Z-machine science other than CO

Karl M. Menten

(Max-Planck-Institut für Radioastronomie)

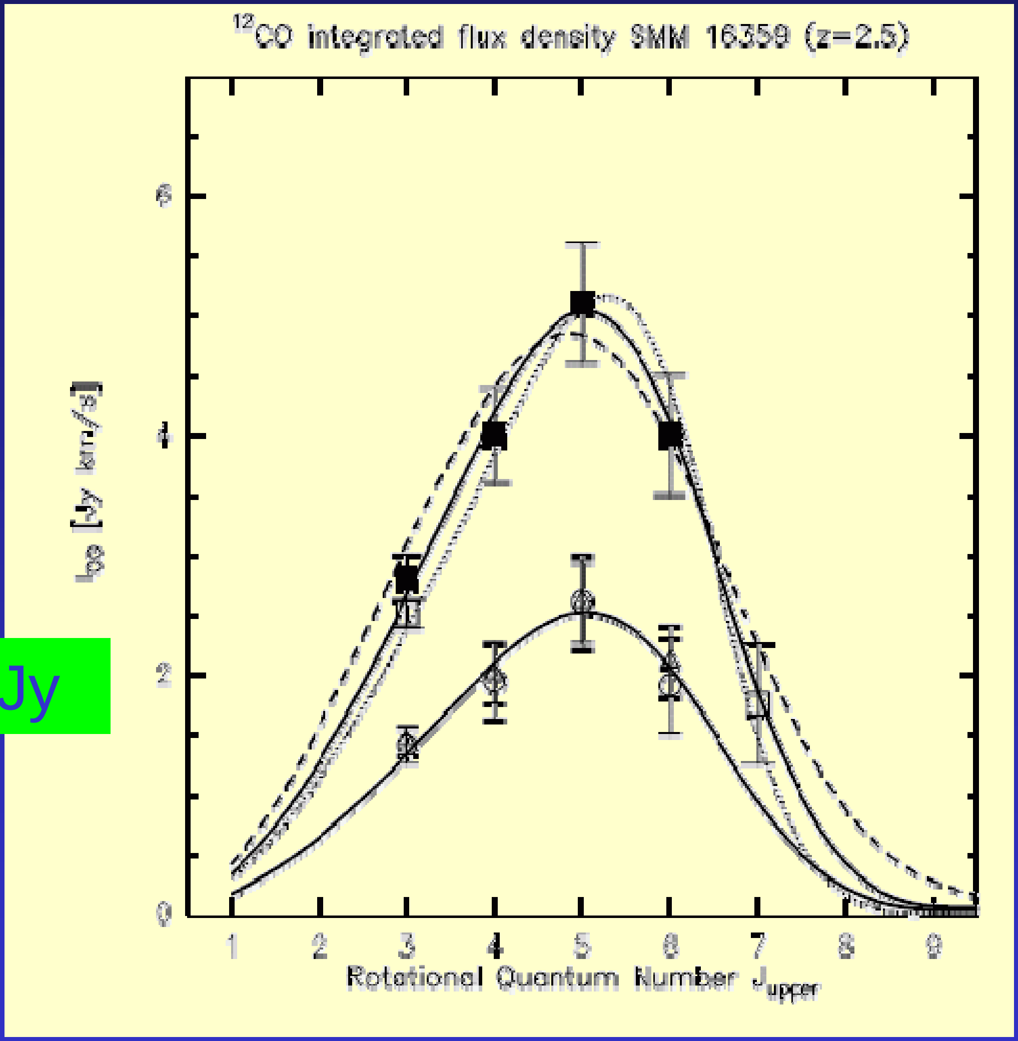
Existing and planned very wideband spectrometers

- Z-Spec/CSO: 185 – 293 GHz R = 800 km/s
- ZEUS/CSO: submm bands R = 300 km/s
- Ultra wide band RX and Spectrometer/LMT
  - 74 – 110 GHz / 100 km/s
- Zpectrometer/GBT
  - 28.5 – 34.5 GHz / 150 km/s

Zpectrometer (Ka-band) targets low-J CO lines (J = 1-0) and (J = 2-1).

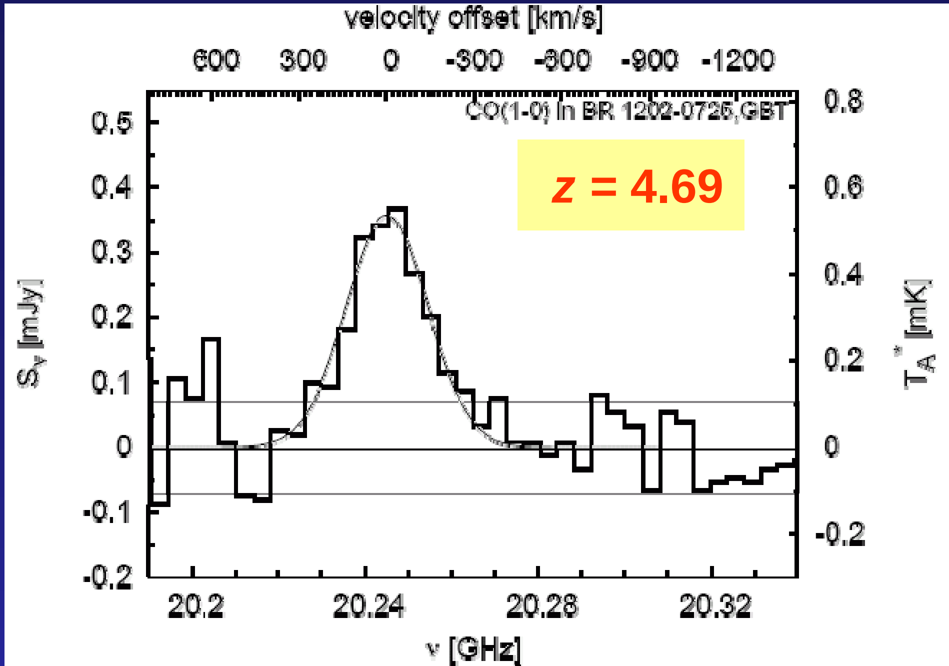
These are *very* weak

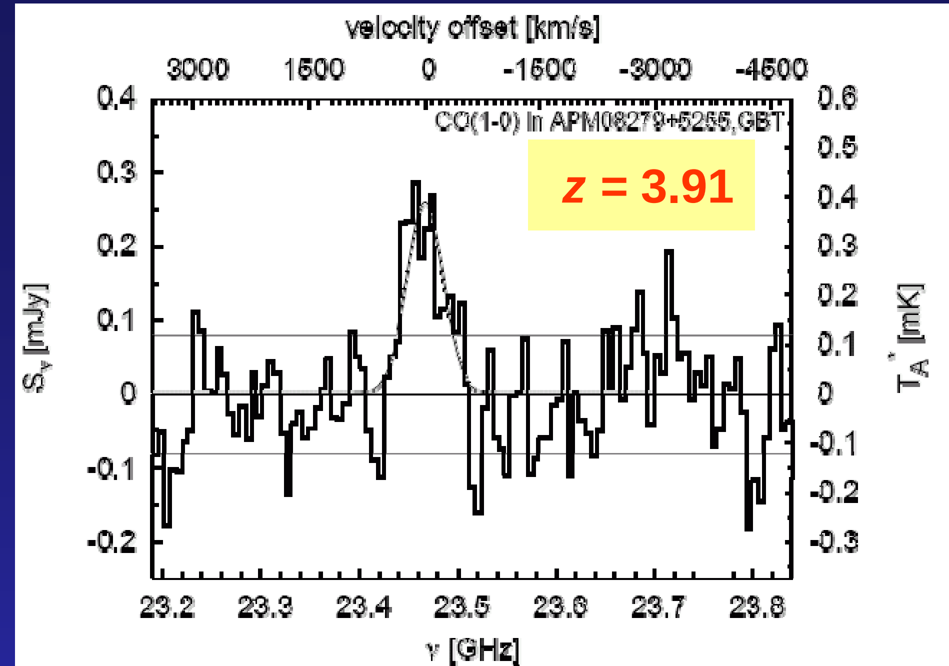
= sub mJy

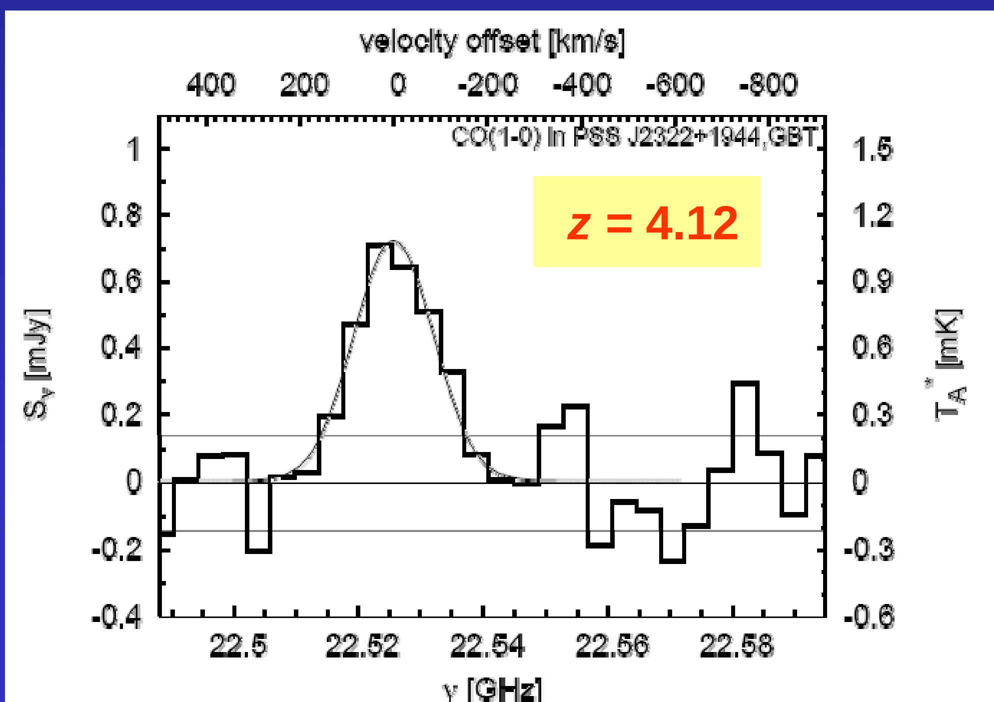


Weiss et al. 2005

→Talk this morning







GBT data CO J = 1-0
Riechers et al. 2006

No extra component of cool CO!

