An introduction to extragalactic (sub)mm astronomy: dust, gas and star formation at high redshift

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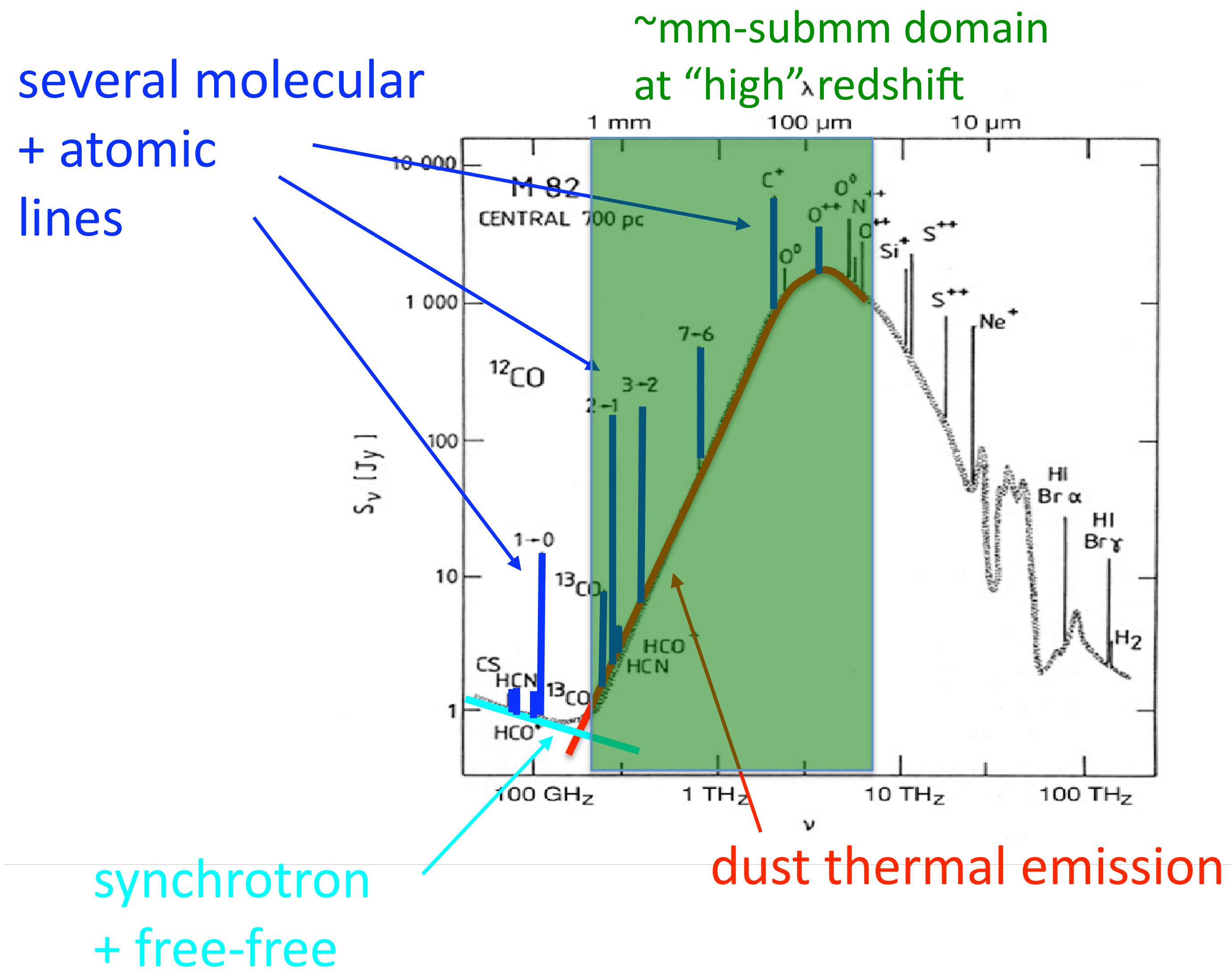
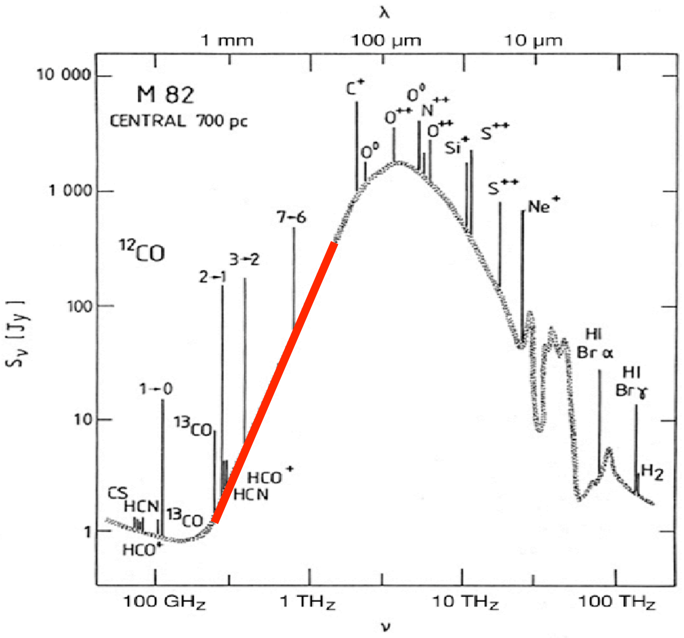
IR-mm spectrum of a starburst galaxy





Dust thermal emission

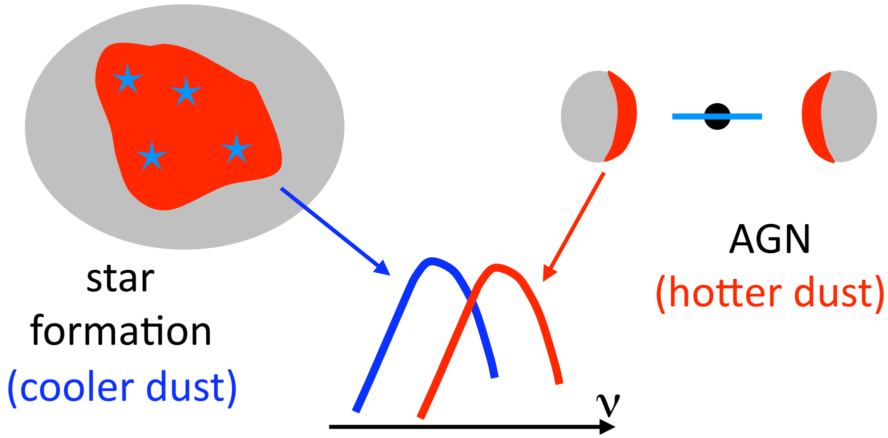
Dust is mostly heated by UV photons

IR SED depends from:

emissivity

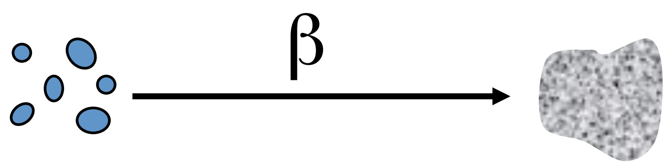
temperature distribution

$$S_\nu = \nu^\beta B(\nu,T)$$



Temperature depends on the strength of UV radiation field, but also on emissivity

Emissivity depends on the dust grain properties (~size, to first order)



Dust thermal emission in high-z galaxies useful to:

- Detect high-z galaxies (especially the dust obscured ones)

- Measure the star formation rate (extinction-free):

  If dust heated by young stars

  $L_{FIR} \sim L(UV)_{*} \sim SFR$

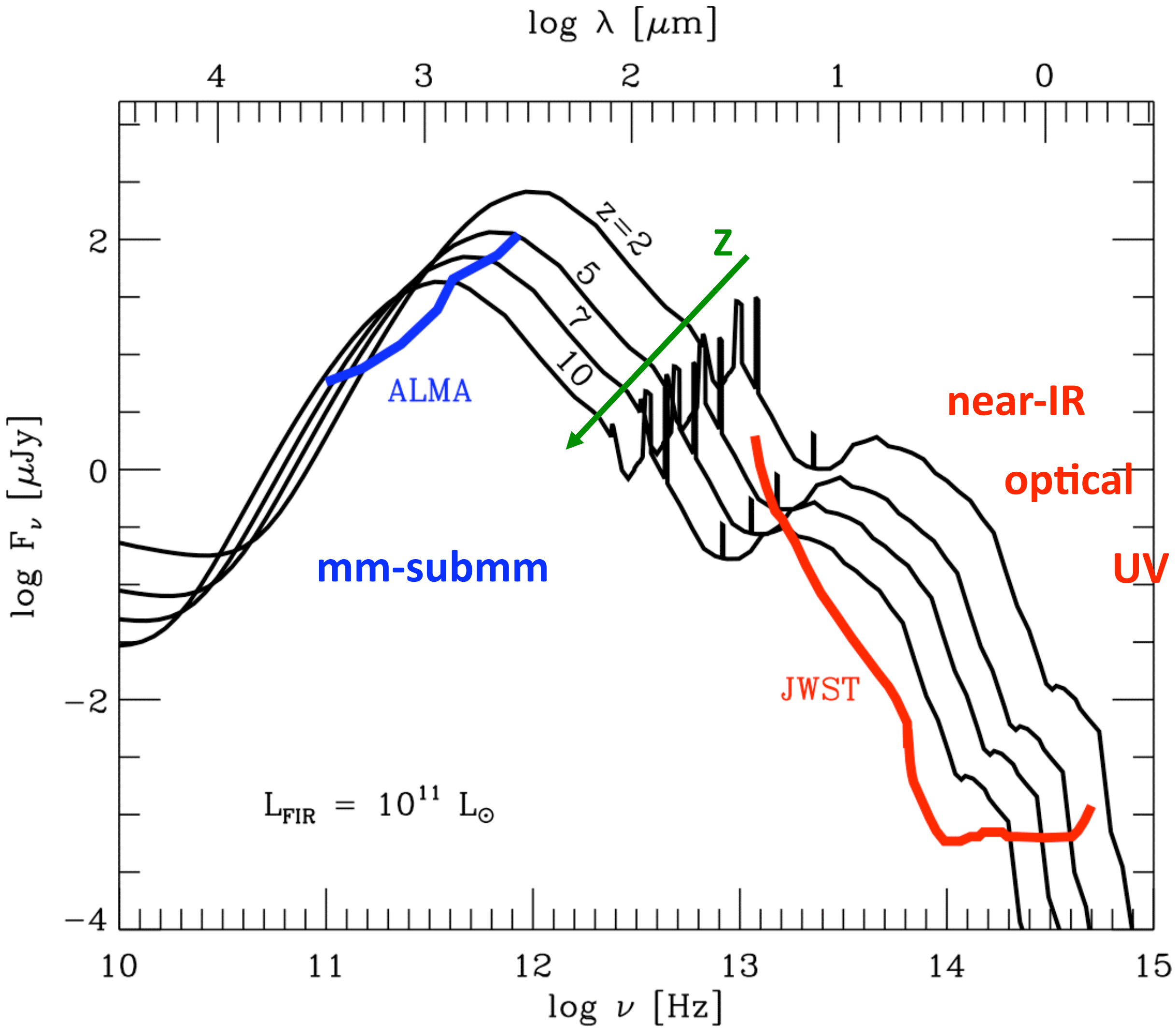
  (actually depends on history of SF & IMF)

$$\dot{M}_{\rm SF} = \delta_{\rm MF}\,(L_{\rm FIR}/10^{10}\,L_\odot)\;\;M_\odot\;{\rm yr}^{-1}$$

- Measure dust mass

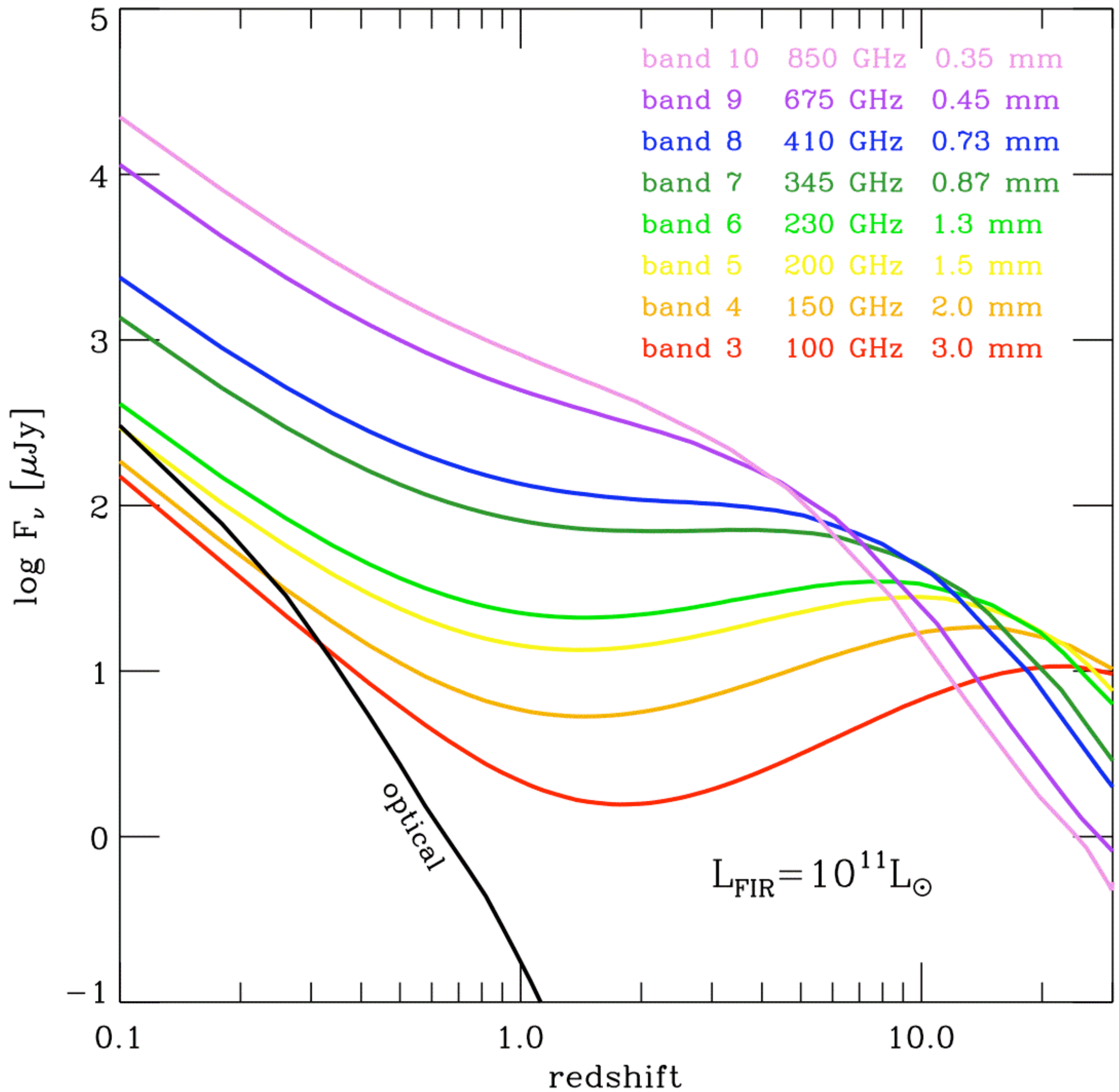
$$M_{\rm d} = \frac{S_{250}\,D_{\rm L}^2}{(1+z)\,\kappa_{\rm d}(\nu_{\rm r})\,B(\nu_{\rm r},T_{\rm d})}$$

Distant galaxies



Strong negative K-correction at mm-submm wavelengths that compensates for cosmological dimming:
the flux observed at λ~1mm is nearly constant

Observed flux for a given template and luminosity as a funciton of redshift

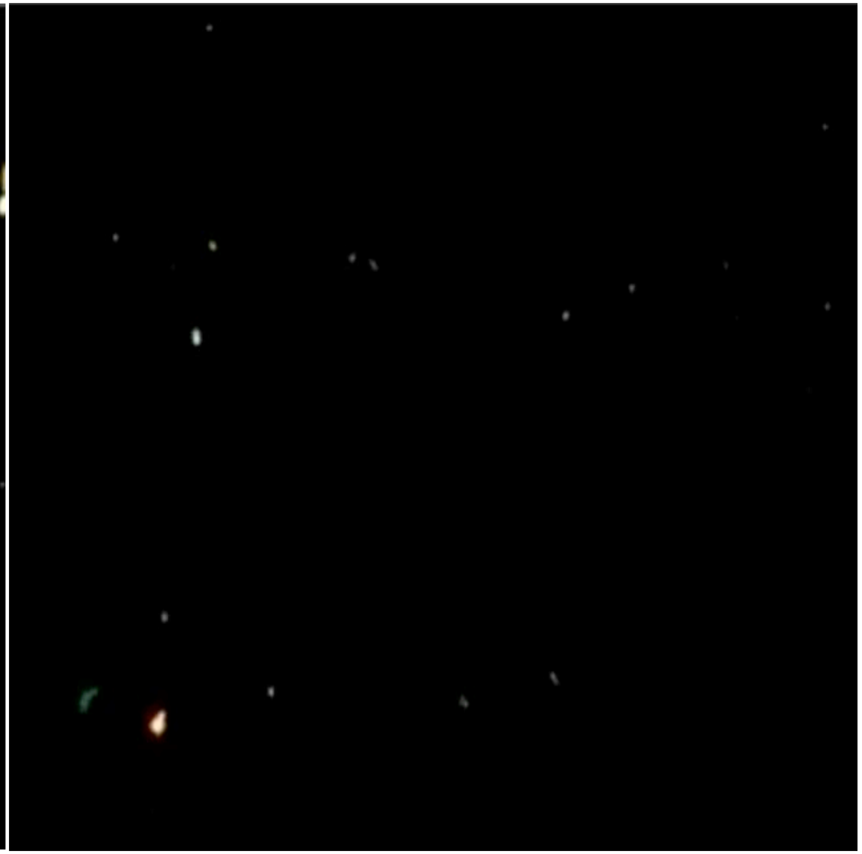


This makes the mm-sky at a given flux much more populated by high-z sources than low-z sources (just the opposite of the optical)

Deep optical field (HDF): rich in low-z galaxies, poor in high-z galaxies.

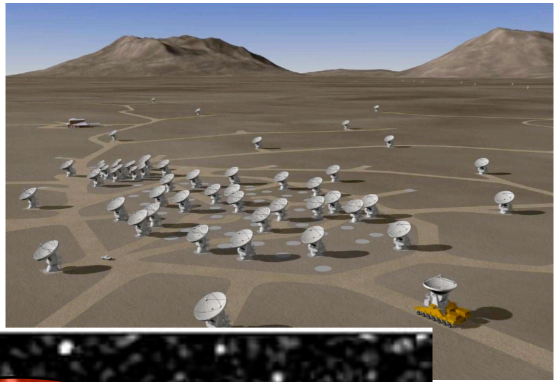
(12 days of integration)

z<1.5

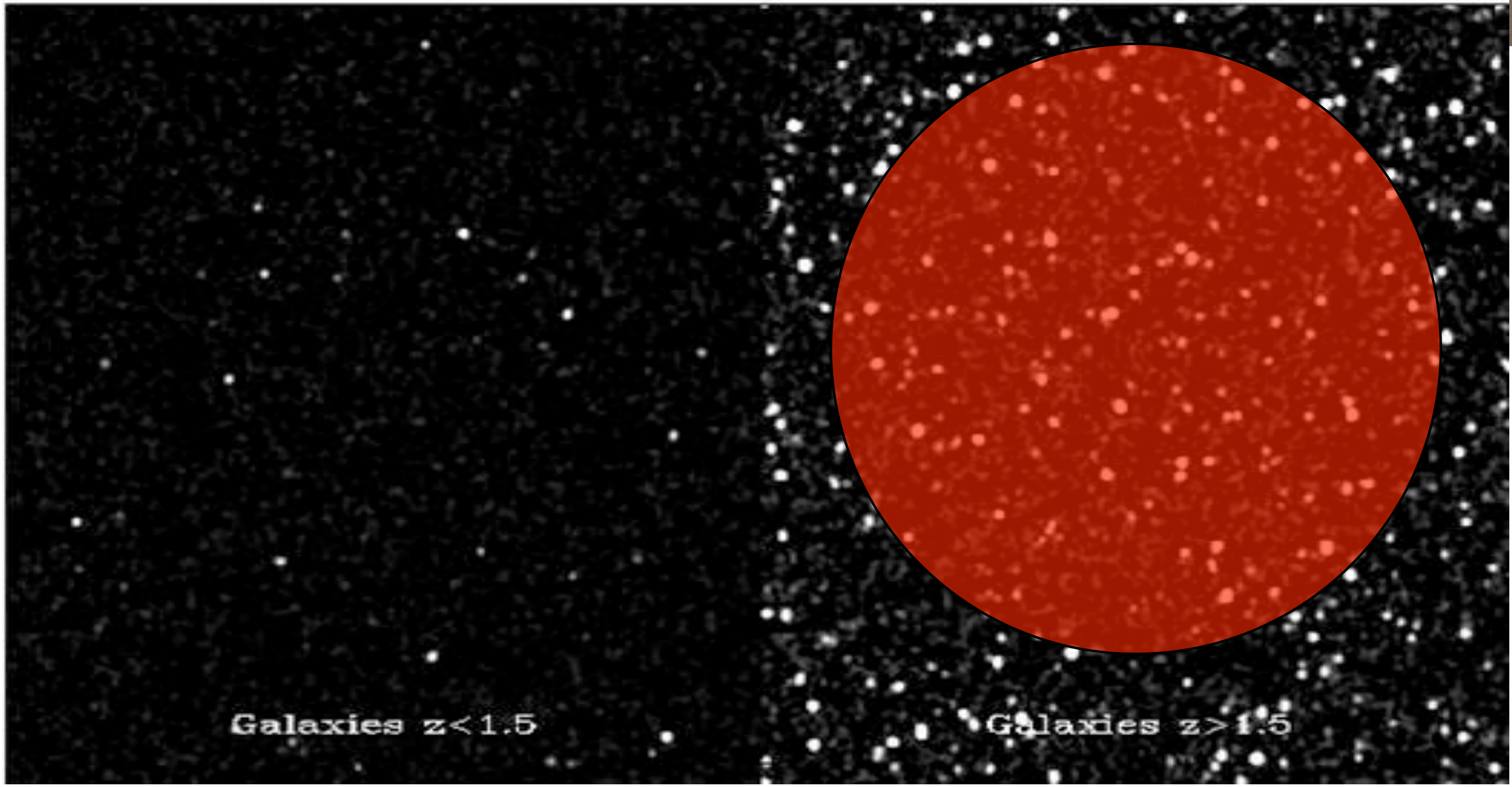


z>1.5

ALMA deep field: poor in low-z galaxies, rich in high-z galaxies.



