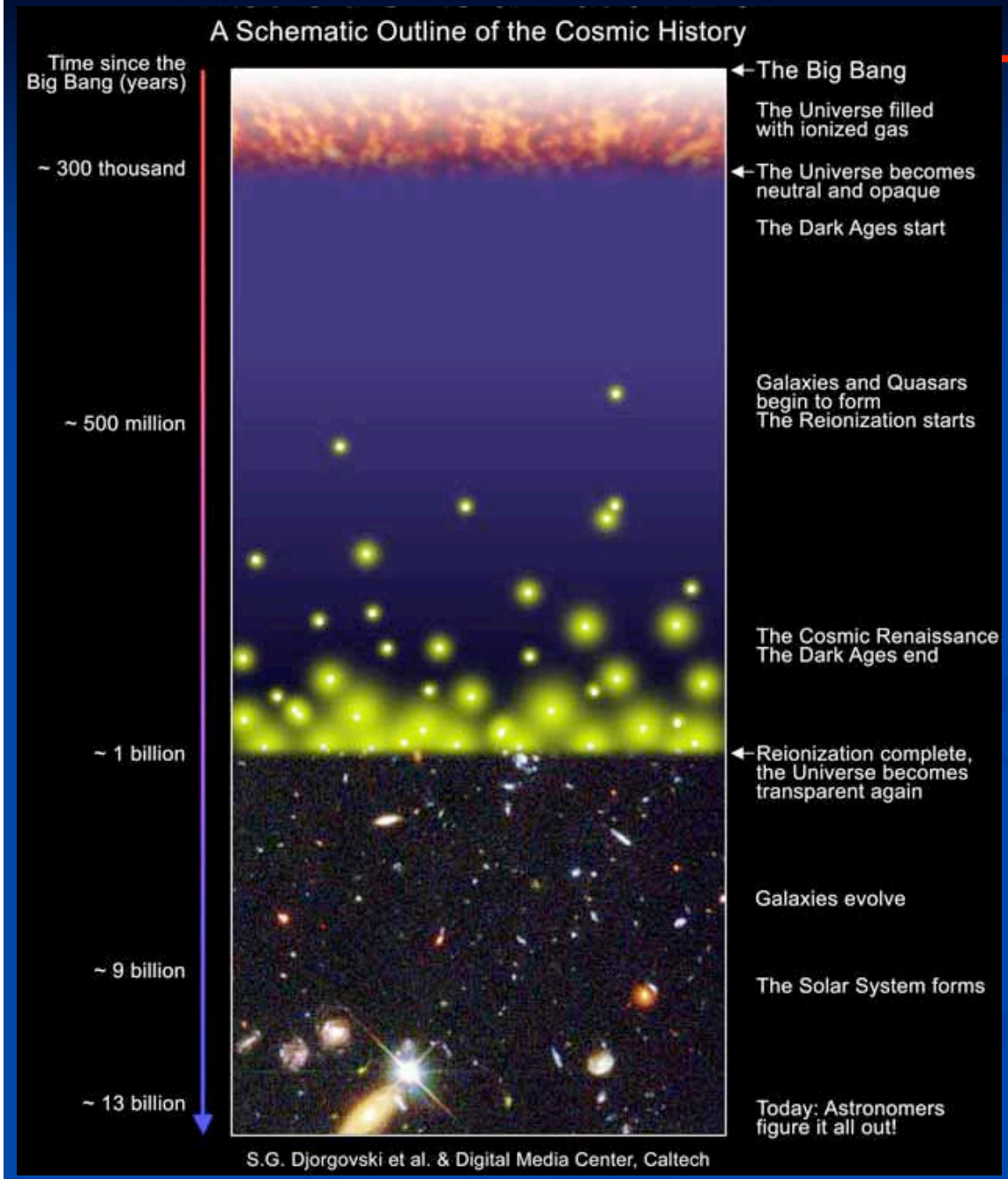
Resolved Molecular Gas at High Redshift

Fabian Walter (MPIA)

D. Riechers, C. Carilli,
F. Bertoldi, P. Cox, K. Menten, A. Weiss



- *high redshift 'zoo':*
  - Lyman Break galaxies
  - Lyman α galaxies
  - Submm ('SCUBA') galaxies
  - EROs
  - DRG
  - BzK galaxies
  - faint blue galaxies
  - radio galaxies
  - QSO host galaxies

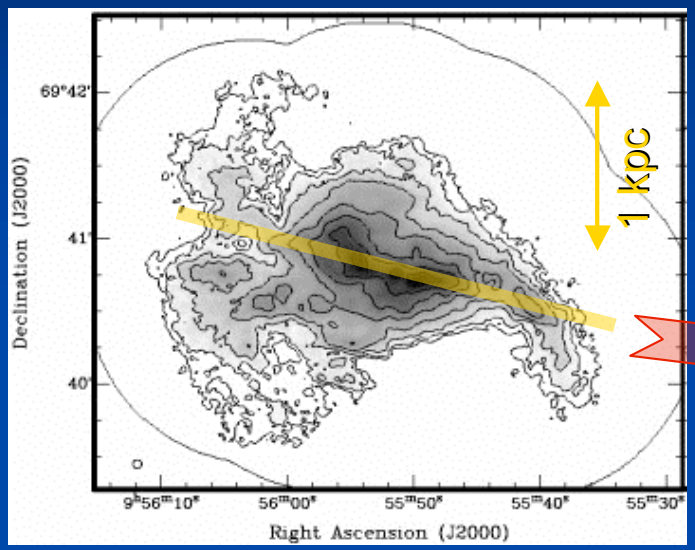
  ...

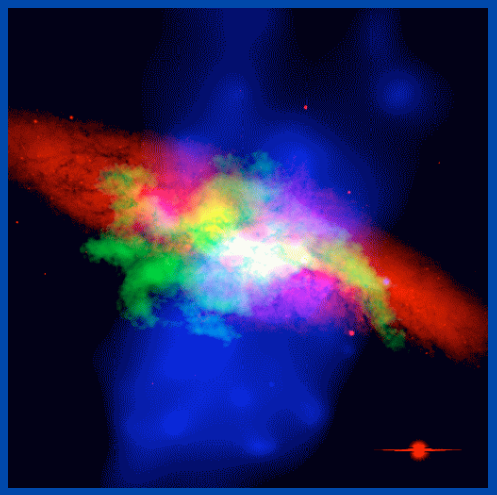
molecular gas: fuel for SF!

