Molecular complexity around evolved stars

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The Cosmic Cycle of Dust and Gas in the Galaxy: From Old to Young stars

9-13 July 2018, Guy Nhon (Vietnam)

Interstellar and circumstellar molecules

2 atoms		3 atoms		4 atoms	5 atoms	6 atoms	7 atoms	8 atoms
H_2	CP	H_3^+	MgCN	CH_3	NH_3D^+	C_2H_4	CH_3NH_2	CH_3CHNH
LiH ?	AlO	CH_2	NaCN	NH_3	CH_4	CH_3OH	CH_3C_2H	CH_2CHCHO
CH								
CH^+								
NH								
OH								
OH^+								
HF								
C_2								
CN	SO^+	HCO^+	AlNC	C_3H	HNCNH	H_2C_4	CH_3NCO	H_2C_6
						HC_4N	**9 atoms**	C_7H $(NH_2)_2CO$
						HC_3NH^+	CH_2CHCH_3	**10 atoms**
						HC_2CHO	CH_3OCH_3	CH_3COCH_3 C_3H_6O
						$c\text{-}H_2C_3O$	CH_3CH_2OH	$OHCH_2CH_2OH$ CH_3OCH_2OH
						C_5H	CH_3CH_2CN	CH_3CH_2CHO
						C_5N	CH_3CONH_2	CH_3C_5N
						C_5N^-	CH_3C_4H	**11 atoms**
						C_5S	C_8H	C_2H_5OCHO
						SiH_3CN ?	C_8H^-	CH_3COOCH_3
SH		AlOH		C_3N	CNCHO		HC_7N	CH_3C_6H
SH^+		CO_2		C_3N^-	C_5			
HCl		HCS^+		C_3O	H_2NCO^+			
HCl^+		C_2O		HNCS	$NCCNH^+$			
SiC		C_3		HSCN	CH_3Cl			
SiN		MgNC		$c\text{-}SiC_3$				
ArH^+		CCN		C_3S				
NO^+ ?		Si_2C		HMgNC				
NS^+		S_2H		MgCCH ?				
		HCS, HSC		NCCP ?				
		NCO		HCCO CNCN		$c\text{-}C_6H_5CN$		

Large prevalence of organic molecules

≈3/4 (all with 6 or more atoms) contain at least one C atom

Large organic molecules around evolved stars:

- Presence of unsaturated carbon chains
- No saturated O-, N-bearing stable molecules

Metal-bearing molecules (Mg, Al, Ti, Fe, Na, K)

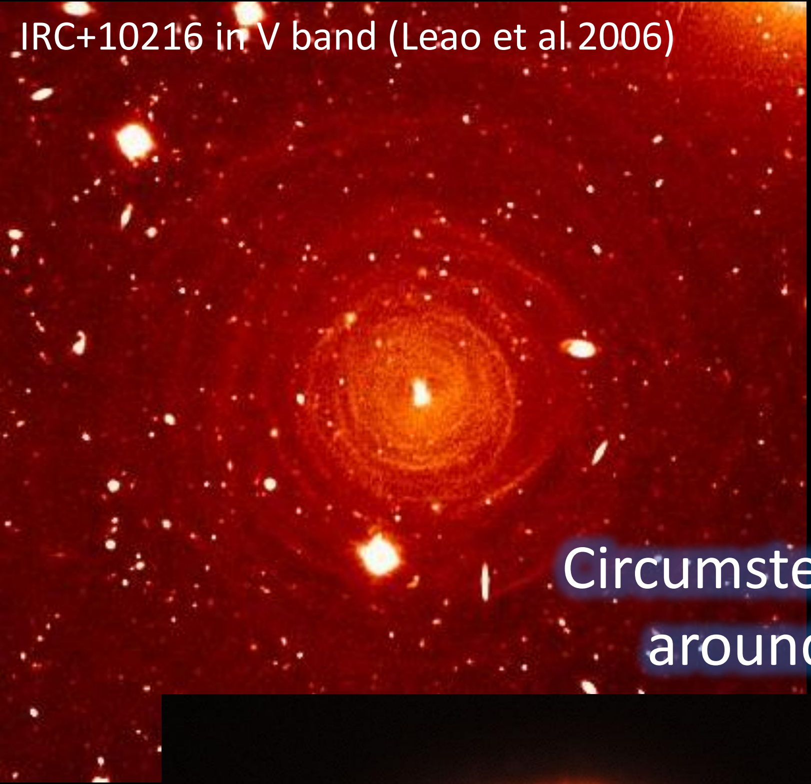
They are only found around evolved stars

