The molecular gas reservoirs of large disk galaxies at z~1.5

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Motivation

Cold streams ? (Dave; Dekel talks)

Merging or 'in situ' growth of stellar mass ?
(many talks)

Clumpy galaxy media due to large gas fraction, turbulence
(Elmegreen talk)

Dynamic of galaxies from Ha, etc
(Shapiro, etc)

Direct Observations of the cold (molecular) gas in high-z massive galaxies is clearly crucial --> CO emission lines

At 1.4<z<2.5, a number of non orthodox findings… (Daddi et al 2005; 2007ab)

Typical massive (~10^11Msun) SF galaxies are ULIRGs (100-200 Msun/yr SFR)
space density >10^{-4} Mpc^{-3}, 1000 times the local one

but… unlike local ULIRGs

- transparent in UV (not optically thick)
- long lived/high duty cycle (because predominant phase)
- part of SFR/Mass relation with small scatter

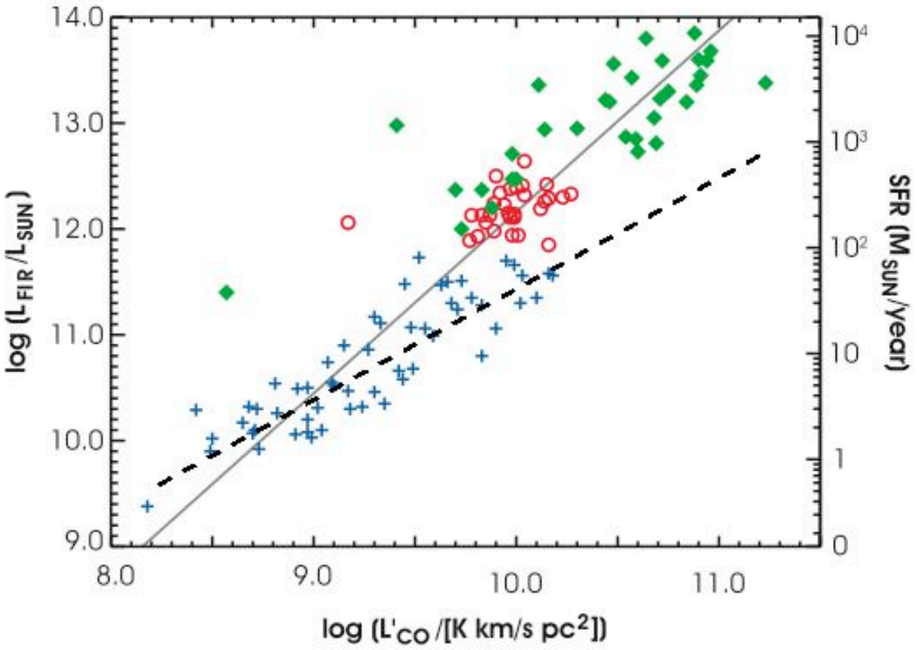
--> z~2 ULIRGs not major merging powered, most likely,
just the typical formation mode of massive high-z galaxies

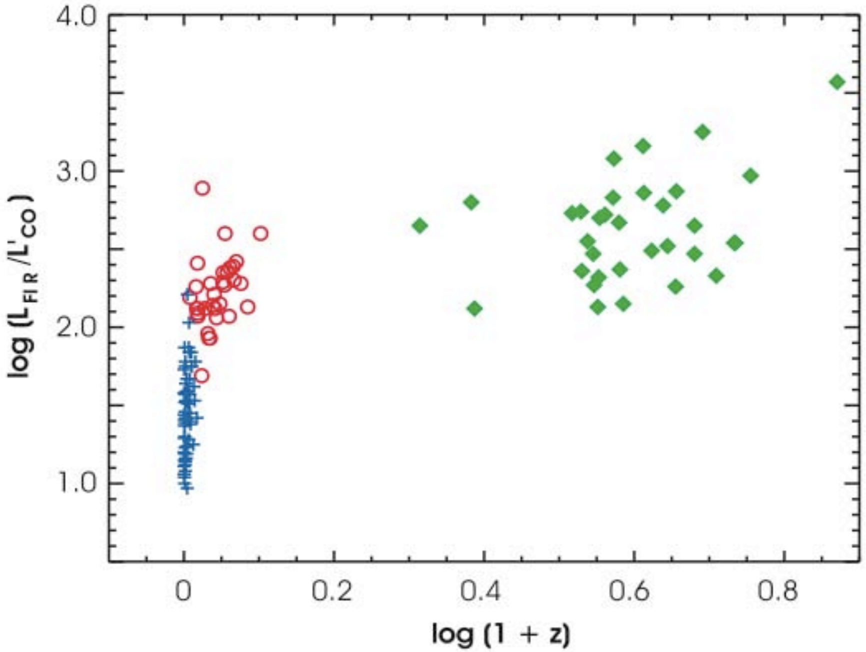
To really make progress and confirm or disregard this picture
of star formation in the high-z Universe, we need to know more
about the gas, primary ingredient to SF

High duty cycle --> lots of stars formed --> need lots of gas
(in place ? Or accreted over time and rapidly consumed ?)

But too low SFR to hope detecting the gas if typical correlations hold

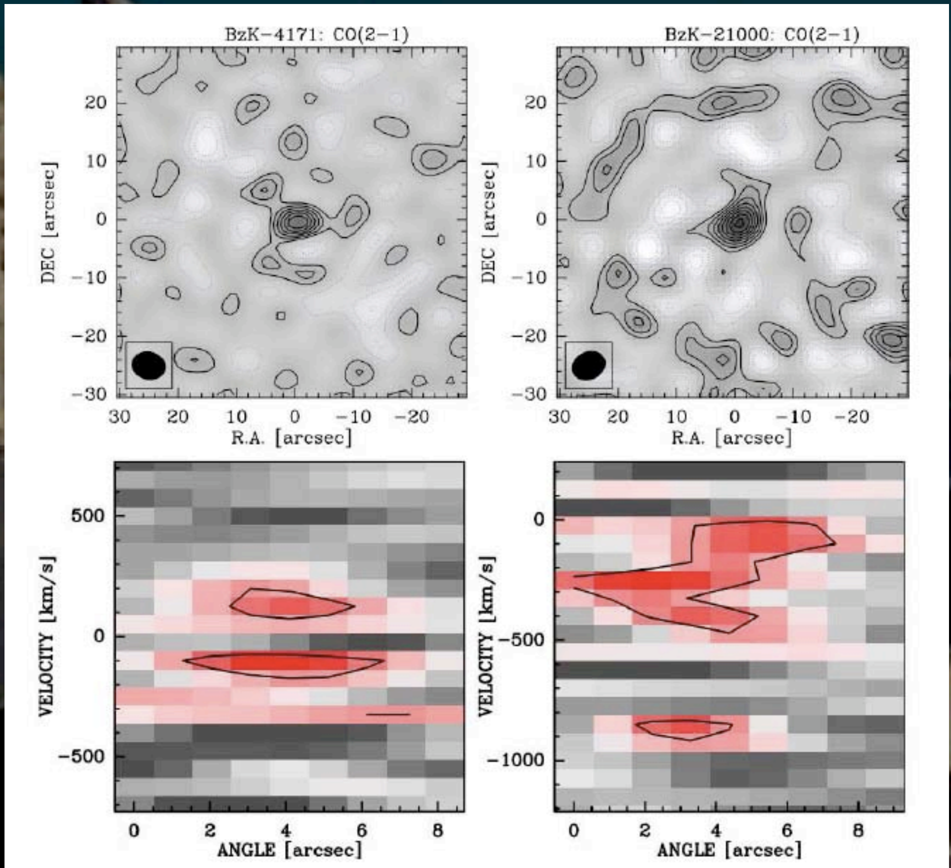
Are the gas properties different from low-z ULIRGs ?

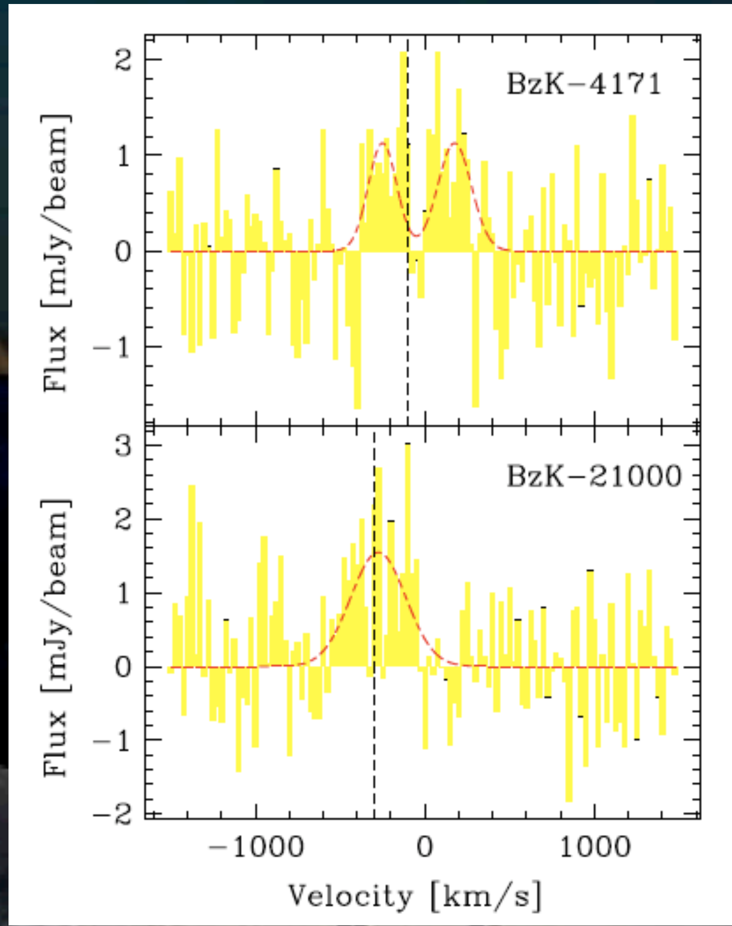




Solomon & van den Bout 2005

Daddi et al. 2008 ApJL (First detection of CO in normal high-z galaxies)



