Applying LVG modeling to galaxy simulations: first results

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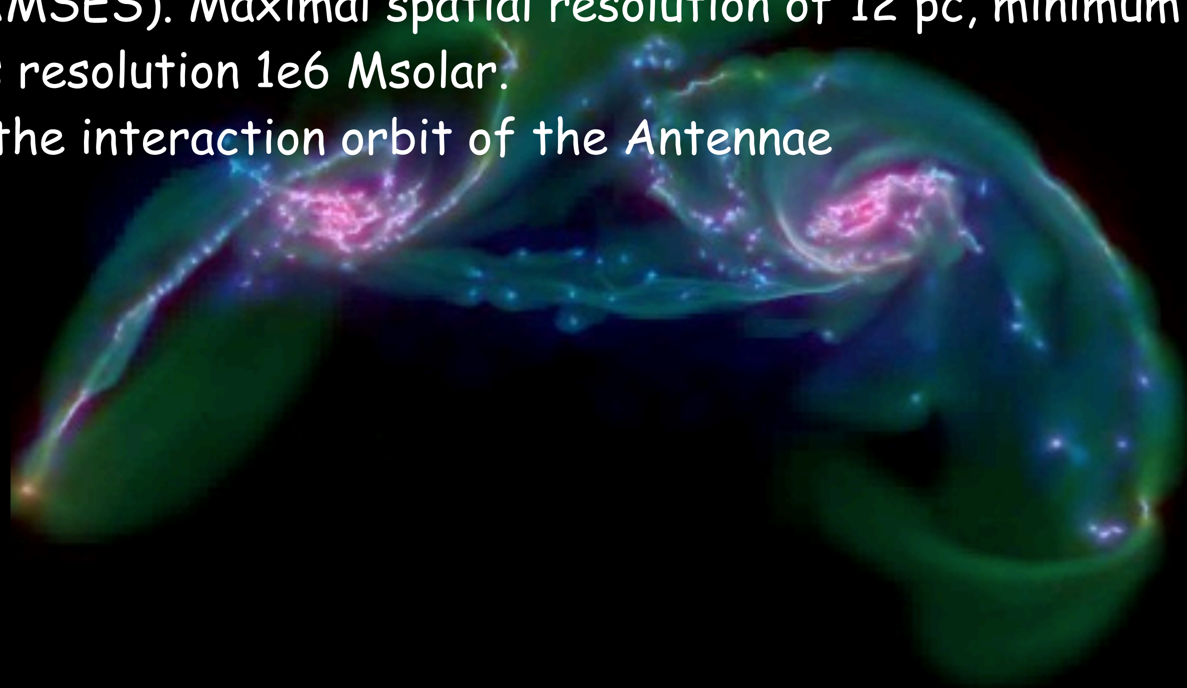
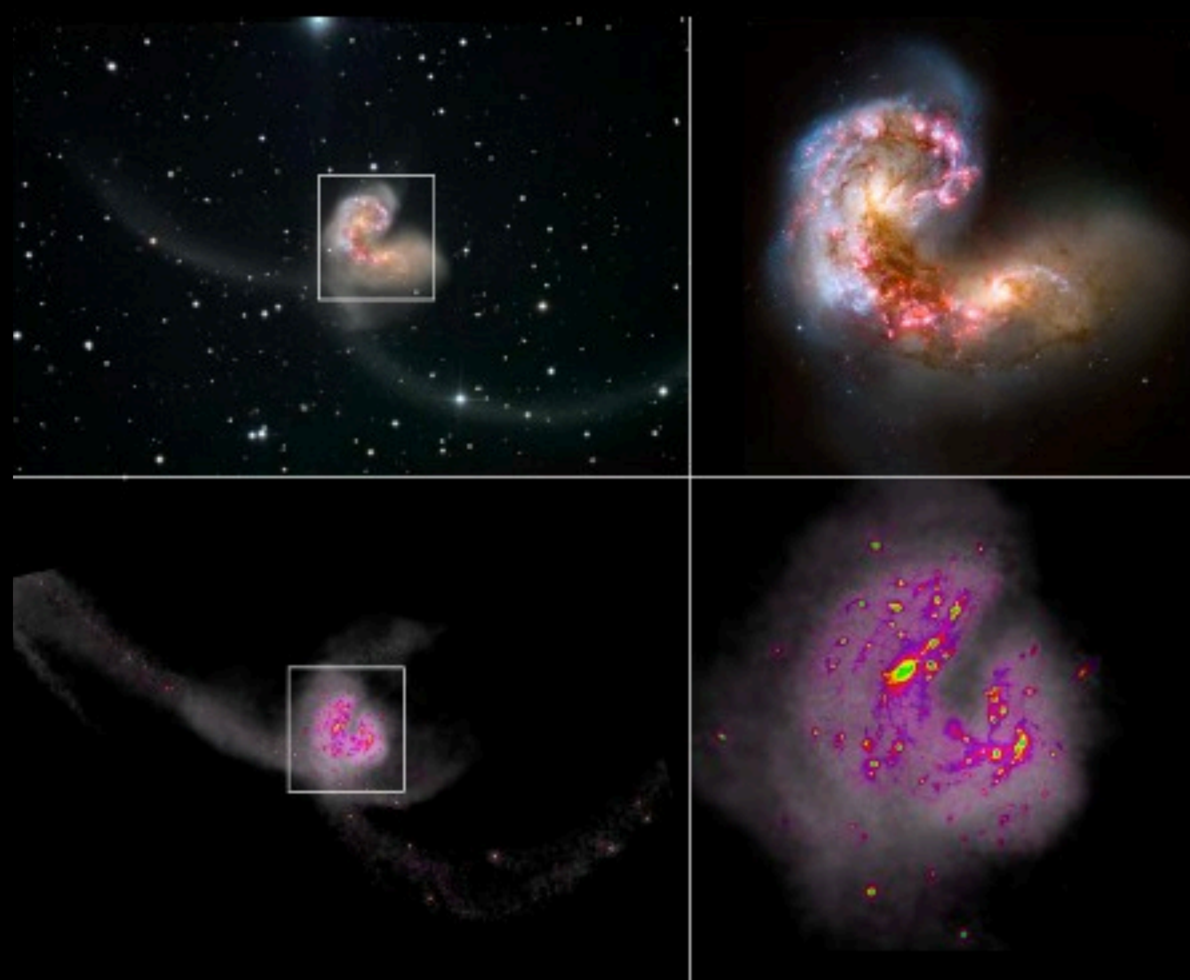
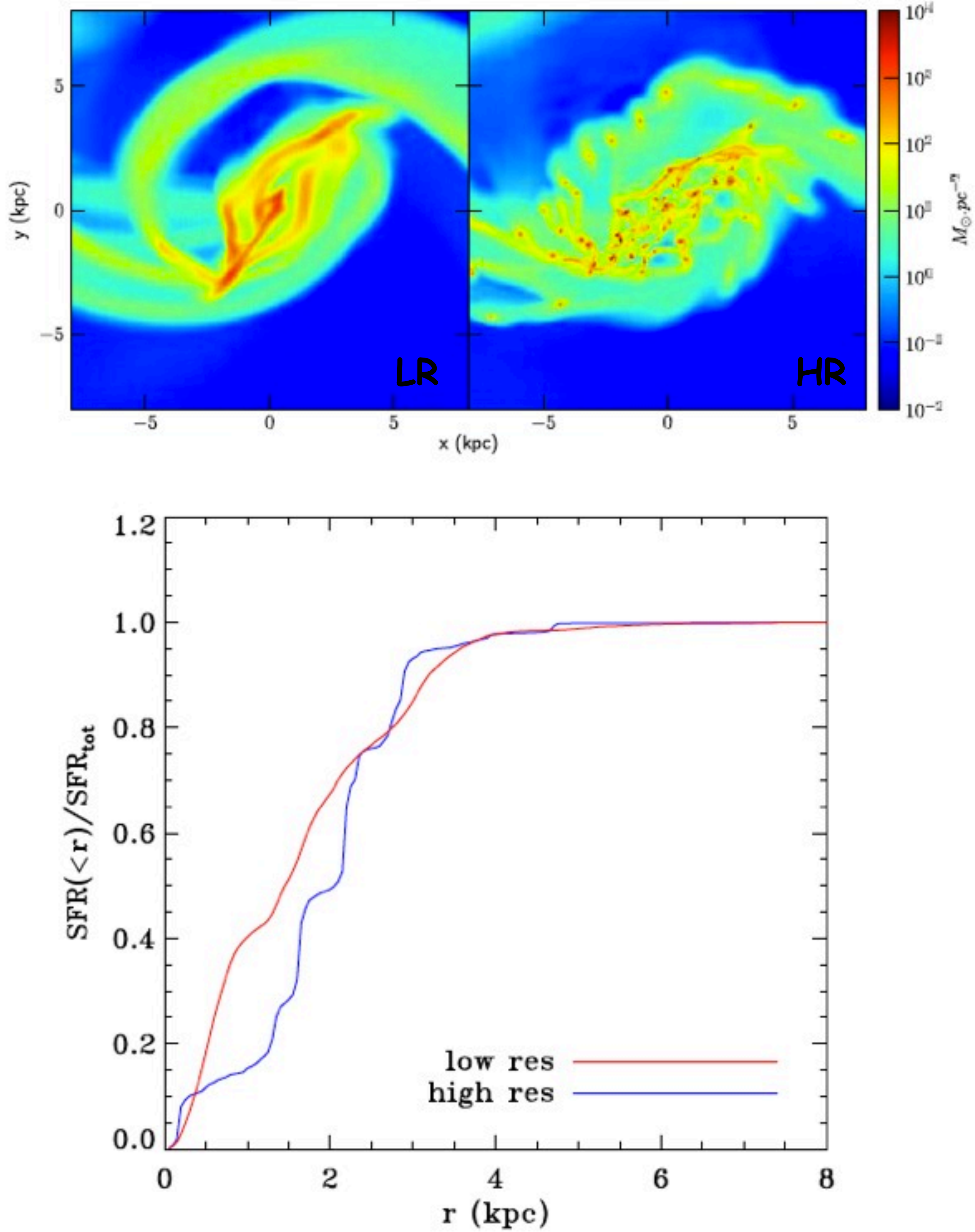
Teyssier et al 2010
Adaptive mesh refinement (AMR) hydrodynamic simulations
of a major galaxy merger (RAMSES). Maximal spatial resolution of 12 pc, minimum
temperature few 100 K. Mass resolution 1e6 Msolar.
Merger of two galaxies with the interaction orbit of the Antennae
galaxies (Renaud et al 08).

