UNIVERSITY OF CALGARY

Lines at THz Frequencies: Lessons Learned from ~~HIFI~~ HEXOS

René Plume

UNIVERSITY OF CALGARY

MO SHÙILE TOGAM SUAS

CAT

Connecticut Center for Advanced Technology, Inc.

CCAT

CALGARY COUNCIL FOR ADVANCED TECHNOLOGY

Possibilities for THz Spectroscopy from CCAT

ccat

campus coalition against trafficking

CCAT

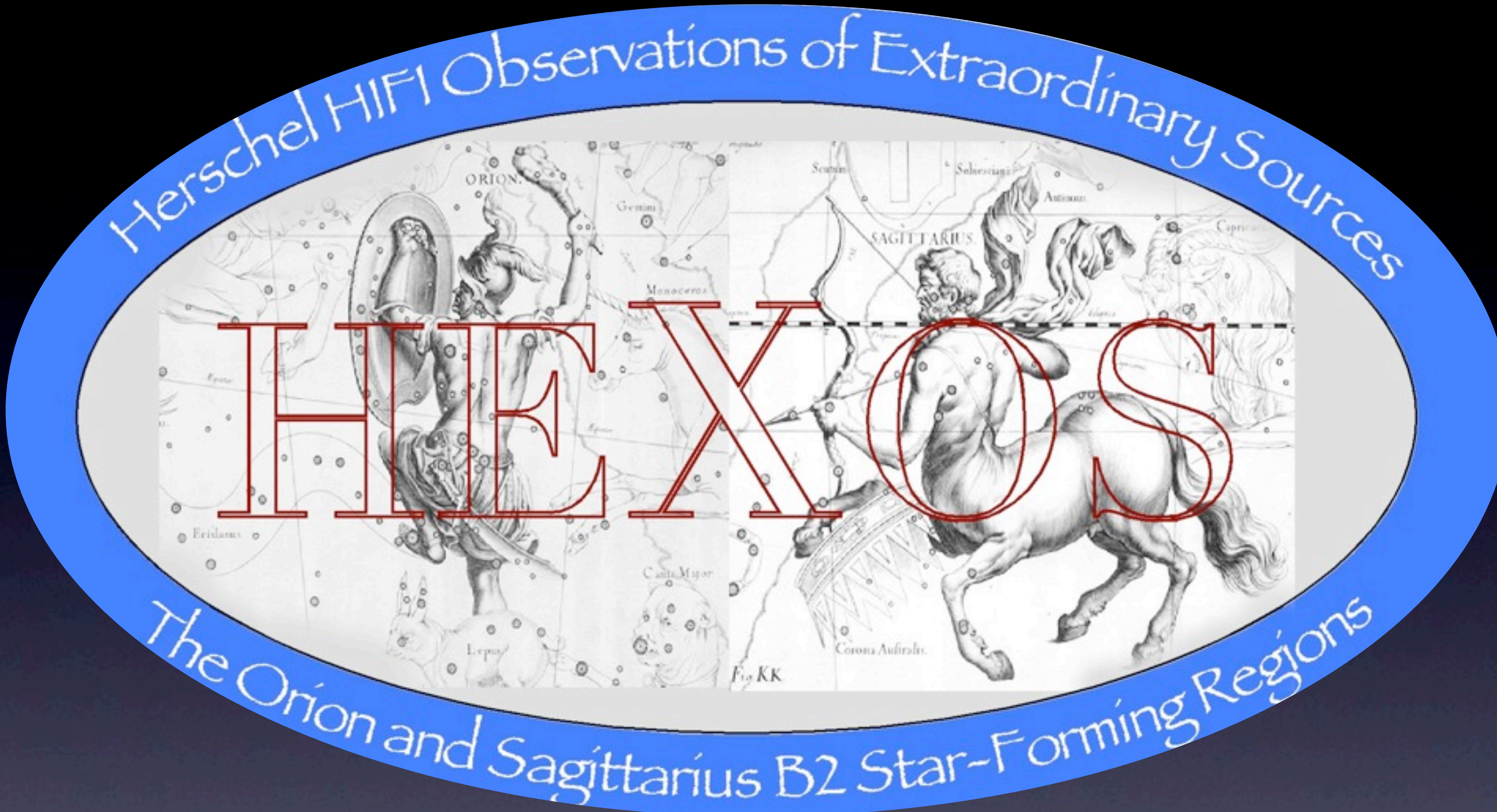
Colorado Citizens Against ToxicWaste, Inc.

Cinnamon Cat

unique cross-stitch designs by Jane Lydia Henderson

CCAT CANADIAN COALITION AGAINST TERROR

René Plume



Herschel observations of EXtra-
Ordinary Sources (HEXOS)
PI: E. Bergin (2010, A&A, 521,20)

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Jonas Zmuidzinas

I'm Sorry!

- First detection of H2O$^+$ (Ossenkopf et al. 2010) and H_2CL^+ (Lis et al. 2010)
- ortho/para ratio of H_2O in diffuse gas (Lis et al. 2010)
- ortho/para ratio of H_2O^+ in diffuse gas (Schilke et al. 2010)
- OH+ and H_2O^+ in the Orion outflow (Gupta et al. 2010)
- high frequency spectrum (Crockett et al. 2010)
- Probing infall with HCN (Rolffs et al. 2010)
- HF as a probe in Orion (Phillips et al. 2010)
- HDO in Sgr B2 (Comito et al. 2010)
- Detection of $HD^{18}O$ (Bergin et al. 2010)
- CH in spiral arm clouds (Qin et al. 2010)
- Observations of H_2O and its isotopologues towards Orion KL (Melnick et al 2010)
- Herschel observations of ortho- and para-oxidaniumyl (H_2O^+) in spiral arm clouds toward Sagittarius B2(M) (Schilke et al 2010)
- The Terahertz spectrum of Orion KL (Croclkett, et al 2010)

Broad Perspective

- Stars are born in molecular clouds that exhibit a high degree of chemical complexity - clearly dominated by water, carbon monoxide, and carbon dioxide etc but there are many complex organics

Complex Molecules

H_2CHO $HOCH_2CHO$ C_3H_7CN $c\text{-}C_3H_2O$

C_8H CH_2CNH CH_3CONH_2 CH_3NH_2

CH_3NC $HCOOCH_3$

CH_3COOH C_8H^-

NH_2CH_2CN CH_3C_3N

$HOCH_2CH_2OH$ HC_5N HC_6H HC_4H

C_2H_5CN C_2H_4

C_2H_3OH H_2C_6 $HCOOC_2H_5$

CH_3CHCH_2 CH_2CCHCN

$HC_{11}N$ H_2C_4 C_2H_5OH

C_6H^- C_6H HC_3NH^+ CH_3OCH_3

NH_2CHO CH_3CHO CH_3CN

C5H

C_7H CH_3C_6H CH_3C_4H C_5N

HC_7N CH_3OH CH_3SH

HC_4N C_2H_3CHO

CH_3C_2H C_6H_6 CH_3C_5N

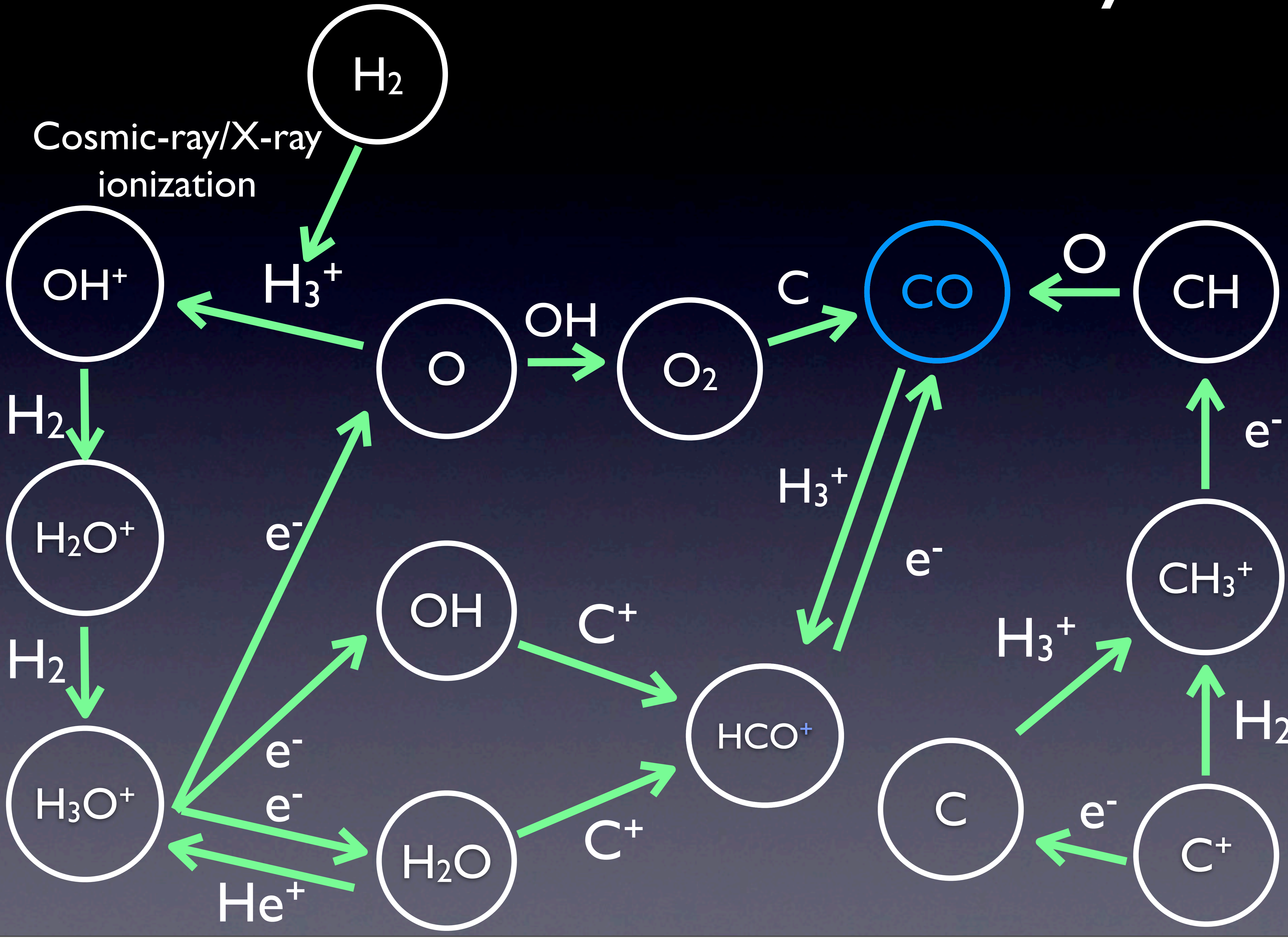
C_2H_5CHO $c\text{-}CH_2OCH_2$ C_2H_3CN HC_9N

