Properties of the molecular gas in starburst galaxies and AGN

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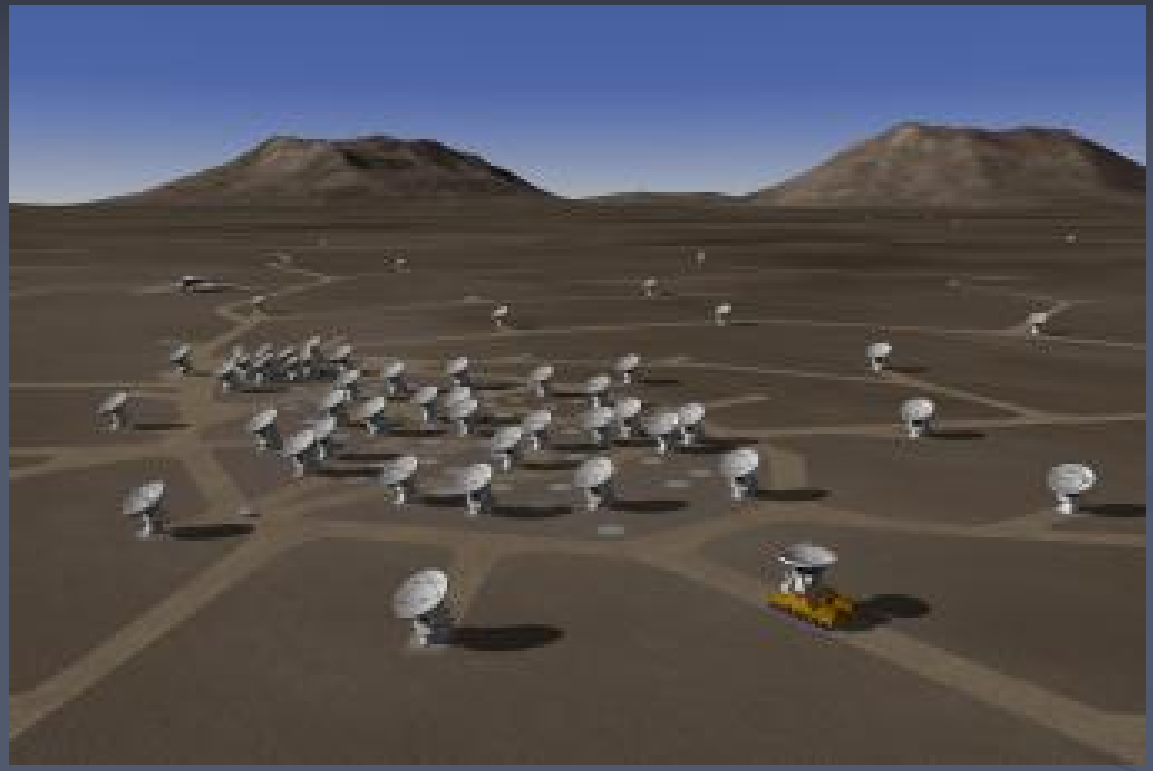
The Golden Age of Radio Astronomy



ALMA:

50-64 12-m dishes 84-720 GHz

milliarcsec resolution: 14 mas at 218 GHz

The Golden Age of Radio Astronomy

e-VLA:

- 1.0-50 GHz
- 5-20 x better cont. sensitivity
- up to 8 GHz bandwidth
- new correlator (16,384 chan.)

e-MERLIN:

- 1.5-24 GHz
- optical fibre network
- new receivers
- new correlator

The Golden Age of Radio Astronomy

VLBA:

- upgrade of K-band receivers

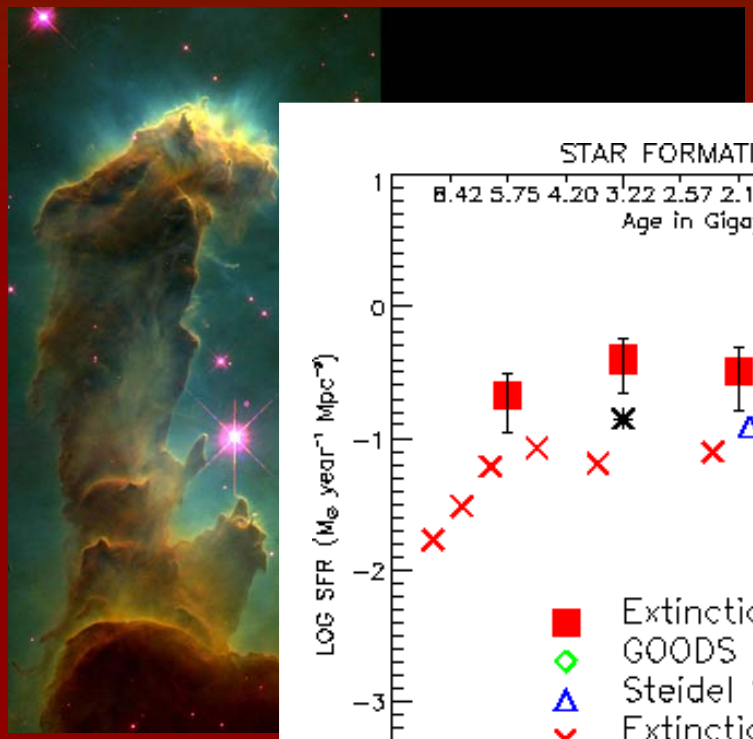
EVN:

- Yebes 40-m (first fringes at K-band in May 2008)
- Sardinia Radio Telescope (0.3-100GHz) …

Outline:

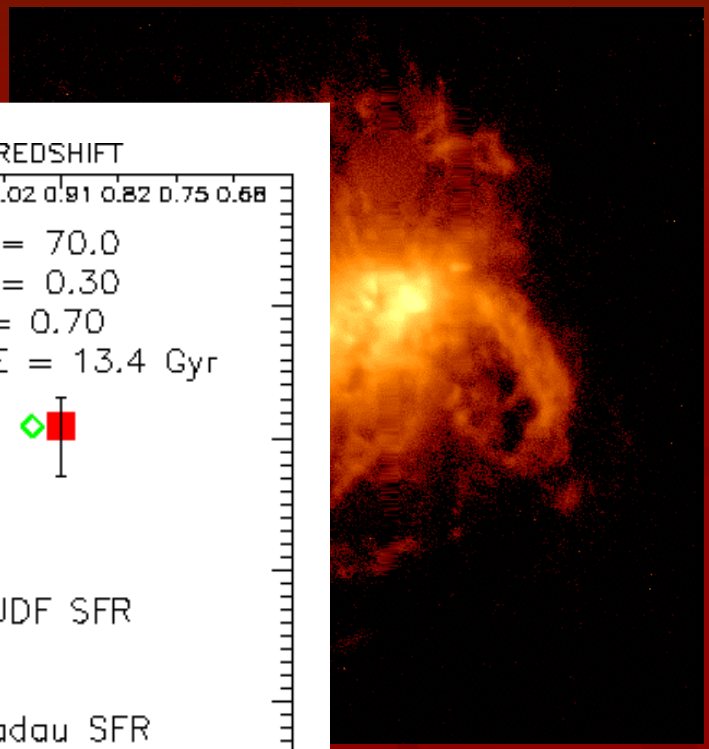
- Why care about molecular gas?
  (motivation)
- How do we study it?
  (a brief introduction to molecular spectroscopy)
- What's going on in M82?
  (a case study)
- What can we expect in the future?
  (outlook)

