Massive galaxy (and black hole) formation in the early Universe

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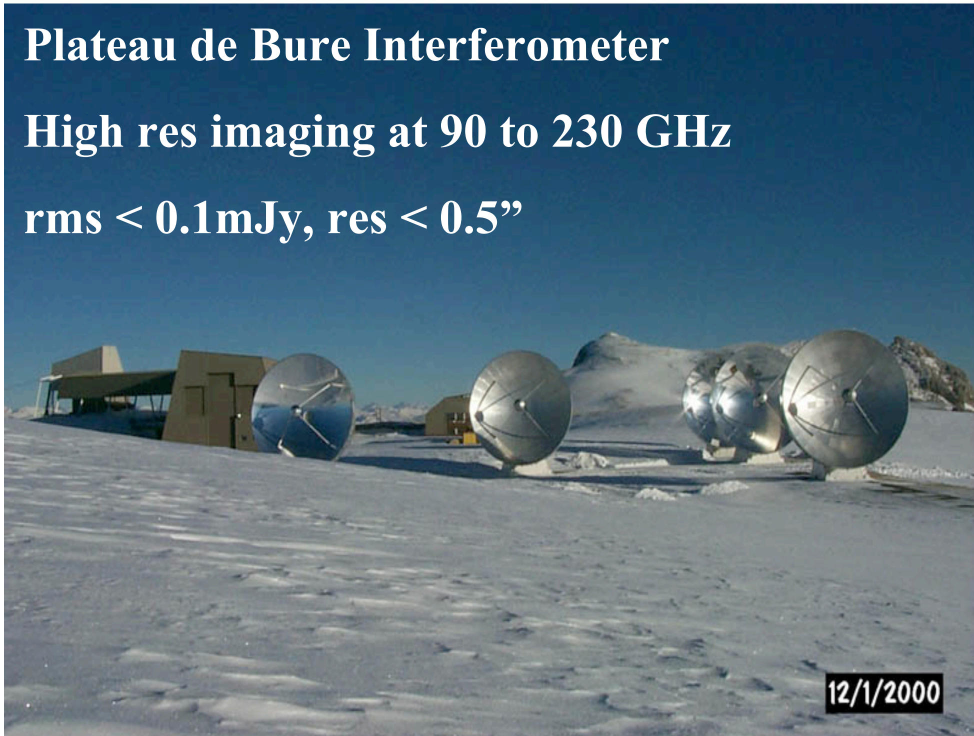
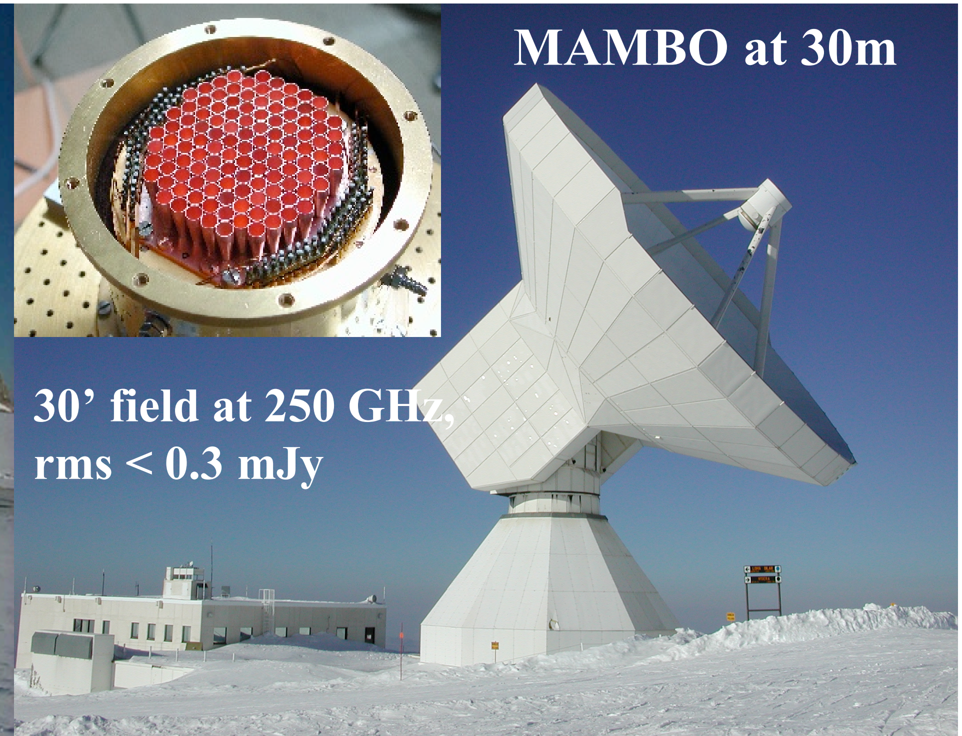
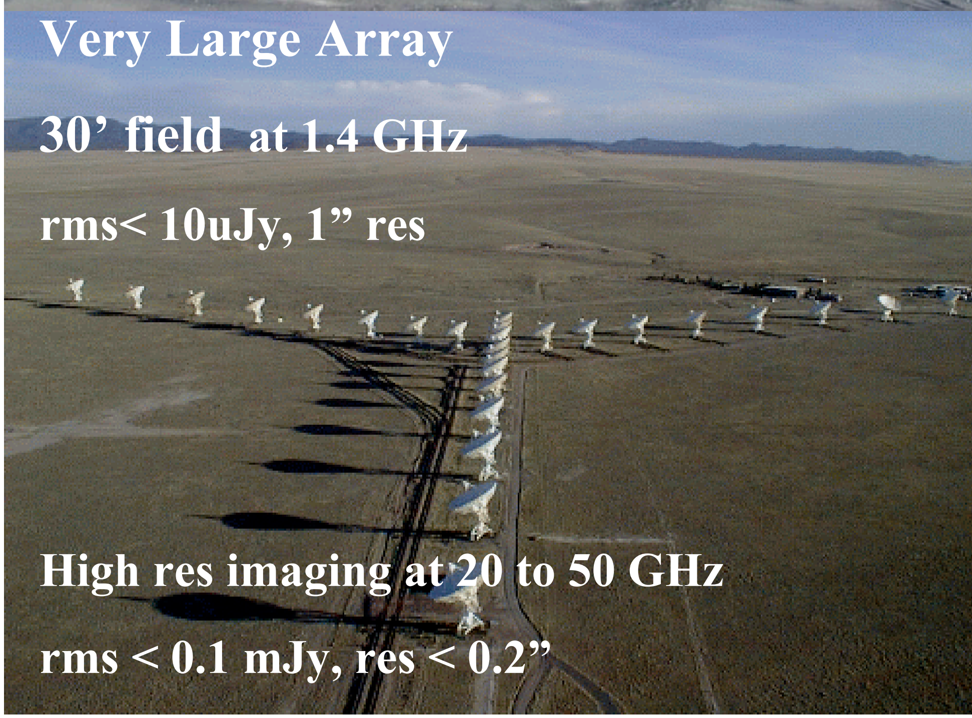
Berkeley, February 10, 2009

- Intro: telescopes, techniques, massive galaxies, and quasars
- Massive galaxy and SMBH formation within 1 Gyr of the Big Bang: gas, dust, and star formation in quasar host galaxies at z~6
- Future: probing normal galaxy formation with the next generation telescopes
- [sBzK galaxies: the 'dawn of downsizing' during the epoch galaxy assembly (z ~ 2)]

Collaborators: Ran Wang, Walter, Menten, Cox, Bertoldi, Omont, Strauss, Fan, Wagg, Riechers, Neri







Pushing back to first galaxies

- **Spectroscopic imaging of molecular gas, fuel for star formation in galaxies: gas mass, ISM conditions, dynamics**
- **Fine structure lines: dominant ISM gas coolant**
- **Dust + synchrotron imaging: cm-to-mm SEDs => obscuration-free star formation rates, ISM conditions, AGN**

Massive galaxy and SMBH formation at z~6: gas, dust, and star formation in quasar hosts

Why quasar hosts?

- Spectroscopic redshifts
- Extreme (massive) systems

  $M_B < -26 \Rightarrow$

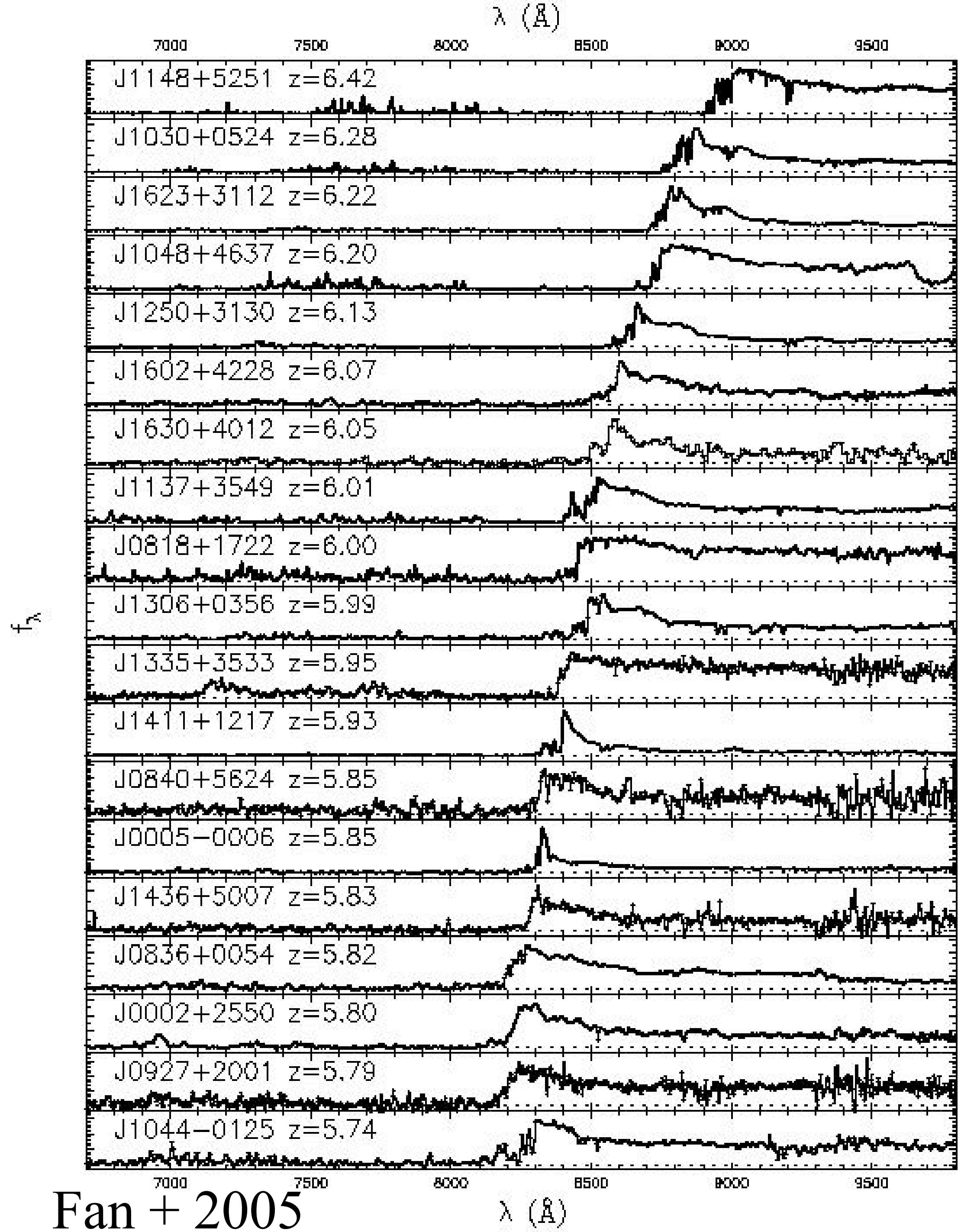
  $L_{bol} > 1e14\ L_o$

  $M_{BH} > 1e9\ M_o$

- Rapidly increasing samples:

  z>5: > 100

  z>6: > 20

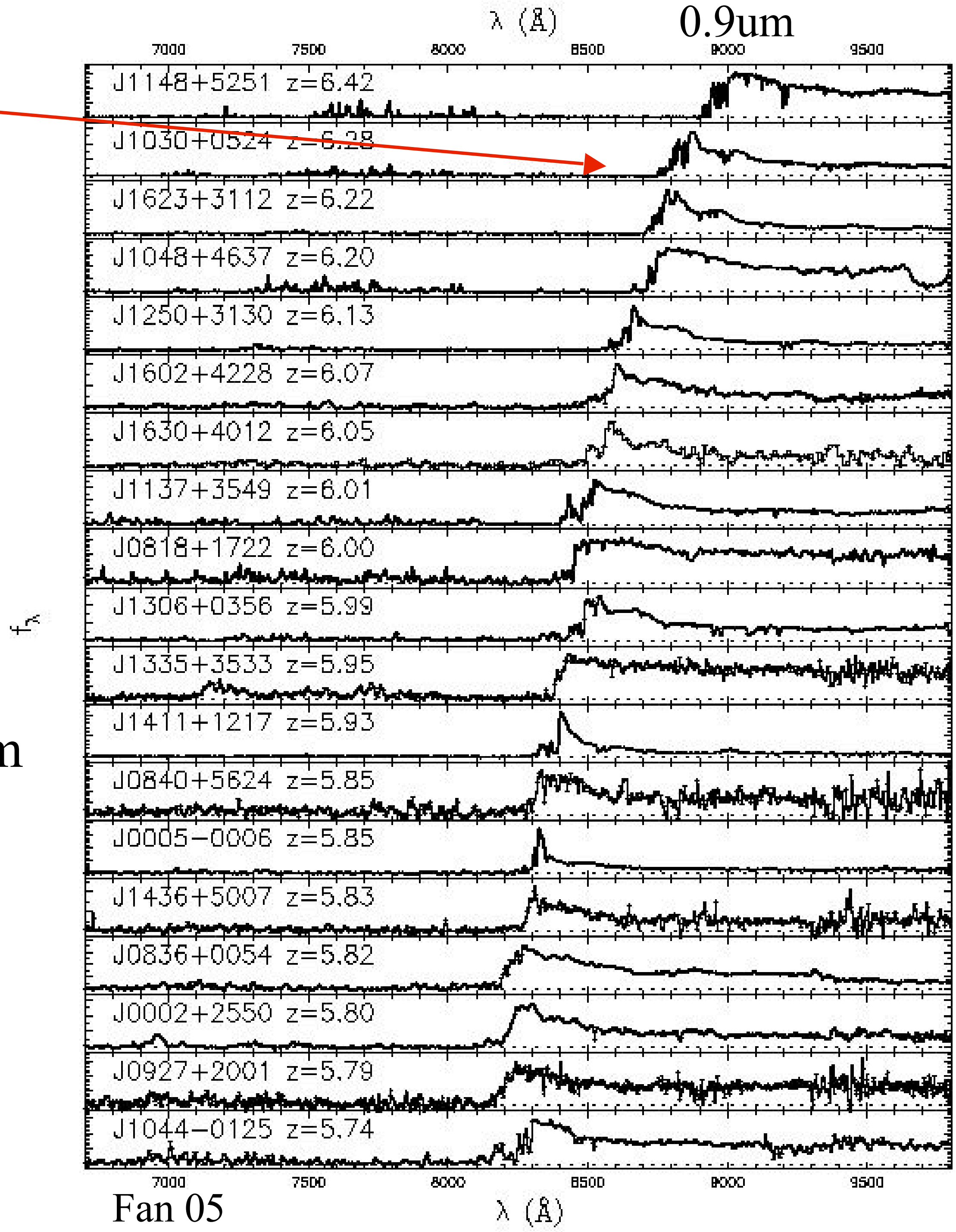


Fan + 2005

Gunn-Peterson effect toward z~6 SDSS QSOs

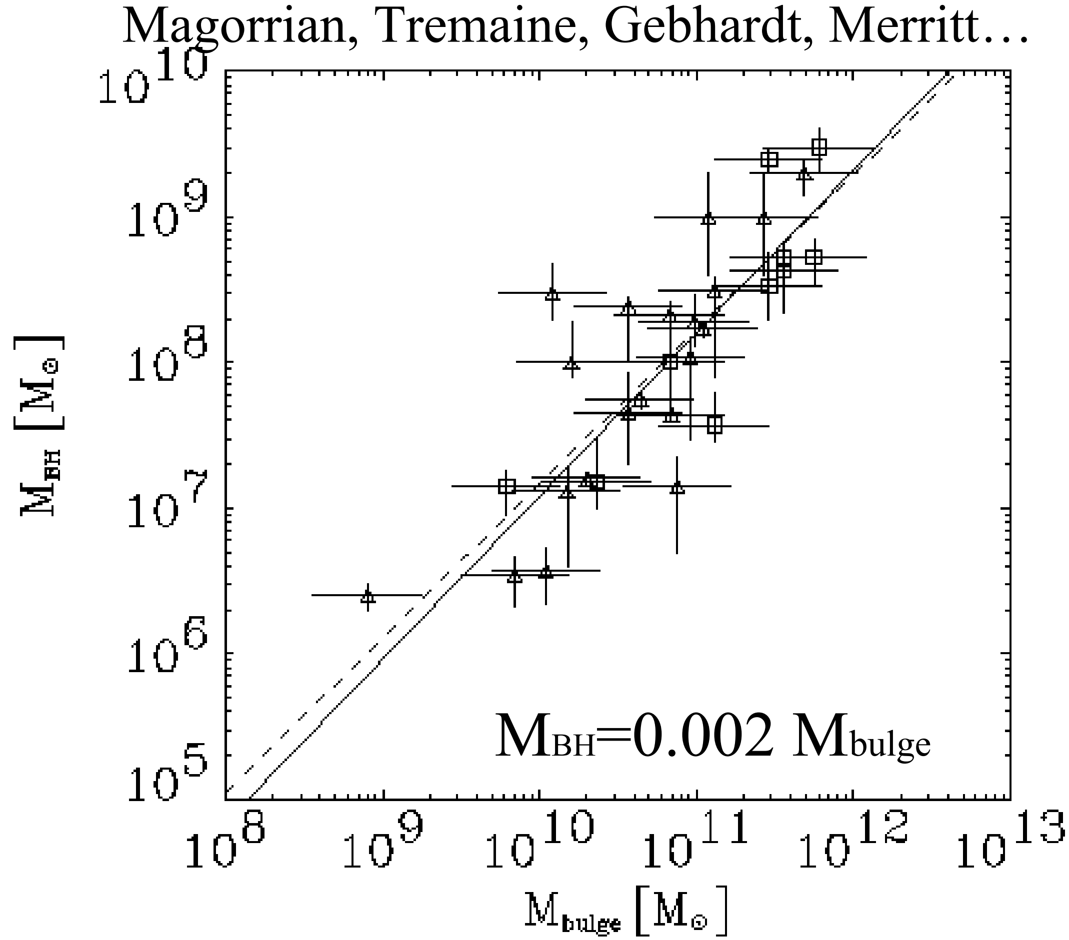
▪Pushing into the tail-end of cosmic reionization => sets benchmark for first luminous structure formation

▪GP effect => study of 'first light' is restricted to λ_{obs} > 1um



Fan 05

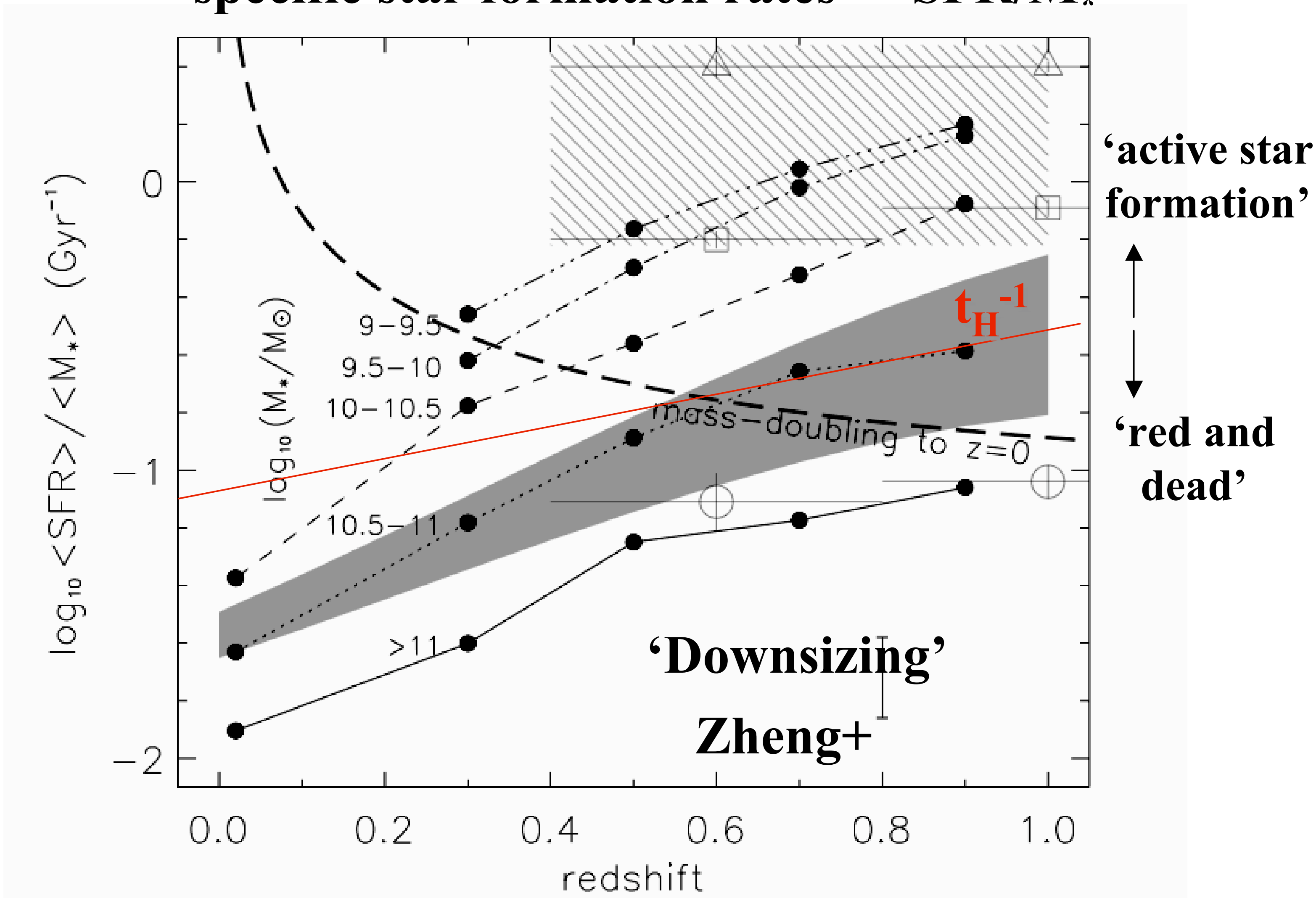
QSO host galaxies – M_{BH} -- M_{bulge} relation



- Most (all?) low z spheroidal galaxies have SMBH
- 'Causal connection between SMBH and spheroidal galaxy formation'
- Luminous high z QSOs have massive host galaxies (1e12 $M_\odot$)

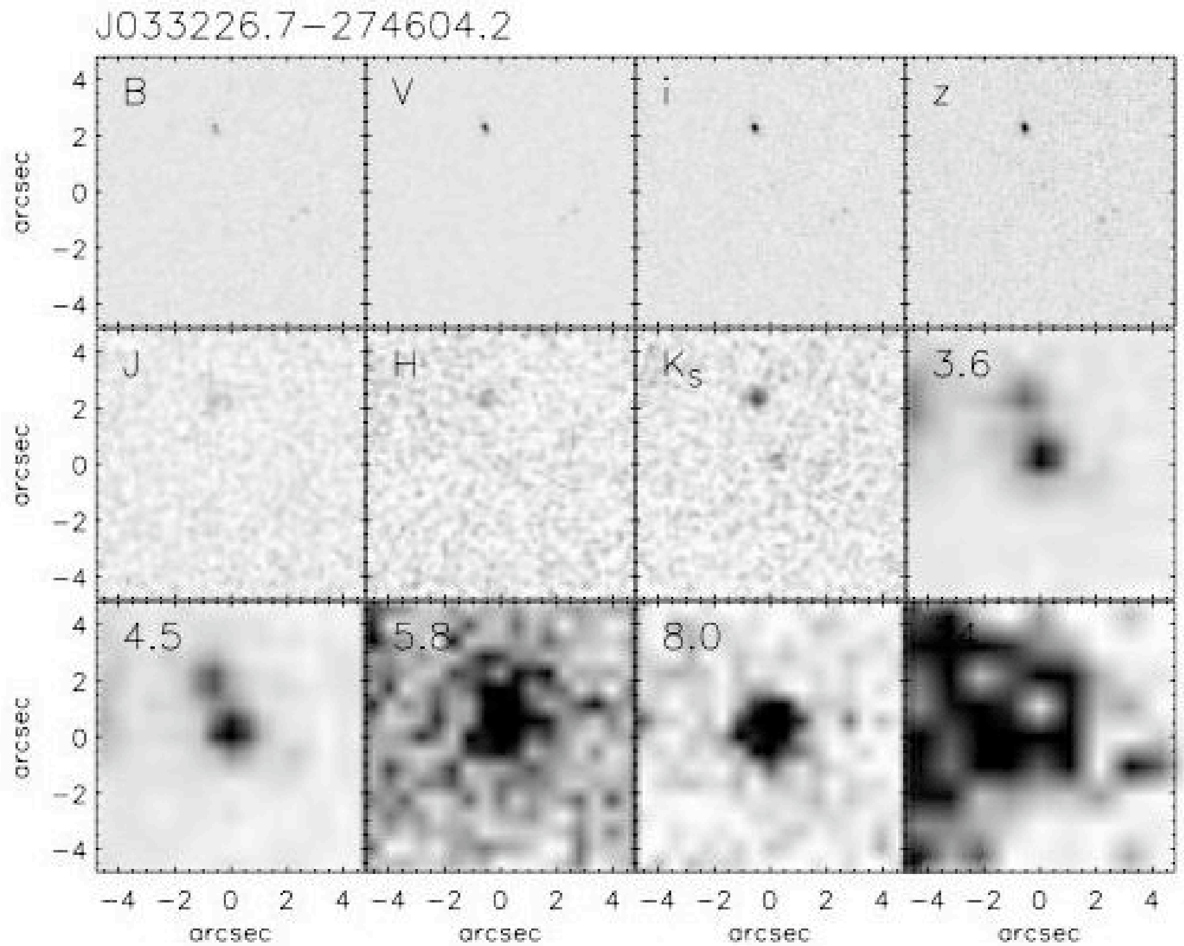
Galaxy formation as function of M_*

'specific star formation rates' = SFR/M_*



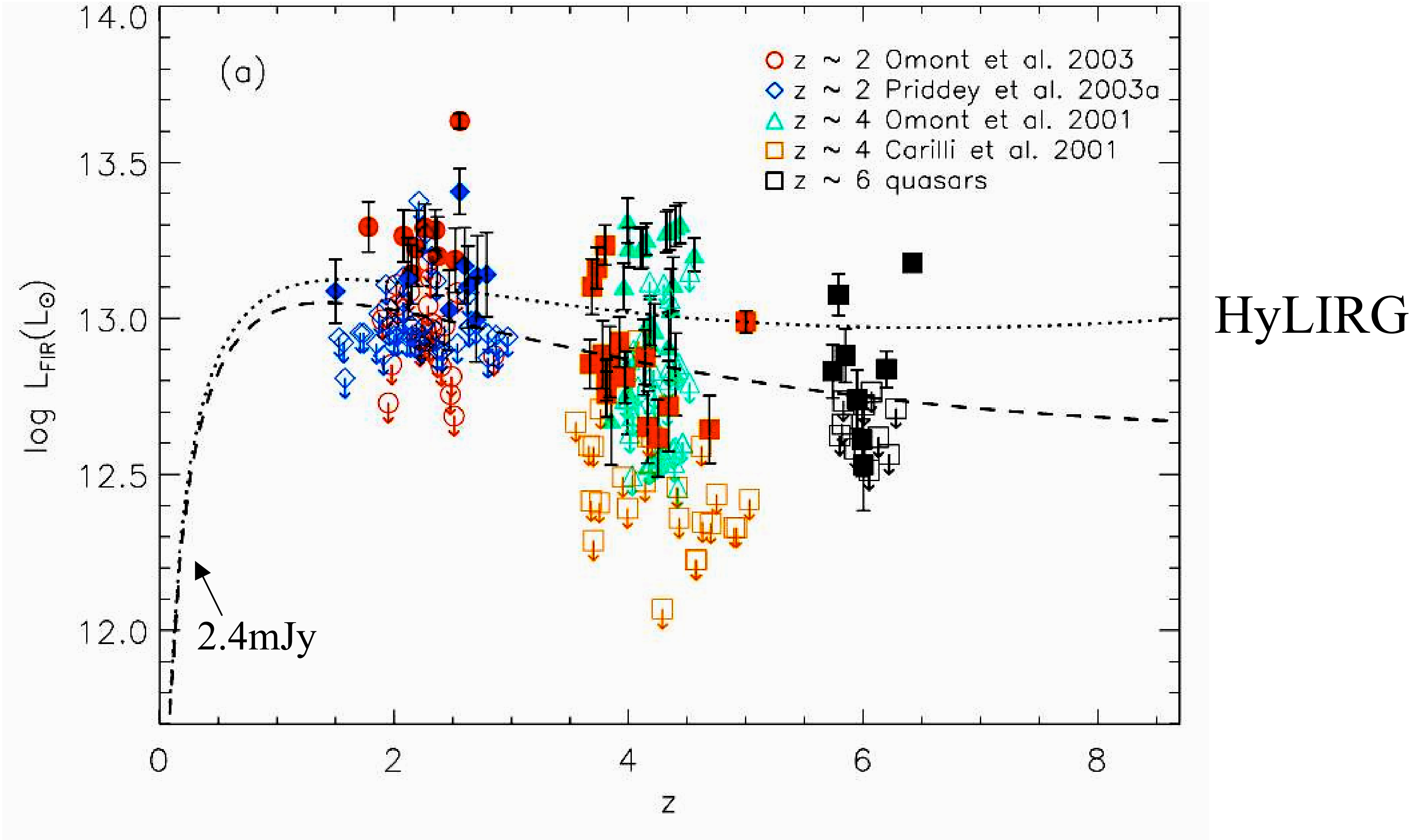
=> Massive galaxies form most of their stars at high z

Old, massive galaxies at high redshift: $z_{form} > 10$? Wiklind et al.



