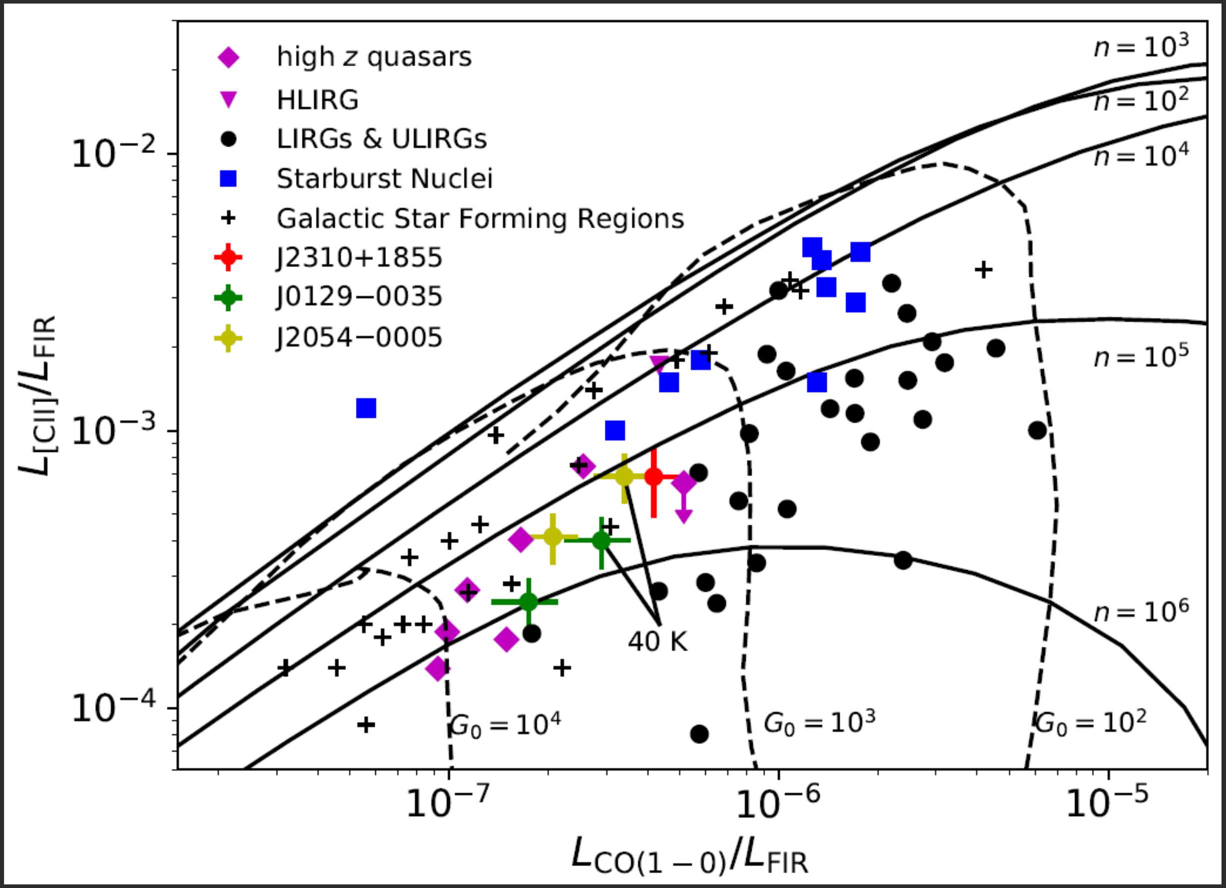




Wang et al. 2019

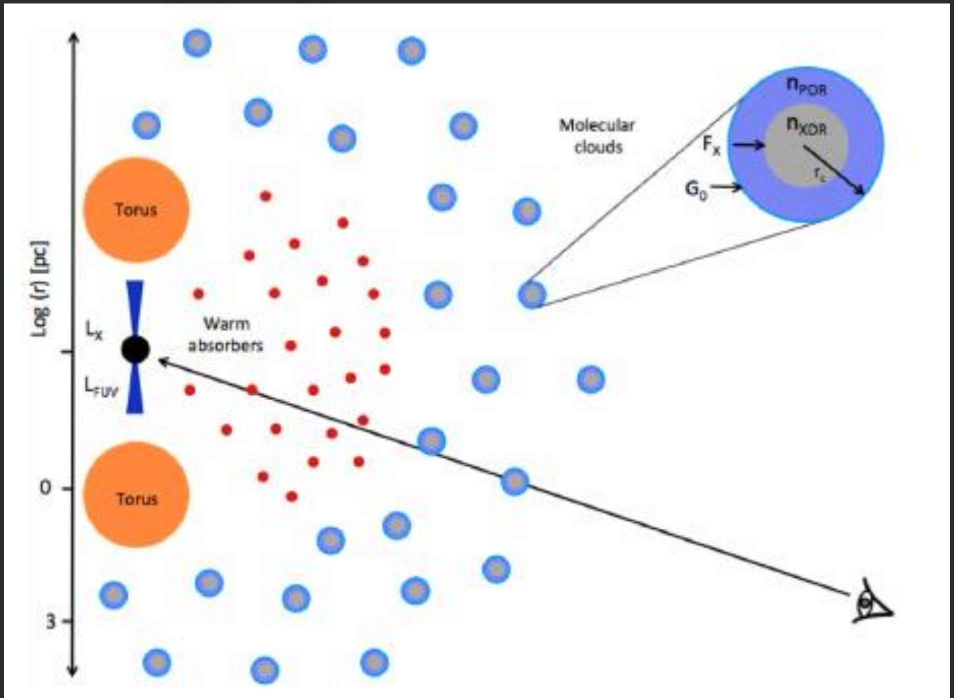
Physical condition and excitation of the ISM

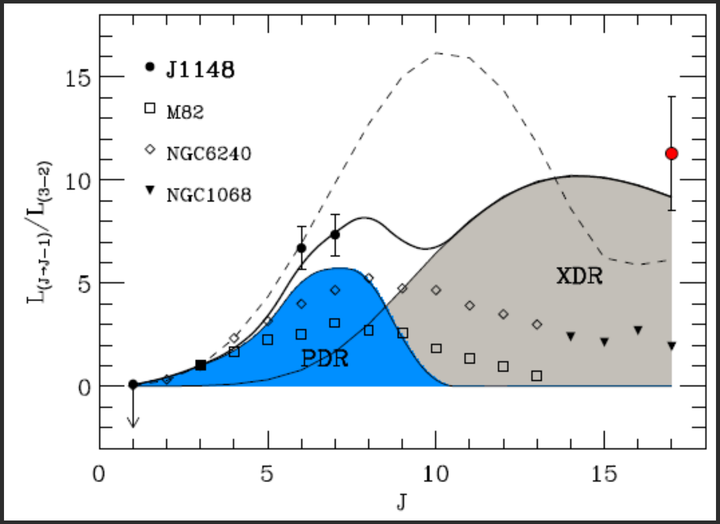
- [C II] , low/mid-J CO suggest emission from PDR regions powered by star formation (Venemans et al. 2017; Shao et al. 2019)