Star formation here, there and everywhere



Eagle Nebula
STScI, J. Hes

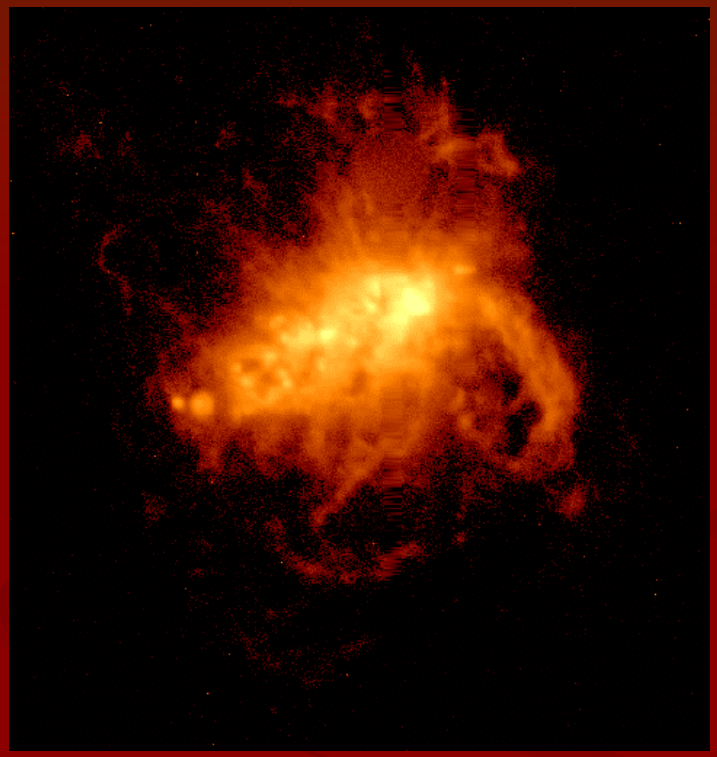
(Thompson et al. 2006)



lunter et al. 1993)

Starbursts – just scaled-up star formation?

M82 (NASA, ESA, The Hubble Heritage Team)



NGC 1569 (Hunter et al. 1993)

- **Non-standard conversion $I_{CO(1-0)} \rightarrow N_{H2}$**
- **Warm molecular gas?** (Mauersberger et al. 2003)
- **Initial mass function?** (Klessen et al. 2007)

Emission from molecular gas clouds

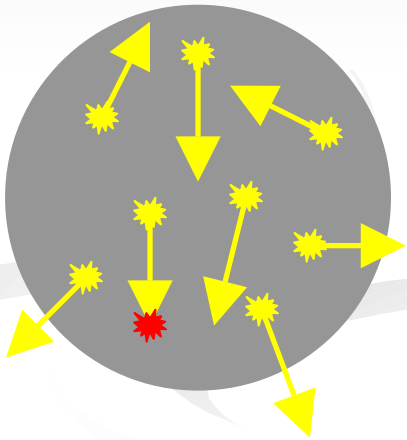
The fundamental dilemma: Photon trapping

- Molecular excitation

$$n_i \sum_{j=1}^{k} A_{ij}+B_{ij}u_{ij}+C_{ij} = \sum_{j=1}^{k} n_j(B_{ji}u_{ji}+C_{ji})$$

- Radiative transfer

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$



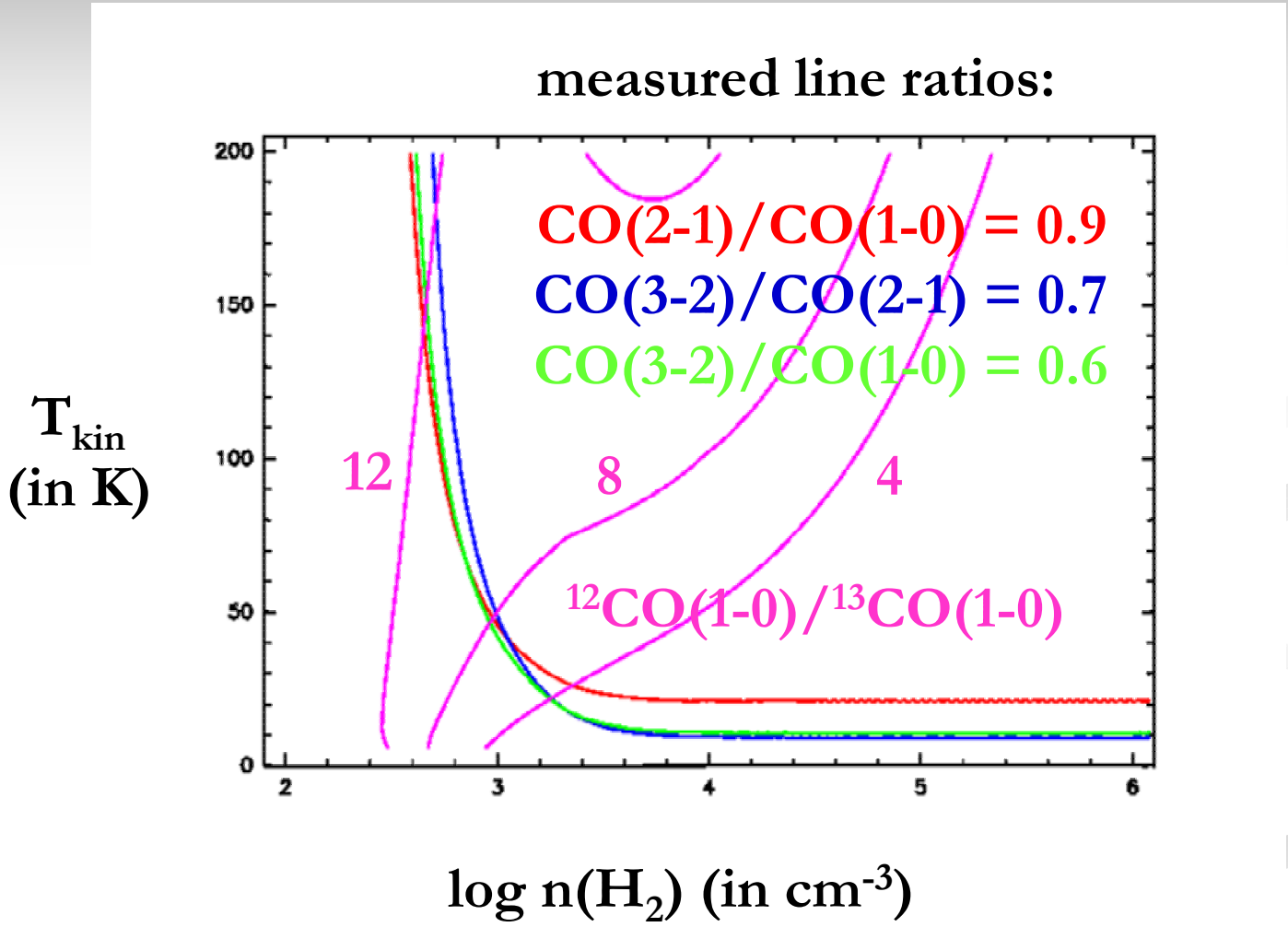
⇨ make a (simple) model, e.g. a large velocity gradient (LVG) model:

T_{kin}, n_{H2}, abu_{mol}/grad(v)

to observer

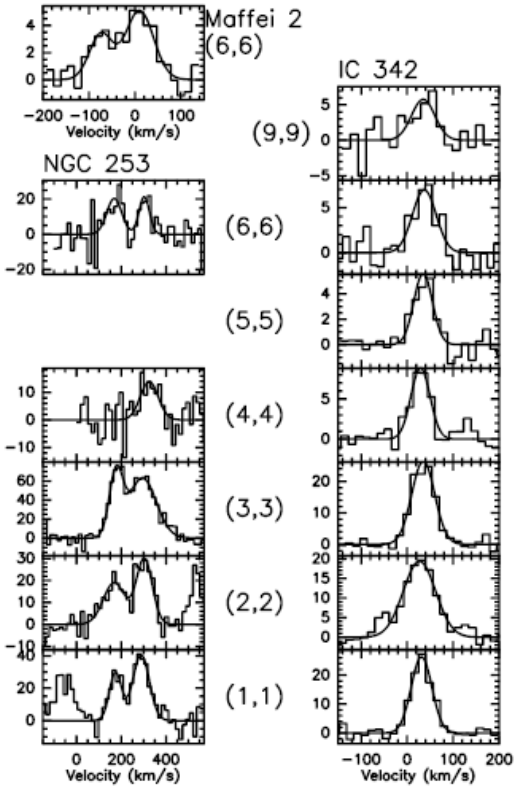
Problem: T_{kin} – n_{H2} degeneracy!

Problem: T - n degeneracy

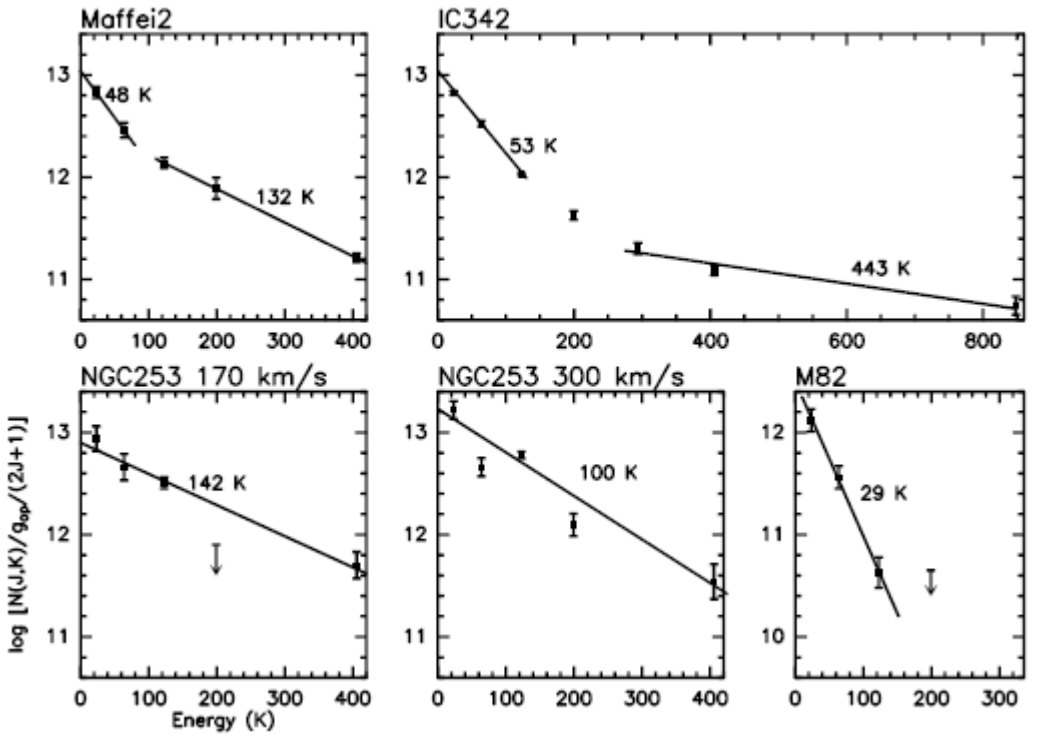


The standard thermometer: NH_3

- Metastable inversion lines of ammonia NH_3(K,K) at ~24 GHz
- optically thin gas, T_{ex} = const: Boltzmann plot yields $T_{rot} < T_{kin}$



