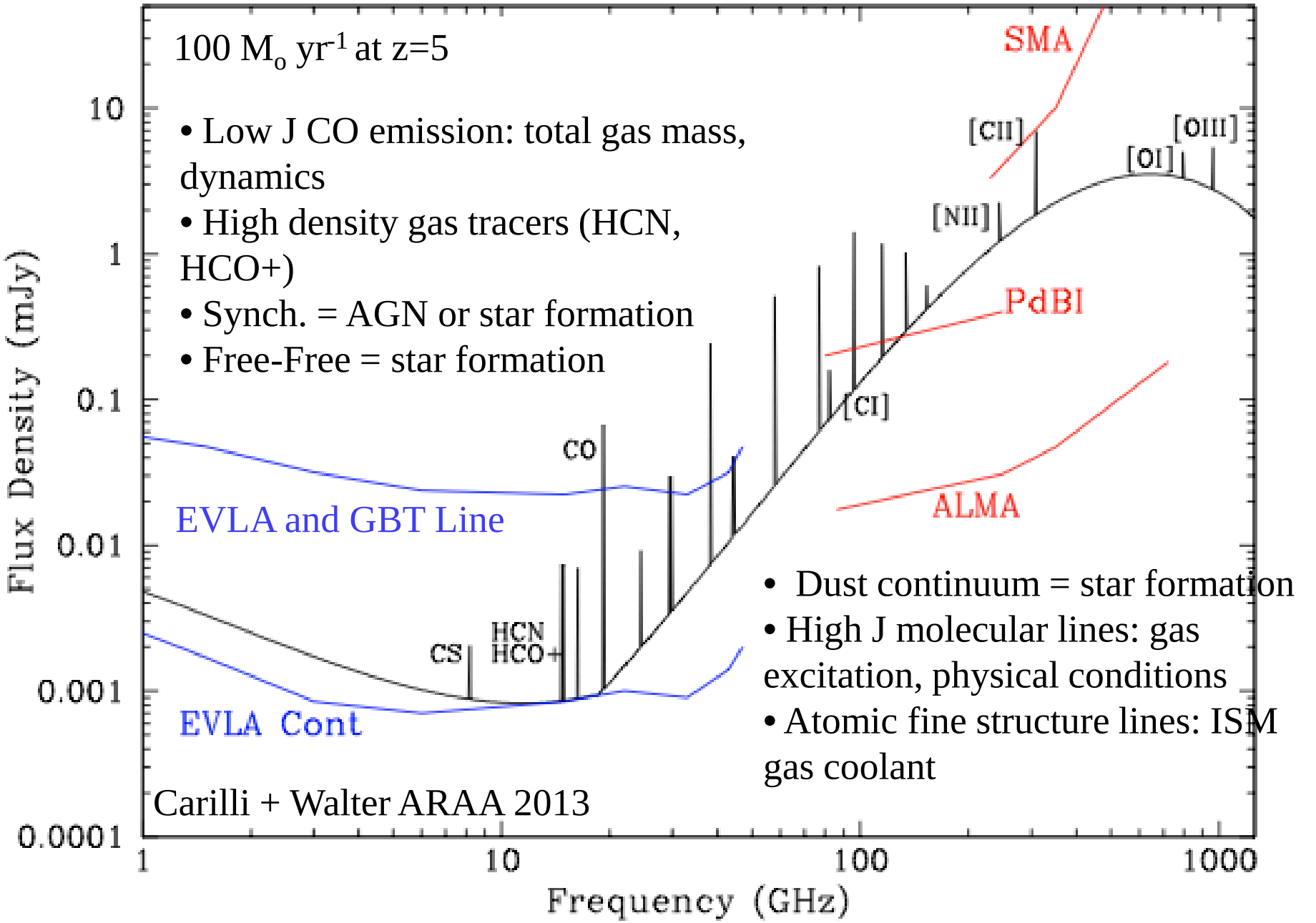
Dust, cool gas, and star formation in z>6 SMBH host galaxies

C. Carilli Kavli, UCSB, July 2013

- $M_{BH} - \sigma_{bulge}$ relation: origin, evolution, reality?
- Formation of 10^9 M_o SMBH at t_{univ} < 1Gyr?
- Early, coeval formation massive galaxies + SMBH?
- Early formation of dust in AGN/starburst?

PhD thesis: Ran Wang

cm to submm diagnostics of galaxy formation



Massive galaxy and SMBH formation at z~6: Quasar host galaxies at t_{univ}<1Gyr

Why quasars?

- Rapidly increasing samples:

z>4: > 1000 known

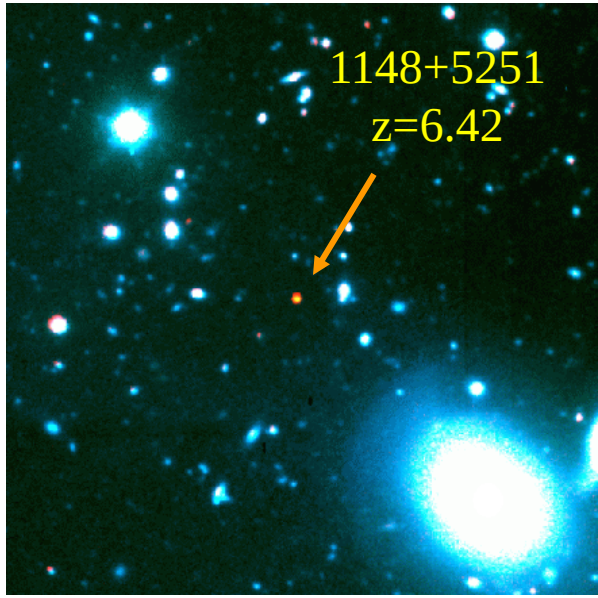
z>5: > few hundred

z>6: > 30

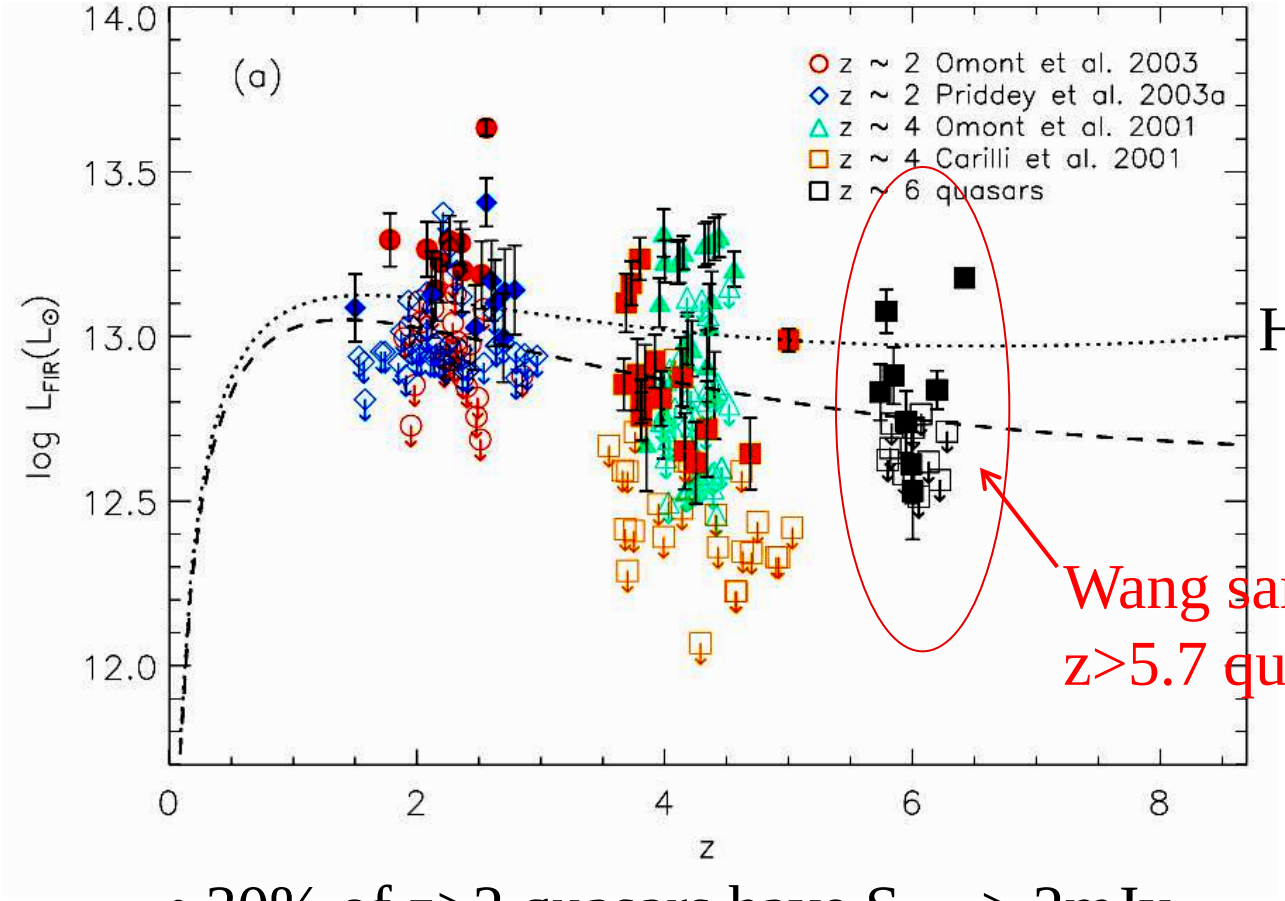
- Spectroscopic redshifts

- Extreme (massive) systems: L_{bol} ~10^{14} L_o=> M_{BH}~ 10^9 M_o => M_{bulge} ~ 10^{12} M_o

- Massive galaxies form most of their stars early, and quickly (SSFR vs z, low z stellar pops, old ellipticals at z~ 2).