> 6 atoms; Herbst & van Dishoeck 2009

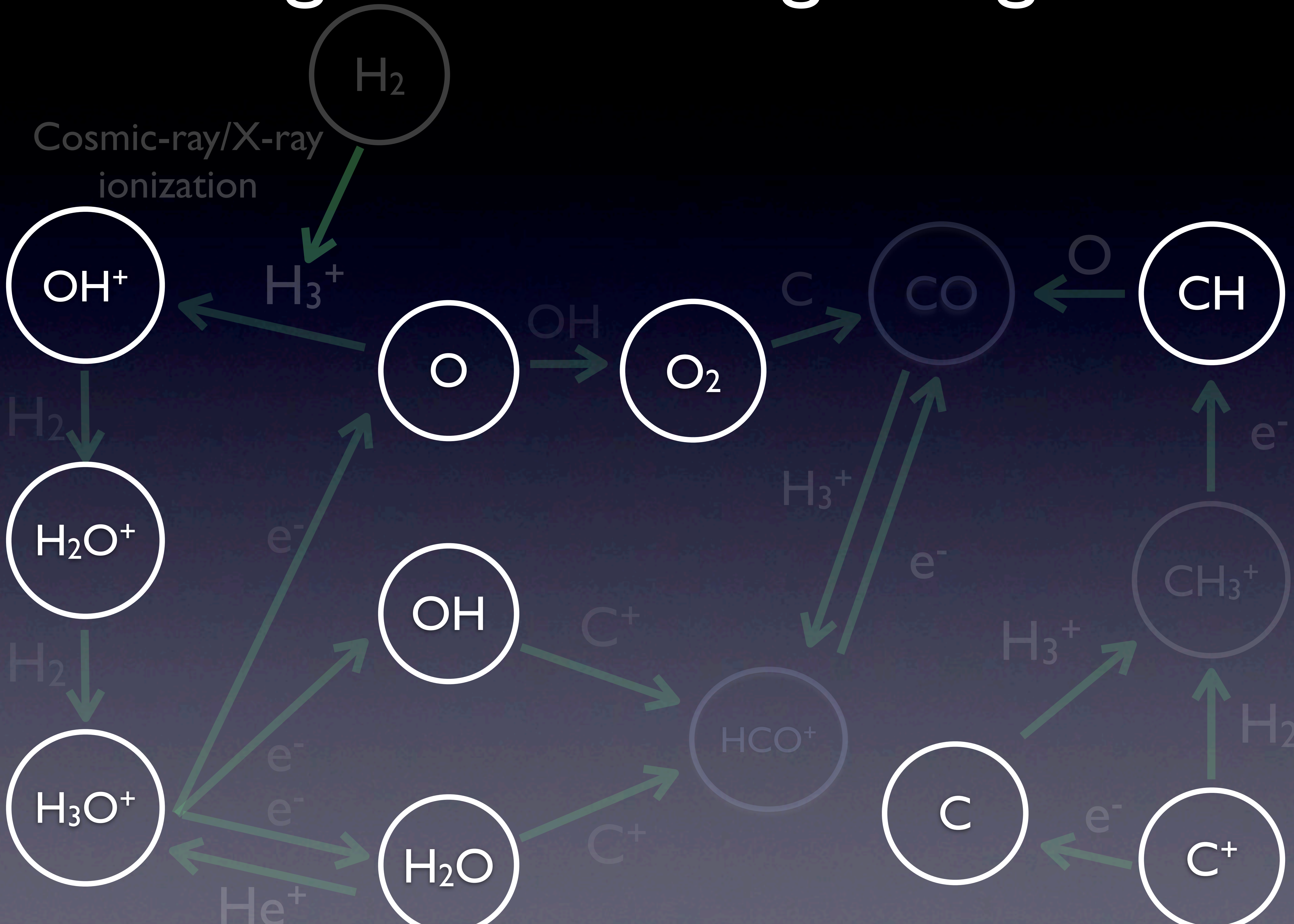
Broad Perspective

- Stars are born in molecular clouds that exhibit a high degree of chemical complexity - clearly dominated by water, carbon monoxide, and carbon dioxide etc but there are many complex organics
- How this complexity develops is uncertain -- gas phase? catalytic chemistry on grain surfaces? What are the reaction rates and branching ratios of the first key reactions? What are the abundances of the key species?

Main Gas-Phase C/O Pathways



Probing chemical beginnings….

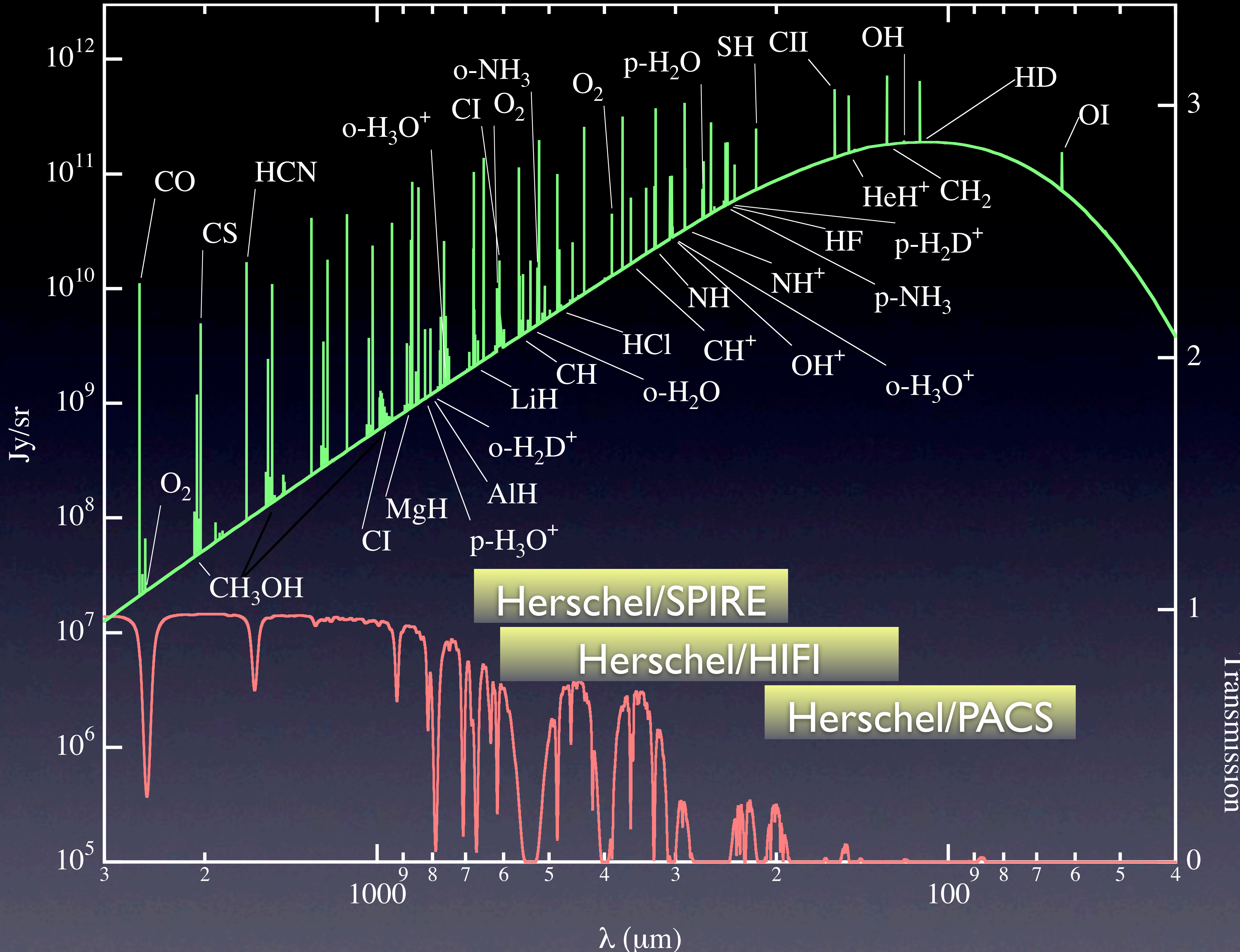


Broad Perspective

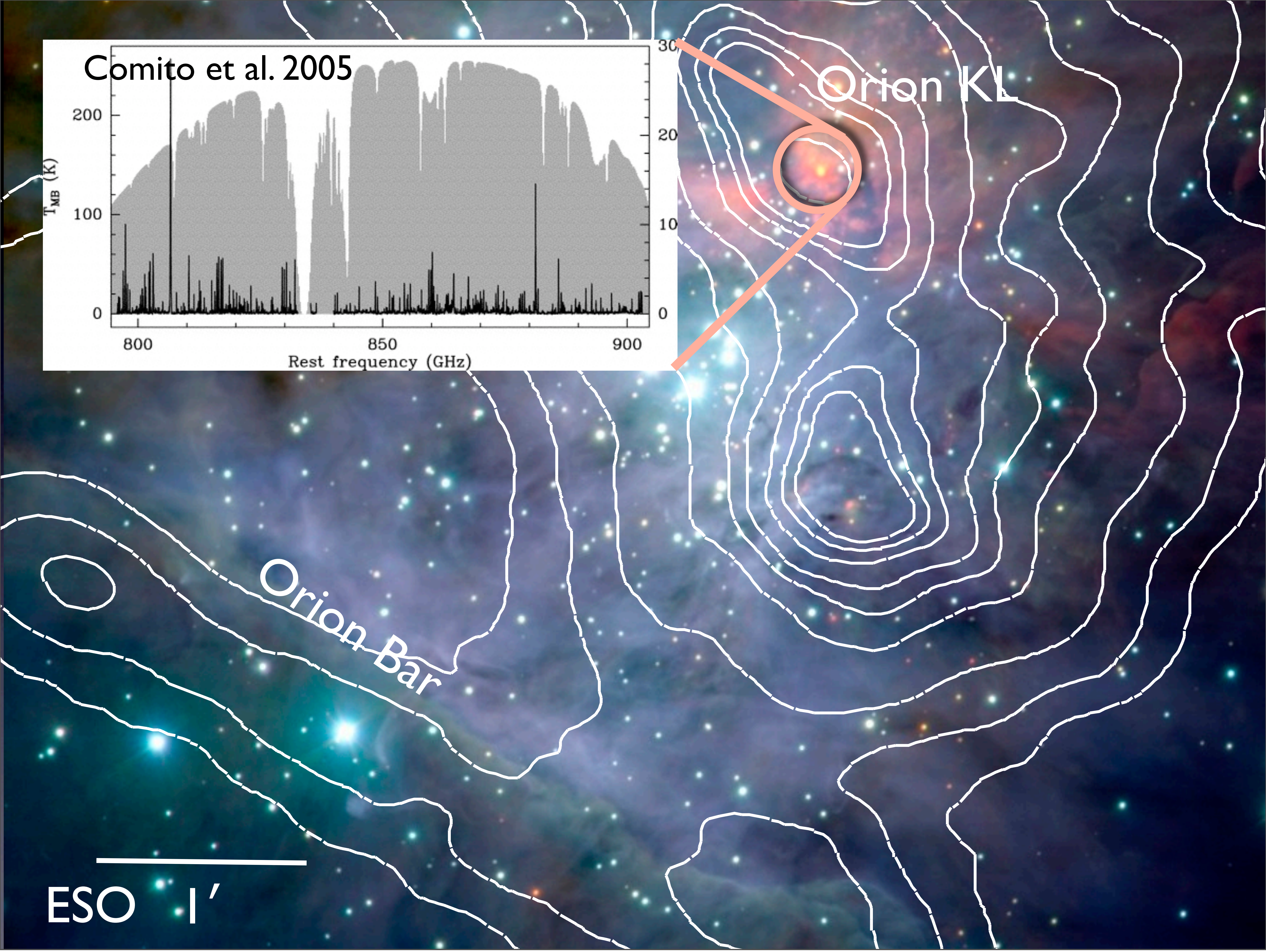
- Stars are born in molecular clouds that exhibit a high degree of chemical complexity - clearly dominated by water, carbon monoxide, and carbon dioxide etc but there are many complex organics
- How this complexity develops is uncertain -- gas phase? catalytic chemistry on grain surfaces? What are the reaction rates and branching ratios of the first key reactions? What are the abundances of the key species?
- How can we use the rich variety of chemical species to provide key understandings of the physical conditions in molecular clouds?

