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

(Submm/far-infrared astronomy from Antarctica)

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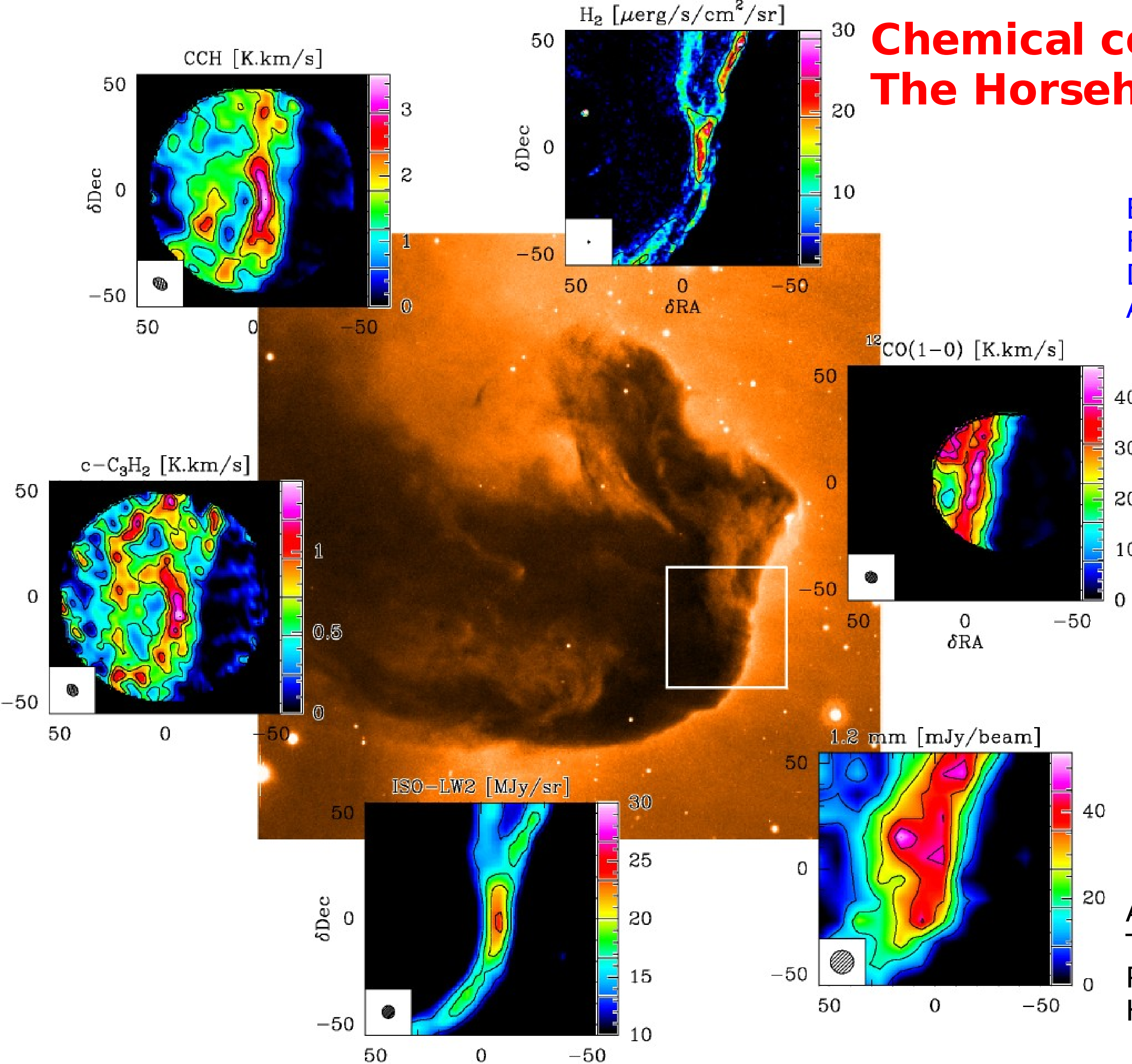
- **Atomic and ionic lines: [NII], [CII], [CI]**
- **CO high-J rotational transitions**
- **HCN, HCO^+ high-J rotational transitions**
- **Light Hydrides:**

  H_2D^+, D_2H^+, NH_2, NH^+, H_2O isotopes, LiH, ...
- **...many more...**

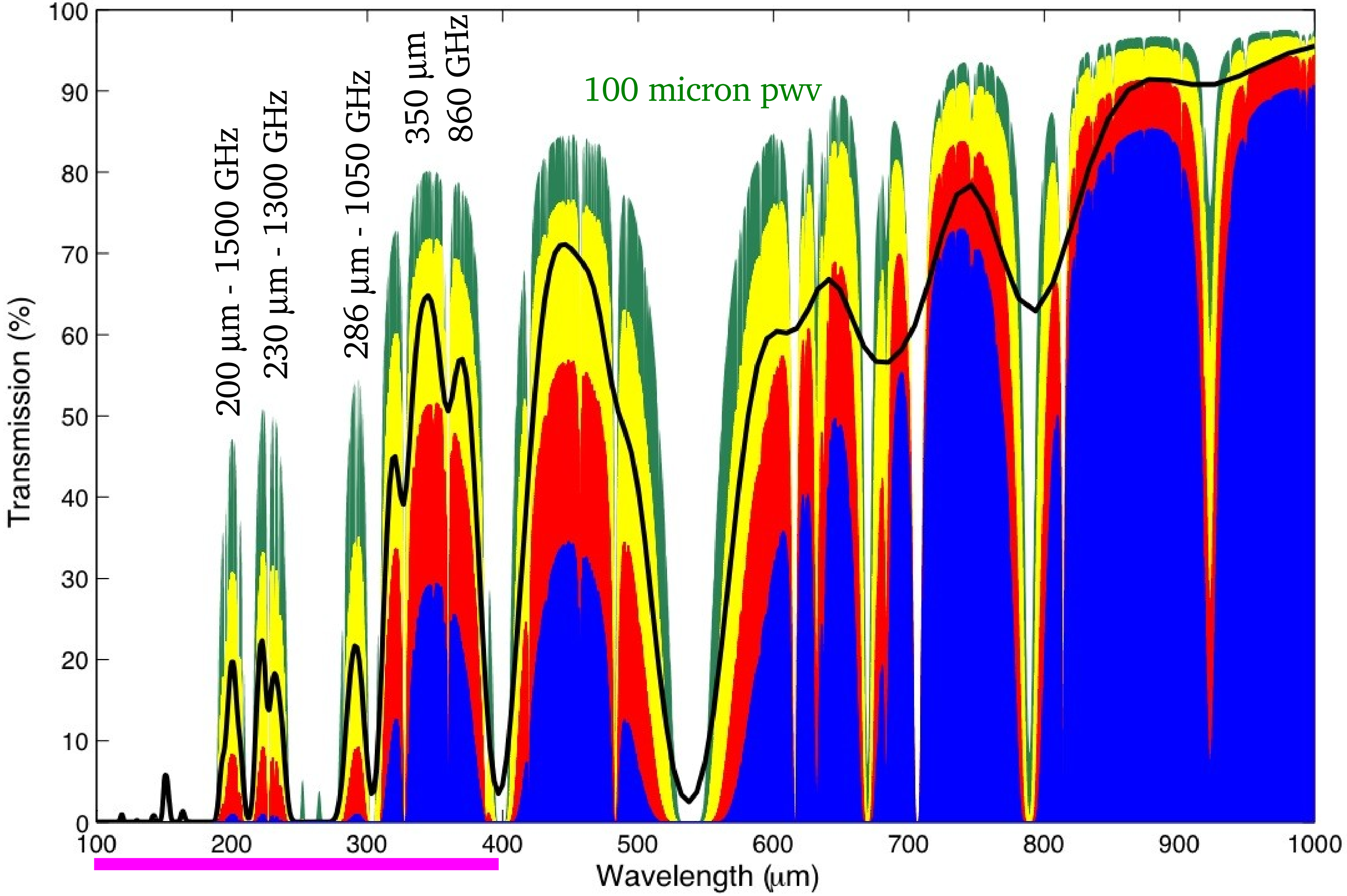
Chemical complexity: The Horsehead Nebula



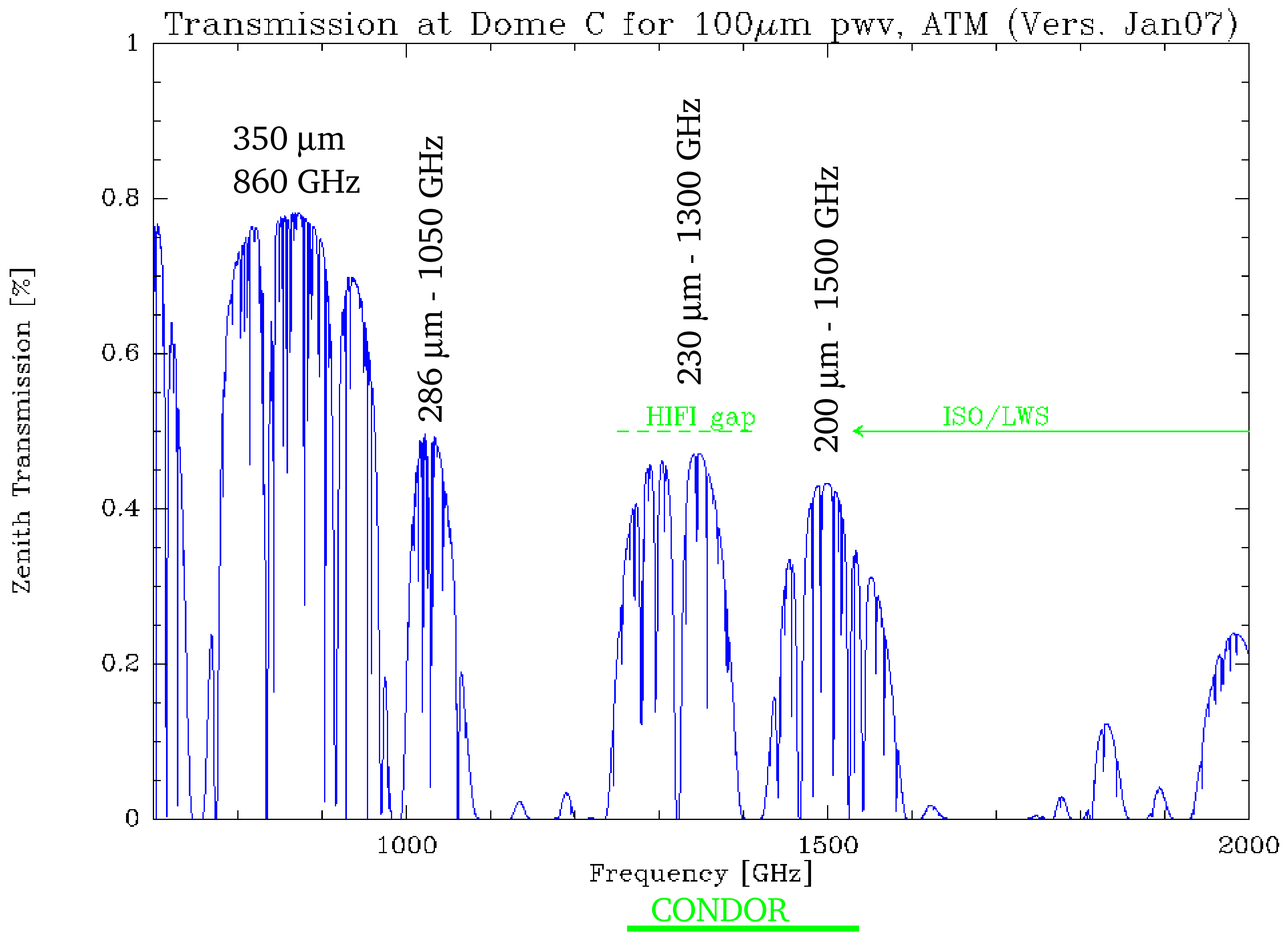
Edge-on PDR
FUV = 30
Distance = 400 pc
A_v = 20 mag