Dust in high z quasar host galaxies: 250 GHz surveys

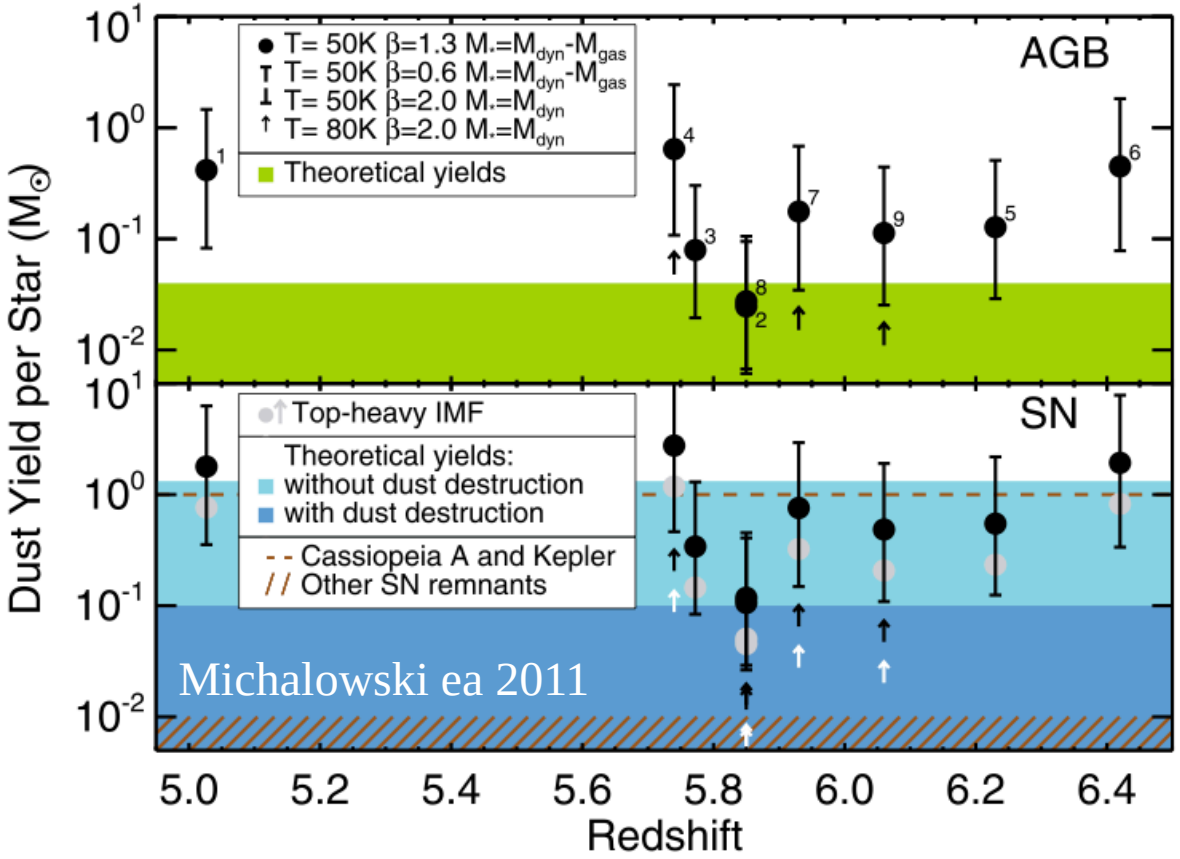


HyLIRG

Wang sample 33
z>5.7 quasars

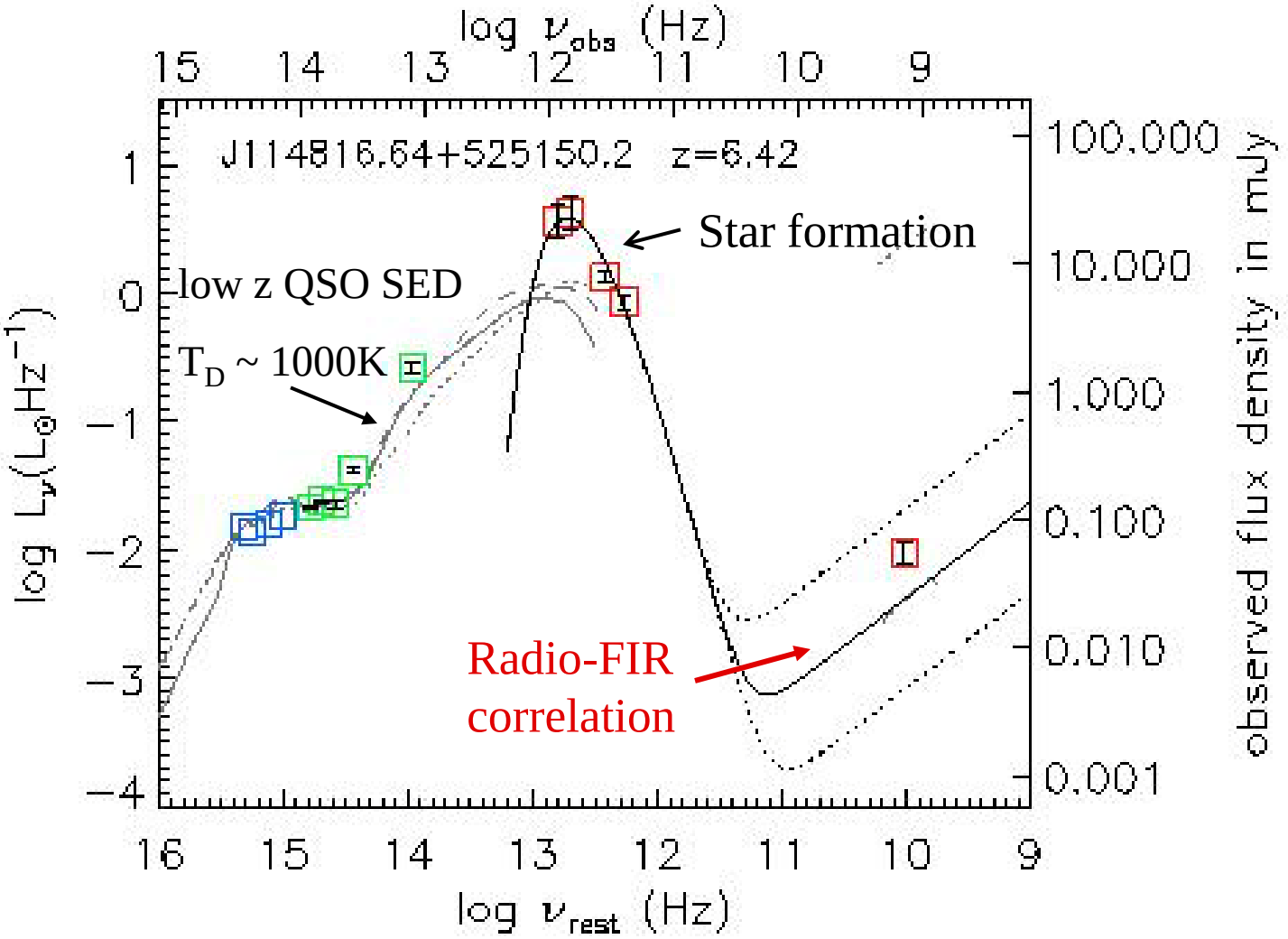
- 30% of z>2 quasars have S_{250} > 2mJy
- L_{FIR} ~ 0.3 to 2 x10^{13} L_o
- M_{dust} ~ 1.5 to 5.5 x10^8 M_o (κ_{125um} = 19 cm^2 g^{-1})

Dust formation at t_{univ}<1Gyr?



- AGB stars: insufficient in most instances
- SN: sufficient only if no dust destruction
- AGN-related dust formation?
- Extinction curve => different dust properties: silicates/amorphous carbon (no 2000A bump)

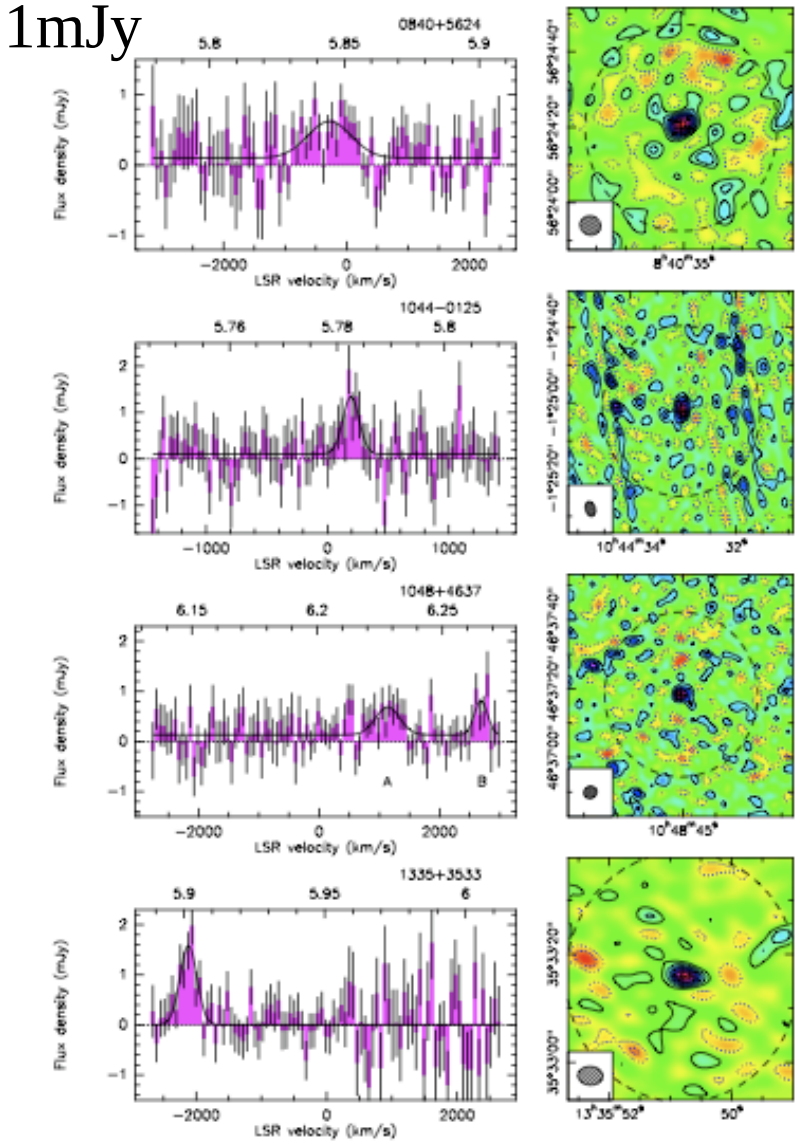
Dust heating? Radio to near-IR SED

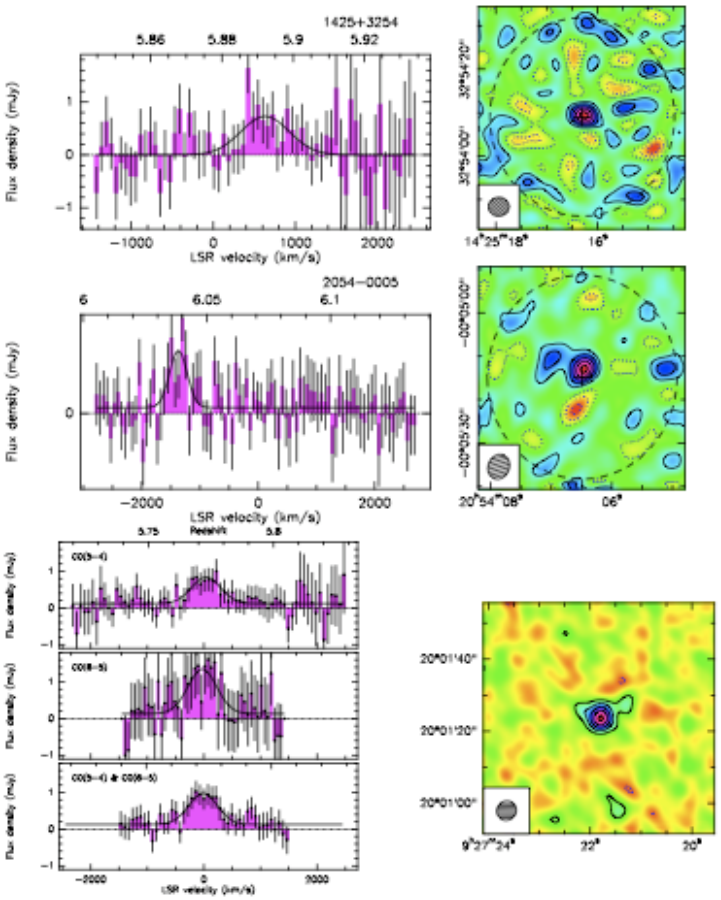


- FIR excess = 47K dust
- SED = star forming galaxy with SFR ~ 400 to 2000 M_o yr^{-1}