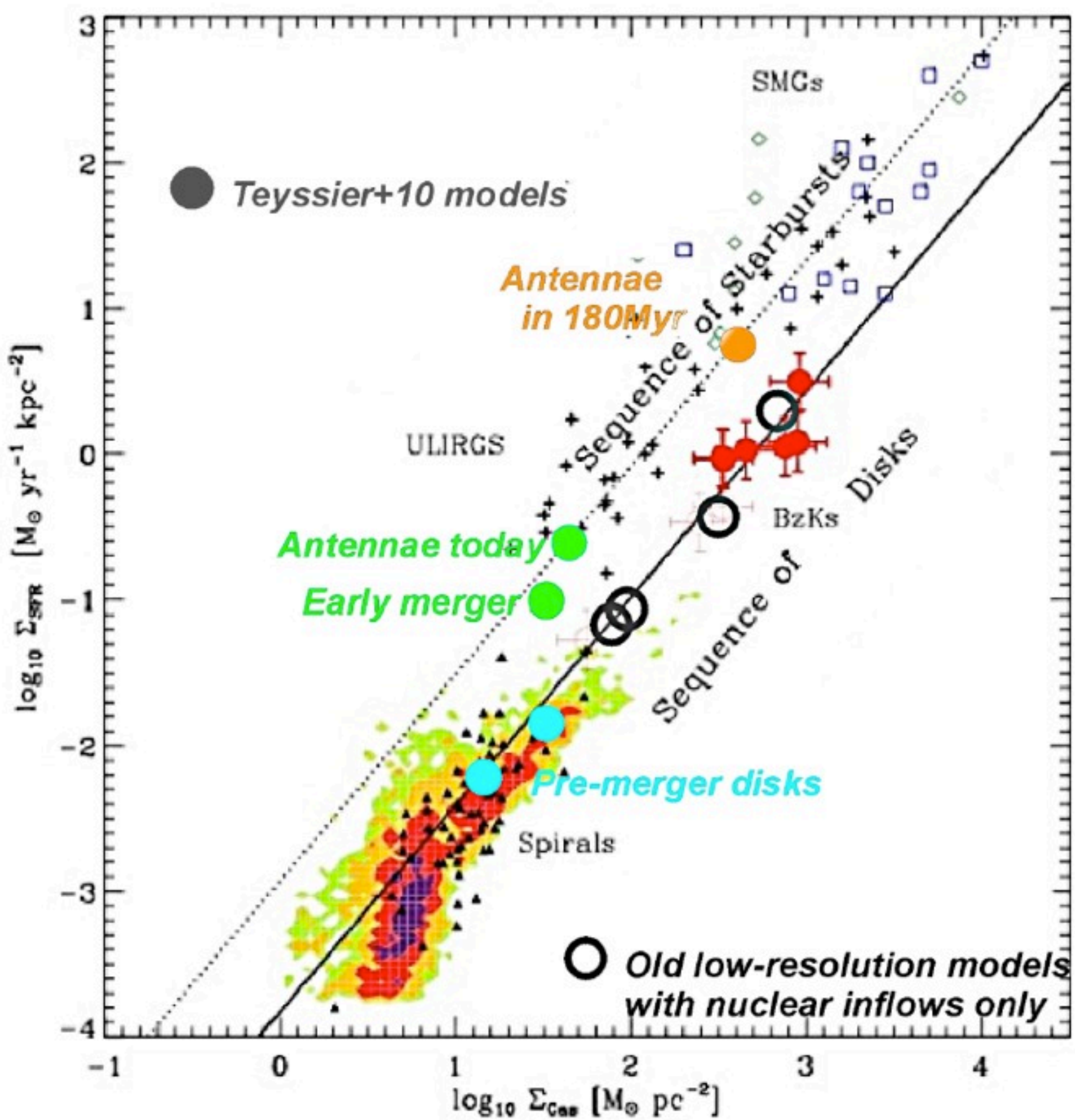






Teyssier et al 2010

Several SSCs far away from the center (Wang et al. 04)

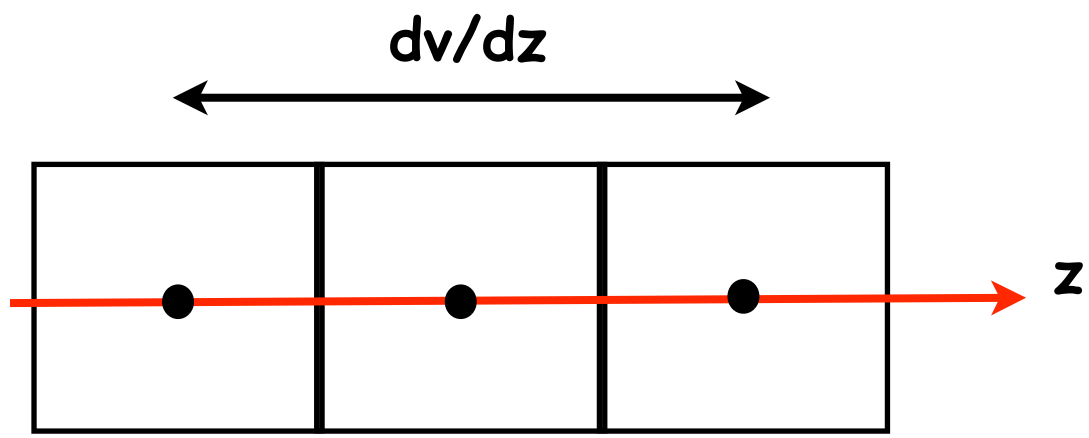


Data from Daddi et al. 10

LVG (Large Velocity Gradient approach) modeling is applied to simulations.

Goldreich & Kwan 74
Scoville & Solomon 74

Radiative transfer of molecular lines in interstellar clouds having flow velocities large compared with random motions.



dv/dz ~ 0/5 km/s/pc

The observed radiation is contributed equally by molecules along the entire line of sight
Each point of the cloud is indistinguishable from any other
Radiative transfer: local problem with analytic solutions.

T, rho, dv/dr : independent variables in the calculation.

LVG model by Weiss et al. 05
Collision rates from Flower (2001) with an ortho/para H2 ratio of 3.
CO standard abundance for the MW (Fixsen et. al 99)

$$[CO]/dv/dr = 8 \times 10^{-5} pc(\mathrm{km\ \ s})^{-1}$$

HCN (Martin et al. 06): $[HCN]/dv/dr = 4.2 \times 10^{-9} pc(kms)^{-1}$

Each cell in the simulation with n>100 atoms/cm3 and T<2000 K is source of CO emission

Flux densities are then obtained for each cell as:

$$S_{CO} = \frac{2k\nu_{\rm obs}^2}{c^2} \frac{T_b}{1+z} \frac{\Delta x^2}{D_A^2} \qquad [{\rm Jy}]$$

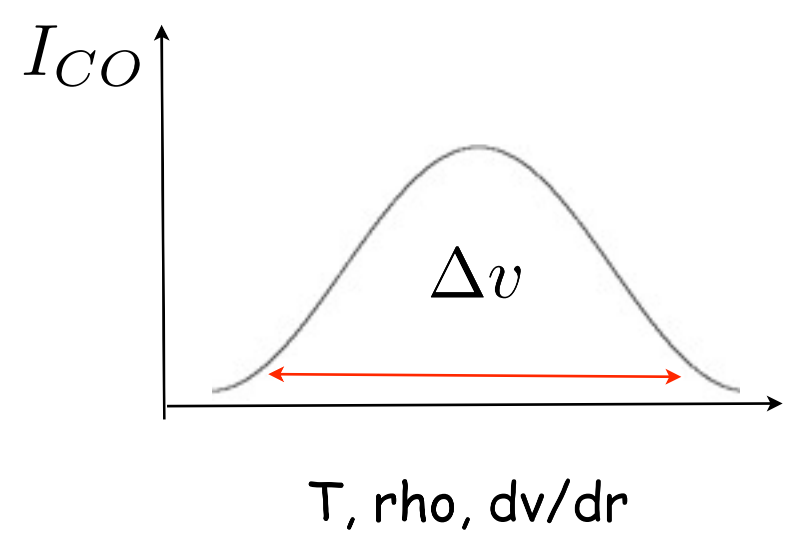
where T_b is the LVG line temperature, Δx the cell size and D_A the angular size distance at z.

$$L_{CO} = 3.25 \times 10^7 S_{CO} \Delta v \, v_{\rm obs}^{-2} D_L^2 (1+z)^{-3} \quad [{\rm K\,km\,s^{-1}pc^2}]$$

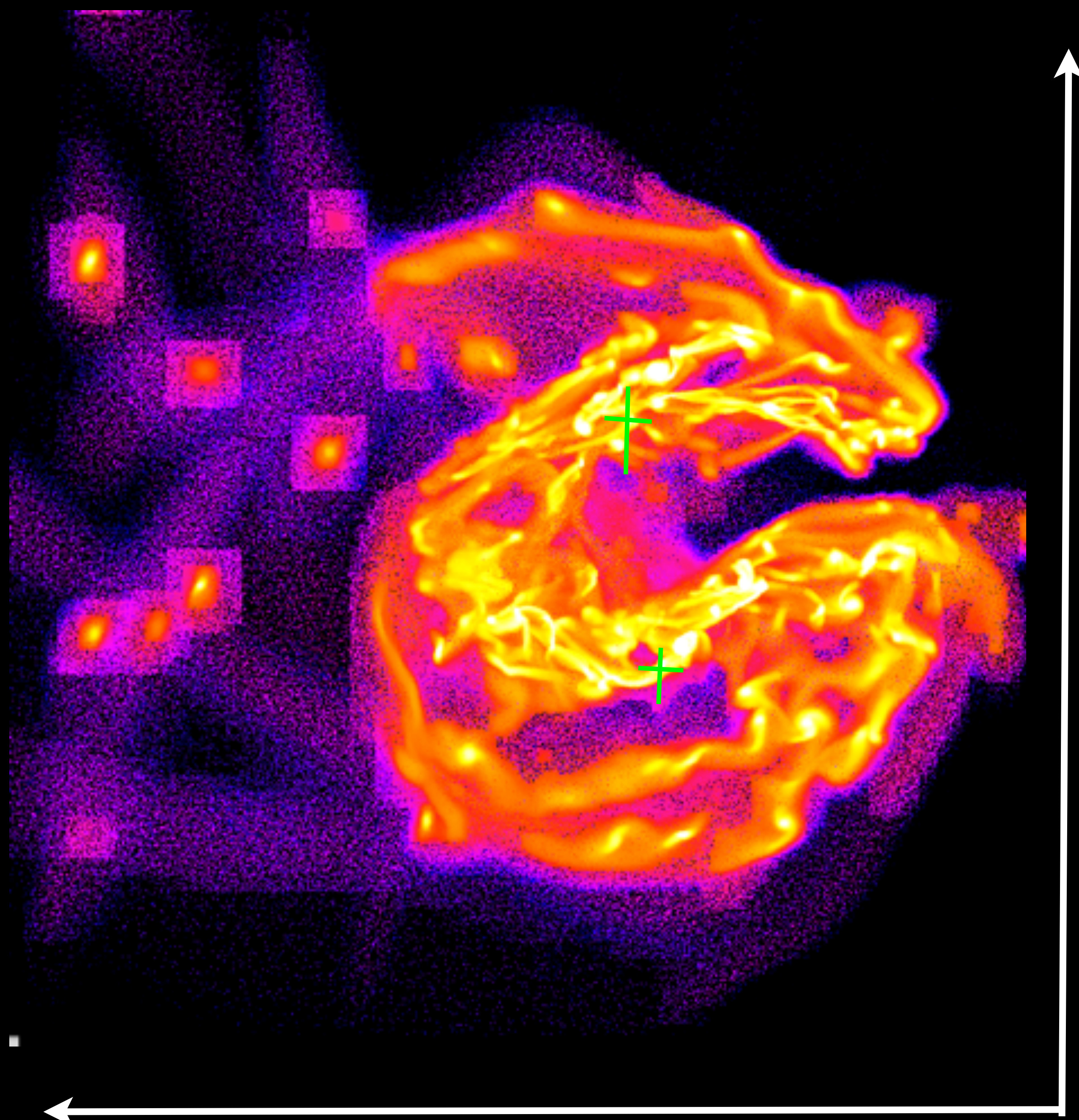
(Solomon et al. 97)