Physical condition and excitation of the ISM

- Detections of very high-J CO suggest CO excitation by the central AGN



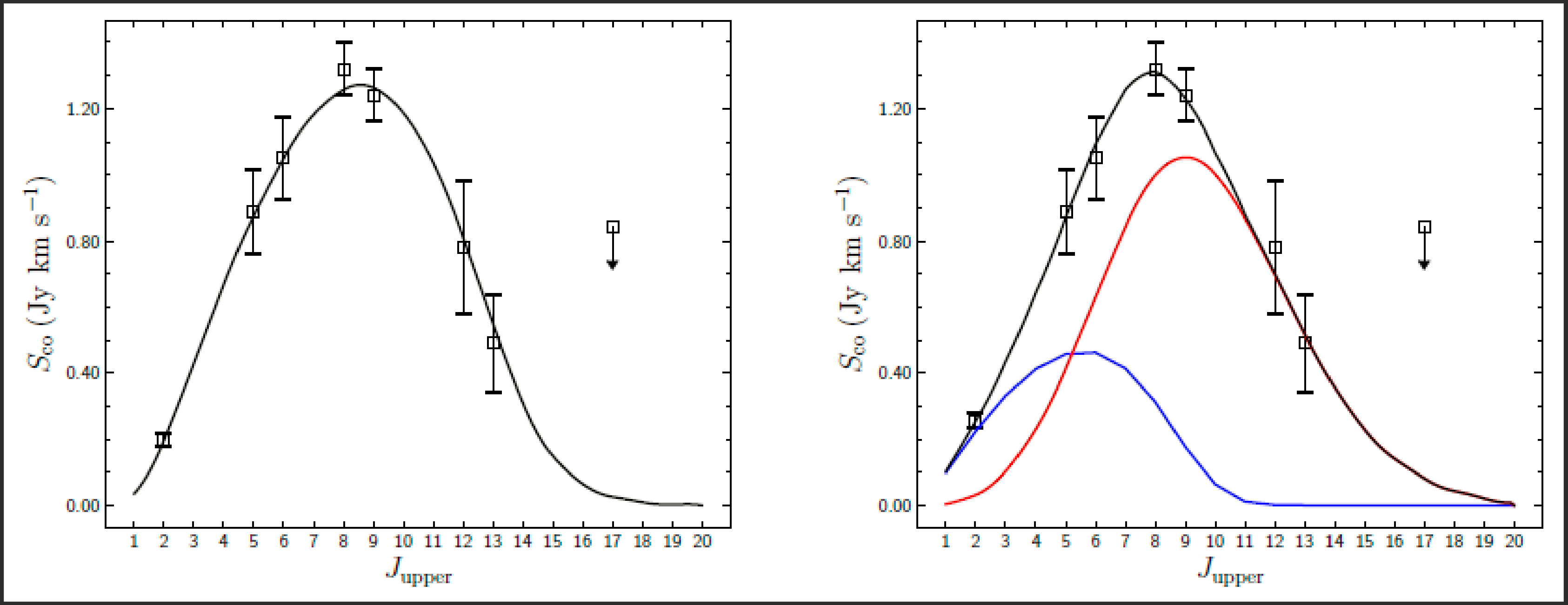


Gallerani et al. 2014

ALMA/NOEMA observations of the most FIR luminous object, Jianan Li et al.

- SDSS J2310+1855, at z=6.0, FIR luminous with luminosity of 10^{13} $L_{\odot}$;
- We search for CO (8-7) (9-8) line with ALMA, ~0.6" resolution;
- CO (13-12), (12-11), (5-4) with NOEMA;
- Preliminary results : the CO SLED and molecular gas excitation;

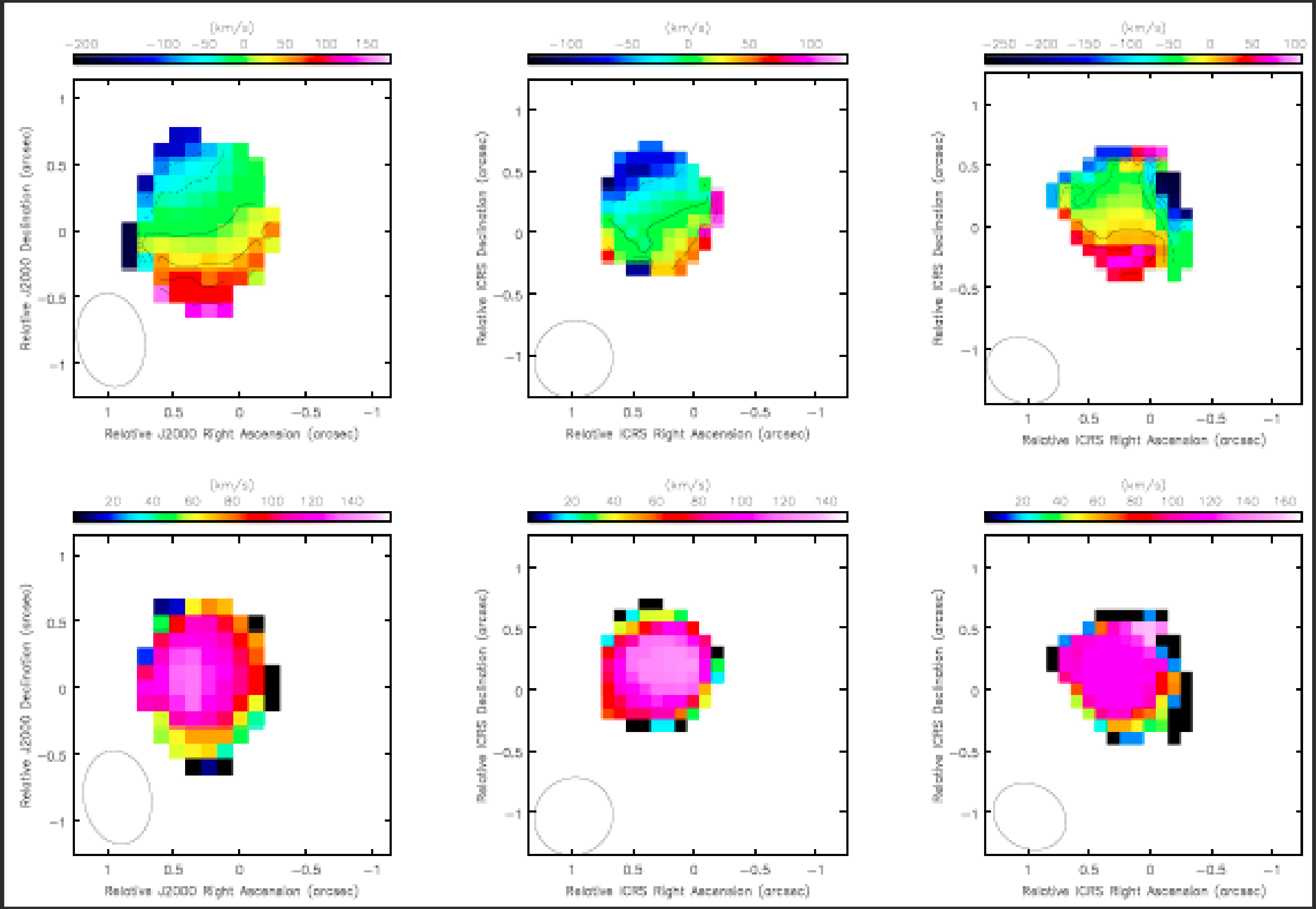
- The CO SLED could be described with a single molecular gas component with the LVG model;
- Left : single component, T_K ~hundred K, $n(H_2) \sim 10^5\ cm^{-3}$;
- Right : double components, J1148 + hotter and denser component;



- The ALMA observation at 0.6” resolution, we are looking at the dense gas in the nuclear region;