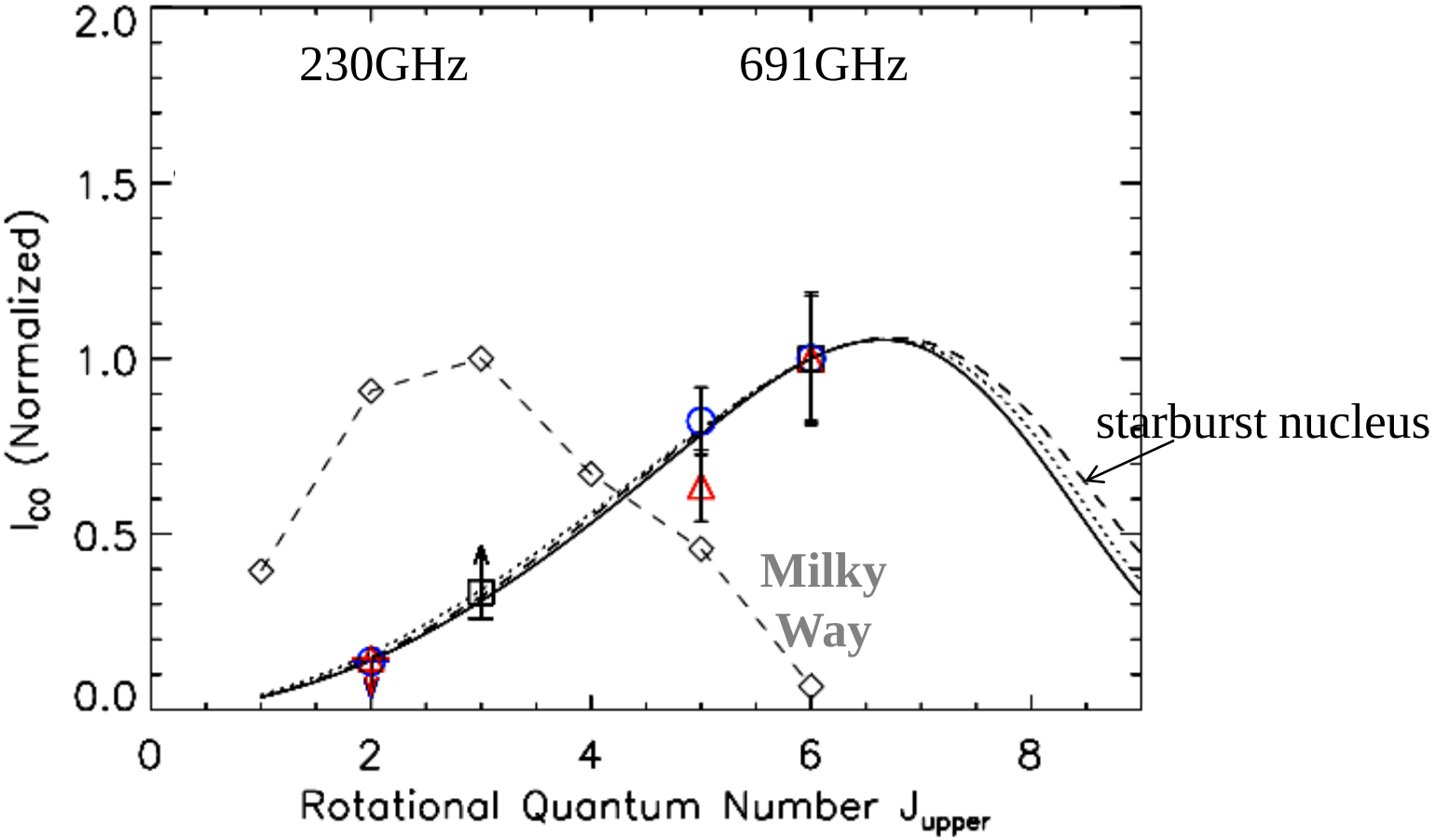
Fuel for star formation? Molecular gas: 11 CO detections at z ~ 6 with PdBI, VLA

- $M(H_2) \sim 0.7$ to 3 $x10^{10}$ $(\alpha/0.8)$ M_o
- Δv = 200 to 800 km/s
- Accurate host galaxy redshifts





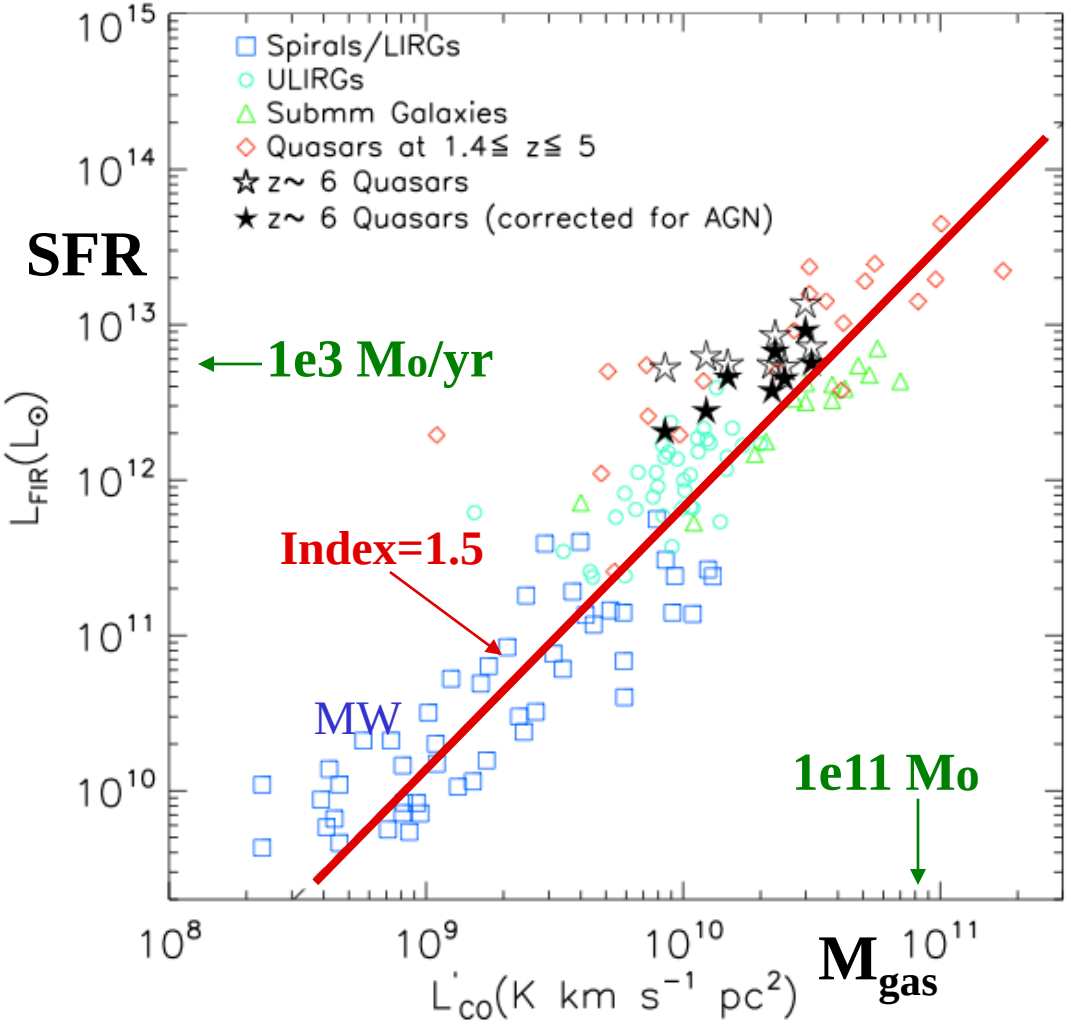
CO excitation: Dense, warm gas, thermally excited to 6-5



- Radiative transfer model => $T_k > 50K$, $n_{H2} = 2x10^4$ cm^{-3}
- Galactic Molecular Clouds (50pc): $n_{H2} \sim 10^2$ to 10^3 cm^{-3}
- GMC star forming cores (~1pc): $n_{H2} \sim 10^4$ cm^{-3}

=> Entire ISM (kpc-scales) ~ GMC SF cloud core!

L_{FIR} vs L'(CO): 'integrated K-S Star Formation relation'



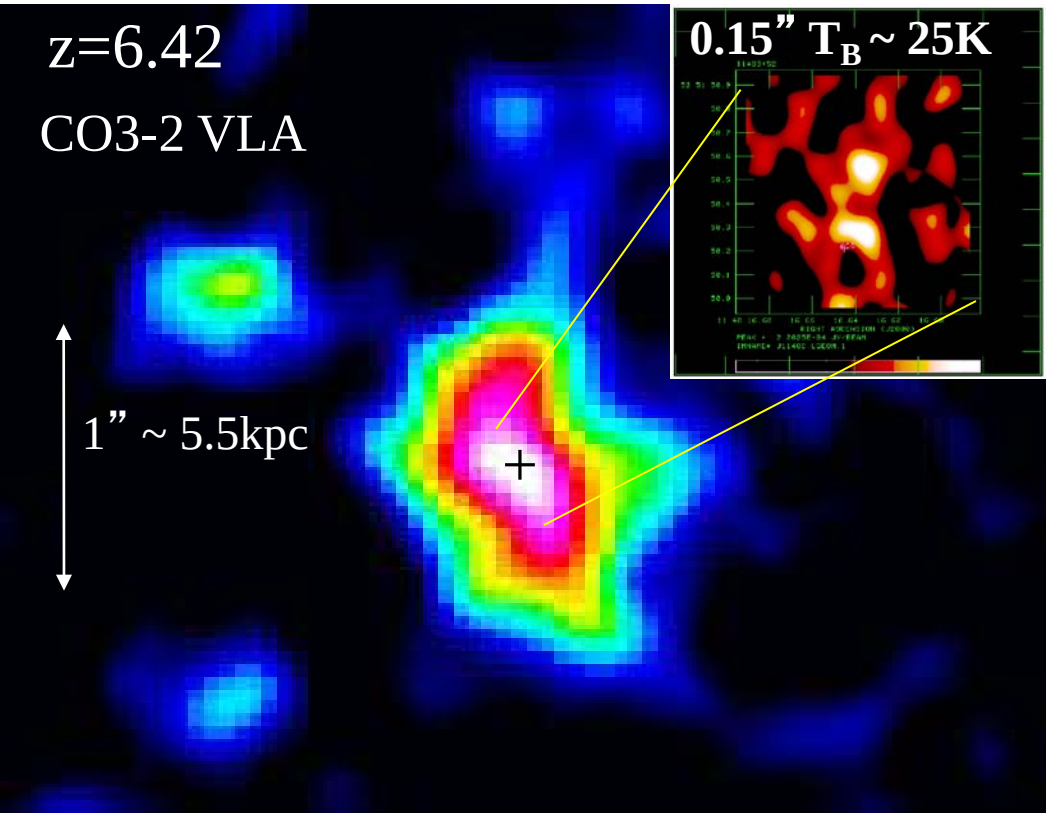
- Further circumstantial evidence for star formation