D_L luminosity distance

$$\Delta v = \Delta x \, \frac{dv}{dr}$$



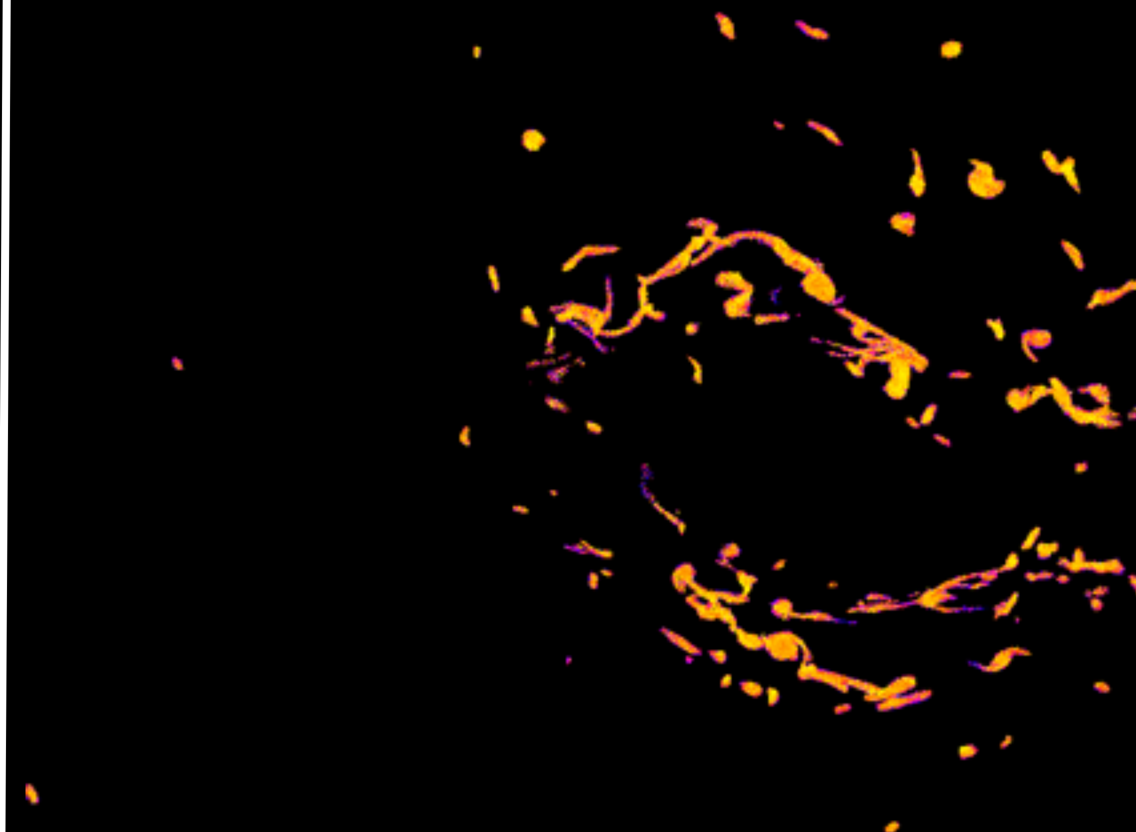
Weighted with the size of the emitting cell.



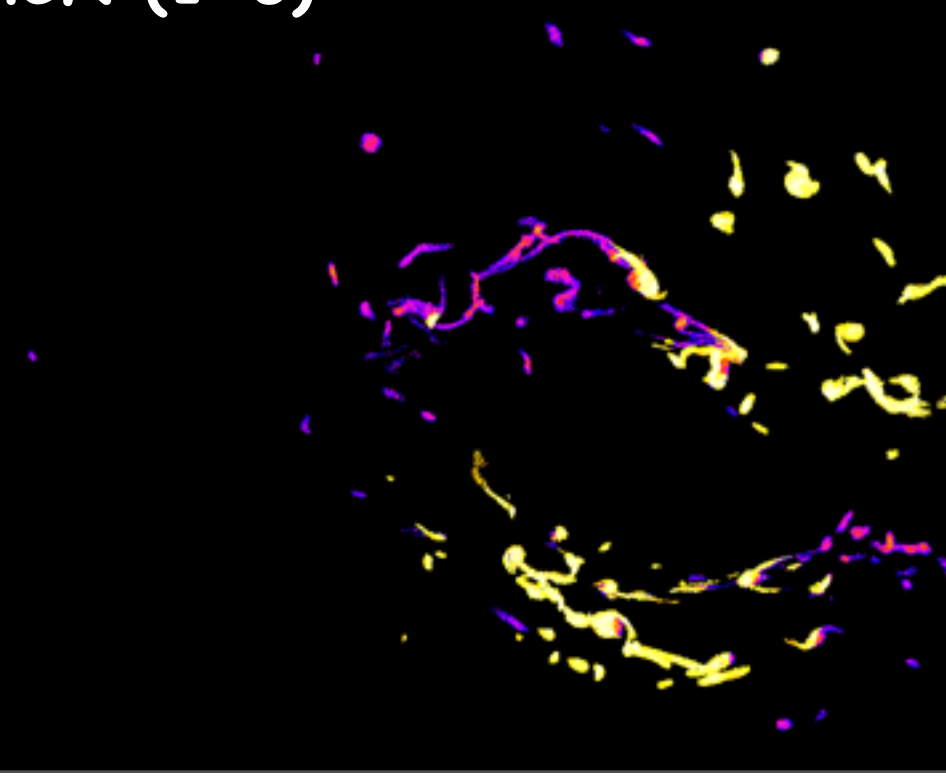
12 kpc

Log scale

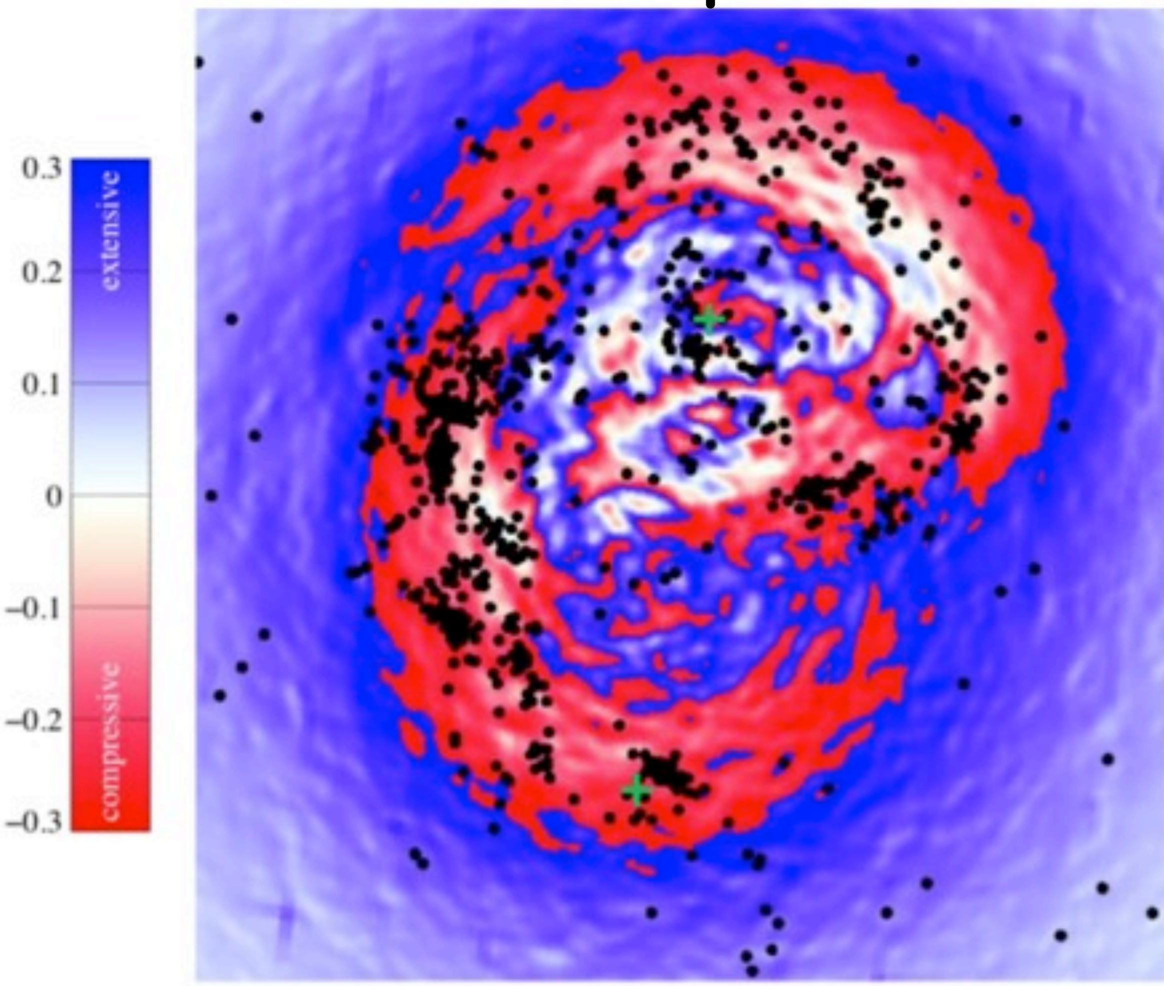
CO (1-0)



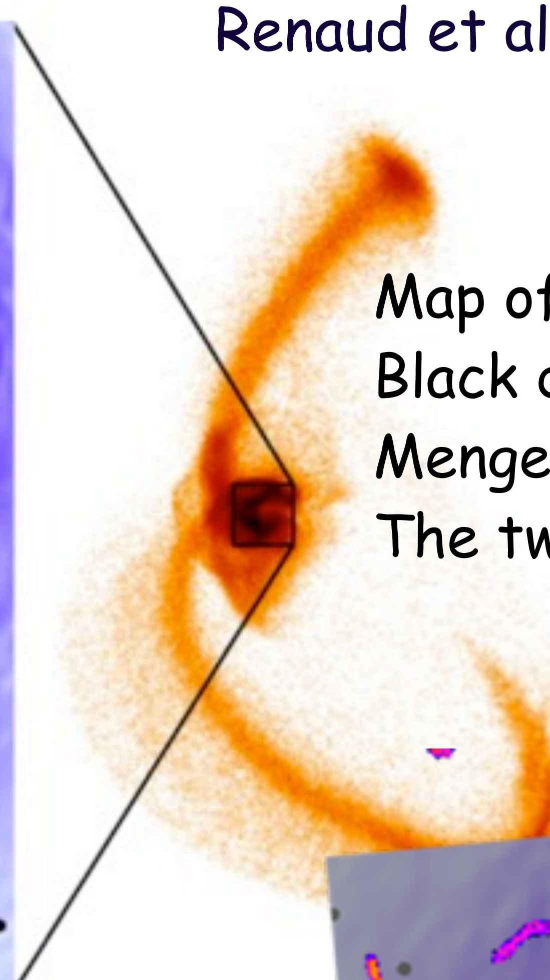
HCN (1-0)