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

Atmospheric windows

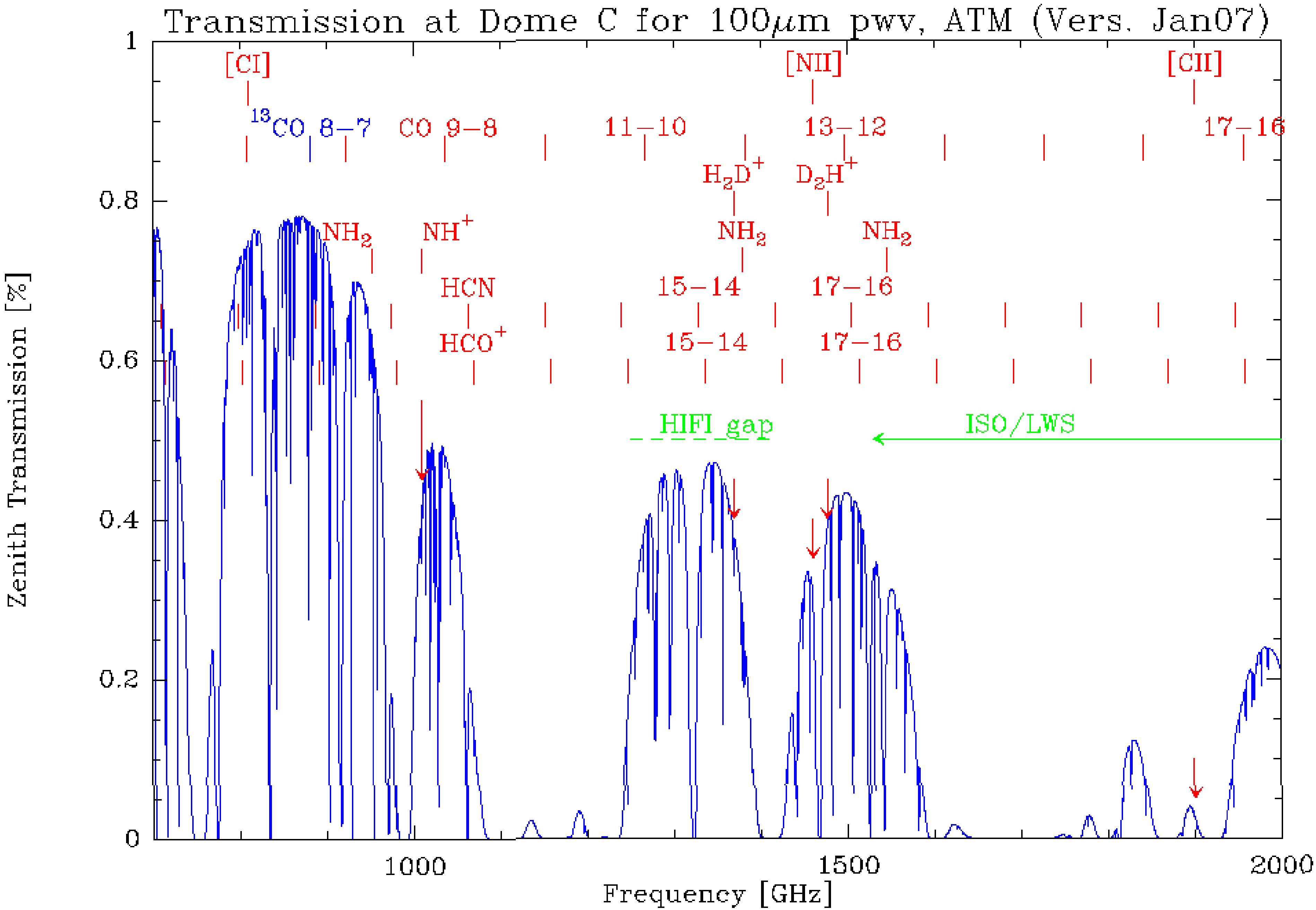


Atmospheric windows due to H_2O, O_2, ...

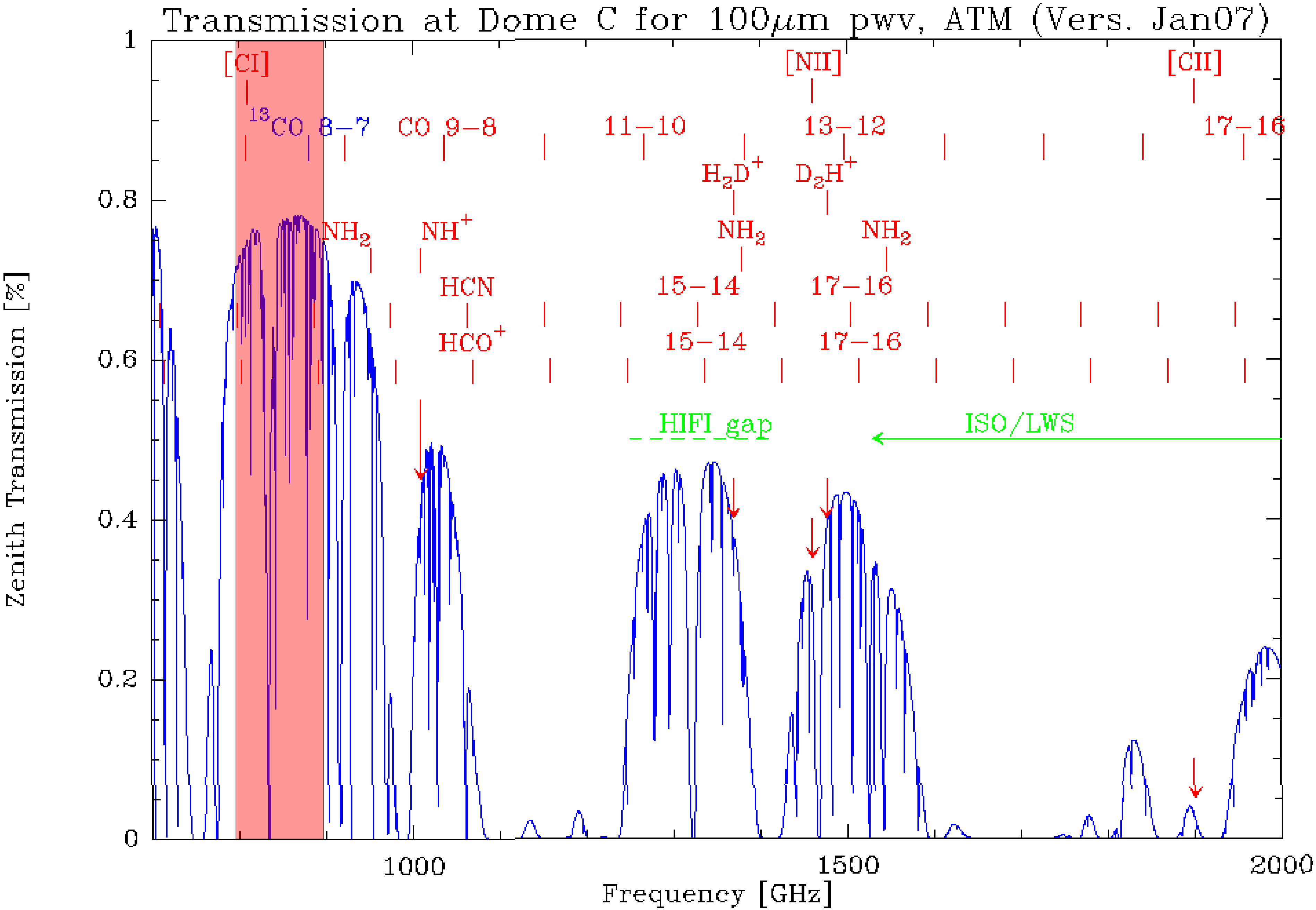


- ATM by J.Pardo et al. (2001)
- cf. FTS spectrum taken at Cerro Sairecabur/Chile by Marrone, Blundell et al. 2005: Measured water vapour: pwv = 93 μm