& M_{dyn}

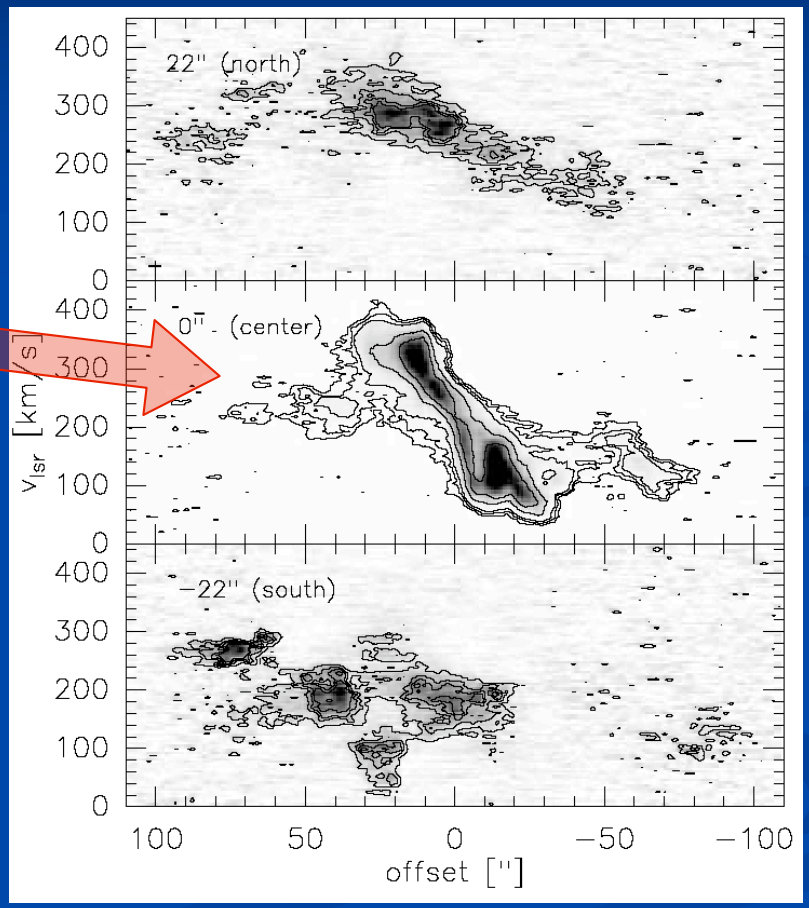
Dynamical masses from CO measurements

- e.g., CO in M82





Walter, Weiss & Scoville 2002

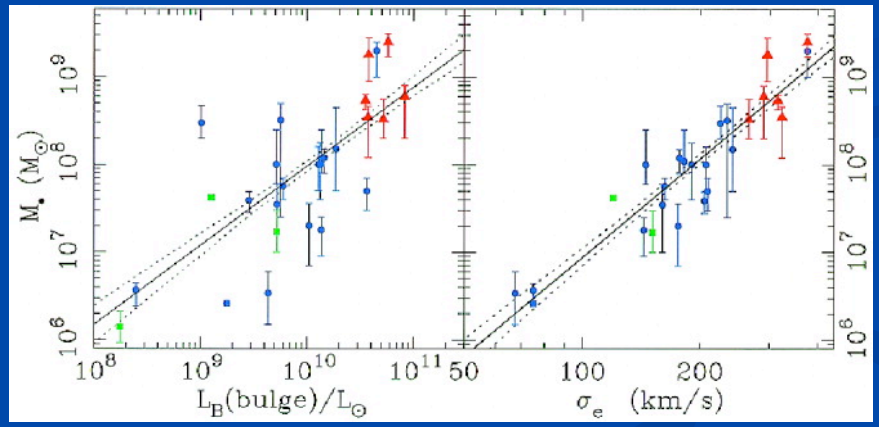


- -> M_{dyn}

Resolving Host Galaxies / Dynamical Masses

- *some science drivers:*
  - mass/galaxy assembly <-> comparison to CDM simulations
  - frequency of mergers at high z
  - evolution(?) of M_{BH}-σ relation

Gebhardt et al.



[-> co-evolution of BH and bulge]

-> unified picture of galaxy evolution
(e.g. ALMA DSRP)

Resolution is Key

ultimate goal: resolve CO emission spatially/kinematically
- compare to optical/NIR imaging
- dynamical masses

1” ~ 7.5kpc [8.5 kpc @ z=2, 5.8 kpc @ z=6]
-> need ~0.15” resolution to get 1 kpc resolution

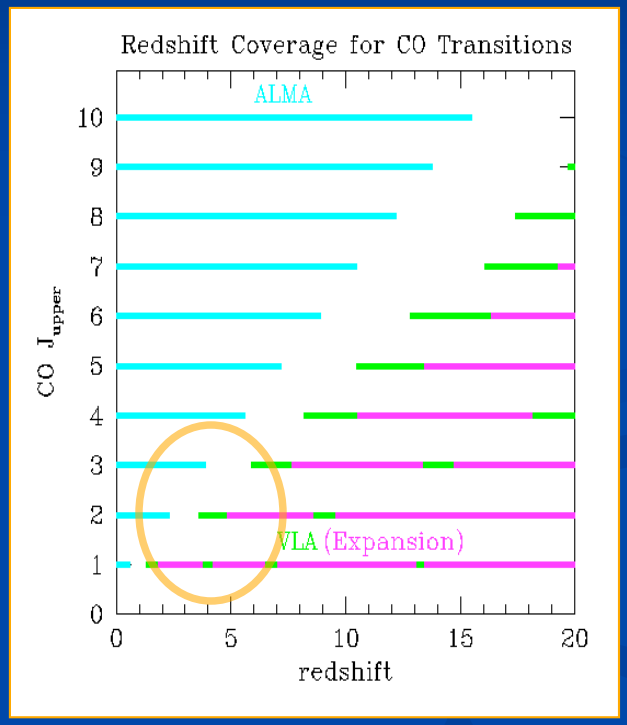
z=2.5 CO(3-2): 100 GHz (band 3): 4 km baselines
CO(6-5): 230 GHz (band 6): 1.8 km baselines
z=6.5 CO(7-6): 100 GHz (band 3): 4 km baselines

