l'Observatoire de Paris | LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

# Molecular Excitation at high z

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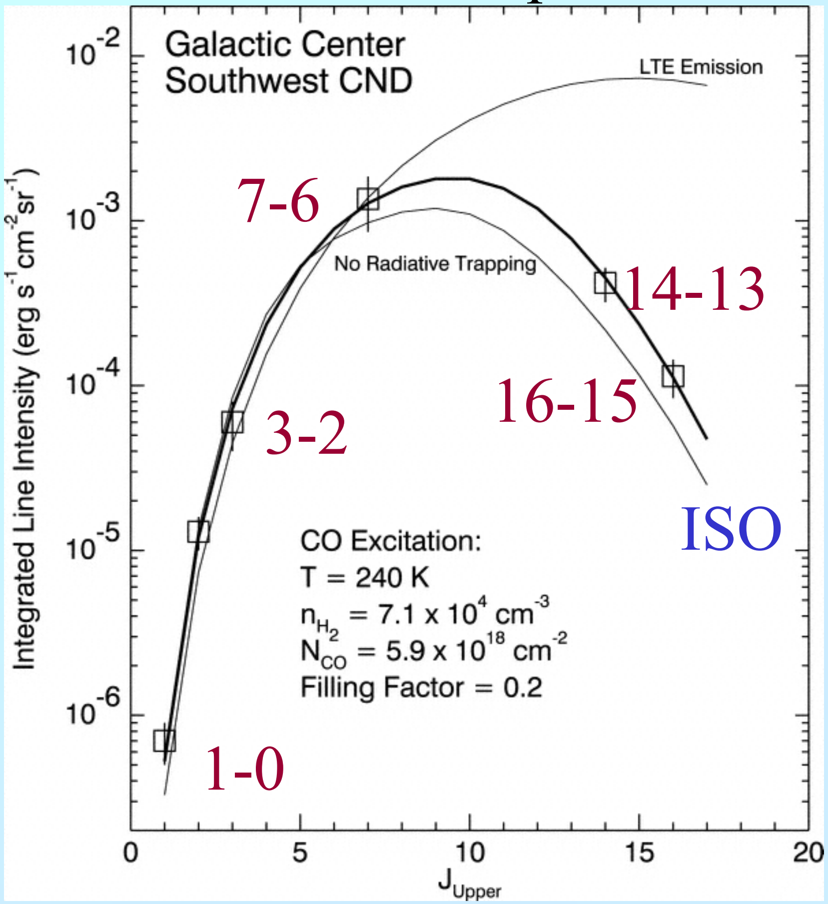
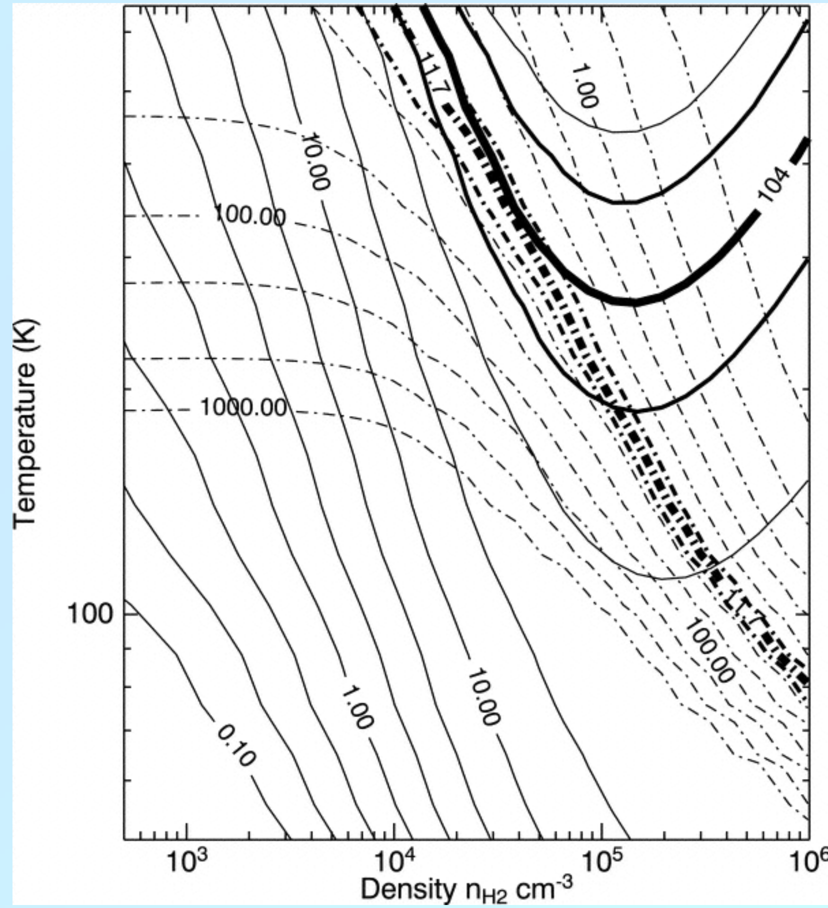
*Z-machines, January 2006*

# Local examples: Galactic Center Clouds

CND 2pc

Bradford et al 2005 JCMT-SPIFI




Heating due to turbulence (not UV)