Any high-*z* lines from species other than CO are much weaker than CO lines

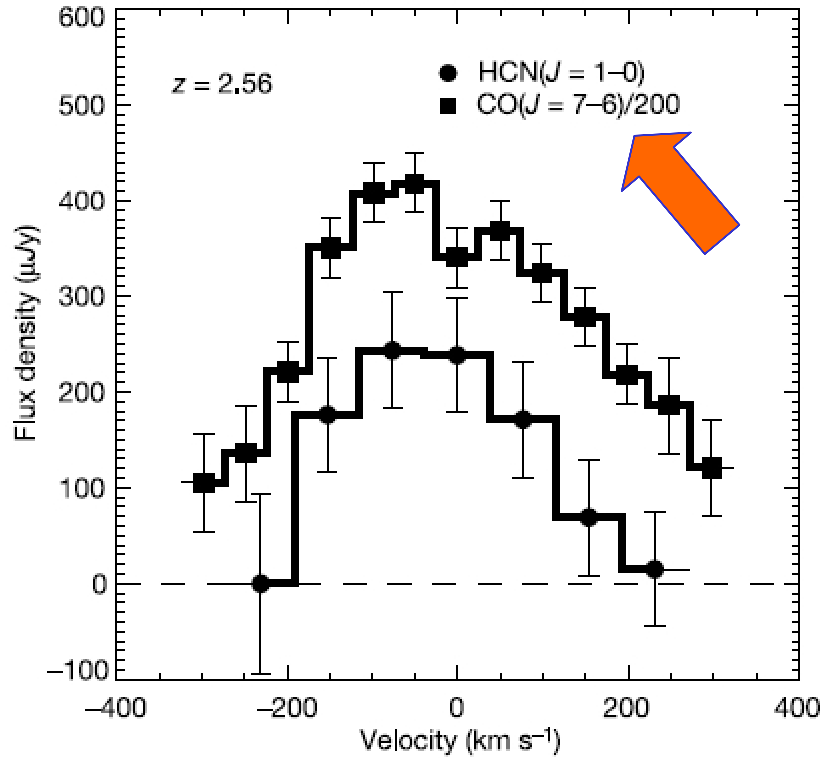


Figure 2 Spectrum of HCN($J = 1$–0) emission observed in the Cloverleaf together with the observed[9] spectrum of CO($J = 7$–6), scaled down by a factor of 200. Zero velocity

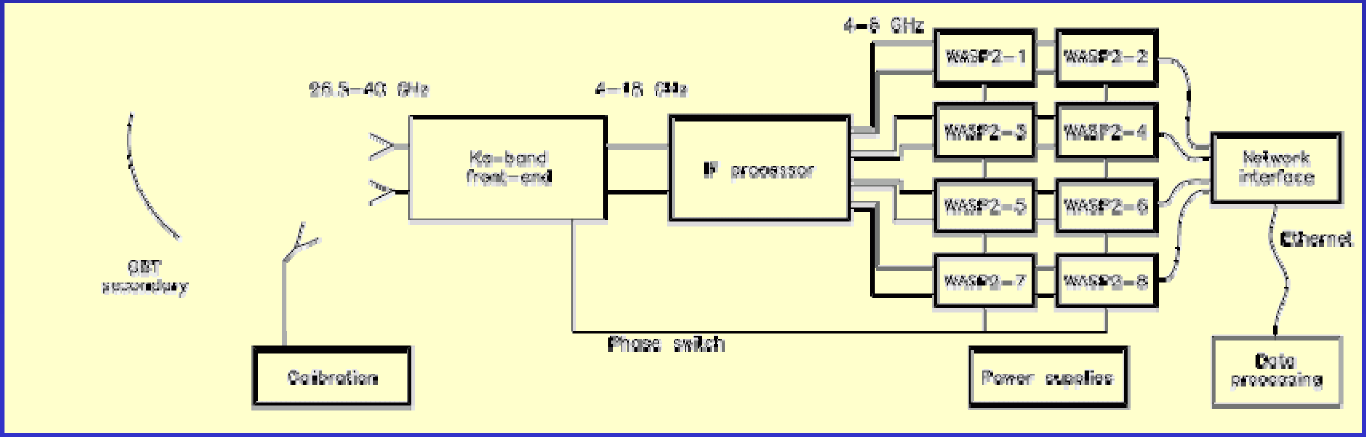
Solomon et al. 2003

Laura Hainline & Andrew Blain (this meeting)

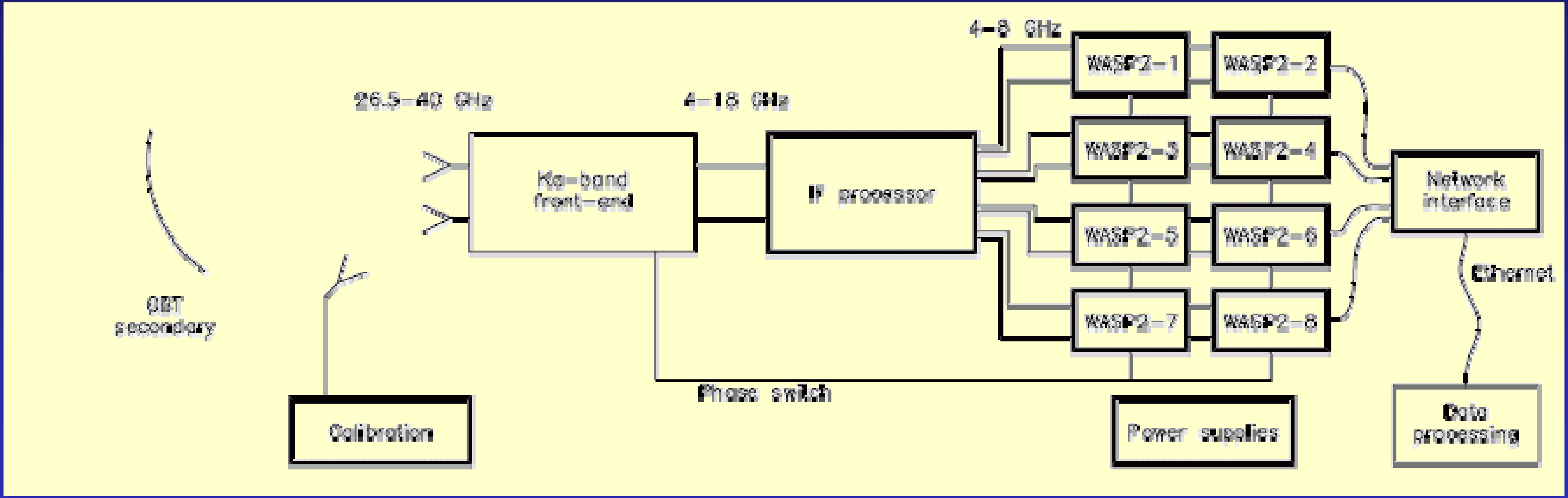
These features (of the GBT), together with the ~100-m filled aperture of the GBT, have promise for minimizing some difficulties of single-dish radio spectroscopy that hamper attempts to observe the emission from low-J molecular rotational transitions from distant galaxies, such as spectral baseline shapes caused by reflections and scattering of light from more traditional feed structures. However, in attempting to use the K- and Ka-band receivers at the GBT we have found that the reality of the telescope's current performance does not yet match these high expectations.

→ Extra effort must go into spectrometer and RX design

And is does → talks by Erickson & Harris



Zpectrometer/GBT (Harris et al.)

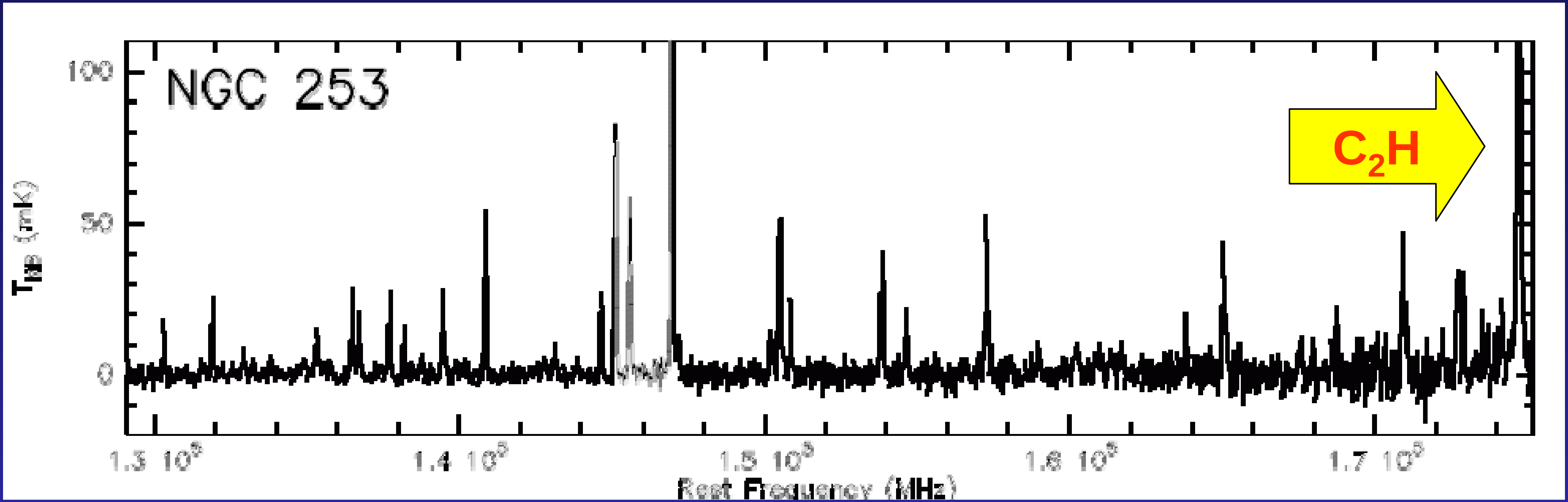


Since high-z CO will be very difficult to do and other molecules even (much) more difficult, what other science can one do with wideband spectrometers?

Extragalactic Molecules (other than CO)

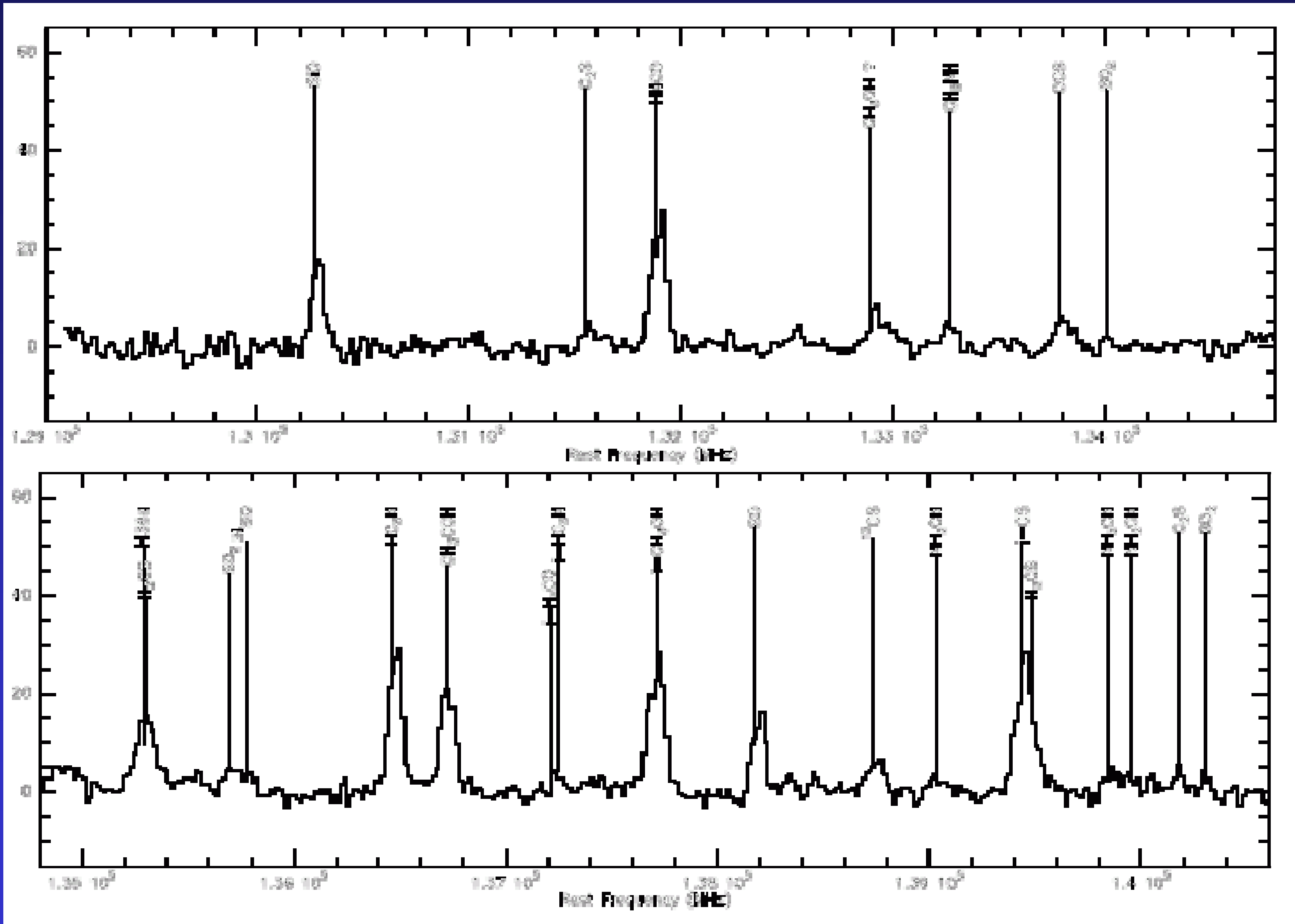
Since the late 1980s Henkel & Mauersberger and their collaborators have detected a large number of molecules toward the nuclei of local galaxies