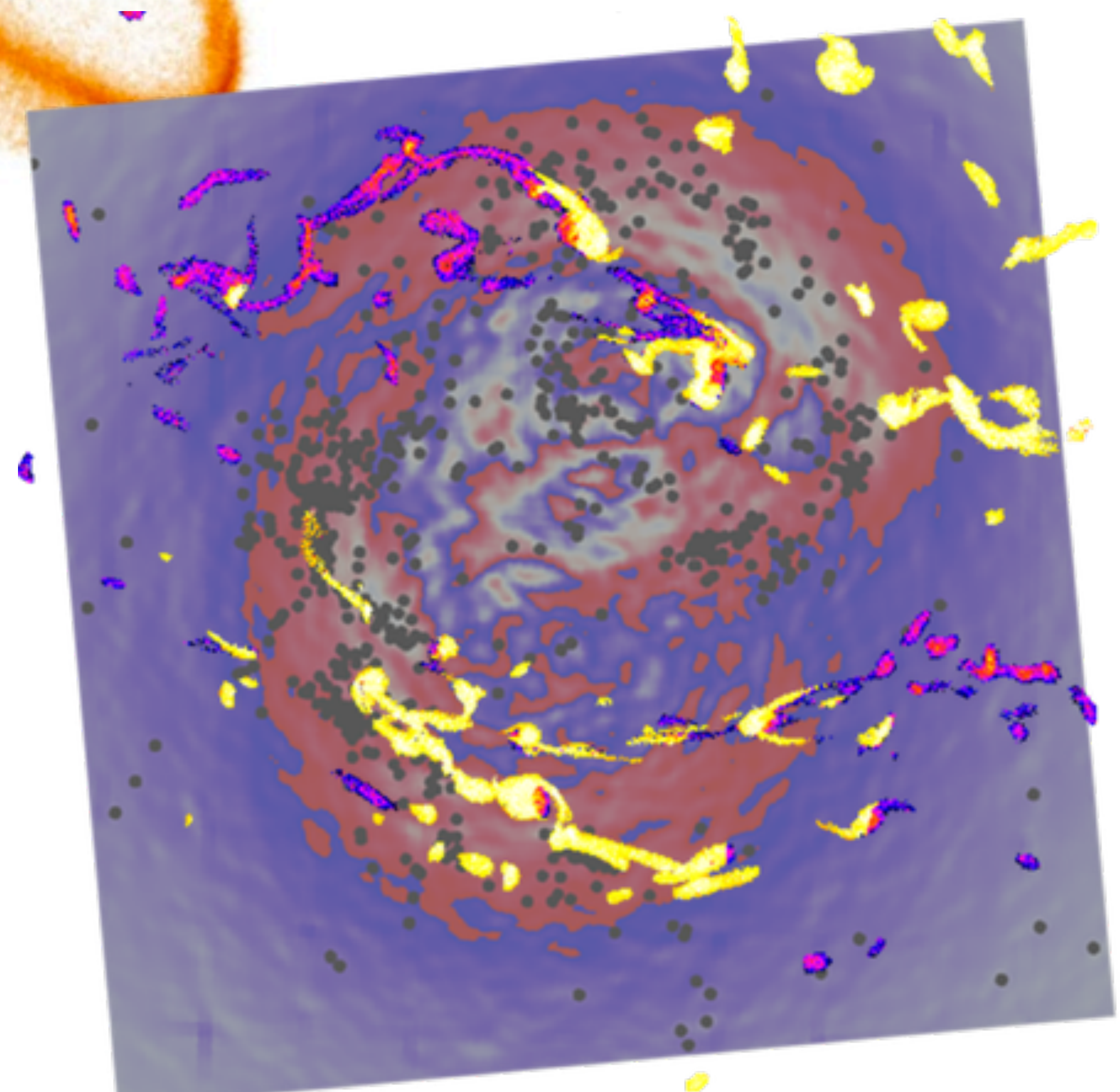
12 kpc



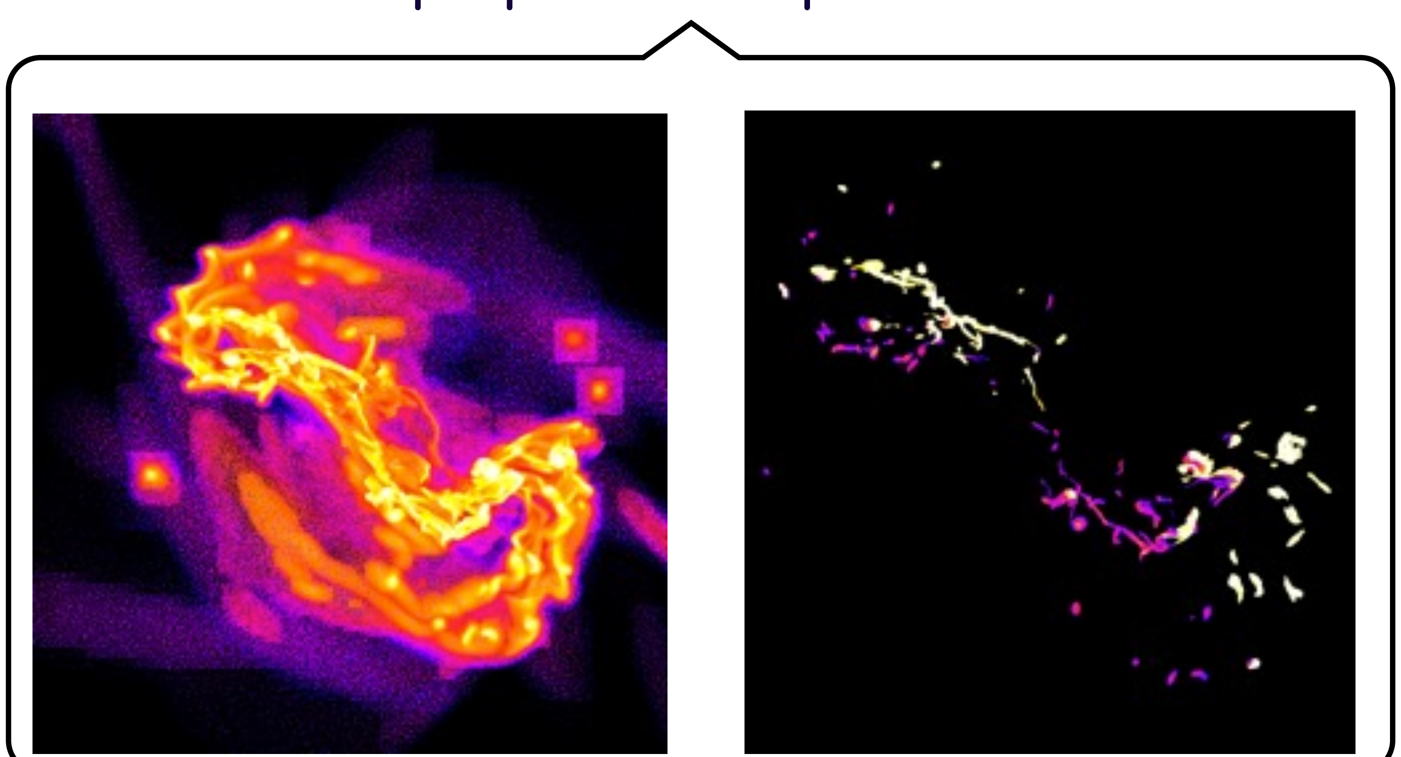
Renaud et al. 08

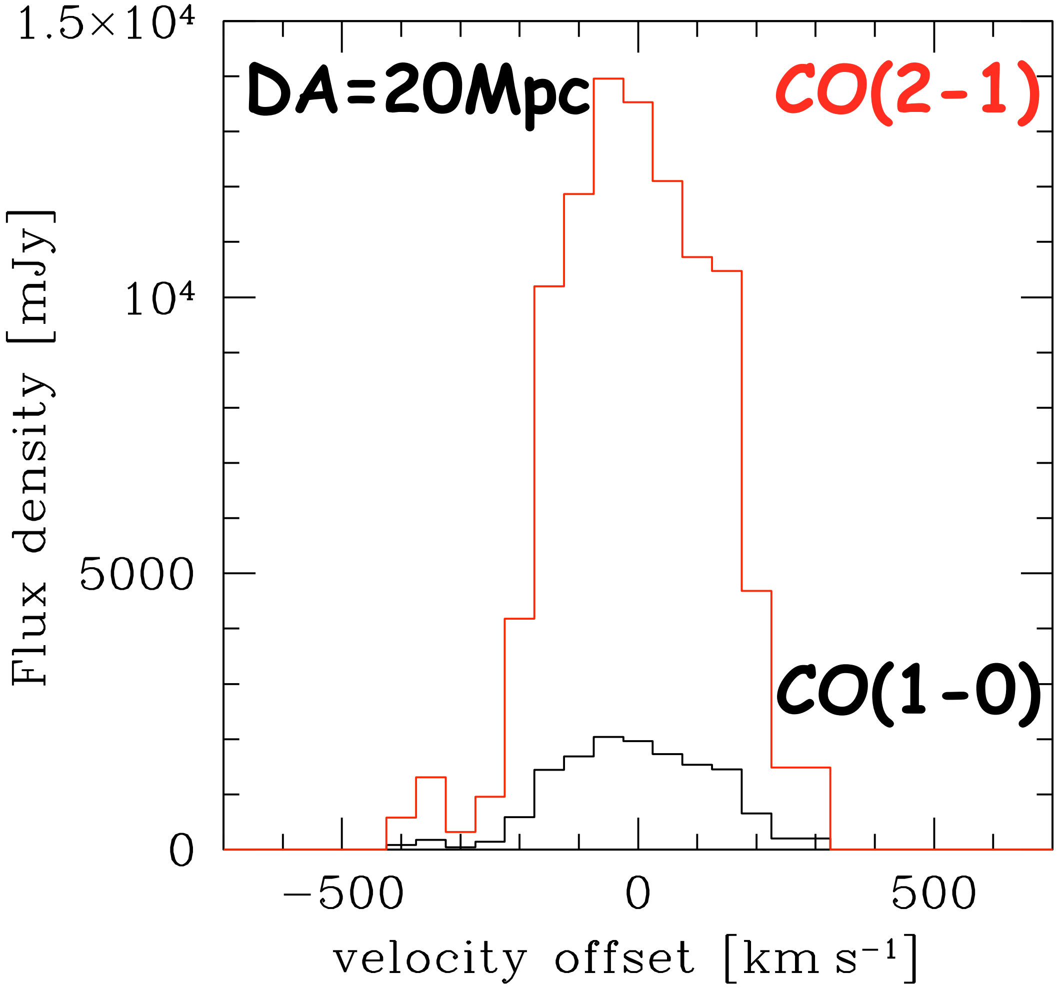


Map of gravitational tides in the Antennae.
Black dots are candidate clusters by
Mengel et al. (2005) from VLT images.
The two nuclei are marked by green crosses