2000 Mo, 75% at 25K, 25% at 200K

From $NH_3$

Clumpy, infalling gas

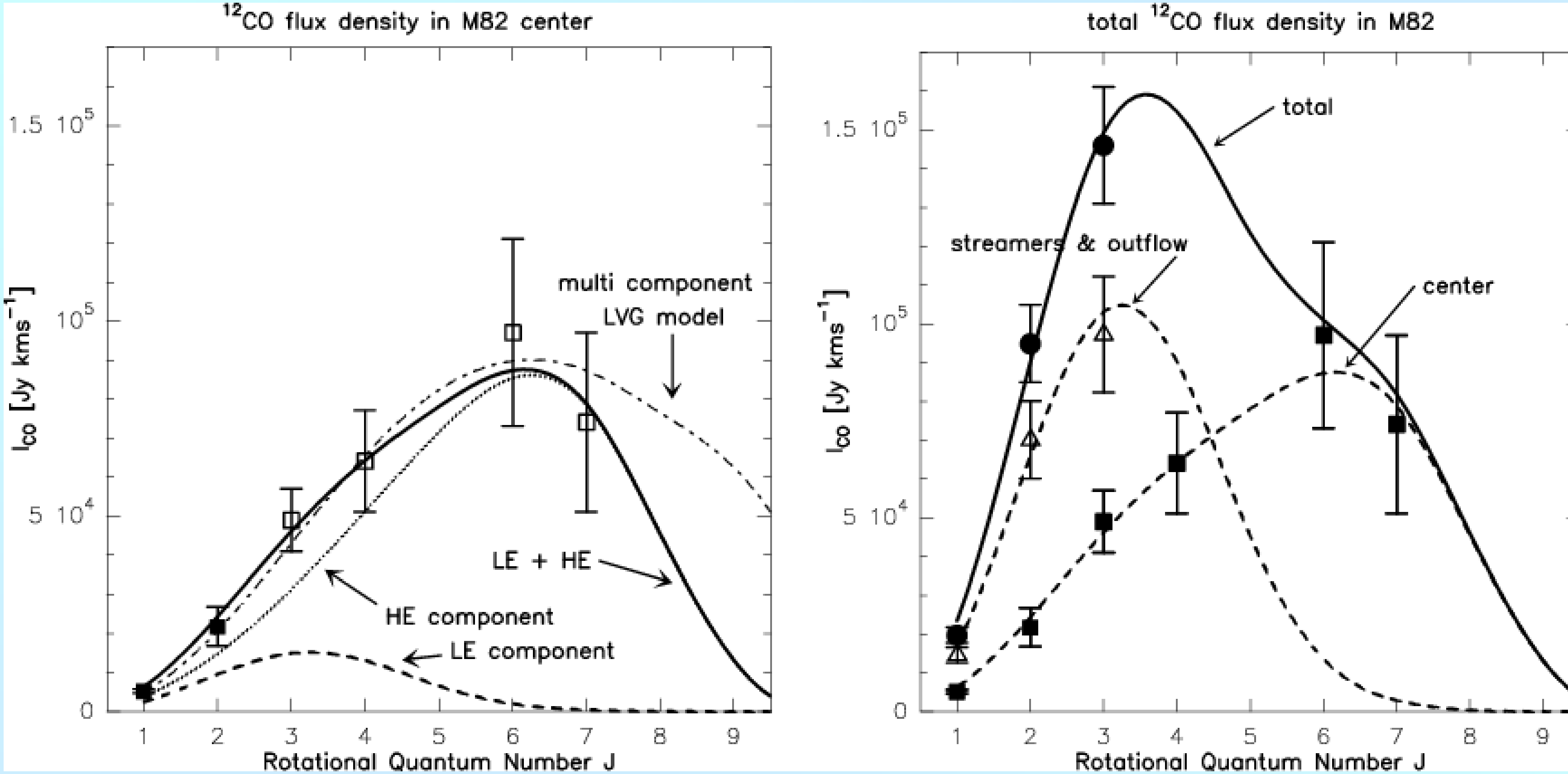
—— 7-6/2-1

---- 7-6/16-15

LVG model

# Excitation center-outer parts in M82

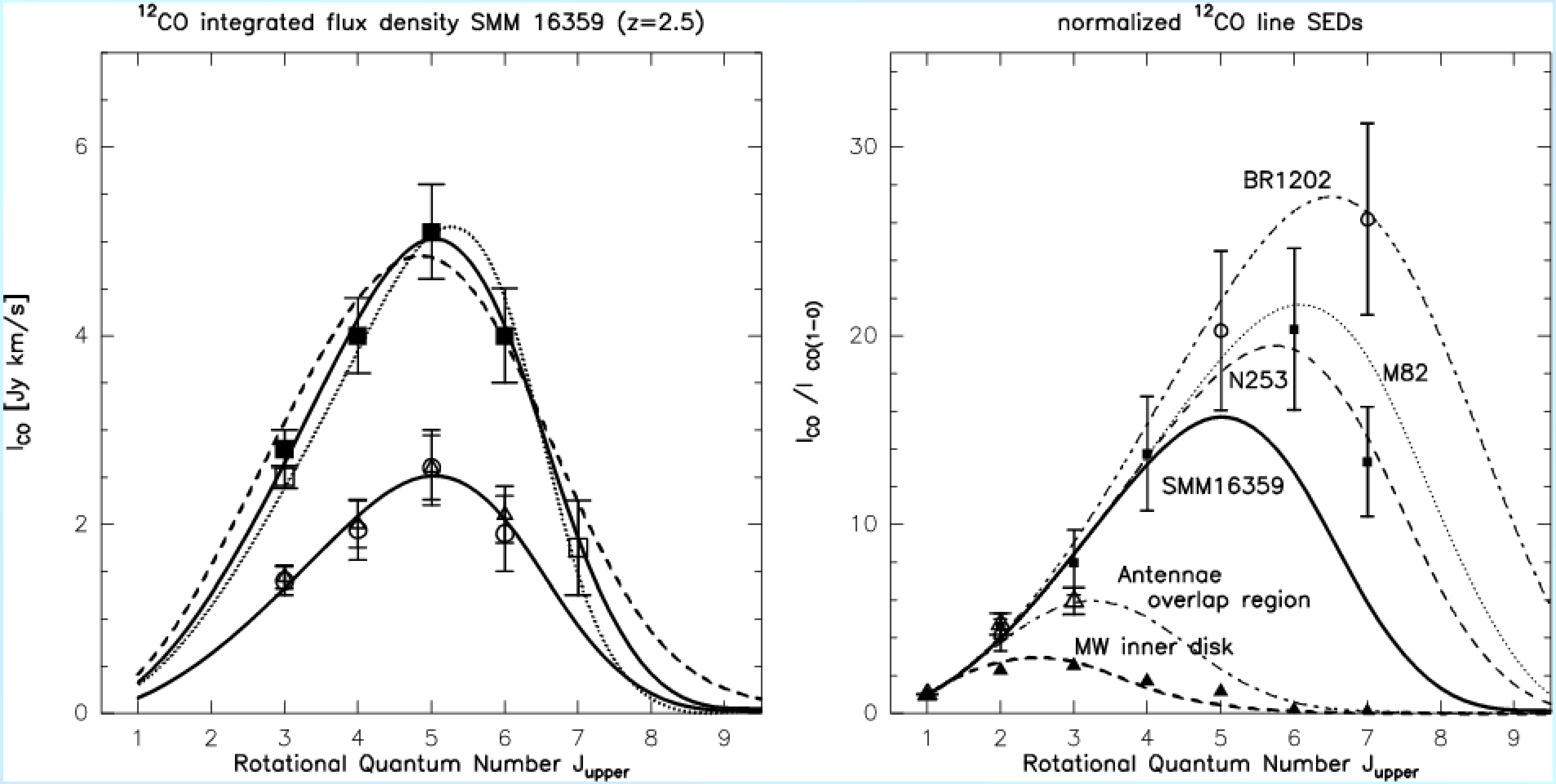
Weiss et al 2005




Density 10 times lower in the outer parts (streamer/outflow) ($nH_2 \sim 10^3$ $cm^{-3,}$ T > 50K) while the starburst disk is dense $nH_2 \sim 10^4$ $cm^{-3,}$ T = 50K *(solution not unique).*