- Species include:
  CH_3OH, CN, C_2H, HCN, HNC, HCO^+, HC_3N, CS, N_2H^+, SiO, HNCO, CH_3CCH, CH_3CN, SO_2, NS, NO, H_2CO
- Sources include:
  NGC 253, IC 342, NGC 6946, M82, NGC 4945, NGC 6946, Maffei 2
  - mostly starbursts
- For many species rare isotopes are detected
- For many species multi-transition studies afford excitation analyses



- 129 – 175 GHz (46 GHz)
- 25 Species
- 2 SiS RX/1 GHz BW each
- ca. 50 h obs. time total

S. Martin et al. (2005)


60
40
20
0
Rest Frequency (MHz)
Rest Frequency (MHz)

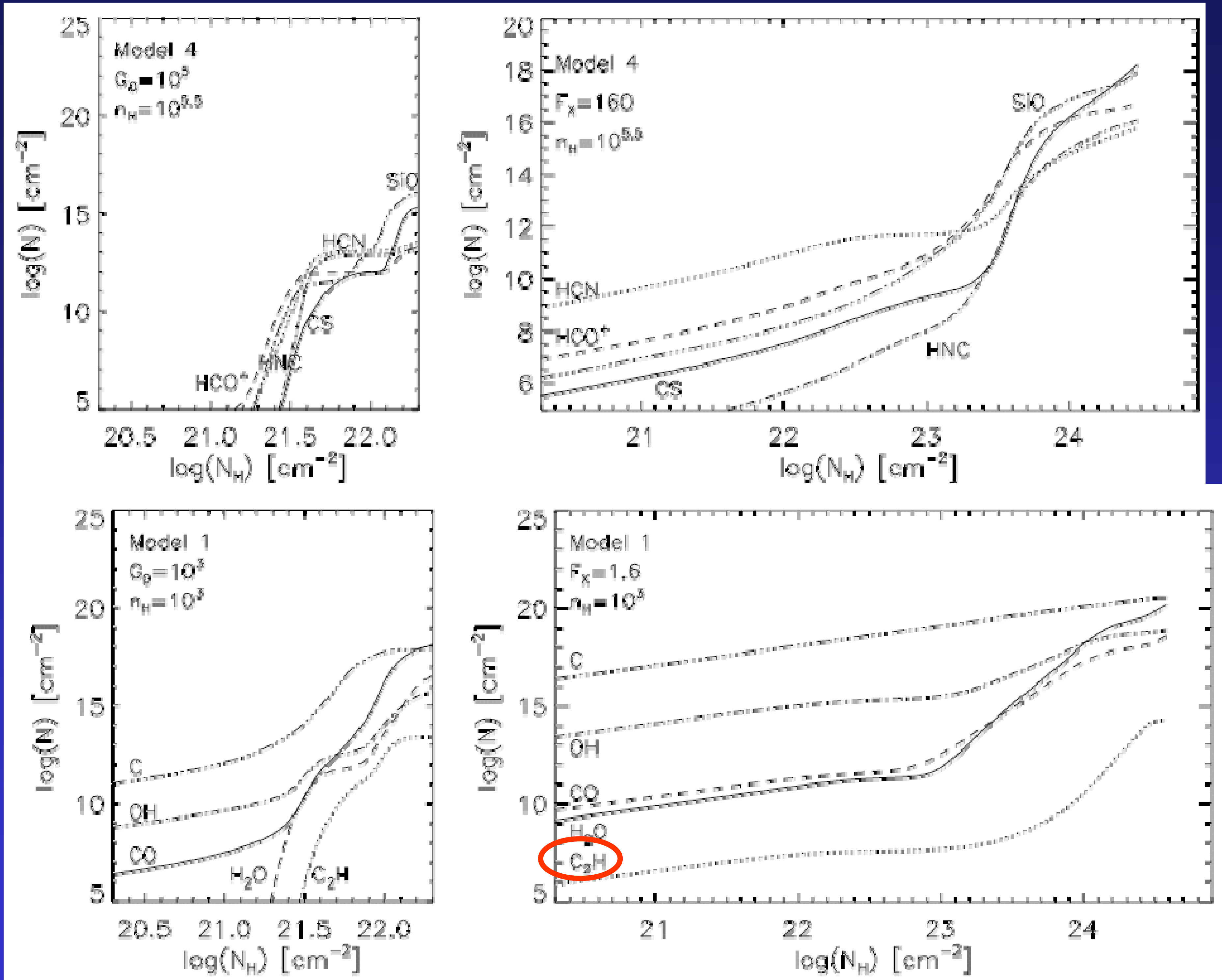
A&A 436, 397–409 (2005)
DOI: 10.1051/0004-6361:20042398

Astronomy & Astrophysics

Diagnostics of irradiated gas in galaxy nuclei

I. A far-ultraviolet and X-ray dominated region code*

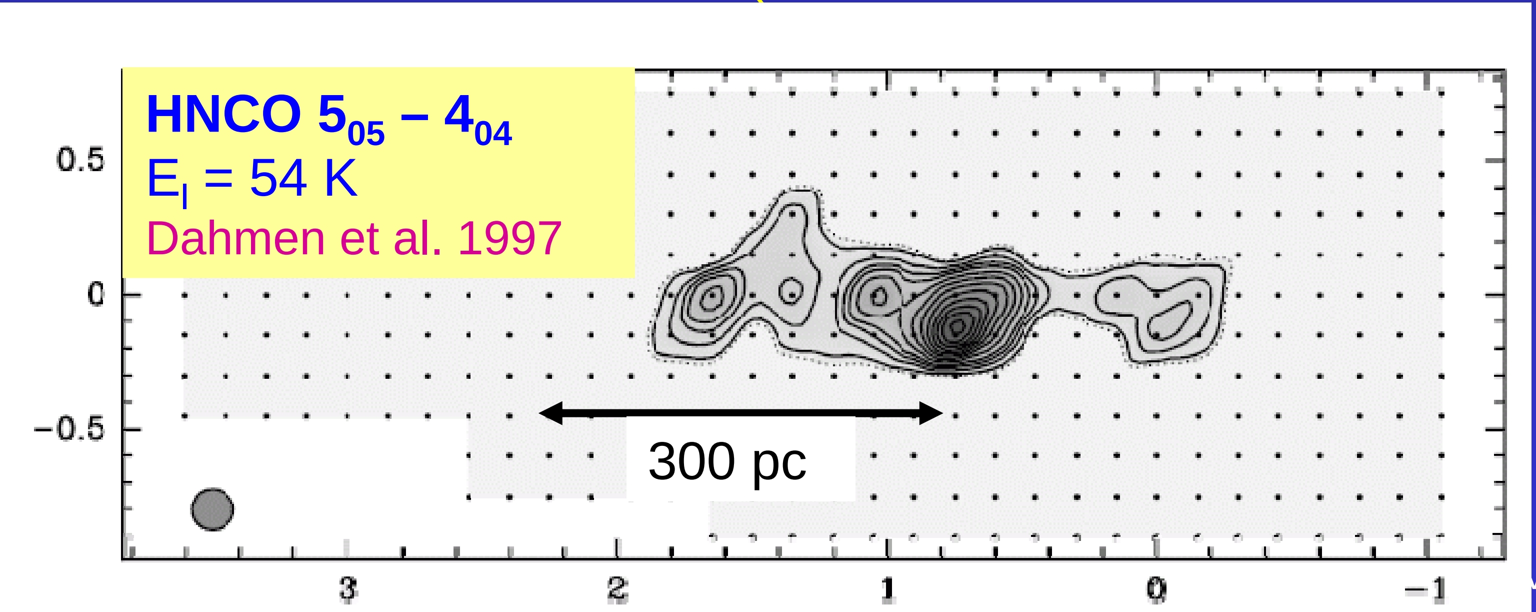
R. Meijerink[1] and M. Spaans[2]

