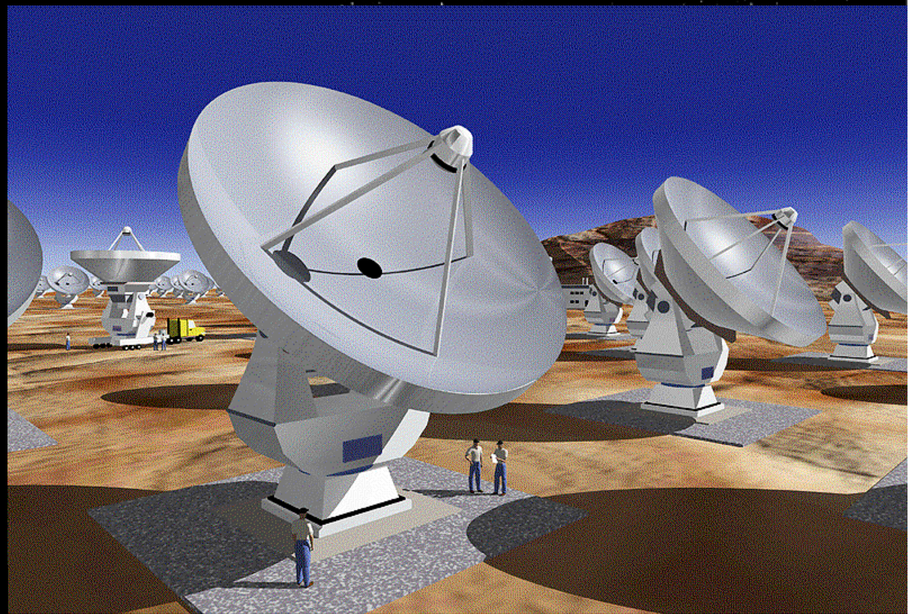
TeraHertz Spectroscopy in the Space : New Submillimeter and Far-IR Astronomical Instruments

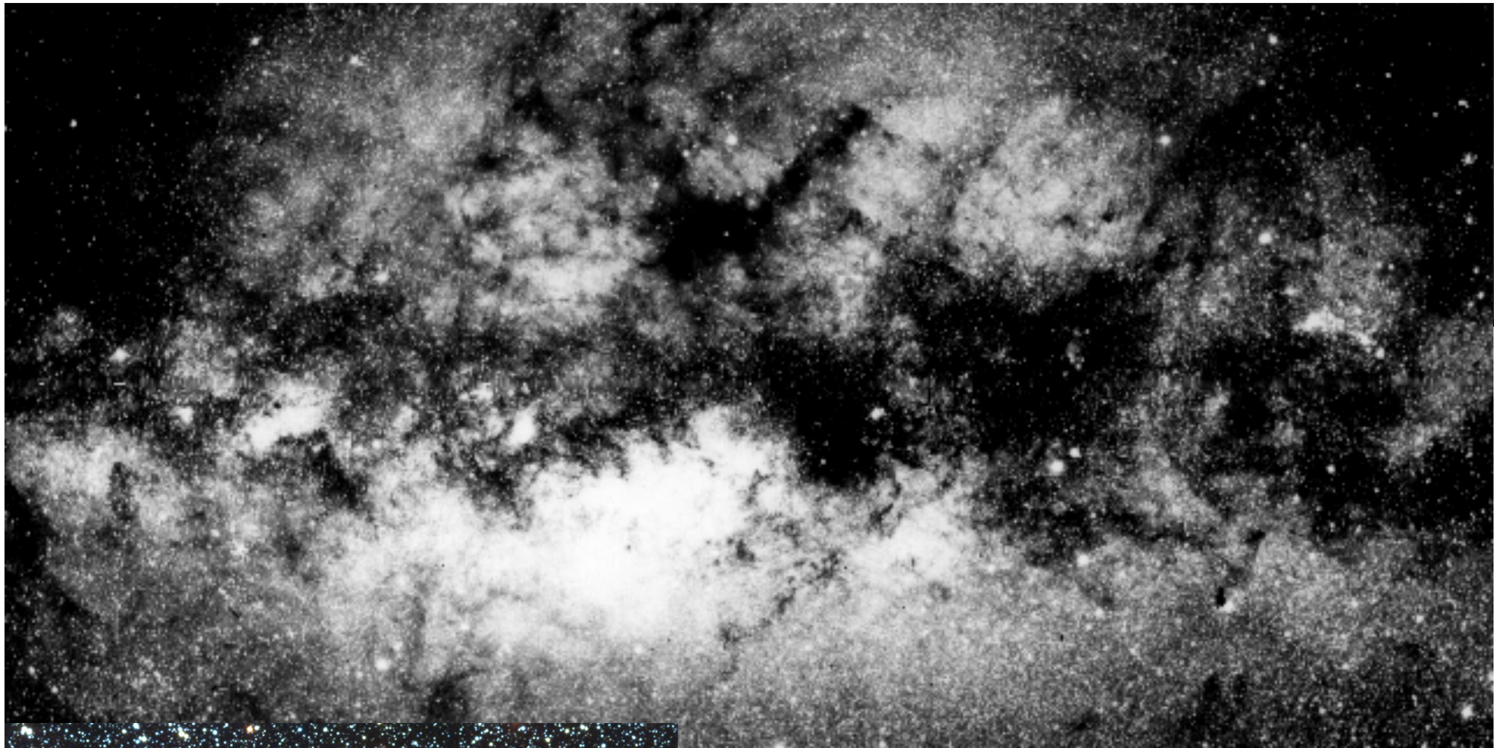
José Cernicharo
CSIC. IEM
Dpt. Molecular and Infrared Astrophysics (DAMIR)
Madrid. Spain

4/12/06 14:45



ESO PR Photo 24a/99 (8 June 1999)

Artist's Impression of ALMA
(Atacama Large Millimetre Array)



Strong UV field from nearby bright stars. Photodissociation region : Large complex molecules (100-200 atoms)

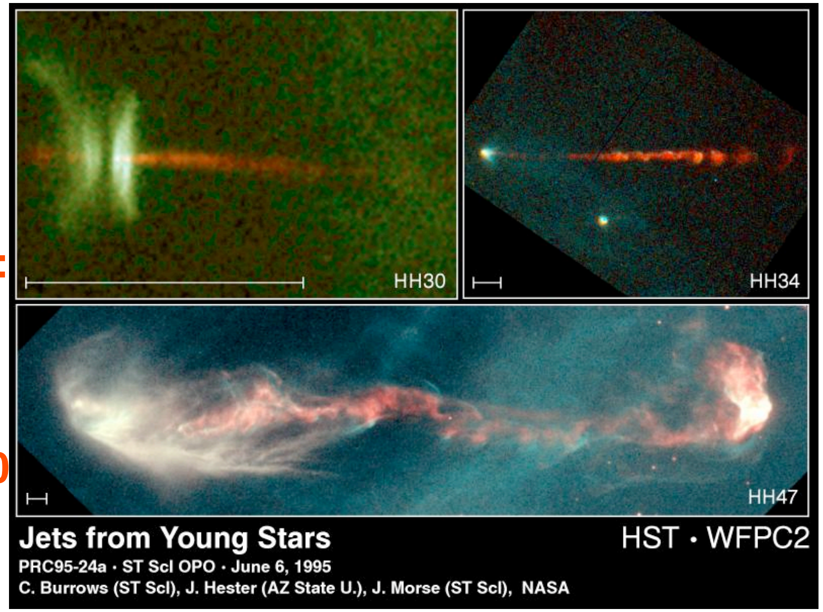
T_K=10-15 K

$n(H_2)=10^3$-10^5 cm^{-3}

$N(H_2)=10^{22}$-10^{23}cm^{-2}

Abundant molecules: CO, HCO^+, HCN, NH_3, CS,…

MGas/Mdust=100-200



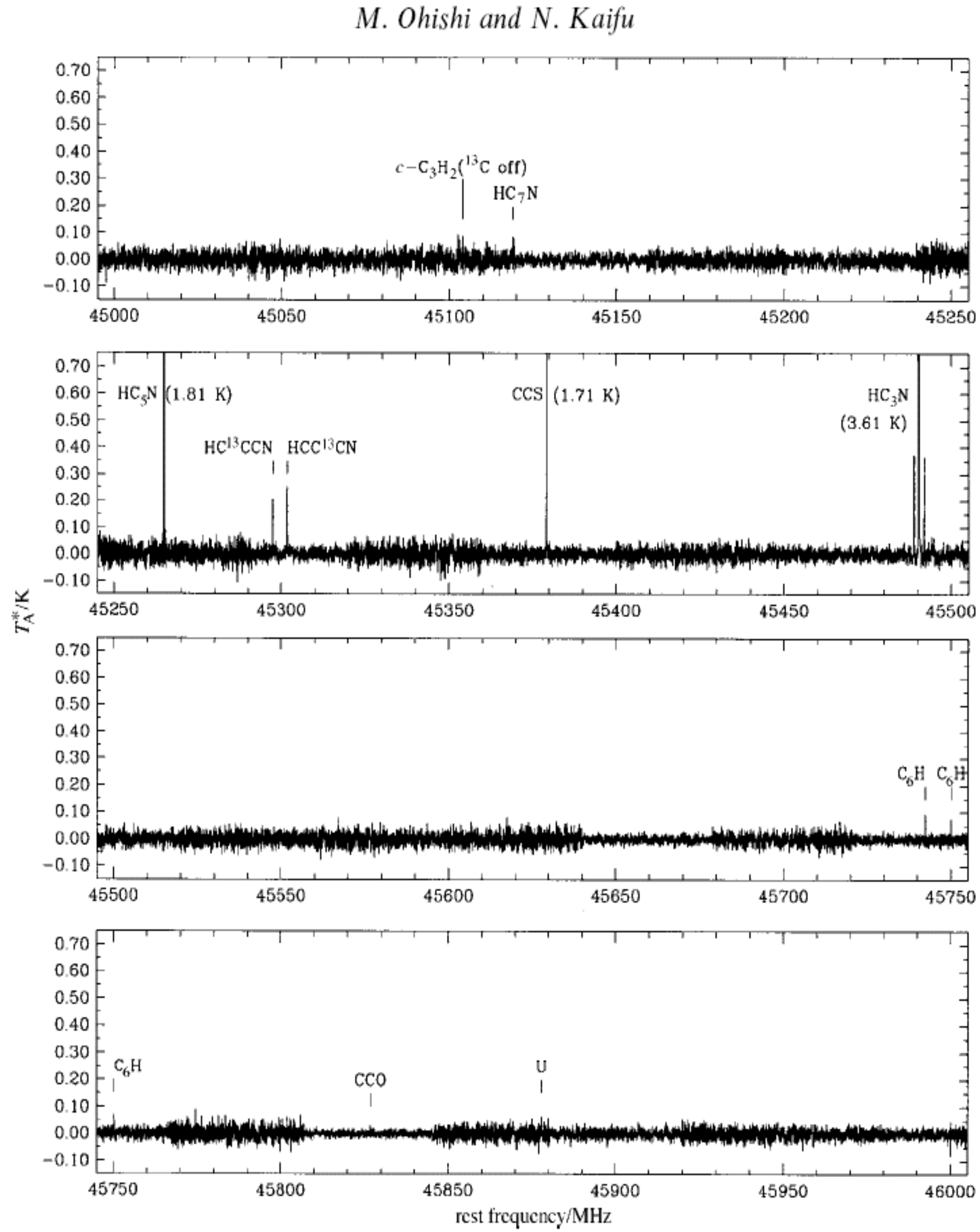
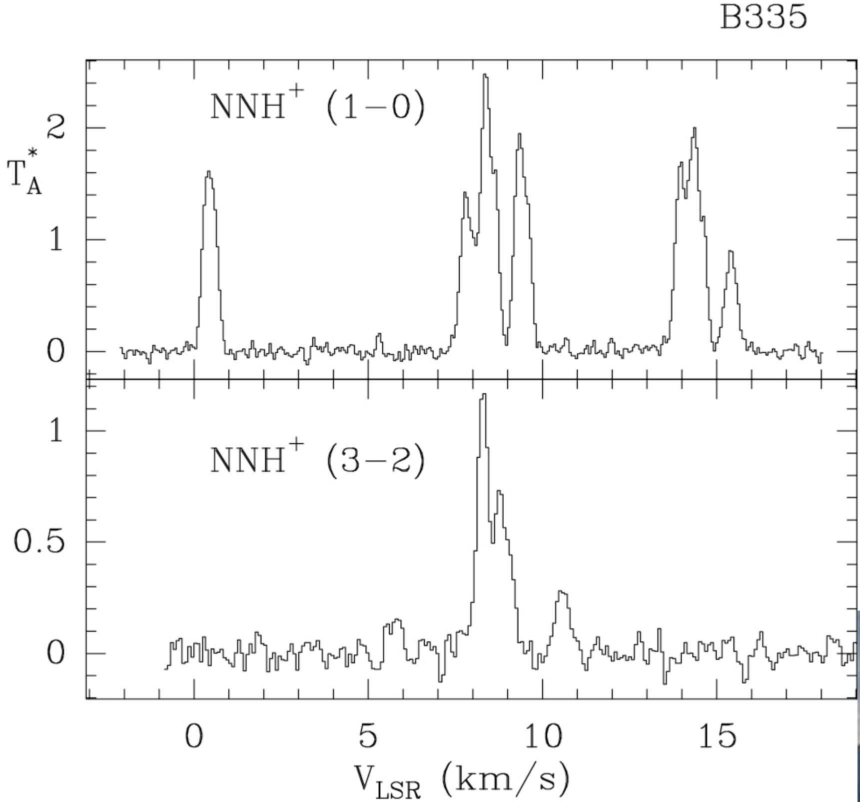


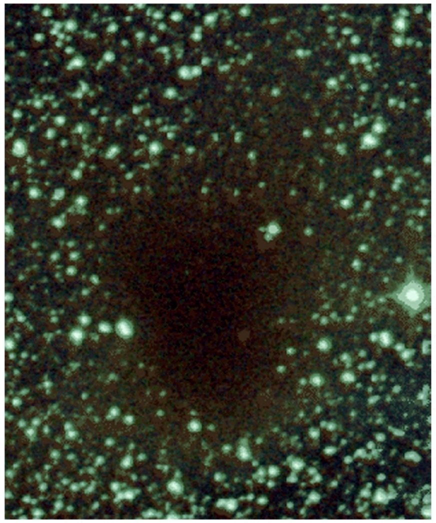
Fig. 2 Sample spectrum from 45 000 to 46 000 MHz

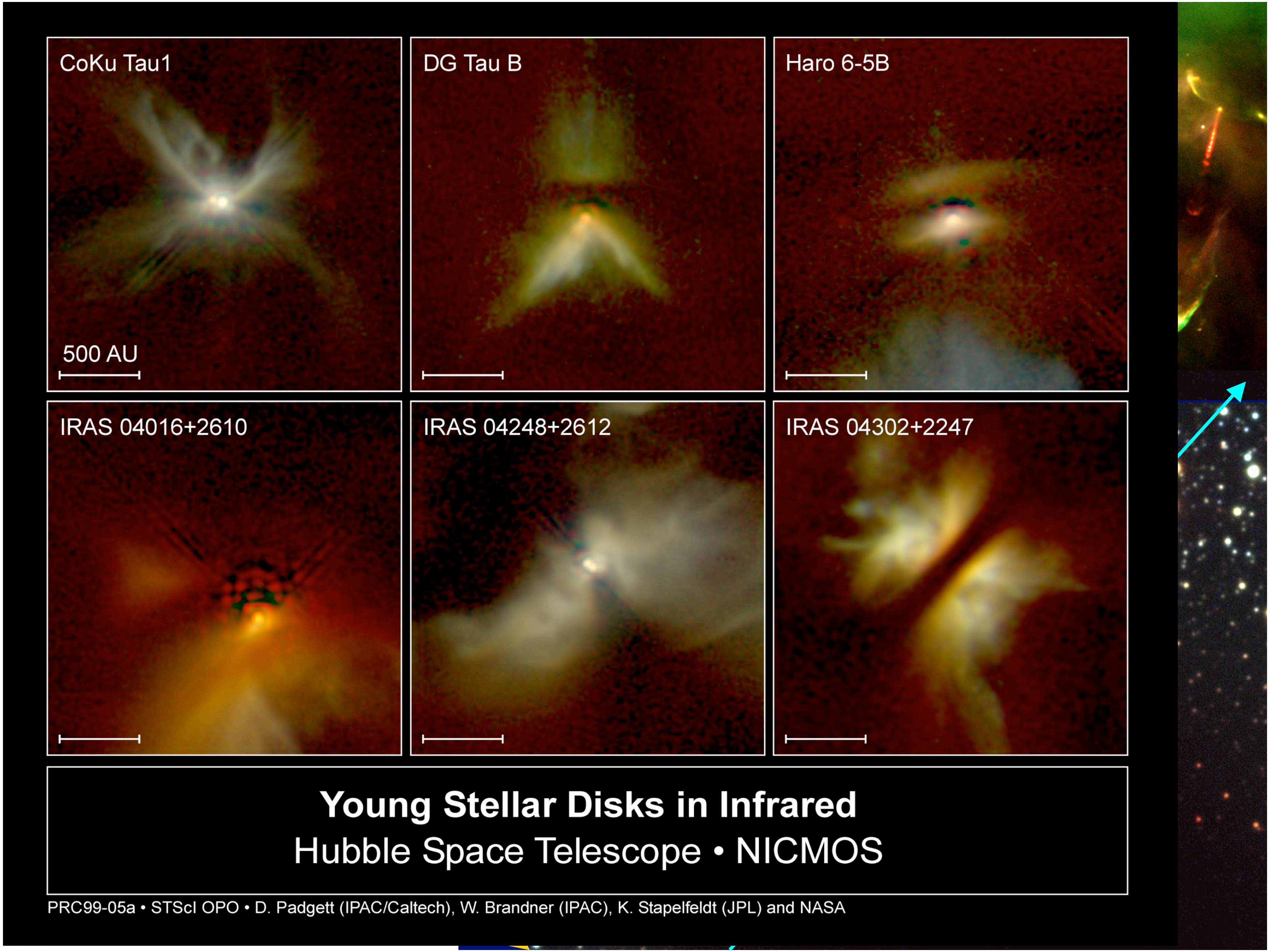
Most ISM clouds are cold, T_K=10 K, and tenous, $n(H_2)$=1000-10000 cm^{-3}

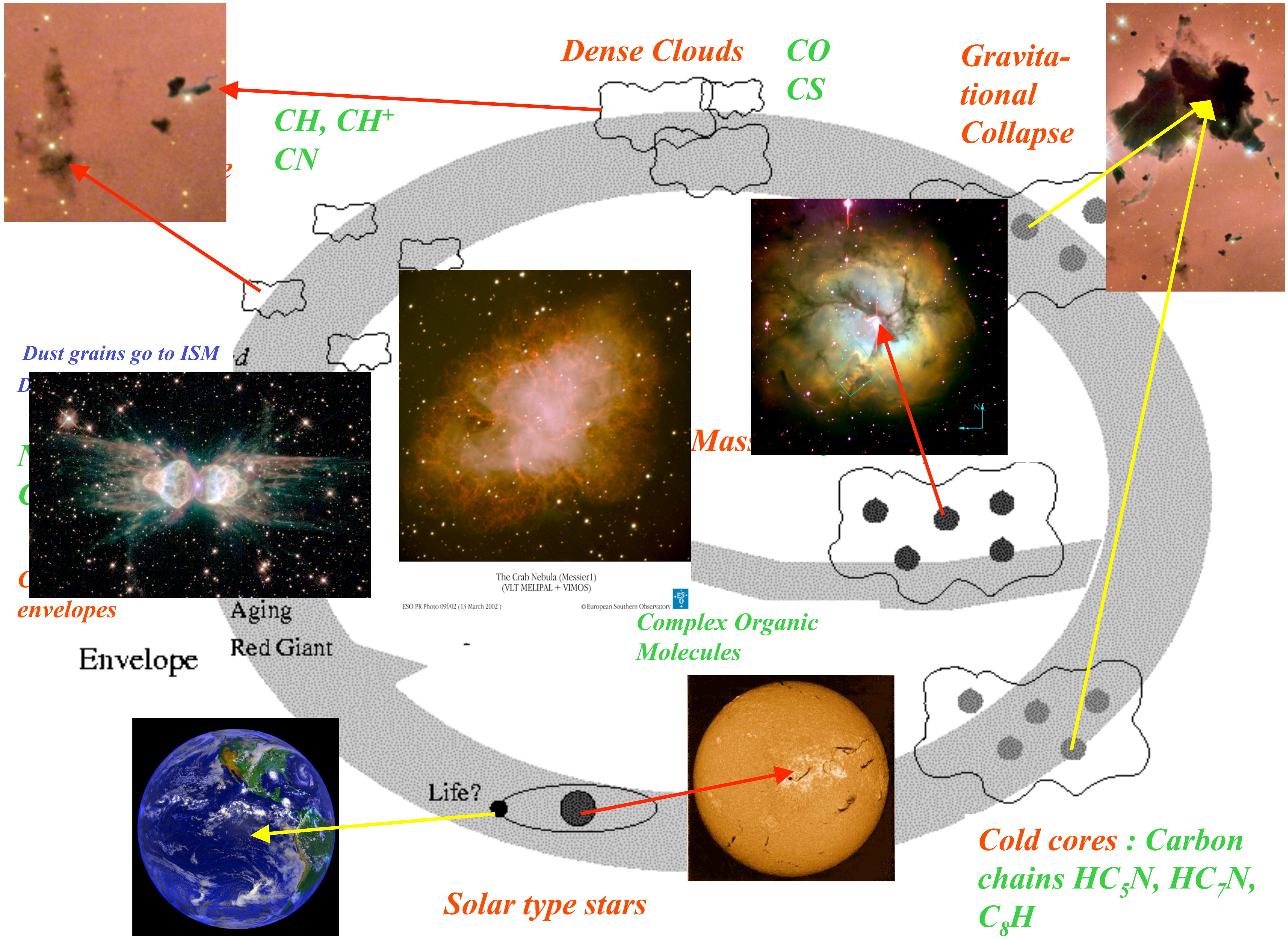
The chemistry is complex, heavy molecules, like $HC_{11}N$ are formed, but the line density is rather low.