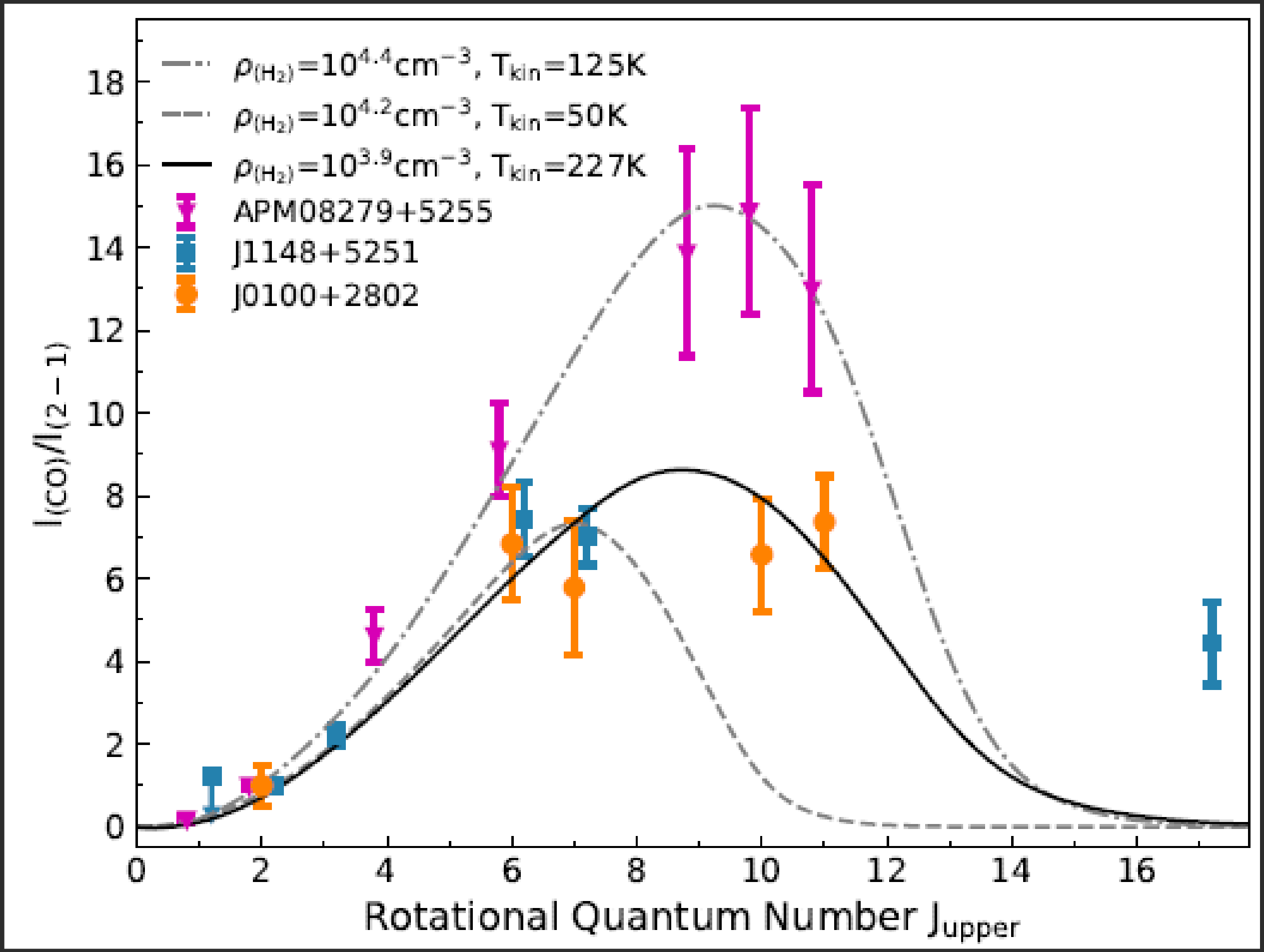
Li et al. 2019, to be submitted

- Velocity maps : compared between [C II], CO (8-7), CO (9-8), Li et al. 2019 to be submitted



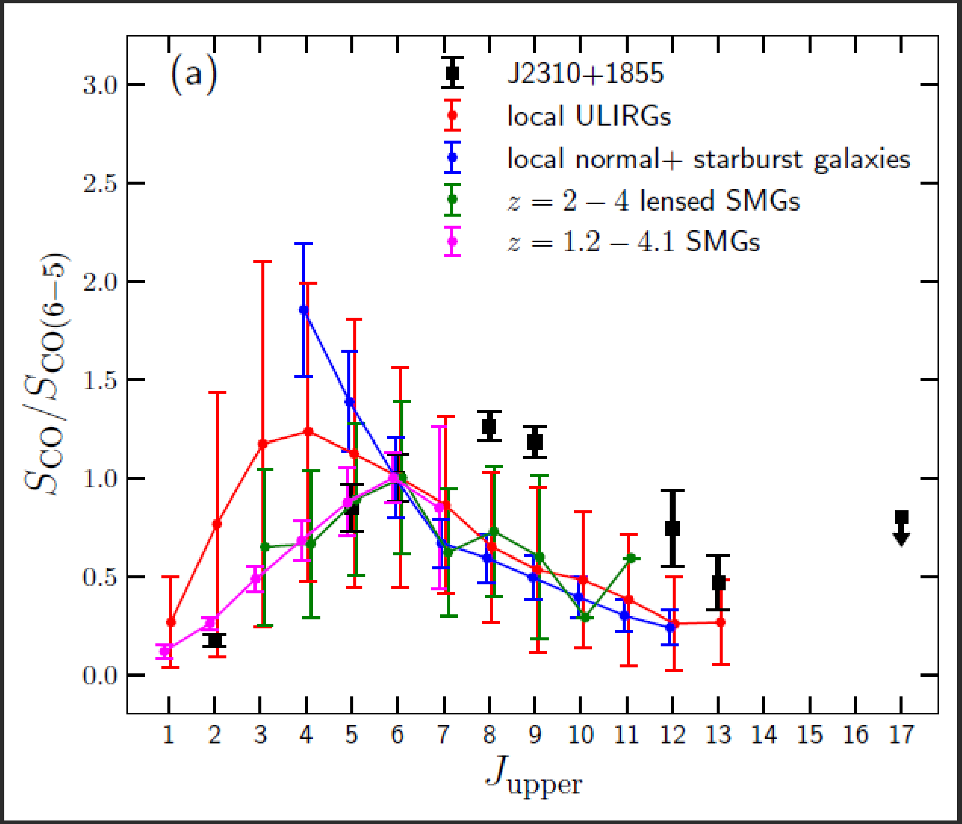
CO SLED of the most massive quasar J0100+2802 at z=6.3 Wang, F. et al. 2019

- Best fitted with two components:



Physical condition and excitation of the ISM

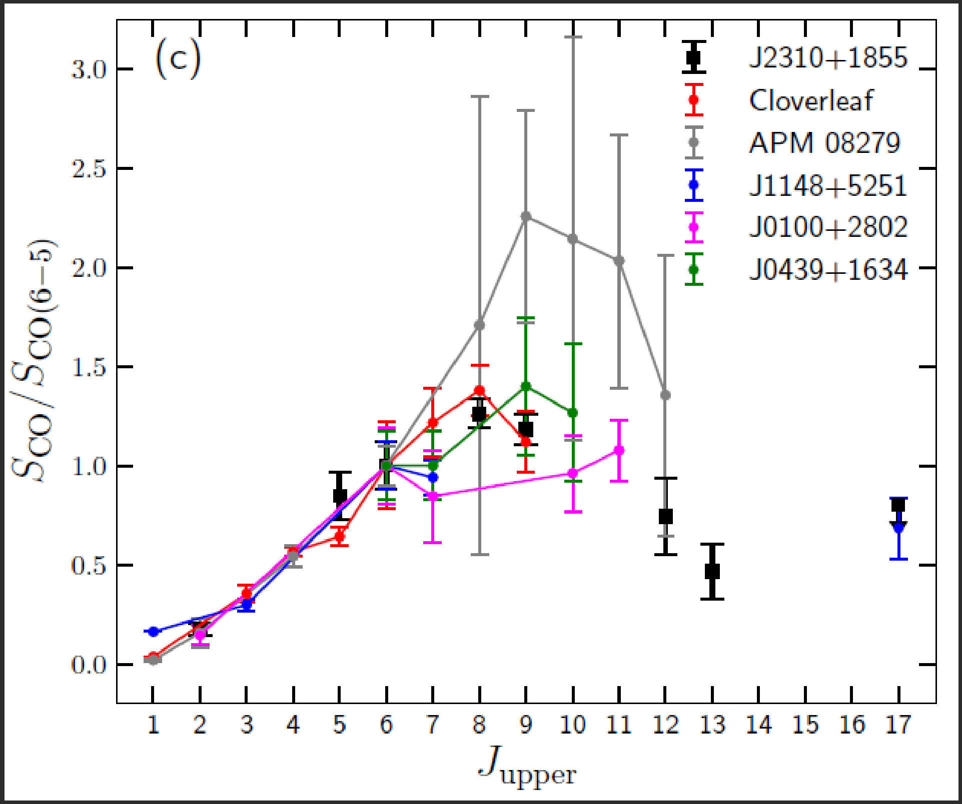
- CO SLED of one of the mm bright z~6 quasar (black square):
- Compared to the starburst systems.
- Highly excited molecular gas that dominated the high-J CO SLED.



