How warm is the molecular gas in active environments?

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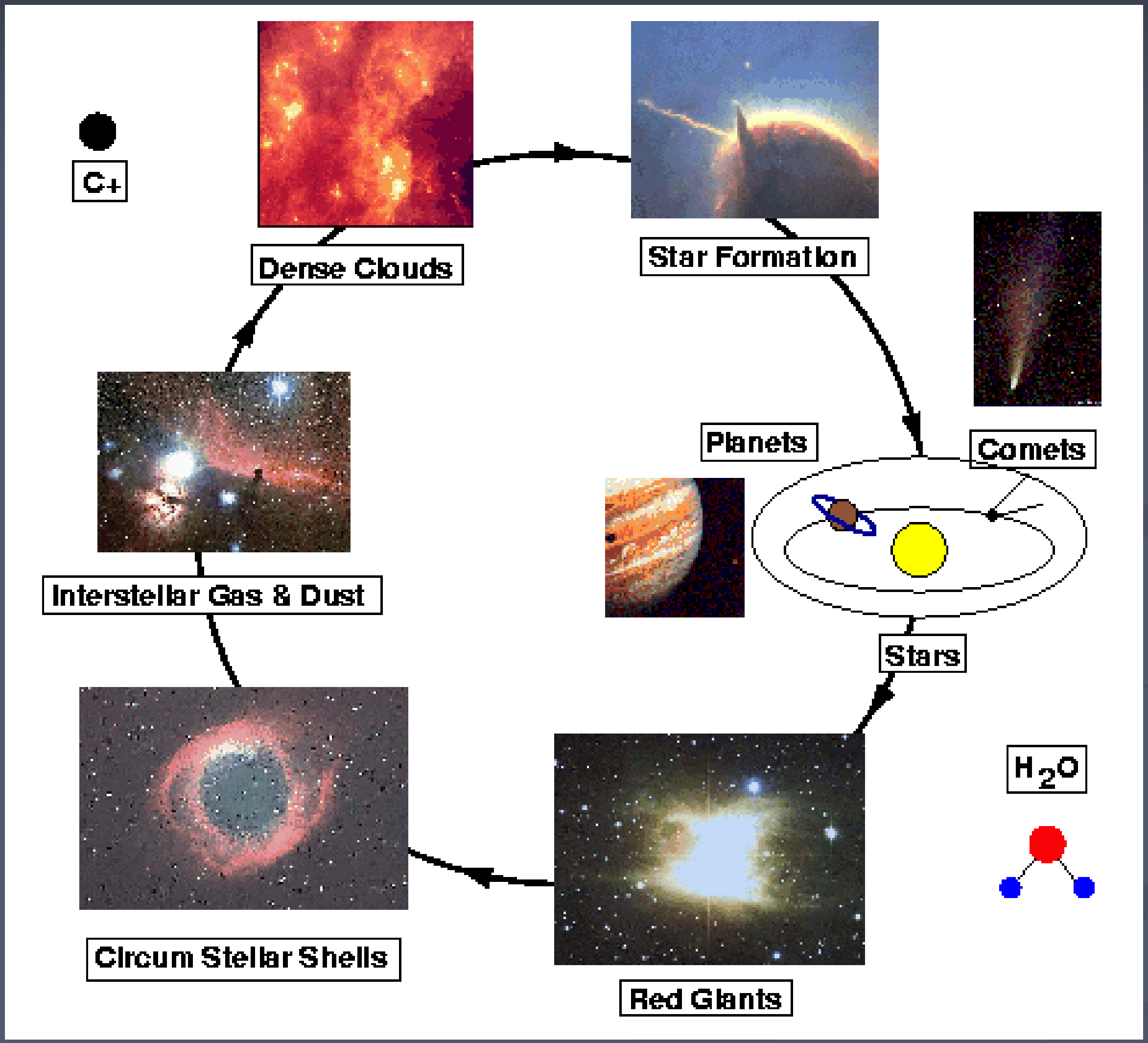
The cycle of interstellar matter



http://www.sron.rug.nl/hifiscience/sitemap.hml

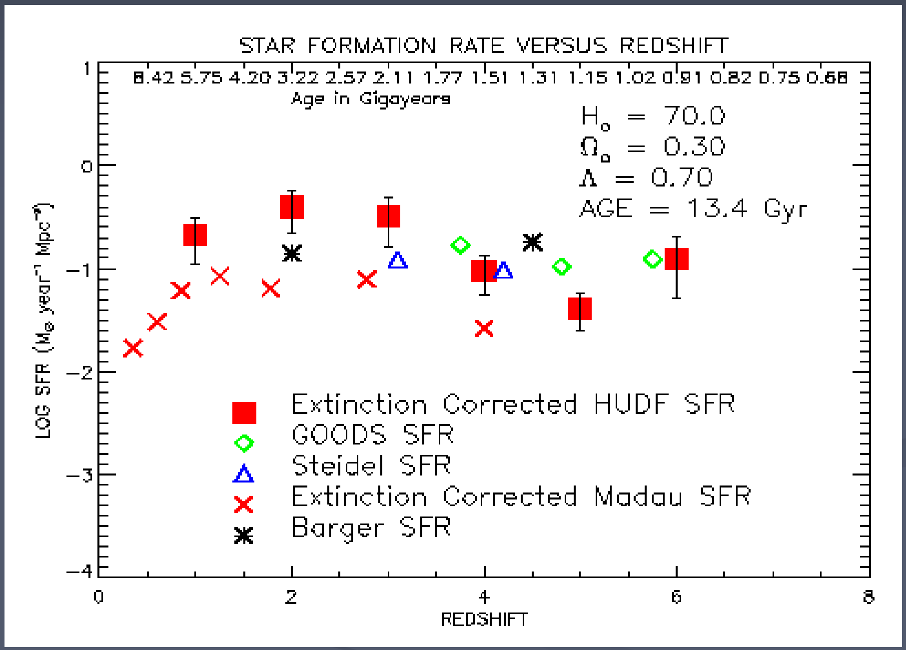
in the Milky Way, stars form out of collapsing clouds of cold, dense **molecular gas**

~63% H_2
~36% He
~1% other molecules + dust

is that true for all galaxies?

Starbursts: just scaled-up star formation?

M82 (NASA, ESA, The Hubble Heritage Team)



(Thompson et al. 2006)

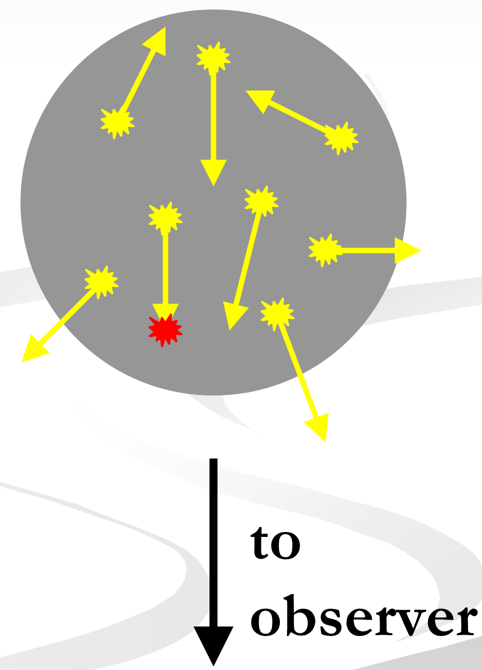
- **non-standard conversion $I_{CO(1\text{-}0)} \rightarrow N_{H2}$**
- **non-standard initial mass function?** (Klessen et al. 2007 + obs.)
- **evidence for warm molecular gas** (e.g. Mauersberger et al. 2003)