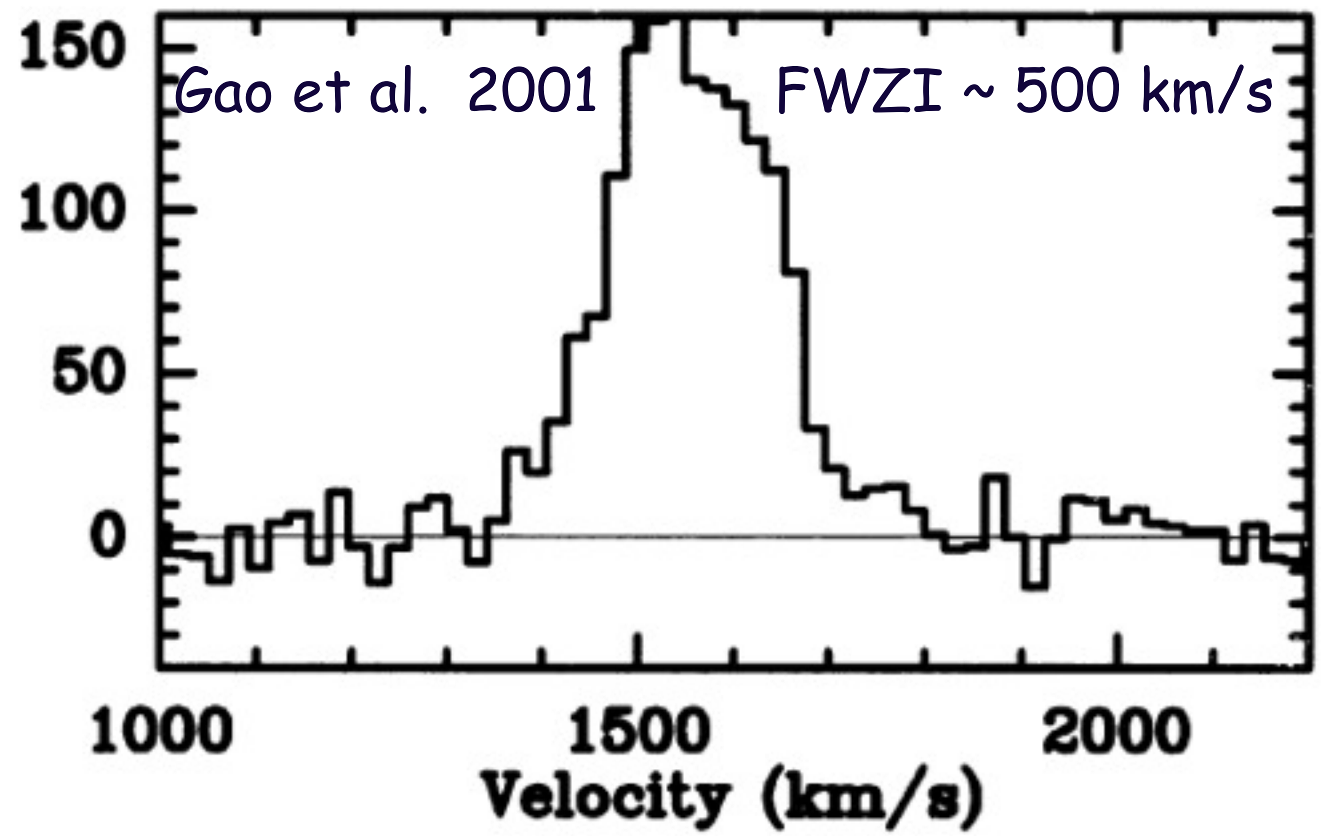


perpendicular plane

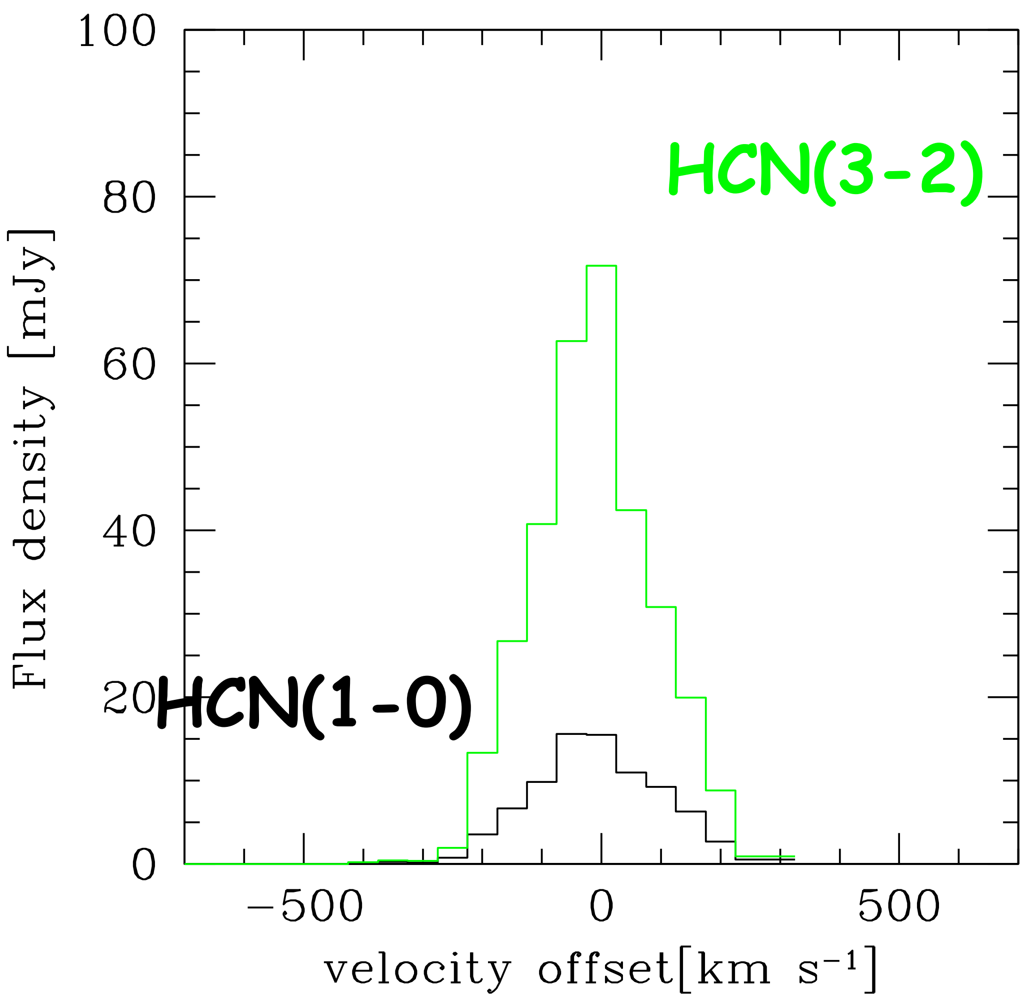




1.5×10⁴
10⁴
5000
0
DA=20Mpc
CO(2-1)
CO(1-0)
Flux density [mJy]
−500
0
500
velocity offset [km s⁻¹]

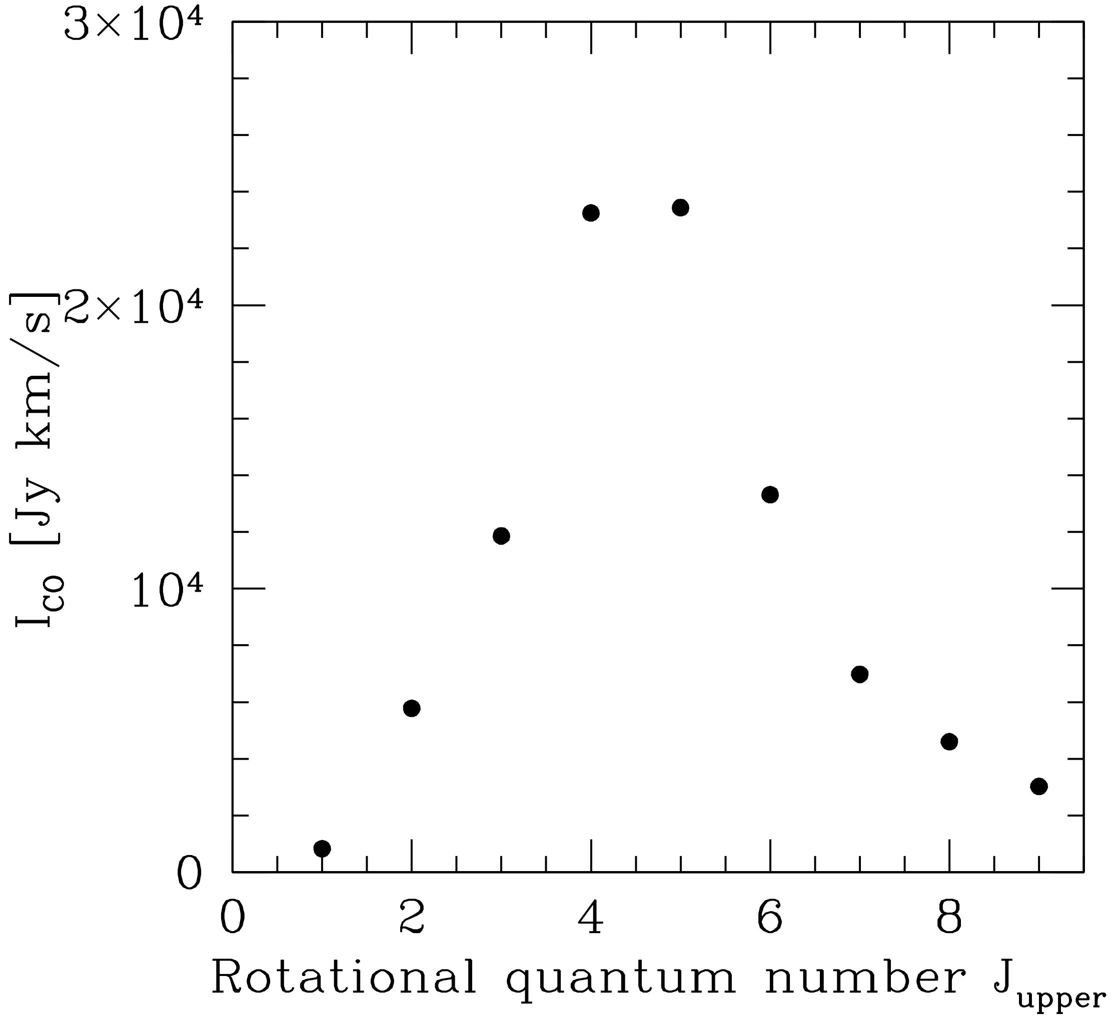


150
100
50
0
Gao et al. 2001
FWZI ~ 500 km/s
1000
1500
2000
Velocity (km/s)

