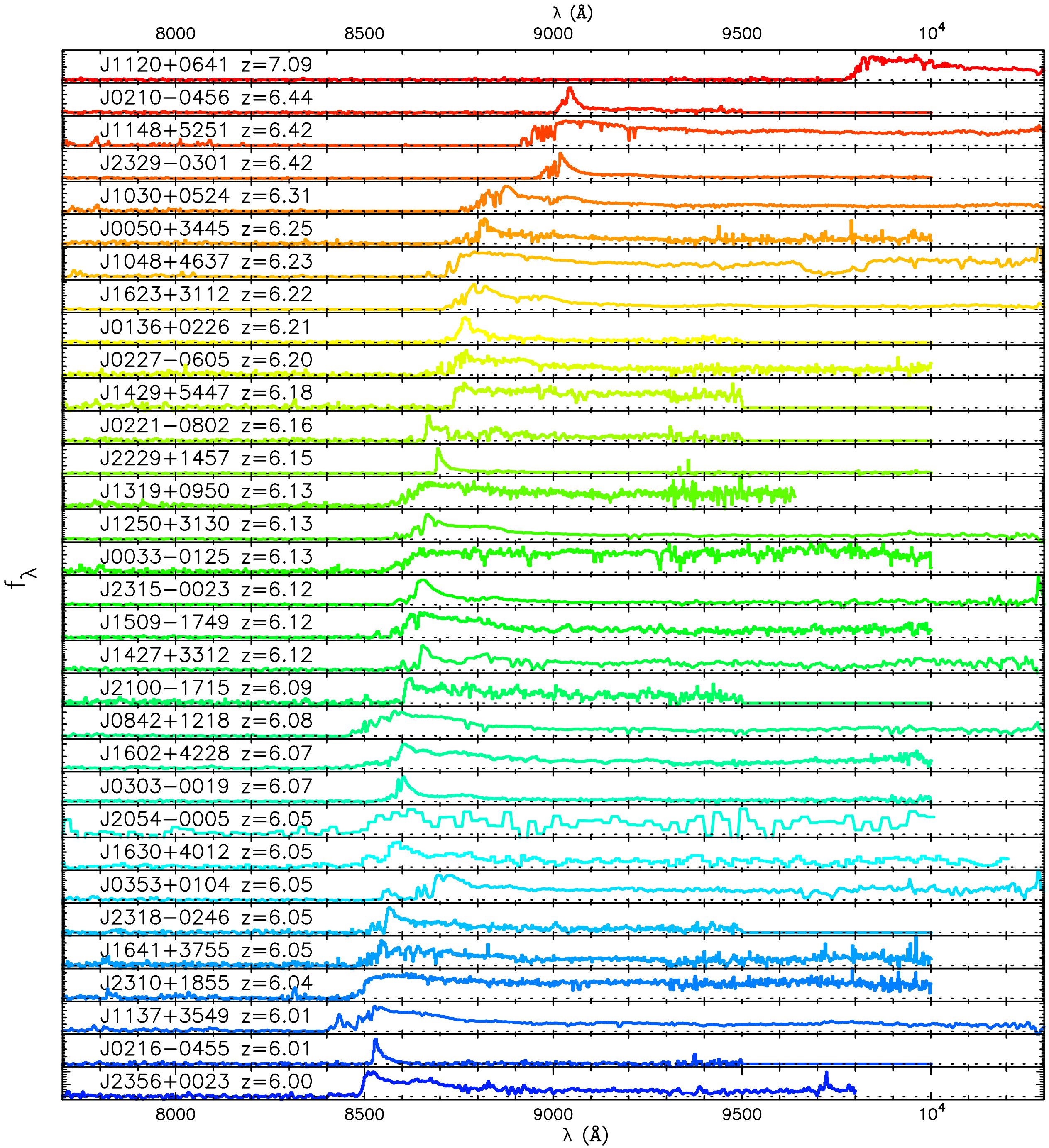
It might yet prove possible to account for the observed high-redshift (z~4) quasar populations with ... conventional cosmic structure formation theory

--- Ed Turner 1991


λ (Å)
8000
8500
9000
9500
10^4
f_λ
J1120+0641 z=7.09
J0210−0456 z=6.44
J1148+5251 z=6.42
J2329−0301 z=6.42
J1030+0524 z=6.31
J0050+3445 z=6.25
J1048+4637 z=6.23
J1623+3112 z=6.22
J0136+0226 z=6.21
J0227−0605 z=6.20
J1429+5447 z=6.18
J0221−0802 z=6.16
J2229+1457 z=6.15
J1319+0950 z=6.13
J1250+3130 z=6.13
J0033−0125 z=6.13
J2315−0023 z=6.12
J1509−1749 z=6.12
J1427+3312 z=6.12
J2100−1715 z=6.09
J0842+1218 z=6.08
J1602+4228 z=6.07
J0303−0019 z=6.07
J2054−0005 z=6.05
J1630+4012 z=6.05
J0353+0104 z=6.05
J2318−0246 z=6.05
J1641+3755 z=6.05
J2310+1855 z=6.04
J1137+3549 z=6.01
J0216−0455 z=6.01
J2356+0023 z=6.00

Star Formation in z~6 Quasar Host Galaxies

Xiaohui Fan (Arizona)

Uluru, July 2013

ALMA Program: Ran Wang, Carilli, Walter, Wagg, Riechers, Bertoldi, Omont, Cox, Strauss, Menton, Narayanan, Knudsen, Jiang +

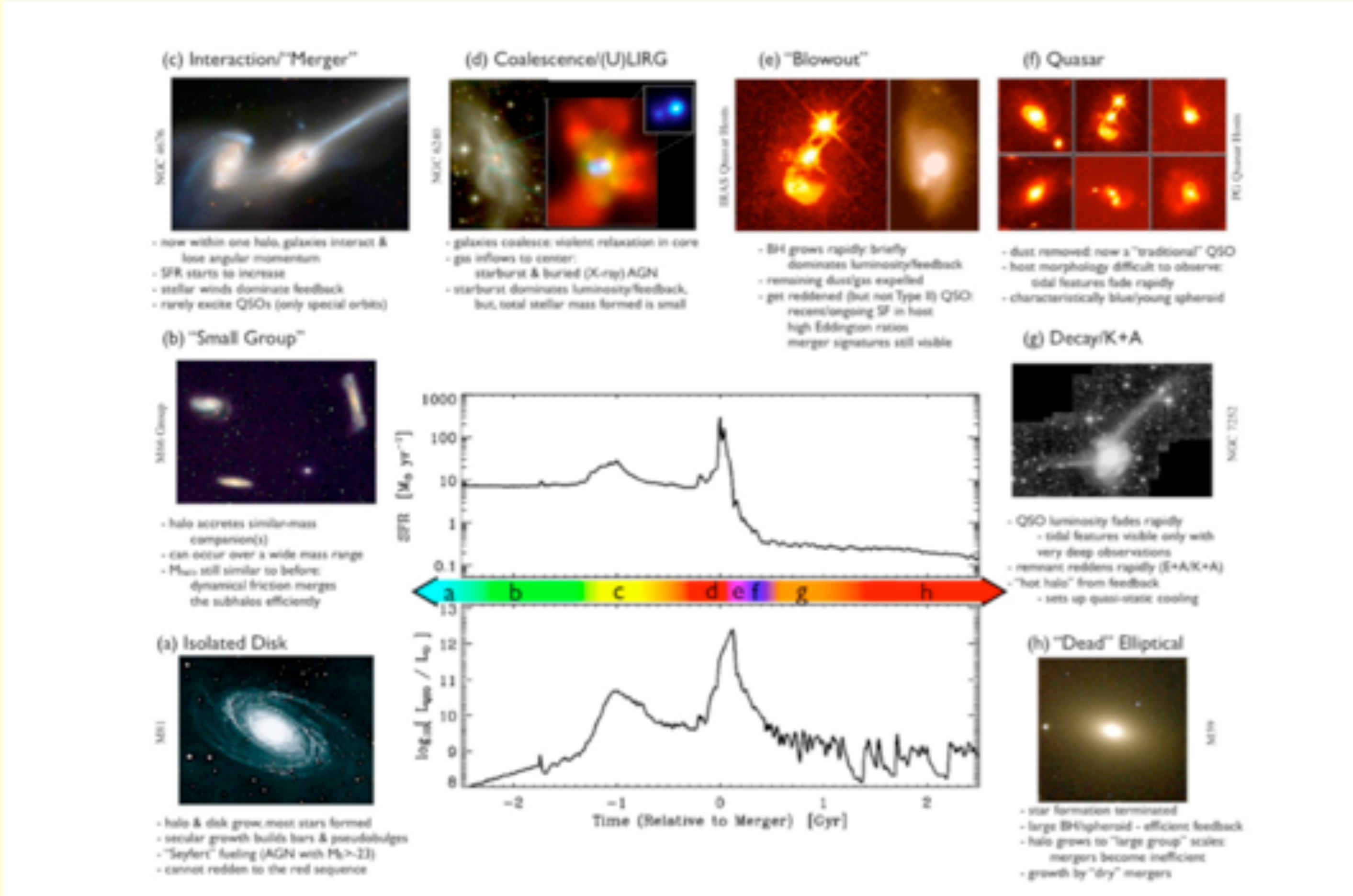
Optical Program: Decarli, Walter, Yang, Carilli, Hennawi, Mechtely, Windhorst, Schneider, Wang, McGreer, Cai, Tang, Zuo +