CARBON-RICH: The ~80 molecules detected in IRC+10216

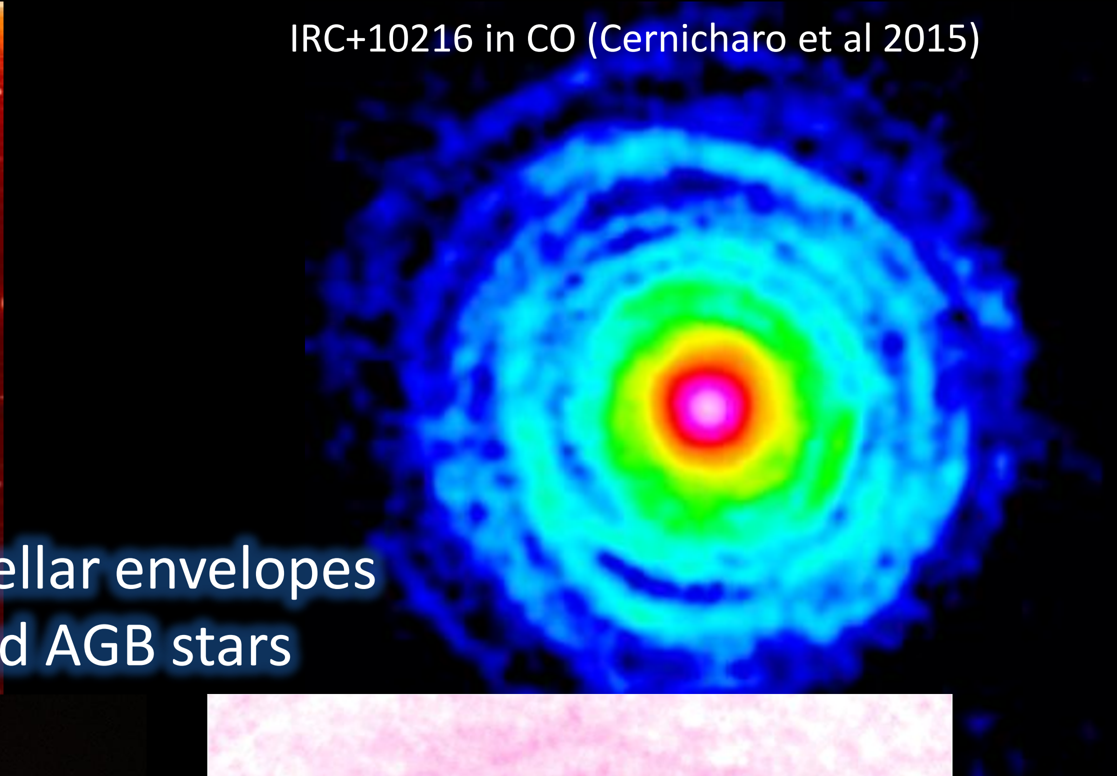
10^{-3}	CO						
10^{-4}							
		C_2H_2					
			HCN				
10^{-5}							
		CH_4					
		C_2H	NH_3				
		C_4H	CN				
		C_2	HC_3N		SiC_2		
10^{-6}		C_3			SiS		
			C_3N	CS	Si_2C		
					SiH_4		
			HC_5N		SiO		HCl
10^{-7}	H_2O	C_5	HNC				
		l-C_3H	CN-				
	OH	C_6H			SiC		
		C_5H	CH_3CN	C_2S			AlCl
		c-C_3H_2					
		CH_3C_2H					
		c-C_3H	HC_7N			HCP	
		C_2H_4					NaCN
	H_2CO	H_2C_4		C_3S	CH_3SiH_3		
10^{-8}						CP	HF
		C_8H	HC_9N	H_2CS	SiN	PH_3	MgNC
			CH_2CN				AlF
			HC_2N				
			C_5N				
		C_7H	HCCNC				
		H_2C_6	C_2H_3CN	H_2S	c-SiC_3		
		C_6H-	C_5N-		SiC_4		
	C_3O	C_8H-	HC_4N		SiCN		
		H_2C_3	C_3N-	C_5S	SiNC	PN	NaCl
10^{-9}						C_2P	AlNC
	HCO+		HNCCC				MgCN HMgNC
		C_4H-					KCl FeCN KCN
10^{-10}							

OXYGEN-RICH: The ~20 molecules detected in IK Tau
10^-3
10^-4
CO
H2O
10^-5
OH
SO2
SO
SiO
SiS
PO
H2S
10^-6
HCN
CS
NH3
PN
H2CO
NaCl
10^-7
CN
NS
10^-8
HCO+
HNC
10^-9
10^-10

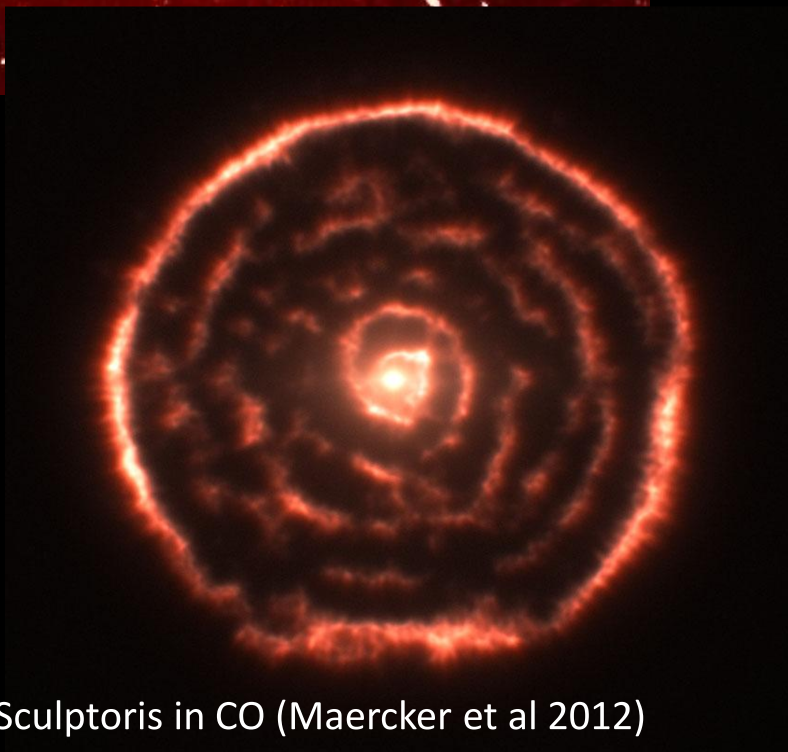
Circumstellar envelopes around AGB stars