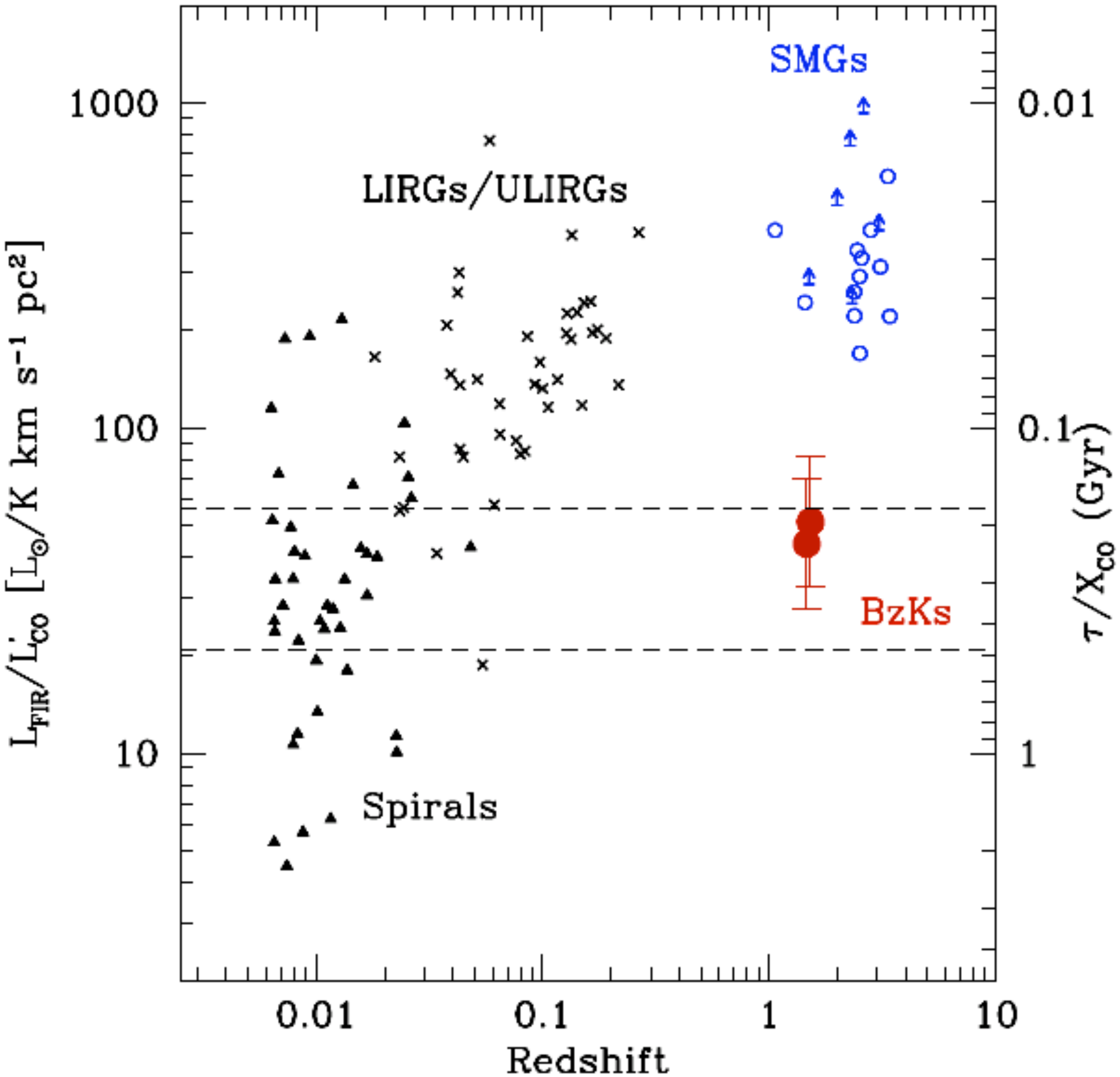


Observed 2 near-IR selected galaxies at z=1.5 with L_{IR}~10^{12}Lsun

2/2 secure PdBI detections (both >6 σ)

CO [2-1] fluxes 0.6-0.8 Jy km/s (detectable in ~8 hours total time)