$M_* = 2e11\ M_o$, z=5.2, age = 1Gyr

MAMBO 250 GHz surveys of z>2 QSOs

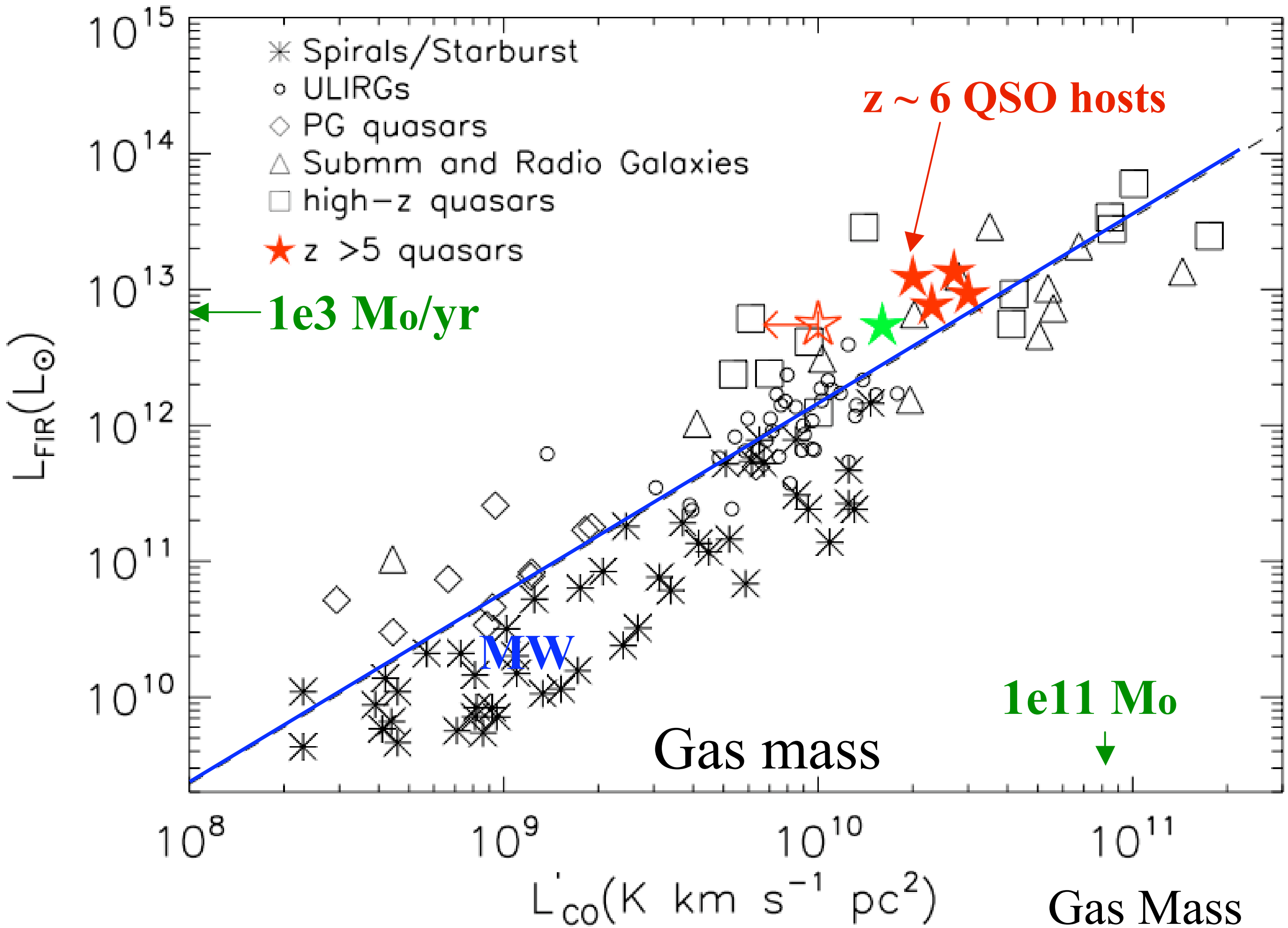


• 1/3 of luminous QSOs have S_{250} > 2 mJy, *independent of redshift* from z=1.5 to 6.4

• L_{FIR} ~1e13 L_o ~ 0.1 L_{bol}: Dust heating by starburst or AGN?

Dust => Gas

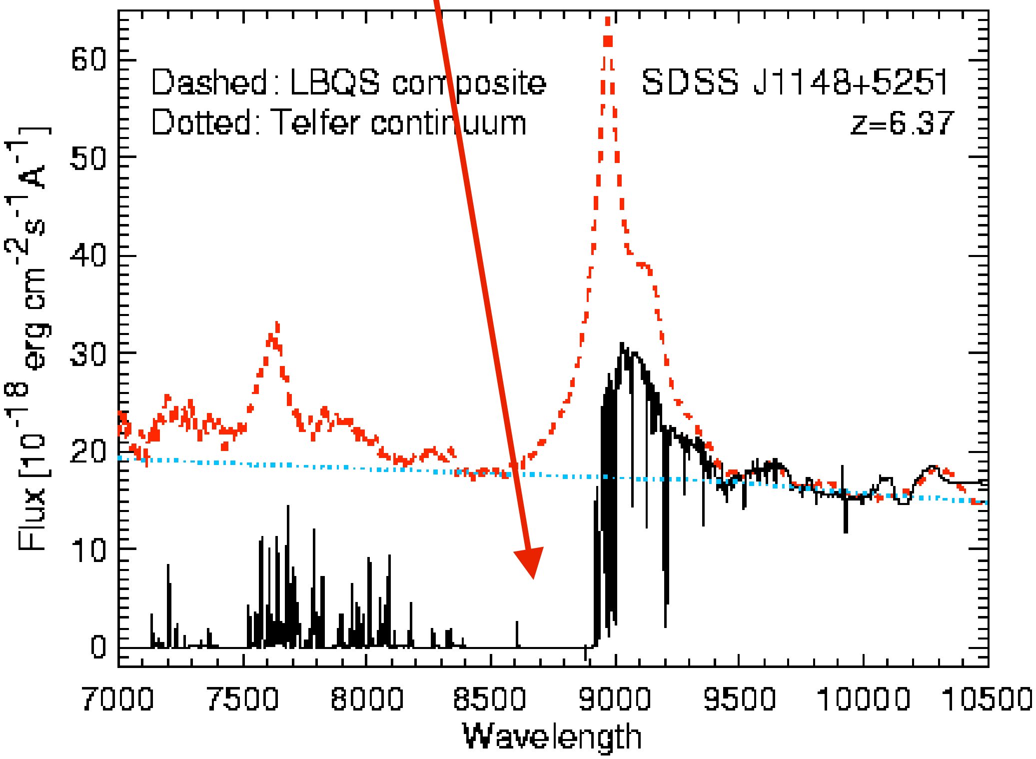
Star formation rate

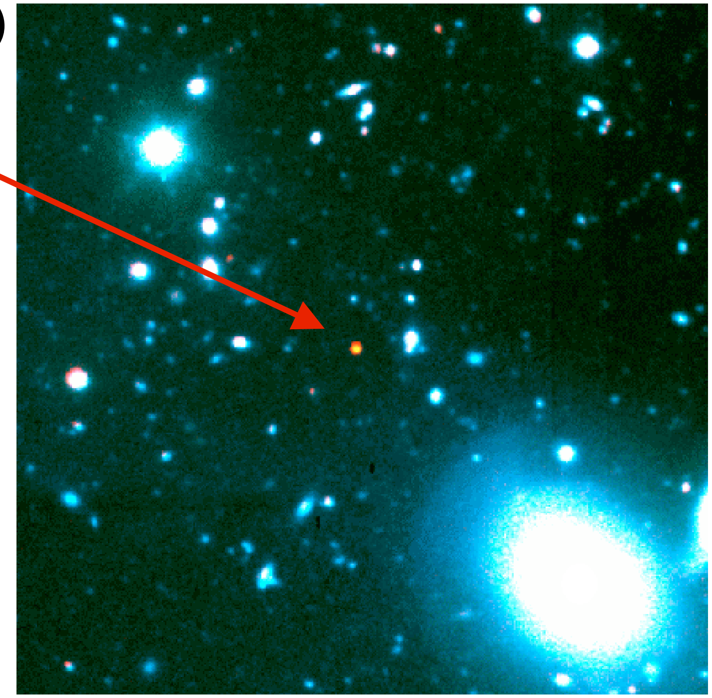


- Massive gas reservoirs > 10^{10} M_o
- SFR > 1000 M_o/yr
- Detect dust ~ 1hr, CO in 10hr

Pushing into reionization: Host galaxy of J1148+5251 at z=6.42

- Highest redshift SDSS QSO (t_{univ} = 870Myr)
- L_{bol} = 1e14 L_o
- Black hole: ~3 x 10^9 M_o (Willot etal.)
- Gunn Peterson trough (Fan etal.)



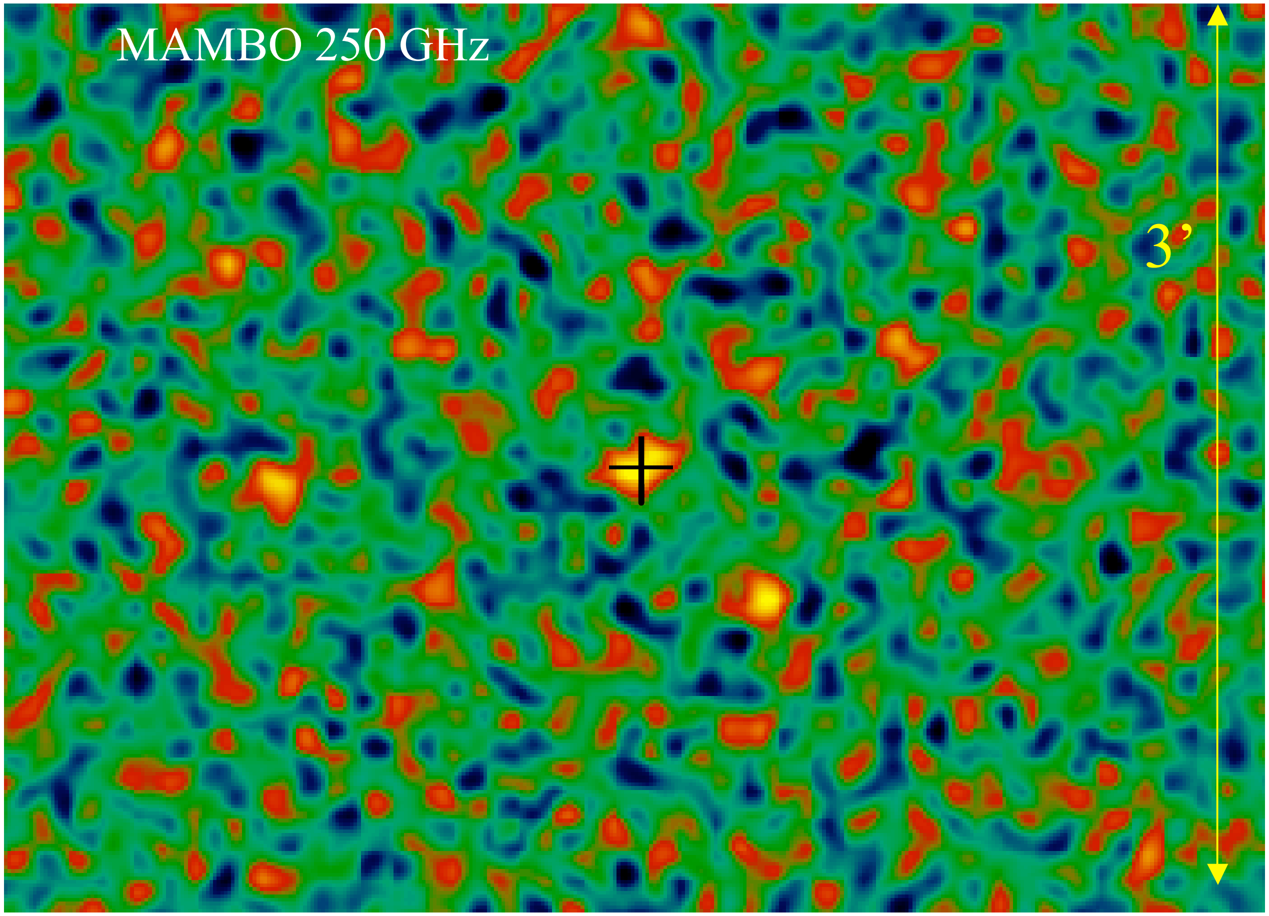


1148+52 z=6.42:
Dust detection

S_{250} = 5.0 +/- 0.6 mJy

L_{FIR} = 1.2e13 L_o

M_{dust} =7e8 M_o



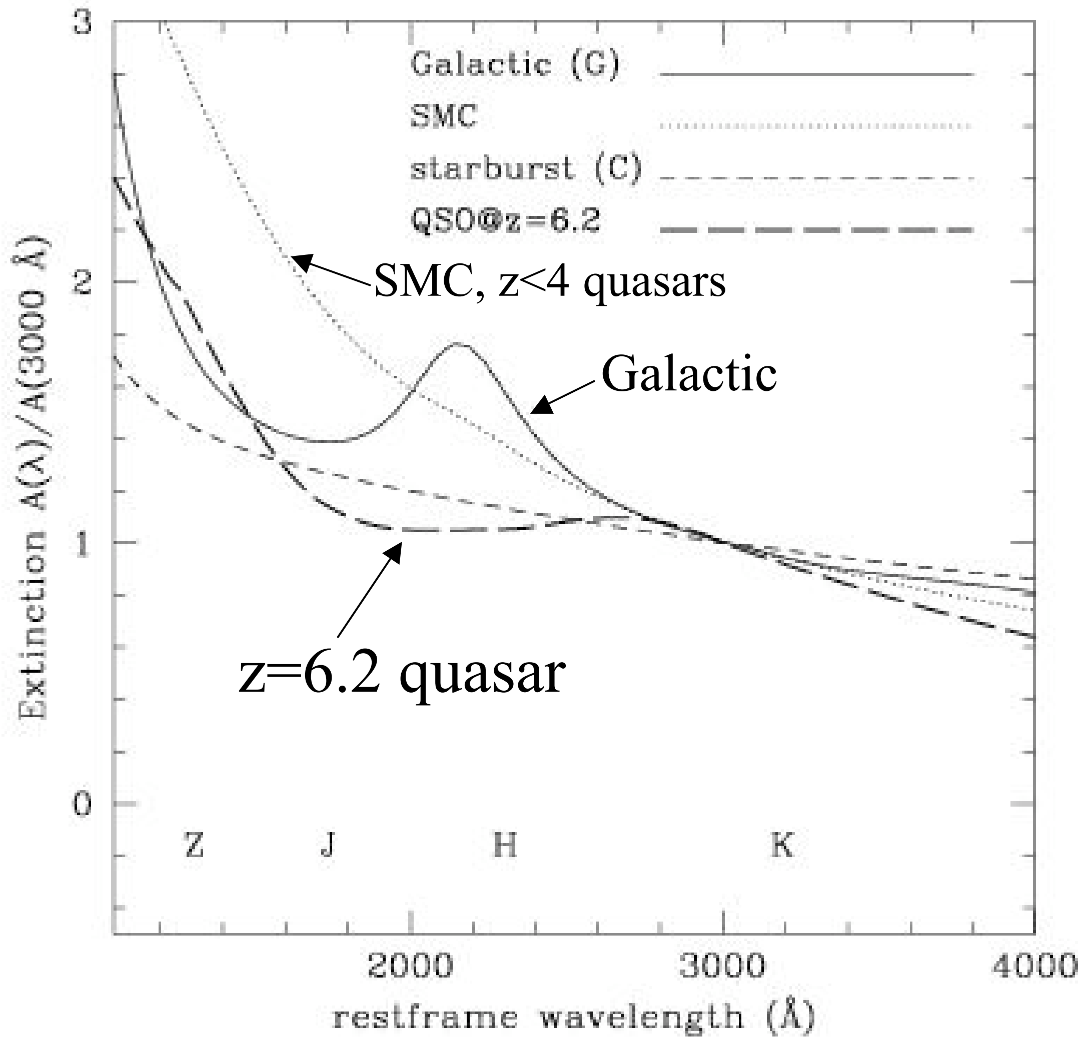
Dust formation?

AGB Winds ≥ 1.4e9yr > t_{univ} = 0.87e9yr

=> dust formation associated with high mass star formation?

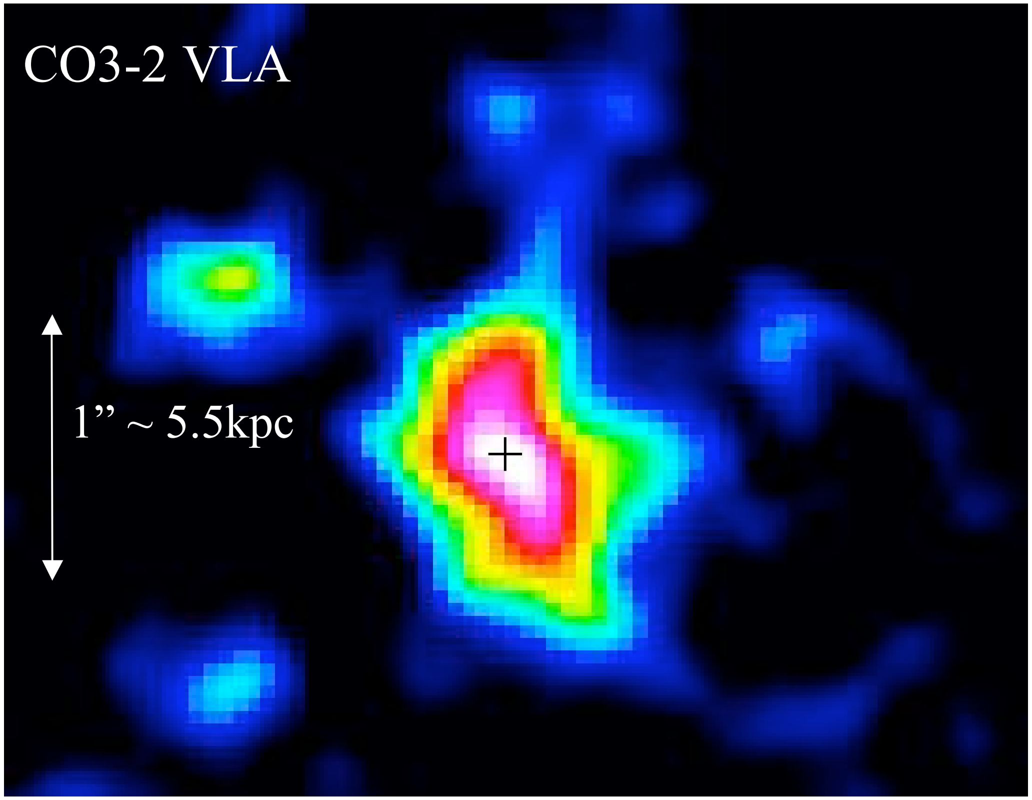
Dust formation at t_{univ}<1Gyr

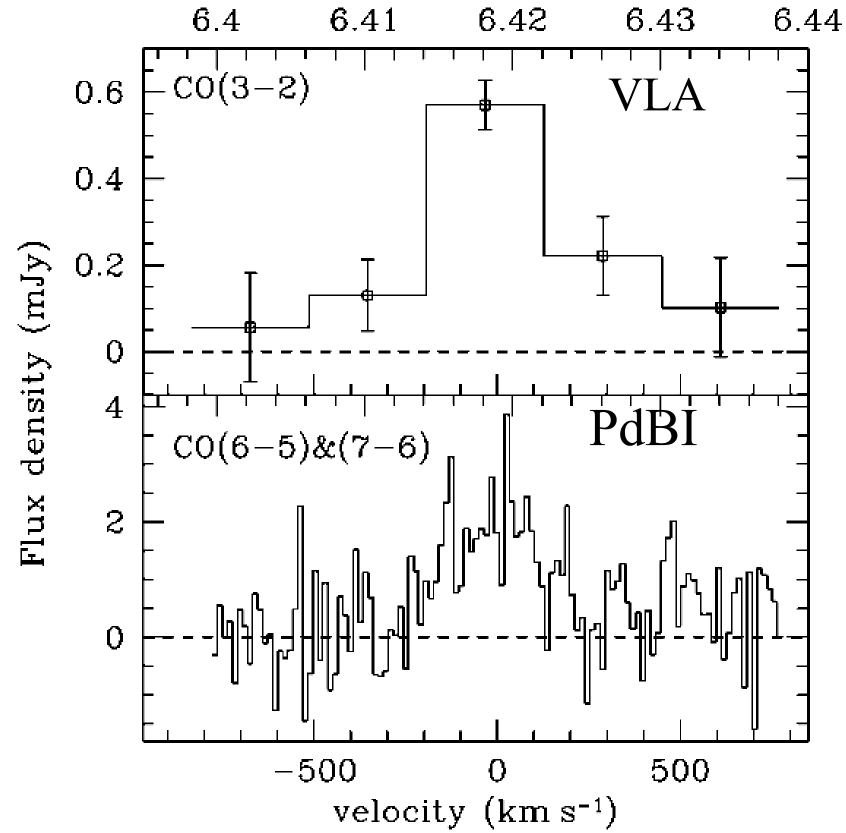
Extinction toward z=6.2 QSO and 6.3 GRB ~ starburst model => larger, silicate + amorphous carbon dust grains (vs. eg. graphite) formed in core collapse SNe?



