

Molecular spectroscopy and star formation in the 1-2 THz regime

(Submm/far-infrared astronomy from Antarctica)

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+ Atomic and ionic lines: [NII], [CII], [CI]

+ CO high-J rotational transitions

+ HCN, HCO⁺ high-J rotational transitions

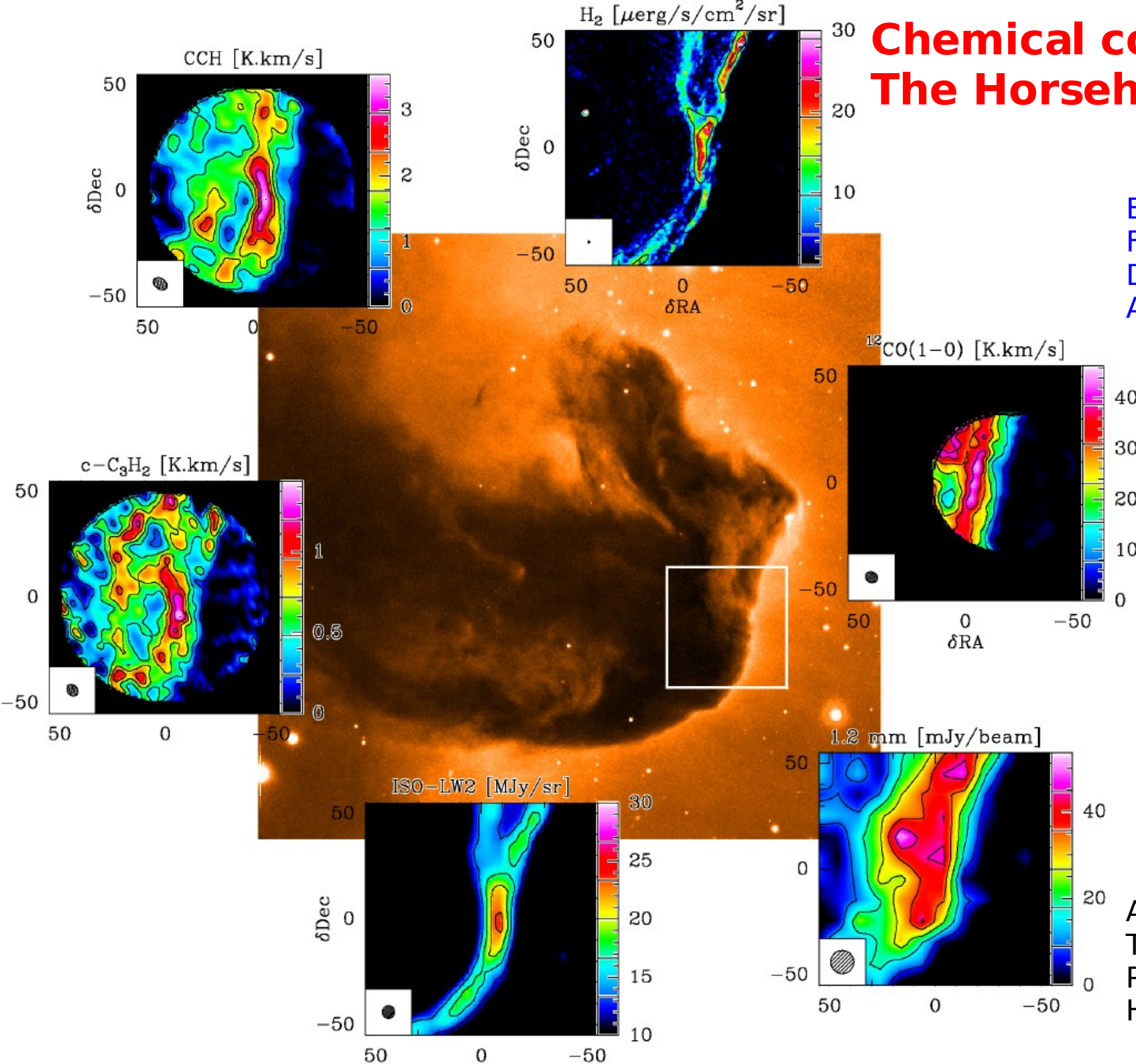
+ Light Hydrides:

H_2D^+ , D_2H^+ , NH_2 , NH^+ , H_2O isotopes, LiH, ...

+ ...many more...

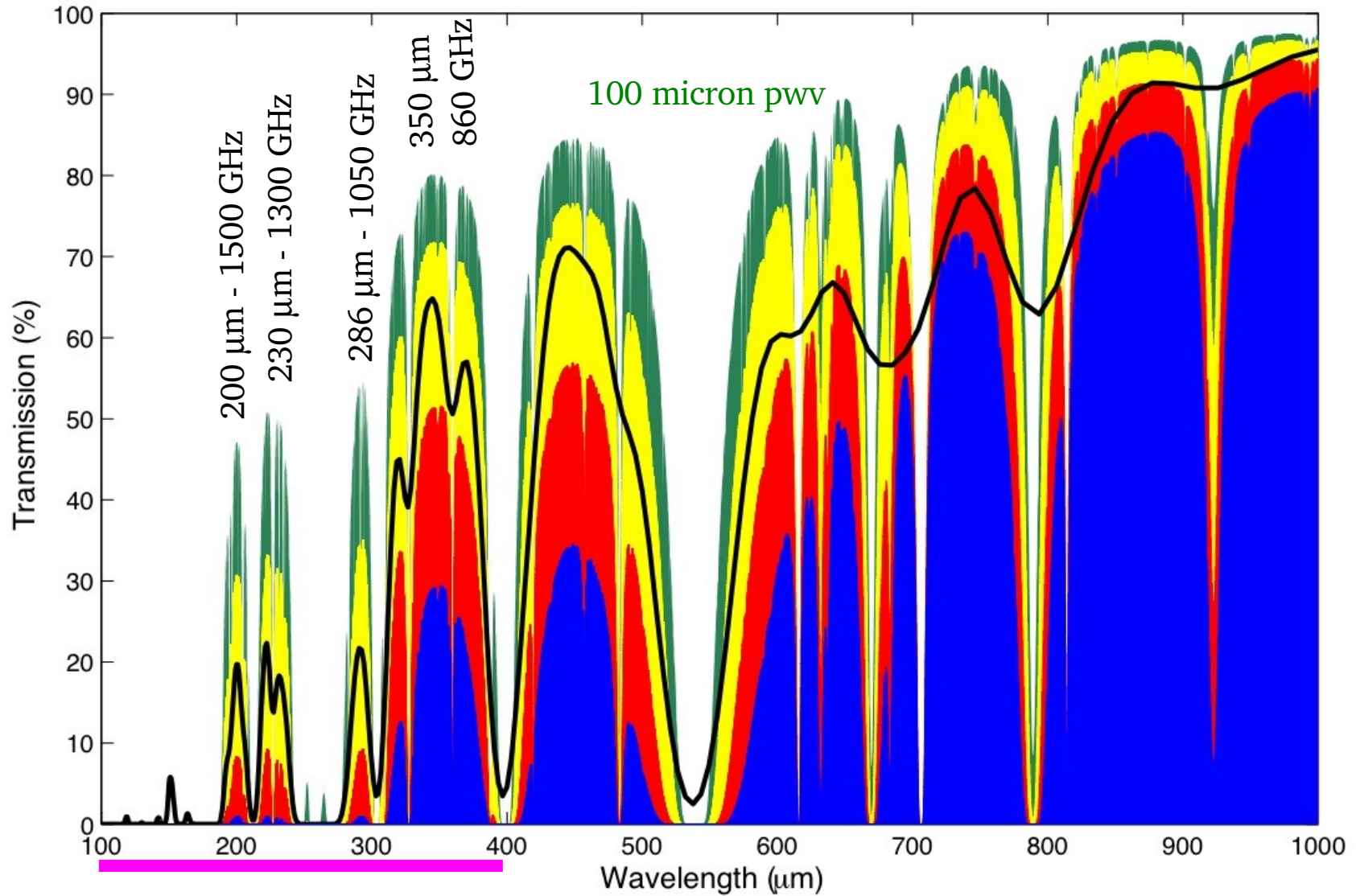
Chemical complexity: The Horsehead Nebula