Star formation efficiencies and timescales

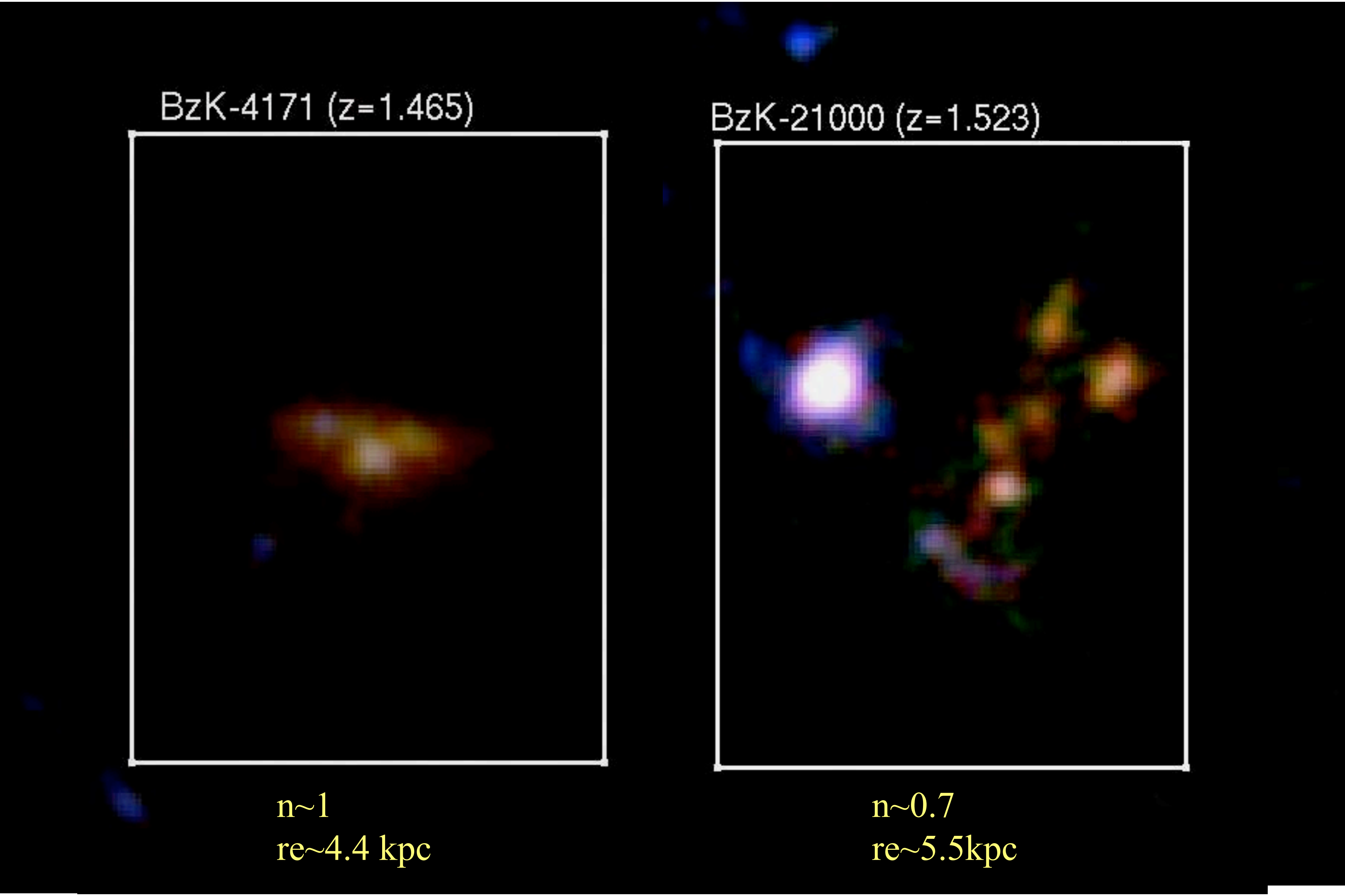


Consistent with being « scaled up » spirals for SF efficiency

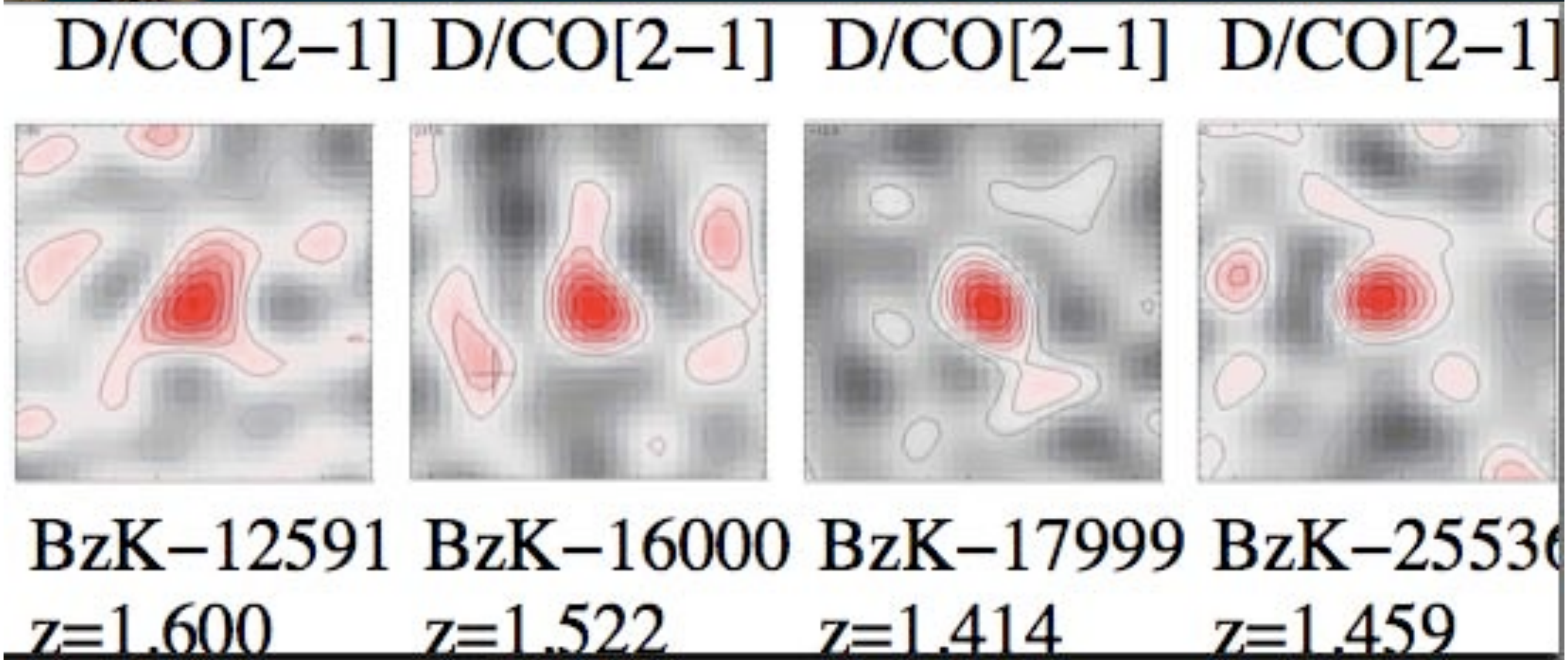
Timescales much longer than SMGs

200-300 Xco Myr

Indications for 'spirals-like' Xco
1) SFE
2) sizes


BzK-4171 (z=1.465)
BzK-21000 (z=1.523)
n~1
re~4.4 kpc
n~0.7
re~5.5kpc

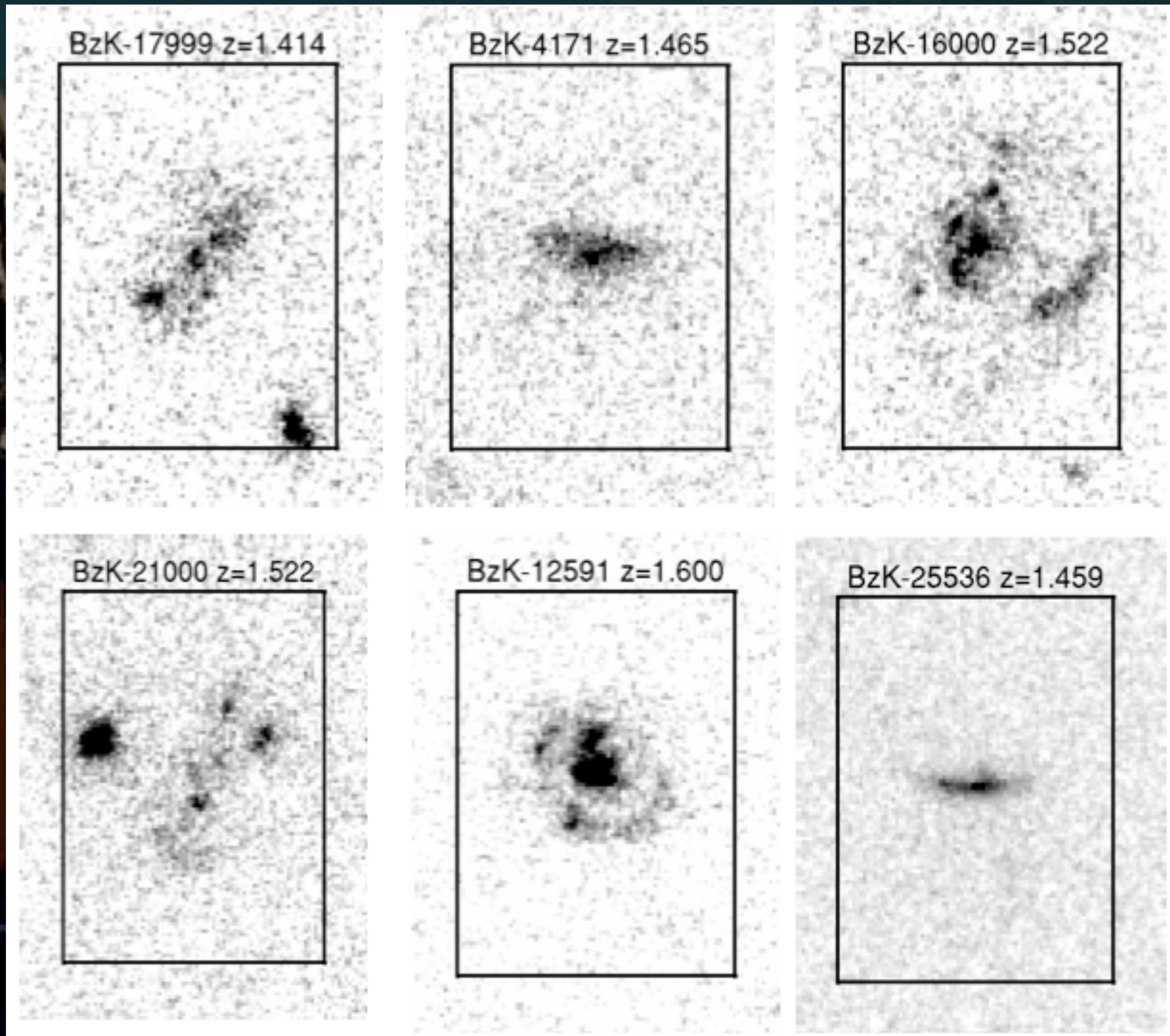
New 2008 results



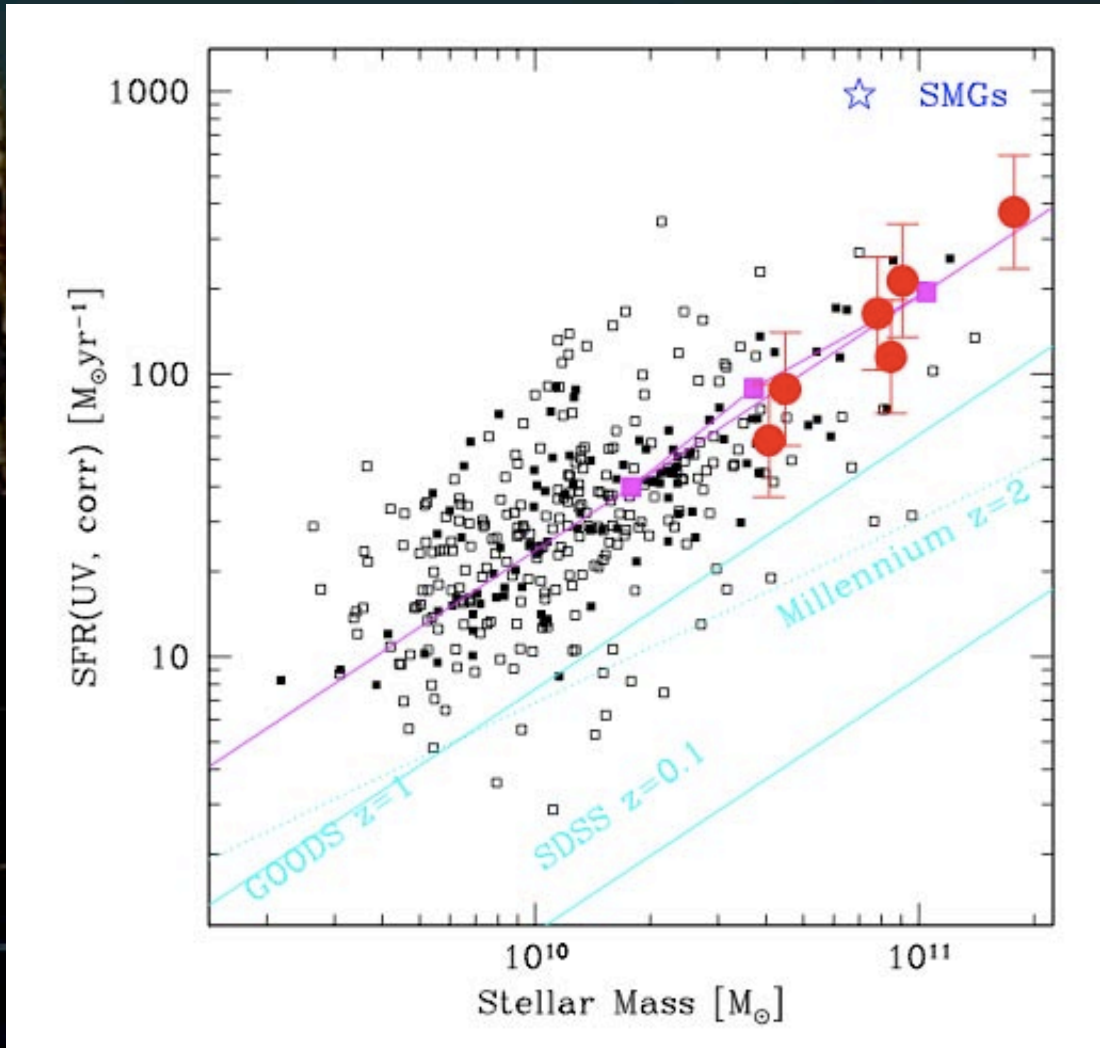
6 galaxies observed to now, 6 galaxies detected in CO

Selection: near-IR flux limited + BzK; secure redshift (Keck)
faint but detected at VLA (--> $L_{IR}=10^{12}$Lsun at z=1.5)

