Hydrides in Circumstellar Envelopes

Why are they so abundant while they shouldn't?

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The Hydride Toolbox
12-15 December 2016, Université Pierre et Marie Curie, Paris, France

Talk outline:

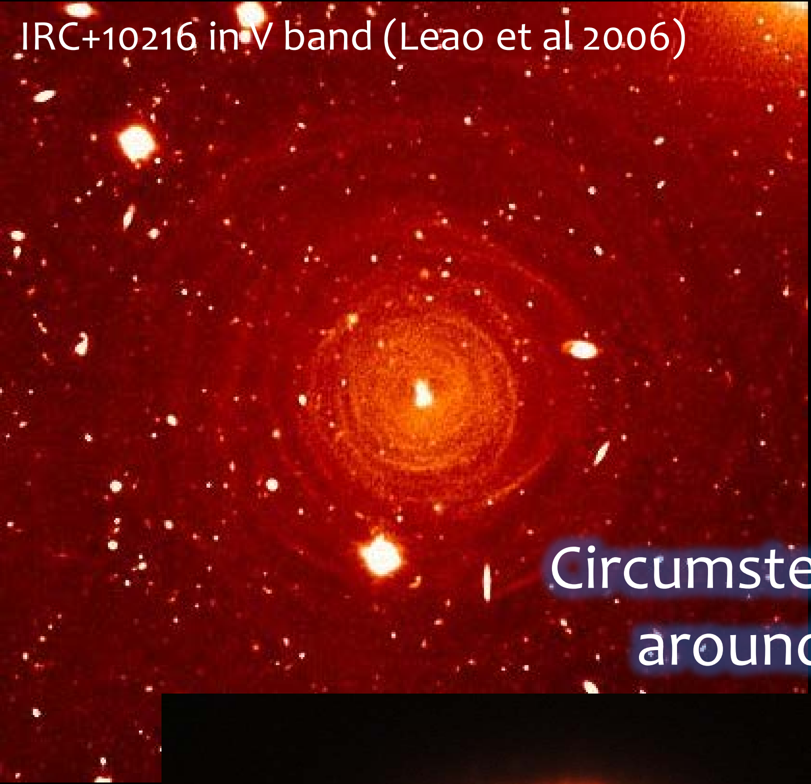
1) Introduction to circumstellar envelopes

1) Expectations from chemical equilibrium

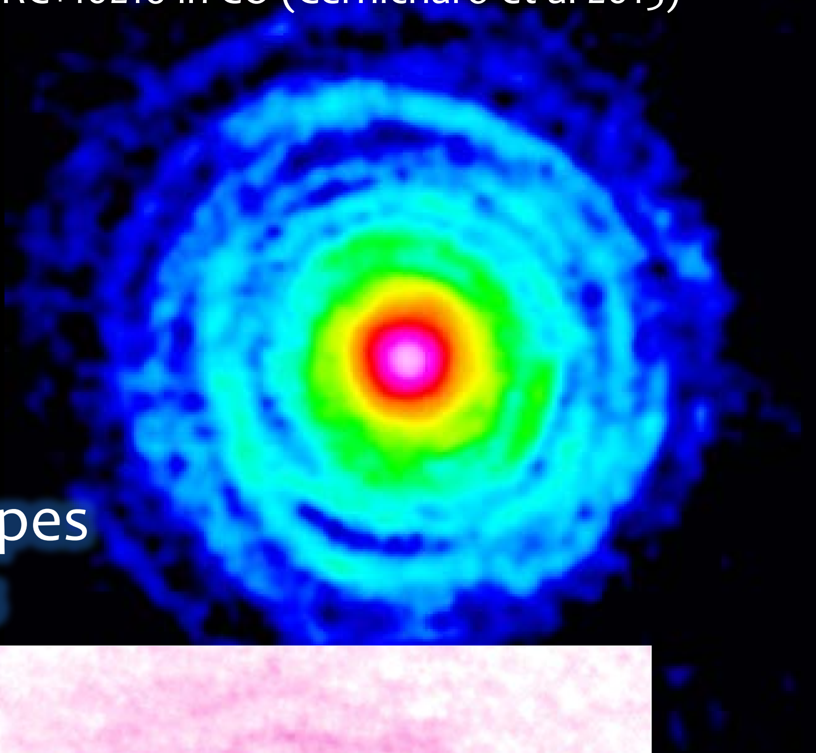
2) Observations of hydrides in circumstellar envelopes

3) What is understood and what is not

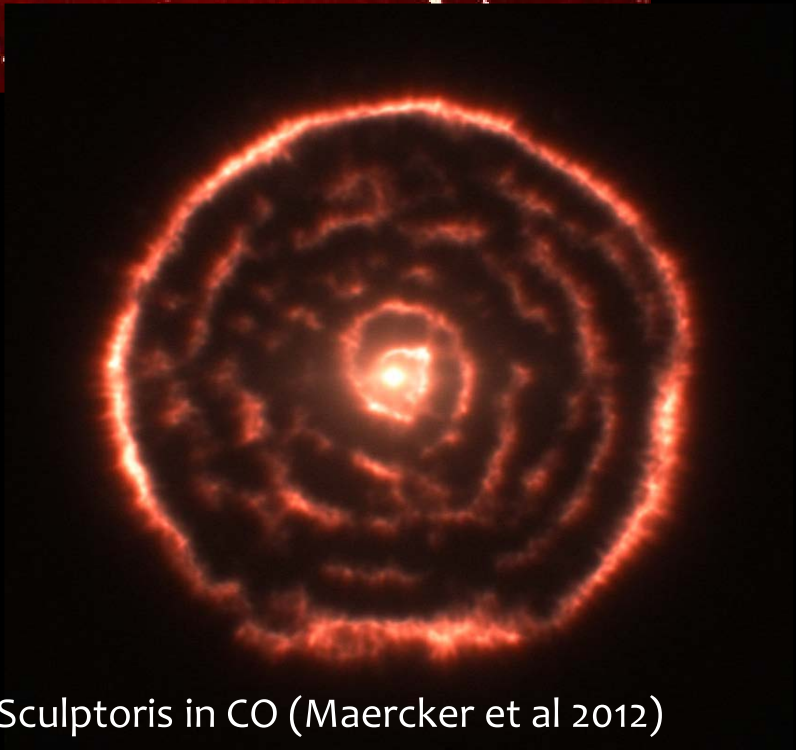
Circumstellar envelopes around AGB stars



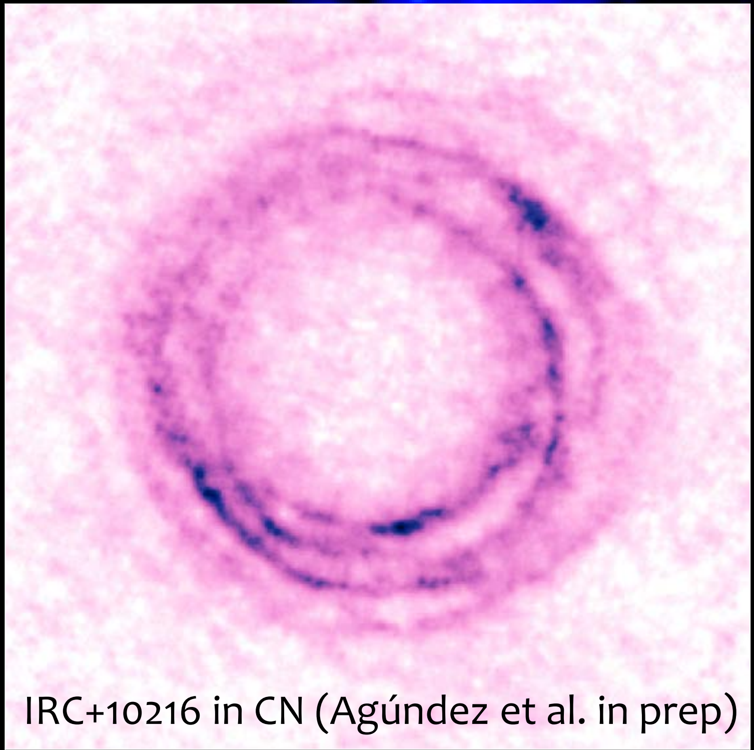
IRC+10216 in V band (Leao et al 2006)



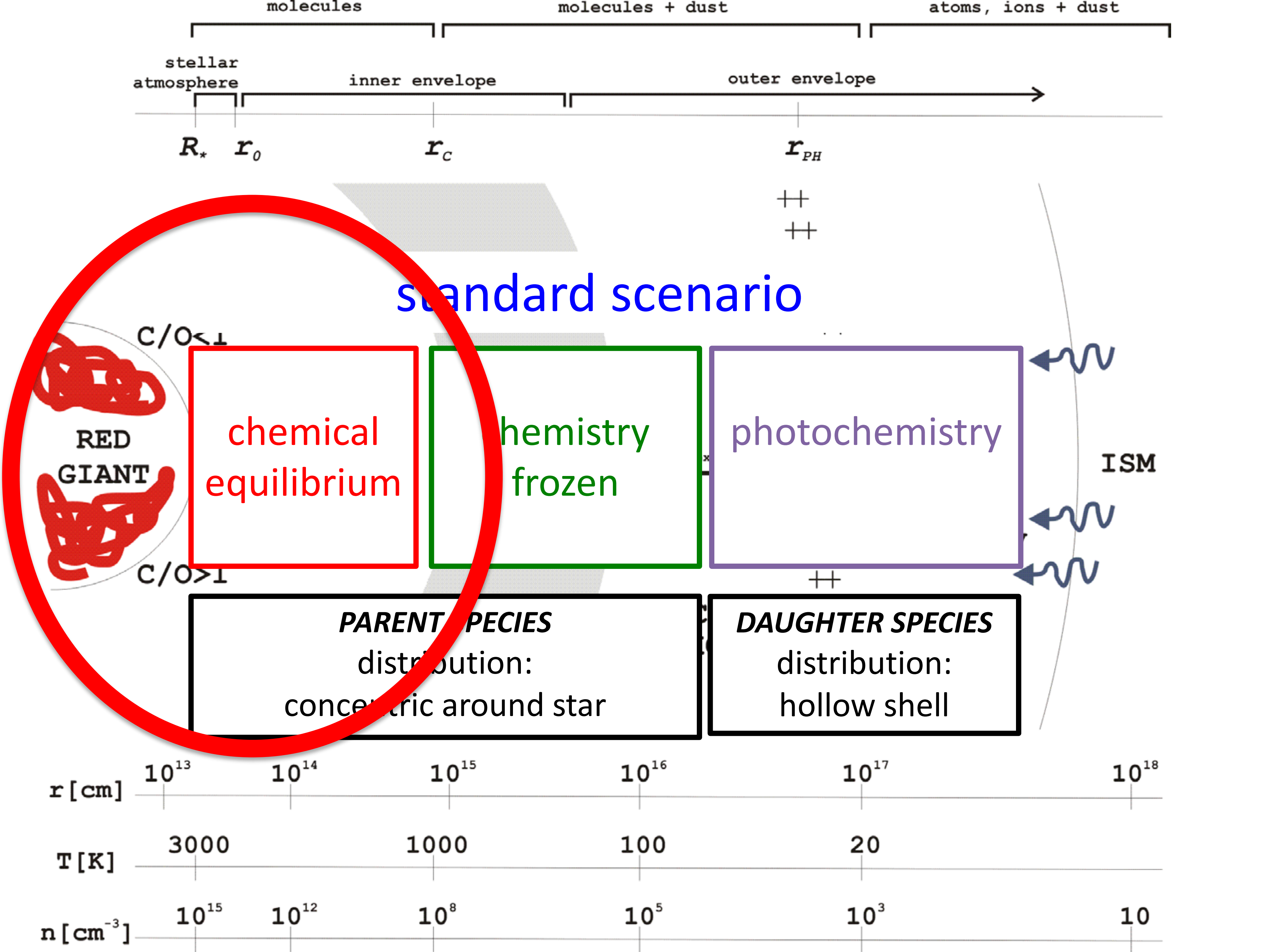
IRC+10216 in CO (Cernicharo et al 2015)



R Sculptoris in CO (Maercker et al 2012)



IRC+10216 in CN (Agúndez et al. in prep)

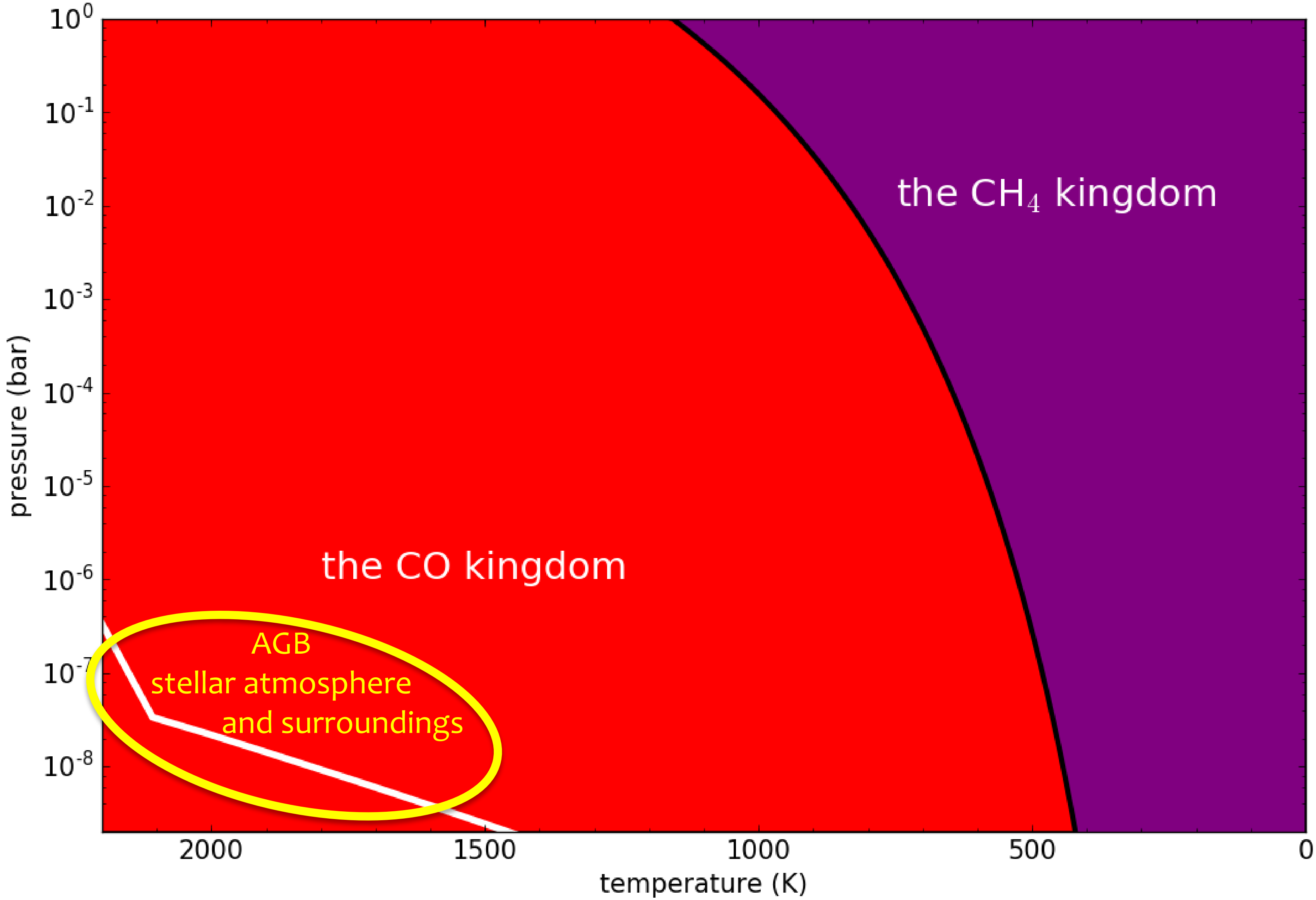


molecules
molecules + dust
atoms, ions + dust
stellar atmosphere
inner envelope
outer envelope
R_*
r_0
r_C
r_{PH}
standard scenario
C/O<1
C/O>1
RED GIANT
chemical equilibrium
hemistry frozen
photochemistry
ISM
PARENT PECIES
distr bution:
conce tric around star
DAUGHTER SPECIES
distribution:
hollow shell
r [cm]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
T [K]
3000
1000
100
20
$n\ [cm^{-3}]$
10^{15}
10^{12}
10^{8}
10^{5}
10^{3}
10