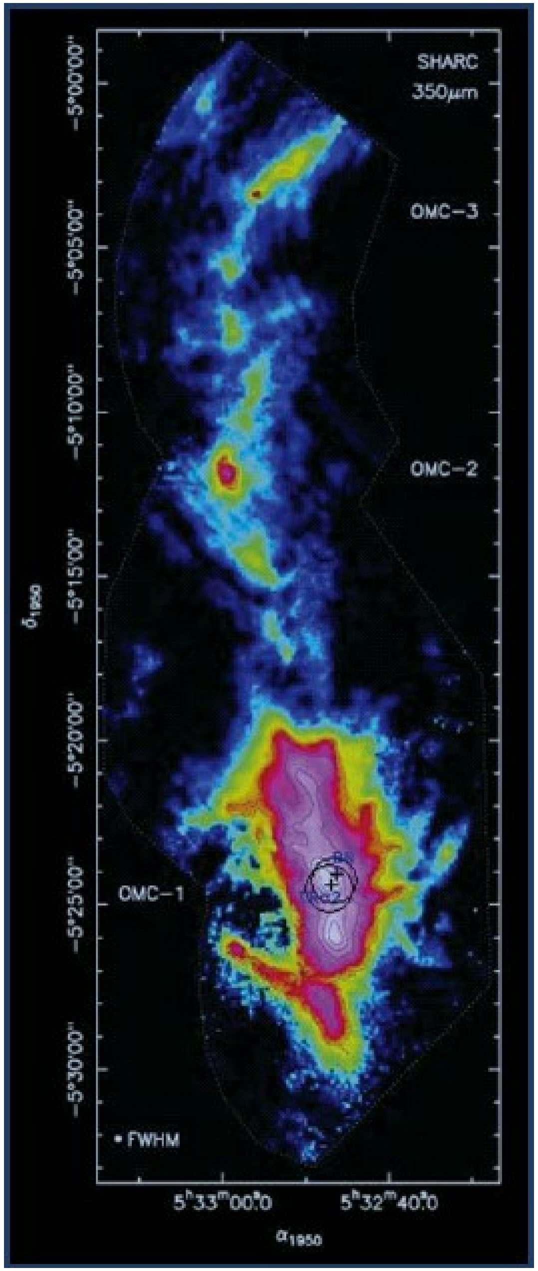
Atmospheric windows



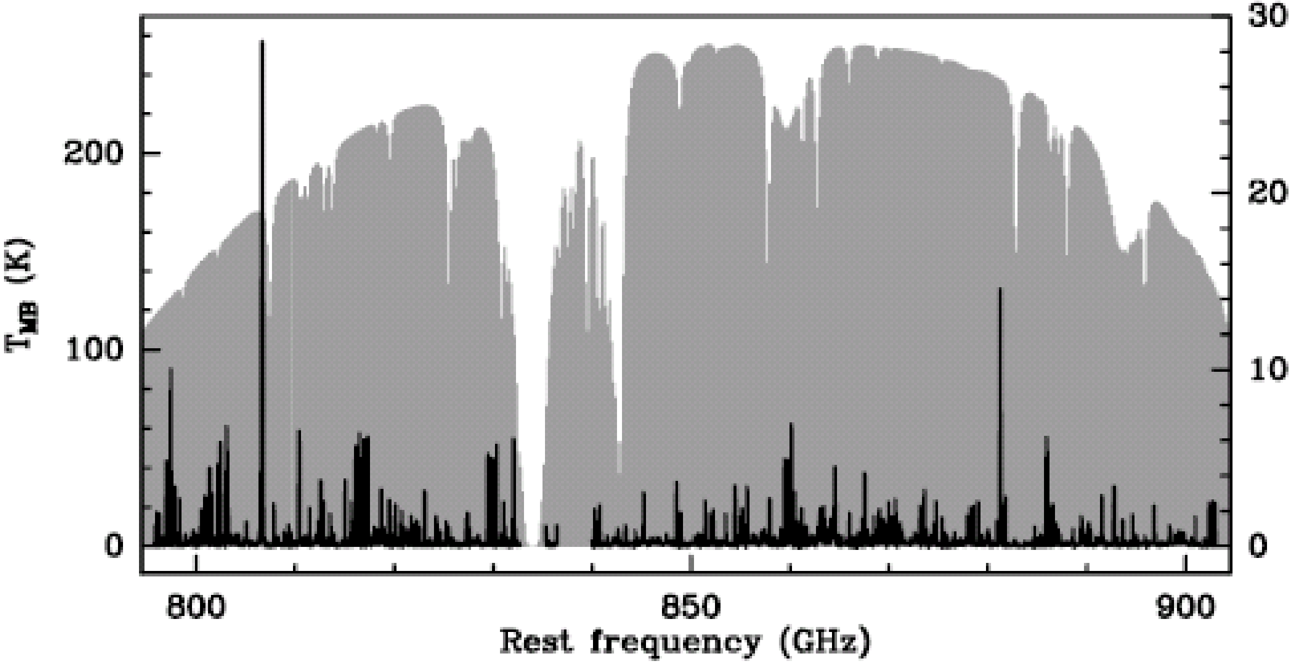
Atmospheric windows



The THz regime is rich in lines

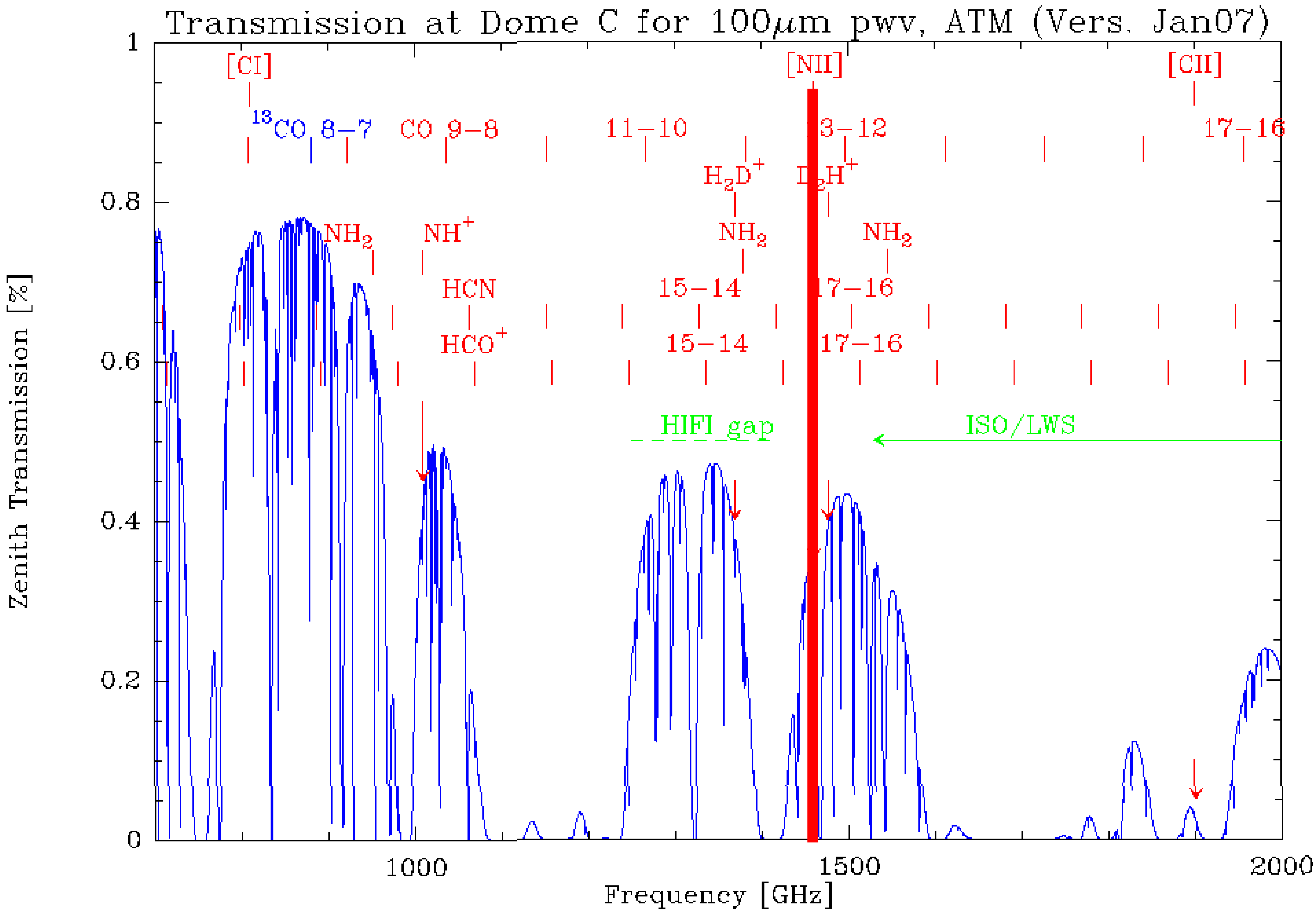


SHARC/CSO 350micron dust emission map of Orion A (Lis et al. 1998)



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: SO_2, CH_3OH, CO, SO, H_2CO, HCN,...
(HCN contains 25% of SO_2 cooling intensity)

[NII]



Transmission at Dome C for 100μm pwv, ATM (Vers. Jan07)
[CI]
[NII]
[CII]
13CO 8–7
CO 9–8
11–10
13–12
17–16
H2D+
D2H+
NH2
NH+
NH2
NH2
HCN
15–14
17–16
HCO+
15–14
17–16
HIFI gap
ISO/LWS
Zenith Transmission [%]
Frequency [GHz]
1
0.8
0.6
0.4
0.2
0
1000
1500
2000

[NII]

[NII] stems from HII regions:
$E_{io}(N) = 14.53eV$
122 μm (2.46 THz) $^3P_2$-$^3P_1$
205 μm (1.46 THz) $^3P_1$-$^3P_0$

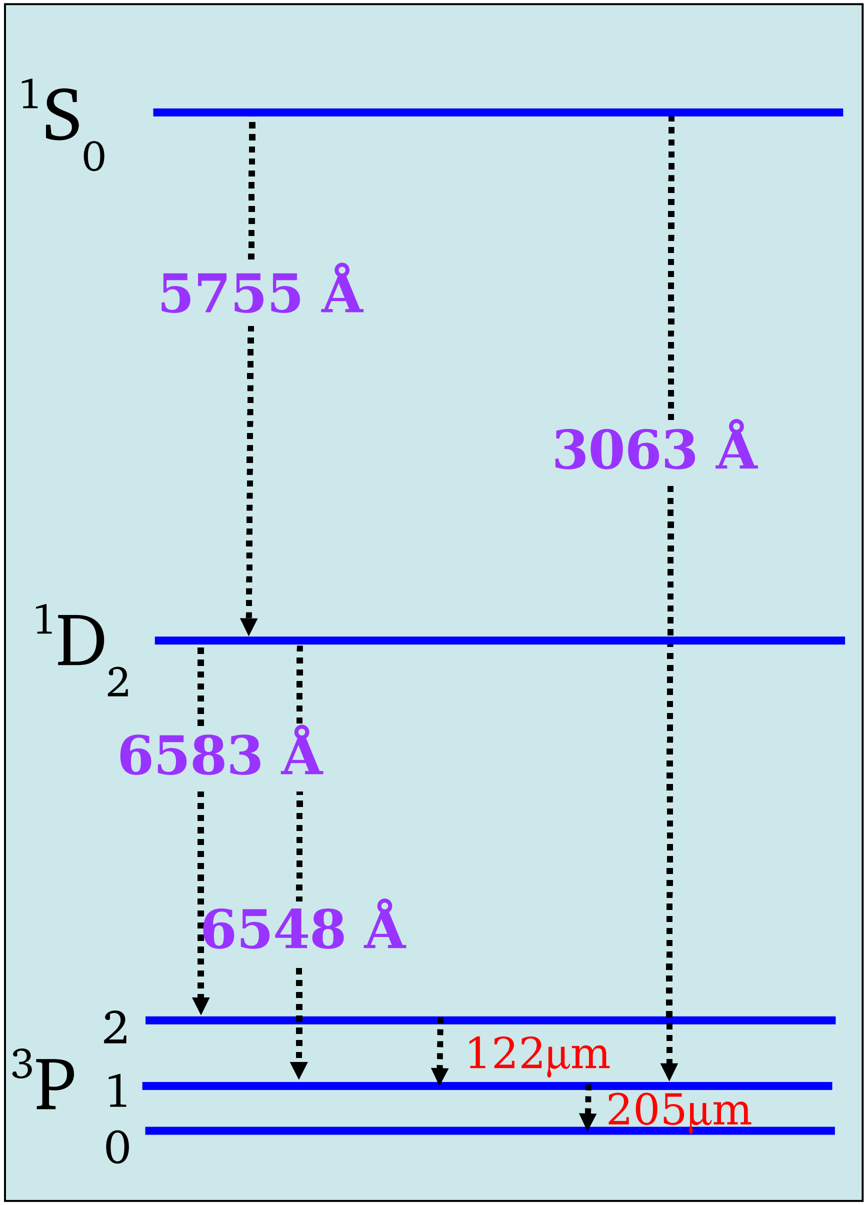
n_{cr} = 293 cm^{-3} for 122 μm line
n_{cr} = 44 cm^{-3} for 205 μm line
for T_e=8000 K

- Excellent probes of the low-density ionized gas

- Extinction free, in contrast to optical lines

- supplementing lines of [OIII] 88 and 52μm tracing high density ionized gas

[NII]



[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

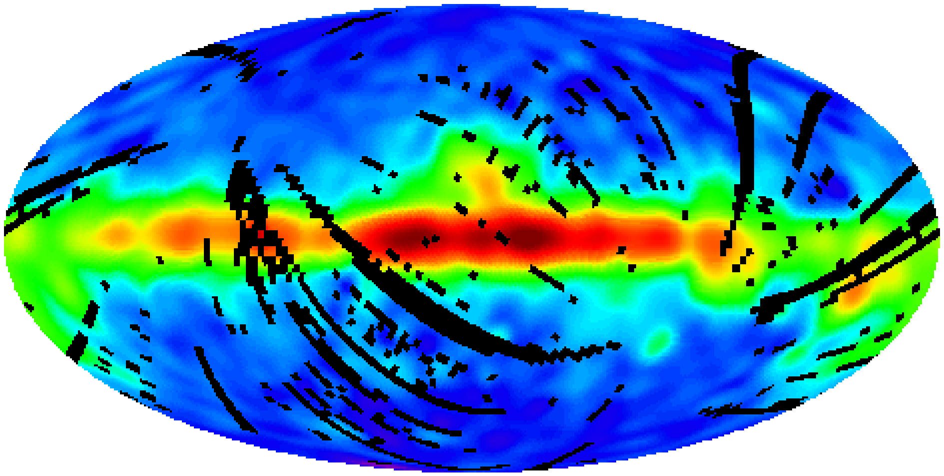
- FIRAS/COBE (Fixsen et al. 1999): [NII] lines are strongest after [CII] for $\lambda > 100\mu m$

- ISO/LWS: 122μm line strong also in disks of spiral galaxies: e.g. Contursi et al. 2002, Kramer et al. 2005

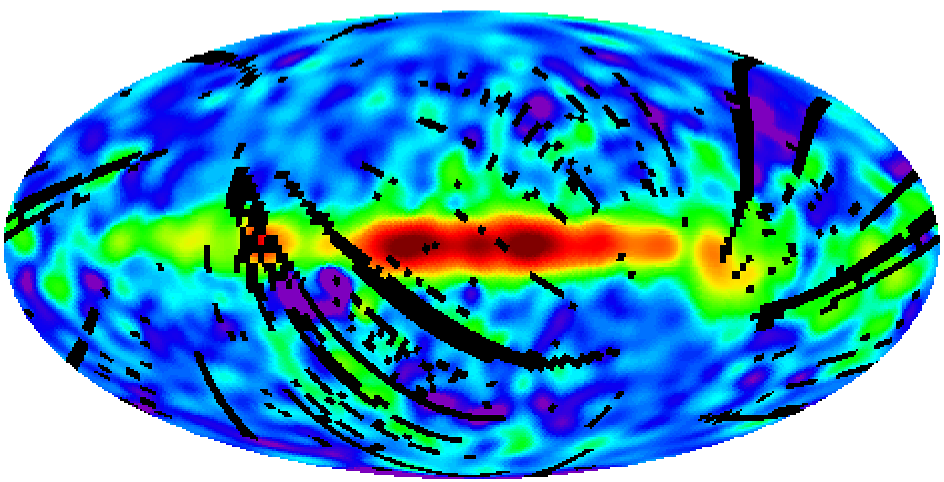
- SPIFI/AST/RO: 205μm line detected from ground in Carina I HII region (Oberst et al. 2006)