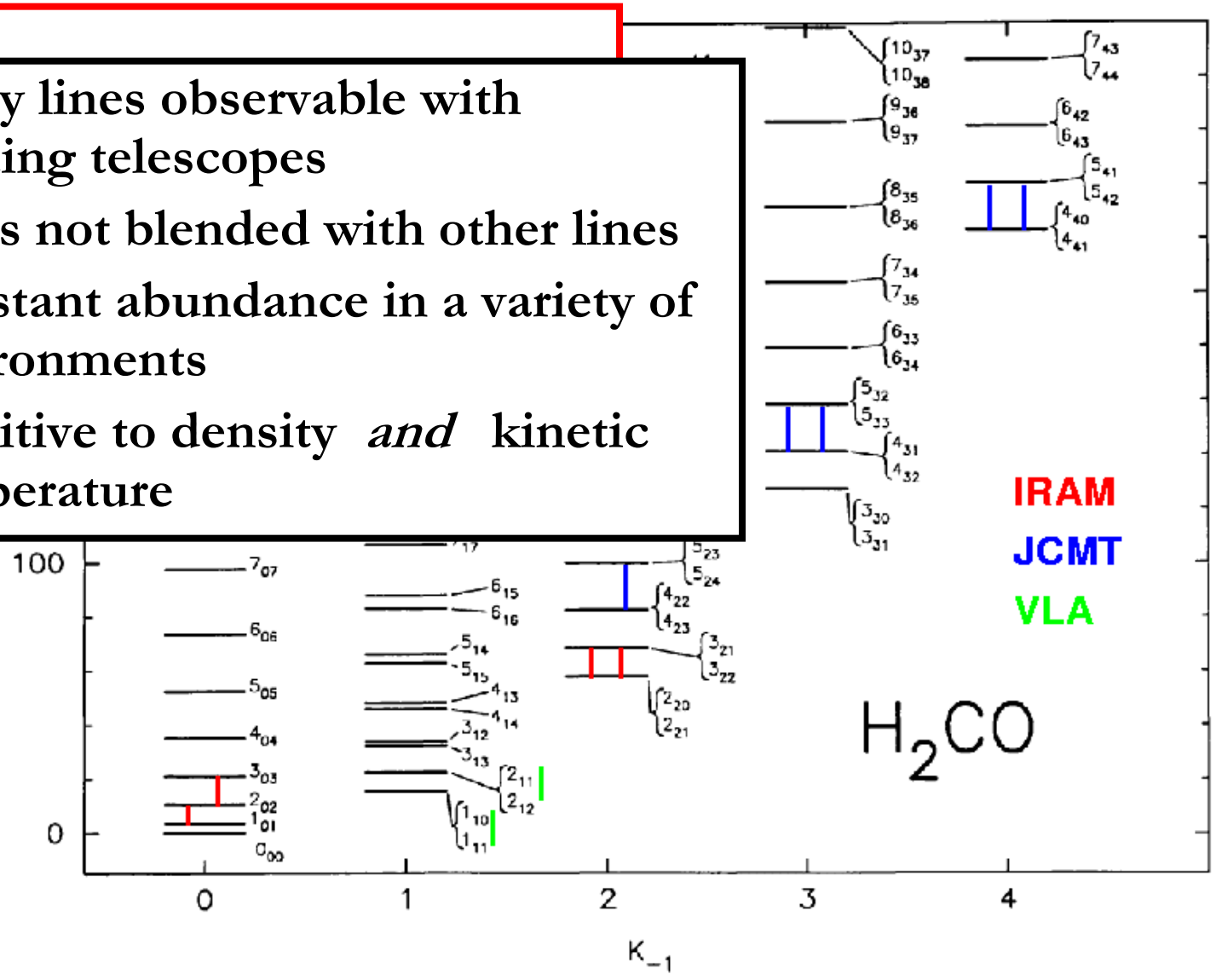
(Mauersberger et al. 2003)



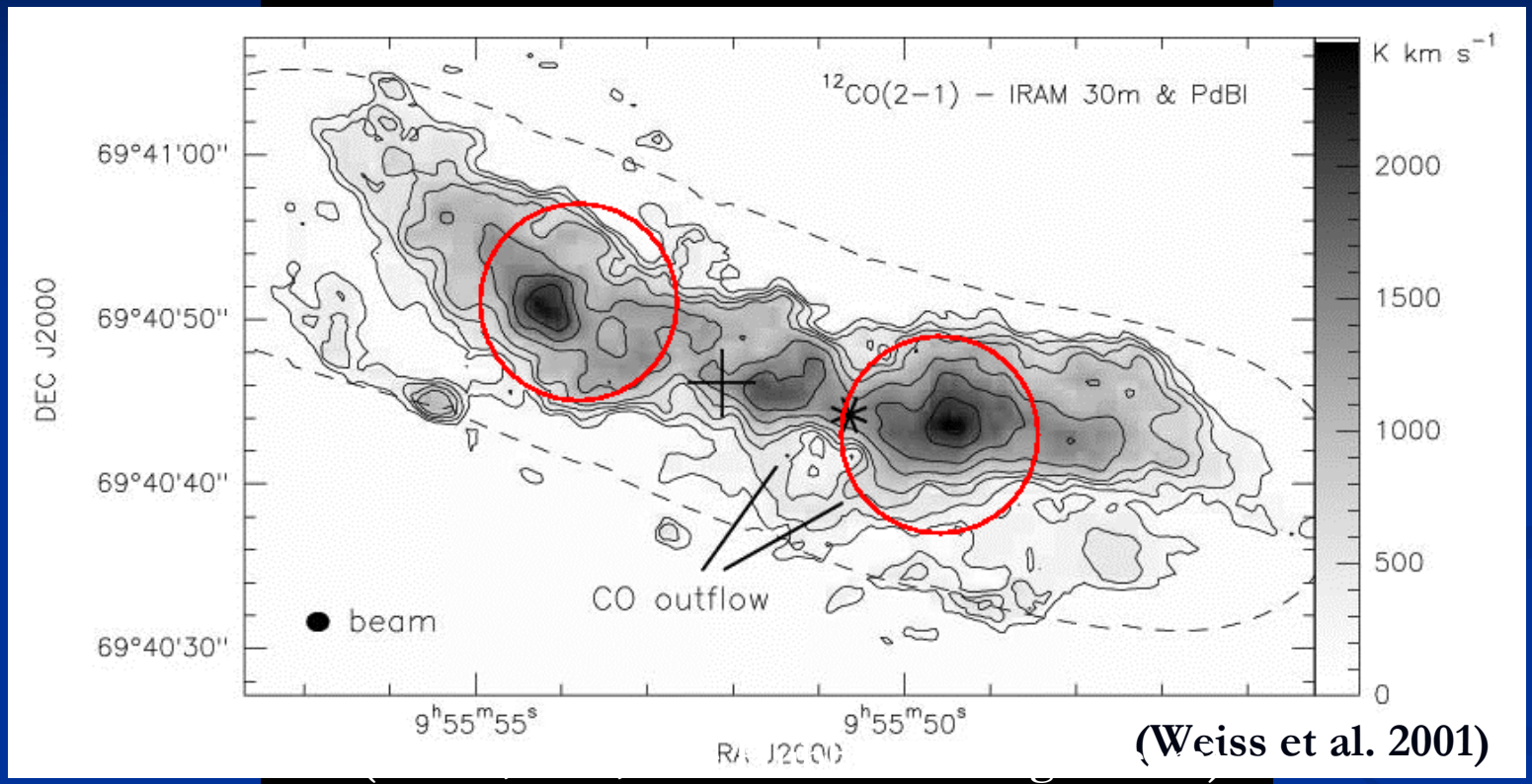
M82: T_{rot} ~ 29 K?