BH Accretion and Star Formation at High Redshift

- Bench-mark z~6 quasar
  - M_BH ~ 2x10^9 M_sun
  - Eddington accretion
  - accretion rate: 30 M_sun/yr (0.1 radiative efficiency)
- Hopkins and Quataert (2010):

$$\dot{M}_{\rm BH} \sim 0.5\,{\rm M_\odot\,yr^{-1}} \left(\frac{\dot{M}_*}{50\,{\rm M_\odot\,yr^{-1}}}\right)^{1.5}$$

  - Star formation rate: 800 M_sun/yr
- Haring and Rix:
  - log(M_BH) = 8.2 + 1.12 log(M_bulge/10^11)
  - M_bulge ~10^12 M_sun
  - age of the universe: 10^9 yr
  - Star formation rate ~ 1000 M_sun/yr

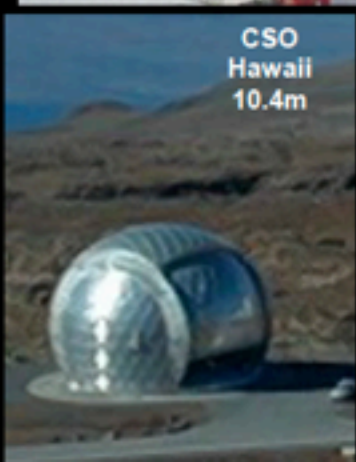


- In merger driven galaxy evolution sequence:
  - quasars have high SFR
  - come after the ULIRG/SMG phase
  - quasar/hosts less obscured through “blowout”
  - quasar radiation provides energy for feedback through winds/outlows

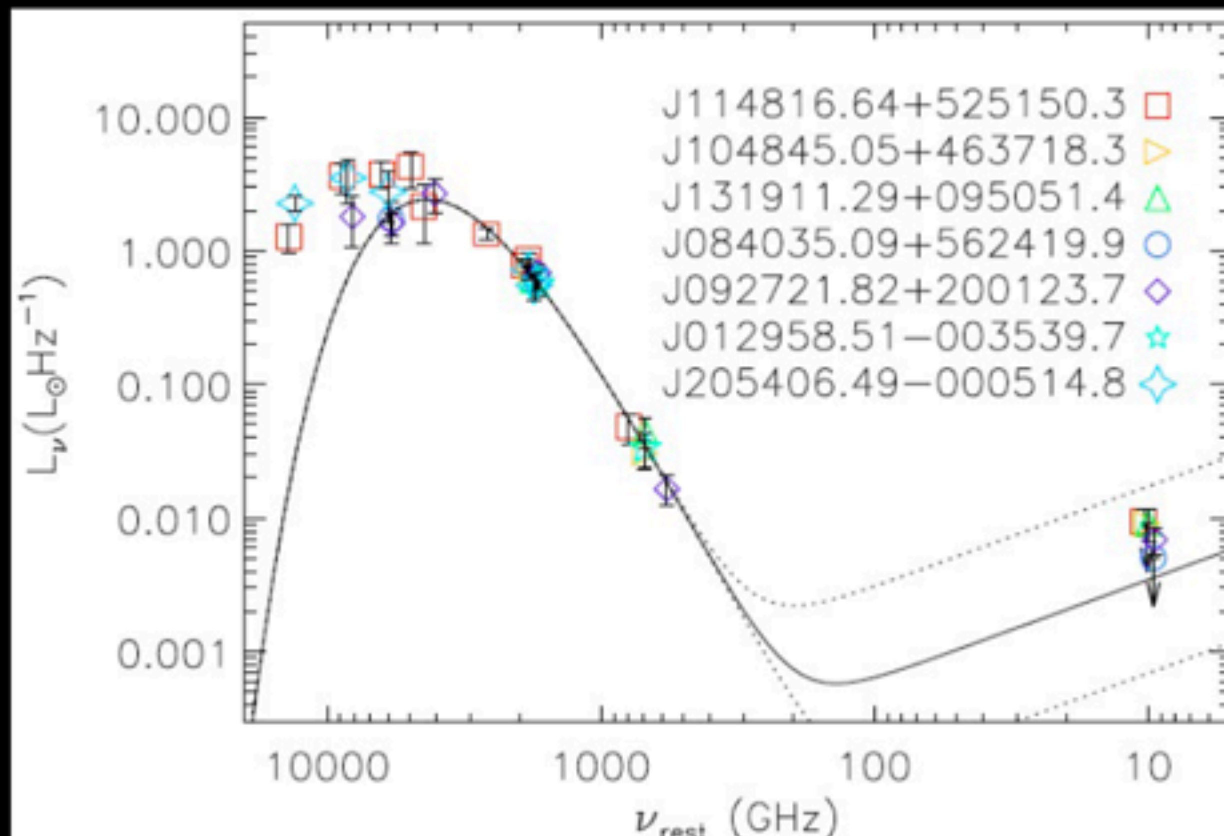
Sub-mm and Radio Observation of High-z Quasars

- Probing dust and star formation in the most massive high-z systems
- Advantage:
  - minimum AGN contamination (?)
  - Give measurements to
    - Star formation rate
    - Gas morphology
    - Gas kinematics
- ALMA!