Li et al. 2019 submitted

Physical condition and excitation of the ISM

- CO SLED of quasar hosts, including four quasars at z~6;
- Dense (10^5 cm^{-3}) and warm (10^2 K) molecular gas component that dominates the high-J transition;
- Powered by AGN ?
- Cold component associated with the 40-50 K dust ?

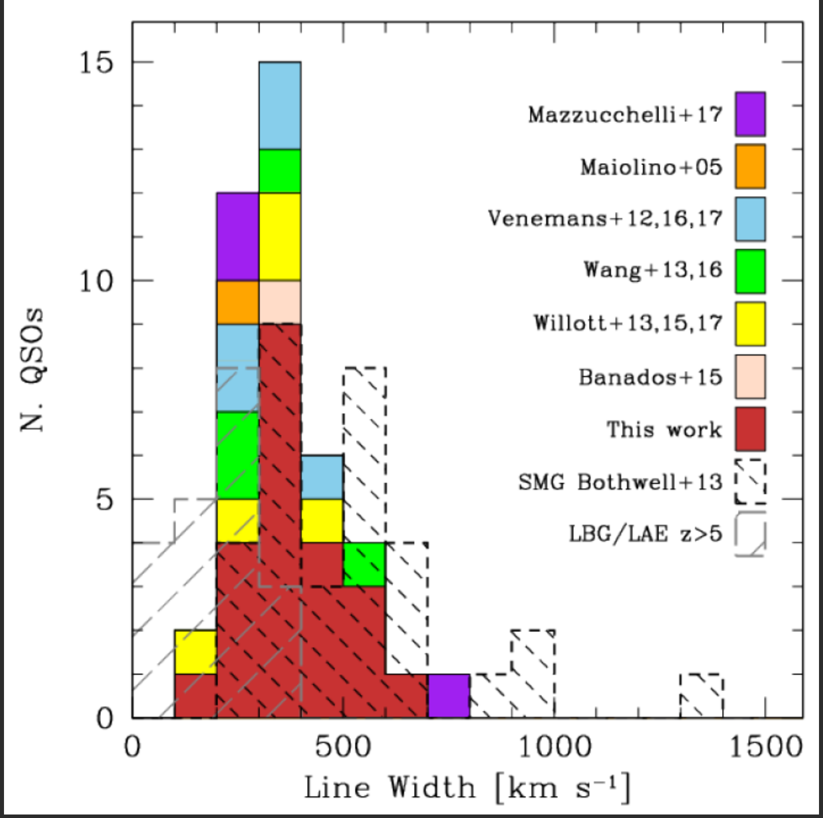


Li et al. 2019 submitted

Gas kinematics

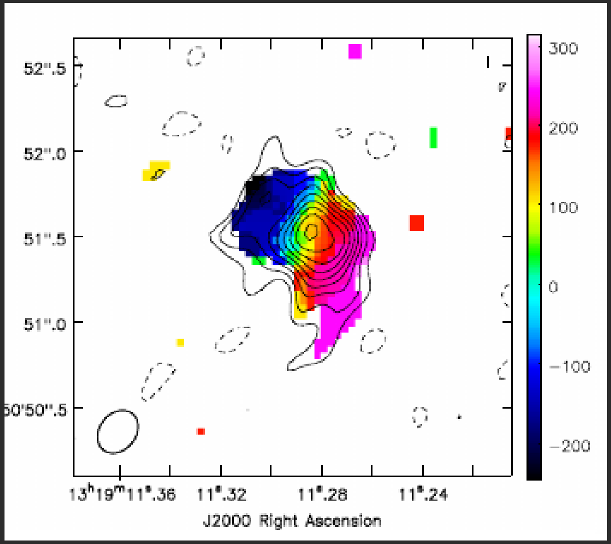
- Surveys of [CII] line in the z~6 quasar hosts:

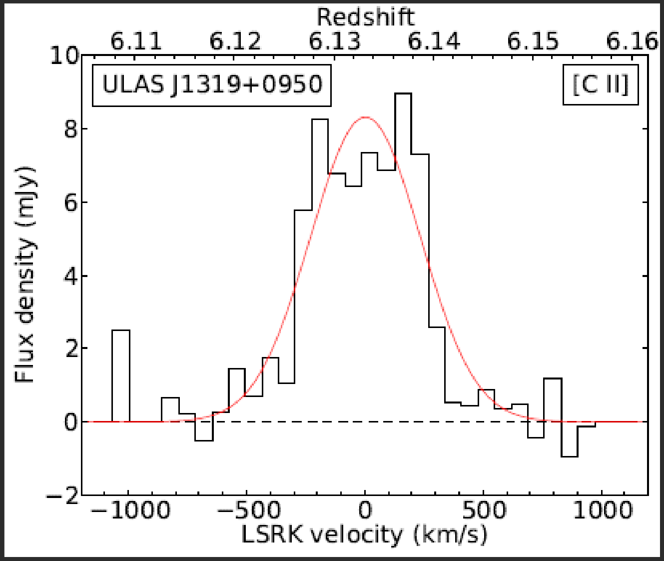
  Similar [C II] line width distributions between quasars and SMGs (Decarli et al. 2018);



Gas kinematics – a range of activities

- Observations of the [C II] and CO emission lines from these young quasar hosts at z>5.7 at sub-arcsecond to arcsecond resolution reveal a range of kinematic properties:
- Velocity gradients: (Willott et al. 2013, 2017; Venemans et al. 2016; Shao et al. 2017) rotating motion.