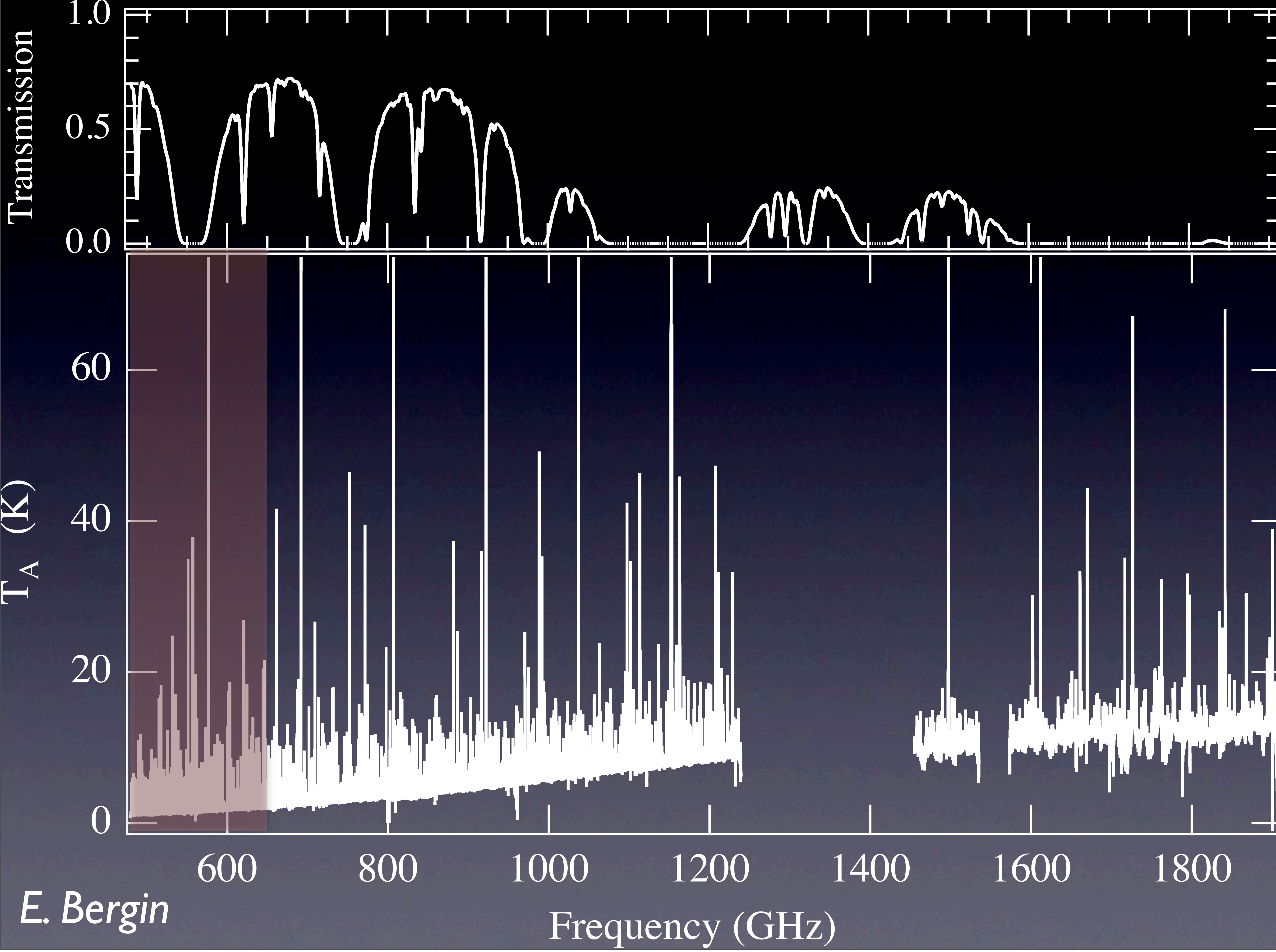
Broad Perspective

- Our ability to answers these questions has been hindered by our inability to view the entire spectrum of star forming gas.
  - We have not been able to observe many of the key species in the early (simple) chemical networks
  - We have also not been able to trace the key coolants (e.g. C II, O I, CO ladder)



FIR Spectrum of Ambient Gas

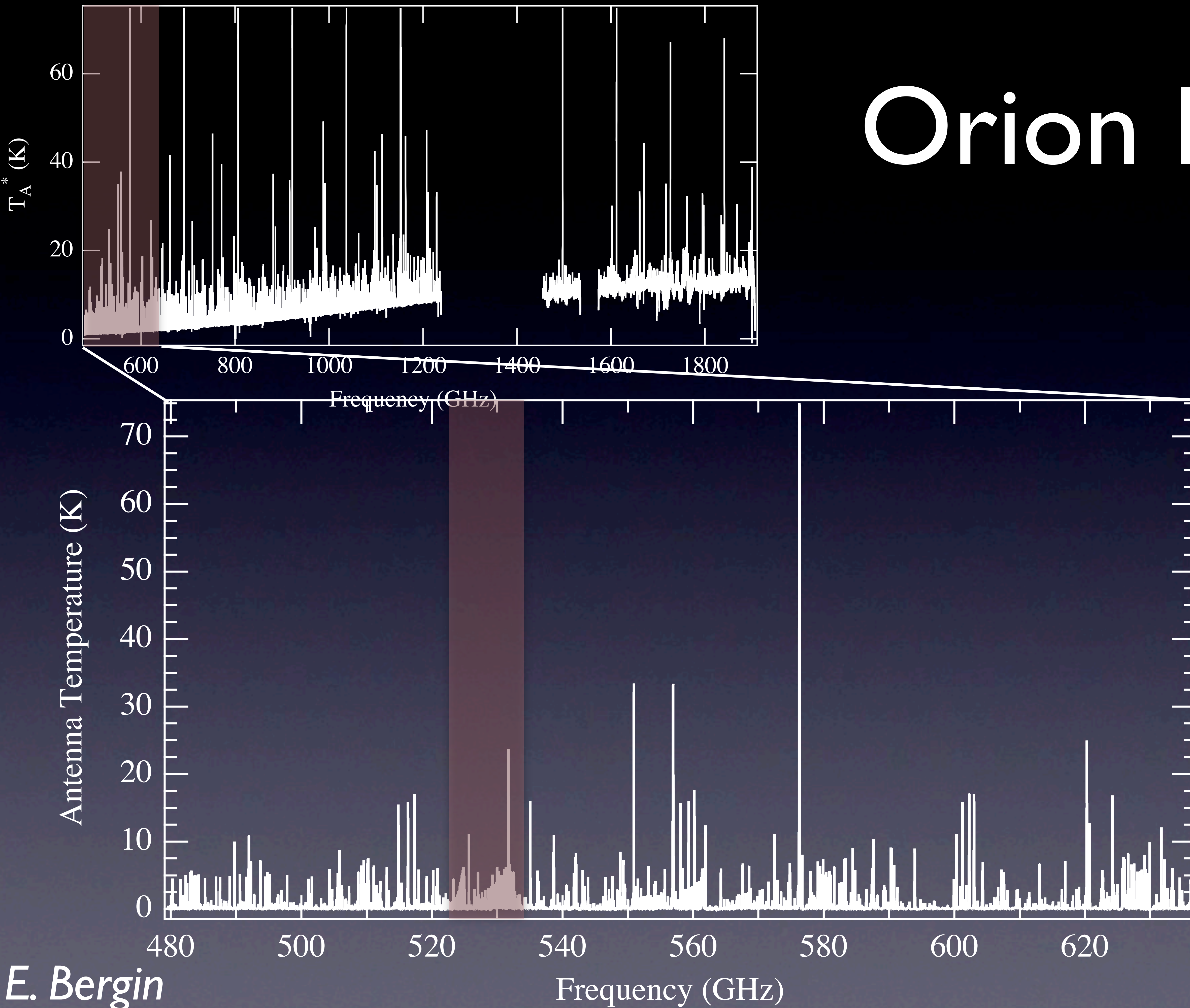

Comito et al. 2005
T_{MB} (K)
0
100
200
800
850
900
Rest frequency (GHz)
0
10
20
30
Orion KL
Orion Bar
ESO
1′