Formaldehyde (H_2CO)

- Many lines observable with existing telescopes
- Lines not blended with other lines
- Constant abundance in a variety of environments
- Sensitive to density *and* kinetic temperature



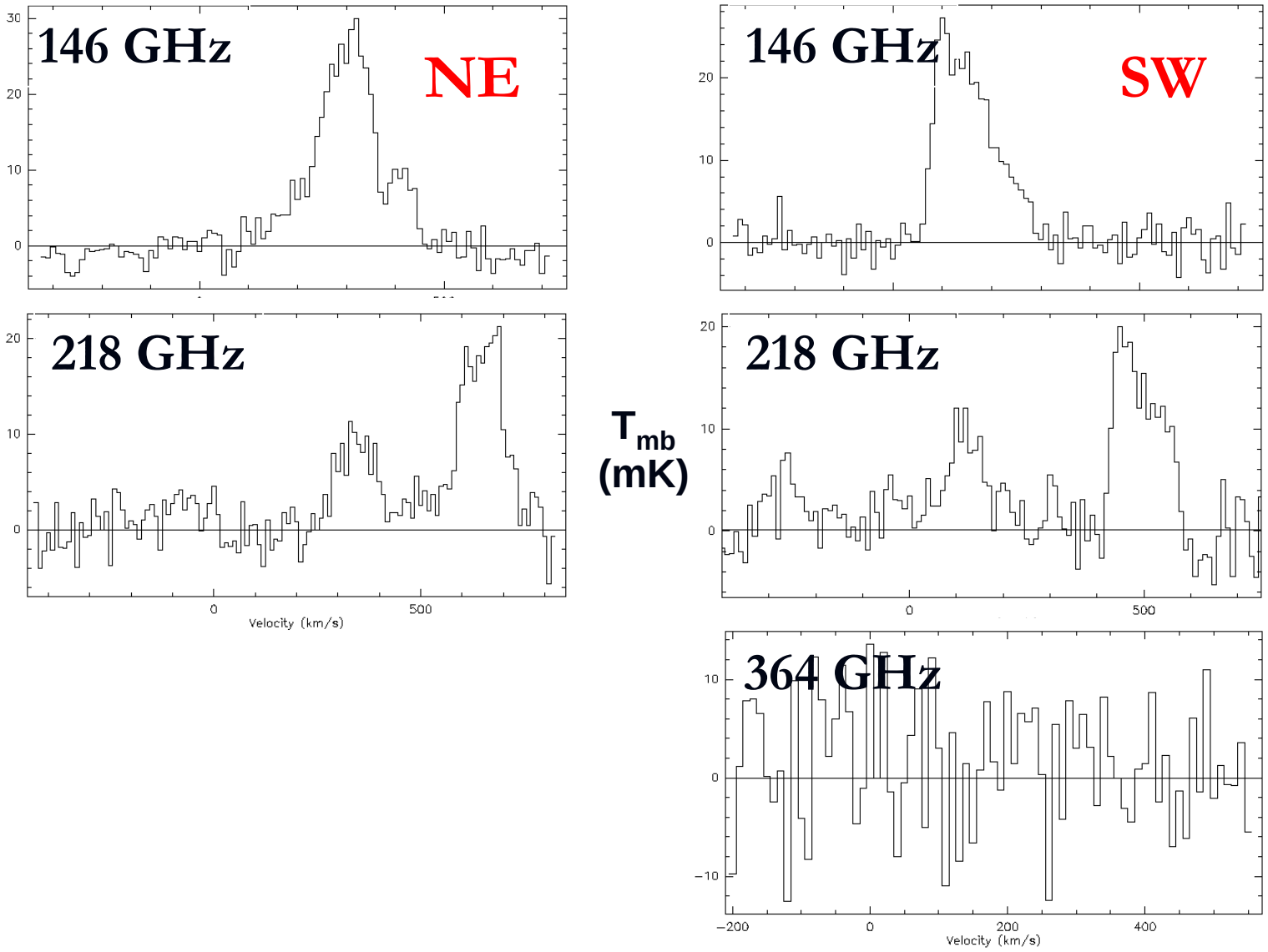
The starburst galaxy M82



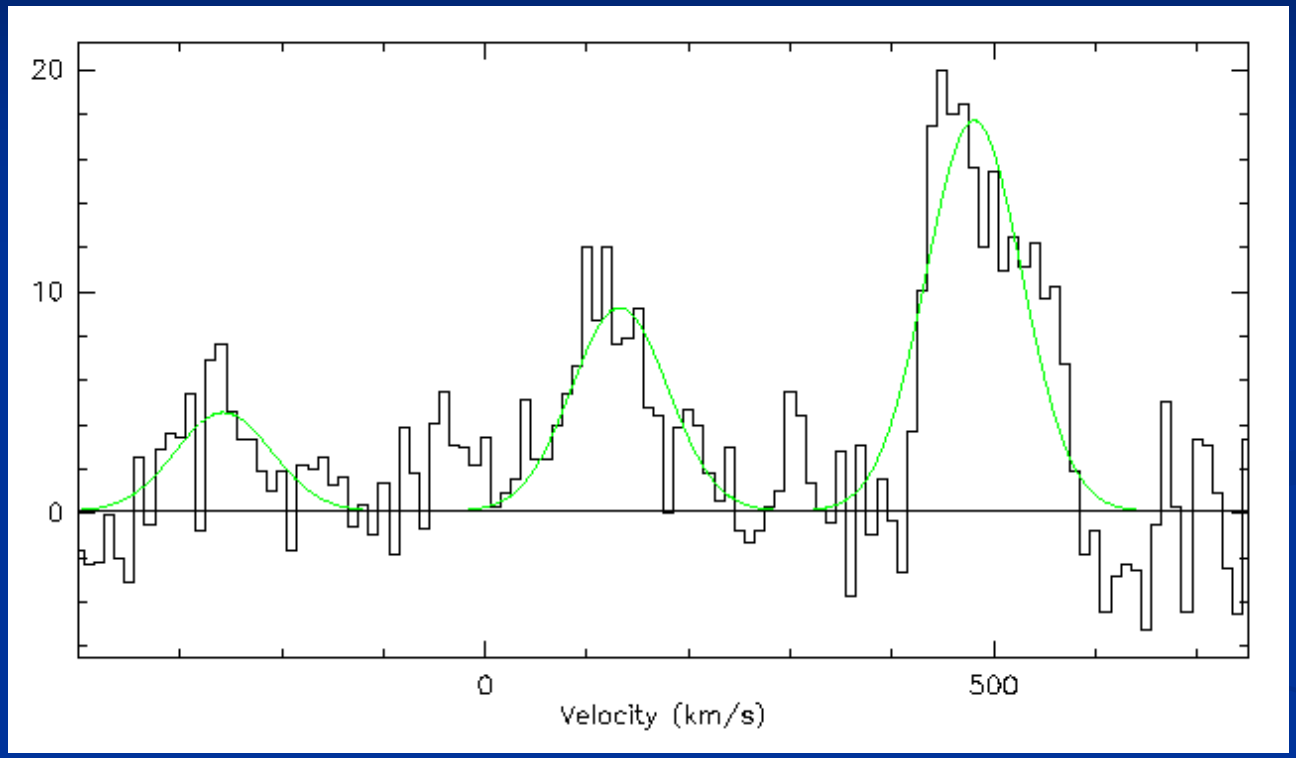
(Weiss et al. 2001)

- nuclear starburst / high IR luminosity /galactic wind
- dense molecular gas concentrated towards the centre
- peculiar chemical abundances