# Excitation in high-z starbursts

SMM J16359 at z=2.5 Weiss et al 2005




— $nH_2=10^{3.4}cm^{-3}$, T=35K

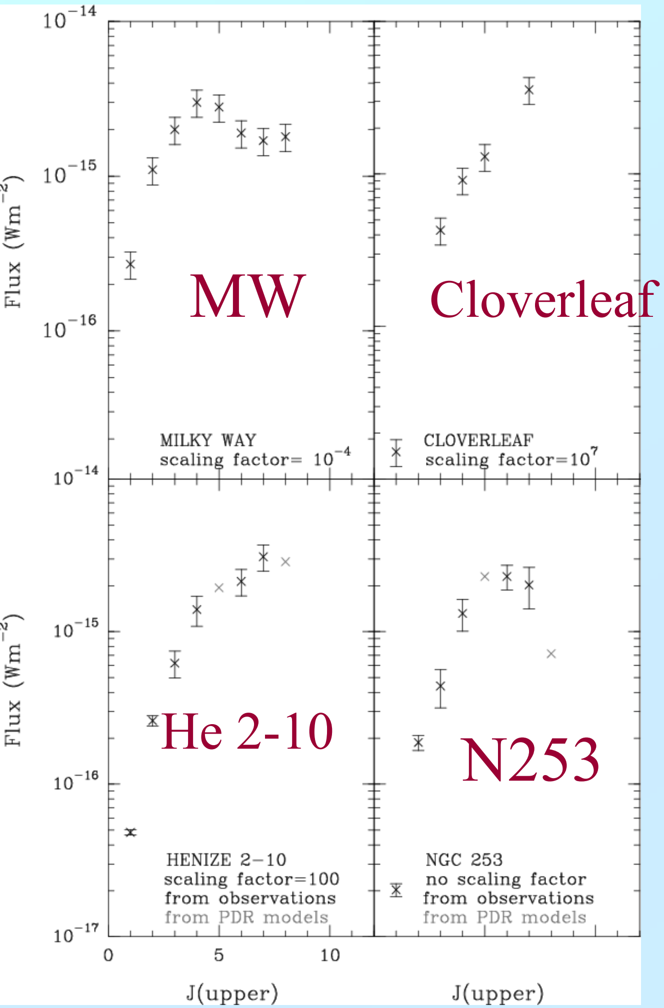
--- $nH_2=10^{3.1}cm^{-3}$, T=80K

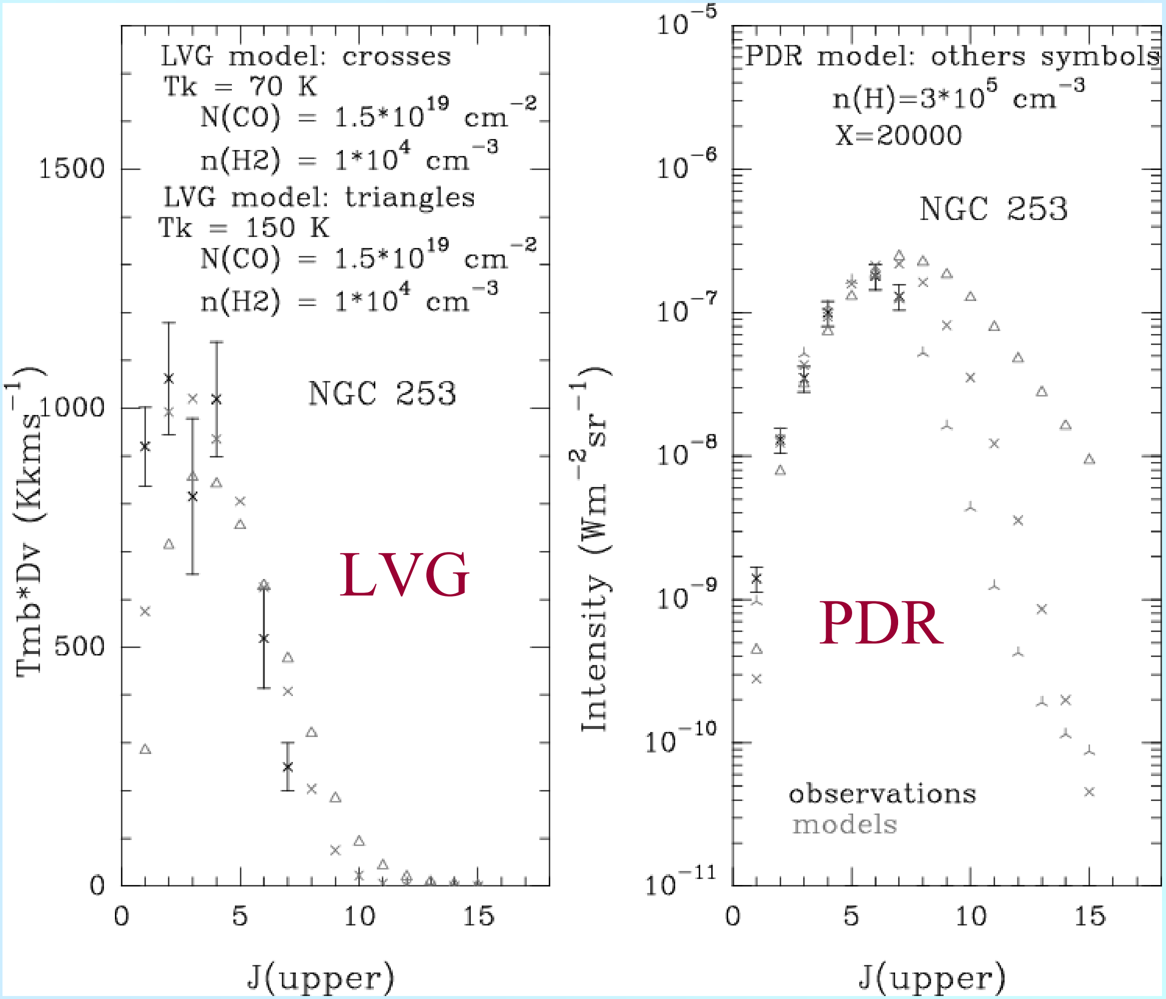
…. $nH_2=10^{3.8}cm^{-3}$, T=20K

Comparison with various galaxies

M82: starburst disk only

# Excitation in HE 2-10, N253, MW



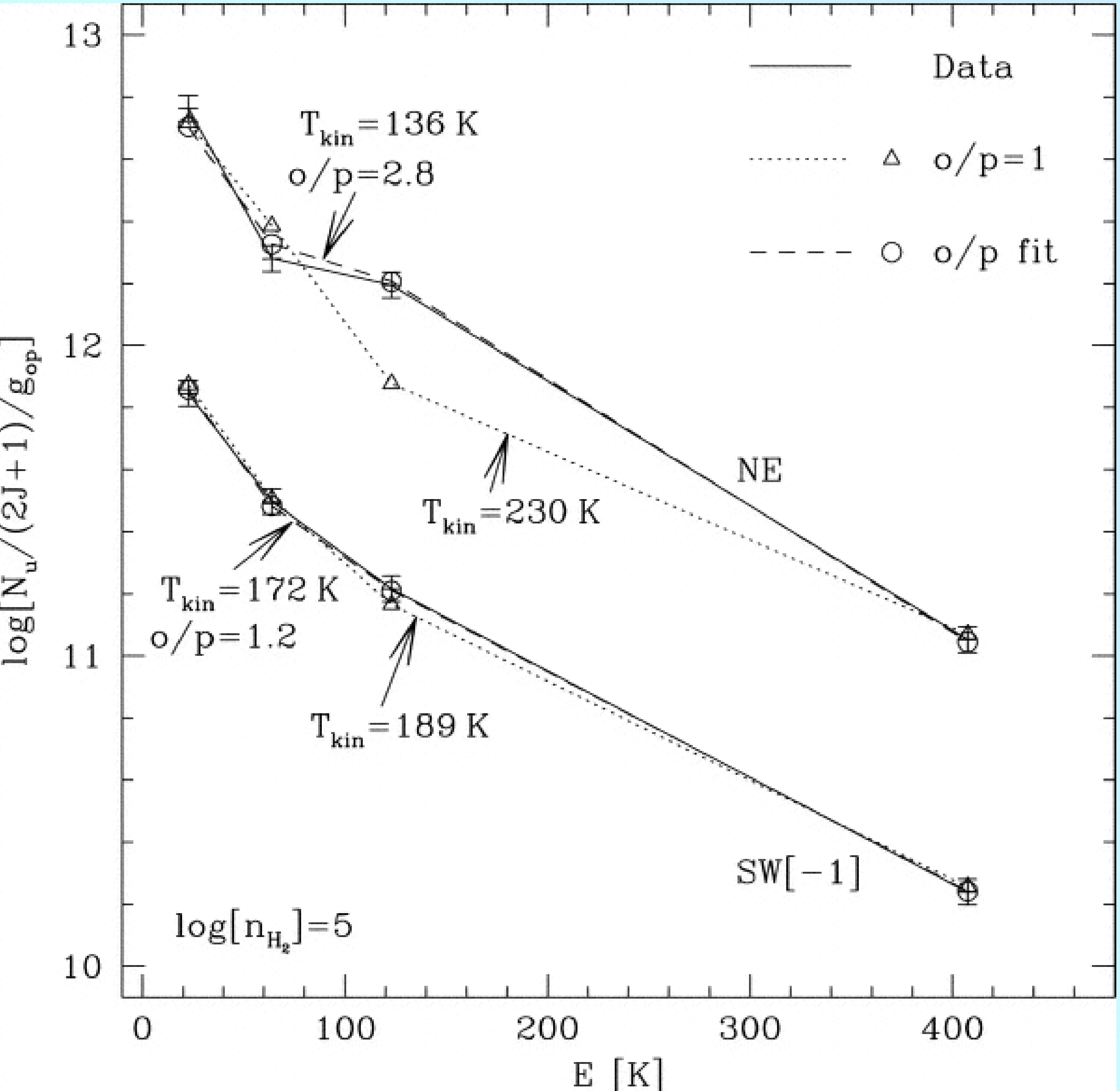




➔All similar excitation, except the MW

Bayet et al 2004

# Temperatures from $NH_3$ in N253

Ott et al 2005




CMD of 250pc

Several knots/clumps

SW T ~ 200K

NE T ~140K

T($NH_3$ formation) ~30K

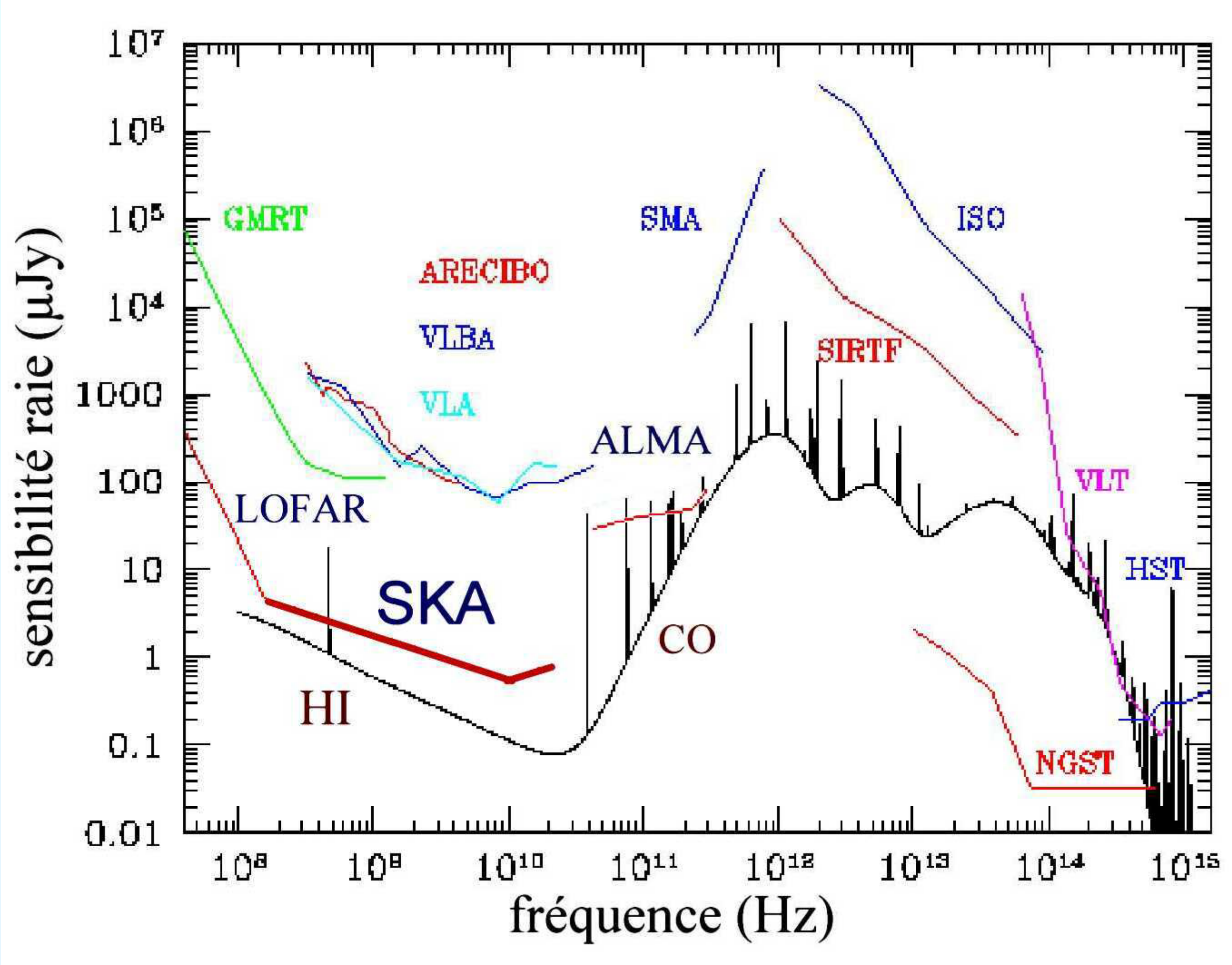
$T_{12}$ and $T_{36}$ different

2.8 Mo/yr SFR

M($H_2$) ~6 $10^8$ Mo

τ(SB) =200 Myr

# Complementarity of future large instruments

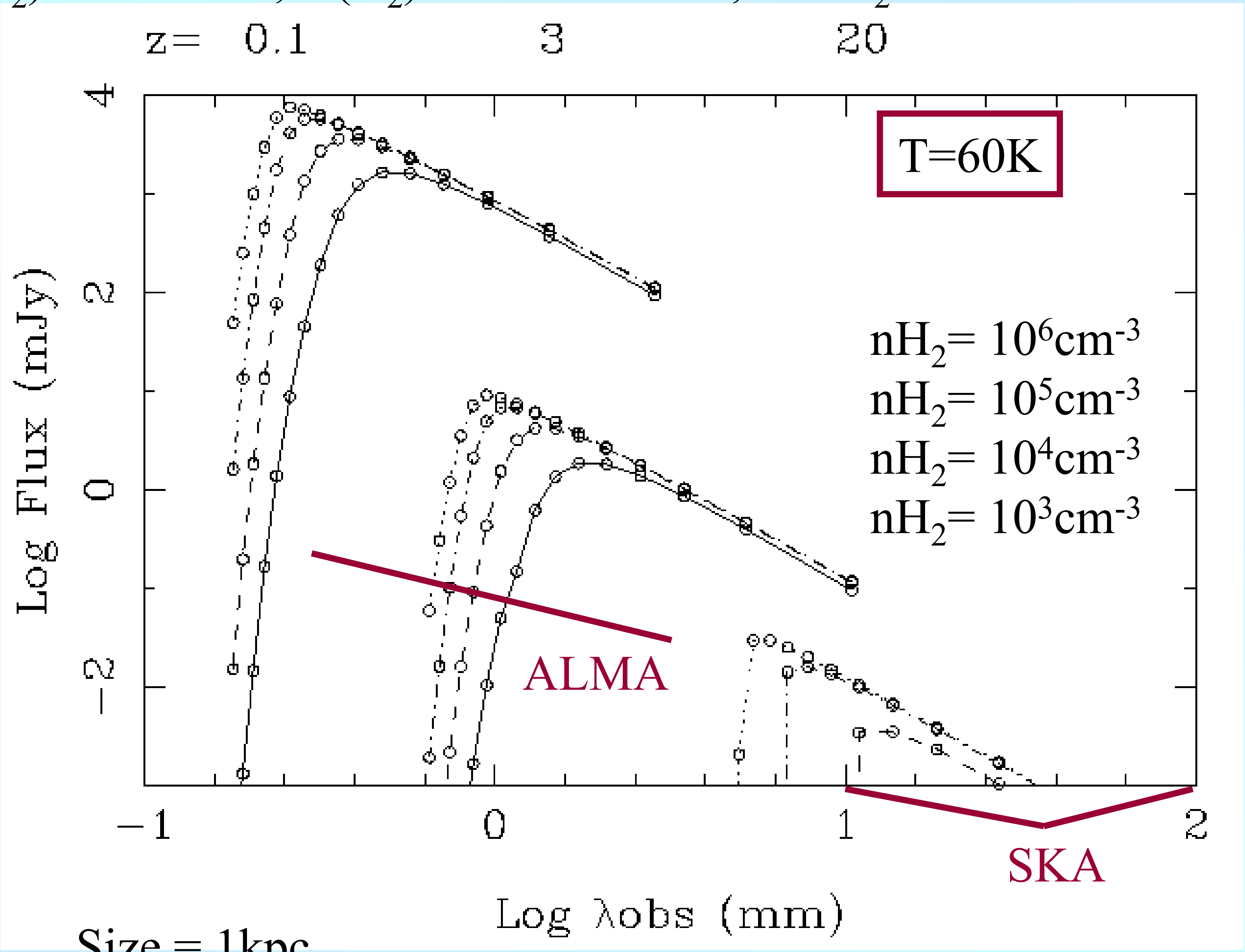



Detection of spectral lines of a ‘standard’ spiral galaxy at $z = 2$

$5\sigma$ in 1hour

# Influence of density

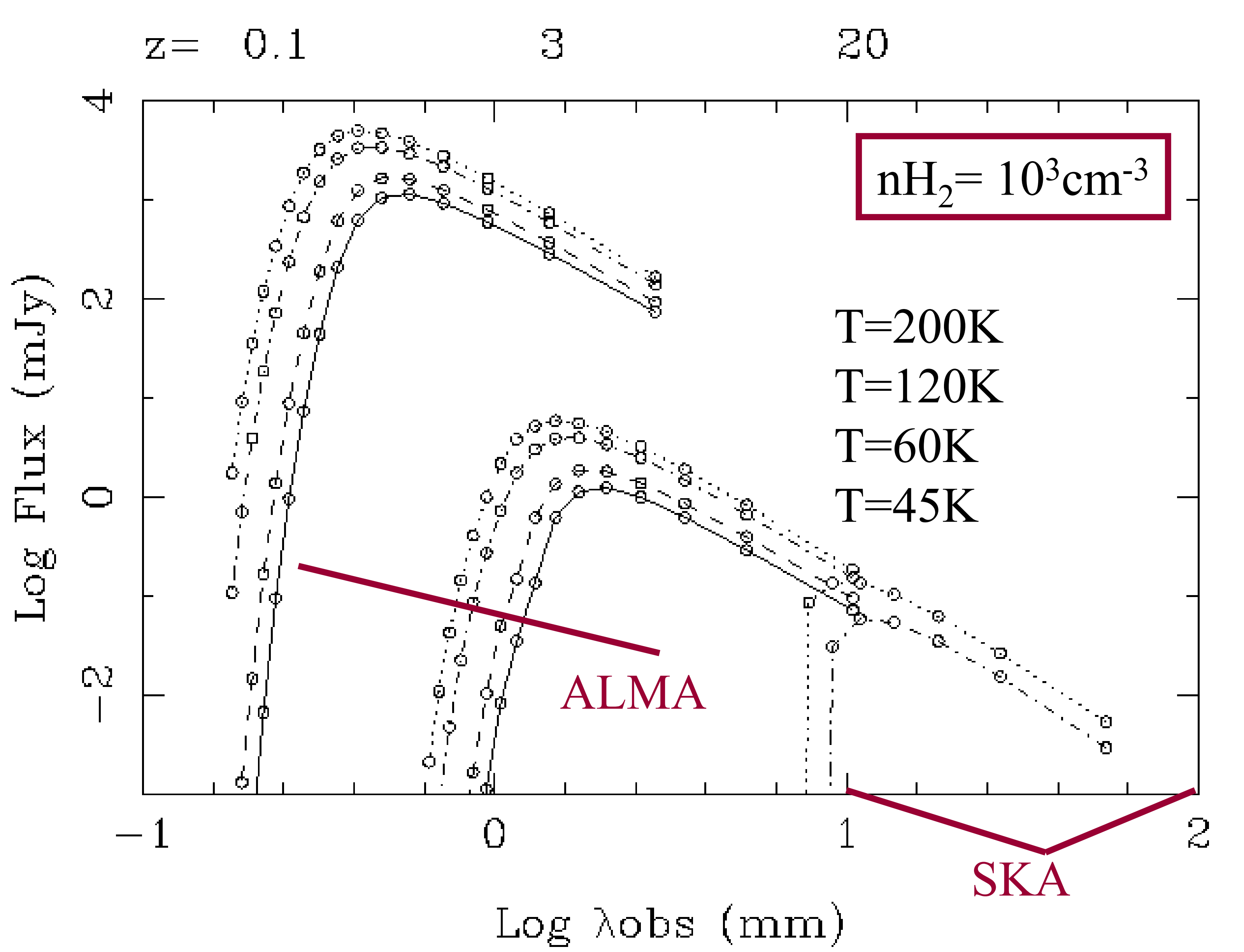
$M(H_2) = 6\ 10^{10} Mo$, $N(H_2) = 3.5\ 10^{24}\ cm^{-2}$, $CO/H_2 \sim 10^{-4}$




Size = 1kpc

# Influence of temperature

$M(H_2) = 6\ 10^{10} Mo$, $N(H_2) = 3.5\ 10^{24}\ cm^{-2}$, $CO/H_2 \sim 10^{-4}$



**Up to now: 37 systems detected in CO lines z > 2**
**of which > 18 are strong lenses**

At high z, more frequent and intense starbursts

• More gas in galaxies

• More efficiency to form stars
(interacting and merging galaxies)

• Shorter dynamical time-scales, etc..

Assuming that physical conditions are similar to GMC cores (Orion)
But these cores are packed in a small volume
typically 8.6 $10^7$ clouds of $700 M_o$ each)

➔Optically thick gas, at least for all low-J lines

# Modelisation of a starburst

Very high molecular masses $10^{10}$ - $10^{11}$ Mo
High temperatures of dust: 30-50K up to 100K (or 200K)

**Very small sizes:** below 1kpc (300pc disks)
In these conditions, the average column density is around $10^{24}$cm$^{-2}$
and the dust becomes optically thick at $\lambda < 150\mu$

**Two components**, both with low filling factor

1-the dense and hot component: star forming cores $10^{6}$cm$^{-3}$, 90K
2-each embedded in a cloud $10^{4}$cm$^{-3}$, 30K

Individual velocity dispersion of 10km/s
Embedded in the rotational gradient of the galaxy, 300km/s