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

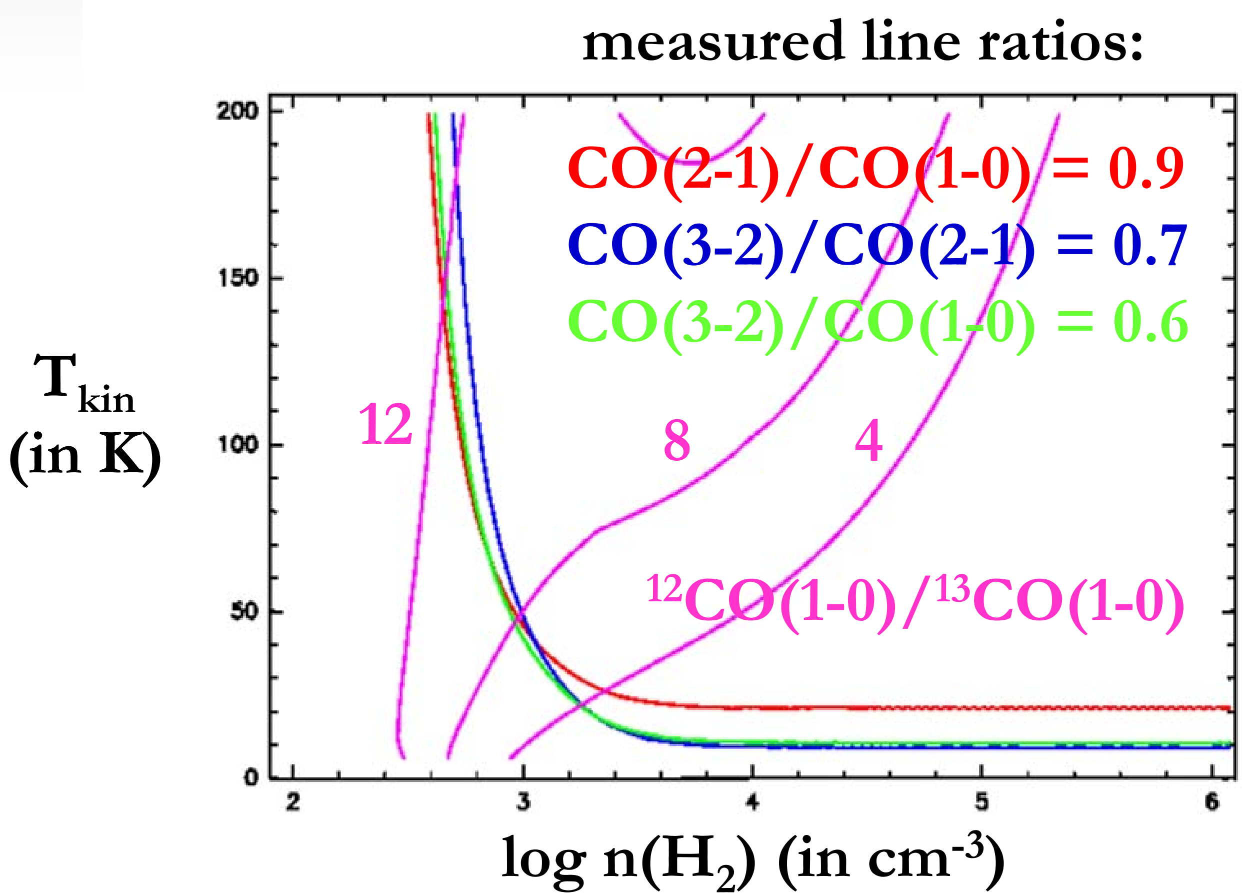
$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

⇨ make a (simple) model, e.g.

large velocity gradient (**LVG**) **model**: T_{kin}, n_{H2}, $abu_{mol}/grad(v)$

Why formaldehyde (H_2CO)?

- many gas tracers suffer from a T-n degeneracy



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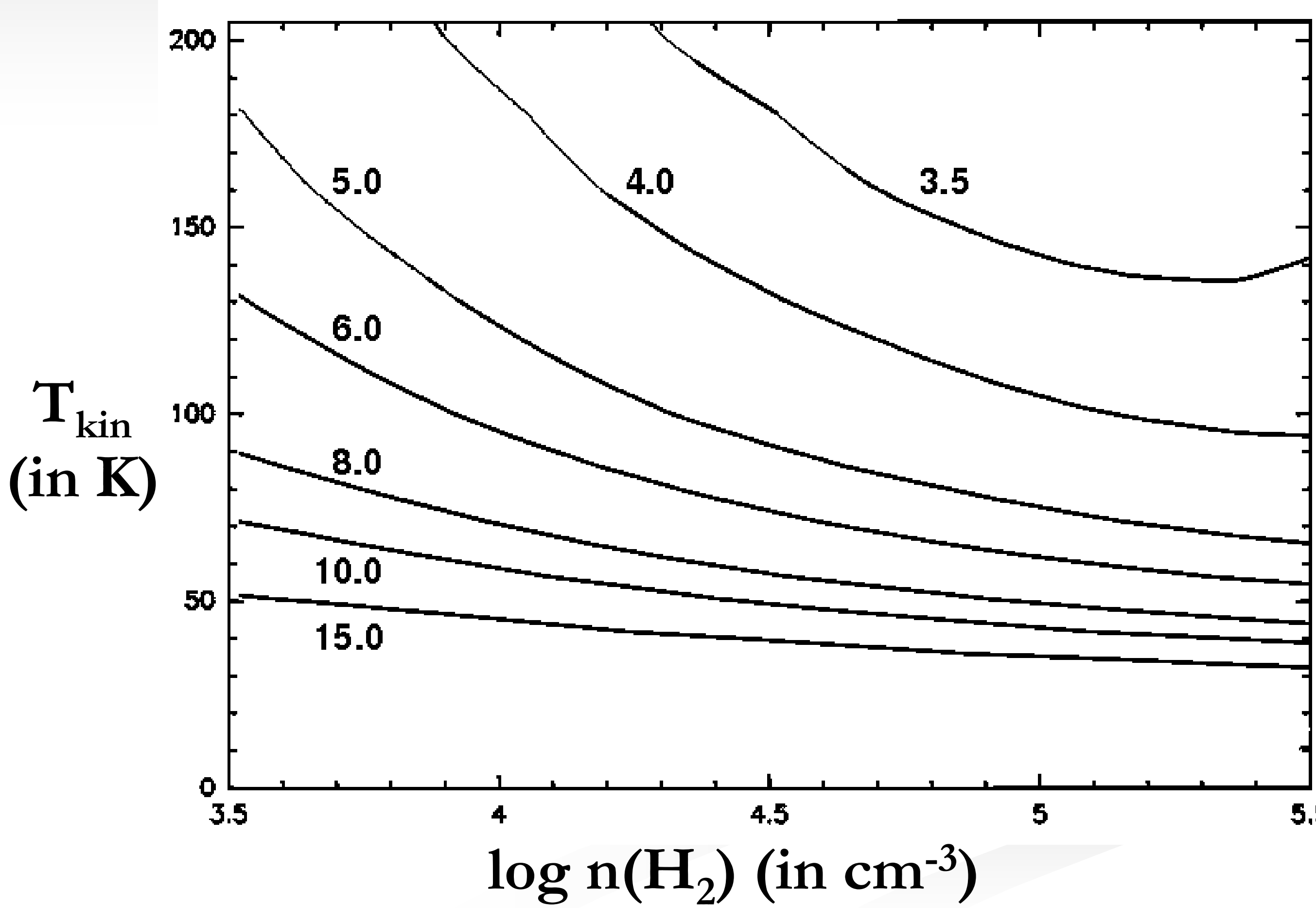