simulation 3 days of integration 4'x4' arcmin

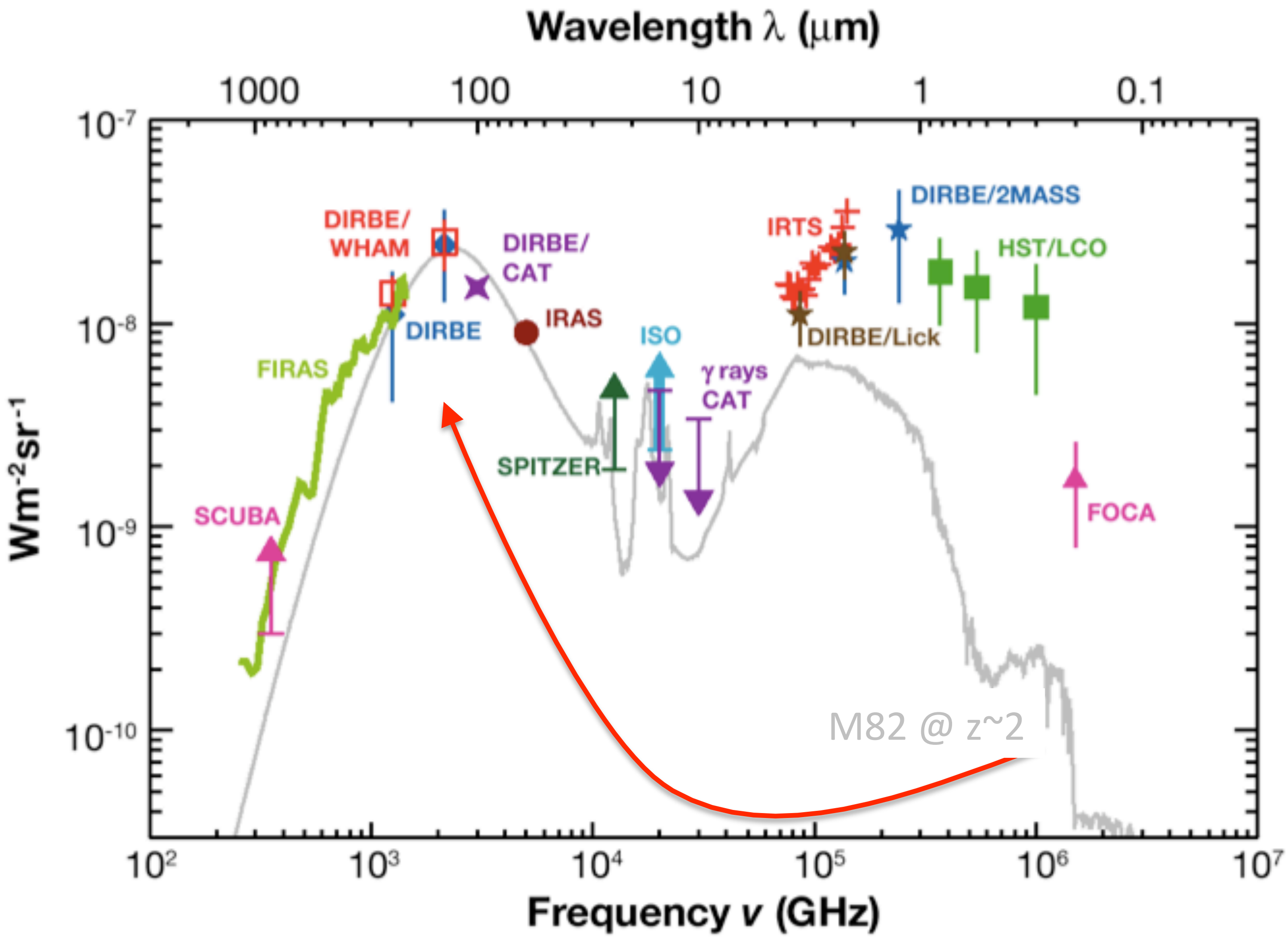


z<1.5

z>1.5

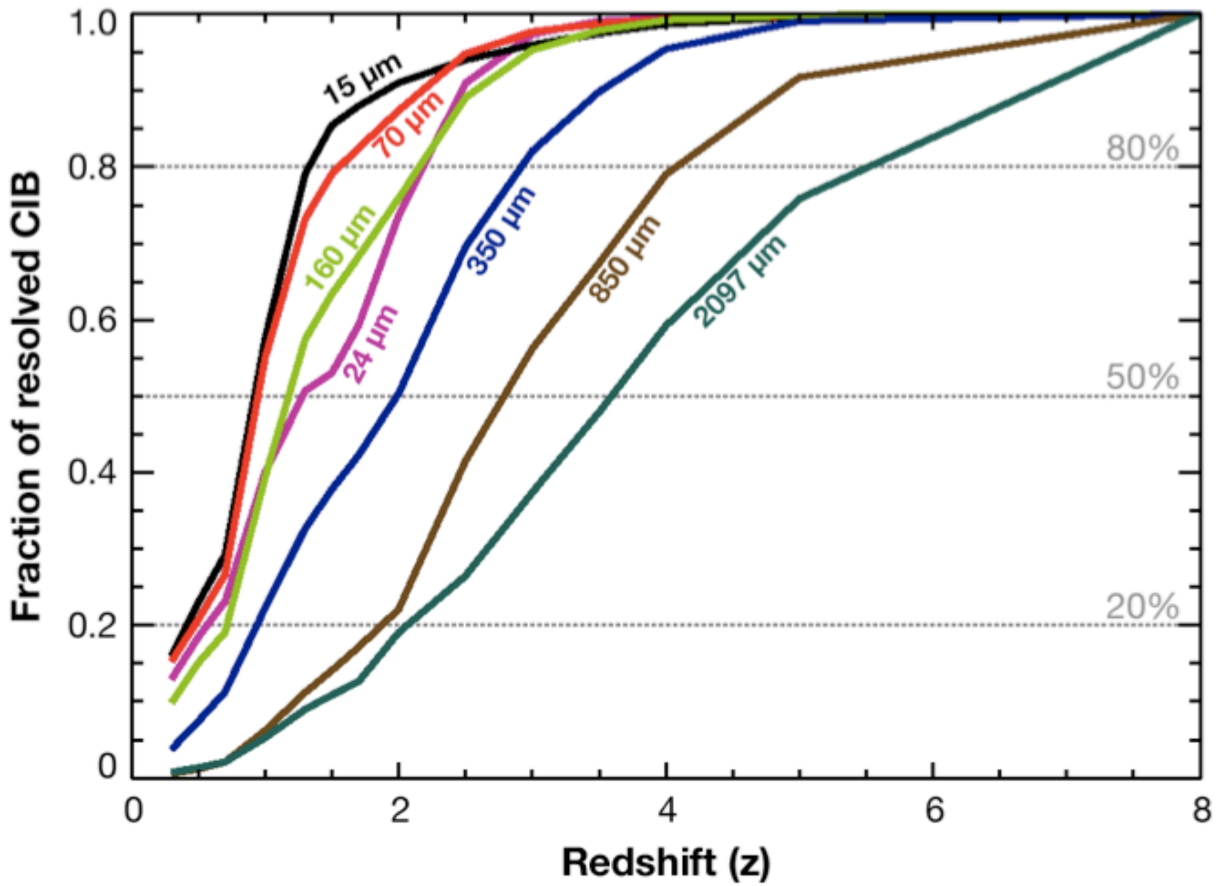
ALMA not available yet… we still have a very limited view of the mm-submm universe… we do know the integrated light from these sources: the far-IR/mm background

Cosmic Infrared Background (CIB)



Powered mostly by star formation

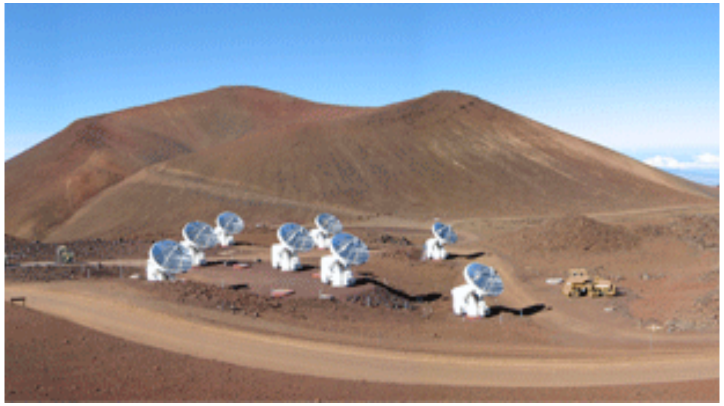
Expected (and partially observed)
redshift distribution
of sources resolving the CIB



what has been achieved with current facilities so far

ALMA not available yet,
but sensitive mm-submm interferometers are already available

IRAM PdBI
6 x 15m antennas
max ang. res = 0.35”
λ= 1-3 mm
(highest sensitivity)



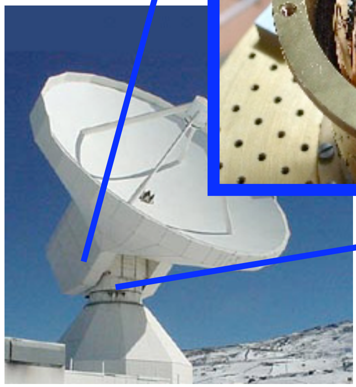
SMA
8 x 6m ant.
λ= 350μm-850μm-1mm
max ang. resol. = 0.1”

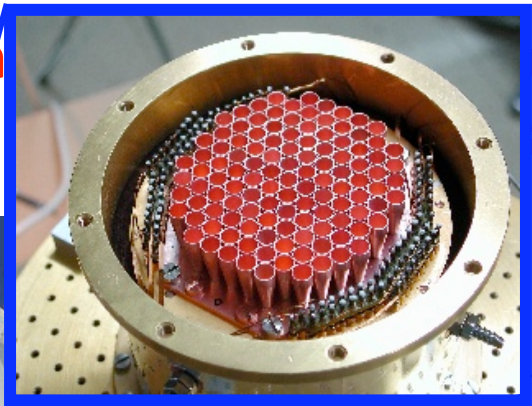
CARMA
6 x 10m + 10x6m antennas
max ang. res = 0.1”
λ= 1-3 mm

NMA
6 x 10m ant.
λ = 1mm-3mm
max ang. res. = 1”

However, small field of view (<1’) => mostly aimed at followup of individual sources (and mostly for line mapping and detection)

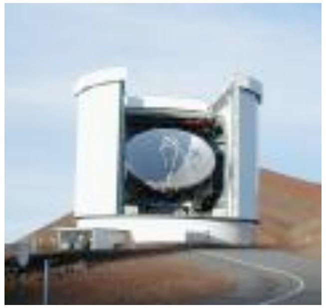
mm ... ostly performed with single dish telescopes equ ... ays of bolometers



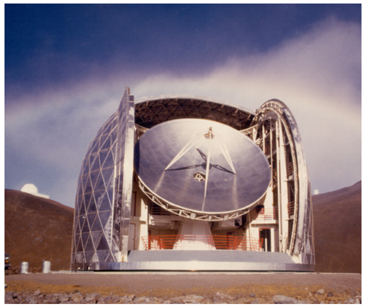


...mm
MAMBO: 117 x bol. array
FOV ~ 3 arcmin^2

APEX 12m
$\Delta\lambda$ = 350μm-1mm
beam ~ 18” at λ=870 μm
LABOCA: 295 x bol. array
FOV ~ 102* arcmin^2
+SABOCA at λ=450 μm



JCMT 15m
$\Delta\lambda$ = 450μm-1mm
beam ~ 15” at λ=850 μm
SCUBA-2: 10^4 x bol. array
FOV ~ 55 arcmin^2
(12xSCUBA)



CSO 10.4m
$\Delta\lambda$ = 350μm-1mm
beam ~ 9” at λ=350 μm
SHARC-II: 384 x bol. array
FOV ~ 2.5 arcmin^2

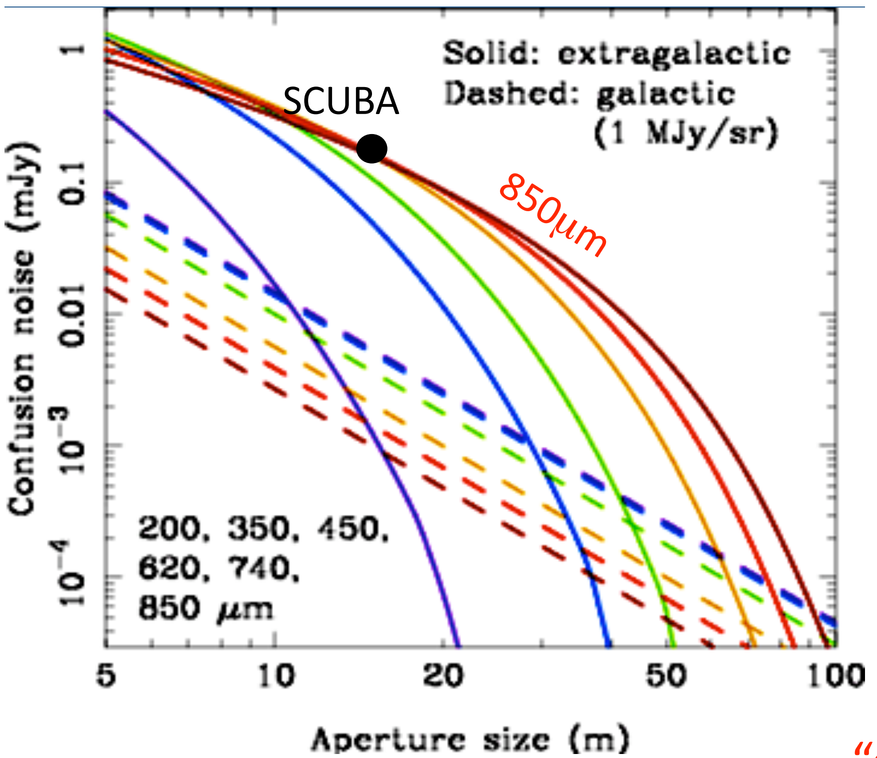
(see Maiolino 2008 for details and a complete list of facilities)

The main problem of these facilities for high-z studies is the very low angular resolution, typically ~15"

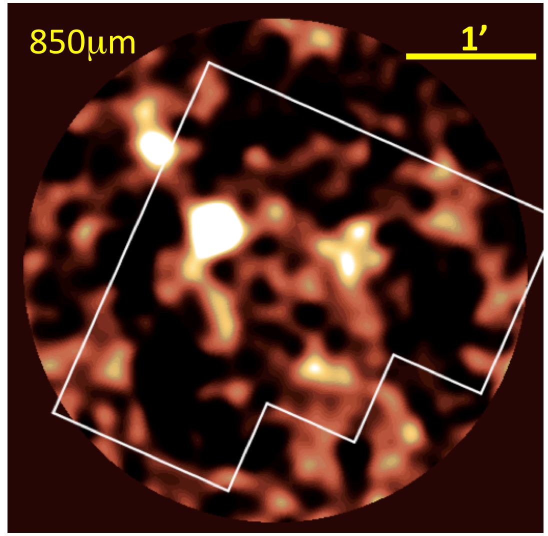
⇒ **Sensitivity limited by "confusion"**

⇒ **Difficult to identify the counterparts at other wavelenghts (especially in the optical for the redshift determination)**

"**confusion**":
below a certain flux limit (which depends on the beam size) most sources blend together

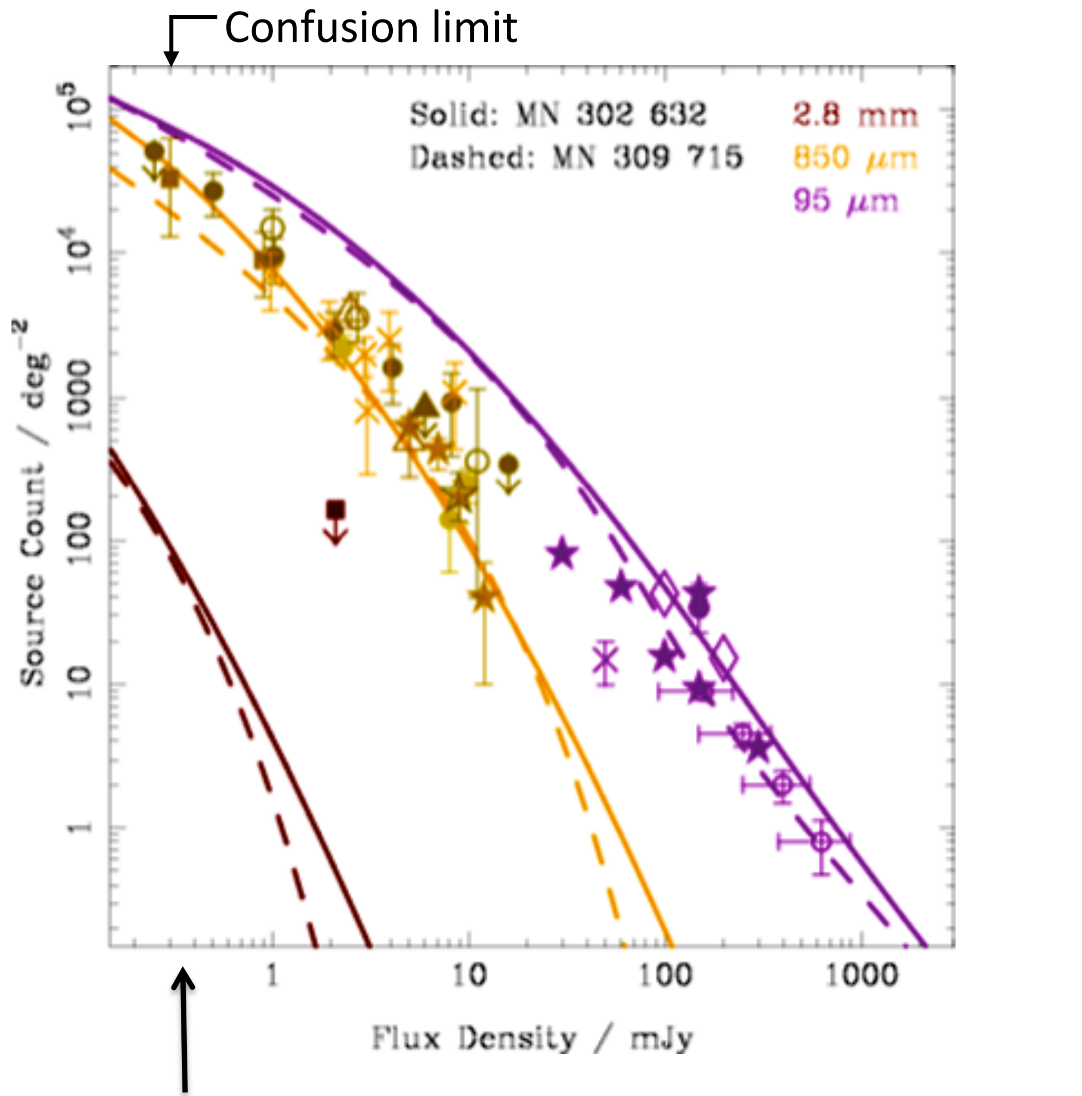


deep SCUBA map (HDF)



"confusion" is not a problem for inteferometers, but small field of view

Initially submm (SCUBA 850μm) surveys high-z surveys provided source number counts

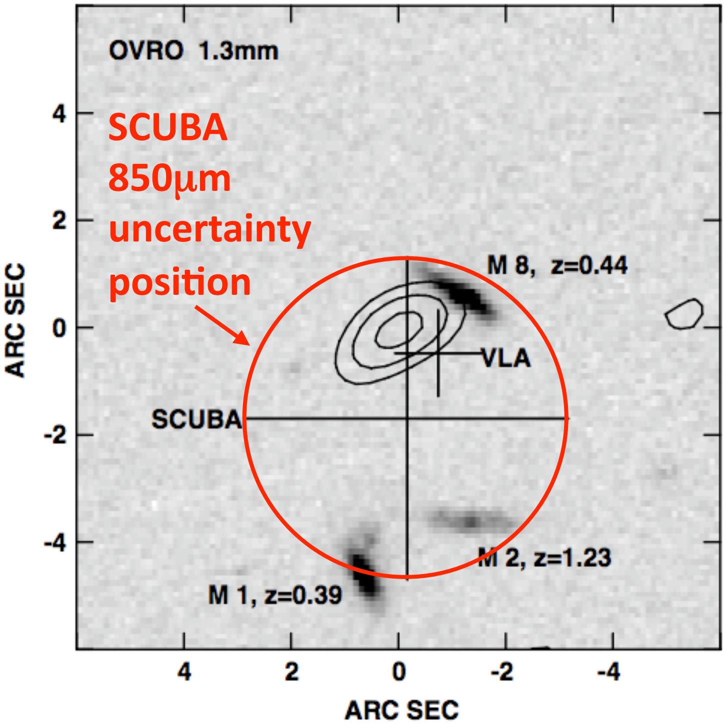


Galaxies detected in the sub-mm dubbed Submm Galaxies (SMG)