Assume same energy coming from stars

Black-body

$T_{dust}^4 - T_{bg}^4 = cste$

or optically thin dust

$\tau \sim \nu^2$

→ $T_{dust}^6 - T_{bg}^6 = cste$

**Table 2.** Parameters of the two-component mode

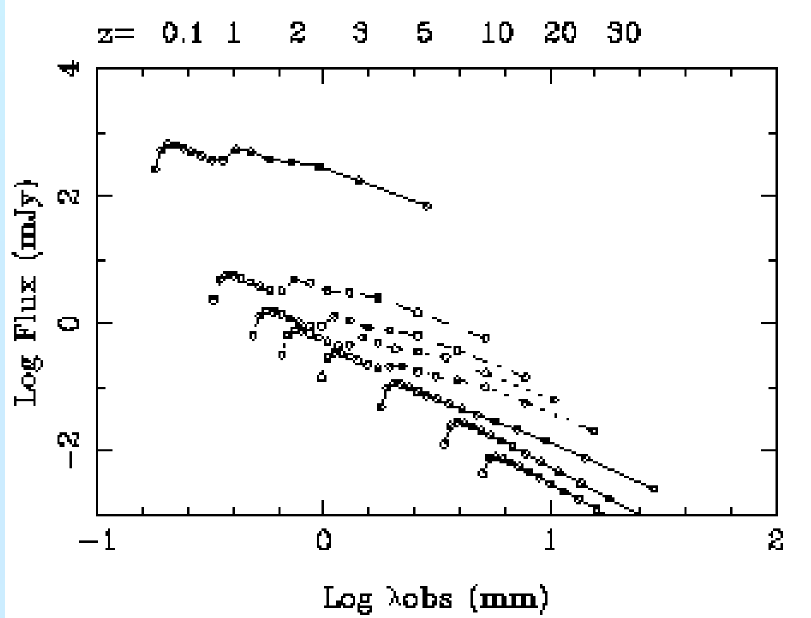
| Parameter | Hot comp. | Warm comp. |
|---|---|---|
| $n(H_2)$ $cm^{-3}$ | $10^6$ | $10^4$ |
| sizes (pc) | 0.1 | 1 |
| $\Delta V$ (km/s) | 10 | 10 |
| $T_K$ $(z = 0.1)$ | 90.0 | 30.0 |
| $T_K$ $(z = 1.0)$ | 90.0 | 30.0 |
| $T_K$ $(z = 2.0)$ | 90.0 | 30.0 |
| $T_K$ $(z = 3.0)$ | 90.0 | 30.0 |
| $T_K$ $(z = 5.0)$ | 90.0 | 30.1 |
| $T_K$ $(z = 10.0)$ | 90.0 | 33.7 |
| $T_K$ $(z = 20.0)$ | 91.0 | 57.5 |
| $T_K$ $(z = 30.0)$ | 98.2 | 84.6 |
| N(CO) $cm^{-2}$ | 3. $10^{19}$ | 3. $10^{18}$ |
| $N(H_2)$ $cm^{-2}$ | 3. $10^{23}$ | 3. $10^{22}$ |
| $f_s^*$ | 1. | 100. |
| $f_v^*$ | 0.03 | 0.03 |
| mass fraction | 0.1 | 0.9 |

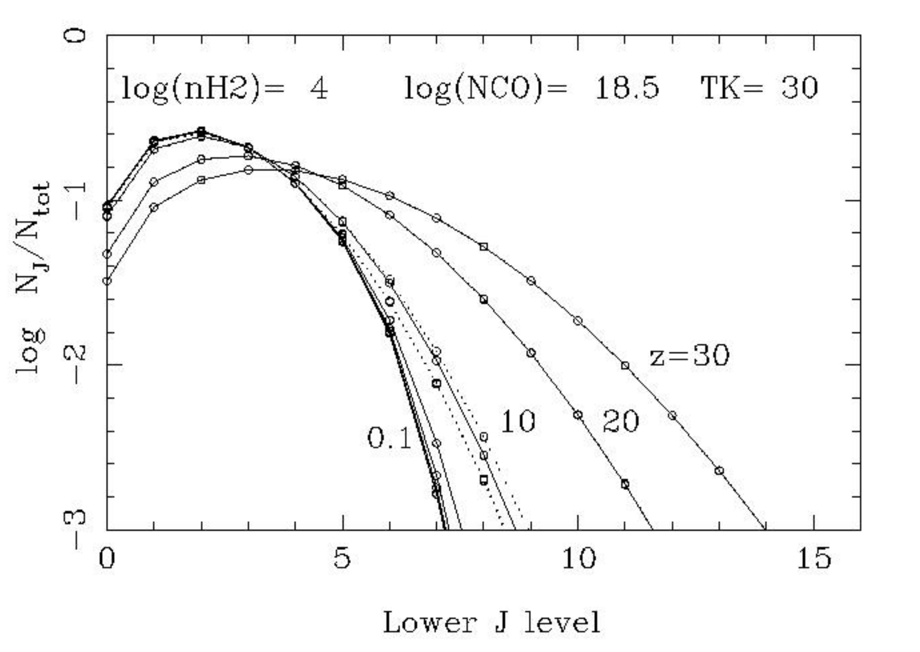
* $f_s$: surface filling factor, $f_v$ velocity filling factor

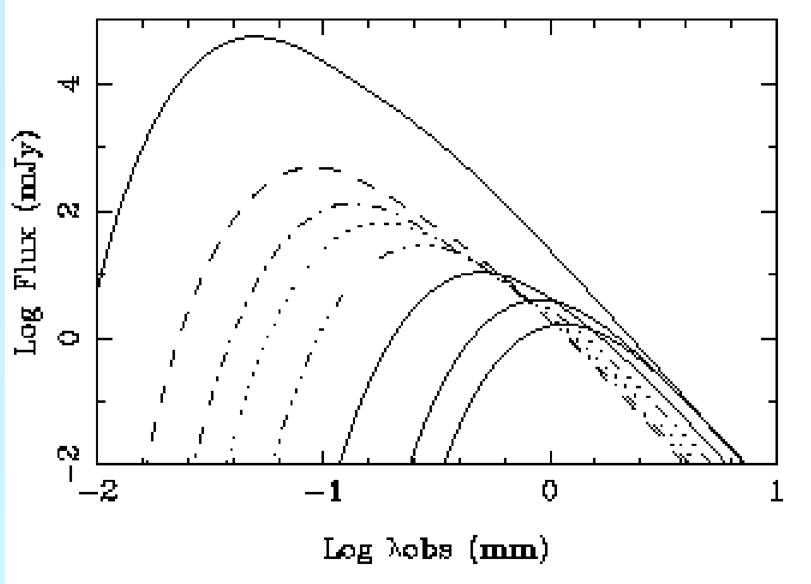
$T_K$ increases with $z$ keeping $T_{dust}^6 - T_{bg}^6$ constant (see

# Model Results

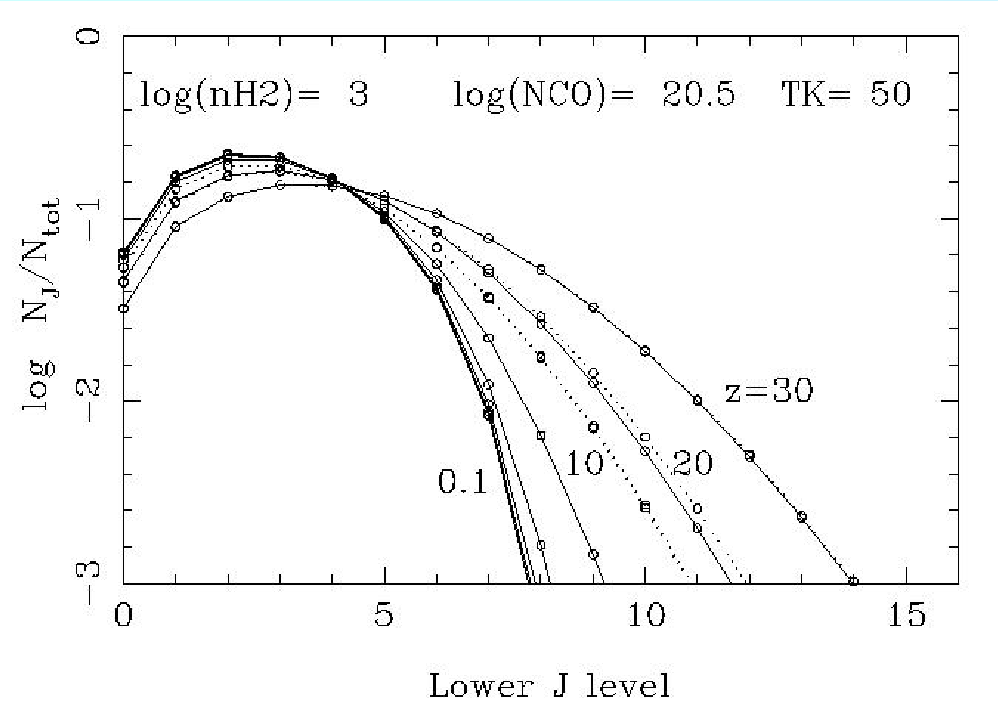
With the two-component models,
At 30 and 90K
$T_{dust}^6 - T_{bg}^6 = cste$