Stratta, Dwek, Maiolino, Shull, Nozawa…

1148+52 z=6.42: Gas detection



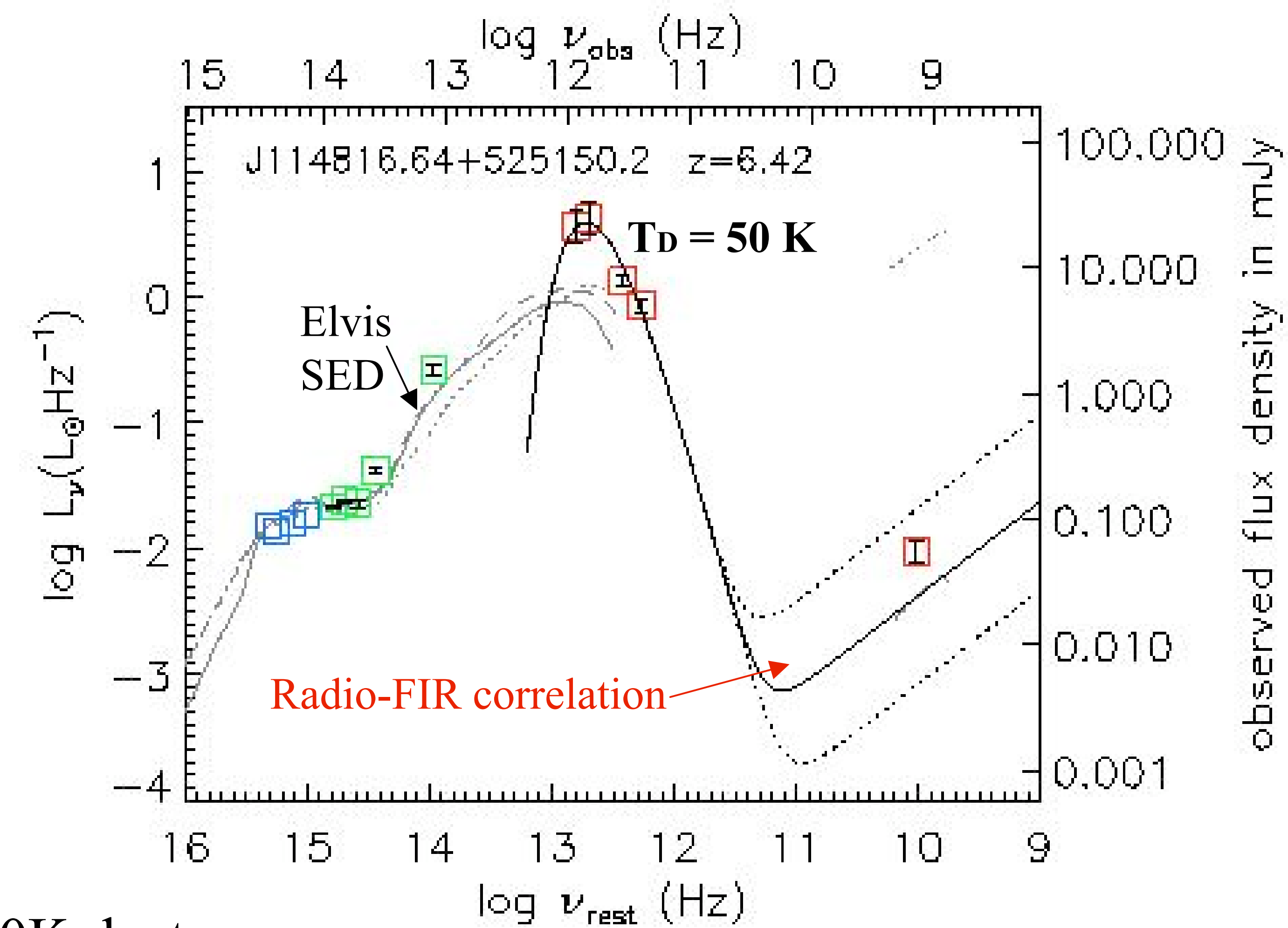


- Size ~ 6 kpc
- $M(H_2) \sim 2e10\ M_o$

- FWHM = 305 km/s
- z = 6.419 +/- 0.001
- $M_{gas}/M_{dust} \sim 30$ ~ starburst galaxies

1148+5251

Radio to near-IR SED



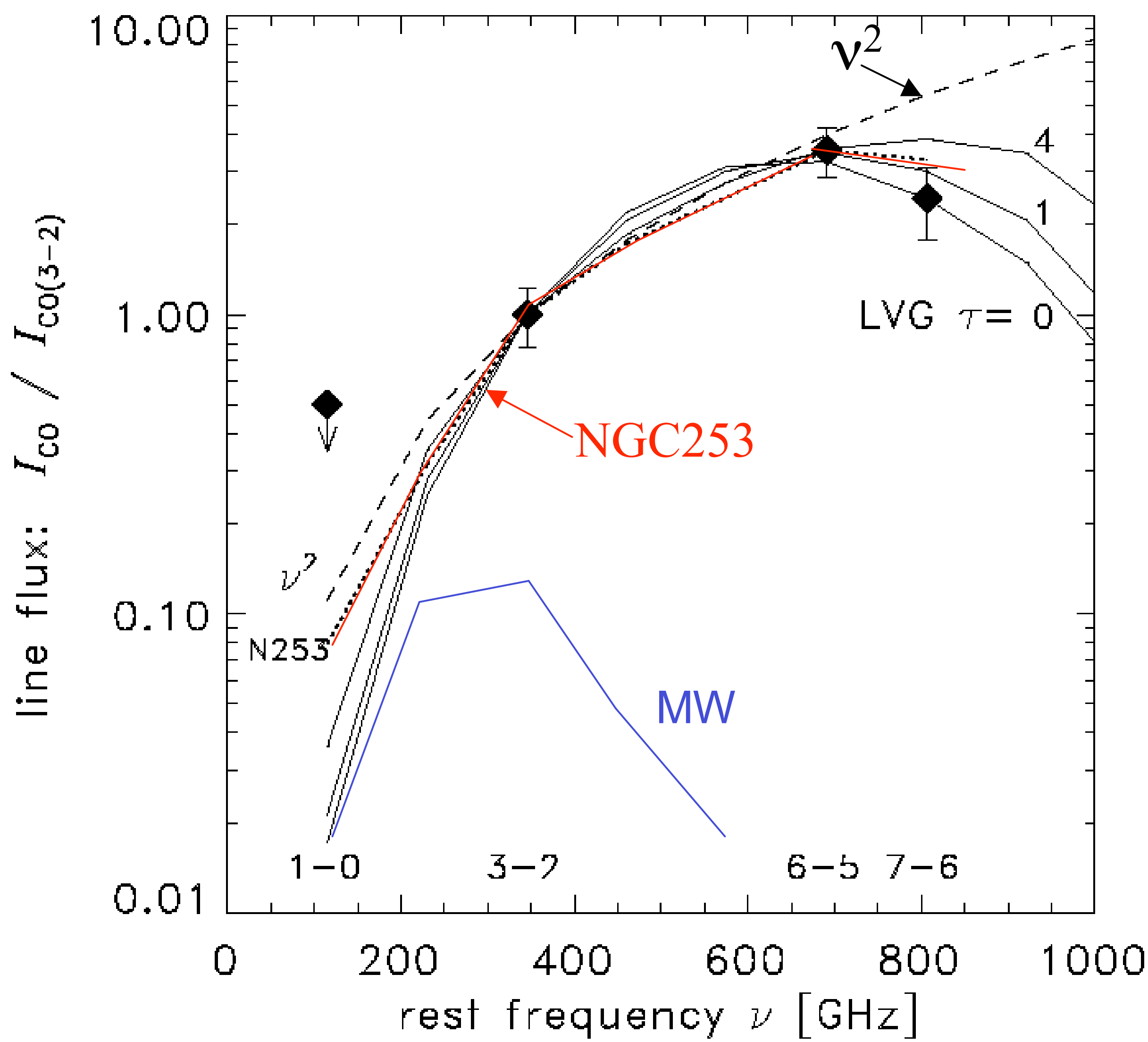
- FIR excess = 50K dust
- Radio-FIR SED follows star forming galaxy
- SFR ~ 3000 Mo/yr

CO excitation ladder

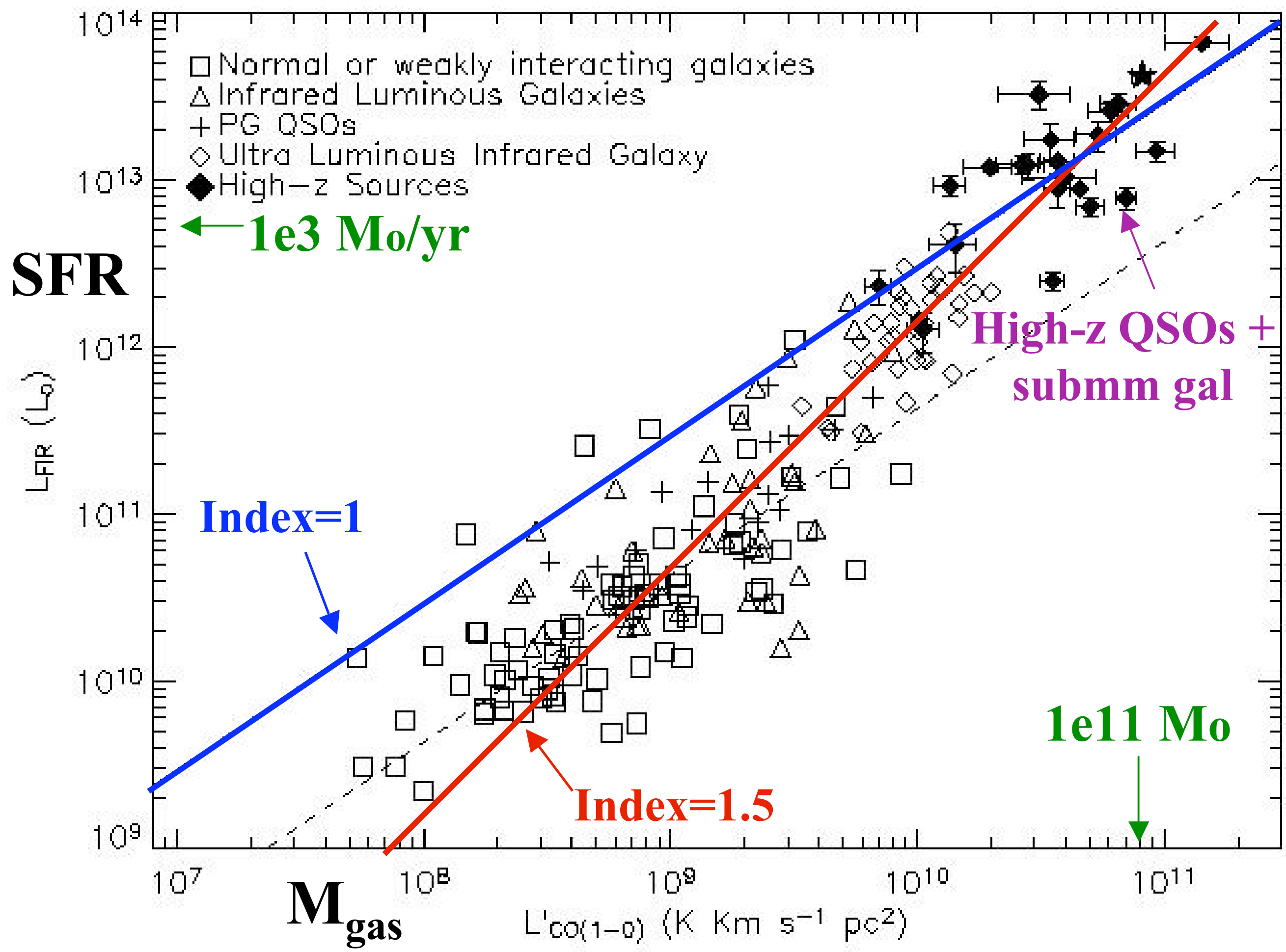
Dense, warm gas: CO thermally excited to 6-5, similar to starburst nucleus

$T_{kin} > 70$ K

$n_{H2} > 1e4$ cm^-3



LFIR vs L'(CO): 'integrated Kennicutt-Schmidt law'



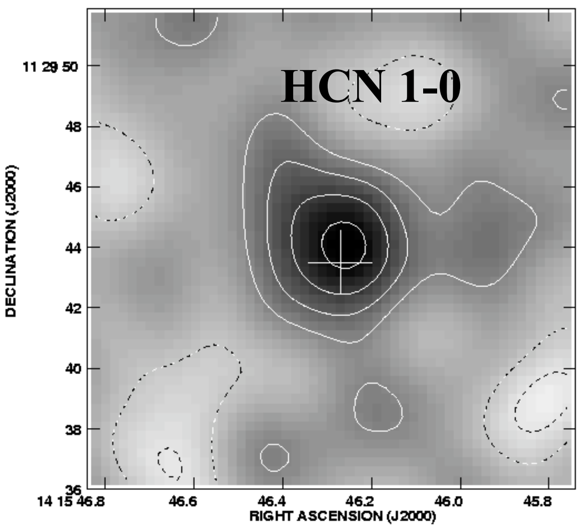
- Star formation efficiency(SFR/M_{gas}) increases with increasing SFR

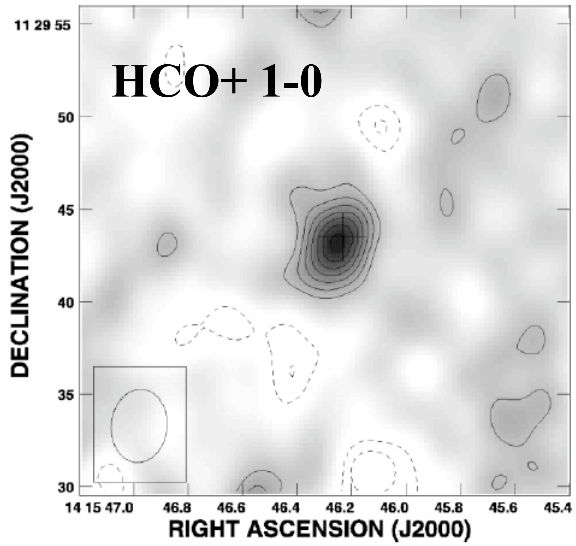
- Gas depletion timescale(M_{gas}/SFR) decreases with SFR

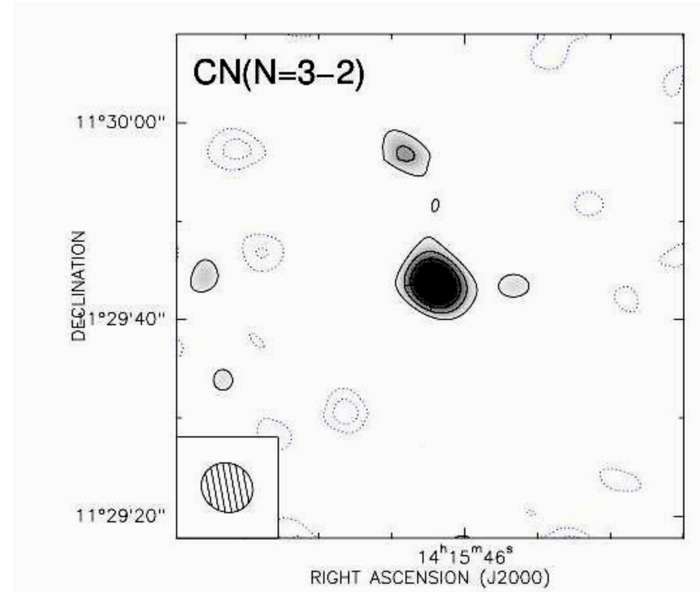
FIR ~ 1e10 Lo/yr => t_{dep} ~ 3e8yr

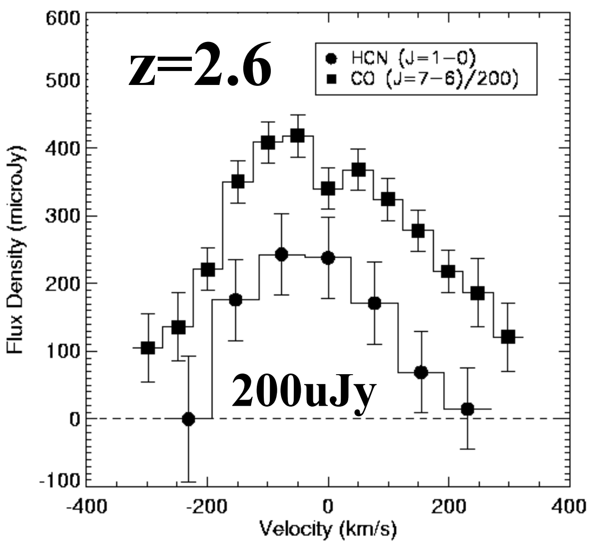
FIR ~ 1e13 Lo/yr => t_{dep} ~ 1e7yr

Higher Density Tracers: HCN, HCO^+



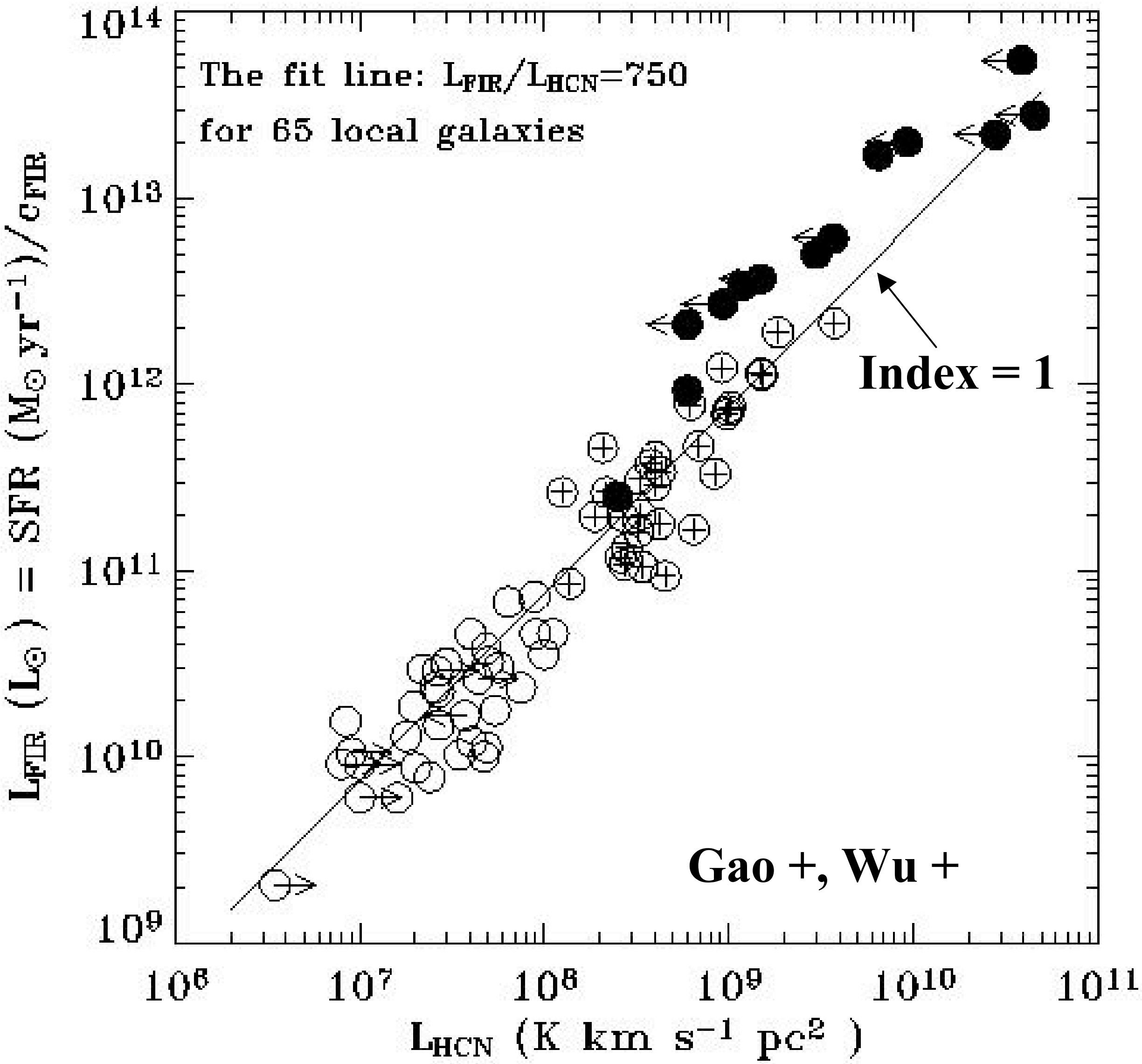






- n_{cr} > 1e5 cm^{-3} (vs. n_{cr}(CO) ~ 10^3 cm^{-3})
- Dense gas lines 5-10 fainter than CO

HCN: Dense gas directly associated with star forming clouds



- FIR -- HCN = linear relation from GMCs to HyLIRGs
- SFR per unit dense gas mass ~ constant in all galaxies

Conclusions:

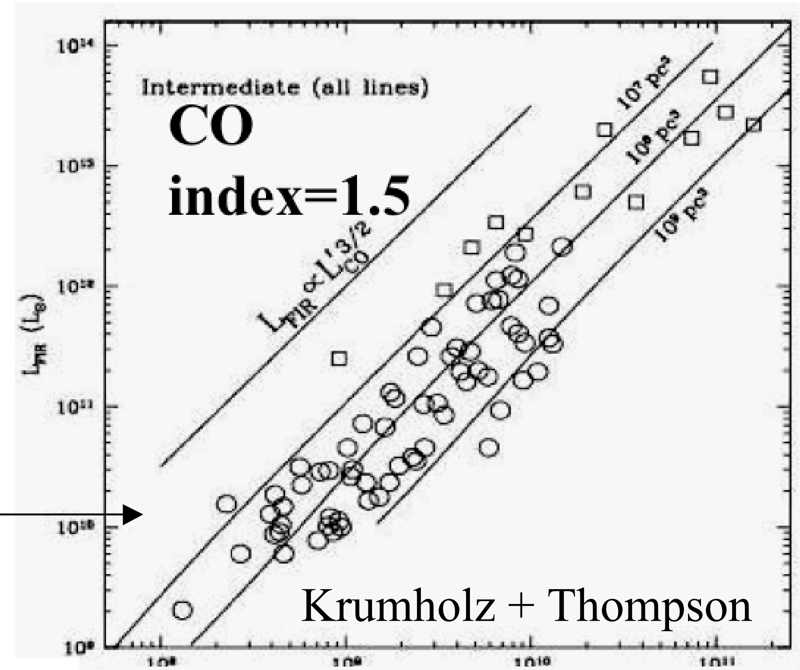
- CO traces all gas
- HCN traces dense gas => 'Counting star forming clouds'

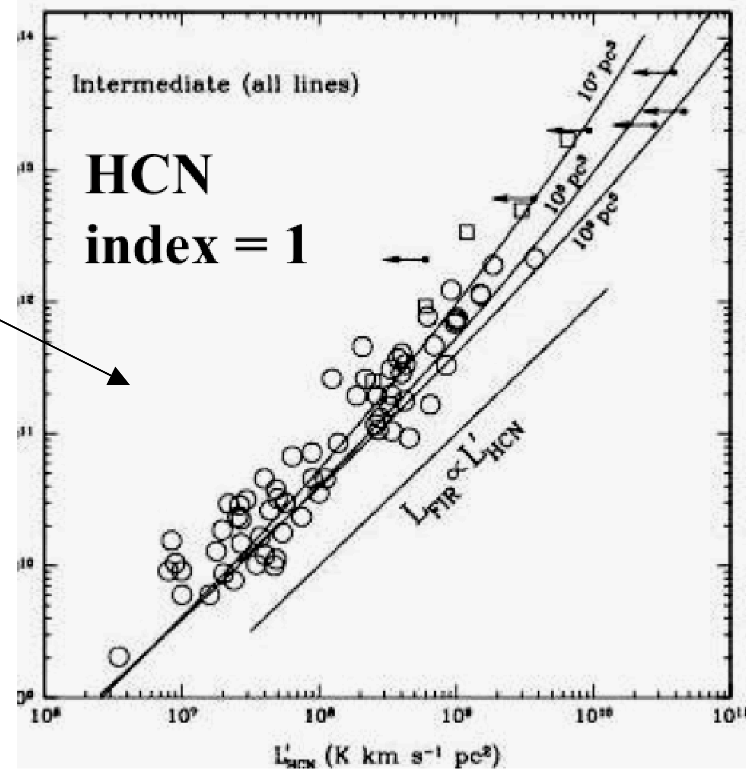
=> dense/total gas increases with SFR

Kennicutt-Schmidt laws

- CO-FIR lum: FIR $\propto L'(CO)^{1.5+/-0.2}$
- K-S law: $\Sigma_* \propto \Sigma_g^{1.4+/-0.15}$
- SFR $\propto \rho$ / timescale
- Low density gas tracers: excited in all gas, such that timescale$\propto$ FF time$\propto \rho^{-0.5}$ => SFR $\propto \rho^{1.5}$
- High density gas tracers: only excited in densest gas, such that all clouds have roughly same (critical) density => timescale is same => SFR $\propto \rho^1 \rho_{cr}^{0.5}$
- Predicts departure from linearity for HCN/HCO+ in galaxies where mean density approaches critical density

=> HyLIRG at high z: entire ISM ~ ρ_{cr}



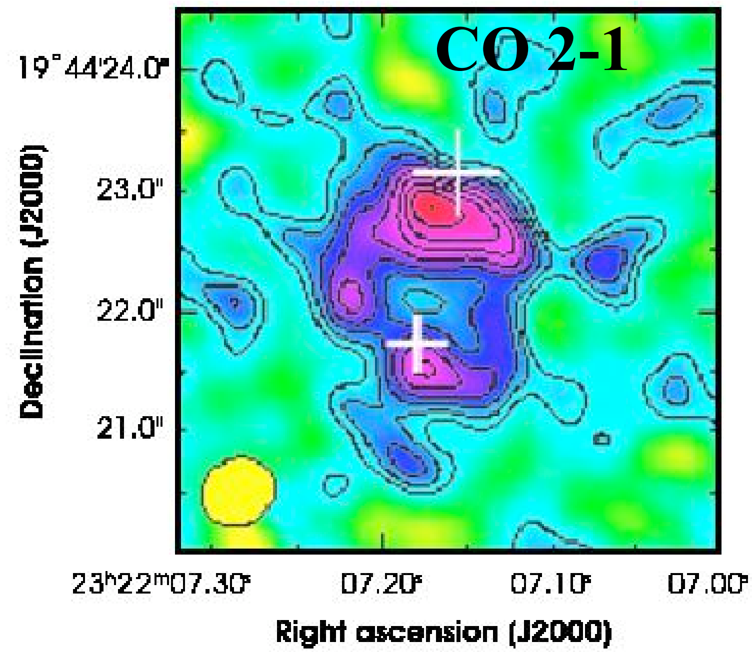


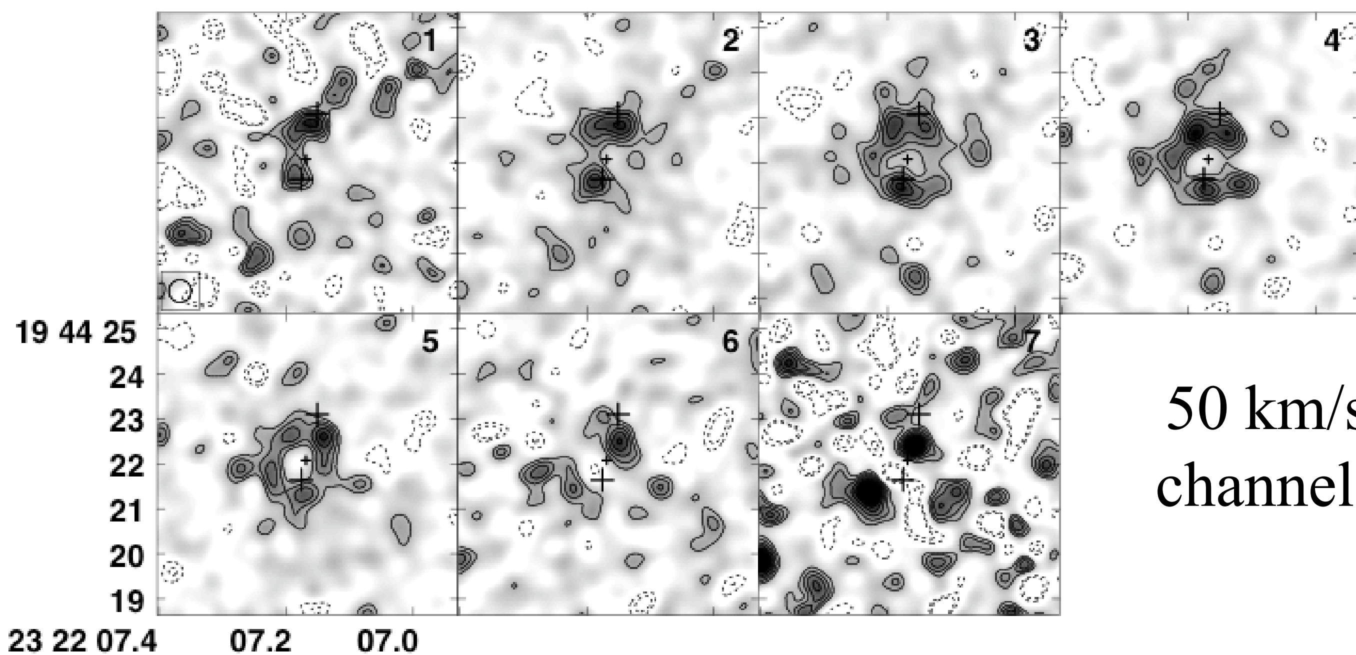
CO rotation curves: QSO host galaxy dynamics at high z