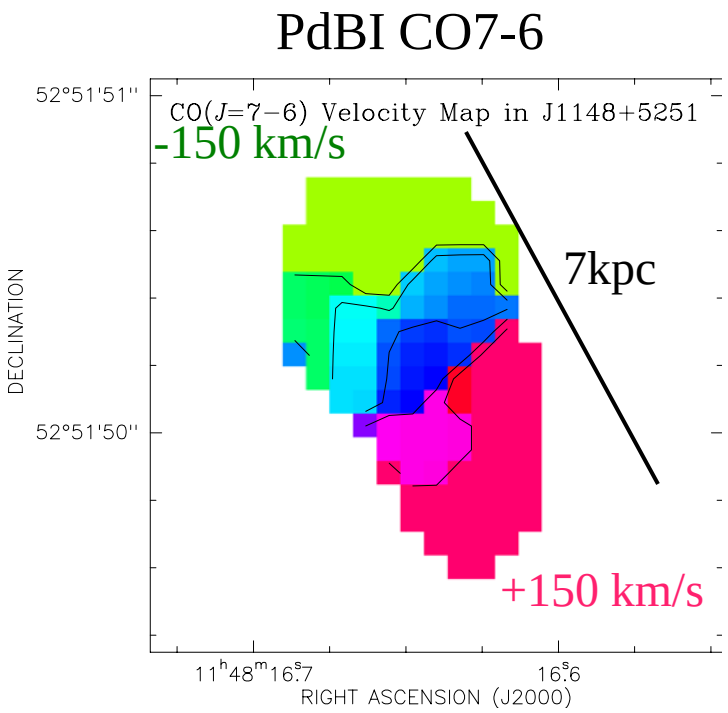
- Gas consumption time (M_{gas}/SFR) decreases with SFR

FIR ~ 10^{10} Lo/yr => $t_c > 10^8$yr

FIR ~ 10^{13} Lo/yr => $t_c < 10^7$yr

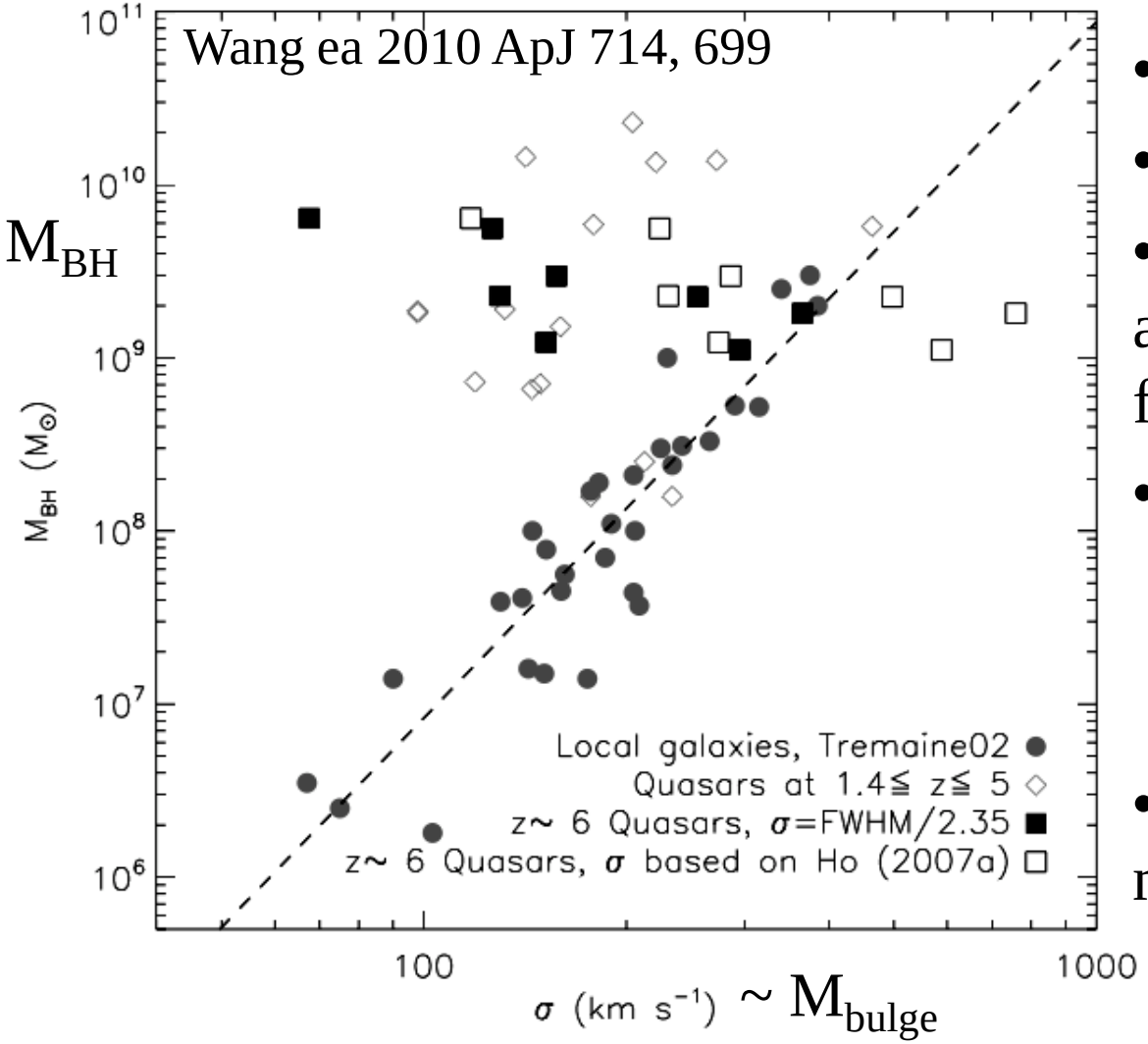
Imaging => dynamics => weighing the first galaxies





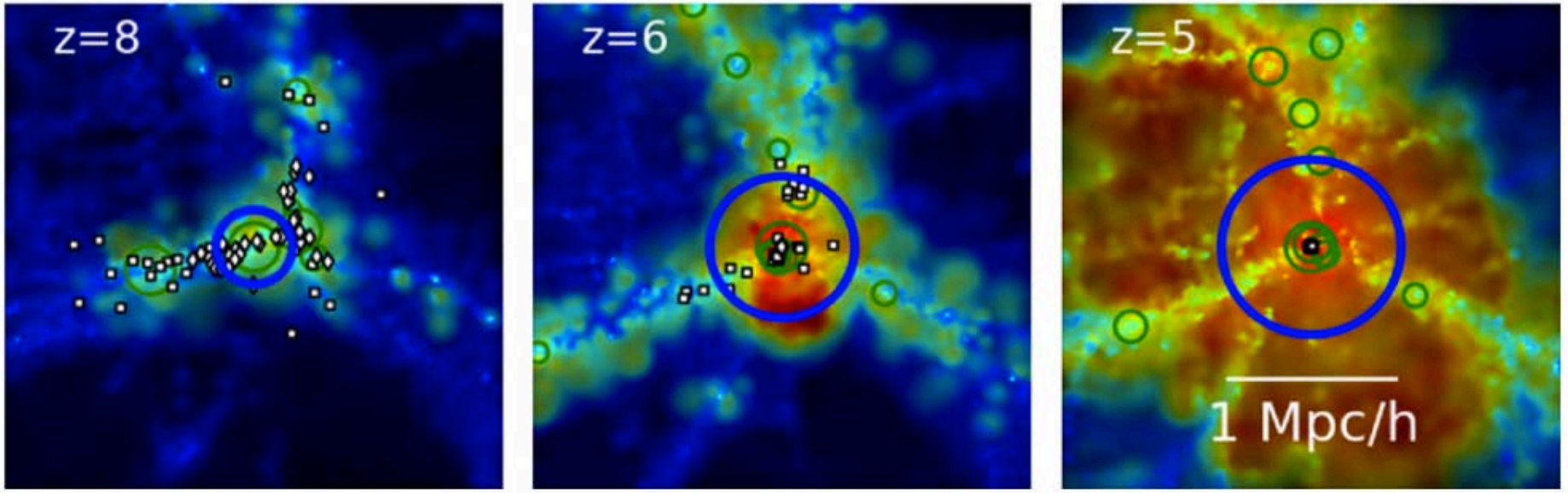
- Size ~ 6 kpc, with two peaks ~ 2kpc separation
- Dynamical mass (r < 3kpc) ~ 6 x10^{10} M_o
- $M(H_2)/M_{dyn}$ ~ 0.3 (α/0.8)

Break-down of $M_{BH} - \sigma_{bulge}$ relation at high z



- M_{BH}: MgII line, Edd.
- σ_{bulge}: CO line width
- $<M_{BH}/M_{bulge}>$ ~ 15 higher at z>4 => Black holes form first?
- Caveats:
  - Better CO imaging (size, *i*)
  - Bias for optically selected quasars?
- At high z, CO+[CII] only method to derive M_{bulge}

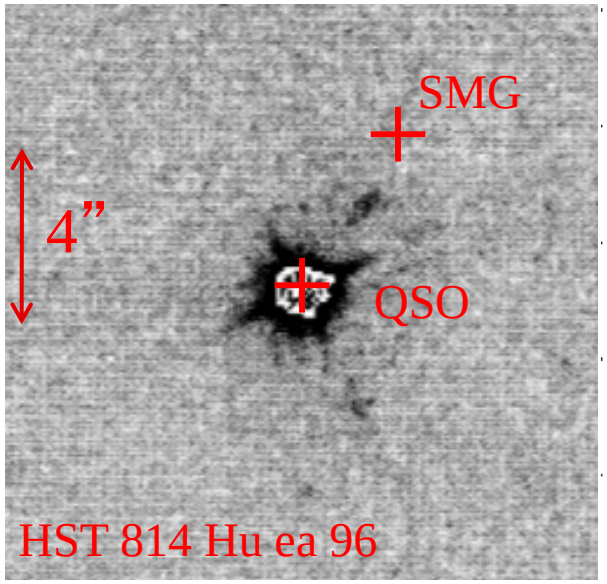
Building a giant elliptical galaxy + SMBH at t_{univ}< 1Gyr

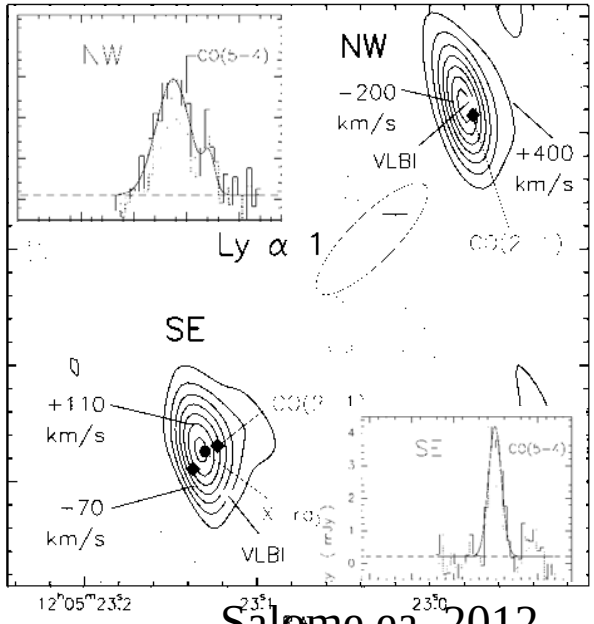


- 'Massive-Black' hydro-simulation ~ 1 $cGpc^3$ (di Matteo ea. 2012)
- Stellar mass > 10^{11} M_o forms via efficient cold mode accretion: SFR ~ gas accretion rate > 100 M_o yr^{-1}
- SMBH ~ 10^9 M_o forms (first) via steady, Eddington-limited accretion starting z~15 (seed = 10^5 M_o?!)
- Evolves into giant elliptical galaxy in massive cluster (10^{15} M_o) by z=0