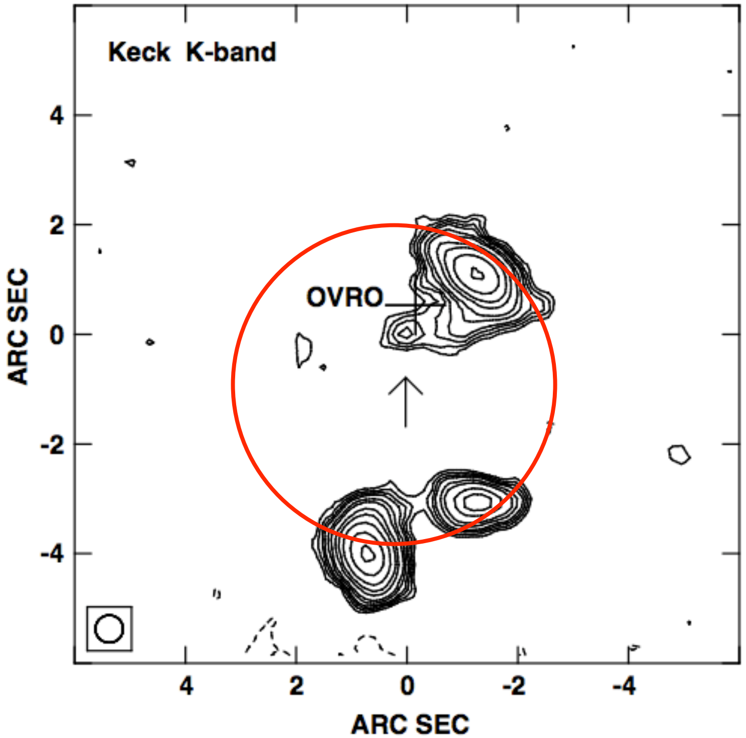
Obtaining the redshift (and activity) information requires spectroscopic identification

The low angular resolution of past/current submm facilities has been a major problem for the optical identification

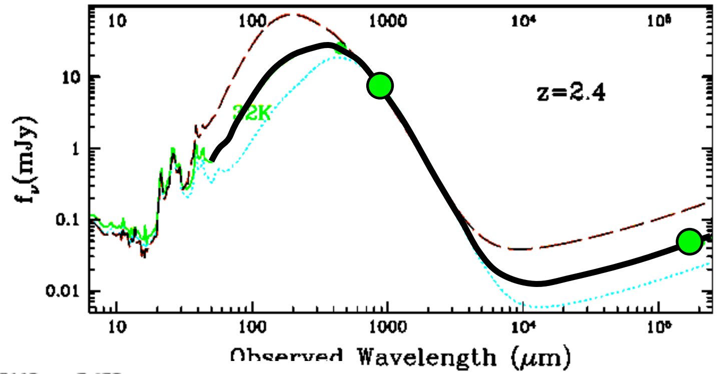
grayscale HST optical



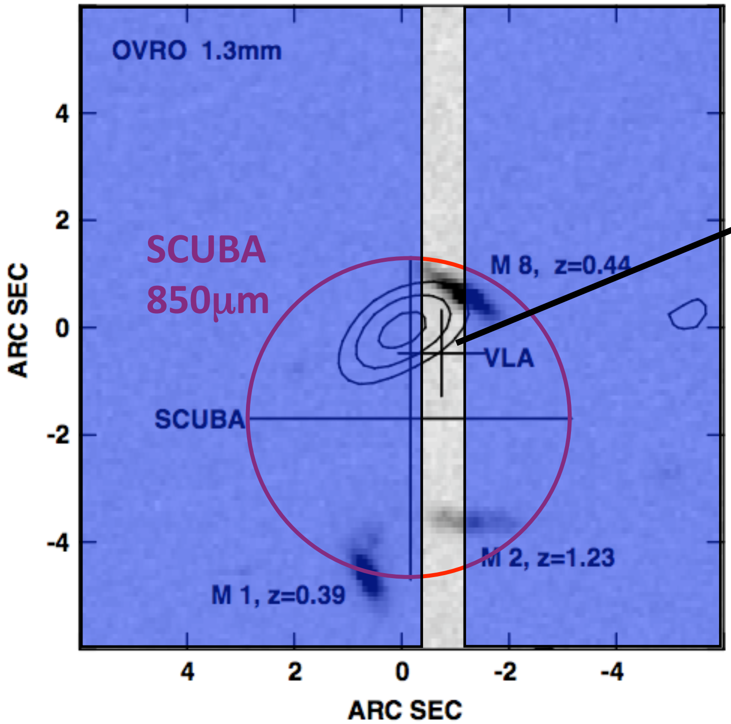
near-IR (2μm) image

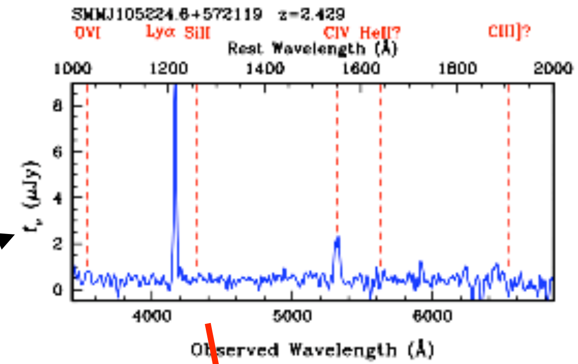


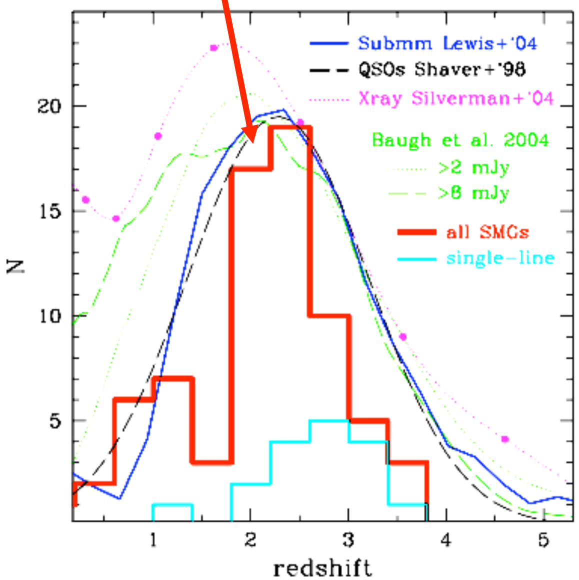
Chapman et al. (2005) exploit the FIR-radio correlation of galaxies to locate the source through the radio-VLA position and "blindly" place the slit for optical spectroscopy



grayscale HST optical

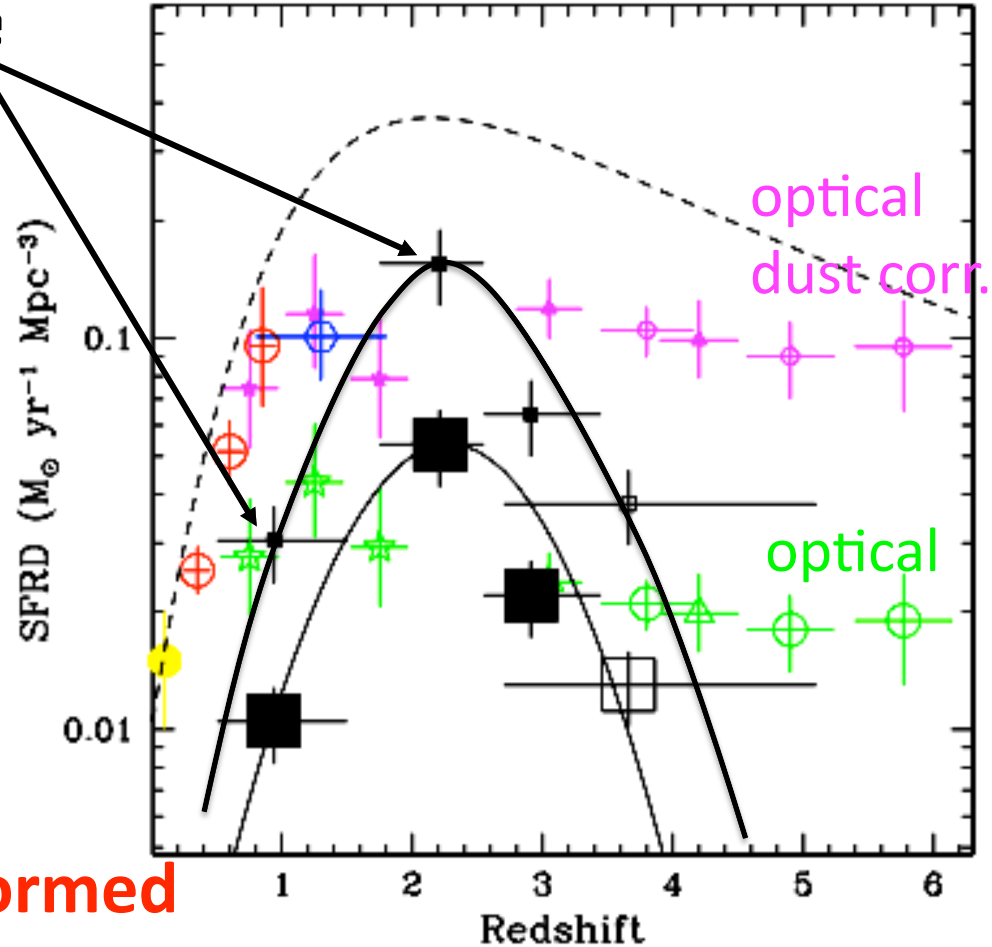






redshift distribution
<z> ~ 2.5

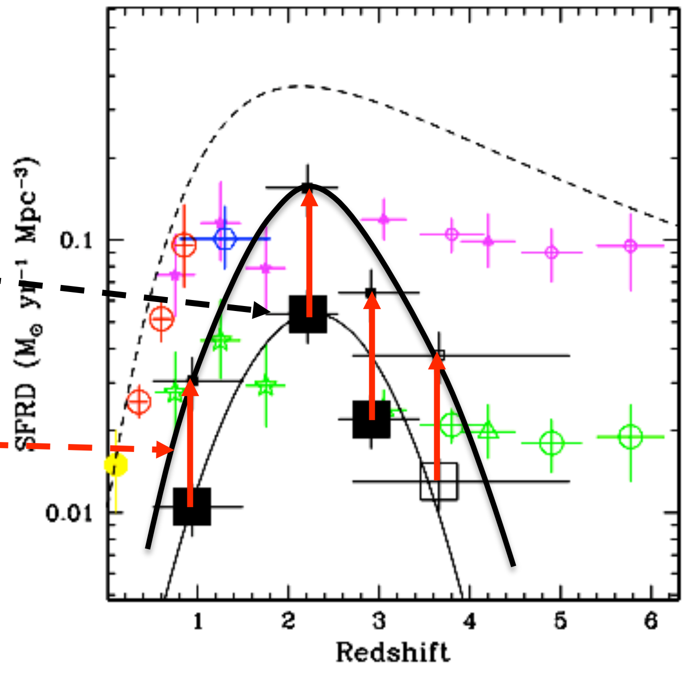
submm inferred evolution of the cosmic star formation rate

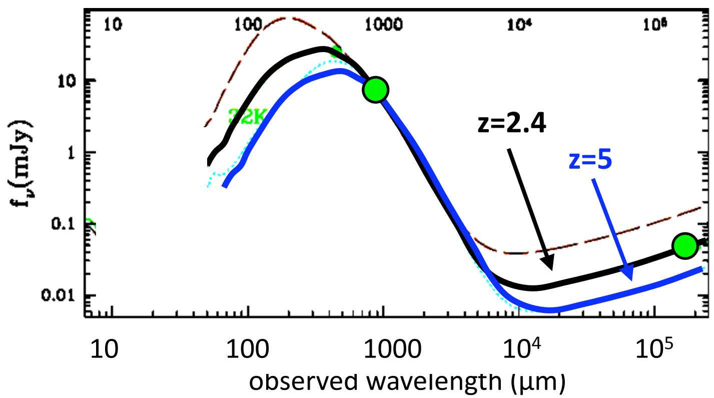


>80% of the stars formed within <40% of the age of the universe and a large fraction of which (~50-80%) through SF obscured by dust

But several problems involved:

- Current submm surveys only sample extremely luminous objects ($L_{IR}>10^{12}\ L_{\odot}$, the tip of the iceberg) correct (by a large factor) with models to get "real" SFR





-Radio identification prevents the identification of high-z sources (radio K-correction goes other way)
- Also bias against cool SED
- Possible radio misidentification (radio sources which are in the beam "by chance")

-The optical (=UV rest frame) spectroscopic identification has missed the most obscured objects

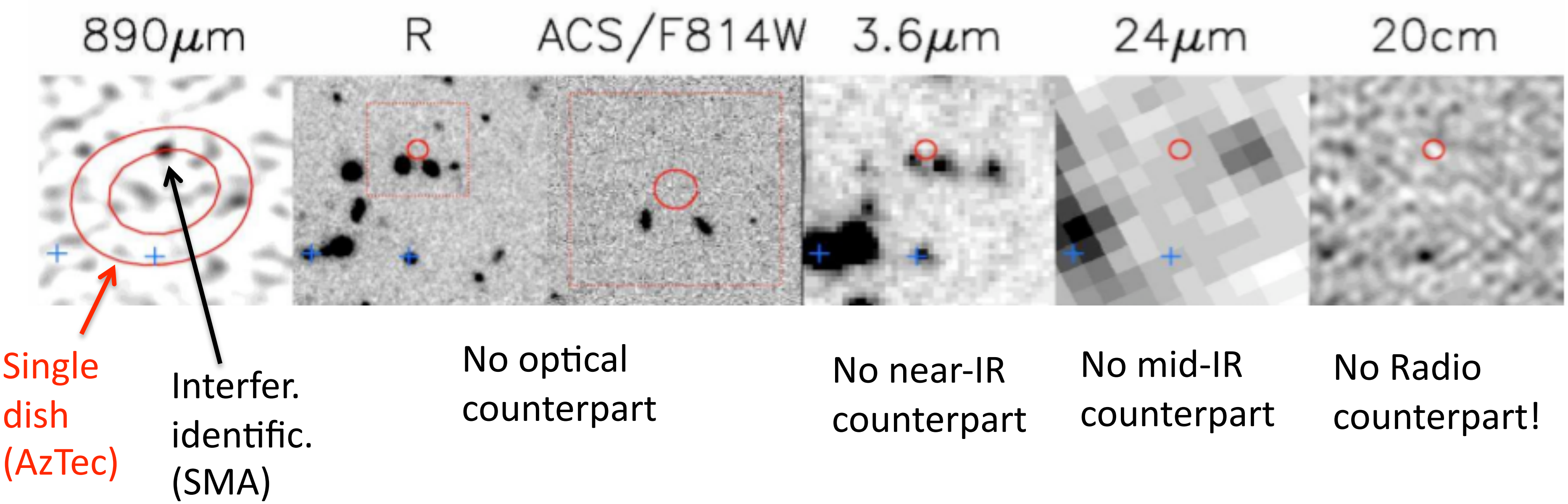
Additional tools to identify counterparts and redshift of (sub)mm sources:

- Mid-IR 24μm counterpart

- Upcoming Herschel far-IR counterparts (angular res. ~5")

- (sub)mm inferferometric followup (IRAM, CARMA, SMA), but time demanding

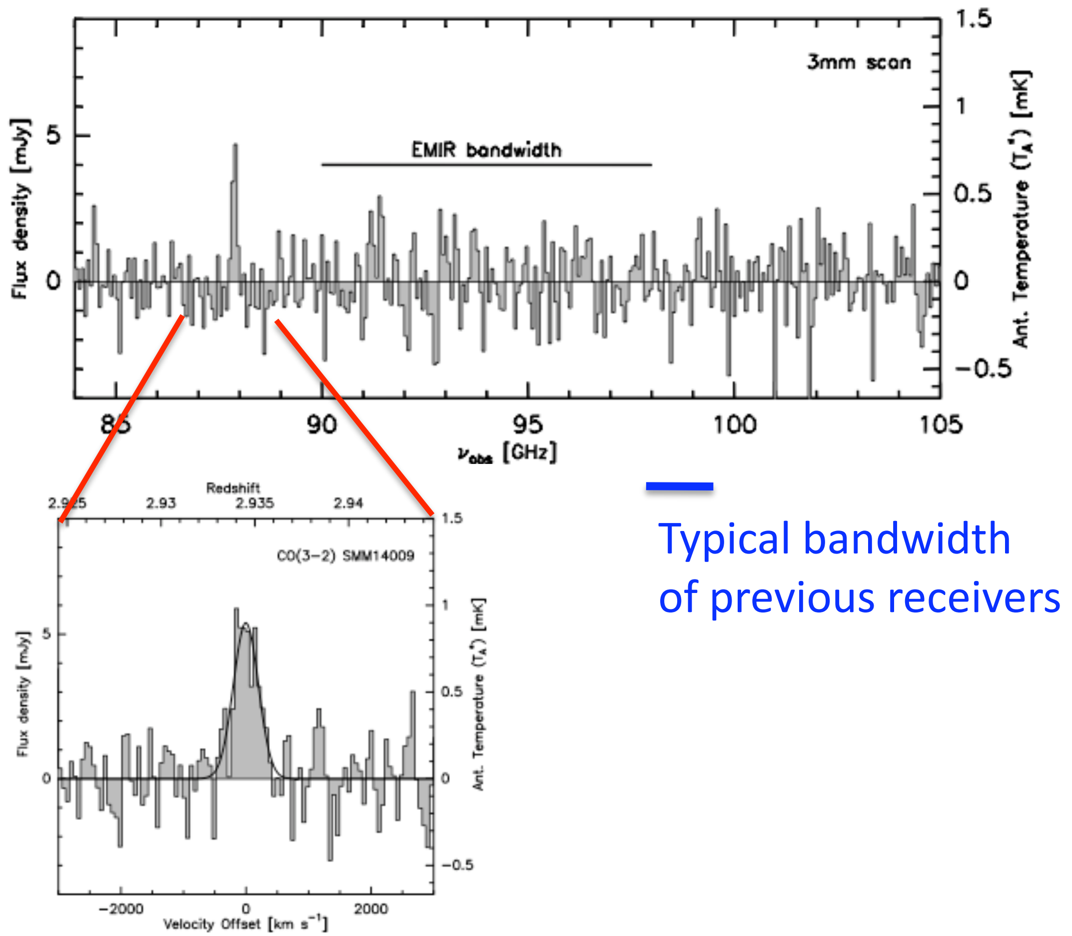
Younger+08



Additional tools to identify counterparts and redshift of (sub)mm sources:

- mm "redshift machines: new mm wide band spectrometers (heterodine) -> can identify one or more CO lines -> redshift

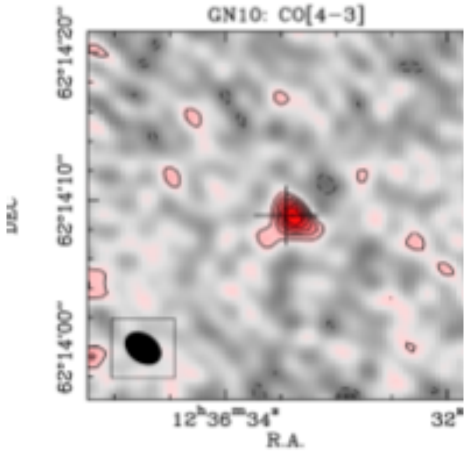
EMIR @ IRAM 30m

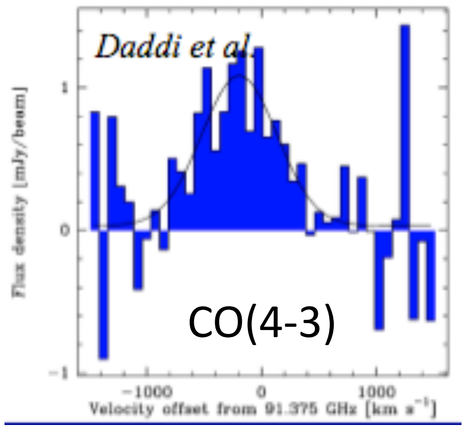


Weiss+09

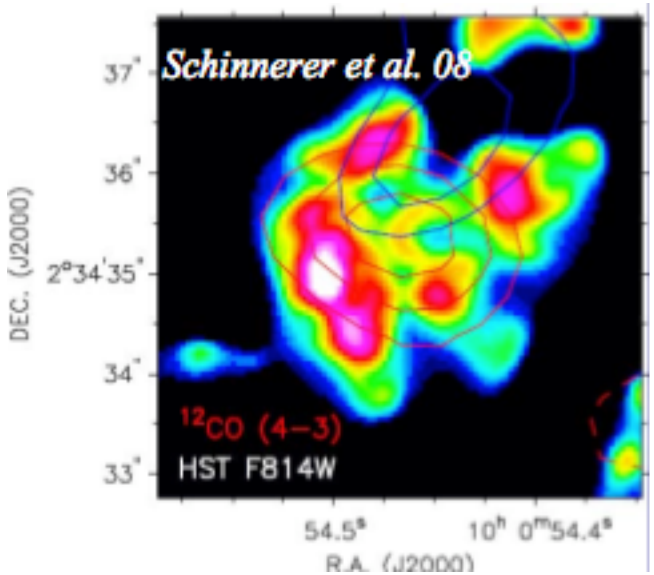
By abandoning the radio-counterpart method, and the requirement for an optical spectrosc. redshift too, a sample of SMGs at high redshift (z>4) has been found