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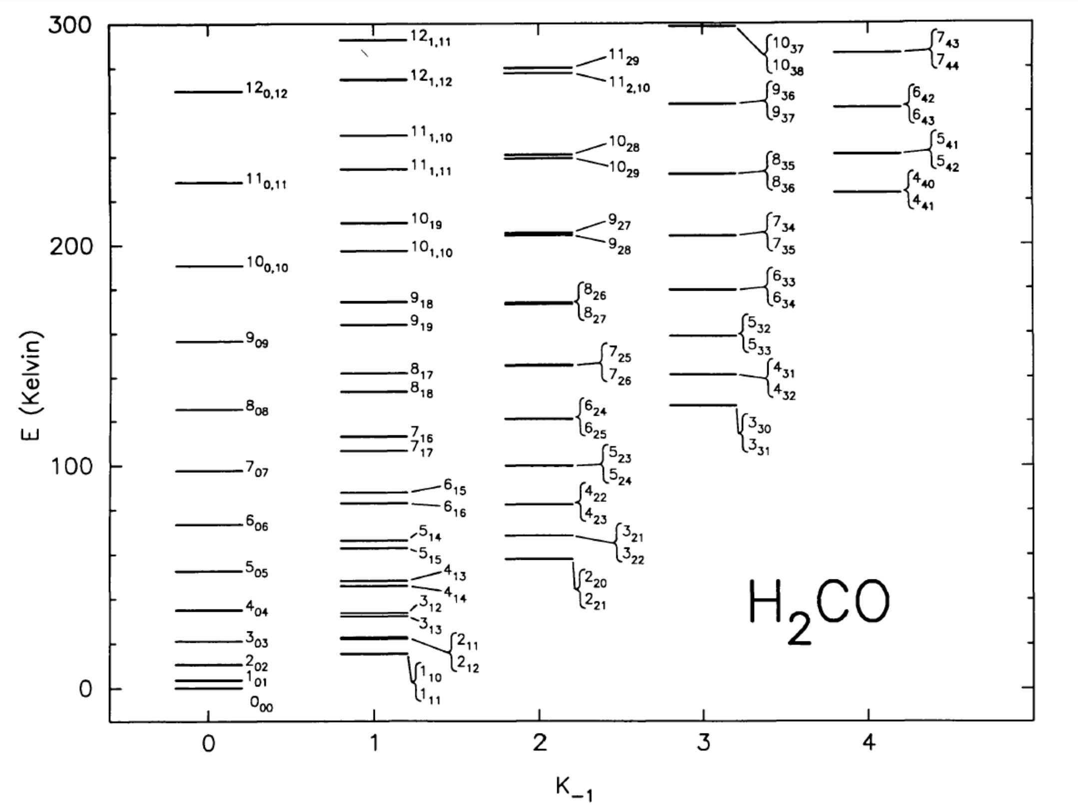
- **H_2CO has a rich spectrum**



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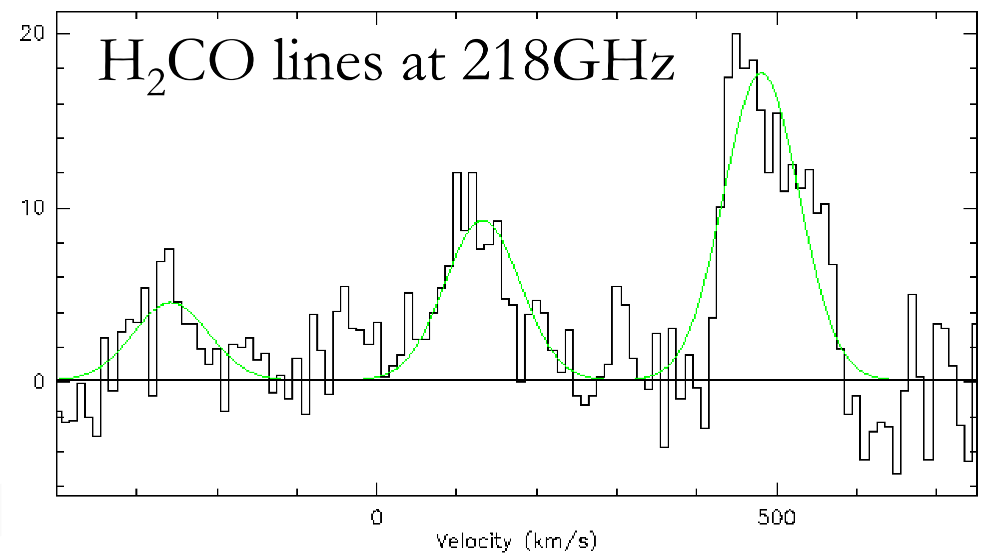
  multiple lines in the same bandpass avoids

  - calibration issues
  - different beam widths
  - pointing uncertainties

- **limited line blending**



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  - calibration issues
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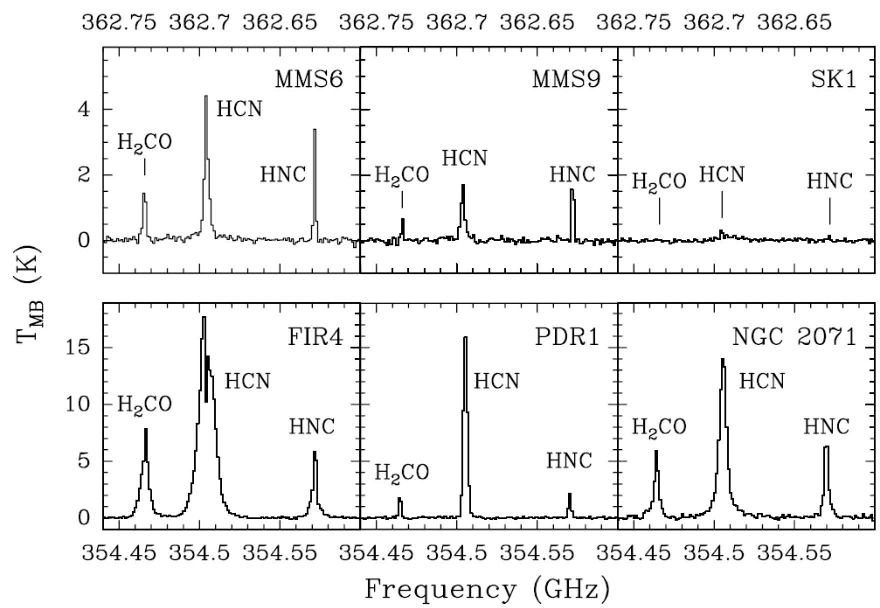
- **limited line blending**
- **constant abundance in a variety of environments**

  $[H_2CO]/[H_2] \sim 10^{-10}$ in MW

  (e.g. Johnstone et al. 2003)



Why formaldehyde (H_2CO)?