BRI1202-0725 z=4.7

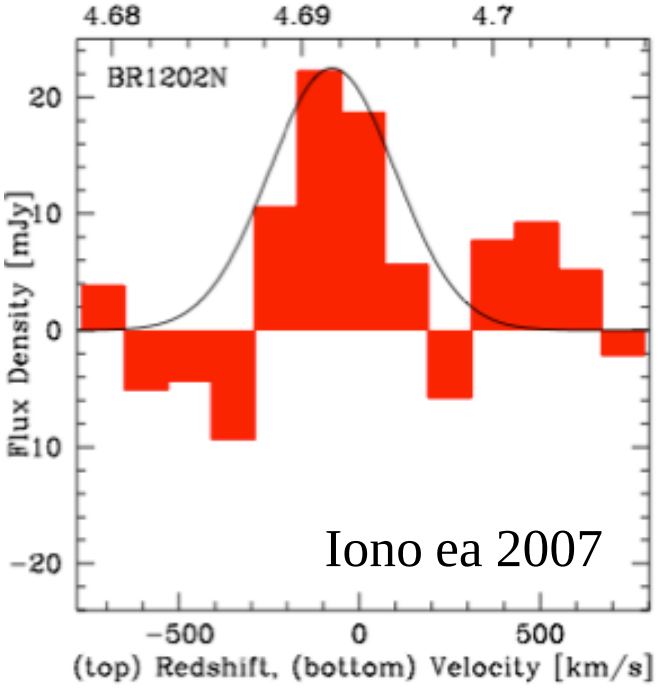
- HyLIRG ($10^{13}L_o$) pair:
  - Quasar host
  - Obscured SMG
- SFR ~ 10^3; $M_{H2} \sim 10^{11}$