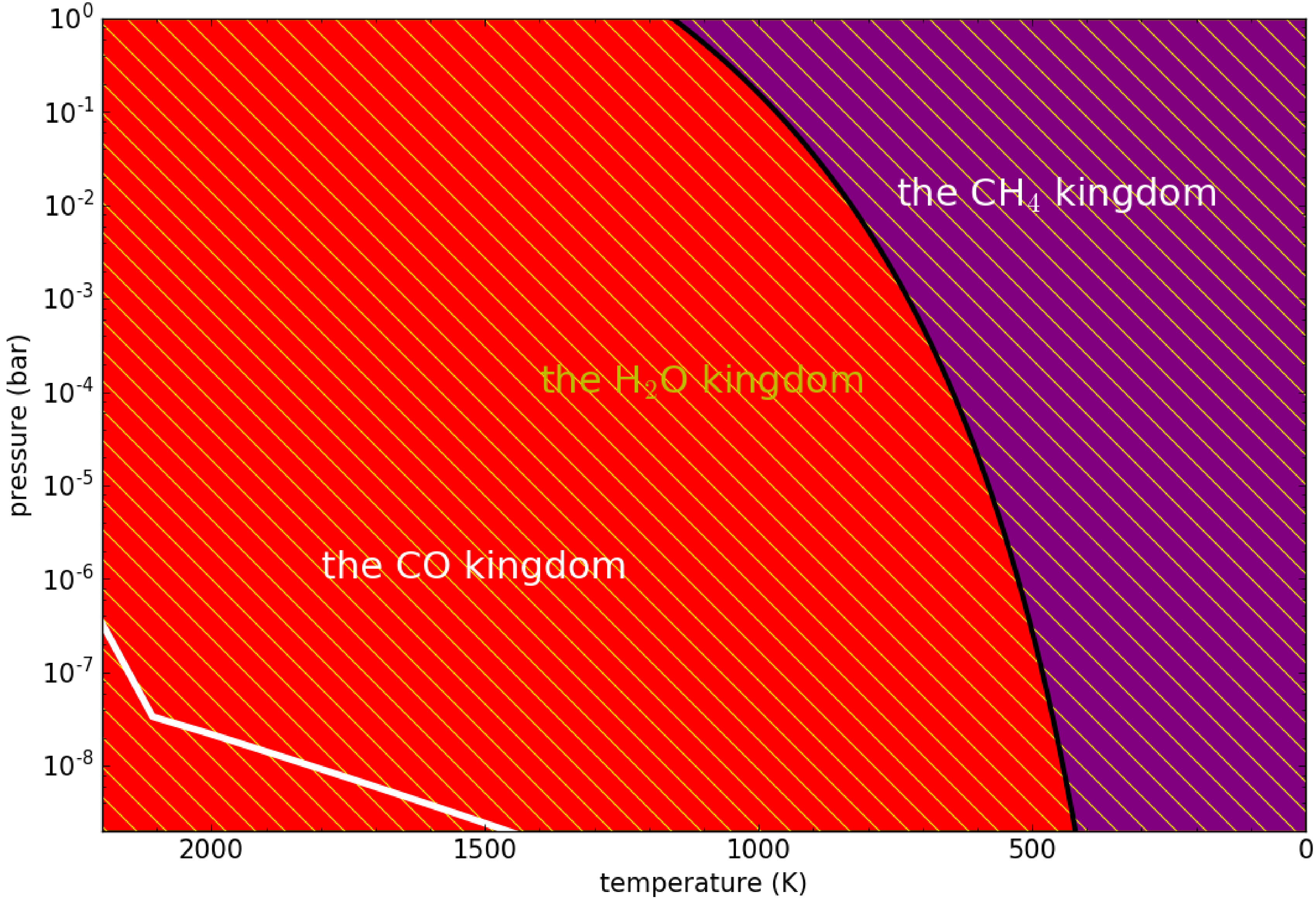
Expectations from chemical equilibrium

(Thermo)chemical equilibrium = minimization of free Gibbs energy

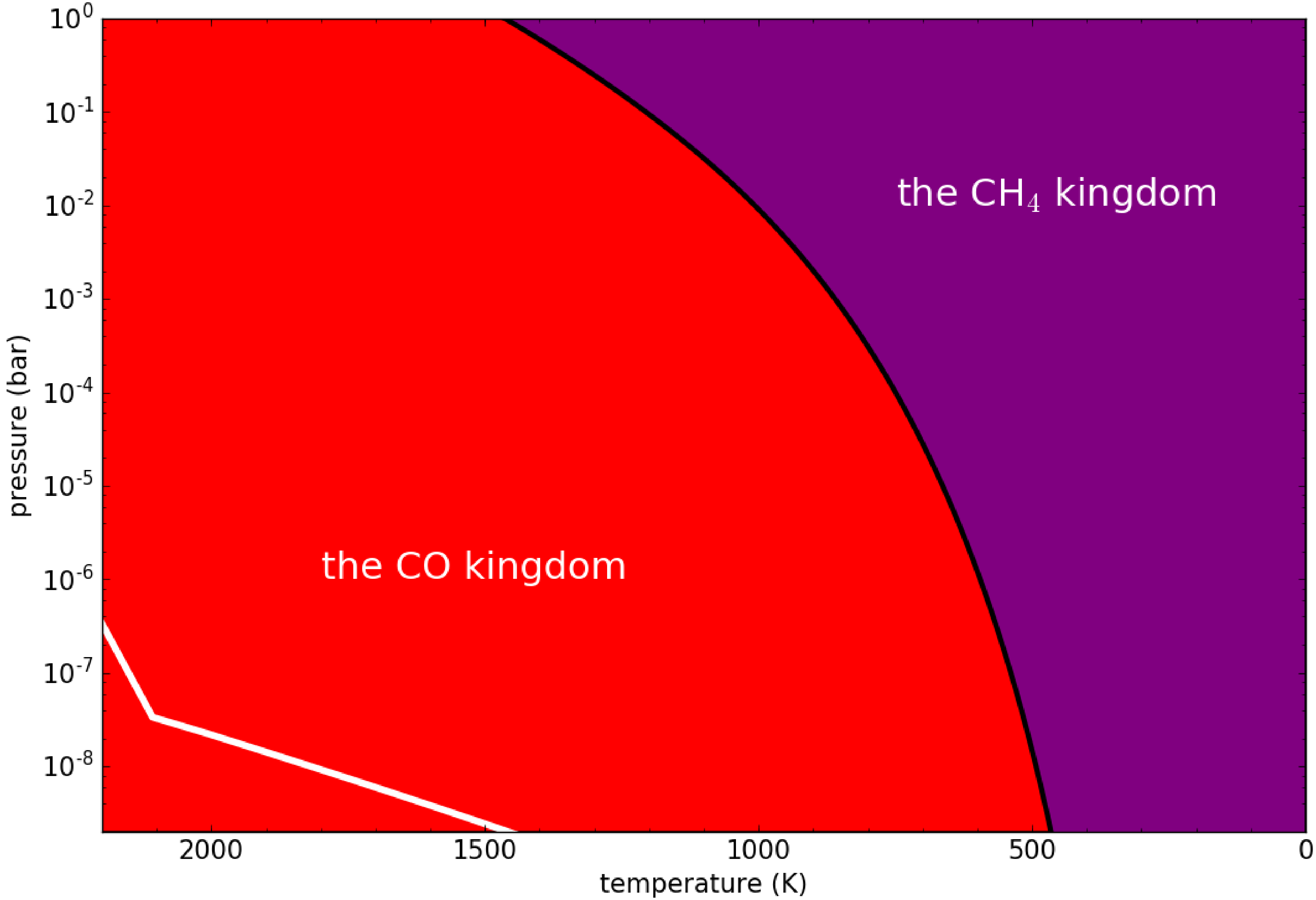
Chemical equilibrium (C/O < 1)
carbon and oxygen budget



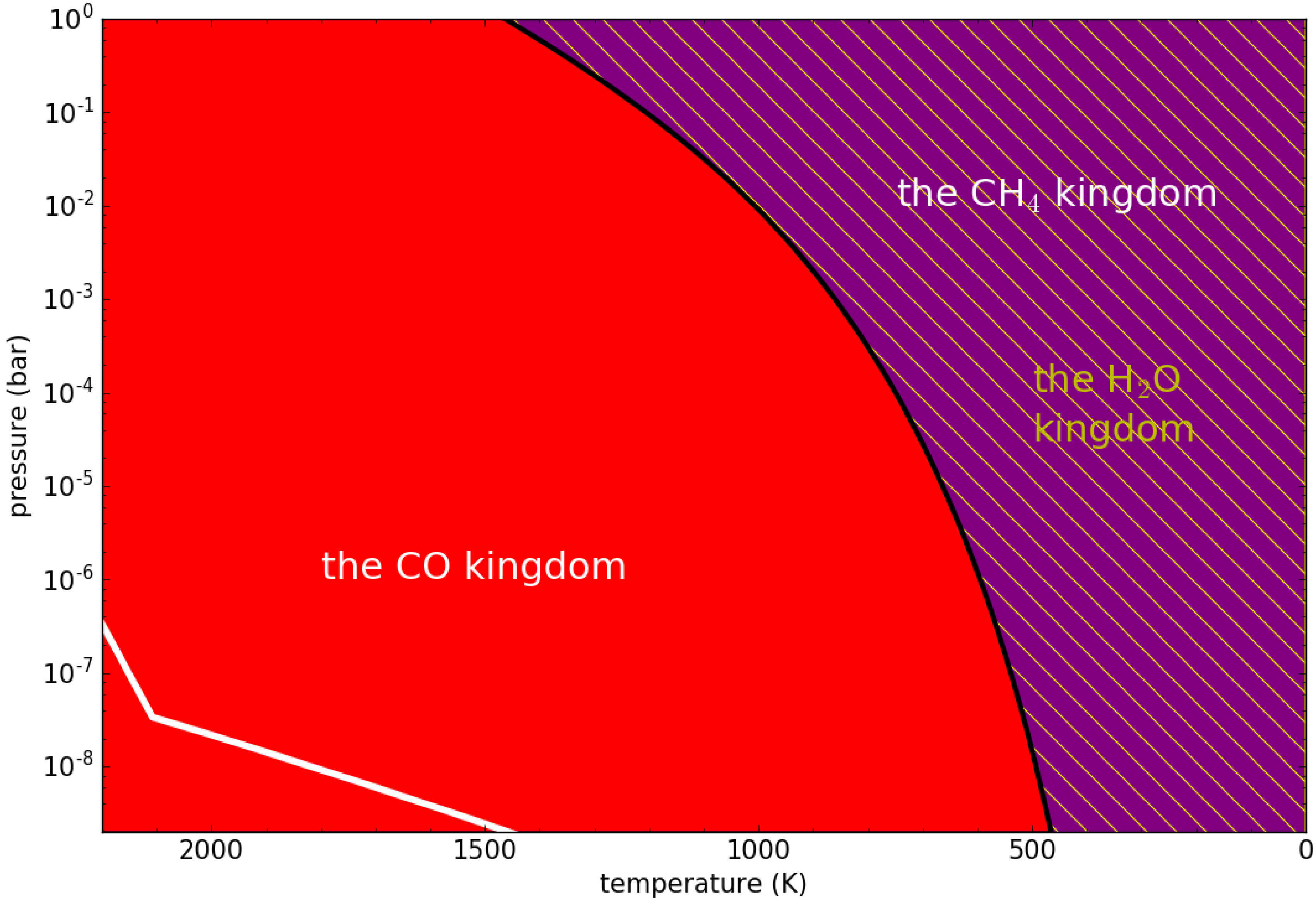
Chemical equilibrium (C/O < 1)
carbon and oxygen budget



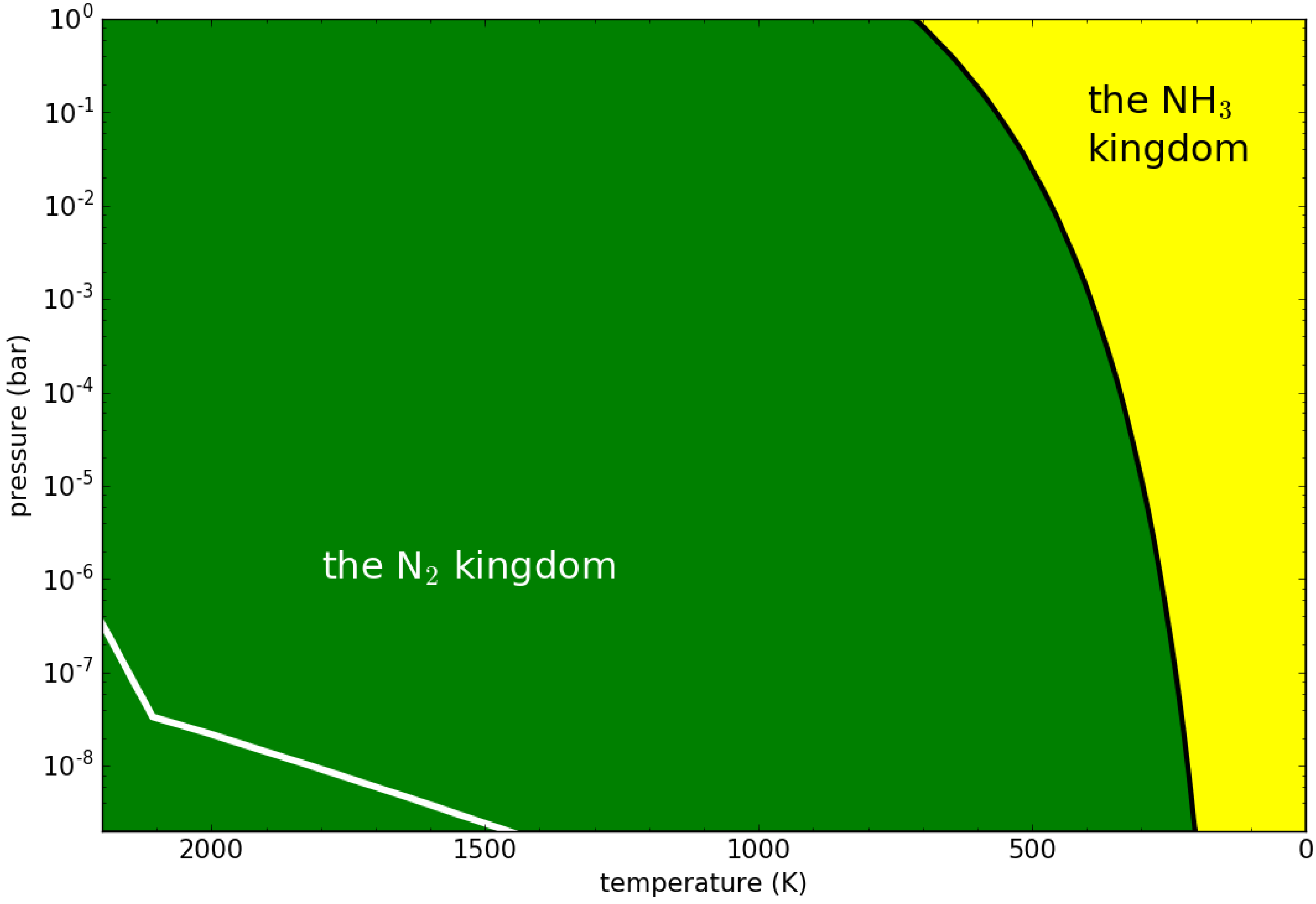
Chemical equilibrium (C/O > 1)
carbon and oxygen budget