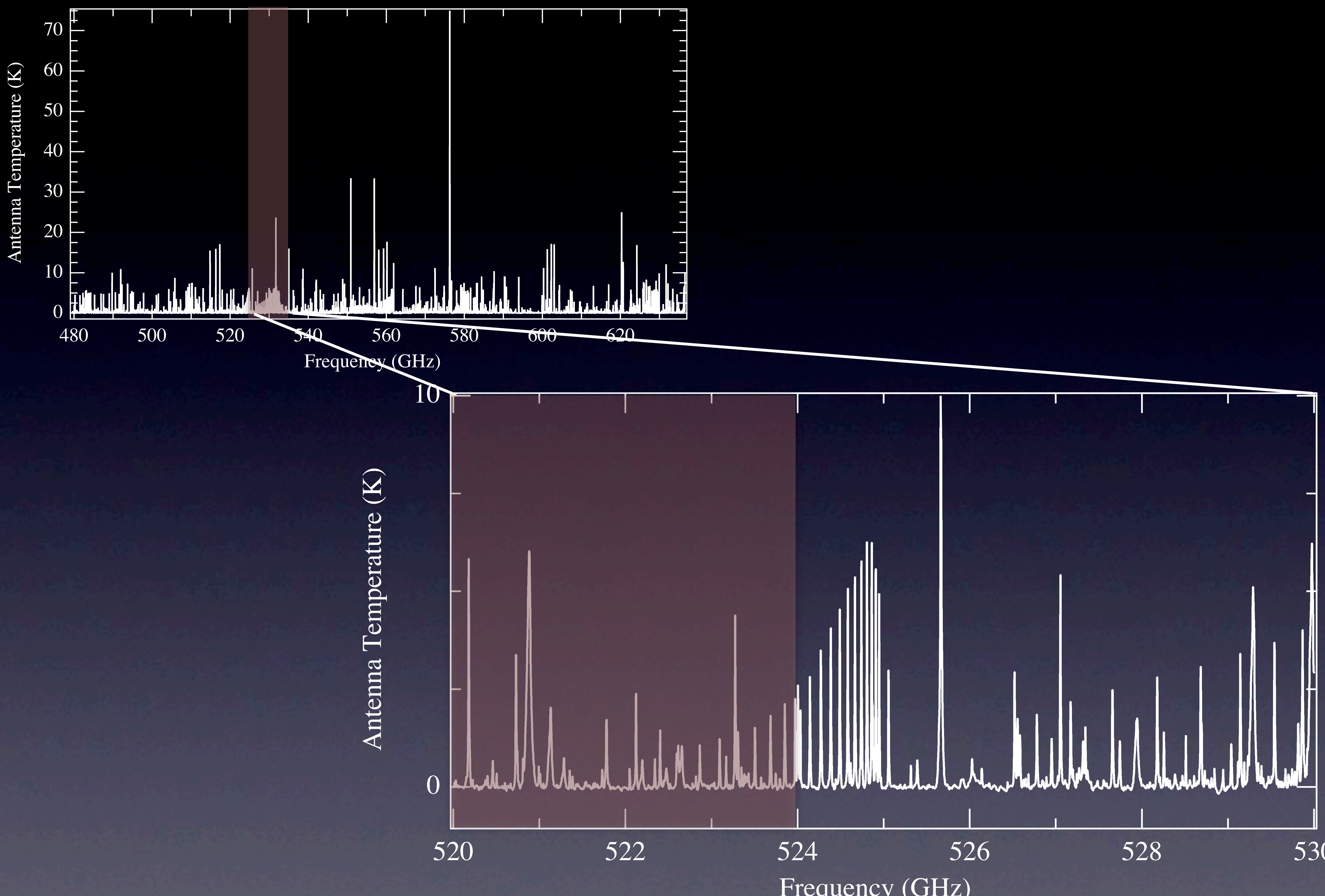
Transmission
1.0
0.5
0.0
T_A (K)
60
40
20
0
600
800
1000
1200
1400
1600
1800
Frequency (GHz)