Edge-on PDR
FUV = 30
Distance = 400 pc
 $A_v = 20$ mag

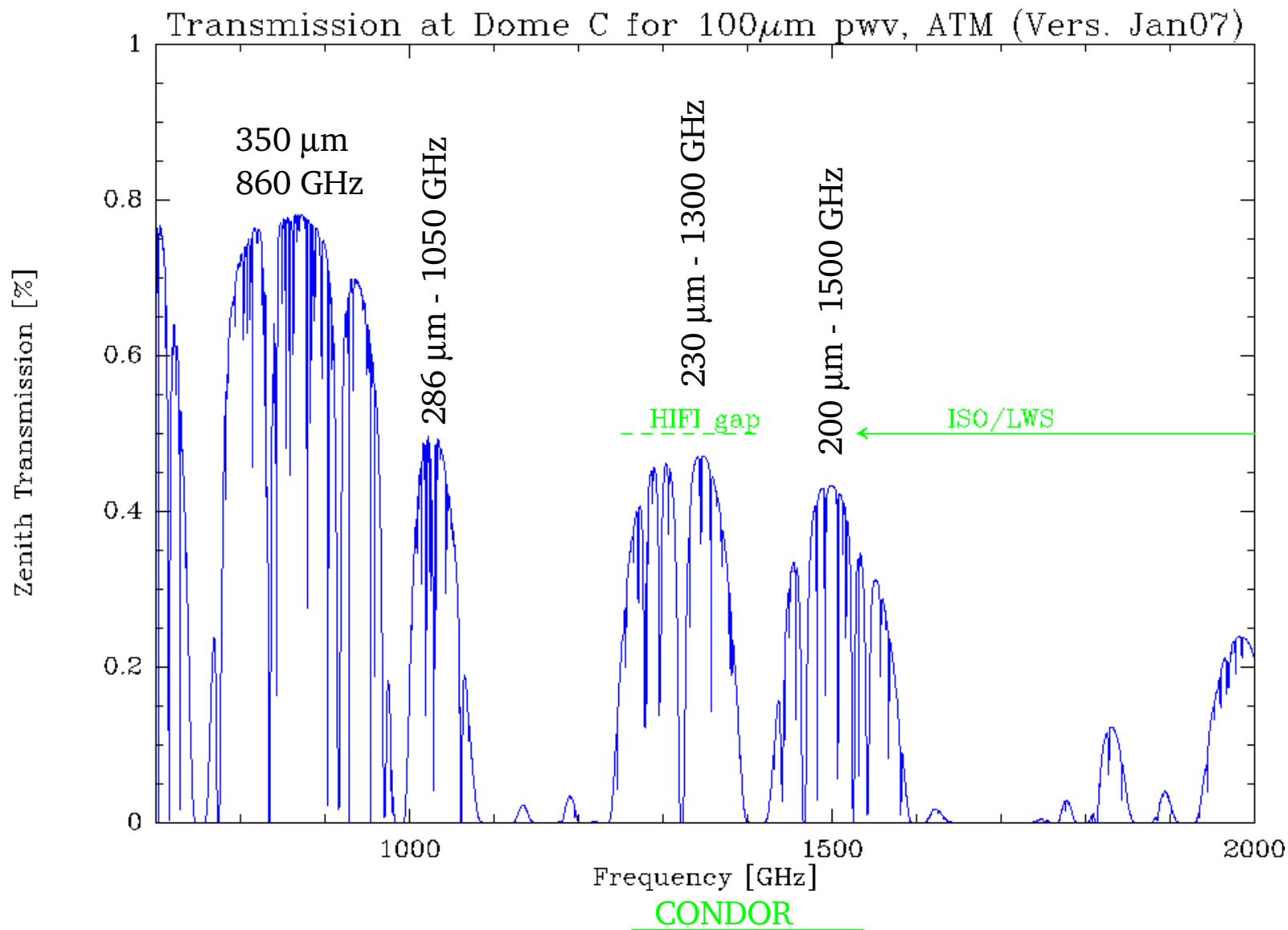


Abergel et al. 2003
Teyssier et al. 2004
Pety et al. 2005
Habart et al. 2005

Atmospheric windows

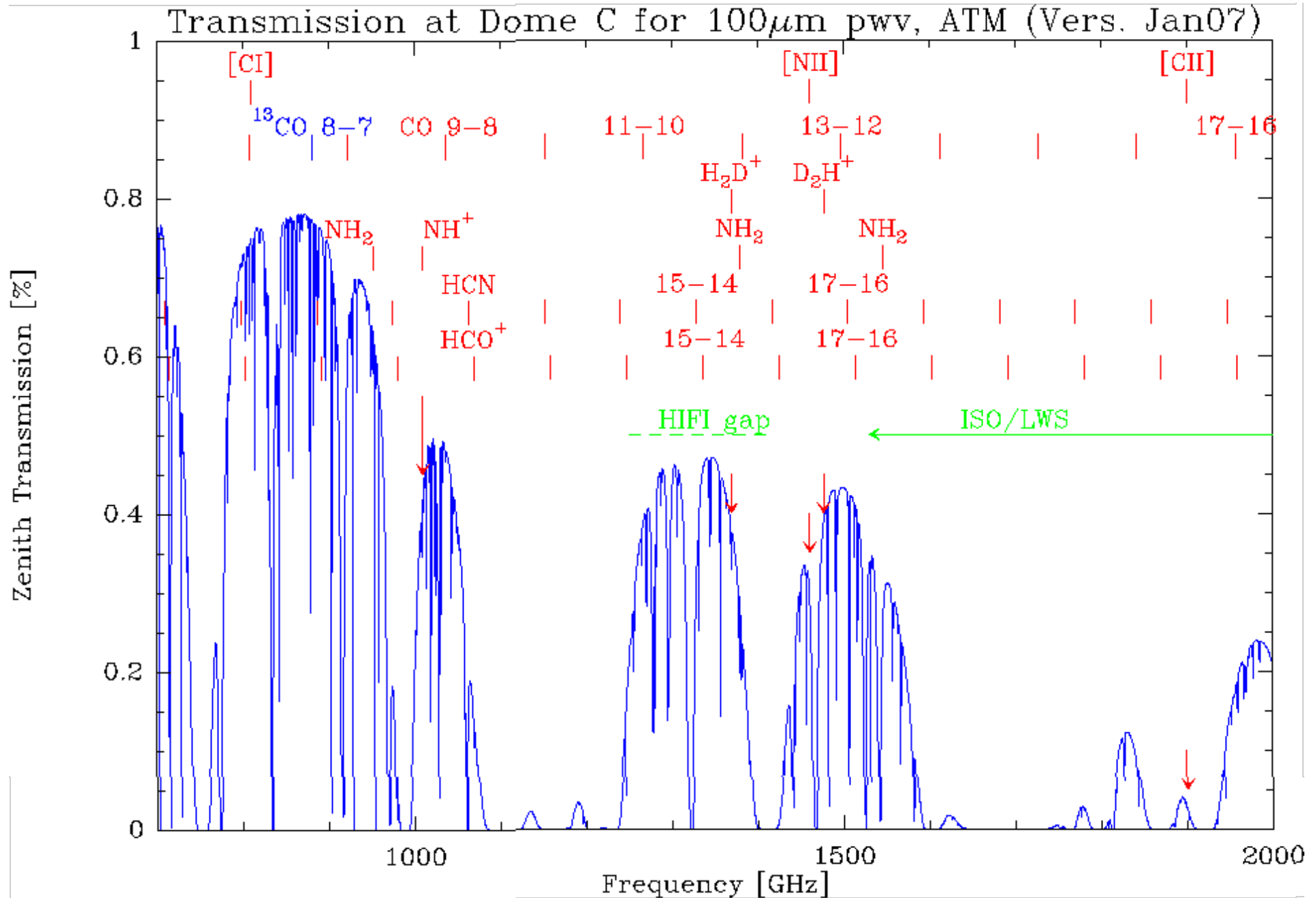


Atmospheric windows due to H₂O, O₂, ...

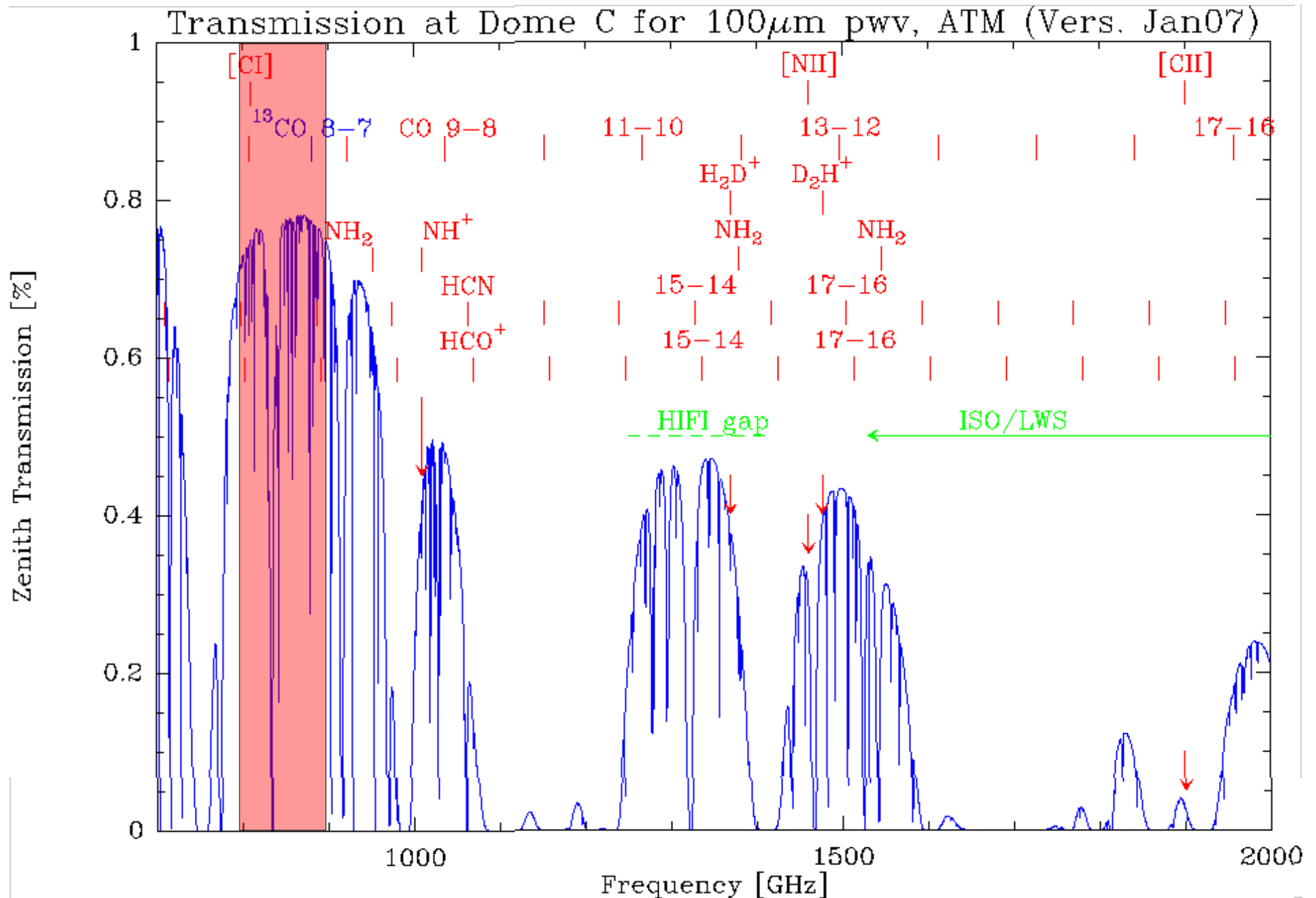


- ATM by J.Pardo et al. (2001)
- cf. FTS spectrum taken at Cerro Sairecabur/Chile
by Marrone, Blundell et al. 2005: Measured water vapour: pwv = 93 μm

Atmospheric windows

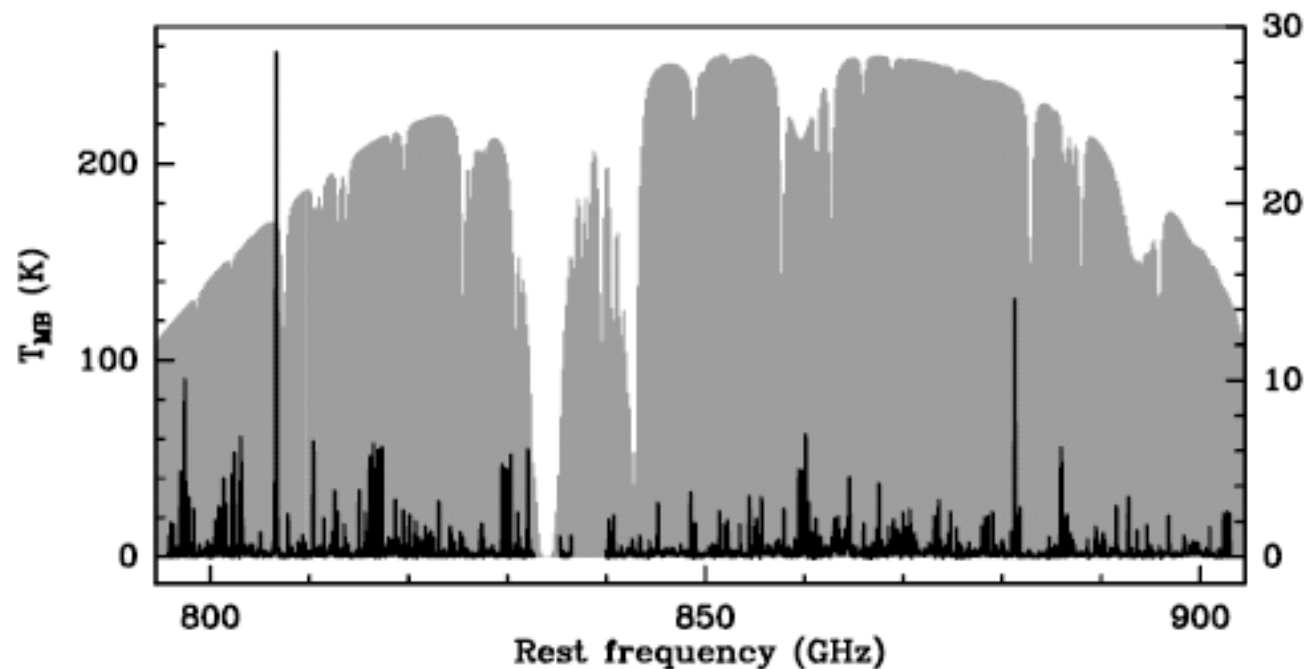
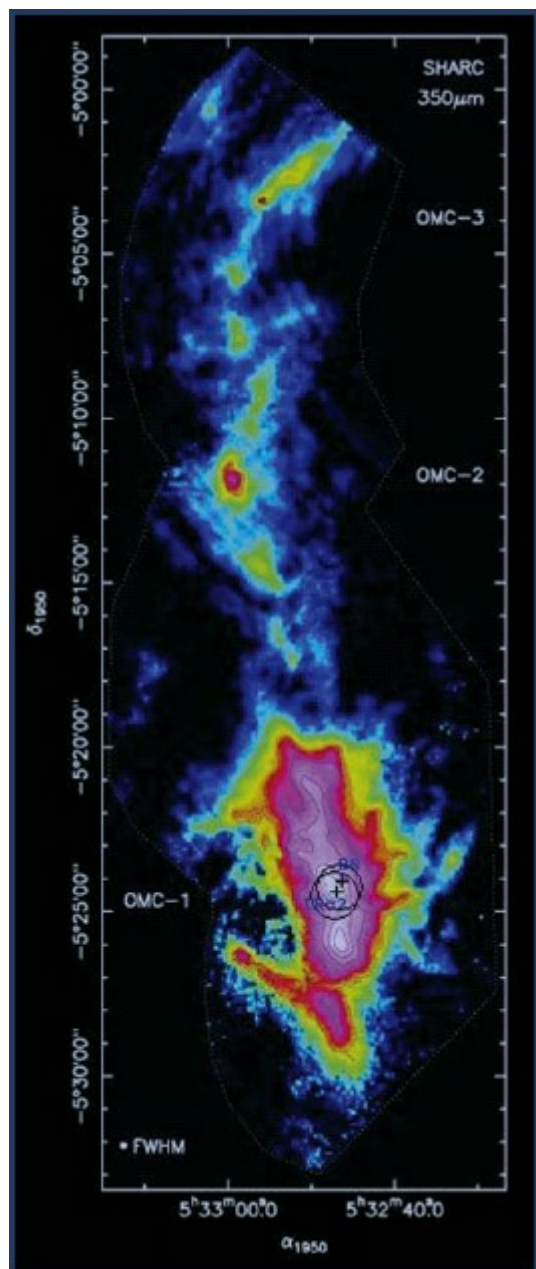