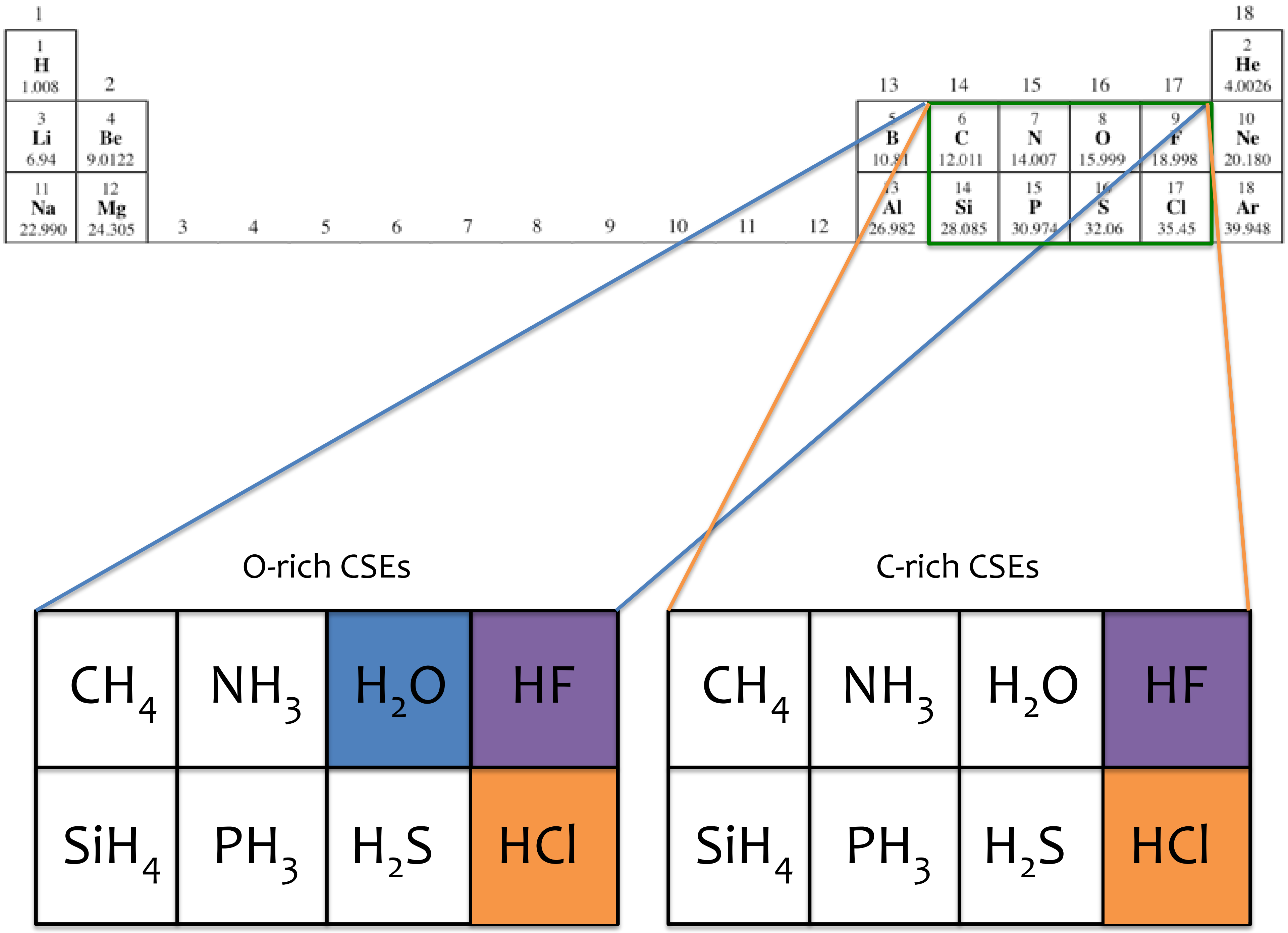
Chemical equilibrium (C/O > 1)
carbon and oxygen budget



Chemical equilibrium (C/O < 1 and C/O > 1)
nitrogen budget



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** 1.008																	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305											13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.867	23 **V** 50.942	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.845	27 **Co** 58.933	28 **Ni** 58.693	29 **Cu** 63.546	30 **Zn** 65.38	31 **Ga** 69.723	32 **Ge** 72.630	33 **As** 74.922	34 **Se** 78.97	35 **Br** 79.904	36 **Kr** 83.798
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.95	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89-103 #	104 **Rf** (265)	105 **Db** (268)	106 **Sg** (271)	107 **Bh** (270)	108 **Hs** (277)	109 **Mt** (276)	110 **Ds** (281)	111 **Rg** (280)	112 **Cn** (285)	113 **Nh** (286)	114 **Fl** (289)	115 **Mc** (289)	116 **Lv** (293)	117 **Ts** (294)	118 **Og** (294)


1
18
1 H 1.008
2
2 He 4.0026
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16
17
3 Li 6.94
4 Be 9.0122
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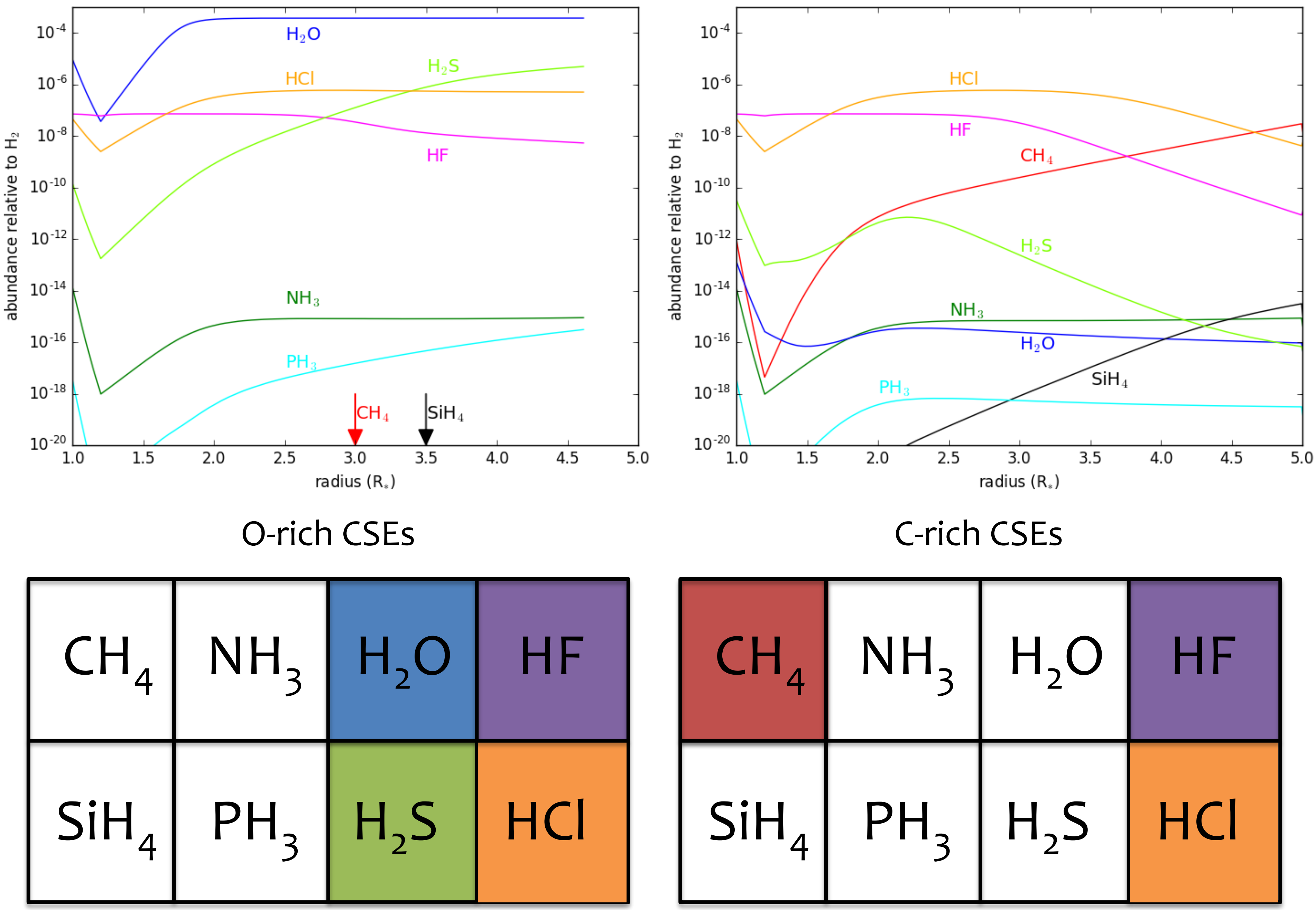
6 C 12.011
7 N 14.007
8 O 15.999
9 F 18.998
10 Ne 20.180
11 Na 22.990
12 Mg 24.305
3
4
5
6
7
8
9
10
11
12
13 Al 26.982
14 Si 28.085
15 P 30.974
16 S 32.06
17 Cl 35.45
18 Ar 39.948
O-rich CSEs
C-rich CSEs
CH4
NH3
H2O
HF
SiH4
PH3
H2S
HCl
CH4
NH3
H2O
HF
SiH4
PH3
H2S
HCl



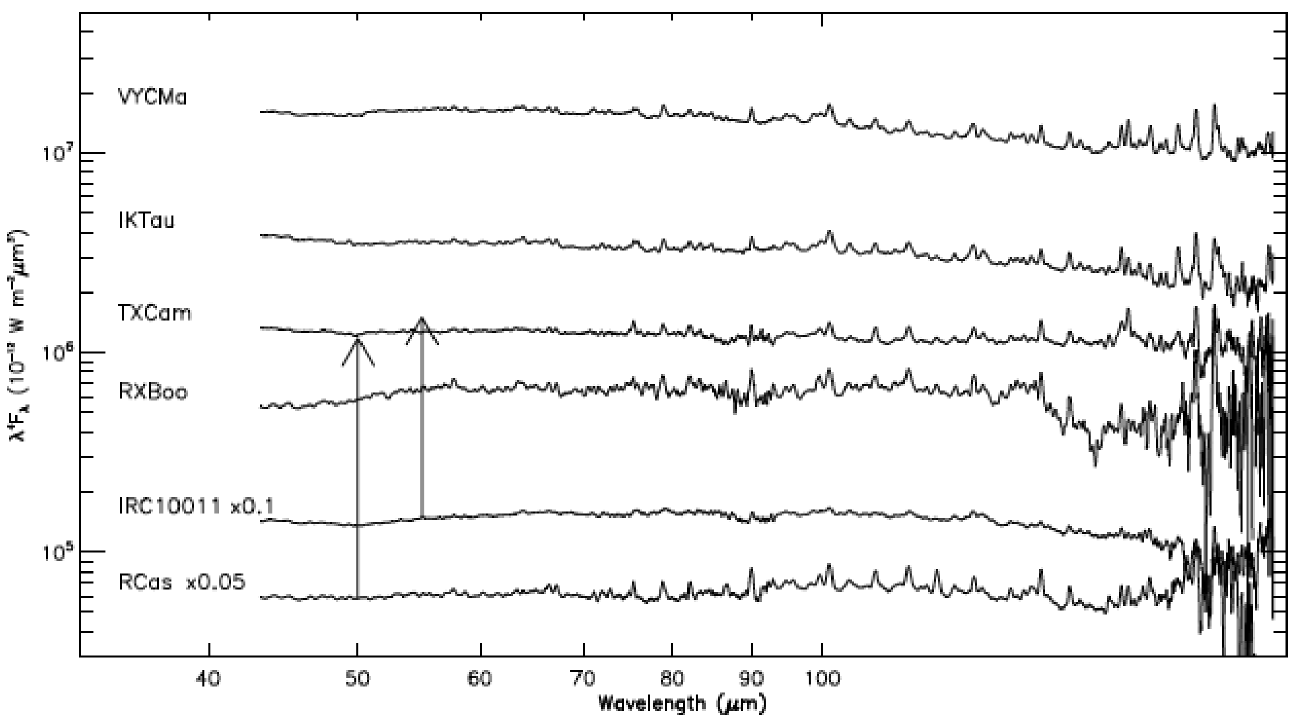
abundance relative to H_2
radius (R_*)
H_2O
HCl
H_2S
HF
NH_3
PH_3
CH_4
SiH_4
O-rich CSEs
C-rich CSEs
CH_4
NH_3
H_2O
HF
SiH_4
PH_3
H_2S
HCl

Observations of hydrides in circumstellar envelopes

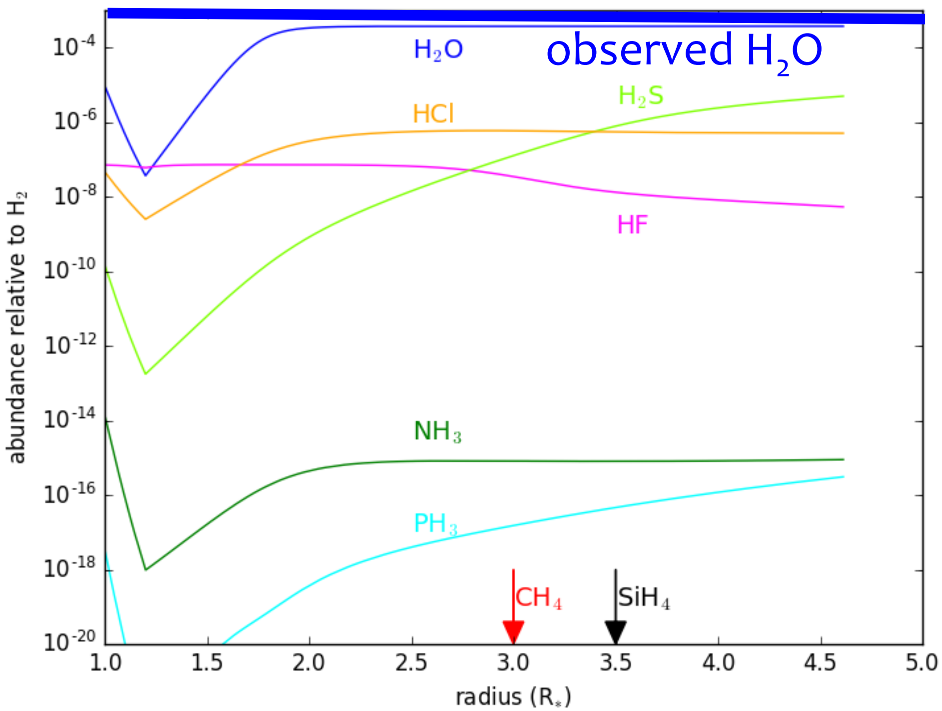
Water vapour around O-rich stars

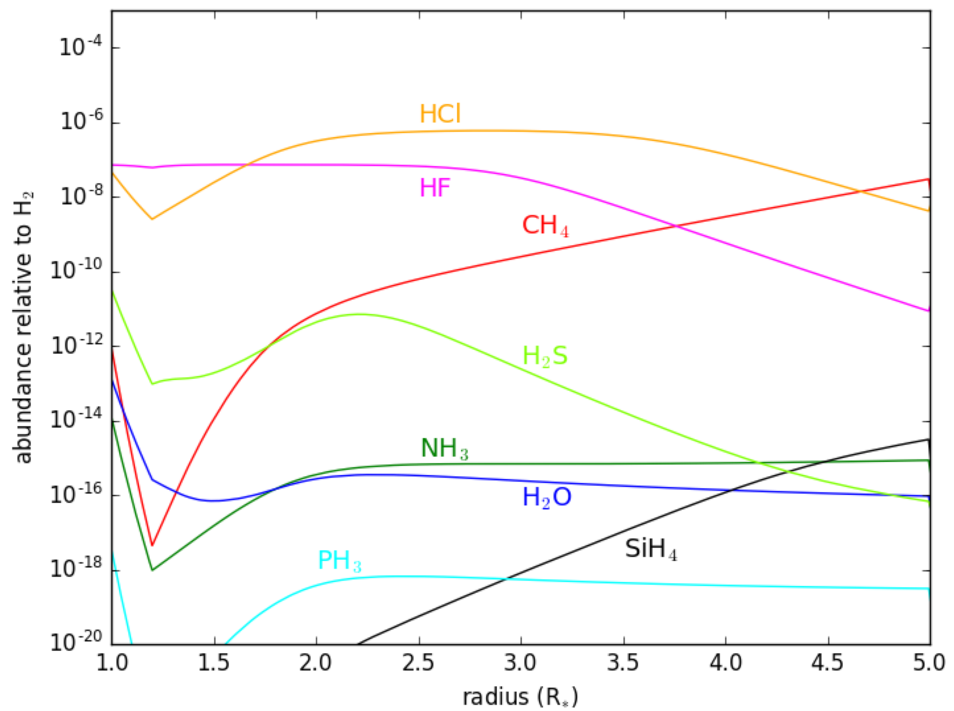
Ground	22 GHz maser line
	183 GHz maser line
ISO	far-IR lines
Odin	1_{10}-1_{01} line at 557 GHz
Herschel	sub-mm and far-IR lines