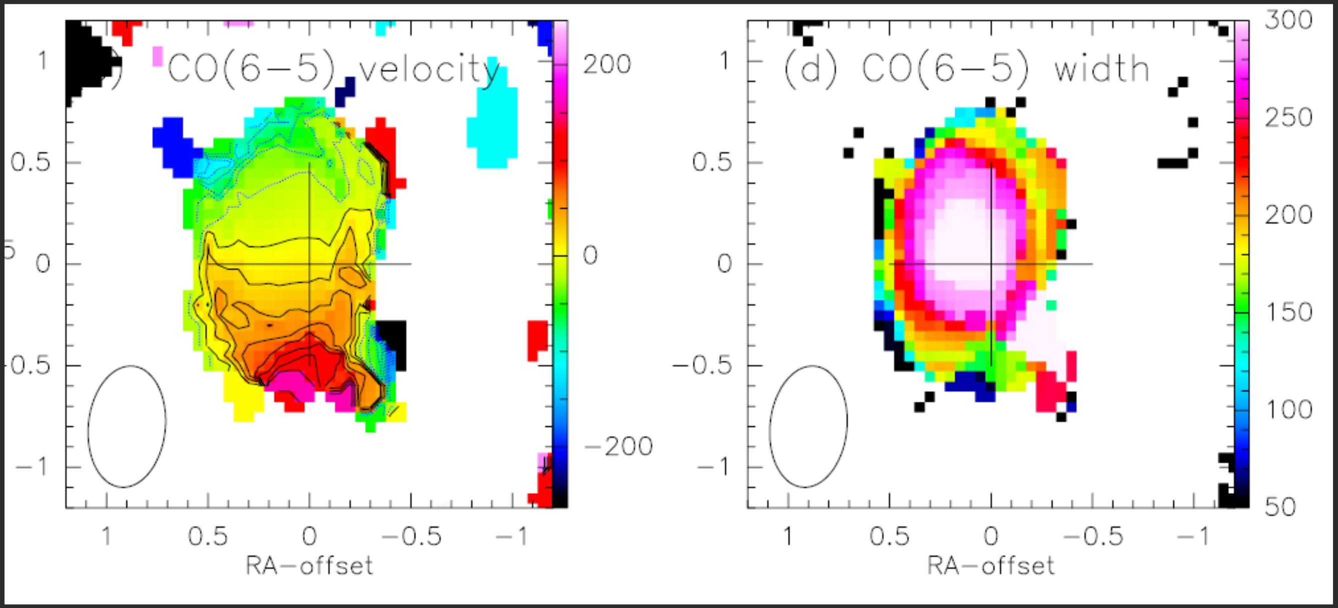




Gas kinematics - a range of activities

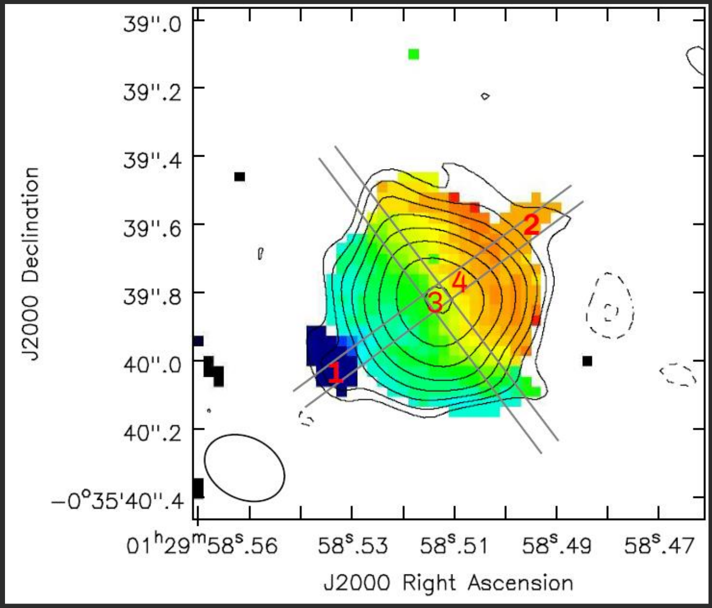
- Large velocity dispersion/turbulence

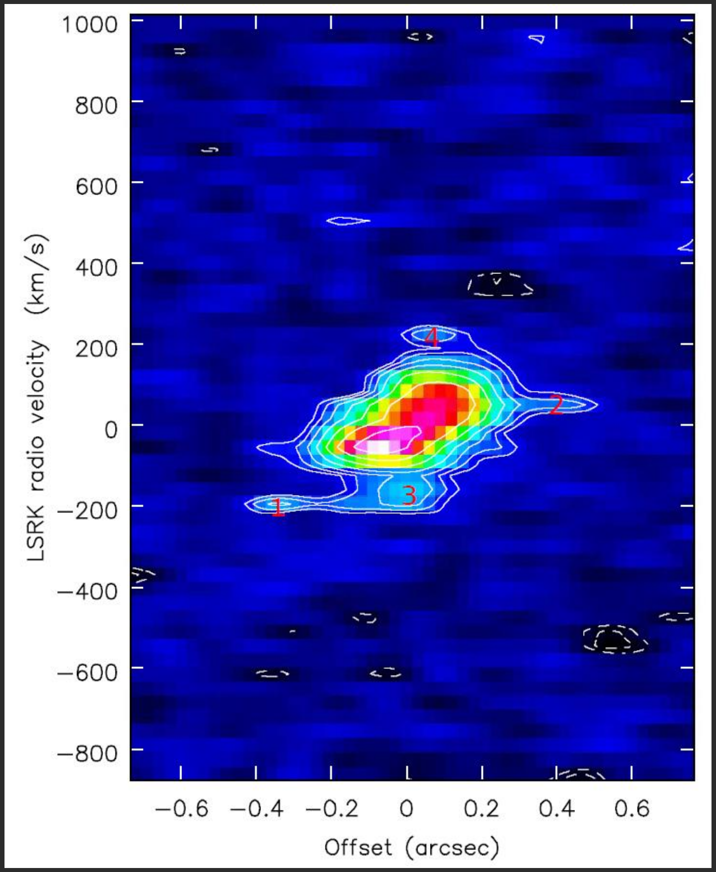
  e.g., SDSS J2310+1855 at z=6.0, $v_{rot}/\sigma \sim$ 1-2, Feruglio et al. 2018;



Gas kinematics – a range of activities

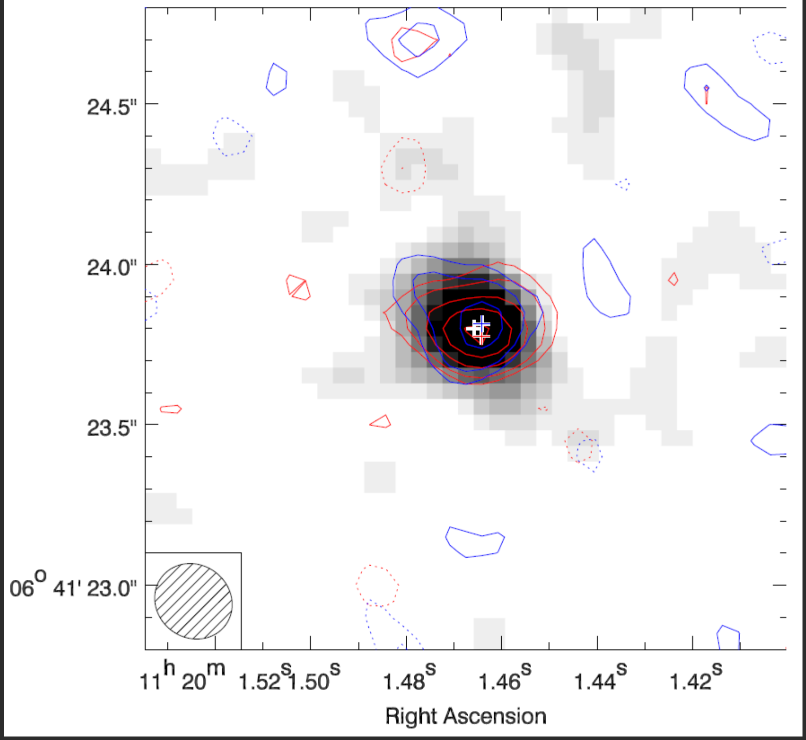
- SDSS J0129-0035 at z=5.78, complex gas kinematics, rotation + turbulent clumps (Wang et al. 2019)



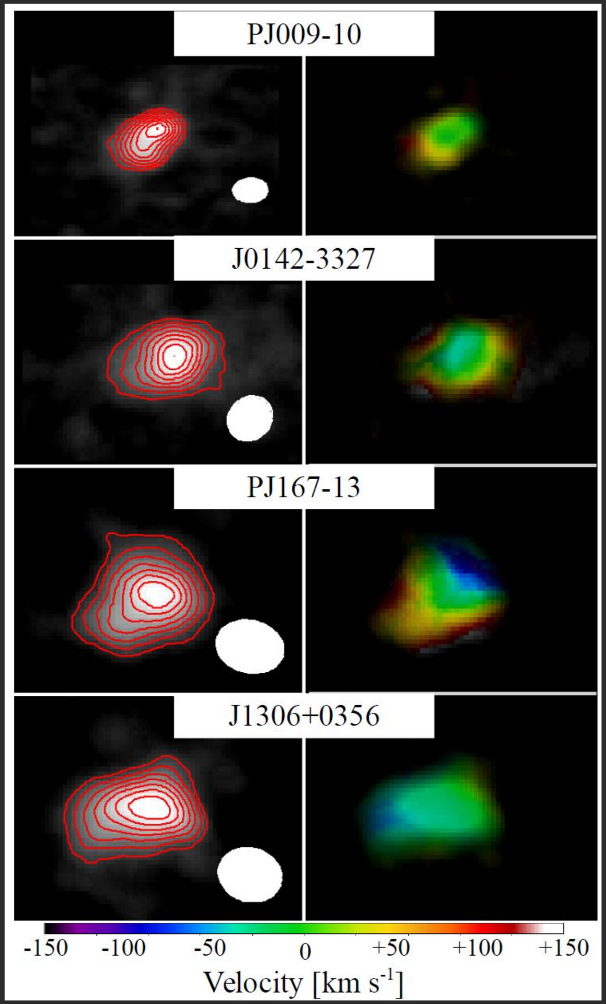


Gas kinematics – a range of activities

- Compact, dispersion-dominate system (Decarli et al. 2018; Venemans et al. 2018)