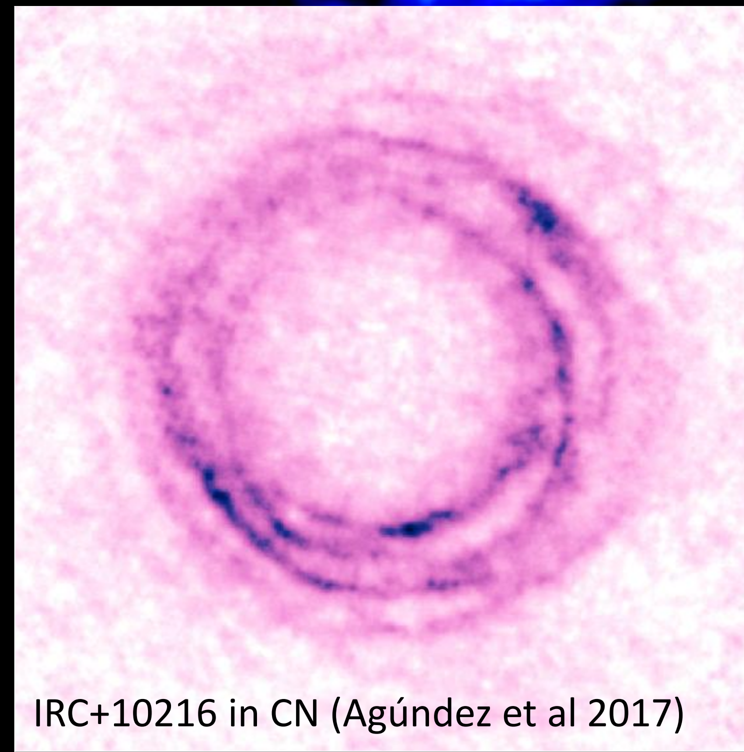
IRC+10216 in V band (Leao et al 2006)



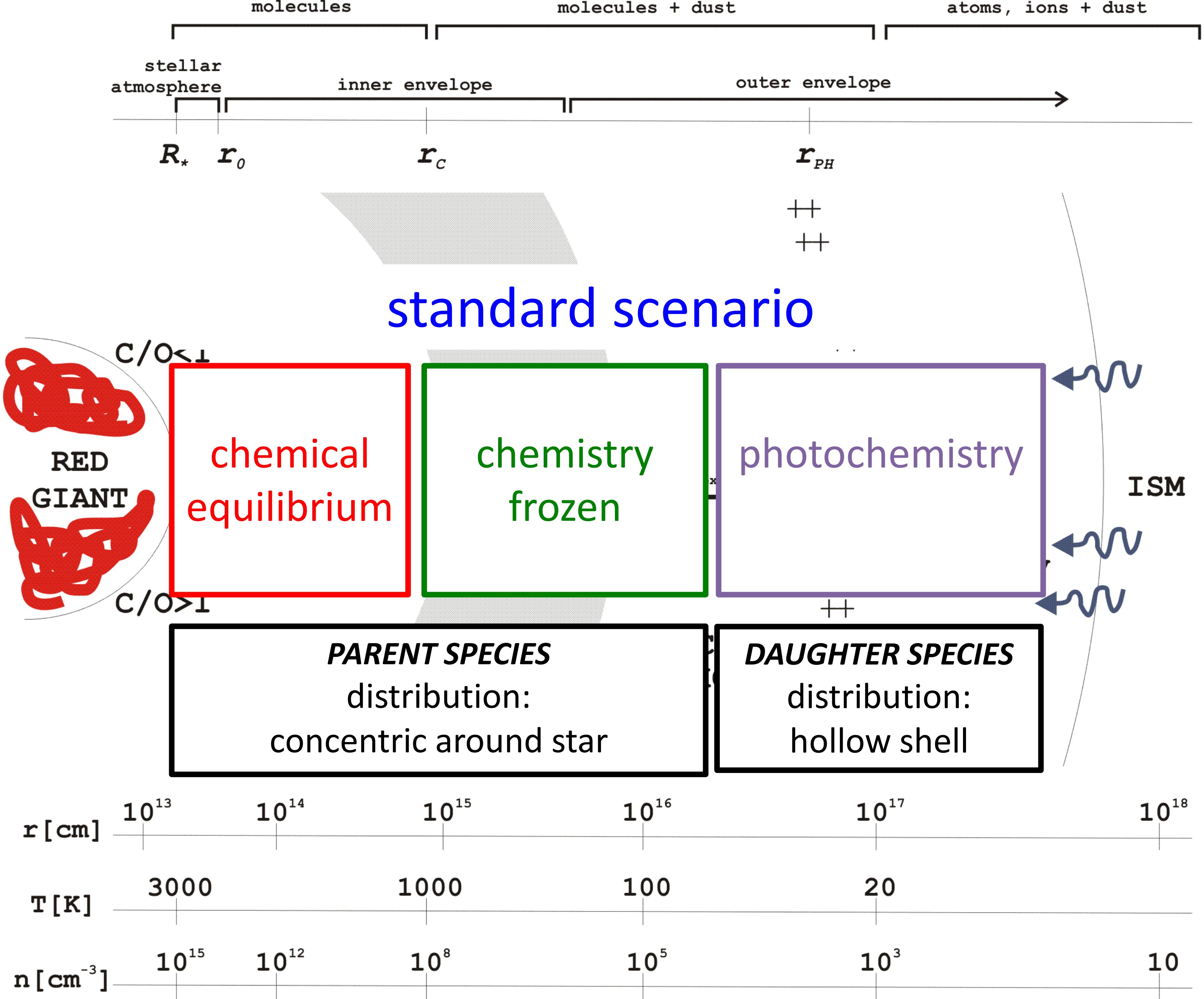
IRC+10216 in CO (Cernicharo et al 2015)



R Sculptoris in CO (Maercker et al 2012)