Observations are consistent with most oxygen (not as CO) locked into H_2O in agreement with chemical equilibrium



Polehampton et al. (2010)





O-rich CSEs

CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl

C-rich CSEs

CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl

THE IRC +10216 CIRCUMSTELLAR ENVELOPE. III. INFRARED MOLECULAR LINE PROFILES

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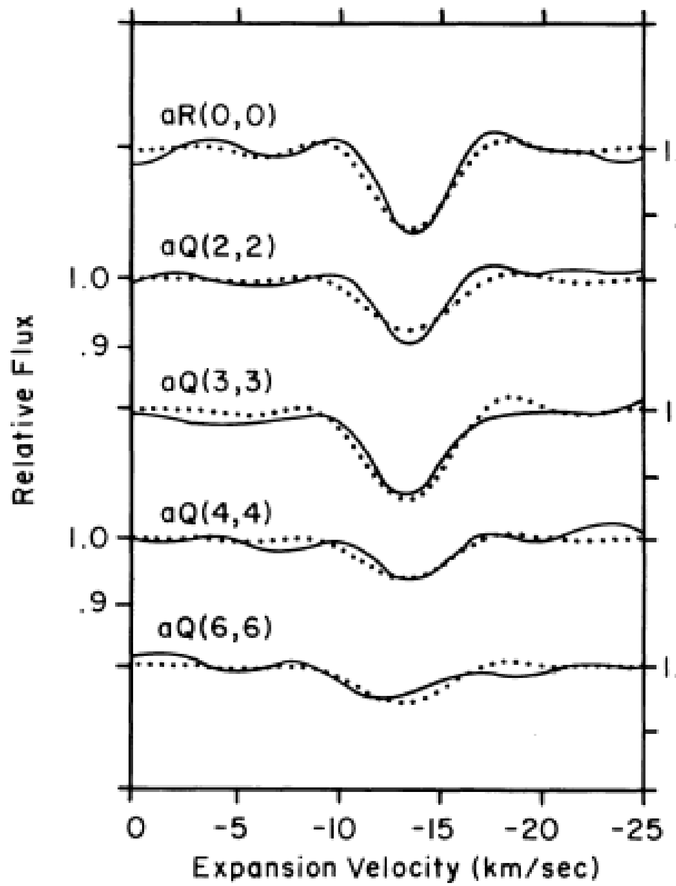
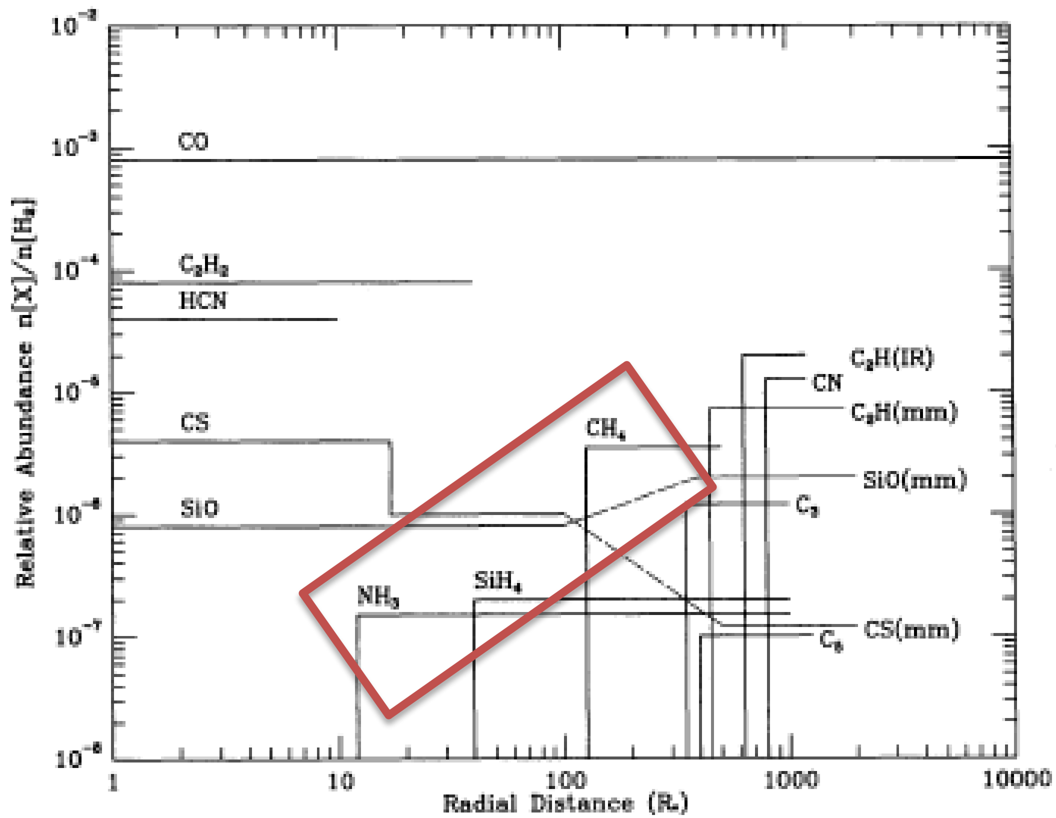
Kitt Peak National Observatory,[2] National Optical Astronomy Observatories, P.O. Box 26732, Tuscon, AZ 85726-6732

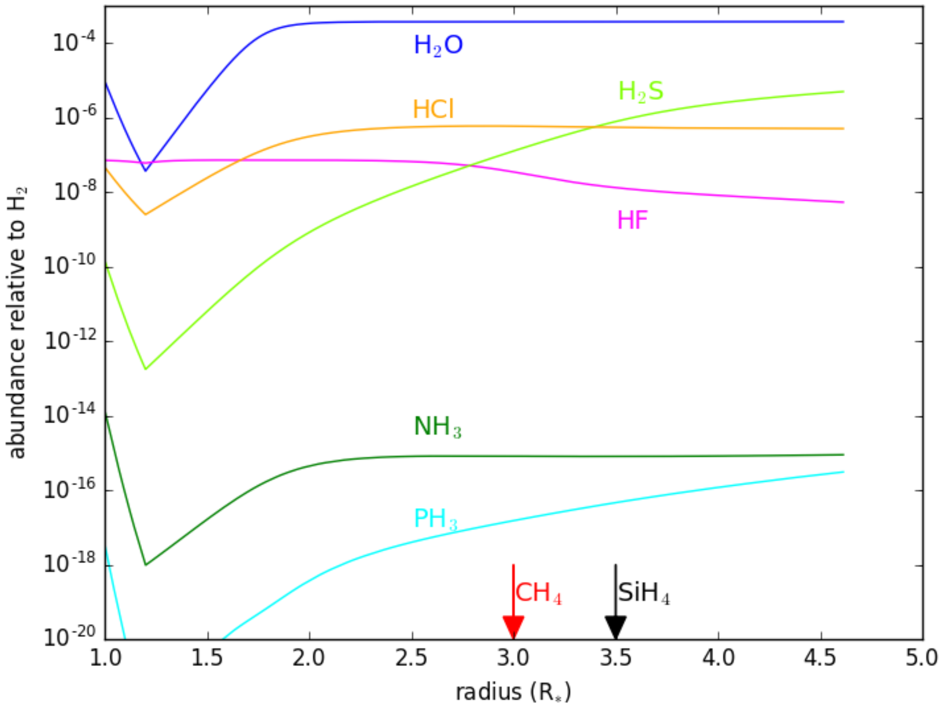
Received 1990 October 1; accepted 1992 September 24

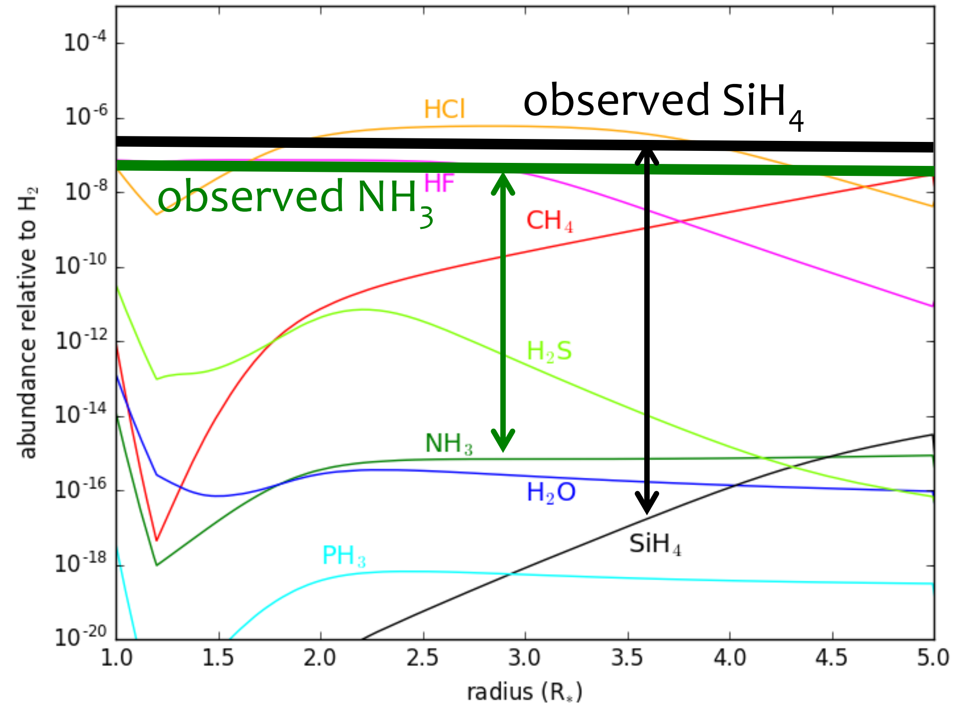


NH$_3$ lines around 10 μm



CH$_4$, SiH$_4$, and NH$_3$ observed
in the C-rich object IRC+10216





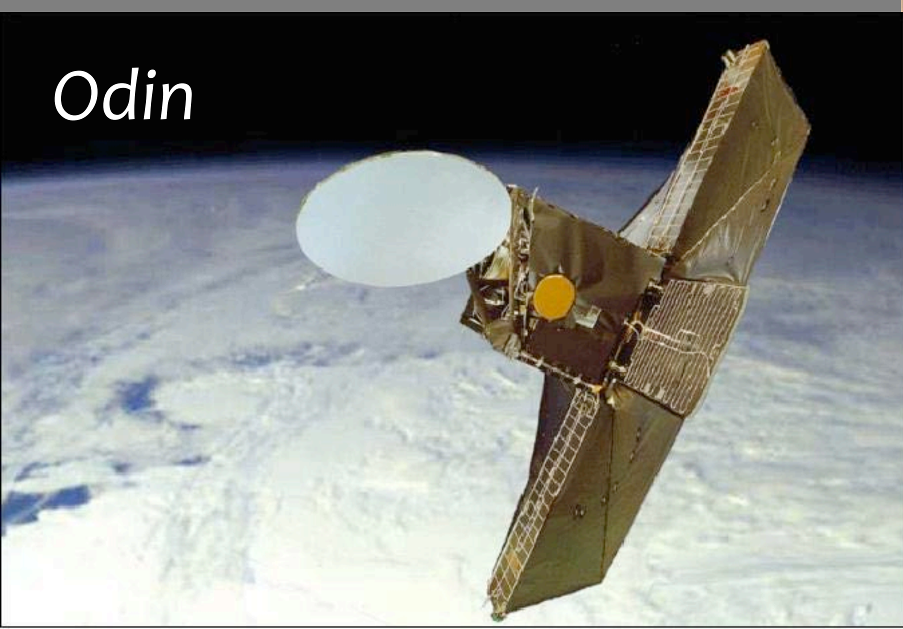
O-rich CSEs

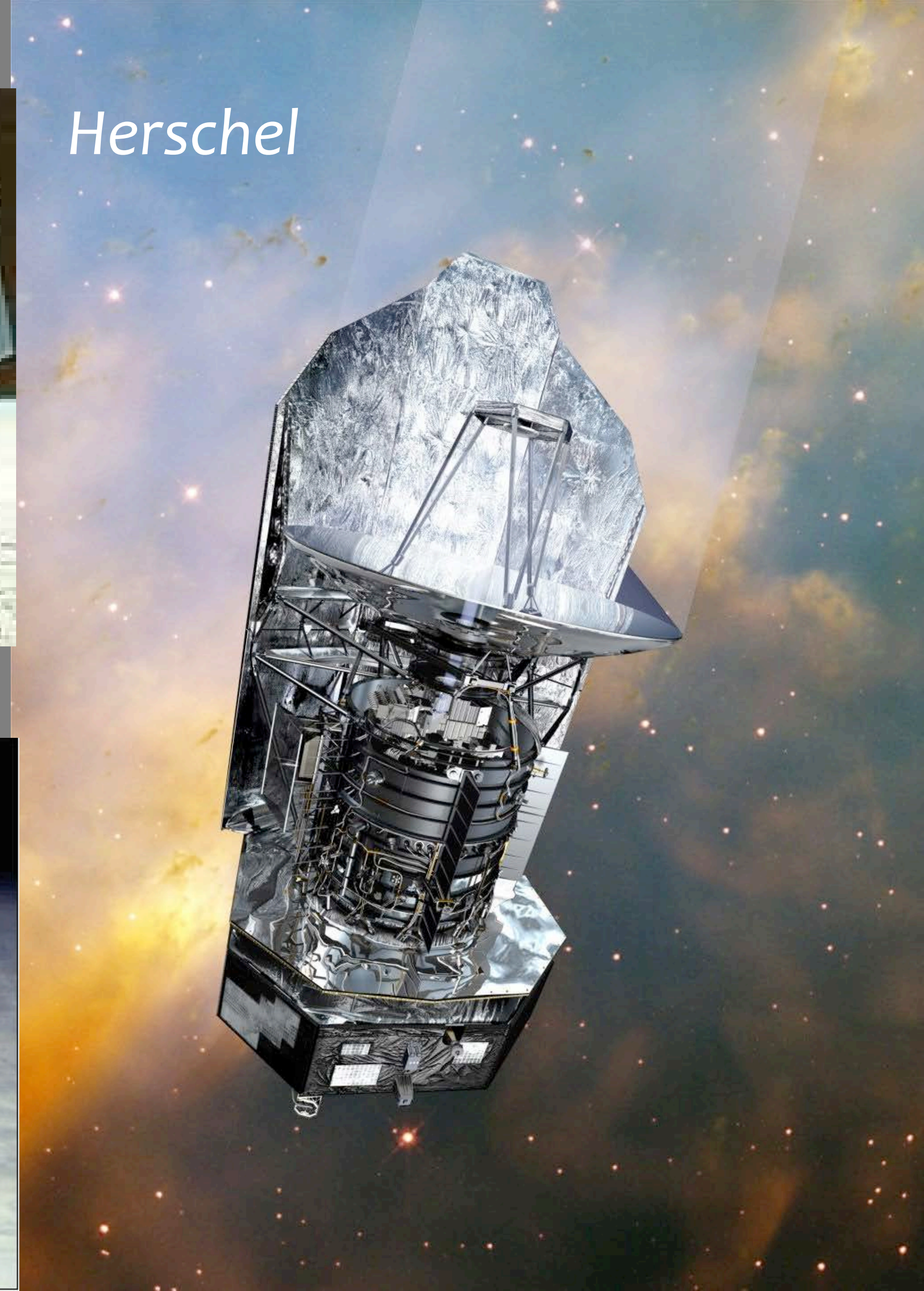
CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl

C-rich CSEs

CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl


SWAS


Odin

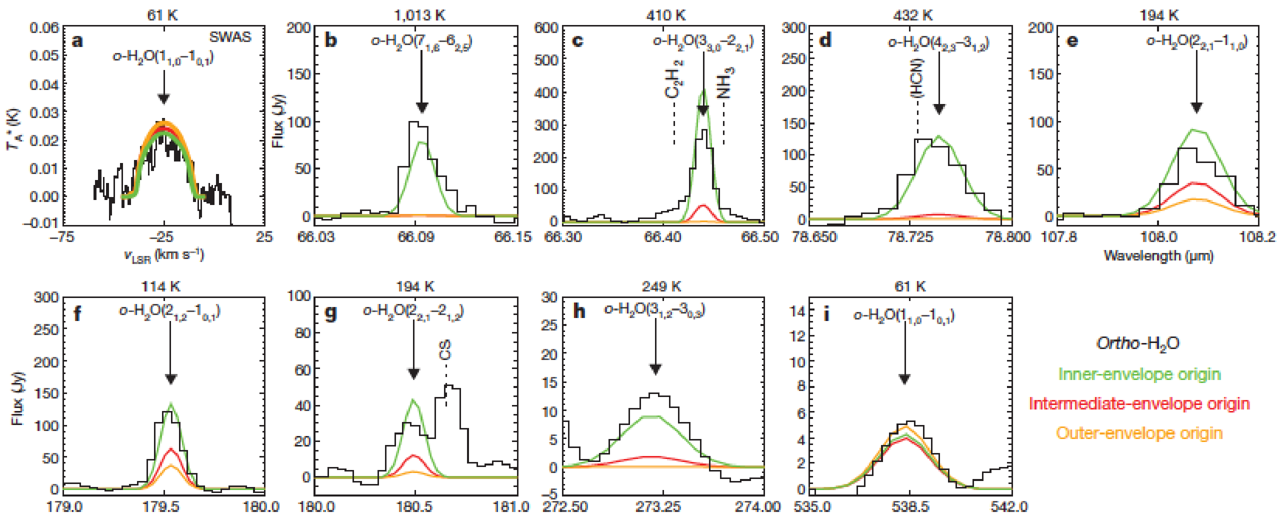

Herschel

Water vapour around carbon stars

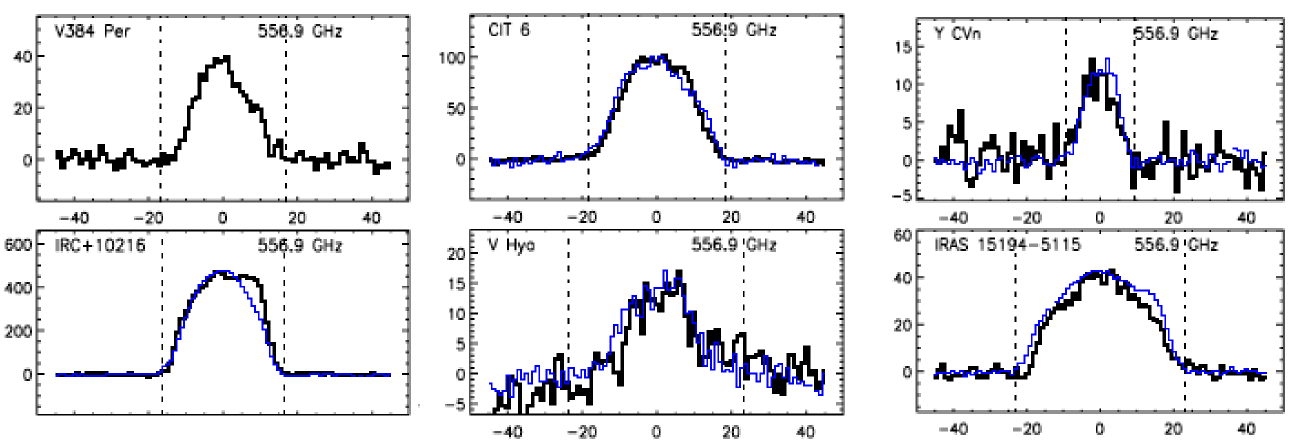
H_2O previously detected in IRC+10216 by SWAS (Melnick et al 2001) and *Odin* (Hasegawa et al 2006)

Inner envelope origin

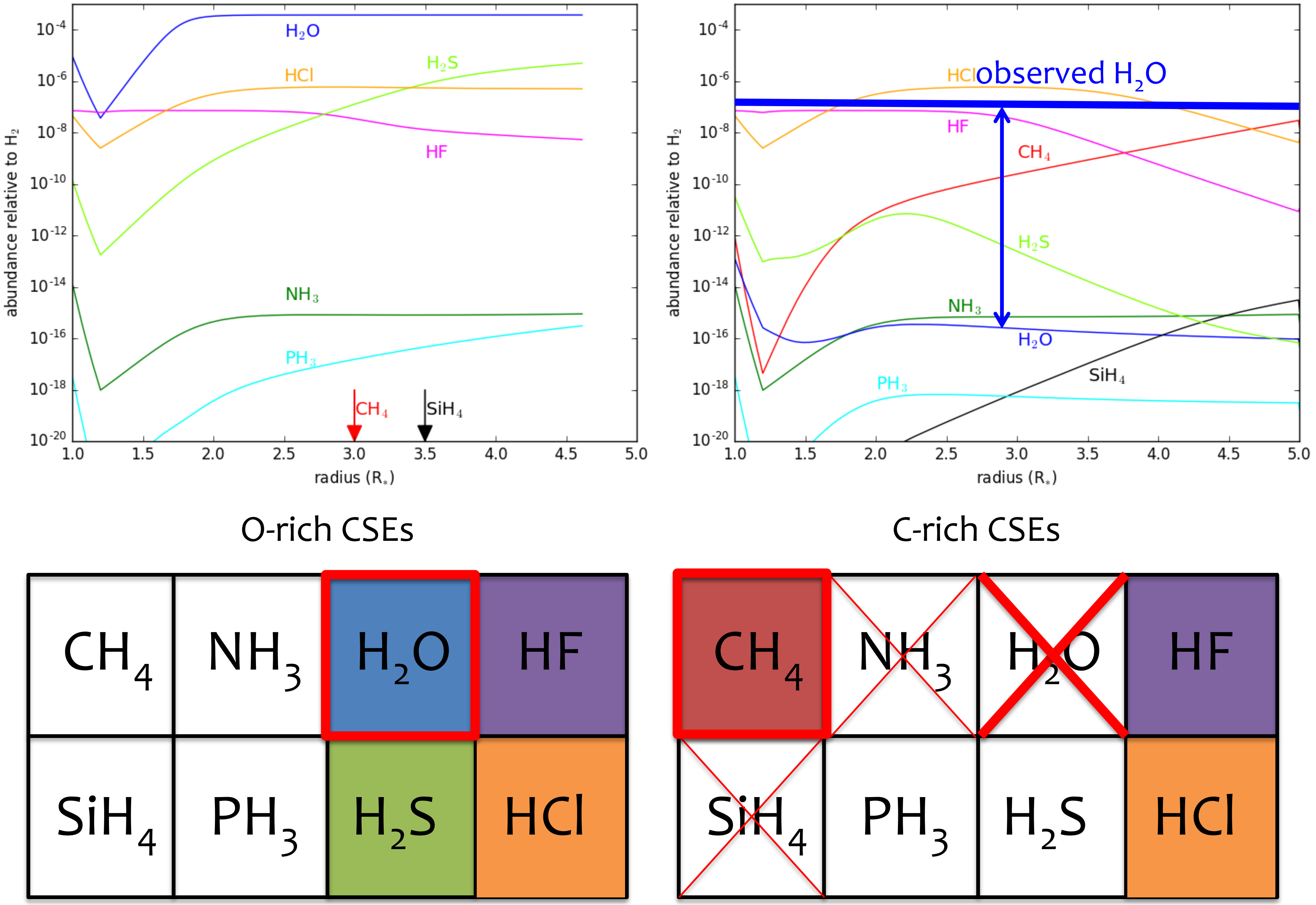
Widespread occurrence in carbon stars



Decin et al (2010)



Neufeld et al (2011)



abundance relative to H2
radius (R*)
H2O
HCl
H2S
HF
NH3
PH3
CH4
SiH4
observed H2O
O-rich CSEs
C-rich CSEs
CH4
NH3
H2O
HF
SiH4
PH3
H2S
HCl

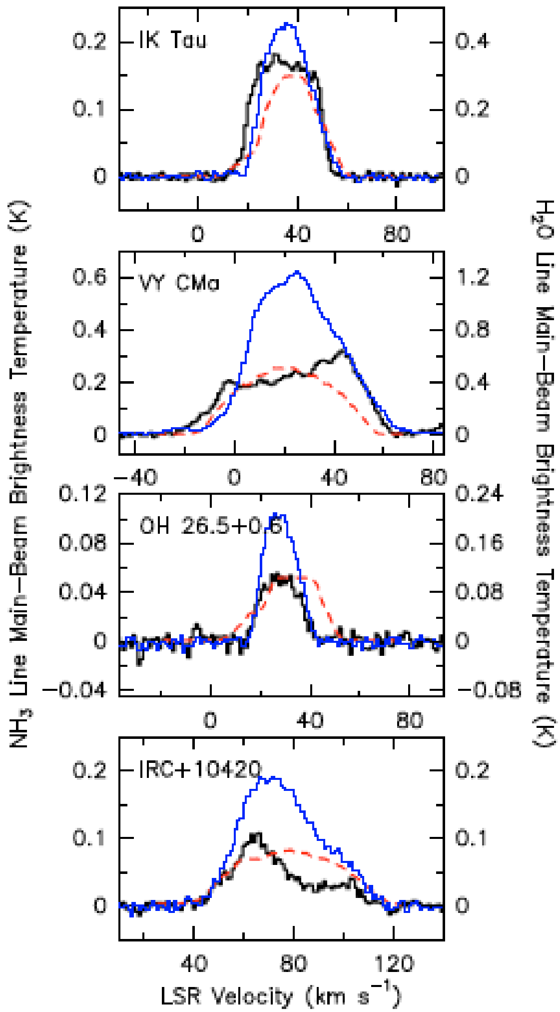
Ammonia around both O- and C-rich stars

NH_3 previously observed in IRC+10216

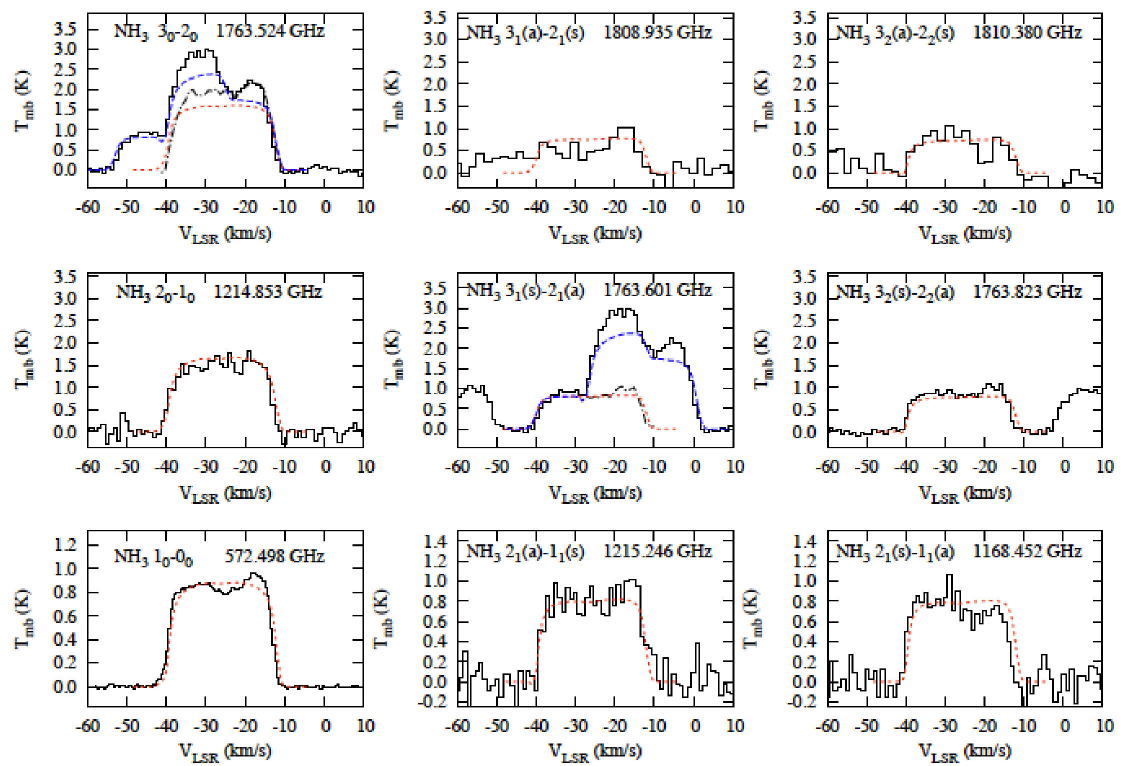
ro-vibrational absorption lines around 10 µm(Keady & Ridgway 1993)

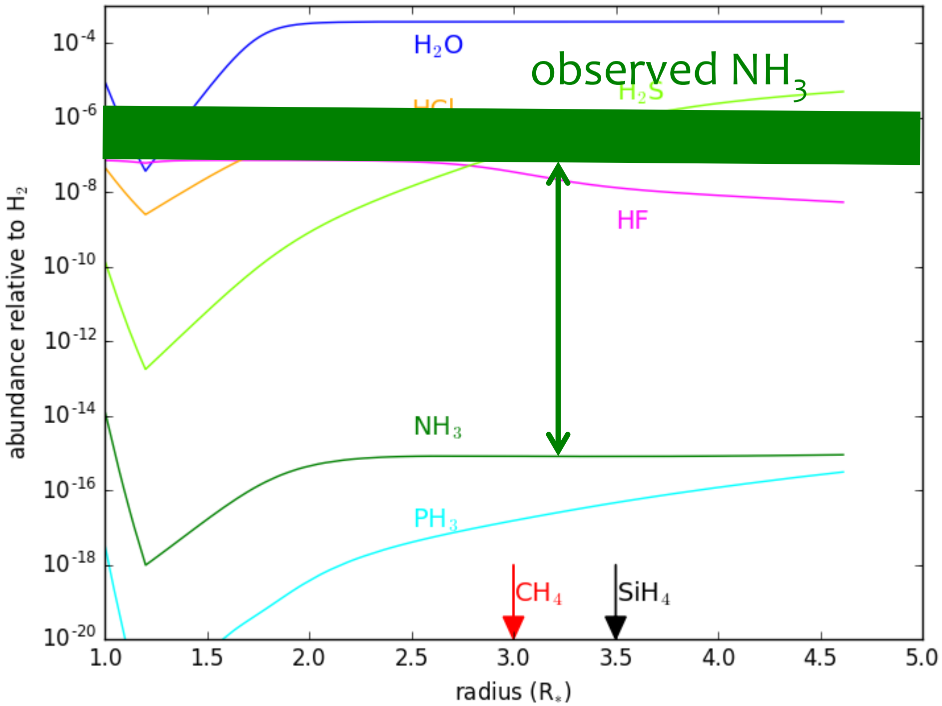
1_0-0_0 rotational line observed with *Odin* (Hasegawa et al 2006)

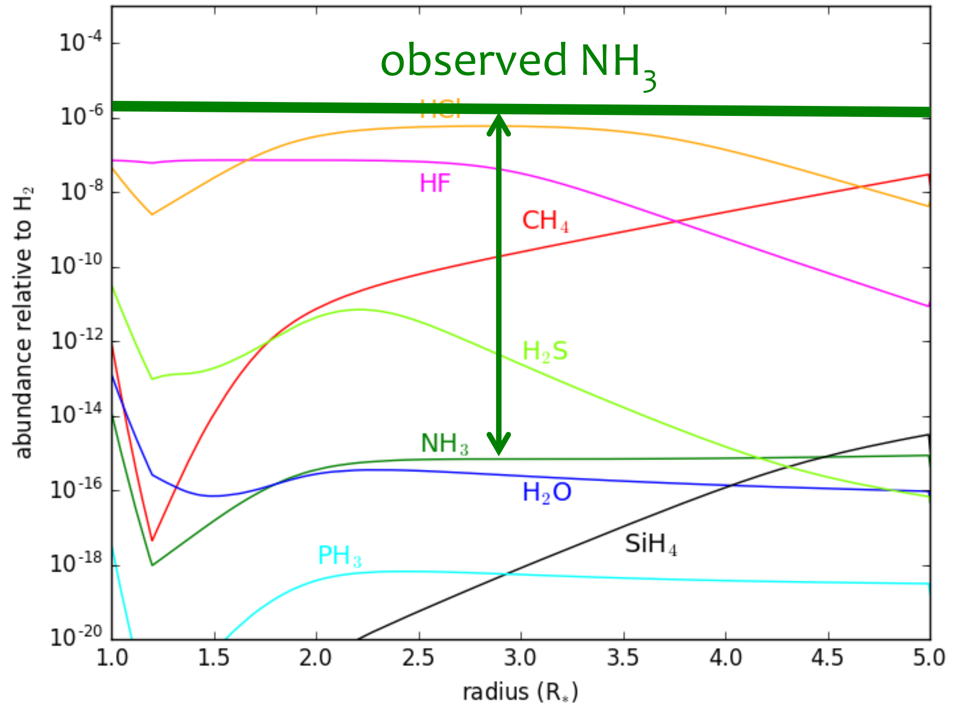
NH_3 observed in 4 O-rich stars (Menten et al 2010)