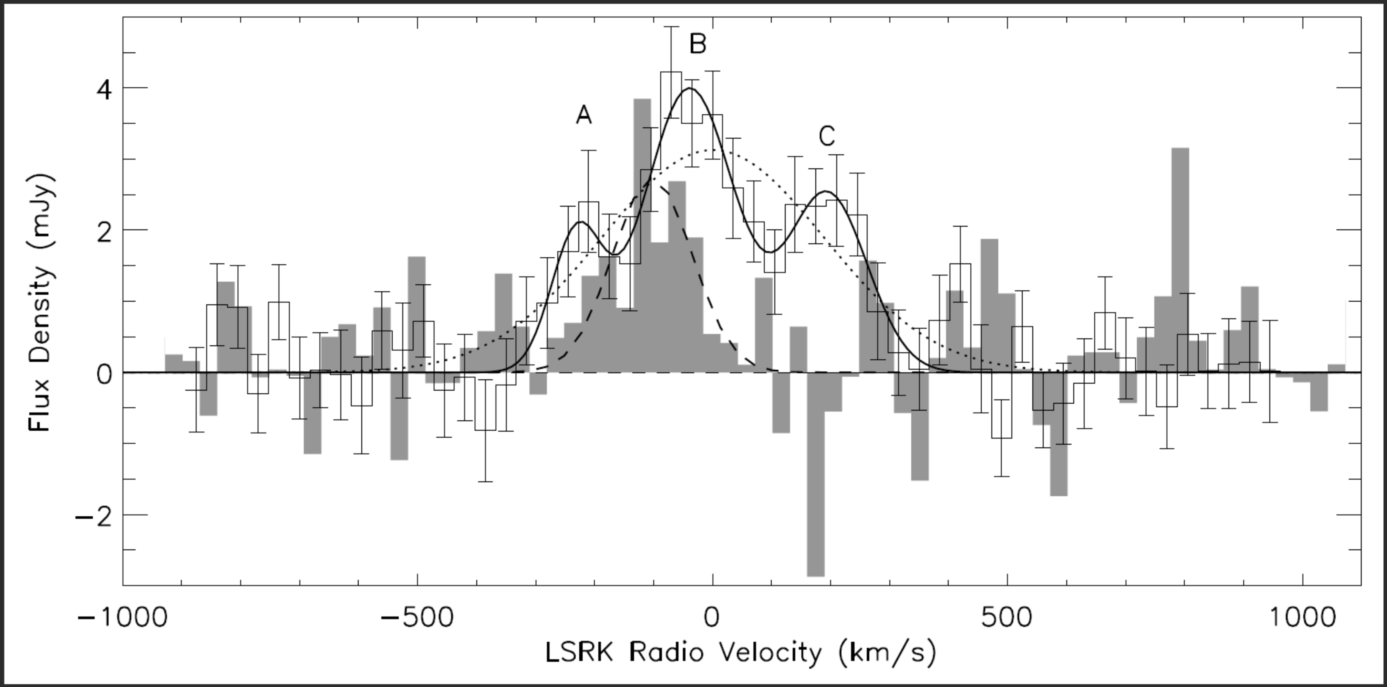


z=7.1 quasar, Venemans et al. 2017



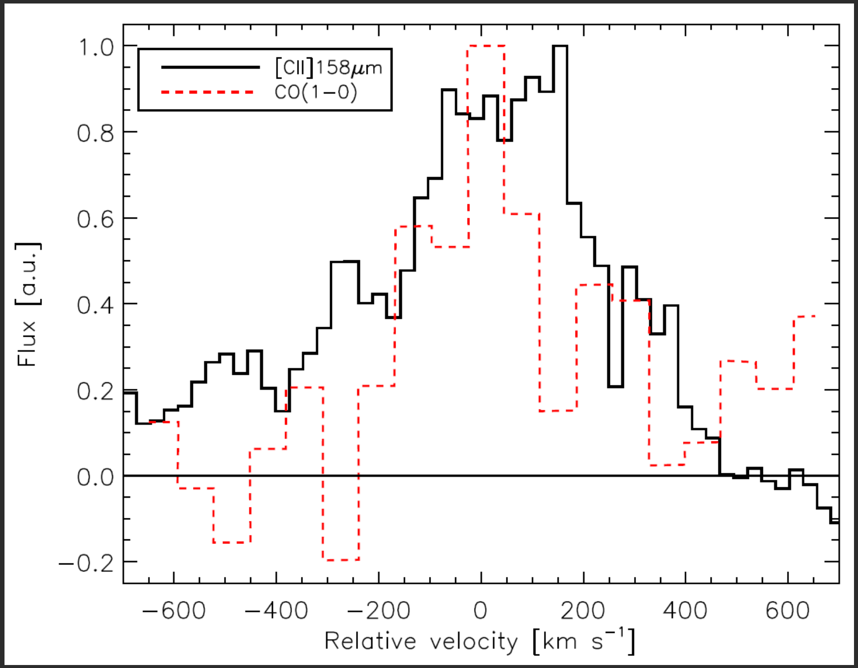
Different line profile between the [C II] and CO

- SDSS J1044-0125 at z=5.78, A warmer gas component traced by [C II] ?



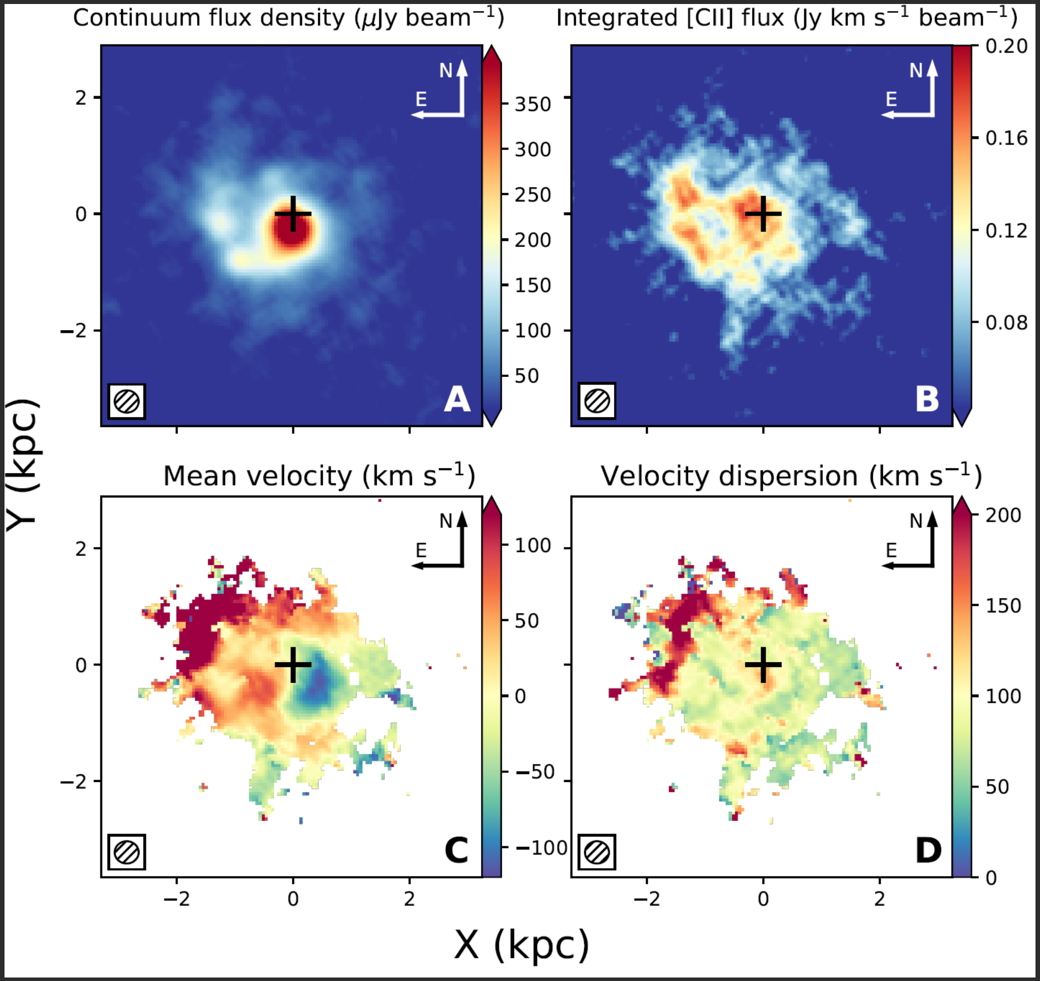
Wang et al. 2019

- CO(6-5) trace the dense molecular gas from star forming region;
- [C II] : trace the disk gas and star forming regions, as well as the warm diffuse neutral/ionized medium, could also powered by the central AGN;
- e.g., Asymmetric [C II] line emission that is broader than the molecular CO emission was detected the radio galaxy 3C 326N, suggest [C II] emission from a warm diffuse and turbulent molecular gas component powered by AGN-jet activity (Figure from Guillard et al. 2015).