Millimeter Radiotelescopes

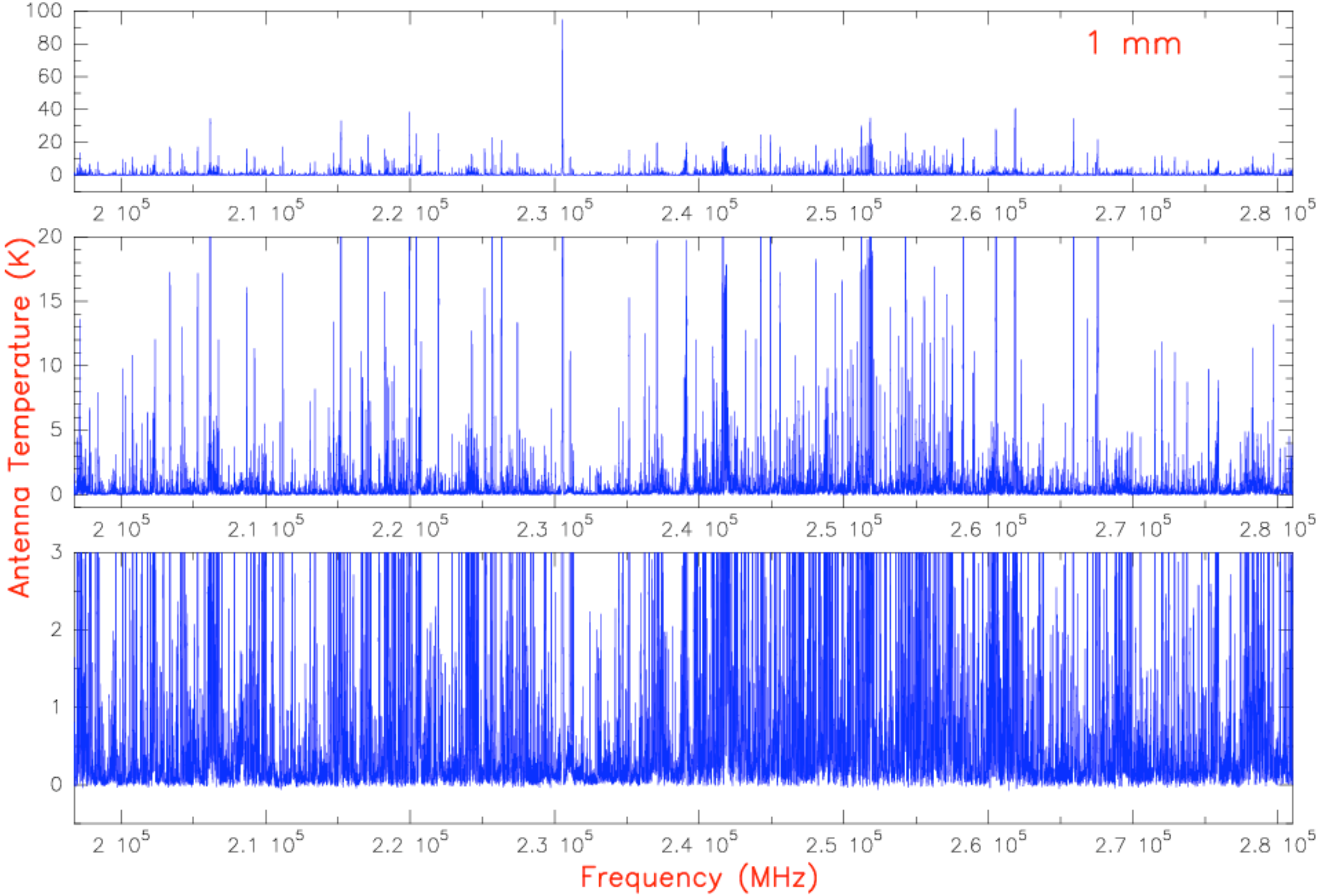

B335
NNH+ (1–0)
NNH+ (3–2)
T*A
2
1
0
0.5
0
5
10
15
VLSR (km/s)

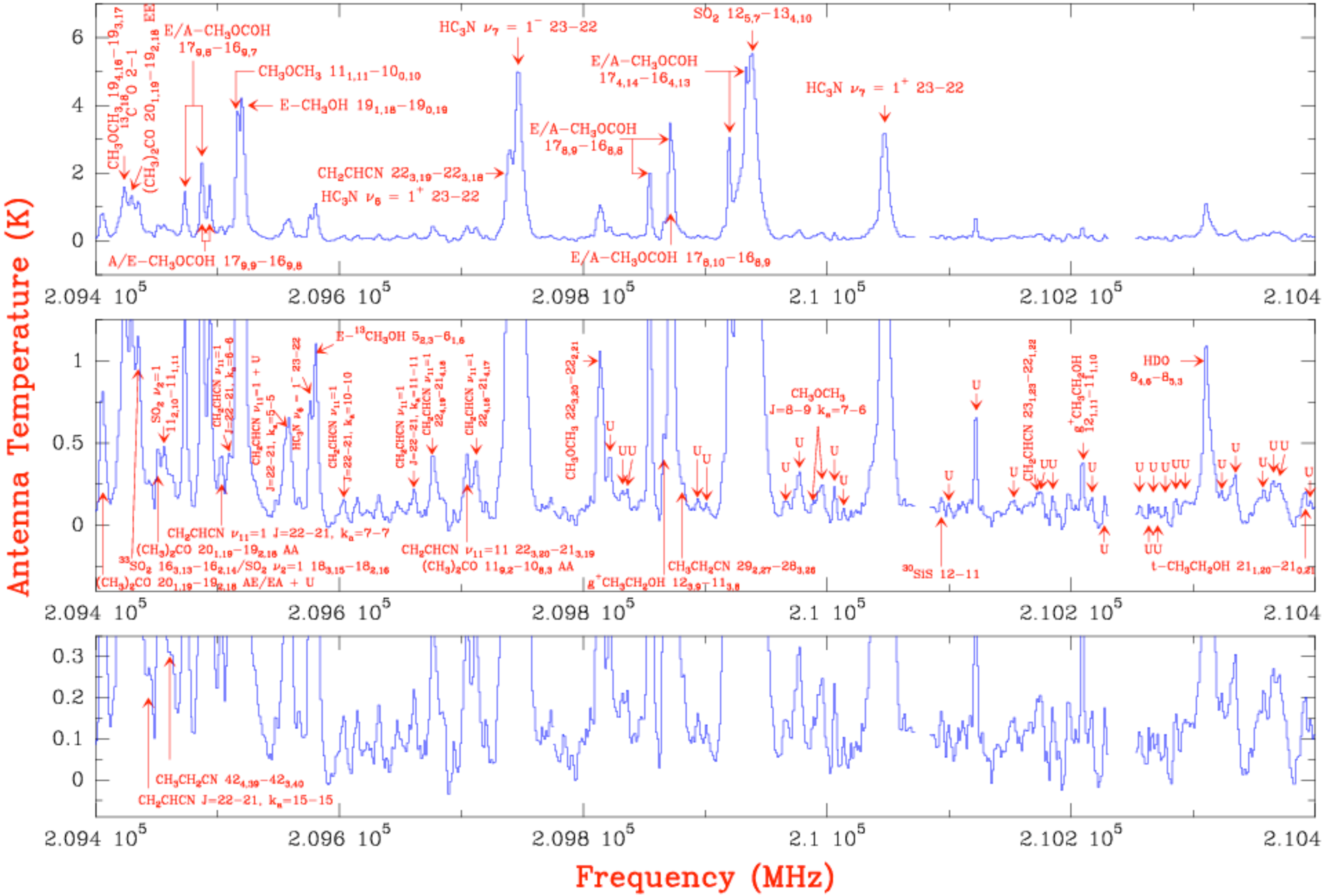



CoKu Tau1
500 AU
DG Tau B
Haro 6-5B
IRAS 04016+2610
IRAS 04248+2612
IRAS 04302+2247
Young Stellar Disks in Infrared
Hubble Space Telescope • NICMOS
PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA


Dense Clouds
CO
CS
CH, CH^+
CN
Gravita-
tional
Collapse
Dust grains go to ISM
The Crab Nebula (Messier1)
(VLT MELIPAL + VIMOS)
ESO PR Photo 09f/02 (13 March 2002)
© European Southern Observatory
envelopes
Aging
Red Giant
Envelope
Complex Organic
Molecules
Life?
Solar type stars
Cold cores : Carbon
chains HC_5N, HC_7N,
C_8H

The real world of warm gas in space : molecular lines every where !





Antenna Temperature (K)
Frequency (MHz)
6
4
2
0
1
0.5
0.3
0.2
0.1
2.094 10^5
2.096 10^5
2.098 10^5
2.1 10^5
2.102 10^5
2.104
E/A−CH3OCOH 179,8−169,7
CH3OCH3 111,11−100,10
E−CH3OH 191,18−190,19
HC3N ν7 = 1− 23−22
SO2 125,7−134,10
E/A−CH3OCOH 174,14−164,13
HC3N ν7 = 1+ 23−22
E/A−CH3OCOH 178,9−168,8
CH2CHCN 223,19−223,18
HC3N ν6 = 1+ 23−22
A/E−CH3OCOH 179,9−169,8
E/A−CH3OCOH 178,10−168,9
E−13CH3OH 52,3−61,6
CH3OCH3 J=8−9 ka=7−6
HDO 94,6−83,3
CH2CHCN ν11=1 J=22−21, ka=7−7
(CH3)2CO 201,19−192,18 AA
CH2CHCN ν11=11 223,20−213,19
(CH3)2CO 119,2−108,3 AA
CH3CH2CN 292,27−283,26
30SiS 12−11
t−CH3CH2OH 211,20−210,21
CH3CH2CN 424,39−423,40
CH2CHCN J=22−21, ka=15−15

2 atoms	**3 atoms**	**4 atoms**	**5 atoms**	**6 atoms**	**7 atoms**
H_2	C_3*	c-C_3H	C_5*	C_5H	C_6H
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N
CH	CH_2 2005	C_3S	c-C_3H_2	CH_3NC	CH_3CHO
CH^+ 2005	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2
CN	HCO	NH_3	CH_4*	CH_3SH	c-C_2H_4O
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	
CP	HOC^+	HNCO	HCOOH	NH_2CHO	
SiC	H_2O	HNCS	H_2CNH	C_5N	
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H	
KCl	HNC	H_2CO	H_2NCN	l-HC_4N	

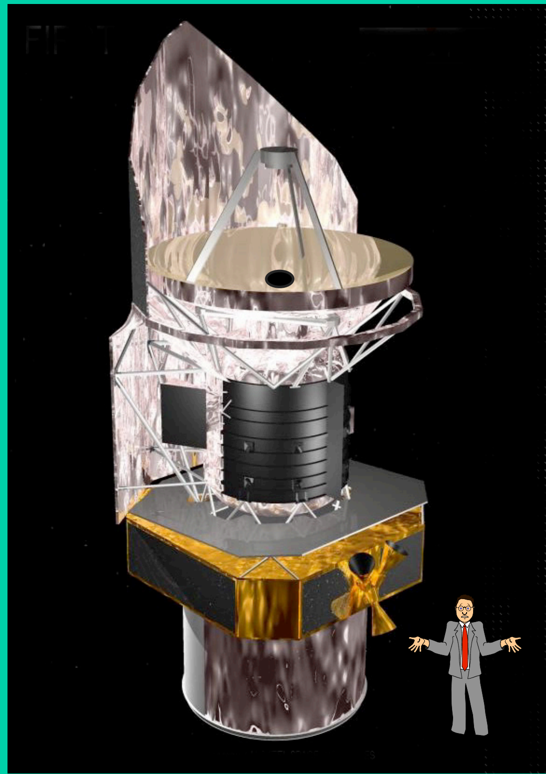
NH	HNO	H_2CN	HNC_3	c-H_2C_3O
NO	MgCN	H_2CS	SiH_4*	H_2CCNH
NS	MgNC	H_3O^+	H_2COH^+	
NaCl	N_2H^+	c-SiC_3		
OH	N_2O	CH_3*		
PN	NaCN			
SO	OCS			
SO^+	SO_2			
SiN	c-SiC_2			
SiO	CO_2*			
SiS	NH_2			
CS	H_3^+*			
HF	H_2D^+, HD_2^+			

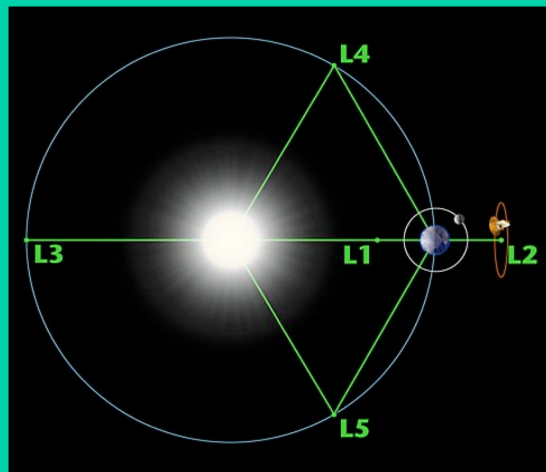
8 atoms	**9 atoms**	**10 atoms**	**11 atoms**	**12 atoms**
CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6
$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$
CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$		
C_7H	CH_3CH_2OH	CH_3CH_2CHO		
H_2C_6	HC_7N			
CH_2OHCHO	C_8H			
l-HC_6H	$CH_3C(O)NH_2$			
CH_2CHCHO				

Herschel Spacecraft and Telescope

• Telescope diameter	3.5 m
• Telescope temp.	70-90 K
• Effective emissivity	< 4%
• Pointing	< 3.7” (*1.5”*)
• Operational lifetime	> 3 years
• Helium capacity	2200 ltr
• Height	9 m
• Launch mass	3300 kg
• Orbit	L2
• Launch date	2008
• Launch vehicle	Ariane 5
• 3 instruments	HIFI PACS SPIRE

- Photometry and spectroscopy between 50 and 670 μm (15-200 cm^{-1})





Herschel Main Scientific Objectives

Formation and evolution of galaxies and clusters in the early universe

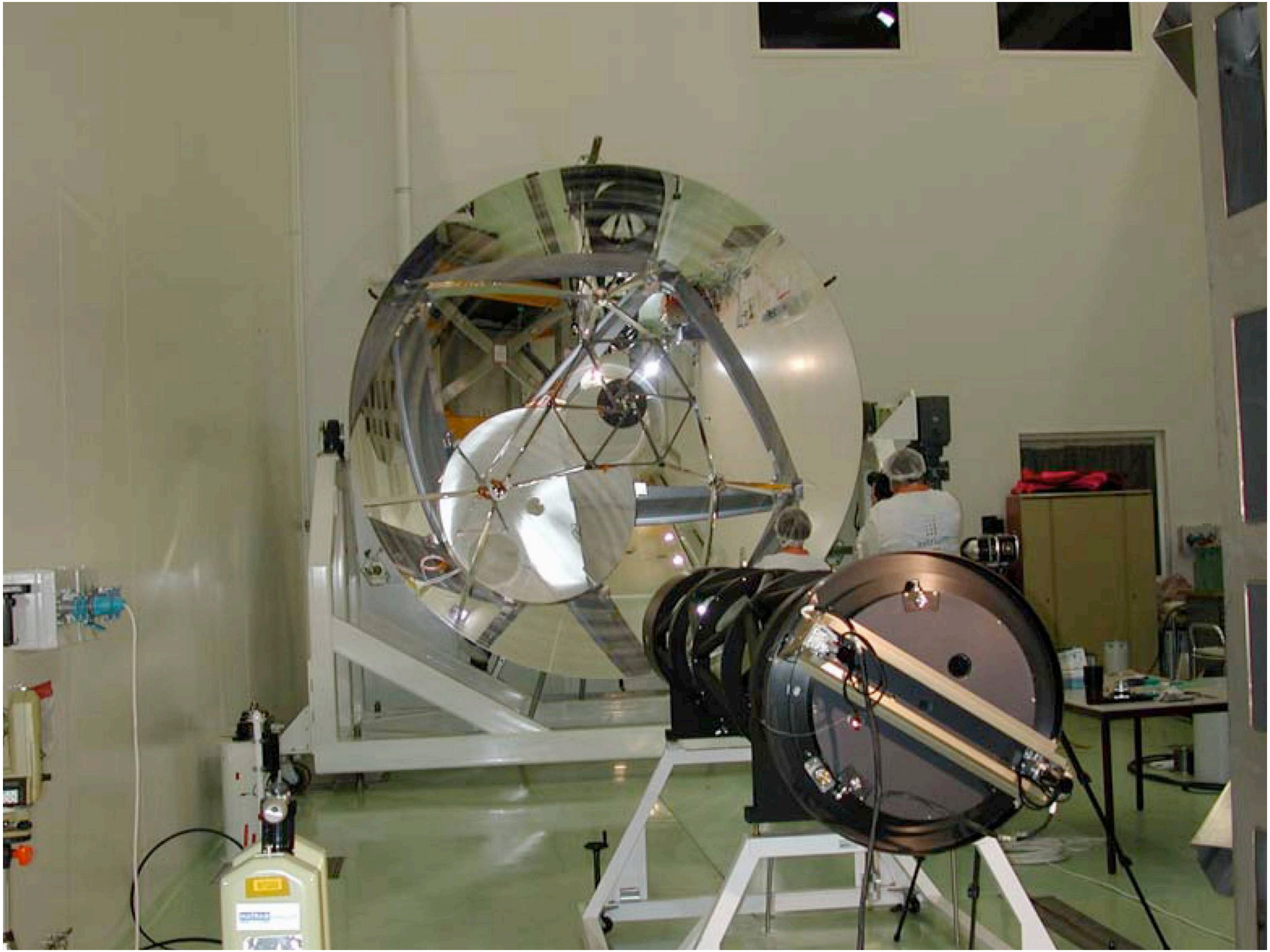
– Star formation history, bolometric luminosities, fraction of AGN
– Origin of the cosmic infrared background
– Formation of spheroids/ellipticals at z > 1
– History of chemical elements – metal production at high z

Formation of stars and physics of the interstellar medium

– Structure, dynamics, composition of the ISM
– Pre-stellar and young stellar cores
– Circulation/enrichment of the interstellar medium - astrochemistry
– Detailed studies of nearby resolvable galaxies
- Astrochemistry