Atmospheric windows



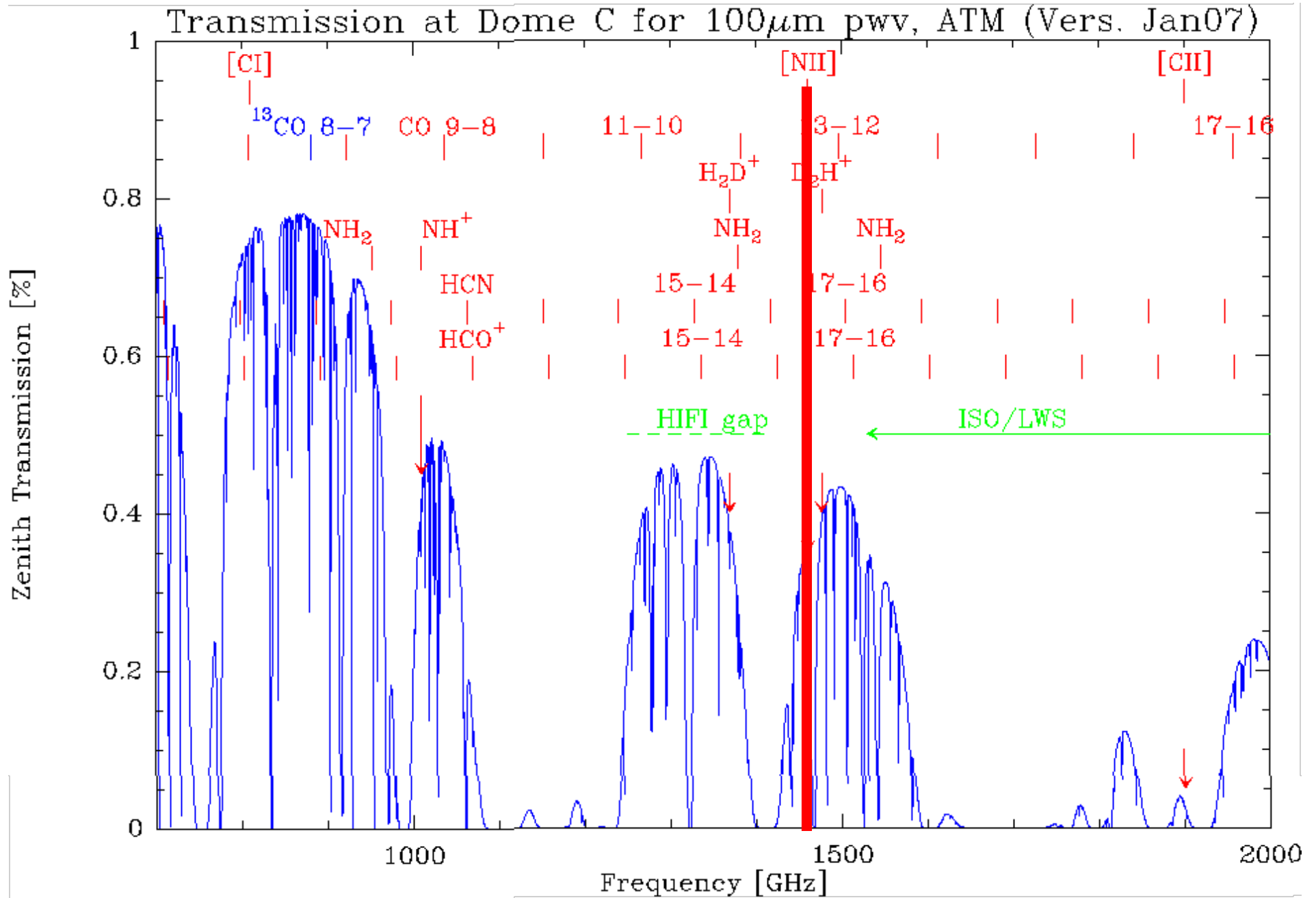
The THz regime is rich in lines

SHARC/CSO 350micron dust emission map of Orion A
(Lis et al. 1998)



Unbiased spectral line survey of Orion KL at 350 micron
by Comito et al. (2005) at the CSO:
26 species and 929 transitions
Dominant coolants: SO₂, CH₃OH, CO, SO, H₂CO, HCN,...
(HCN contains 25% of SO₂ cooling intensity)

[NII]



[NII]

[NII] stems from HII regions:

$$E_{\text{io}}(\text{N}) = 14.53\text{eV}$$

$$122\ \mu\text{m}\ (2.46\ \text{THz})\ ^3\text{P}_2 - ^3\text{P}_1$$

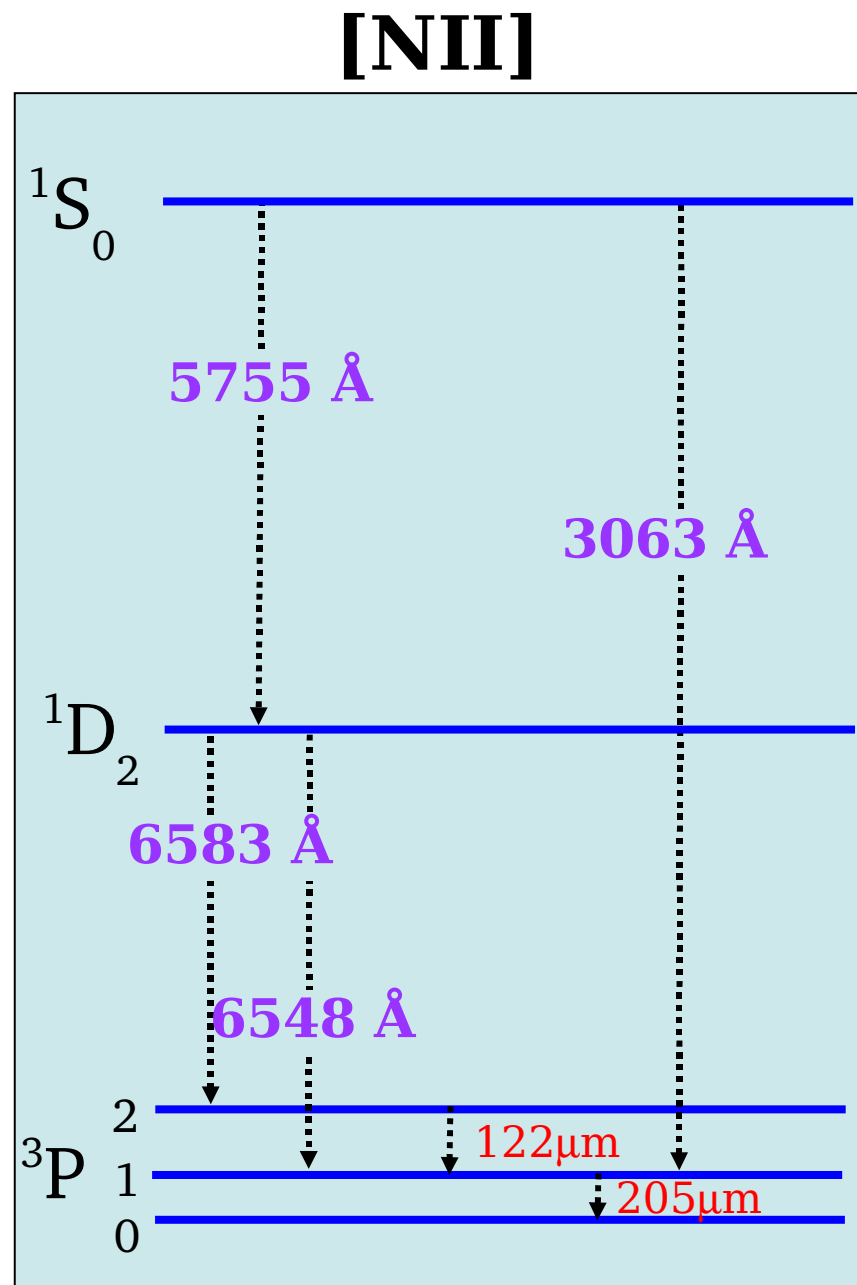
$$205\ \mu\text{m}\ (1.46\ \text{THz})\ ^3\text{P}_1 - ^3\text{P}_0$$

$$n_{\text{cr}} = 293\ \text{cm}^{-3}\ \text{for}\ 122\ \mu\text{m}\ \text{line}$$

$$n_{\text{cr}} = 44\ \text{cm}^{-3}\ \text{for}\ 205\ \mu\text{m}\ \text{line}$$

for $T_e = 8000\ \text{K}$

- Excellent probes of the low-density ionized gas
- Extinction free, in contrast to optical lines
- supplementing lines of [OIII] 88 and 52 μm tracing high density ionized gas



[NII] Energy level diagram
(from Stacey, Oberst et al.)

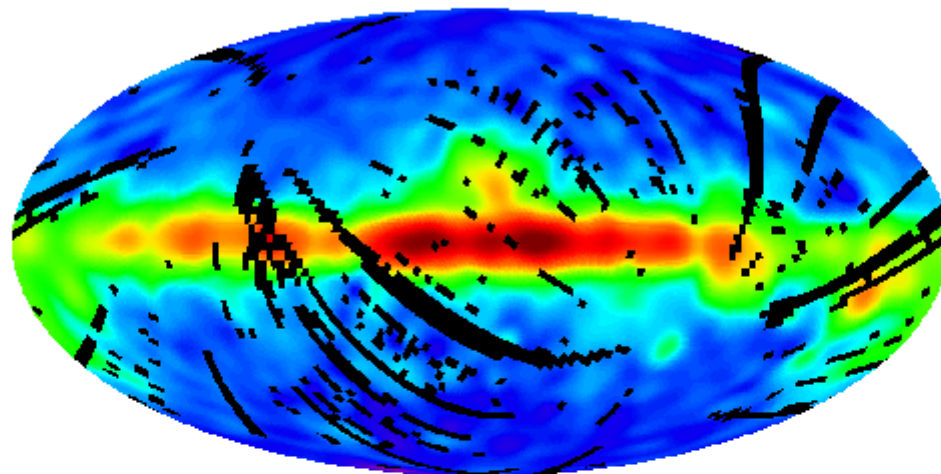
[NII]

Observations so far:

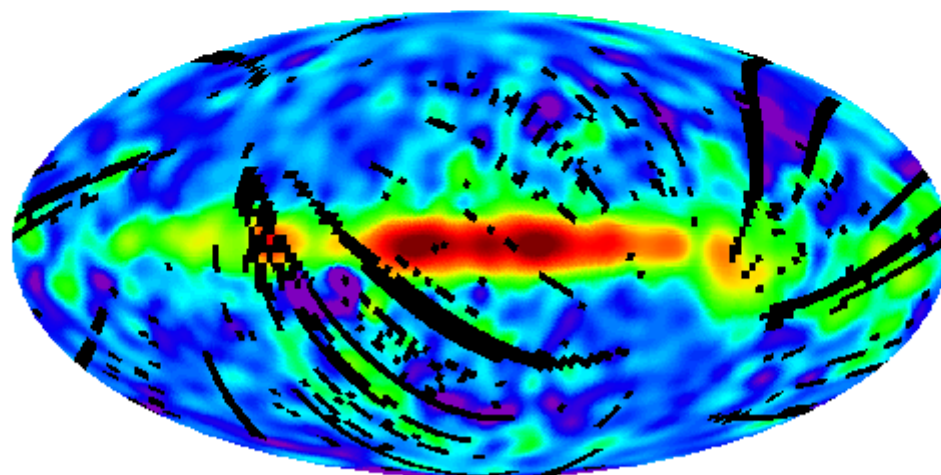
- KAO: Both lines observed in the Galactic HII region G333.6-0.2: Colgan et al. 1993
- FIRAS/COBE (Fixsen et al. 1999): [NII] lines are strongest after [CII] for $\lambda > 100\mu\text{m}$
- ISO/LWS: $122\mu\text{m}$ line strong also in disks of spiral galaxies: e.g. Contursi et al. 2002, Kramer et al. 2005
- SPIFI/AST/RO: $205\mu\text{m}$ line detected from ground in Carina I HII region (Oberst et al. 2006)

The Milky Way with FIRAS/COBE

COBE FIRAS $158\mu\text{m}$ C⁺ Line Intensity



COBE FIRAS $205\mu\text{m}$ N⁺ Line Intensity



[NII] stems from the diffuse warm ionized medium (WIM), [CII] partly

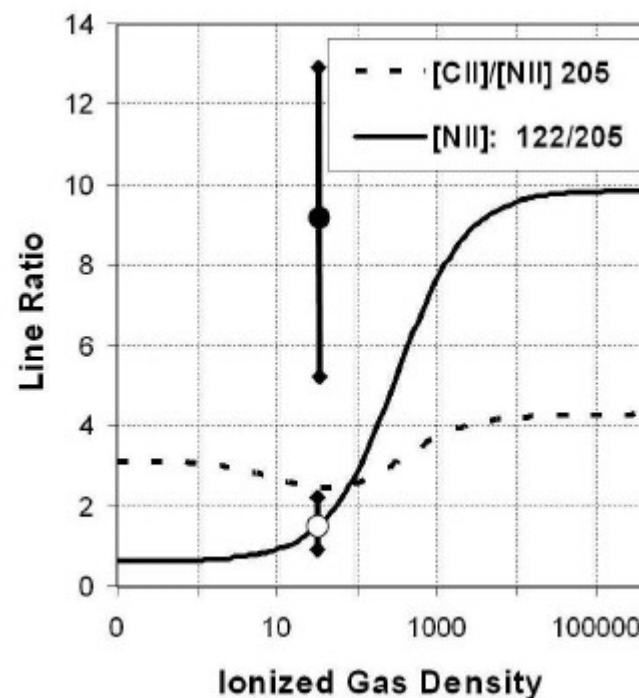
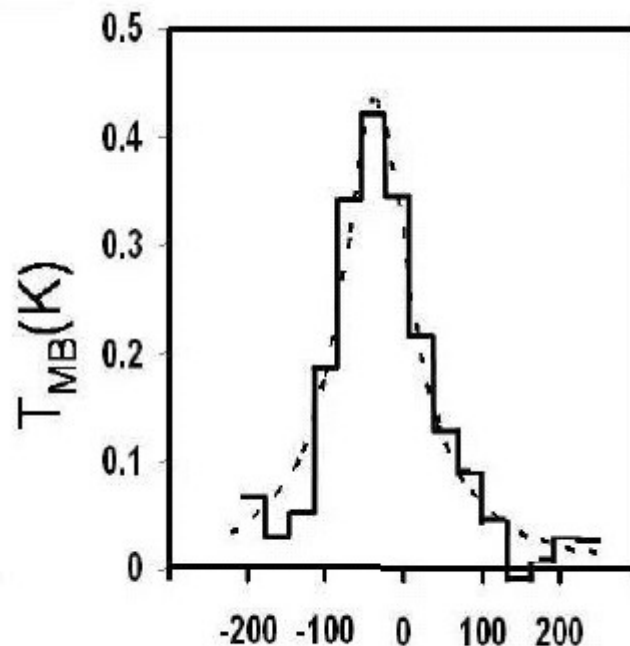
[NII]