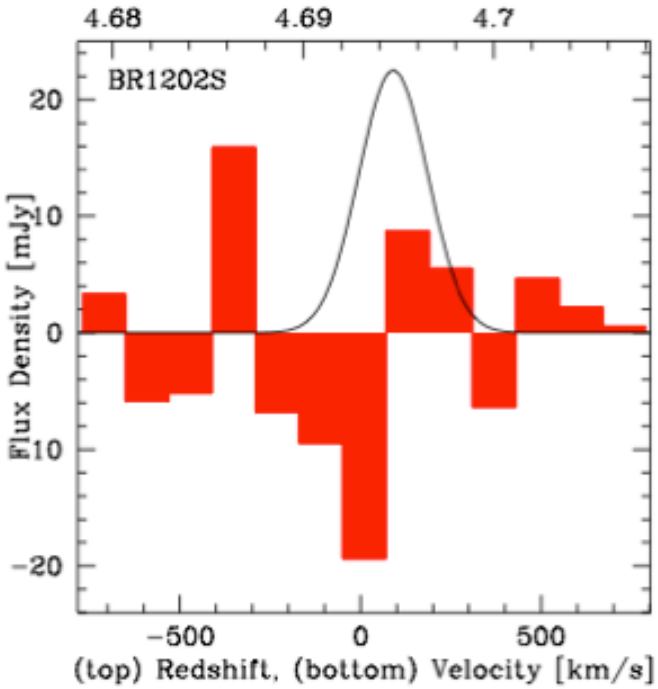


Salome ea. 2012

SMA
[CII] 158um
334GHz, 20hrs



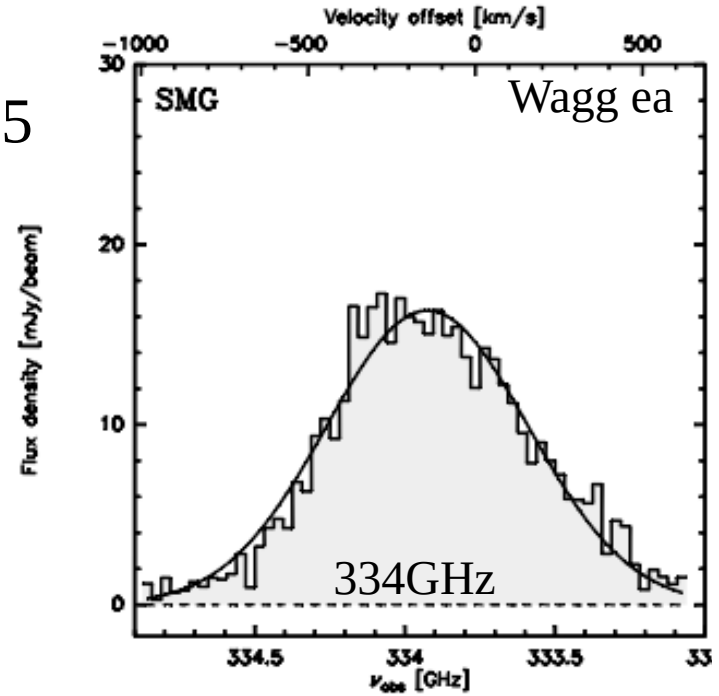
Iono ea 2007

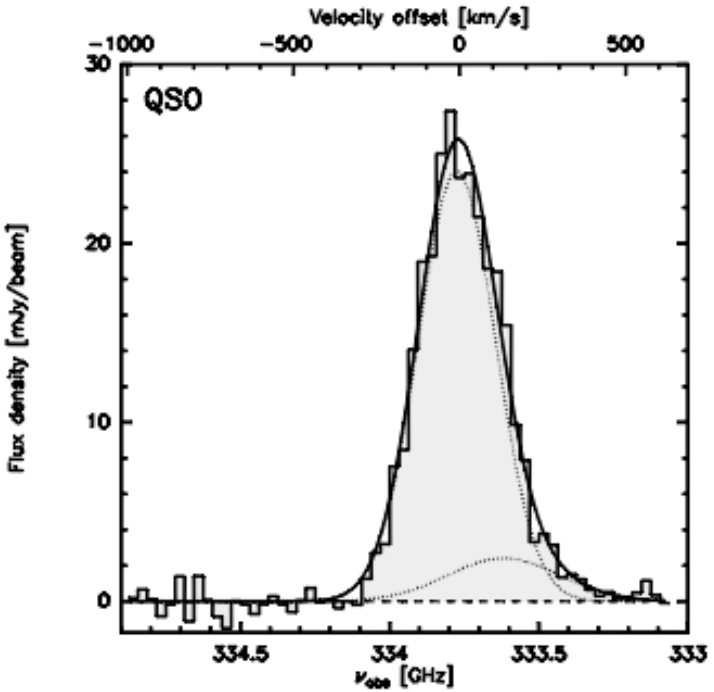


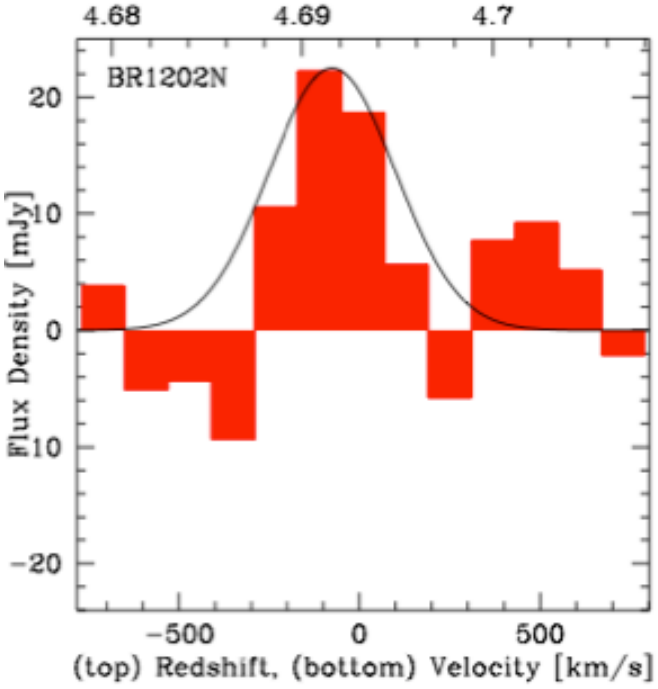
[CII] in 1202-0725

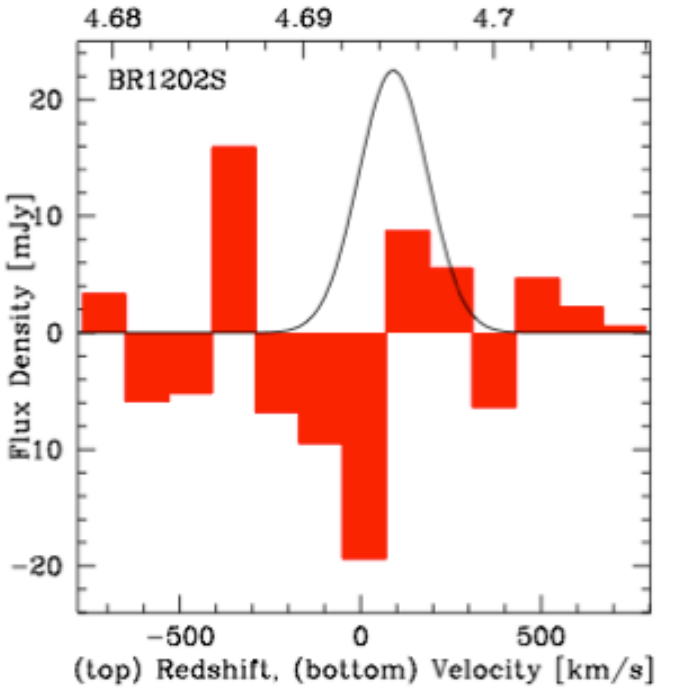
ALMA SV
20min, 16 ants

SMA
20hrs



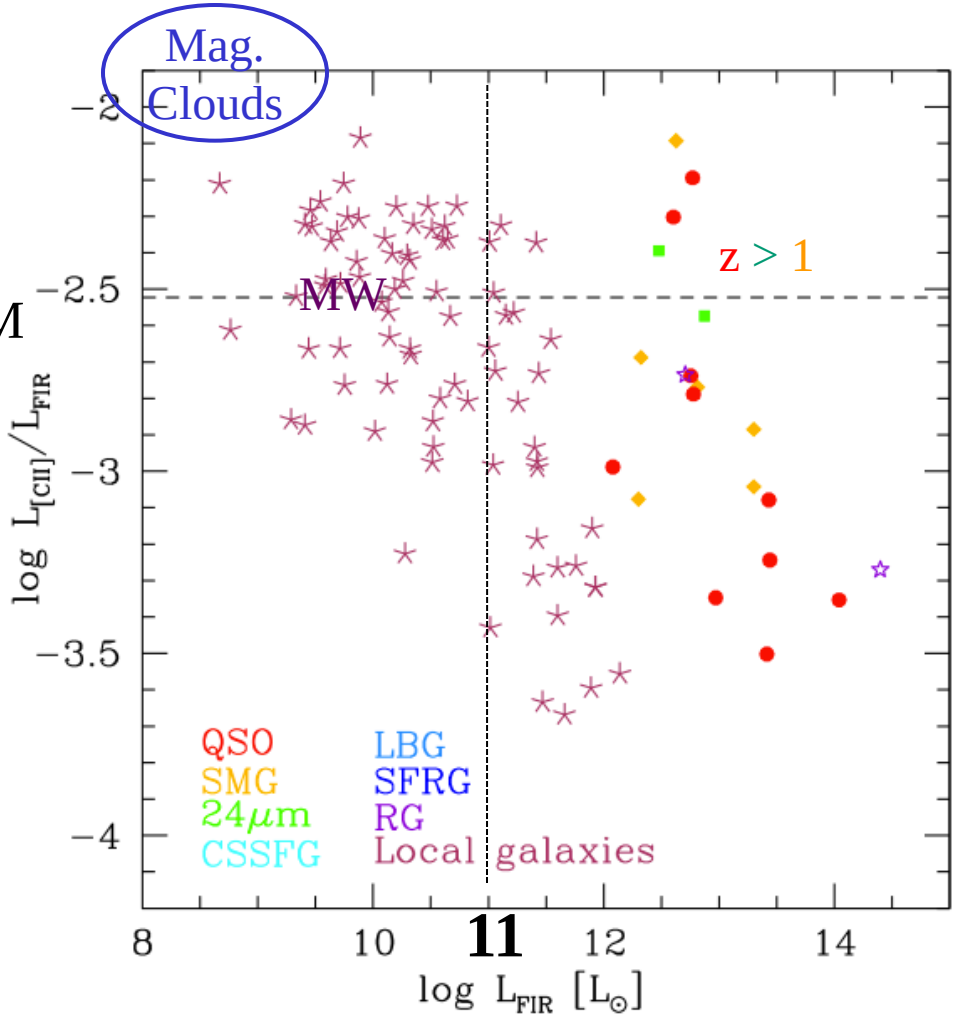






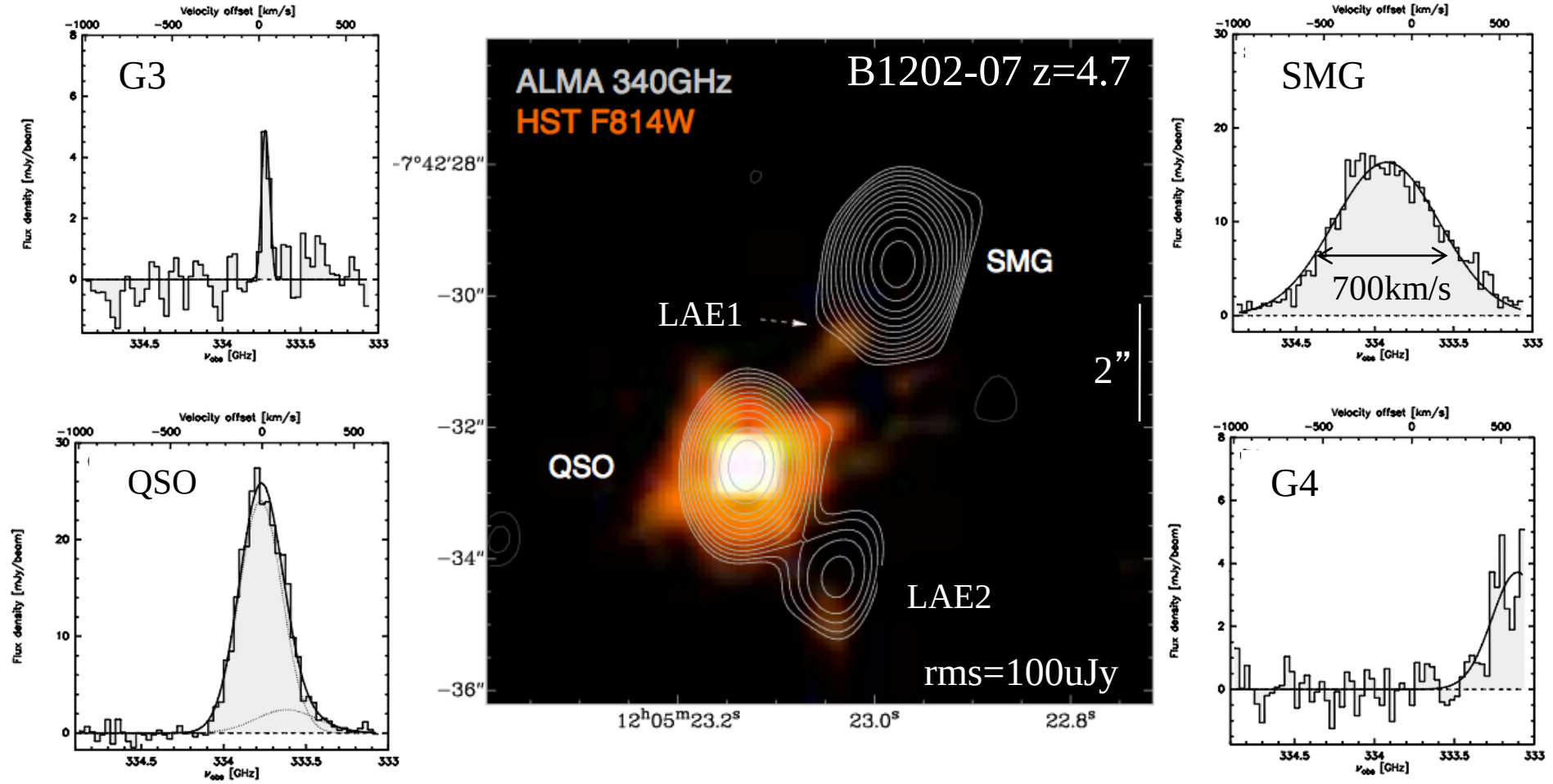
[CII] 158um FSL line

- Brightest line from cool gas in star forming galaxies: ~0.3% of FIR for MW-type galaxies. Traces CNM+WIM
- FIR > 10^{11}: large scatter (~ 20dB)
  - AGN-dominated: low
  - SF dominated: 'MW'
- [CII] powerful tool for:
  - Gas dynamics
  - Redshift determinations z>6
- Low metallicity: enhanced [CII]/FIR (lower dust attenuation => large UV heating zone)



Carilli & Walter 2013

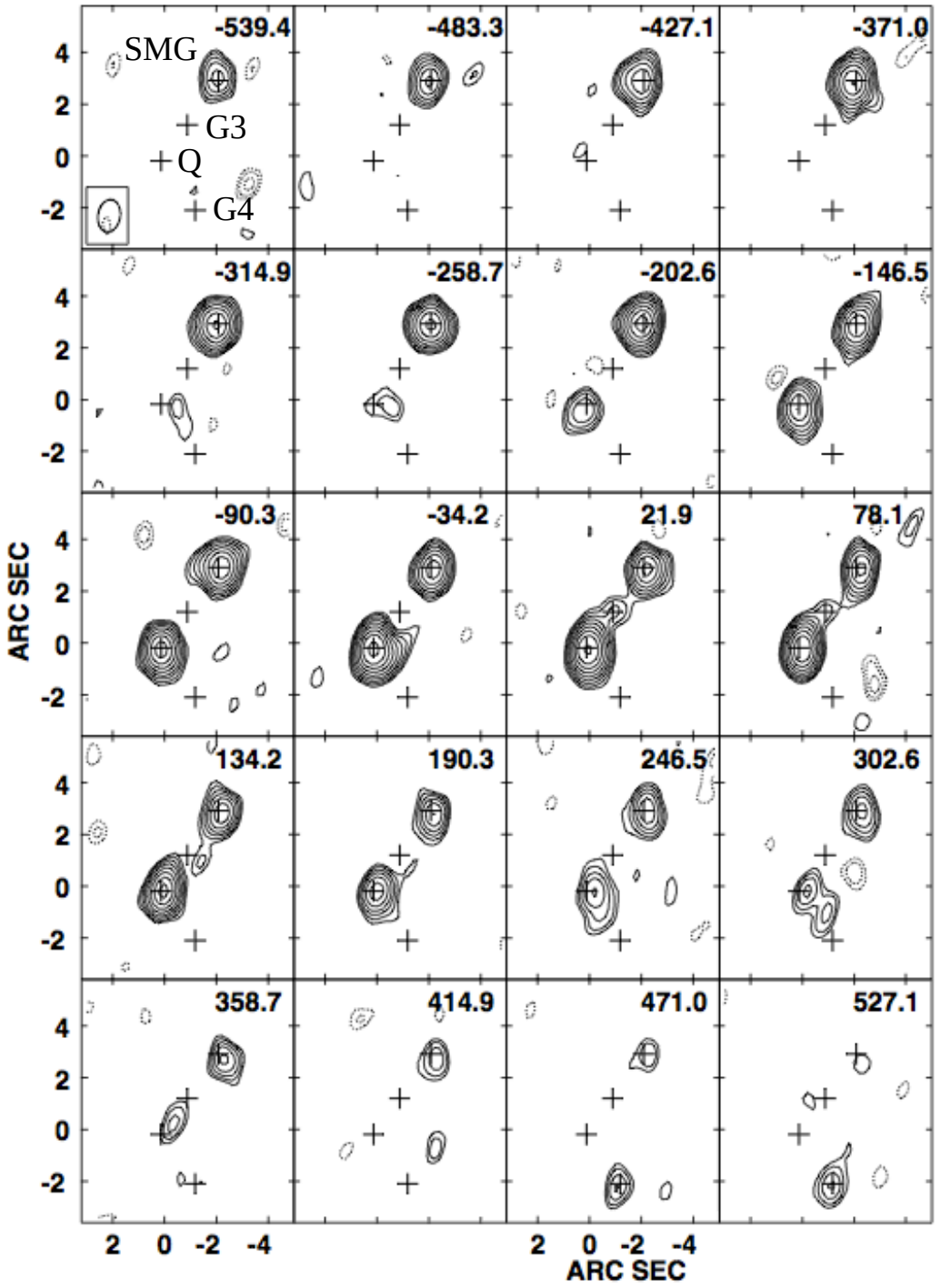
SMGs: Dust-obscured hyper-starbursts
Imaging massive galaxy formation