H_2CO in M82: results



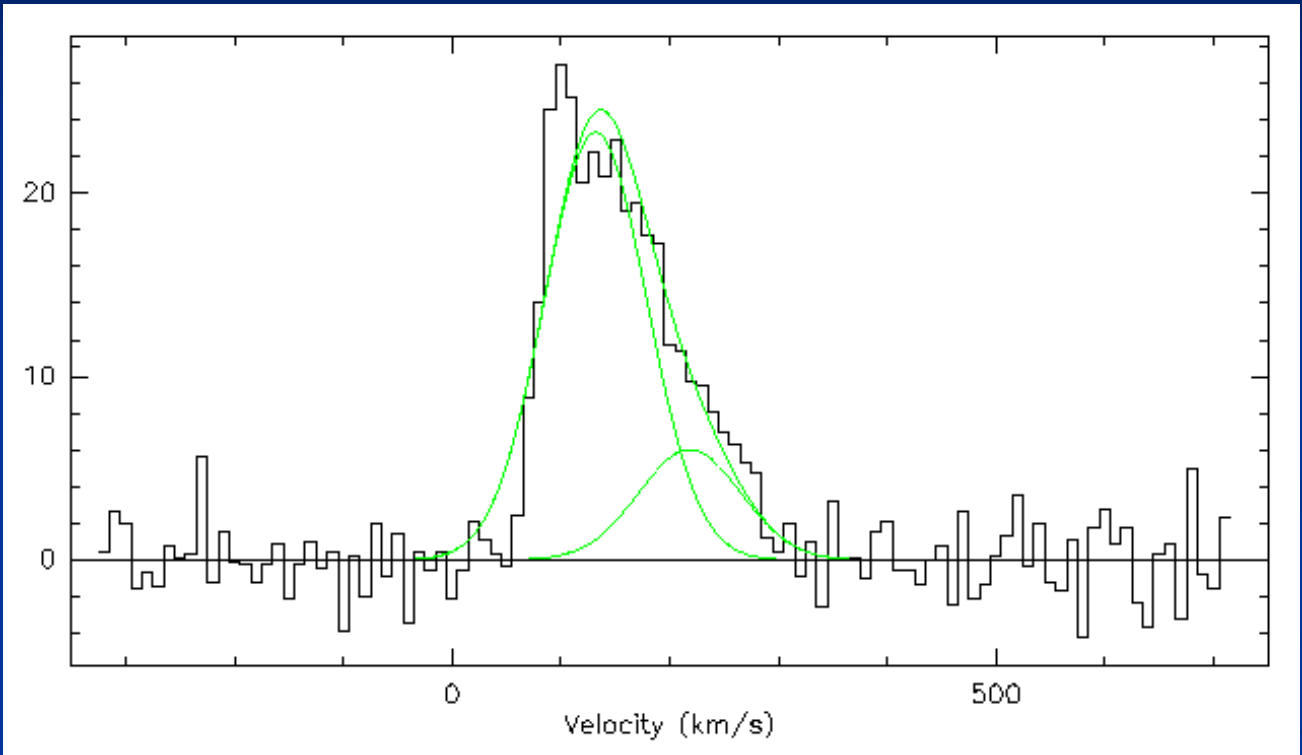
H_2CO in M82: SW lobe, 218 GHz



$H_2CO(3_{03}\text{-}2_{02})$
$H_2CO(3_{22}\text{-}2_{21})$
$H_2CO(3_{21}\text{-}2_{20})$

v = 132 km/s, w = 111 km/s

H_2CO in M82: SW lobe, 146 GHz

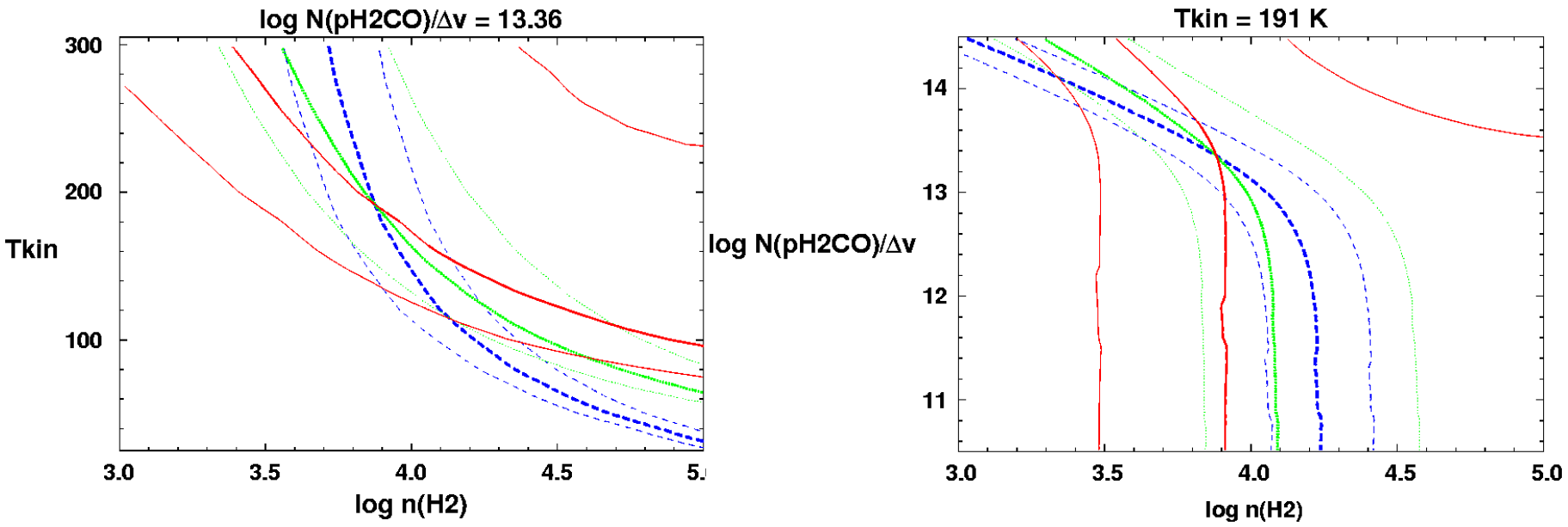


$H_2CO(2_{02}\text{-}1_{01})$
$HC_3N(16\text{-}15)$

v = 132 km/s
w = 111 km/s

H_2CO	$3_{21}\text{-}2_{20}$	$3_{22}\text{-}2_{21}$	$3_{03}\text{-}2_{02}$	$2_{02}\text{-}1_{01}$	$5_{24}\text{-}4_{23}$
ν_0(GHz)	218.76	218.48	218.22	145.60	363.95
Int.(K km/s)	0.53(0.14)	1.09(0.15)	2.09(0.16)	2.76(0.10)	<0.36

H_2CO in M82: LVG analysis



$H_2CO(3_{03}\text{-}2_{02})/H_2CO(3_{21}\text{-}2_{20})$ $H_2CO(2_{02}\text{-}1_{01})/H_2CO(3_{03}\text{-}2_{02})$ $H_2CO(2_{02}\text{-}1_{01})/H_2CO(3_{21}\text{-}2_{20})$

T_{kin} ~ 191 K (NE)/ 209 K (SW) $n_{H2} \sim 7 \times 10^3$ cm^{-3}

$N_{H2CO}/\Delta v \sim 2 \times 10^{13}$ cm^{-2}/km s^{-1} $M_{mol} \sim 1.4/1.7 \times 10^8 M_{sun}$

$X_{H2CO}/gradv \sim 1 \times 10^{-9}$ km^{-1} s pc

A kinetic temperature of ~ 200 K?