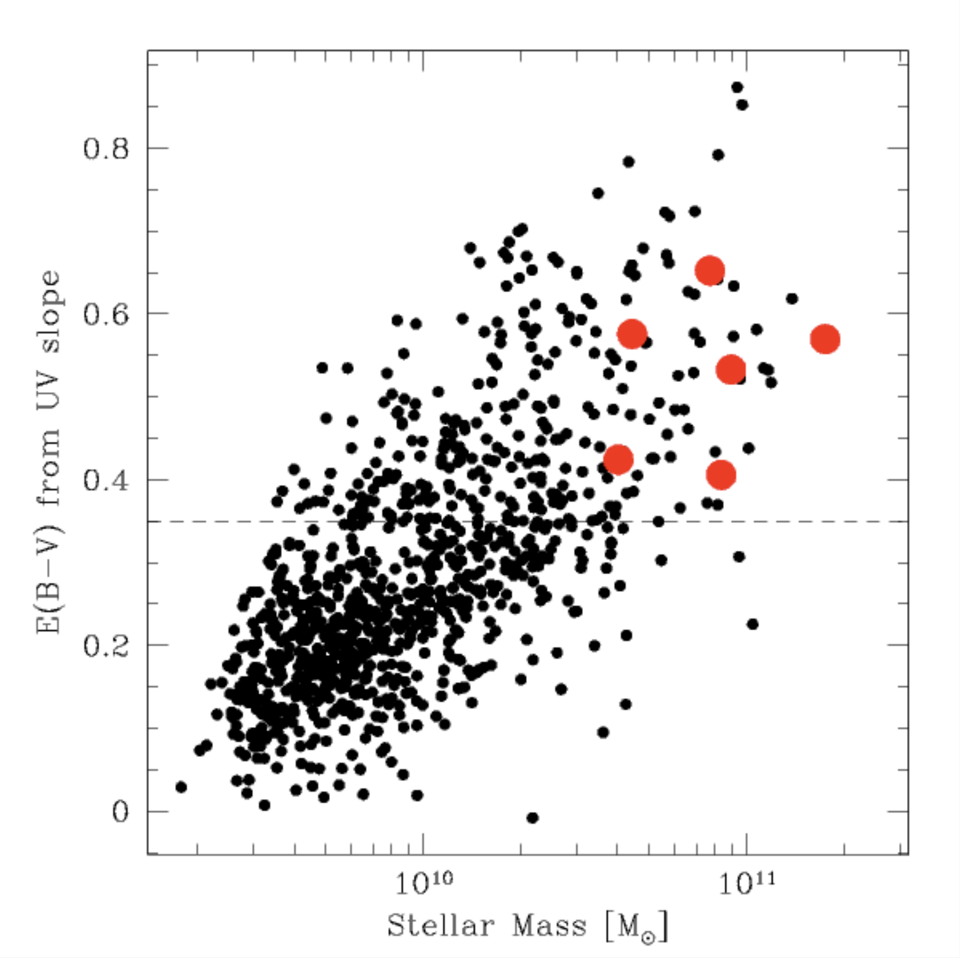
UV morphology



Virtually all massive galaxies at z~1.5-2 are gas rich



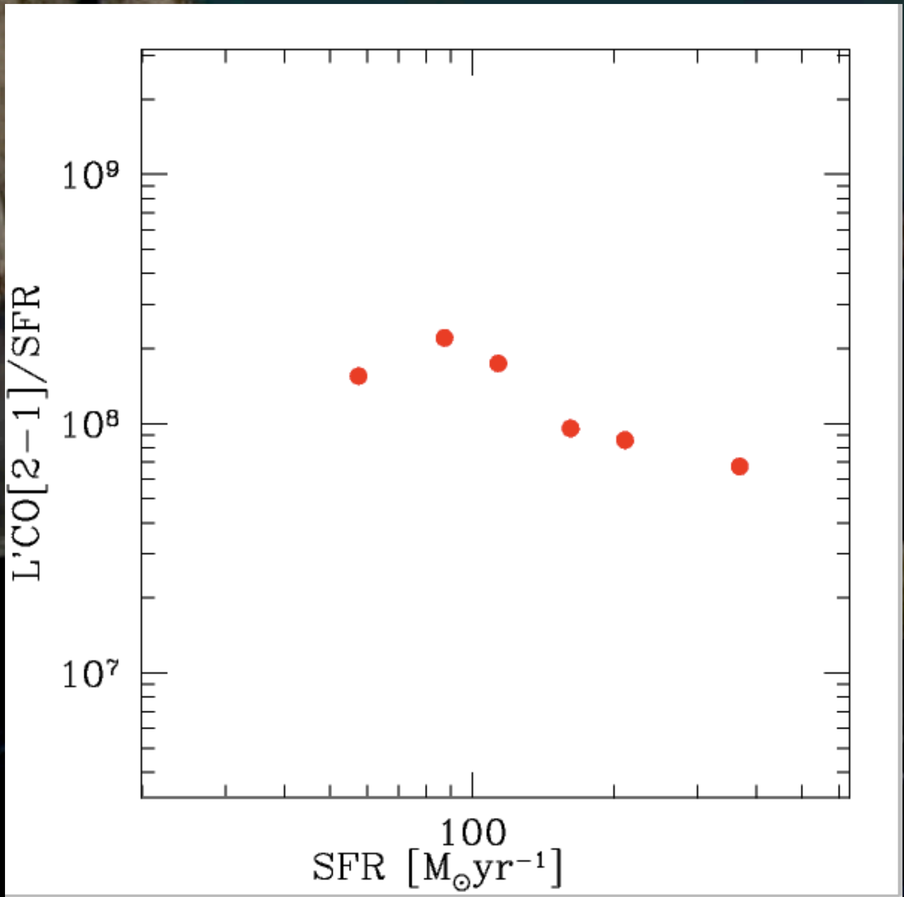
Massive galaxies are red/dusty

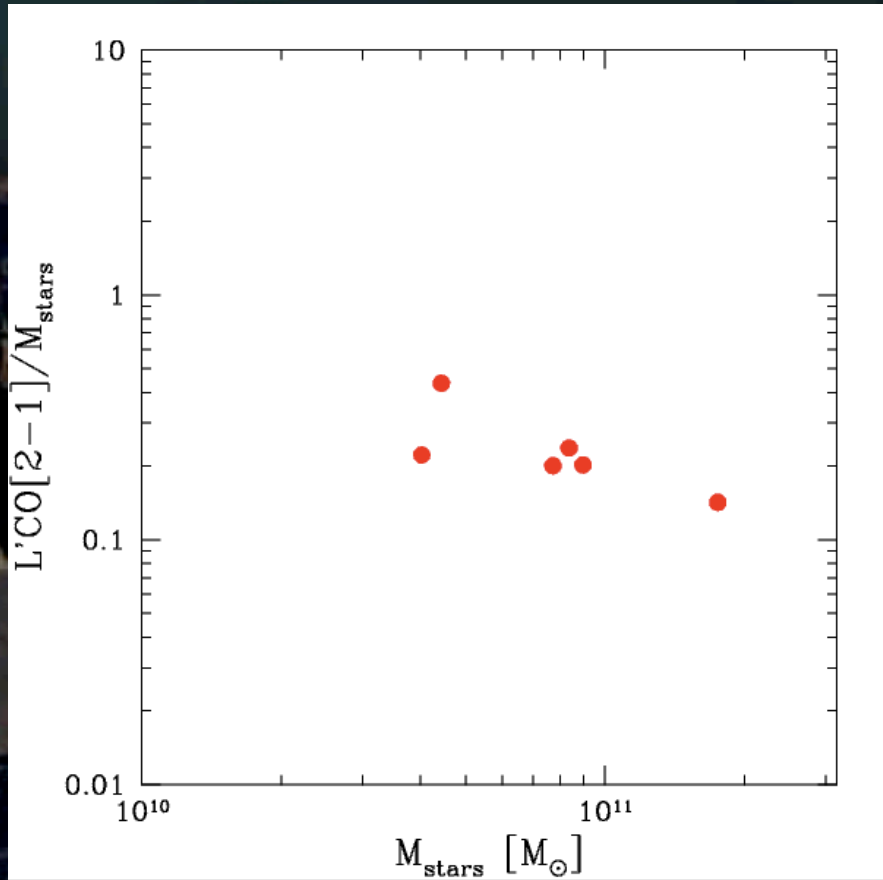


Generally beyond the BM/BX galaxy limit

High reddening
→lots of metal ?
→lots of gas ?

Gas luminosity vs SFR/Mass

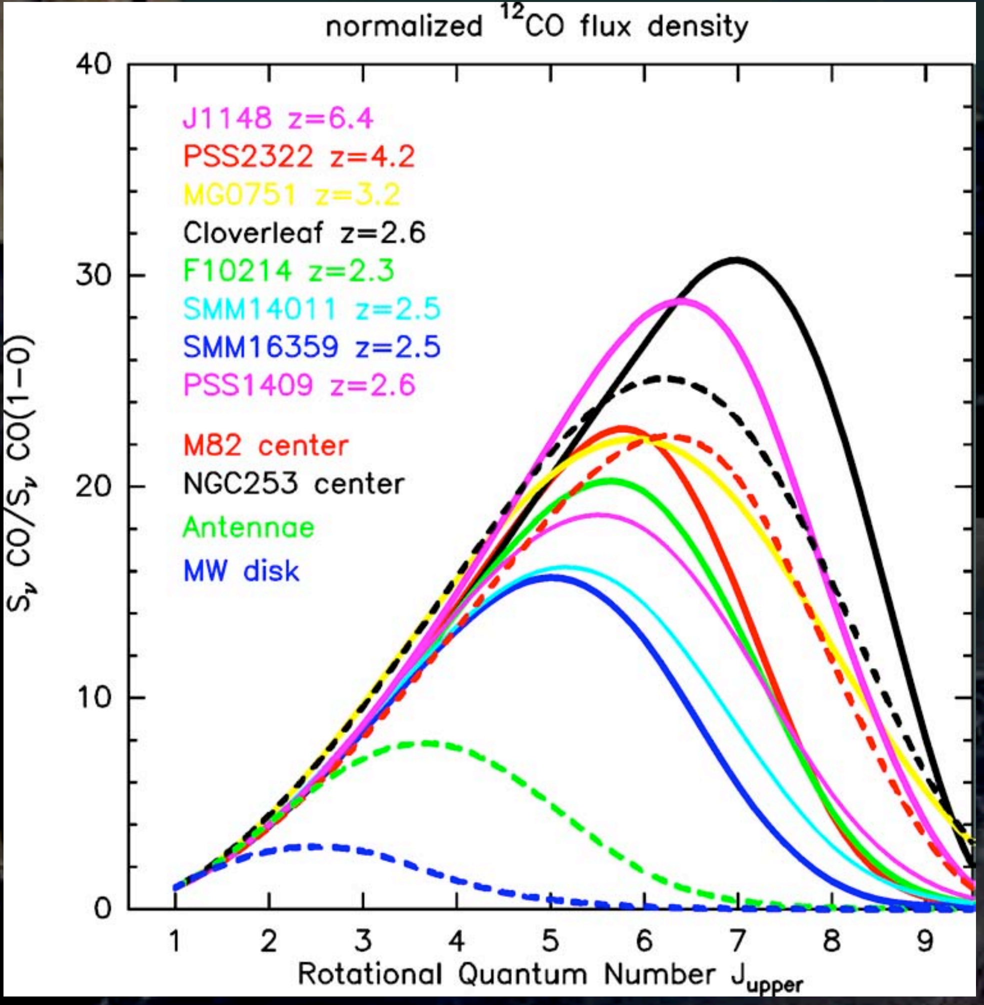




Scatter ~x2 only: striking regularity
Possible trend, ratios increase perhaps to low SFR/masses

What are the CO excitation properties ?

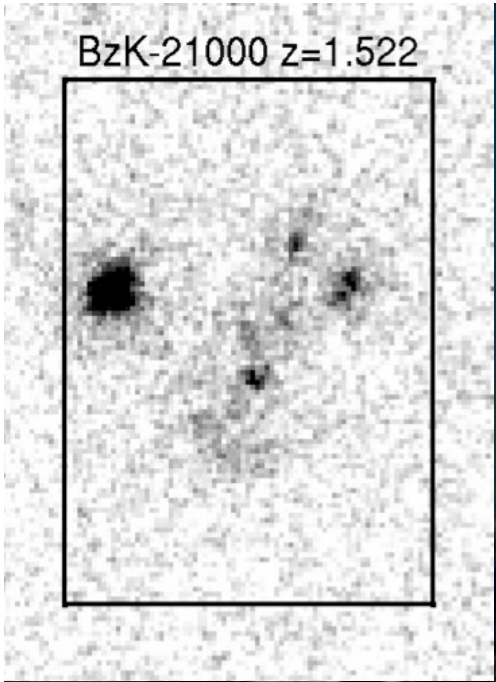
Weiss et al 2006



All CO SED known so far at high-z reveal warm gas, brightest CO fluxes are transitions J 5 to 7

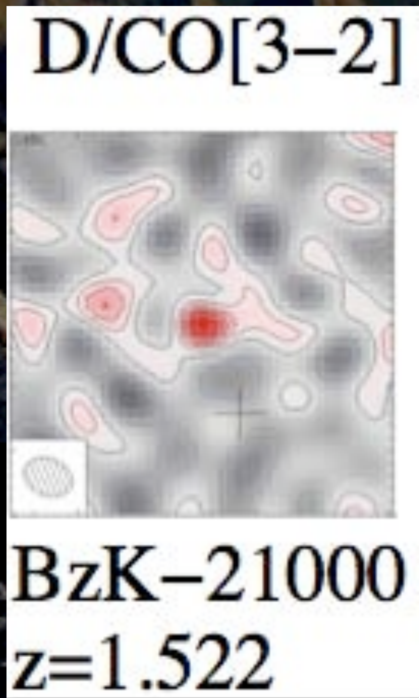
Similar to M82 nucleus

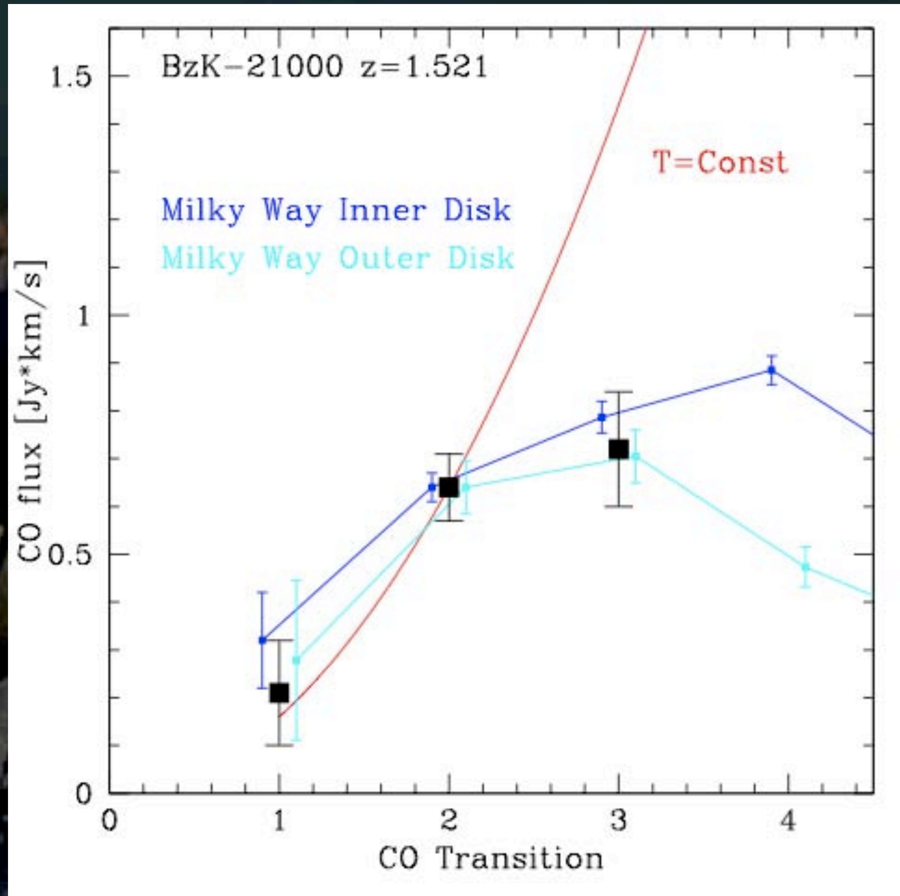
The gas density is high, probably merging driven