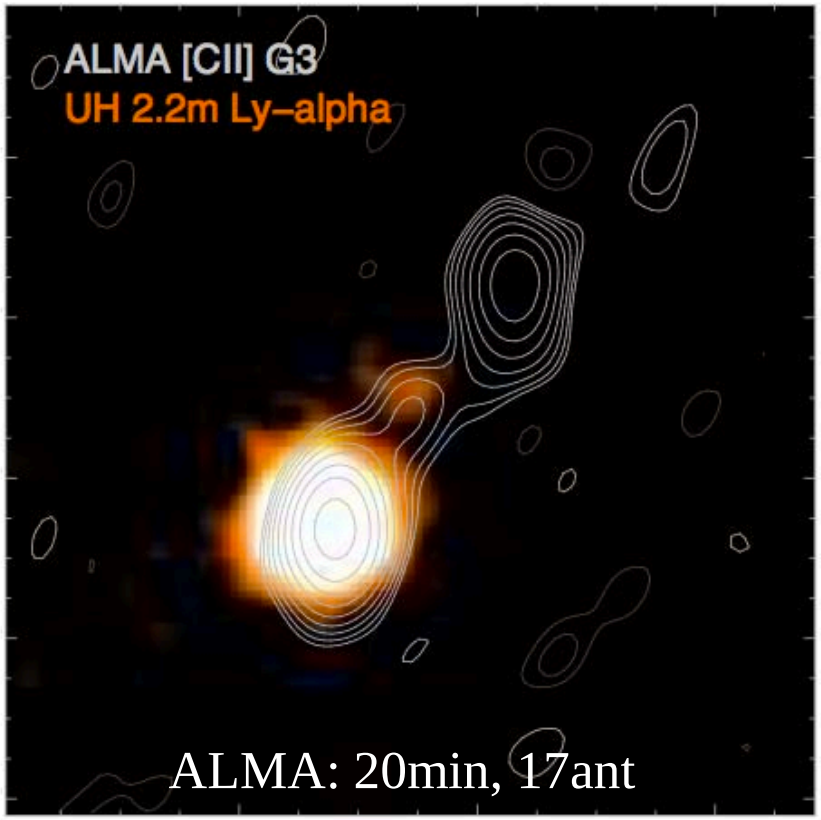
- Two hyper-starbursts (SMG and quasar host): SFR ~ 10^3 M_o/yr
- Two ‘normal’ LAE: SFR ≤ 10^2 M_o/yr

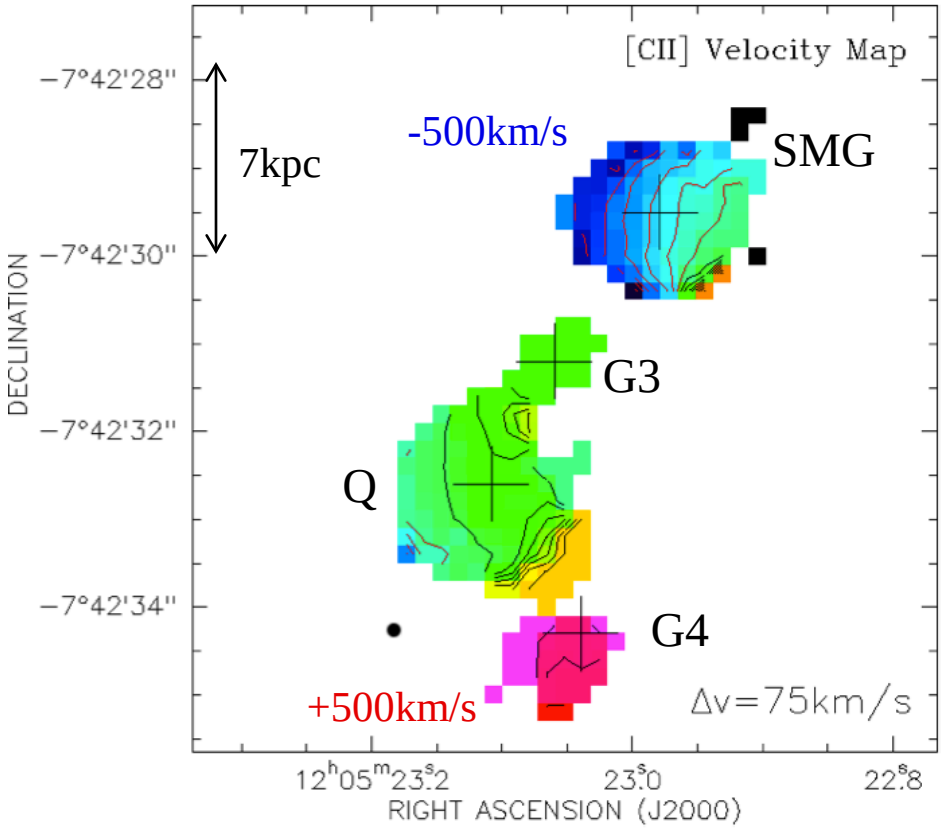
[CII] in 1202: Imaging cool gas dynamics at z=4.7

- Quasar, SMG: Broad, strong lines
- Tidal bridge across G3, as expected in gas-rich merger
- Possible quasar outflow, or further tidal feature, toward G4

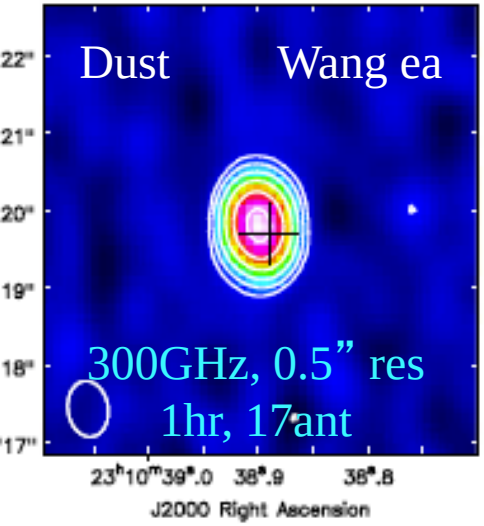


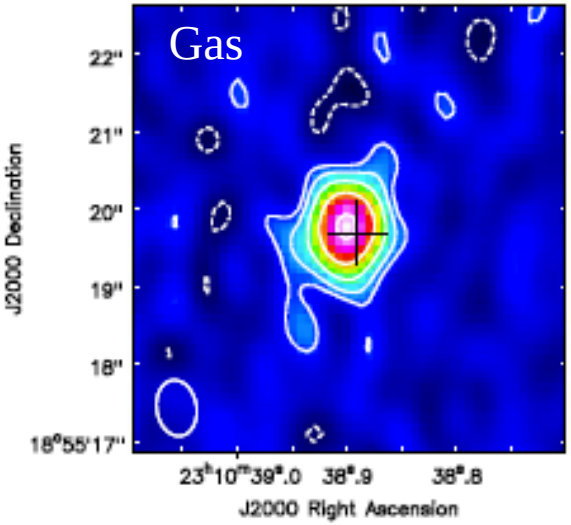
BRI1202: ‘smoking gun’ for major merger of gas rich galaxies

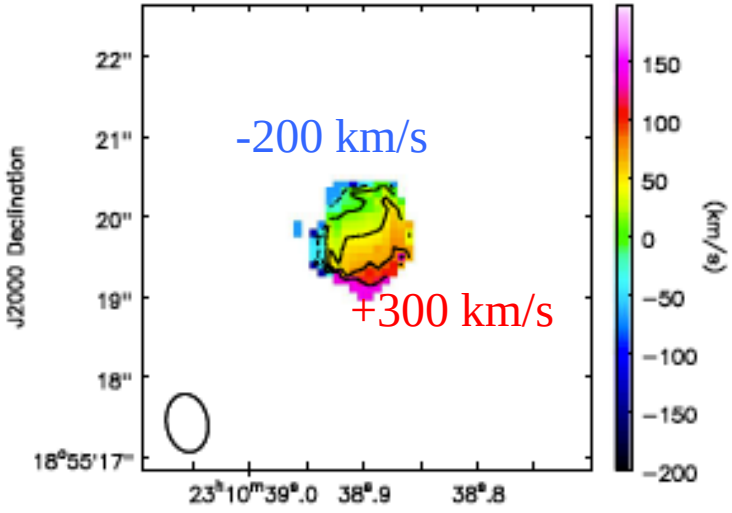




- Tidal stream connecting hyper-starbursts
- SMG: warped disk, highly optically obscured
- HyLIRG QSO host, with outflow seen in [CII] and CO
- G3: Ly-alpha + [CII] in tidal gas stream
- G4: dust and [CII] in normal LAE

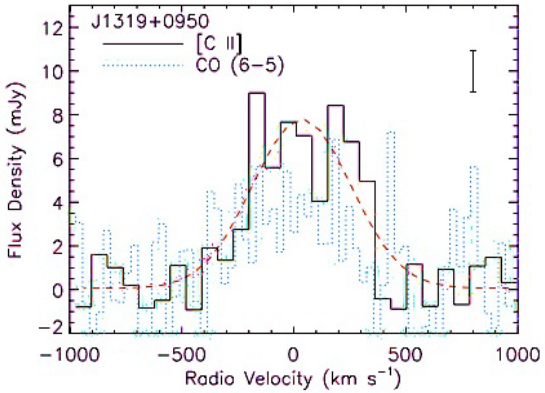






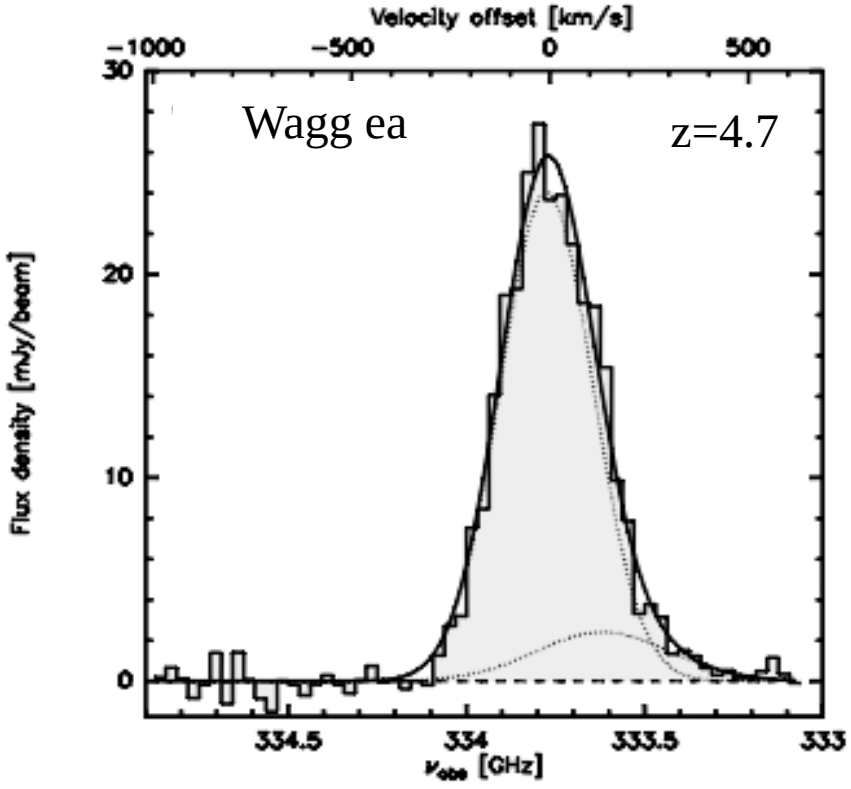
ALMA Cycle 0: 5/5 detected [CII] + dust

- Sizes ~ 2-3kpc, clear velocity gradients
- M_{dyn} ~ 5e10 M_o => support M-σ conclusions