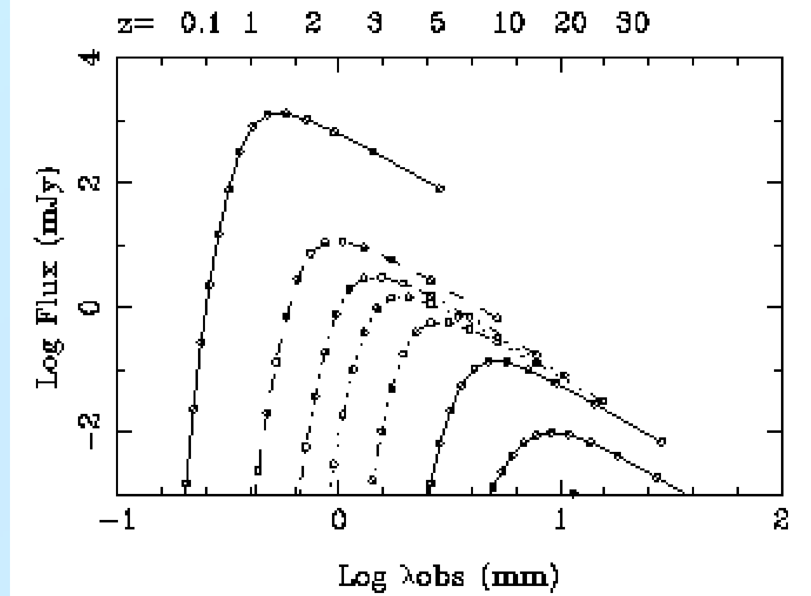


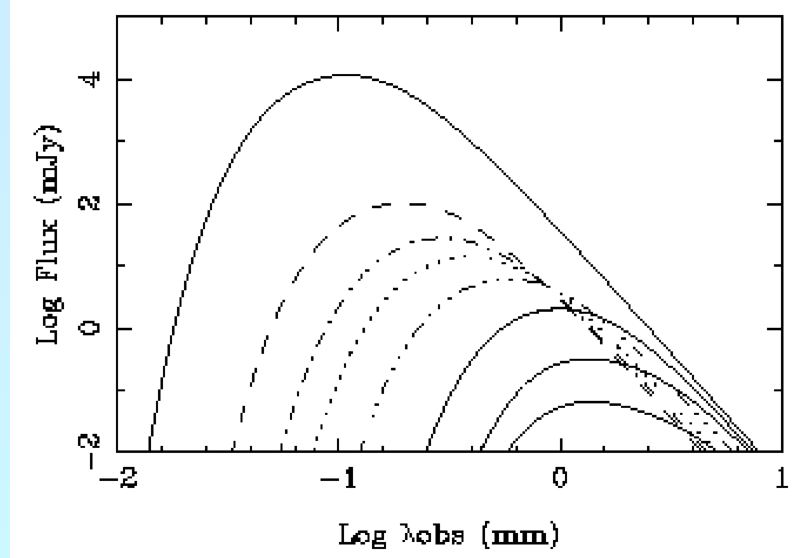
# Homogeneous sphere 50K




$T_{dust}^6 - T_{bg}^6 = cste$

Submm continuum




Ho=70km/s/Mpc

Ω=0.3

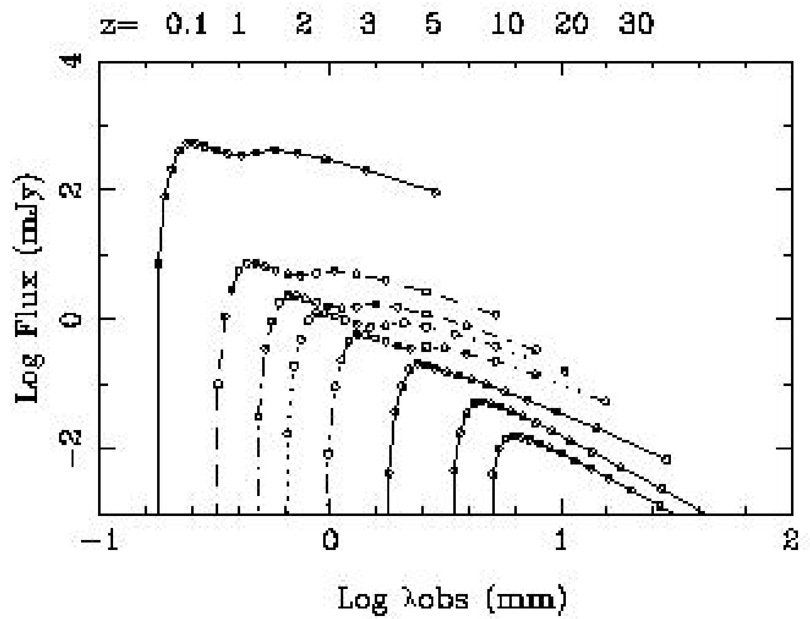
Λ=0.7

Simulations of low metallicity and low CO abundance

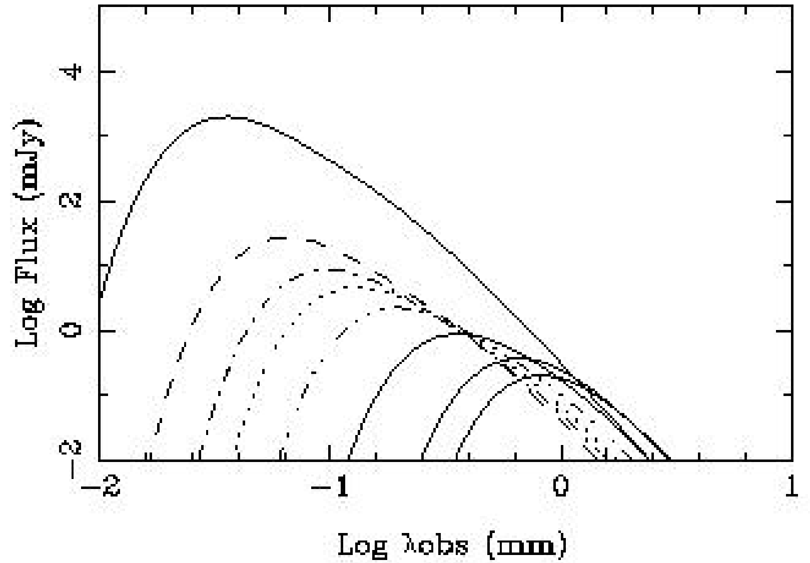
Then the CO lines become optically thin

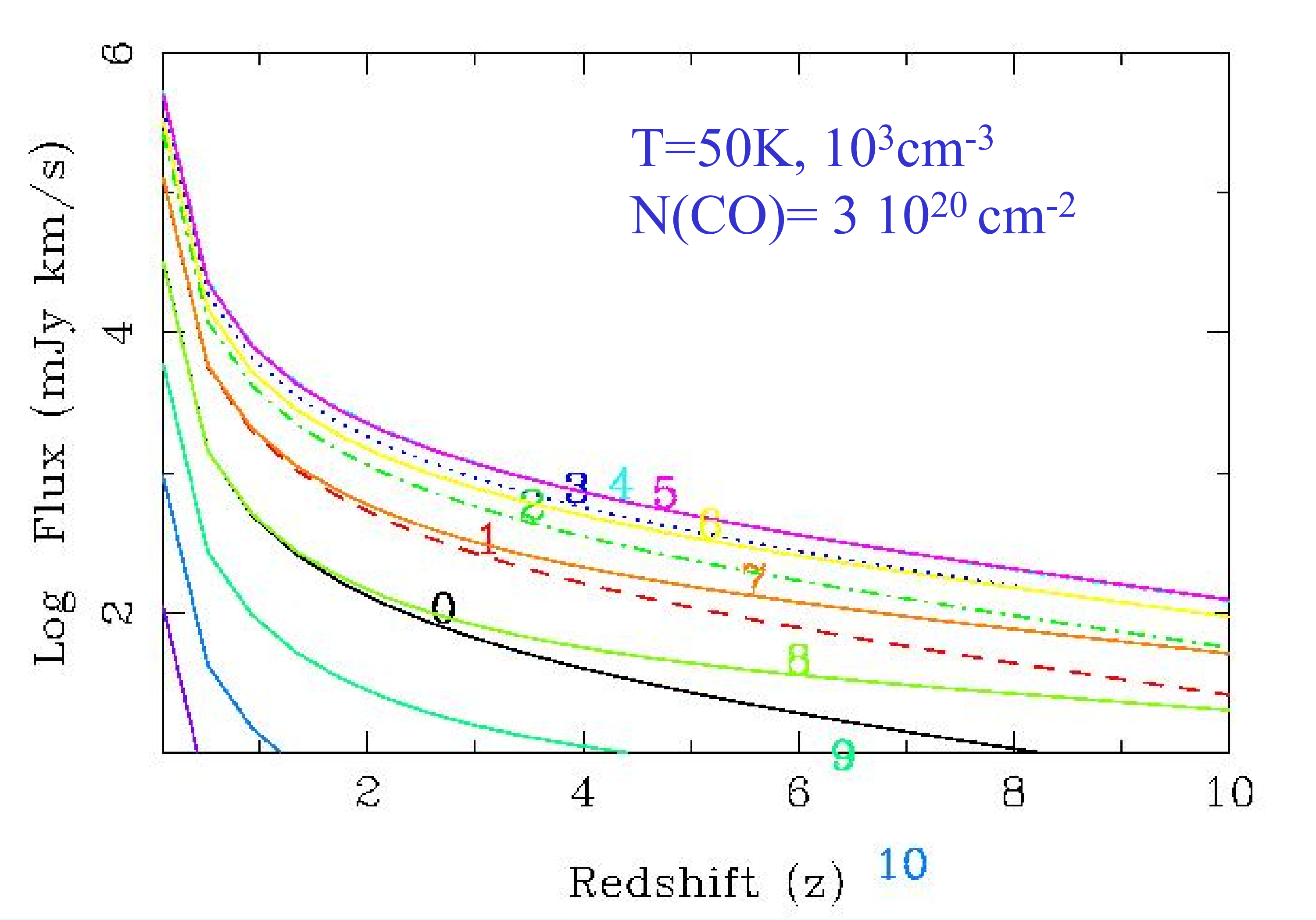
About 2 orders of magnitude lower fluxes

➔Lower continuum to line ratio




$CO/H_2=10^{-6}$






Best strategy to observe a high-z galaxy
Depends on excitation
➔Could be at low frequency