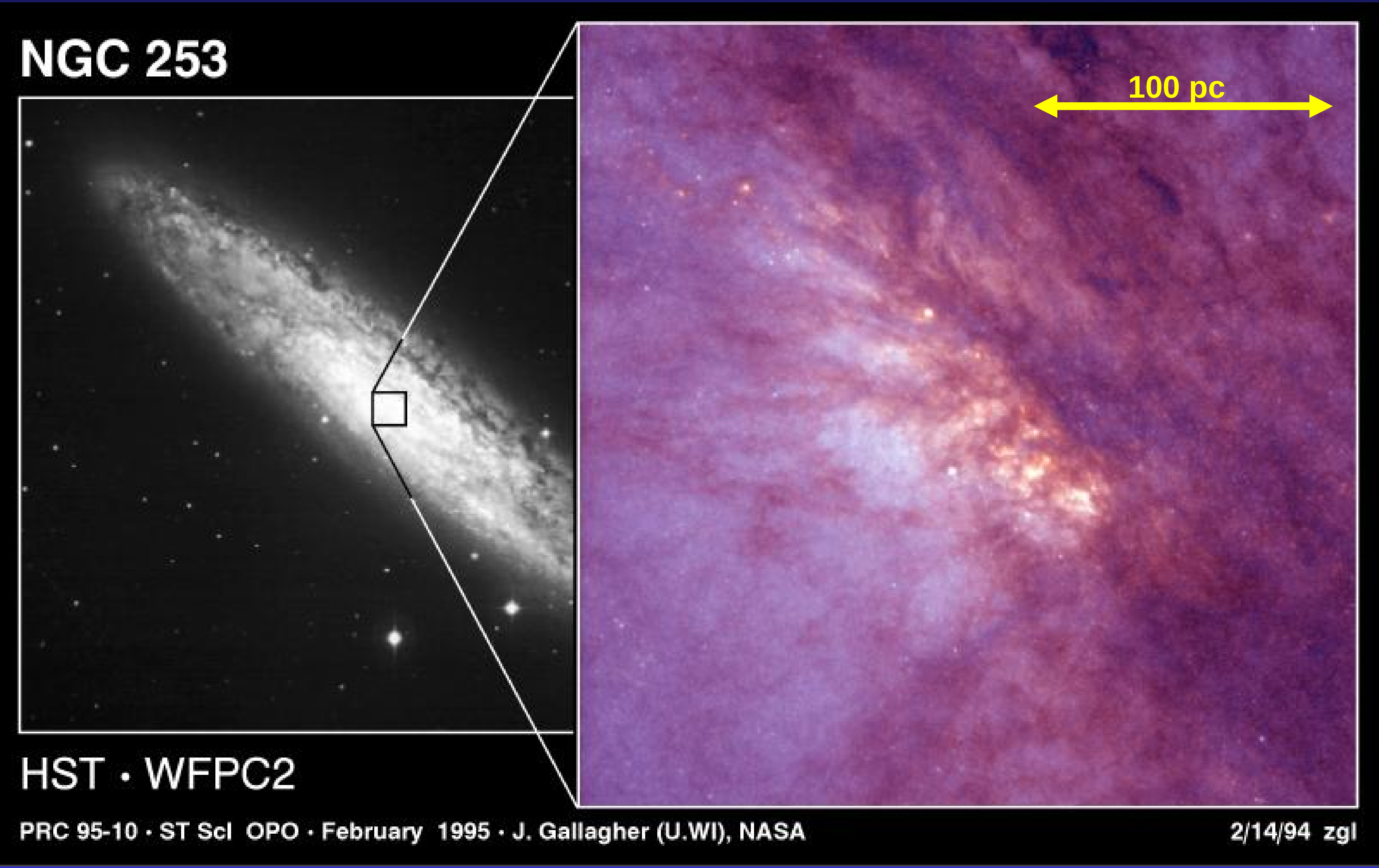

Model 4
$G_0 = 10^5$
$n_H = 10^{5.5}$
SiO
HCN
CS
HNC
HCO^+
log(N) [cm^{-2}]
log(N_H) [cm^{-2}]
Model 4
$F_X = 160$
$n_H = 10^{5.5}$
SiO
HCN
HCO^+
HNC
CS
log(N) [cm^{-2}]
log(N_H) [cm^{-2}]
Model 1
$G_0 = 10^3$
$n_H = 10^3$
C
OH
CO
H_2O
C_2H
log(N) [cm^{-2}]
log(N_H) [cm^{-2}]
Model 1
$F_X = 1.6$
$n_H = 10^3$
C
OH
CO
H_2O
C_2H
log(N) [cm^{-2}]
log(N_H) [cm^{-2}]

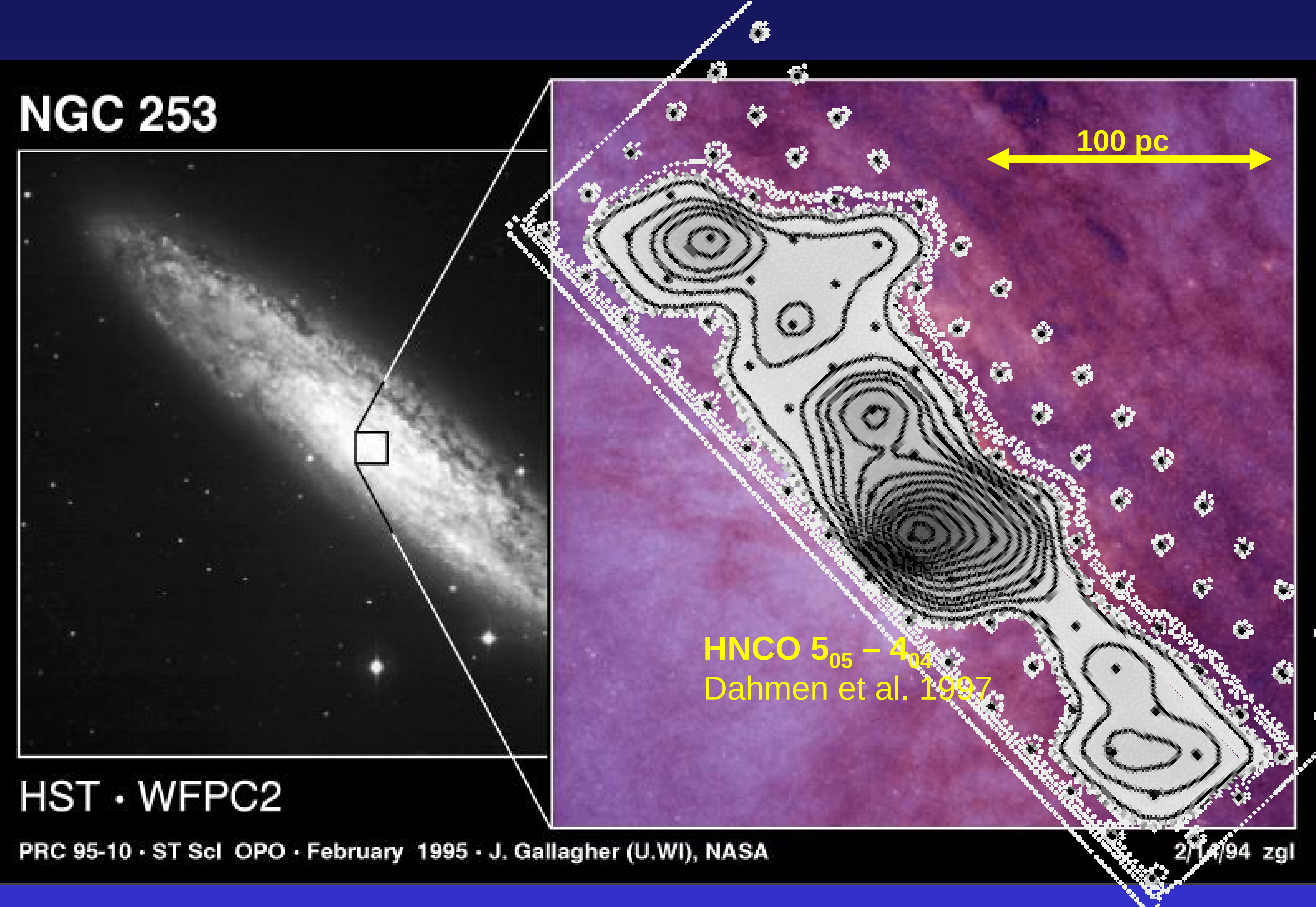
The interstellar medium in the Central Molecular Zone of our Galaxy

The Central Molecular Zone (CMZ)

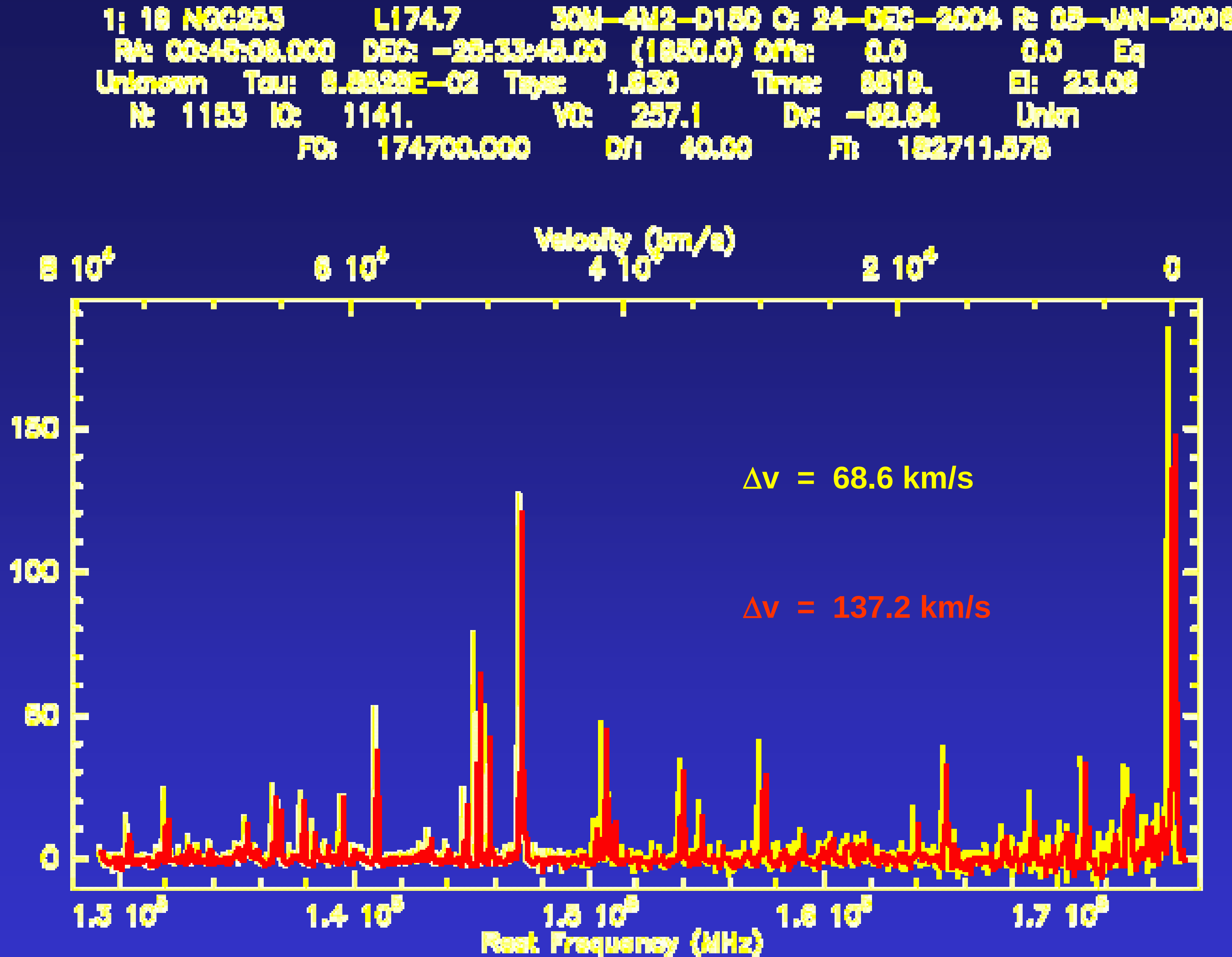
- huge Giant Molecular Cloud (GMC) complex:
  - ~0.3º broad band around the center of our Galaxy from *l* = +1.9º to -1.1º.
- GMCs in CMZ have properties that are quite different from "normal" (i.e. spiral arm) clouds: they are much
  - denser (n ~ 10^4 cm^{-3} vs. 10^2 cm^{-3}),
  - much warmer (60 K < T < 120 K vs. 10 – 20 K),
  - and much more turbulent (Δv ~ 10 – 20 km/s vs. a few km/s).