- Multi-line CO (Mao et al. 2000): high-excit. lines

  T_{kin} ~ 60…130 K n_{H2} ~ $10^{3.3…3.9}$ cm^{-3}

- Multi-line CO (Ward et al. 2003):

  T_{kin} ~ 14 K n_{H2} ~ $10^{3.5}$ cm^{-3}

  T_{kin} ~ 170 K n_{H2} ~ $10^{2.9}$ cm^{-3} (median values)

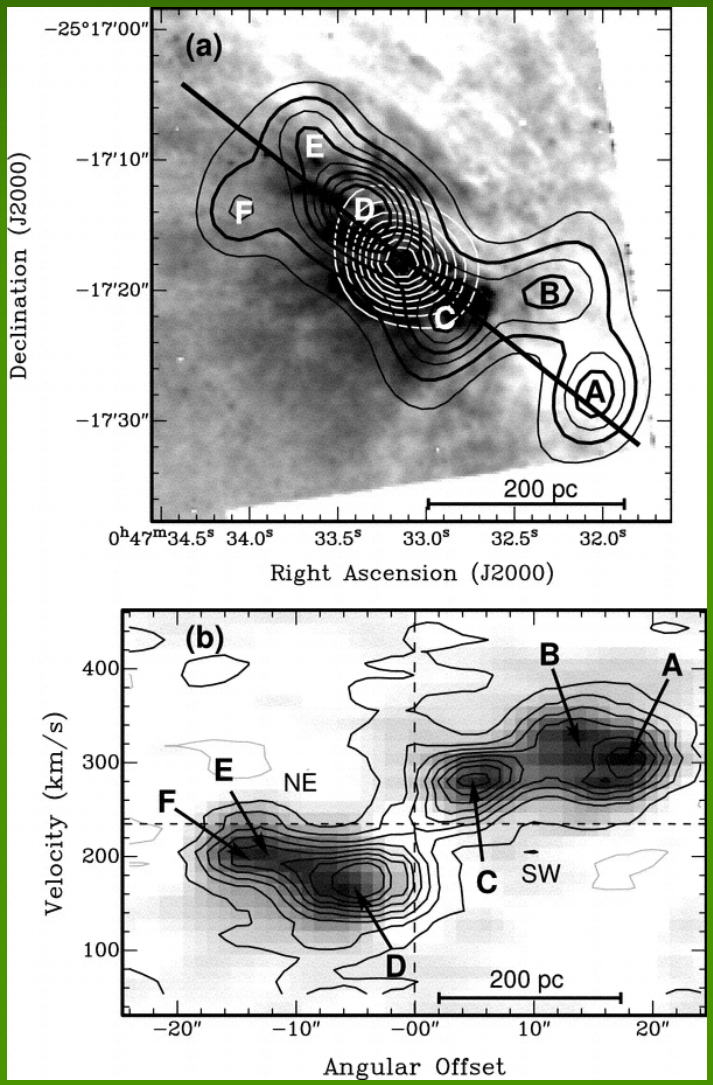
- Multi-line NH_3 and CS (Mauersberger et al. 2003):

  T_{rot} ~ 50 K + > 150 K in other starburst galaxies

- IR quadrupole H_2 transitions (Rigopoulou et al. 2002):

  T_{kin} ~ 150 K in starburst and Seyfert galaxies

The future: High-resolution NH_3



NGC 253:

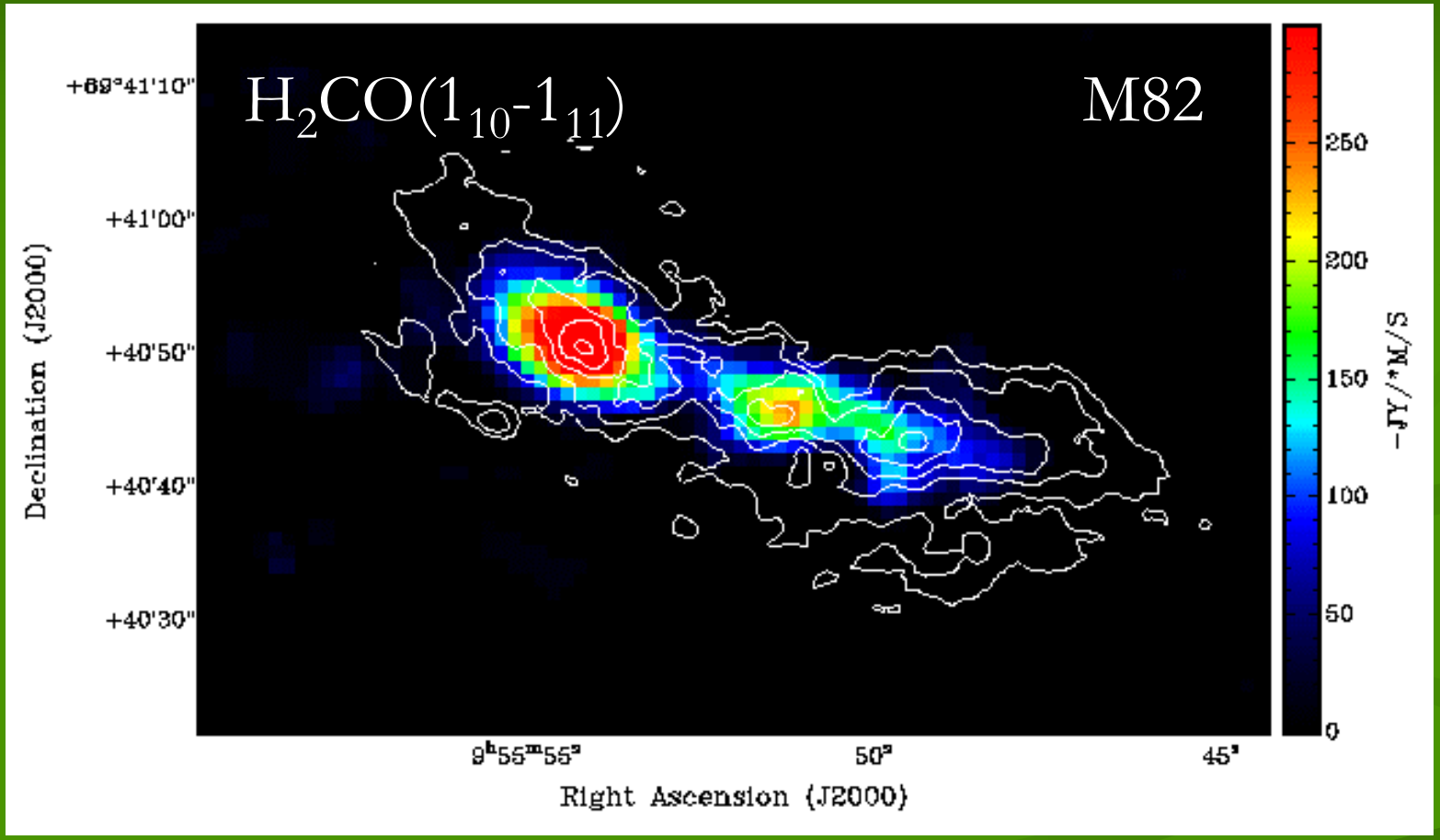
starburst galaxy similar to M82

superresolved $NH_3(3,3)$ emission (5”x5”, ATCA) as contours on HST WFPC2 image

- 6 complexes
- T_{kin} = 200K (SW), 140K (NE)

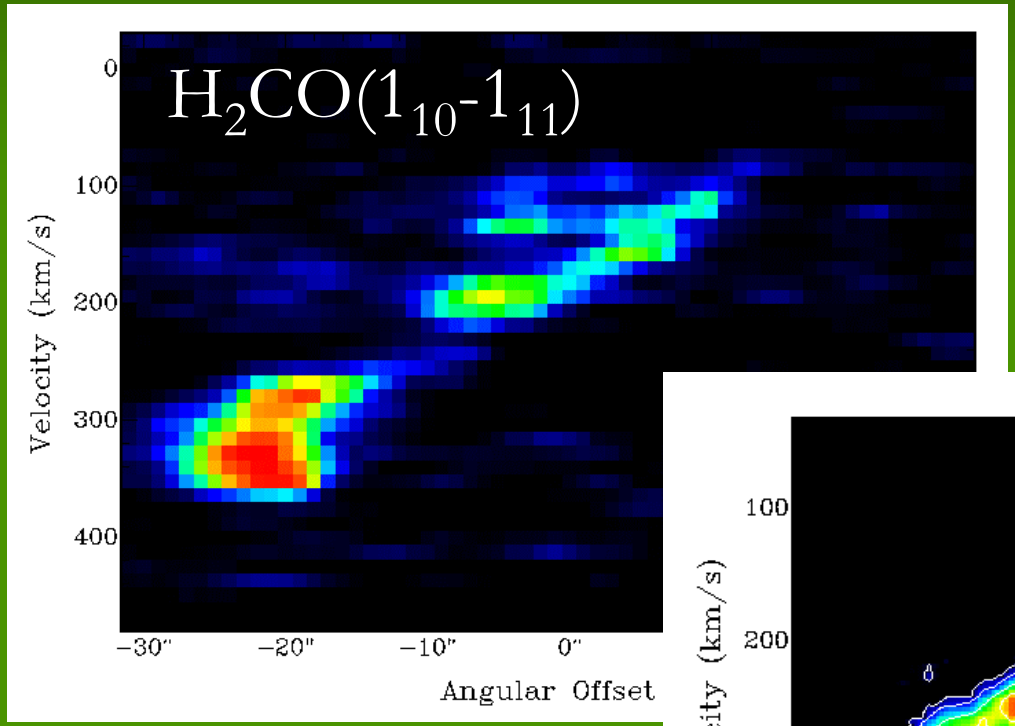
Ott et al. 2005

The future: High-resolution H_2CO

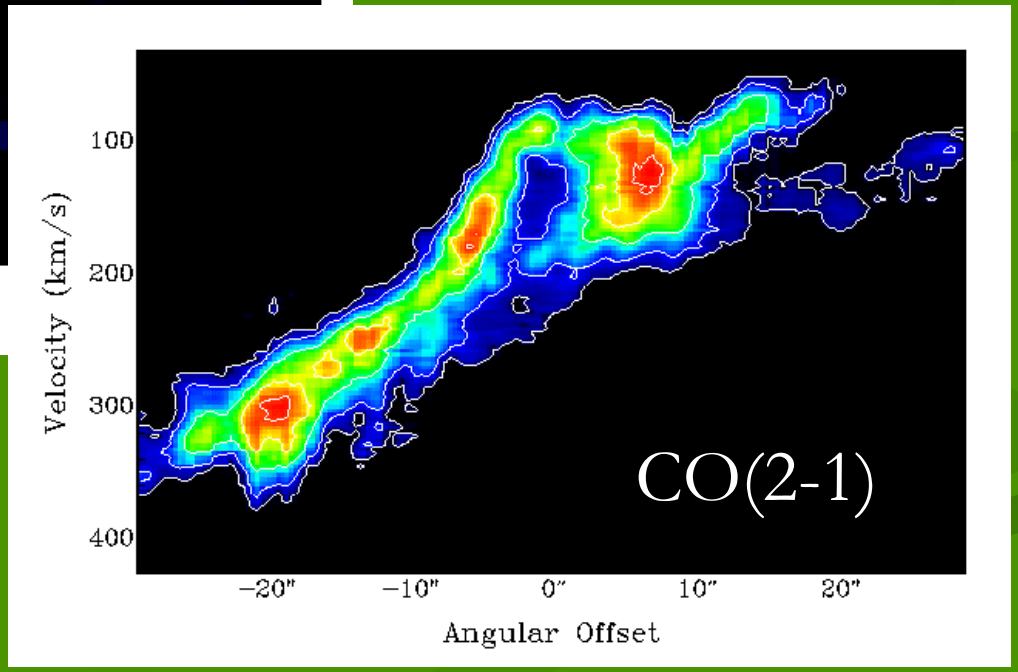


- $H_2CO(1_{10}\text{-}1_{11})$ at 6 cm seen in absorption, follows the CO emission
- difference between the two lobes?

The future: High-resolution H_2CO



a look at the position-velocity diagrams …



Muehle et al. in prep.

Summary

- In starburst galaxies and AGN, the molecular gas may have a kinetic temperature of a few hundred Kelvin
- NH_3 and H_2CO lines in the cm- and mm-range are powerful diagnostics of the properties of the molecular gas
- Our H_2CO study suggests warm, moderately dense molecular gas near the centre of M82 in very good agreement with comprehensive CO and other surveys:

  $T_{kin} \sim 200$ K, $n_{H2} \sim 7 \times 10^3$ cm^{-3}, $M_{mol} \sim 3 \times 10^8$ M_{sun}
- few high-resolution maps of extragalactic system in NH_3 and H_2CO yet, but …

  … the future looks promising!