# Prediction of source counts

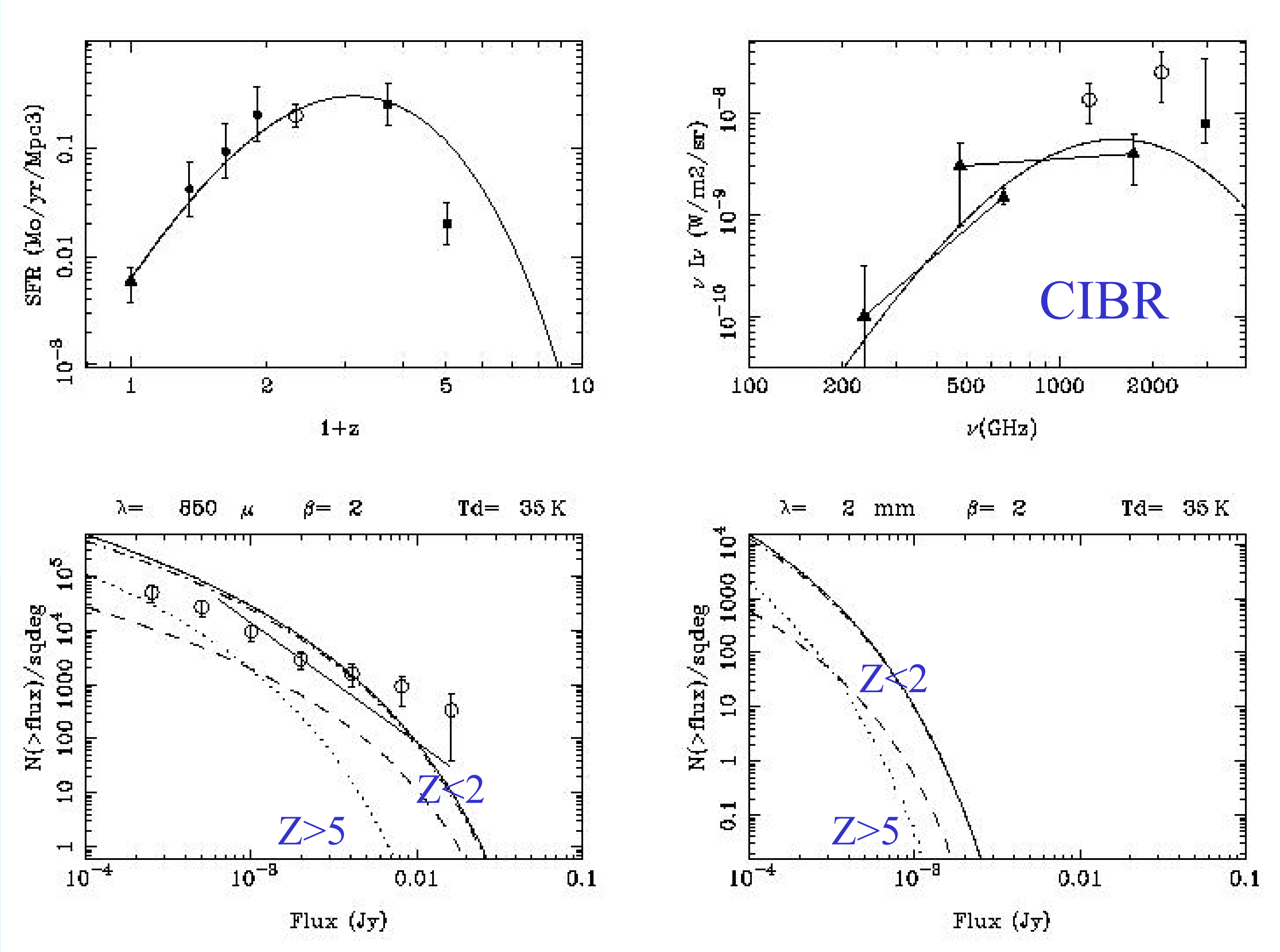
•Hierarchical theory of galaxy formation
Ho = 70km/s/Mpc, with $\Omega$ =0.3 $\Lambda$=0.7
•Number of mergers (z) from Press-Schechter
but efficiency of star formation must also vary considerably with redshift with a peak at z=2

Integration over z should equal CIBR background
To fit source counts: life-time of merger much shorter at high z

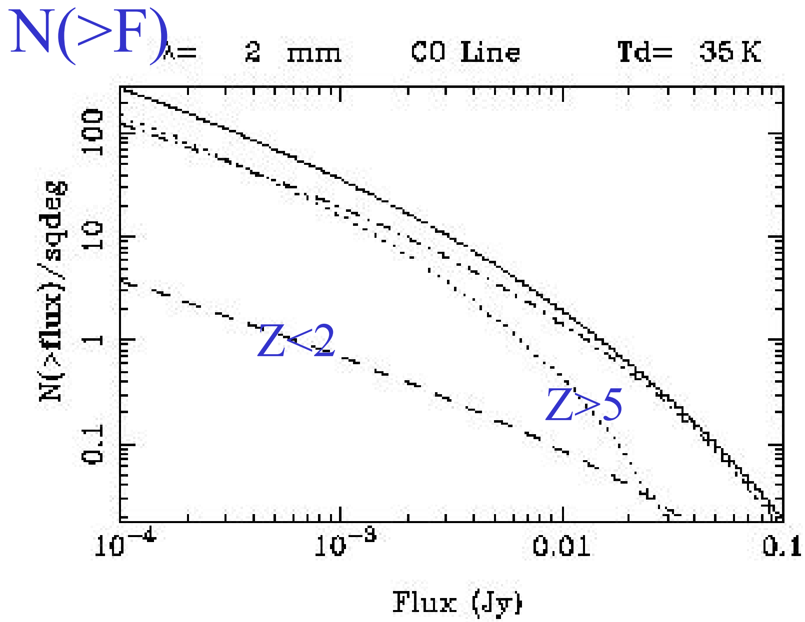
Once the counts are fit to the submm observations, the model indicates what must be the contribution of the various redshifts to the counts
The bulk of the contribution is $2 < z < 5$

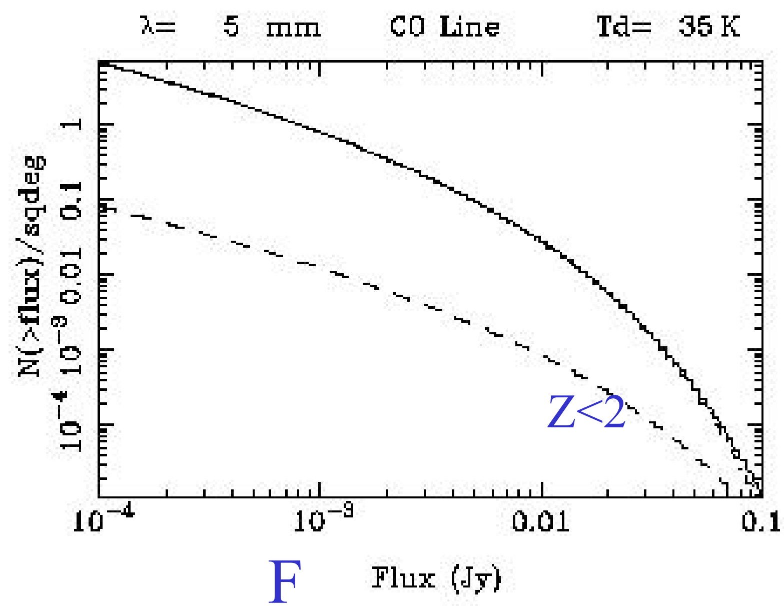
Results depend on the shape of the SF efficiency

SFR




Data on source counts:Barger et al 99, Carilli et al 01
Blain et al 02



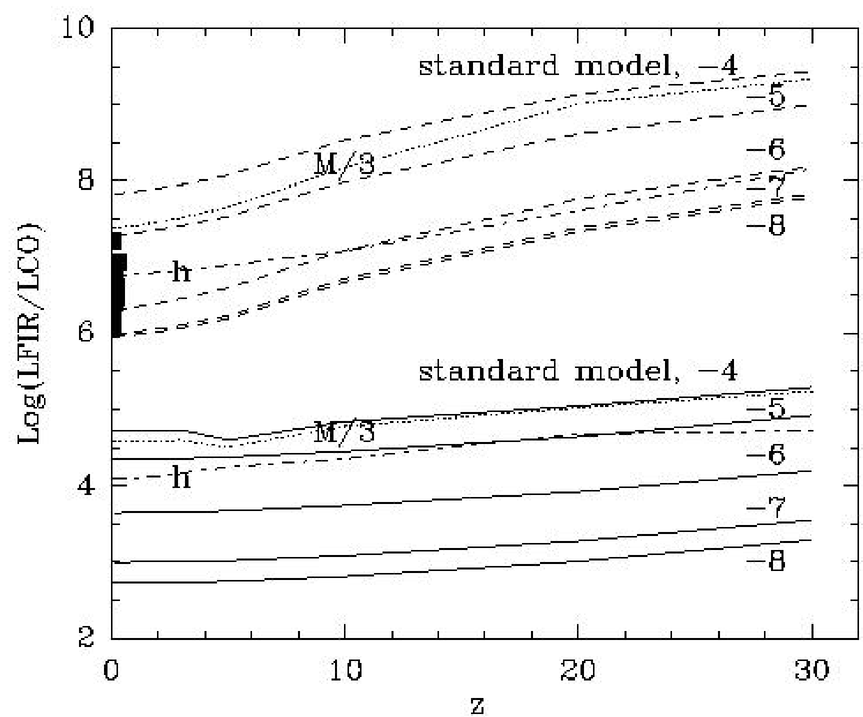




At 2mm wavelength, the dominant contribution is from

2 < z < 5

At 5mm, the dominant is from z > 5

Continuum/line ratio increases with z



# Other lines CII 158 micron, CI, NII…

Difficult to predict: how much ionised/neutral gas? Optical depth?