GN10 z=4.09



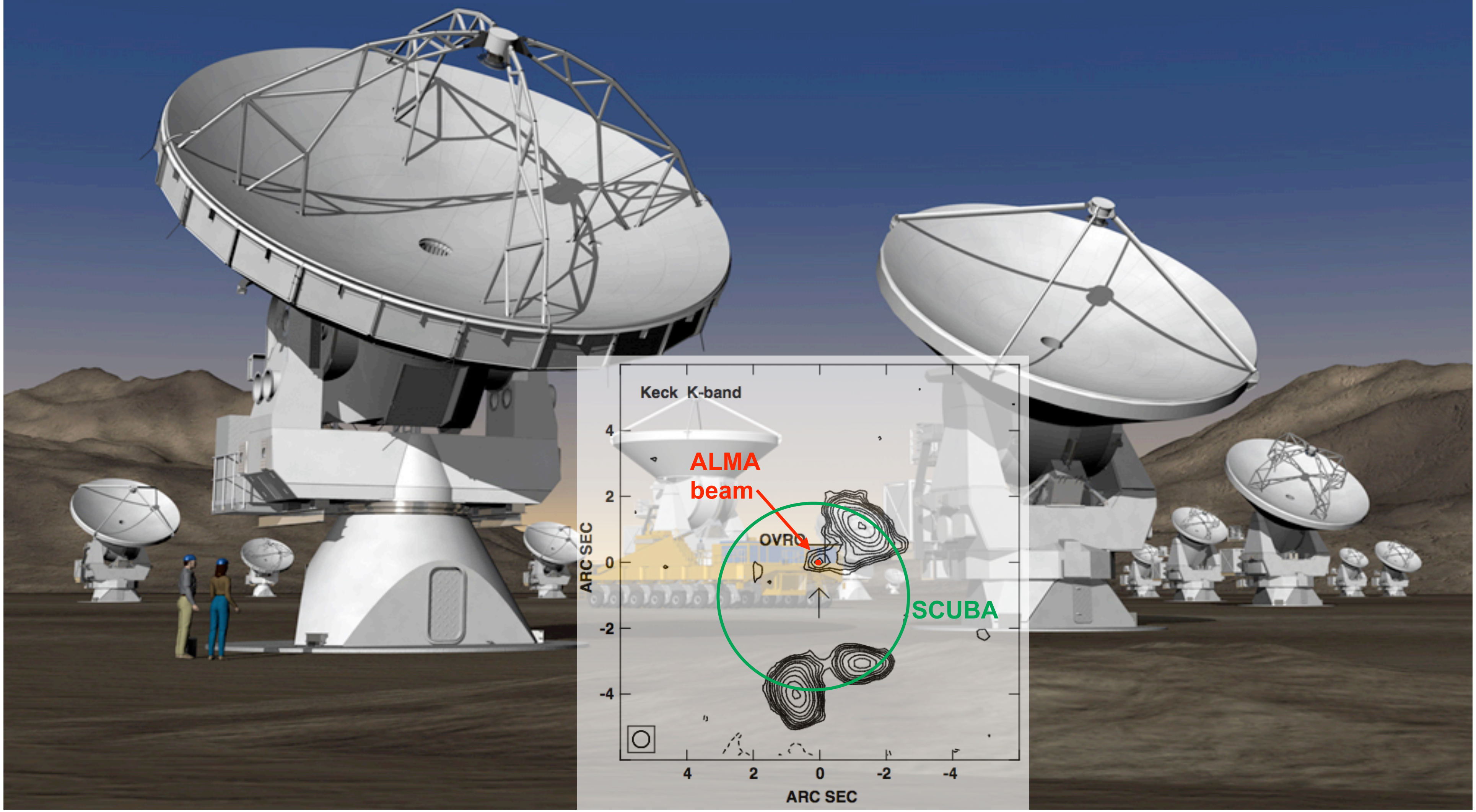


COSMOS J100054+023436 z=4.5



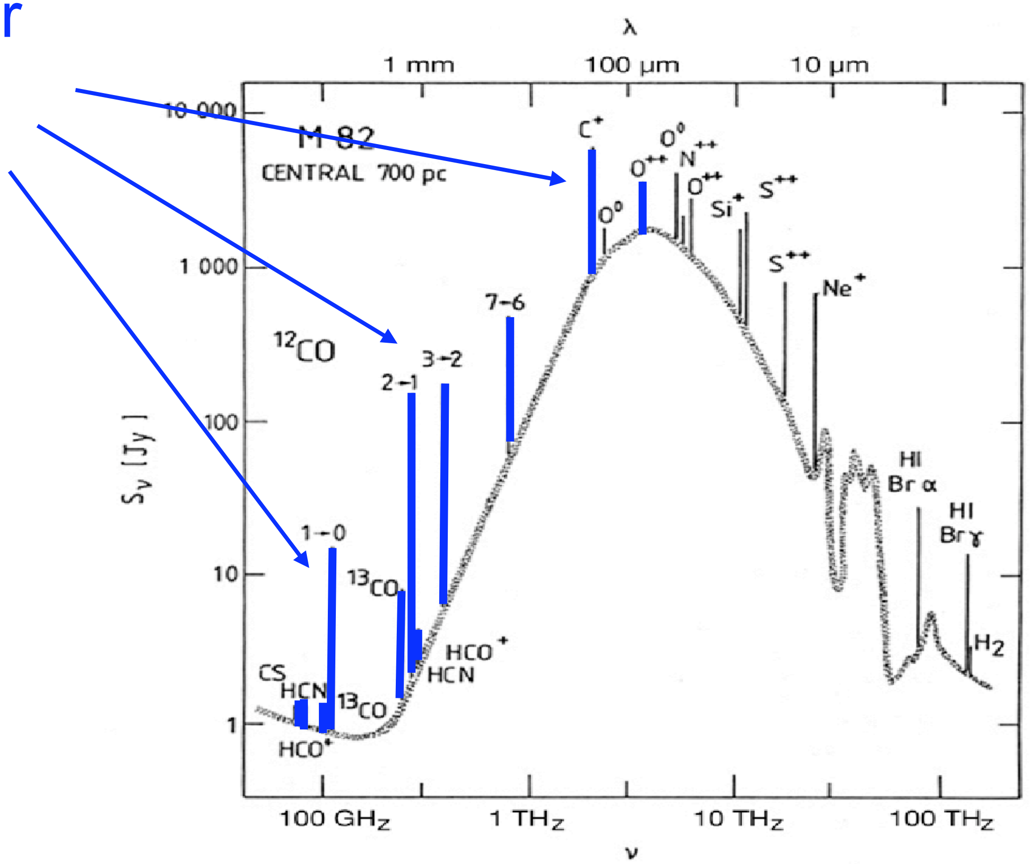
Younger+08: the fraction of SMGs' at z>4 could possibly approach ~**half** of the total SMG population!
-> would be challenging for current models of galaxy formation, but also for dust formation…

Starting from 2011 ALMA will rapidly solve these open issues: ALMA can pin down the (sub)mm counterparts with subarsec accuracy with a few seconds of integration, and it will automatically deliver the redshift by detecting CO lines

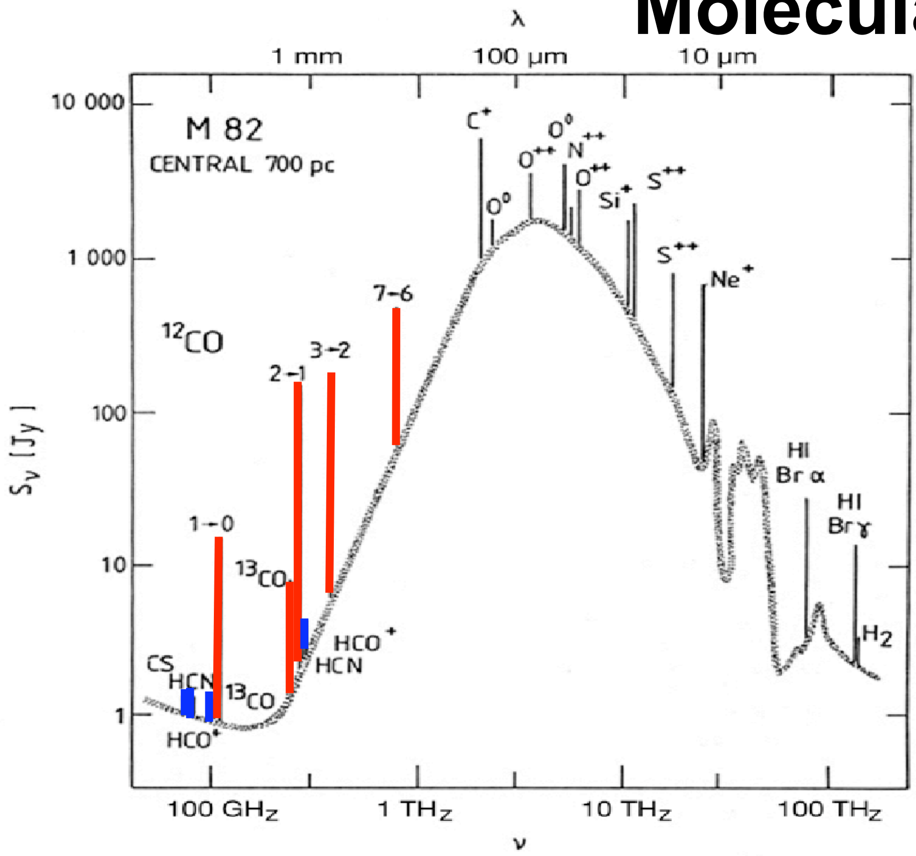


What additional information do (sub)mm emission lines provide on high-z galaxies?

molecular
+ atomic
lines



Molecular gas



Cold H_2 (which is the bulk of molecular gas) cannot be detected directly, because it has no dipole moment

CO second most abundant molecule, excited by collision with H2 (brightest mol. lines)

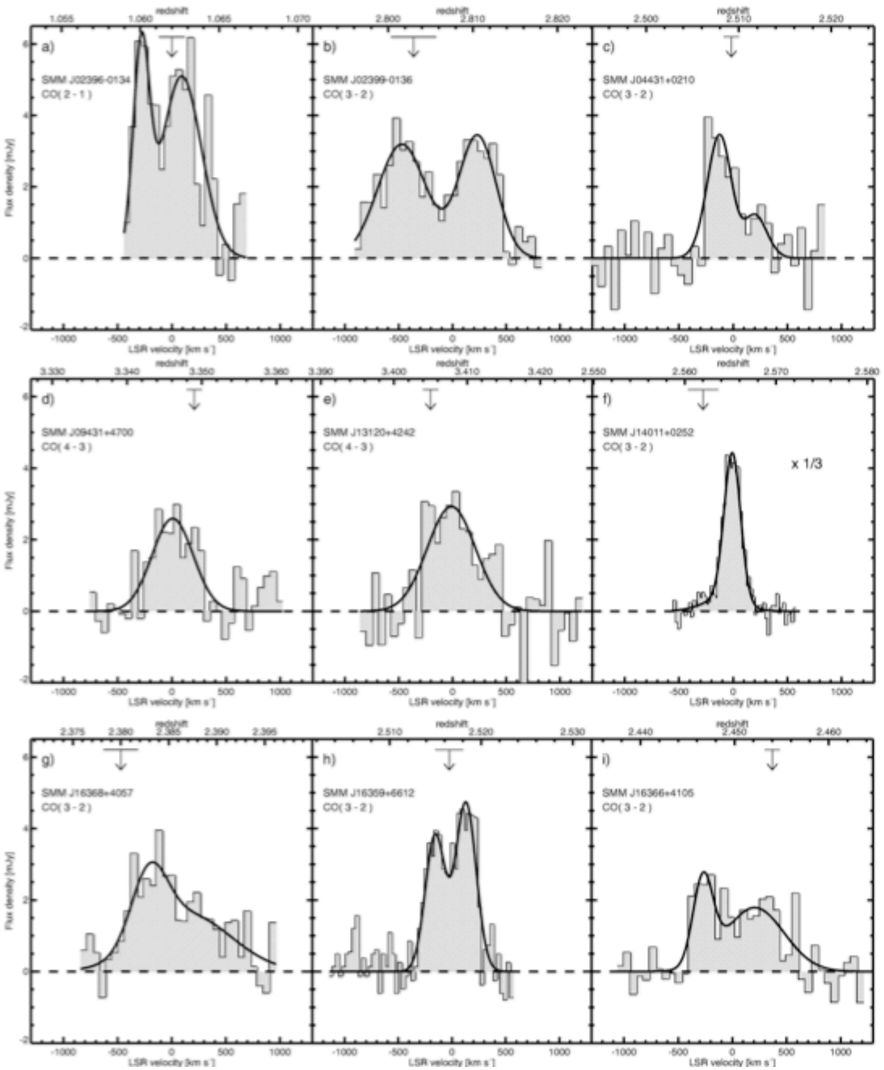
Widely used as H_2 tracer

$$L_{CO} = \alpha \, M(H_2)$$

(conversion factor depends on metallicity and temperature/density)

Tracers of high density gas: HCN, HCO+, ...
critical densities ~10^6-10^7 cm^{-3} (while n_{cr}(CO)~4×10^4 cm^{-3}), but:
- much fainter than CO
- may actually trace "XDR" produced by AGNs

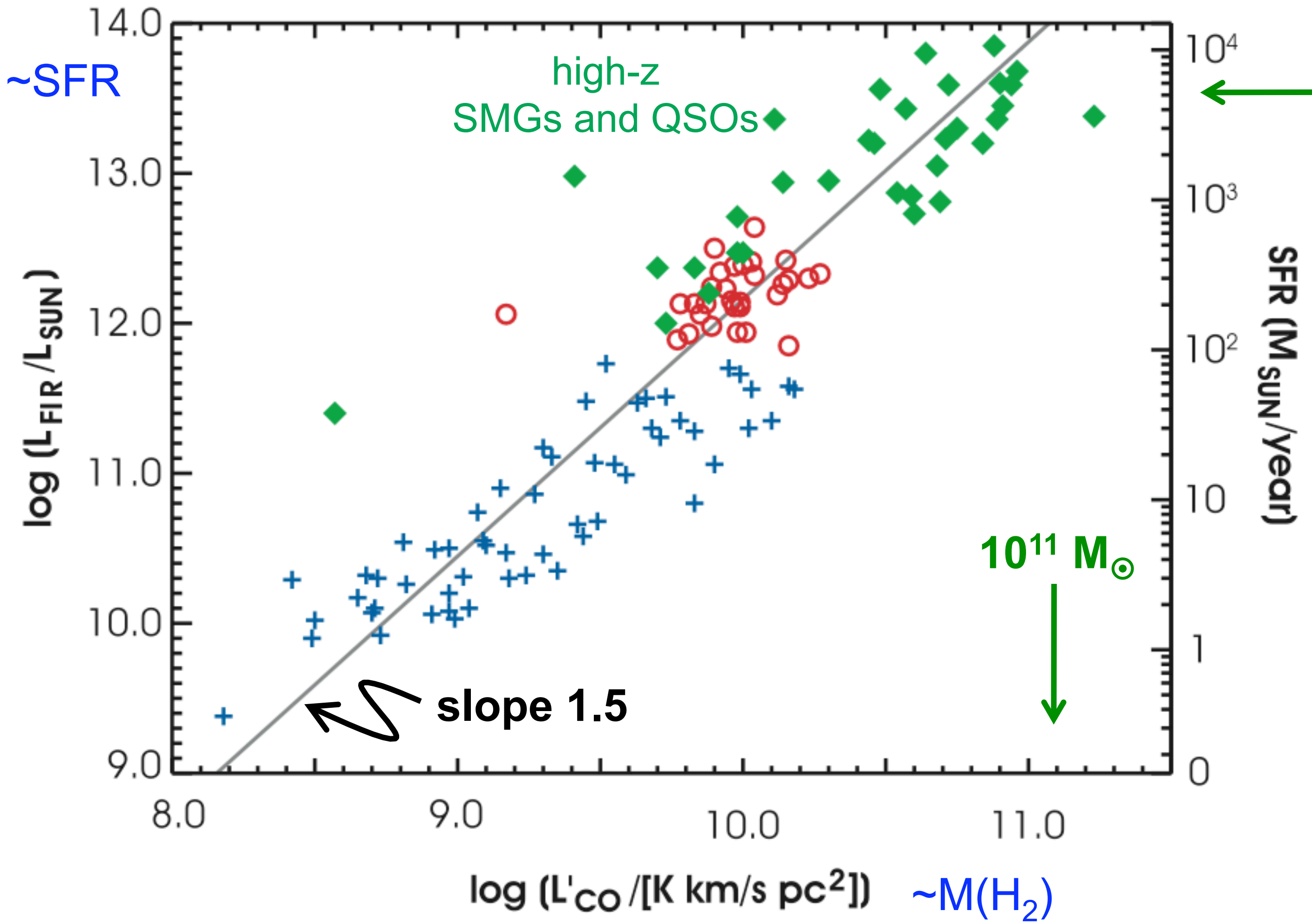
CO lines have now been detected in several high-z galaxies (see reviews by Solomon & Vanden Bout 2005, Omont 2006)



CO in SMGs

Greve+05

L_{FIR} vs L'_{CO}: 'integrated Kennicutt-Schmidt law'



~a few 1000 $M_\odot$/yr

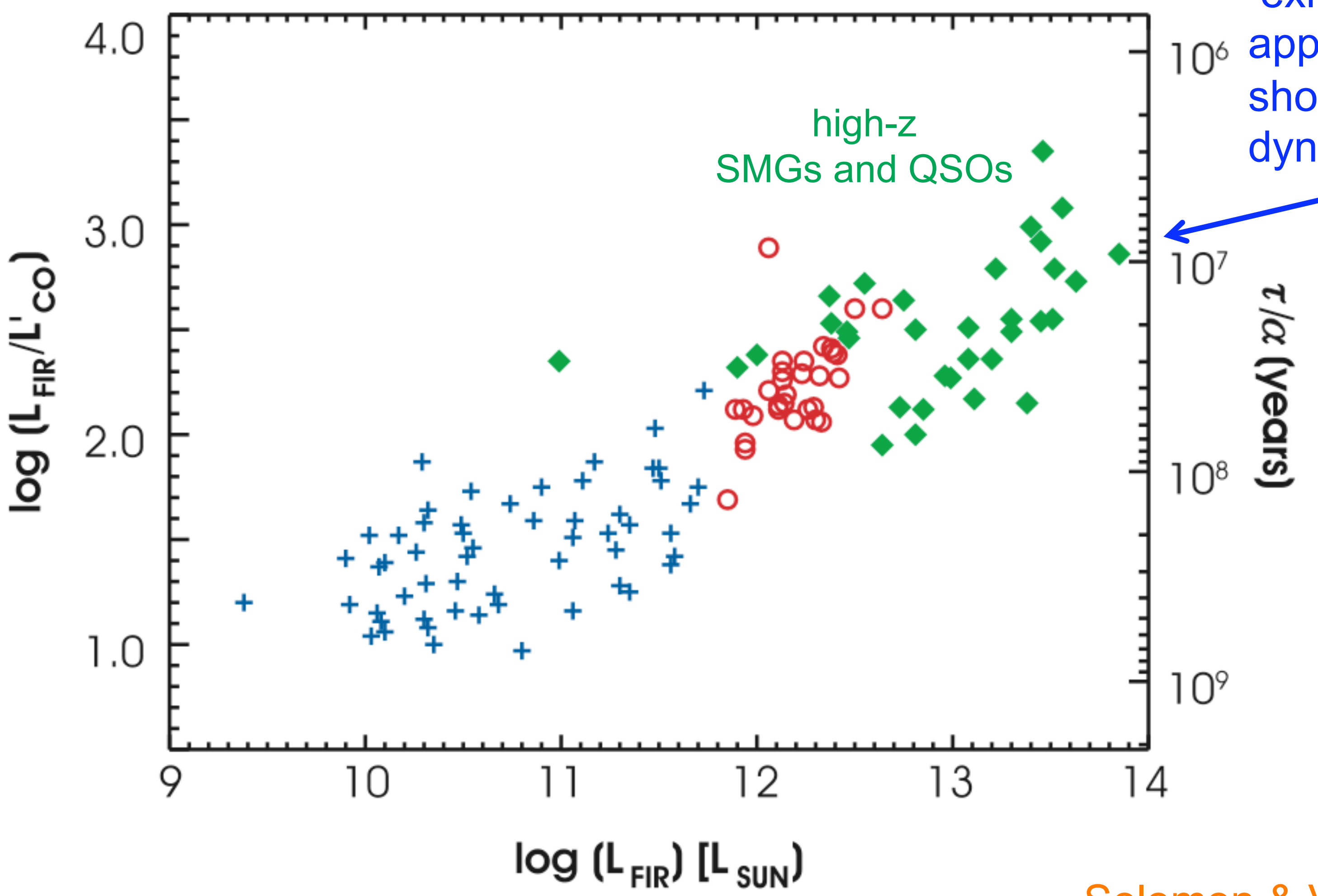
Solomon & Vanden Bout '05

- Star formation efficiency (SFR/M_{gas}) increases with increasing SFR
- Gas depletion timescale (M_{gas}/SFR) decreases with SFR
- Apparently **Gas resupply** is required to form Giant Ellipt. ~ 10^{12} M_*

Star formation efficiency and life-time

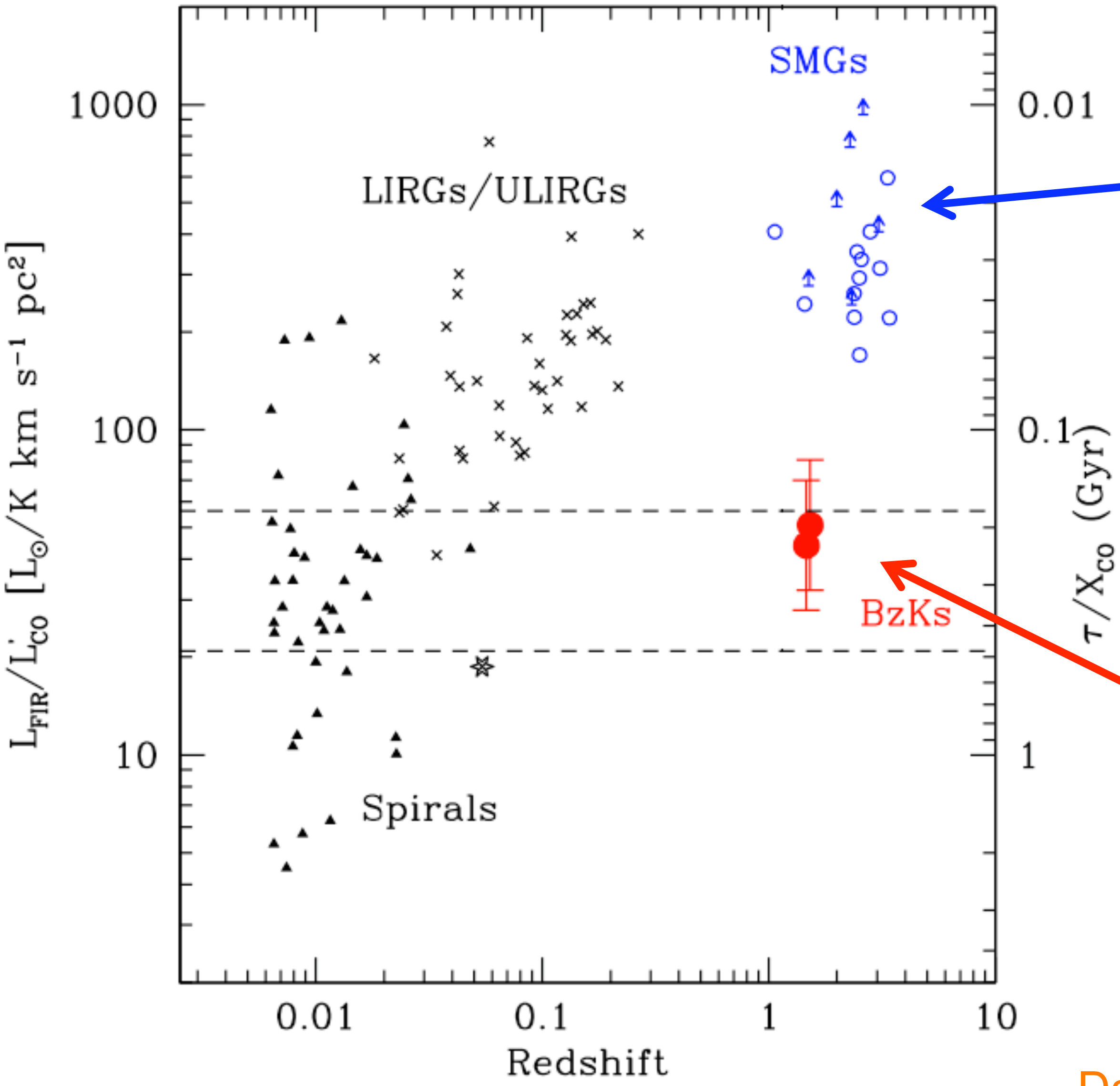
~SFR/M(H_2)