Secure detection of CO[3-2], 2 tracks

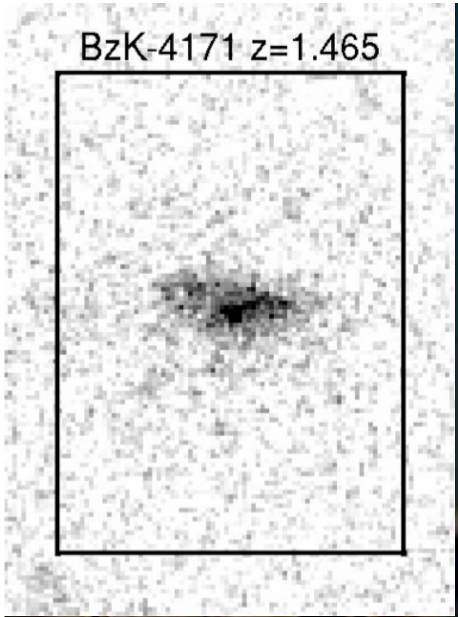
Milky Way type excitation





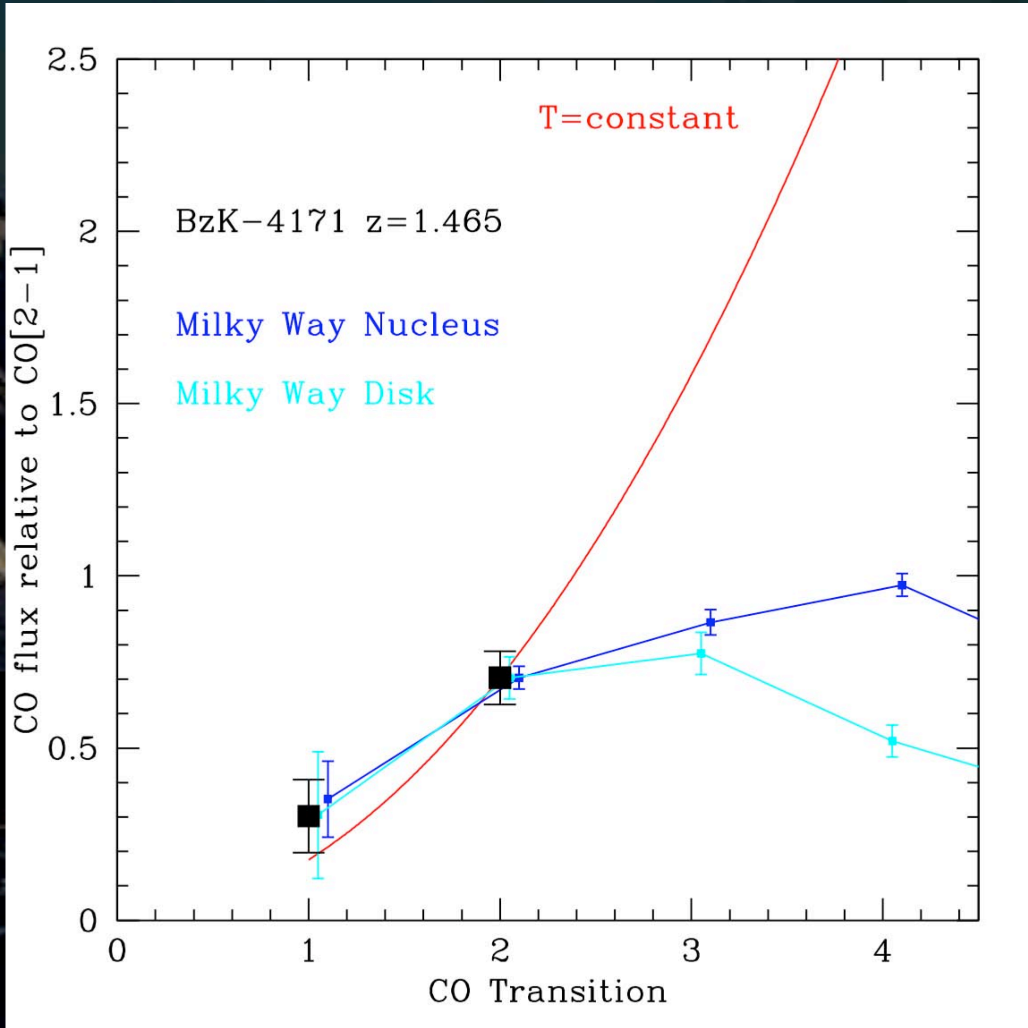
First MW-like cold CO SED ever seen at high-z

Dannerbauer et al., in preparation



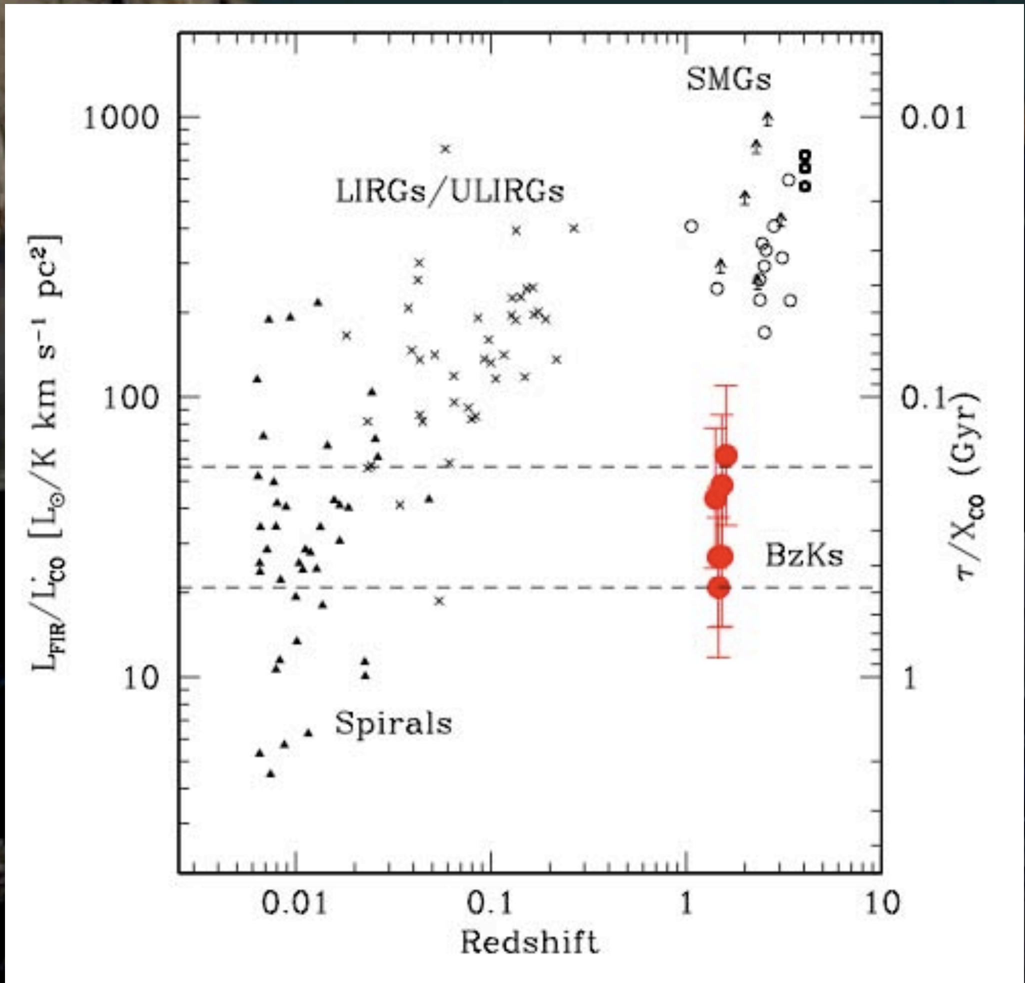
VLA CO[1-0] 3-sigma signal from BzK-4171

MilkyWay type excitation at least consistent



Overall, L'_{CO} from [1-0] is likely twice that from [2-1], as in MW

Star Formation Efficiencies

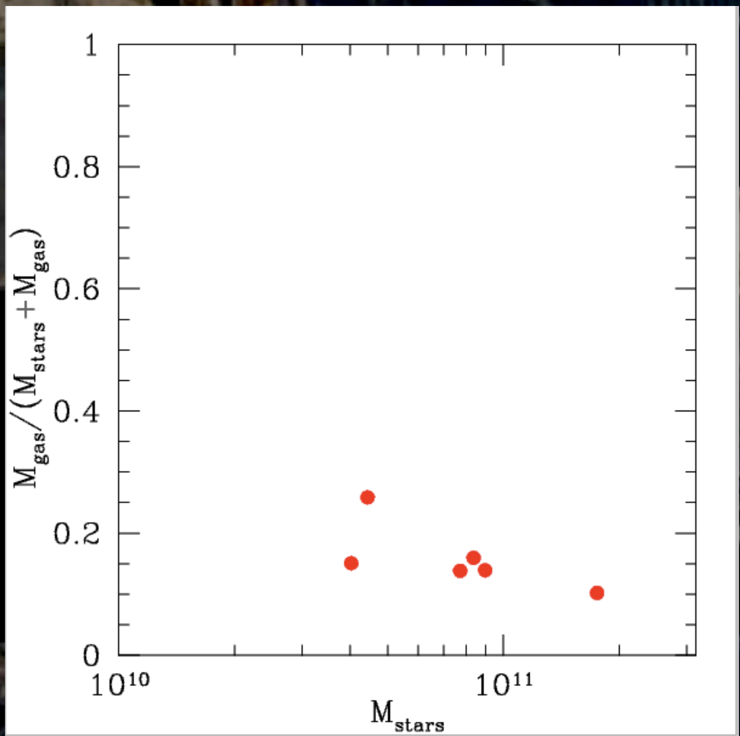


Applied x1.5 correction to CO[2-1] -> CO[1-0] based on SED

Median and scatter fully similar to local spirals and MW

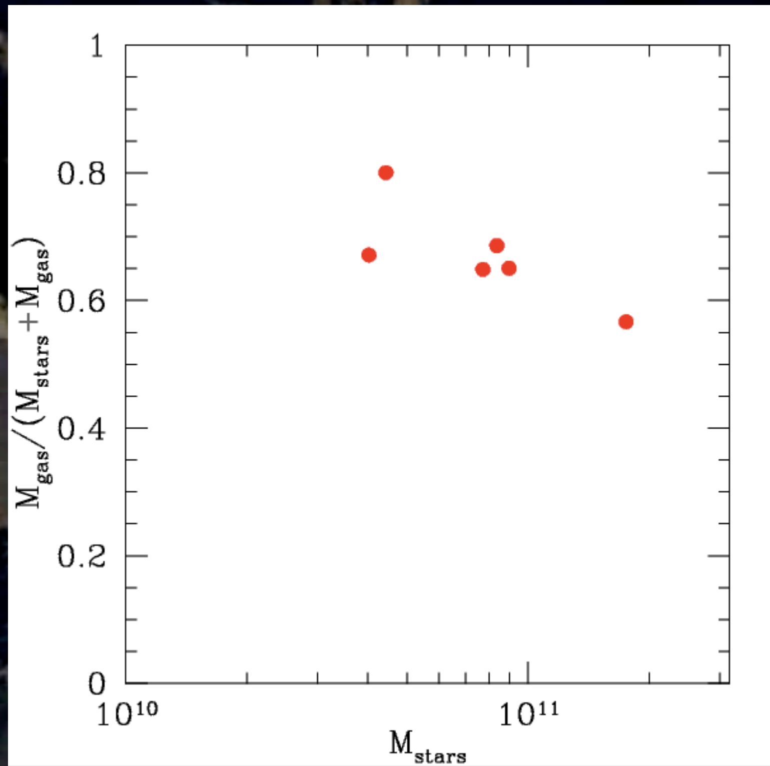
Implication for Xco, gas masses, gas fractions