2322+1944, z=4.2

Molecular Einstein ring

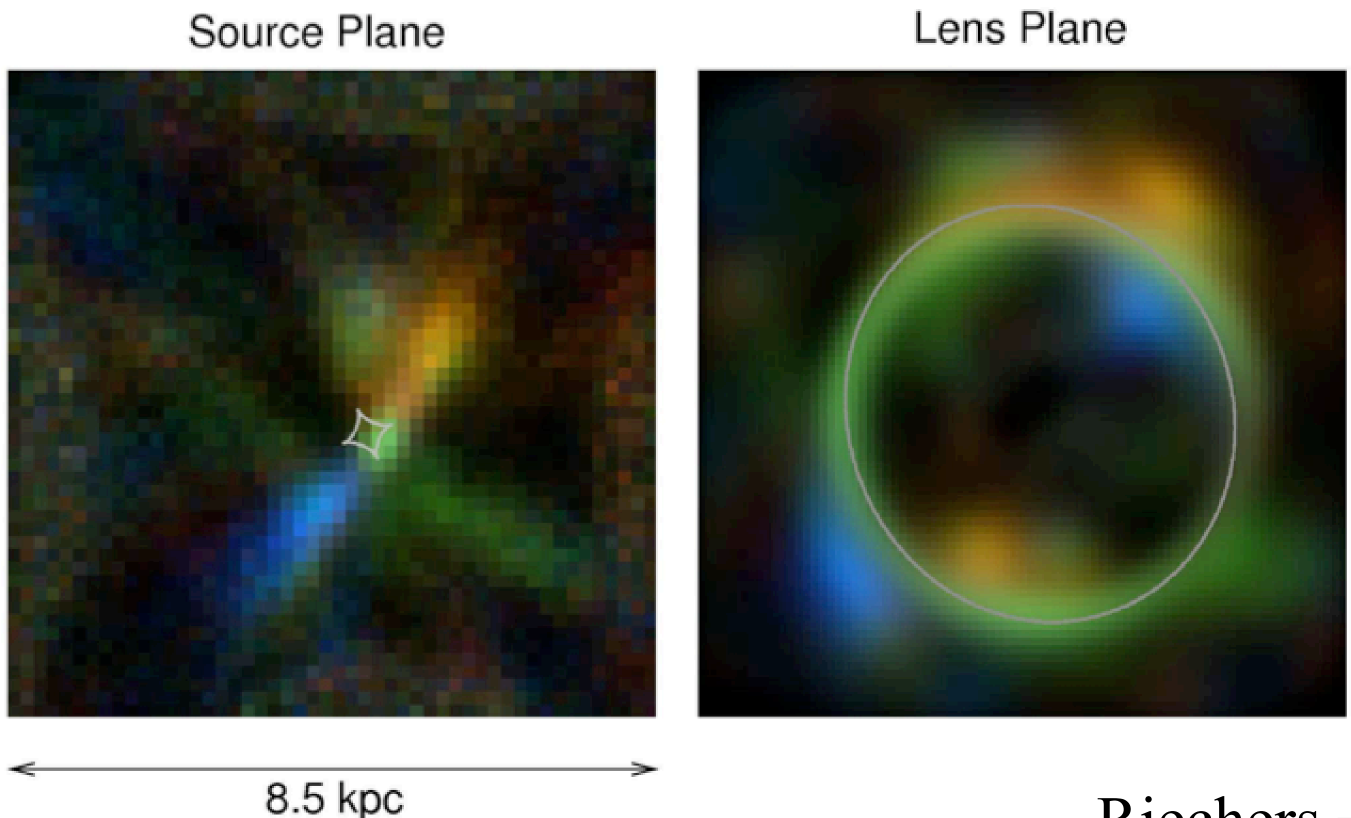
Riechers et al. 2008





50 km/s channels

2322+1944 CO rotation curve: lens inversion and QSO host galaxy dynamics

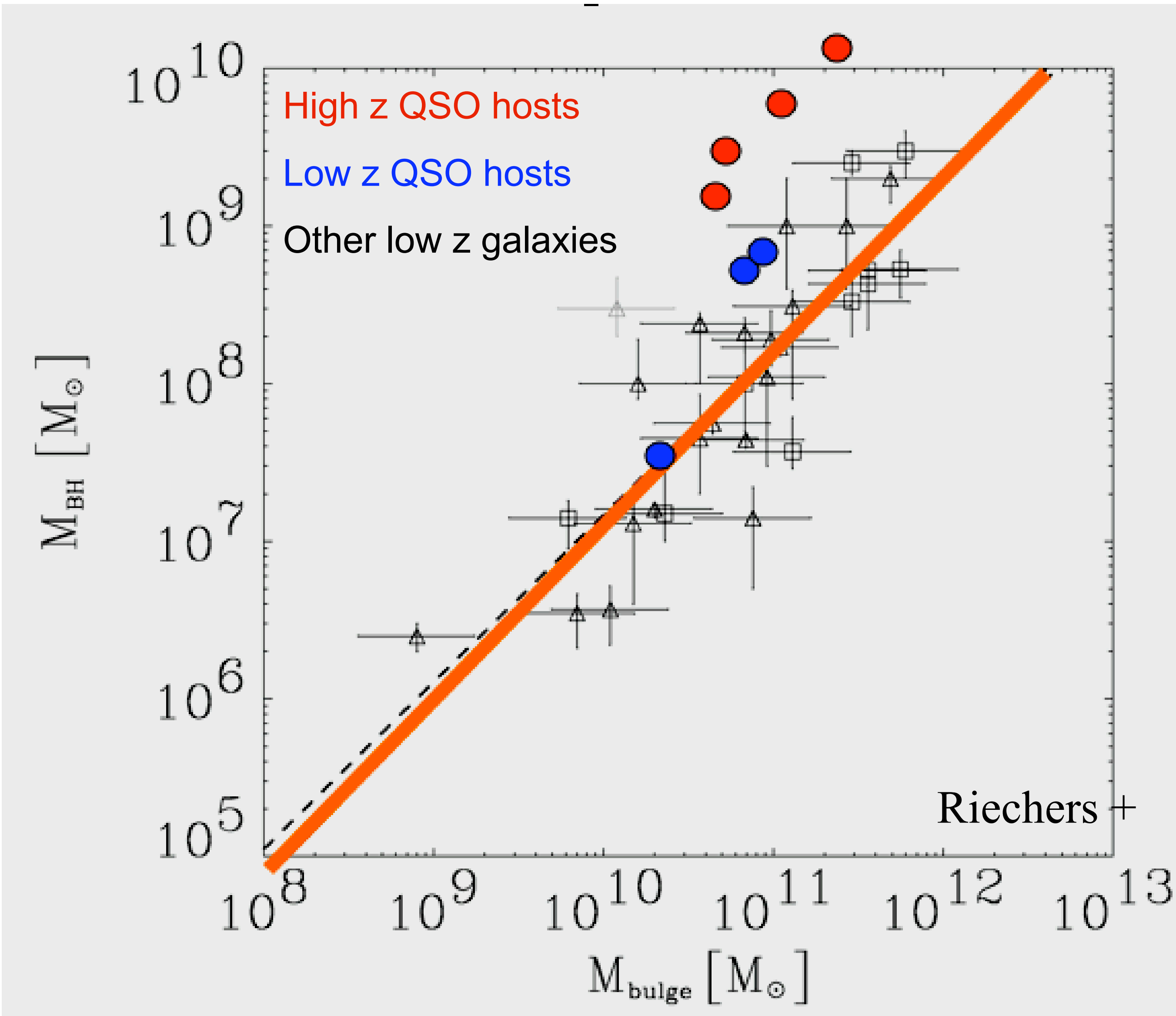


Riechers + 08

- Galaxy dynamical mass (r<3kpc) ~ 4.4e10 M_o
- $M(H_2)$ ~ 1.7e10 M_o
- M_{BH} ~ 1.5e9 M_o (from MgII lines, Eddington)

Break-down of M_{BH} -- M_{bulge} relation at very high z

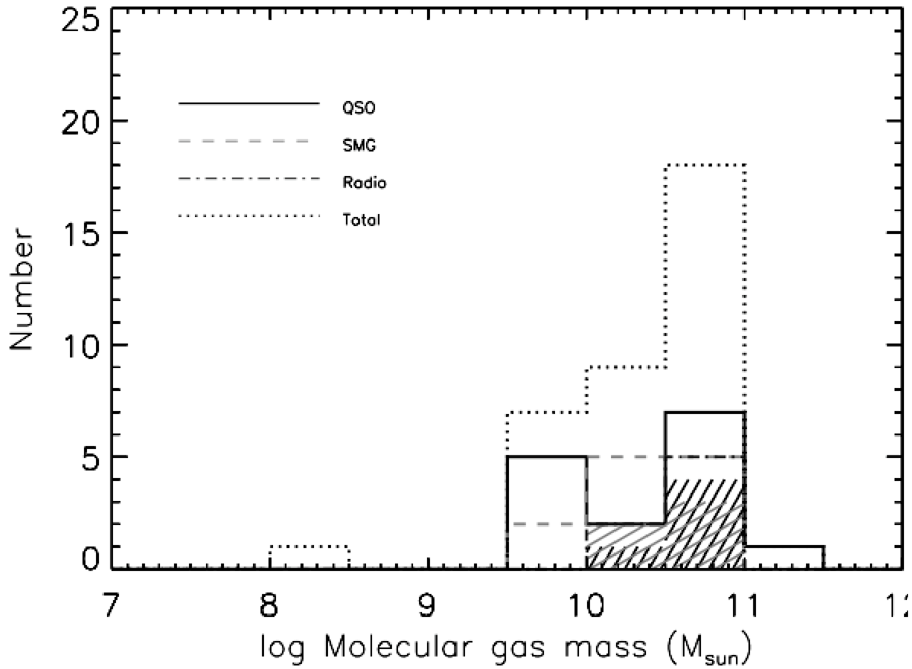
Use CO rotation curves to get host galaxy dynamical mass

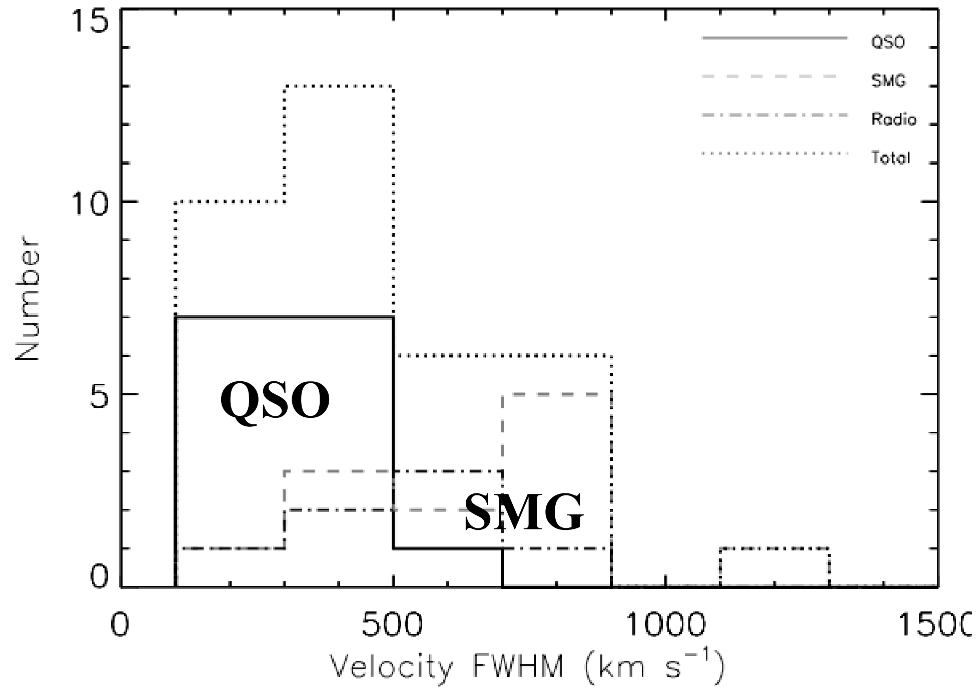


Perhaps black holes form first?

High z quasar hosts vs. Submm galaxies

Gas mass and line widths



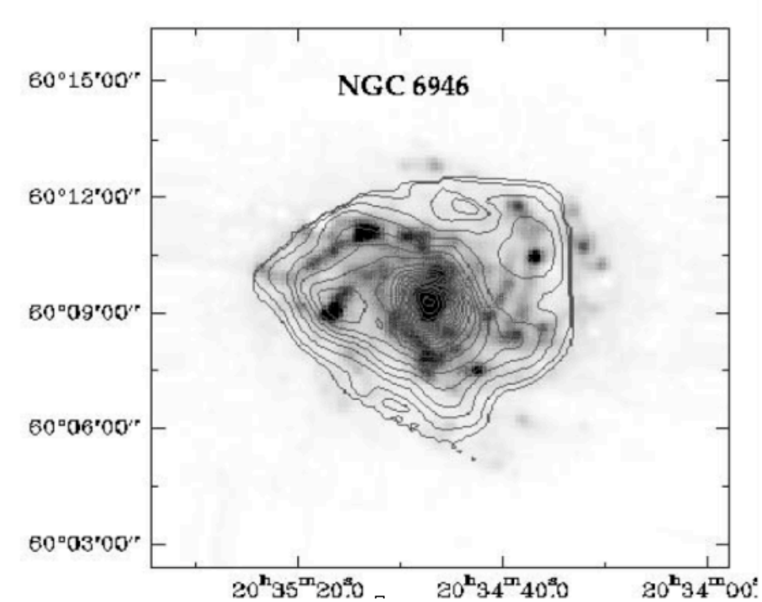


- **Gas mass distribution similar: $<M_{H2}> \sim 3e10\ M_o$**
- **$<V_{QSO}> \sim 300$ km s^{-1}**
- **$<V_{SMG}> \sim 700$ km s^{-1}**

=> Quasar hosts preferentially 'face-on': $<\theta_I> \sim 13^o$

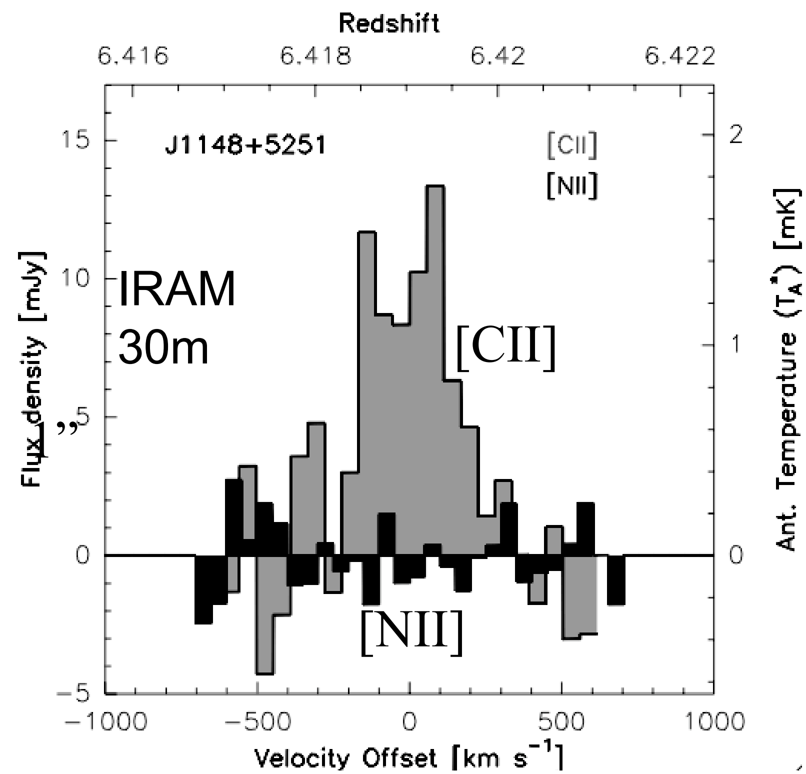
[CII] 158um

- Dominant ISM gas cooling line
- Traces CNM and PDRs
- z>4 => FS lines observed in (sub)mm bands

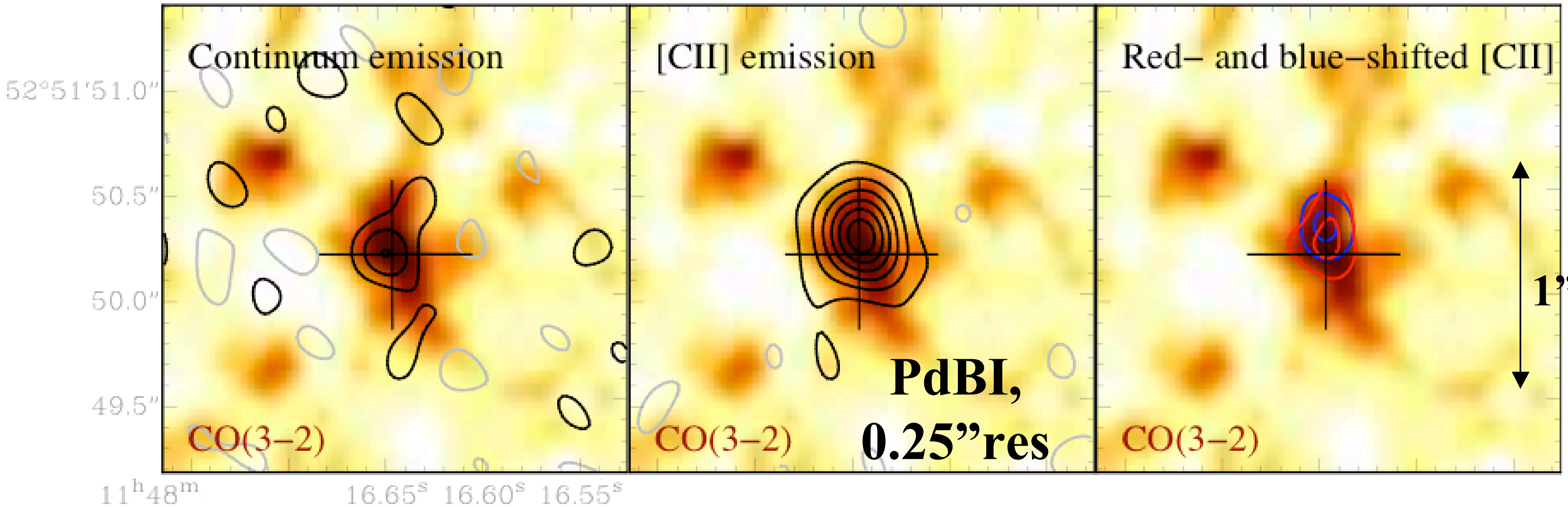


J1148+5251 z=6.42

- $L_{[CII]} = 4x10^9 L_o$ ($L_{[NII]} < 0.1L_{[CII]}$)
- SFR ~ 6.5e-6 $L_{[CII]}$ ~ 3000 Mo/yr



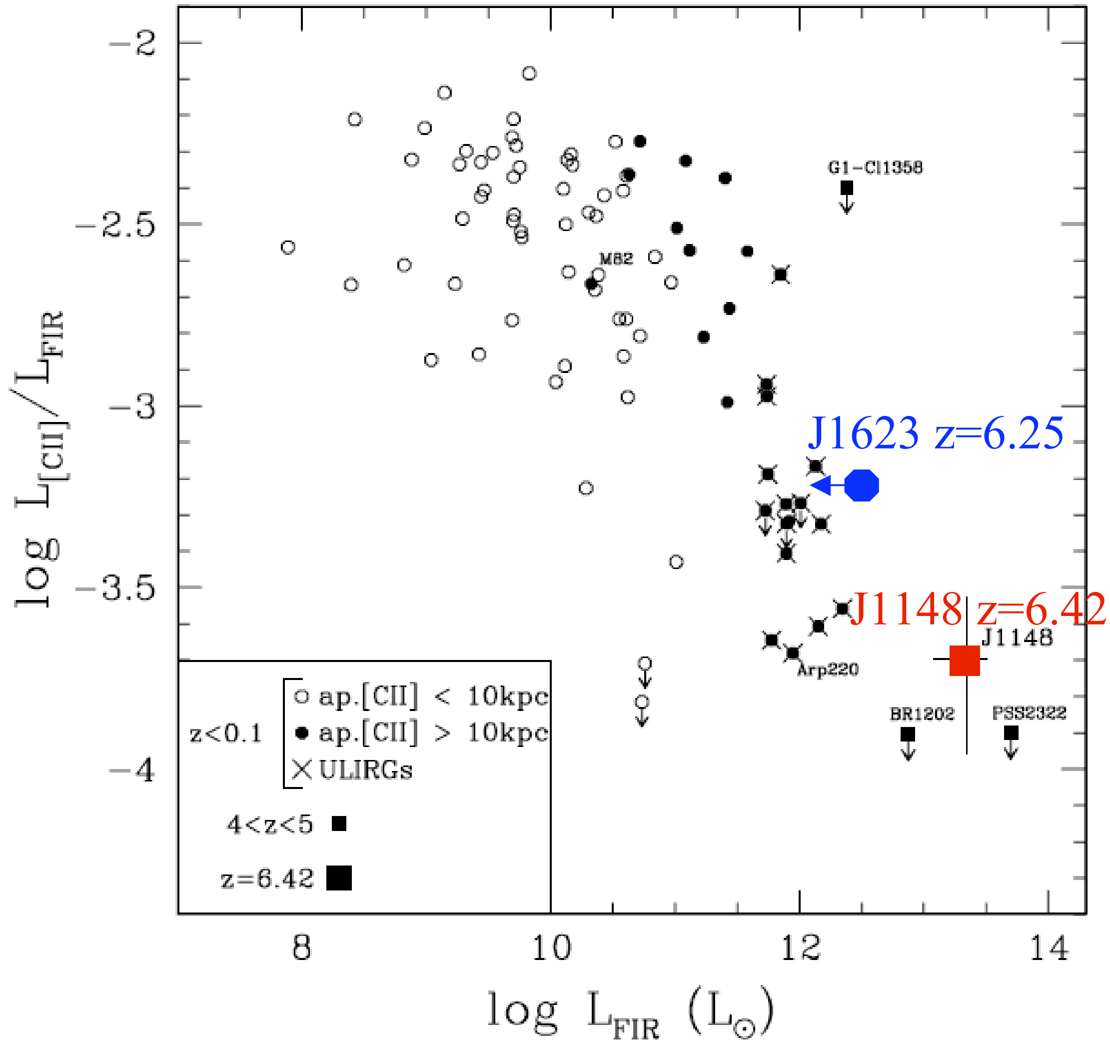
‘Maximal star forming disk’ (Walter + 2009)



- [CII] size ~ 1.5 kpc => SFR/area ~ 1000 M_o yr^{-1} kpc^{-2}
- Maximal starburst: (Thompson, Quataert, Murray 2005)
    - Self-gravitating gas disk
    - Vertical 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 on 0.1pc scale

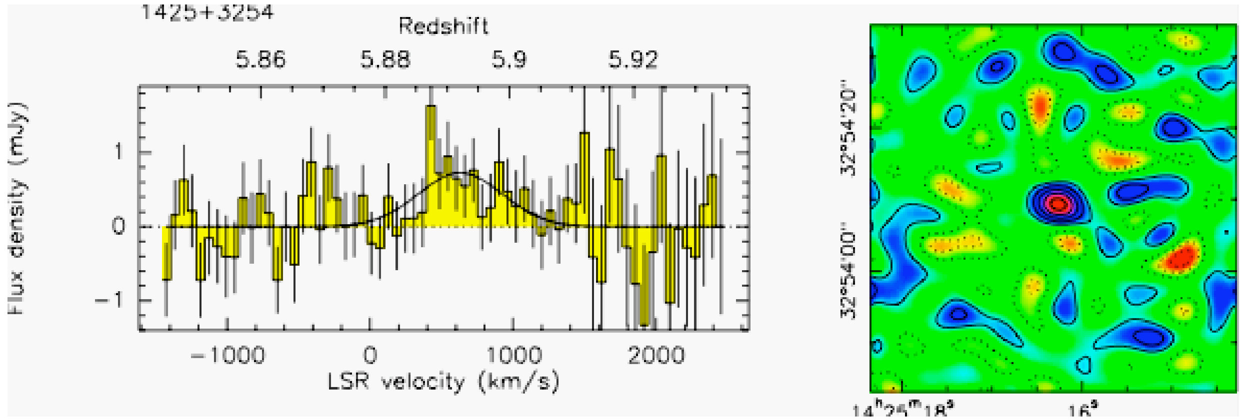
[CII] -- the good and the bad

- [CII]/FIR decreases rapidly with LFIR (lower heating efficiency due to charged dust grains?) => luminous starbursts are still difficult to detect in C+
- Normal star forming galaxies (eg. LAEs) are not much harder to detect
- Don't pre-select on dust