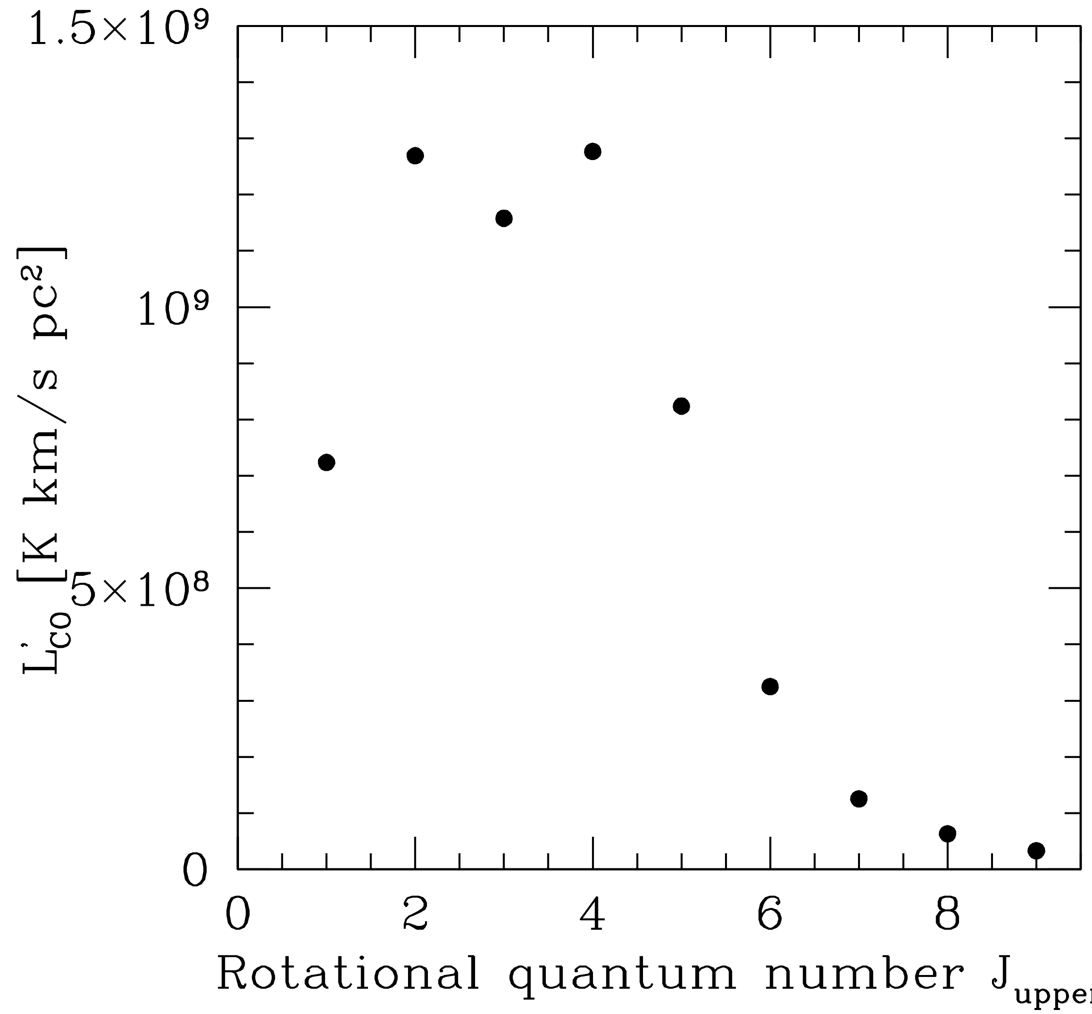


100
80
60
40
20
0
HCN(3-2)
HCN(1-0)
Flux density [mJy]
−500
0
500
velocity offset[km s⁻¹]