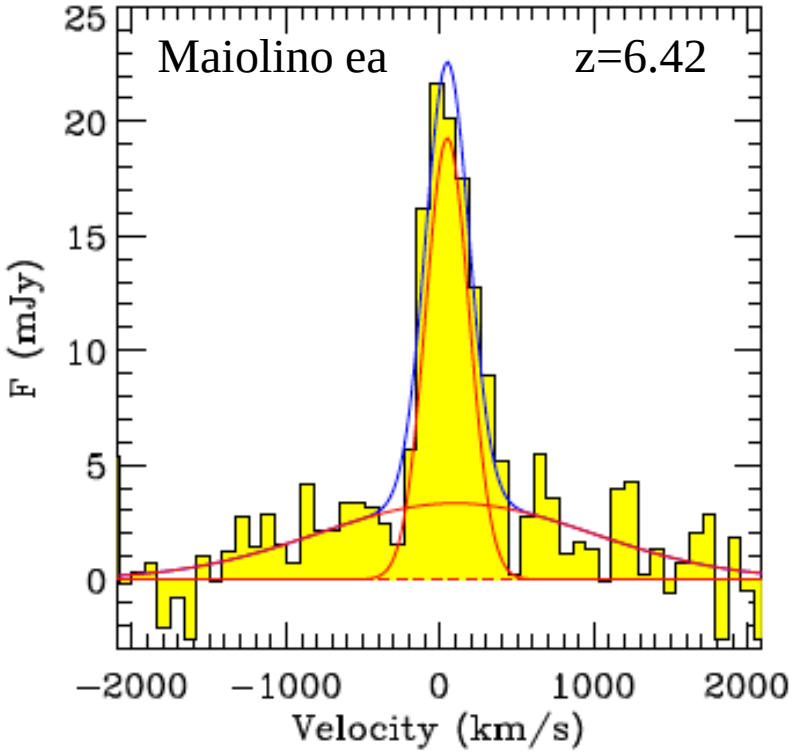


- Maximal SB disk: SFR/area ~ 1000 M_o yr^{-1} kpc^{-2} (Thompson ea 2005)
  - ➢ Self-gravitating gas disk, support by radiation pressure on dust grains
  - ➢ ‘Eddington limited’ SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}
  - ➢ eg. Arp 220 on 100pc scale, Orion < 1pc scale

Feedback: [CII] outflows?



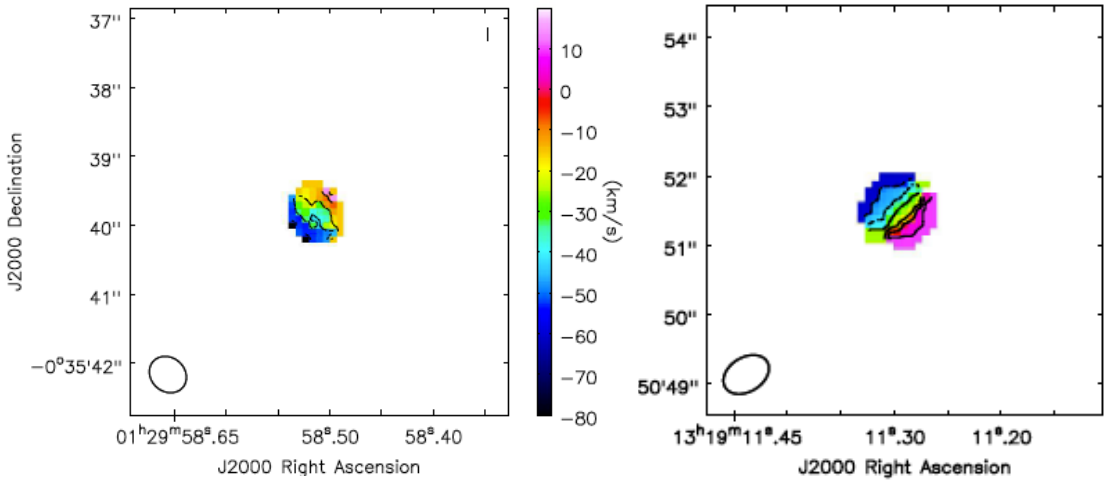
dM/dt ~ 300 M_o/yr



dM/dt ~ 3500 M_o/yr

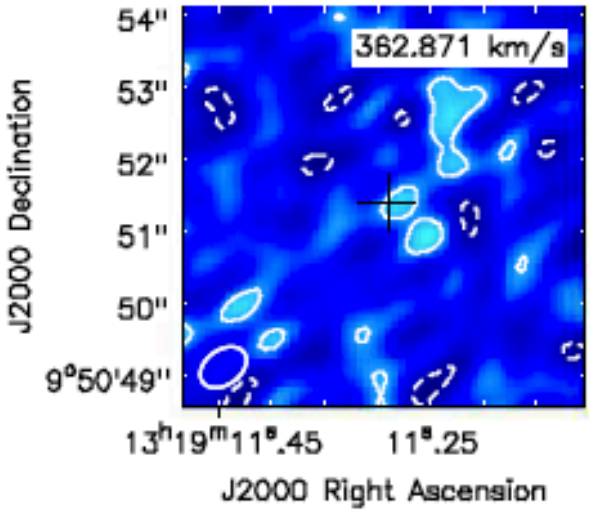
Summary

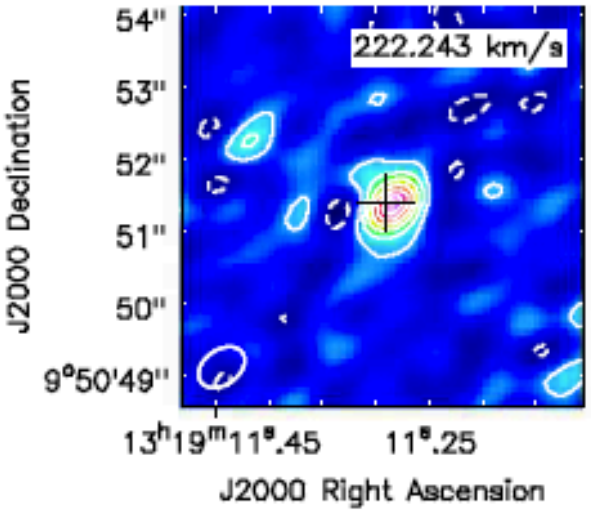
cm/mm obs of 33 quasars at z~6: only direct probe of the host galaxies

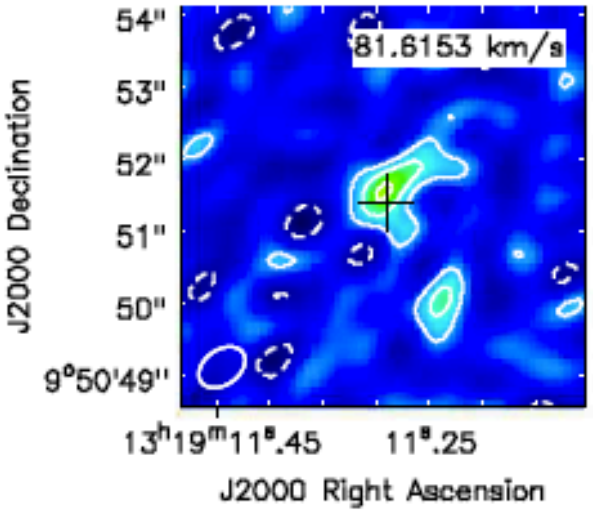


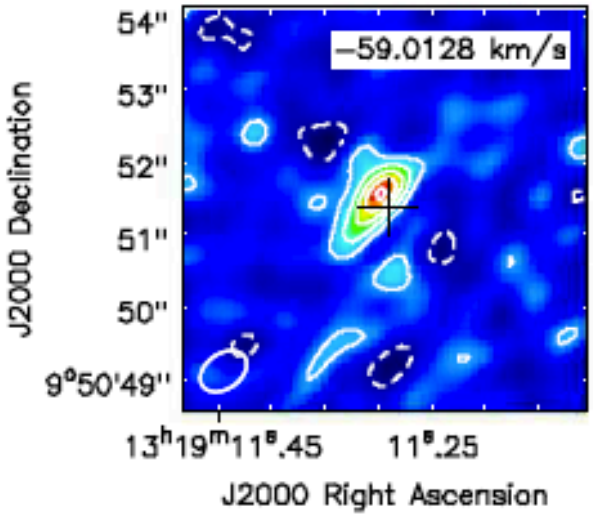
- 12 in mm continuum => $M_{dust} \sim 10^8\ M_o$: Dust formation?
- 10 at 1.4 GHz continuum: Radio to FIR SED => SFR ~ 1000 M_o/yr
- 11 in CO => $M_{gas} \sim 10^{10}\ (\alpha/0.8)\ M_o$ = Fuel for star formation
  - High excitation ~ GMC cloud cores, but on kpc-scales
  - Follow star formation relation: $t_c \sim 10^7$ yr
- Departure from $M_{BH} - M_{bulge}$ at z~6: BH form first?
- 8 in [CII] => gas dynamics, outflows, maximal star forming disks

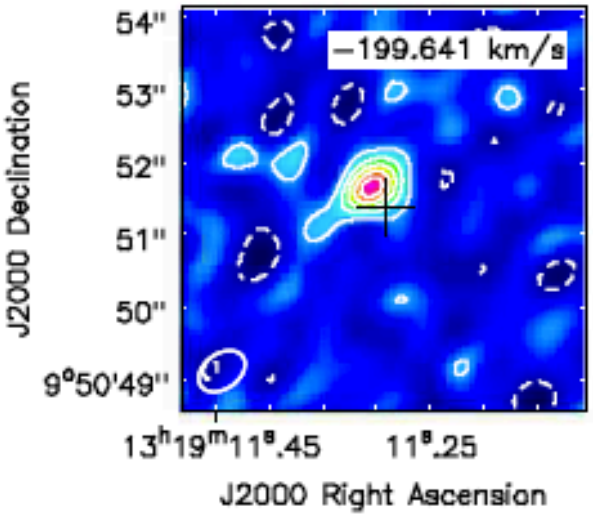
J1319+0951 z=6.1

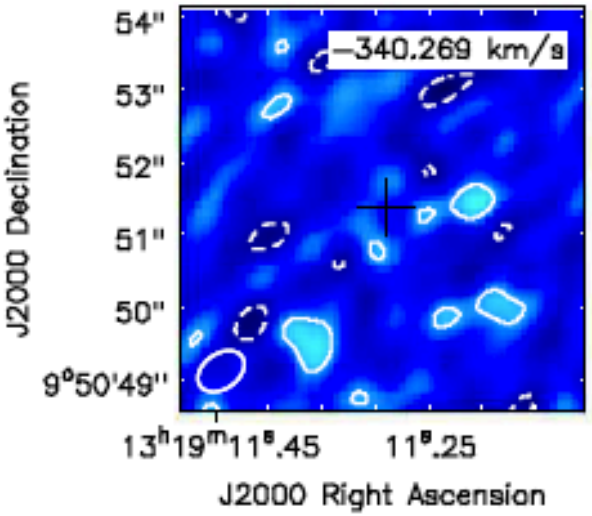












Comparison to low z quasar hosts