-> high-res (1 kpc, ~0.15”) CO studies at high z need long baselines

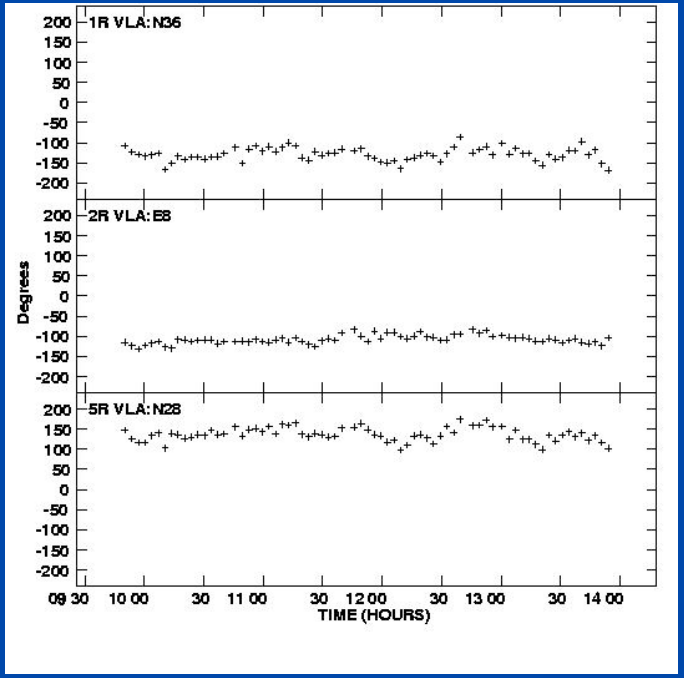
currently only doable with VLA in B array!

High Frequency Observations at the Very Large Array

CO ‘discovery space’ at VLA
-> currently only few sources doable



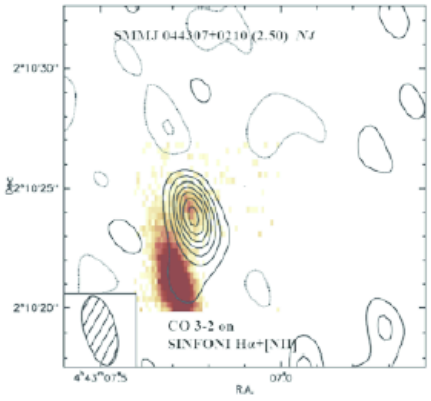
needed: good phase stability

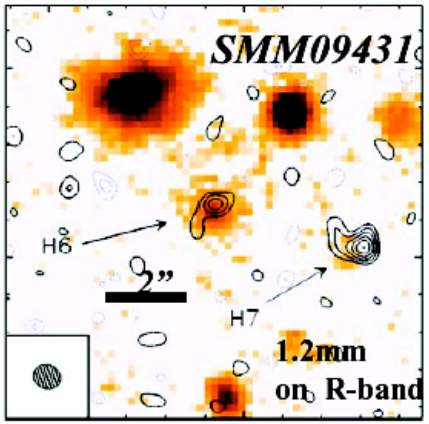


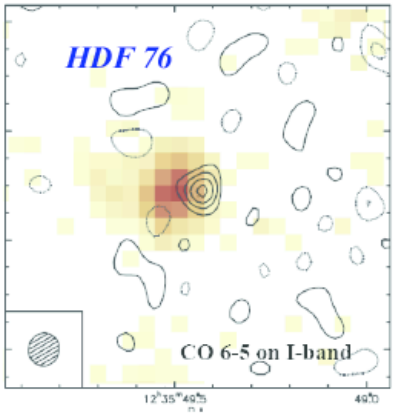
‘problem’: only 50 MHz bandwidth...

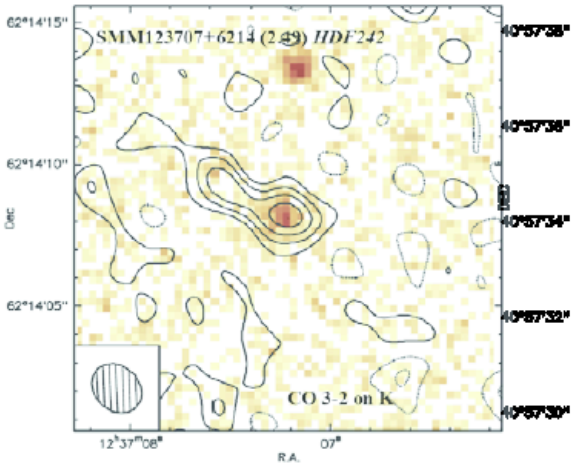
[50MHz ~ 300 km s^{-1} in Q band]