Nagamine et al 2006: (HIM), WNM, CNM-
Anyway, can be used at larger frequency. Less numerous than CO
Not optimum for a z-machine

**Sensitivity:** detection of CO lines of 300km/s at 300 GHz, of 0.3 mJy, i.e. $10^{-21}$ $Wm^{-2}$ at $5\sigma$ in 1hr with ALMA,
Lines spaced by 33GHz (if z=2.5), so about one source per $arcmin^2$, with a bandwidth of 16 GHz

With a primary beam of 0.15 $arcmin^2$
➔Large mosaics should be done

Most will be detected at z=1-3, so at 1mm for CO54-CO98
Might be better to go to even lower frequency

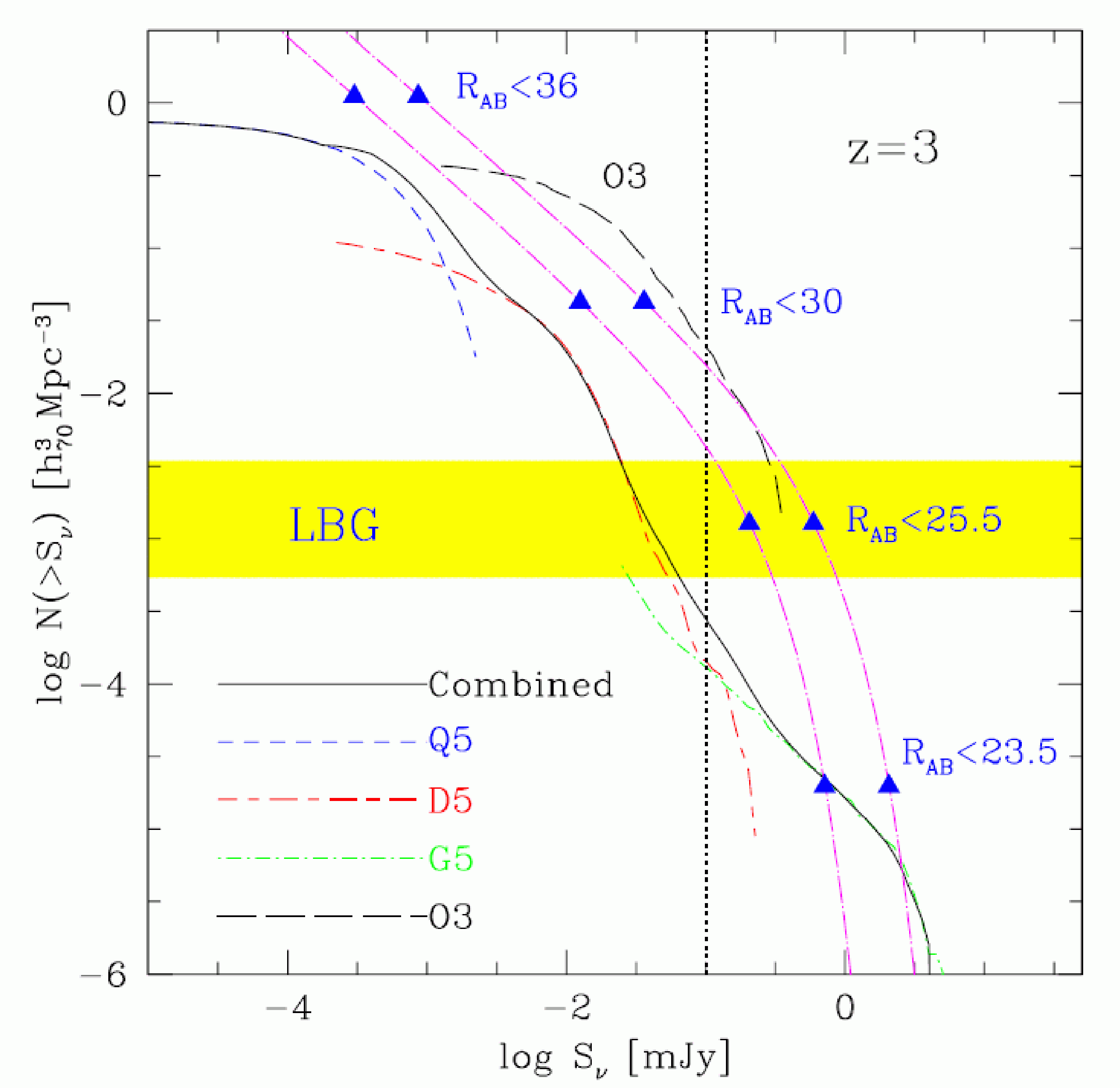
# Nagamine et al, CII estimation

Vertical dotted line
ALMA and SPICA
Sensitivity limit

SPH model +
Analytic multi-phase

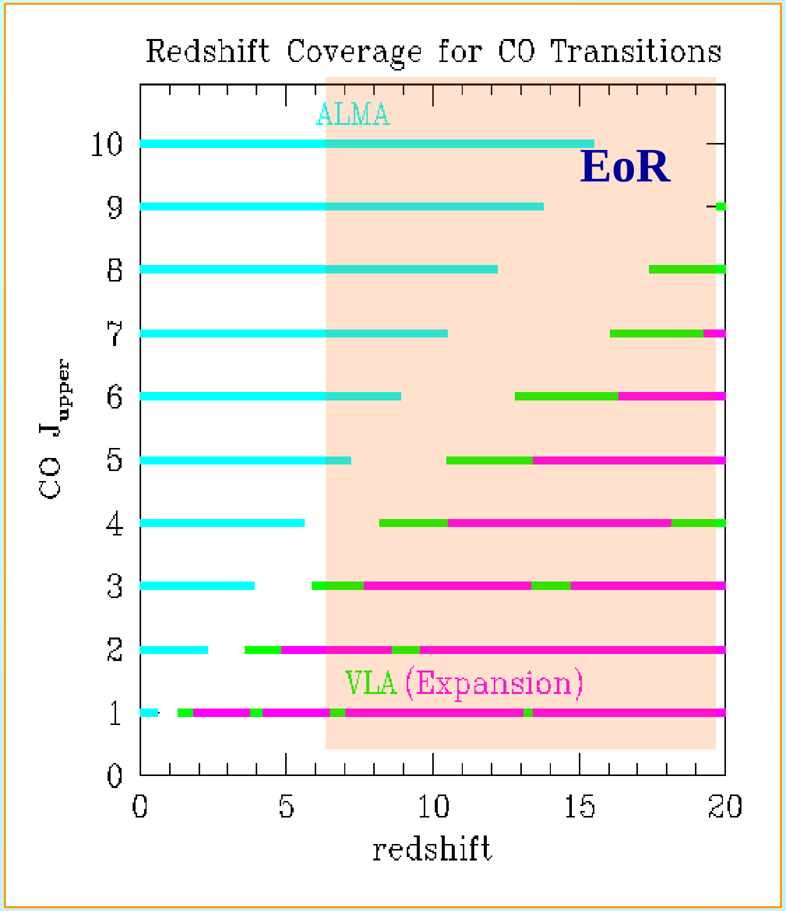
Most galaxies have
S < 0.1 mJy

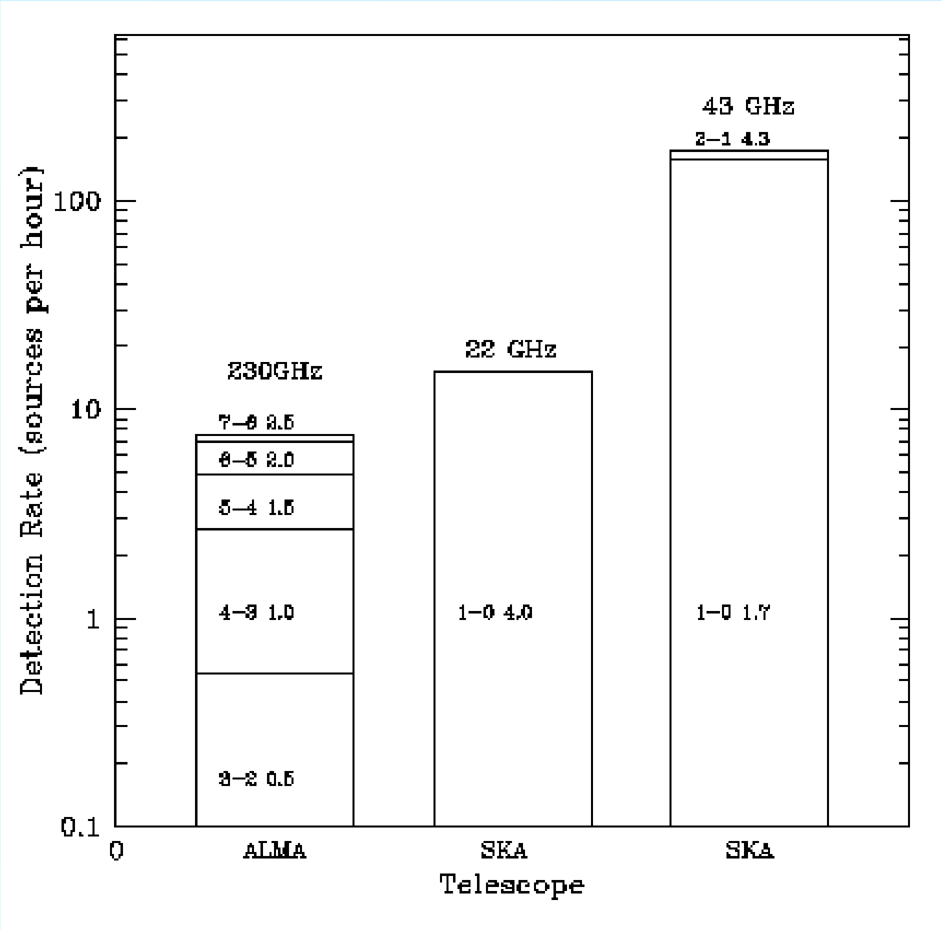
➔Concentrate on
known bright LBG



# SKA and ALMA: Optimal CO searches

## (Carilli & Blain 02, 05)




- SKA/ALMA – comparable speed at 22 GHz, SKA clearly faster at 43 GHz (FoV, fractional bandwidth, sensitivity)
- SKA/ALMA – complementary: high vs. low order transitions

# Conclusions

•Whatever the redshift, 30 sources per sq arcmin could be detected by ALMA in continuum, and for CO lines 2 < z < 5 about 1-3 sources per sq arcmin

•Deep fields should be done with the widest area (mosaic)

•No need to go to high frequency for the Redshift Machine: 2-3mm band is optimum

•Much more information than the continuum, in giving the mass of $H_2$ in the galaxy, the efficiency of star formation as a function of redshift, the kinematics

But more time is require to resolve the galaxy