Many lines of NH_3 observed in IRC+10216 (Schmidt et al 2016)







O-rich CSEs

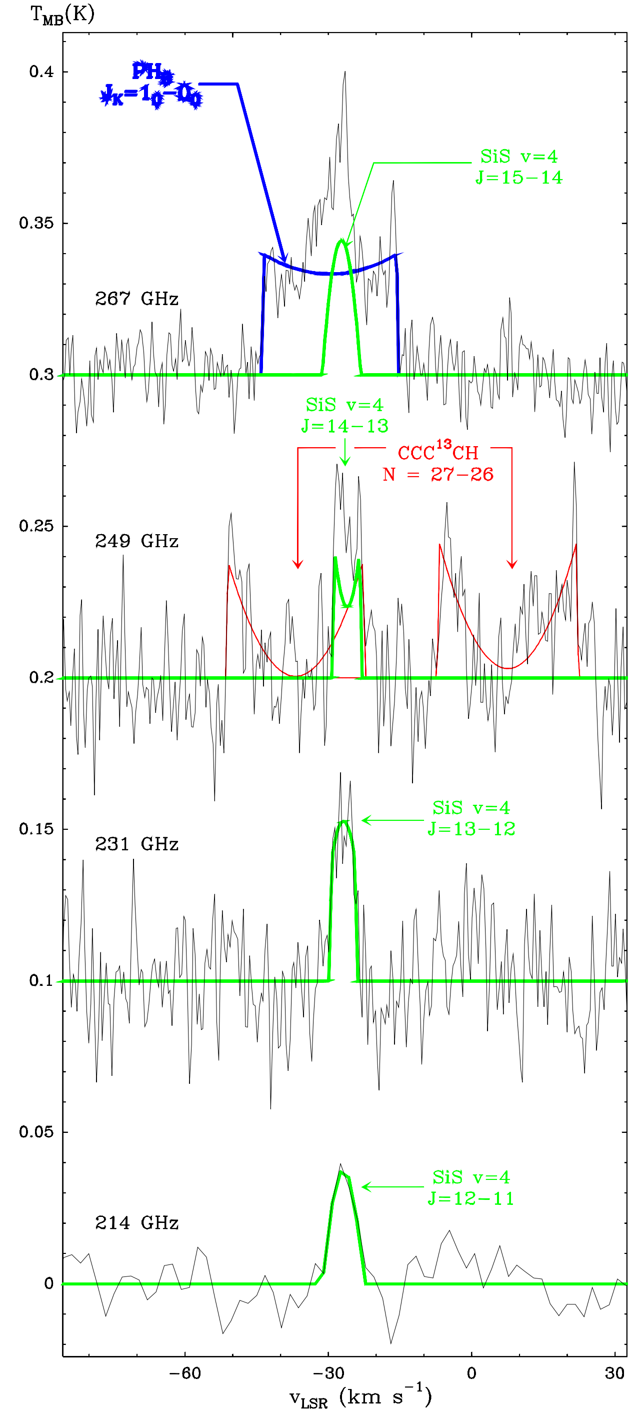
CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl

C-rich CSEs

CH_4	NH_3	H_2O	HF
SiH_4	PH_3	H_2S	HCl

Phosphine around carbon stars

PH_3 tentatively identified in IRC+10216 from ground at mm-wavelengths (1_0-0_0 rotational line at 267 GHz) (Agúndez et al 2008)



Same detection reported by Tenenbaum & Ziurys (2008)

Phosphine around carbon stars

Detection of PH_3 in IRC+10216 confirmed by *Herschel*/HIFI

CONFIRMATION OF CIRCUMSTELLAR PHOSPHINE

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[2] Sterrenkundig Instituut Anton Pannekoek, University of Amsterdam, Science Park 904, NL-1098 Amsterdam, The Netherlands
[3] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
[4] LERMA, Observatoire de Paris, 61 Av. de l'Observatoire, F-75014 Paris, France
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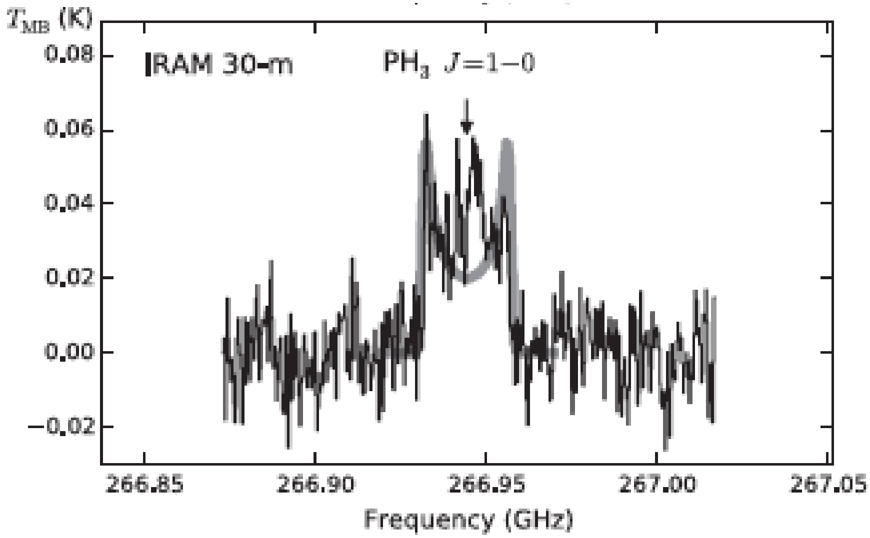
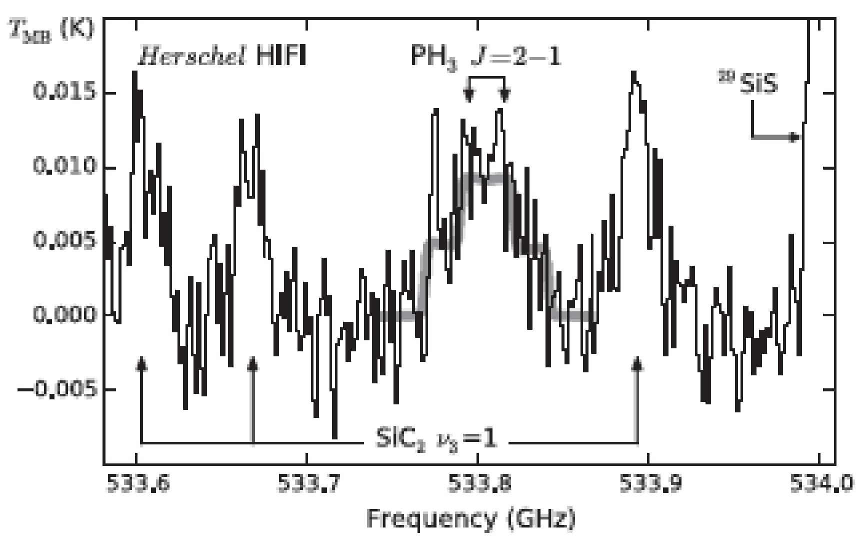
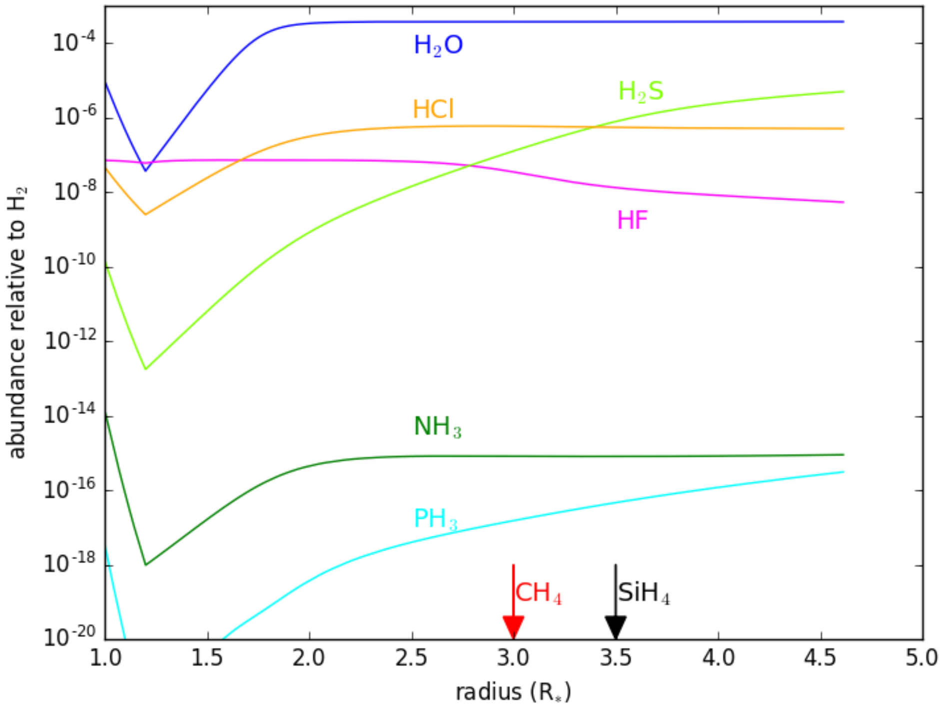
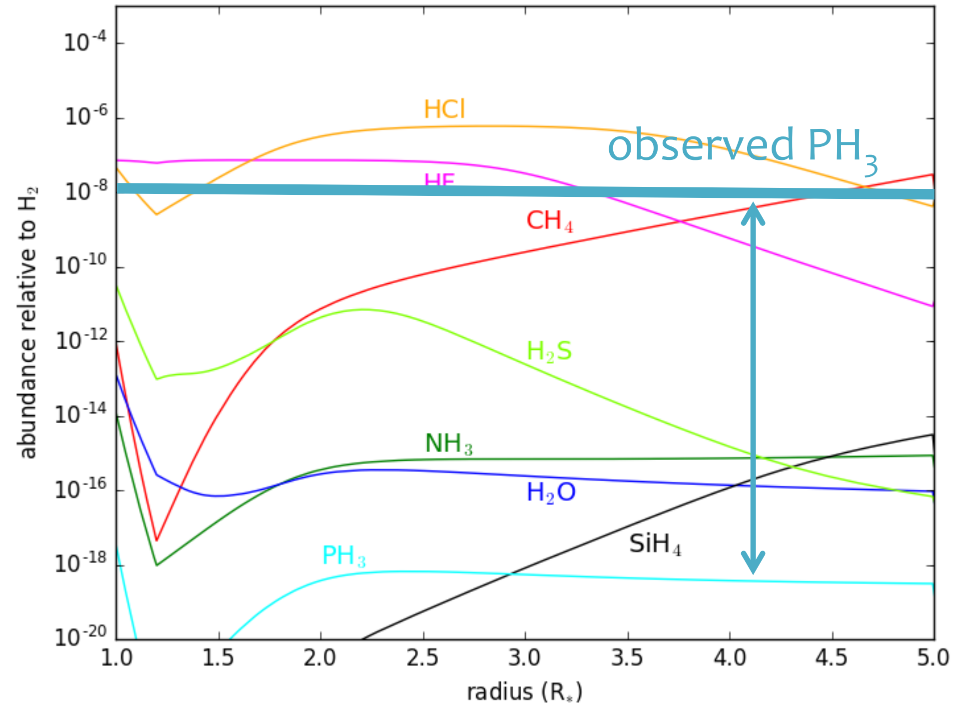
Received 2014 June 16; accepted 2014 July 3; published 2014 July 16