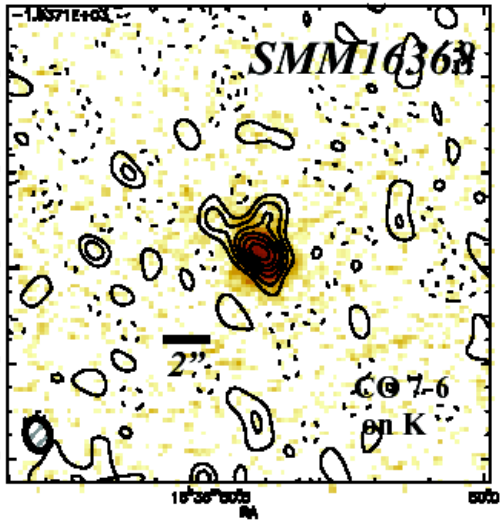
Resolving Submillimeter Galaxies

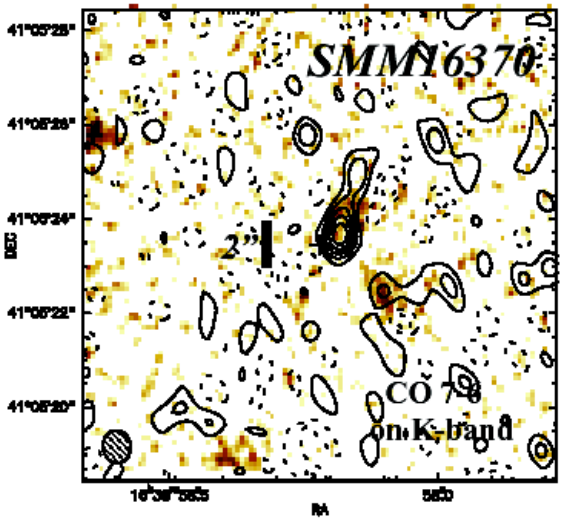








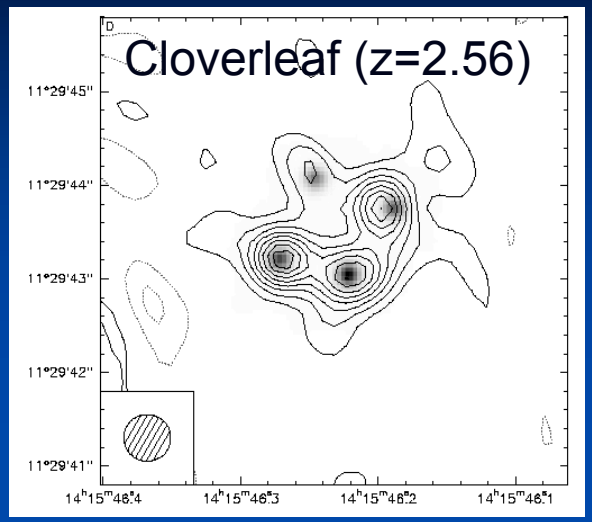




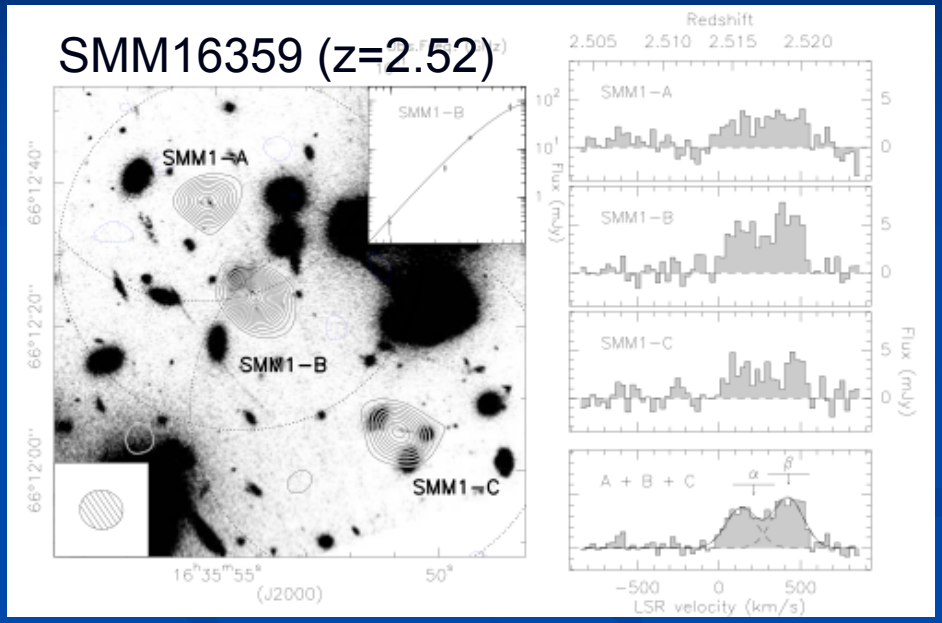
Plateau de Bure survey: some sources resolved at >0.6” - $T_{on\ source}$~35 h

Neri et al. 2005, Tacconi et al. 2006

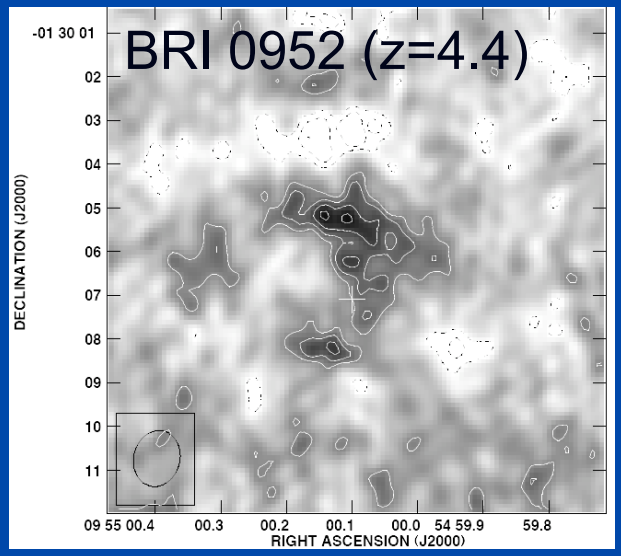
Lensing Helps...



Alloin et al. 1997, Yun et al. 1998



Sheth et al. 2004, Kneib et al. 2004

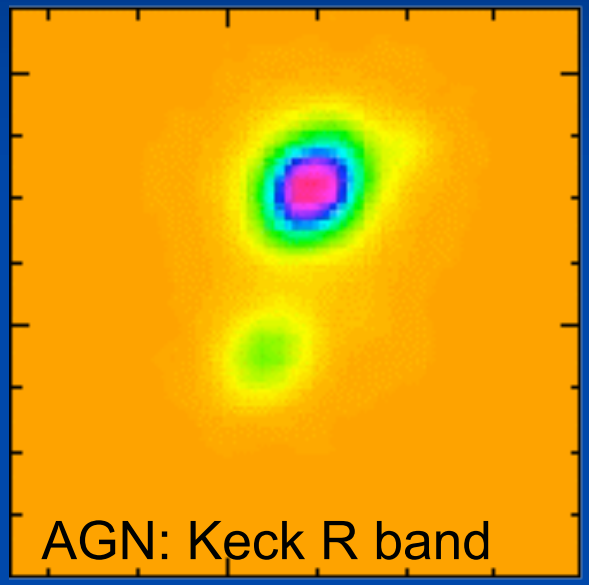


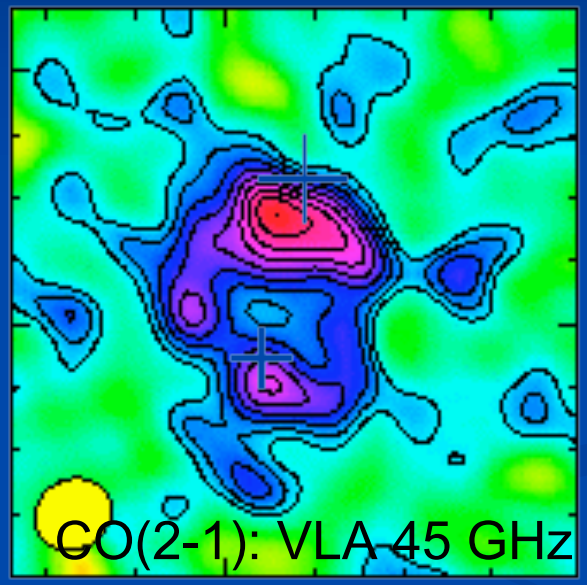
new C/D array obs. rms: 35 μJy!