Submm/mm/radio observations of the earliest quasars

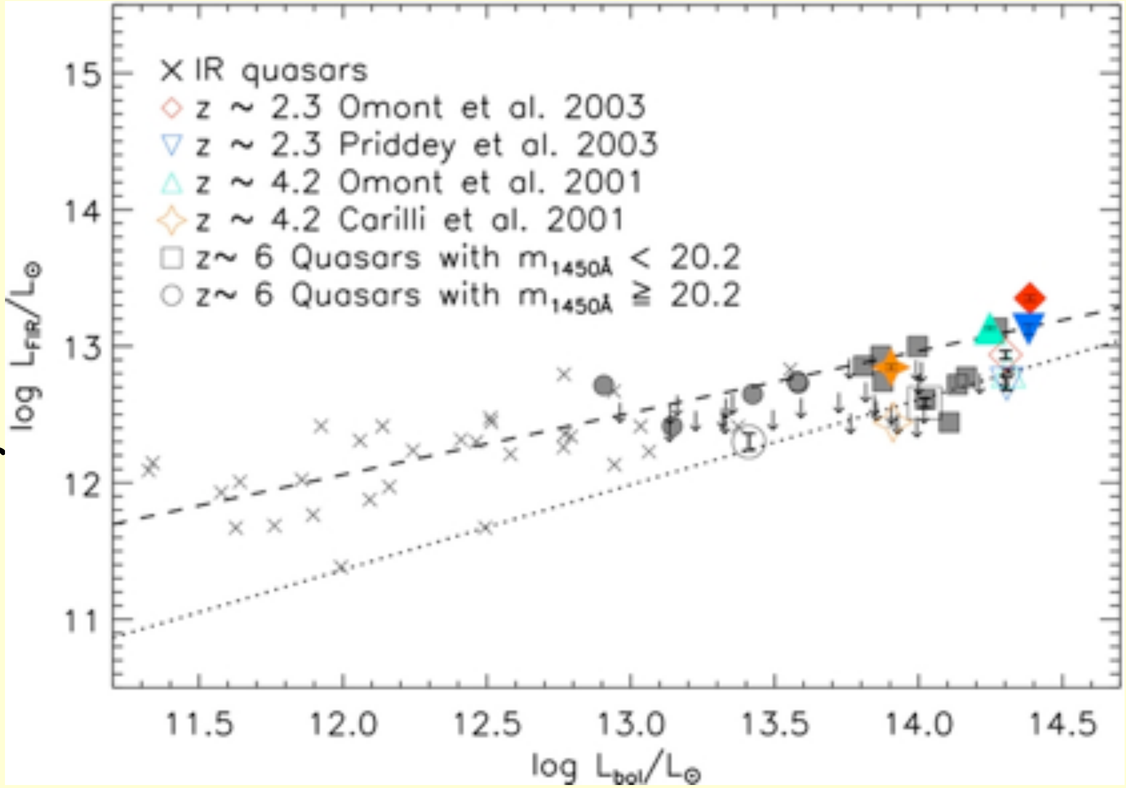


T_{dust}~43 K, β~1.9



Star Formation in z~6 Quasars

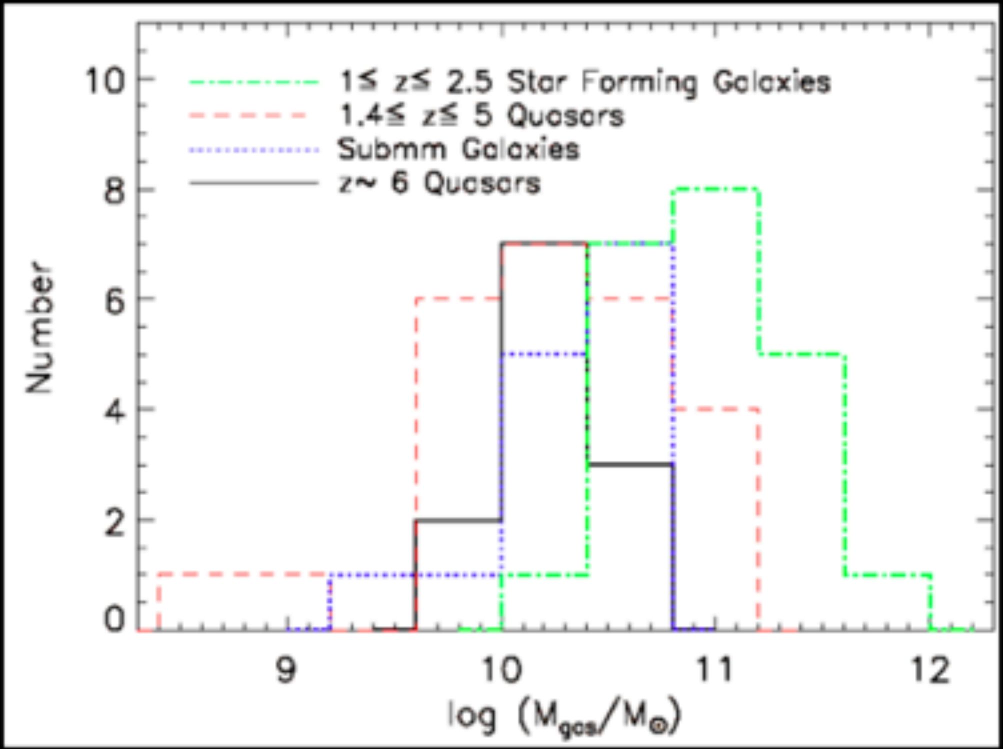
- 30% of z~6 quasars detected at 1mJy level in 1-mm ->
  - L_{FIR}~ $10^{13}L_{sun}$
  - T~50K
  - **SFR~1000 $M_{sun}yr^{-1}$** (if dust heated by SB)
- submm-faint quasars also show detections after stacking
  - average SFR > 100 $M_{sun}yr^{-1}$

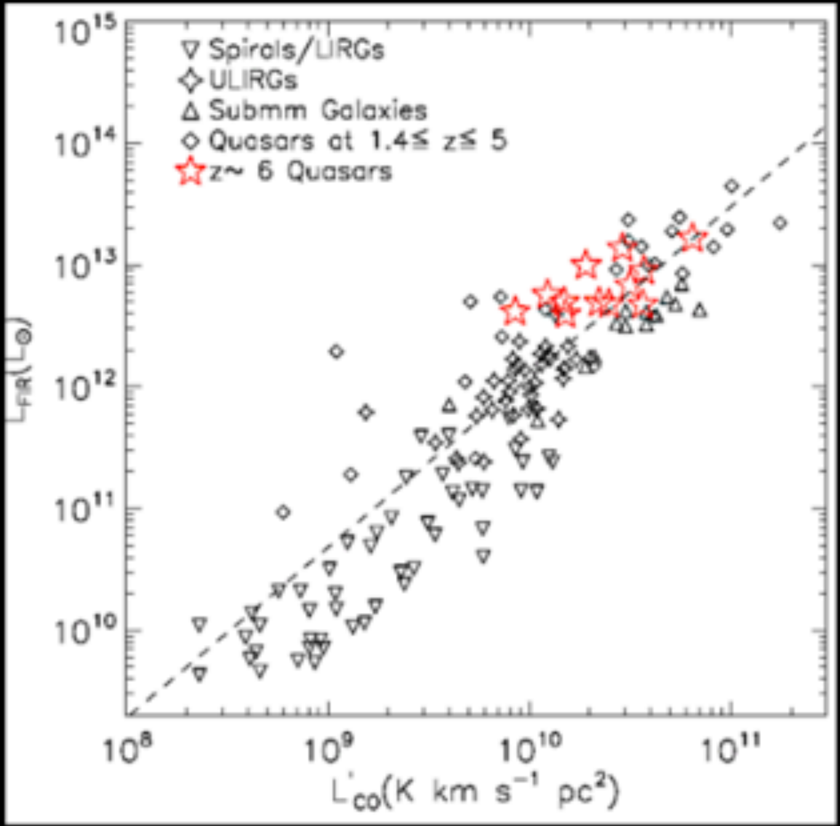


Wang et al. 2008, 2009,2011

Molecular CO : tracer of molecular gas

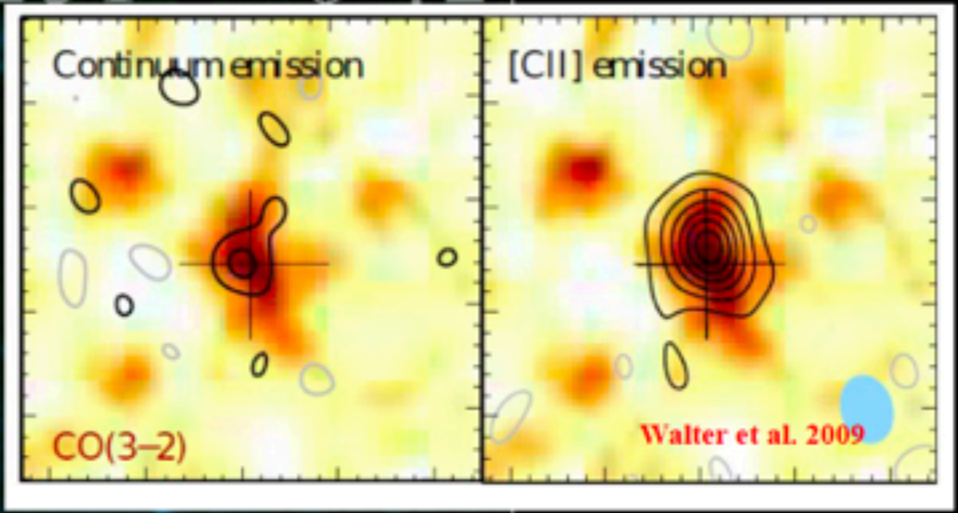
- CO detected in 12 FIR luminous quasars at z~6;
- CO luminosity: 0.6 to 2.7 x10^{10} K km s^{-1} pc^2 ; on order of 10^{10} M_{sun};
- Molecular gas mass distributions :
  - similar to that of the SMGs and 1.4≤z≤5.0 CO-detected quasars.
  - Smaller than that of the star forming galaxies found at z~1 to 2 (eg. Daddi et al. 2010; Tacconi et al. 2010).
- Line widths: 160 to 800 km s^{-1}.