Bertoldi, Maiolino, Iono, Malhotra

Summary of cm/mm detections at z>5.7: 33 quasars

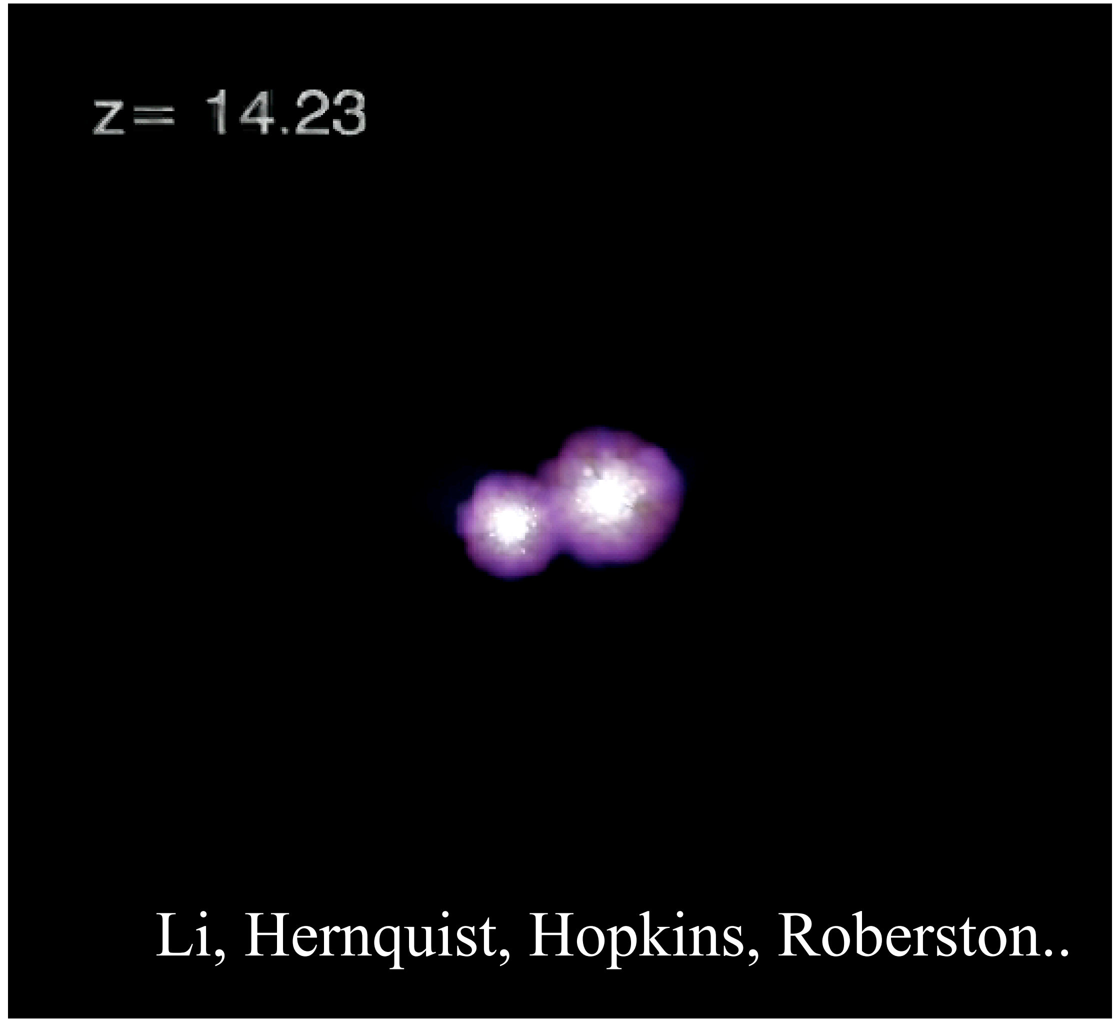


Plateau de Bure is routinely detecting 1mJy lines, and 0.1 mJy continuum

- Only direct probe of host galaxies
- 10 in dust => M_{dust} > 1e8 M_o: Dust formation in SNe?
- 5 in CO => M_{gas} > 1e10 M_o: Fuel for star formation in galaxies
- 10 at 1.4 GHz continuum: SED => SFR > 1000 M_o/yr (radio loud AGN fraction ~ 6%)
- 2 in [CII] => maximal star forming disk: 1000 M_o yr^{-1} kpc^{-2}

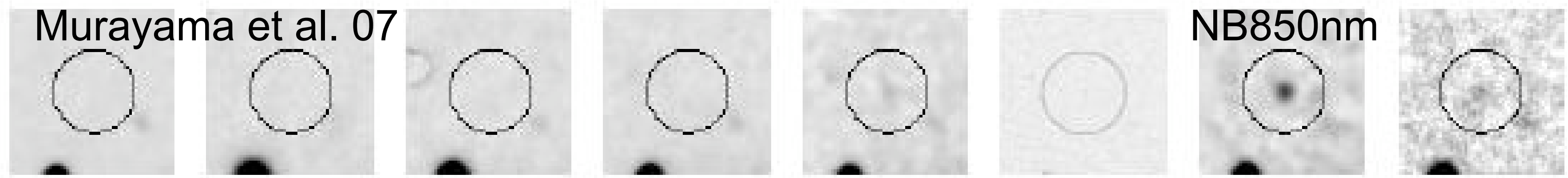
Building a giant elliptical galaxy + SMBH at t_{univ}< 1Gyr

- Multi-scale simulation isolating most massive halo in 3 Gpc^3
- Stellar mass ~ 1e12 Mo forms in series (7) of major, gas rich mergers from z~14, with SFR ≥ 1e3 Mo/yr
- SMBH of ~ 2e9 Mo forms via Eddington-limited accretion + mergers
- Evolves into giant elliptical galaxy in massive cluster (3e15 Mo) by z=0

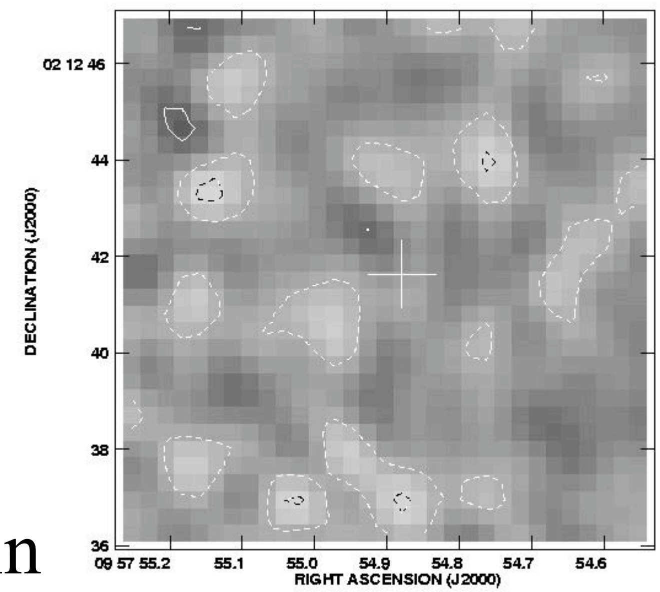


- Rapid enrichment of metals, dust in ISM (z > 8)
- Rare, extreme mass objects: ~ 100 SDSS z~6 QSOs on entire sky
- Integration times of hours to days to detect HyLIGRs

Pushing to 'normal galaxies' during reionization, eg. z=5.7 Lyα galaxies in COSMOS



- SUBARU: Lyα => <SFR> ~ 10 M_o/yr
- ~ 100 sources in 2 deg^{-2} in Δz ~ 5.7 +/- 0.05



Stacking analysis (100 LAEs)

- MAMBO: S_{250} < 2mJy => SFR<300
- VLA: $S_{1.4}$ < 2.5uJy => SFR<125

=> Need order magnitude improvement in sensitivity at radio through submm wavelengths in order to study earliest generation of normal galaxies.

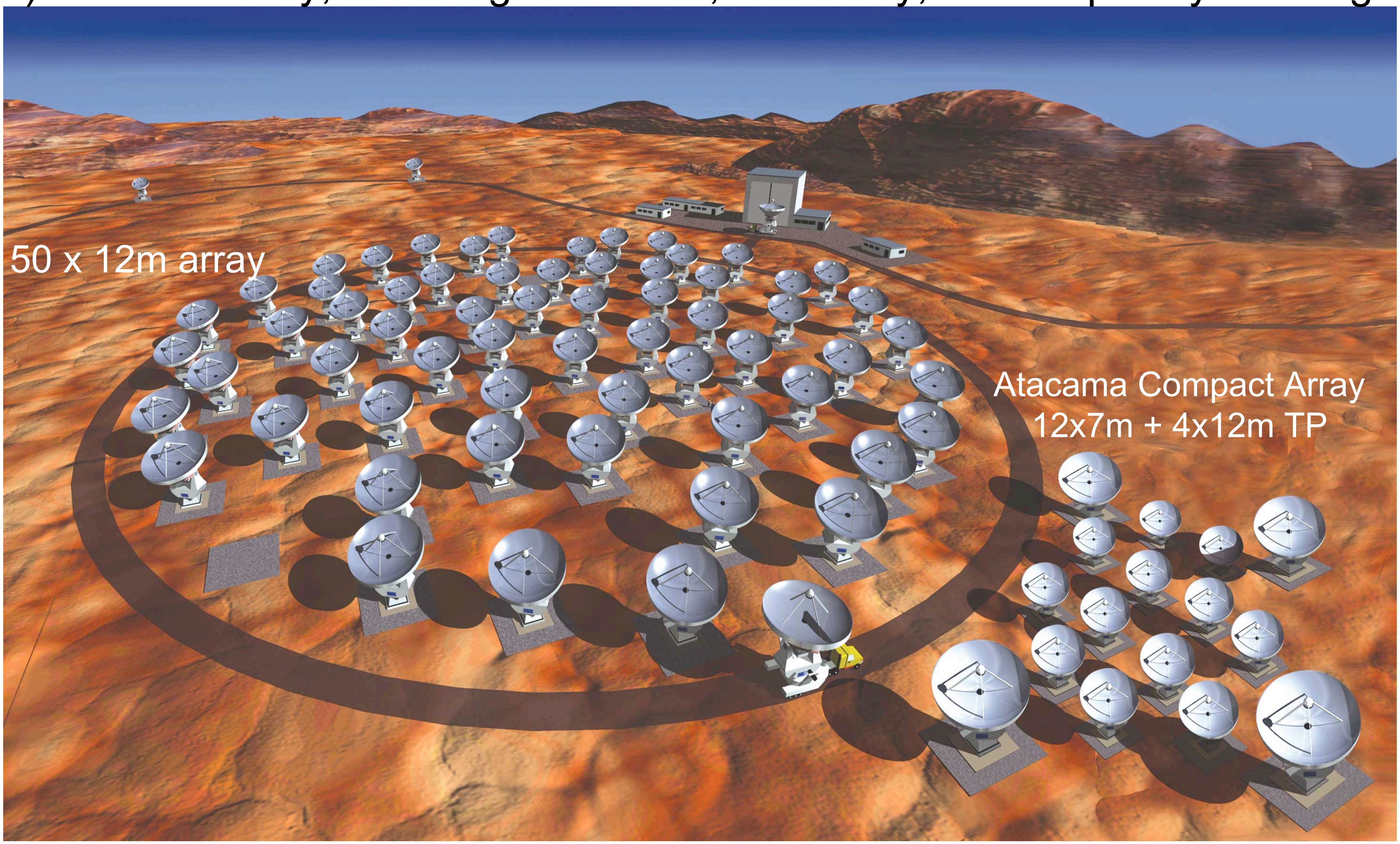
What is EVLA? First steps to the SKA-high

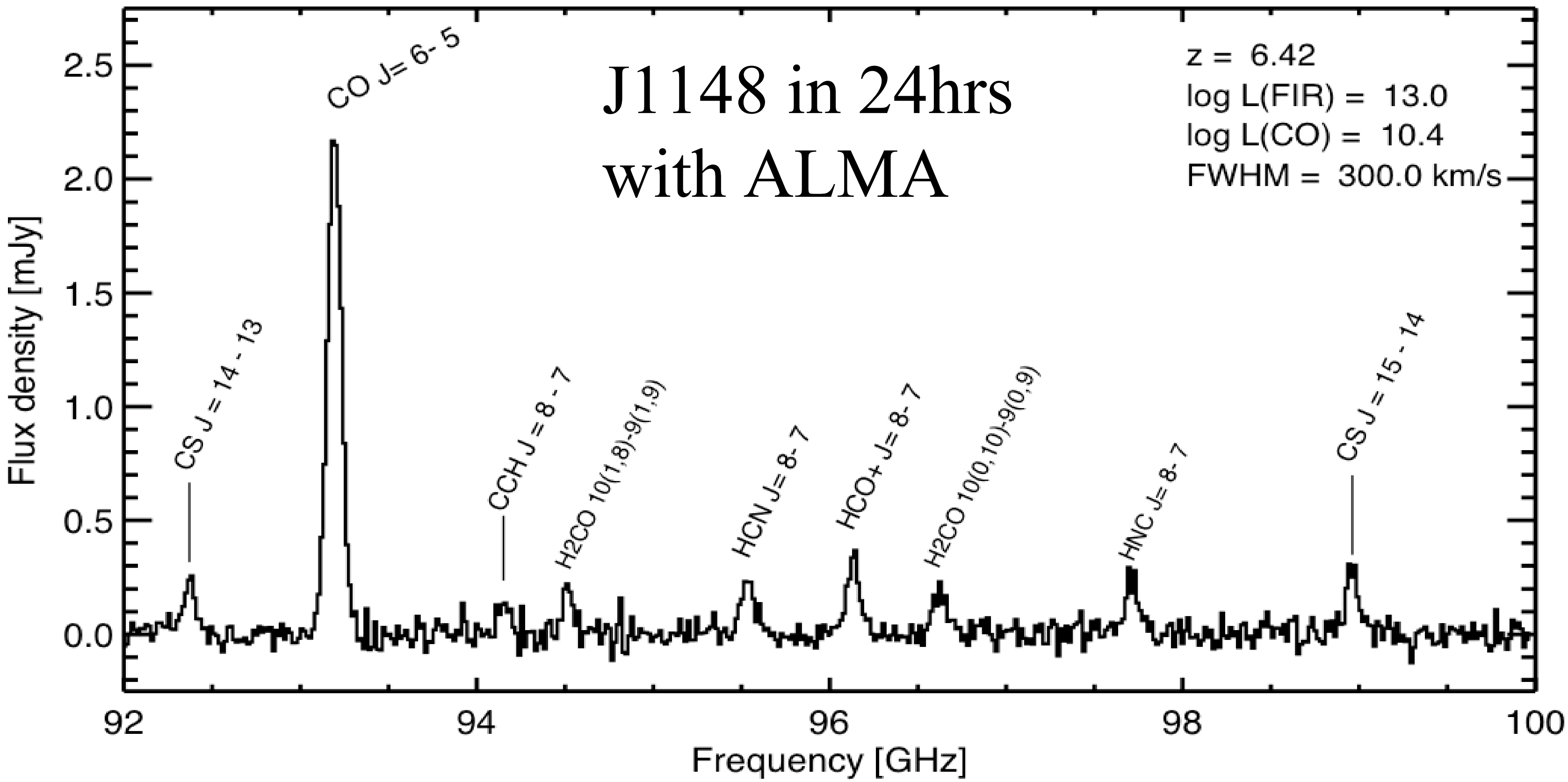
By building on the existing infrastructure, multiply ten-fold the VLA’s observational capabilities, including:

- 10x continuum sensitivity (<1uJy)
- full frequency coverage (1 to 50 GHz)
- 80x BW (8GHz)

What is ALMA?

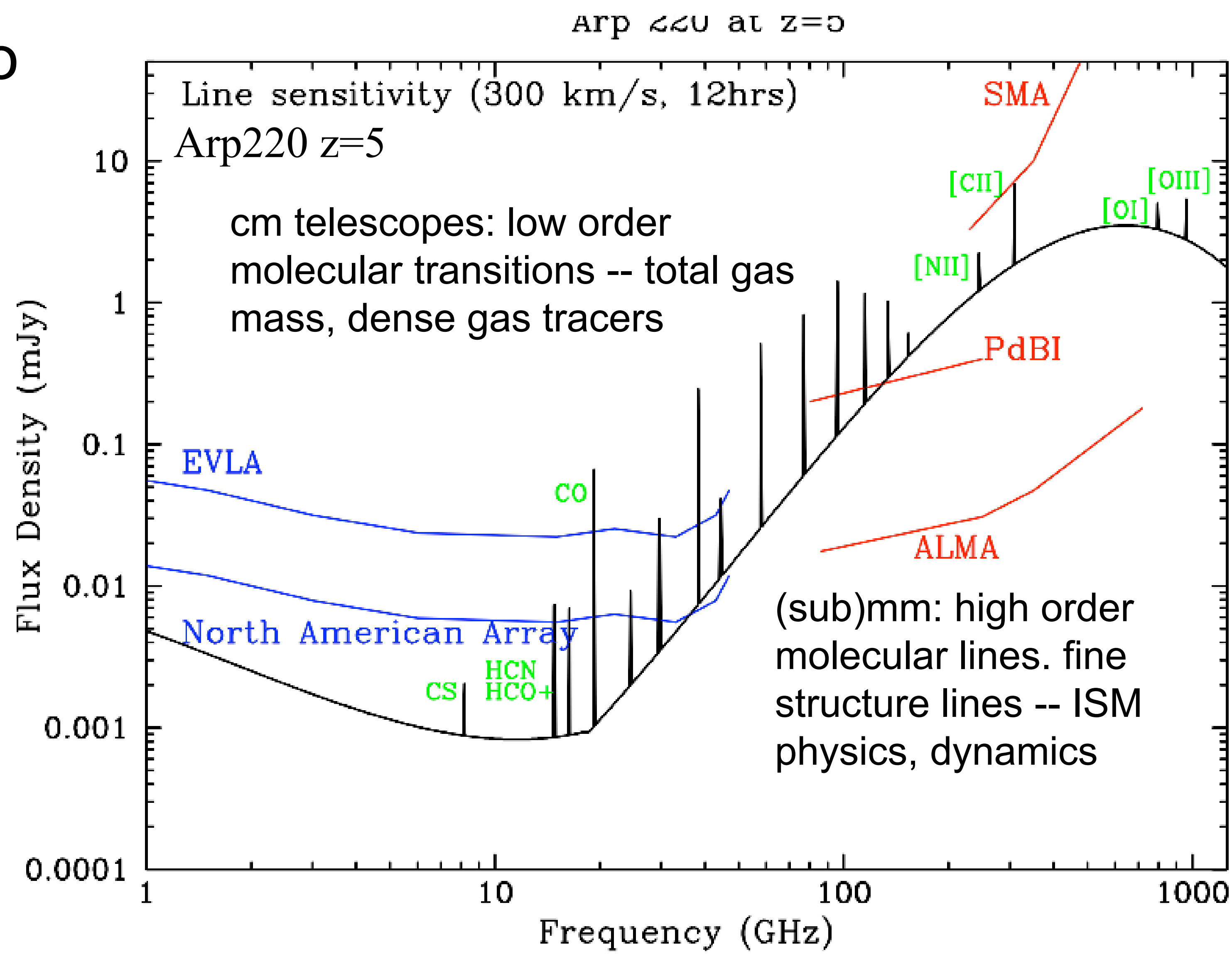
North American, European, Japanese, and Chilean collaboration to build & operate a large millimeter/submm array at high altitude site (5000m) in northern Chile -> order of magnitude, or more, improvement in all areas of (sub)mm astronomy, including resolution, sensitivity, and frequency coverage.





- Detect dust emission in 1sec (5σ) at 250 GHz
- Detect [CII] in minutes
- Detect multiple lines, molecules per band => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics, K-S
- LAE, LBGs: detect dust, molecular, and FS lines in 1 to 3 hrs

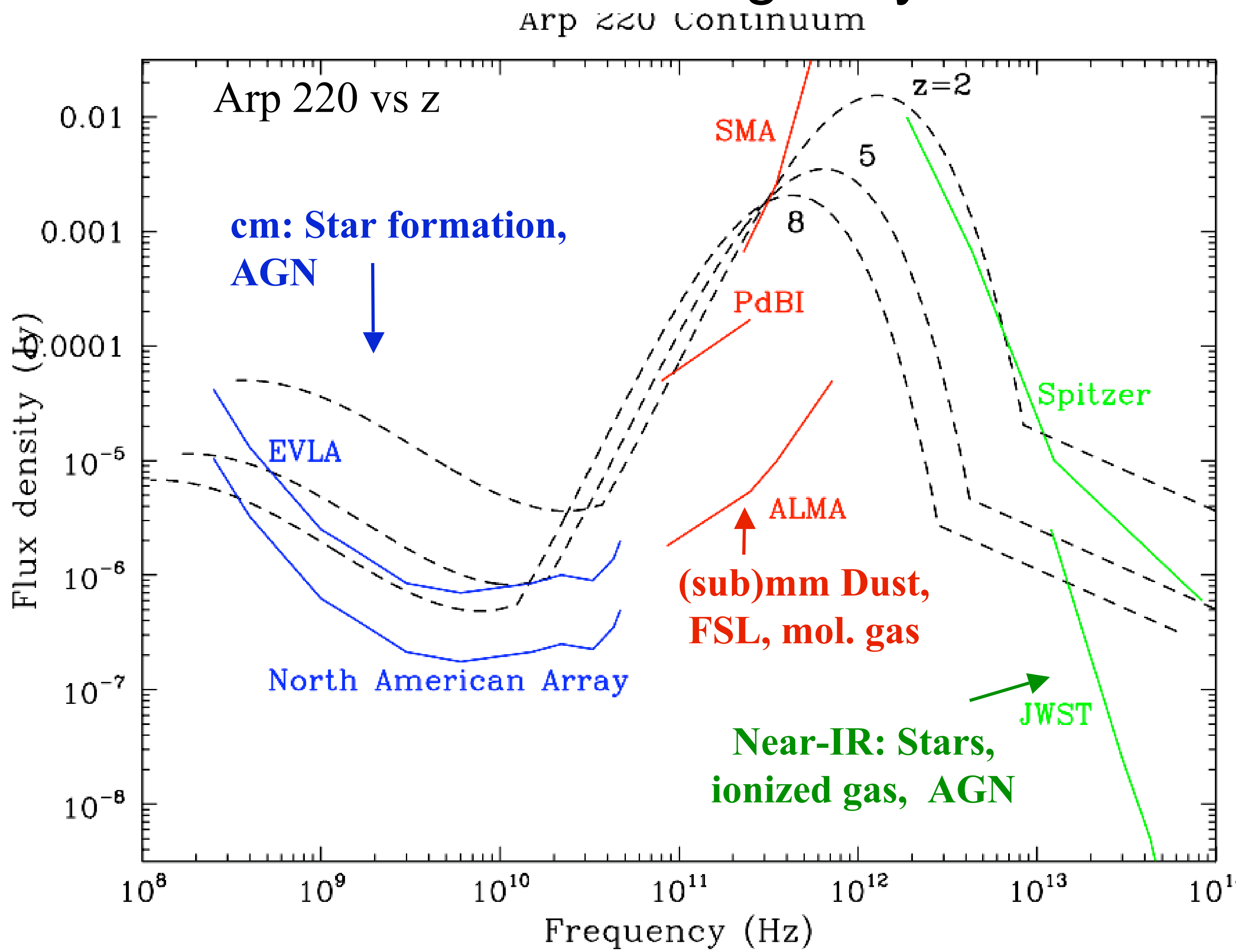
Pushing to normal galaxies: spectral lines



- FS lines will be workhorse lines in the study of the first galaxies with ALMA.
- Study of molecular gas in first galaxies will be done primarily with cm telescopes