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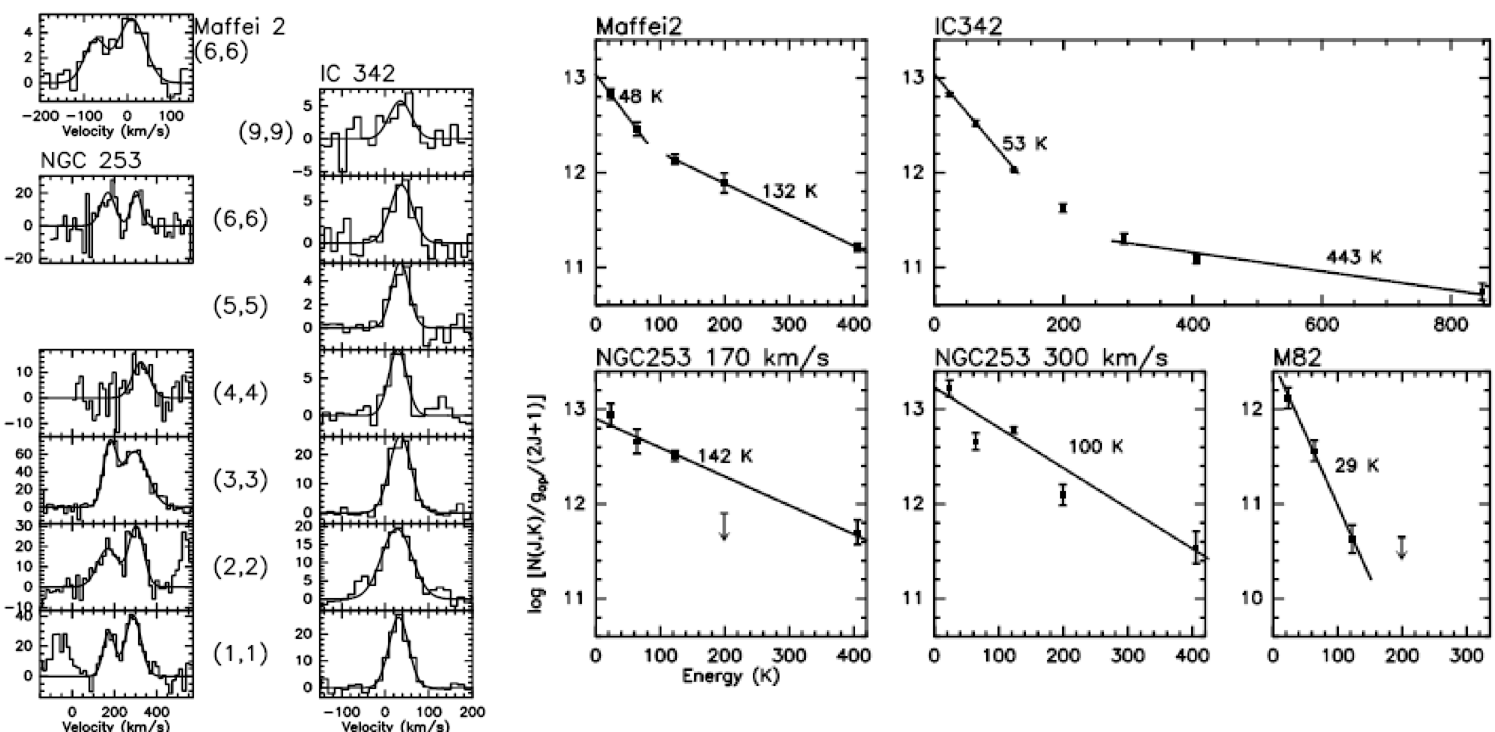
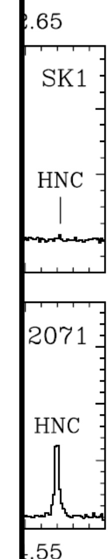
The Galactic thermometer: NH_3

$[NH_3]/[H_2] \sim 10^{-5} \ldots 10^{-8}$ in MW

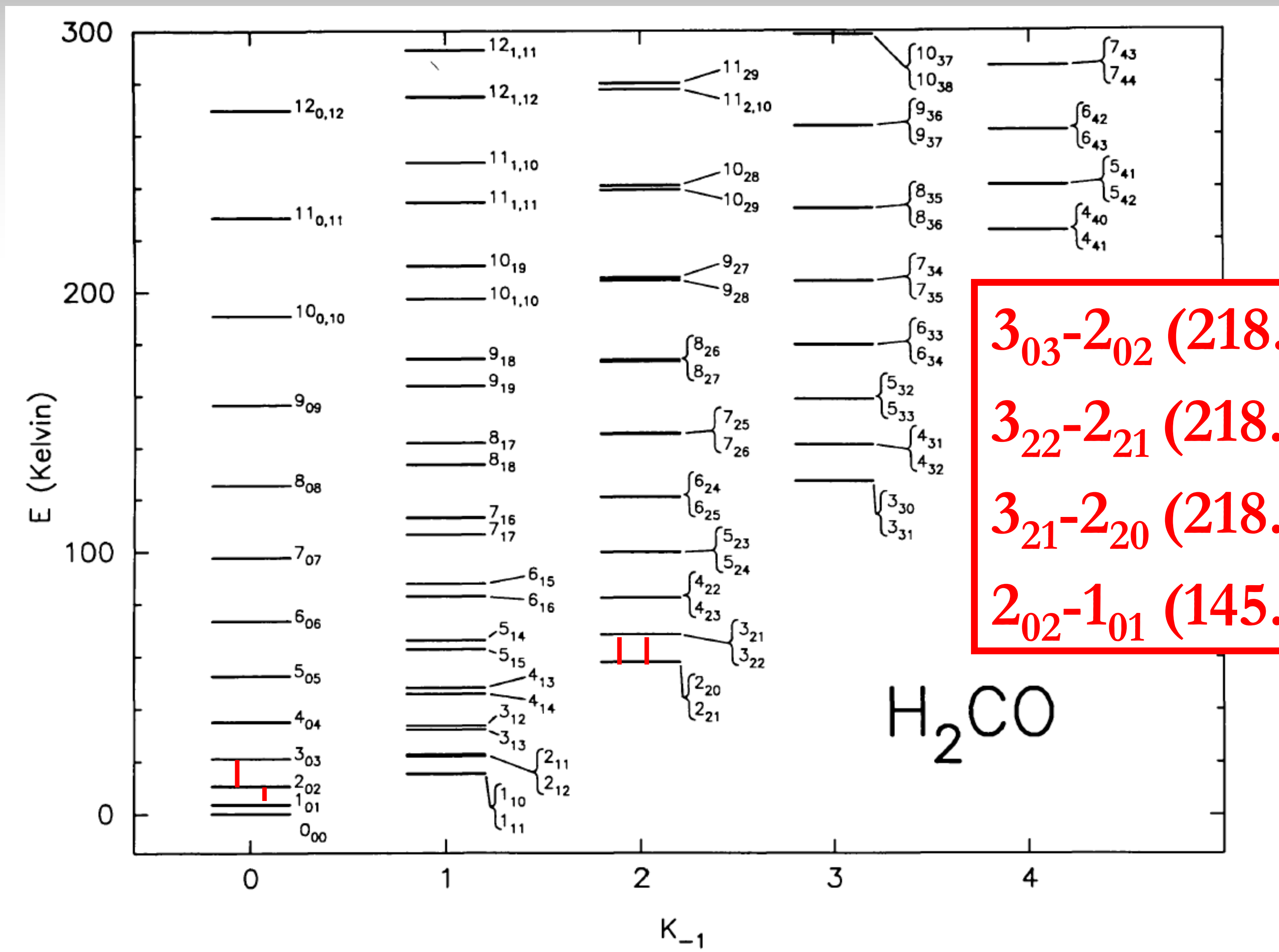


(Mauersberger et al. 2003)

M82: $T_{rot} \sim 29$ K?