Lifetime = gas exhaustion timescale approaching or shorter than the dynamical timescale



Solomon & Vanden Bout '05

But possibly biased view… evidence for a population of star forming galaxies with moderate star formation efficiency -> long lifetime



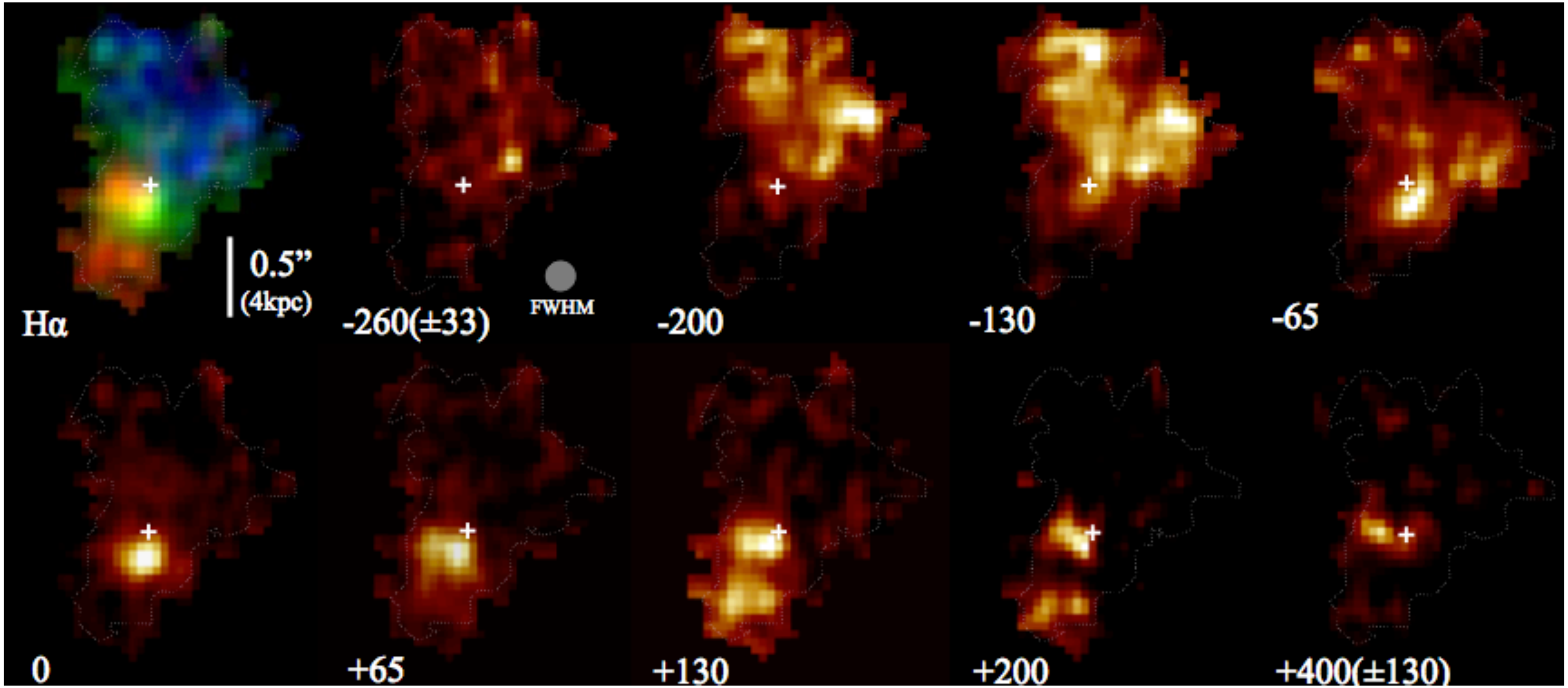
gas rich, highly dissipative merging systems (similar to local ULIRGs)

two modes of star formation at high-z

gas rich SF disks secular evolution due to disk instabilities

Daddi+08

Dynamical evidence for clumpy, globally unstable disks at high-z (SF enhanced by disk instabilities, not by mergers)

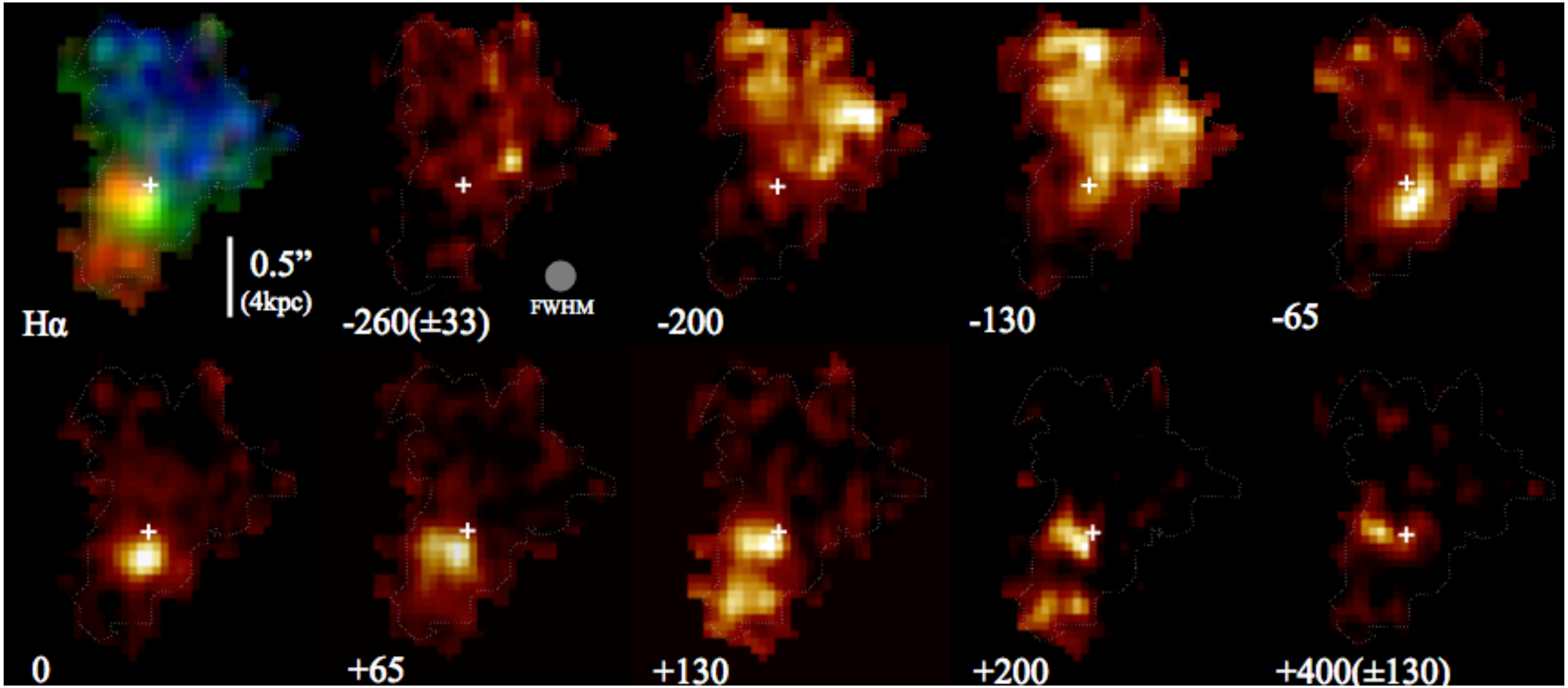


Large velocity dispersion

Genzel+05, Forster-Schreiber+09

$<V_{rot}/\sigma>_{z\sim2} = 4$ while in local spirals: $<V_{rot}/\sigma>_{z=0} = 15$

Dynamical evidence for clumpy, globally unstable disks at high-z (SF enhanced by disk instabilities not by mergers)



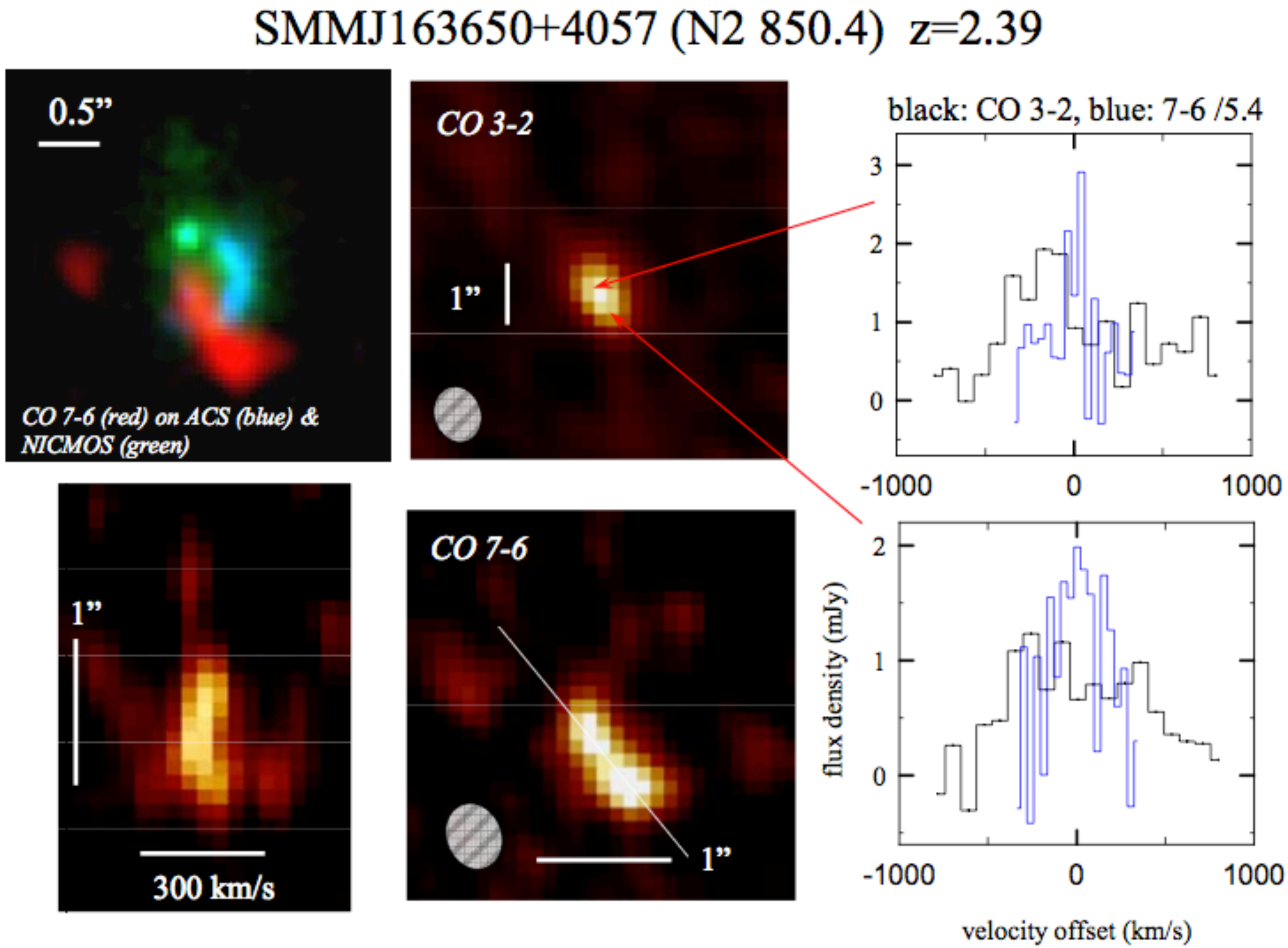
Timescale for instabilities (disk fragmentation)

$$t_{df} \sim (V_{rot}/\sigma)^2\ t_{dyn}$$

$t_{df}(z=0) \sim 10$ Gyr

$t_{df}(z=2) \sim 100$ Myr

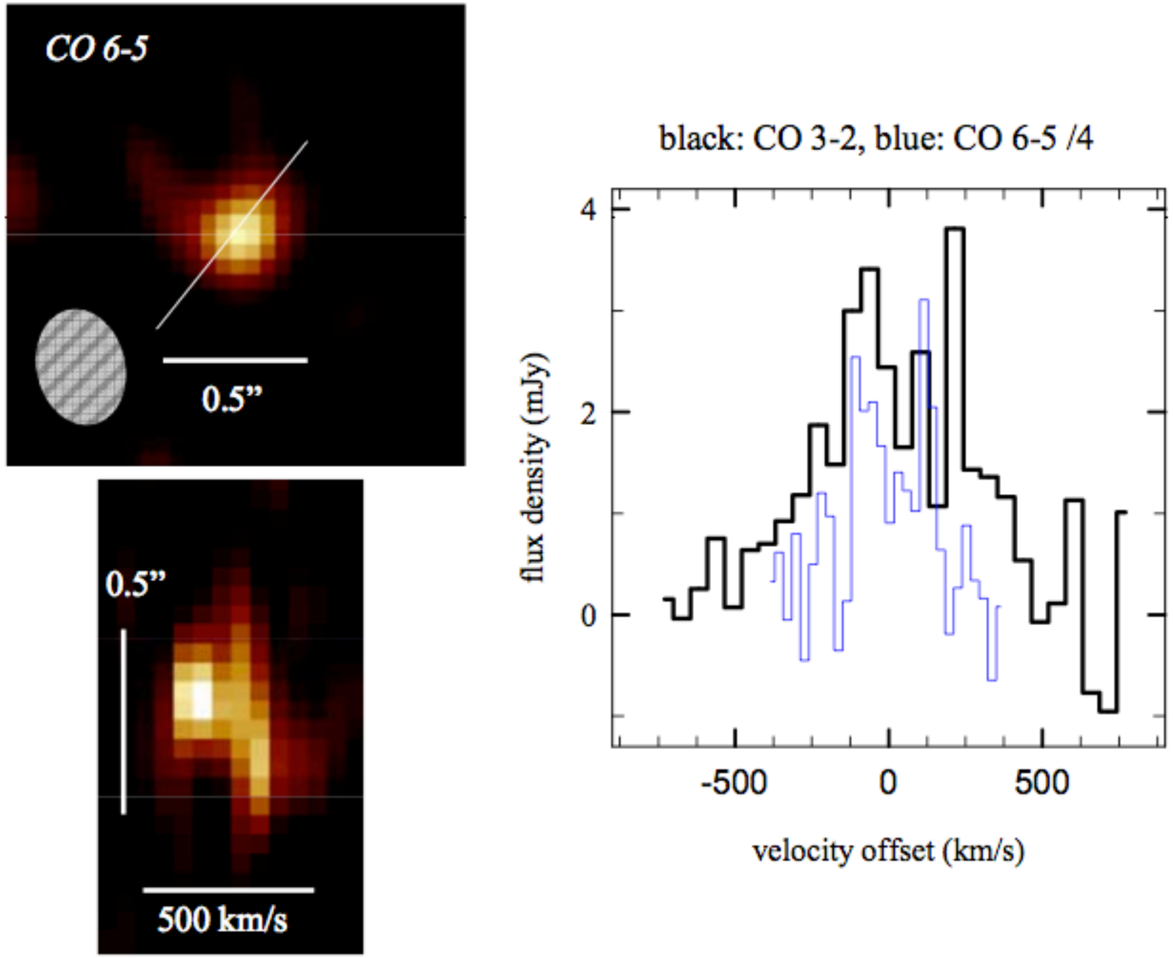
Evidence for merging nature of SMG from the complex morphology and kinematics



Tacconi+08

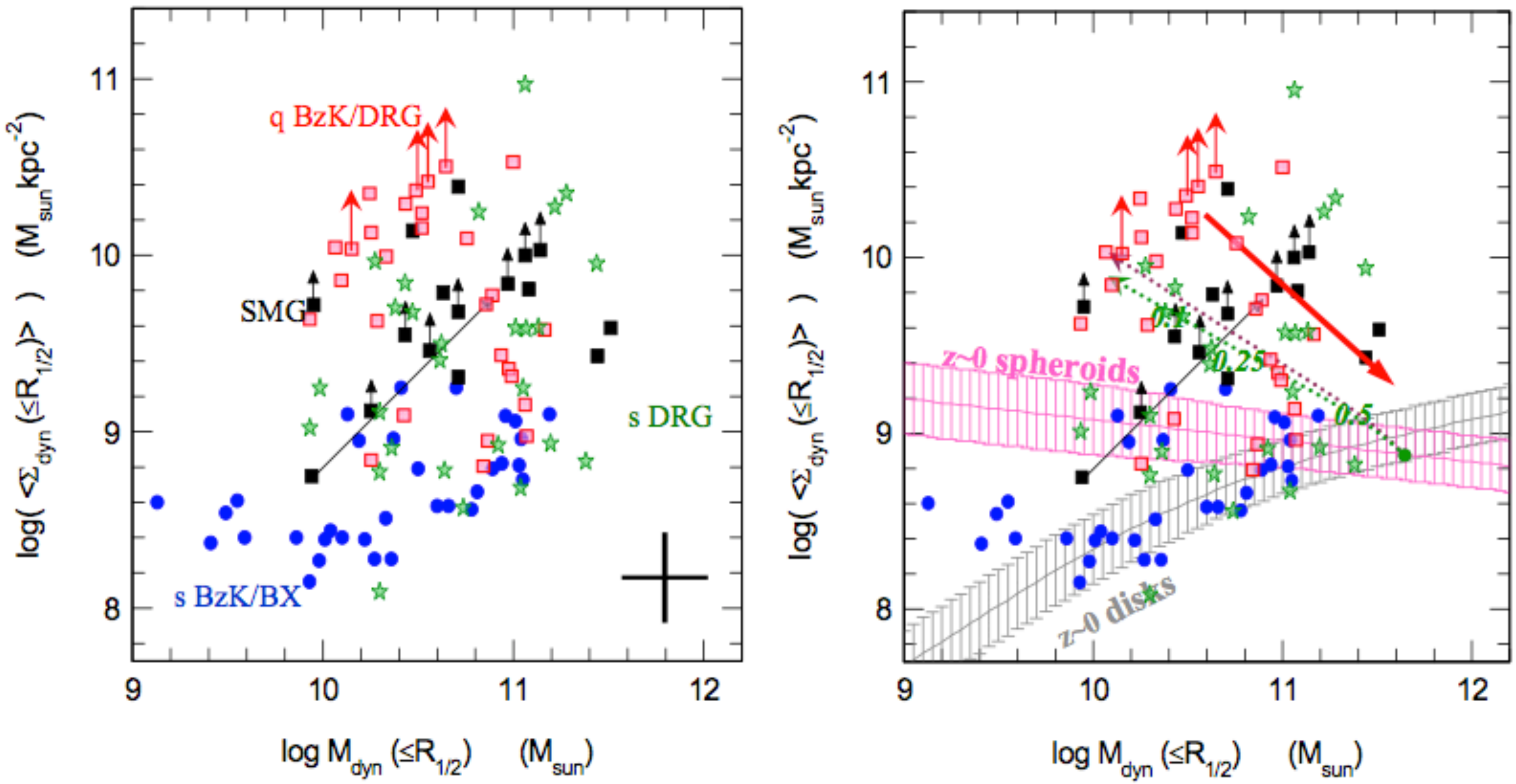
When rotation curves are detected in SMGs very high mass concentrations are inferred

SMMJ123549+6215 (HDF76) z=2.20



Tacconi+08

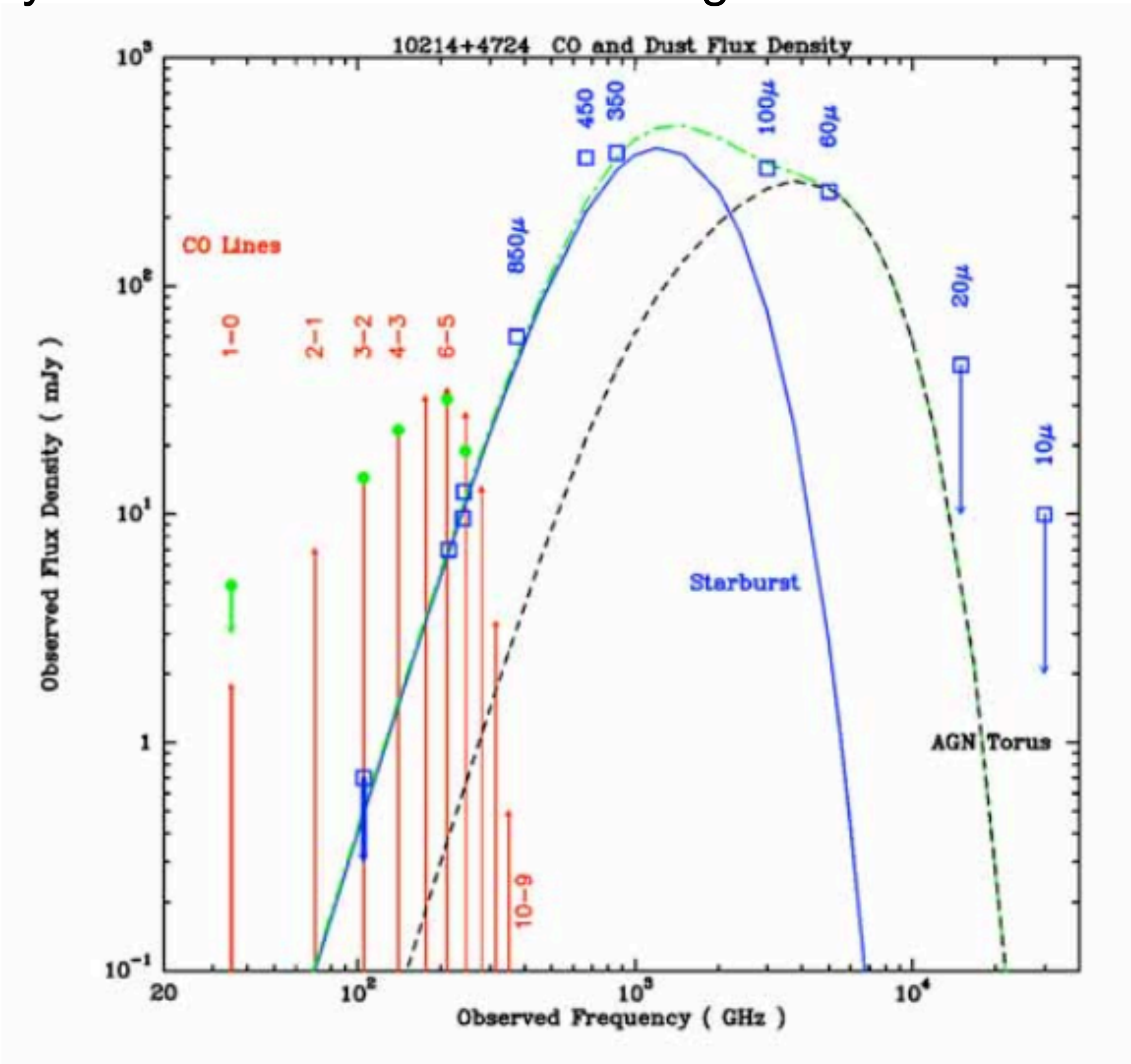
Probably SMG are forming the compact quiescent, red galaxies found at z~2
Not enough mass to evolve into local giant ellipticals -> later dry merging
is probably required