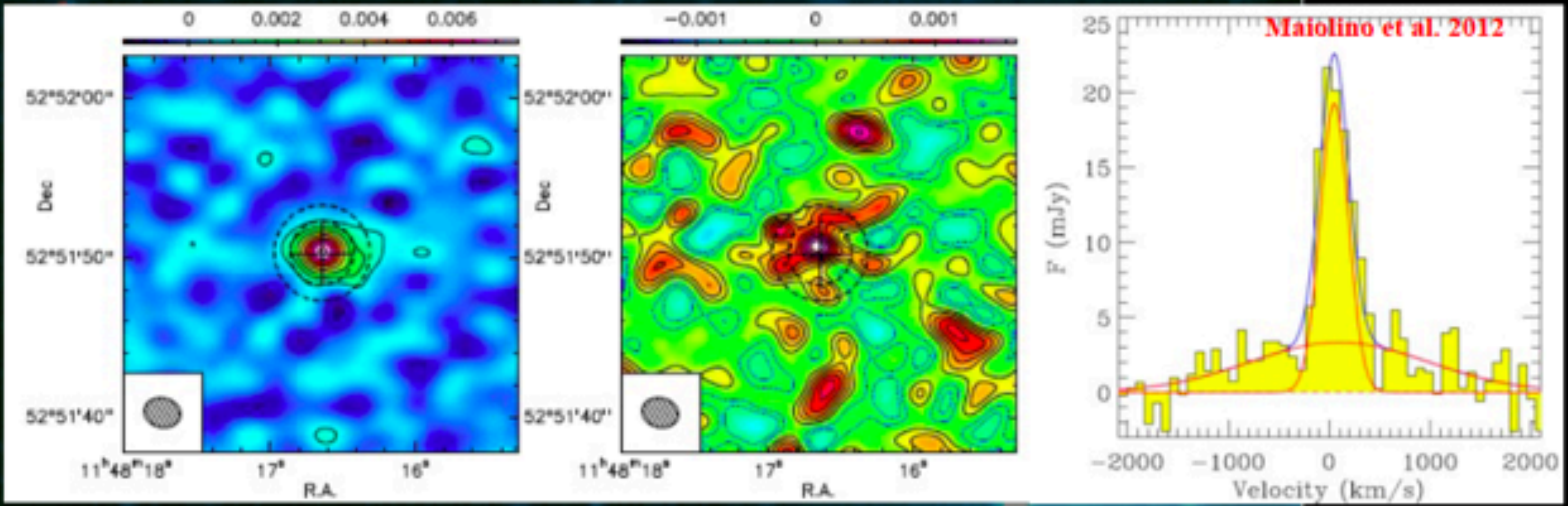




[C II] fine structure line : atomic gas and star formation

- First detection and map from the most FIR luminous z~6 quasar, J1148+5251 at z=6.42 (Maiolino et al. 2005; Walter et al. 2009; Maiolino et al. 2012).

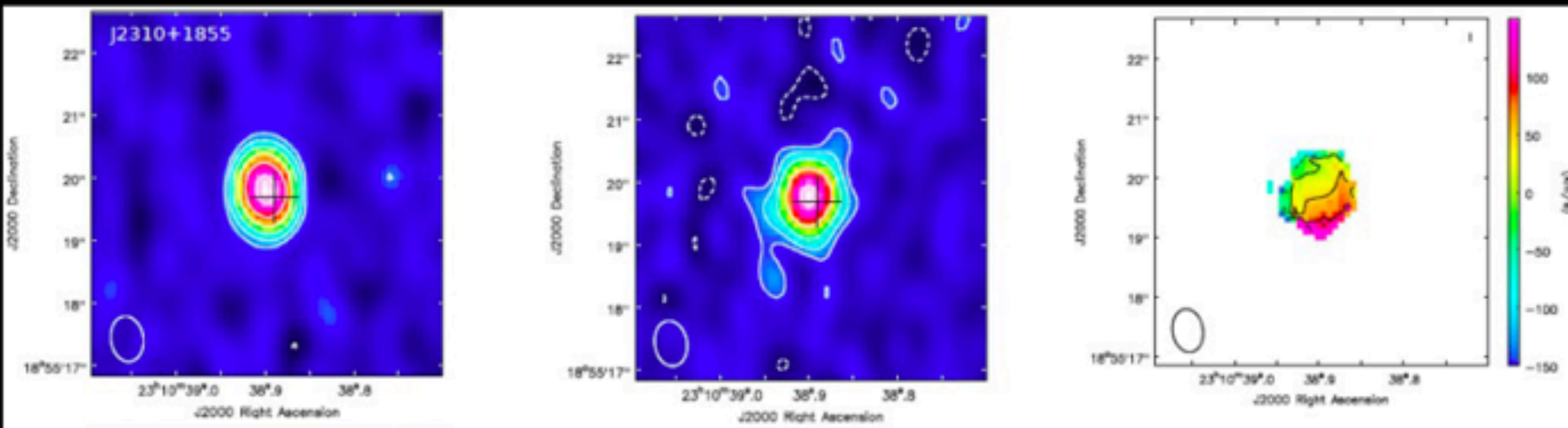




ALMA Cycle 0 observation of [C II] from z~6 quasars

- Sample：Five FIR and CO luminous z~6 quasars;
- Half mJy spectral sensitivity per 70 km/s channel in about 40min to 80 min with 14 to 20 antennas;
- 0.6”~0.7” resolution: Detection, line profile, and size measurement;
- All the five objects are detected in strong [C II] and dust continuum emission.

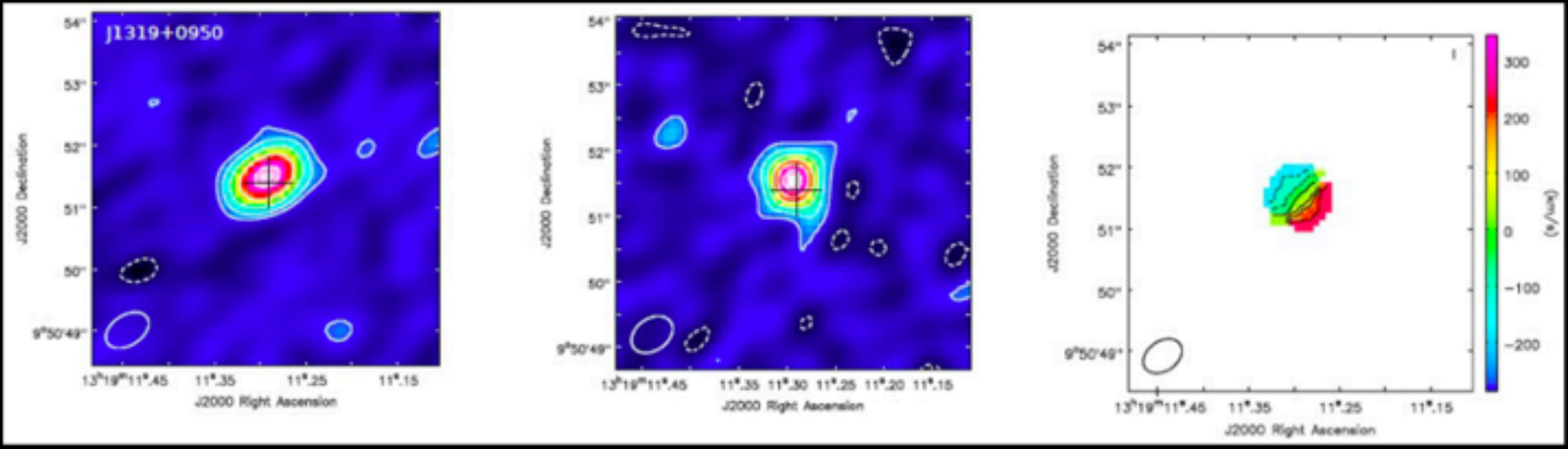
SDSS J2310+1855 at z=6.0025 from SDSS Main Survey