X_{CO}=0.8   T1-0=T2-1



Mgas ~2x10^{10}Msun

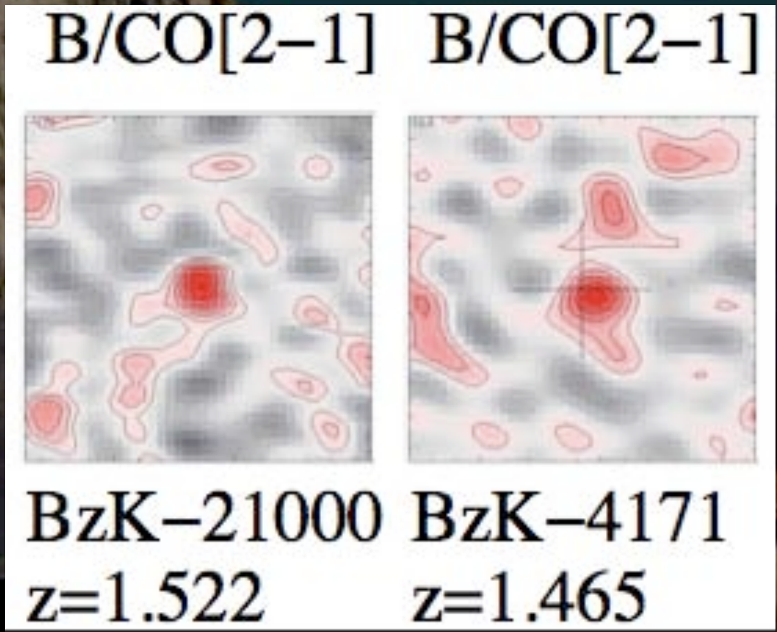
X_{CO}=4.6   T1-0=2xT2-1

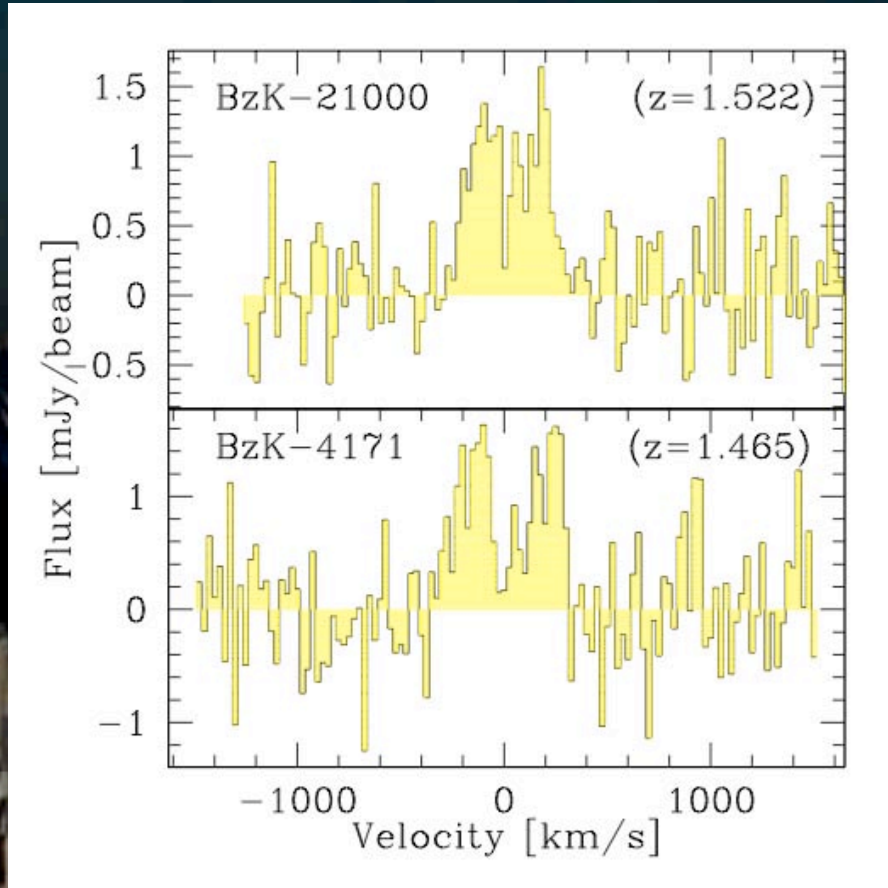


Mgas ~ 2x10^{11}Msun

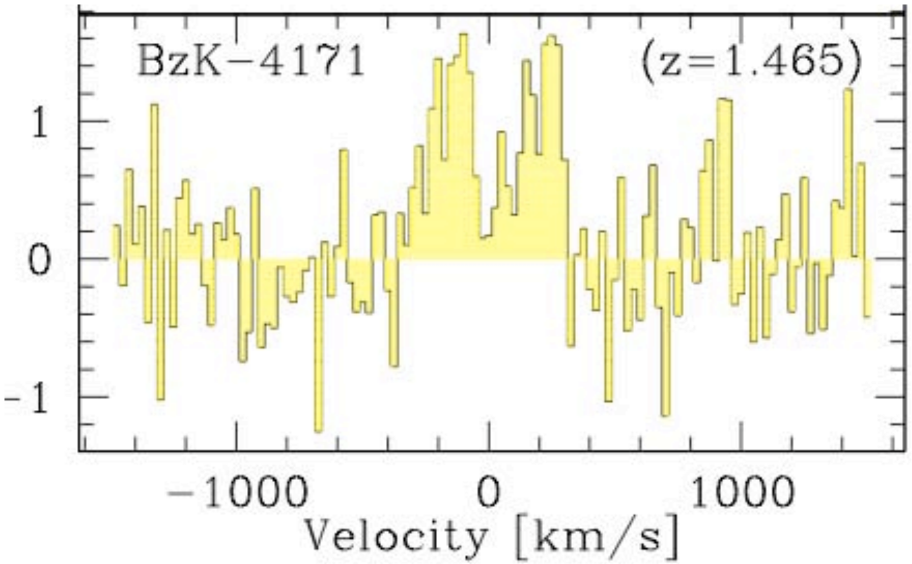
Extended PdBI configuration size estimates

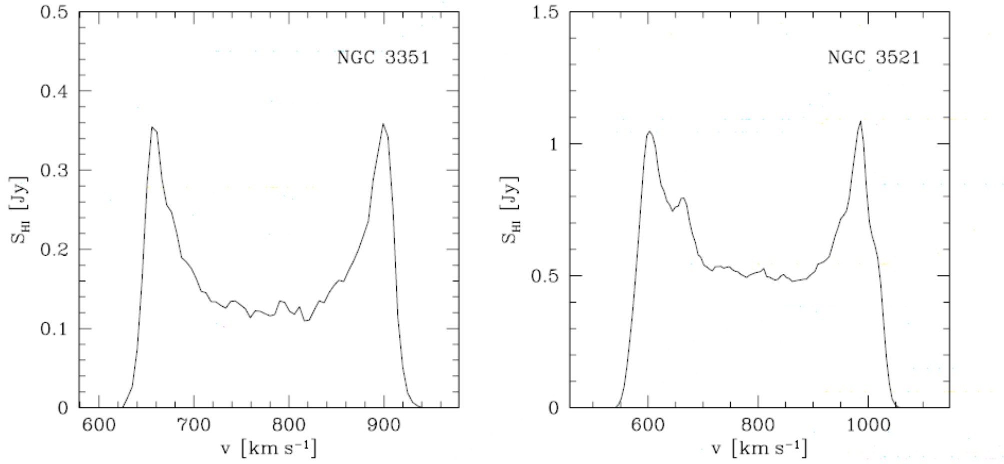
beam ~1.2” (B-conf)

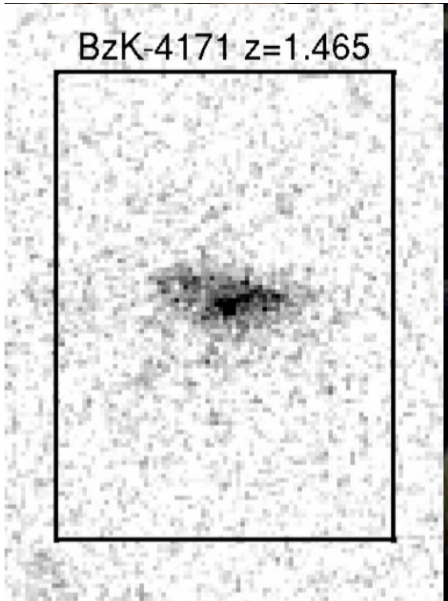




Fitting the uv-visibilities with circular Gaussian sources:
FWHM~1.5”+- 0.3”   --> radii ~ 6-7kpc (3 times larger than SMGs)
Spatially big gas reservoirs, never seen before at high-z
(SMGs median size ~2kpc, 10x larger SFR)







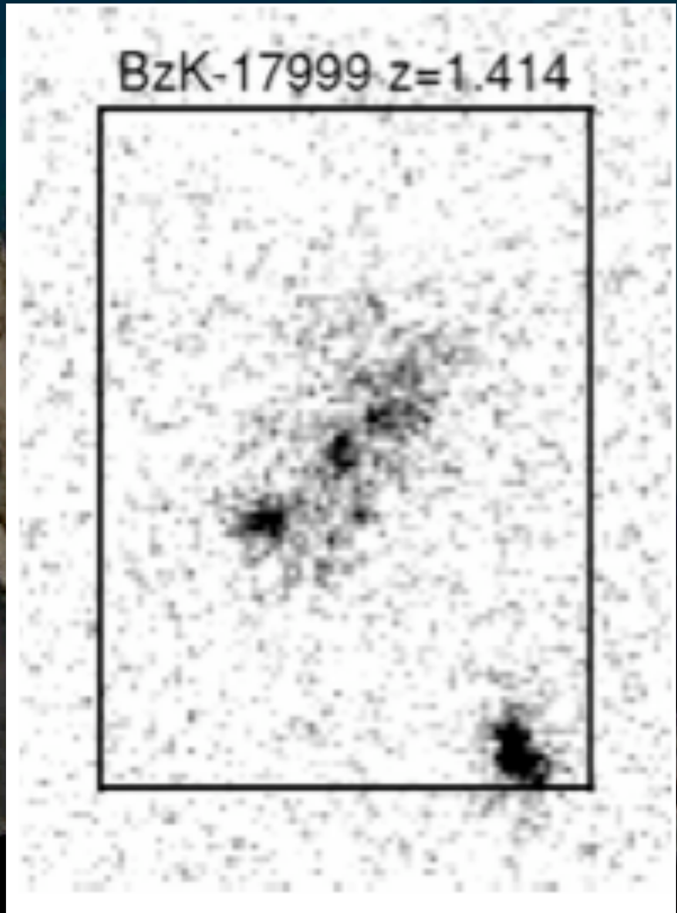
Delta-V = 620 km/s (total)