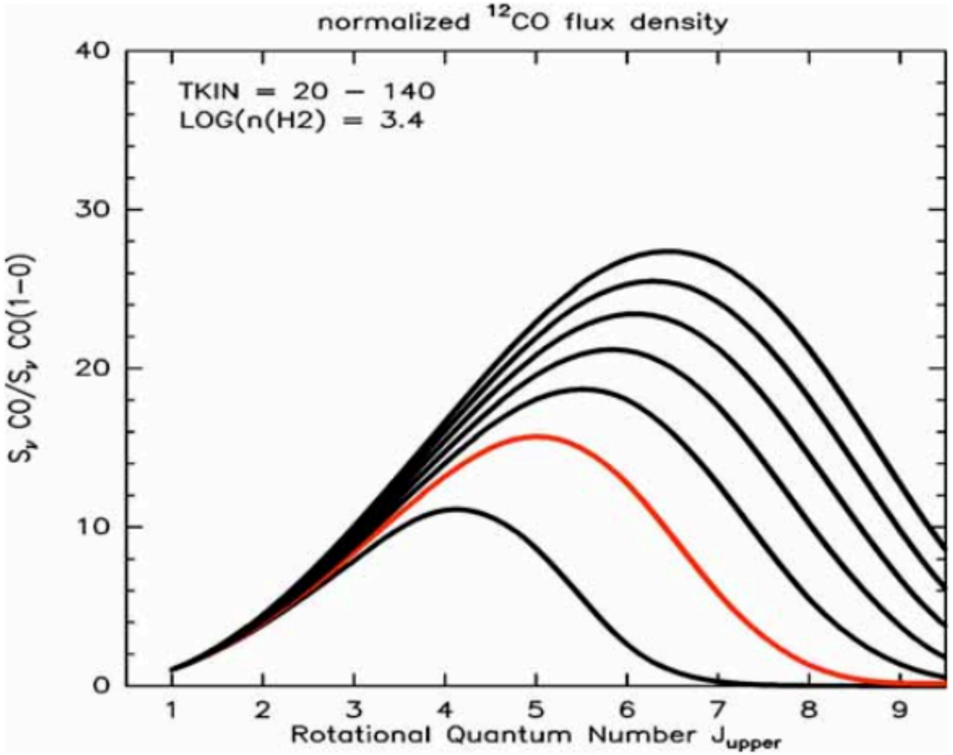
Tacconi+08

Excitation of the CO lines

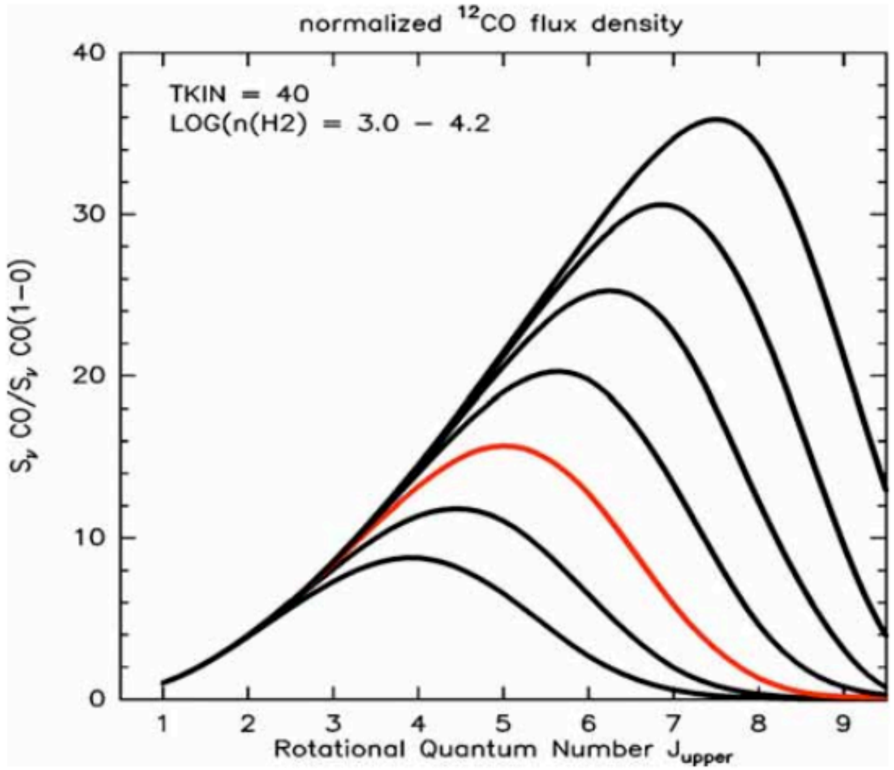
Measuring the various CO rotational transitions require observations at several frequencies, but it provides information about the physical status of the molecular gas



Temperature variations

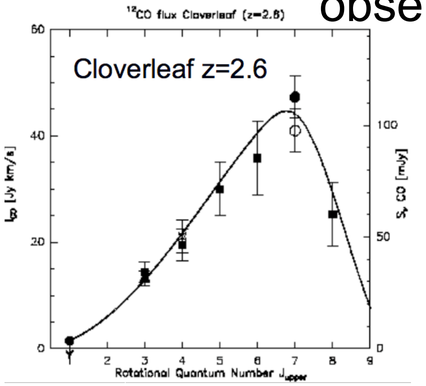


Density variations

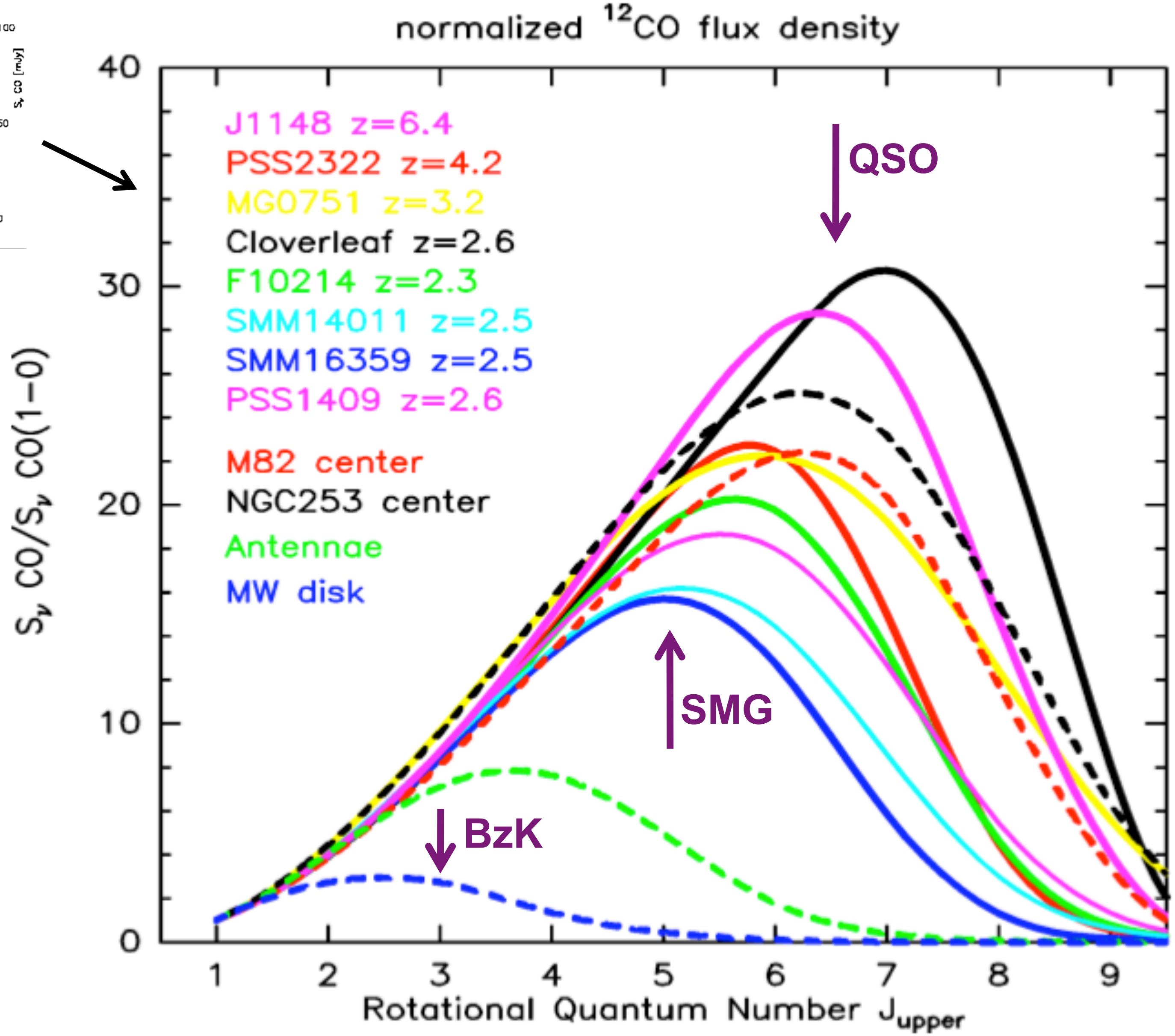


- The flux density quantum number of the turnover provides information on the physical status of the molecular gas

- The low-J transitions are generally thermalized in most cases, i.e. $S_\nu \sim \nu^2$ -> i.e. benefits of the same **negative K-correction** as the thermal continuum… out to the J of turnover…

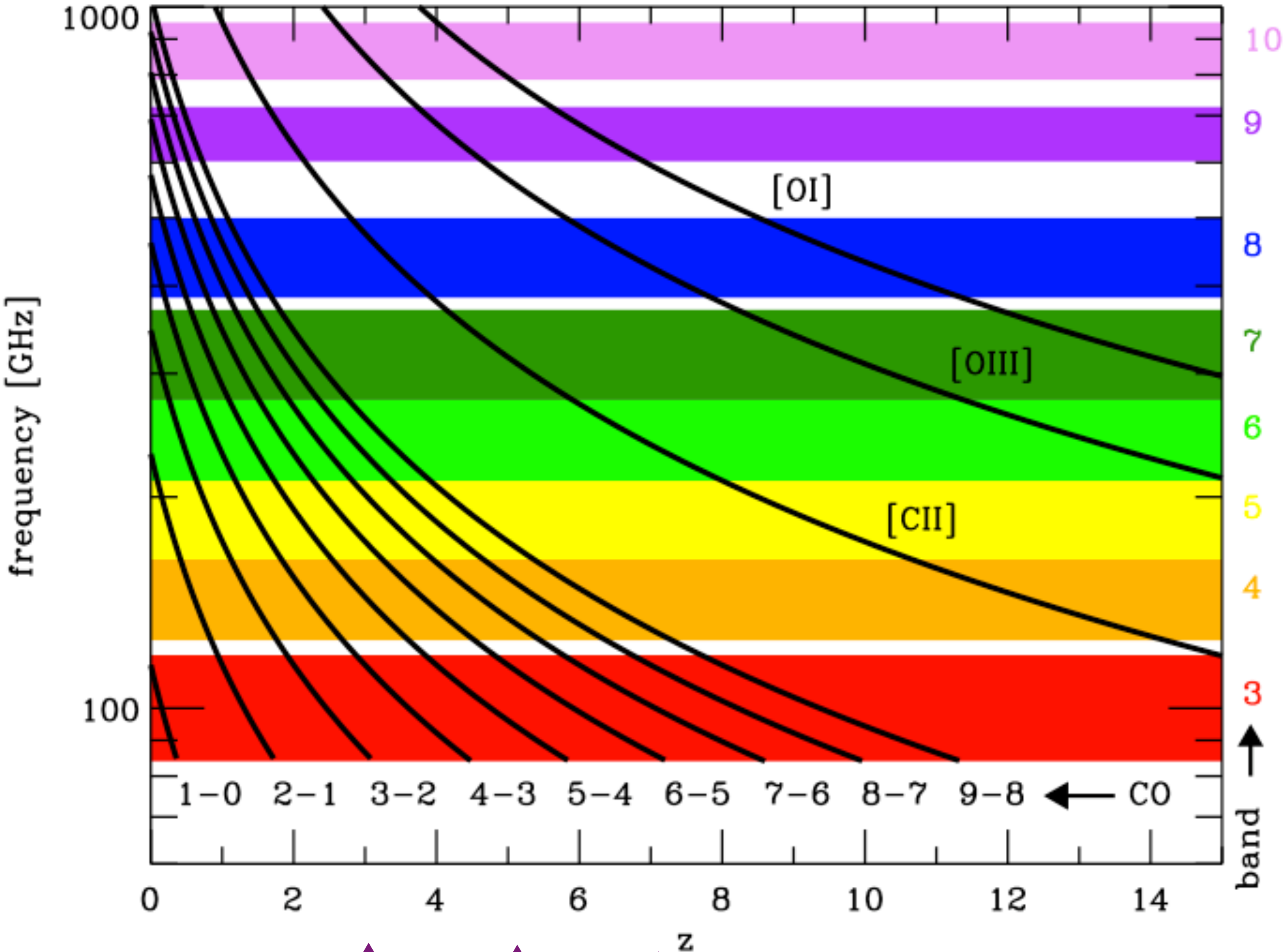


observations



Weiss+09

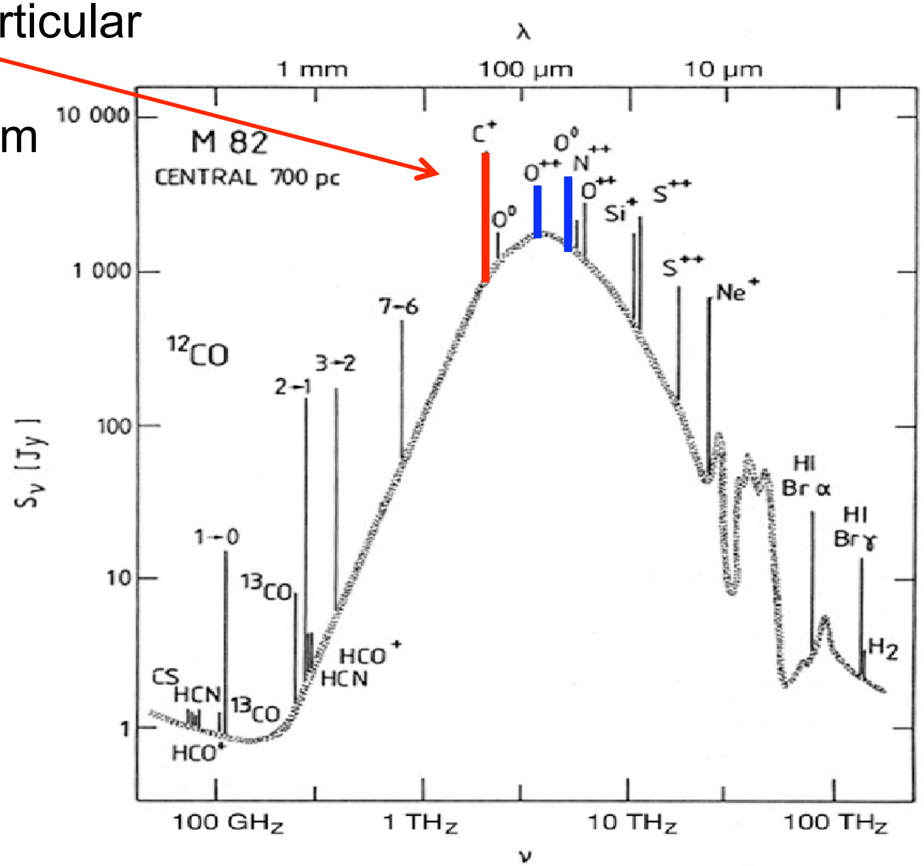
The CO turnover has implications on the use of CO for the detection and redshift determination of high-z sources (especially in the ALMA era)



Z_{max}(CO): ↑BzK ↑SMG ↑QSO

Alternative lines that can be used at high redshift: far-IR fine structure lines

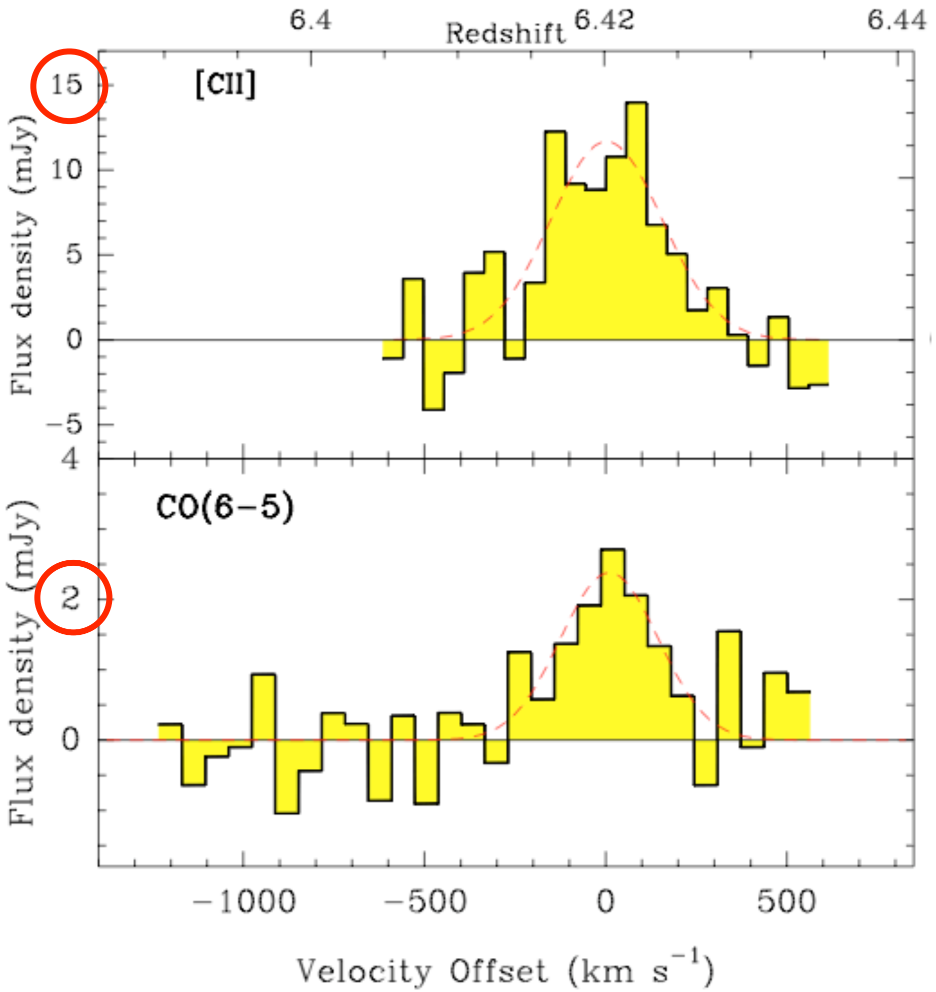
[CII] 158μm in particular is the strongest line in the spectrum of any galaxy



This single line can account for as much as 1% of the bolometric luminosity of a galaxy

Difficult to observe at low redshift because in the region of atmospheric opacity … but at high redshift is shifted into the mm range…

First detection of [CII] at high redshift



In the most distant QSO at z=6.4

Maiolino+05

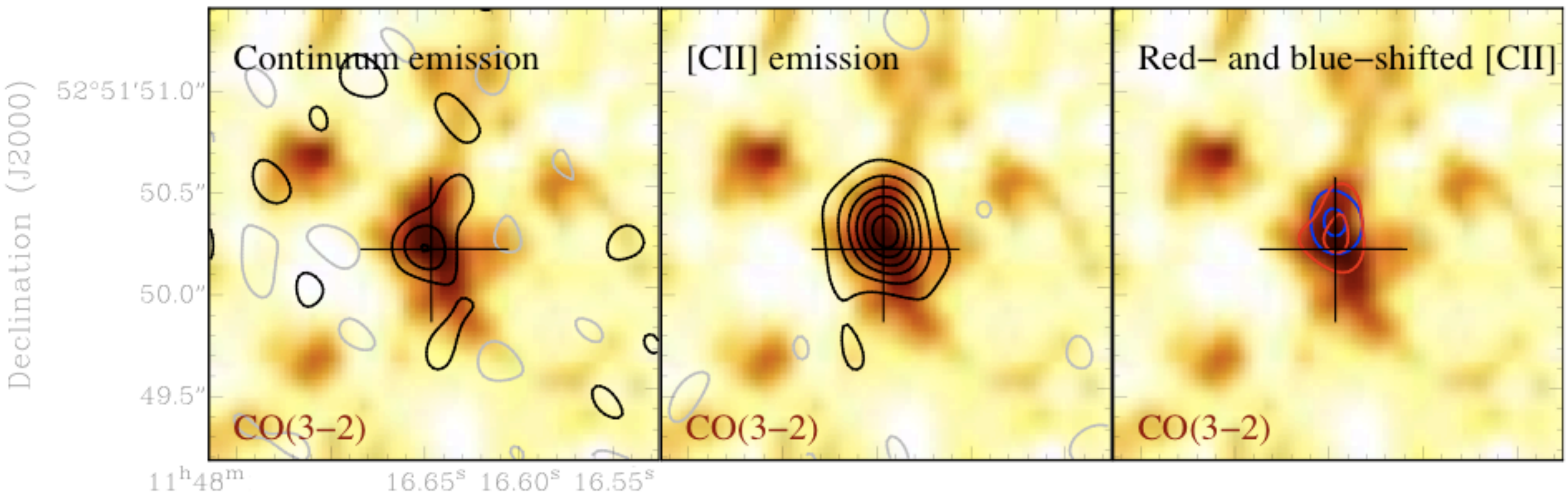
followed by a few more

Iono+06, Maiolino+09, Knudsen+09, Bertoldi+09

Provides information on the SFR

[CII] emission at z=6.4 resolved with the interferometer

Walter+09



- [CII] size ~ 1.5 kpc => Σ_{SFR} = SFR/area ~ 1000 M_o yr^{-1} kpc^{-2} (vs. SMGs ~50)
- 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