IRC+10216 in CN (Agúndez et al 2017)



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
chemistry frozen
photochemistry
ISM
PARENT SPECIES
distribution:
concentric 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




Outline of the rest of the talk:

1) Some introduction (already done)

1) Chemistry in the inner layers

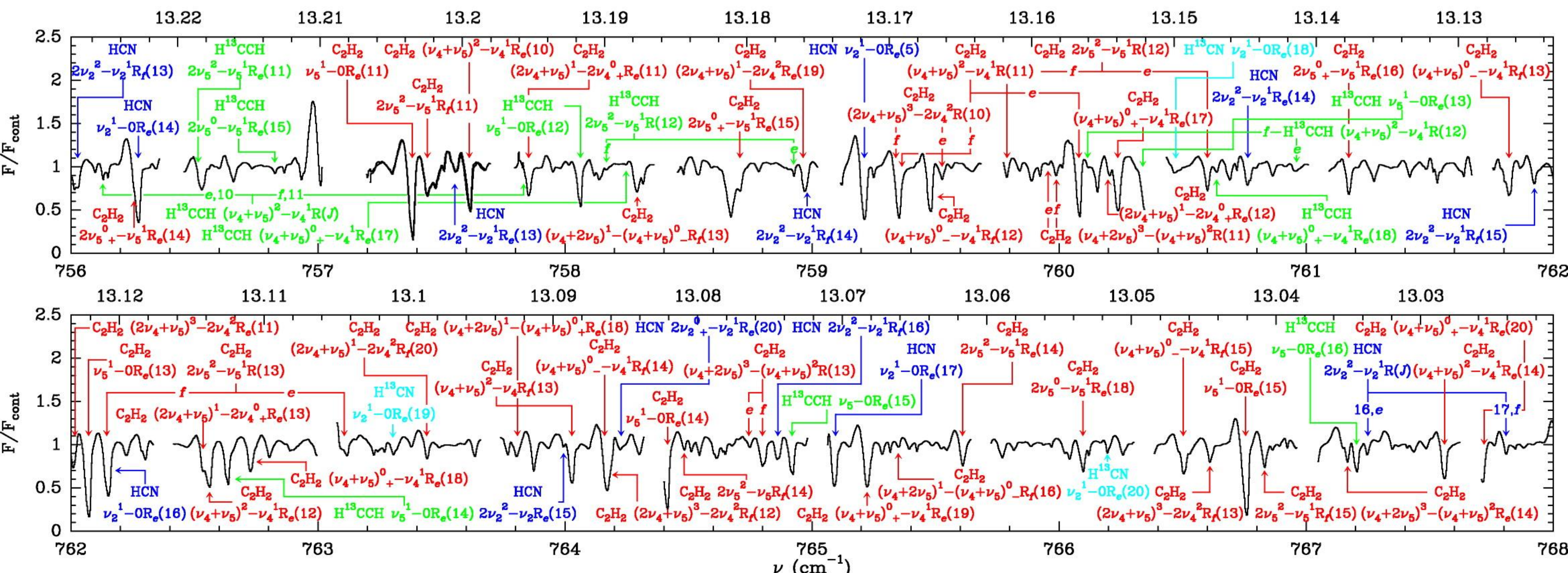
1) Chemistry in the outer envelope

1) Concluding remarks

The inner circumstellar layers

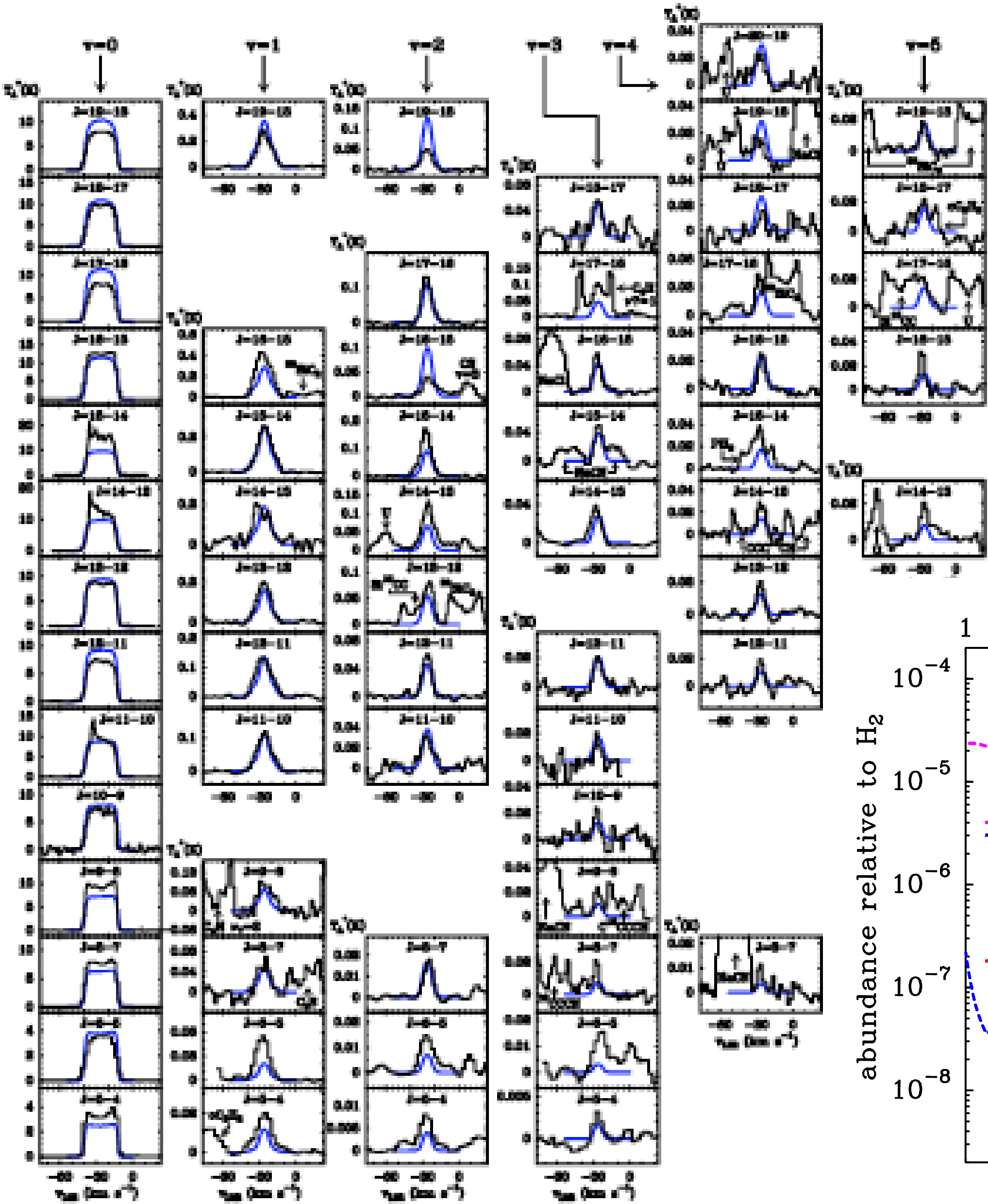
CW Leo observed in the MIR (11-14 µm) with IRTF/TEXES (Fonfría et al 2008)