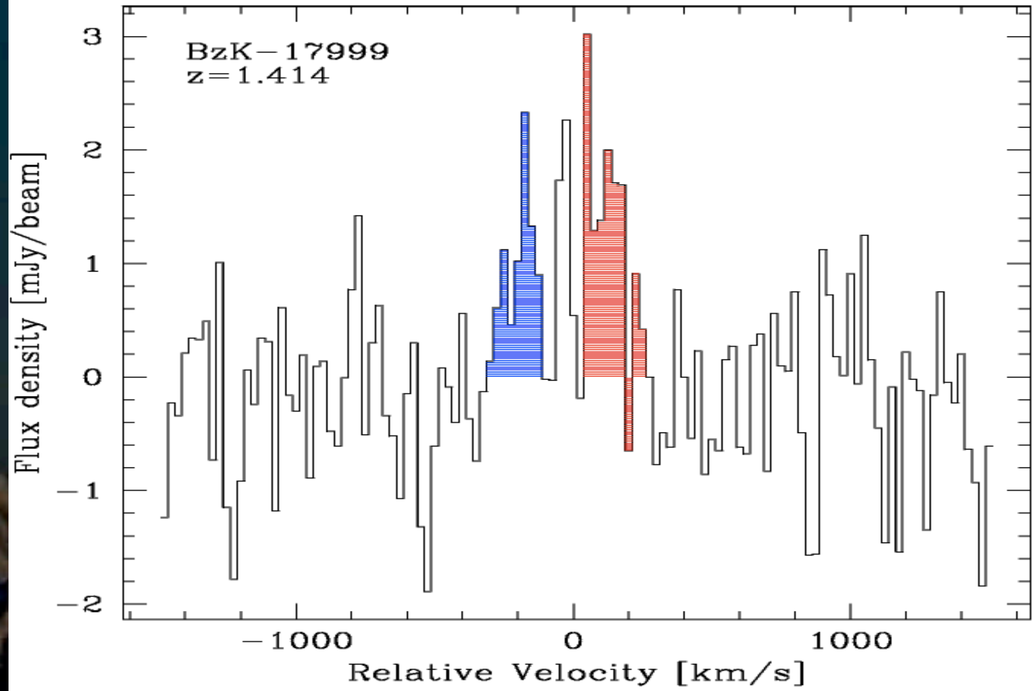
r = 5.8 kpc

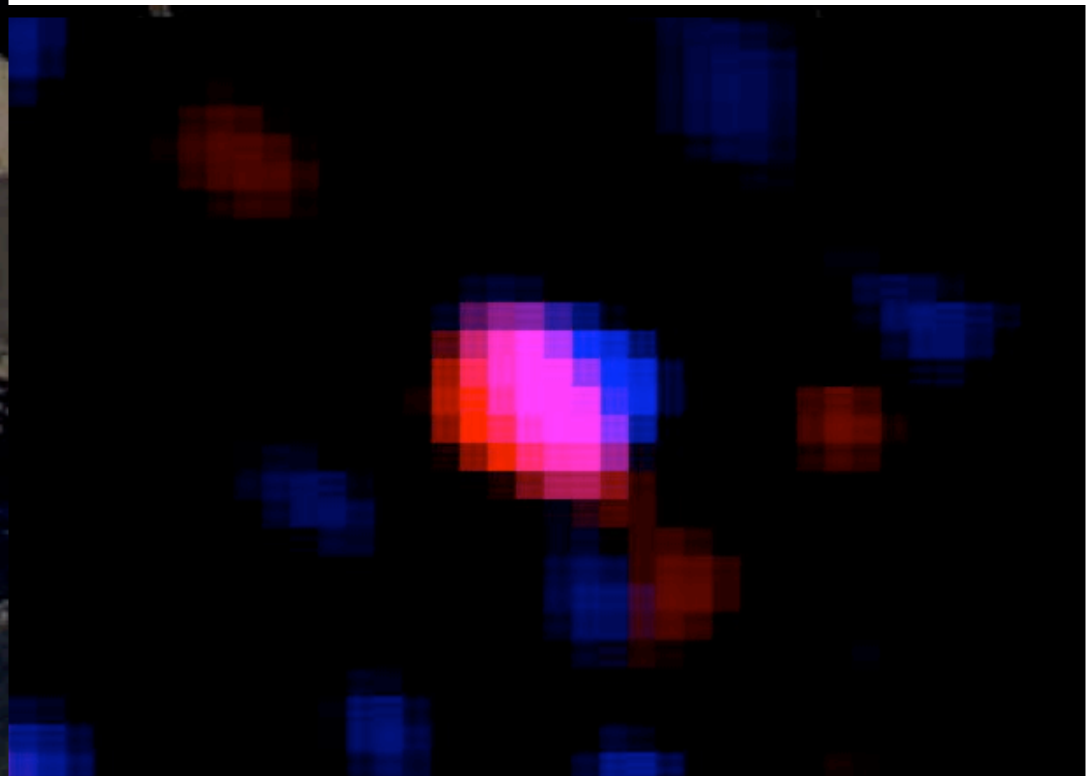
Mdyn = 1.3e11 Msun within 5.8 kpc

Mstar = 0.4e11 Msun (Chabrier IMF)

Mgas = 1.1e11 Msun (for X_CO = 4.6 (MW) and 1-0/2-1 = 1.3)



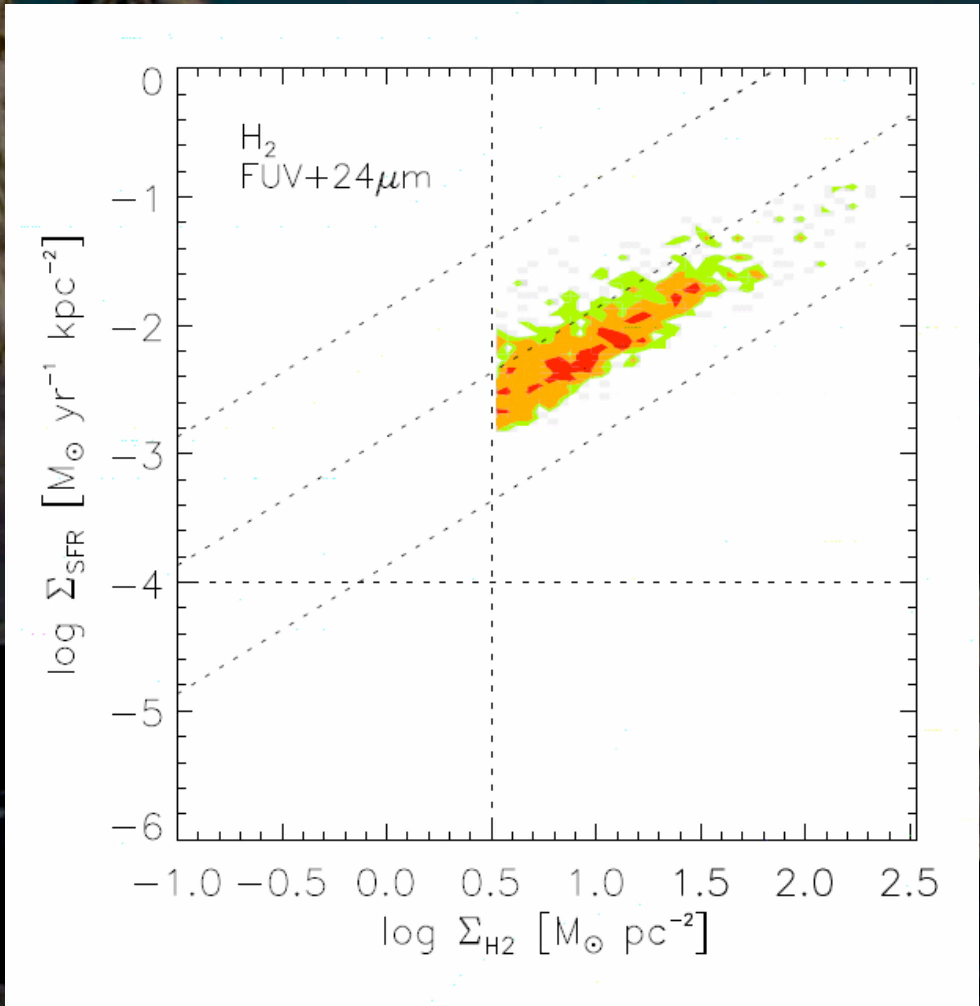




Consistent with rotation (5.5'' beam data)

Again, support space for huge Mgas ~10^11 Msun

How does this fit with the Schmidt law ?

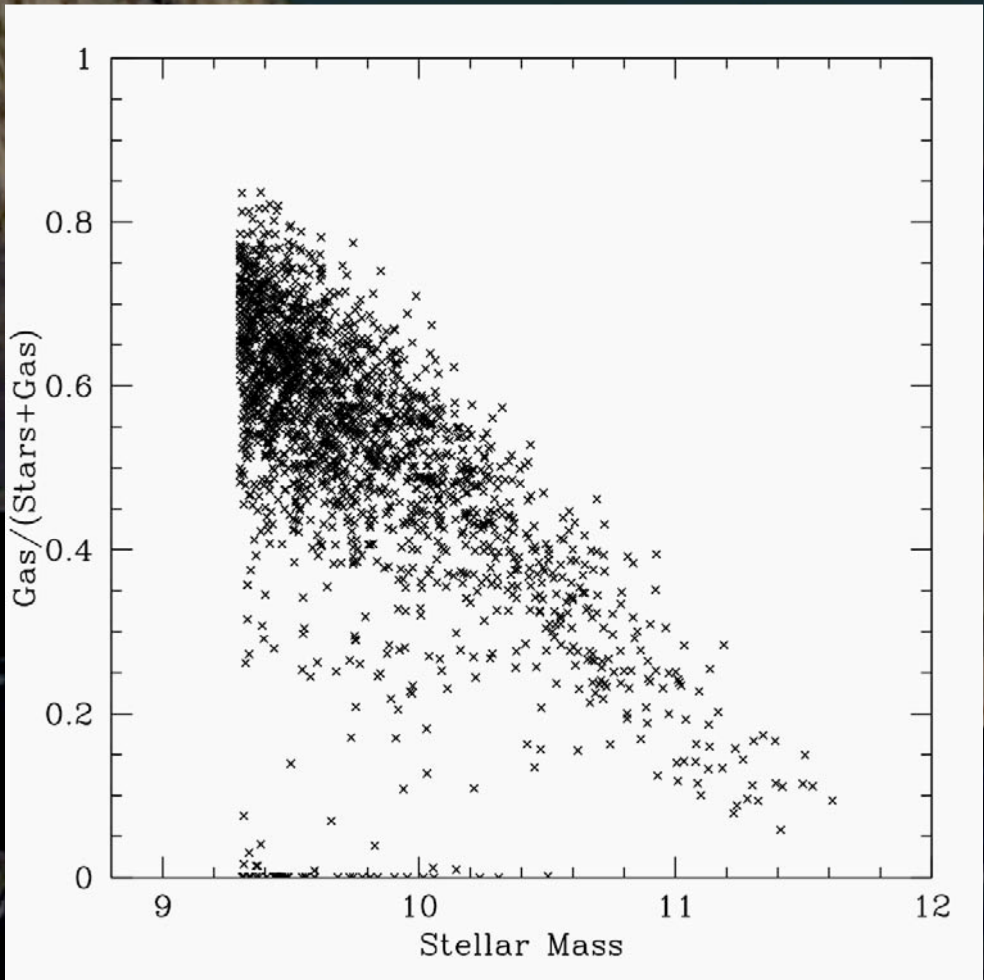


'Molecular gas SK law for spirals' is linear with SFE~1-2 Gyr

Agrees very well with our numbers if Xco is MW like

Bigiel et al 2008; THINGS survey

Molecular gas in normal high-z galaxies: input for disk formation models



Oppenheimer, Dave et al models

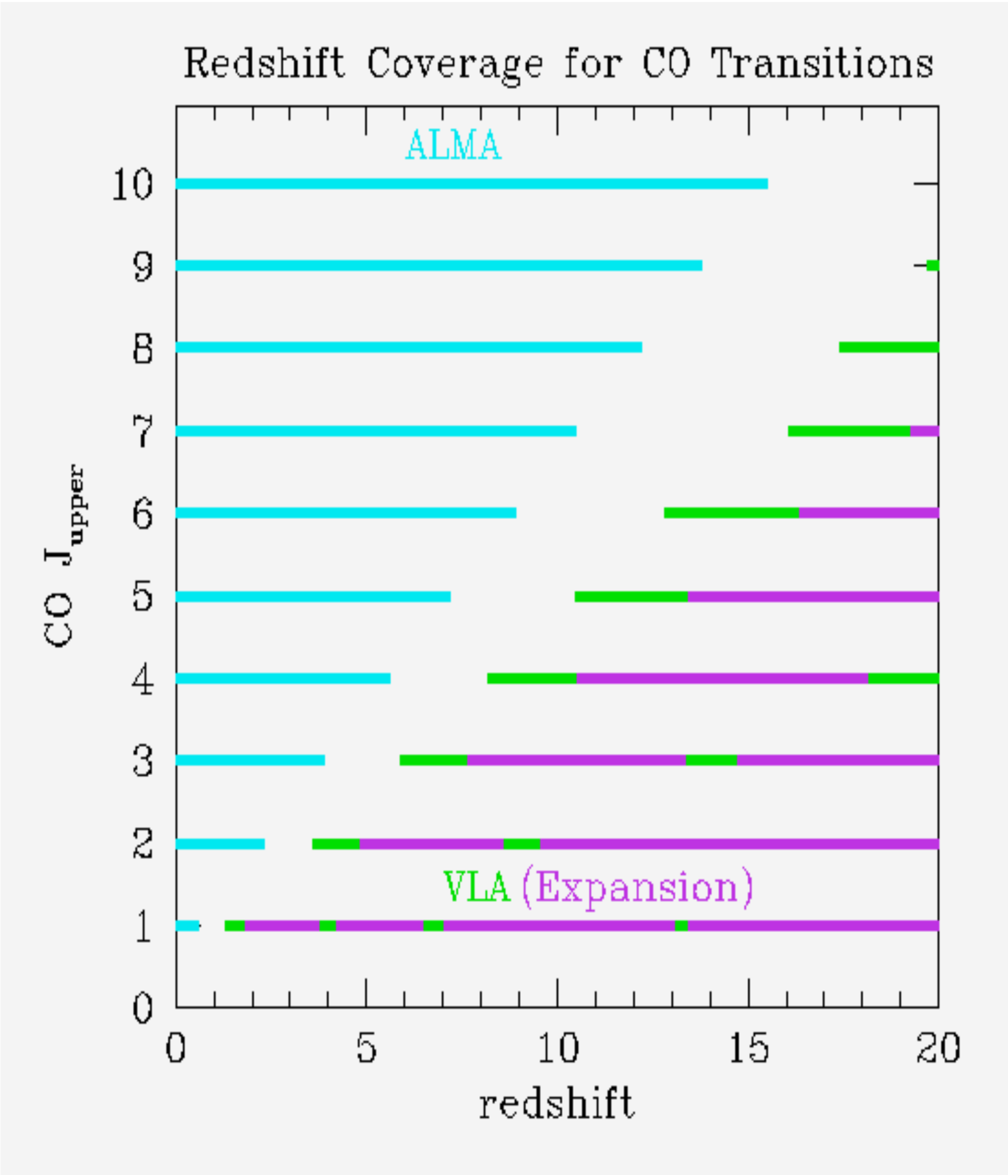
Cannot reproduce SFR/mass relation (invoke evolving IMF) (too low SSFR by x2-3)