Cometary, planetary, and satellite atmospheres

– Composition of giant planets
– Pristine material in comets
– Water activity

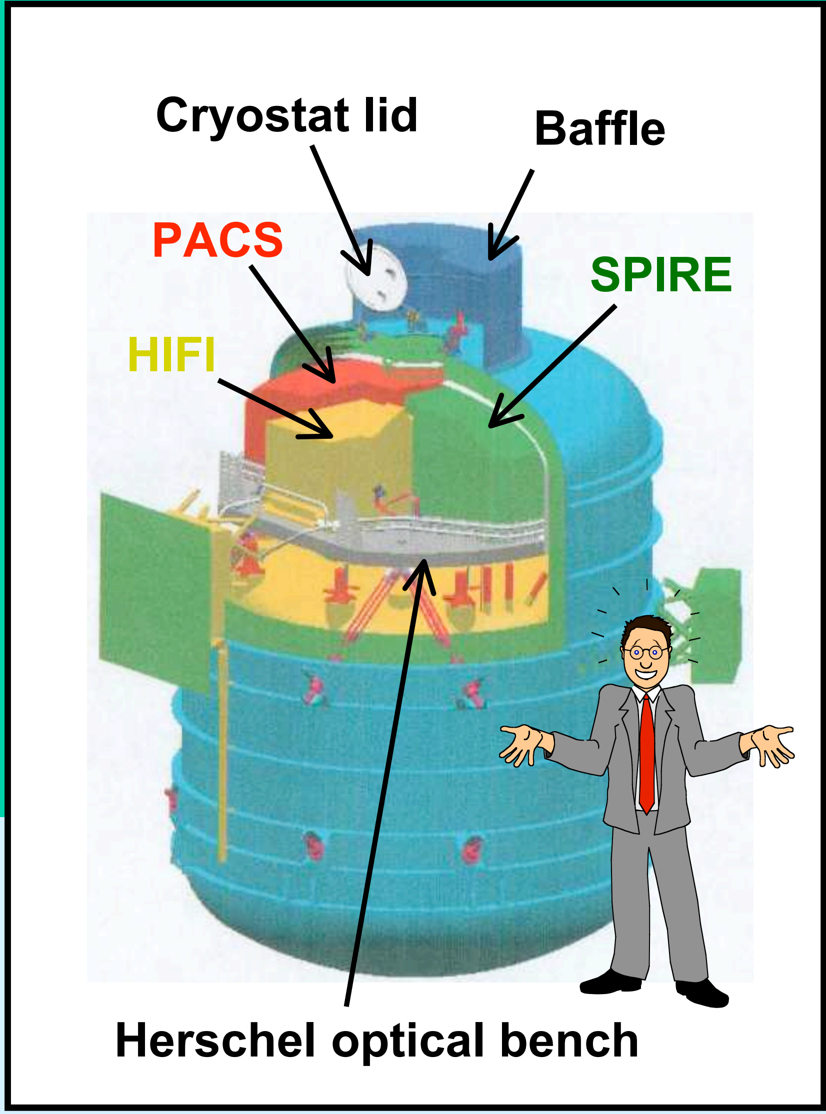



APCO
APCO

Provided by M. Griffin

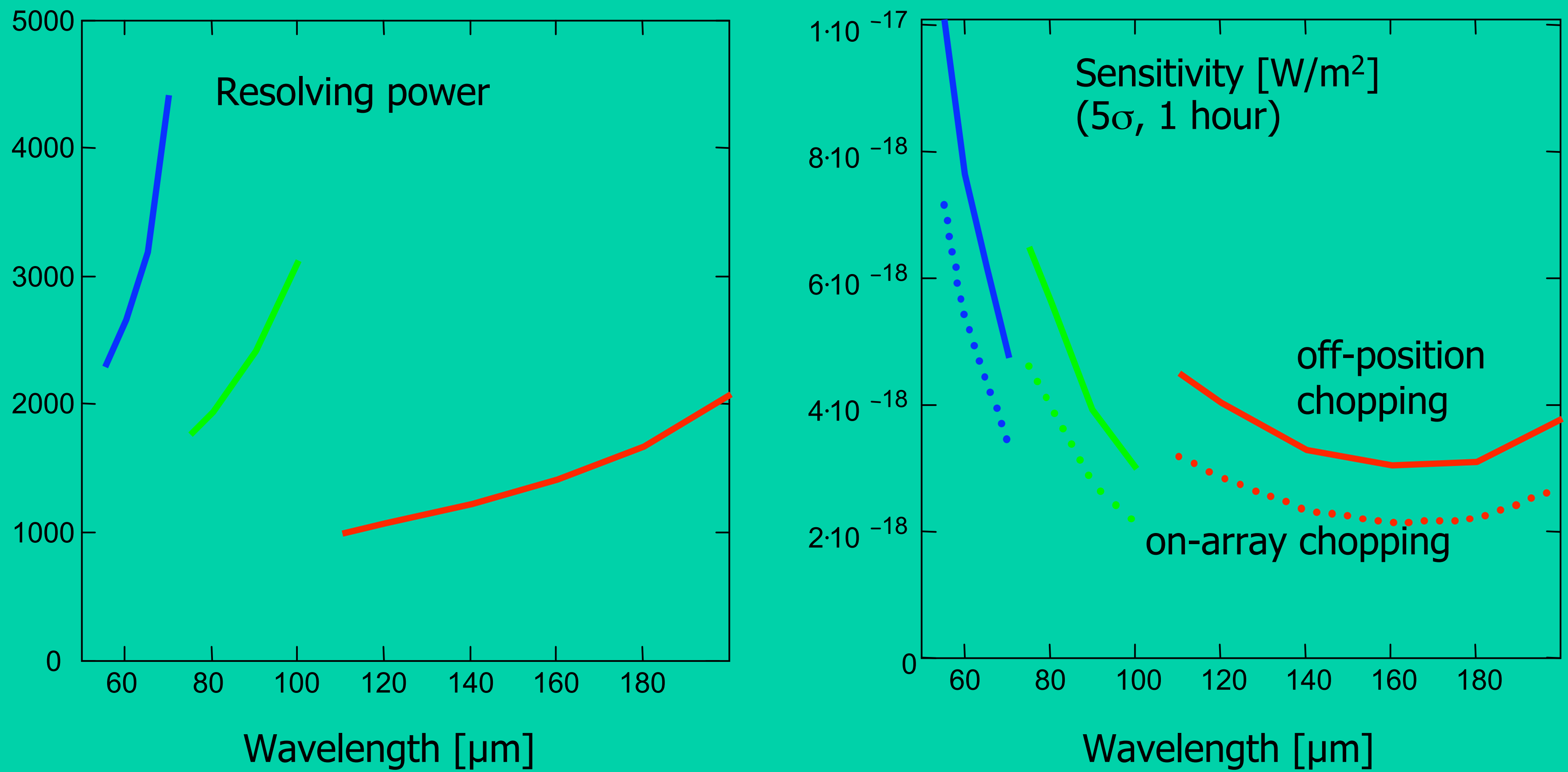
Instruments

- PACS (57 - 210 μm)
  - Imaging photometer
  - Imaging grating spectrometer
    - Lines: λ/Δλ ~ 1500
- SPIRE (200 - 670 μm)
  - Imaging photometer
  - Imaging Fourier transform spectrometer
    - Survey: λ/Δλ = 20-1000
- HIFI (157- 212 μm and 240 - 625 μm)
  - Non-imaging heterodyne receiver
    - Lines: $\lambda/\Delta\lambda = 10^4 - 10^6$



- Large cold focal plane units
- Complex opto-mechanical design
- Cryogenic mechanisms
- Large-format FIR/submm arrays

Predicted Spectrometer Performance



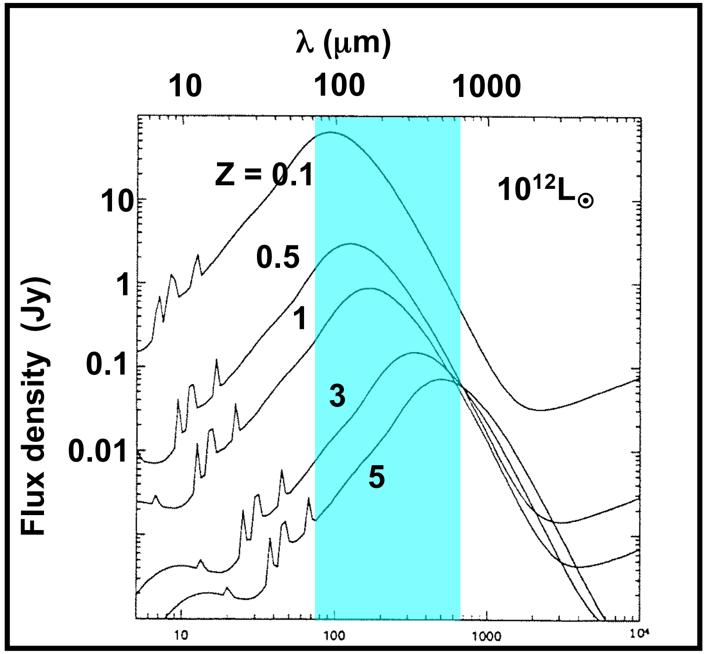
SPIRE: The Spectral and Photometric Imaging Receiver

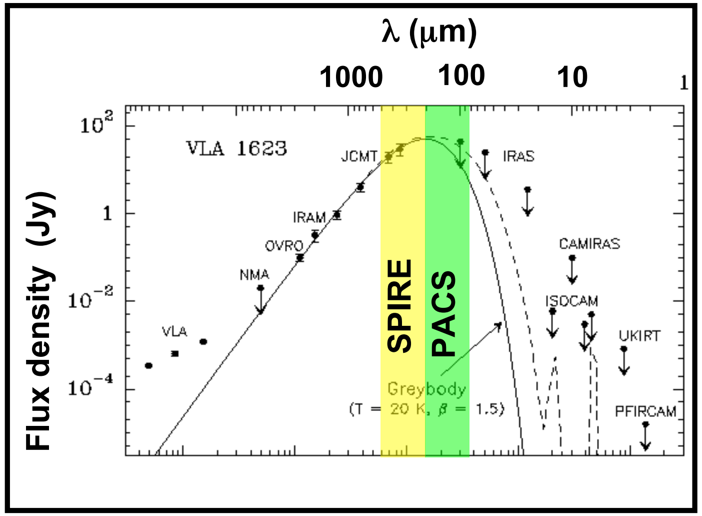
- **Main scientific design drivers**
  - **Wide-area extragalactic and galactic surveys with spectroscopic follow-up**
  - **Medium-resolution imaging spectroscopy of the ISM and star-forming regions in our own and nearby galaxies**

- **Sensitivity limited by thermal emission from the Herschel telescope (80 K; ε = 4%)**

- **^{3}He cooled bolometer detector arrays (0.3 K)**

- **Minimal use of mechanisms**
  - **Photometer beam steering mirror**
  - **FTS mirror drive**

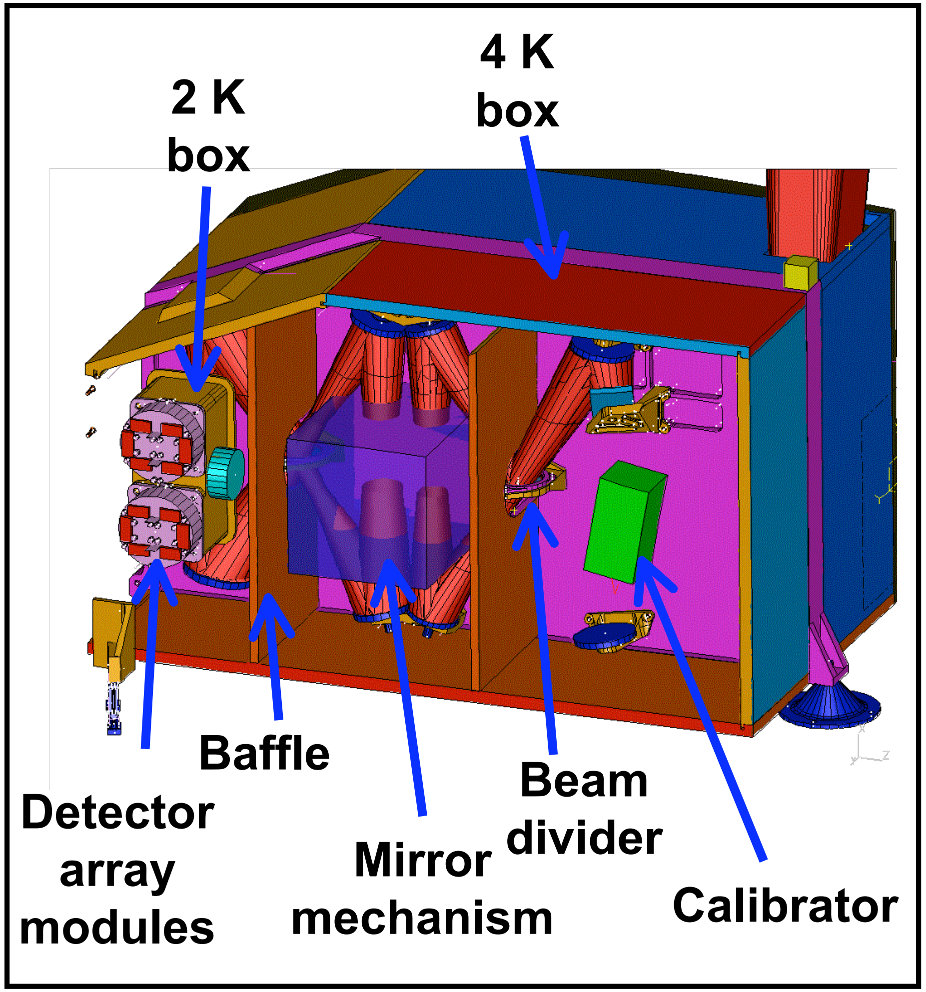




From M. Griffin and the SPIRE project

SPIRE Imaging Fourier Transform Spectrometer

- $\lambda = 200 - 670\ \mu m$
- 2 arcminute field of view
- $\Delta\sigma = 0.4\ cm^{-1}$ (goal $0.04\ cm^{-1}$) ($\lambda/\Delta\lambda \sim 20 - 100$ (1000) at 250 μm)
- Double-beam FTS with broadband intensity beam dividers
- Feedhorn coupled NTD Ge bolometer arrays
- Low-power linear scan mechanism
- 2nd port calibrator to null telescope background
- Observing modes
  - Continuous scan
  - Step-and-integrate

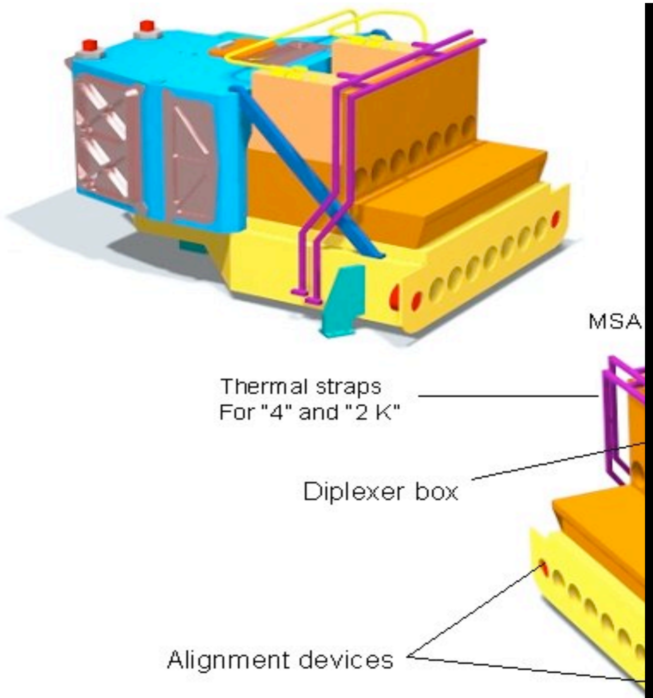


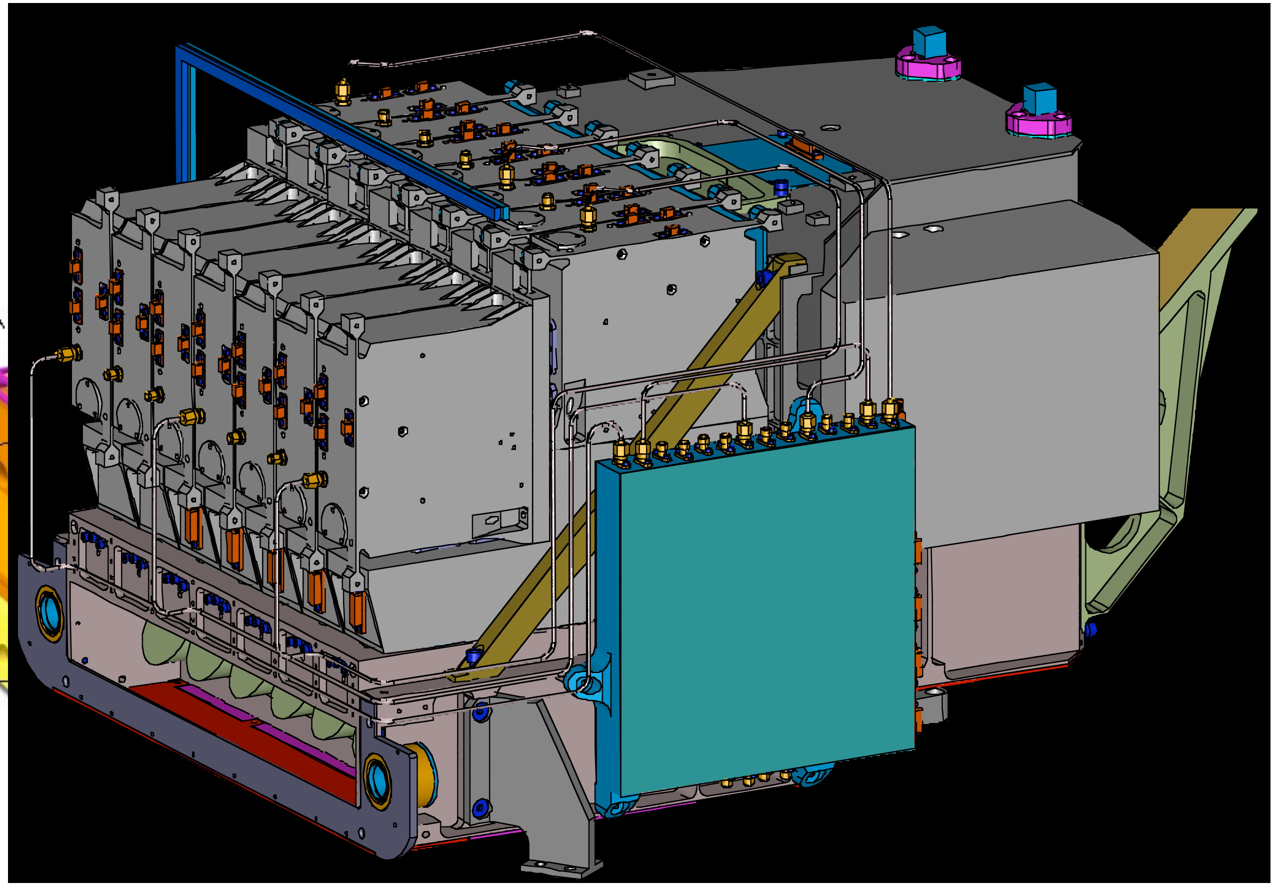
From SPIRE project

HIFI: The Heterodyne Instrument for the Far-Infrared

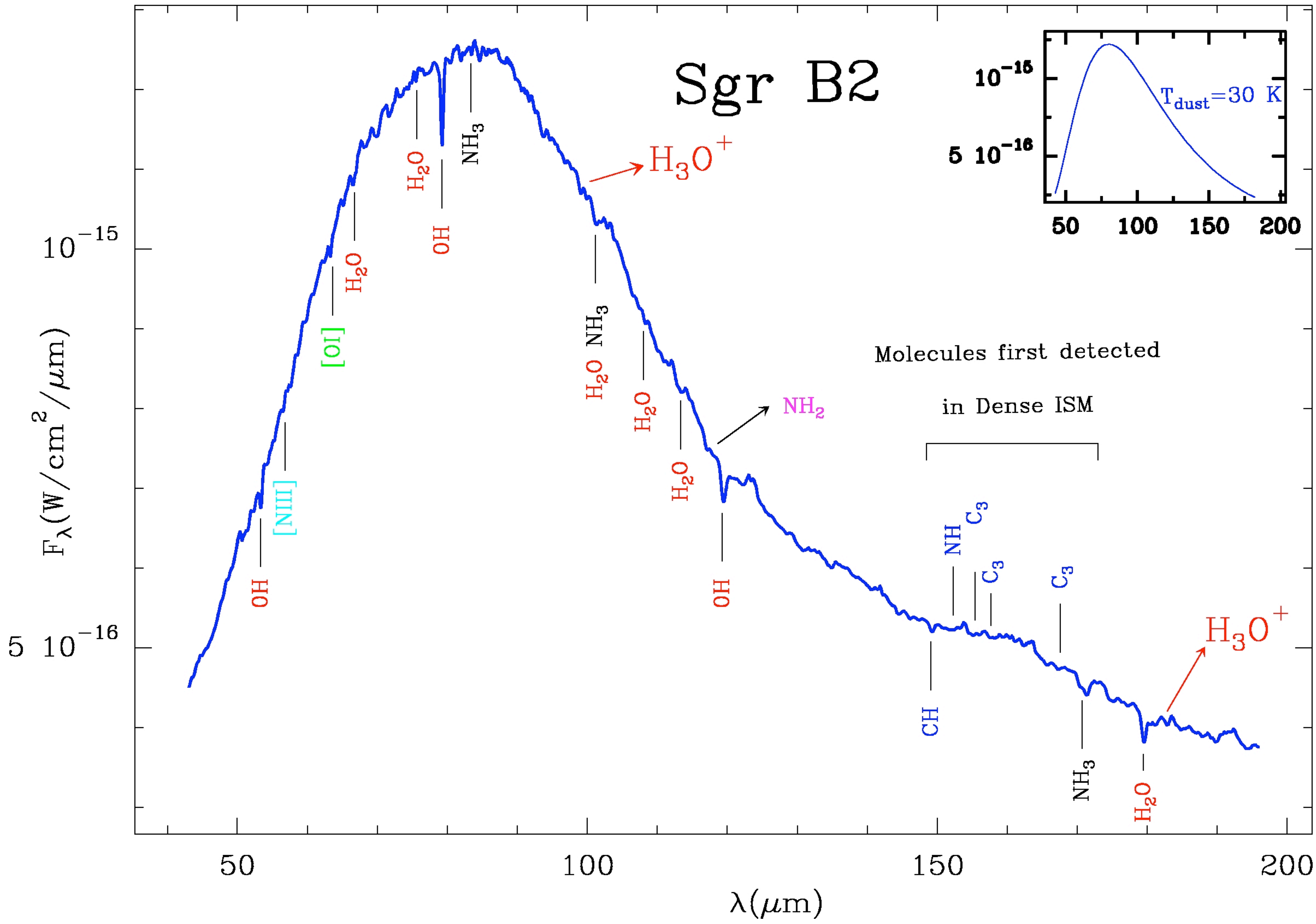
Science Capabilities:

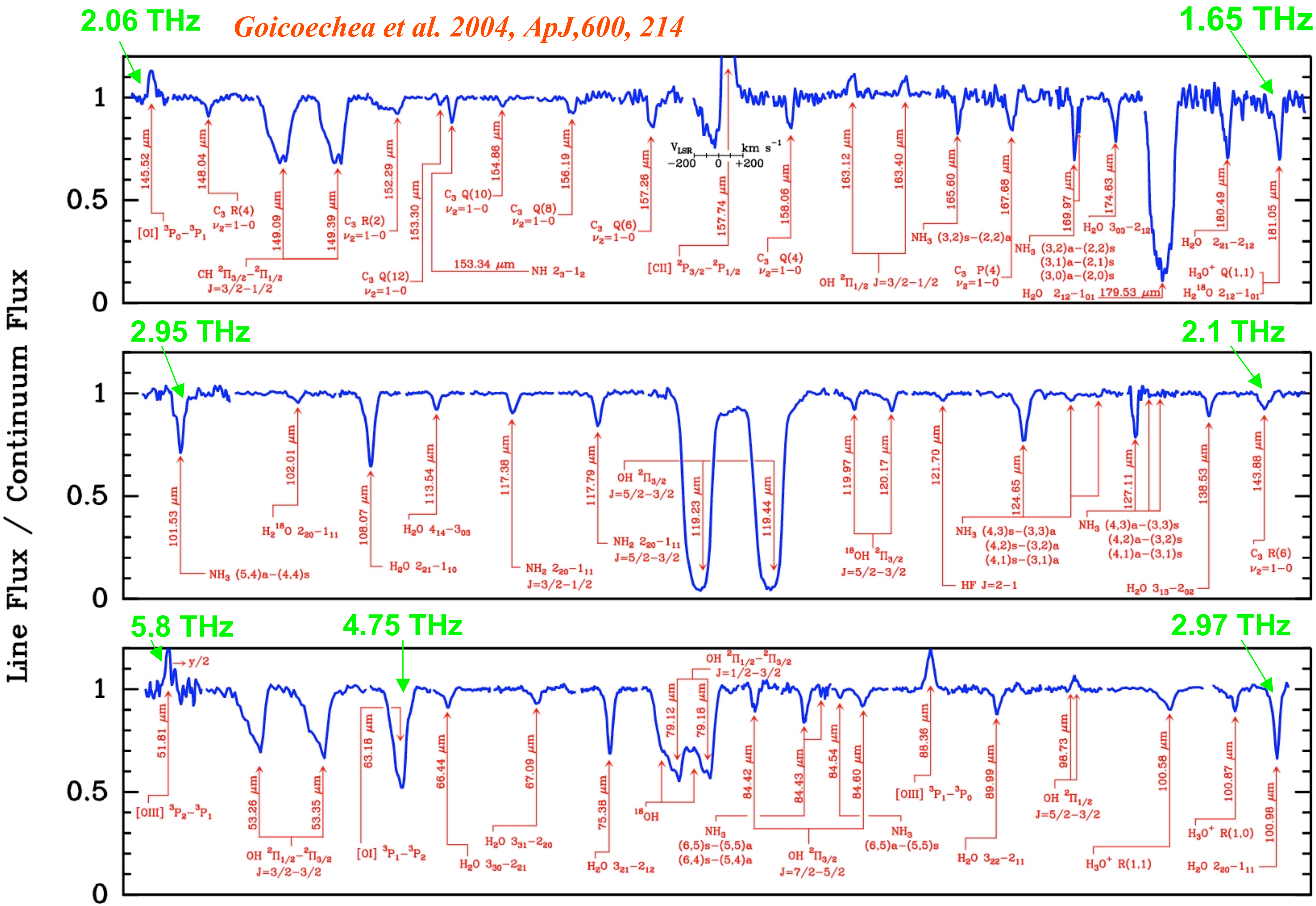
- Frequency coverage:
  - 480 - 1250 GHz (625 - 240 μm) [Bands 1 - 5]
  - 1410 - 1910 GHz (212 - 157 μm) [Bands 6L, 6H]
- Near-quantum noise limit sensitivity (goal < 3hν/k)
- Instantaneous IF bandwidth: 4 GHz
- Frequency Resolution 140 kHz - 280 kHz - 1 MHz
- Calibration Accuracy: 10% baseline; 3% goal





Cernicharo et al., A&A, 1997, 323, L25





Low resolution Spectroscopy with ISO (Infrared Space Observatory)

Herschel : Water Vapor

Galaxies

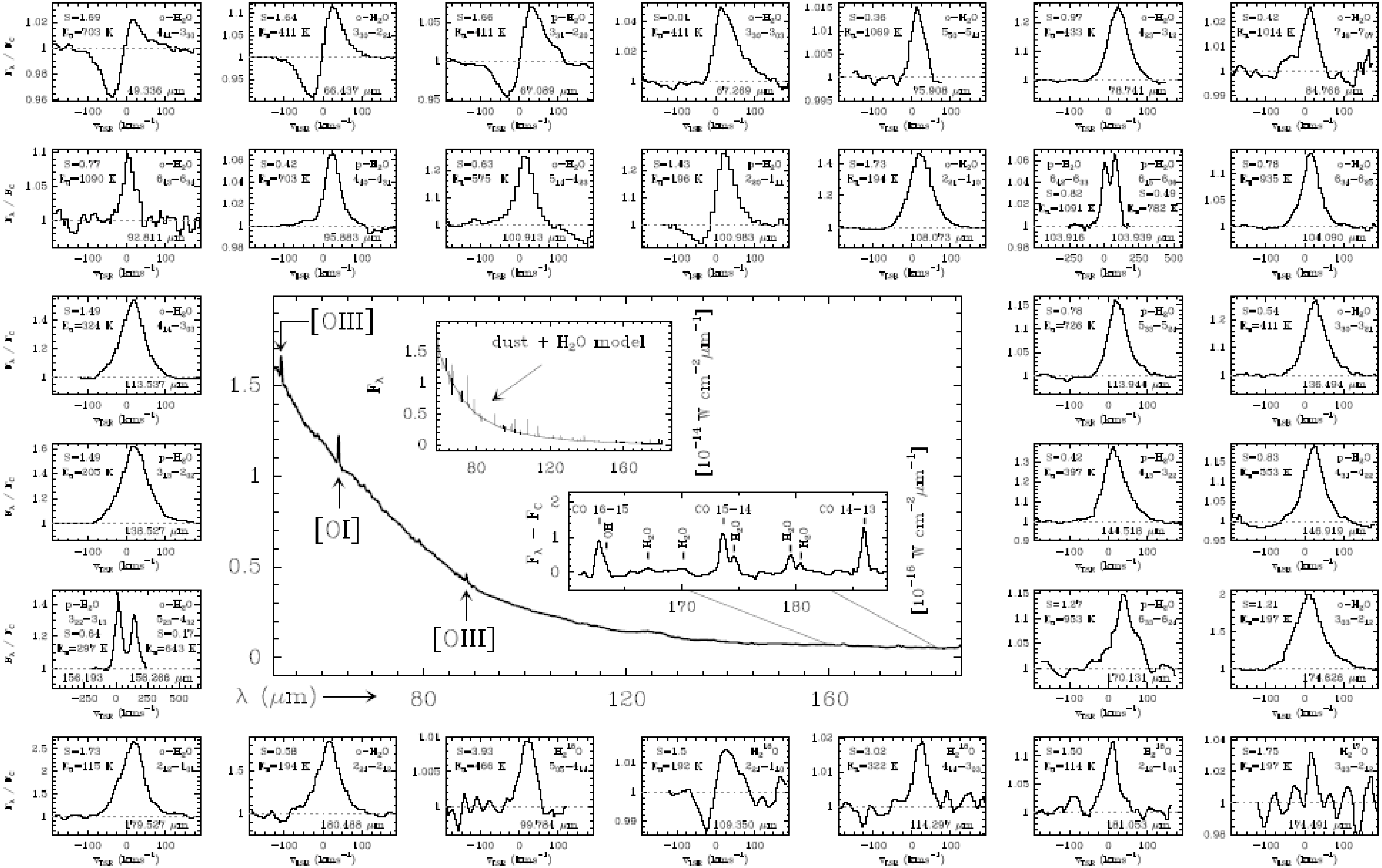
ISM

Star Formation

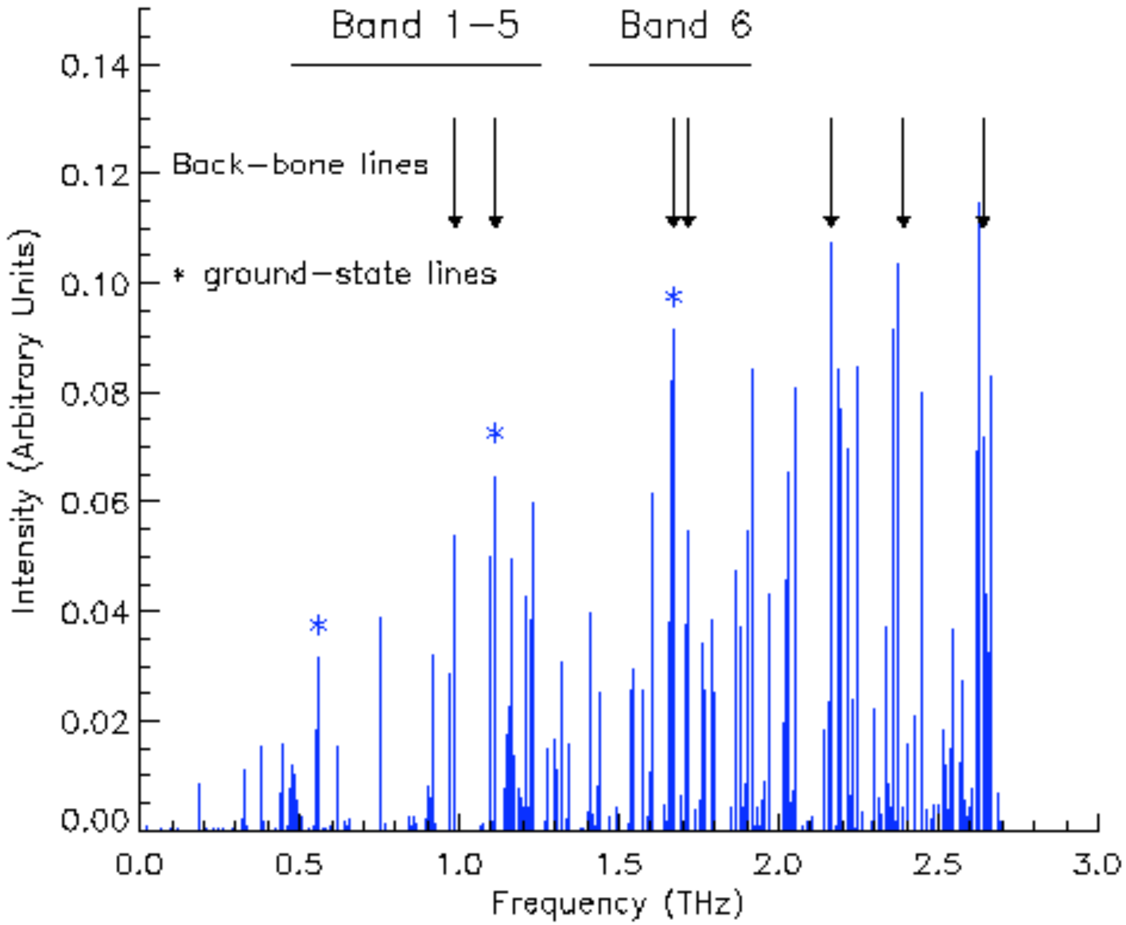
Evolved Stars

Water Vapor in Warm Gas around Massive Star Forming Regions : Orion

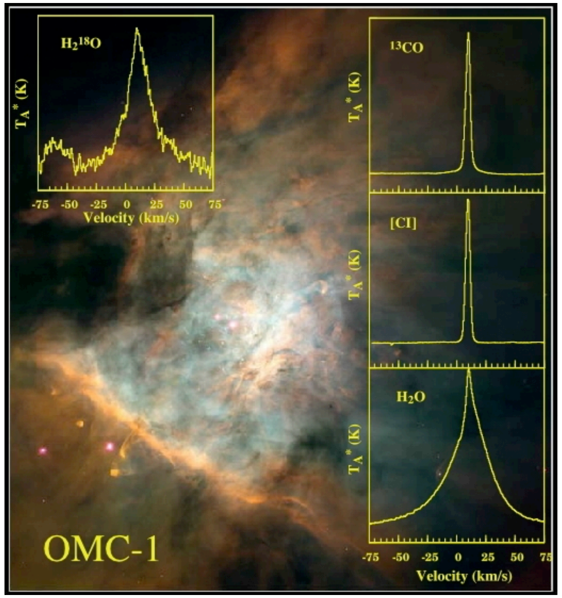
Cernicharo et al., 2006, ApJ Letters, 649, L33 (ISO spectral resolution 7000 :: Herschel 10^6)



Science with HIFI - Water

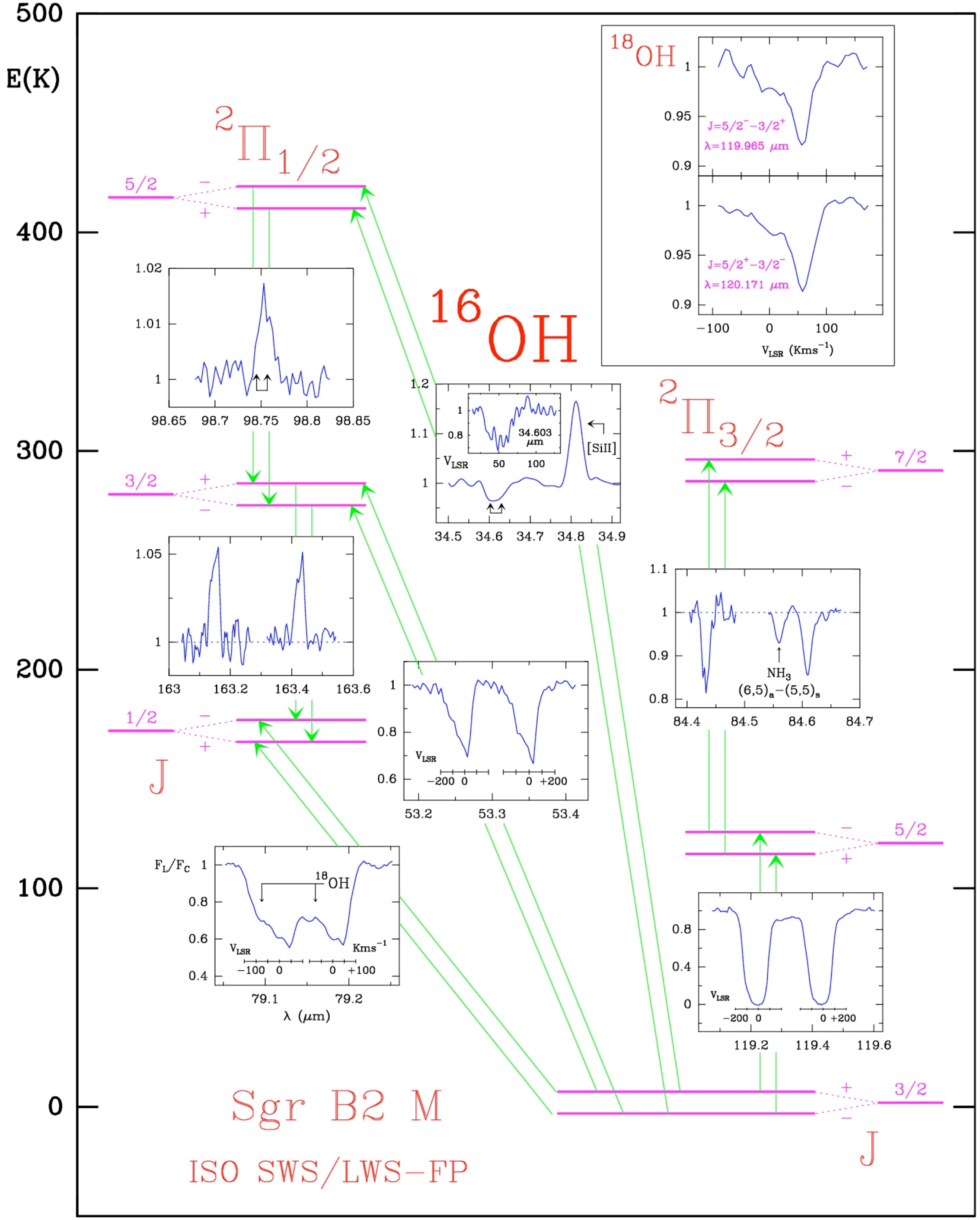


Laboratory Data



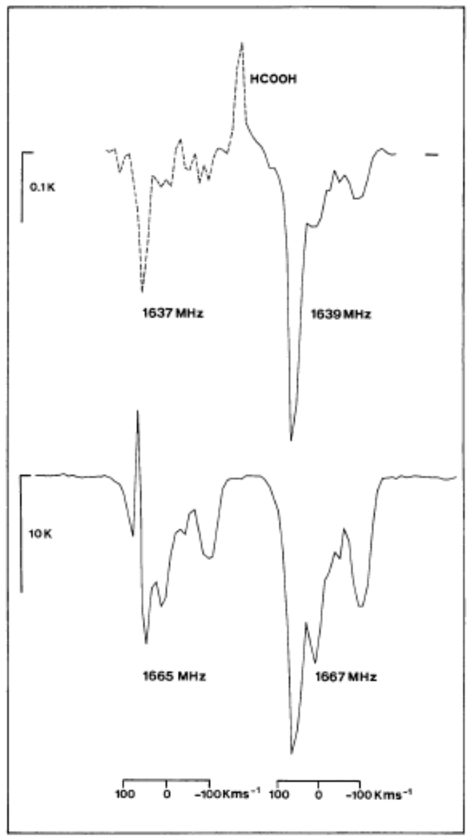
SWAS observations of the Orion Region OMC-1

Courtesy HIFI Project

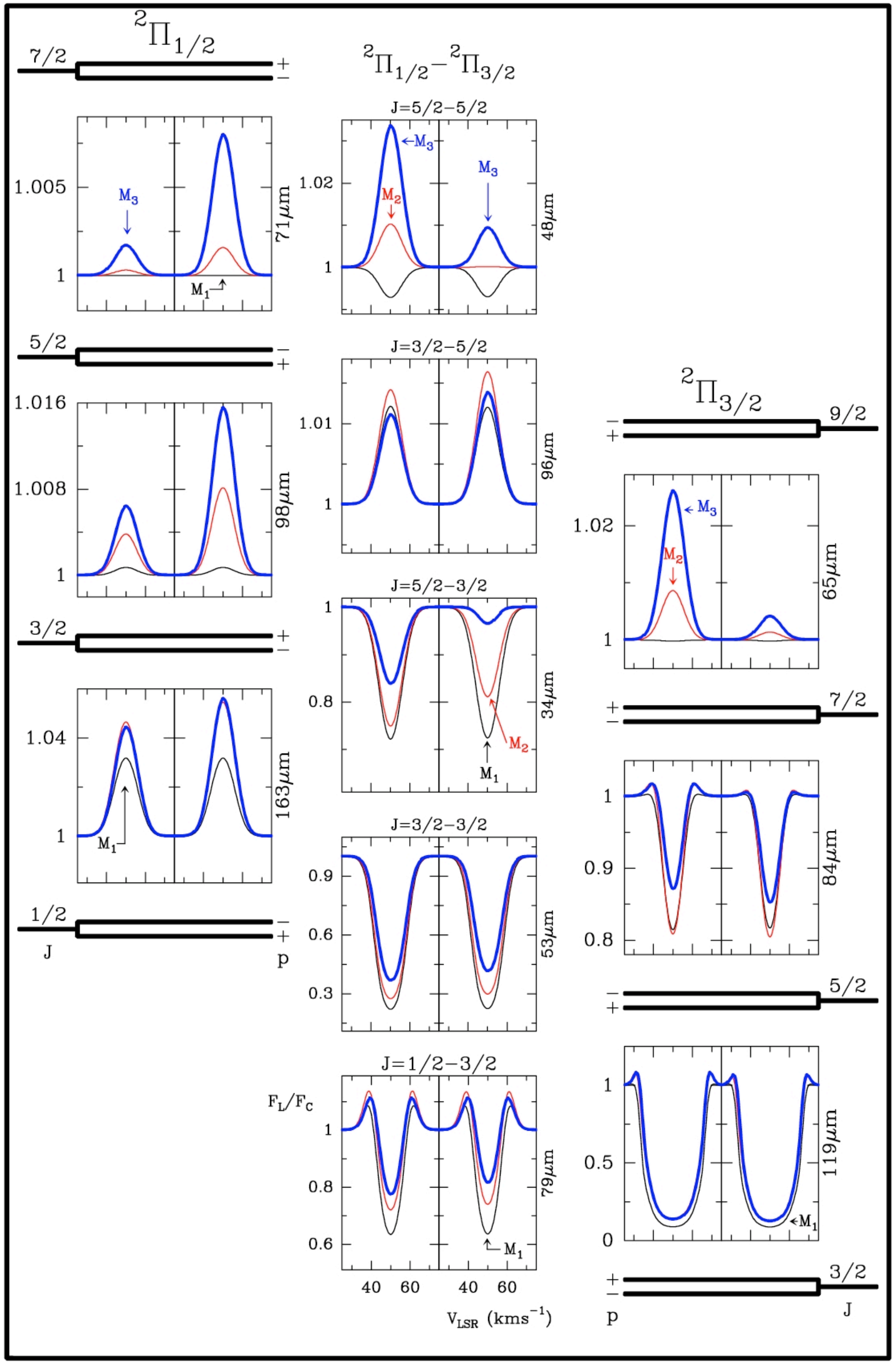


Goicoechea and Cernicharo, 2002, ApJ Letters, 576, L77

Strong asymmetries predicted for OH-H_2(J=0) non observed.