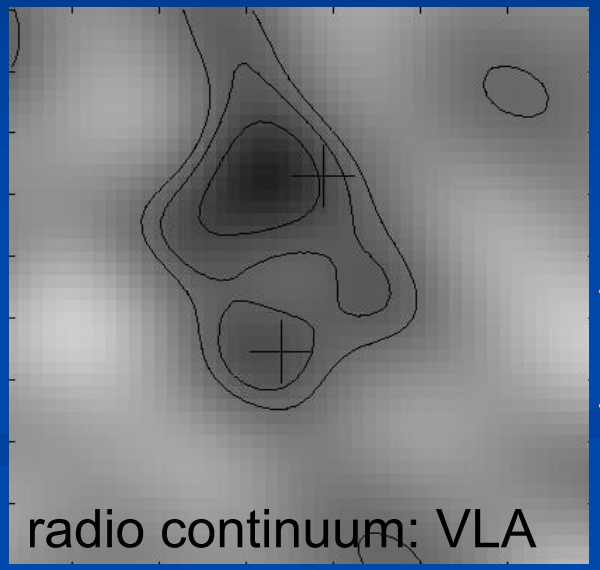
- but you need good lens model!
- add'l complication: lensing factor of gas potentially different from AGN

Lensing Helps...

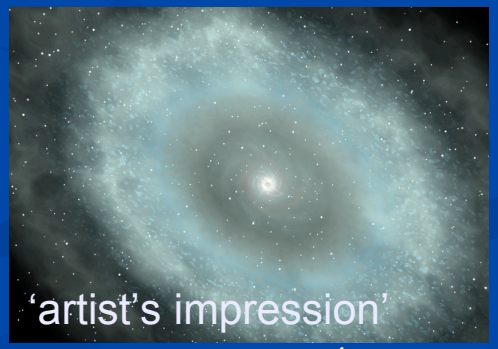
J2322+1922: Lensed QSO at z=4.12







Carilli et al. (2003)



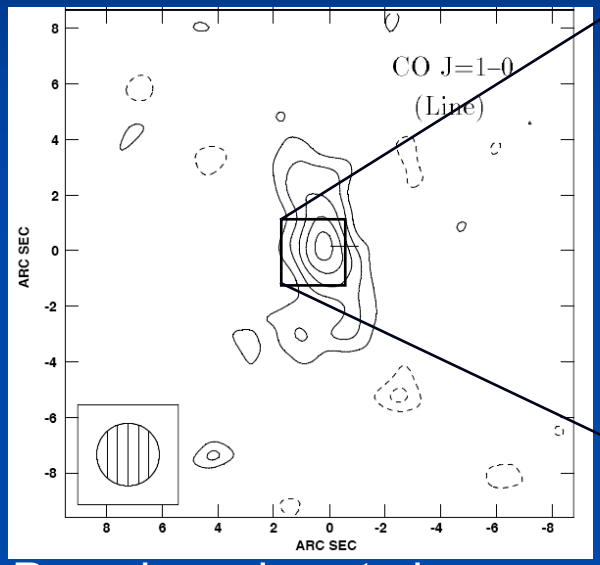
Molecular Einstein Ring:

RC *cospatial* w/ Gas, not AGN, r ~ 2kpc

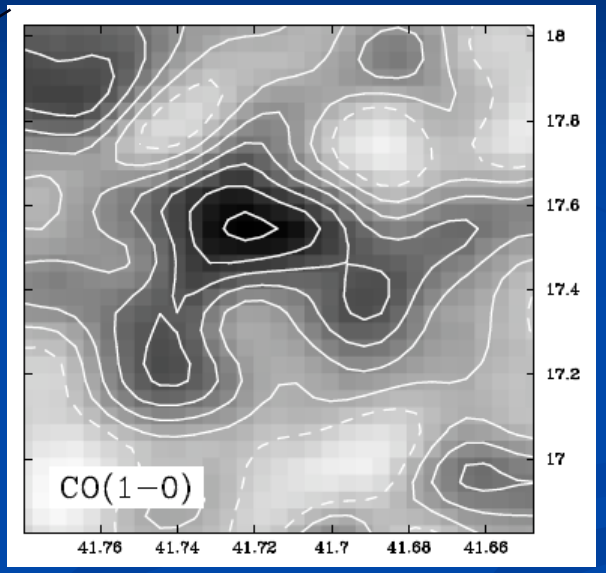
$\Rightarrow$ dust emission heated by SF *not* AGN, SFR~3000 $M_{sun}yr^{-1}$ (!)

Lensing Helps...Not always!

example: ***APM08279 (z=3.91)***



Papadopoulos et al. 2001



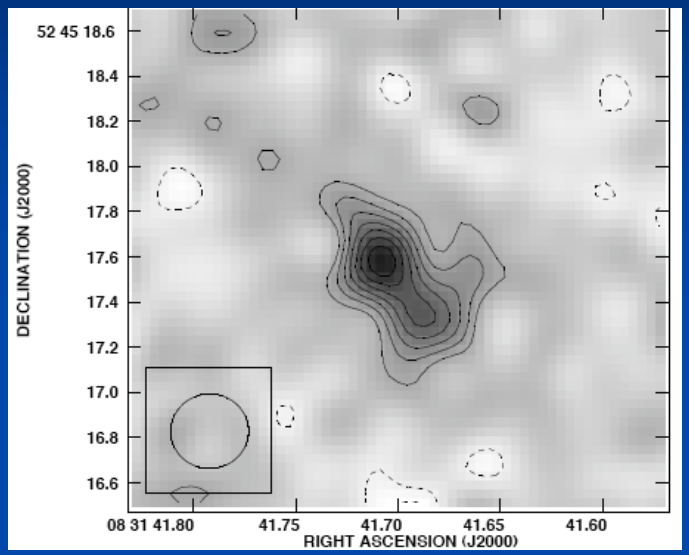
Lewis et al. 2002

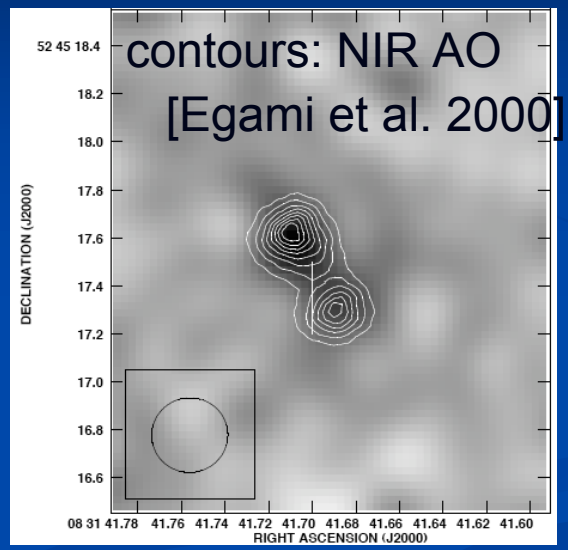
Lensing Helps...Not always!