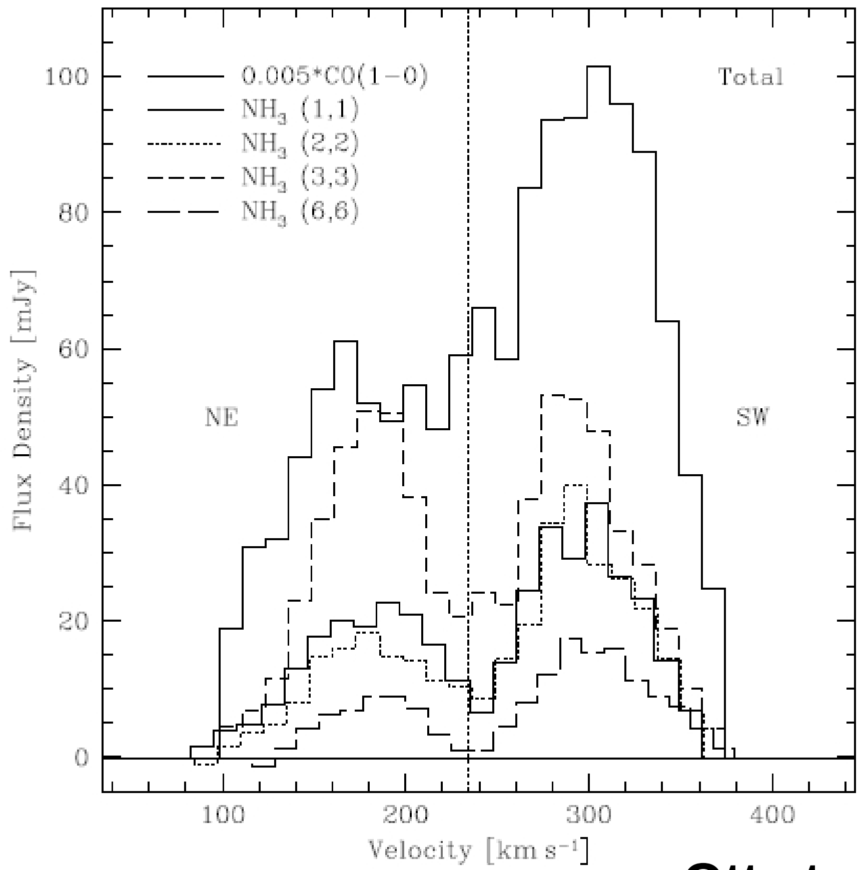



NGC 253
100 pc
HST • WFPC2
PRC 95-10 • ST ScI OPO • February 1995 • J. Gallagher (U.WI), NASA
2/14/94 zgl

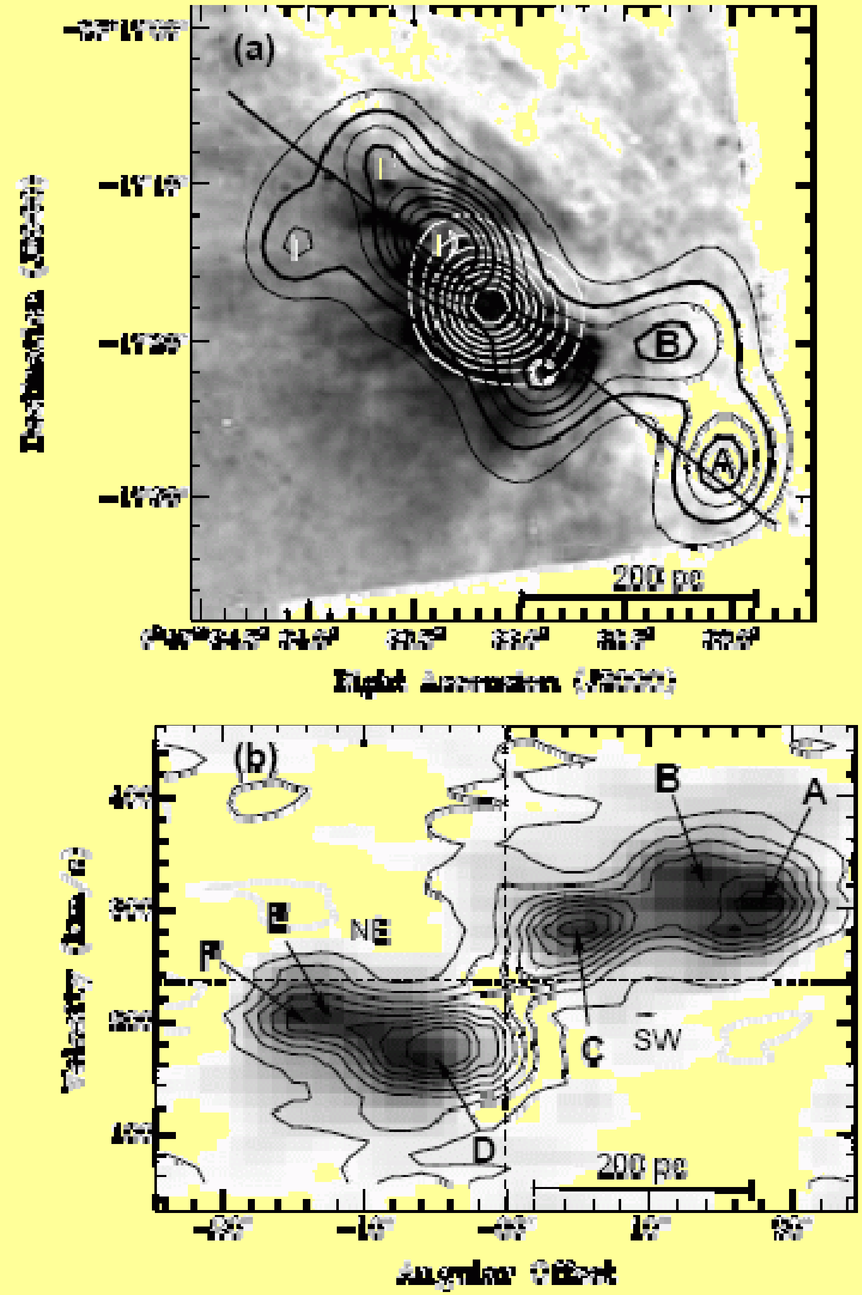


NGC 253
HST • WFPC2
PRC 95-10 • ST ScI OPO • February 1995 • J. Gallagher (U.WI), NASA
2/14/94 zgl
100 pc
HNCO $5_{05} - 4_{04}$
Dahmen et al. 1997


1; 19 NGC253 L174.7 30M-4M2-D150 O: 24-DEC-2004 R: 05-JAN-2006
RA: 00:45:08.000 DEC: -25:33:45.00 (1950.0) Offs: 0.0 0.0 Eq
Unknown Tau: 6.8828E-02 Tsys: 1.930 Time: 6619. El: 23.06
N: 1153 I0: 1141. V0: 257.1 Dv: -68.64 Unkn
F0: 174700.000 Df: 40.00 Fi: 182711.578
Velocity (km/s)
8 10^4
6 10^4
4 10^4
2 10^4
0
150
100
50
0
Δv = 68.6 km/s
Δv = 137.2 km/s
1.3 10^5
1.4 10^5
1.5 10^5
1.6 10^5
1.7 10^5
Rest Frequency (MHz)

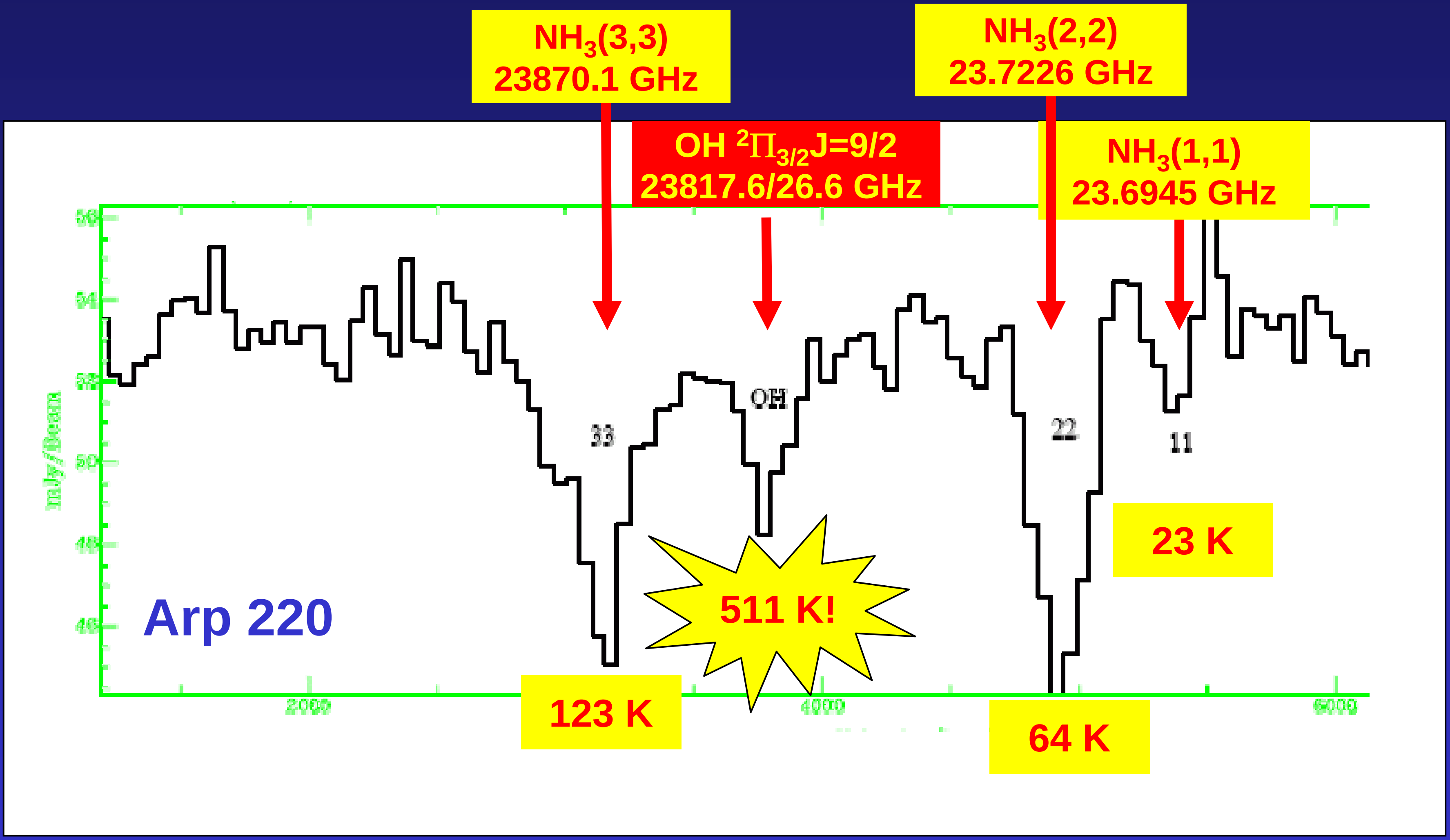


Ott et al. 2005



NH$_3$ in NGC 253
~ 24 GHz

ATCA – Ott, Weiss, Henkel, & Walter (2005)