Selected H_2CO transitions



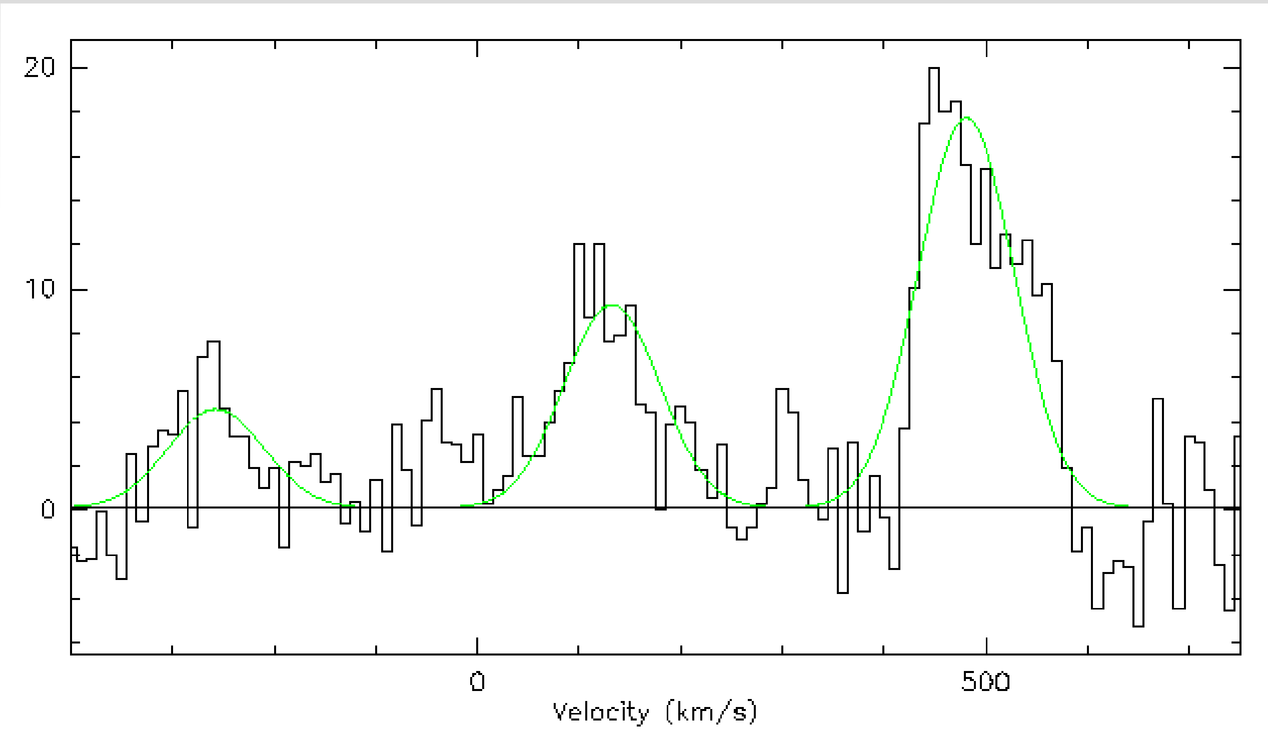
3_{03}-2_{02} (218.2 GHz)

3_{22}-2_{21} (218.5 GHz)

3_{21}-2_{20} (218.8 GHz)

2_{02}-1_{01} (145.6 GHz)