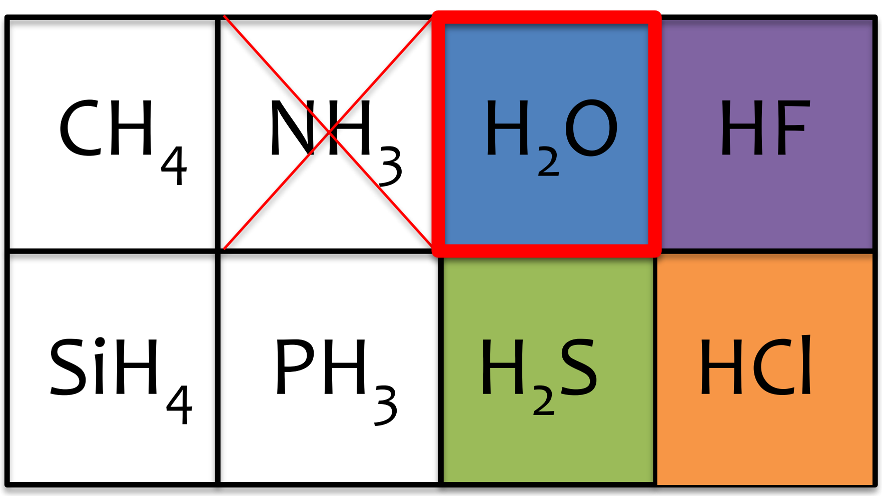




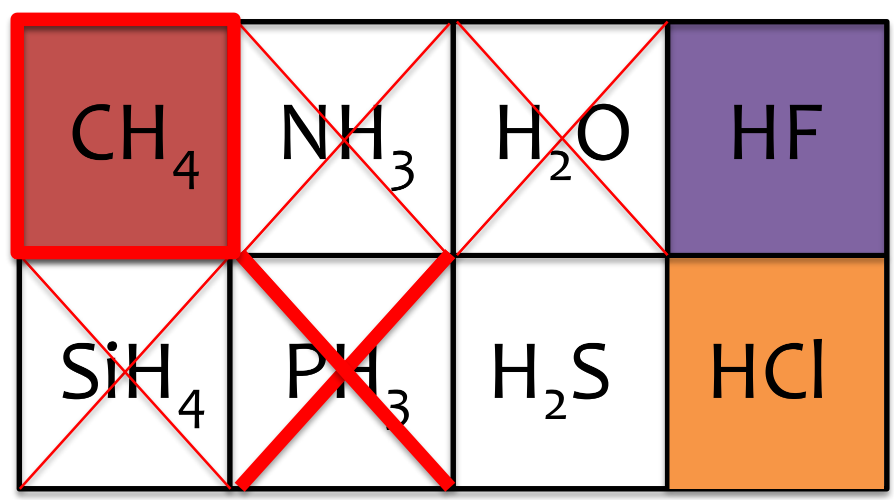




O-rich CSEs



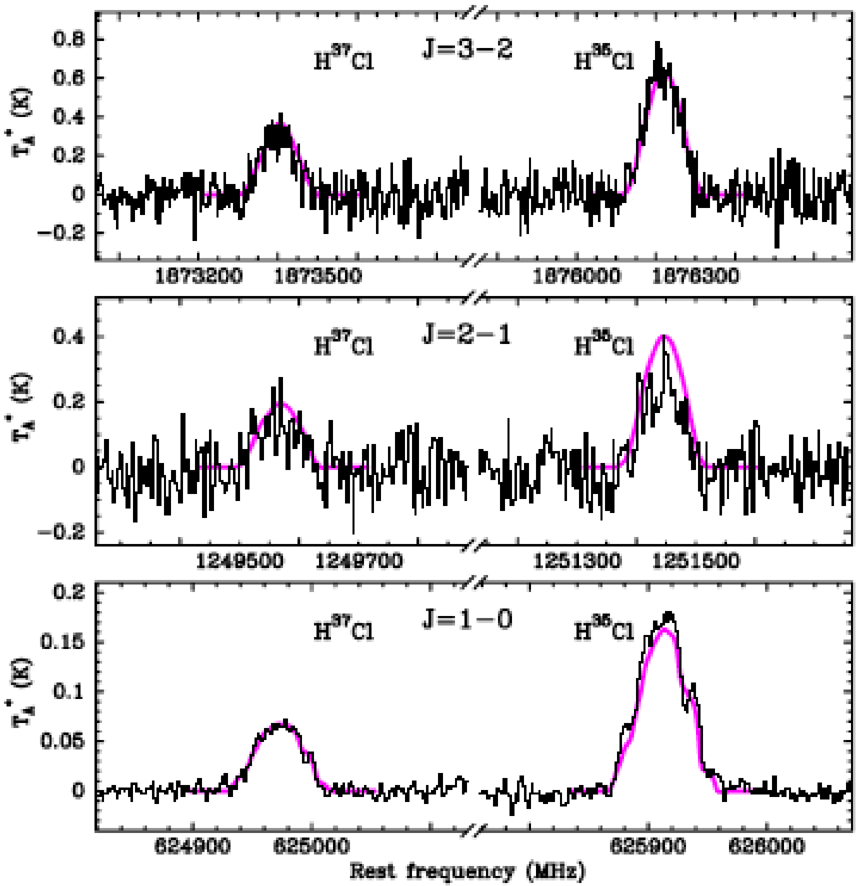
C-rich CSEs

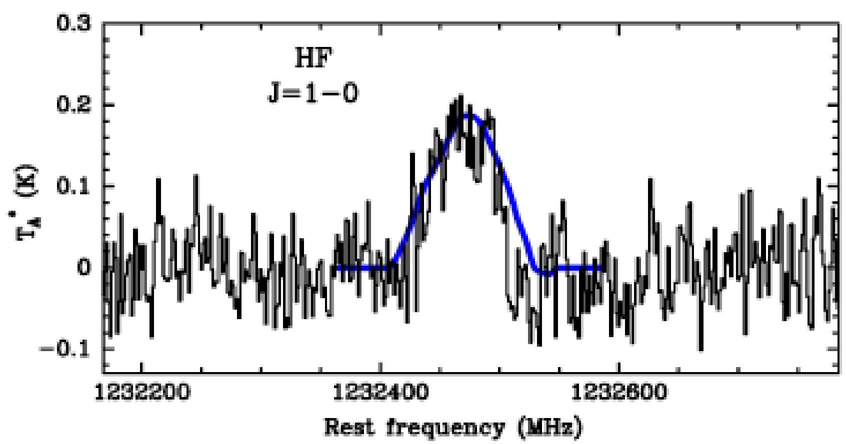


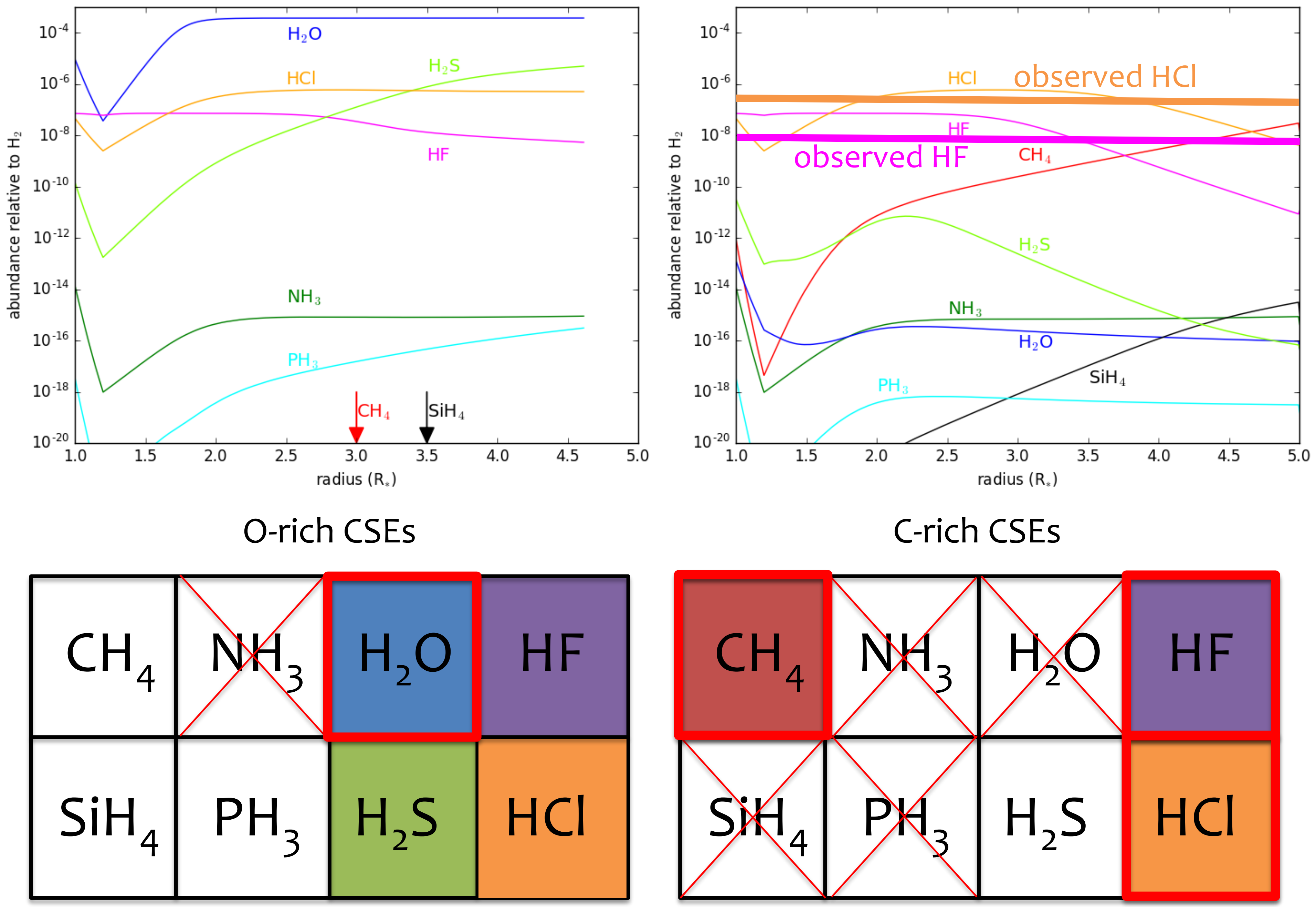
Hydrogen halides (HF and HCl) around carbon stars

HCl observed by Herschel/SPIRE & PACS
(Cernicharo et al 2010)

HF and HCl observed by Herschel/HIFI
(Agúndez et al 2011)



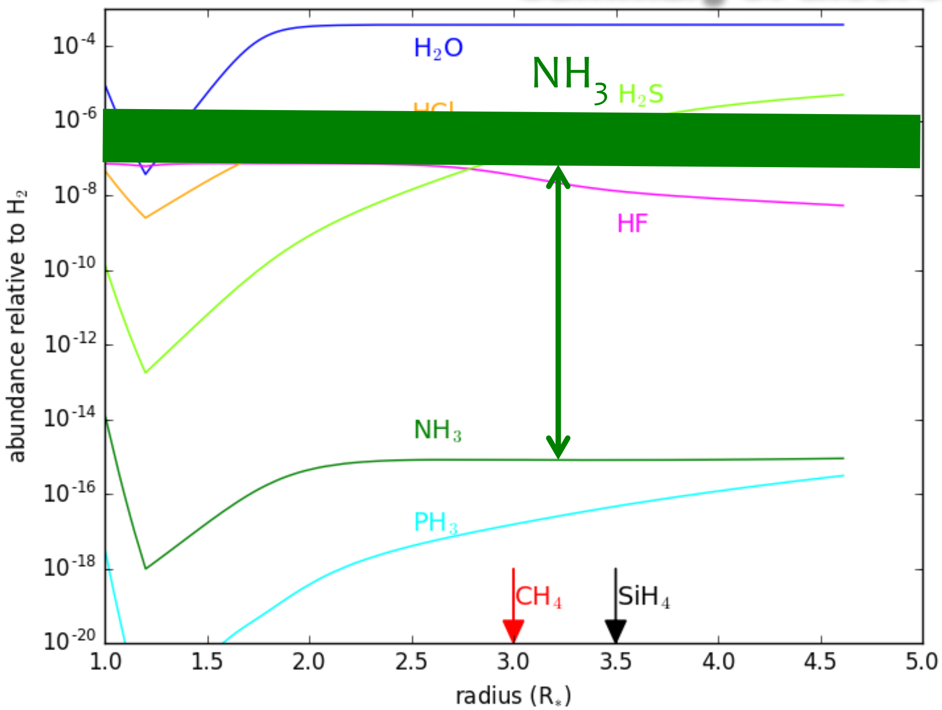


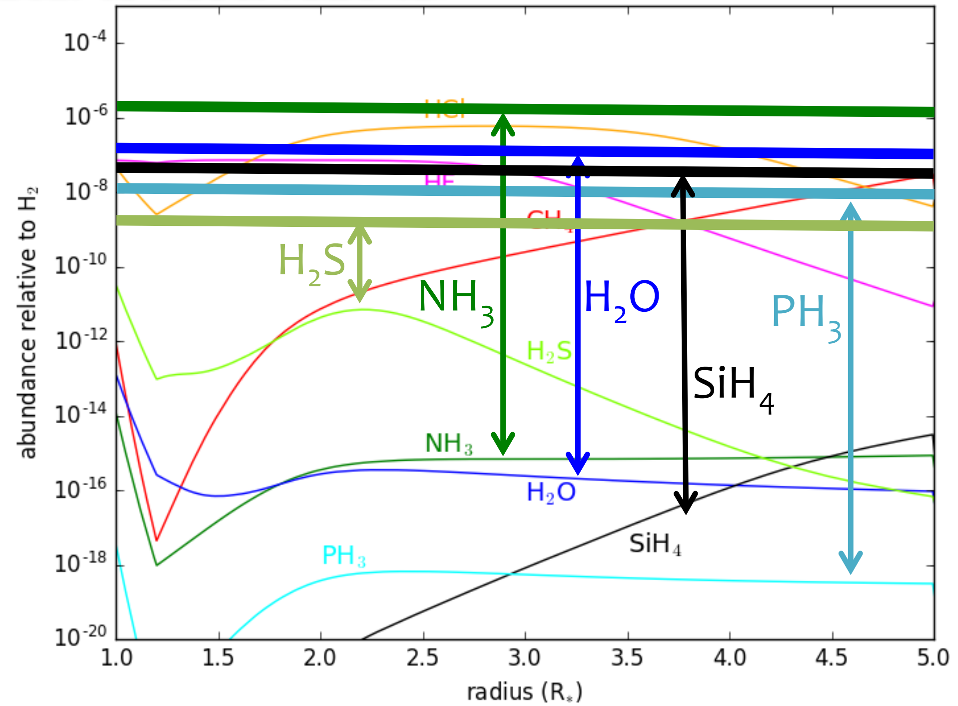


abundance relative to H2
radius (R*)
H2O
HCl
H2S
HF
NH3
PH3
CH4
SiH4
observed HCl
observed HF
O-rich CSEs
C-rich CSEs
CH4
NH3
H2O
HF
SiH4
PH3
H2S
HCl