Wang et al. 2012, in prep

- The brightest millimeter source at z>5 with FIR luminosity of 1.7×10^{13} Lsun;
- Bright [C II] detection with luminosity of 8.8×10^{9} Lsun;
- Velocity gradient;
- Marginally resolved with source size of 0.9"x0.7" (0.56"x0.39" deconvolved size, or 3.2x2.3 kpc^2).

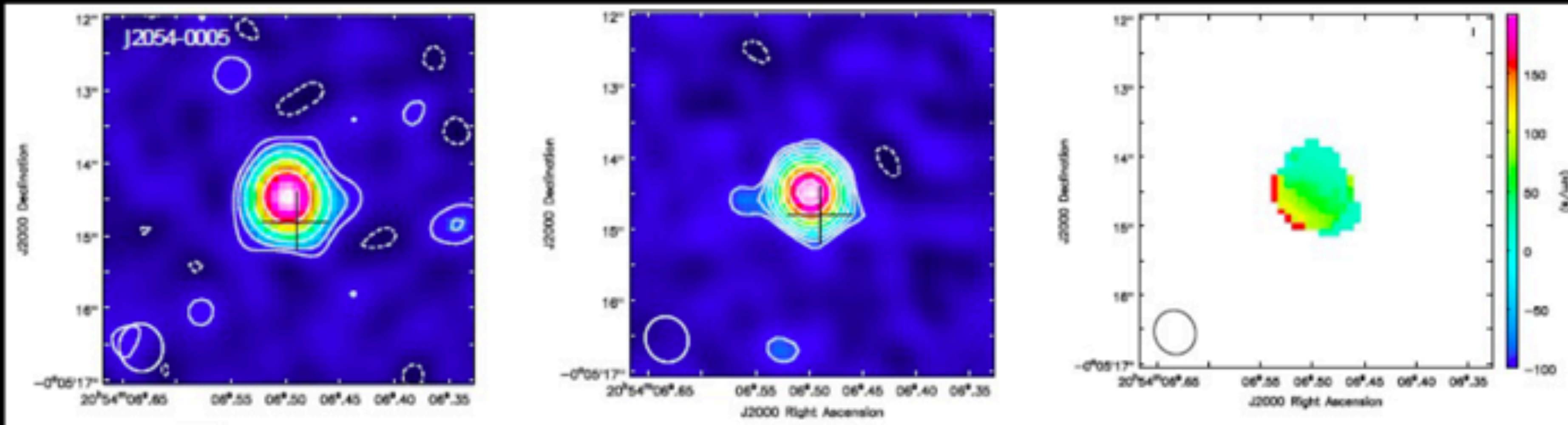
ULAS J1319+0950 at z=6.13 from the UKIRT Infrared Deep Sky Survey



Wang et al. 2012, in prep

- Another bright millimeter source, FIR luminosity of 10^{13} Lsun;
- Bright [C II] detection with [C II] luminosity of 4.3×10^{9} Lsun;
- Line velocity map：clear velocity gradient;
- Source marginally resolved：0.8”x0.7” (0.6”x0.3” deconvolved size, or 3.5×1.7 kpc^2).

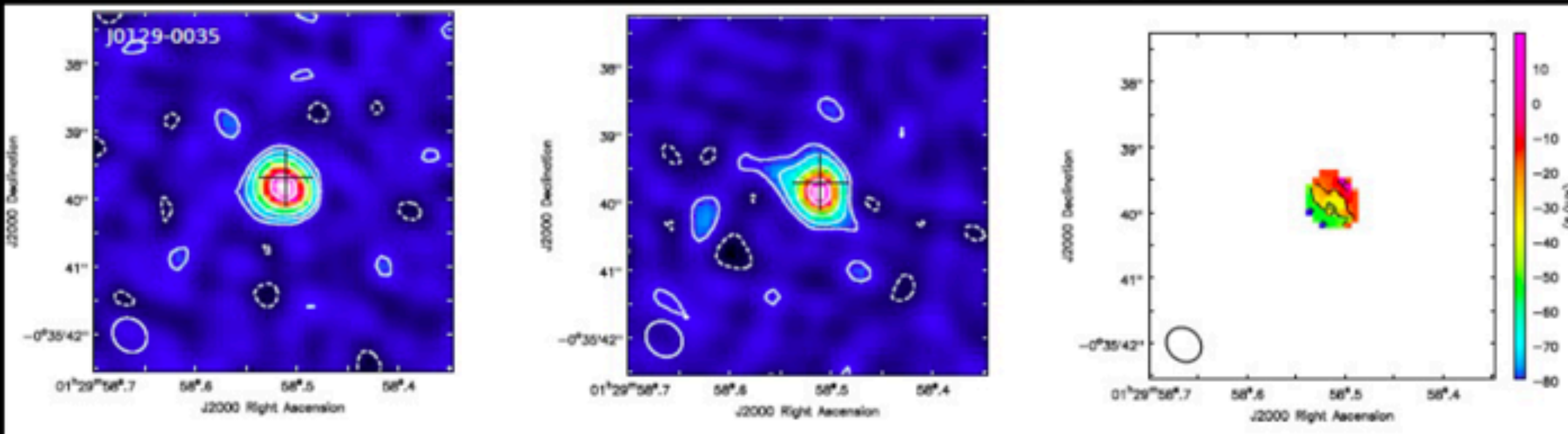
SDSS J2054-0005 at z=6.039 from SDSS Stripe 82



Wang et al. 2012, in prep

- FIR luminosity of 6.1×10^{12} Lsun;
- Bright [C II] detection with [C II] luminosity of 3.4×10^{9} Lsun;
- Line velocity map;
- Source marginally resolved : 0.73”x0.68” (0.35”x0.32” deconvolved size, or 2.0x1.9 kpc^2).