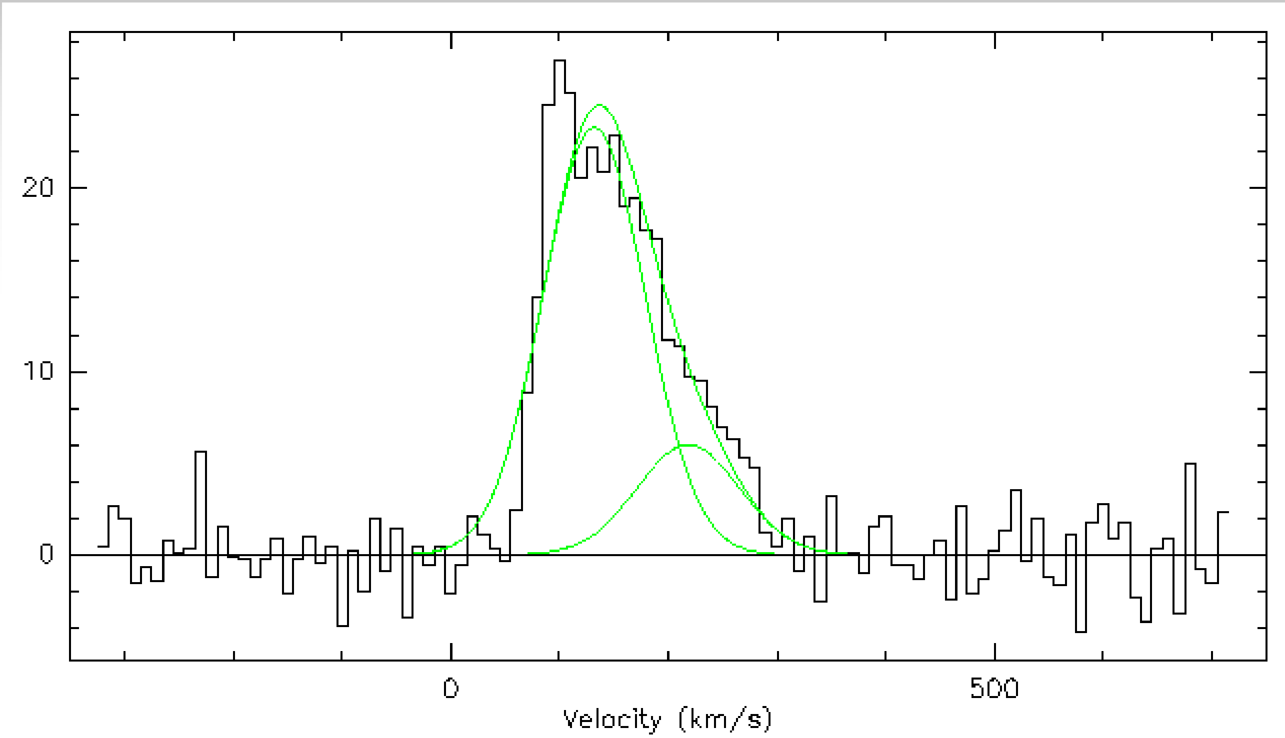
H_2CO at 218 GHz: dependent lines



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

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

H_2CO at 146 GHz: blended lines

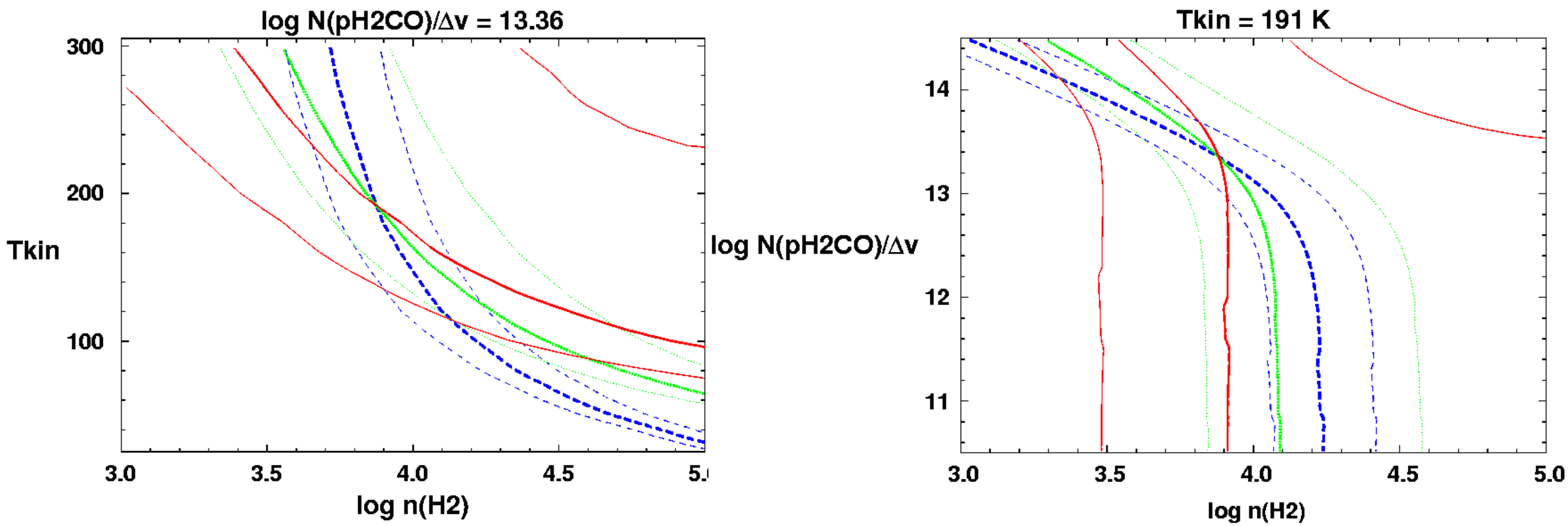


$H_2CO(2_{02}\text{-}1_{01})$
$HC_3N(16\text{-}15)$

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

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

From data to properties: LVG analysis



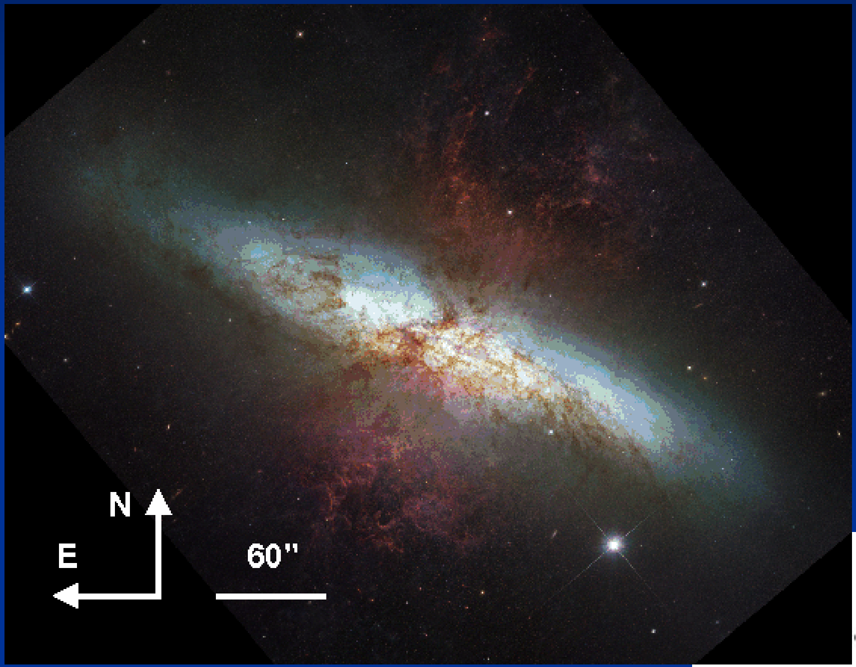
$H_2CO(3_{03}\text{-}2_{02})/H_2CO(3_{21}\text{-}2_{20})$

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

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

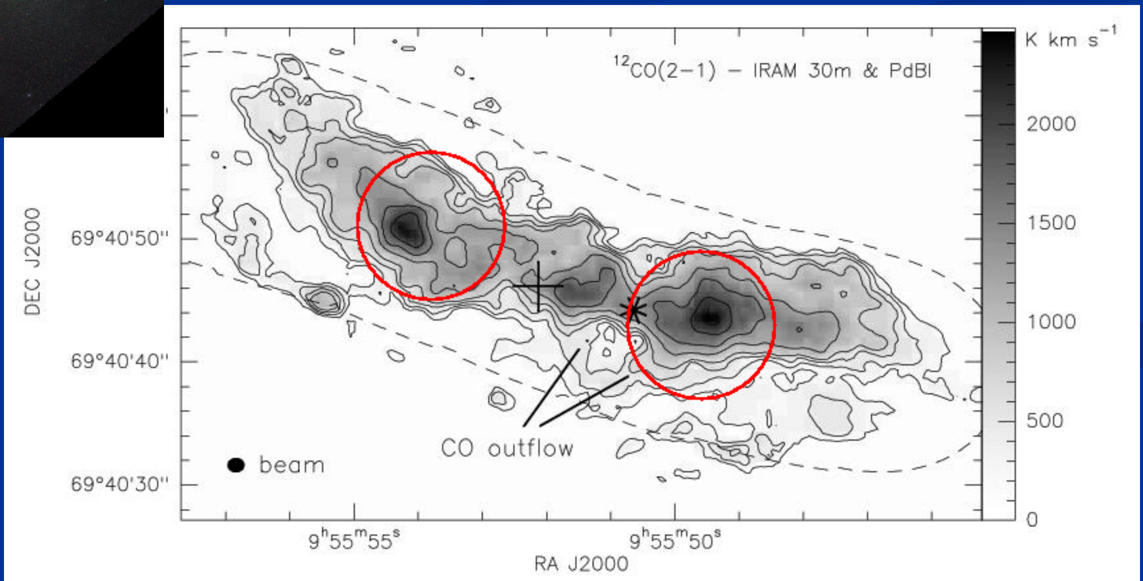
⇨ T_{kin}, n_{H2}, $N_{H2CO}/\Delta v$ or X_{H2CO}/gradv, M_{mol} …