The Milky Way with FIRAS/COBE

COBE FIRAS 158 μm C^+ Line Intensity



COBE FIRAS 205 μm N^+ Line Intensity



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

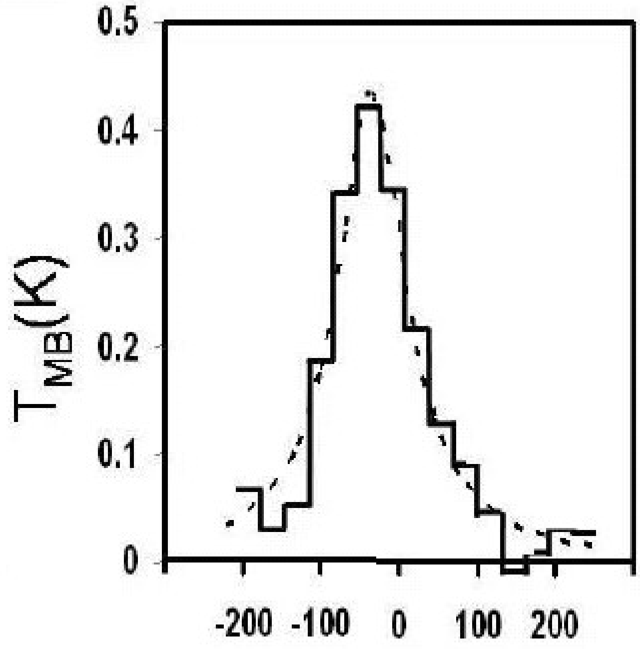
[NII]

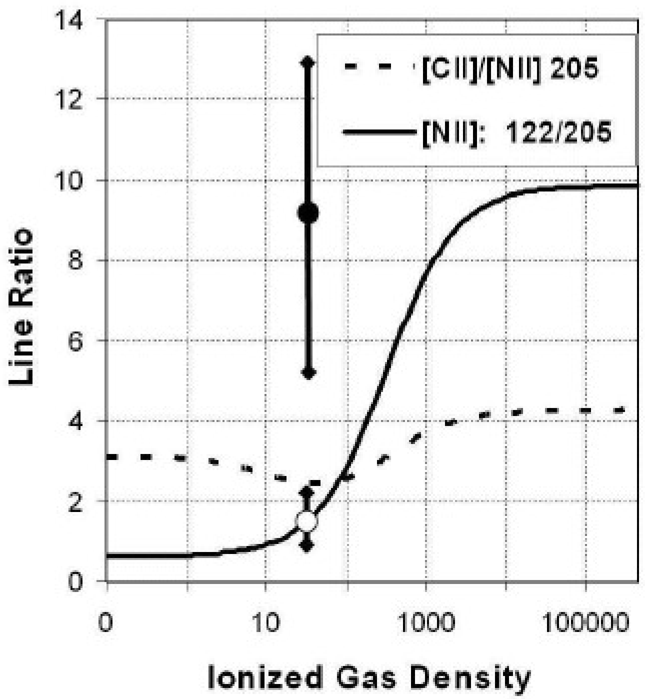
Observations:
SPIFI/AST/RO:
205μm (1.46 THz) line
detected from ground
in Carina I HII region

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

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

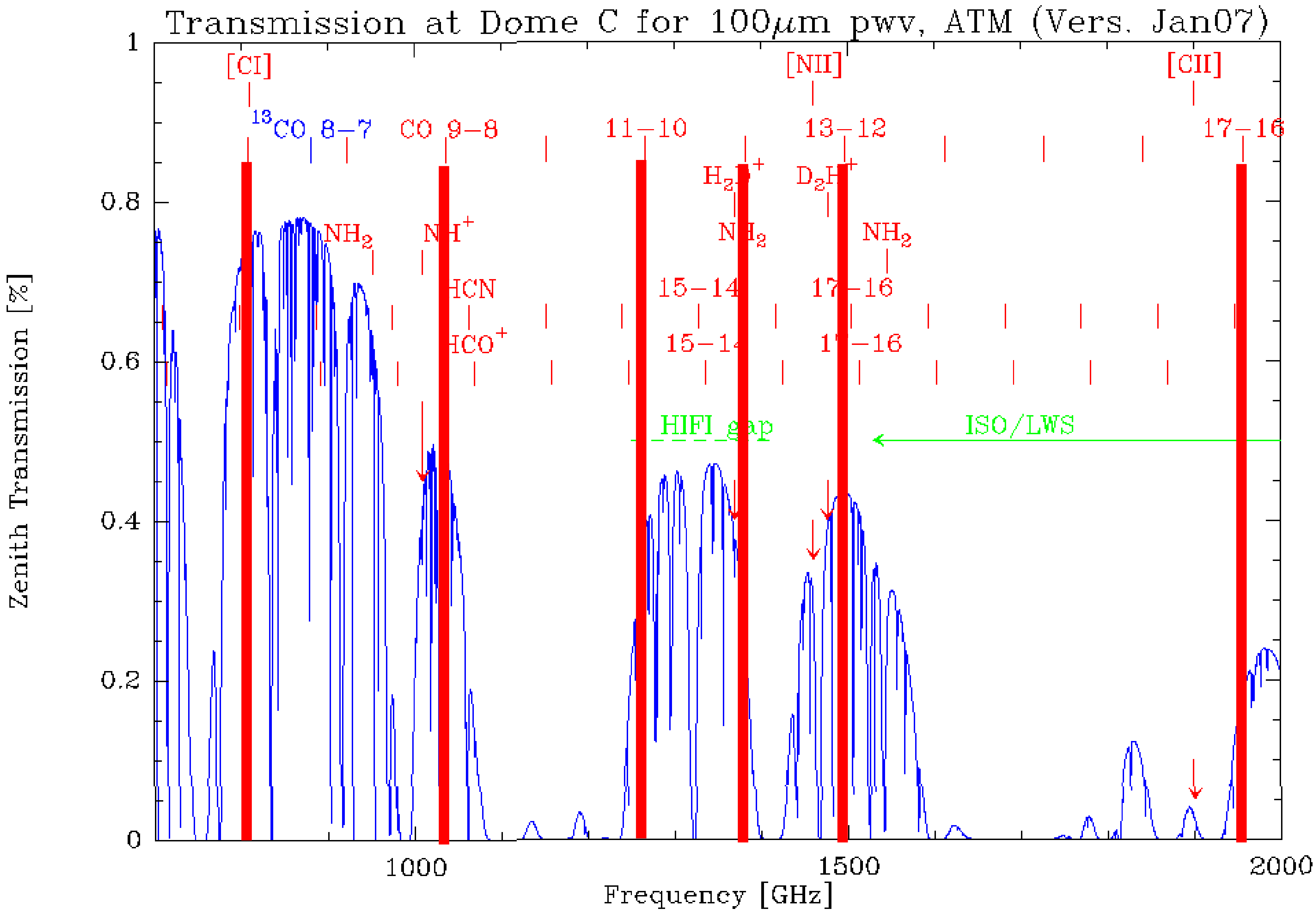
Models of the ionized gas:
~30% of [CII] emission stems from
the diffuse ionized medium





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

CO



Transmission at Dome C for 100μm pwv, ATM (Vers. Jan07)
Zenith Transmission [%]
Frequency [GHz]
1
0.8
0.6
0.4
0.2
0
1000
1500
2000
[CI]
[NII]
[CII]
13CO 8–7
CO 9–8
11–10
13–12
17–16
NH2
NH+
HCN
HCO+
15–14
HIFI gap
ISO/LWS

CO

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

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

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

e.g.

CO 14-13: 590 K, 1.1 x 10^7 cm^{-3}

CO 7-6: 157 K, 1.4 x 10^6 cm^{-3}

CO 4-3: 56 K, 2.6 x 10^5 cm^{-3}

Unresolved observations:

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

Velocity resolved observations:

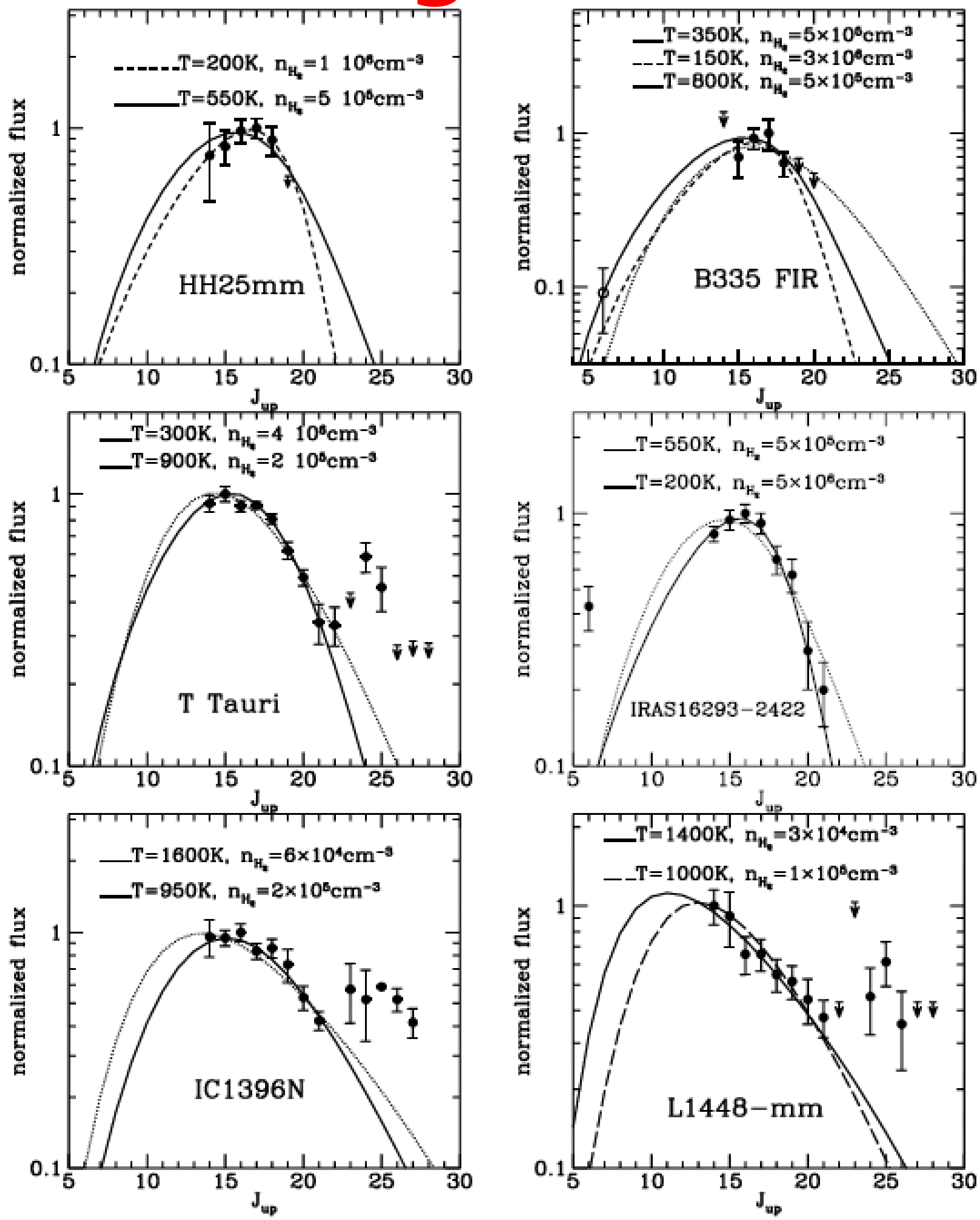
- CO 7-6: several observations (+galactic nuclei upto z=6.4)
- CO 9-8: very few observations so far:

  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 350μm:

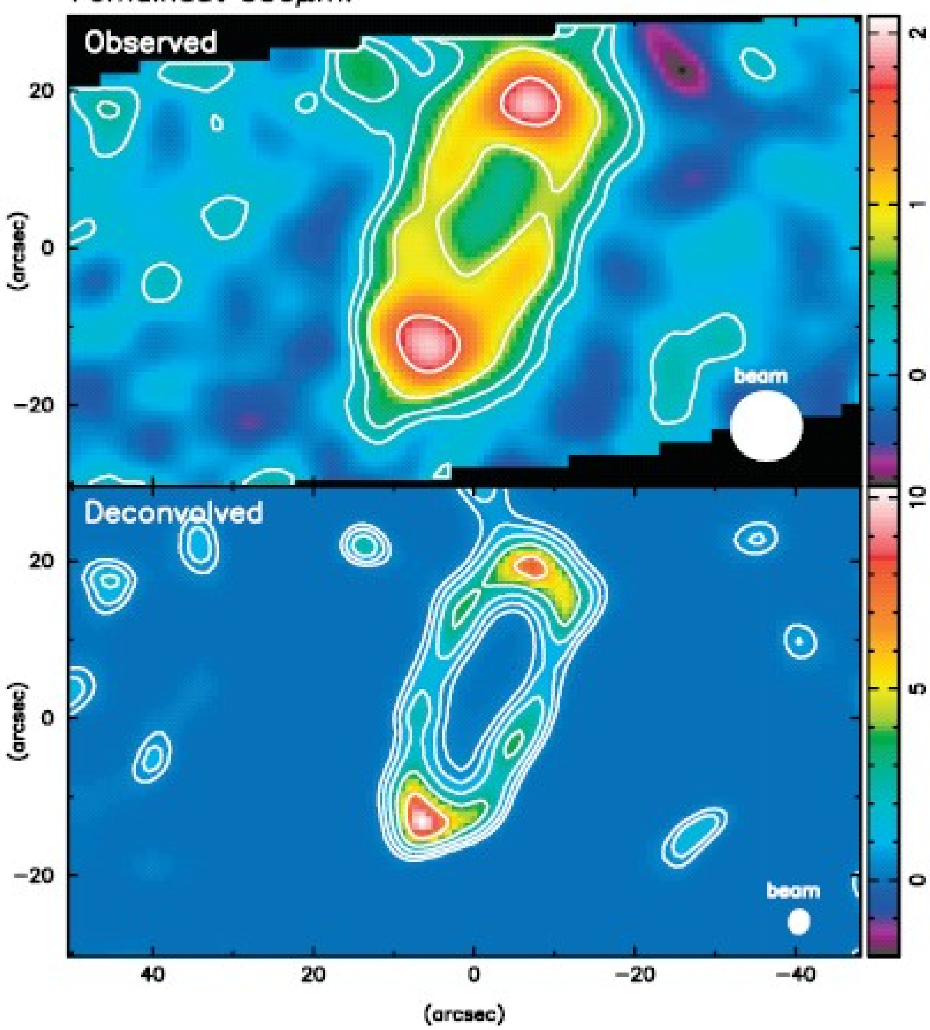
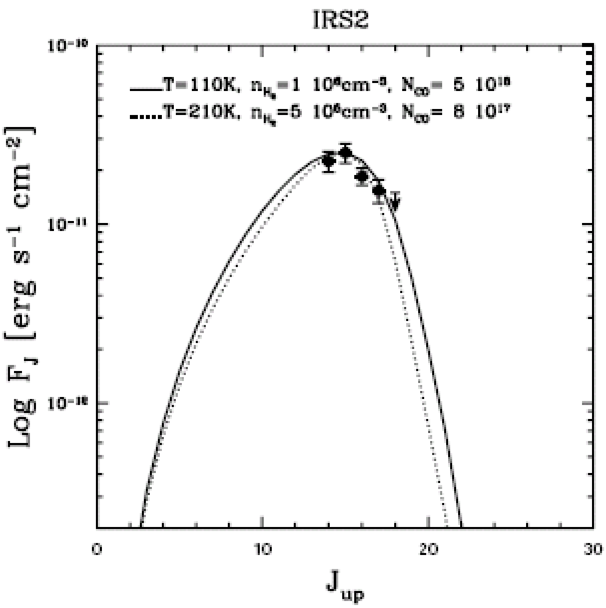


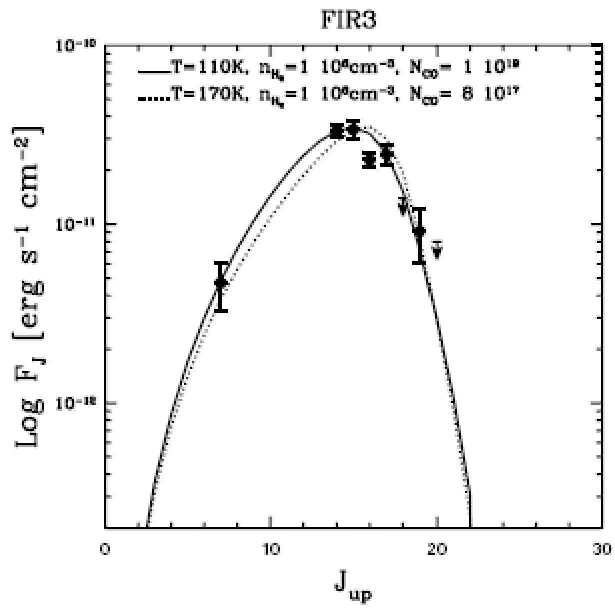
FIG. 1.—Fomalhaut at 350 μm. The upper and lower panels represent the observed and deconvolved images, respectively. In the observed image, the contours are at 0.2, 0.4, 0.8, and 1.6 mJy arcsec^{-2}, and the rms noise is 0.15 mJy arcsec^{-2}. In the deconvolved image, the contours are at 0.4, 0.8, 1.6,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

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

see Talk by P.Andre

CO: PDRs and hot cores

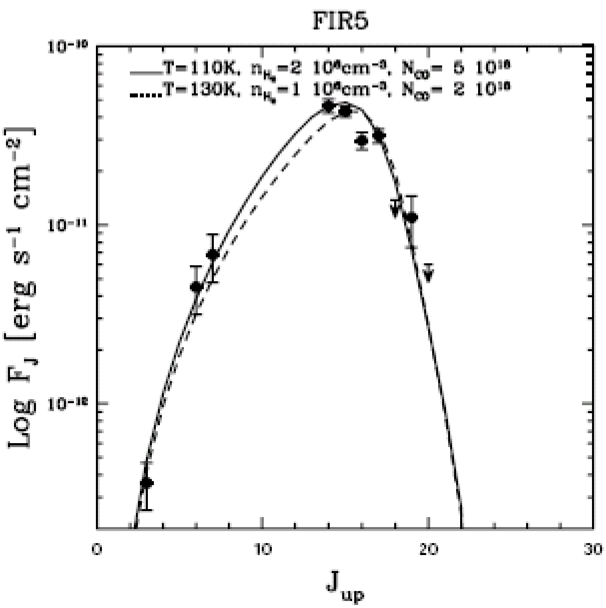


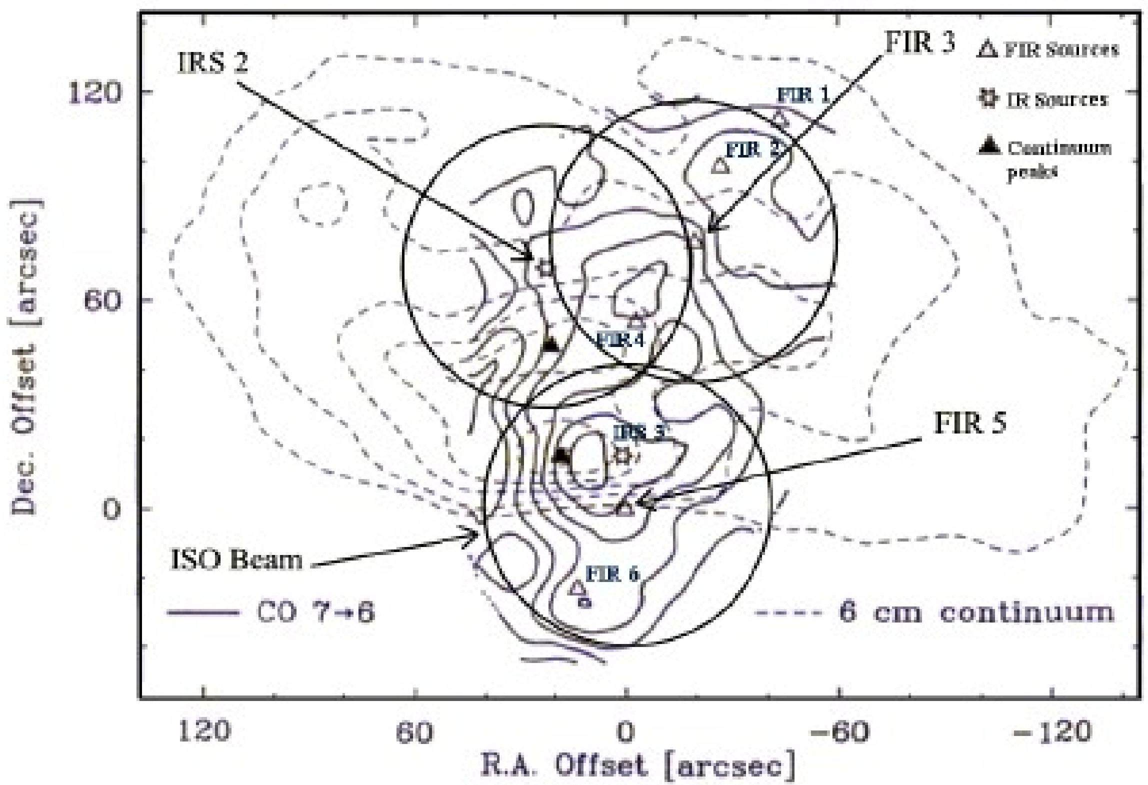


Embedded sources and photon dominated regions (PDRs) in the star forming complex NGC2024/Orion B

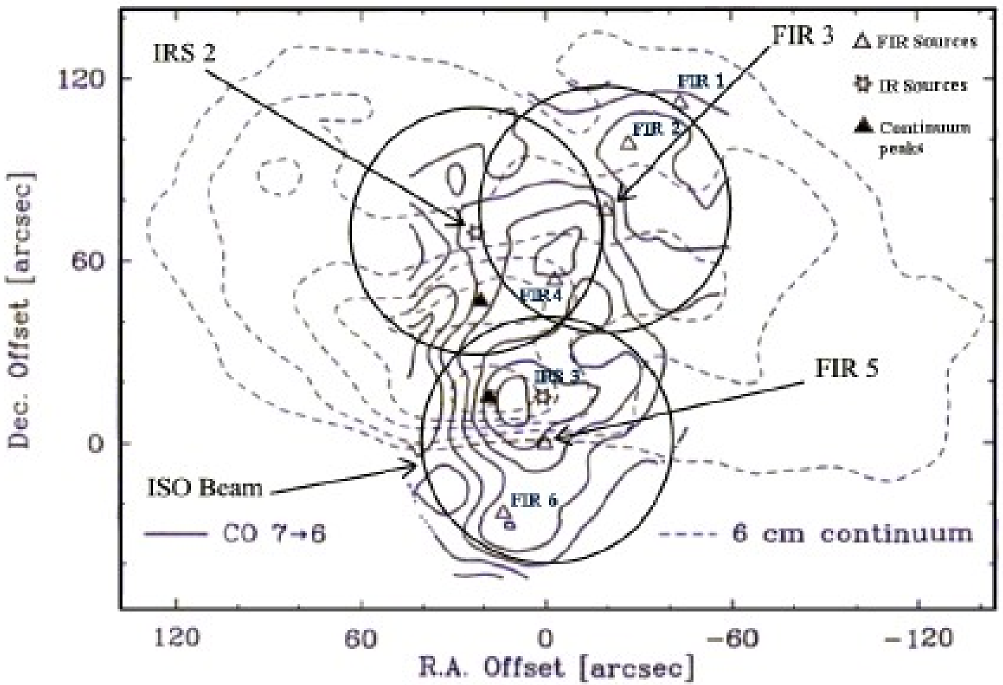
ISO/LWS
(Giannini et al. 1999)