example: ***APM08279 (z=3.91)***

new C/B array:

rms: 130 μJy





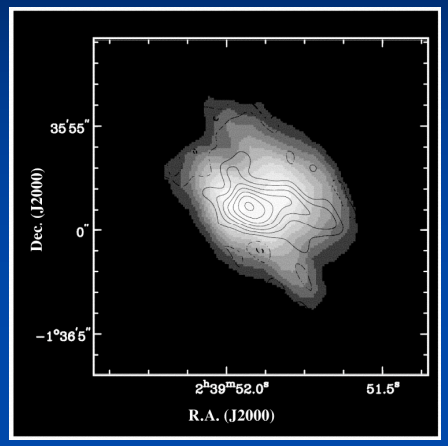
-> μ~100(!) for gas

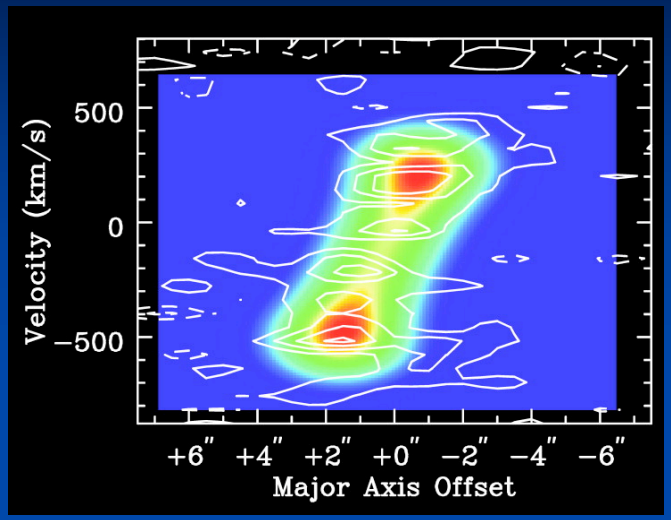
no extended component consistent with:

- **new VLA C and D array obs.**
- **total CO(1-0) flux measured by GBT (Riechers et al. 2006)**
- **CO line SED (Weiss et al. 2006)**

Non-lensed resolved (res. ~10 kpc) sources

SMM J02399, z=2.8





r~8 kpc

$M_{dyn} > 3\ 10^{11}\ M_{sun}$

Genzel, Baker, Tacconi et al. 2002

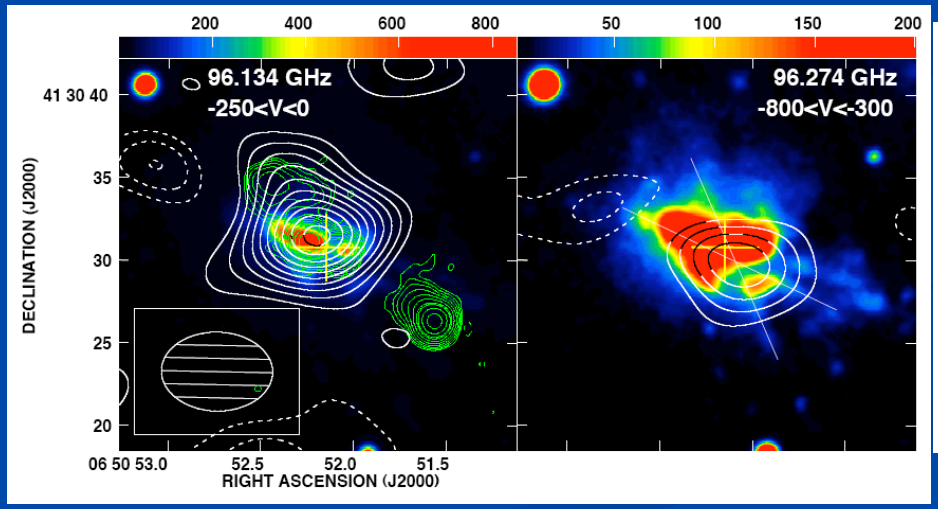
4C41.17, z=3.8

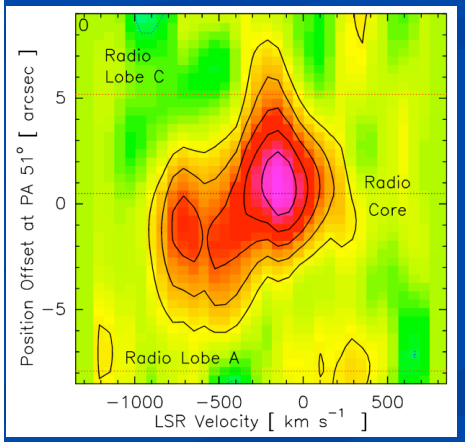
color: Lyα

contour: CO

2 components?