Pushing to normal galaxies: continuum

A Panchromatic view of 1st galaxy formation

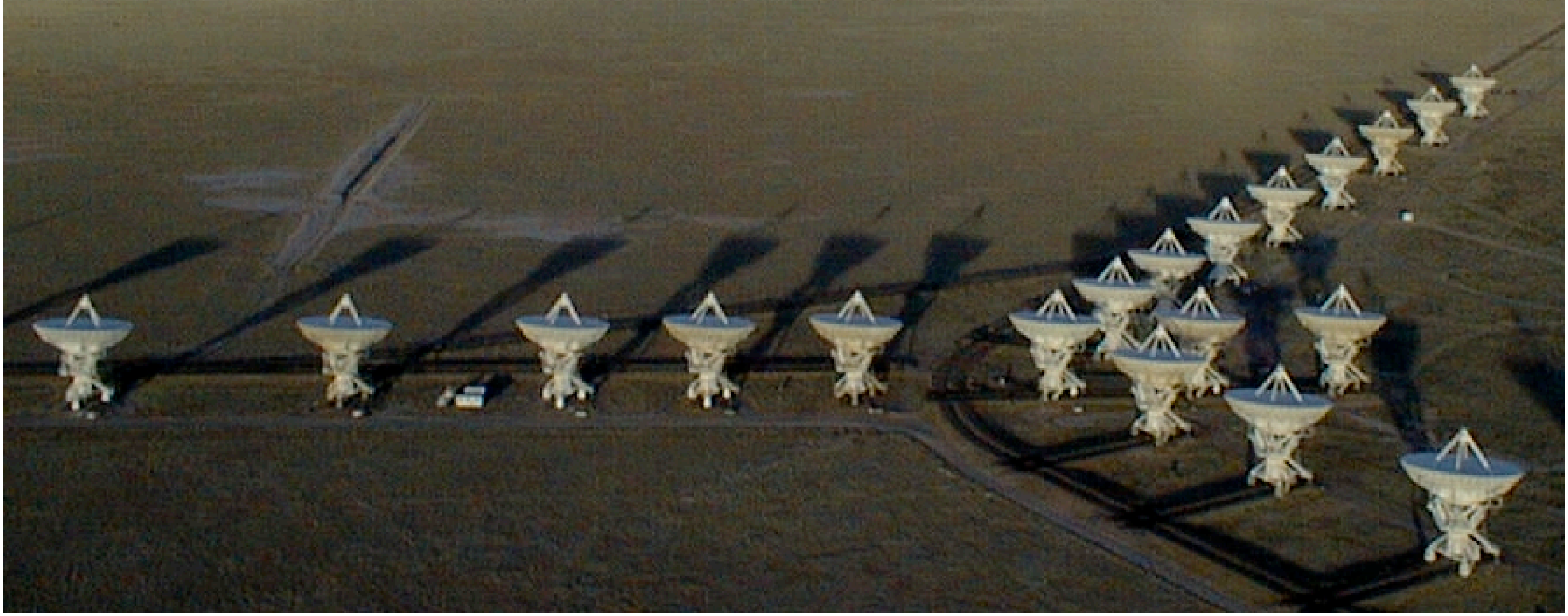


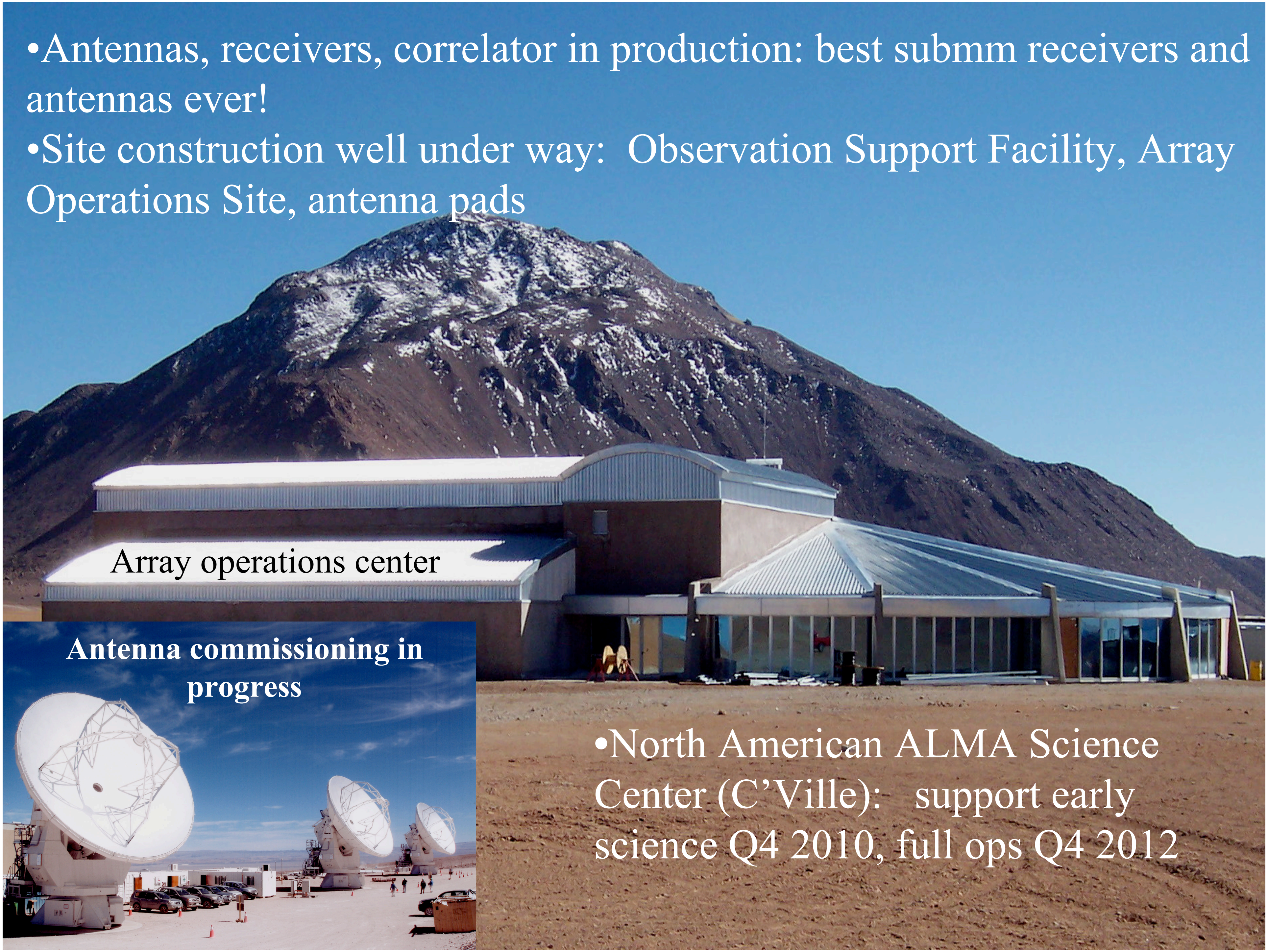
EVLA Status

•Antenna retrofits now ~ 50% completed.

•Early science start in Q4 2009, using new correlator: proposal deadline June 1, 2009 for shared-risk obs!!

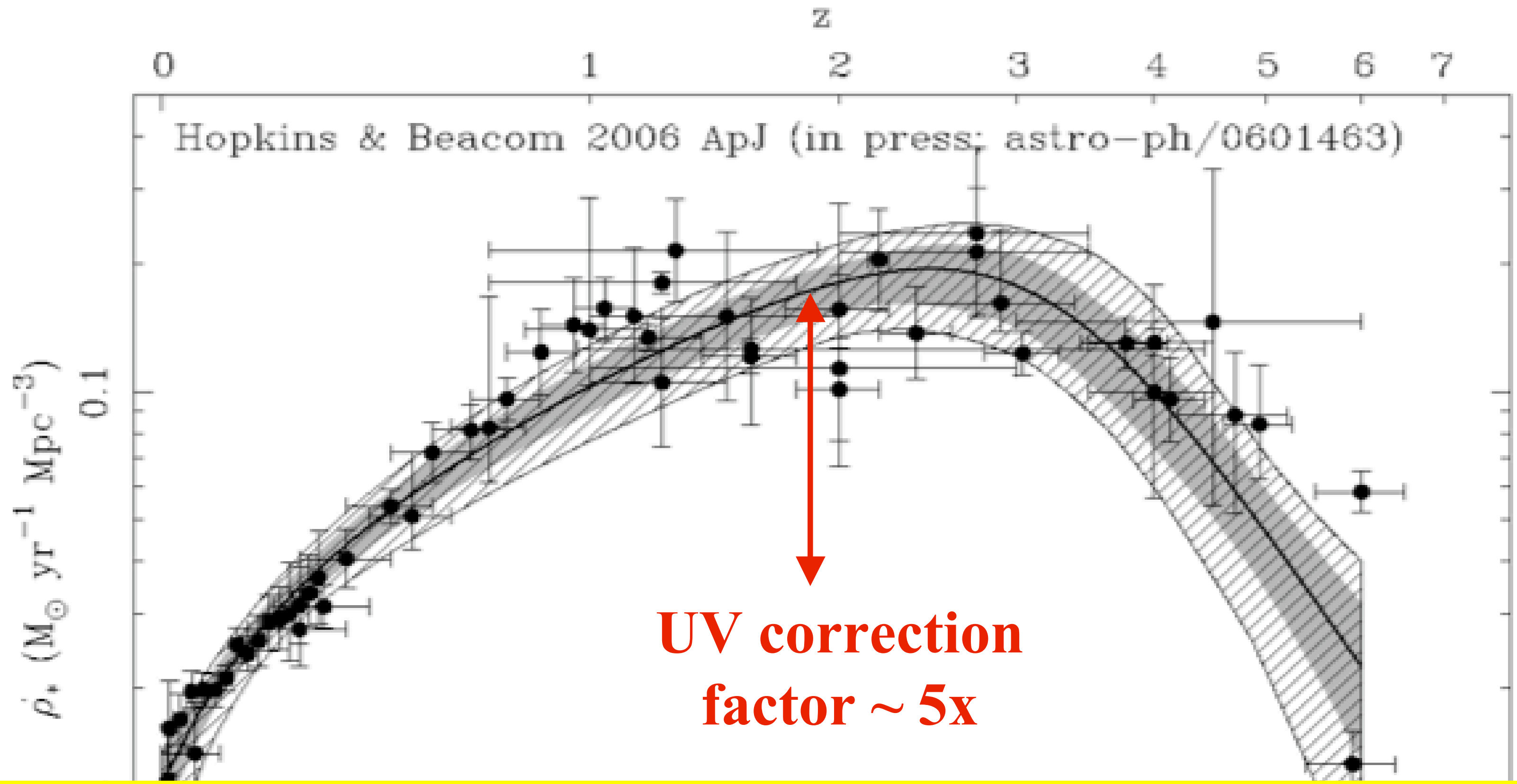
•Full receiver complement completed 2012.




•Antennas, receivers, correlator in production: best submm receivers and antennas ever!
•Site construction well under way: Observation Support Facility, Array Operations Site, antenna pads
Array operations center
Antenna commissioning in progress
•North American ALMA Science Center (C'Ville): support early science Q4 2010, full ops Q4 2012


END (I)
ESO

Star formation history of Universe: dirty little secret

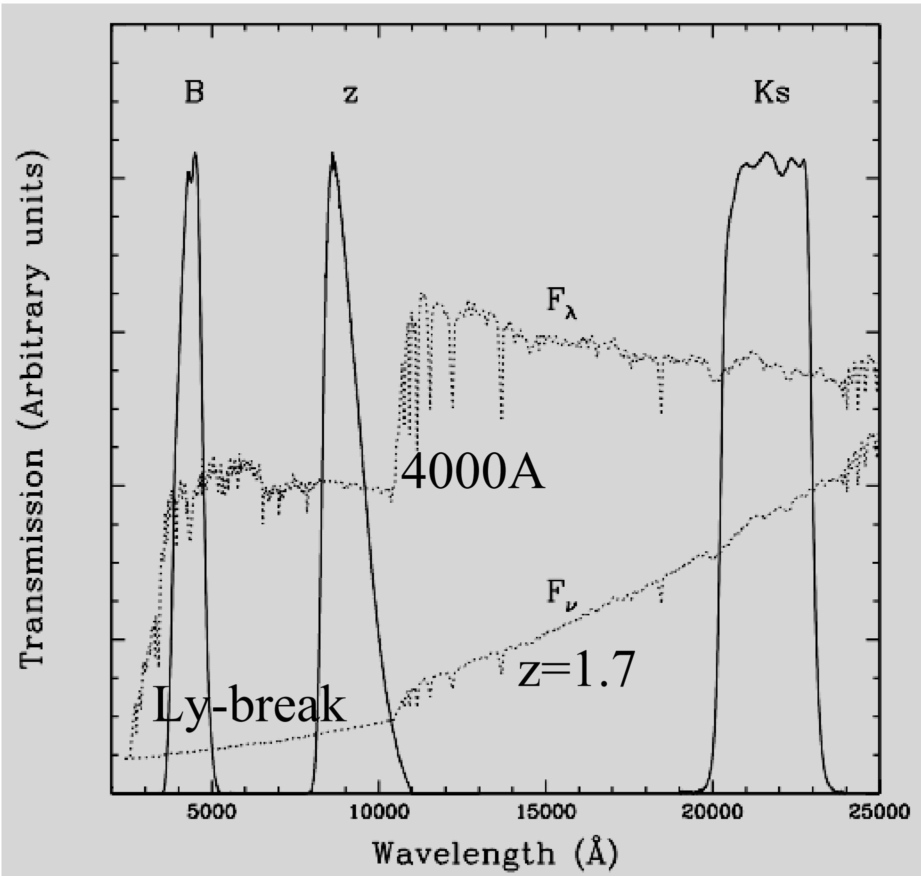


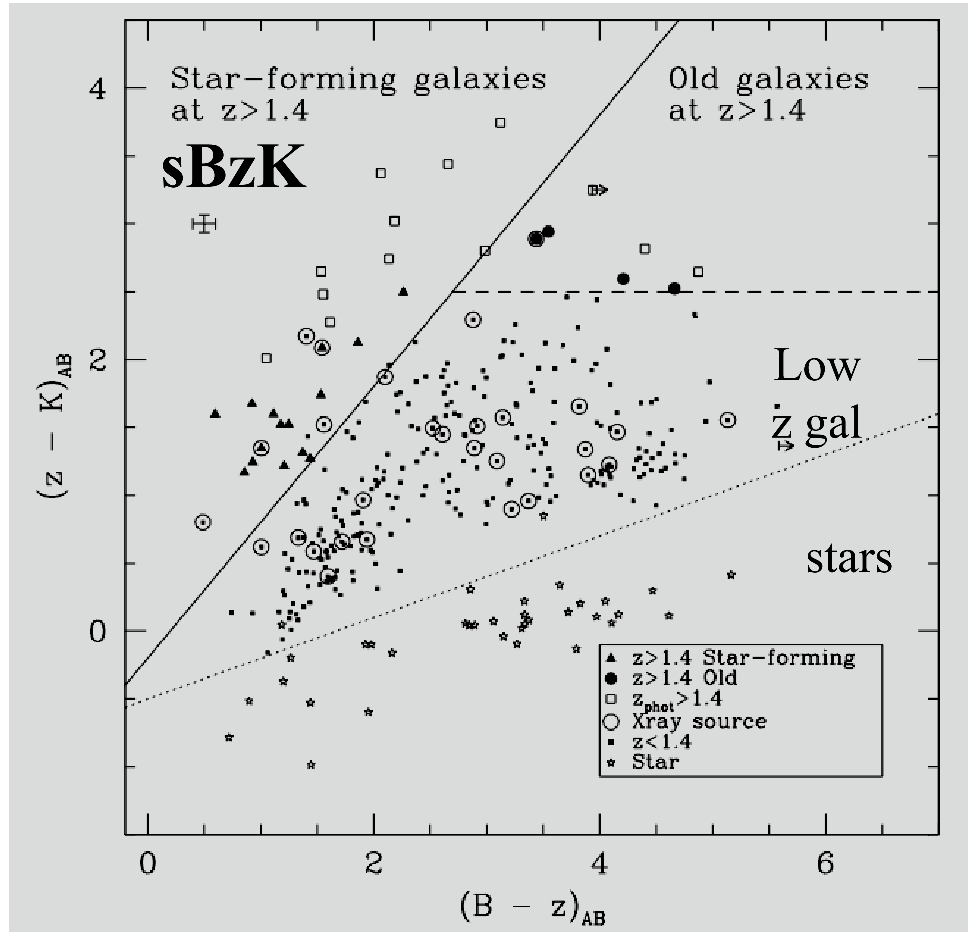
Optical limitations

- **Dust obscuration: missing earliest, most active phases of galaxy formation**
- **Only stars and star formation: not (cold) gas => missing the other half of the problem = 'fuel for galaxy formation'**

sBzK galaxies (K<20): Star forming galaxies at z~ 1.5 to 2.5

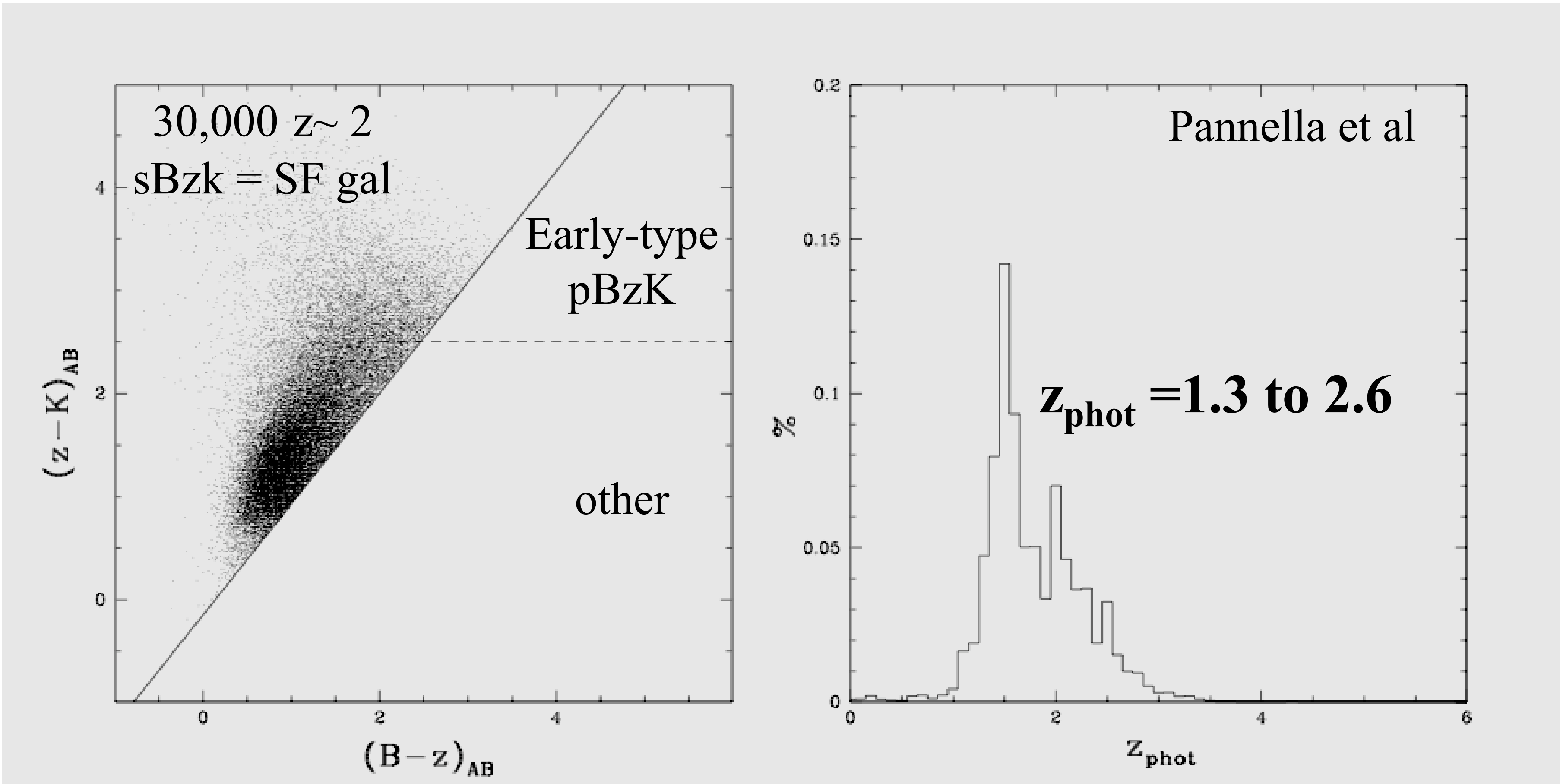
Daddi et al 2004



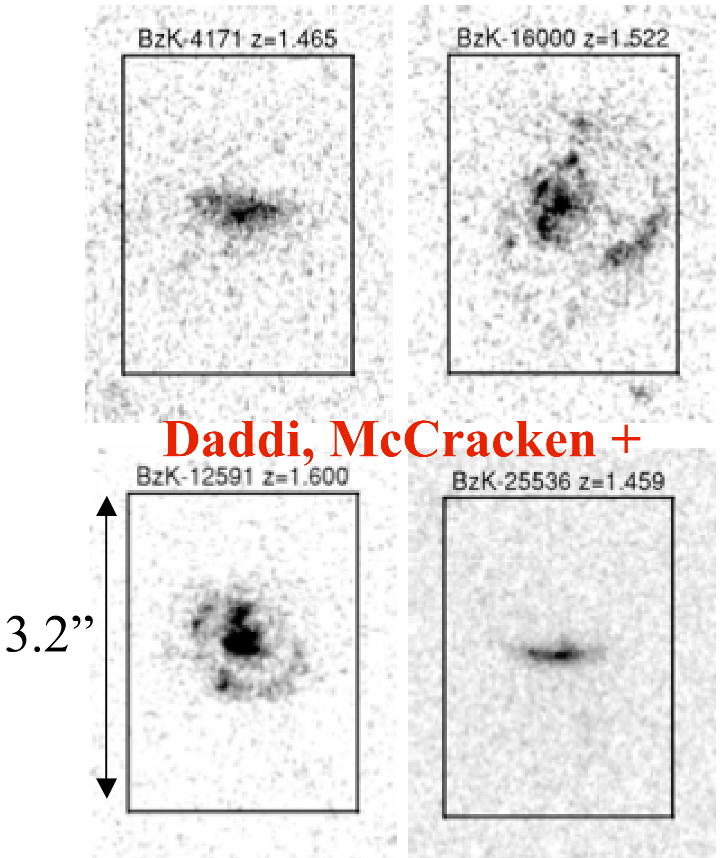


- near-IR selected: $K_{AB} \sim 23$
- $M_* \sim 10^{10}$ to 10^{11} M_o
- Density ~ few x10^{-4} Mpc^{-3} ~ 30x SMG
- Forming 'normal' ellipticals, large spirals?

30,000 sBzK galaxies in Cosmos (Daddi, McCracken+)

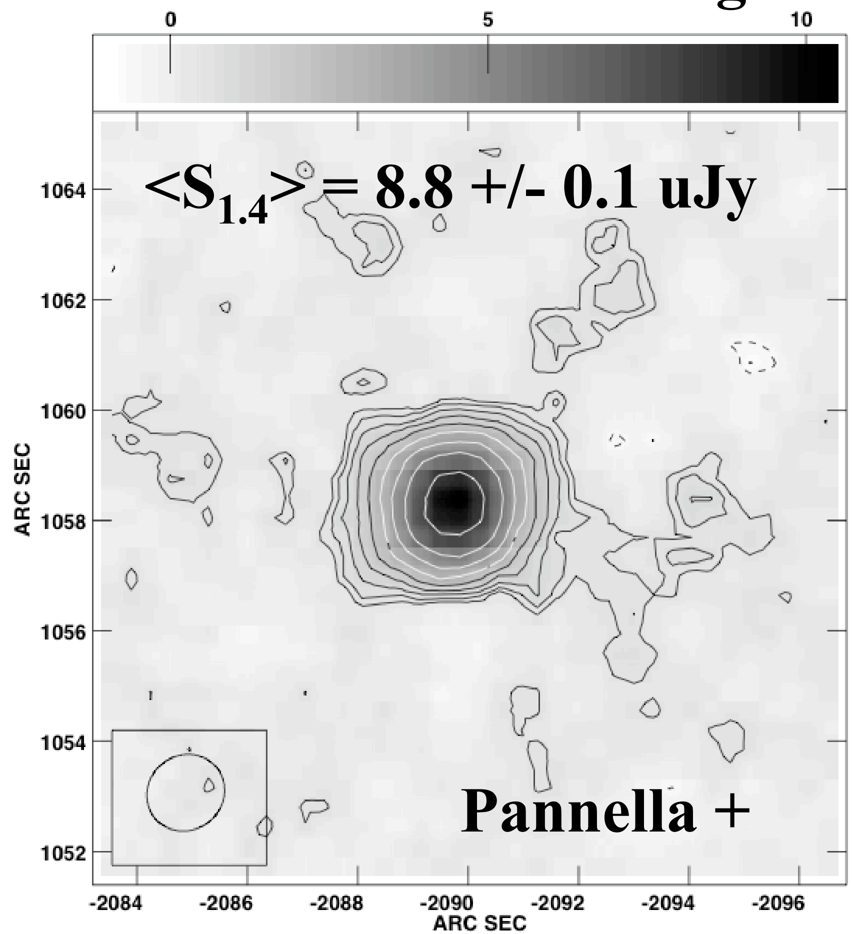


HST



HST sizes ~ 1” ~ 9kpc

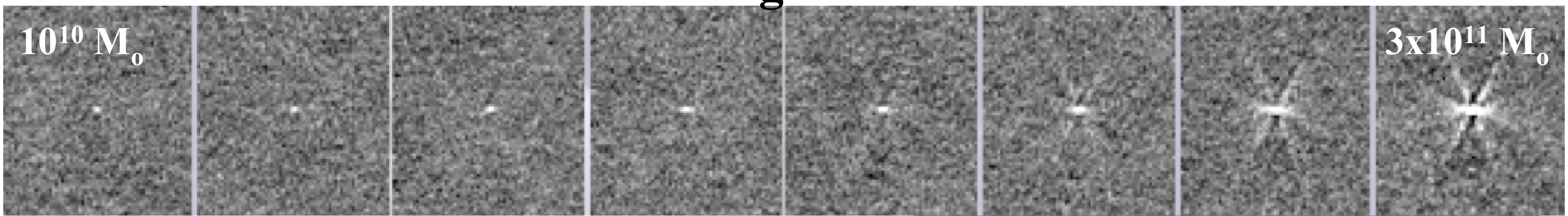
VLA radio stacking

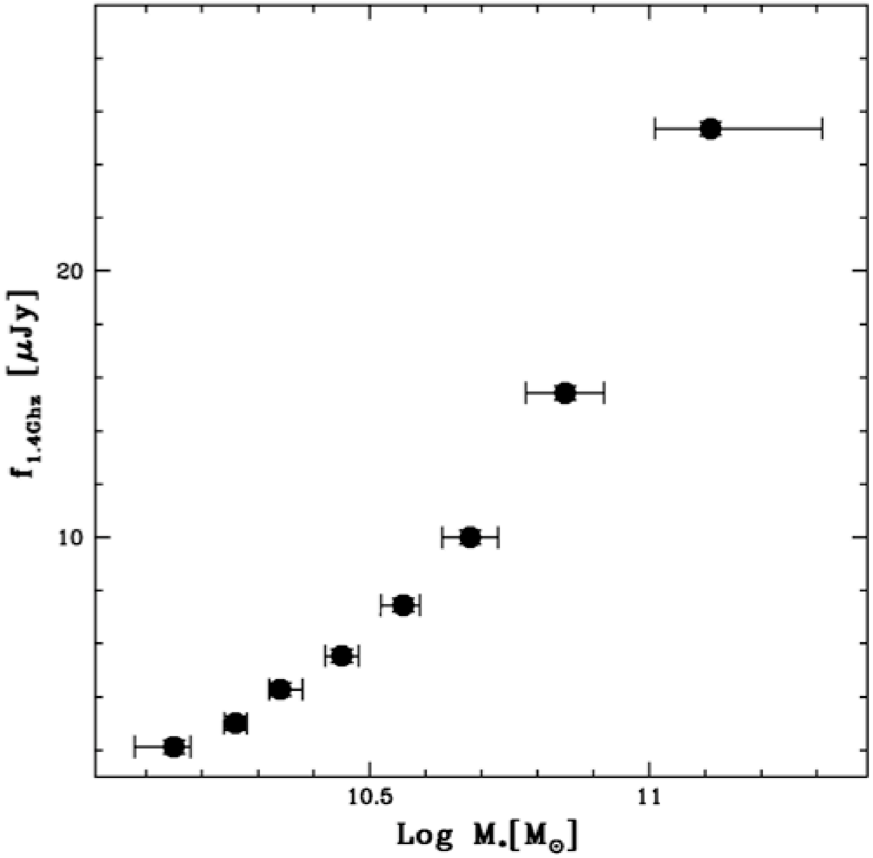


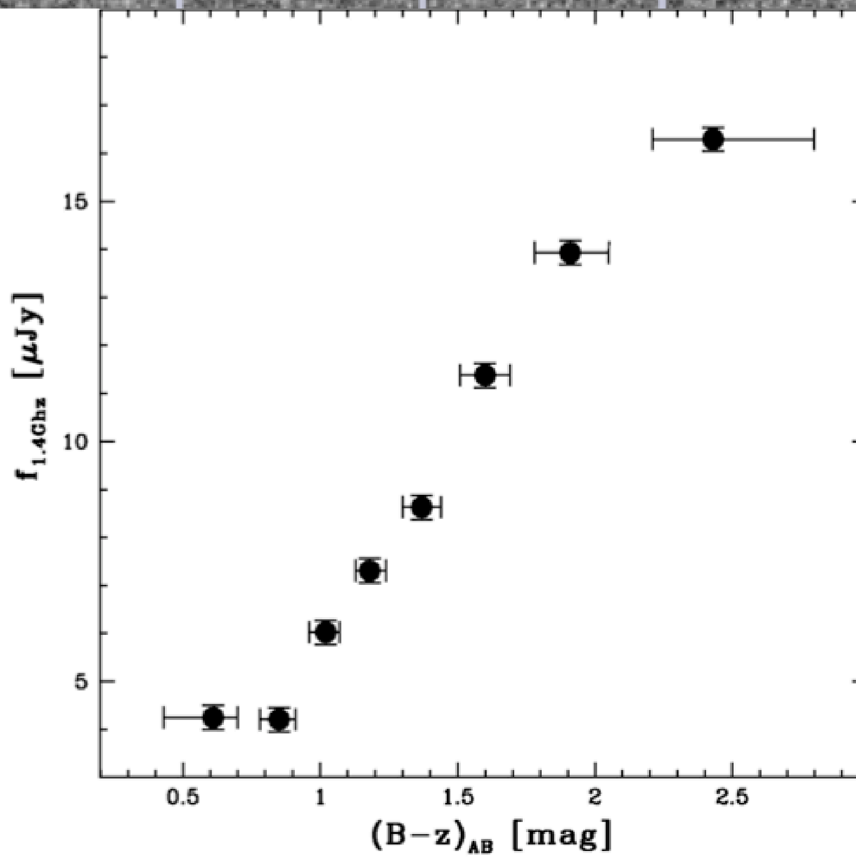
- $\langle$SFR$\rangle$ ~ 96 M_o yr^{-1}
- VLA size ~ 1”

SKA science before the SKA!