Spectra shows absorption lines from C_2H_2 and HCN present in the inner circumstellar envelope

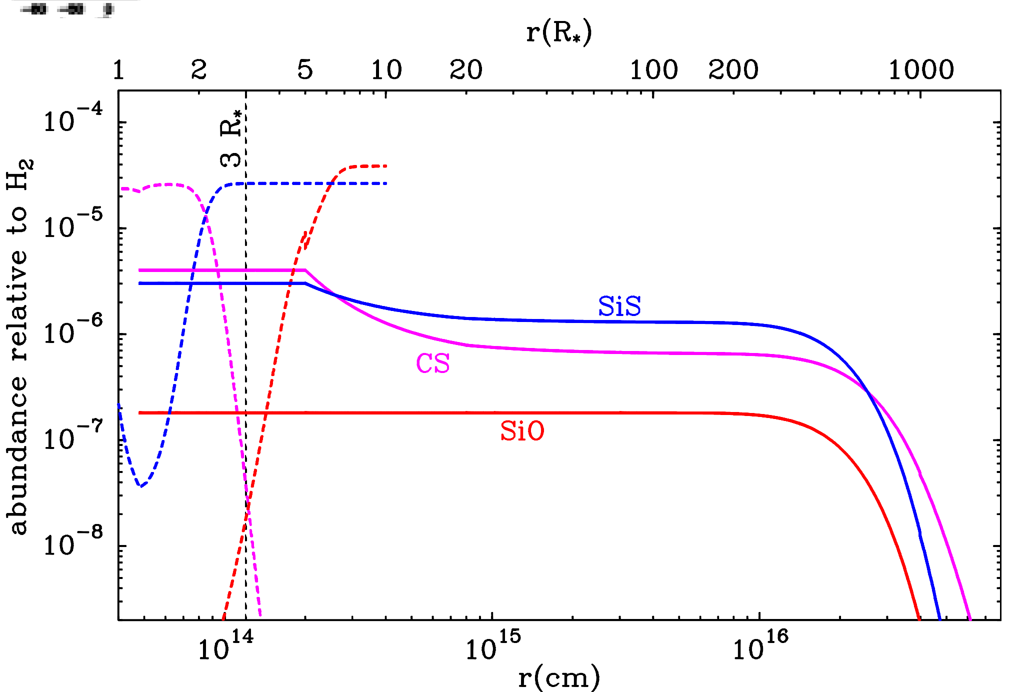


Single-dish millimeter observations

SiS (v=0-6) lines in IRC+10216 (Agúndez et al 2012)