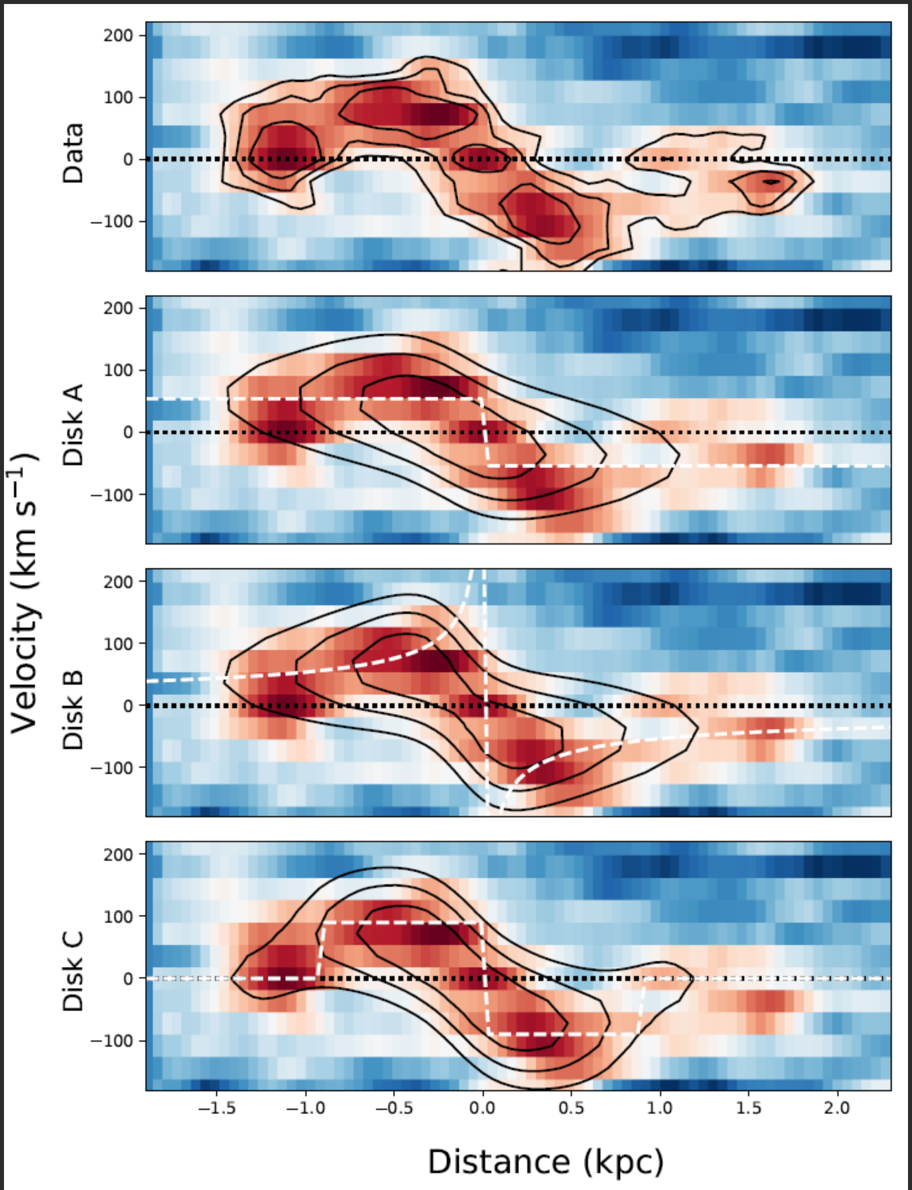
Gas kinematics – more details with ALMA image, recent work from Venemans et al. 2019

- 0.076” resolution with ALMA of a z=6.6 quasar host, Venemans et al. 2019;

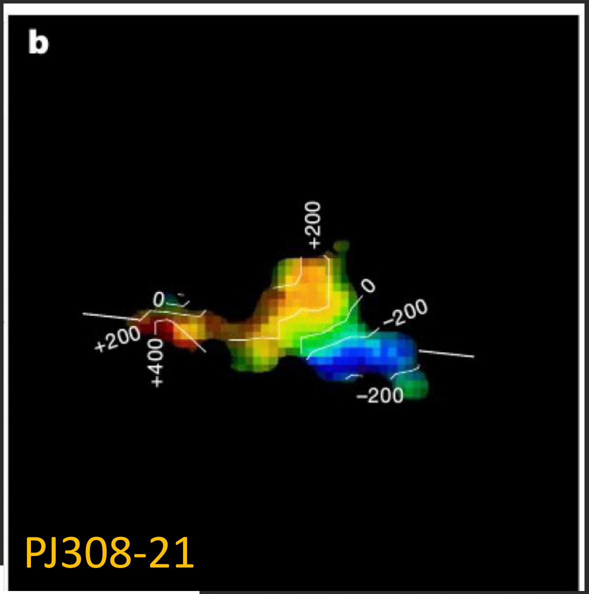


- Gas kinematics : dispersion + rotation in the central kpc.

- This implies that most of the gas has not yet settled in a disk ?
- Or heated/disrupted by the AGN ?

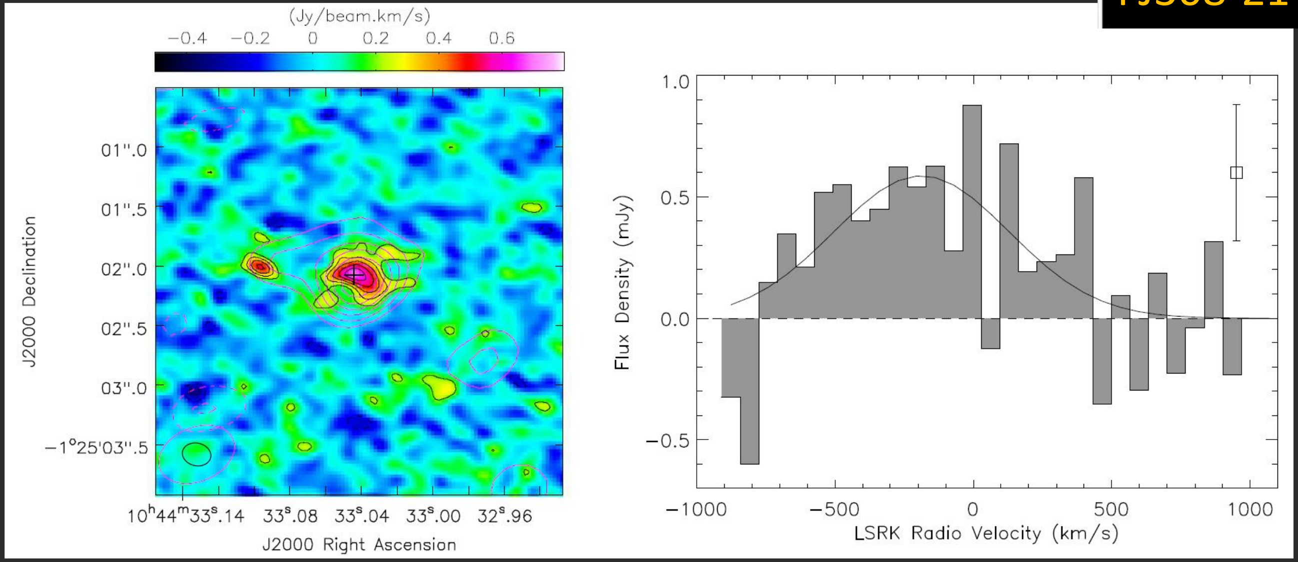


Gas kinematics – a range of activities



- Galaxy interactions/companions:

e.g., Decarli et al. 2017;