Stacking in bins of 4000



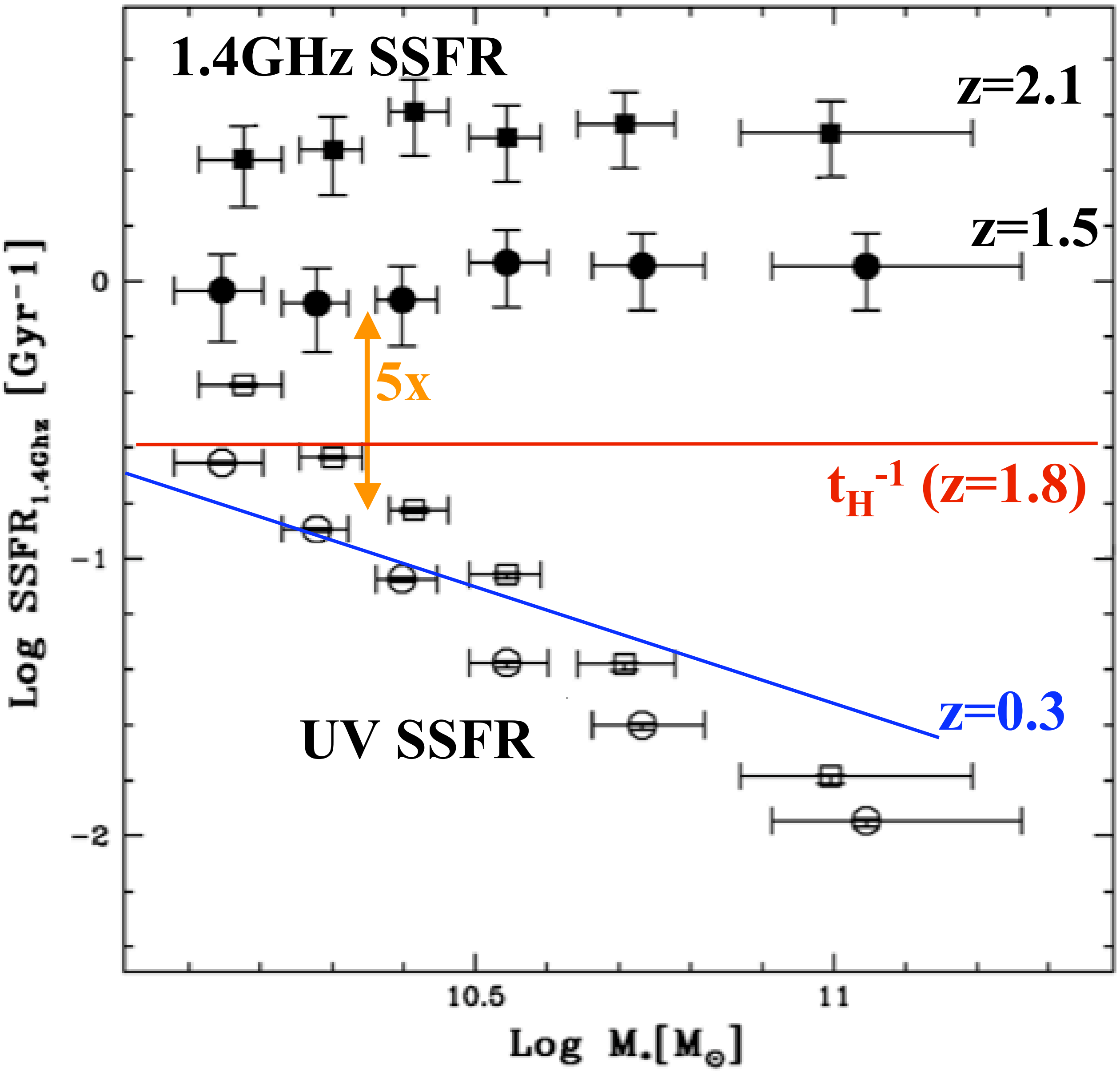




$S_{1.4}$ increases with M_* => SFR increases with stellar mass

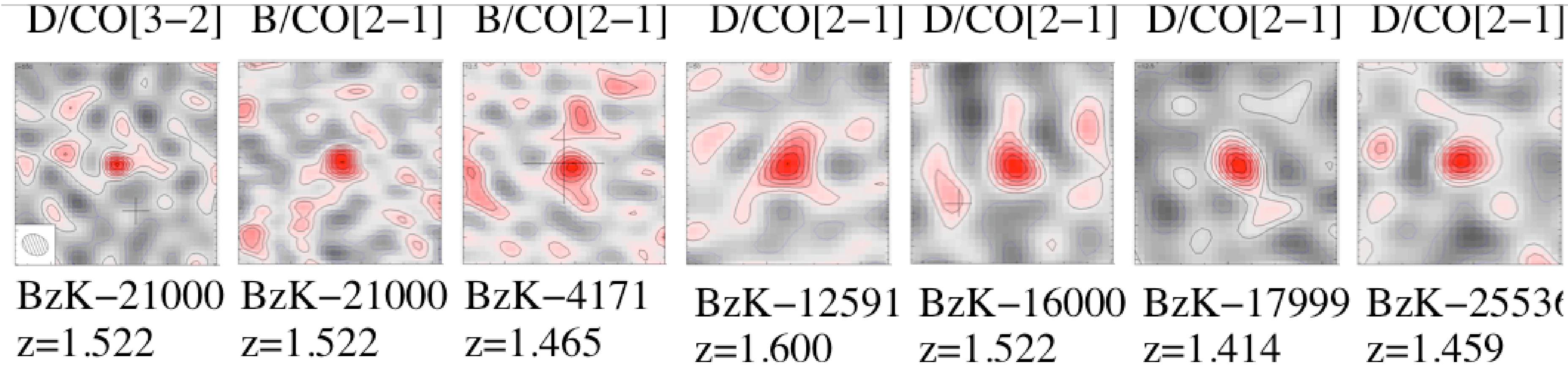
$S_{1.4}$ increases with B-z => dust extinction increases with SFR (or M_*)

Dawn of Downsizing: SFR/M$_*$ vs. M$_*$



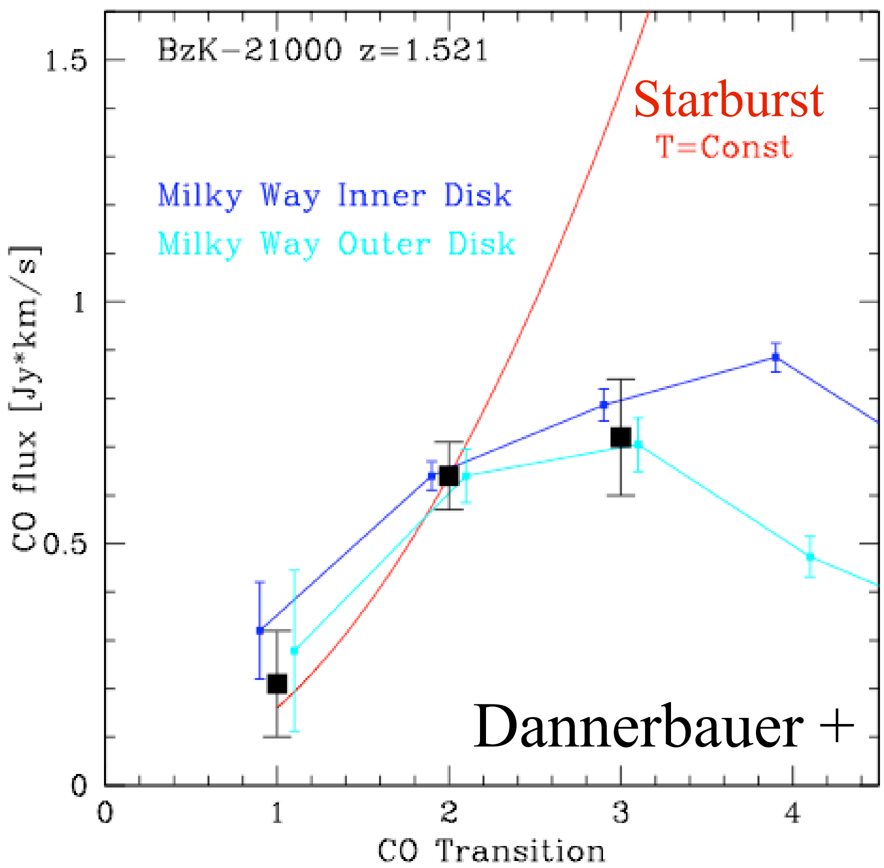
- SSFR increases with z
- SSFR constant with M$_*$, unlike z<1=> ‘pre-downsizing’
- z>1.5 sBzK well above the ‘red and dead’ galaxy line
- Extinction increases with SFR, M$_*$
- <factor 5> UV dust correction needs to be differential wrt SFR, M$_*$

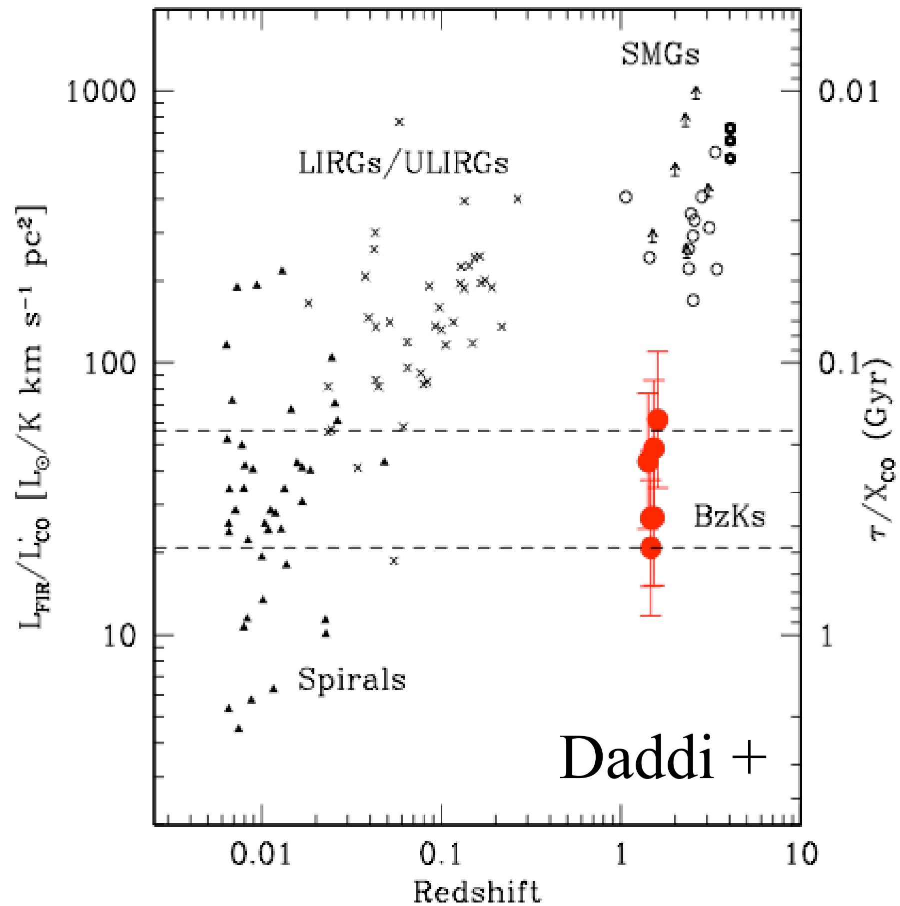
sBzK: not extreme starbursts, but massive gas reservoirs



Daddi + 2008

- **6 of 6 sBzK detected in CO with Bure**
- **Gas mass > 10^{10} M_o ~ submm galaxies, but**
- **SFR < 10% submm gal**
- **5 arcmin^{-2} (~50x submm galaxies)**





Excitation = Milky Way

FIR/L’CO = Milky Way

- Extreme gas rich galaxies without extreme starbursts
- Gas depletion timescales > 5 x10^{8} yrs

=> secular galaxy formation during the epoch of galaxy assembly

Blind molecular line commensal surveys

EVLA: CO 1-0 at z = 1.4 to 1.9 (48 to 40 GHz)

- FoV ~ 1 $arcmin^2$ => ~ 2 or 3 sBzK ($M_* > 10^{10}$ M_o)
- rms (10hr, 300 km/s) = 50 uJy => L'(CO) = 1.9e9 K km/s pc^2
- 4σ mass limit: $M(H_2) = 3\times10^{10}$ M_o (Galactic X factor)

=> Every 'Q-band' full synthesis will have ~ 1 sBzK CO detection

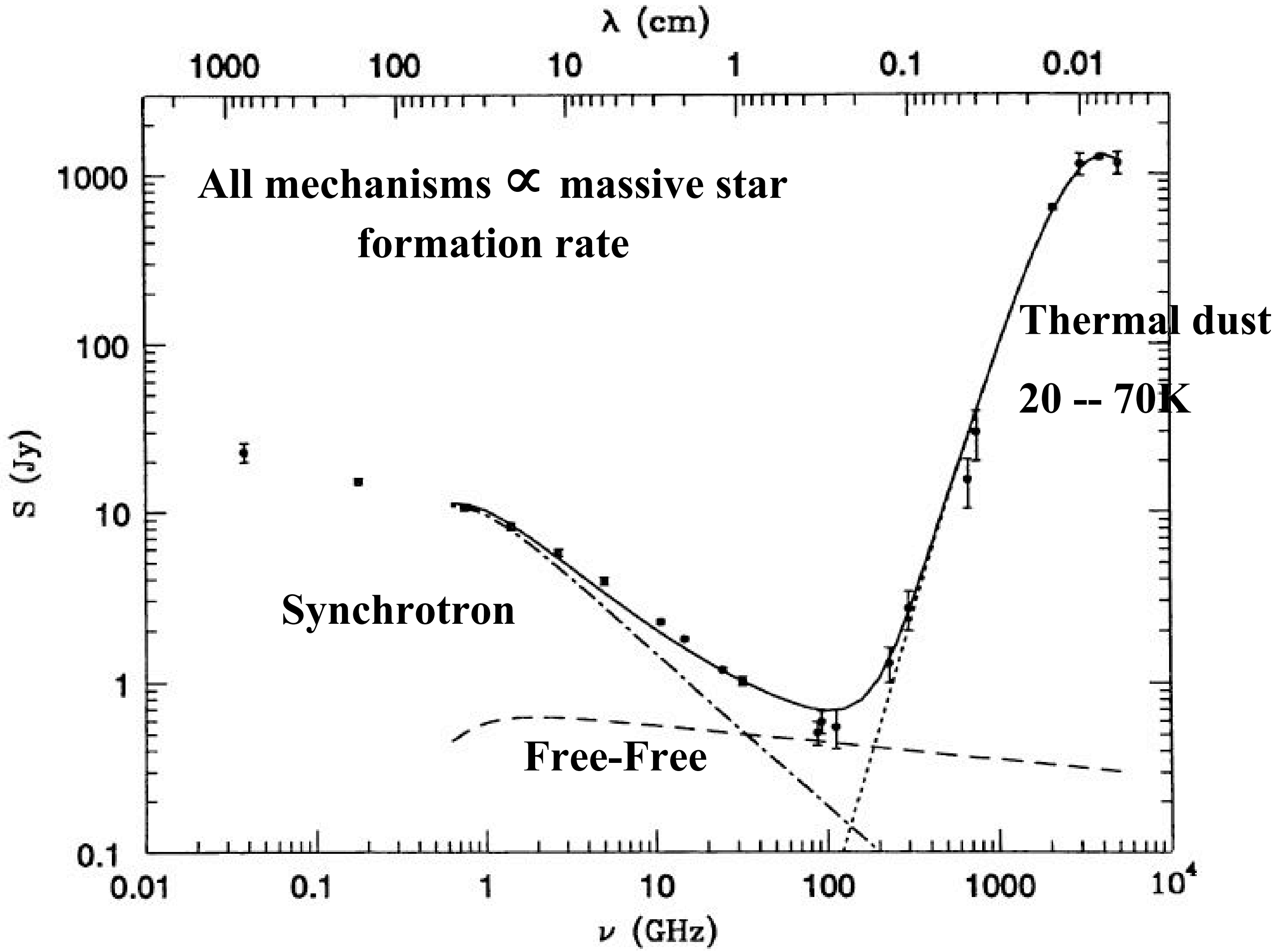
ALMA: CO 2-1 at z = 1.45 to 1.7 (93 to 85 GHz)

- FoV ~ 1 $arcmin^2$, but fractional BW (Δz) ~ 1/2 EVLA
- $S_{2\text{-}1}$ ~ $4\times S_{1\text{-}0}$ (in Jy) and rms (300 km/s) ~ 30uJy
- Mass limit ~ 5×10^9 M_o

=> Every 'Band 3' full synthesis will have ~ 3 sBzK CO detections


END (II)
ESO

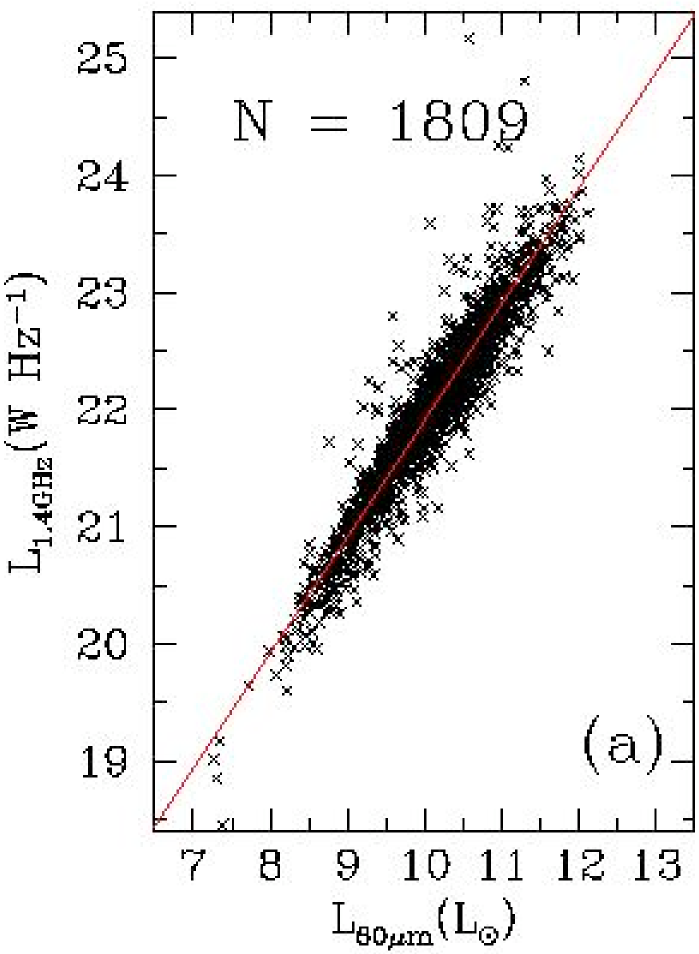
Radio through FIR spectrum of star forming galaxy (M82)

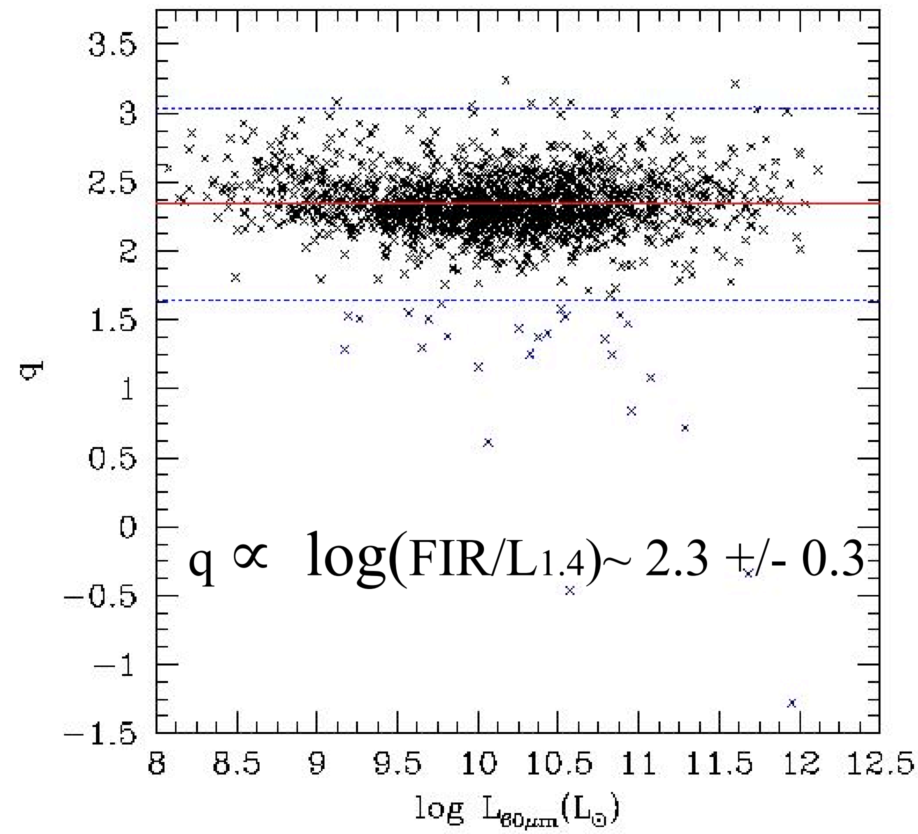


Total SFR in Mo/yr (0.1 to 100 Mo)

- SFR = 3e-10 L_{FIR} (L_o) (42 -- 122um) (Kennicutt 1998, ARAA)
- Only massive stars (>5Mo) => factor 5.6 lower

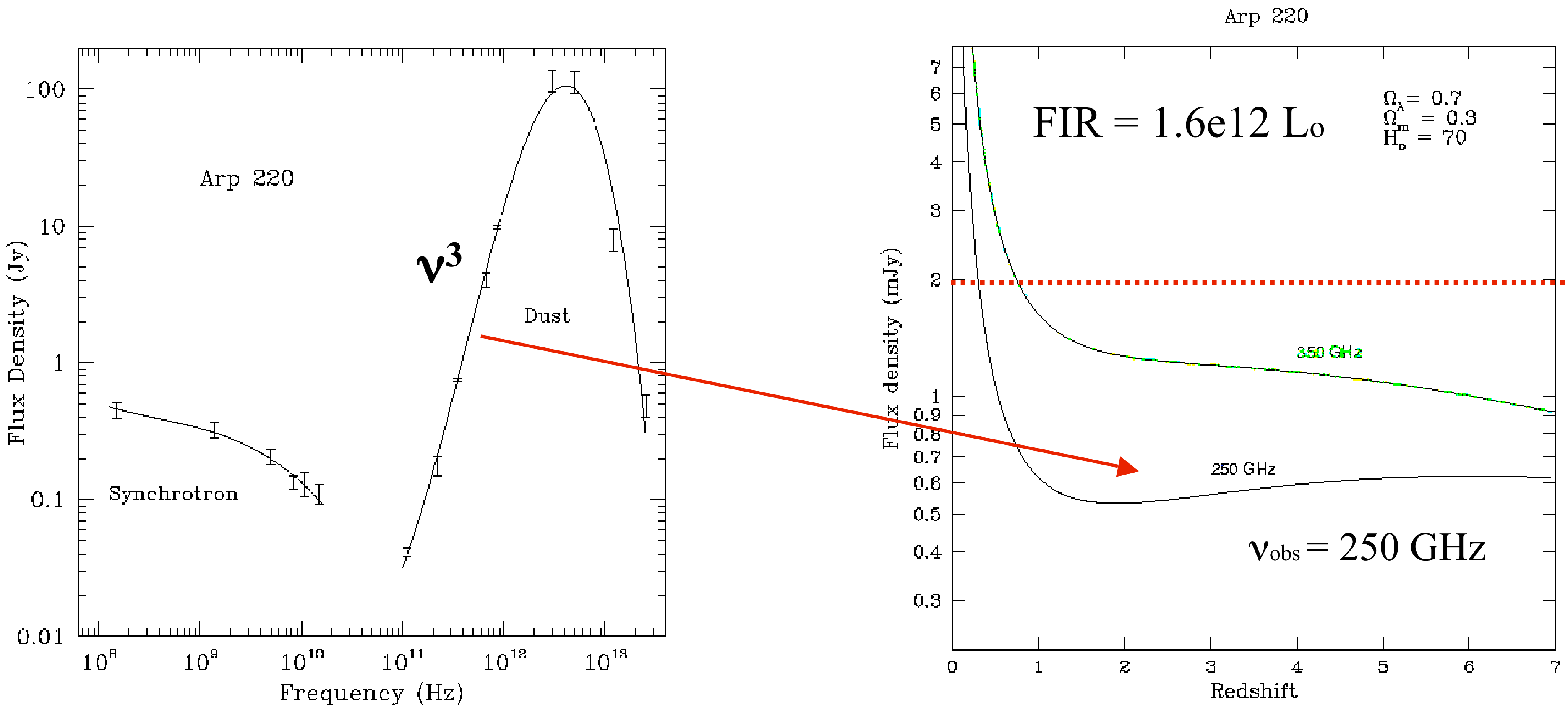
Radio-FIR correlation: NVSS/IRAS galaxies (Yun + 02)