Observations:
SPIFI/AST/RO:
205 μ m (1.46 THz) line
detected from ground
in Carina I HII region

deconvolved, intrinsic velocity
width = 50 kms^{-1} , 0.42 K T_{pk}

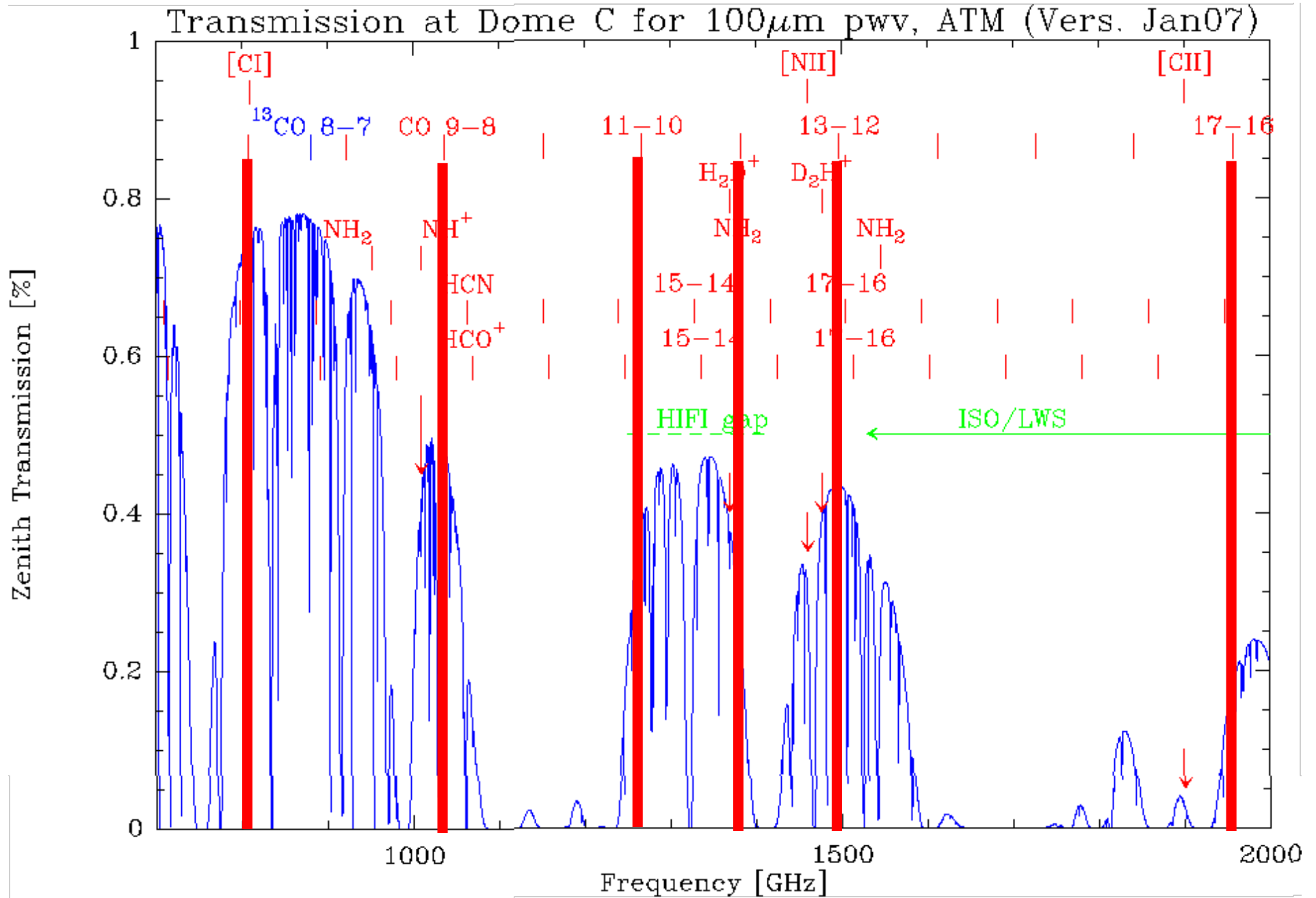
[NII] 122/205 = 1.5
[CII] 158/[NII] 205 = 9.2

Models of the ionized gas:
~30% of [CII] emission stems from
the diffuse ionized medium



(Oberst, Parshley, Stacey, Nikola, et al. 2006)

CO



CO

- Very stable: abundance insensitive to physical conditions, $E_{\text{diss}} = 11.1\text{eV}$
- CO traces a large range of excitation conditions in molecular clouds:

$$E_{\text{up}}/K = 2.8 J (J+1)$$

$$n_{\text{cr}}/\text{cm}^{-3} = 4 \cdot 10^3 J^3$$

e.g.

CO 14-13: 590 K, $1.1 \times 10^7 \text{ cm}^{-3}$

CO 7-6: 157 K, $1.4 \times 10^6 \text{ cm}^{-3}$

CO 4-3: 56 K, $2.6 \times 10^5 \text{ cm}^{-3}$

Unresolved observations:

- High-J CO lines: FIRAS/COBE, KAO, 0.6m ISO

Velocity resolved observations:

- CO 7-6: several observations (+galactic nuclei upto $z=6.4$)

- CO 9-8: very few observations so far:

Marrone et al. 2004 (0.8m RLT), Kawamura et al. 2002 (10m HHT),
Boreiko & Betz 1991, 1997 (0.9m KAO)

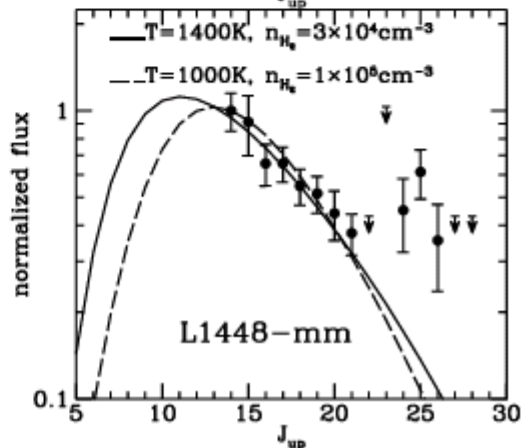
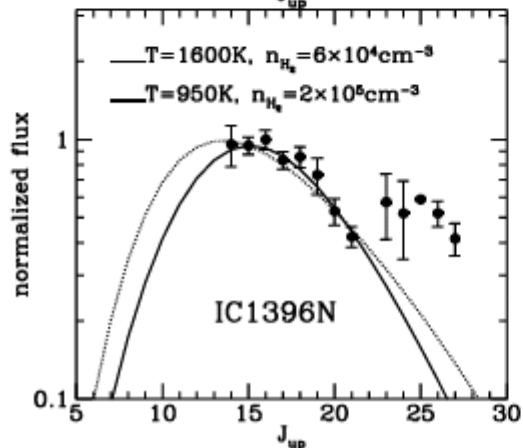
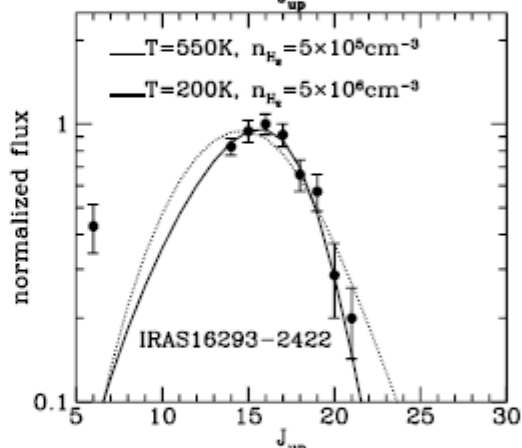
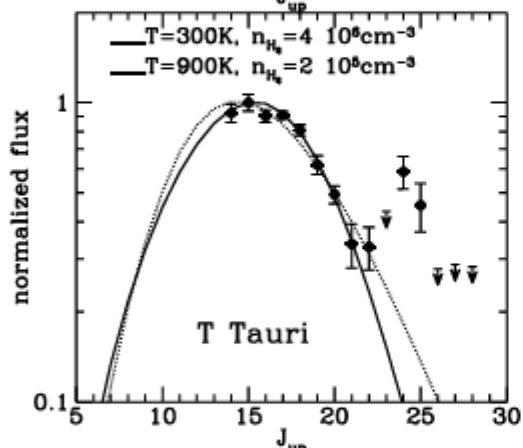
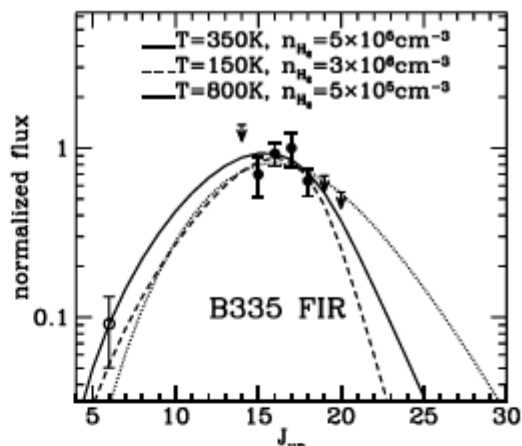
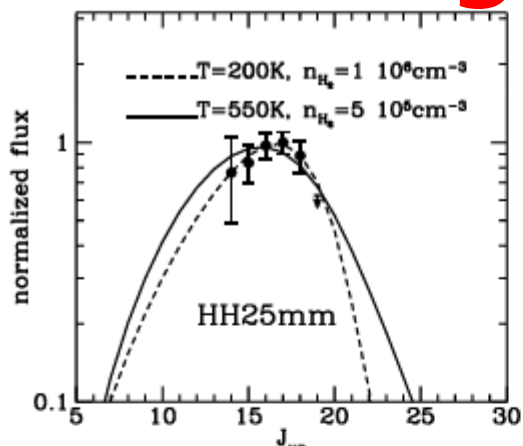
- CO 11-10, 13-12: very few observations so far:

Wiedner et al. 2006 (CONDOR @ 12m APEX),
Marrone et al. 2005 (0.8m RLT)

- CO 17-16:

Boreiko, Betz, et al. 1989, 1997 (0.9m KAO)