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

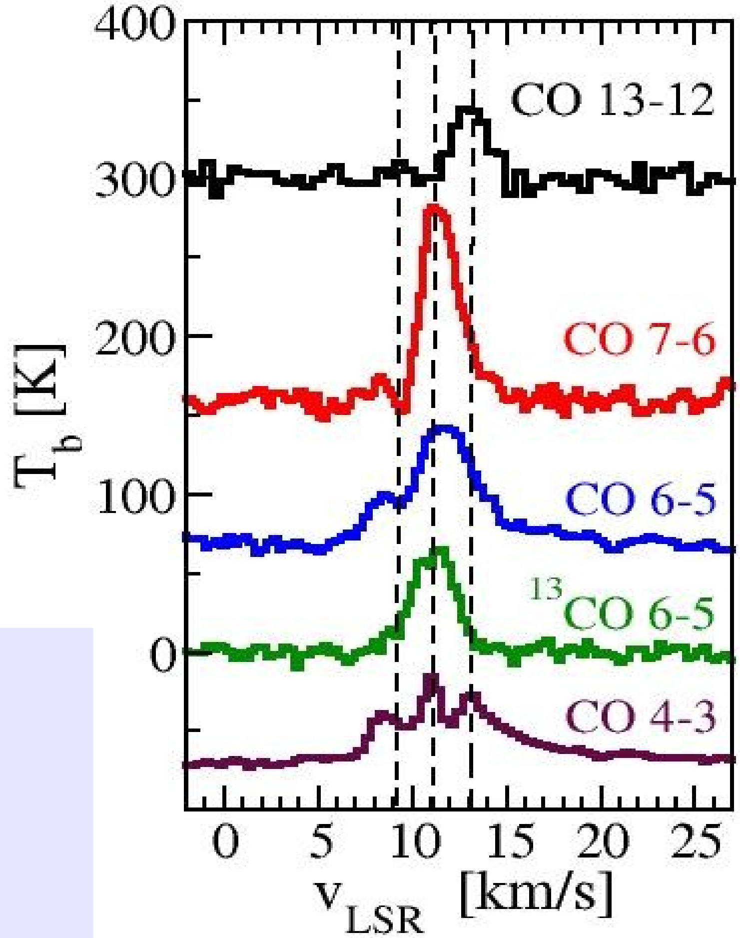




CO: PDRs and hot cores



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 kms^{-1}

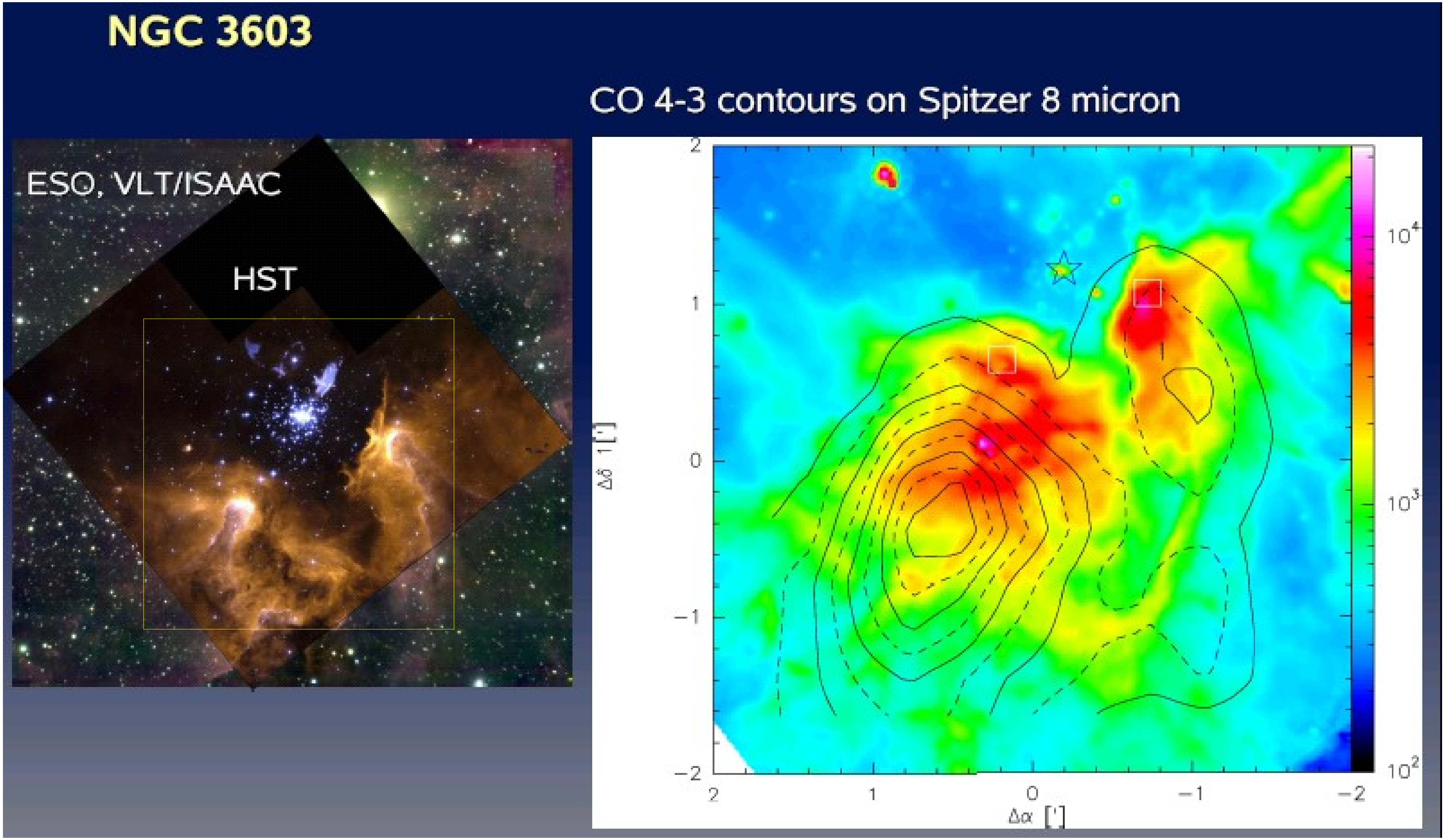
10min ON-time, 15% transmission

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

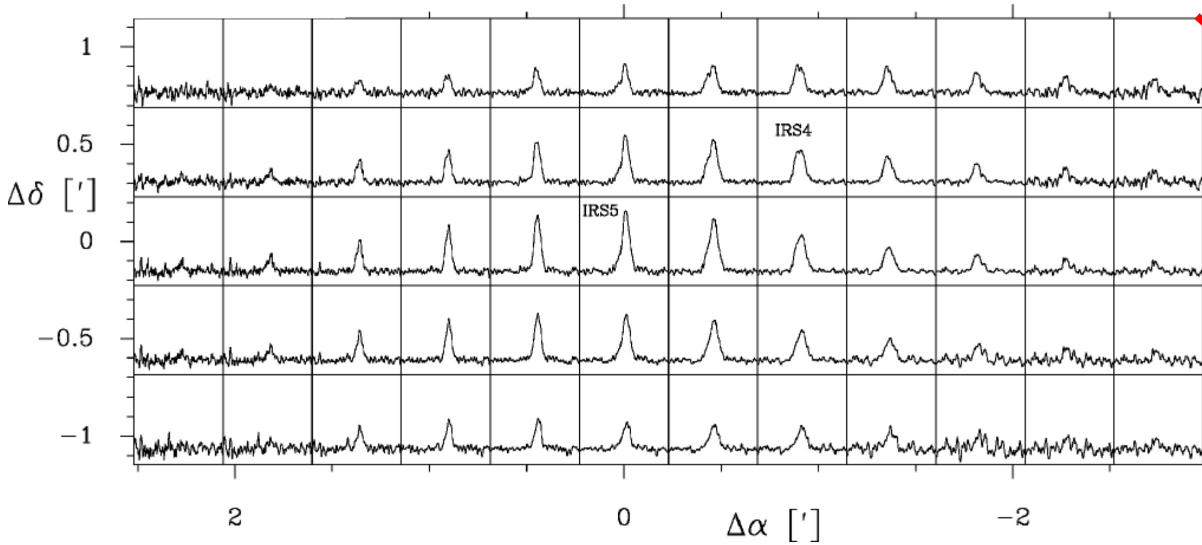
CO: Galactic starburst regions

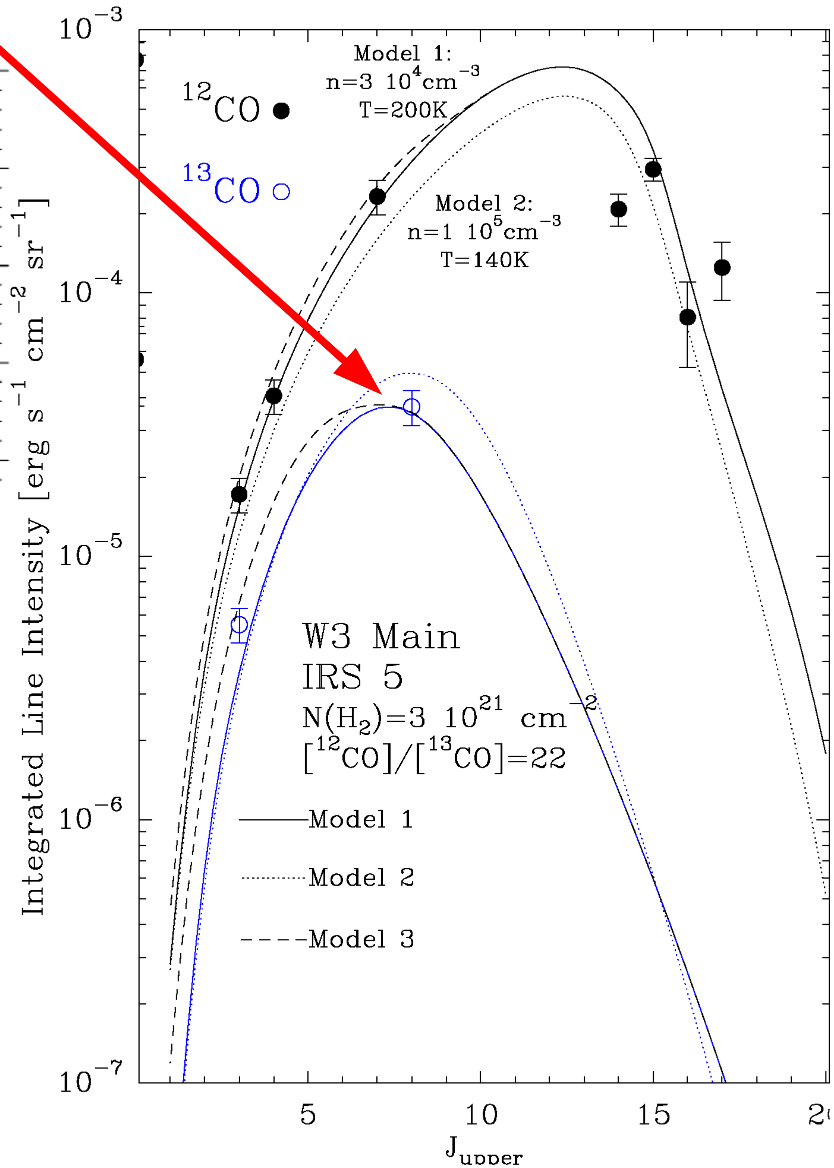


NGC3603 @ 7.7 kpc in CO 4-3, 7-6, [CI] 1-0, 2-1 @ NANTEN2-4m telescope
Röllig et al. (in prep.)