E. Bergin

Orion KL

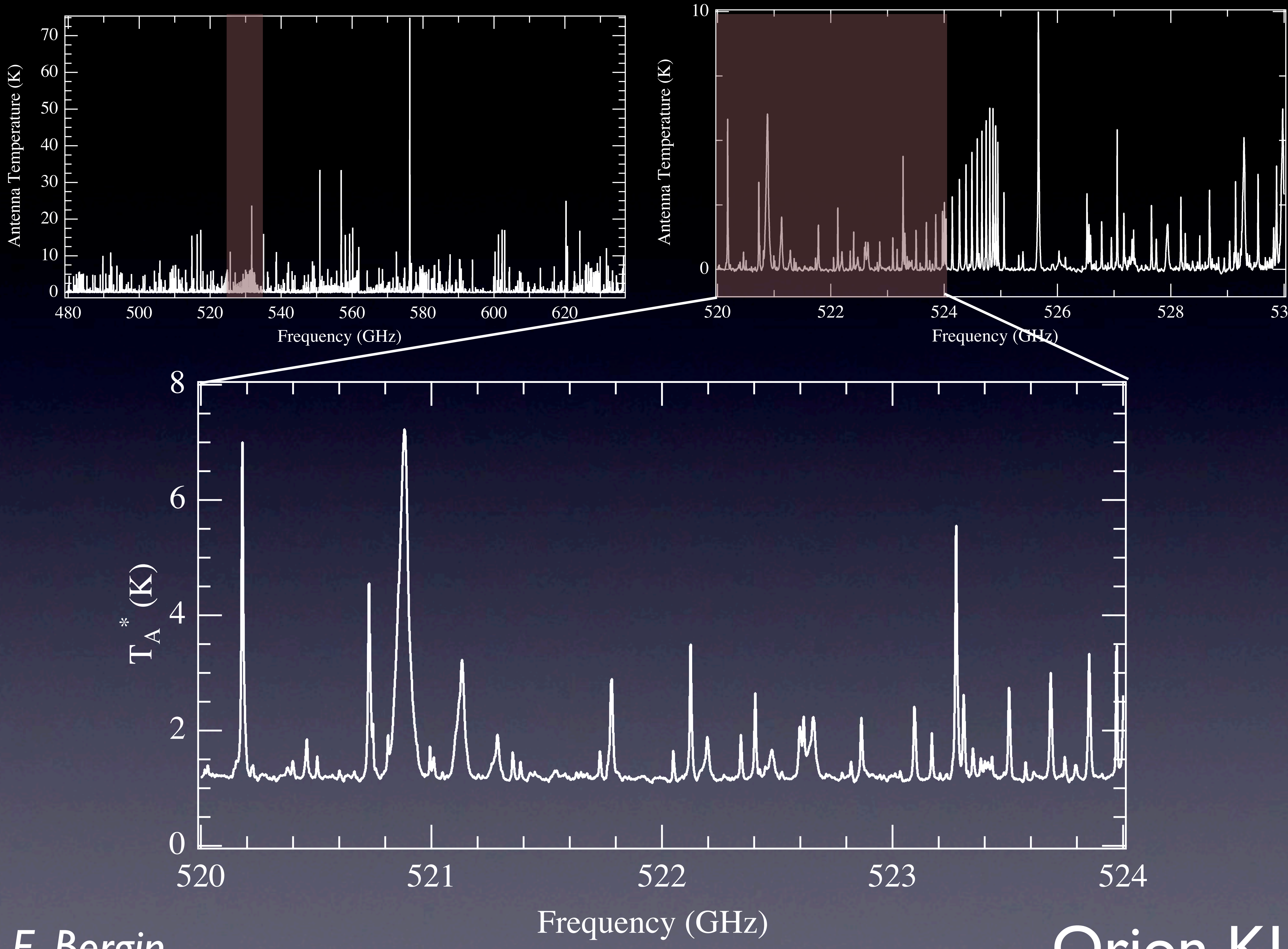


E. Bergin



Orion KL - Band 1

E. Bergin

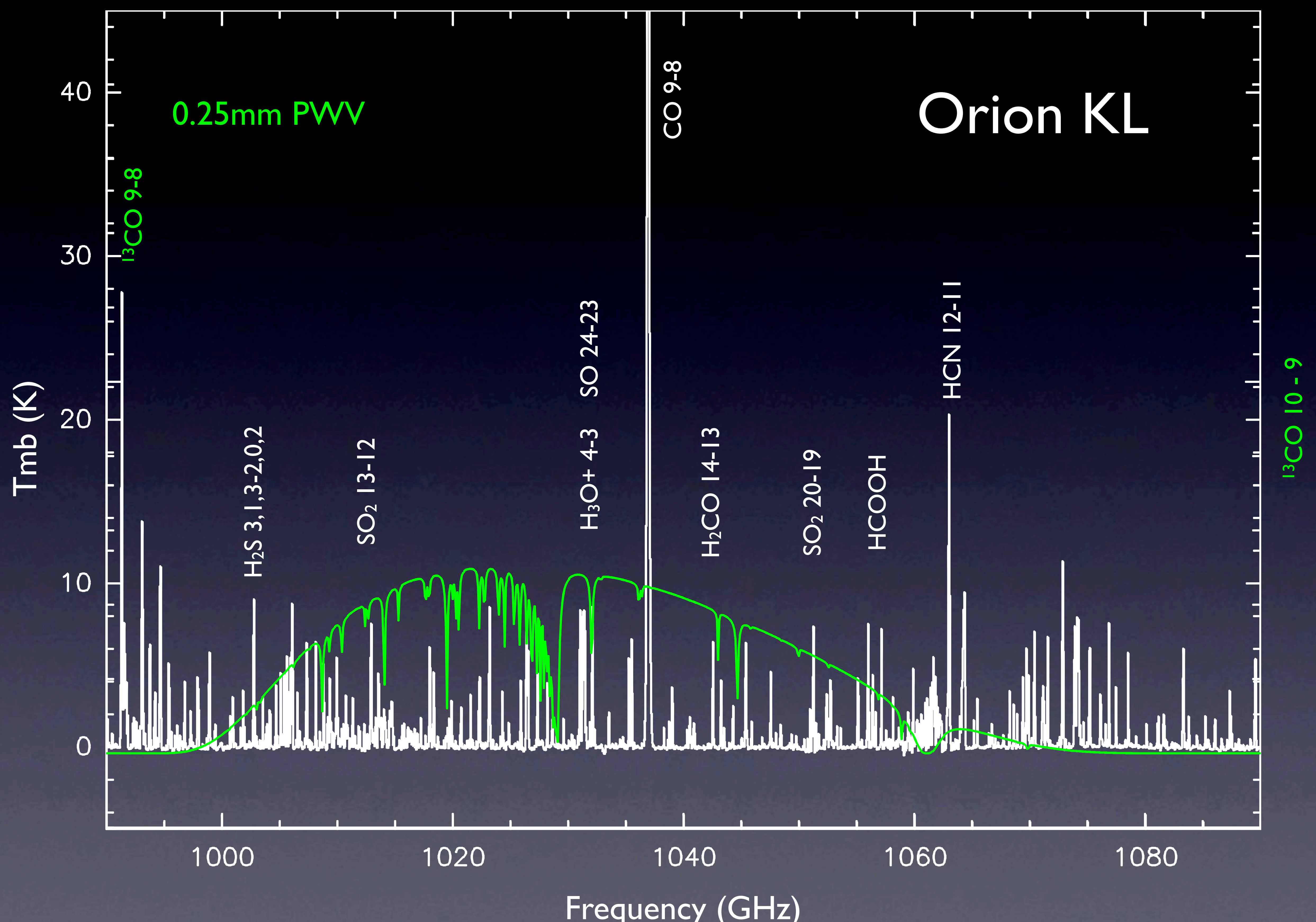


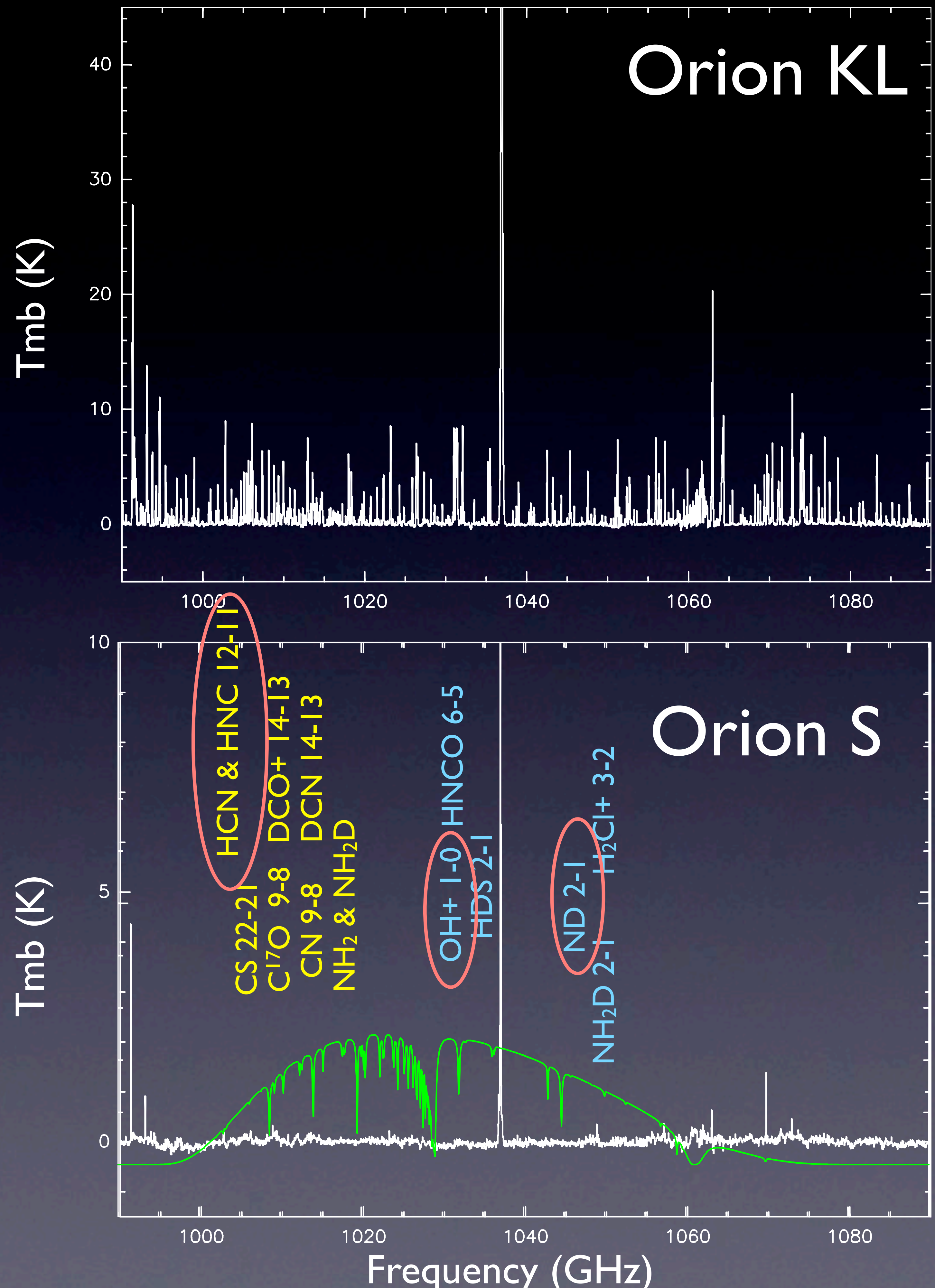
E. Bergin

Orion KL

Montag, 10. Oktober 2011

THz Bands Accessible to CCAT


Orion KL
0.25mm PWV
Tmb (K)
Frequency (GHz)
13CO 9-8
CO 9-8
13CO 10 - 9
H2S 3,1,3-2,0,2
SO2 13-12
H3O+ 4-3
SO 24-23
H2CO 14-13
SO2 20-19
HCOOH
HCN 12-11
0
10
20
30
40
1000
1020
1040
1060
1080