Gas fractions are likely also substantially low

(but trend SFR/mass qualitatively well predicted, possibly also gas fraction trend)

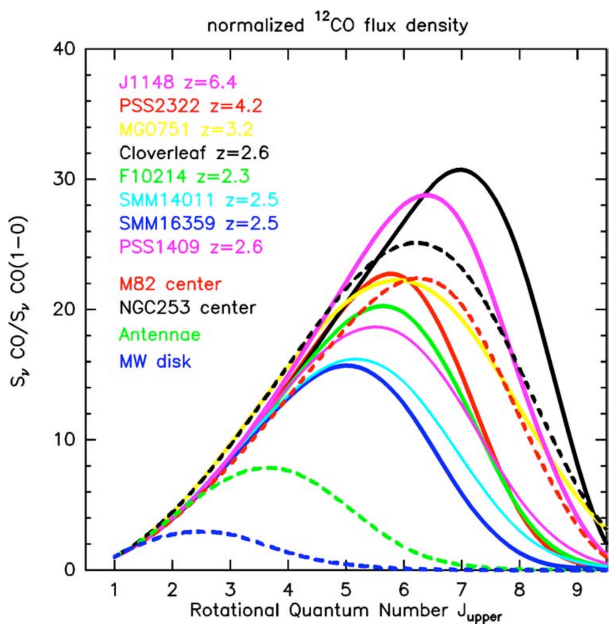
More in general:
How did the gas came there ?
Why is it not rapidly consumed ?

Great news for ALMA (lots of gas) But…focus on mm/submm

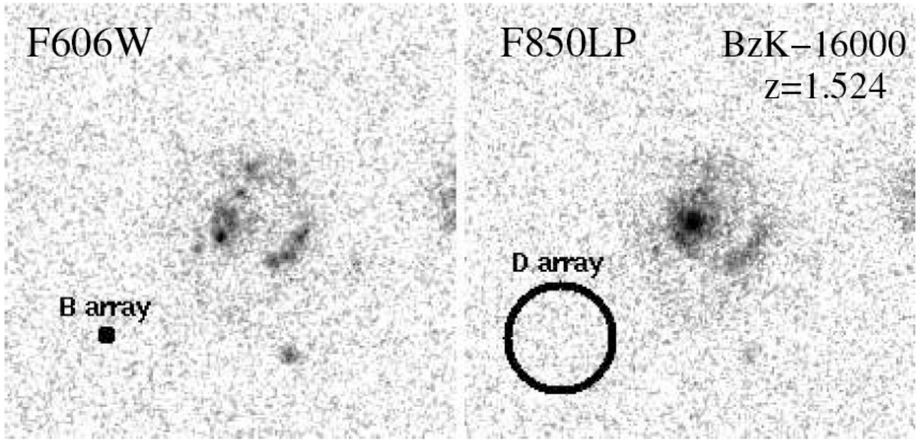


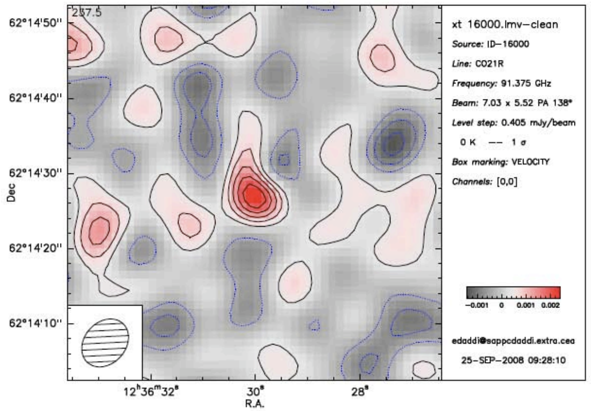
Limited to high-J transition for very high redshift

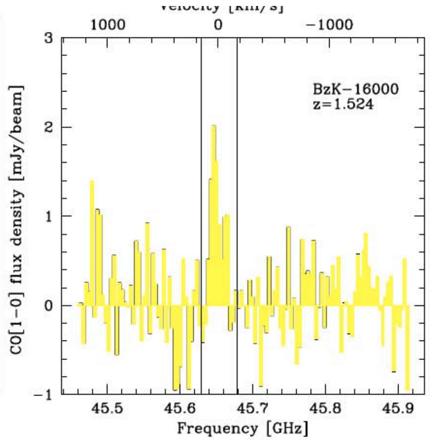
If cosmic reionization sources are cold as the BzK galaxies we might largely miss them



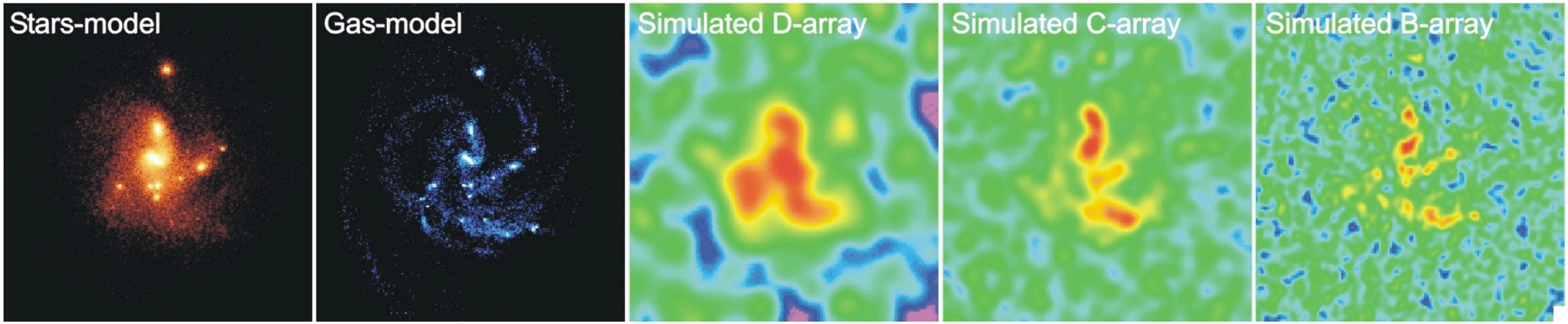
Great news for VLA/EVLA





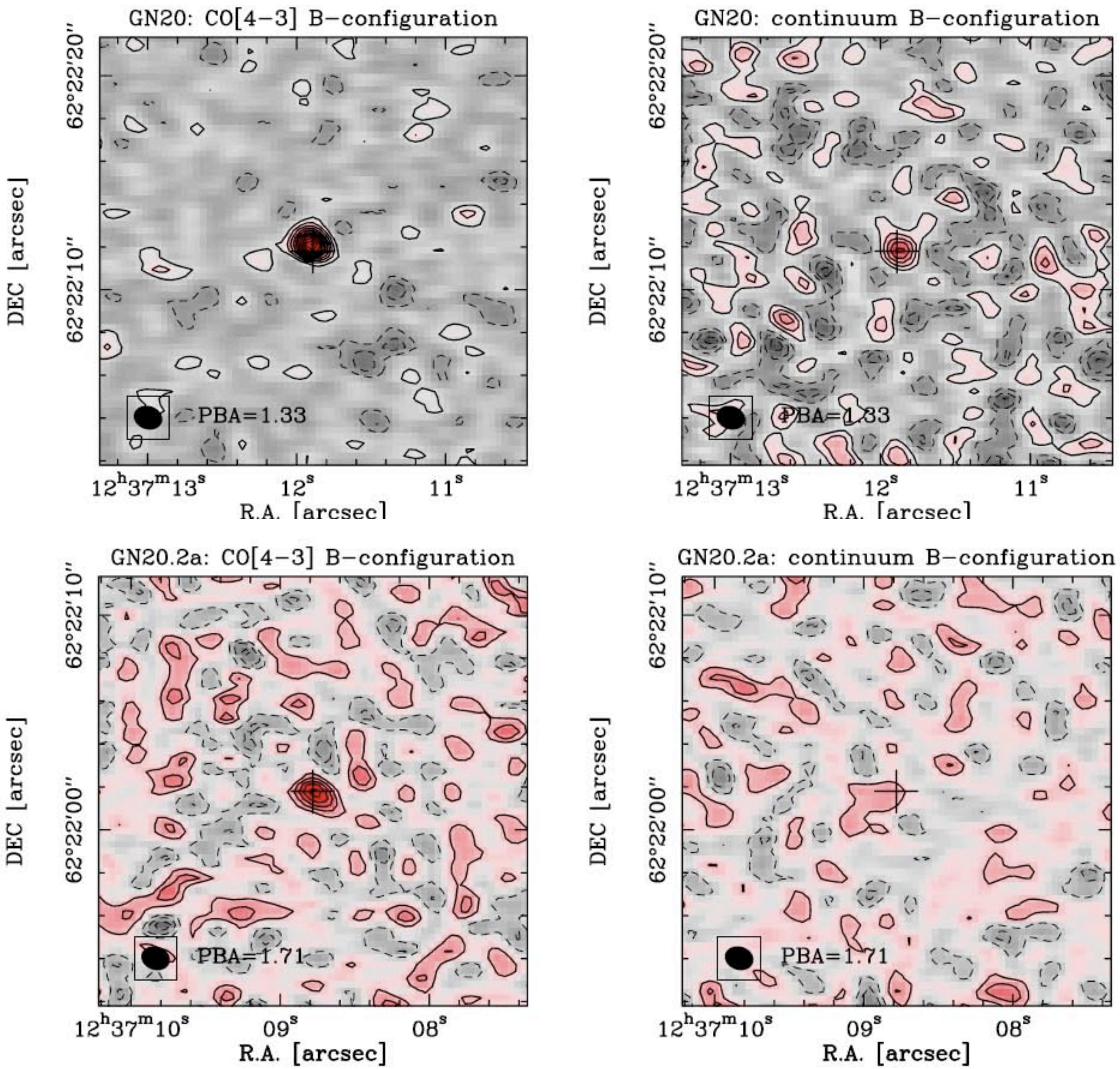


Bournaud, Elmegreen & Elmegreen 2007 clumpy disk model simulation



Already, we could study the molecular gas at 0.15'' resolution!

Little surprise while observing BzK-21000



In the same observations: serendipitous CO detections:

GN20 z=4.055

GN20.2 z=4.051

Daddi et al
arXiv:0810.3108

Conclusions (given present evidence…)

- massive z~1.5 SF galaxies are virtually all gas rich
- SFE are low, milky-way like --> secular evolution
- gas excitation is Milky-Way like (1-2 sources only…)
- molecular gas fraction must be at least 40-50%
- ULIRGs can stay active for cosmological timescales
- gas is distributed galaxy wide (not compact mergers)
- SSFR, SFE, gas density, excitation different from SMGs

These look like spirals, with ULIRG level SFRs…

Galaxies with similar properties never seen before at high-z, but this is likely how most high-z galaxies are

Powerful new window of research for galaxy formation and evolution at high-z that we were lucky to open up