^{13}CO: PDRs

Another example: W3Main



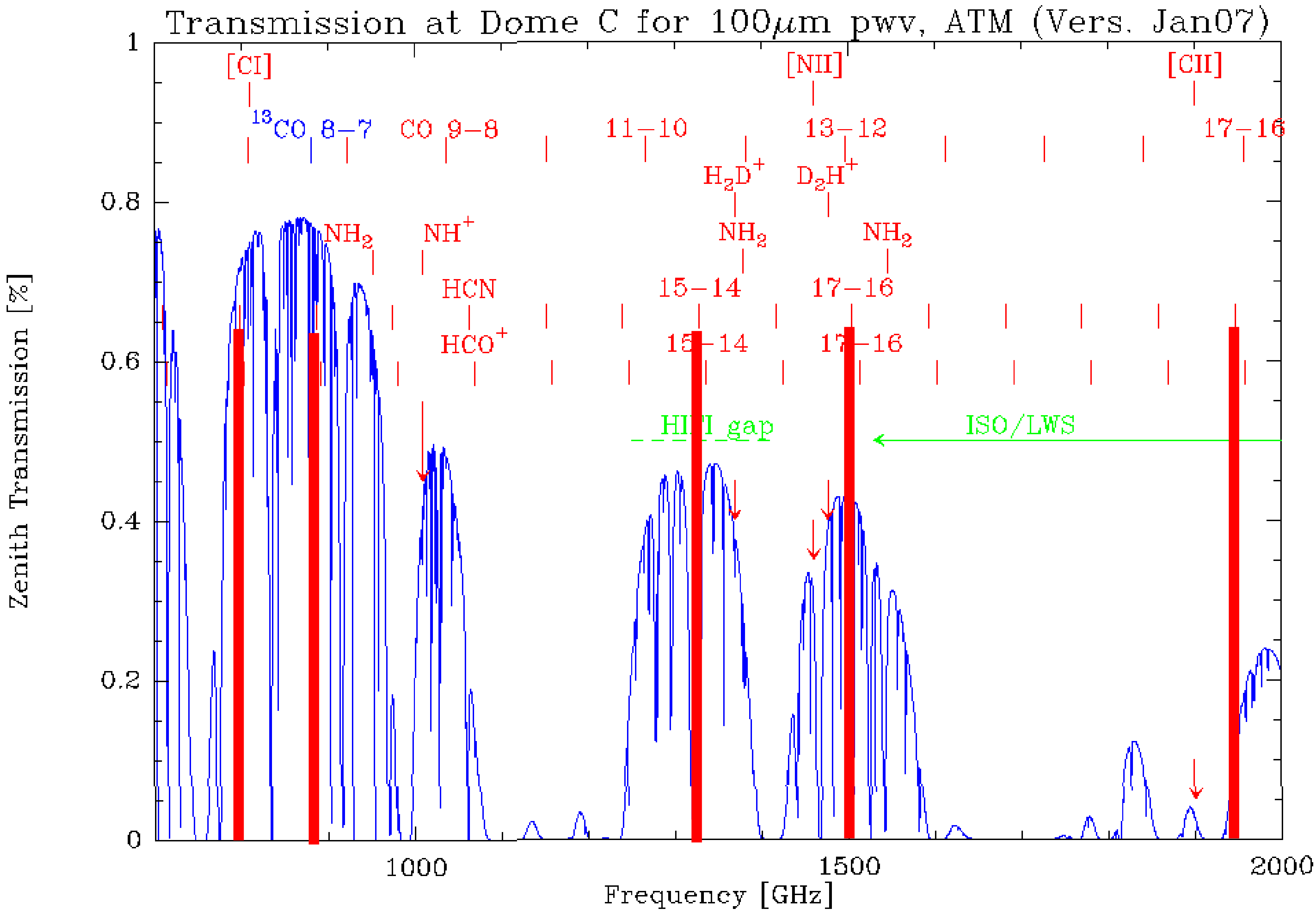


^{13}CO 8-7

- warm and dense gas component
- extended: ~3.4pc
- 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^+)



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HIFI gap
ISO/LWS
Zenith Transmission [%]
Frequency [GHz]
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2000

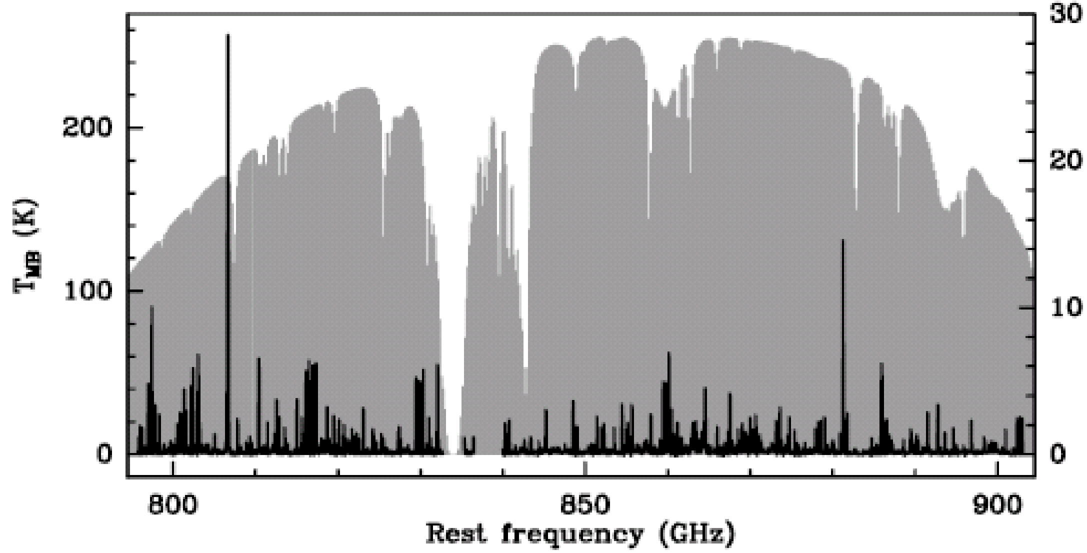
HCN & HCO^+

High-lying rotational transitions in the THz regime

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

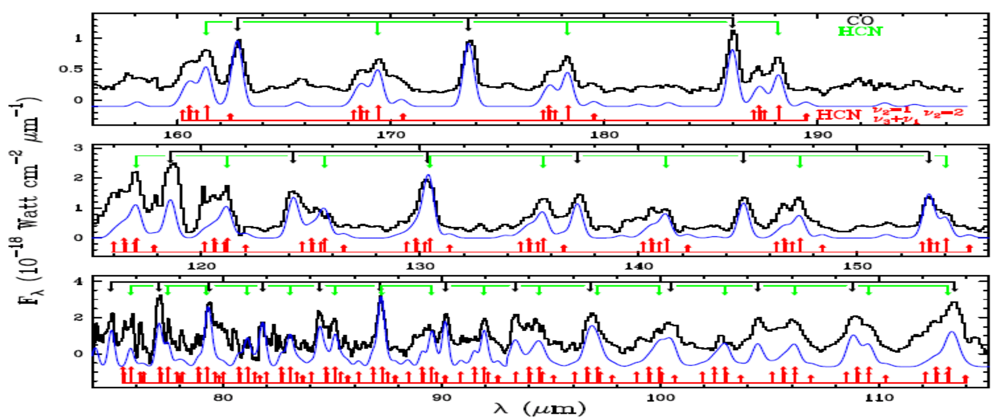
HCN 9-8	797GHz	95K Tmb
HCN 10-9	886GHz	57K
HCO^+ 9-8	802GHz	56K
HCO^+ 10-9	892GHz	30K

Trot=150K, n=$10^{7\text{-}8}$ cm^{-3}
(if collisionally excited, IR pumping?)

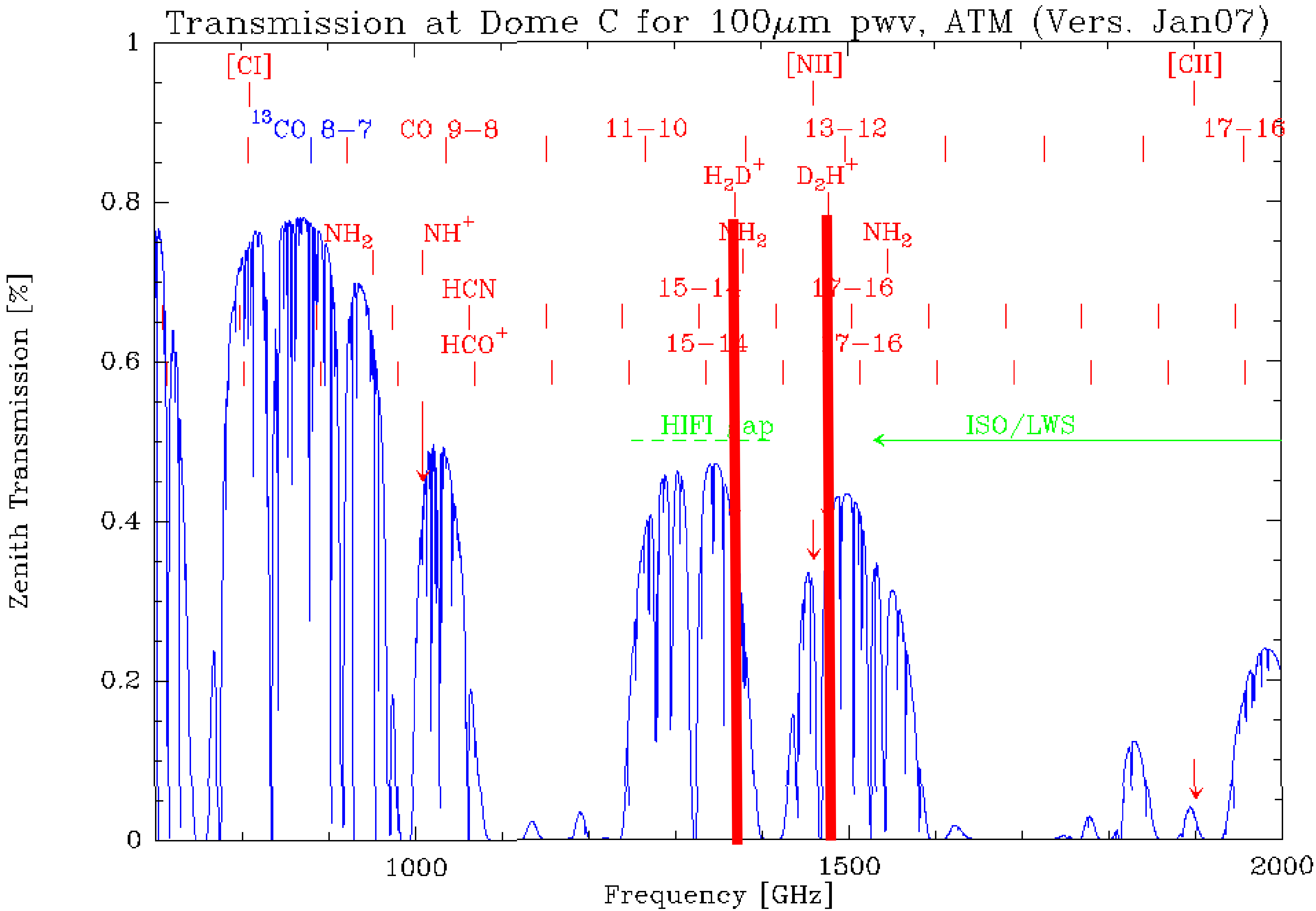


In addition:
$H^{13}CN$, $HC^{15}N$, HCN-v2, DCN

- 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: $H_3^+ + HD \Rightarrow H_2D^+ + H_2 + 230K$

The H_2D^+/H_3^+ abundance ratio would exceed unity at 10K, IF there were no destruction pathways

Reactions with heavy species spread deuteration:

$X + H_2D^+ \rightarrow XD^+ + H_2$

e.g. increasing the DCO^+/HCO^+ and N_2D^+/N_2H^+ abundances.

Freeze-out of heavy species leads to increased H_2D^+/H_3^+ abundance ~1

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

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

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

H_2D^+

o-H_2D^+ @ 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)

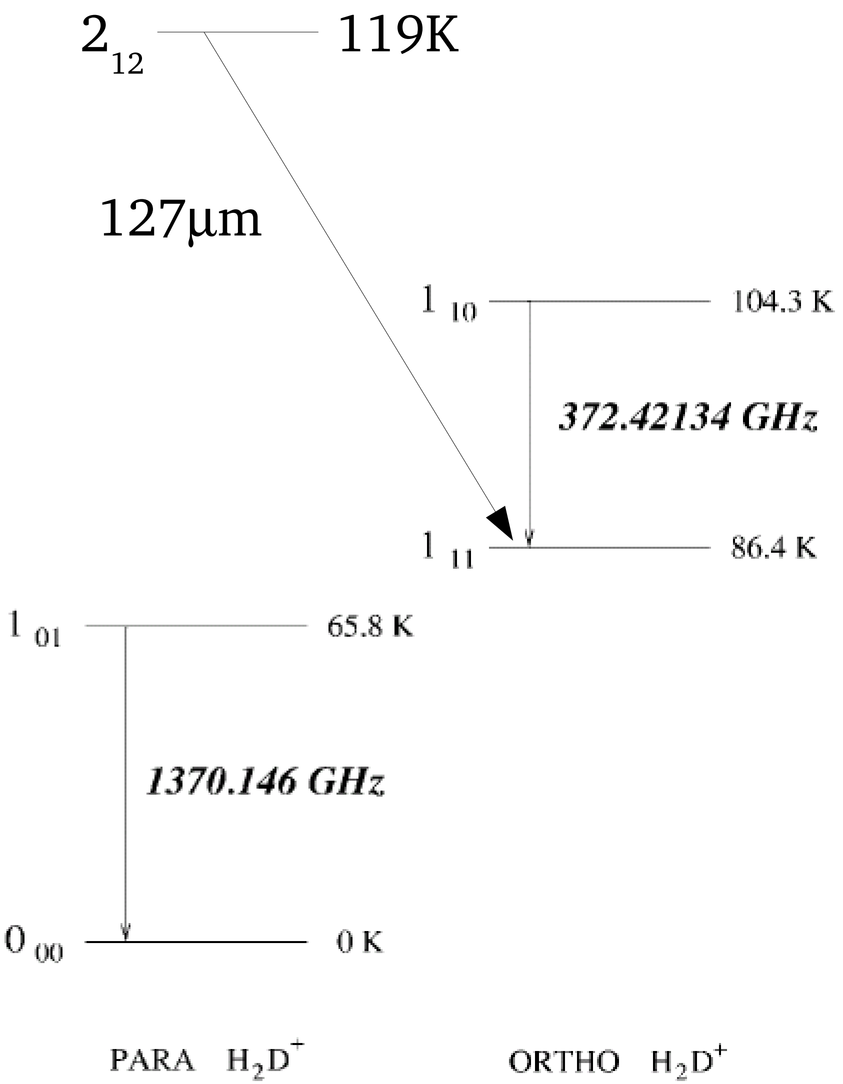
p-H_2D^+ @ 1370 GHz

several attempts unsuccessful
(e.g. Phillips et al. 1985, Boreiko & Betz 1993)