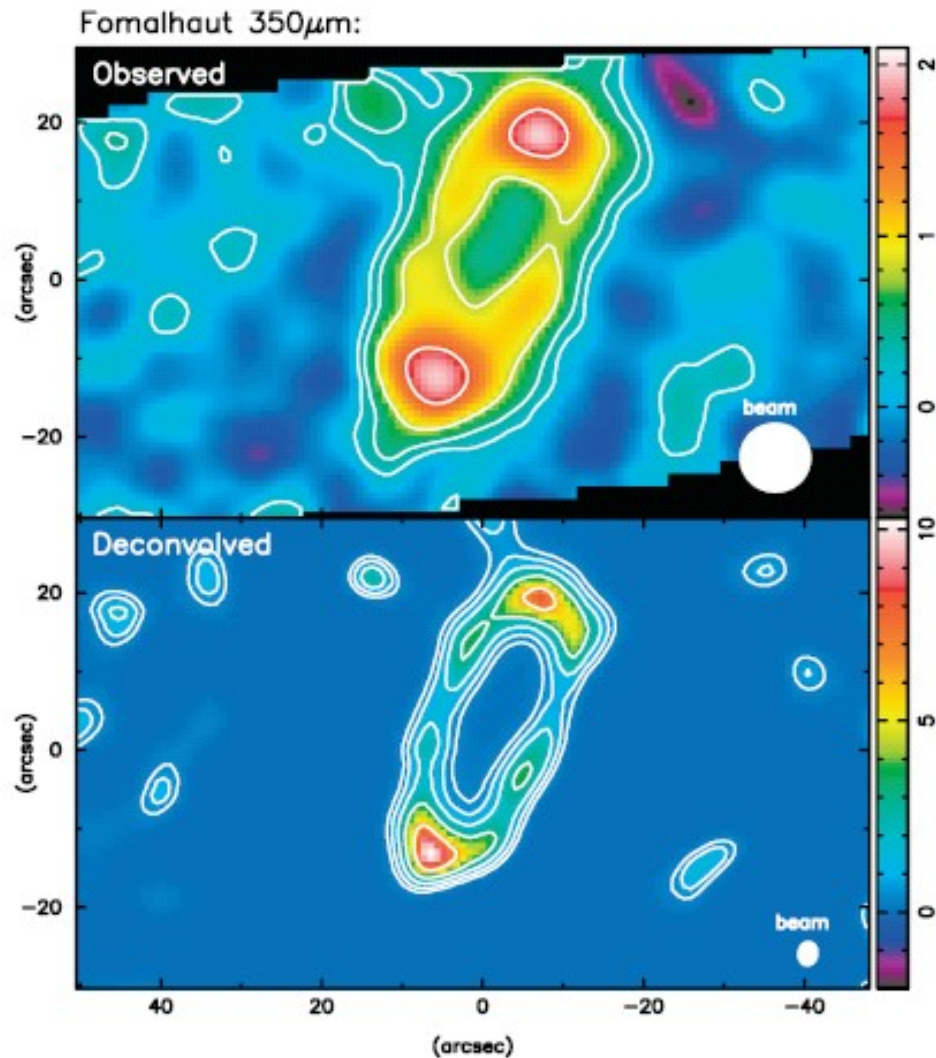
CO: Young stars



ISO/LWS study of Pre-Main Sequence Stars (Class 0, I, II) by Saraceno et al. 1999

- Very hot gas of $> 1000K$ in L1448 ($d=300pc$, cf. Nisini et al. 1999)
- Maxima of CO flux in the THz region.
- Column densities of hot gas, unpolluted by cold gas
- Resolving the structure: accretion disk, outflow lobes: 4" HPBW for 12m telescope at 1.5 THz (1200 AU @ 300 pc) relative to 80" ISO/LWS
- Prime targets for Bolometer arrays
- Circumstellar disks around brown dwarfs (Klein et al. 2003)

Dusty debris disks around main-sequence stars:

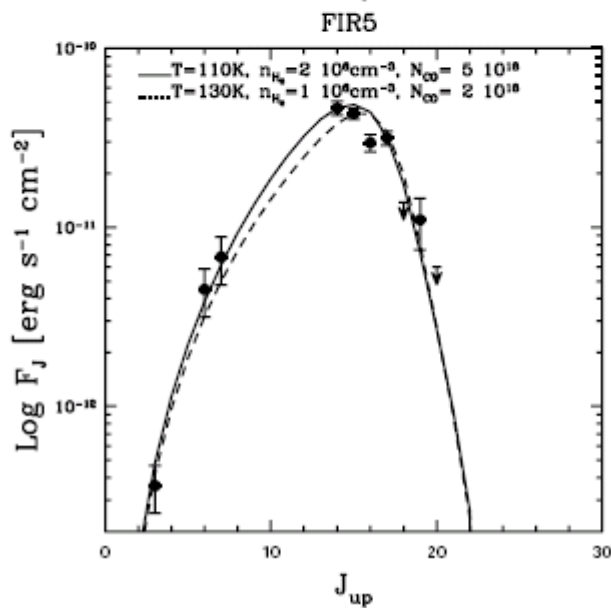
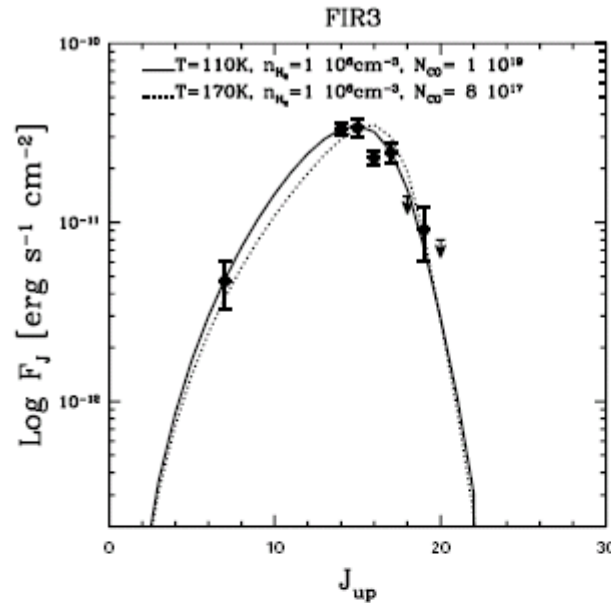
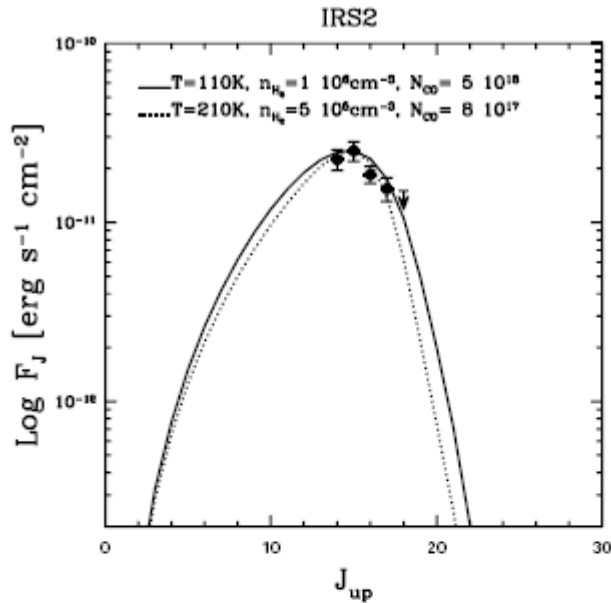


Fomalhaut at 350 μ m with SHARCII/CSO at 9" original resolution and at 3" deconvolved resolution using HIRES (Marsh et al. 2005)

FIG. 1.—Fomalhaut at 350 μ m. The upper and lower panels represent the observed and deconvolved images, respectively. In the observed image, the contours are at 0.2, 0.4, 0.8, and 1.6 mJy arcsec $^{-2}$, and the rms noise is 0.15 mJy arcsec $^{-2}$. In the deconvolved image, the contours are at 0.4, 0.8, 1.6, 3.2, and 6.4 mJy arcsec $^{-2}$, and the rms noise is 0.18 mJy arcsec $^{-2}$.

see Talk by P.Andre

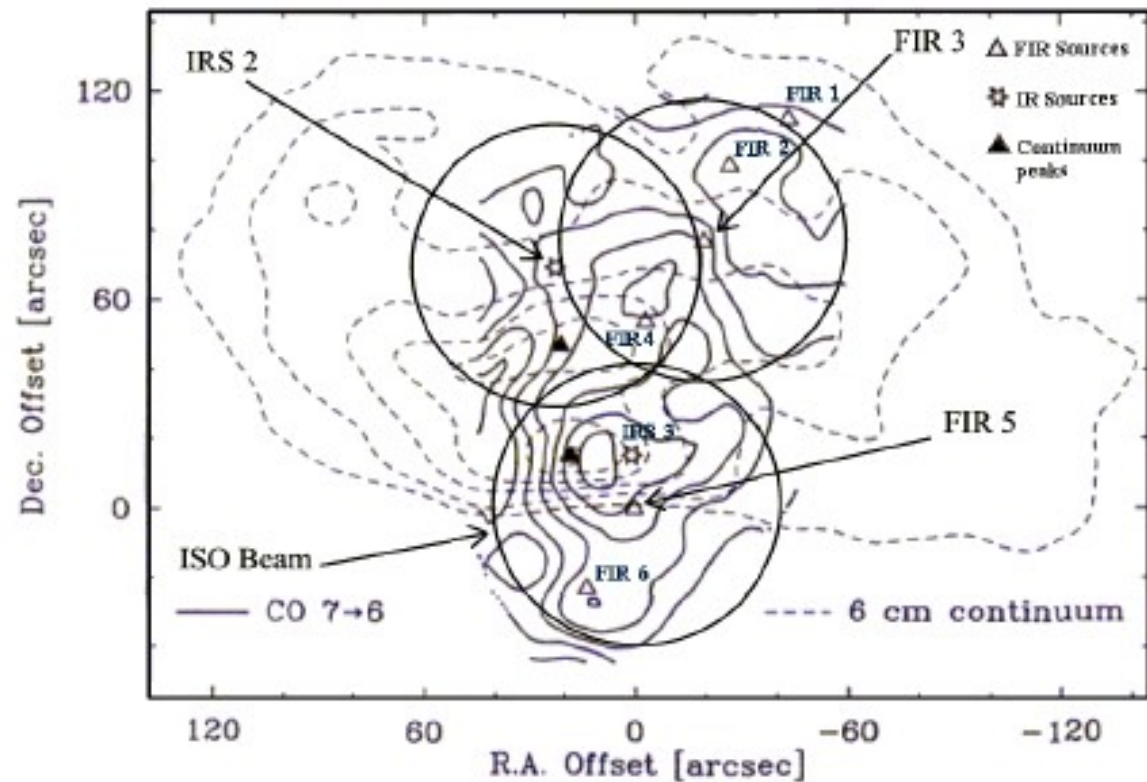
CO: PDRs and hot cores



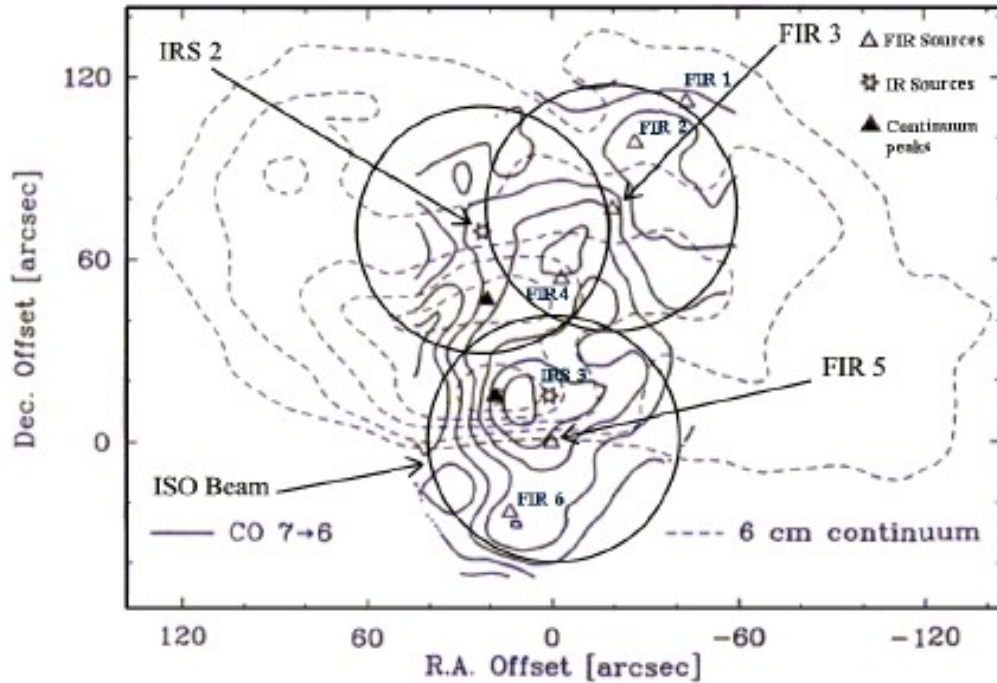
Embedded sources and photon dominated regions (PDRs) in the star forming complex NGC2024/Orion B

ISO/LWS
(Giannini et al. 1999)

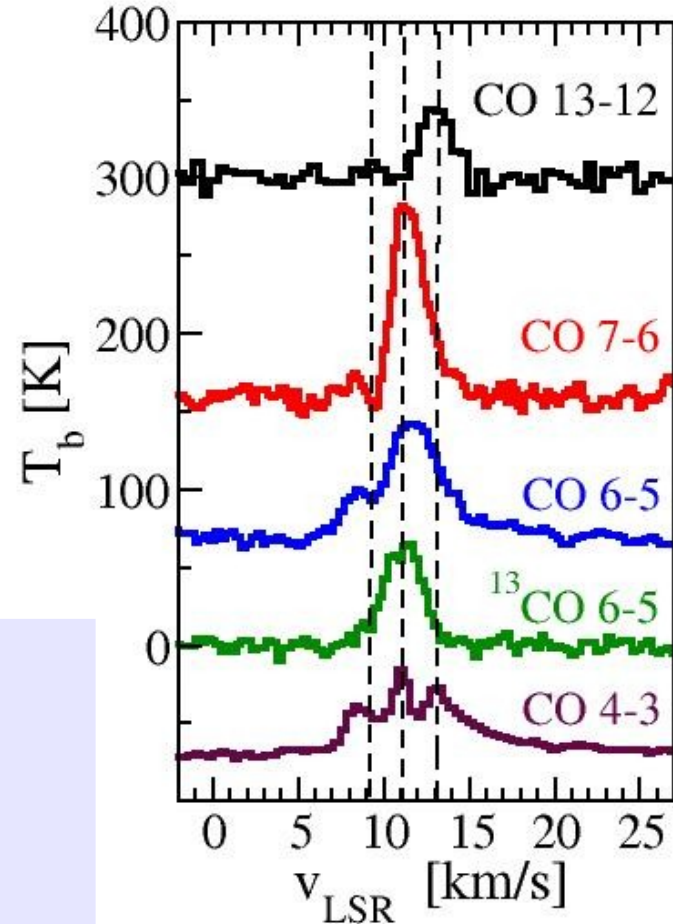
CO 7-6 by Graf et al. (1993)