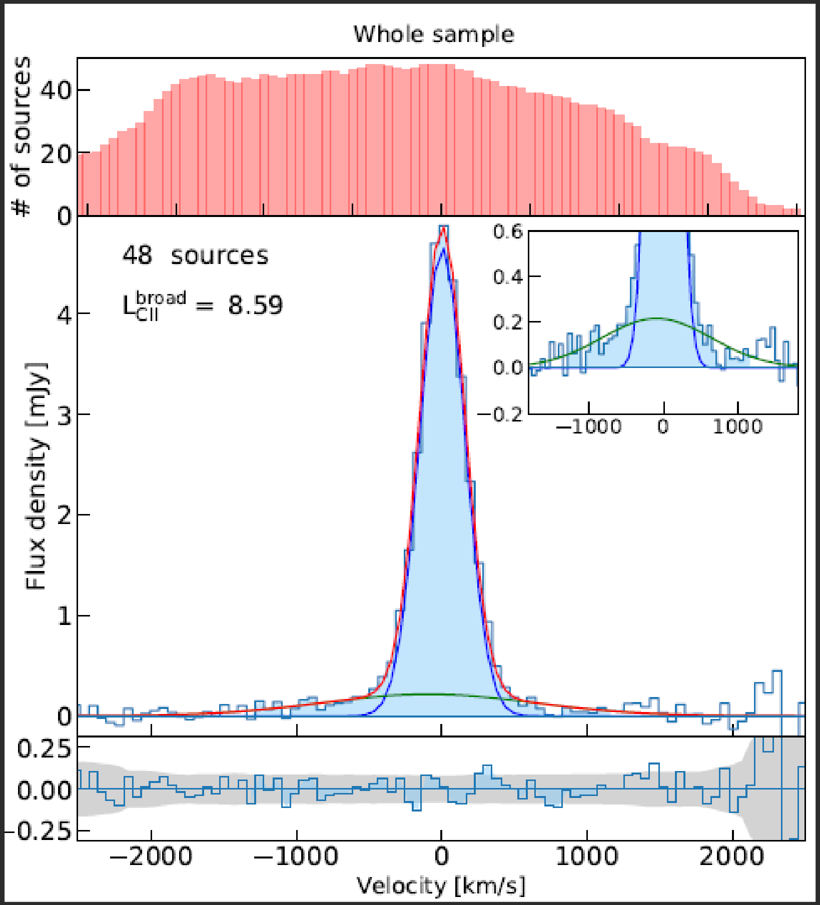
SDSS J1044-0125 at z=5.78, Wang et al. 2019

- Or gas outflows ?

Gas kinematics – a range of activities, recent work from Bischetti et al. 2018

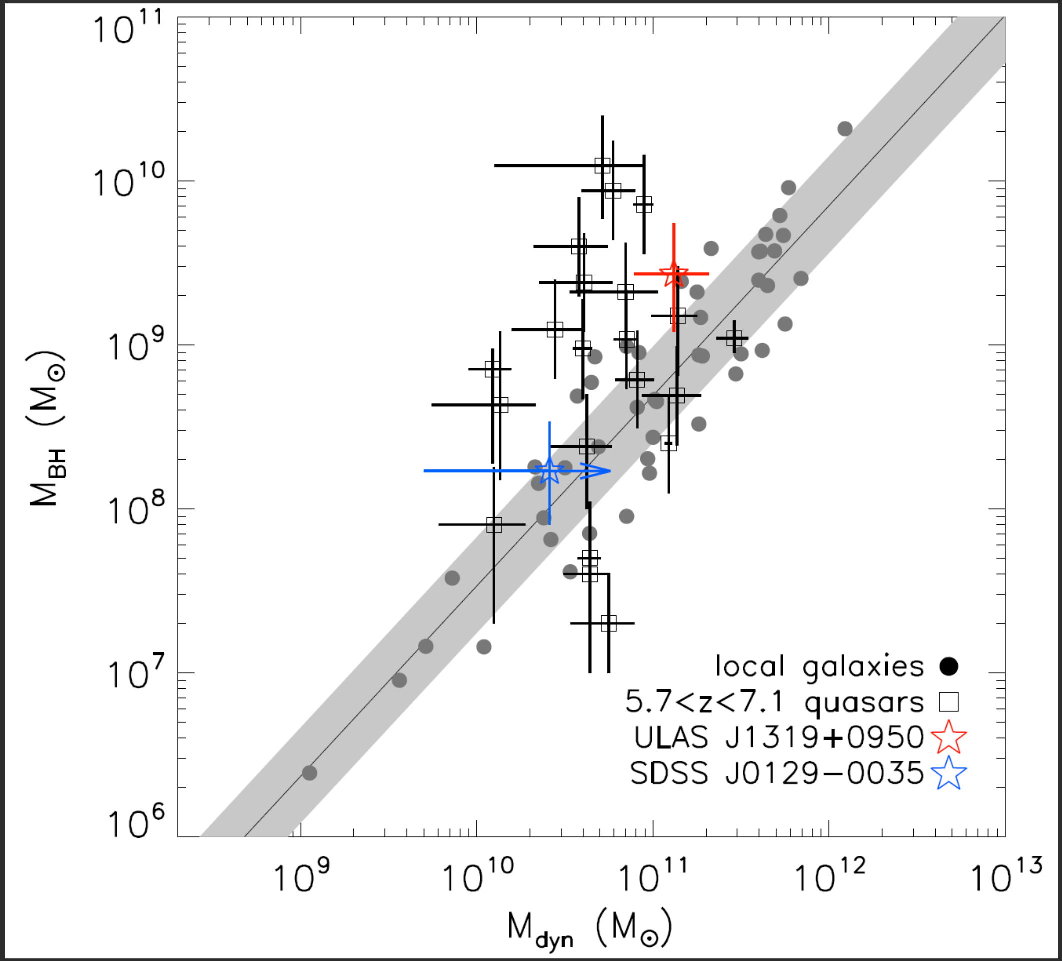
- Gas outflows: detections of low surface brightness, extended emission is indeed difficult.

Bischetti et al. 2018



M_{BH} - M_{dyn} : compared to local systems

- The dynamical mass constraints on these z6 to 7 quasars suggest that, in the early universe, the most massive SMBHs with masses of 10^9 to 10^{10} $M_\odot$ may grows faster than that of their host galaxies (Walter et al. 2004; Venemans et al. 2016;Wang et al. 2016; Decarli et al. 2018);
- The less massive systems (10^7~10^8 $M_\odot$) are evolving more closer to the trend of local galaxies (Willott et al. 2017; Izumi et al. 2018).



Discussions: Dynamical mass of the quasar host

- Can the [C II], or CO emitting region trace the stellar component in the quasar hosts ?
- Line width from the observing spectrum → circular velocity (rotating system) / velocity dispersion (dispersion-dominated system);
- Uncertainties in the SMBH mass ;
- Will need JWST to directly image the stellar component.

Summary

- Large samples of quasars at z>6 are now selected from deep optical and near-IR surveys: these objects allow us to study the formation of the first SMBHs and galaxies;
- The mm and radio telescopes allow us to observe the dust and gas components in these earliest galaxies;
- Detections of strong dust continuum, molecular CO, [C II] in quasar host galaxies at z~6 and higher provide evidence of massive star formation, co-eval with rapid SMBH accretion;
- Line and FIR luminosity ratios : physical conditions of the ISM.
- Spatially resolved dust and gas emission : provide constraints on the dynamics of the quasar host galaxies, and evidence of AGN feedback;
- Preliminary constraints on the M_{BH}-M_{bulge} relationships.

Open questions and Opportunities

- Evolutionary connections between different systems at the highest redshift;
- Star formation and ISM excitation in different systems: quasar host galaxy, dusty starburst galaxy with no visible AGN, normal star forming galaxies;
- SMBH-galaxy co-evolution : M-σ relationships, accurate measurement of the host galaxy masses, stellar velocity dispersion; directly imaging of stellar component;
- Modern millimeter and radio facilities : provide the required spatial resolution and sensitivity to detect the faint continuum and line emission from the most distant galaxies;
- Together with future optical and near-IR telescopes, e.g., JWST, TMT, will fully probe the formation of the first galaxies.