It might yet prove possible to account for the observed high-redshift  $(z\sim4)$  quasar populations with ... conventional cosmic structure formation theory

--- Ed Turner 1991



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# 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
  - $\ M\_BH \sim 2x10^{\land}9 \ M\_sun$
  - Eddington accretion
  - accretion rate: 30 M\_sun/yr (0.1 radiative efficiency)
- Hopkins and Quataert (2010):

$$\dot{M}_{\rm BH} \sim 0.5 \,{\rm M_{\odot} \, yr^{-1}} \left(\frac{\dot{M}_{*}}{50 \,{\rm M_{\odot} \, yr^{-1}}}\right)^{1.2}$$

- 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  $\sim 1000 \text{ M}_sun/yr$



- 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<sub>dust</sub>~43 K, β~1.9





# Star Formation in z~6 Quasars

- 30% of z~6 quasars detected at 1mJy level in 1-mm ->
  - L<sub>FIR</sub> $\sim 10^{13}$ L<sub>sun</sub>
  - T~50K
  - SFR~1000 M<sub>sun</sub>yr<sup>-1</sup> (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<sup>-1</sup> pc<sup>2</sup>; on order of  $10^{10}$  M<sub>sun</sub>;
- Molecular gas mass distributions :
  - similar to that of the SMGs and  $1.4 \le z \le 5.0$  CO-detected quasars.
  - Smaller than that of the star forming galaxies found at z $\sim$ 1 to 2 (eg. Daddi et al. 2010; Tacconi et al. 2010).
- Line widths: 160 to 800 km s<sup>-1</sup>.



# [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.



Wang et al. 2012, in prep

- The brightest millimeter source at z>5 with FIR luminosity of 1.7x10<sup>13</sup> Lsun;
- Bright [C II] detection with luminosity of 8.8x10<sup>9</sup> Lsun;
- Velocity gradient;
- Marginally resolved with source size of 0.9"x0.7" (0.56"x0.39" deconvolved size, or 3.2x2.3 kpc<sup>2</sup>).

# 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<sup>13</sup> Lsun;
- Bright [C II] detection with [C II] luminosity of 4.3x10<sup>9</sup> Lsun;
- Line velocity map : clear velocity gradient;
- Source marginally resolved : 0.8"x0.7" (0.6"x0.3" deconvolved size, or 3.5x1.7 kpc<sup>2</sup>).

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



Wang et al. 2012, in prep

- FIR luminosity of 6.1x10<sup>12</sup> Lsun;
- Bright [C II] detection with [C II] luminosity of 3.4x10<sup>9</sup> Lsun;
- Line velocity map;
- Source marginally resolved : 0.73"x0.68" (0.35"x0.32" deconvolved size, or 2.0x1.9 kpc<sup>2</sup>).

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



Wang et al. 2012, in prep

- Optically faint with z<sub>AB</sub>=22.16, or quasar bolometric luminosity 6x10<sup>12</sup>Lsun; L<sub>FIR</sub> 4.7x10<sup>12</sup> Lsun;
- [C II] detection with [C II] luminosity of 1.9x10<sup>9</sup> 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<sub>BH</sub>~ 6x10<sup>9</sup> Msun, L<sub>bol</sub> ~ 10<sup>14</sup> Lsun; L<sub>FIR</sub> 5.3x10<sup>12</sup> Lsun;
- [C II] detection with [C II] luminosity of 1.6x10<sup>9</sup> Lsun;
- Faintest [C II] line source, marginal constraint on source size of 0.6"x0.3".

### [CII] - FIR luminosity relation

- [C II]-FIR luminosity ratio on order of 10<sup>-4</sup>: 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?**

Source	M <sub>dyn</sub> sin <sup>2</sup> i 10 <sup>10</sup> M <sub>☉</sub>	i degree	M <sub>dyn</sub> 10 <sup>10</sup> M <sub>☉</sub>	М <sub>ВН</sub> 10 <sup>9</sup> М⊙	M <sub>BH</sub> /M <sub>dyn</sub>
(1)	(2)	(3)	(4)	(5)	(6)
J2310+1855	4.9±0.6	$46^{+6}_{-8}$	9.6	3.2	0.034
J1319+0950	$8.8 \pm 3.0$	57-22	12.6	2.1	0.017
J2054-0005	$1.2 \pm 0.2$	$24^{+16}_{-9}$	7.1	0.86	0.012
J0129-0035	$0.9\pm0.2$	$52^{+16}_{-21}$	1.4	0.17	0.012



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

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

#### (c) Interaction/"Merger"



- now within one halo, galaxies interact & lose angular momentum - SFR starts to increase - stellar winds dominate feedback

- rarely excite Q5Os (only special orbits)

#### (b) "Small Group"

#### (d) Coalescence/(U)LIRG



galaxies coalesce violent relaxation in core - gas inflows to center starburst & buried (X-ray) AGN - starburst dominates luminosity/feedback,

1000

5 100 # k ž

7

8 0 .

-2

-1

0 Time (Relative to Merger) [Cyr]

but, total stellar mass formed is small

#### (e) "Blowout"



- BH grows rapidly briefly dominates luminosity/feedback - remaining dust/gas expelled - get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible



(f) Quasar

dust removed new a "traditional" Q50 host morphology difficult to observe: tidal features fade rapidly

characteristically blue/young spheroid

#### (g) Decay/K+A





QSO luminosity fades rapidly - tidal features visible only with very deep observations remnant reddens rapidly (E+A/K+A) "hot halo" from feedback - sets up-quasi-static cooling

#### (h) "Dead" Elliptical



- large BH/spheroid - efficient feedback - halo grows to "large group" scales mergers become inefficient - growth by "dry" margars

37.0 - halo accretes similar-mass companion(s) - can occur over a wide mass range 0.1 - Muss still similar to before: dynamical friction merges the subhalos efficiently (a) Isolated Disk 3 11 J 10

4 - halo & disk grow, most stars formed

- secular growth builds hars & pseudobulges - "Seyfert" fueling (AGN with Mc>-33)

- cannot redden to the red sequence

### 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)</p>



# 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</li>
     erg/s
  - SFR (UV) <=300 M\_sun/yr</p>
  - 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