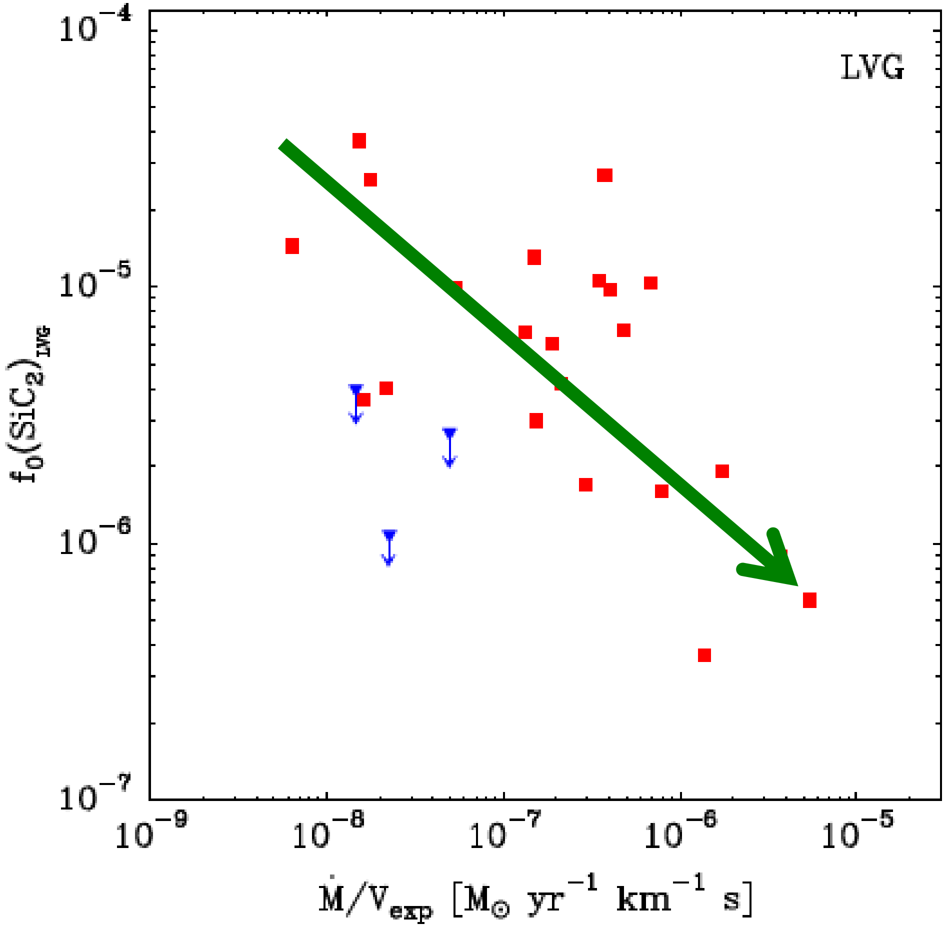


A detailed model allows to derive the radial abundance profile



Single-dish millimeter observations

SiC$_2$ in a sample of carbon stars
(Massalkhi et al 2018)



Gas-phase abundance of SiC$_2$ decreases with increasing density

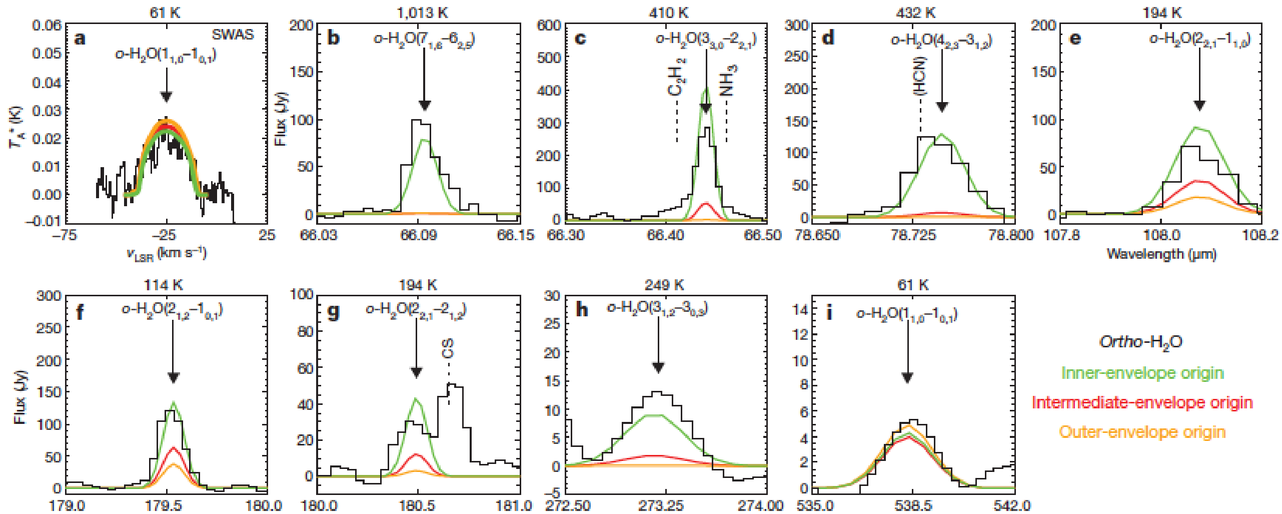
Can be interpreted in terms of a more efficient formation of dust (and incorporation of SiC$_2$ on grains) at high densities

Legacy of Herschel on circumstellar chemistry

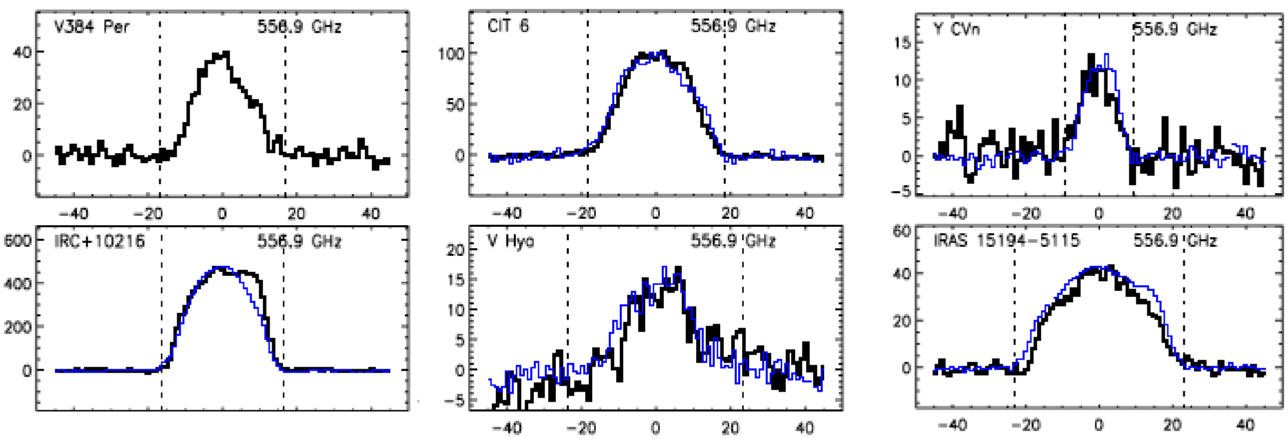
H_2O around carbon stars

Inner-envelope origin

Widespread occurrence in carbon stars



Decin et al (2010)