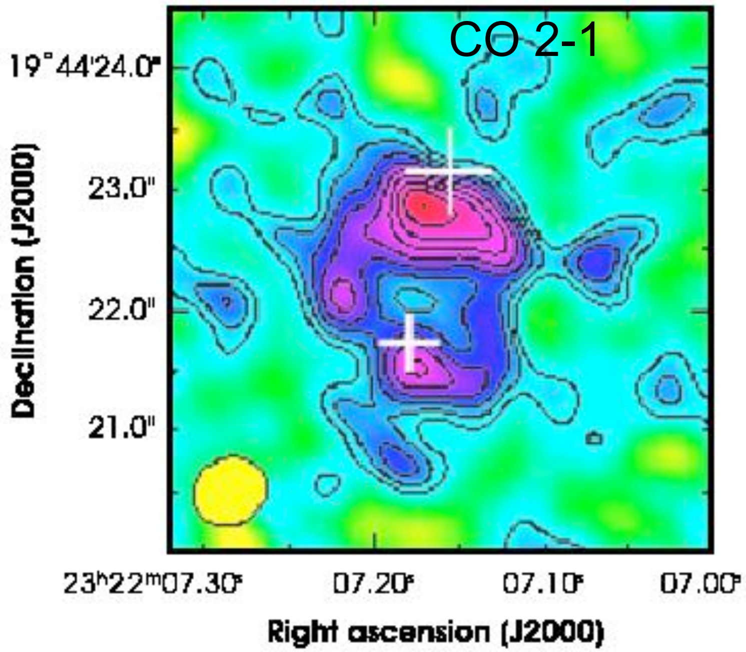
-> Probably witnessing the rapid formation of a bulge

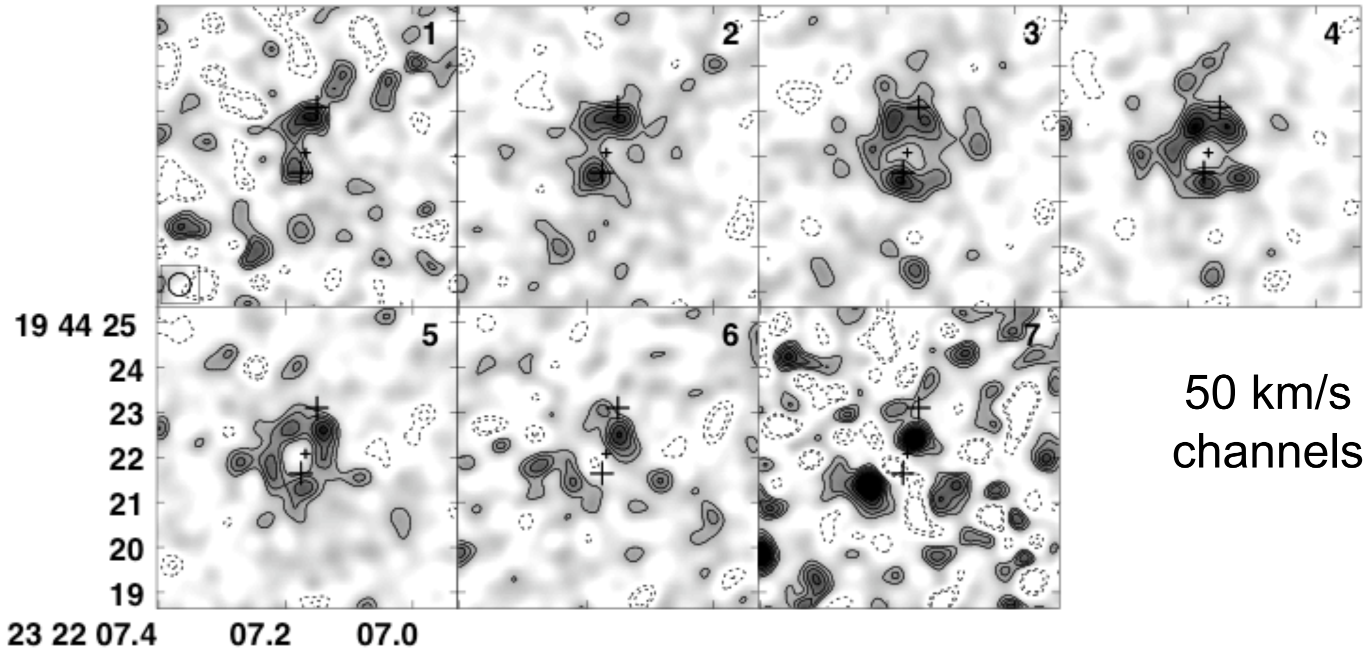
CO and [CII] kinematics measured in interferometric maps allow us to trace the dynamical mass of the QSO host galaxies (much easier than in the optical)

2322+1944, z=4.2

Molecular Einstein ring

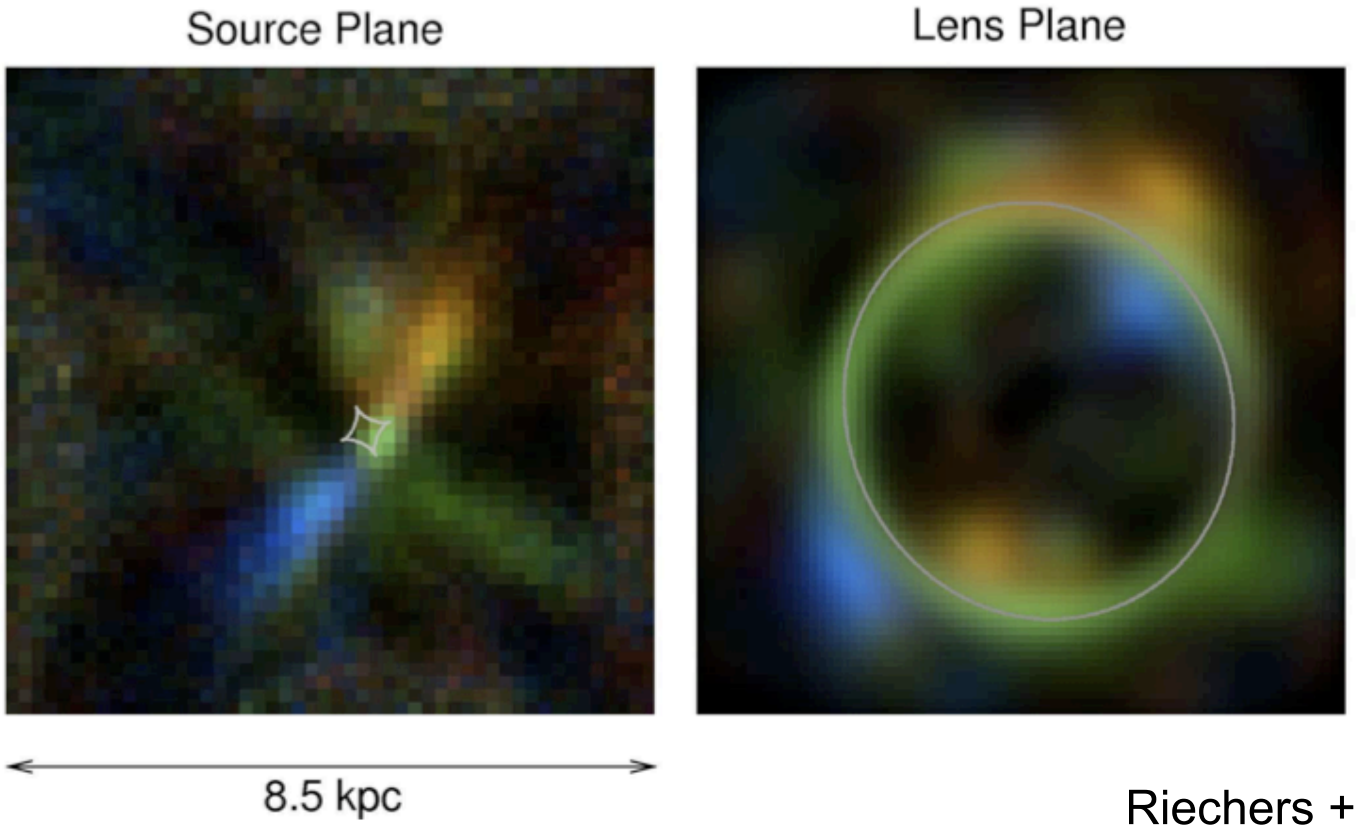
Riechers et al. 2008





50 km/s channels

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

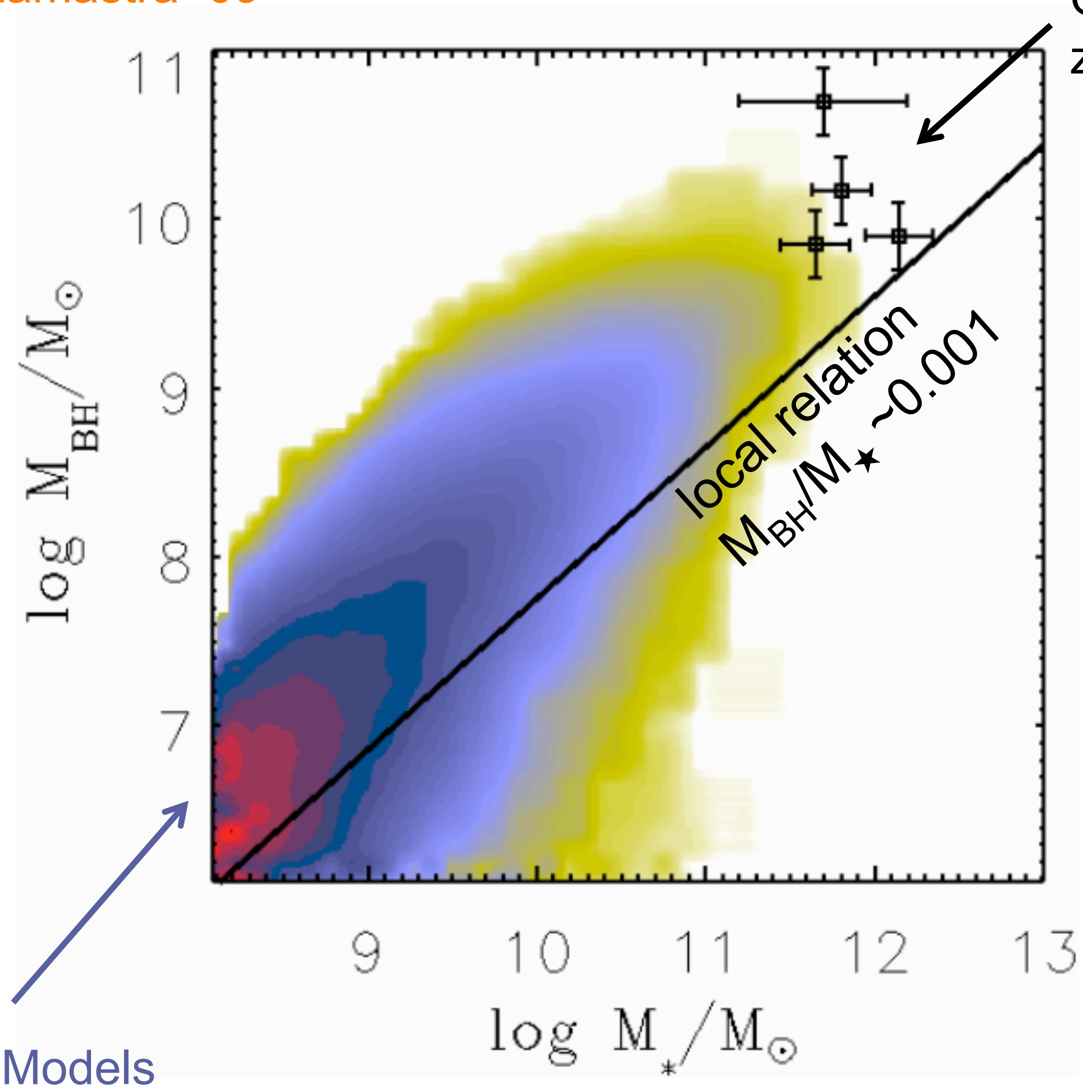


Riechers + 08

- Galaxy dynamical mass (r<3kpc) ~ 4.4e10 M_o
- Black hole mass inferred by the broad emission lines -> virial calibrations

=> M(BH)-M(gal) relation at z>4

Lamastra+09



QSO at z>4

Models

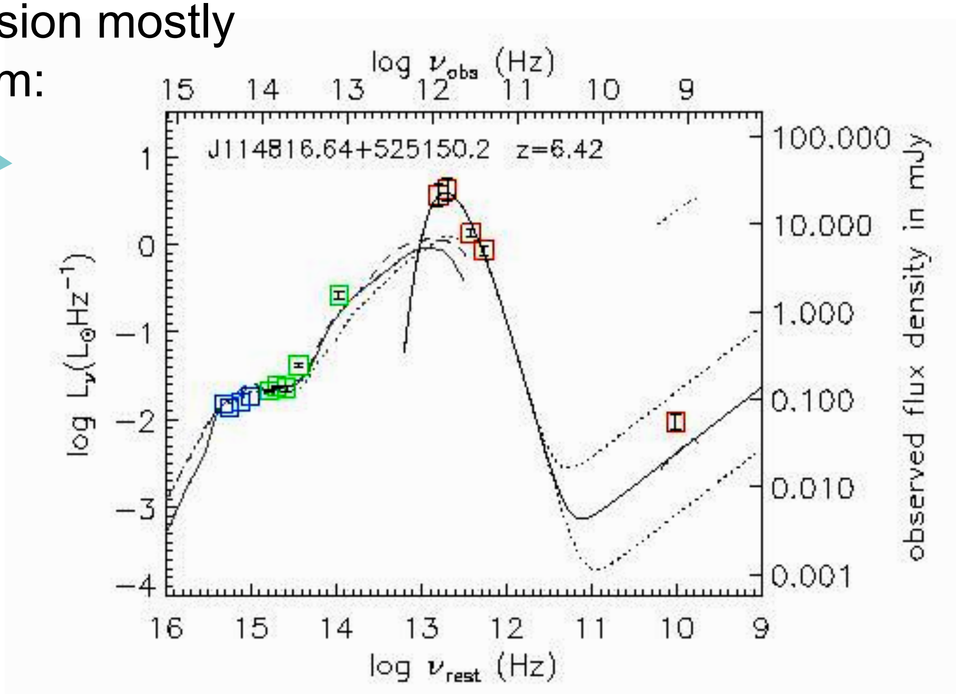
Menci+06

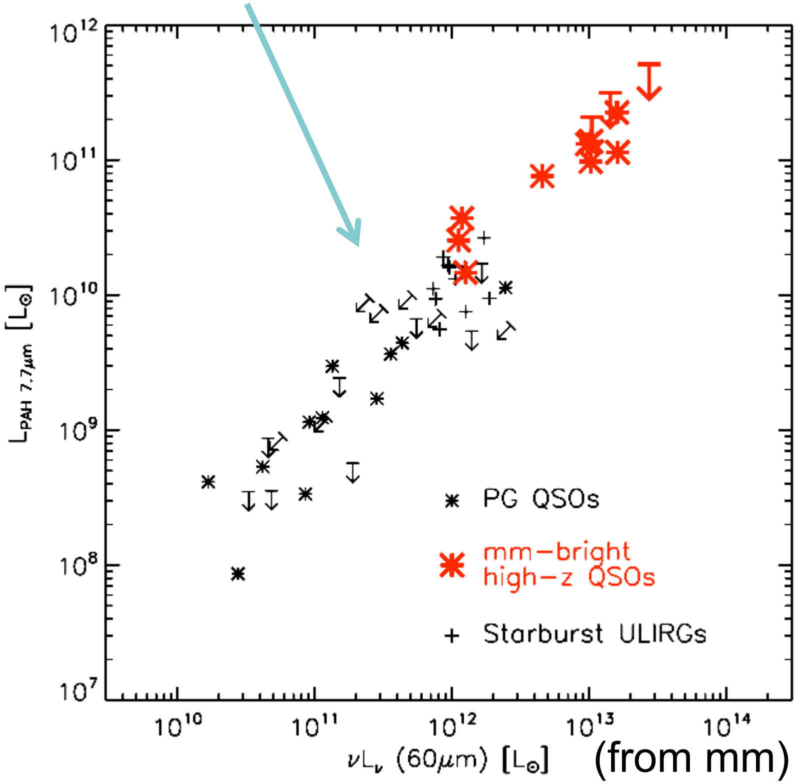
$M_{BH}/M_{\star}$ evolves with redshift:
black holes form faster than their host galaxies…
in agreement with expectations by models

Star formation in high-z quasar hosts

(sub)mm emission detected in ~30% of high-z quasars

Inferred FIR rest-frame dust thermal emission mostly powered by star formation, as inferred from:
- SED fitting
- Radio-FIR correlation
- PAH-FIR correlation



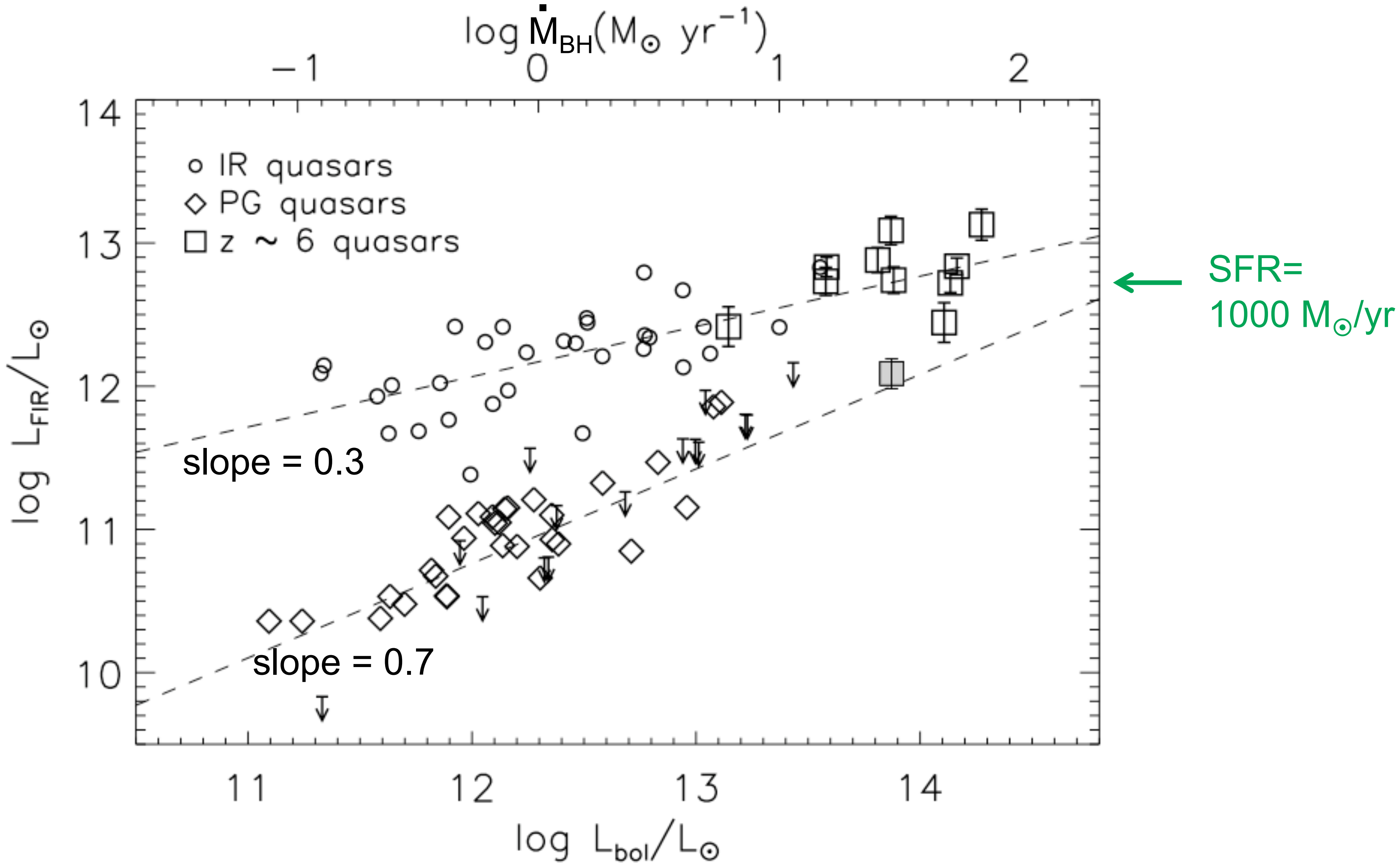


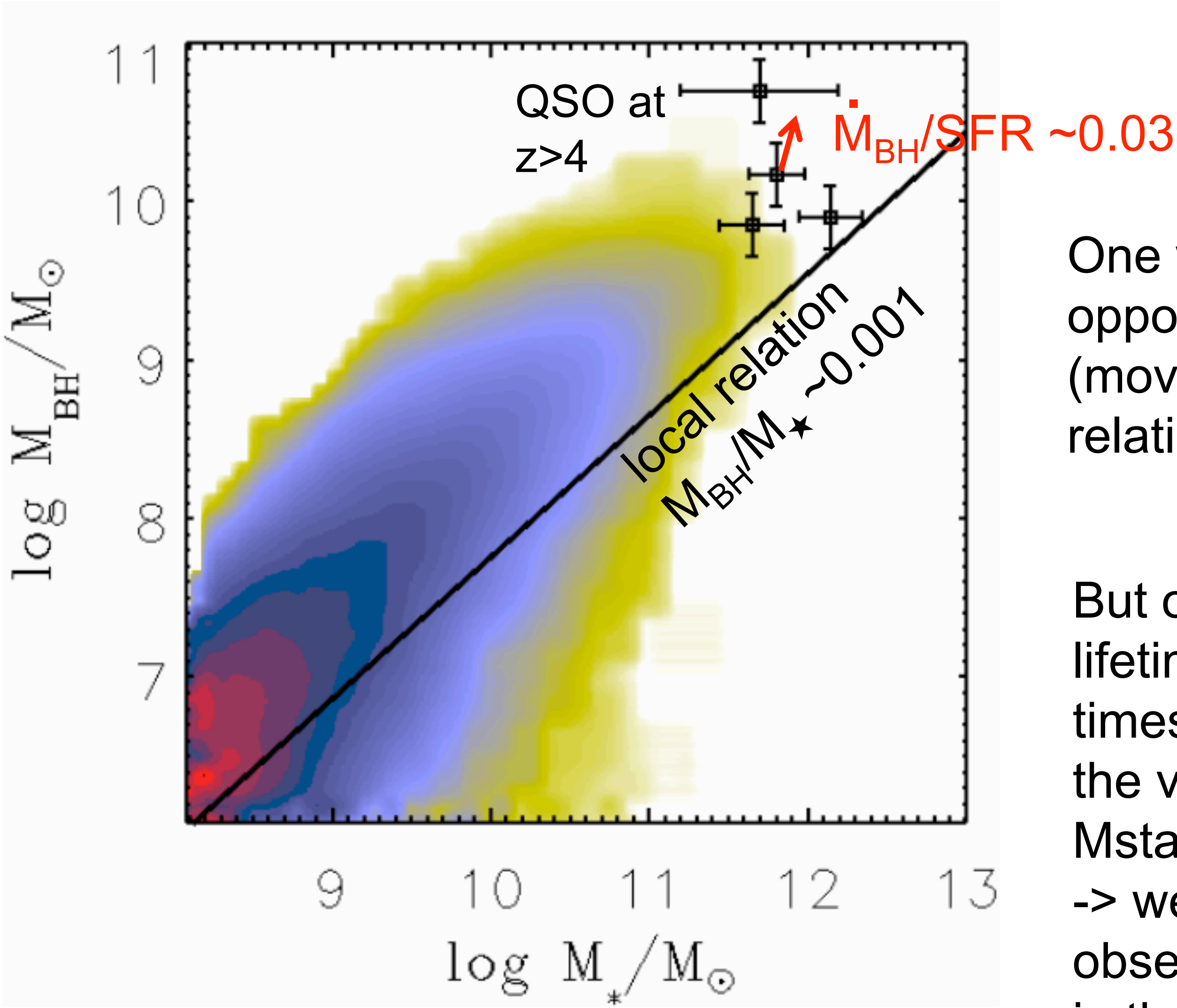
(from mm)