First results: M82



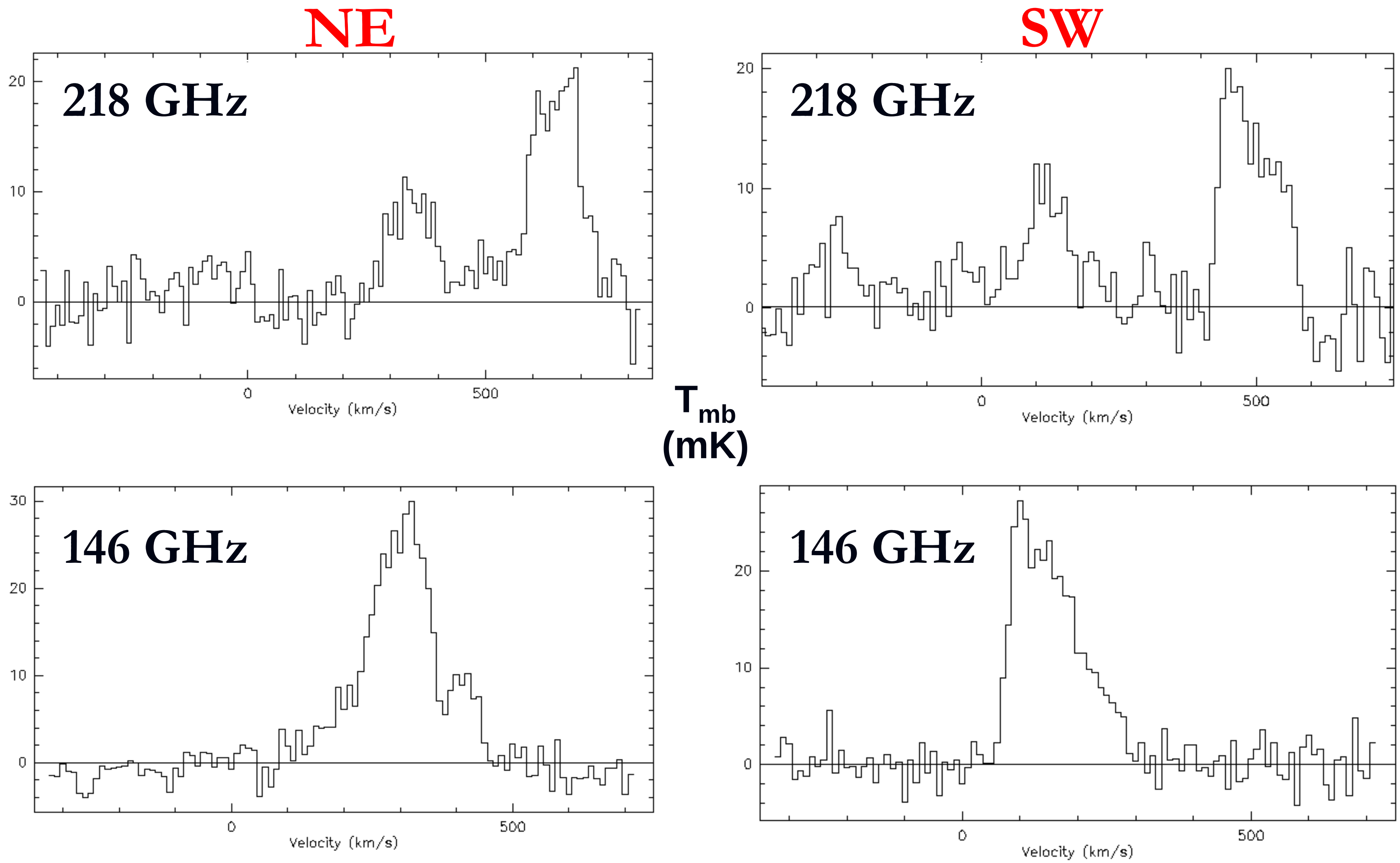
(NASA, ESA, The Hubble Heritage Team)

- prototype of a starburst galaxy
- high IR luminosity
- galactic wind
- dense molecular gas concentrated towards the centre
- an "evolved" starburst?



(Weiss et al. 2001)

First results: M82



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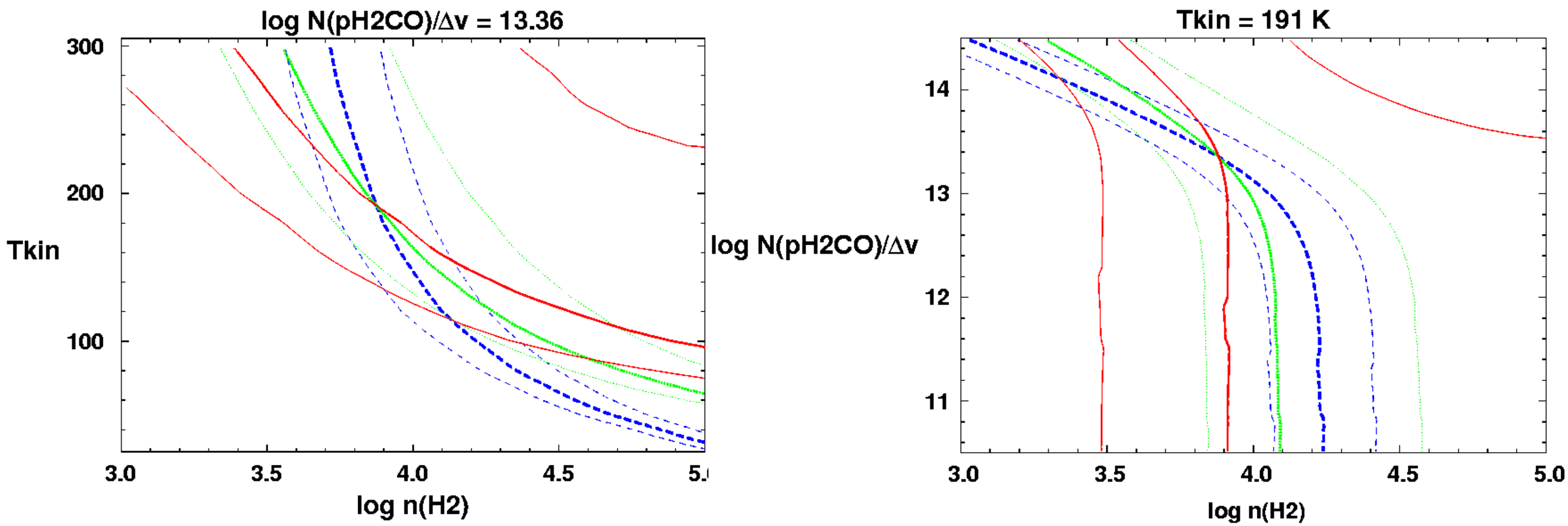


$H_2CO(3_{03}$-$2_{02})/H_2CO(3_{21}$-$2_{20})$ $H_2CO(2_{02}$-$1_{01})/H_2CO(3_{03}$-$2_{02})$ $H_2CO(2_{02}$-$1_{01})/H_2CO(3_{21}$-$2_{20})$