CO flux density

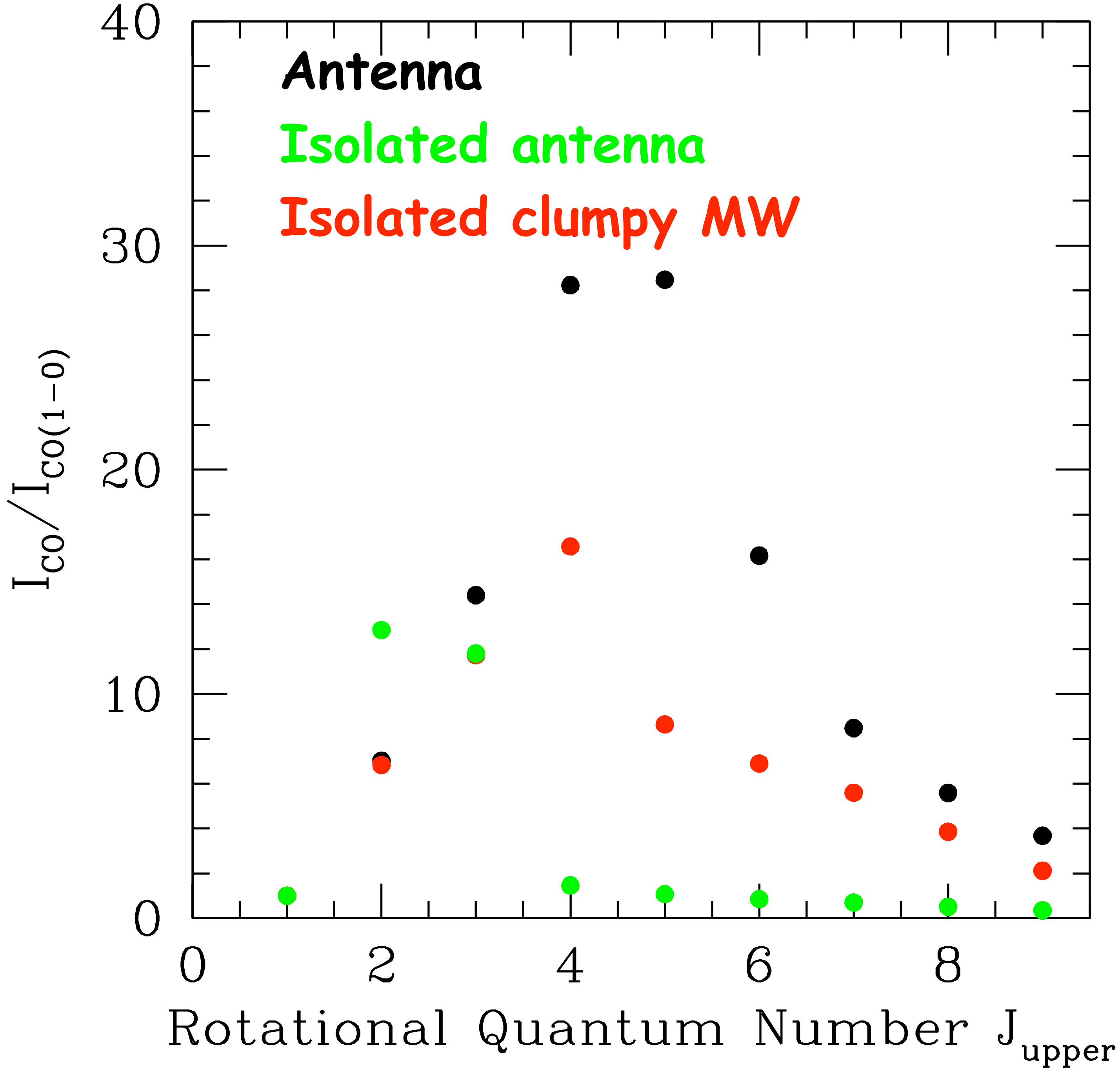


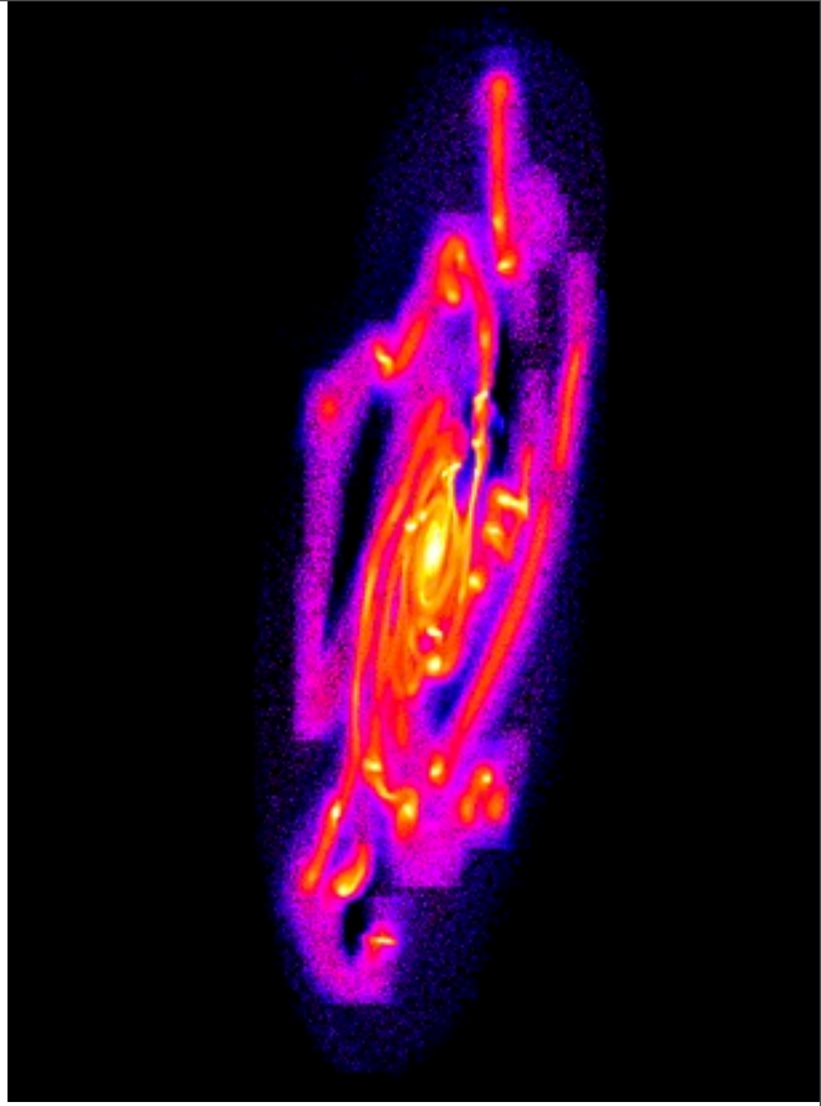
CO luminosity

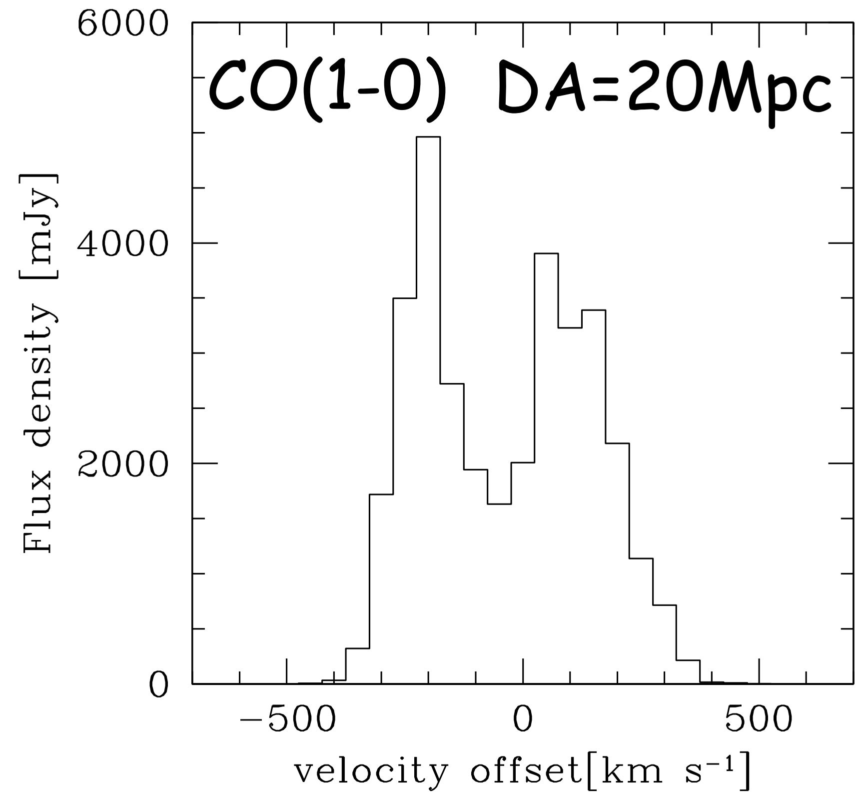


$$\alpha = \frac{M_{H_2}}{L'_{CO(1-0)}} \sim 3.3\, M_{\odot} (\mathrm{K\,km\ s^{-1} pc^2})^{-1}$$

Normalized CO line SEDs



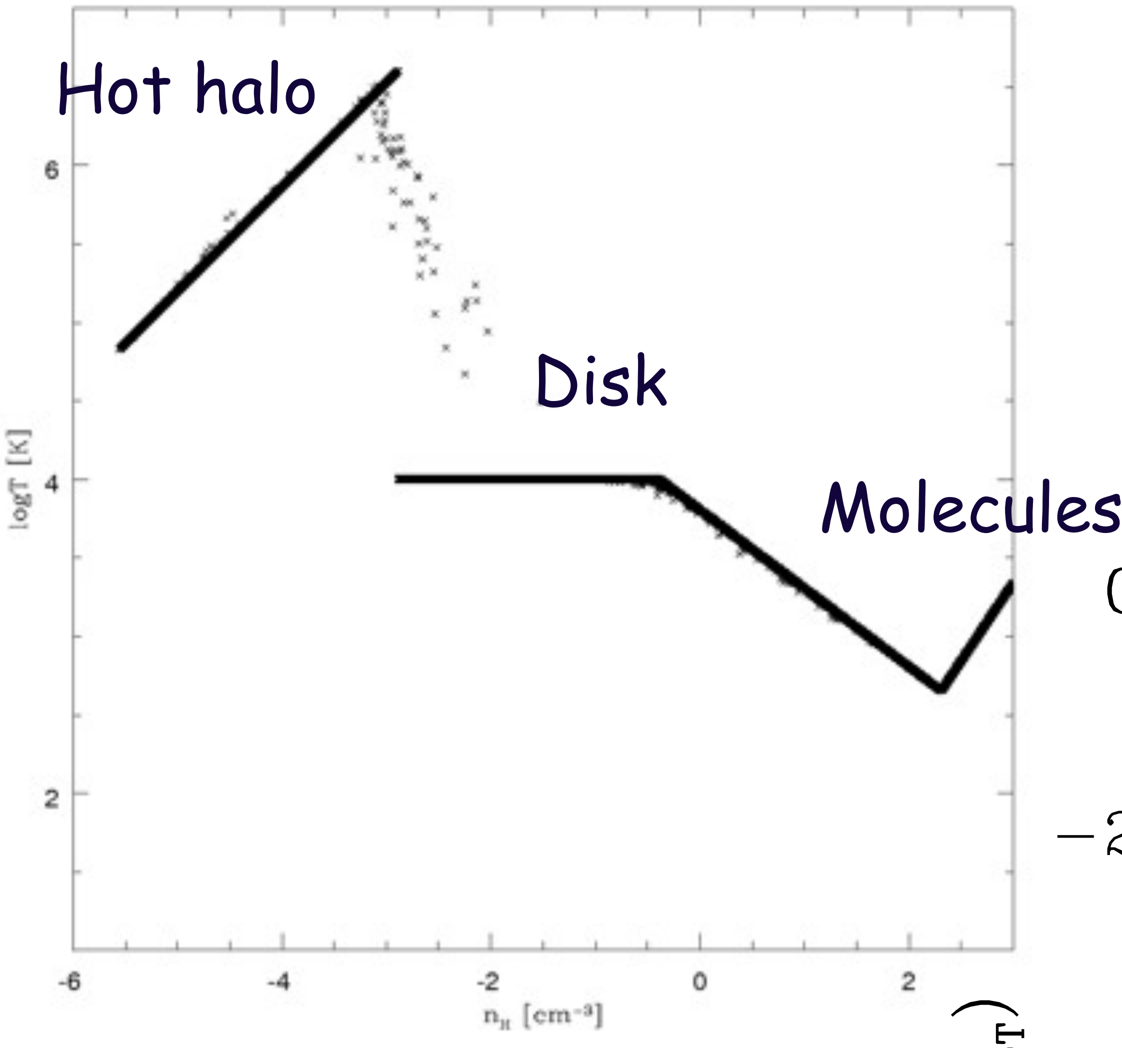


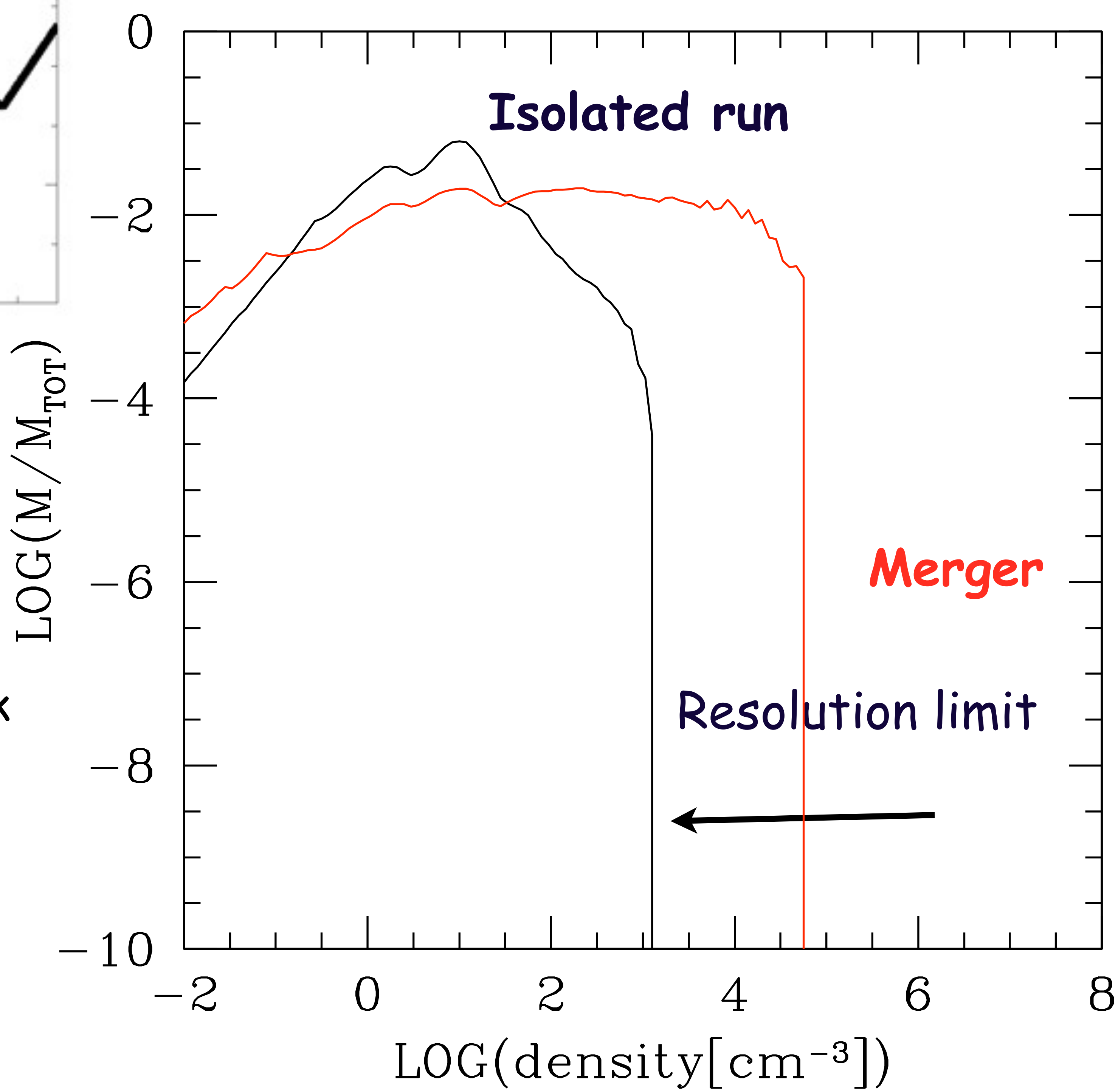


SEDs peak moves to higher transitions

Pseudo-cooling EOS (Teyssier et al.10)

T = T(n)