Some other Species

CH_3OH

D_2CO

H_2CO

H_2Cl^+

NH

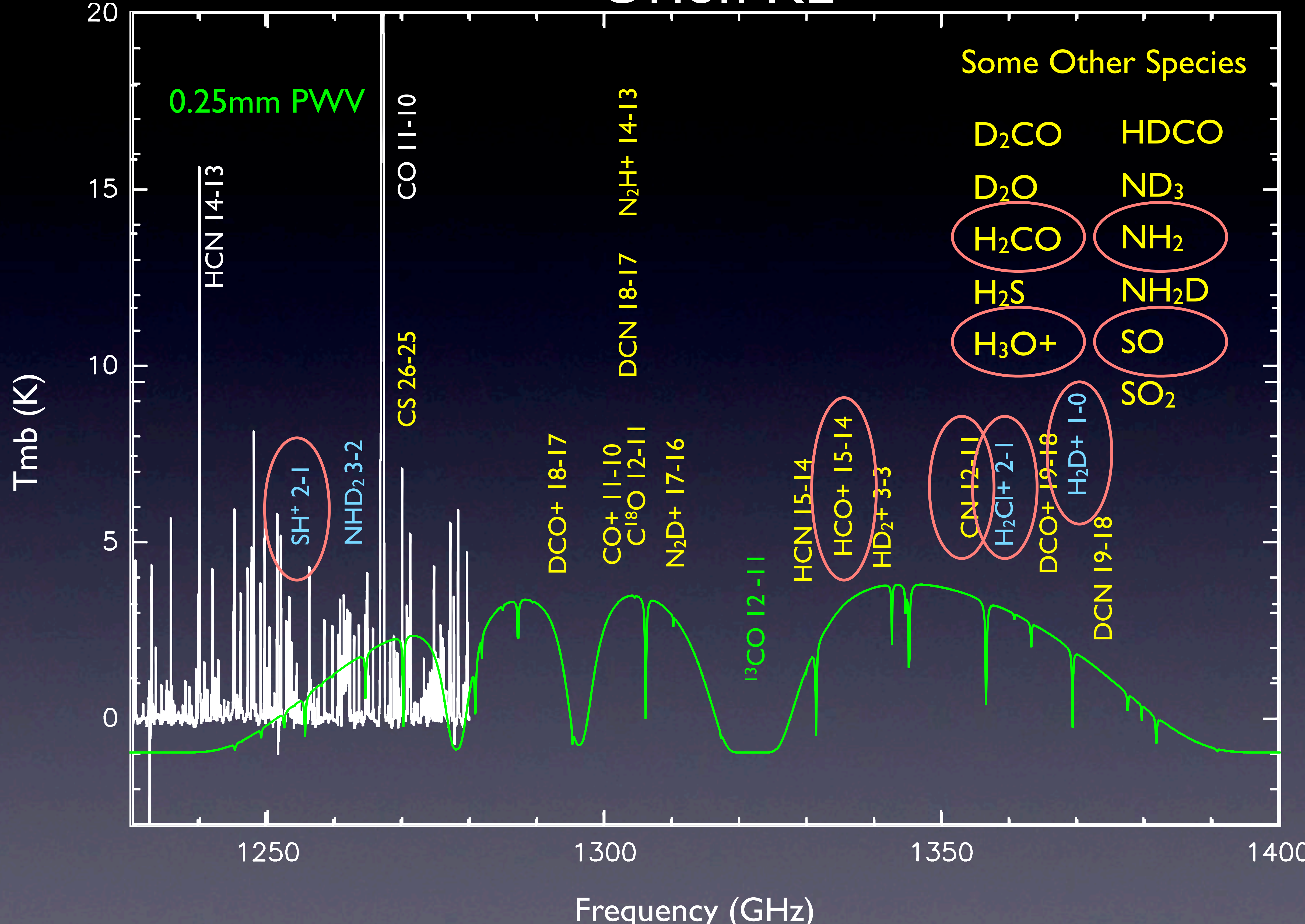
NH_2

SO

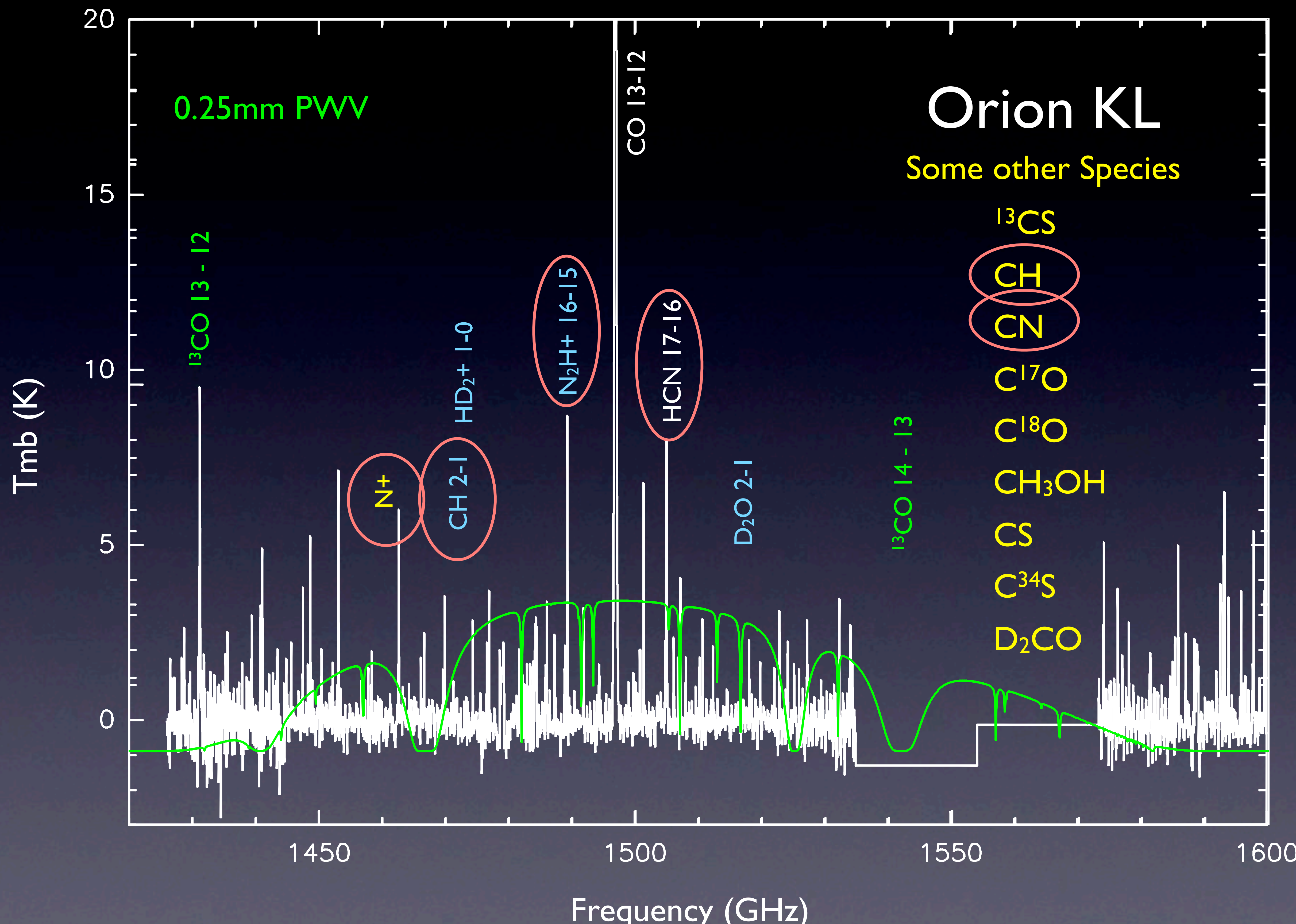
SO_2

H_2COH^+ 3-2

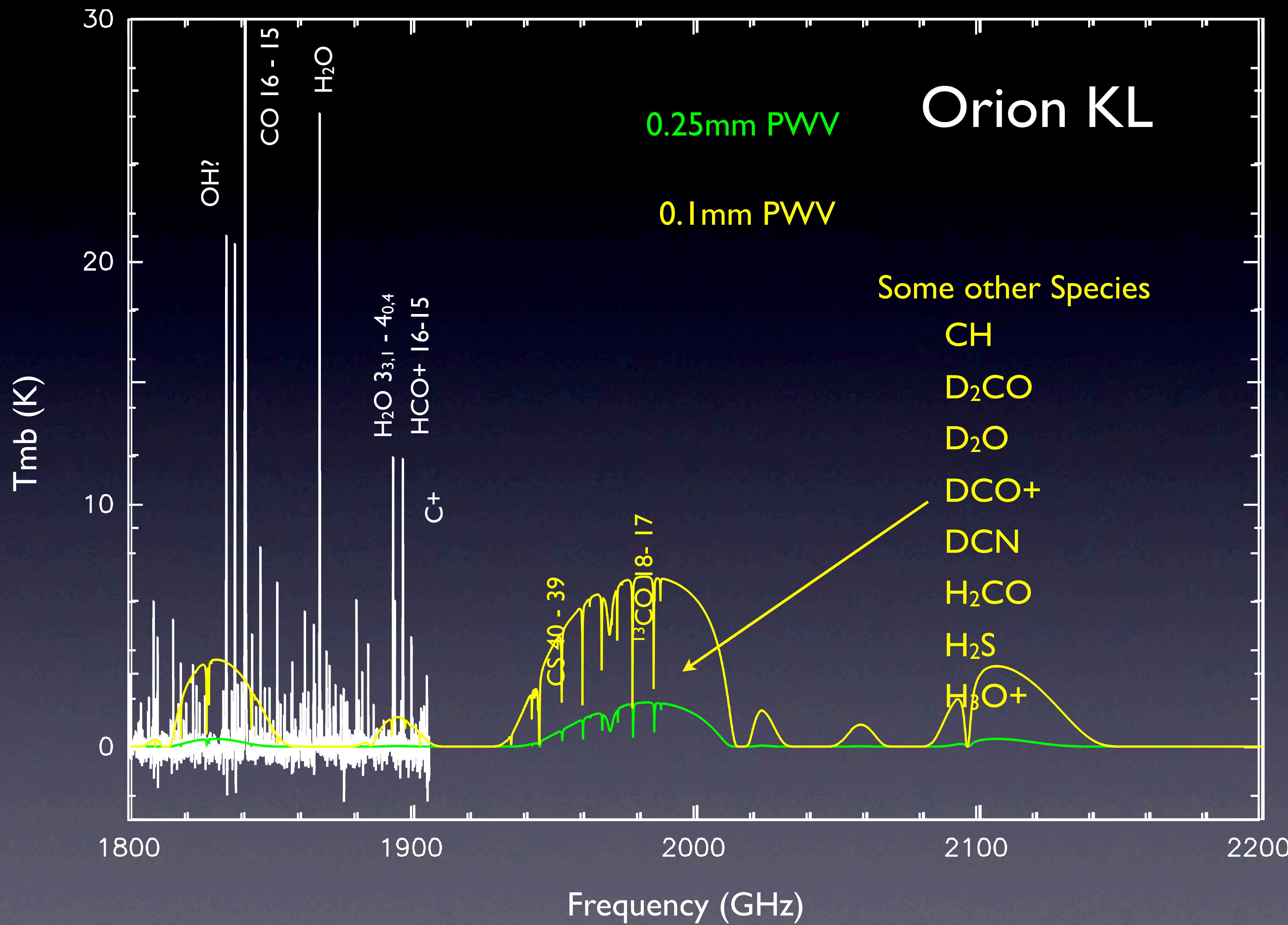
Orion KL



Tmb (K)
20
15
10
5
0
1250
1300
1350
1400
Frequency (GHz)
0.25mm PWV
HCN 14-13
CO 11-10
CS 26-25
N2H+ 14-13
DCN 18-17
SH+ 2-1
NHD2 3-2
DCO+ 18-17
CO+ 11-10
C18O 12-11
N2D+ 17-16
13CO 12-11
HCN 15-14
HCO+ 15-14
HD2+ 3-3
CN 12-11
H2Cl+ 2-1
DCO+ 19-18
H2D+ 1-0
DCN 19-18
Some Other Species
D2CO
HDCO
D2O
ND3
H2CO
NH2
H2S
NH2D
H3O+
SO
SO2



20
15
10
5
0
Tmb (K)
0.25mm PWV
^{13}CO 13 - 12
N+
CH 2-1
HD_2+ 1-0
N_2H+ 16-15
CO 13-12
HCN 17-16
D_2O 2-1
^{13}CO 14 - 13
Orion KL
Some other Species
^{13}CS
CH
CN
$C^{17}O$
$C^{18}O$
CH_3OH
CS
$C^{34}S$
D_2CO
1450
1500
1550
1600
Frequency (GHz)



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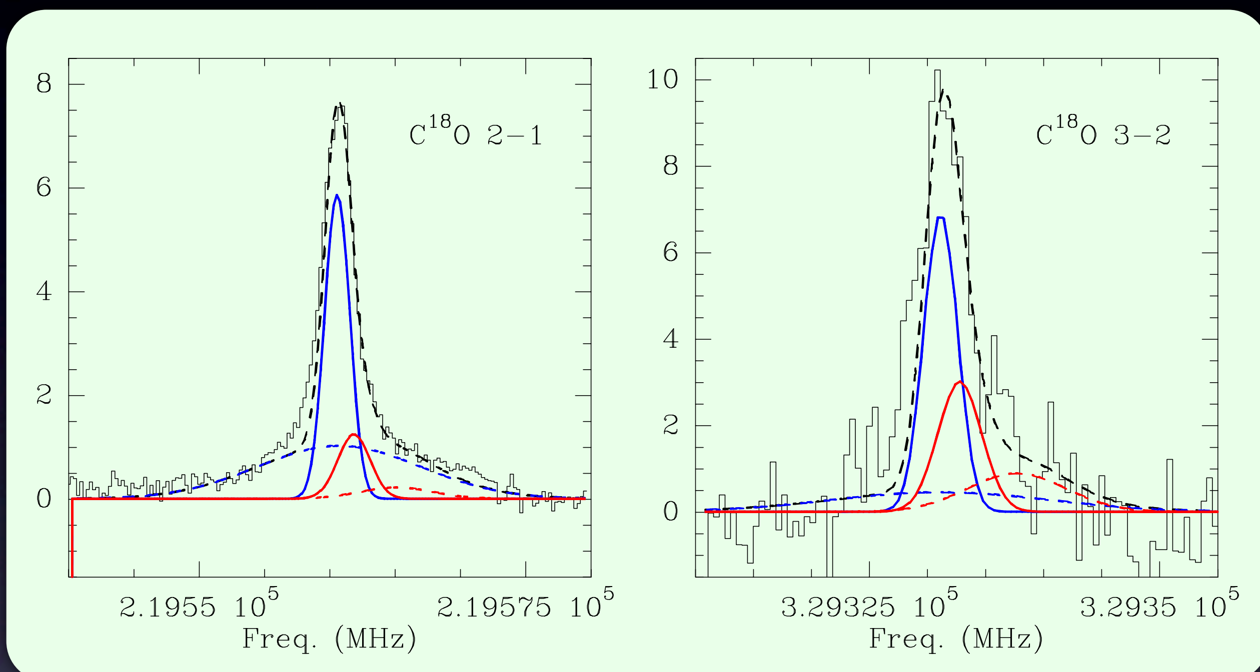
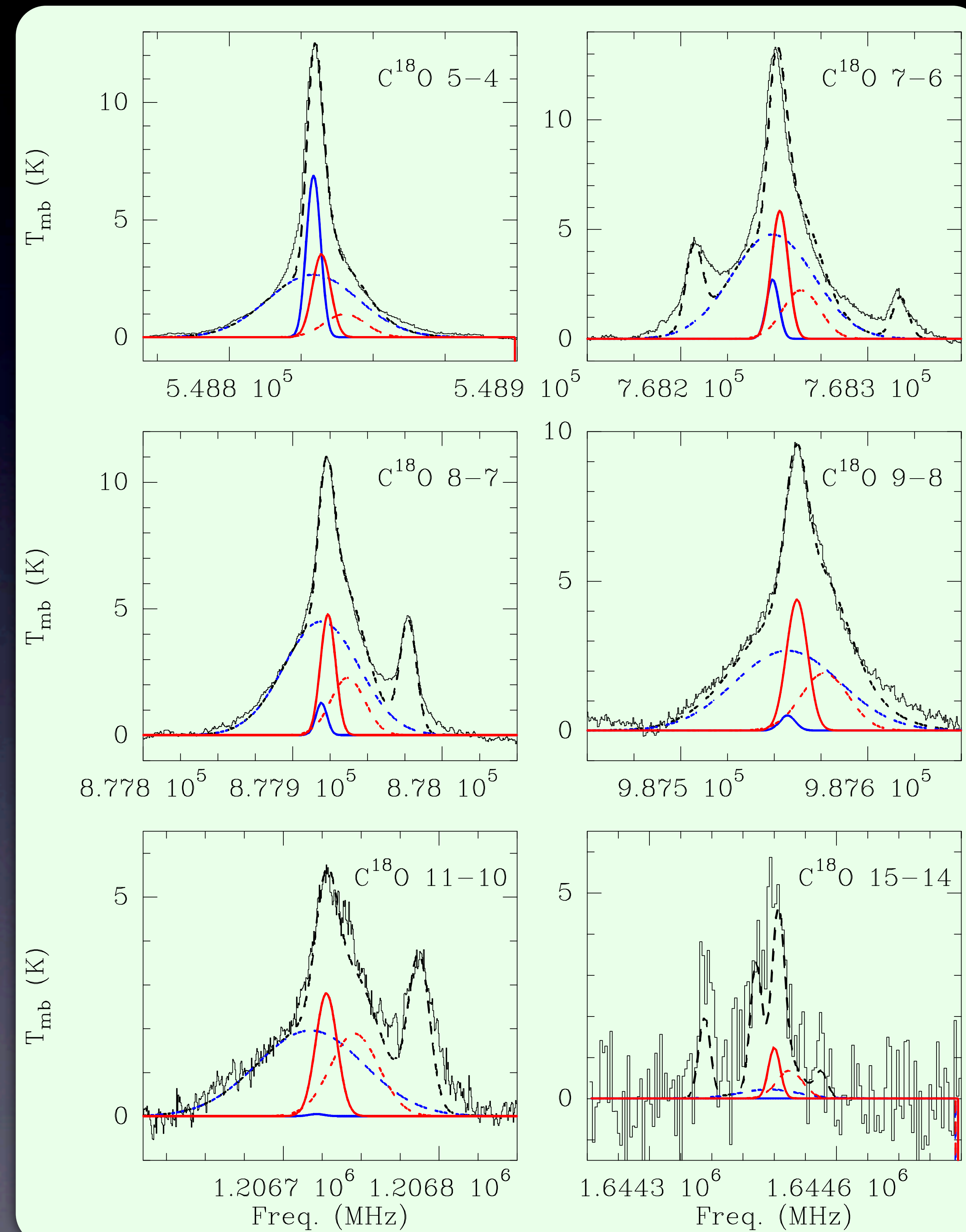
Total $C^{18}O$ Column Density