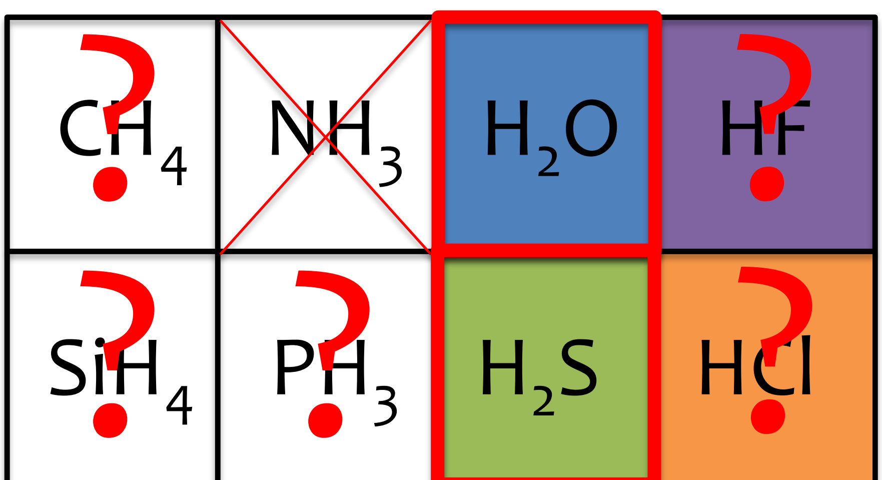
What is understood and what is not

Summary of theoretical vs observational

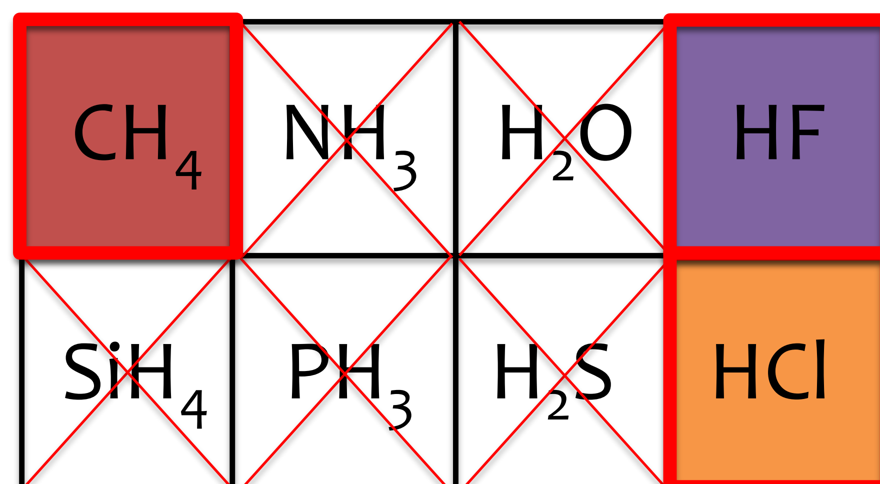




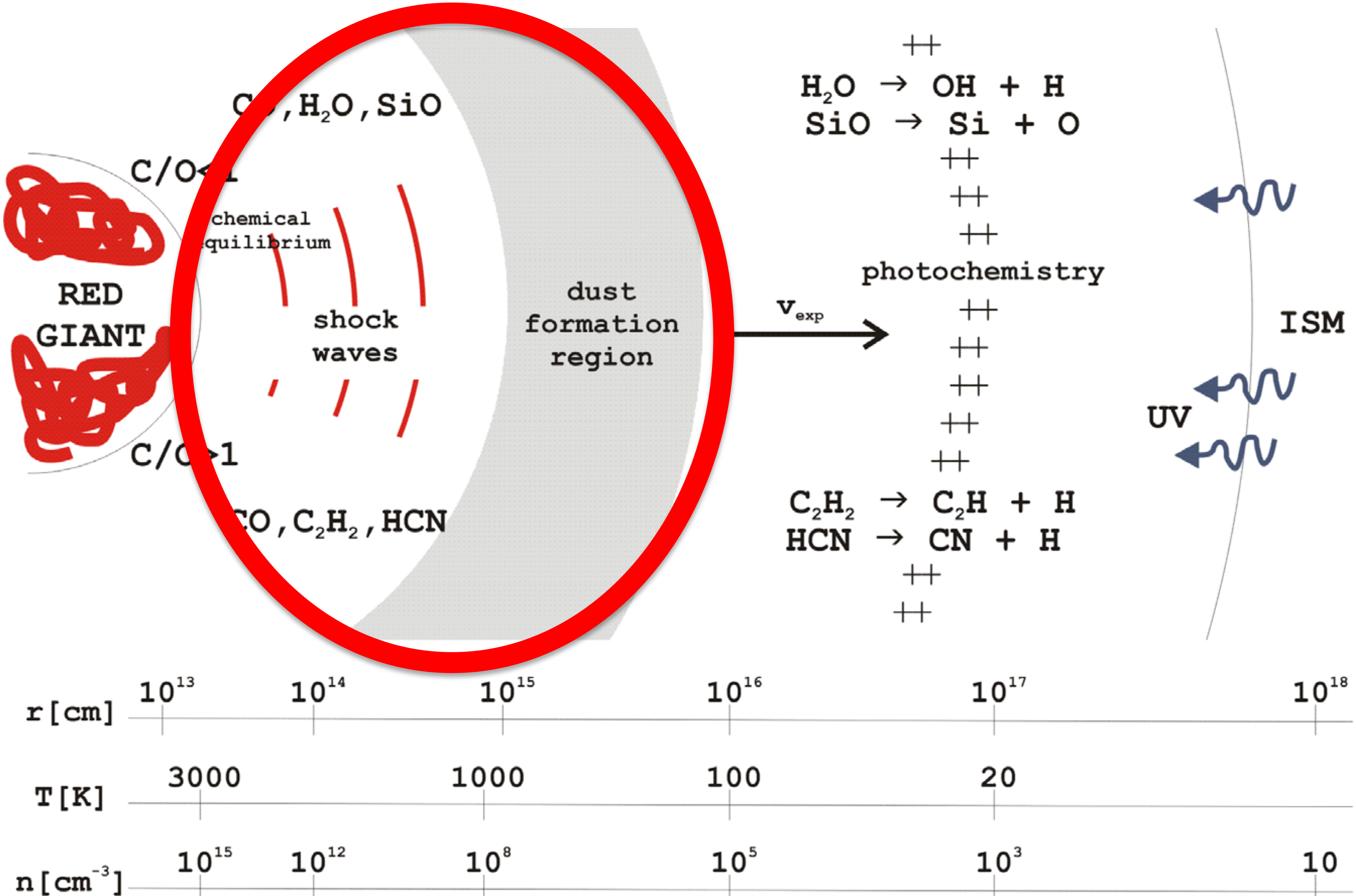
O-rich CSEs



C-rich CSEs

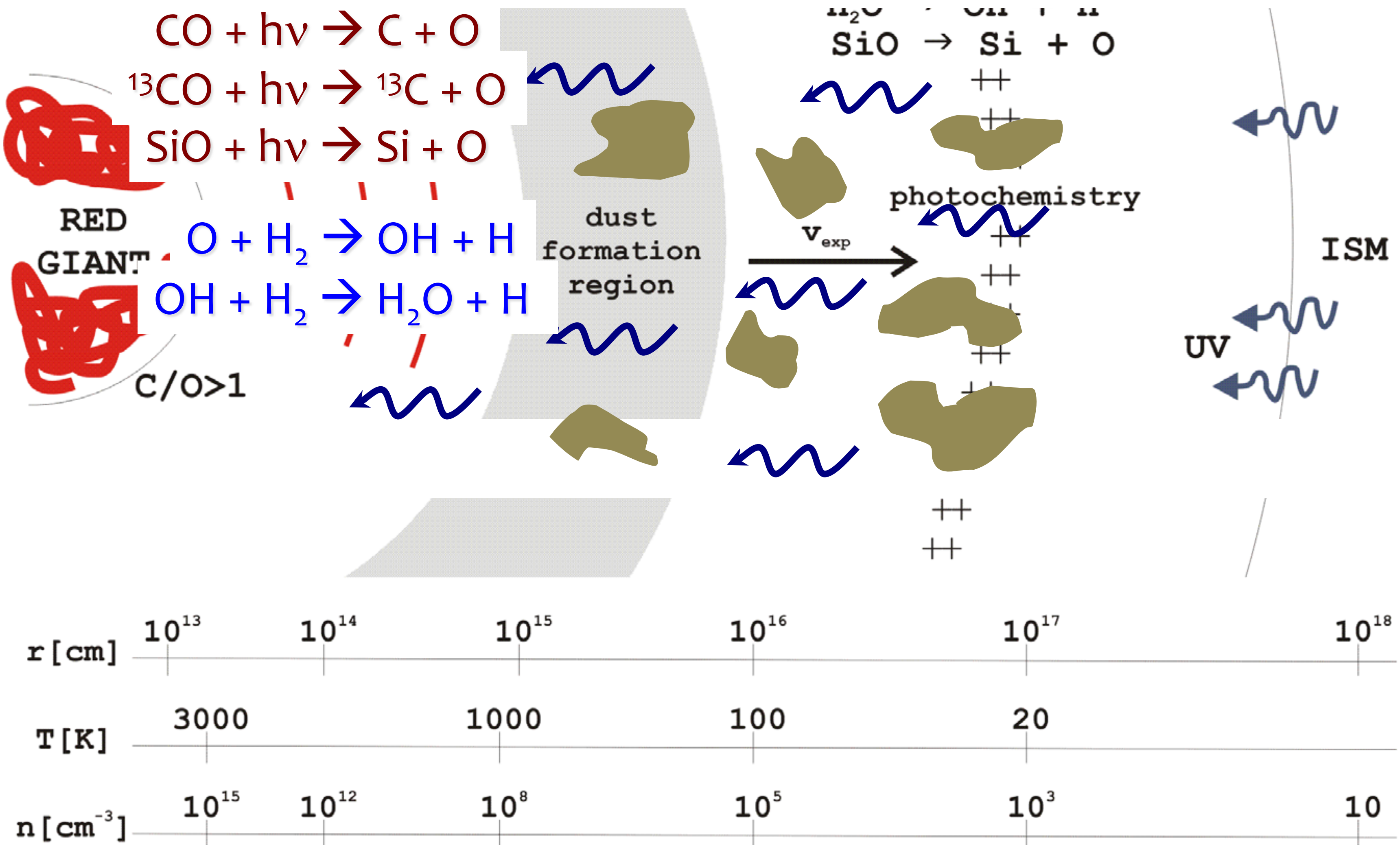


Which disequilibrium processes drive the formation of hydrides?



Which disequilibrium processes drive the formation of hydrides?

Photochemistry in inner layers due to a clumpy envelope (Agúndez et al 2010)



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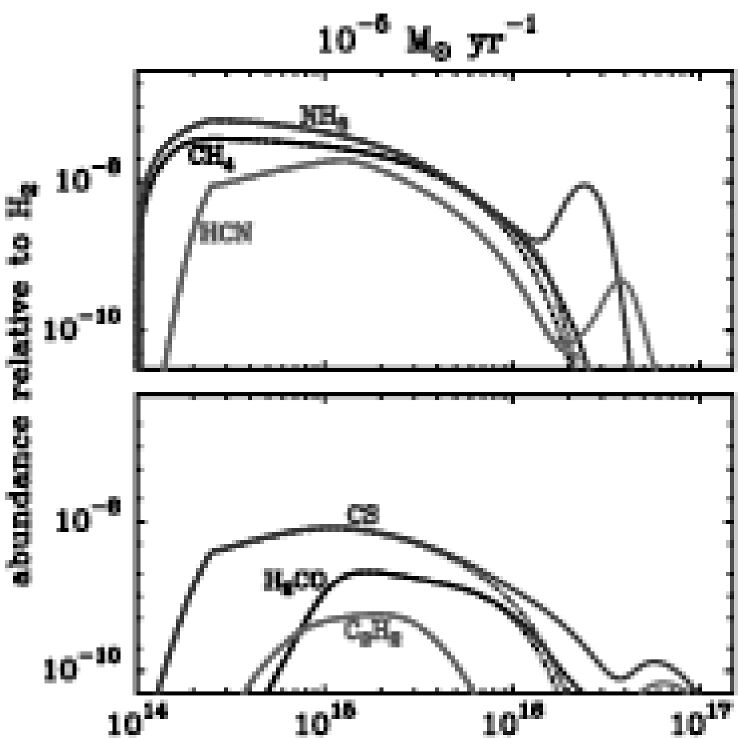
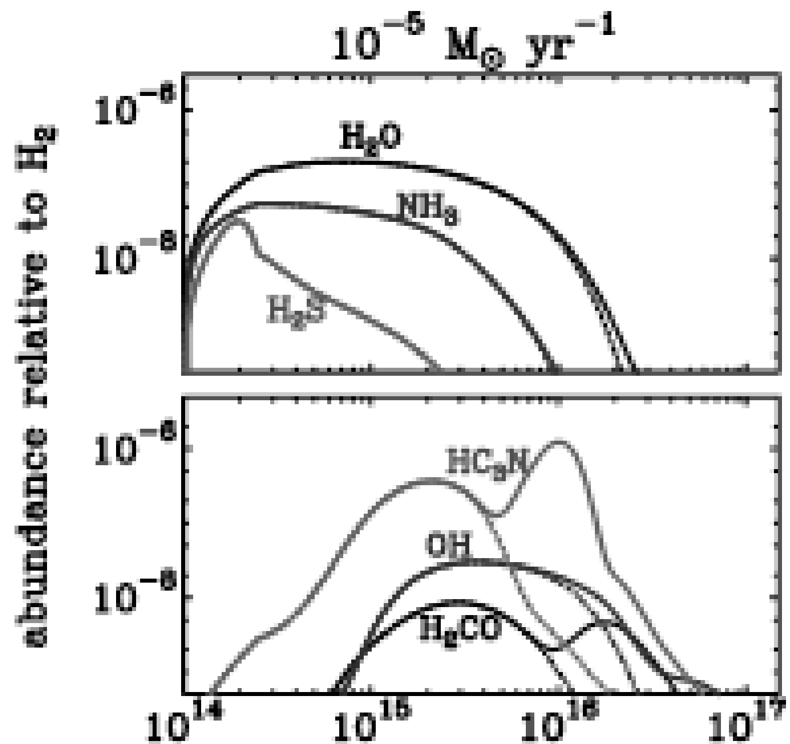
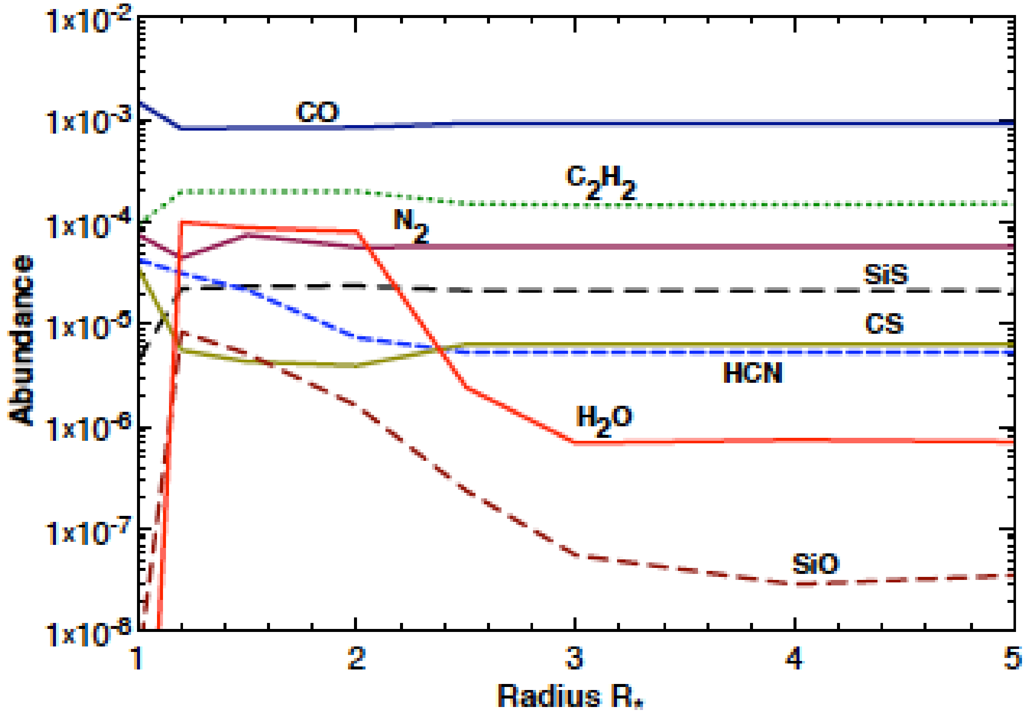


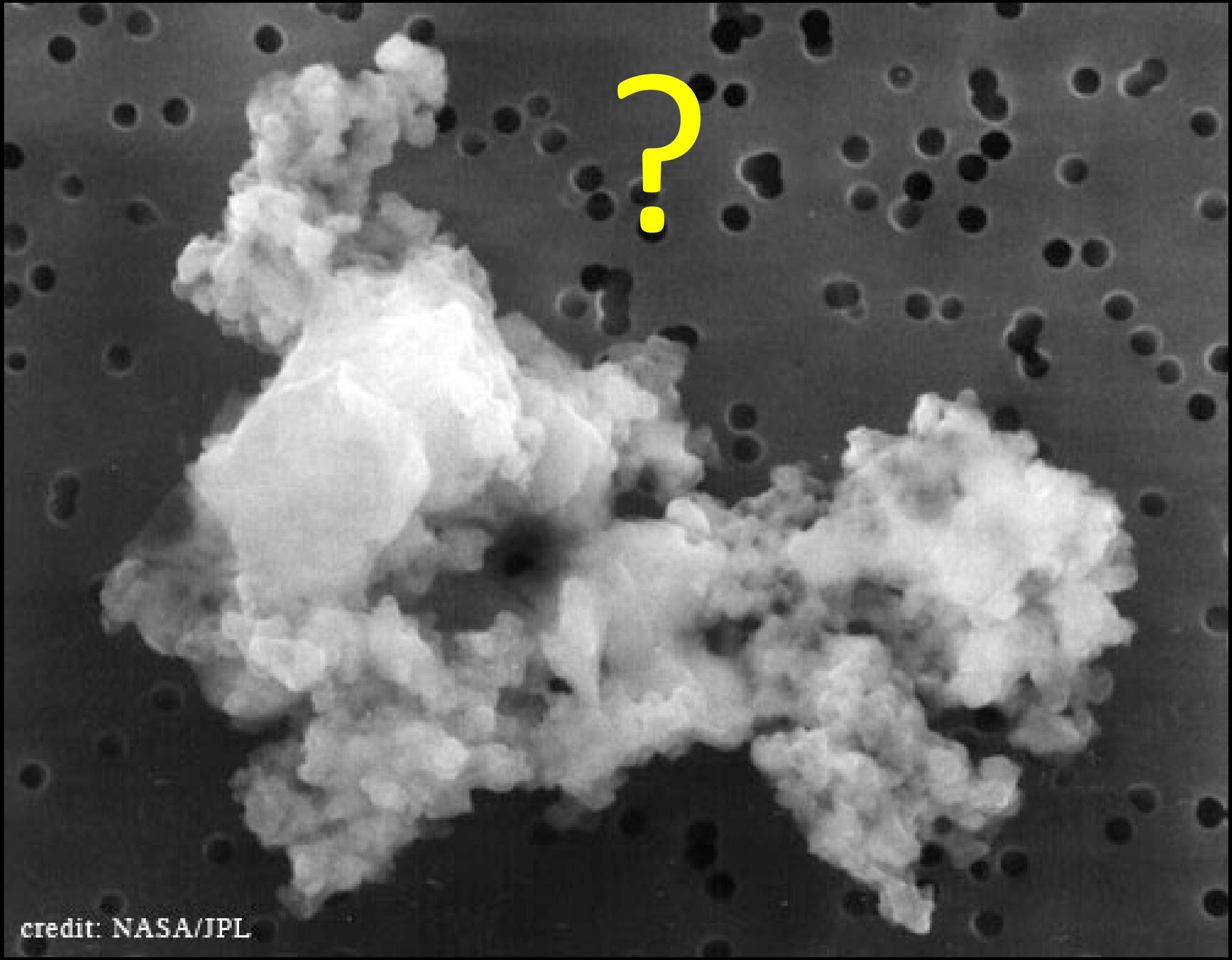
C-rich CSEs



Which disequilibrium processes drive the formation of hydrides?

Chemistry driven by shocks in inner layers (Cherchneff 2011, 2012)

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credit: NASA/JPL

Concluding remarks:

\# Hydrides are not predicted abundant in circumstellar envelopes

\# Hydrides are observed abundant in circumstellar envelopes

\# Predictions by chemical equilibrium are particularly bad for hydrides

\# Some disequilibrium process is at work, but which one?