de Breuck et al. 2005

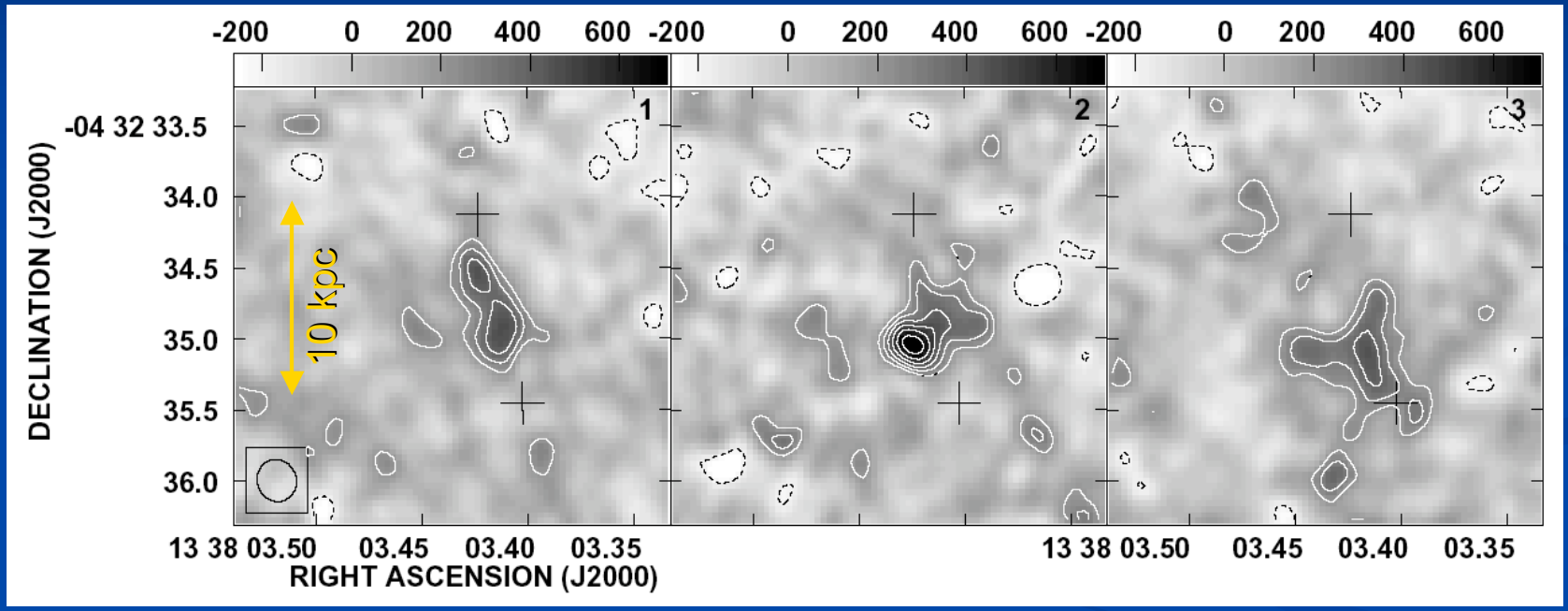




also: **53W002**: Scoville et al. 1997, **BRI 1202**: Carilli et al. 2002, **4C60.07**: Greve et al. 2004
4C60.07, 6C1909: Papadopoulos et al. 2000, **SMM 14011+0252** - Downes & Solomon 2003

VLA imaging at 0.2” (1 kpc) resolution

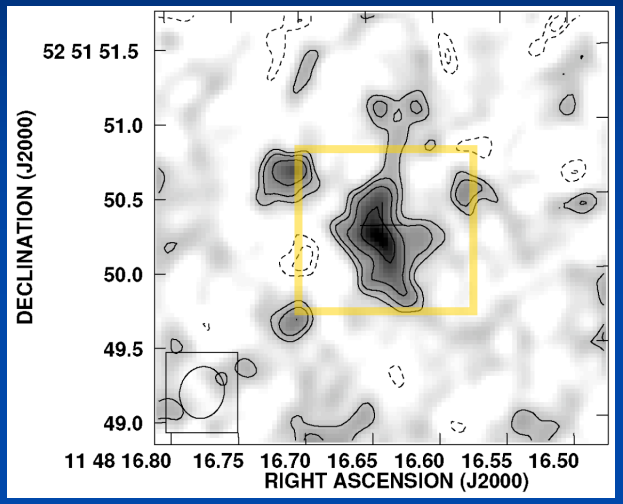
BRI 1335-041 (z=4.407) - CO(2-1) observed Q band

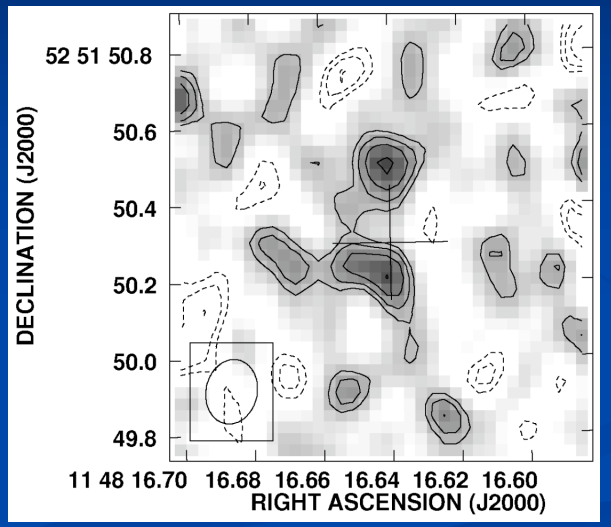


VLA B array - 0.2” res.
channel width: ~15 MHz (100 kms^{-1})

M_{H2} = 7 10^{10} Msun
M_{dyn} = 5 10^{10} Msun
$T_{mb,peak}$ ~ 20 K

CO @ 1kpc Resolution @ z=6.4 (!)





Walter et al. 2004

- M_{H2}=5 x 10^9 M_{sun}, $T_B(z=6.4)$=35 K

[~nearby SB centres, but size is 10 times larger]

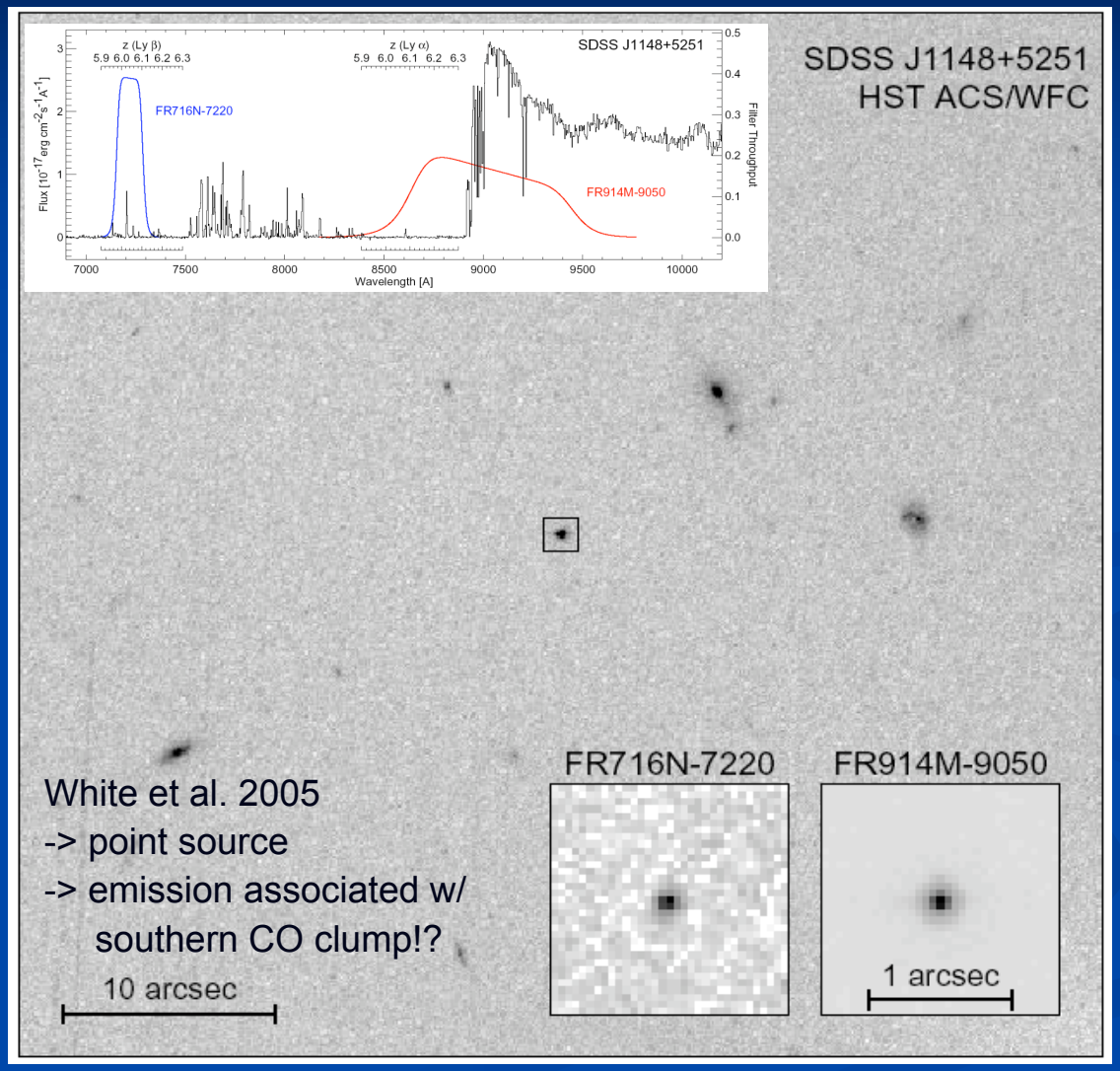
- **from CO lum:** $M(H_2) = 2x10^{10}\ M_{sun}$
- **from size/dyn:** $M_{dyn} = 5.5x10^{10}\ M_{sun}$
- **black hole:** $M_{BH} = 3x10^9\ M_{sun}$