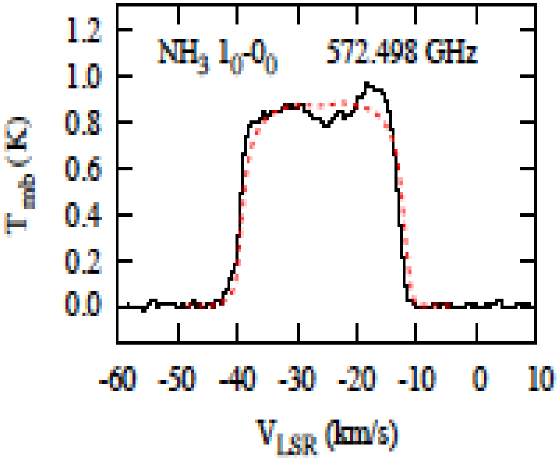


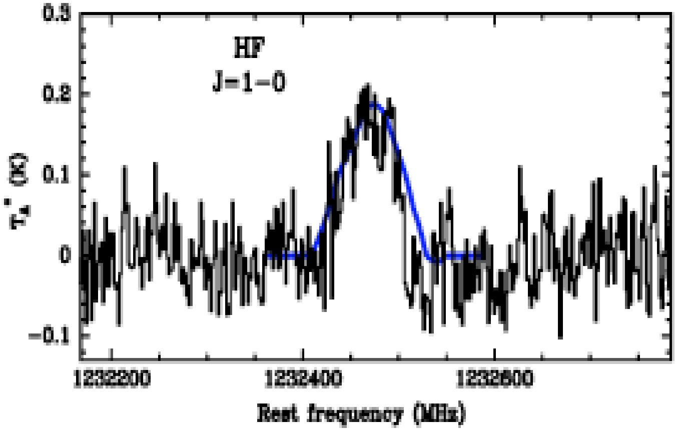
Neufeld et al (2011)

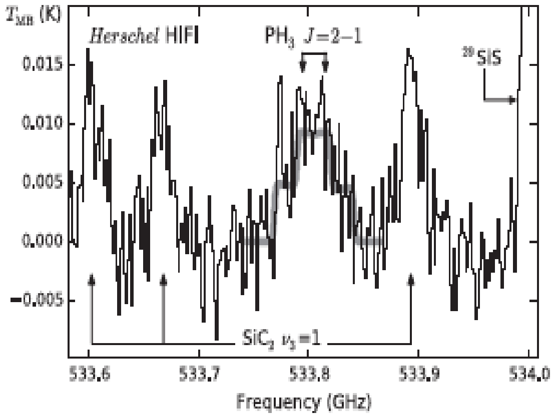
Legacy of Herschel on circumstellar chemistry

H_2O around carbon stars
Inner-envelope origin
Widespread occurrence in carbon stars

Other hydrides around AGB stars
NH_3 (Menten et al 2010; Schmidt et al 2016; Wong et al. 2018)
HCl (Cernicharo et al 2010; Agúndez et al 2011)
HF (Agúndez et al 2011)
PH_3 (Agúndez et al 2014)