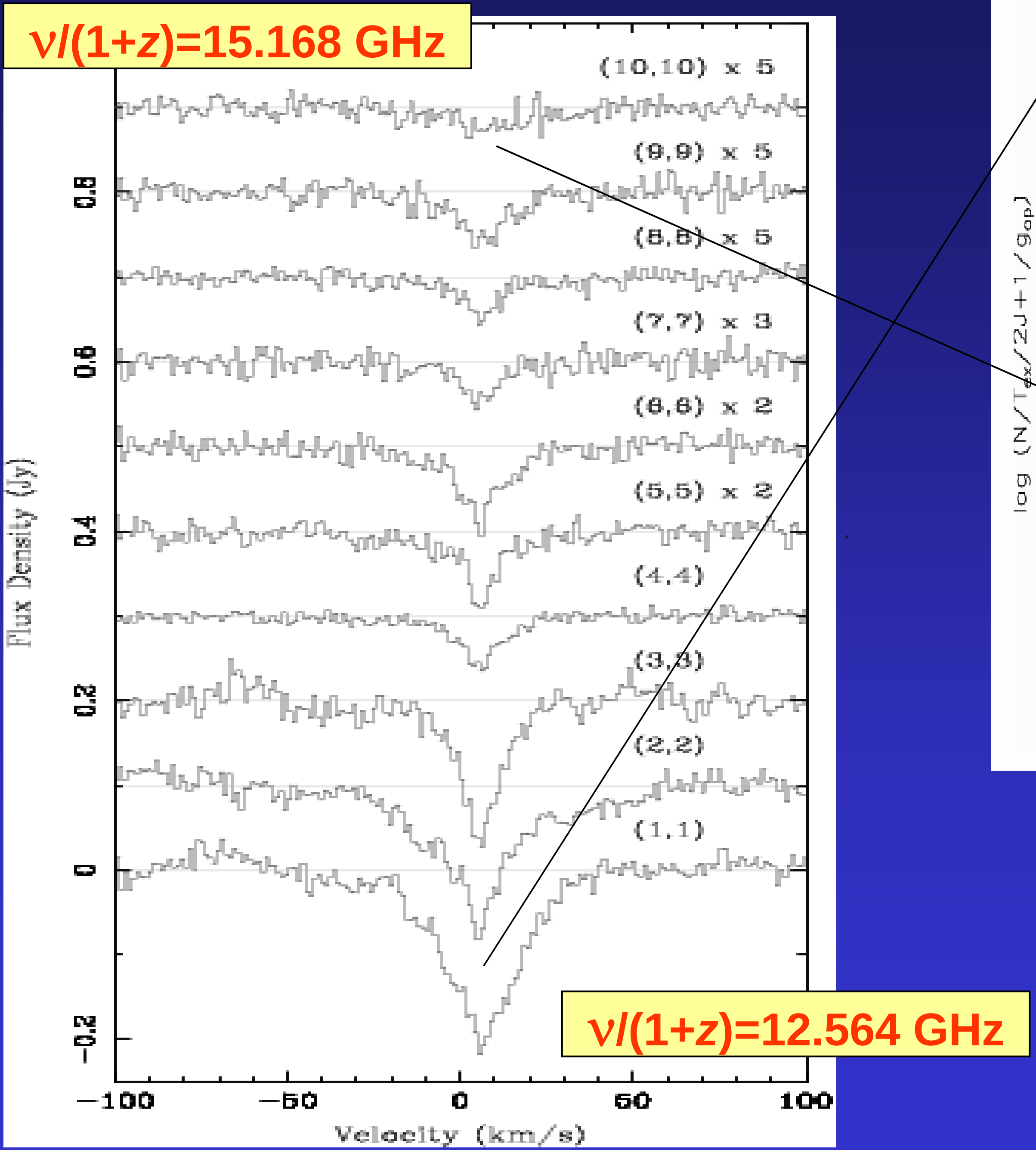


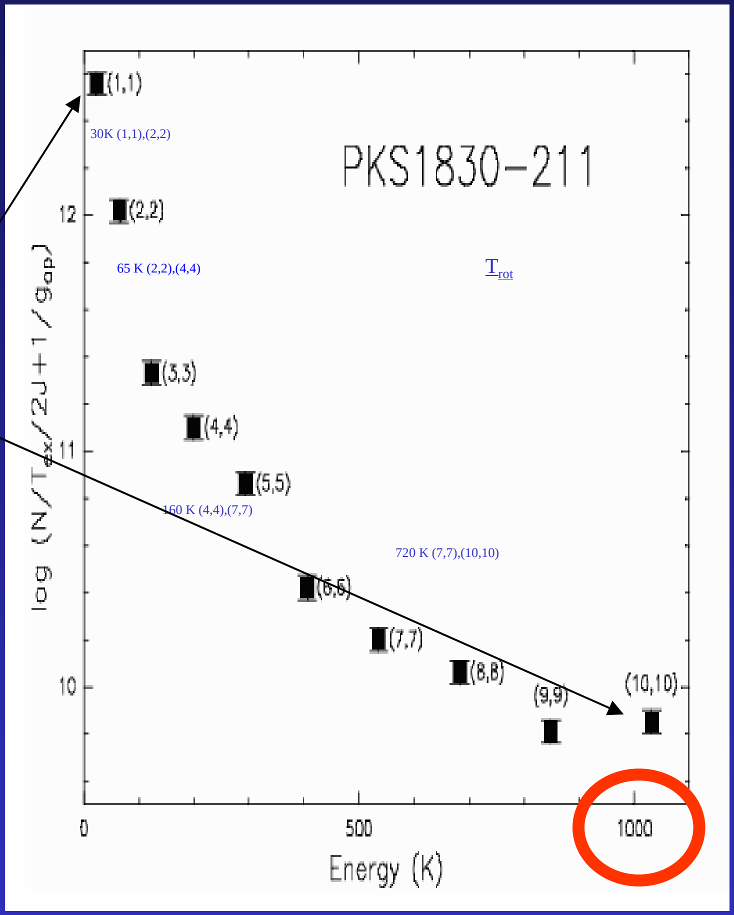
ATCA – Ott, Henkel, Weiss, & Walter (2005)

Projects presented up to now could be done with Zpectrometer

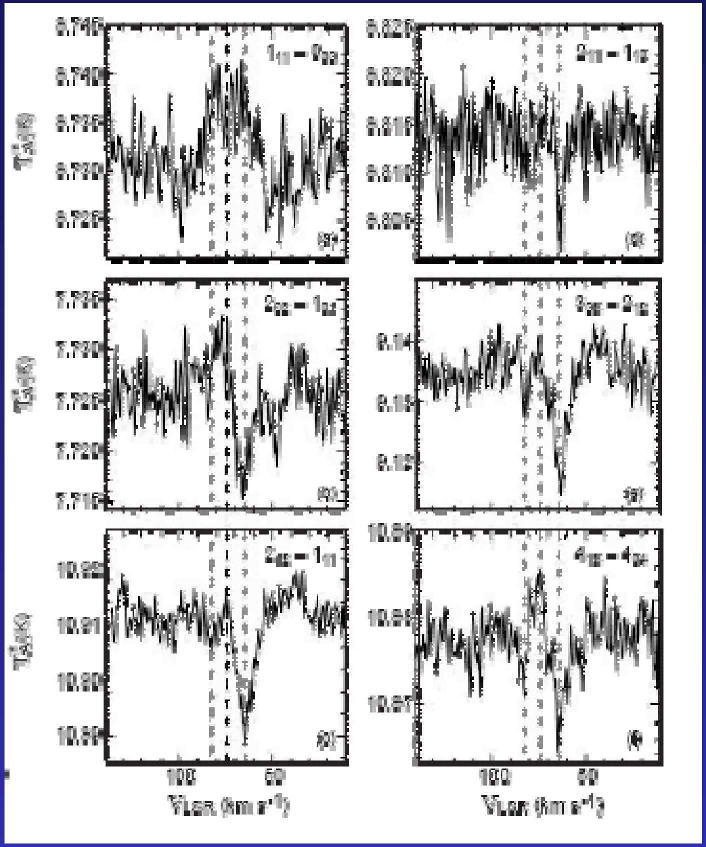
However, there are many interesting projects that require wide frequency coverage and (much) higher frequency resolution

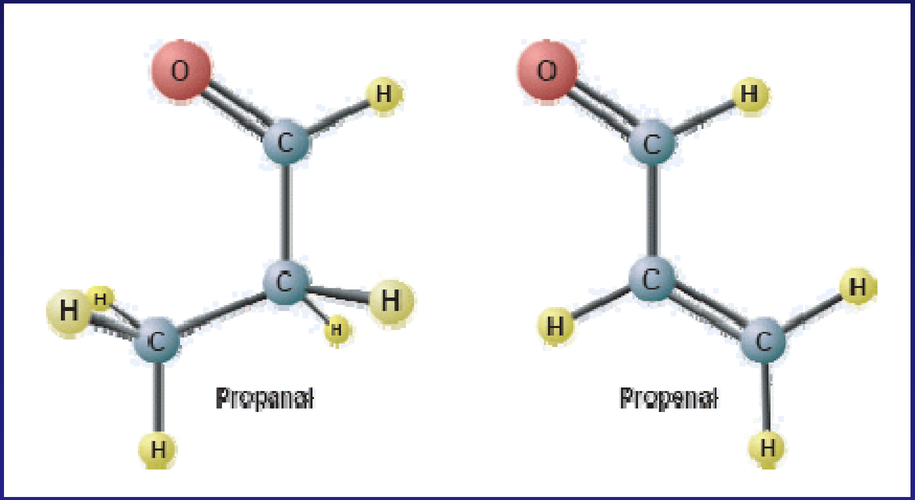
z = 0.89 NH_3 absorption toward Pks 1830-211