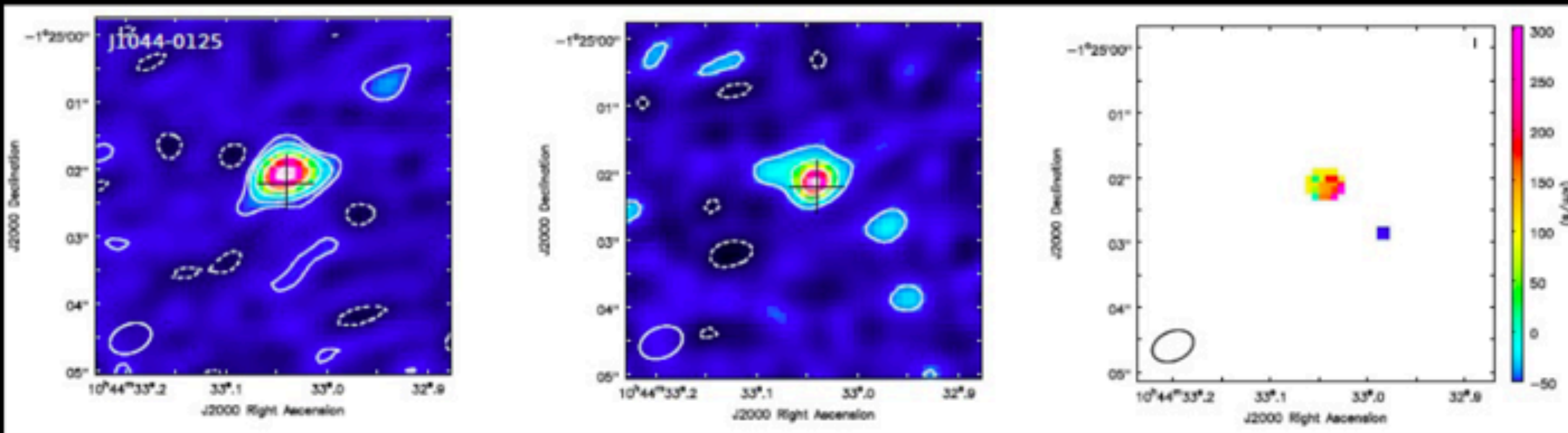
SDSS J0129-0035 at z=5.78 from SDSS Stripe 82



Wang et al. 2012, in prep

- Optically faint with z_{AB}=22.16, or quasar bolometric luminosity $6x10^{12}$Lsun; L_{FIR} $4.7x10^{12}$ Lsun;
- [C II] detection with [C II] luminosity of $1.9x10^{9}$ Lsun;
- Line velocity map : clear velocity gradient;
- Marginally resolved, constrain source size to 0.41"x0.25".

SDSS J1044-0125 at z=5.78 from SDSS main survey

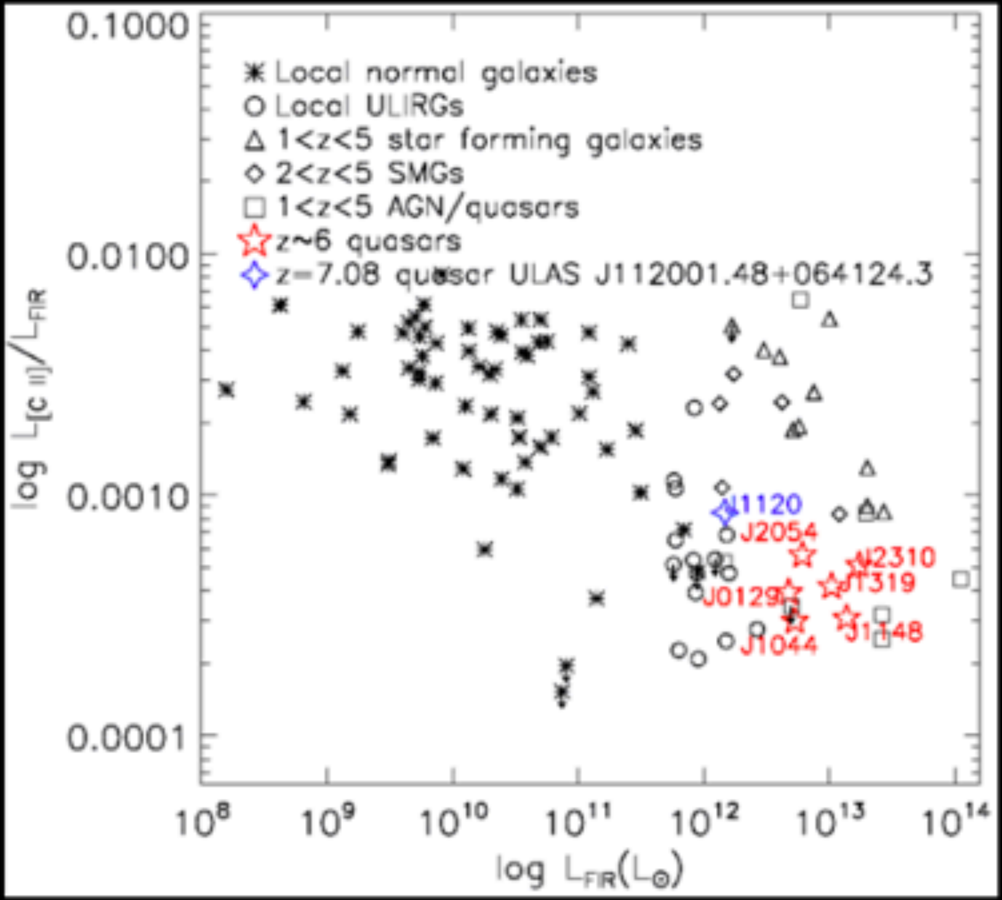


Wang et al. 2012, in prep

- One of the optically most luminous/massive quasar, M_{BH}~ 6x10^9 Msun, L_{bol} ~ 10^{14} Lsun; L_{FIR} 5.3x10^{12} Lsun;
- [C II] detection with [C II] luminosity of 1.6x10^9 Lsun;
- Faintest [C II] line source, marginal constraint on source size of 0.6”x0.3”.

[C II] - FIR luminosity relation

- [C II]-FIR luminosity ratio on order of 10^{-4}: comparable to other high-z [C II] detected quasars, e.g. J1148+5251 (Maiolino et al. 2005); BR1202 (Wagg et al. 2012), a few times lower than that of the star forming galaxies/SMGs (e.g. Stacey et al. 2010).
- Different ISM conditions.

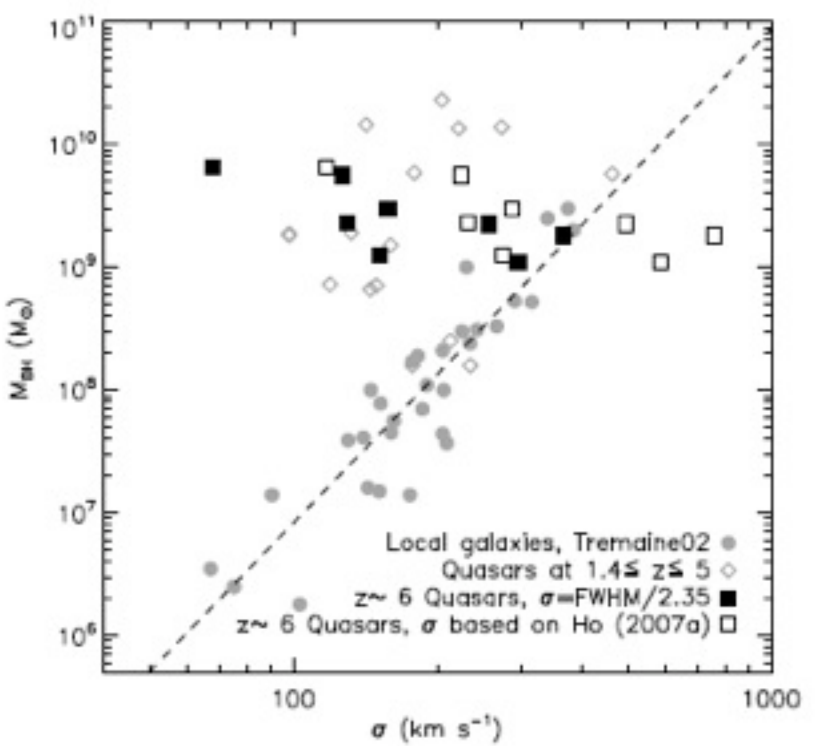


Wang et al. 2012, in prep

Evolution (lack) of M-sigma Relation?