CO: PDRs and hot cores



Spectra at NGC2024/IRS3 show kinematic structure & self absorption:



CO 13-12 @ CONDOR/APEX

$T_{mb} = 46$ K (in 80" error beam, $B_{eff} = 40\%$)

FWHM = 2.1 km s^{-1}

10min ON-time, 15% transmission

Mid-J transitions with NANTEN2, KOSMA

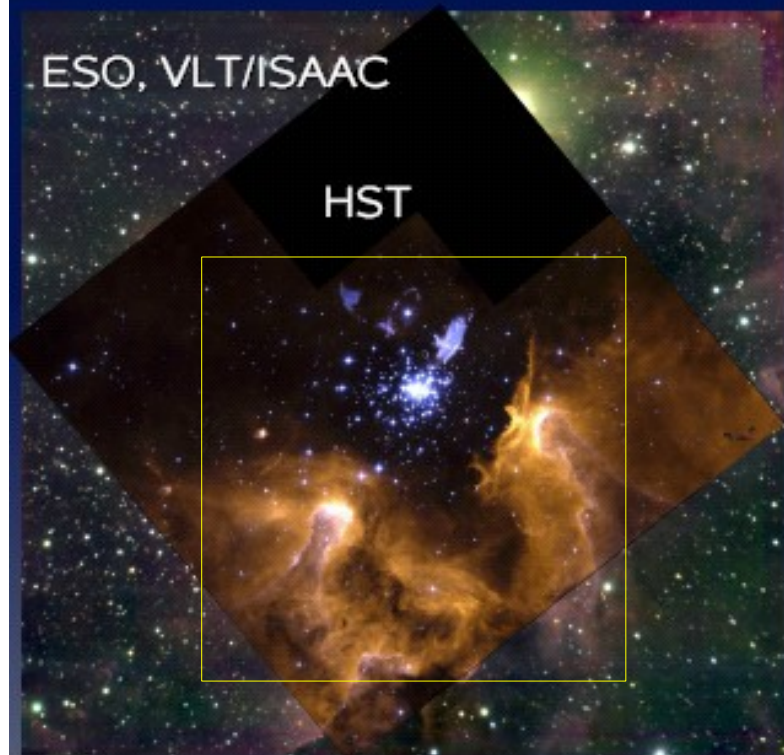
Wiedner et al. 2006, A&A, 454, 33;

Emprechtinger et al. 2007, in prep.

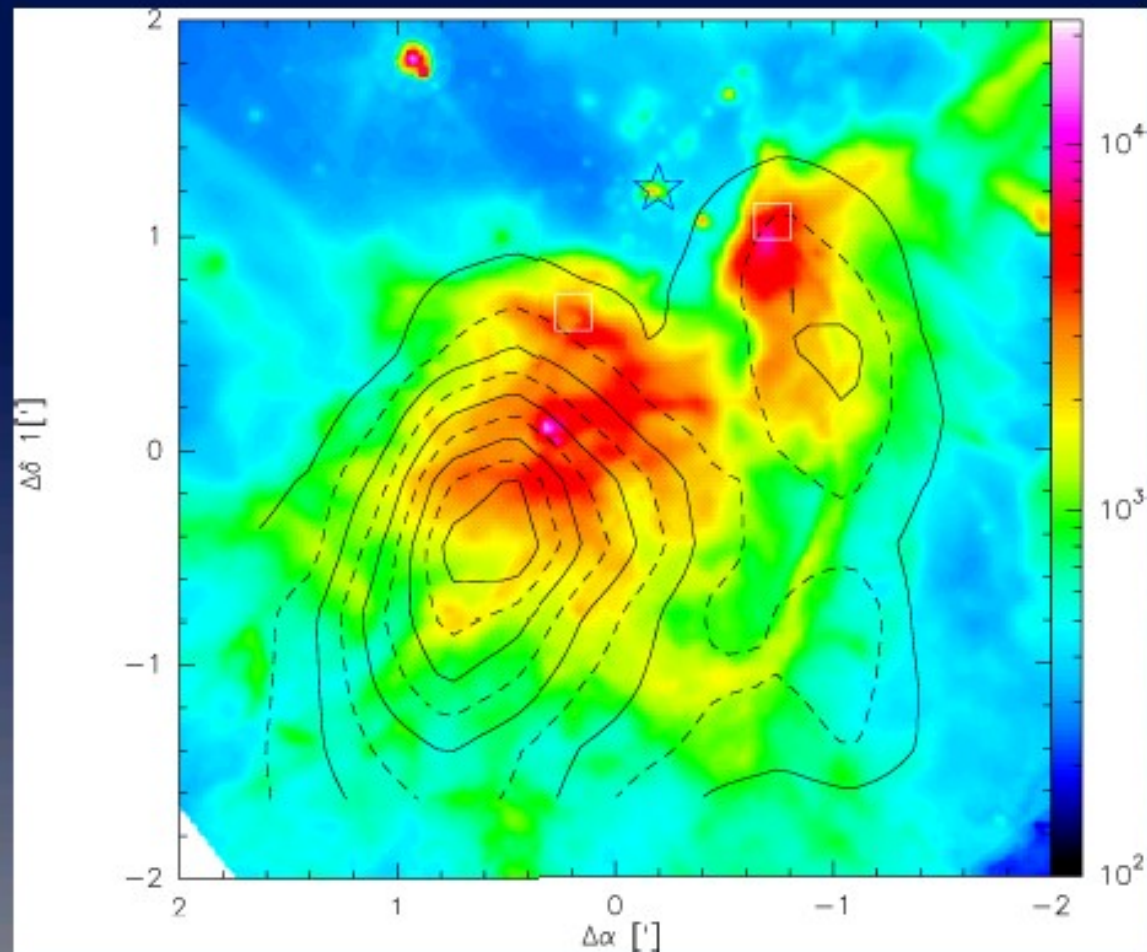
see posters of CONDOR team

CO: Galactic starburst regions

NGC 3603



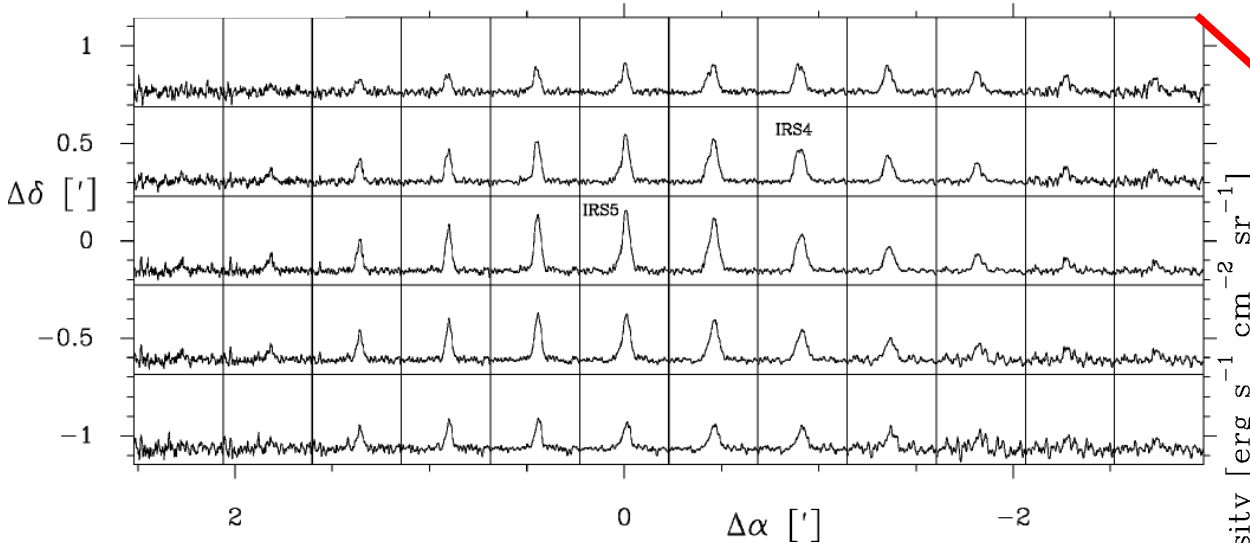
CO 4-3 contours on Spitzer 8 micron



NGC3603 @ 7.7 kpc in CO 4-3, 7-6, [CI] 1-0, 2-1 @ NANTEN2-4m telescope
Röllig et al. (in prep.)

^{13}CO : PDRs

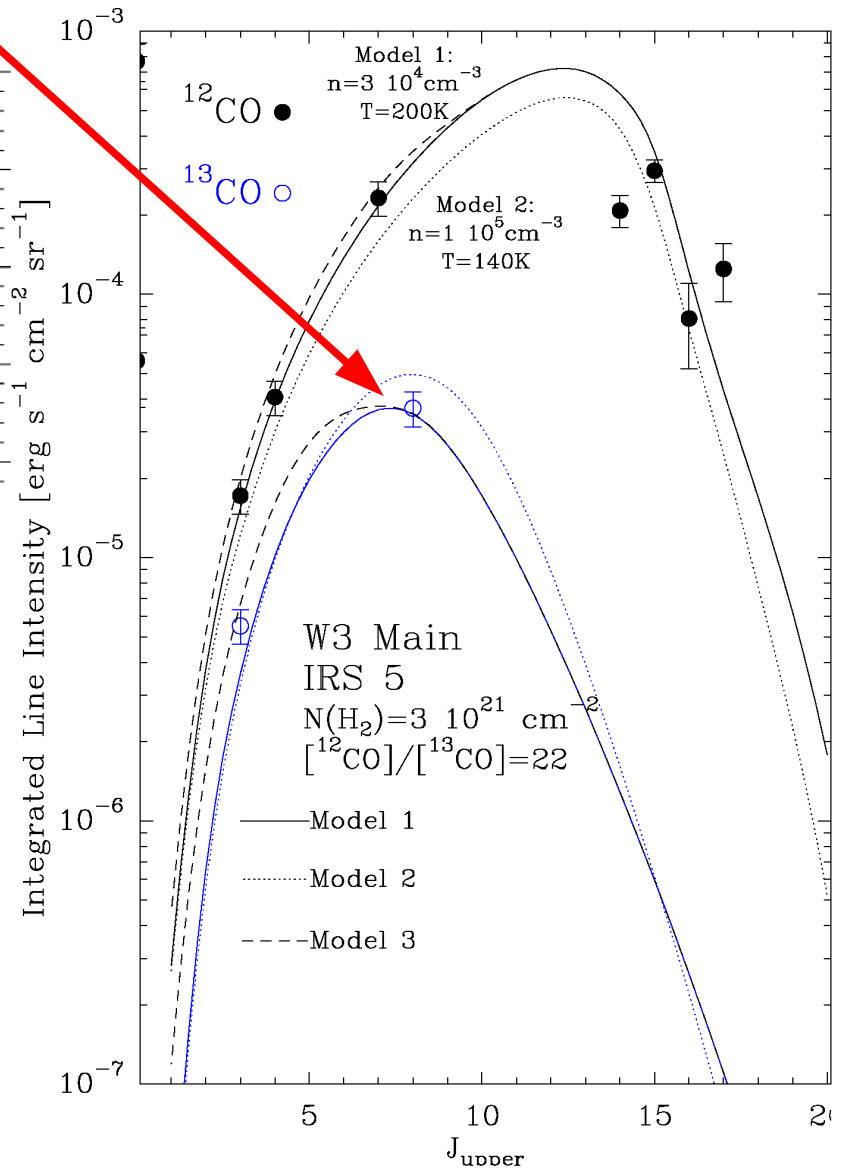
Another example: W3Main



^{13}CO 8-7

- warm and dense gas component
- extended: $\sim 3.4\text{pc}$
- strong: 10 K peak line temperature
- 3m-KOSMA (Kramer et al. 2004)

cf. study of UC HII regions by
Wyrowski et al. 2006, 10mAPEX



HCN & HCO⁺

High-lying rotational transitions in the THz regime

- Orion KL line survey in the 350 μ m window (Comito et al. 2005)