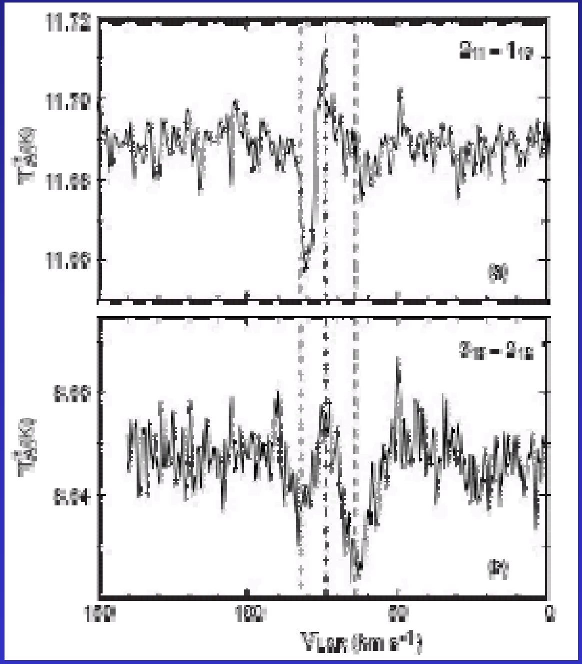




Jethava, Braatz, Henkel,
Carilli, Reid, Menten







Propanal CH_3CH_2CHO

Propenal CH_2CHCHO

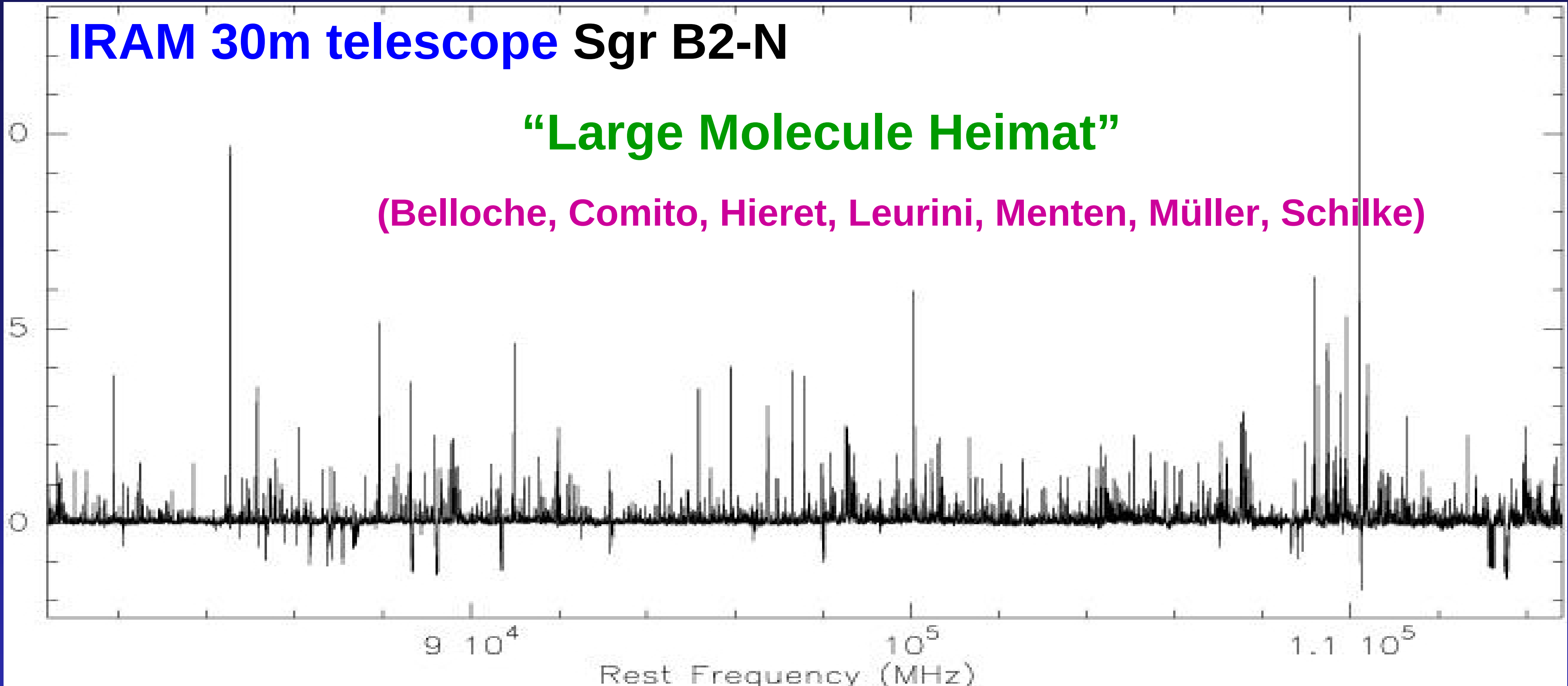
GBT 18 – 26 GHz

Hollis et al. 2004

IRAM 30m telescope Sgr B2-N

"Large Molecule Heimat"

(Belloche, Comito, Hieret, Leurini, Menten, Müller, Schilke)



3 mm region (70 – 116 GHz) in 500 MHz (SiS) chunks

4000 – 5000 lines!!!!

~10 minutes per spectrum **→ (near) confusion limit**

With a HEMT RX and high resolution wideband spectrometer capability this would have taken 2 LO settings

⇒ Factor ~100 savings in observing time

New Backend Option:

Fast Fourier-Transform (FFT)-Spectrometers

Principle:

- Direct sampling of RX IF with 8/10 bit resolution
- Continuous FFT calculation with given window function (to suppress side lobes)
- Calculation of power spectrum
- Power spectrum averaging

All on one chip: FPGA (= Field Programmable Gate Array)

Sensitivity

$$rms = \frac{const \cdot T_{\mathrm{sys}}}{\sqrt{\Delta\nu \cdot t_{\mathrm{int}}}}$$

For FFT spectrometers:
const ≈1 (8/10 bit sampling)

Overwhelming advantages of FFT Spectrometers:

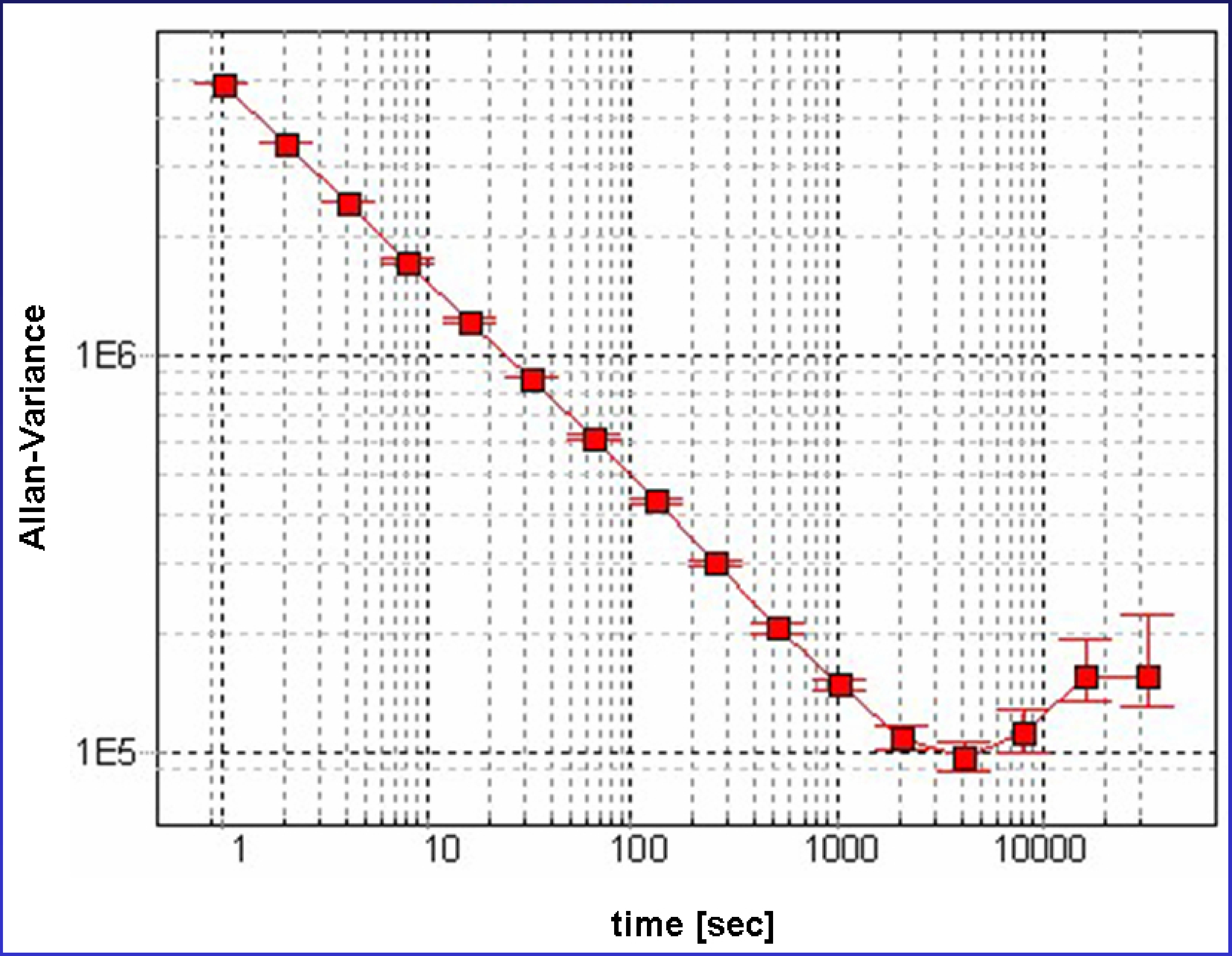
$\longrightarrow$ *FPGAs: Field-Programmable Gate Arrays*

- ADC with 8 or 10 bit sampling (ACs: 2bit)

$\Rightarrow$ higher sensitivity, no need for total power detectors

$\Rightarrow$ Much higher dynamic range $\rightarrow$ Leveling much simpler $\Rightarrow$ simplification of IF module

- 100% mass production chips $\rightarrow$ no custom made chips $\rightarrow$ much better reacion to markets $\rightarrow$ take full advantage of Moore's law
- very high channel numbers:
  - Today: 1 GHz/32768 channels
  - Soon (1 – 2 yrs): 2 GHz/65536 channels
- Very high degree of integration: Integration of a complete spectrometer (digital filters, windows, FFT, power builder and accumulator) on **one chip** (AC's use cascaded chips) $\rightarrow$
  - **can be re-programmed**
  - much lower power consumption (more reliable)


Allan-Variance
1E6
1E5
1
10
100
1000
10000
time [sec]

DRAO/ROE/DAO/NRAO

http://www.drao-ofr.hia-iha.nrc-cnrc.gc.ca/science/jcmt_correlator/

Correlators

IF racks

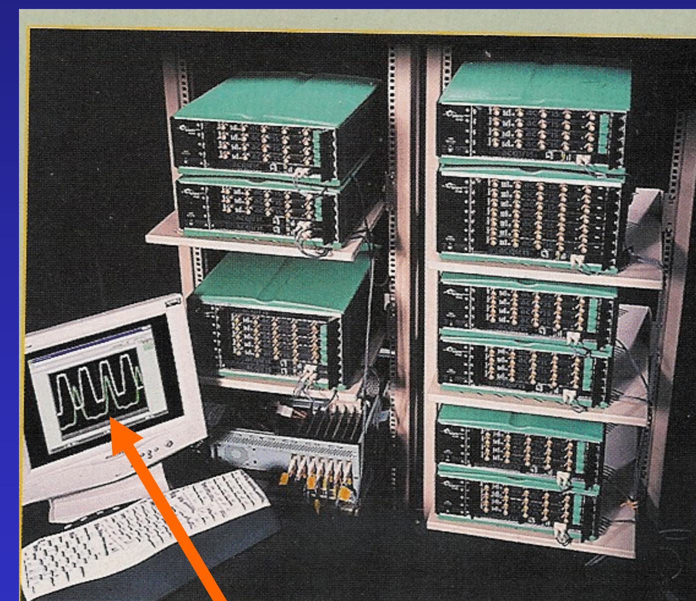
Data reduction machine

32 x 0.8 GHz (32 x 1024 channels)

$\Delta\nu$ = 1 MHz $\leftrightarrow$ Δv = 1km/s@300 GHz

http://www.acquiris.com/

FFTS



FFTS data reduction “machine”

40 x 1 GHz (40 x 32768 channels)

$\Delta\nu$ = 30 kHz $\leftrightarrow$ Δv = 0.03km/s@300 GHz

Reasons for price decay (3 – 4 kEU/GHz *soon*)

- growing demand from industry leads to higher production rates → chips get cheaper
  - main industrial application is wideband communications
- design your own boards and outsource board production