Plume et al. 2011, ApJ, in press

Orion KL



C18O 2−1
C18O 3−2
2.1955 10^5
2.19575 10^5
3.29325 10^5
3.2935 10^5
Freq. (MHz)
Freq. (MHz)



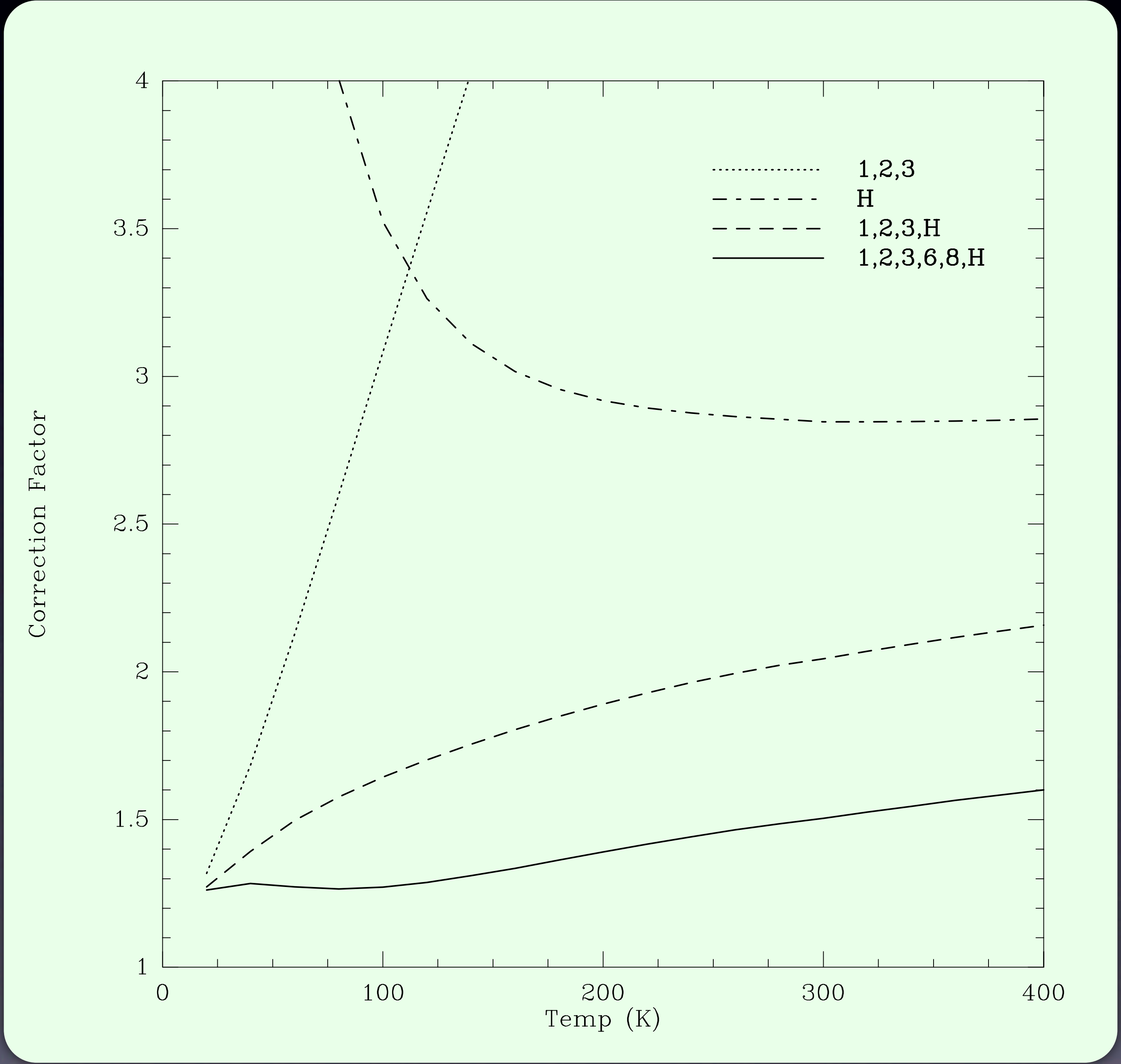
C18O 5−4
C18O 7−6
C18O 8−7
C18O 9−8
C18O 11−10
C18O 15−14
Tmb (K)
5.488 10^5
5.489 10^5
7.682 10^5
7.683 10^5
8.778 10^5
8.779 10^5
8.78 10^5
9.875 10^5
9.876 10^5
1.2067 10^6
1.2068 10^6
1.6443 10^6
1.6446 10^6
Freq. (MHz)
Freq. (MHz)

Correction Factor

- in Hot Cores T > 100 K and correction factors become large with large uncertainties

- Better case - Observe as many lines as possible and add up the column in each transition

- use correction factor to account for any missing transitions



Column Densities - CCAT

- ^{13}CO is problematic since many lines are inaccessible
- $C^{18}O$ still has many high frequency transitions in open windows

Transition	Freq.
6-5	658 GHz
8-7	878 GHz
12-11	1316 GHz
14-13	1535 GHz
~~18-17~~	~~1972 GHz~~

Orion KL

$C^{18}O$

Component	$\sum N_u$ $C^{18}O$ cm^{-2}	f_c	N_{tot} $C^{18}O$ $\pm error$ cm^{-2}		N_{tot} H_2 cm^{-2}
Extended Ridge	7.85×10^{15}	1.81	1.4×10^{16}	$+2.4 \times 10^{15}$ -4.0×10^{14}	7.1×10^{22}
Outflow/Plateau	2.12×10^{16}	1.67	3.5×10^{16}	$+6.3 \times 10^{15}$ -1.2×10^{15}	1.8×10^{23}
Compact Ridge	1.29×10^{16}	1.67	2.2×10^{16}	$+8.2 \times 10^{15}$ -1.9×10^{15}	1.1×10^{23}
Hot Core	3.67×10^{16}	1.69	6.2×10^{16}	$+1.8 \times 10^{16}$ -4.9×10^{15}	3.1×10^{23}

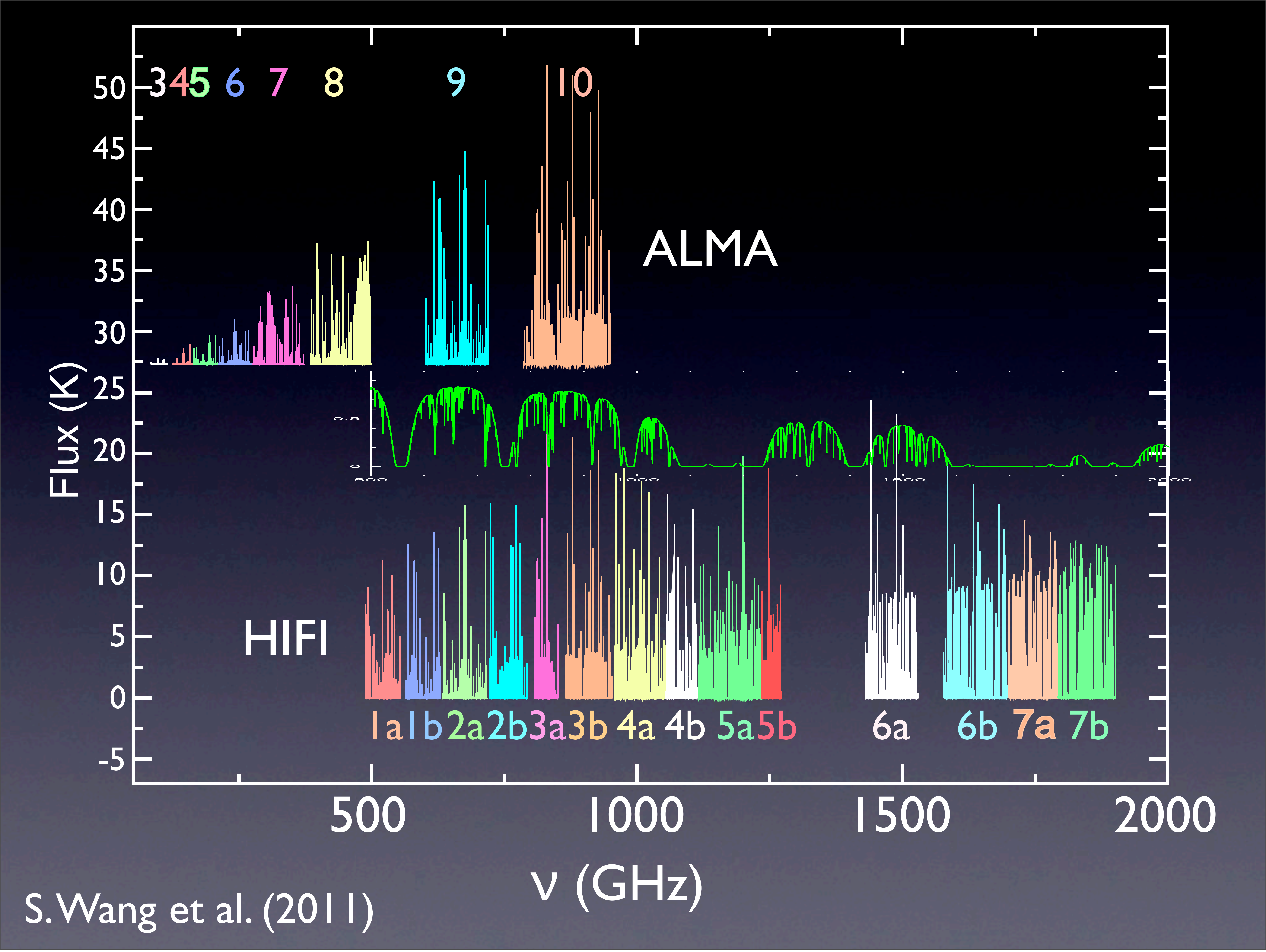
$C^{17}O$

Component	$\sum N_u$ $C^{17}O$ cm^{-2}	f_c	N_{tot} $C^{17}O$ $\pm error$ cm^{-2}		$\frac{N_{tot}(C^{18}O)}{N_{tot}(C^{17}O)}$ $\pm$ $error$	
Extended Ridge	1.53×10^{15}	4.04	6.2×10^{15}	$+1.0 \times 10^{15}$ -1.7×10^{14}	2.3	$+0.5$ -0.5
Outflow/Plateau	7.52×10^{15}	2.79	2.1×10^{16}	$+3.7 \times 10^{15}$ -7.3×10^{14}	1.7	$+0.4$ -0.5
Compact Ridge	2.16×10^{15}	2.50	5.4×10^{15}	$+2.0 \times 10^{15}$ -4.7×10^{14}	4.1	$+2.1$ -1.3
Hot Core	8.97×10^{15}	2.30	2.1×10^{16}	$+6.0 \times 10^{15}$ -1.6×10^{15}	3.0	$+1.2$ -1.1

Summary

- THz Spectroscopy from CCAT would be difficult....but do able
- There are many interesting tracers of the cold & diffuse and hot & dense ISM
- What are the “Killer Apps”?