SFR (M_o/yr) = 6e-29 $L_{1.4}$ (erg/s/Hz)

Magic of (sub)mm: distance independent method of studying objects in universe from z=0.8 to 10

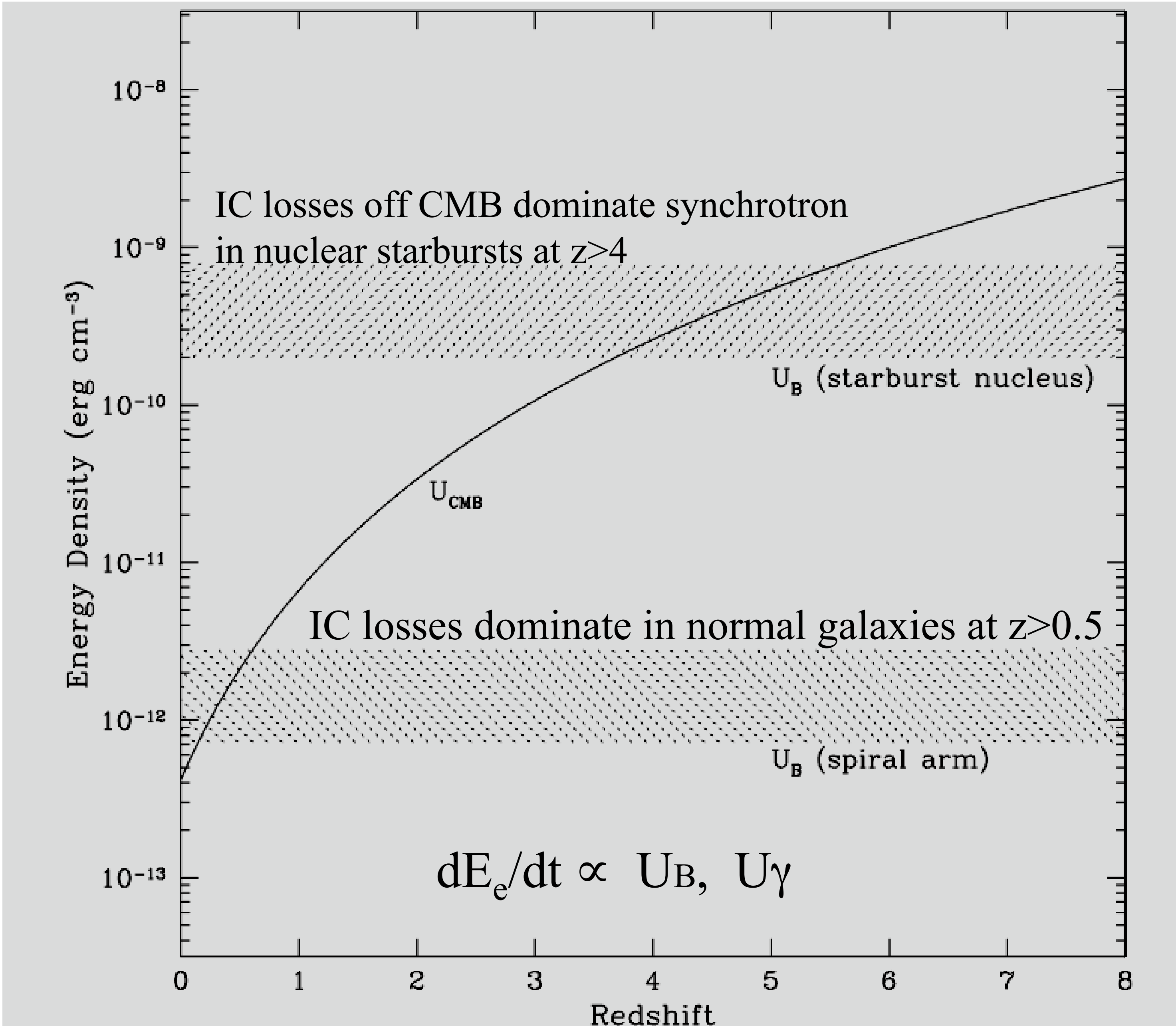


Similar for spectral lines (eg. CO) but not as favorable due to:

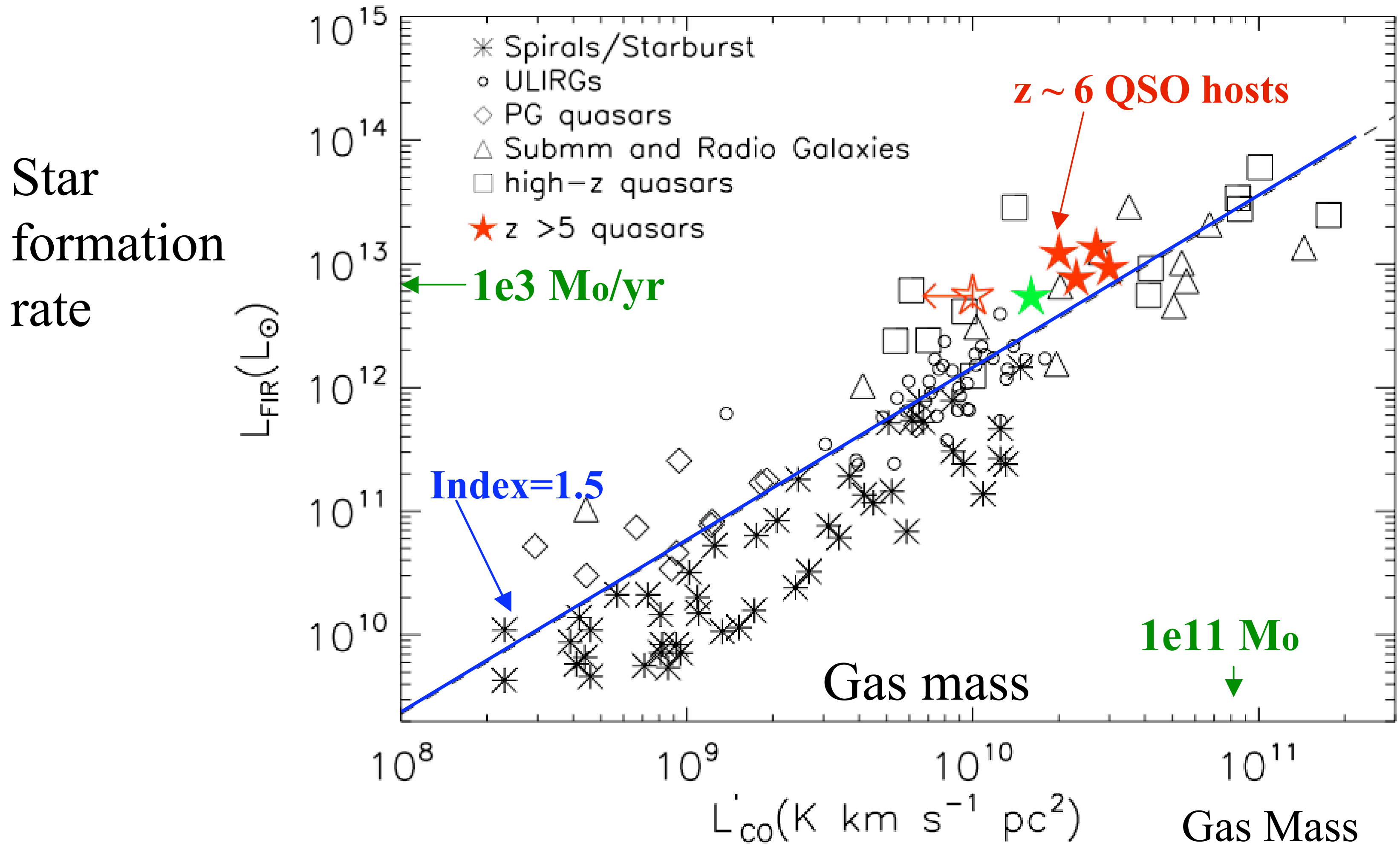
a. Modified RJ power law index for lines ~ 2 lines, while for dust ~ 3 to 4

b. Higher order lines may be subthermally excited due to density limits

Break-down of radio-FIR correlation: inverse Compton losses off CMB?

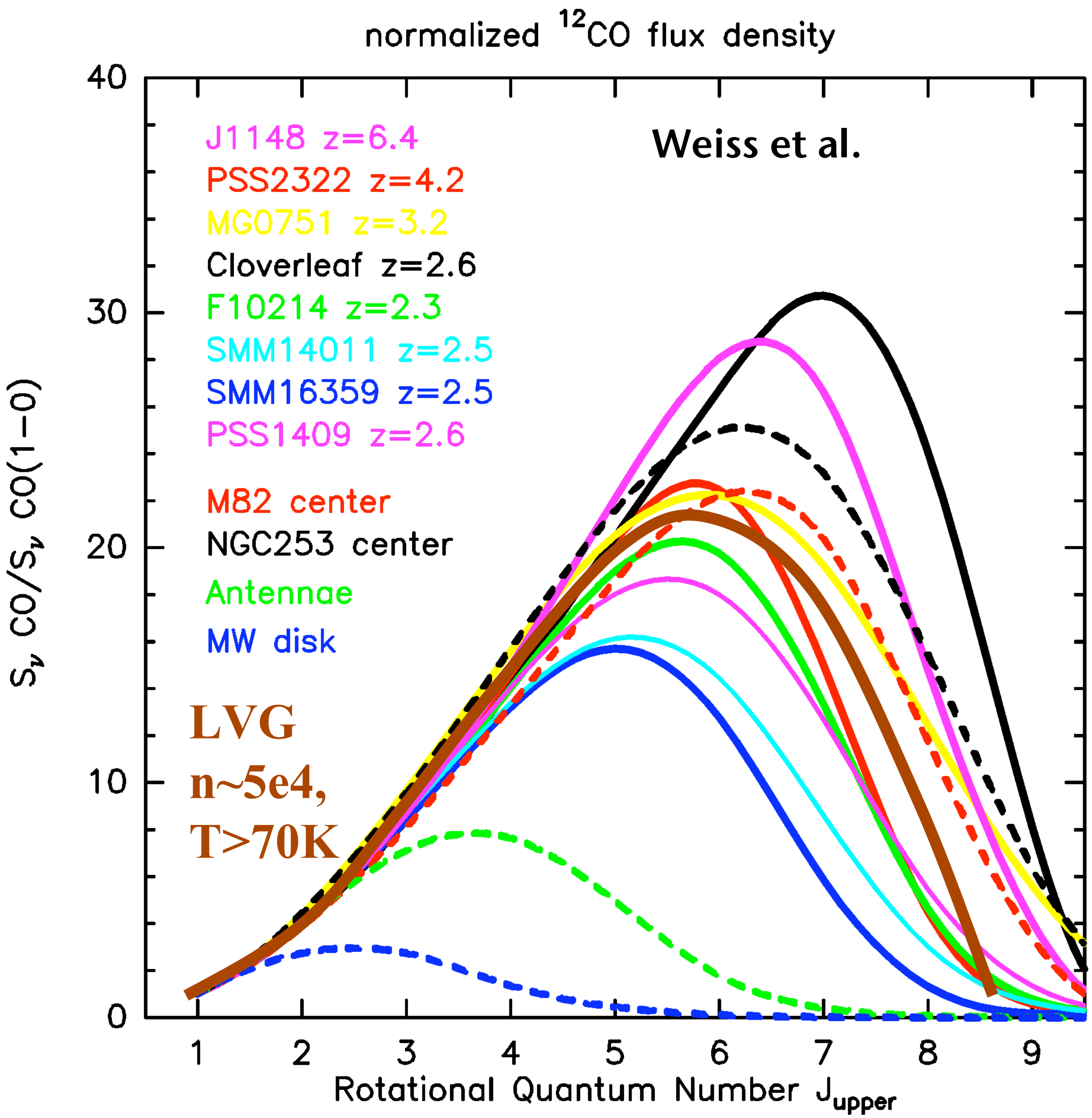


Dust => Gas: LFIR vs L'(CO)



- Massive gas reservoirs > 10^{10} M_o > 10 x MW
- SFR > 1000 M_o/yr

Summary CO Line SEDs

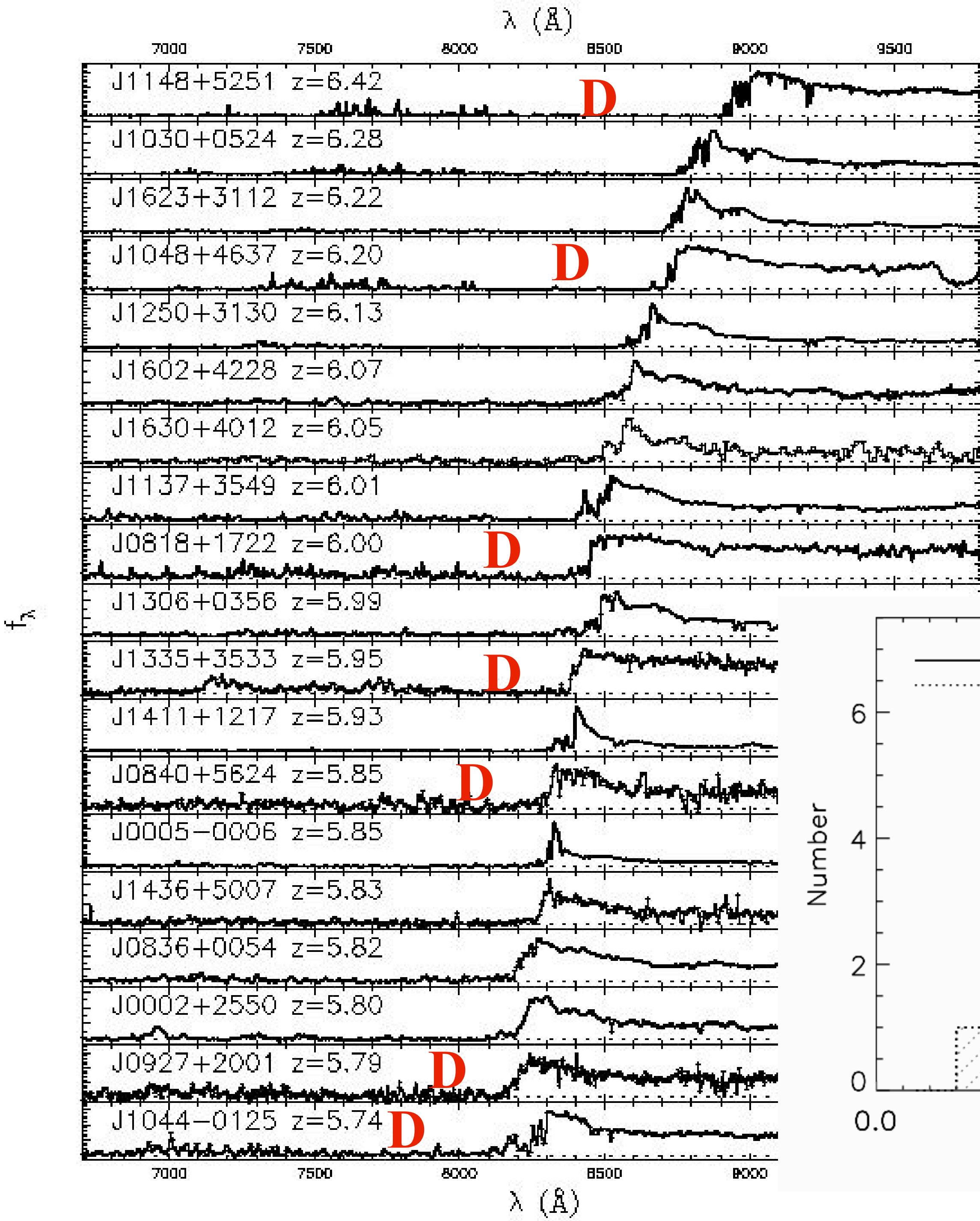


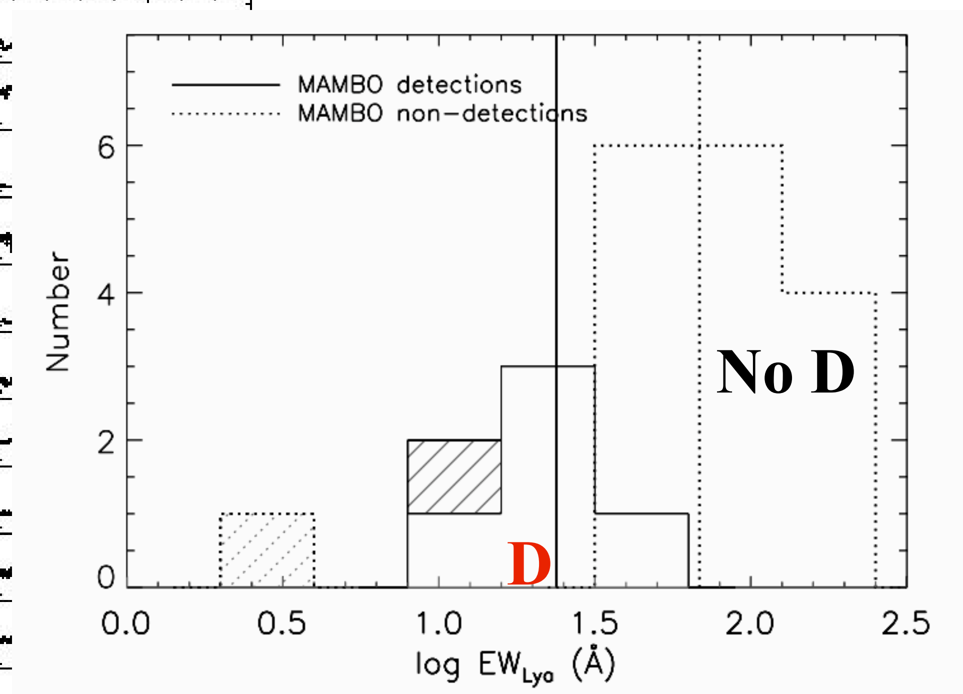
- High z: T> 50K, n> 1e4/cm^3
- MW: T ~ 20K, n ~ 1e3/cm^3
- Similar to SB nuclei, only 10-100x luminosity => 10-100x area.
- Selection effect -- high z systems discovered with mm telescopes => high order transitions.
- Need cm searches for normal excitation galaxies.

Anti-correlation of FIR luminosity and Lya EW

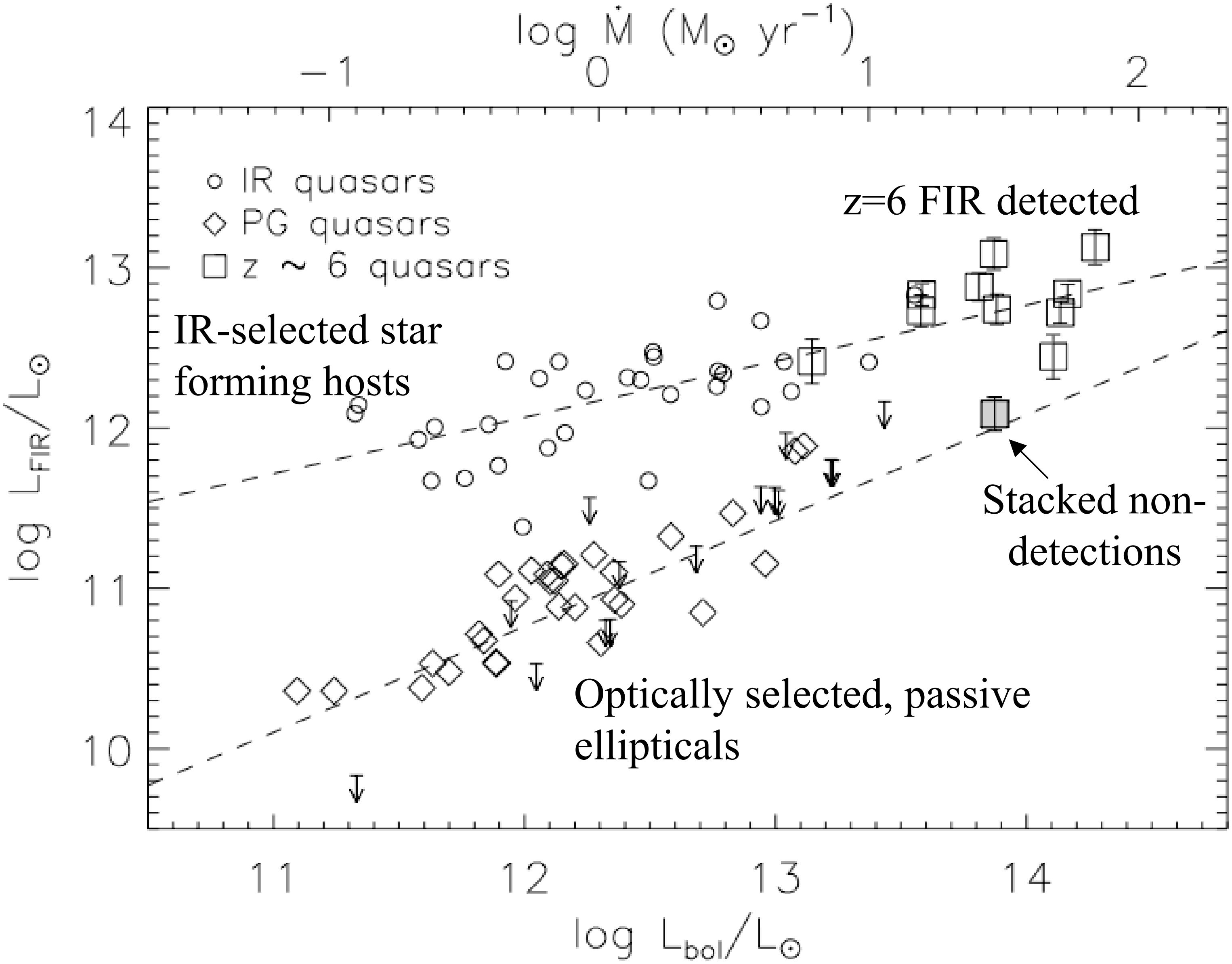
Dust => Log EW < 1.5

No dust => Log EW > 1.5



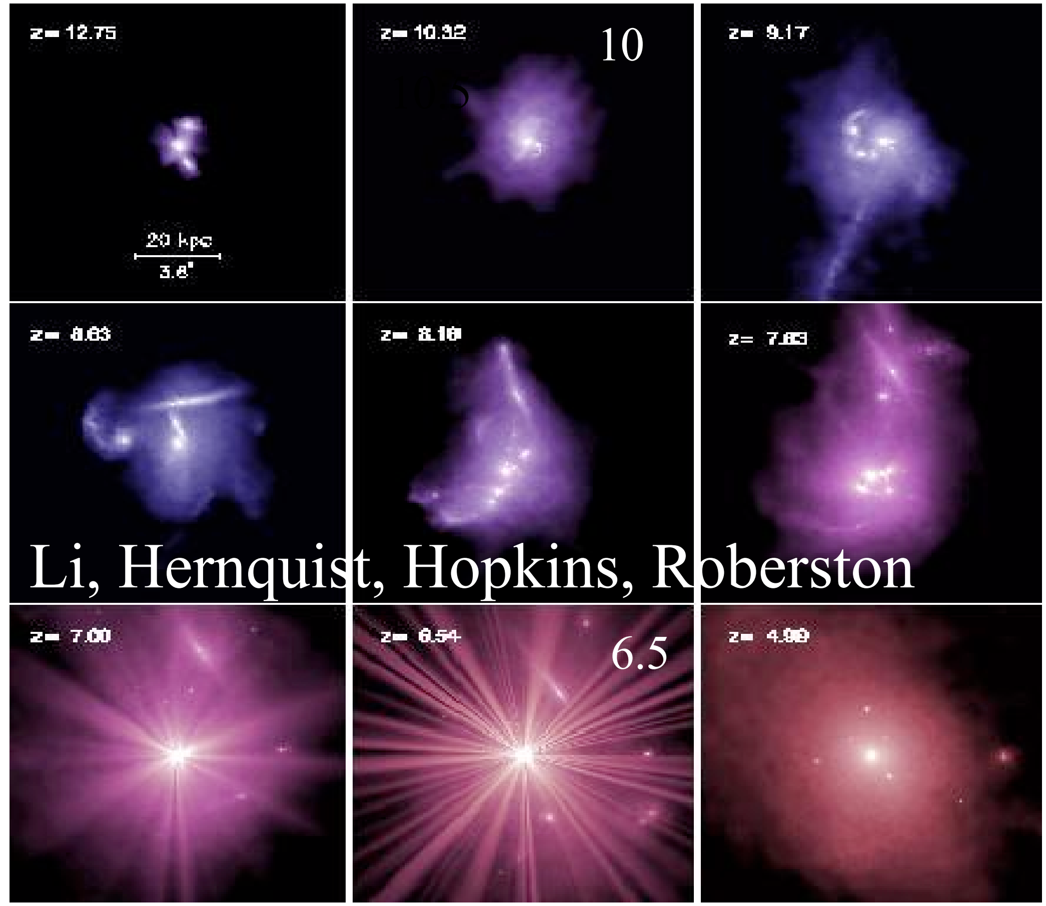


FIR-detected: star forming hosts



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

- Multi-scale simulation isolating most massive halo in 3 Gpc^3 (co-mov)
- Stellar mass ~ 1e12 Mo forms in series (7) of major, gas rich mergers from z~14, with SFR ~ 1e3 - 1e4 Mo/yr
- SMBH of ~ 2e9 Mo forms via Eddington-limited accretion + mergers
- Evolves into giant elliptical galaxy in massive cluster (3e15 Mo) by z=0
- Generally consistent with 'downsizing'



- Rapid enrichment of metals, dust in ISM (z > 8)
- Rare, extreme mass objects: ~ 100 SDSS z~6 QSOs on entire sky
- Integration times of hours to days to detect HyLIGRs