not observable with ISO/LWS nor HIFI.
(HIFI "gap": 1250 - 1410 GHz)

o-H_2D^+ @ 127 μm

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



Vastel et al. 2004

D_2H^+

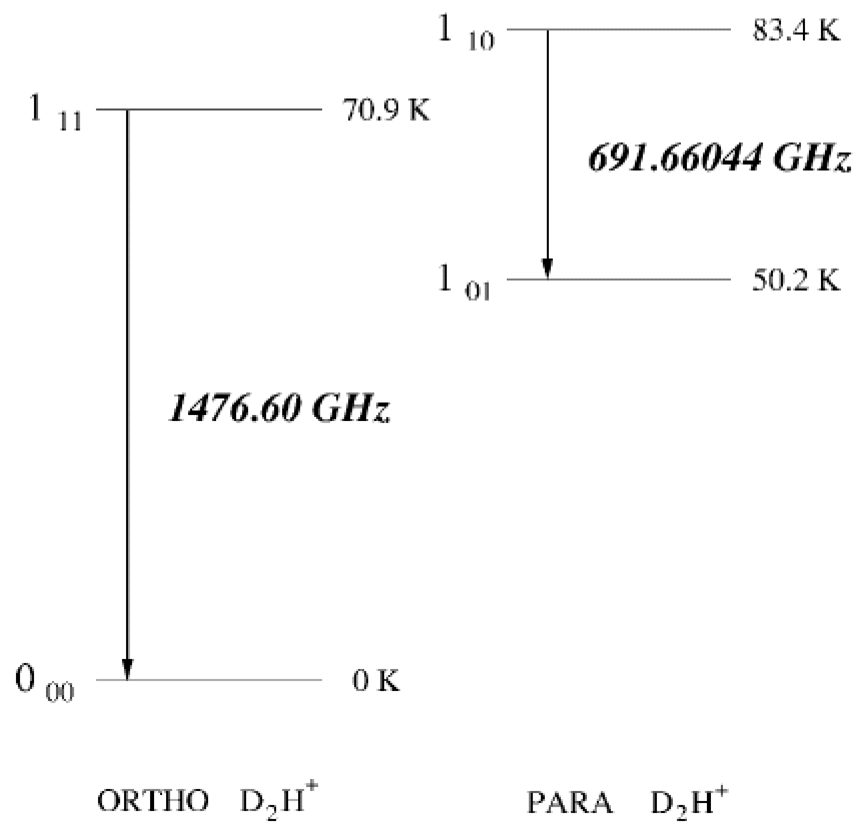
p-D_2H^+ @ 692 GHz

- 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

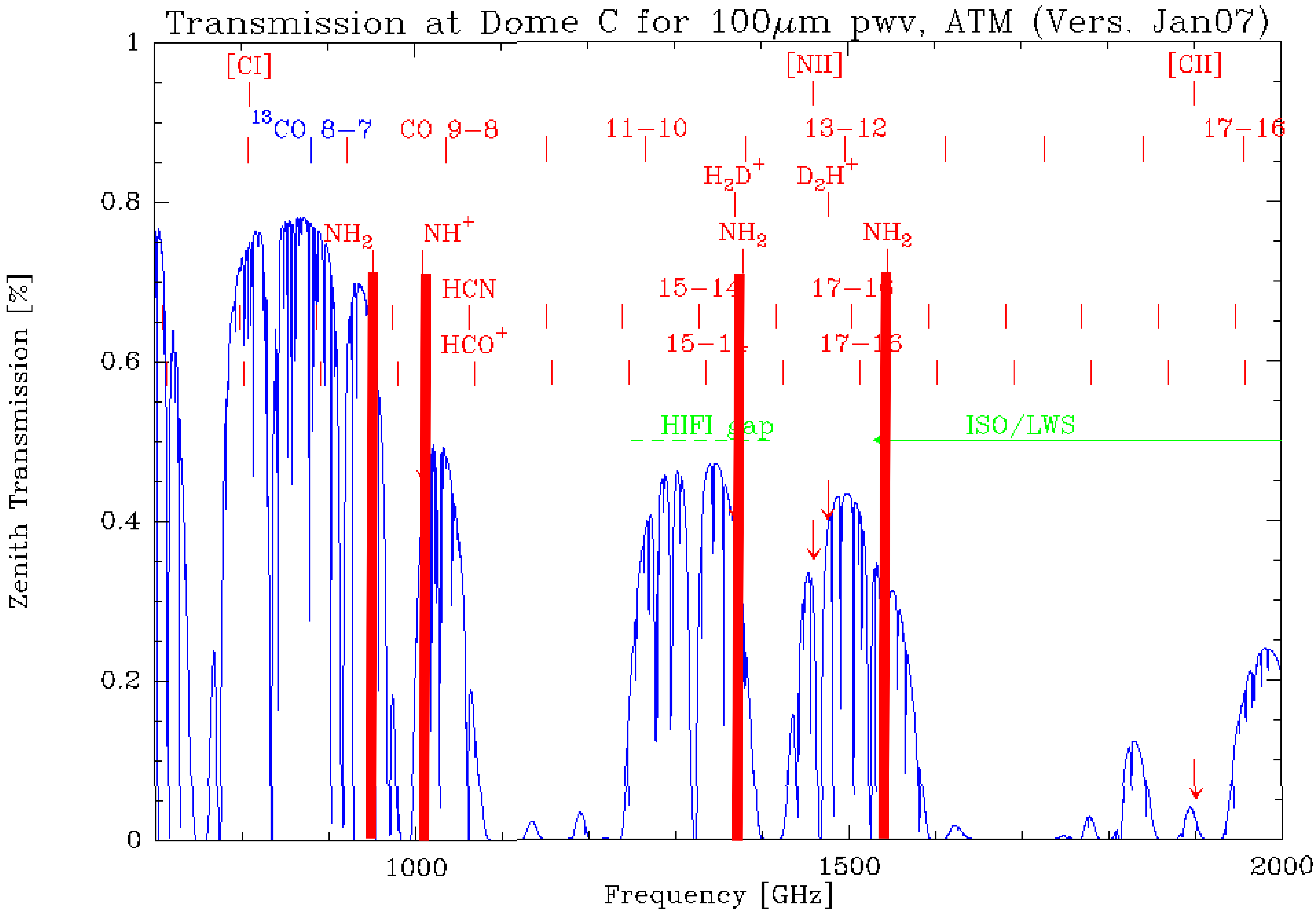
- **the para/ortho ratio reflecting the para/ortho ratio of H_2**
- **the gas phase abundances.**



Vastel et al. 2004

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

Light Hydrides: NH_2, NH^+



NH^+ , NH_2:

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

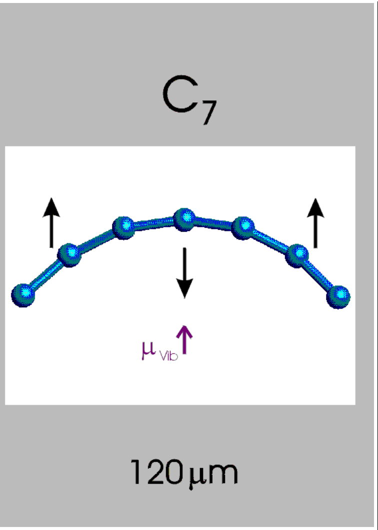
Not yet detected in the ISM

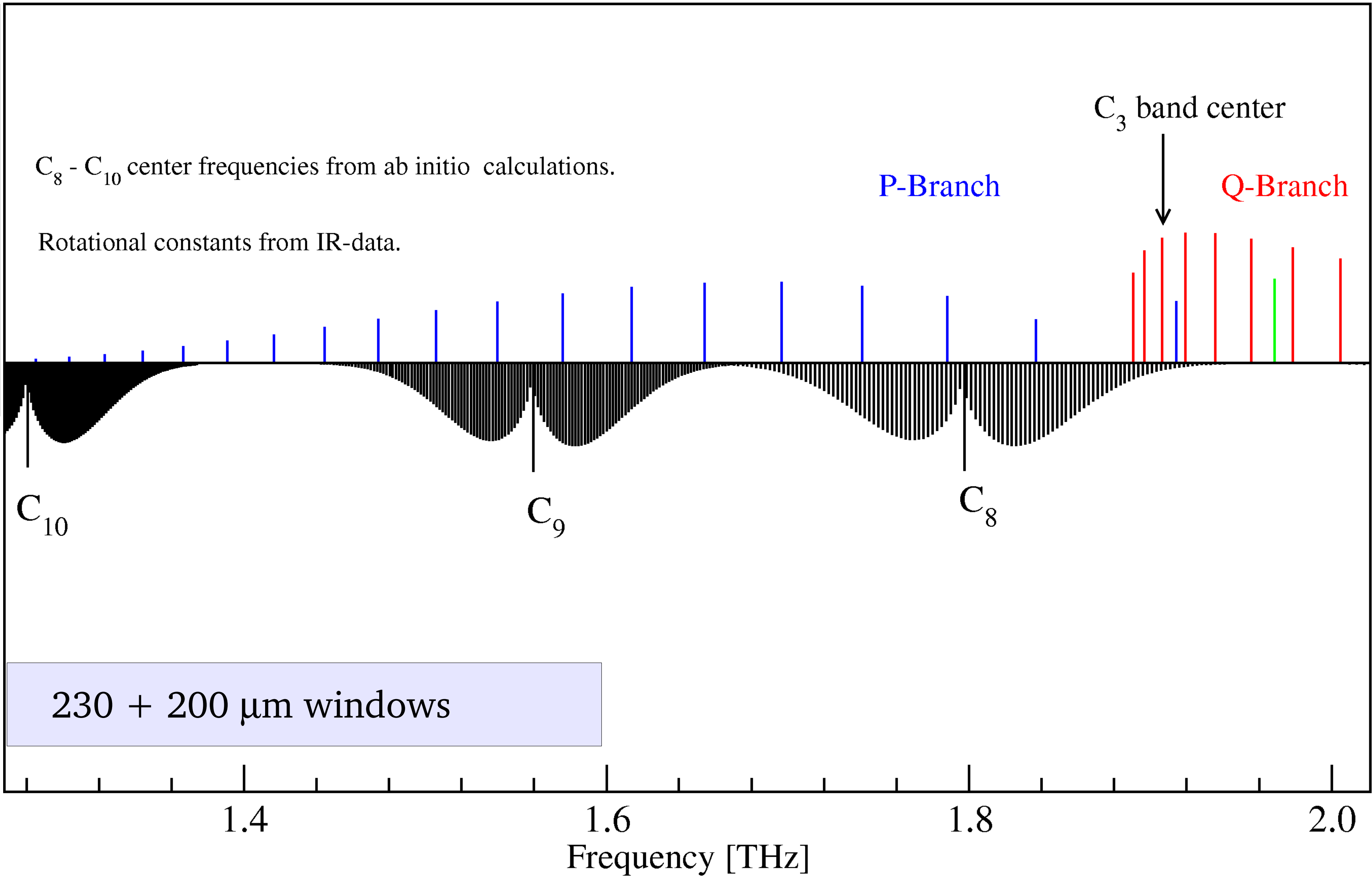
- Great importance for Nitrogen chemical network leading to molecules like NH_3
- Observed $[NH_2]/[NH_3]$ ratio allows to discriminate formation pathways:
    - gas-phase ion-molecule reactions (UV driven chemistry, Sternberg & Dalgarno 1995)
    - shock chemistry
    - grain mantle release

  (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





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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, ...
+ Pure carbon chains
+ ...many more...