A&A 442, 767–773 (2005)
DOI: 10.1051/0004-6361:20053568

Astronomy & Astrophysics

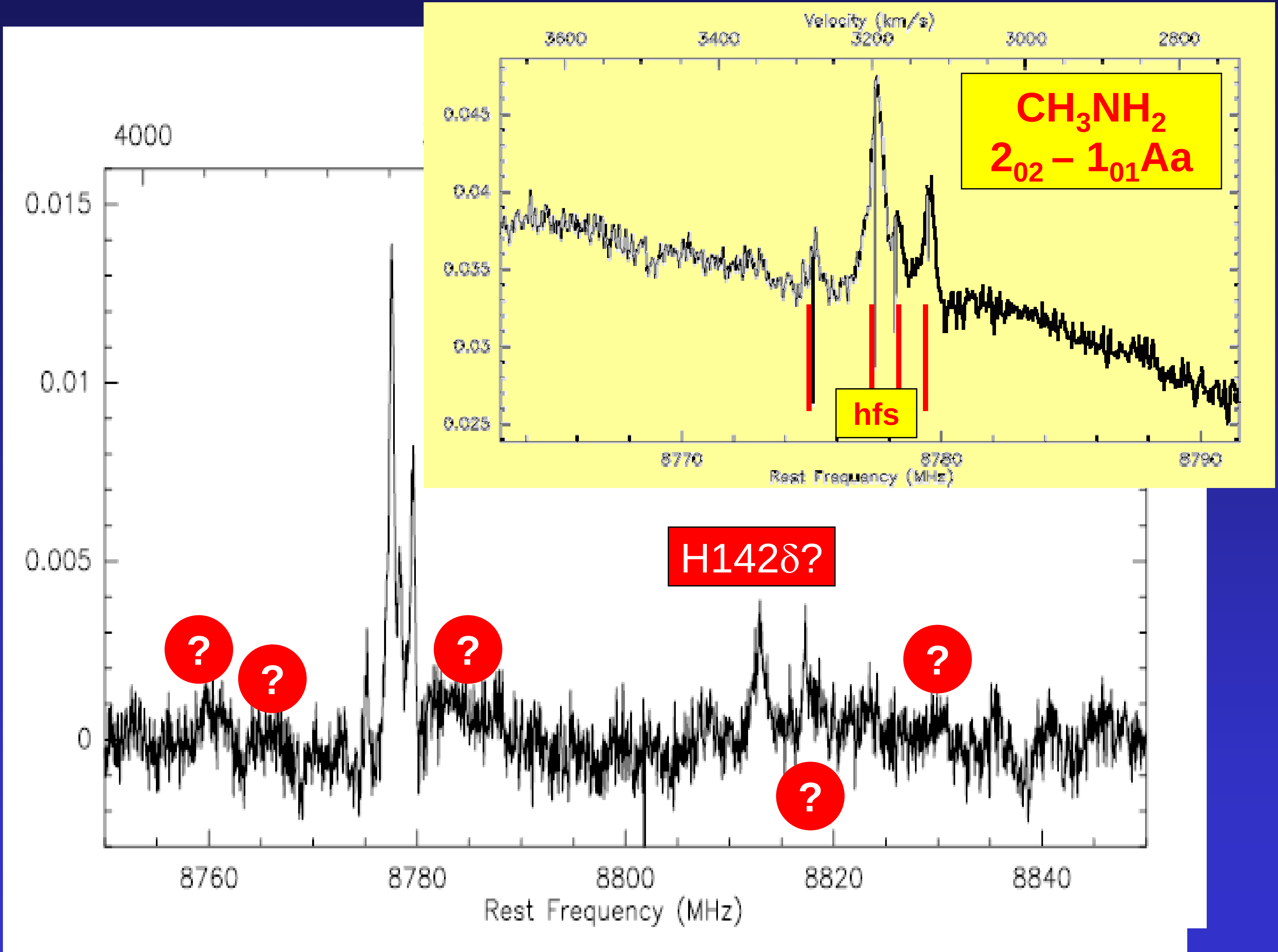
A broadband FFT spectrometer for radio and millimeter astronomy

A. O. Benz[1], P. C. Grigis[1], V. Hungerbühler[2], H. Meyer[1], C. Monstein[1], B. Stuber[3], and D. Zardet[4]

FFT-Spectrometers – State of the Art:

- **2005/MPIfR**: Development of an FFT Spectrometer with
    - 16384 channels
    - 500 MHz bandwidth
- **SUCCESS**: Brought 500 MHz into operation at the 100m telescope (April 2005) and (1GHz/32768channels) at APEX (June 2005)!

$\Rightarrow$ ***FFTS Technology available today!***

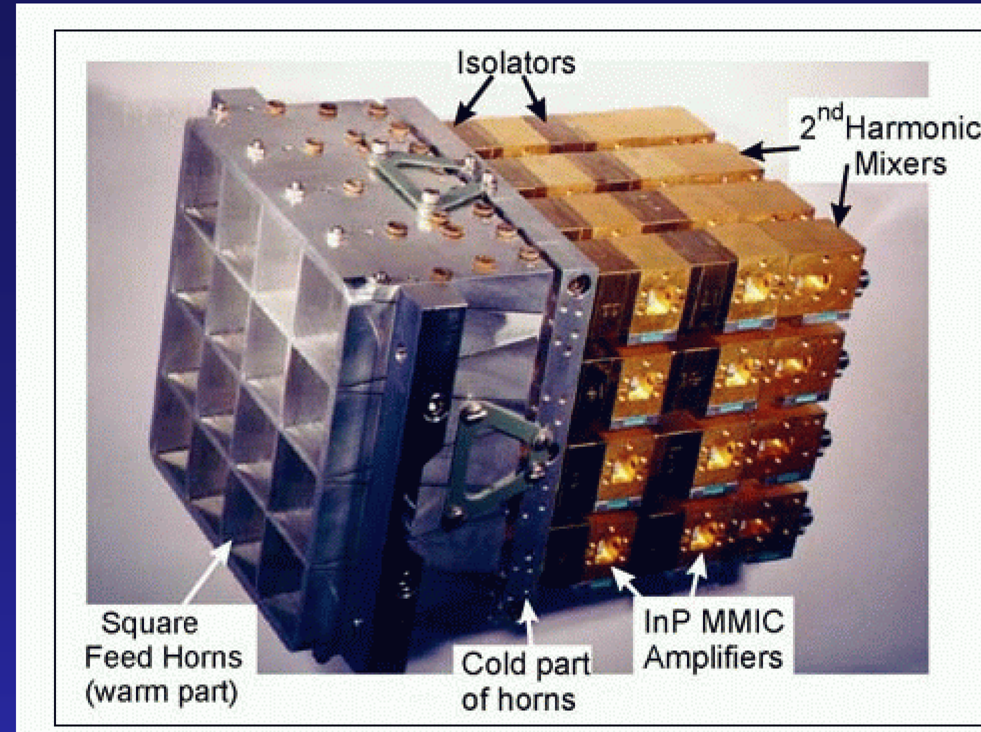


4000
0.015
0.01
0.005
0
8760
8780
8800
8820
8840
Rest Frequency (MHz)
H142δ?
?
Velocity (km/s)
3600
3400
3200
3000
2800
0.045
0.04
0.035
0.03
0.025
8770
8780
8790
Rest Frequency (MHz)
CH_3NH_2
$2_{02} - 1_{01}Aa$
hfs

The ***same*** spectrometer allowing very wide band spectral line surveys toward single positions would allow serving a multi-element MMIC Array Spectrograph

SEQUOIA

The World's Fastest 3mm Imaging Array



http://www.astro.umass.edu/~fcrao/instrumentation/sequoia/seq.html

- focal plane array: 4×4 pattern.
- currently mounted on the FCRAO 14m telescope
- Will be moved to the LMT
- fixed tuning => best performance at all frequencies
- being expanded to 32 elements
- InP MMIC pre-amplifiers: 35-40 dB gain band
- (T_{sys}=50 – 80 K)
- instantaneous bandwidth: 15 GHz (85 – 115.6 GHz with only two local oscillator settings)

SEQUOIA is just the beginning:

MMIC Array Spectrographs (MASs) will

- soon (within a few years) have ~100 elements and
- somewhat later have many 100s of elements
- Large MMIC FPAs currently being developed at JPL (PI Todd Gaier) driven by cosmology (T. Readhead)/space
- (FFTS) backends will be available
- **With LOs integrated, MASs will revolutionize large areas of molecular line astronomy**

- **Question: Will HEMTs become competitive at shorter λλ?**

W-band (80 – 116 GHz) Science with MMIC Array Spectrographs (MASs)

Apart from **CO J=1-0** lines there are **ground- or near-ground-state transitions of HCN, HNC, CN, N_2H^+, HCO^+, CH_3OH, SiO**… all between 80 and 115 GHz

Because of their high dipole moments, these species trace high density gas, $n > 10^4\ cm^{-3}$ ($\leftrightarrow$ CO: $n > 10^2\ cm^{-3}$)

Large-scale distribution of these molecules on larger GMC scales poorly known

Strong emission in these lines, as well as in rare $C^{18}O$ isotope, traces high column densities *($\rightarrow$ star formation)*

These lines are very widespread (= everywhere) over the whole Galactic center region ($-0.5^0 < l < 2^0$)

Other *most interesting* projects include complete (mostly) ^{12}CO and ^{13}CO mapping of nearby galaxies.

These are HUGE (many square arc minutes)!

Such maps would be interesting in their own right and are *absolutely necessary* as zero spacing information for CARMA, the PdBI, and ALMA.

***REALLY FANTASTIC* would be MASs on CARMA and the PdBI!!!**

… and they would make these facilities highly competitive in the ALMA era, as ALMA will (probably) not have MASs for a very long time.

Mapping speed and sensitivity estimates indicate that very large sections (if not all) of the Galactic plane can be imaged

HUGE advantage over SiS arrays: Many lines in HEMT band can be imaged *simultaneously*

Necessary Spectrometer capability:

Example W-Band:

- **Want to do 20 lines simultaneously**
    - **need ~150 km/s (= 50 MHz) each**

$\Rightarrow$ Need N × 20 × 50 MHz = N × 1 GHz

1 GHz FFTS bandwidth cost ~ 20 kEU today/MUCH less next year (~ 3 – 4 kEU)

At today’s prizes, an FFTS for a 100 element array would cost 2 MEU (and 300 – 400 kEU soon)

***HOWEVER:* Above is the *de luxe* correlator. To save money, could do fewer lines, use narrower bandwidths**

Mapping speed (1 square degree)

rms(1 sec) = 0.2 K at 90 GHz

IRAM 30m

24” FWHM@90 GHz

Positions to observe for a Nyquist-sampled map of 1 square degree

90000

Time needed for a map with an N pixel array

25/N hours

K-band MAS Science (18 – 26 GHz)

For temperature and column density determinations ideal: Ammonia (NH_3)

• Multiple K-band lines (23.6 – 25 GHz) that can be done simultaneously

and

• simultaneously with 22.2 GHz H_2O maser line

and

•simultaneously with 25 GHz series of CH_3OH lines (maser and thermal)

⇒**K-band RX array would be *VERY* interesting!**

FFTSs and MASs

Synergy – Pooling resources

FFTSs:

Bernd Klein, MPIfR, bklein@mpifr-bonn.mpg.de

Potential “users” for FFTSs **and** MASs

(= possible co-financers):

- IRAM
- APEX
- LMT
- Effelsberg 100m telescope
- GBT
- Madrid 40m telescope, Sardinia Telescope

+ …

Basic messages:

- High-z low J CO will be very difficult and expensive
- Need integrated RX and spectrometer design
- Telescope characteristics have to be understood at unprecedented level
- There is other interesting science for wideband spectrometers
- High spectral resolution wideband spectrometers are available
- Very powerful combination with MMIC focal plane arrays