Table 3: Dynamical Parameters

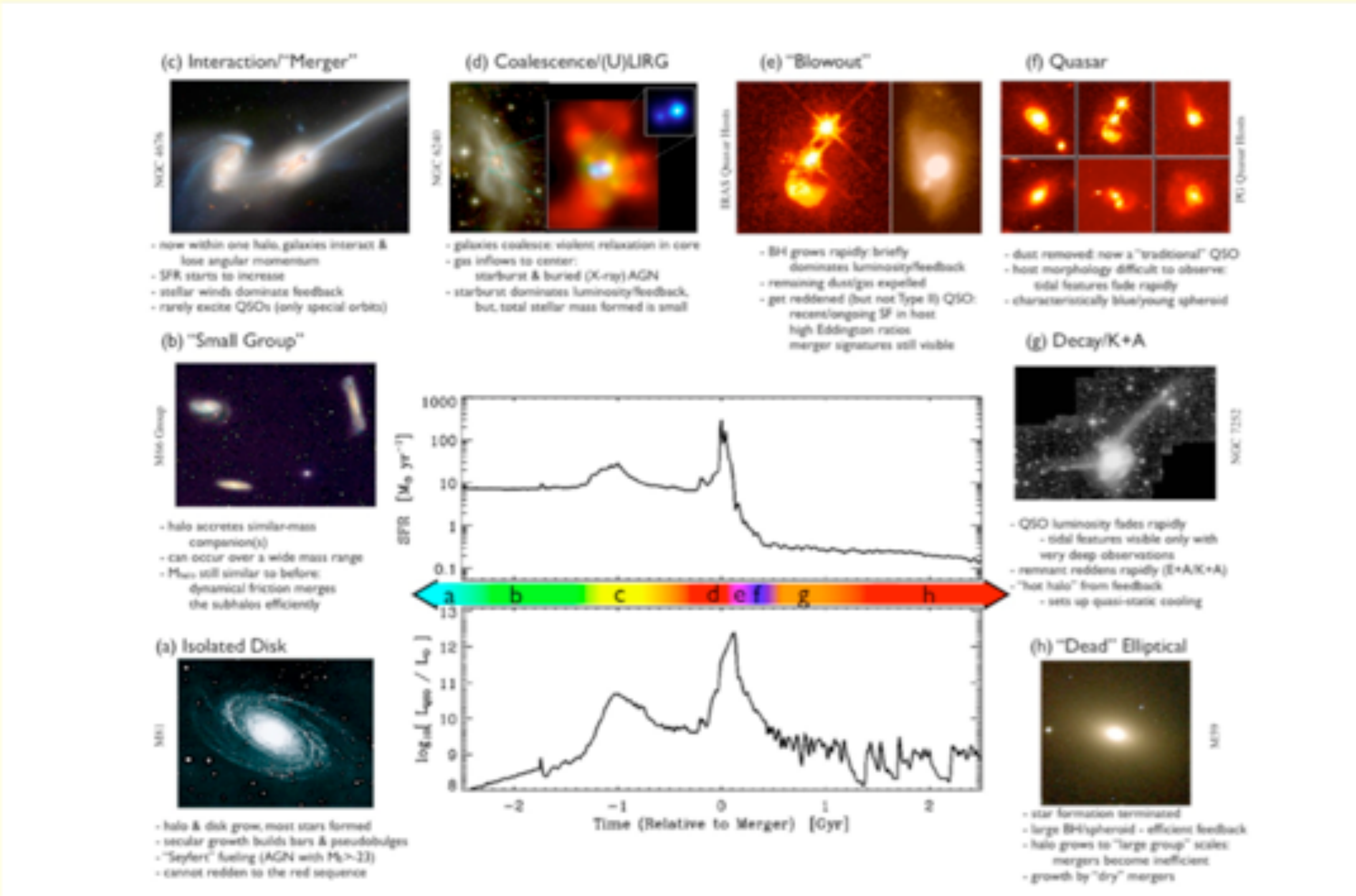
Source	$M_{dyn}\sin^2 i$ $10^{10}\,M_\odot$	i degree	M_{dyn} $10^{10}\,M_\odot$	M_{BH} $10^9\,M_\odot$	M_{BH}/M_{dyn}
(1)	(2)	(3)	(4)	(5)	(6)
J2310+1855	4.9±0.6	46^{+6}_{-8}	9.6	3.2	0.034
J1319+0950	8.8±3.0	57^{+17}_{-22}	12.6	2.1	0.017
J2054−0005	1.2±0.2	24^{+16}_{-9}	7.1	0.86	0.012
J0129−0035	0.9±0.2	52^{+16}_{-21}	1.4	0.17	0.012



- dynamical mass within [CII] emitting region based on [CII] line width, de-convolved size and inclination
- M_BH/M_dyn ~ 0.01 - 0.03
- local relation: ~1.4 x 10^-3
- one order of mag higher at z~6 vs. z~0

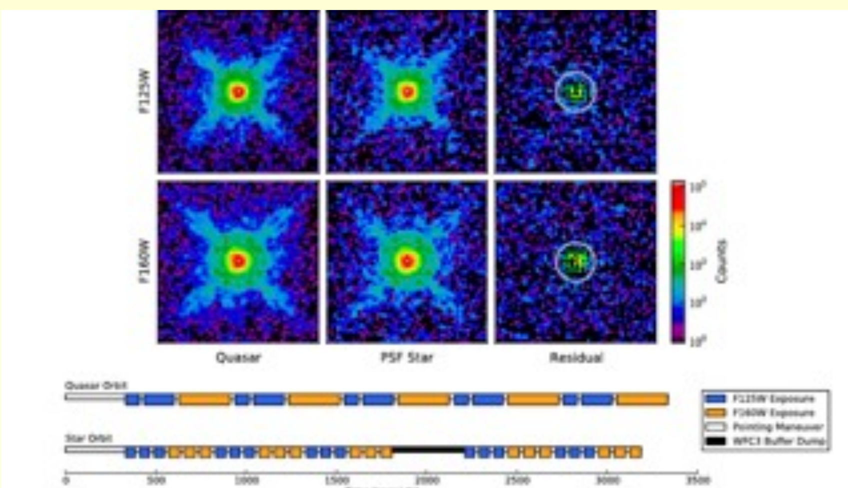
Wang et al. 2008, 2010, 2011, 2013

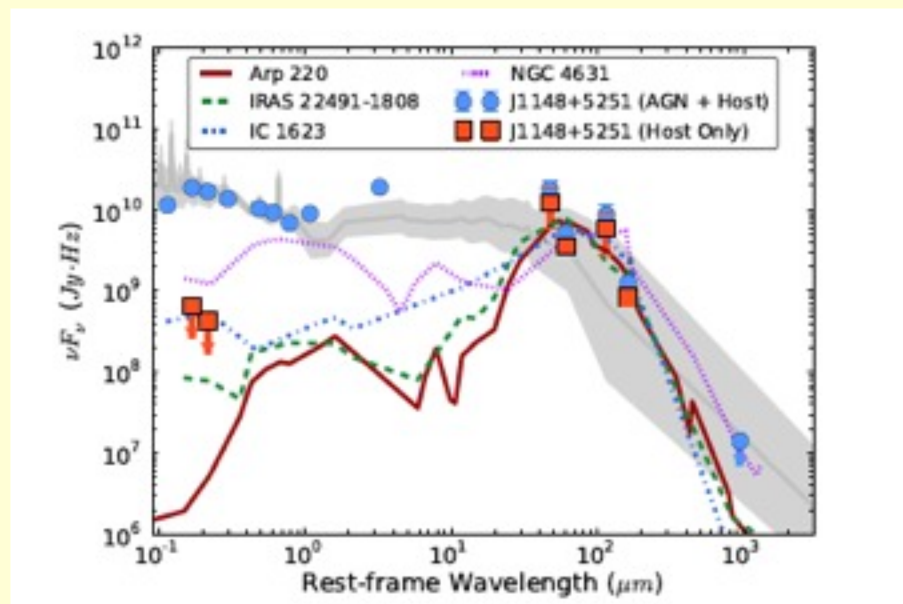
But do we see strong UV/optical emission from the breakout phase?