V. Bujarrabal[1,2], J. Cernicharo[1,3], and M. Guélin[4]
Astron. Astrophys. 128, 355–361 (1983)



OH models :

$T_K \approx 300$ K
$n(H_2) \approx$ a few 10^3 cm^{-3}
$X(OH) \approx$ a few 10^{-6} -10^{-5}
$x(OH)/x(H_2O) \approx 0.1$-1

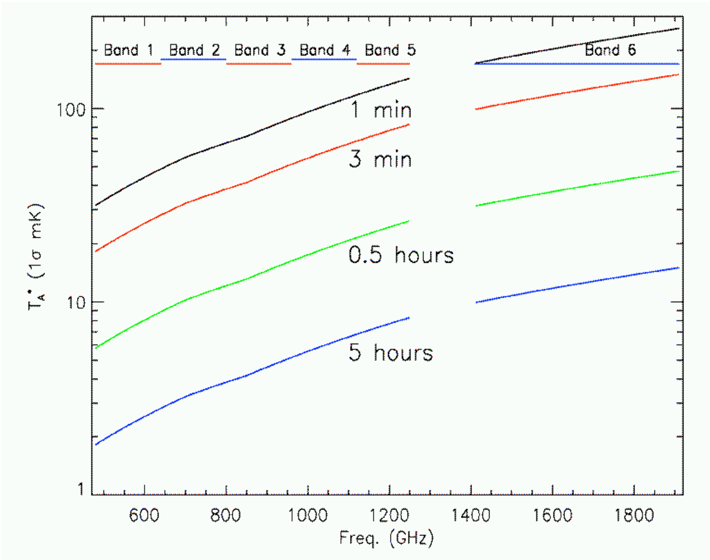
Sgr B2 is embedded in a large PDR (several arc min in size)

Goicoechea and Cernicharo, 2002, ApJ Letters, 576, L77

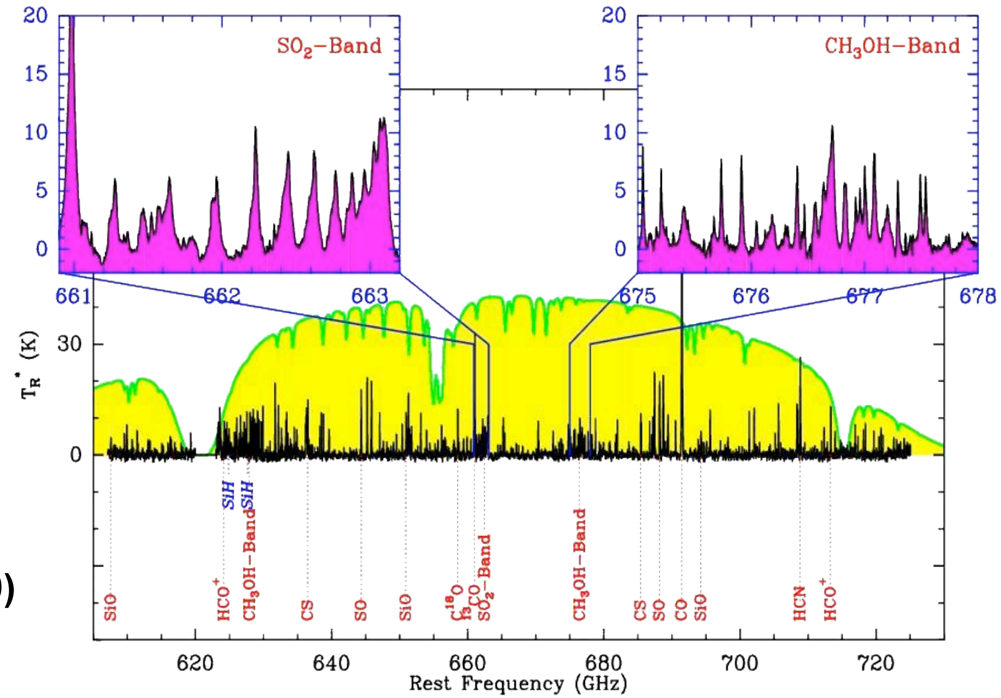
Goicoechea, Rodríguez, Cernicharo, 2004, ApJ, 600, 214

See also Cecarelli et al., 2001, A&A, -NH3-

HIFI Expected Performance



- Noise levels
- Setting 4 GHz
- Resolution 1 MHz
- DSB



- CSO Spectrum of Orion: 8 nights
- Same spectrum for HIFI: expected less than 1 hour
- Total HIFI range in 12 hours

(Schilke et al. 2000)

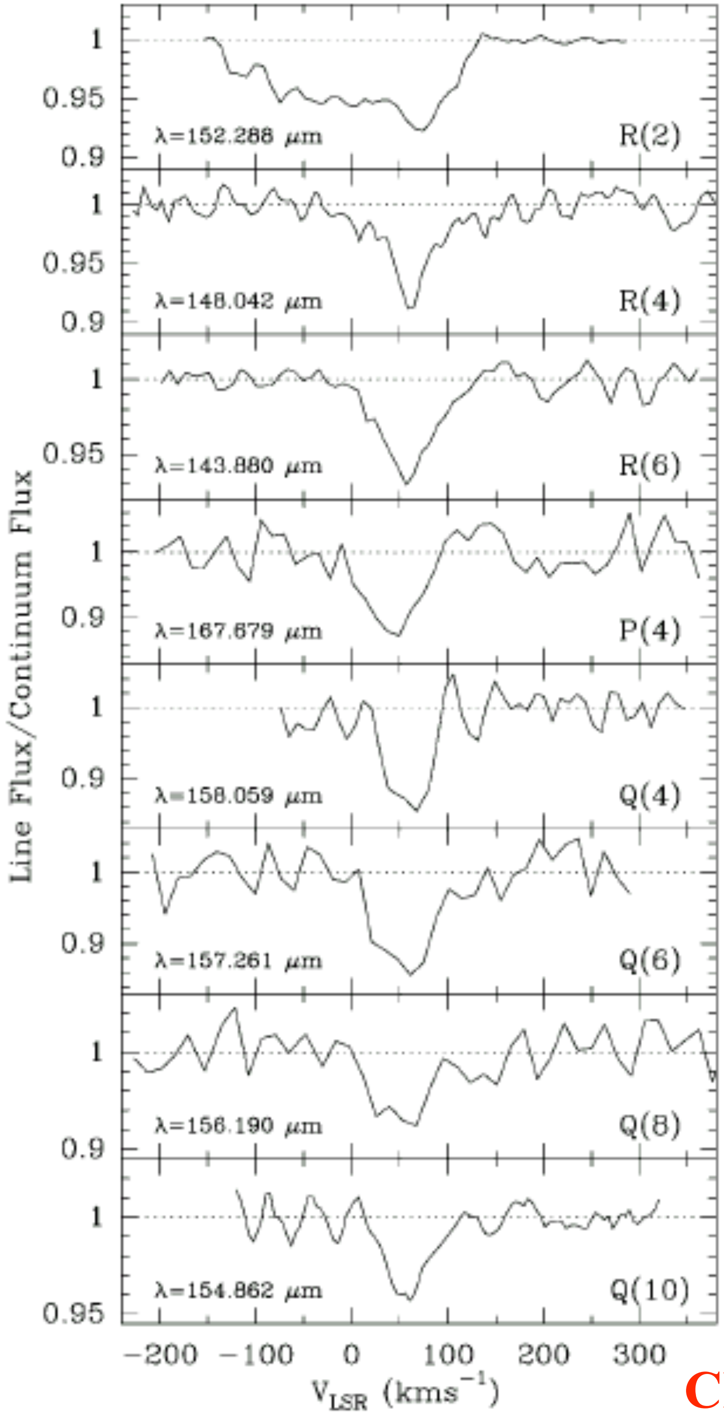
THE ASTROPHYSICAL JOURNAL, 534:L199–L202, 2000 May 10

FAR-INFRARED DETECTION OF C_3 IN SAGITTARIUS B2 AND IRC +10216[1]

JOSÉ CERNICHARO AND JAVIER R. GOICOECHEA
CSIC, Instituto de Estructura de la Materia, Departamento Física Molecular, Serrano 121, E-28006 Madrid, Spain
AND
EMMANUEL CAUX
Centre d'Etude Spatiale des Rayonnements, CESR/CNRS–Université Paul Sabatier, BP 4346 F-31029 Toulouse Cedex, France
Received 2000 February 11; accepted 2000 March 23; published 2000 May 5

ABSTRACT

We report on the detection of nine lines of the ν_2 bending mode of triatomic carbon, C_3, in the direction of Sagittarius B2. The $R(4)$ and $R(2)$ lines of C_3 have been also detected in the carbon-rich star IRC +10216. The abundances of C_3 in the direction of Sgr B2 and IRC +10216 are $\simeq 3 \times 10^{-8}$ and $\simeq 10^{-6}$, respectively. In Sgr B2 we have also detected the 2_3–1_2 line of NH with an abundance of a few times 10^{-9}. Polyatomic molecules will have a weak contribution from their pure rotational spectrum to the emission/absorption in the far-infrared. We suggest, however, that they could be, through their low-lying vibrational bending modes, the dominant carriers of emission/absorption in the spectrum of bright far-infrared sources.



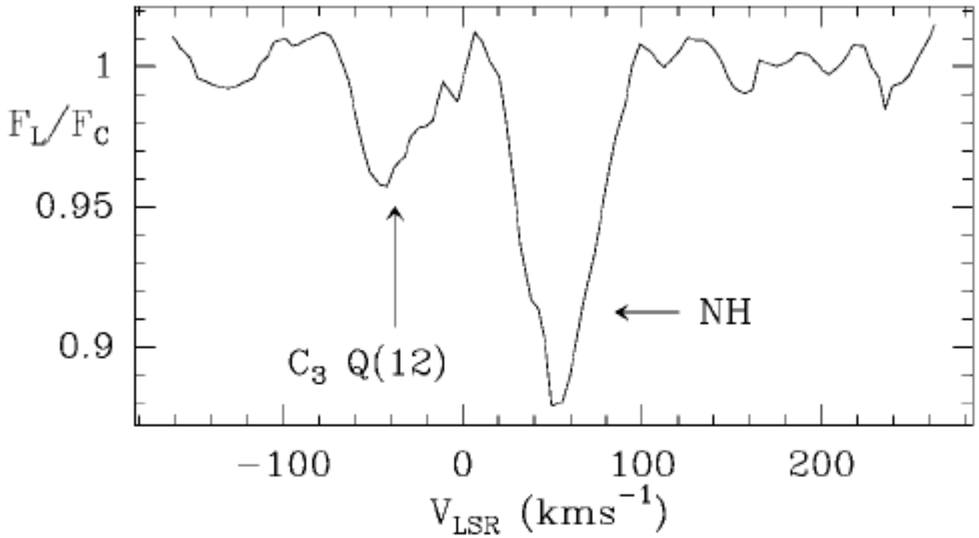
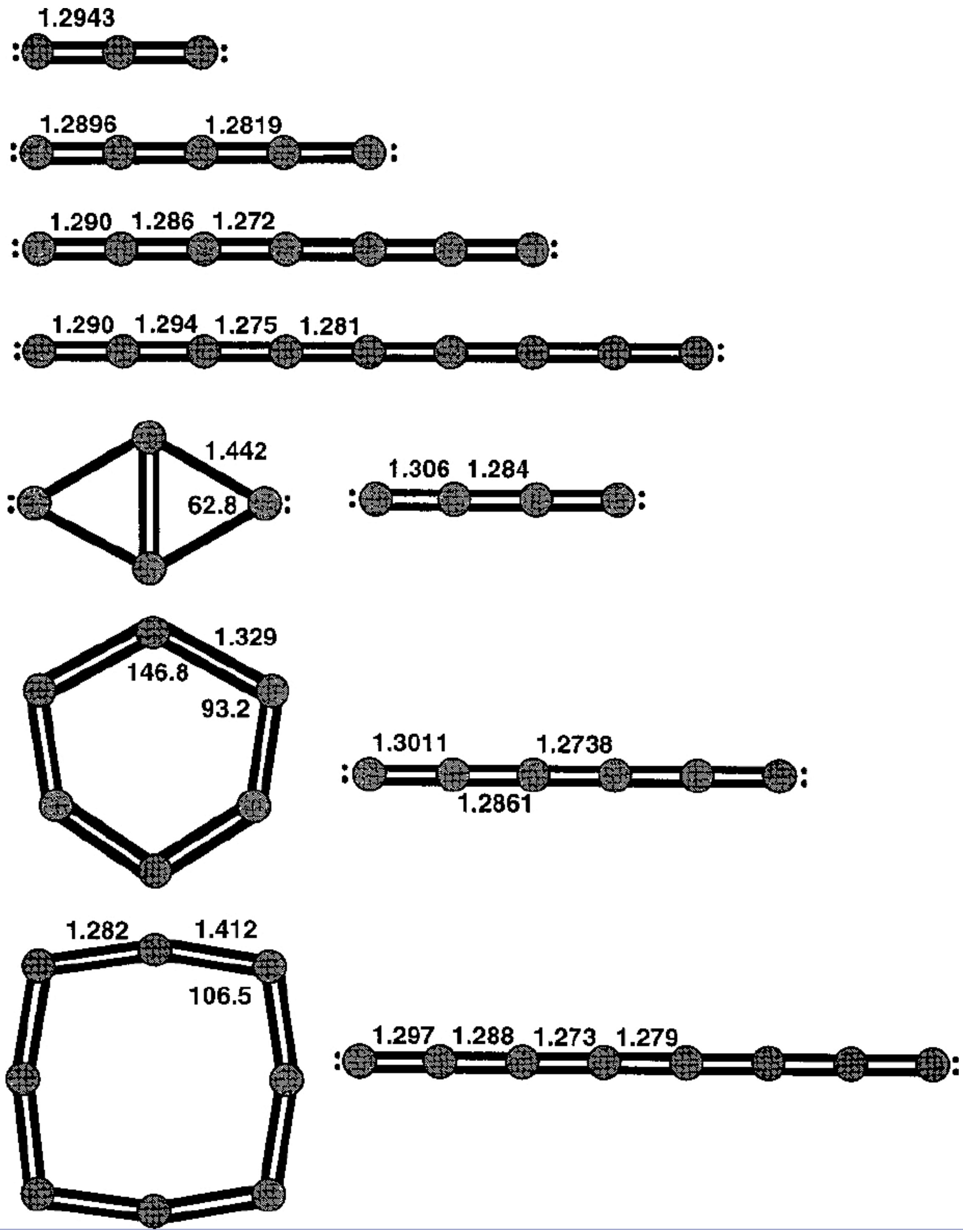


FIG. 3.—The 2_3–1_2 line of NH in Sgr B2. In the same spectrum, the C_3 $Q(12)$ is also detected with an absorption of 3.5%.

CHEMICAL COMPLEXITY WITH HERSCHEL



Cumulenic Carbon Clusters

C_3 ν_2=63.4 cm^{-1} (158 µm)

C_4 ν_5= 160±4 cm^{-1} (61-64 µm)

C_5 ν_7= 107±5 cm^{-1} (89-98 µm)

C_6 ν_9= 90±50 cm^{-1} (71-250 µm)

C_7 ν_{11}= 80 cm^{-1} (125 µm)

C_8 ??

C_9 ν_{15}= 51 cm^{-1} (196 µm)

C_{10} ? (linear isomer observed)

Orden & Saykally 1998
Chem. Rev. 98, 2313

HERSCHEL domain

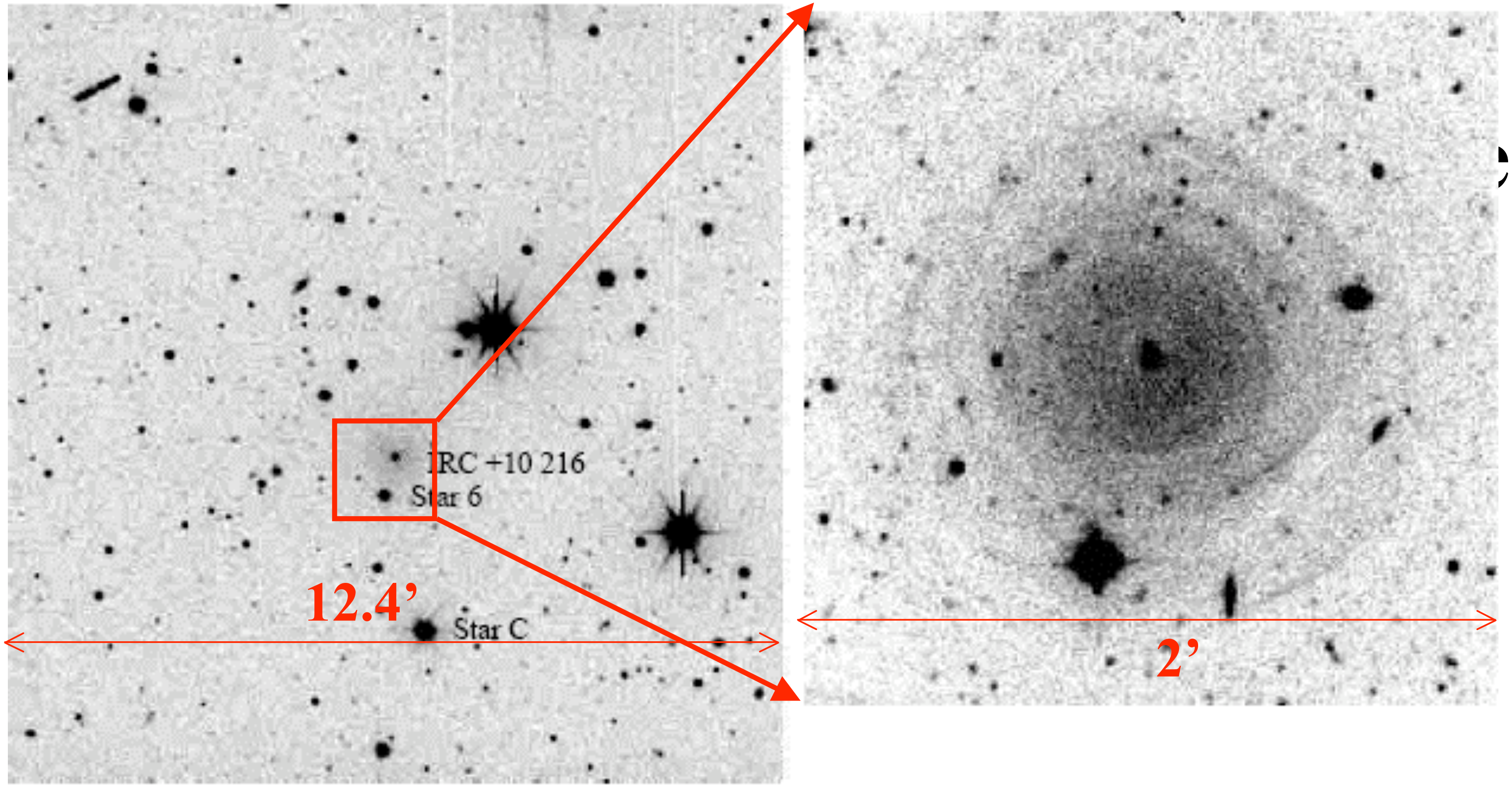
Evolved stars:

O-rich stars : H_2O a key molecule

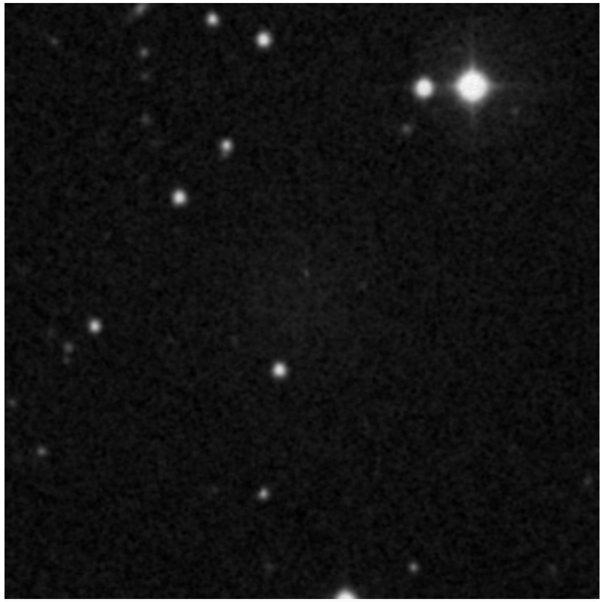
HERSCHEL

C-rich AGBs and ProtoPlanetary Nebula :