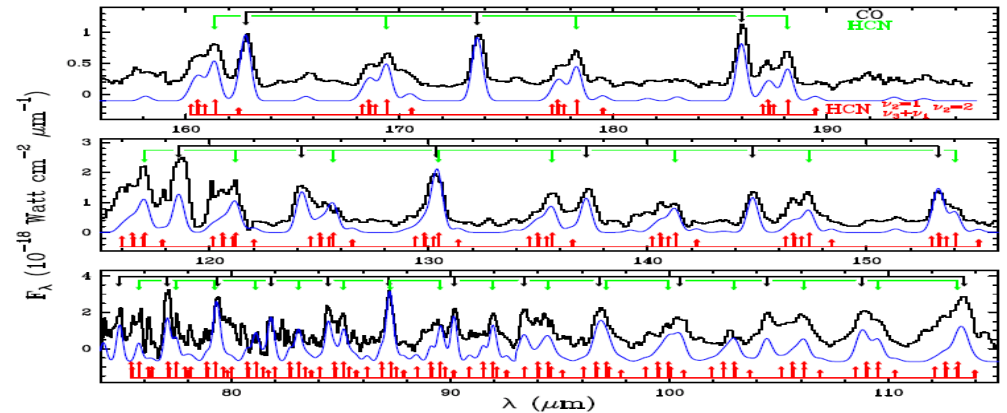
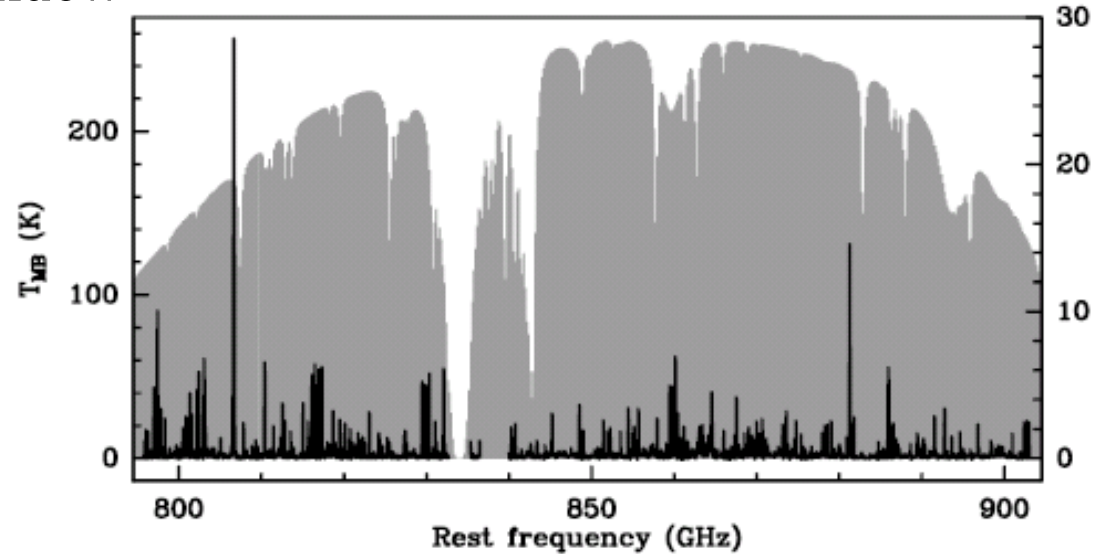
HCN 9-8	797GHz	95K Tmb
HCN 10-9	886GHz	57K
HCO ⁺ 9-8	802GHz	56K
HCO ⁺ 10-9	892GHz	30K

Trot = 150K, n = 10⁷⁻⁸ cm⁻³
(if collisionally excited, IR pumping?)

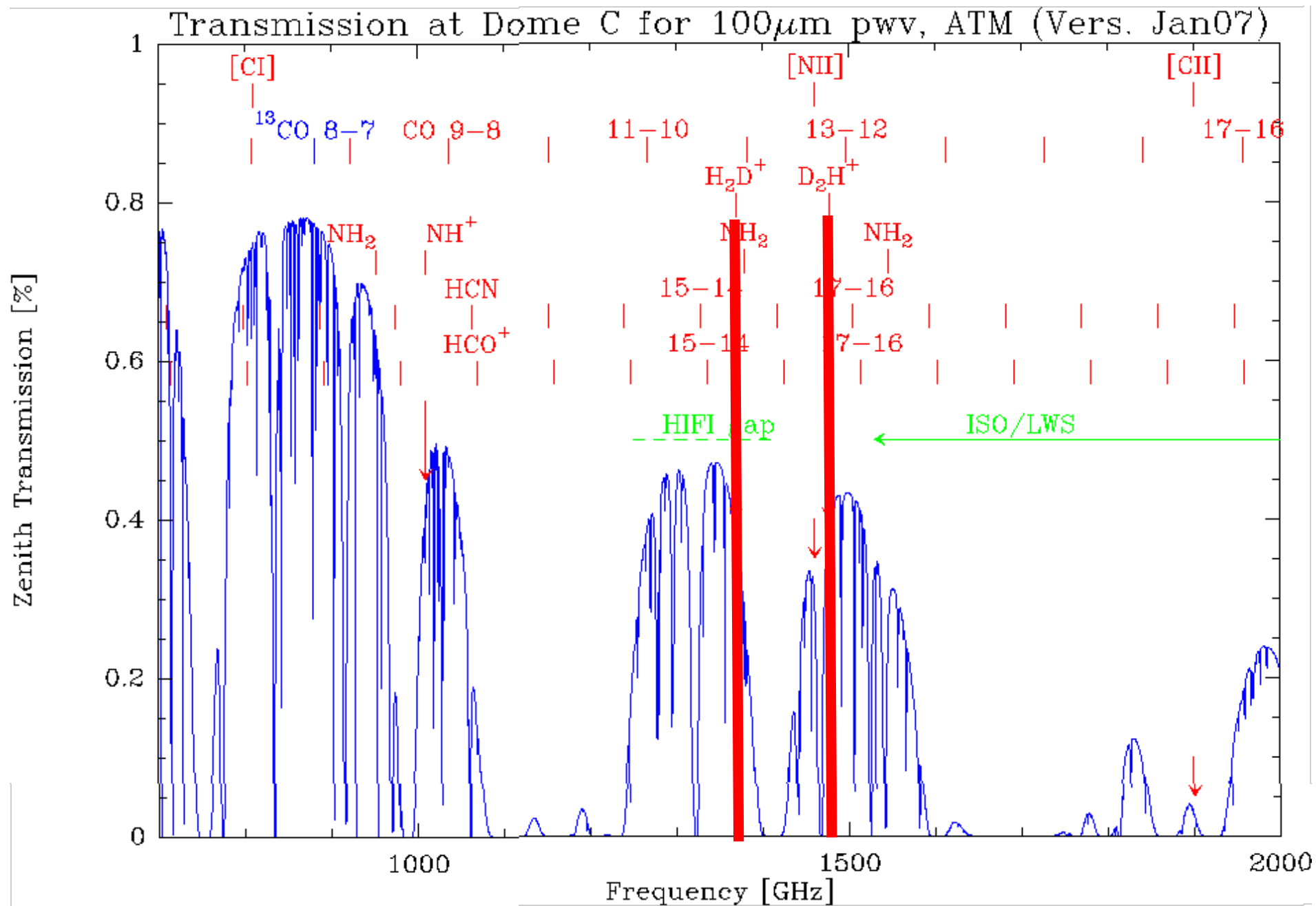
In addition:

H¹³CN, HC¹⁵N, HCN-v2, DCN

- IRC+10216: HCN with ISO/LWS (Cernicharo et al. 1996)



Light Hydrides: H_2D^+ , D_2H^+



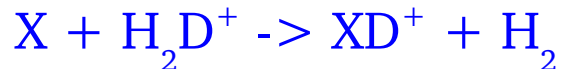
H_2D^+ and D_2H^+ : e.g. in prestellar cores

- Deuterium fractionation: strong indicator of physical conditions
- H_3^+ stays in gas phase when C,N,O have already frozen out
- H_3^+ accessible only via infrared absorption spectroscopy

Key reaction: $\text{H}_3^+ + \text{HD} \rightarrow \text{H}_2\text{D}^+ + \text{H}_2 + 230\text{K}$

The $\text{H}_2\text{D}^+/\text{H}_3^+$ abundance ratio would exceed unity at 10K, IF there were no destruction pathways

Reactions with heavy species spread deuteration:



e.g. increasing the $\text{DCO}^+/\text{HCO}^+$ and $\text{N}_2\text{D}^+/\text{N}_2\text{H}^+$ abundances.

Freeze-out of heavy species leads to increased $\text{H}_2\text{D}^+/\text{H}_3^+$ abundance ~ 1

e.g. in **prestellar cores** (10^{6-7} cm^{-3} , $T < 20\text{K}$).

Creation of D_2H^+ and even D_3^+ via reactions with HD

(e.g. Walmsley et al. 2004, Flower et al. 2004)



$\text{o-H}_2\text{D}^+$ @ 372 GHz

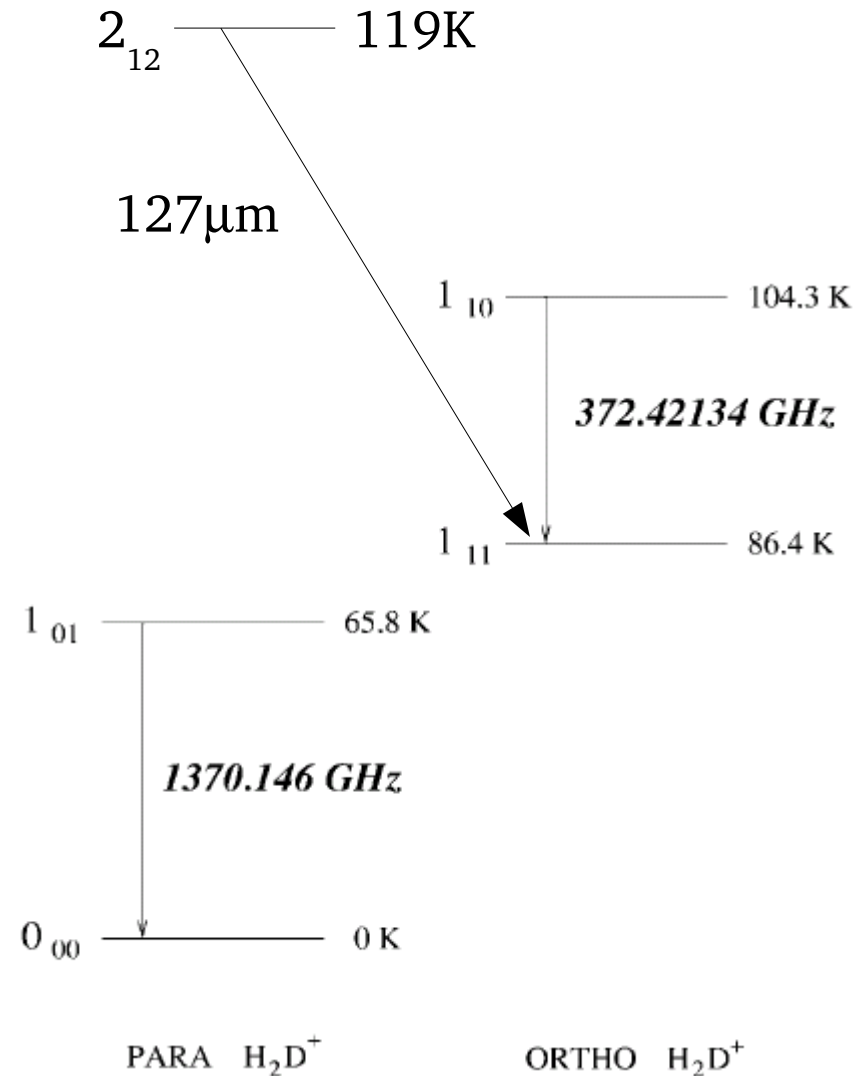
- towards low-mass protostars
(Stark et al. 1999, 2004)
- in dark clouds
(e.g. Vastel et al. 2004, Harju et al. 2006)
- in protoplanetary disks
(Ceccarelli et al. 2004)

$\text{p-H}_2\text{D}^+$ @ 1370 GHz

- several attempts unsuccessful
(e.g. Phillips et al. 1985, Boreiko & Betz 1993)
- not observable with ISO/LWS nor HIFI.
(HIFI “gap”: 1250 - 1410 GHz)

$\text{o-H}_2\text{D}^+$ @ 127 μm

- in absorption against SgrB2
with ISO/LWS (Cernicharo et al. 2007)