Methanol



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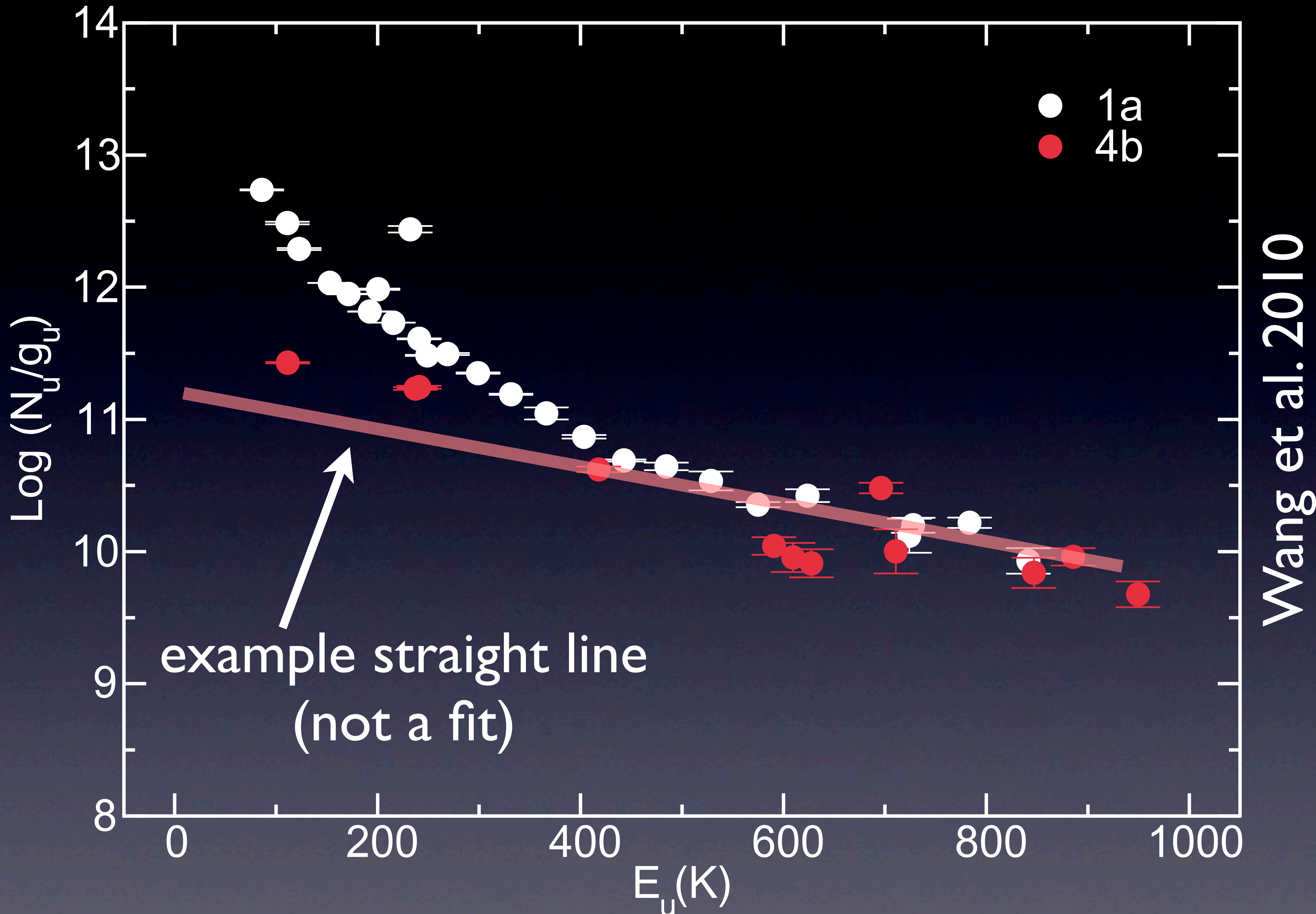
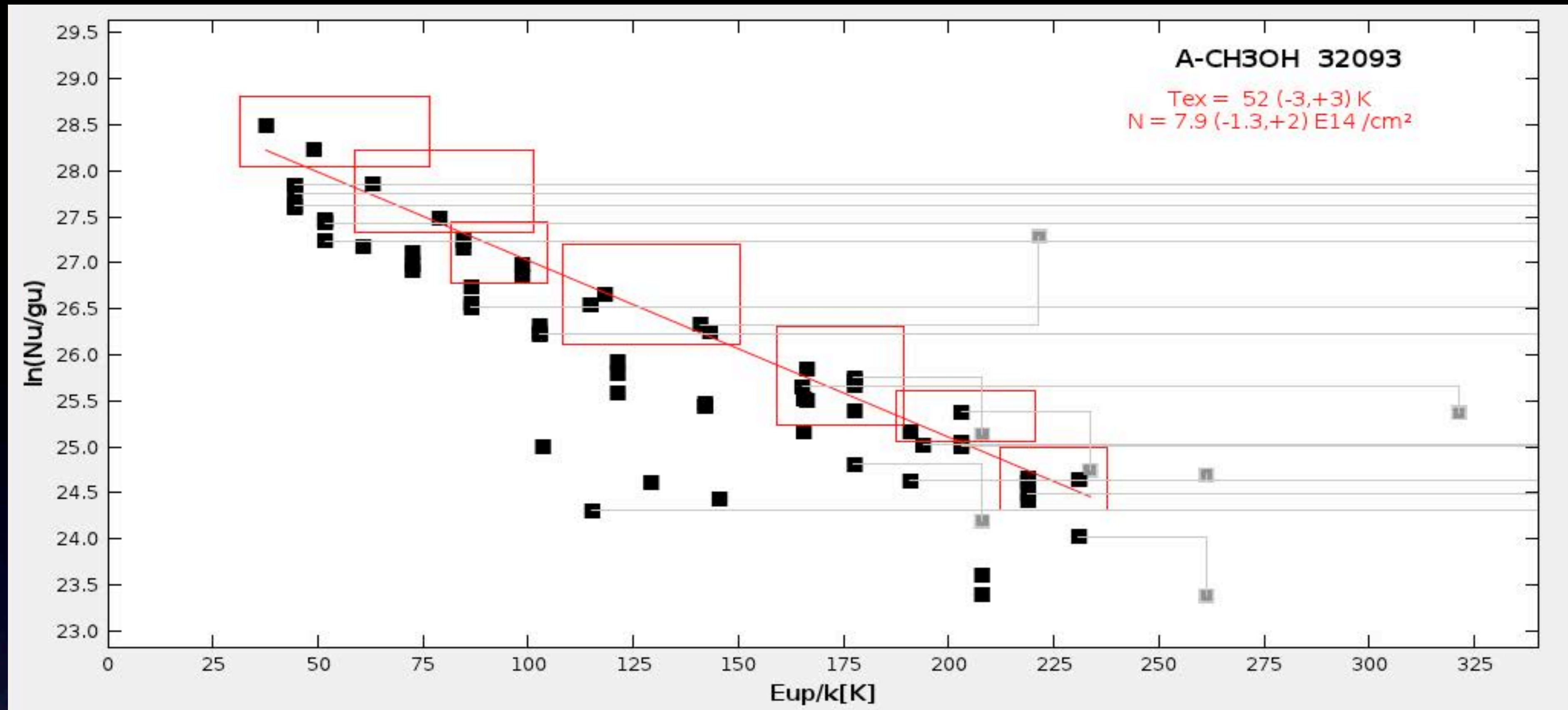
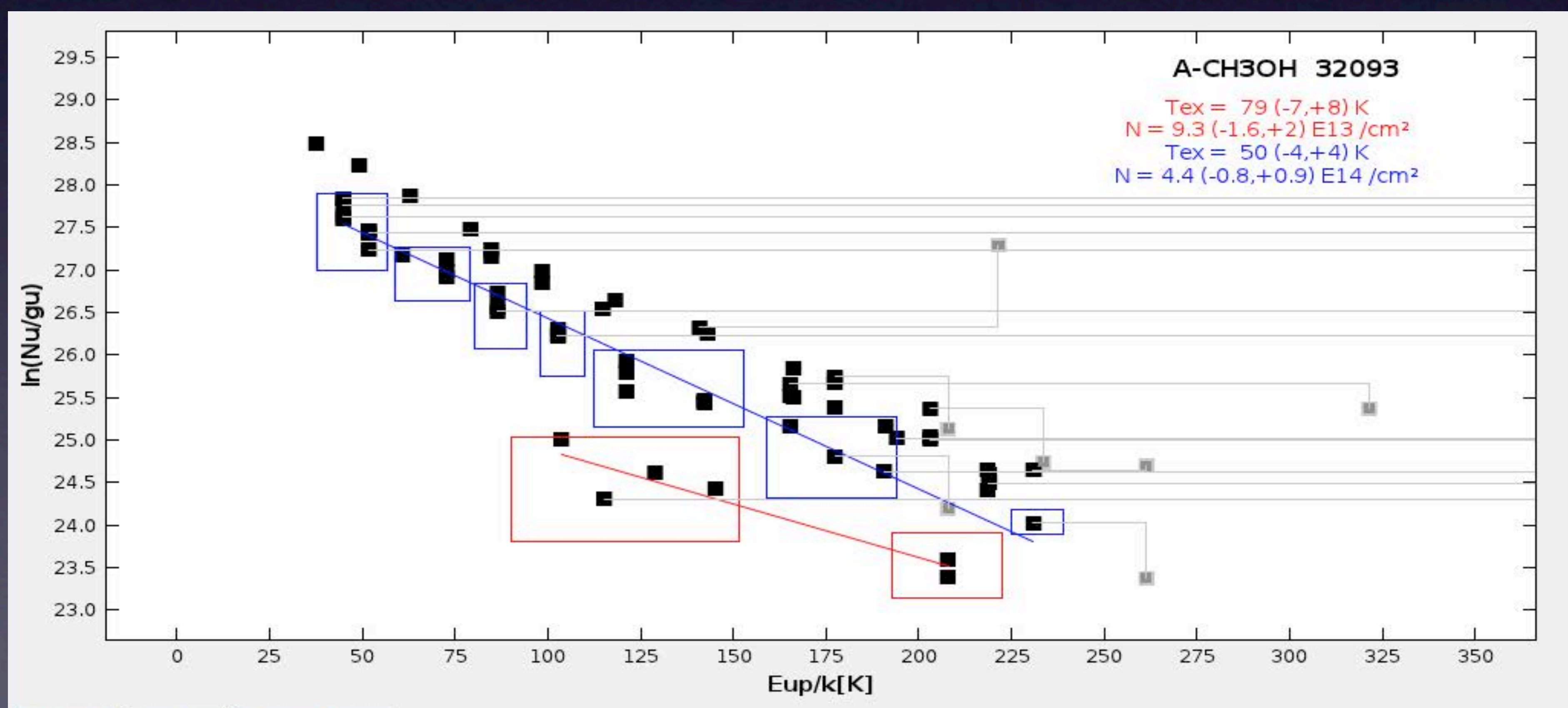


Rotation Diagram

S. Wang et al. (2011)





K.Tahani *Orion S*