HST Continuum Imaging of J1148+5251 (z=6.42)

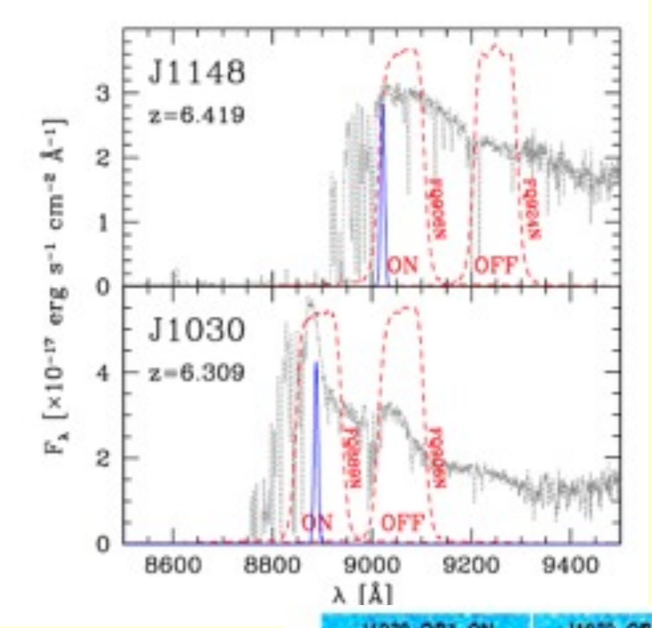
- Mechtley et al. (2012)
  - HST WFC3 J and H bands
  - contemporaneous PSF star observation with similar colors
  - undetected host galaxy: m_(J/H) > 23
  - SFR_UV < 200 M_sun/yr (FIR: 2000 M_sun/yr)

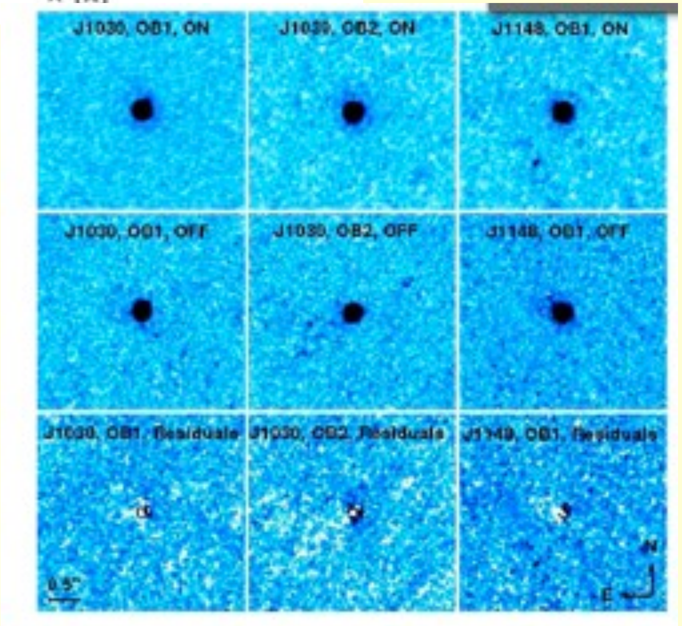




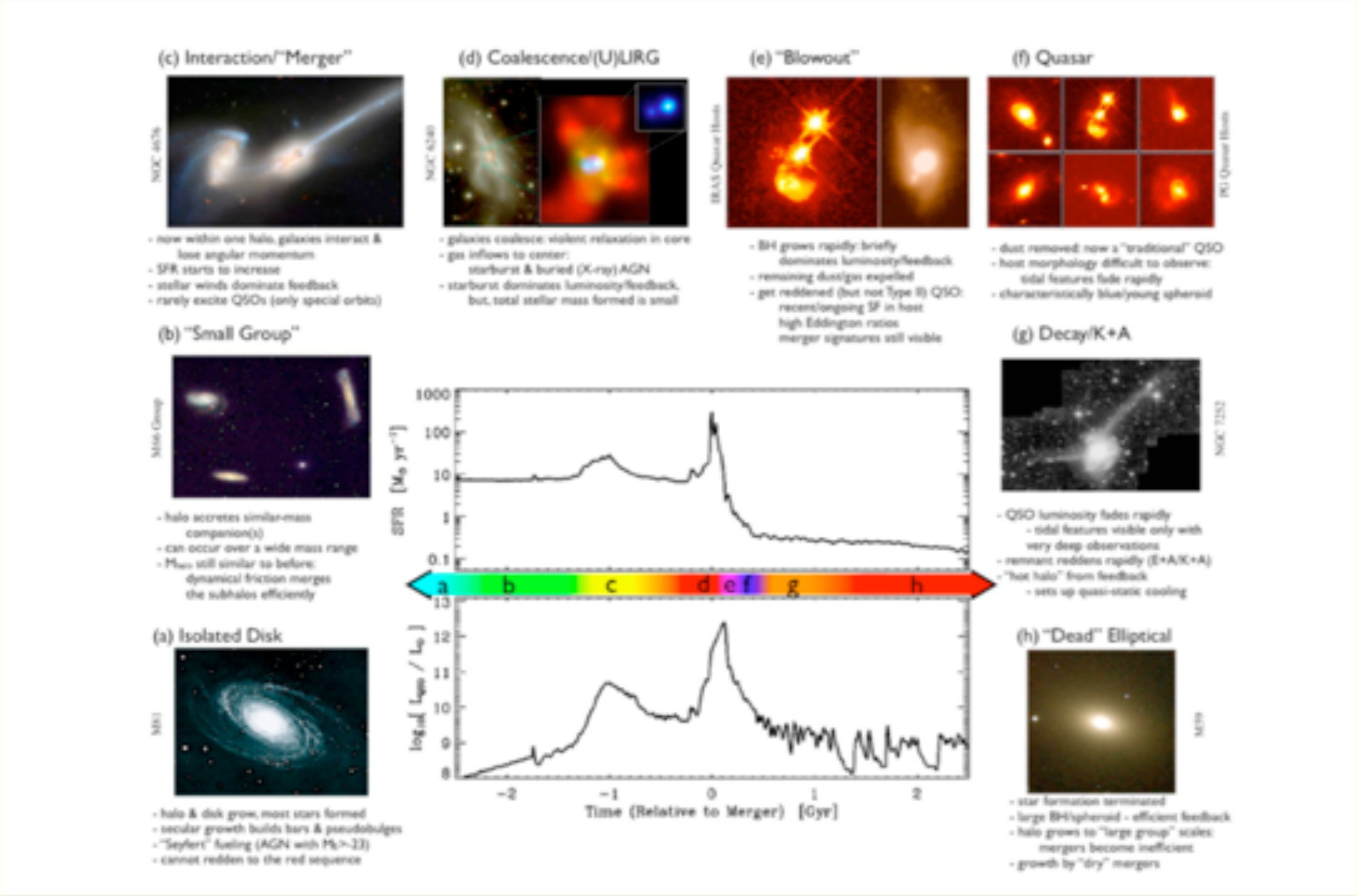
HST Ly alpha Imaging of z~6 Quasars

- Decarli et al. (2012)
  - HST narrow-band imaging
  - blue filter: Ly-alpha +continuum
  - red filter: continuum
  - accurate PSF subtraction to detect faint extended Ly-alpha emission of the host galaxy
  - L(Lya, extended) < 3x10^44 erg/s
  - SFR (UV) <=300 M_sun/yr
  - no evidence for line-of-sight extinction based on quasar spectra..





But do we see strong UV/optical emission from the breakout phase?



- Star formation in quasar hosts have to be highly obscured

Summary

- Intense star formation traced by FIR emission
  - 100 - >1000 M_sun/yr (if FIR heated by star formation)
- compact size in continuum and gas emission
  - <=4kpc
  - high star formation surface density
- many objects show clear velocity gradient in [CII]
  - hint of rotating disk? ALMA Cycle-1 program
- narrow CO and [CII] line width
  - FWHM 150 - 550 km/s
  - implies small dynamical mass
  - BH growth before galaxy assembly?
- lack of strong UV emission from host galaxy
  - star formation in z~6 quasar hosts are highly obscured