HERSCHEL AND ALMA



IRC +10º 216, Kendall 2002



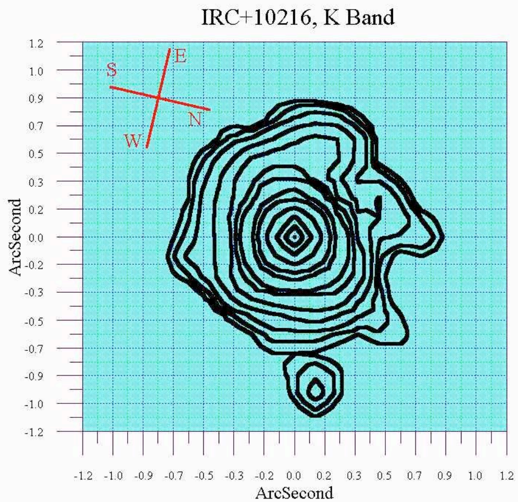
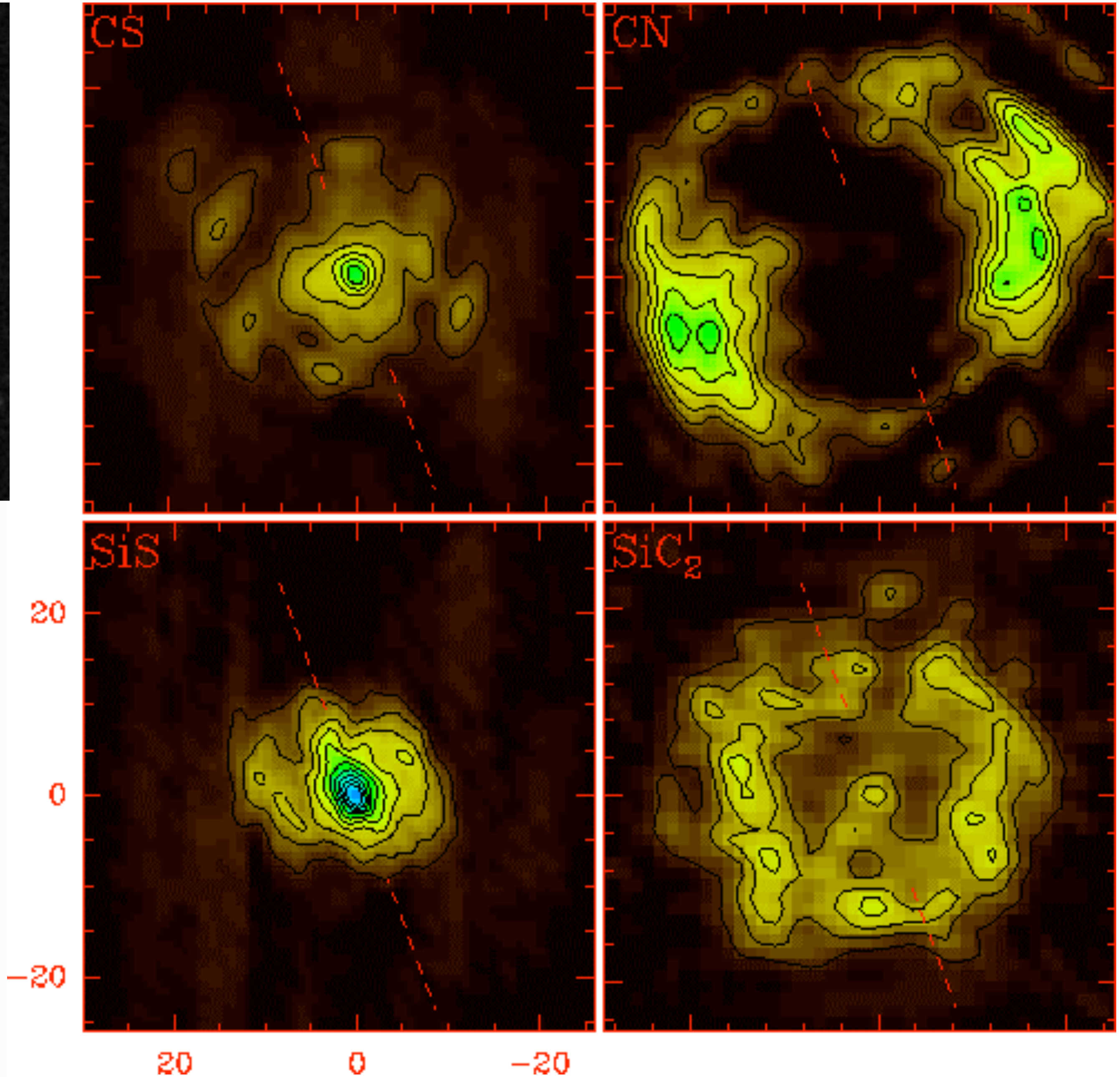
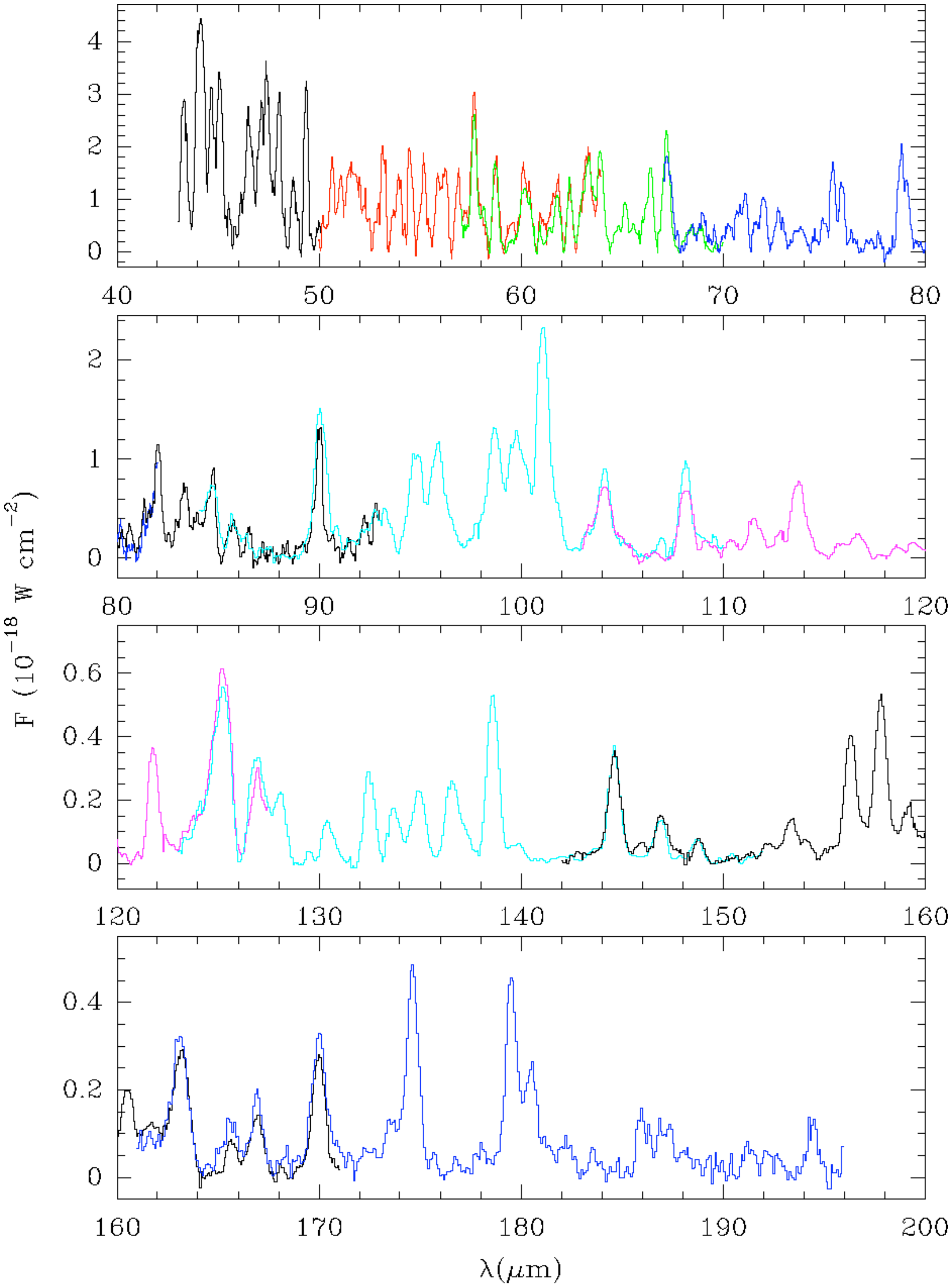


Figure 3: Contour plot of the carbon rich star IRC+10216.



Evolved stars : The space factories of complex organic molecules



ISO DATA

VY CMa (O-rich star)

All features are real

All pure rotational lines of wapour with >43 um detected

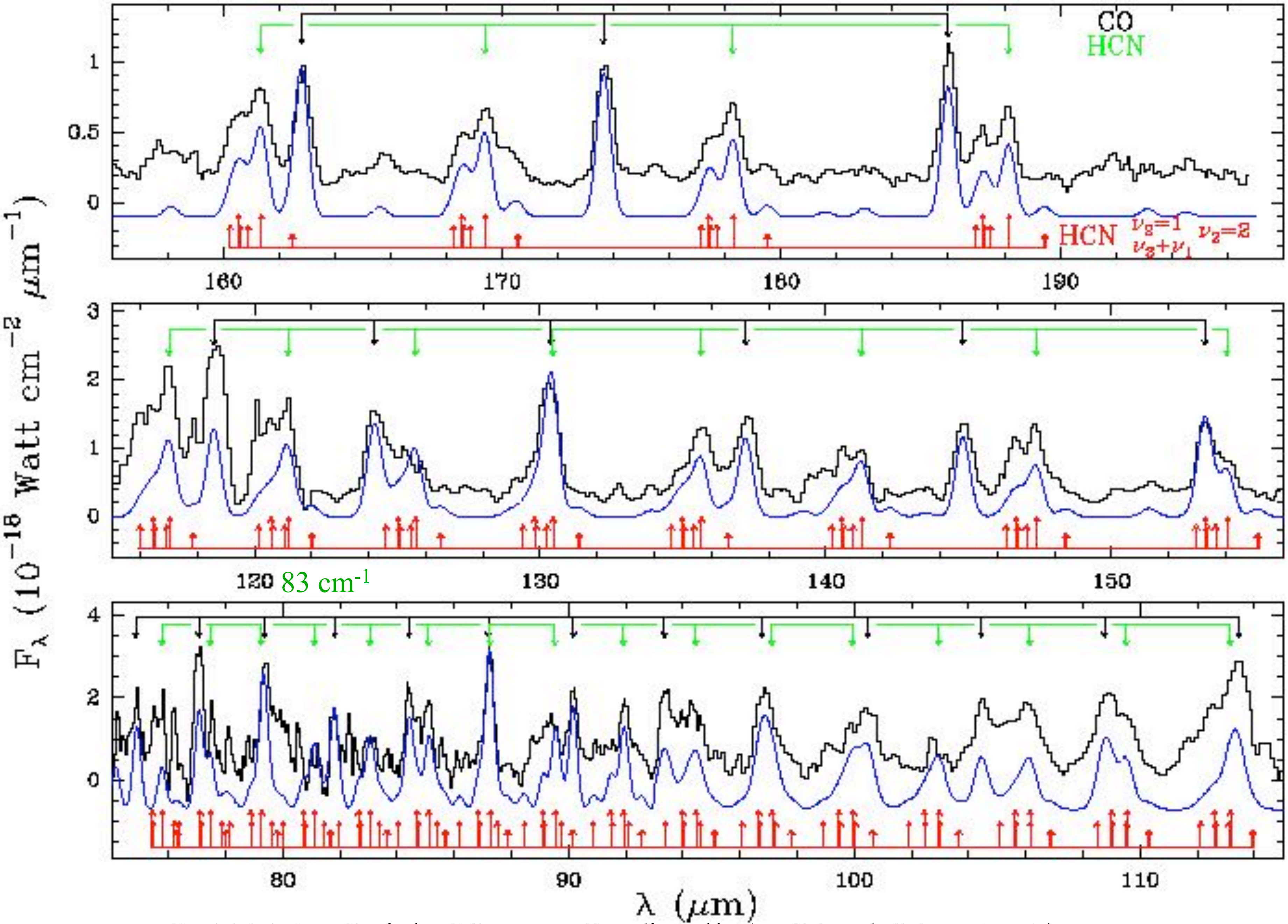
Some lines from the v_2=1 bending level also detected

Modelling requires collisional rates for Tk=20-2000 K including ro-vibrational collisions

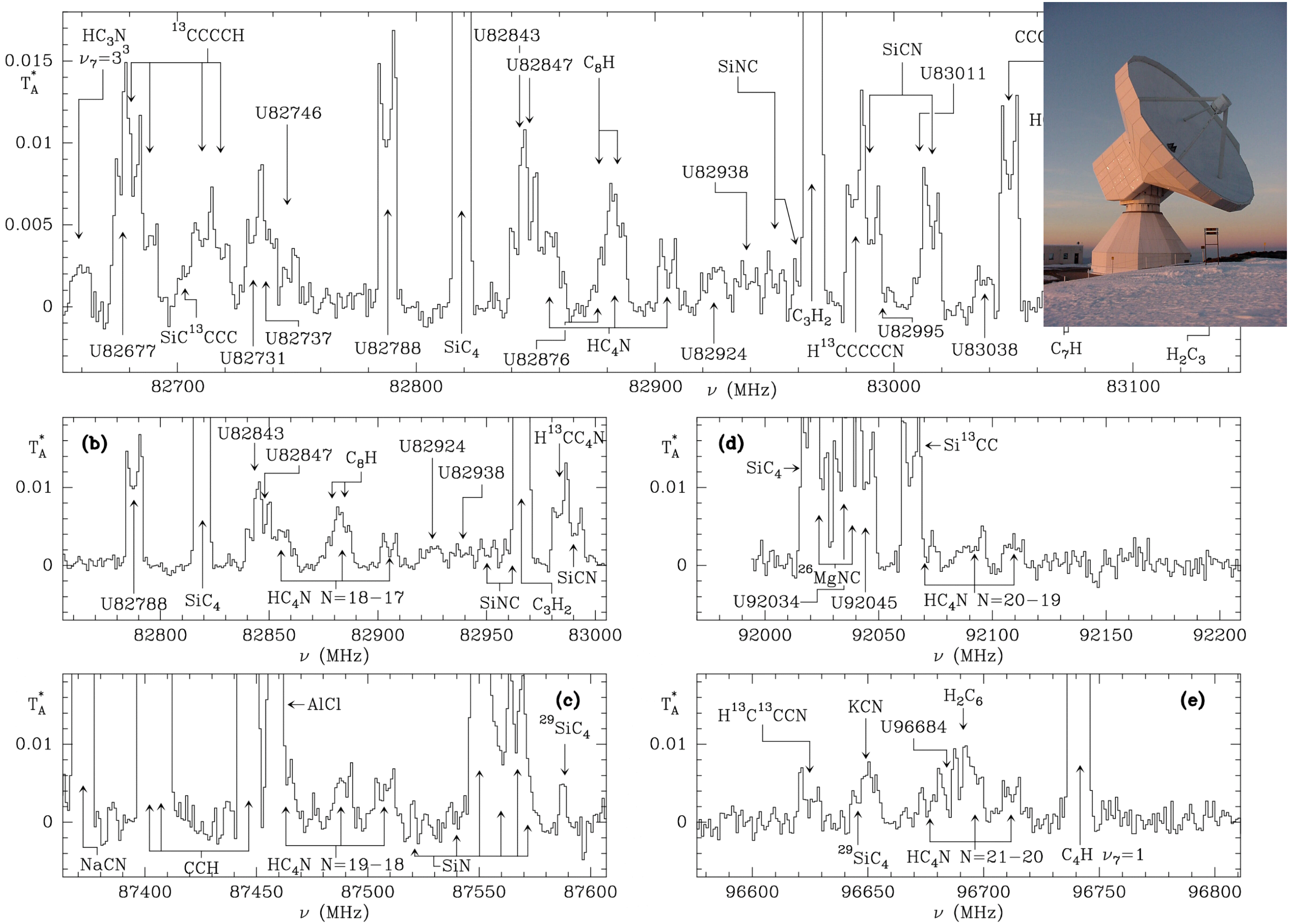
HERSCHEL :HIFI, PACS, SPIRE
ALMA : 183.3 (?) & 325 GHz

Asensio, Cernicharo, González-Alfonso in preparation

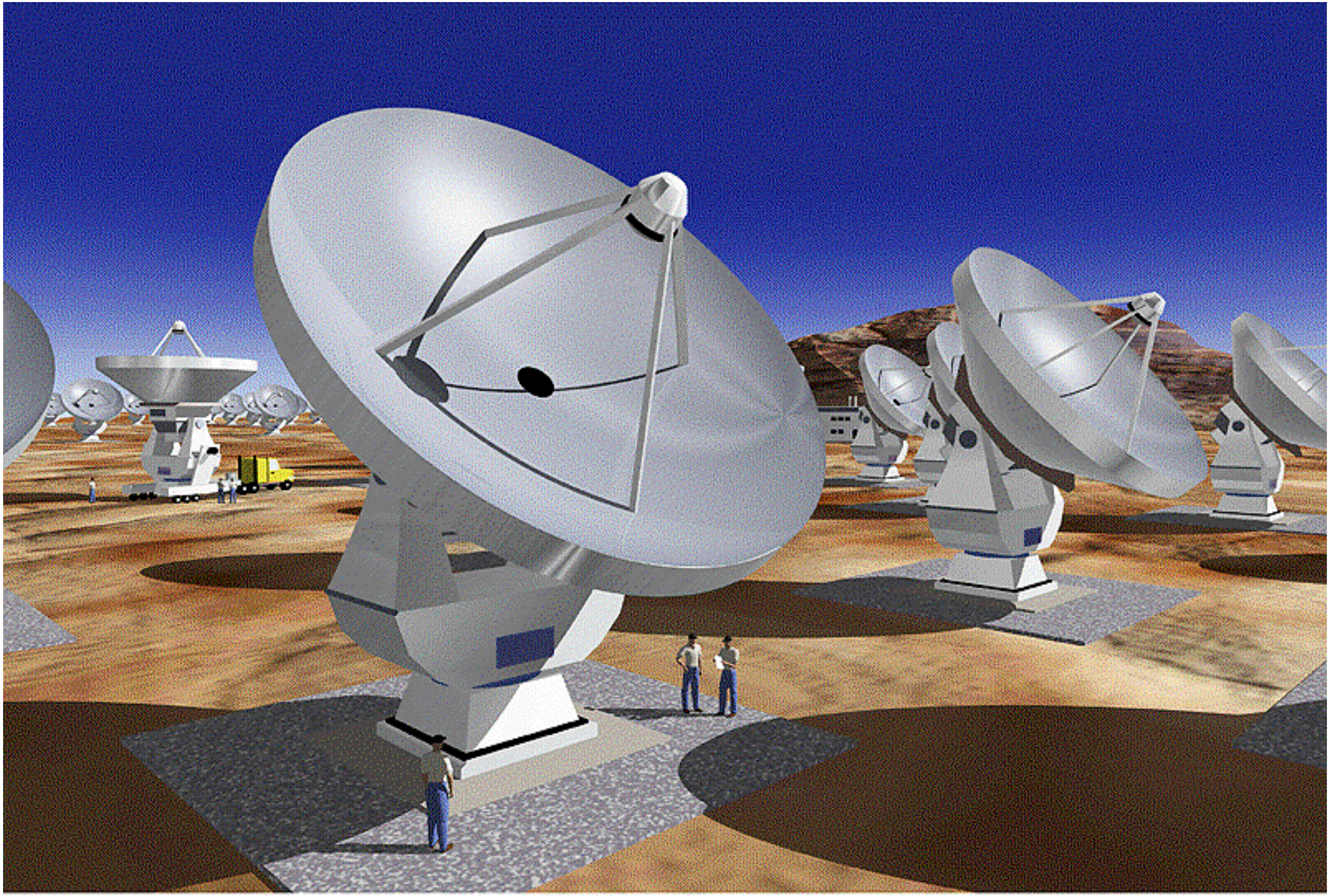
Cernicharo et al., 1996, A.&A., 315, 201



IRC+10216 a C-rich CSE :: HCN (in all v), CO (ISO DATA)