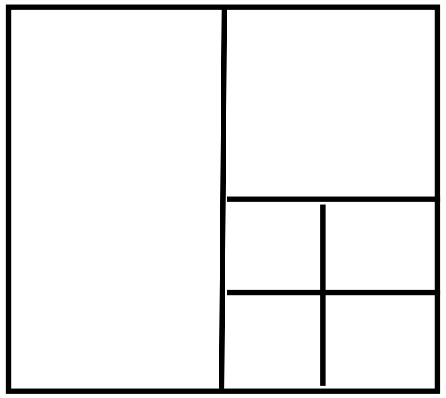


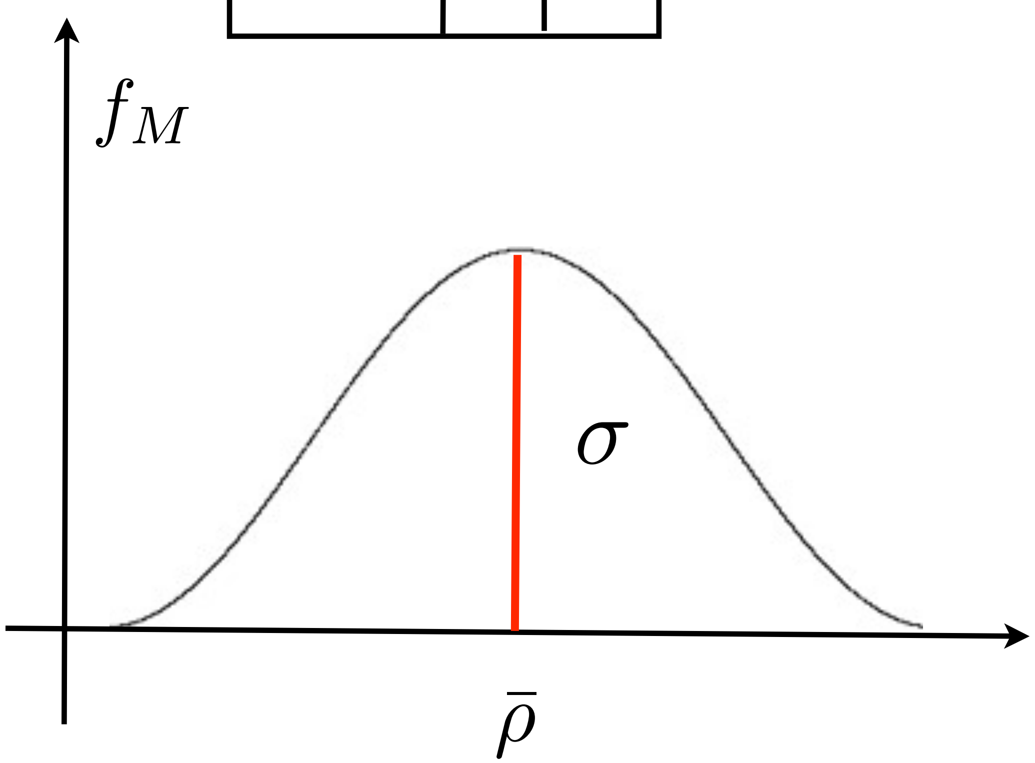
At low density: self-shielding

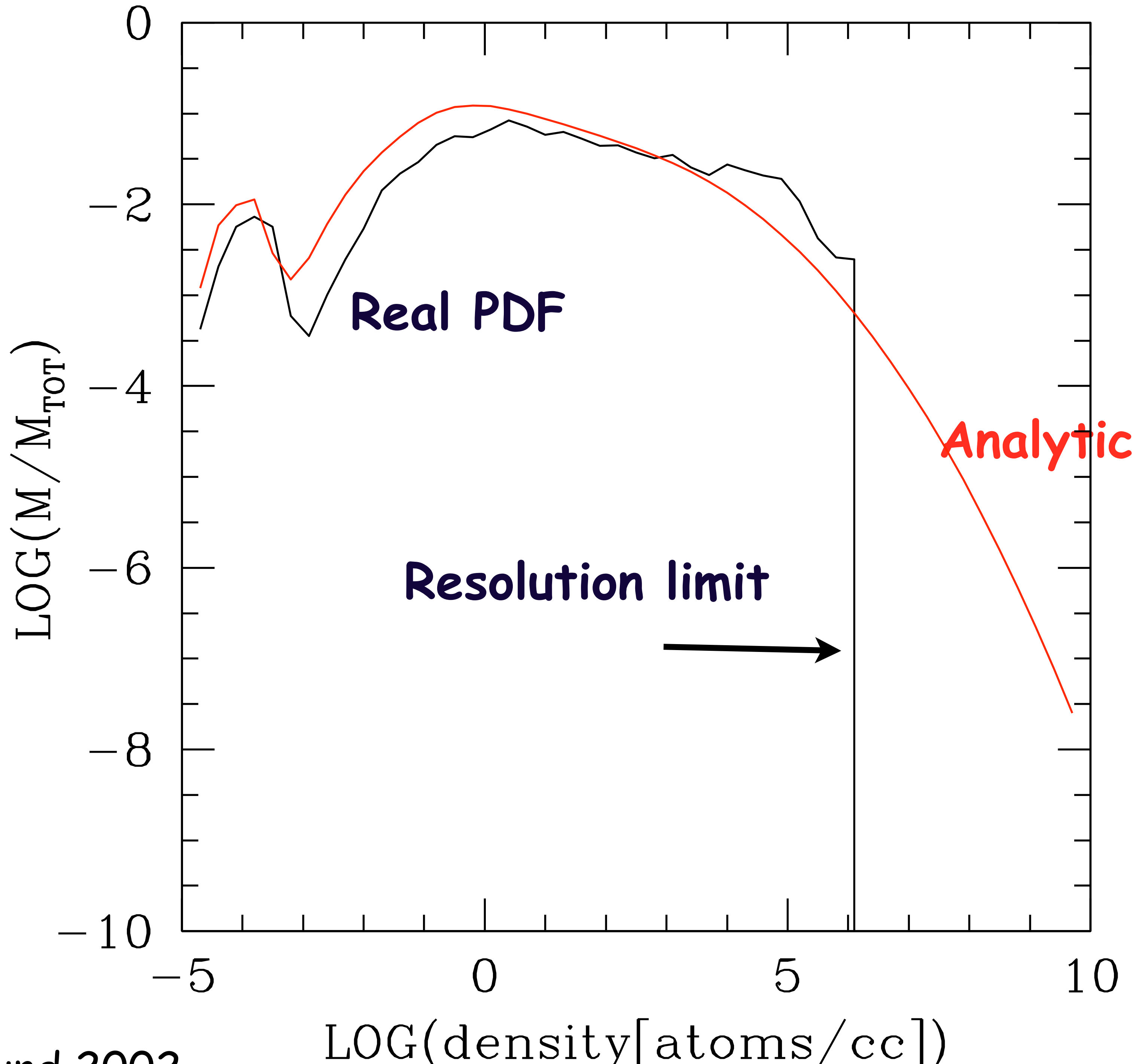
At high density: thermal feedback and SN heating

Wada & Norman 2001:

"in spite of its very complicated spatial structure, the multiphase ISM exhibits
a one-point probability density function (pdf) that is a lognormal distribution"



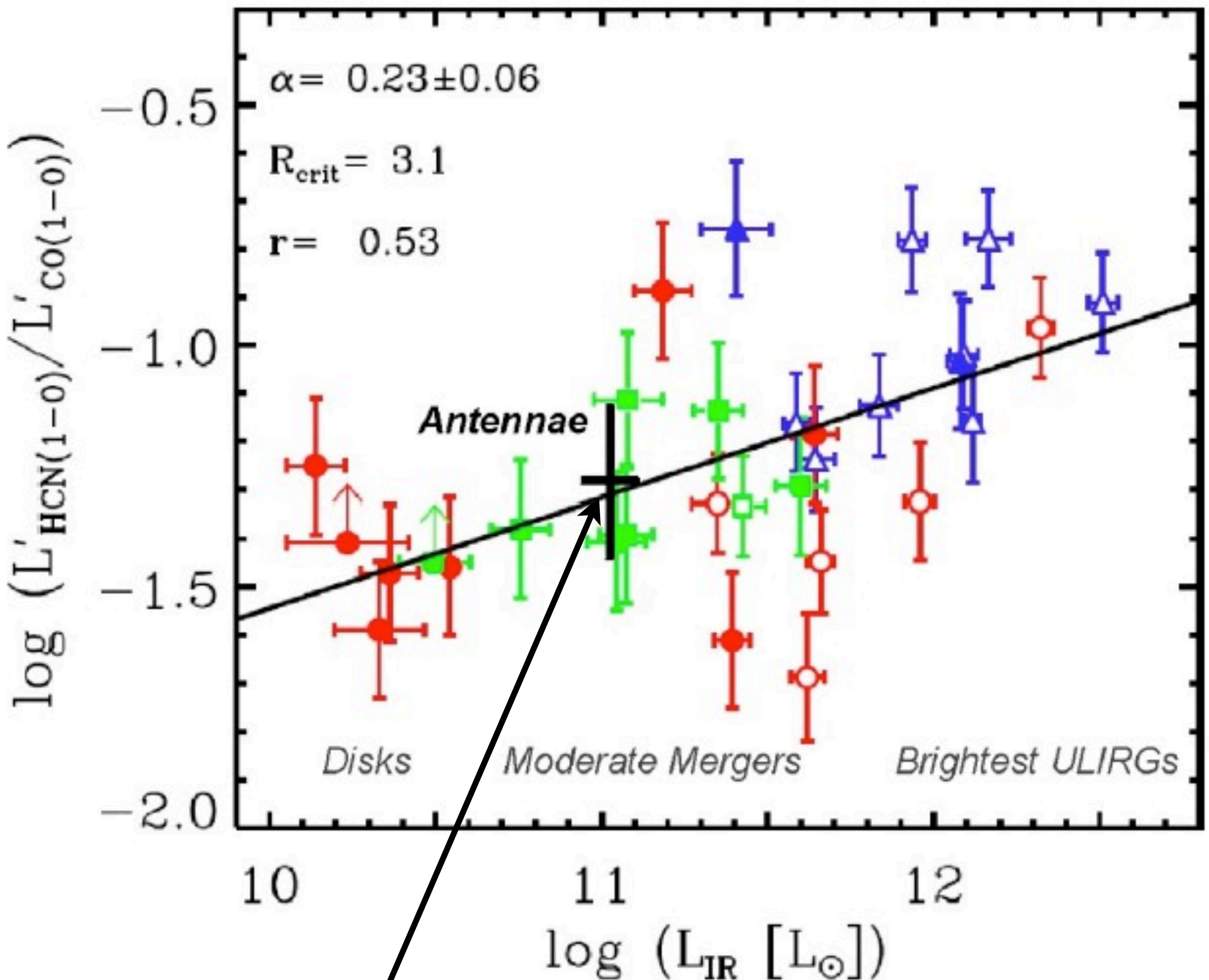




$$\sigma \sim [\ln(1 + \frac{3\mathcal{M}^2}{4})]^{1/2}$$

Empirical relation by Padoan & Nordlund 2002

$$\mathcal{M} = \sigma / c_s$$



Juneau et al. 09

From Gao et al. 01 -- two points in the Antennae

Our value: $\log(L'_{HCN}(1-0)/L'_{CO}(1-0)) \sim -2.2$

Summary

We have coupled LVG modeling of molecular line emission with high resolution simulations of isolated galaxies and the Antennae system

- Both CO and HCN distribution are extended
- A spatially-resolved study of dense molecular gas in the Antennae (P.I. Frederic Bournaud)
- HCN luminosity higher where the tidal field is compressive and where most of the SSCs are located
- CO line SEDs indicate that degree of excitation of moderate density molecular gas is higher in the Antennae (peak J=4-5) with respect to isolated galaxies
- Improvement with higher resolution (pc scale) or with analytical pdf at high densities. Temperature profile (partially improving due to the increase in resolution).