M_{BH}–σ relation:

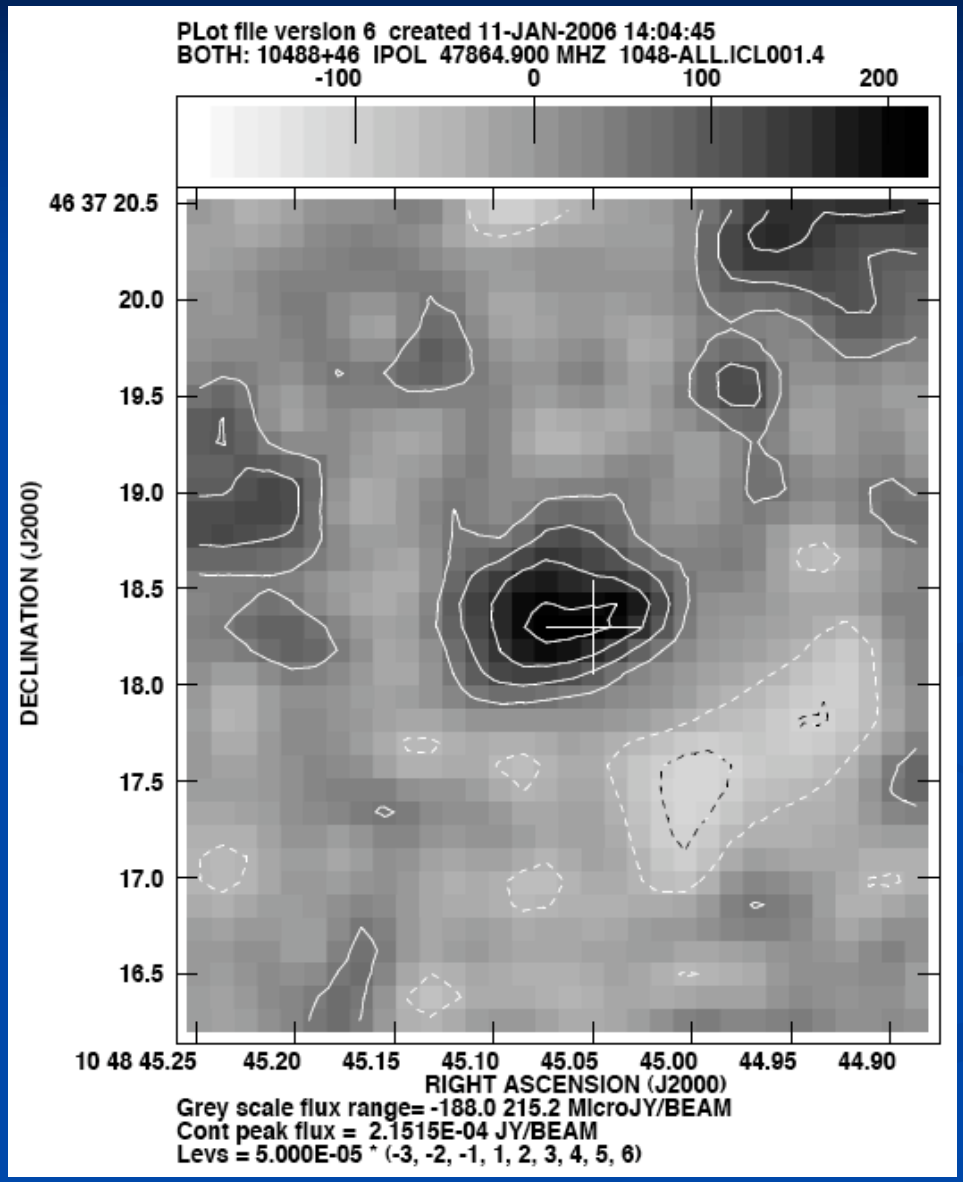
-> $M_{bulge} \sim 1.5x10^{12}\ M_{sun}$

[also: Shields et al. 2006]

CO @ 1kpc Resolution @ z=6.4 (!)



more CO at z>6?



2nd CO detection at z>6?
[VLA CO(3-2)]

4.5 σ 'detection'

Summary

- can resolve distant (z>1) galaxies today
-> but expensive + need best weather
[but can only be done in the radio!]

- 1kpc resolution can be a achieved by:
(E)VLA, ALMA (larger structures: PdBI/CARMA)

-> resolve morpholgy of gas (merger?)
-> dynamical mass (conflict w/ CDM simulations, M-σ ?)

- so far only tip of the iceberg
ALMA 5 σ detection limit: 0.04 Jy kms^{-1}
[current CO(3-2): 0.2 - 10 Jy km s^{-1}]

-> bright future!