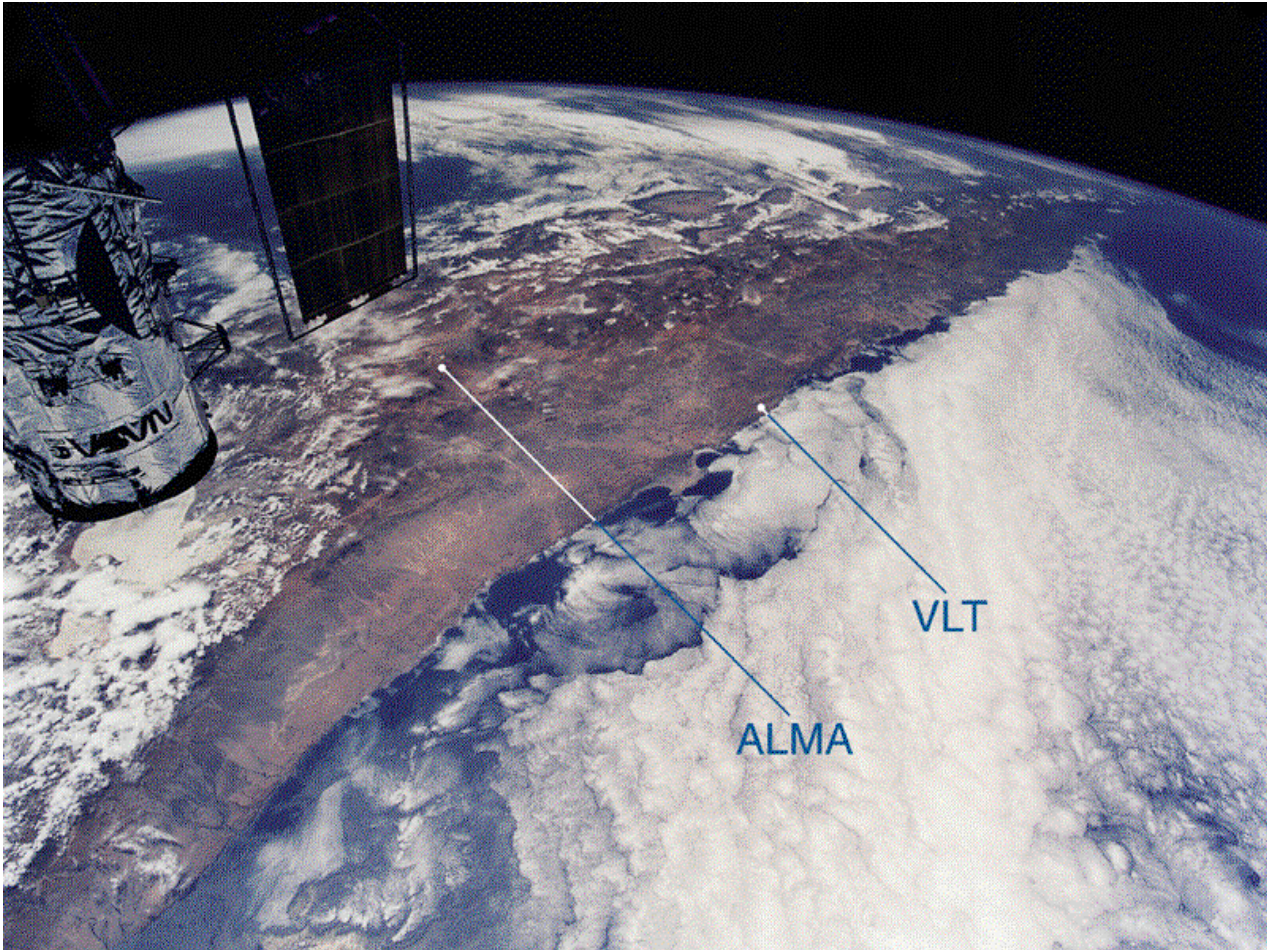


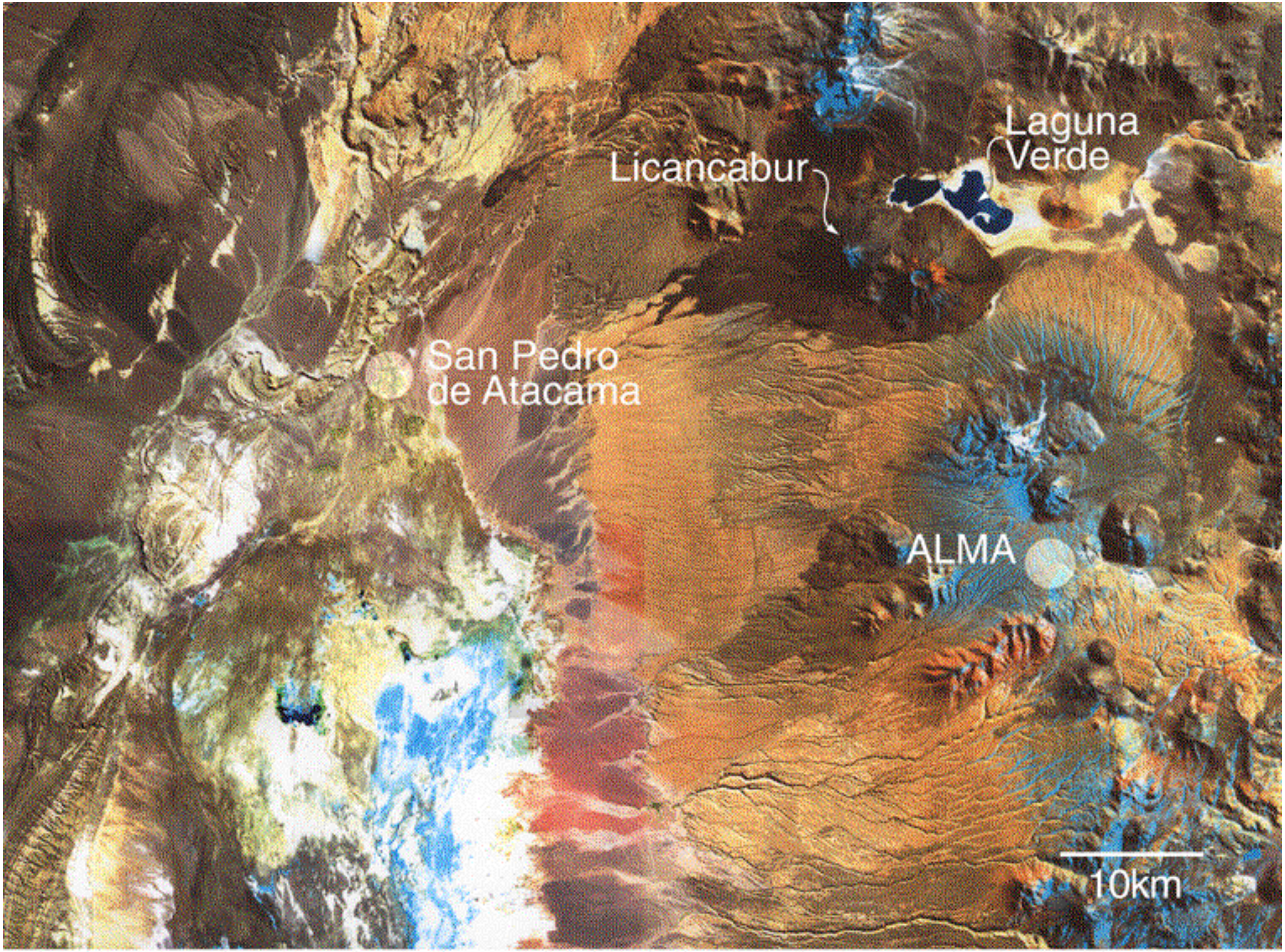
HC_4N :: Cernicharo et al., 2004, ApJLetters, Nov. issue   SiNC: Guélin et al., 2004, A&A

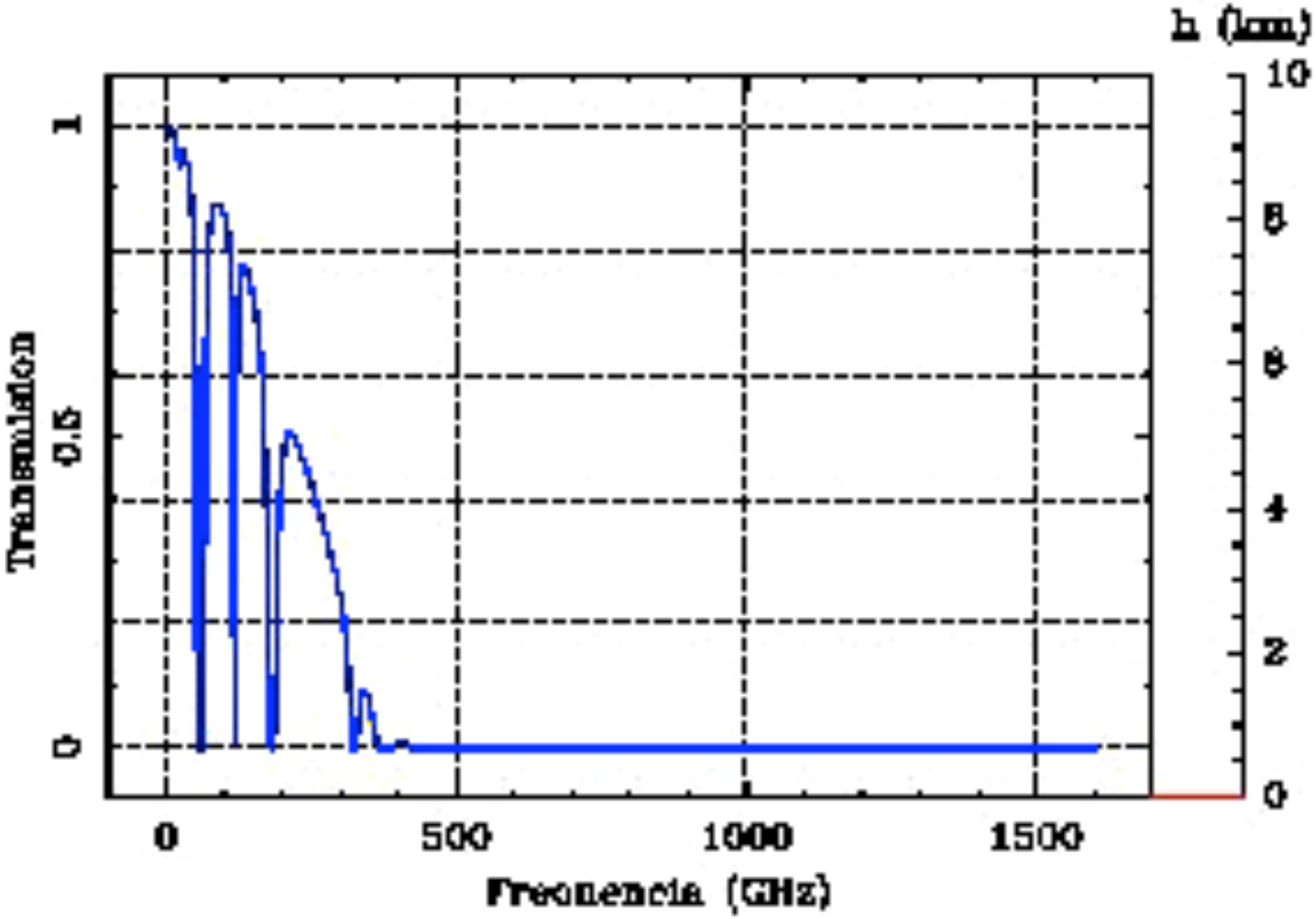


Artist's Impression of ALMA
(Atacama Large Millimetre Array)

ESO PR Photo 24a/99 (8 June 1999)


VLT
ALMA
NASA


Laguna Verde
Licancabur
San Pedro de Atacama
ALMA
10km

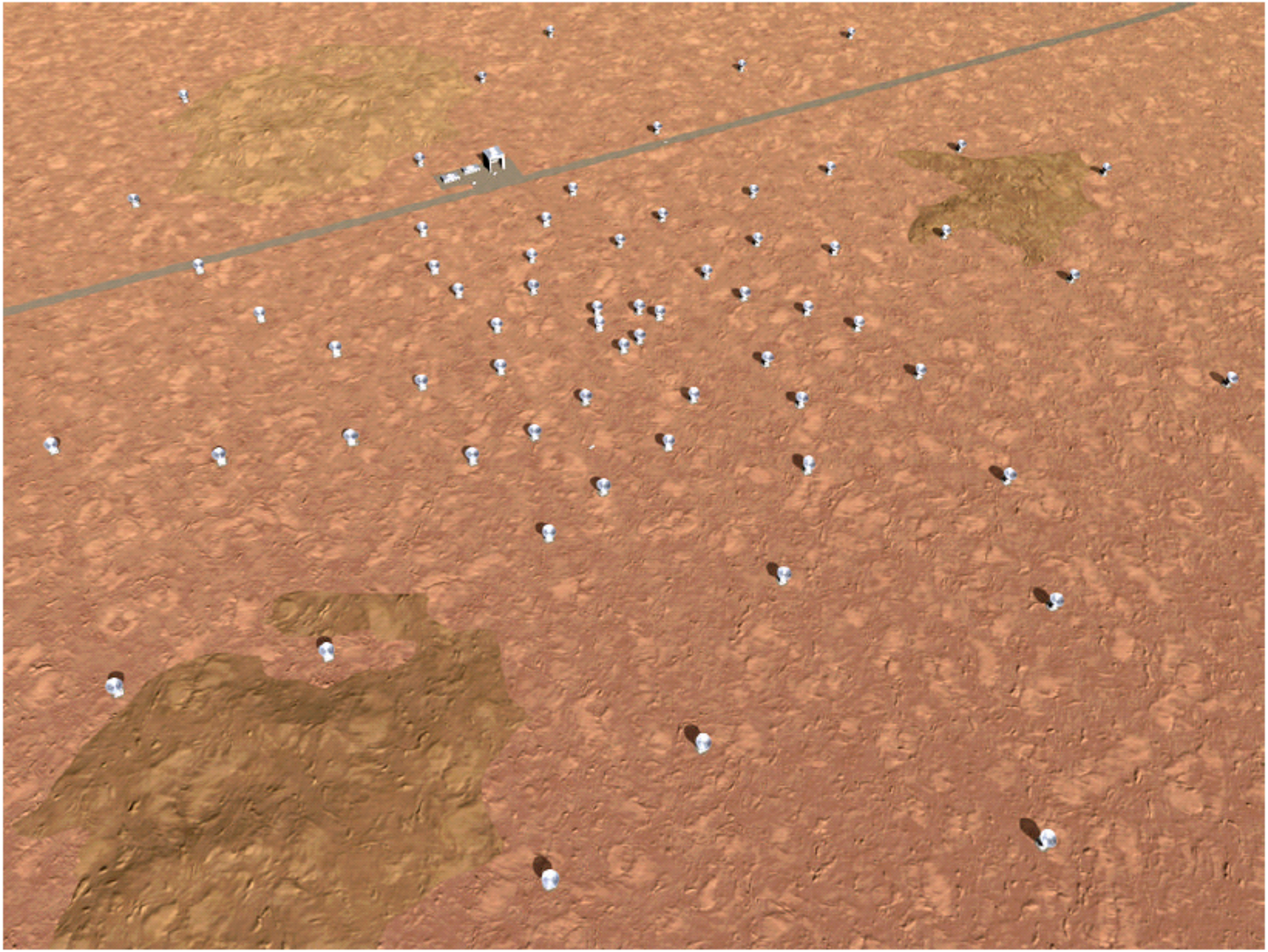

h (km)
10
8
6
4
2
0
1
0.5
0
Transmision
0
500
1000
1500
Frecuencia (GHz)

ALMA

- 64 antennas, transportable **50 after rebaseline !!**
  - 12-m diameter, transportable
  - 25 microns rms surface error
  - 0.6" rms offset pointing error in winds < 9 m/s
  - Fast switching (1.5 degrees in 1.5 sec)
- Configurations from 150-m to 14 km, as continuous as possible.
- 4 frequency bands, dual-polarisation
  - Band 3, 84-119 GHz, SSB
  - Band 6, 211-275 GHz, SSB
  - Band 7, 275-370 GHz, SSB
  - Band 9, 602-720 GHz, DSB
- 183 GHz Water Vapor Radiometers for phase calibration
- 8 GHz bandwidth per polarisation
- High accuracy calibration (3 % absolute, with 1 % goal)
- "Easy to use" instrument

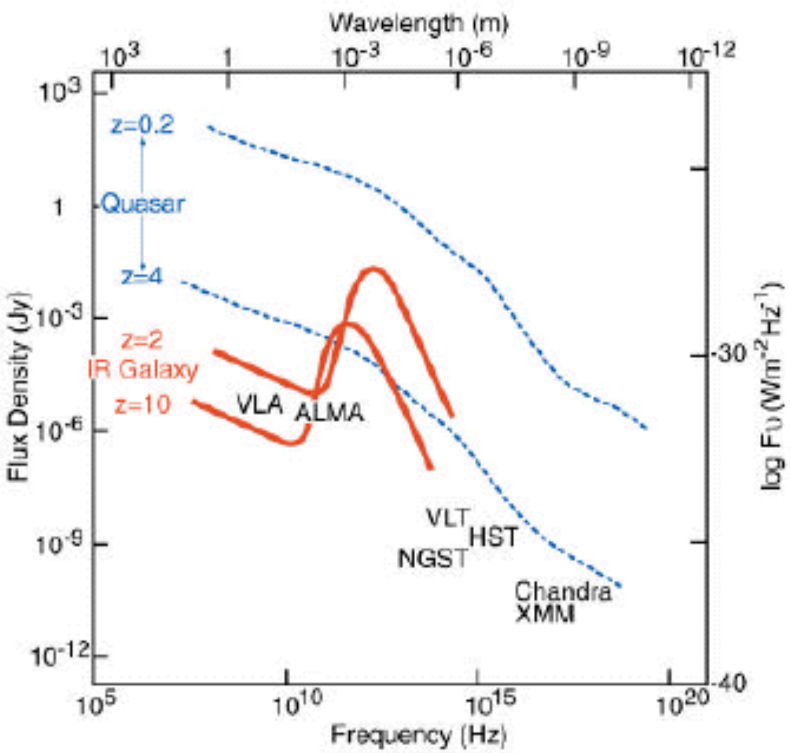
Table .1 – Frequency bands for ALMA

Band	from (GHz)	to (GHz)	
1	31.3	45	
2	67	90	
3	89*	116	**Baseline**
4	125	163	← Japan
5	163	211	
6	211	275	**Baseline**
7	275	370	**Baseline**
8	385	500	
9	602	720	**Baseline**
10	787	950	←