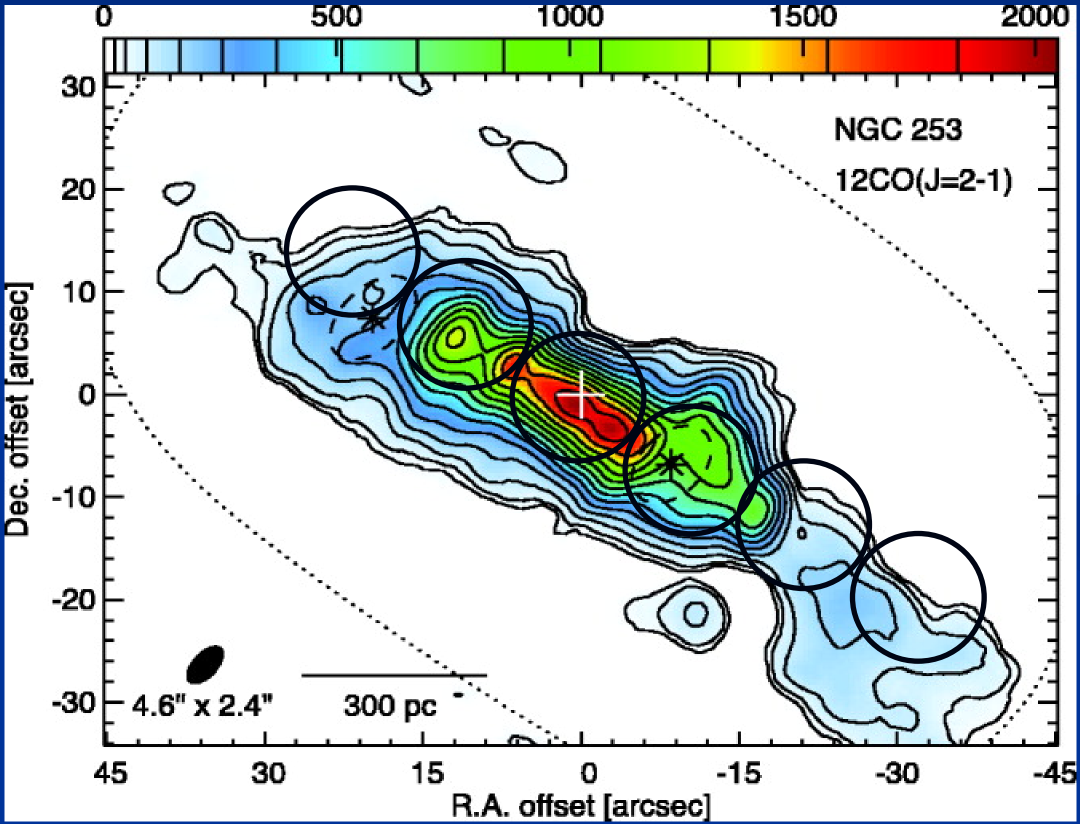
T_{kin} ~ 191 K (NE)/ 209 K (SW) n_{H2} ~ 7 x 10^3 cm^{-3}

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

X_{H2CO}/gradv ~ 1 x 10^{-9} km^{-1} s pc

(Muehle et al. 2007)

First results: NGC 253



(Sakamoto et al. 2006)

- nearby starburst galaxy
- high IR luminosity
- galactic wind
- molecular gas in circum-nuclear disk
- chemical abundances differ from those of M82 ⇨ a younger "twin" of M82?

First results: NGC 253

To be published soon …

A kinetic temperature of ~150 K?

- Multi-transition NH_3 and CS (Mauersberger et al. 2003):
  T_{rot} ~ 50 K + > 150 K in other starburst galaxies (except M82)
- IR quadrupole H_2 transitions (Rigopoulou et al. 2002):
  T_{kin} ~ 150 K in starburst and Seyfert galaxies
- Multi-transition CO, HCN, HCO^+ in SB (Greve et al. 2009):
  T_{kin} ~ 60…120 K n_{H2} ~ $10^{4...6}$ cm^{-3} (warm component)
- Multi-transition CO in M82 (Mao et al. 2000):
  T_{kin} ~ 60…130 K n_{H2} ~ $10^{3.3…3.9}$ cm^{-3} (high-excitation lines)
- Multi-transition CO in M82 (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)
- High-resolution NH_3 in NGC 253 (Ott et al. 2005):
  T_{kin} ~ 150…260 K

Conclusions

- selected H_2CO lines powerful diagnostics for starburst galaxies: T_{kin}, n_{H2}, $N_{H2CO}/\Delta v$
- detection of para-H_2CO lines up to $K_a=2$ (M82, NGC 253)

First results:

- circumnuclear ring in M82:
  $T_{kin} \sim 200$ K, $n_{H2} \sim 7 \times 10^3$ cm^{-3}, $M_{mol} \sim 3 \times 10^8$ M_{sun}
- circumnuclear disk of NGC 253 (prelim. results):
  $T_{kin} \sim 150$ K, $n_{H2} \sim 10^4$ cm^{-3}

Open questions

- Which classes of active galaxies exhibit a warm gas phase?
- How extended is the warm phase?
- Relation warm gas/cold gas?
- Correlation with star formation rate, gas content, age of starburst, AGN activity, …

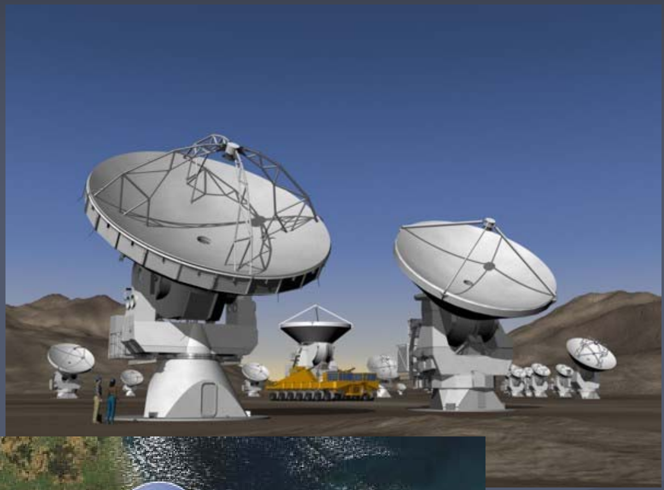
Outlook

ALMA:

- p-H_2CO lines readily detectable
- maps give source sizes, distribution, etc.

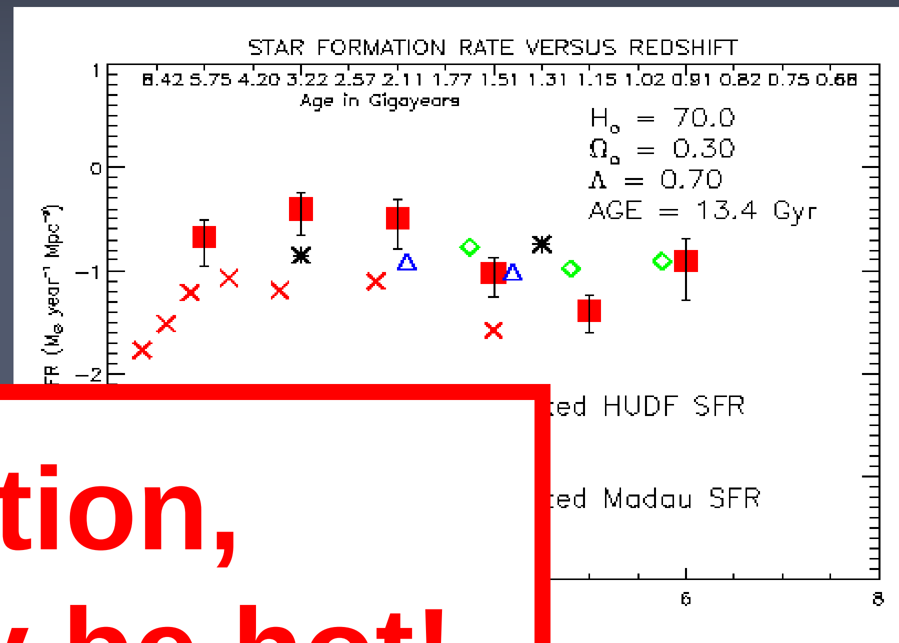
e-MERLIN:

- maps of o-H_2CO line at 6 cm ⇨ o/p ratio, formation temp.
- ammonia lines at 24 GHz



Starbursts:
just scaled-up star formation?

M82 (NASA, E



6)

Caution,
gas may be hot!

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