Vastel et al. 2004



p- D_2H^+ @ 692 GHz

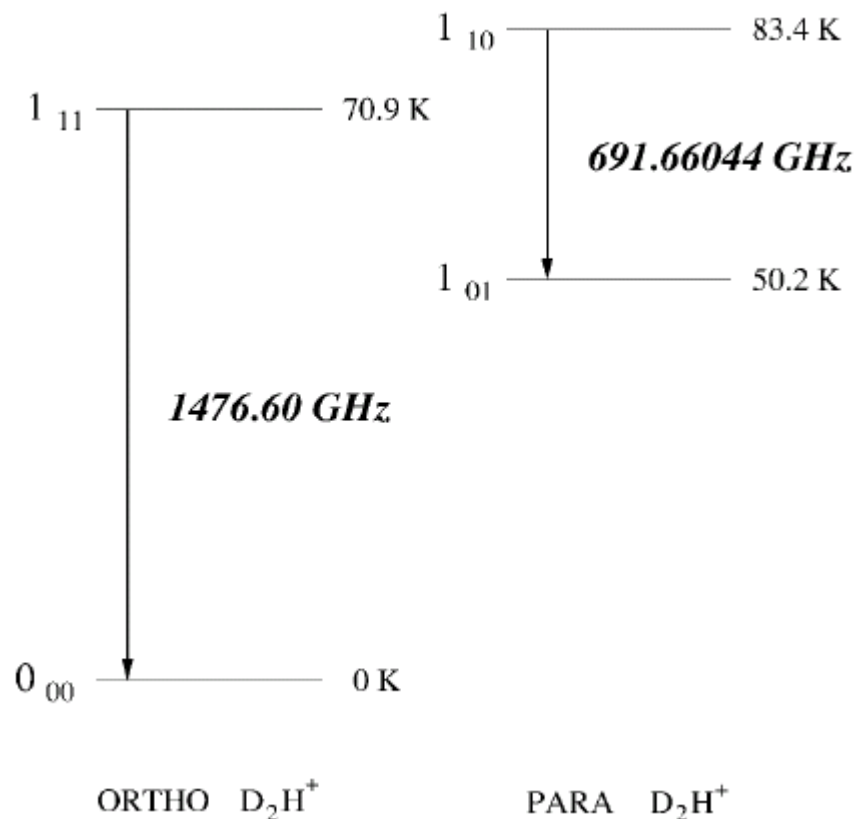
- Vastel et al. 2004
in the core 16293E with CSO

o- D_2H^+ @ 1477 GHz

**Observations of the ground state
transitions of p- H_2D^+ and of o- D_2H^+
would greatly improve knowledge of**

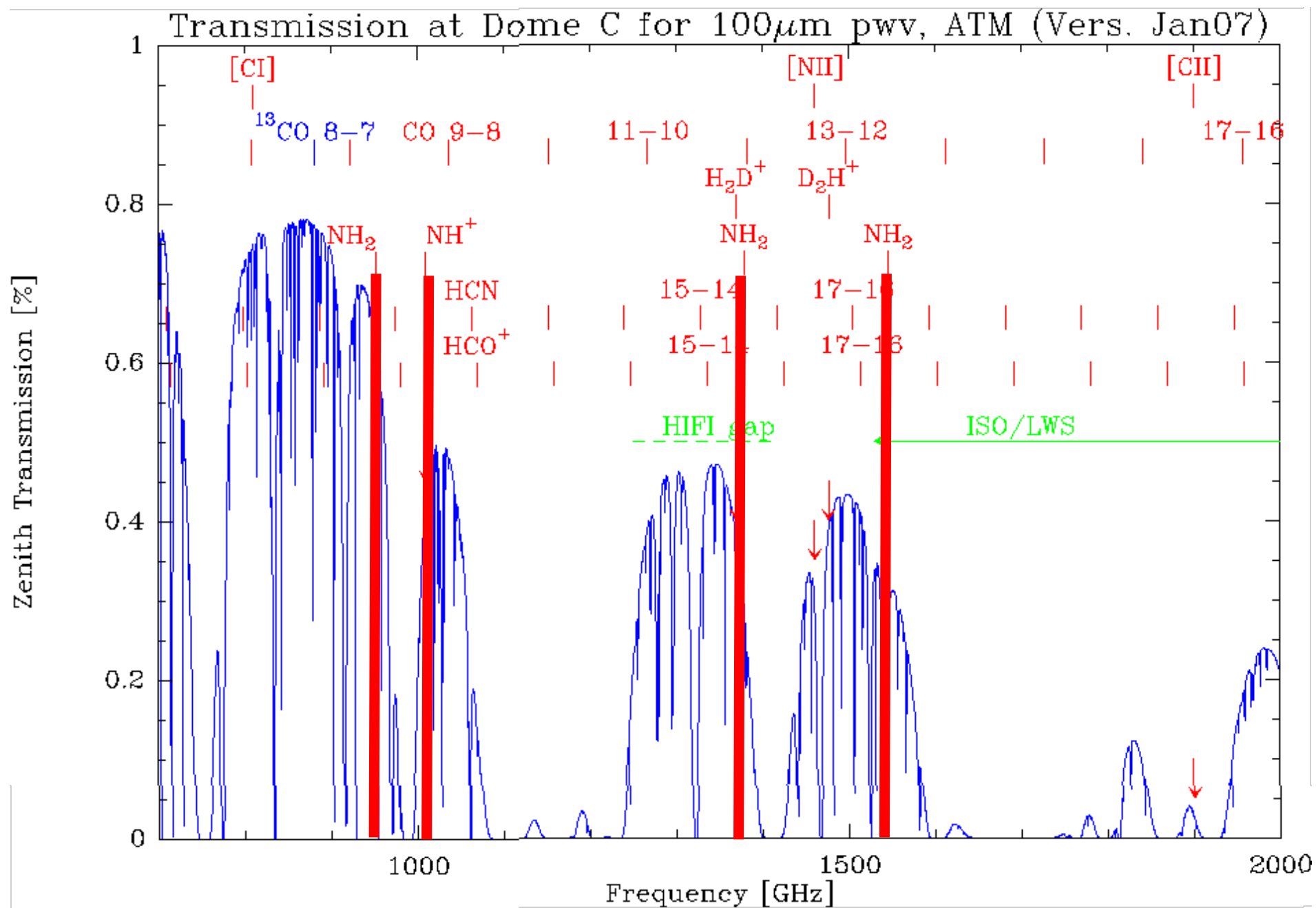
- the para/ortho ratio
reflecting the para/ortho ratio of H_2
- the gas phase abundances.

Note that D_3^+ can only be detected via absorption in the NIR.



Vastel et al. 2004

Light Hydrides: NH_2 , NH^+



NH^+ , NH_2 :

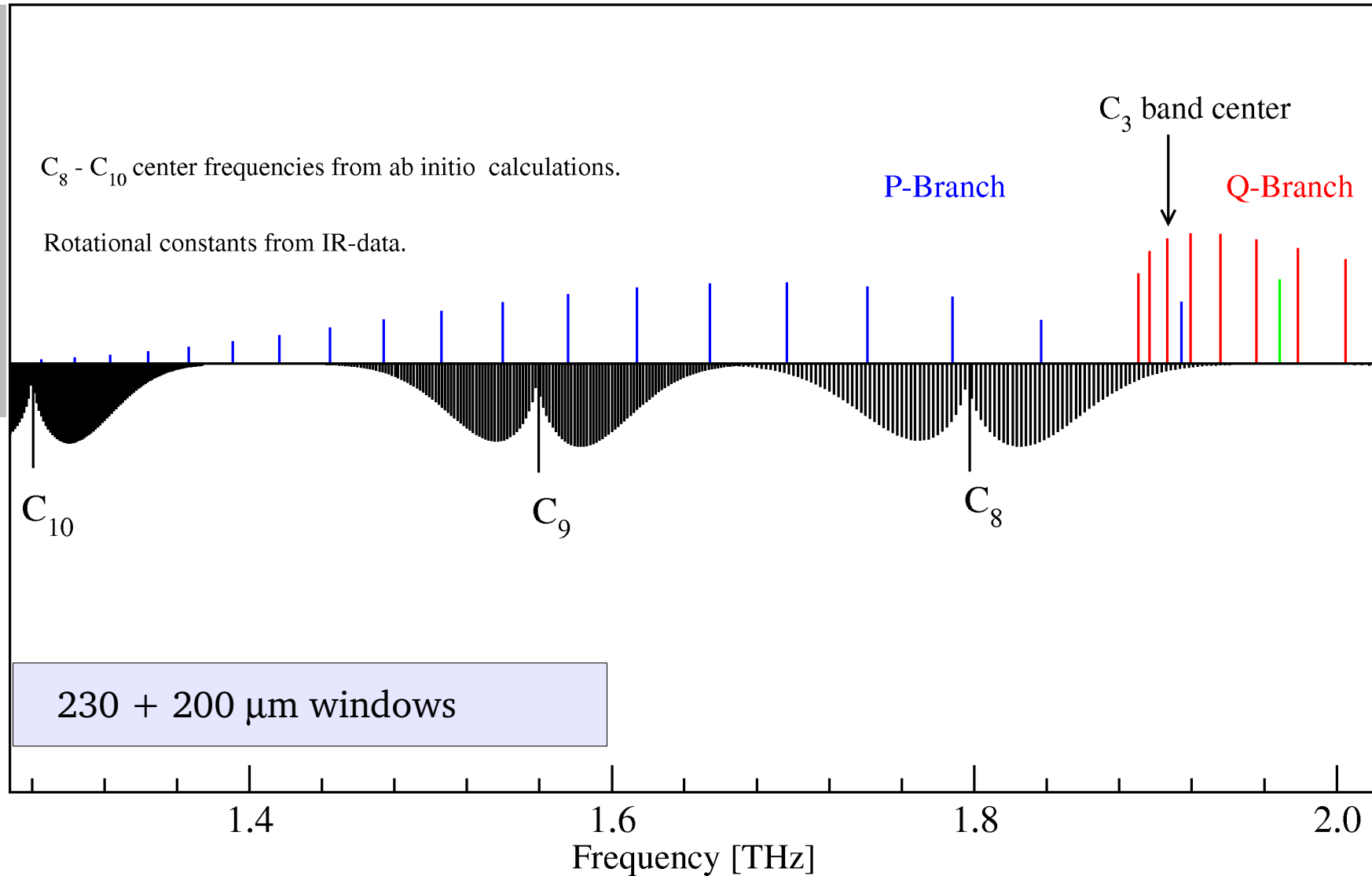
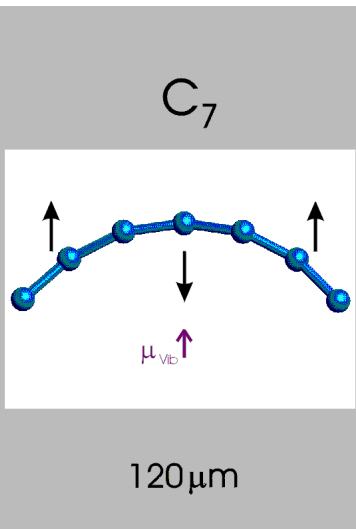
NH^+ : Ground state transition at 1012.6 GHz (296 micron)

Not yet detected in the ISM

- Great importance for Nitrogen chemical network leading to molecules like NH_3
- Observed $[\text{NH}_2]/[\text{NH}_3]$ ratio allows to discriminate formation pathways:
 - gas-phase ion-molecule reactions (UV driven chemistry, Sternberg & Dalgarno 1995)
 - shock chemistry
 - grain mantle release(cf. Comito et al. 2005)
- Probe of collapsing pre-stellar cores, where all heavy molecules are depleted, with the exception of N_2 , NH^+ !? (Bergin & Langer 1997)

- NH detected in absorption against SgrB2 (Cernicharo et al. 2000)
- NH_2 detected in absorption against SgrB2 (van Dishoeck et al. 1993)
- NH_2 @ 462 & 902 GHz tentatively detected in emission in Orion KL (Comito et al. 2005)

Low bending modes of Carbon chains



Molecular Spectroscopy at 1-2 THz from Dome C with a 12m telescope

- + Atomic and ionic lines: [NII], [CII], [CI]
- + CO high-J rotational transitions
- + HCN, HCO⁺ high-J rotational transitions
- + Light Hydrides:
H₂D⁺, D₂H⁺, NH₂, NH⁺, H₂O isotopes, LiH, ...
- + Pure carbon chains
- + ...many more...

Factor 3 better angular resolution compared to Herschel, SOFIA
Complementary science to ALMA

Time estimates:

0.2 mm pwv, 1.5 THz, $\tau_0 = 1.5$, 60° elevation, $T_{rx} = 1000$ K

For NII(205): $\Delta v = 10 \text{ km s}^{-1}$, $T_{pk} > 400$ mK, rms=100 mK, $T_{on} = 45$ min (demanding!)

For CO 13-12: $\Delta v = 0.5 \text{ km s}^{-1}$, $T_{pk} > 10$ K, rms=2 K, $T_{on} = 1$ min (mapping possible)

END

Molecular Spectroscopy at 1-2 THz

- + Atomic and ionic lines: [NII], [CII], [CI]
- + CO high-J rotational transitions
- + HCN, HCO⁺ high-J rotational transitions
- + Light Hydrides:
 H_2D^+ , D_2H^+ , NH_2 , NH^+ , H_2O isotopes, LiH, ...
- + Pure carbon chains
- + ...many more...