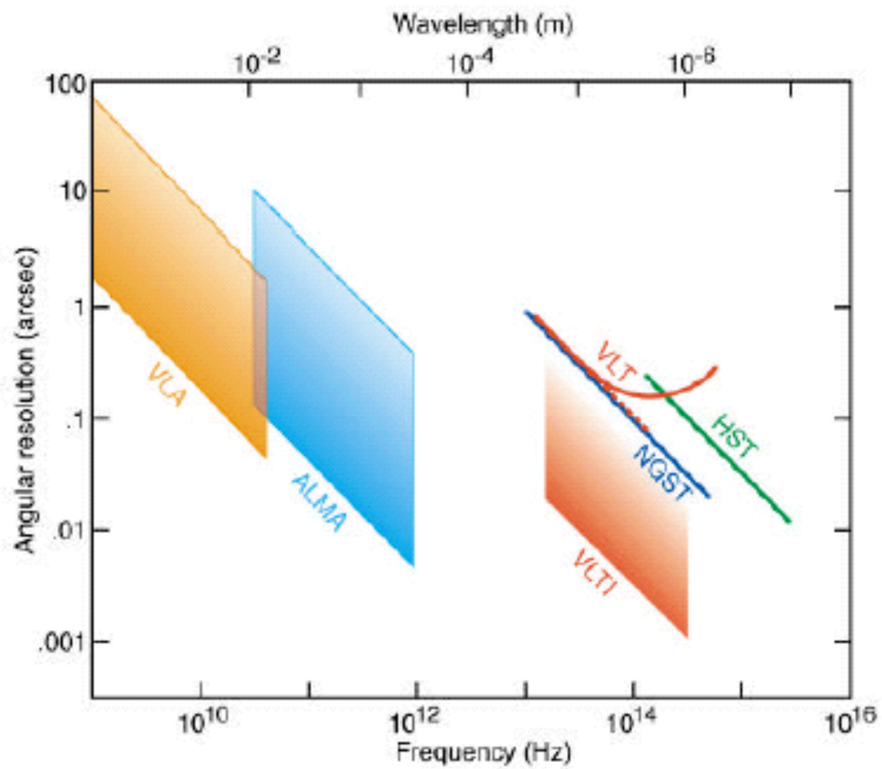


A mm/submm equivalent of VLT, HST, NGST

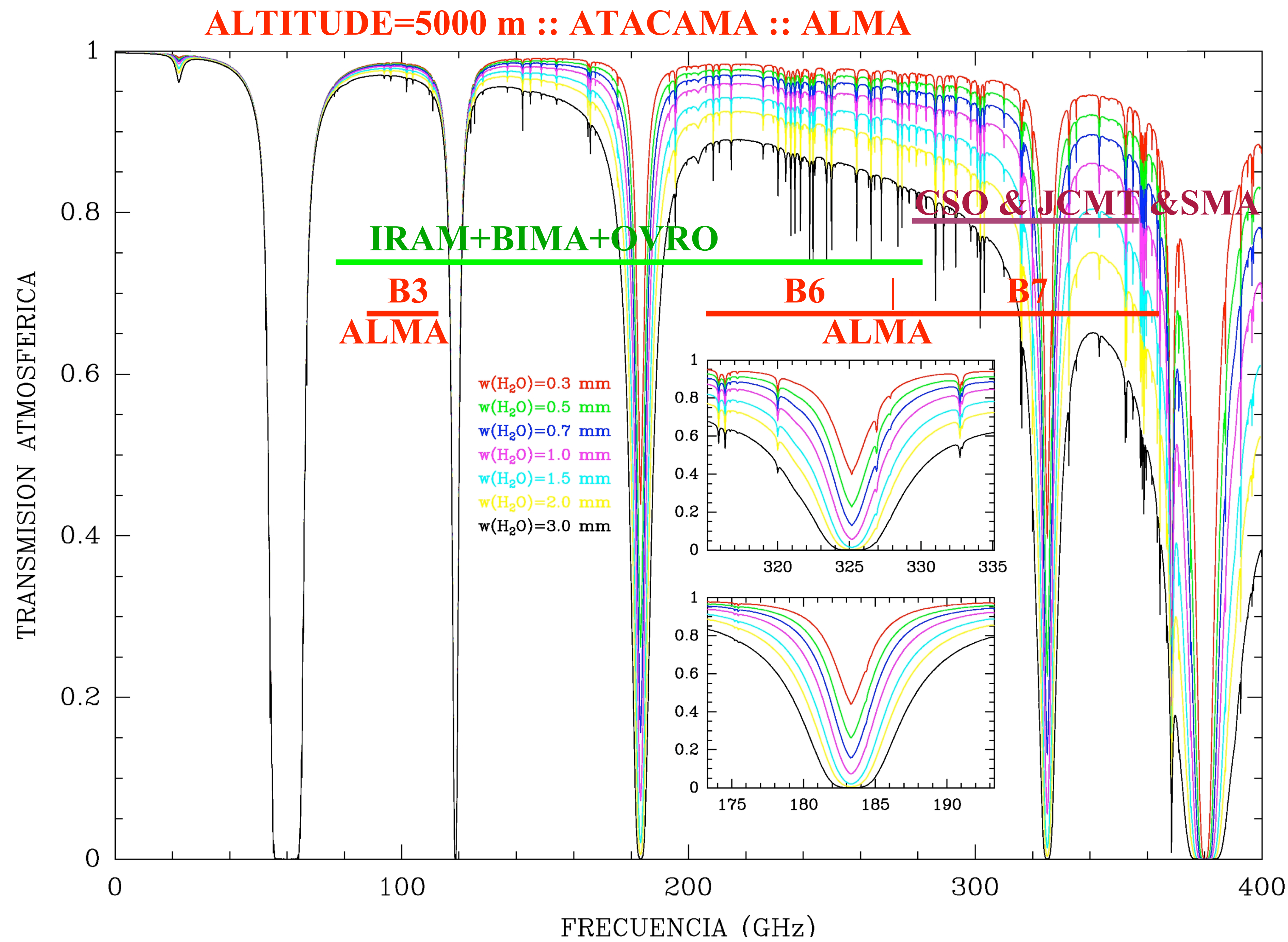
Sensitivity

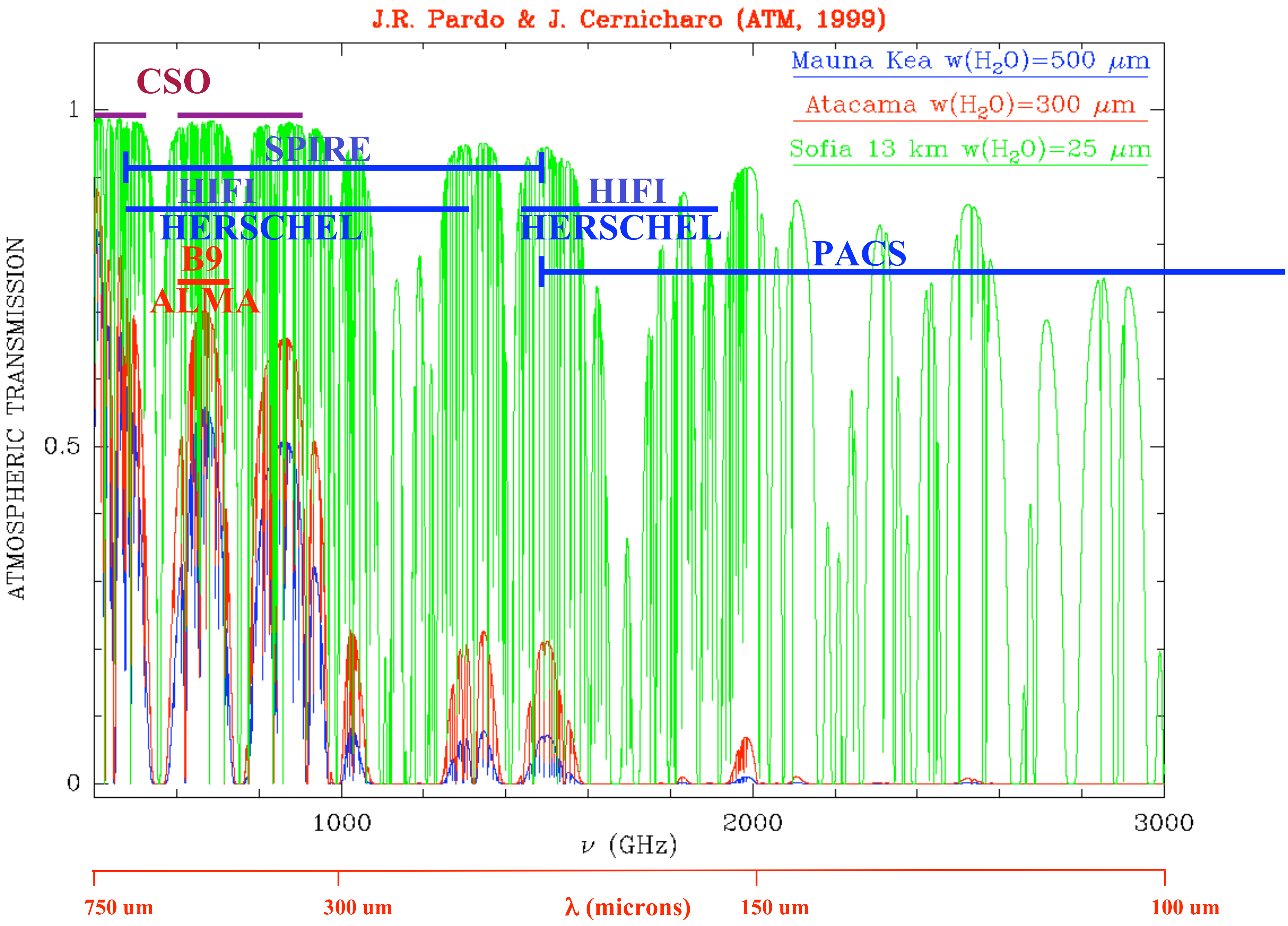


Angular Resolution

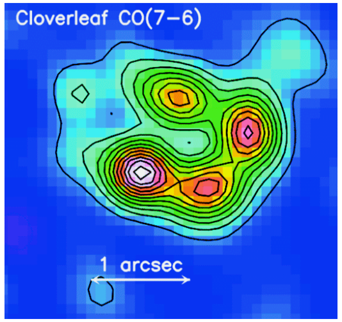


From P. Shaver


ALTITUDE=5000 m :: ATACAMA :: ALMA
TRANSMISION ATMOSFERICA
FRECUENCIA (GHz)
IRAM+BIMA+OVRO
CSO & JCMT &SMA
B3
ALMA
B6
B7
ALMA
w(H2O)=0.3 mm
w(H2O)=0.5 mm
w(H2O)=0.7 mm
w(H2O)=1.0 mm
w(H2O)=1.5 mm
w(H2O)=2.0 mm
w(H2O)=3.0 mm



J.R. Pardo & J. Cernicharo (ATM, 1999)
Mauna Kea w(H_2O)=500 μm
Atacama w(H_2O)=300 μm
Sofia 13 km w(H_2O)=25 μm
CSO
SPIRE
HIFI
HERSCHEL
HIFI
HERSCHEL
PACS
B9
ALMA
ATMOSPHERIC TRANSMISSION
1
0.5
0
1000
2000
3000
ν (GHz)
750 um
300 um
λ (microns)
150 um
100 um



SCIENCE WITH ALMA and HERSCHEL

-Studies of the early Universe

-Gravitational lensing

-QSO molecular absorption lines

-Detailed studies of galaxies

-AGNs

-Interstellar absorption lines

-Astrochemistry

-Protostellar clouds

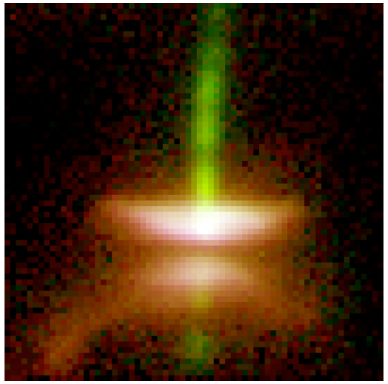
- Young stellar objets

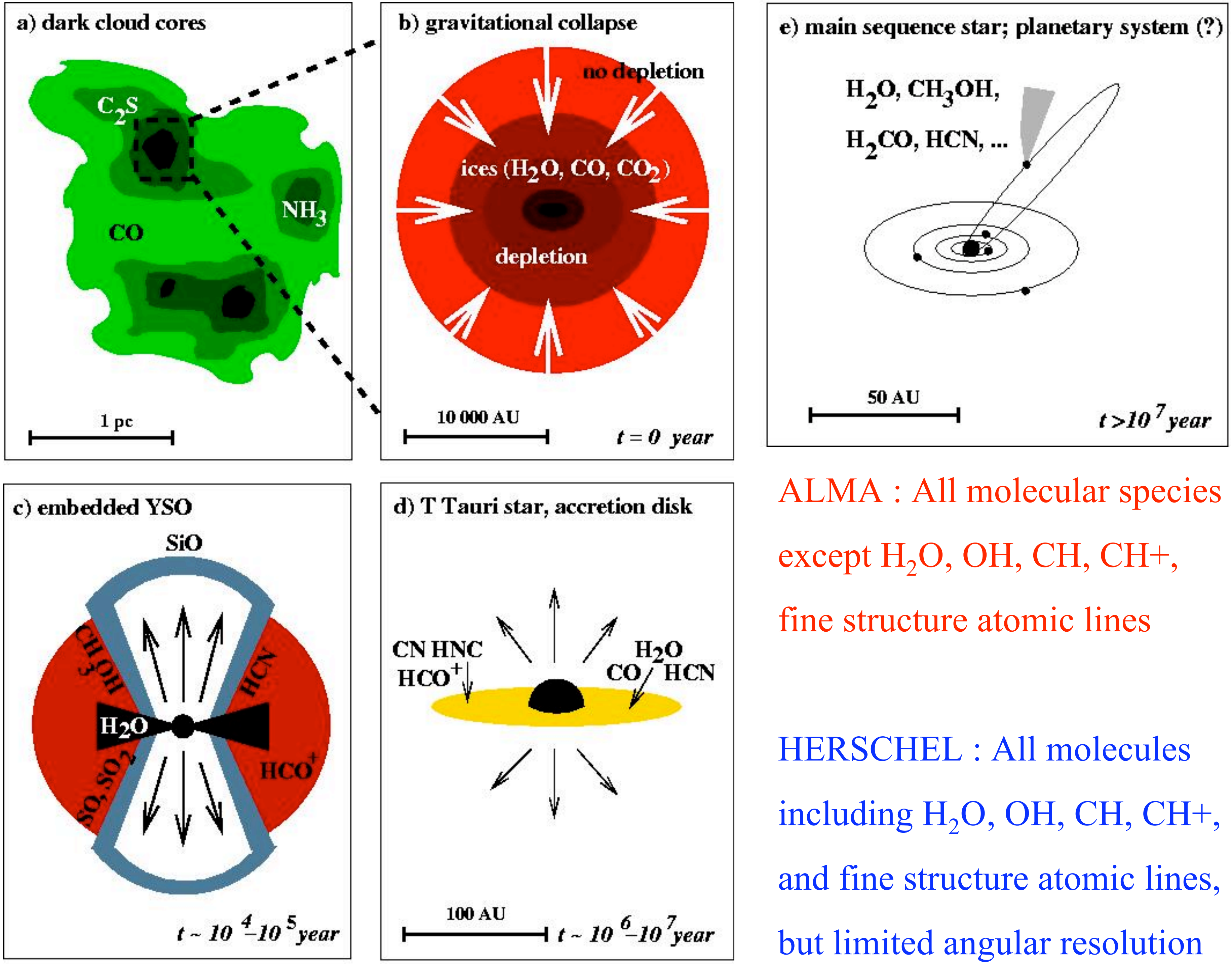
- Outflows

- AGBs

- Protoplanetary Nebulae

- Masers

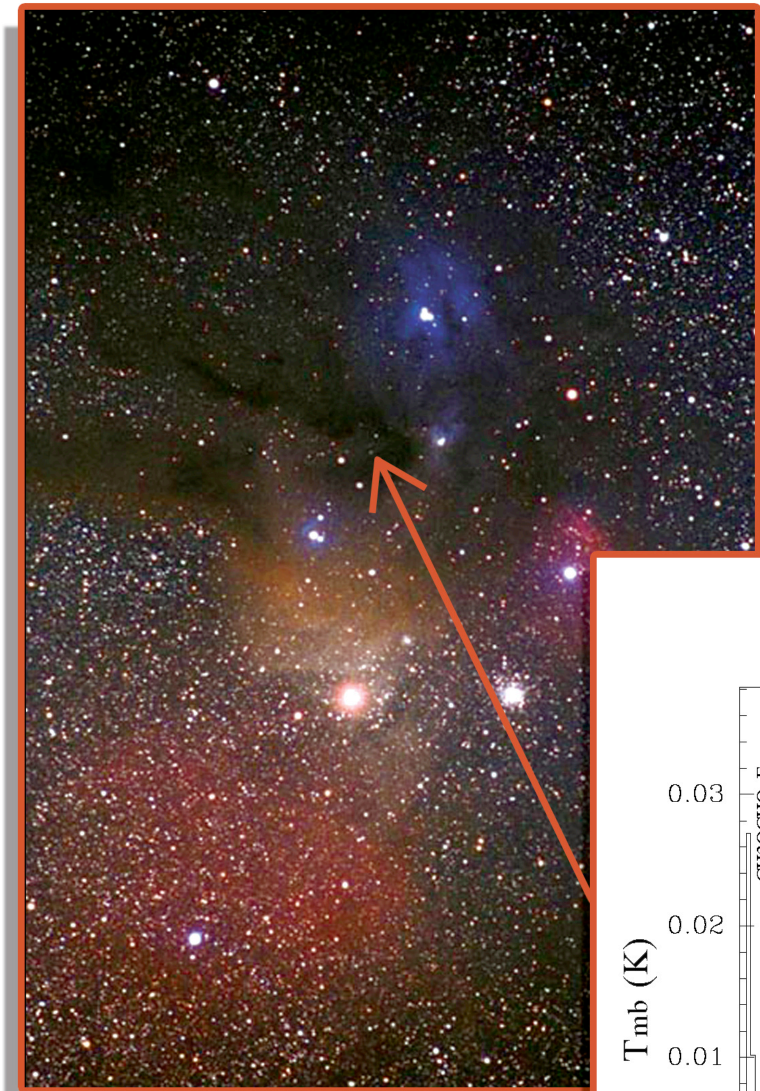


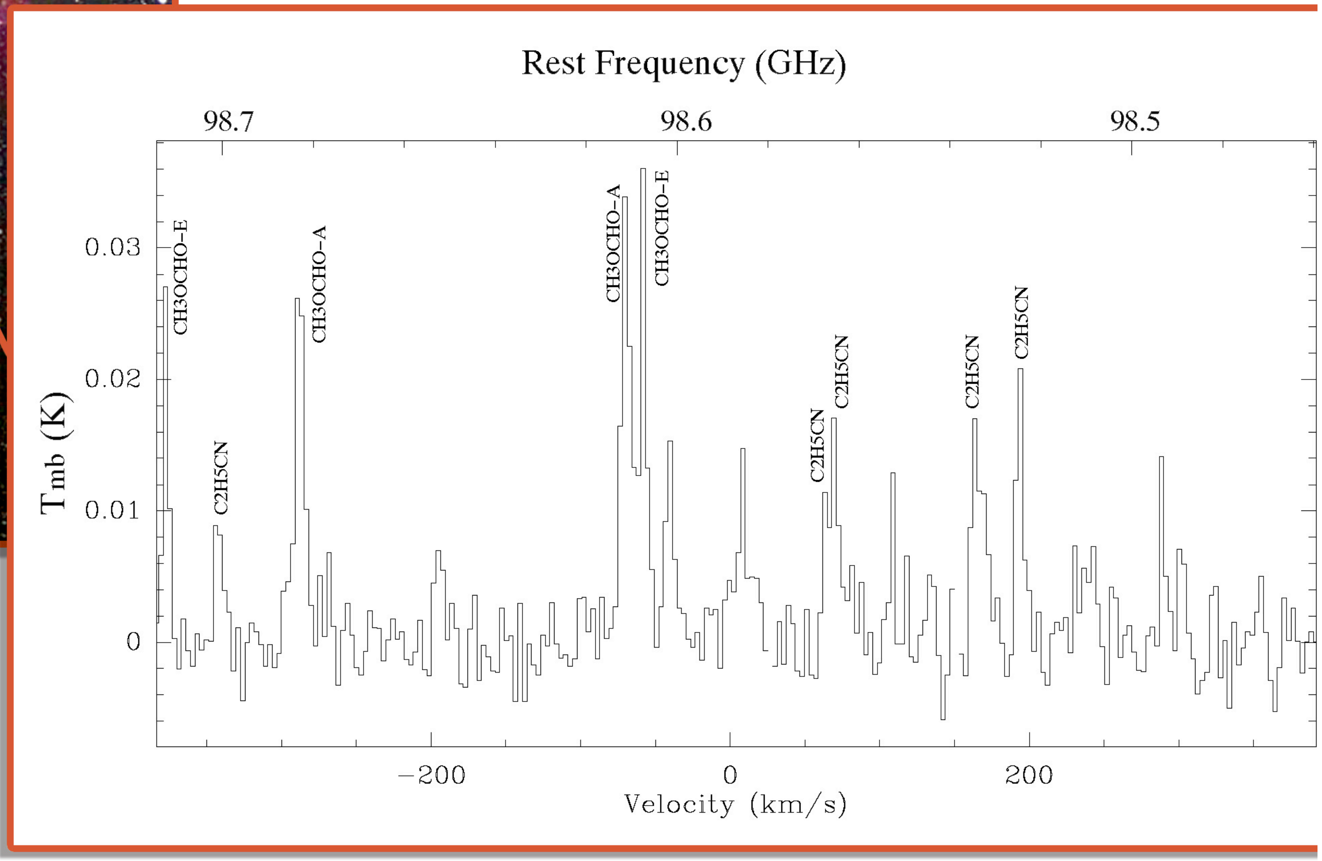


ALMA : All molecular species except H_2O, OH, CH, CH+, fine structure atomic lines

HERSCHEL : All molecules including H_2O, OH, CH, CH+, and fine structure atomic lines, but limited angular resolution

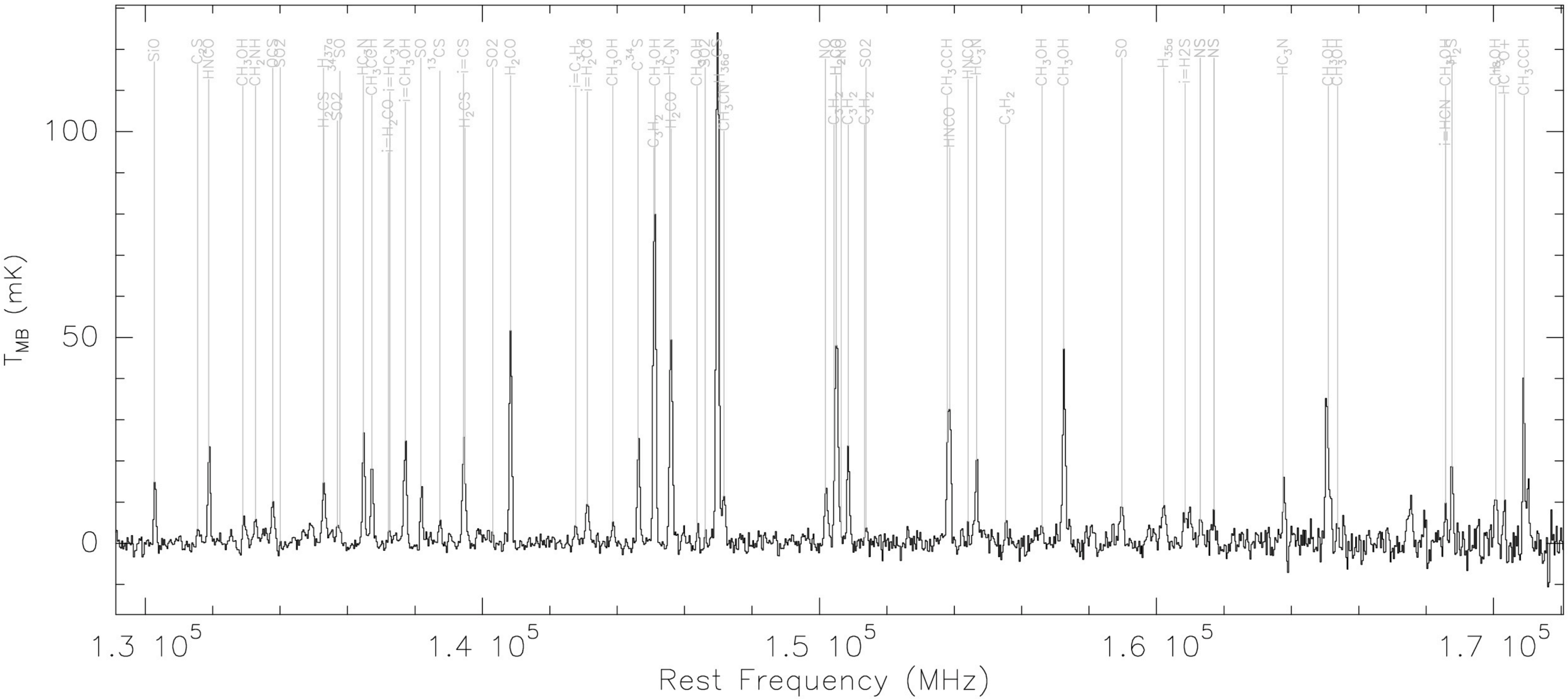
Molecular complexity in solar type protostars





Cazaux et al. 2003

Sergio Martín et al. 2004



***HERSCHEL (2008):**

Complete frequency coverage (excitation conditions of the gas).

New molecular species

Molecules without permanent dipole moment (low bending modes); carbon clusters

***ALMA (2012):**

High sensitivity : all molecular species; complex organic molecules

Protoplanetary disks; molecular content of galaxies;

Cosmology (molecules in high-z objects)

High angular observations of HCN, SiO, and other species in the innermost regions of CSEs (dust formation zone).

***However, the systematic exploration of the full mm,submm and far-IR domain will require additional inputs, at least for the observation of molecular species :**

-Collaboration with scientist from the physical-chemistry world (laboratory and theoretical) to get the molecular parameters needed to interpret the observations

***In addition, the existing ground based facilities have to be used in the best possible way to prepare the science than Herschel and ALMA will do (CSO, JCMT, IRAM -30m and PdBI- , SMA, LMT, CARMA,...)**