Inferred SFR
~ 1000 $M_\odot$/yr for mm-detected
~ a few 100 $M_\odot$/yr for mm-undetected

Probably witnessing co-eval formation of BHs and spheroids

But in the most luminous quasar $\dot{M}_{BH}$/SFR ~0.03, i.e. much higher than expected if they move parallel to (or towards) the local M_{BH}-M_{star} relation



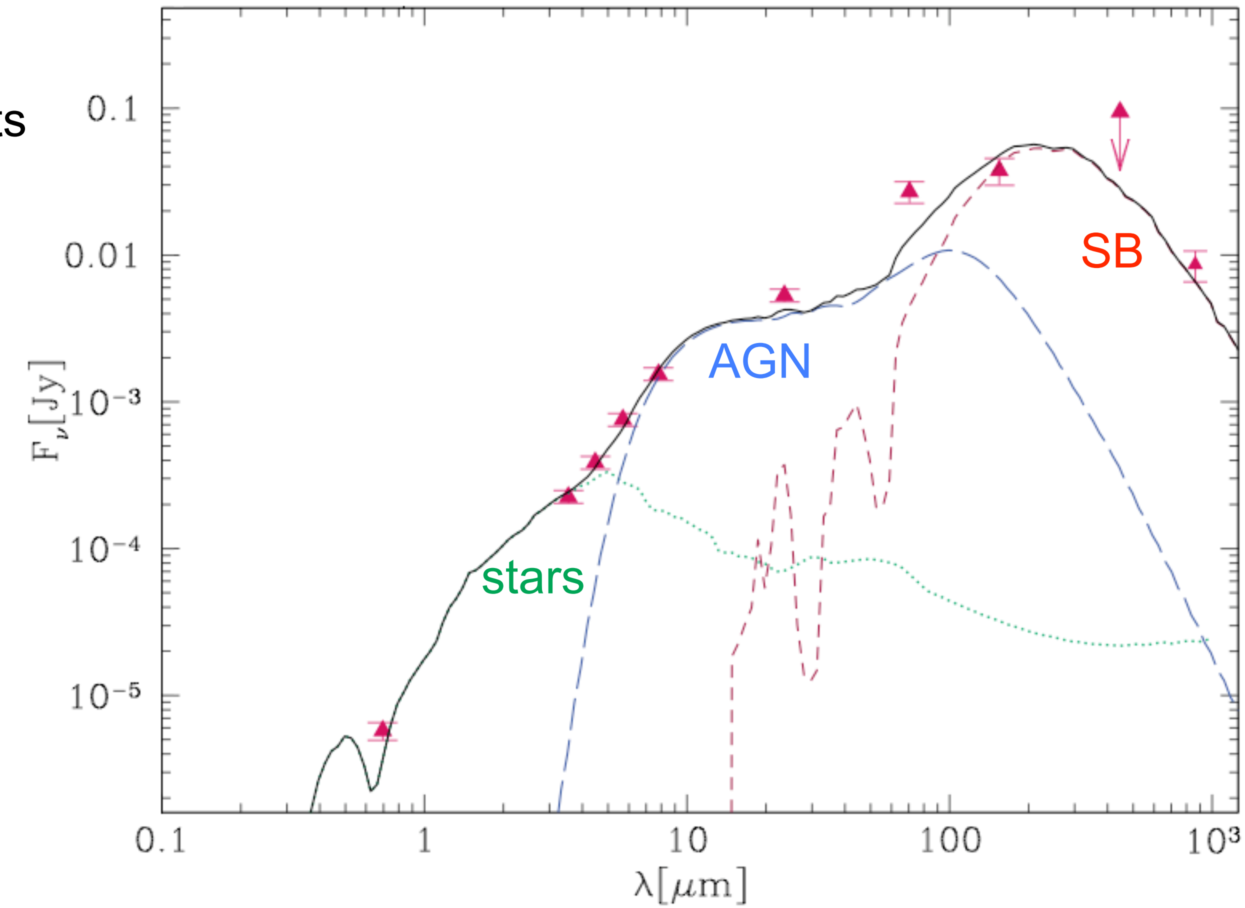


One would expect the opposite gradient (moving towards the local relation)

But over a typical lifetime and dynamical timescale of 108 yrs the variation of MBH and Mstar is minimal (a few %) -> we may be simply observing a peculiar phase in the life of the quasar

Indications of stronger mm (FIR) emission in obscured QSOs at high-z
-> Higher star formation rate and larger dust masses
-> QSO2 in early evolutionary stage than QSO1…

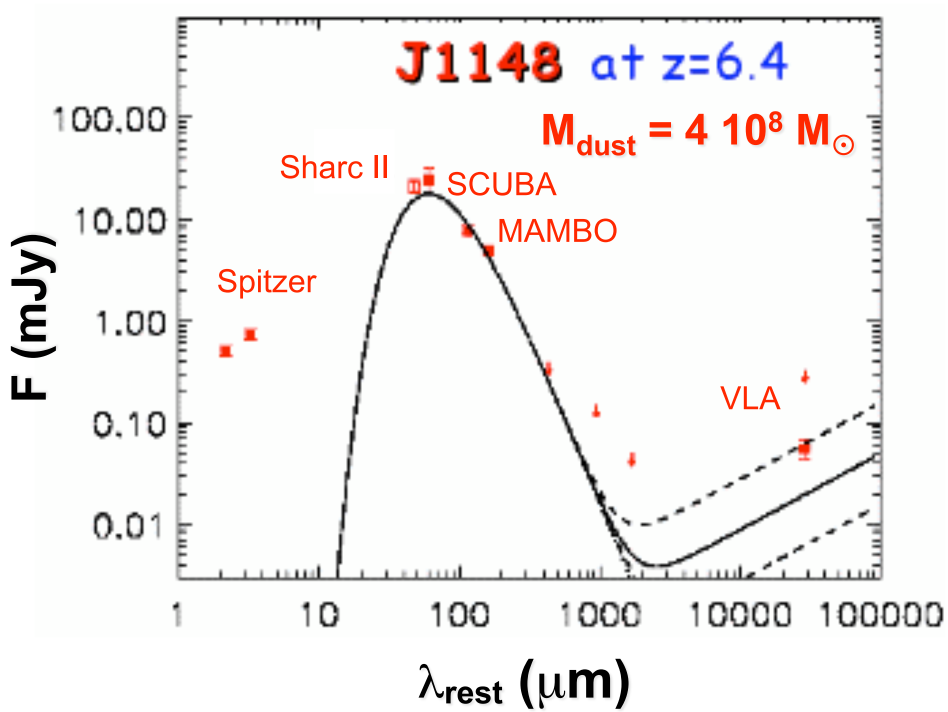
but keep in mind in all samples we are observing the tip of the iceberg… difficult to control selection effects and to make meaningful comparisons



Martinez-Sansigre+09, Page+04, Vignali+09…

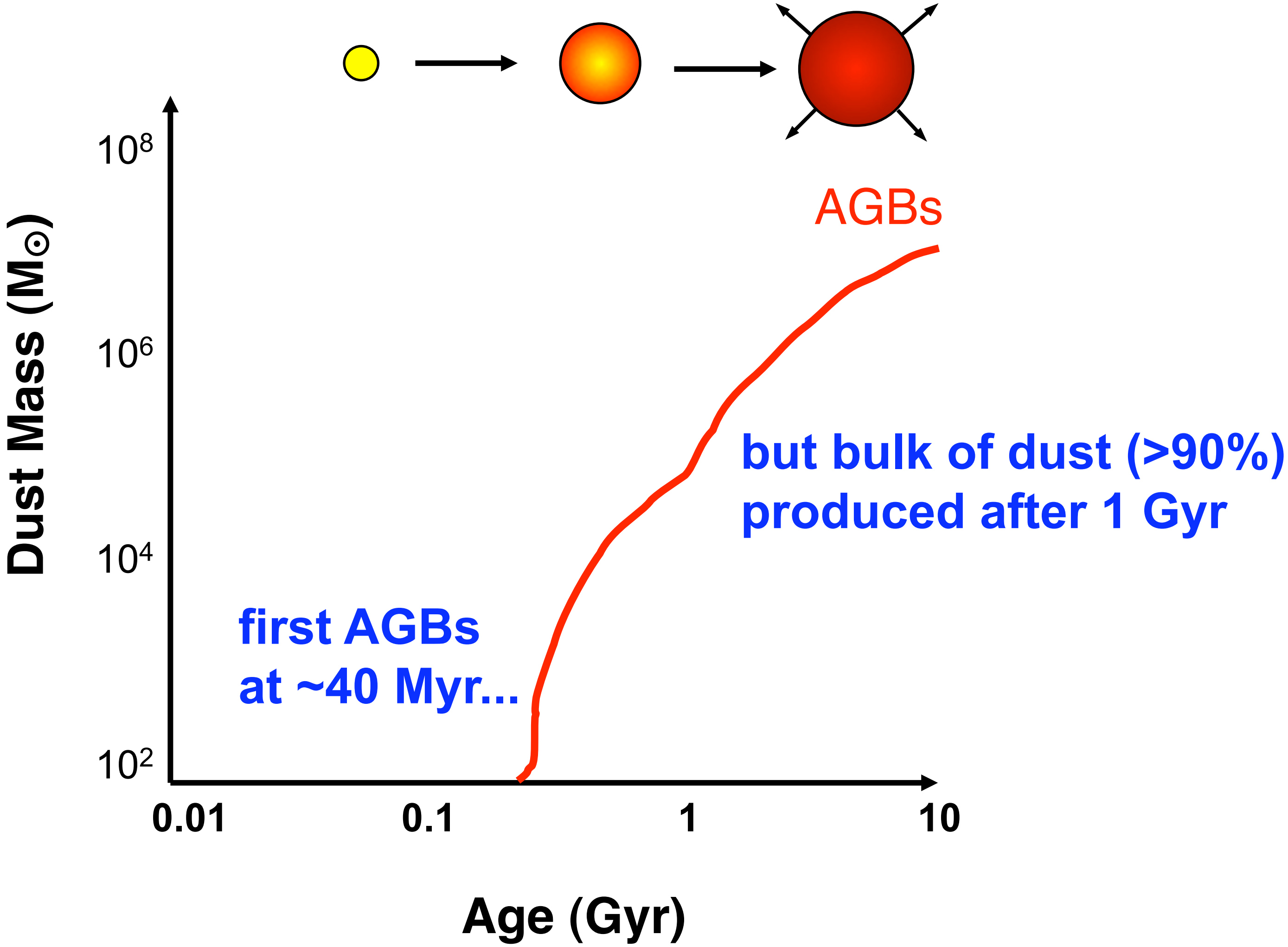
(Sub)mm emission at z>6 :
a problem for theory of dust formation?

Huge masses of dust inferred in some QSO host galaxy at z>6

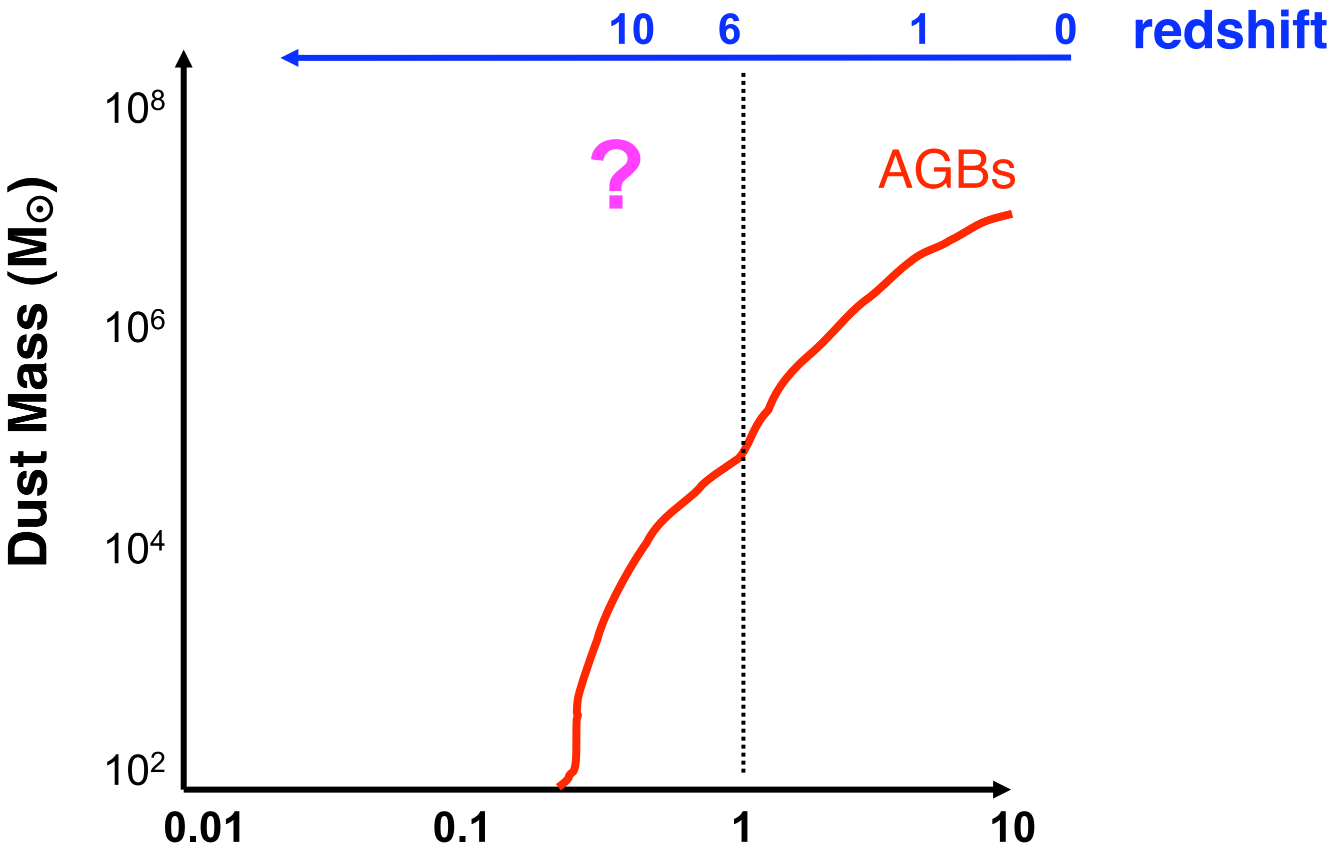


Dust in the local Universe

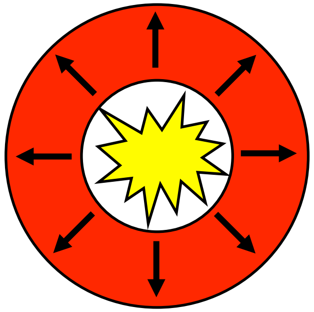
Mostly produced by evolved low mass stars (AGBs)

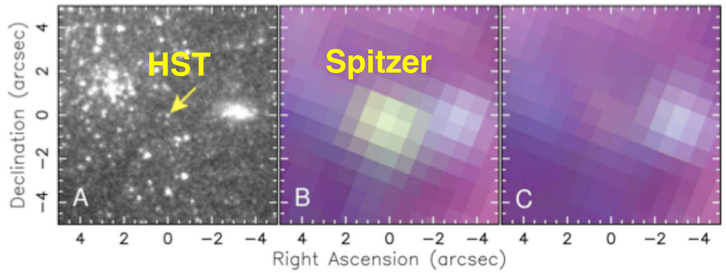


At z>6 age of the Universe < 1 Gyr…
where does the dust come from?



Dust produced in SN ejecta



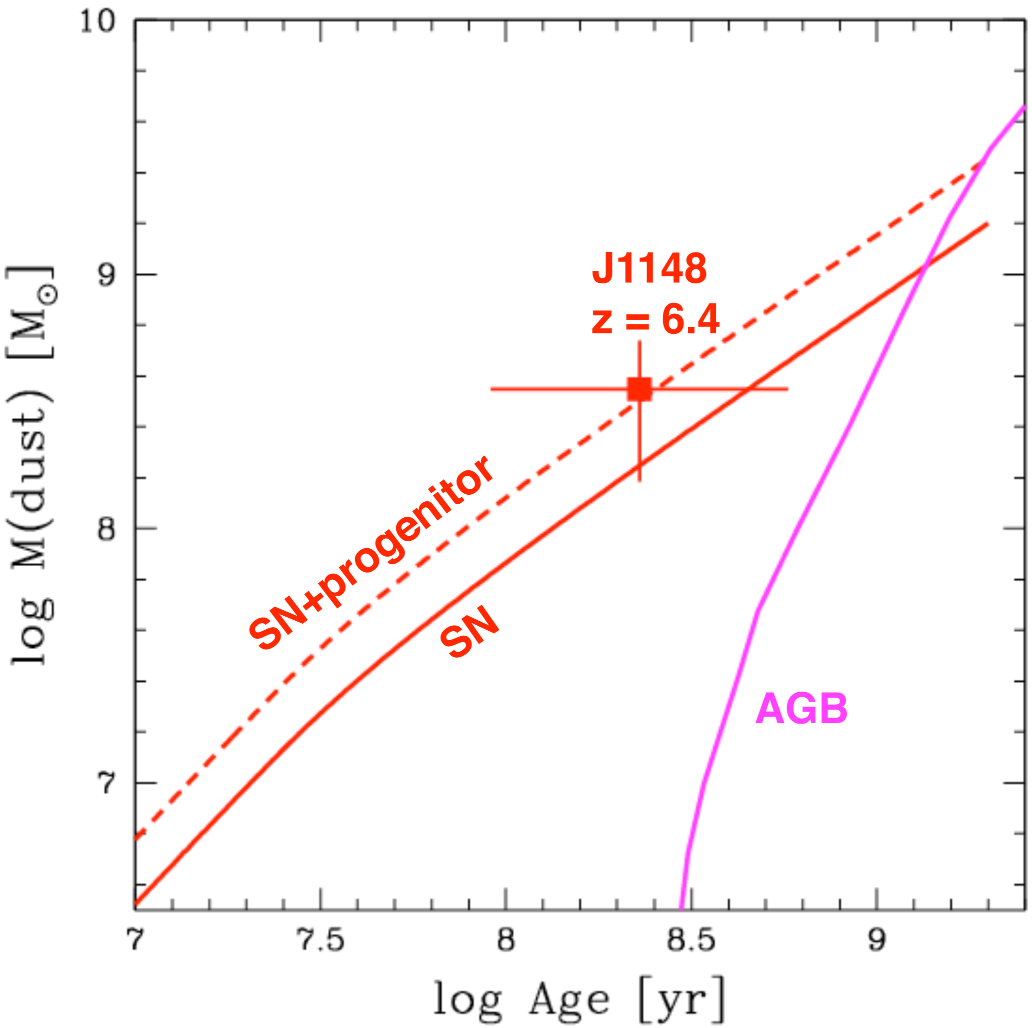


Meikle+07
Sugerman+07

Very short time scale
(in principle can make it by z~6)

But SN dust yields hotly debated

Hotly debated whether SNe can produce the observed dust masses at z>6



Dwek+08
Valiante+09

Crucial implications for the physics of galaxy formation in the early universe and for their observability…

Will be tackled with ALMA and JWST