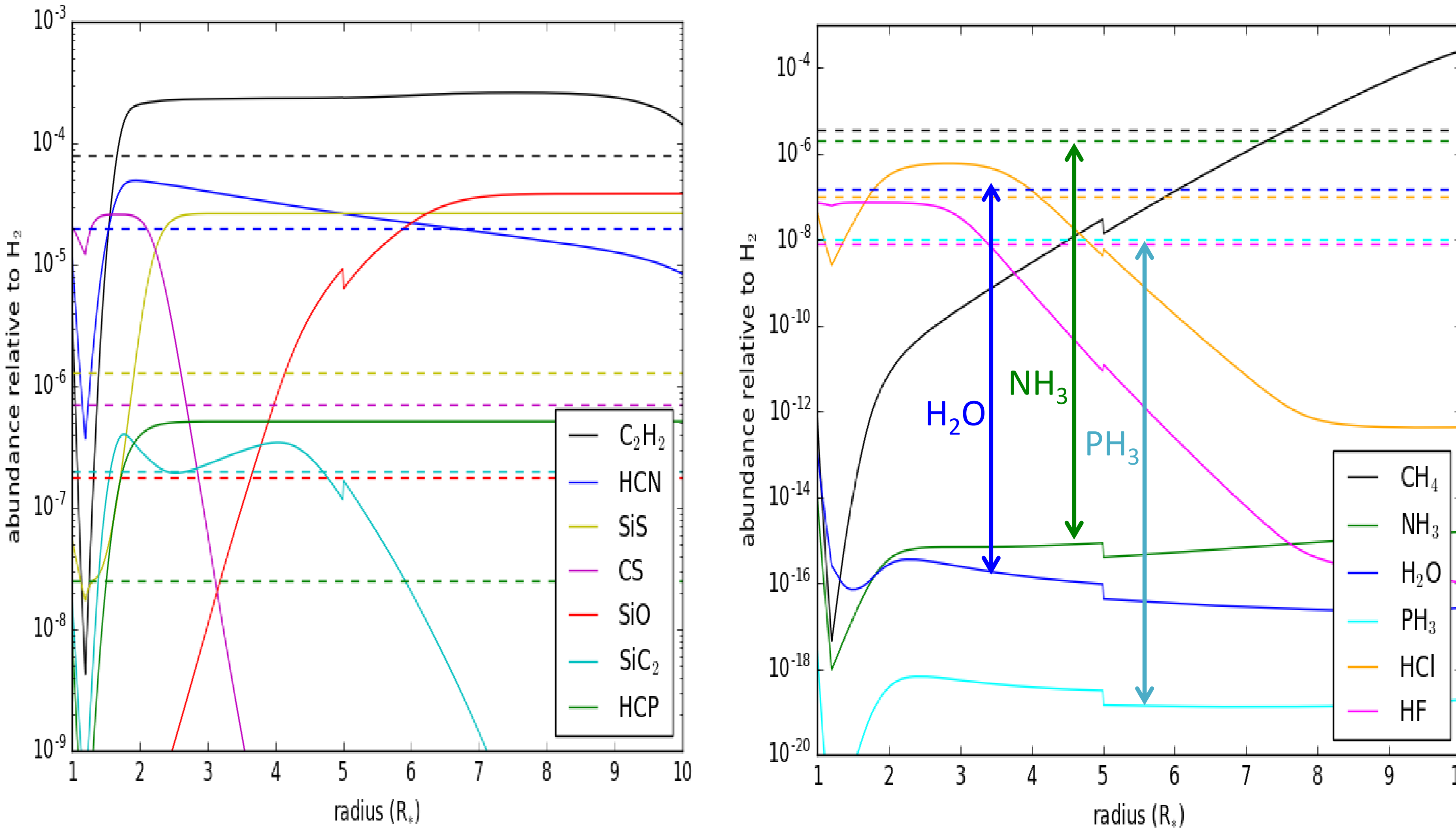


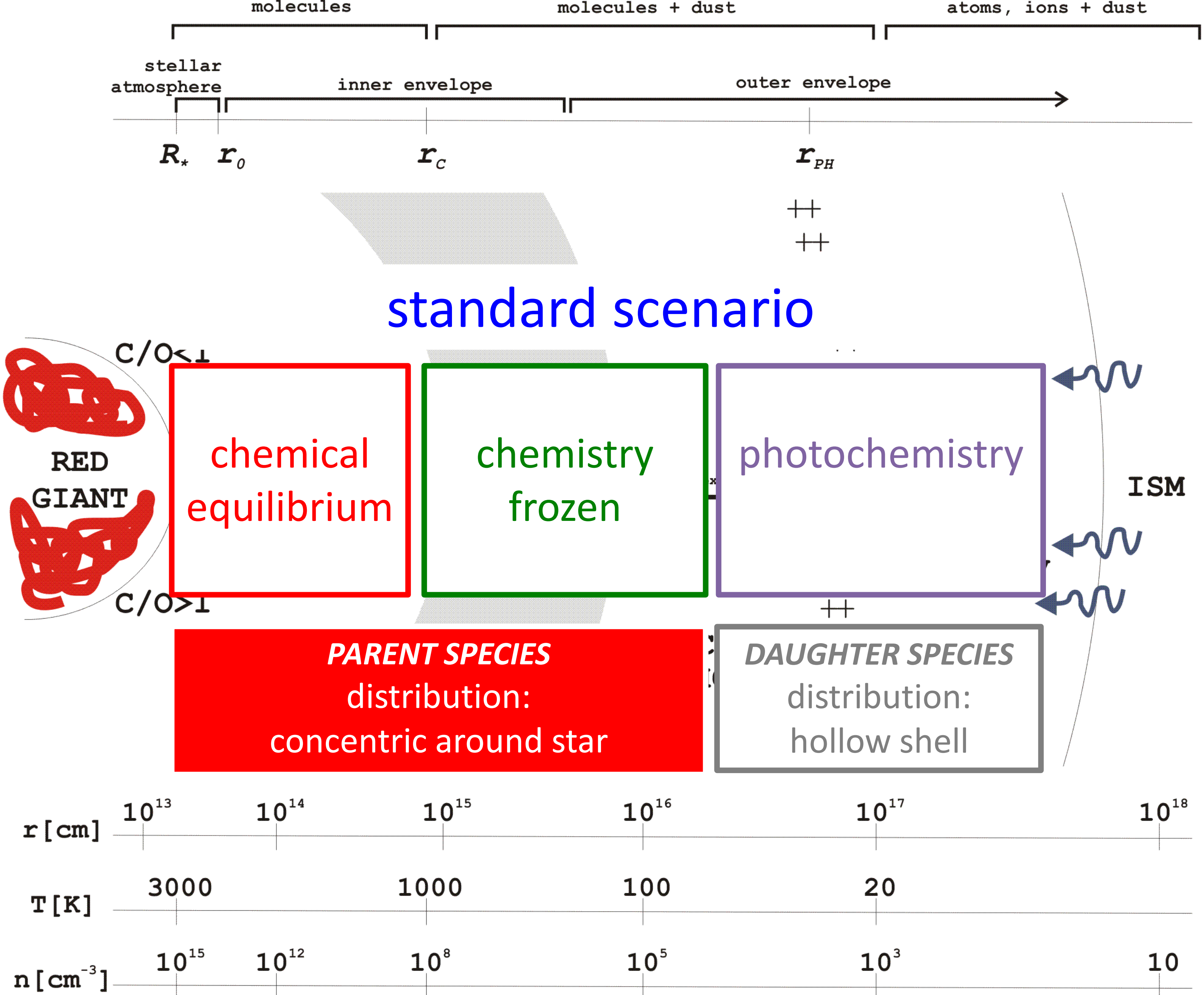




Comparison between observed abundances and calculated abundances at chemical equilibrium for the carbon star IRC+10216

calculated at LTE (solid line)
observed (dashed line)




molecules
molecules + dust
atoms, ions + dust
stellar atmosphere
inner envelope
outer envelope
R*
r0
rC
rPH
standard scenario
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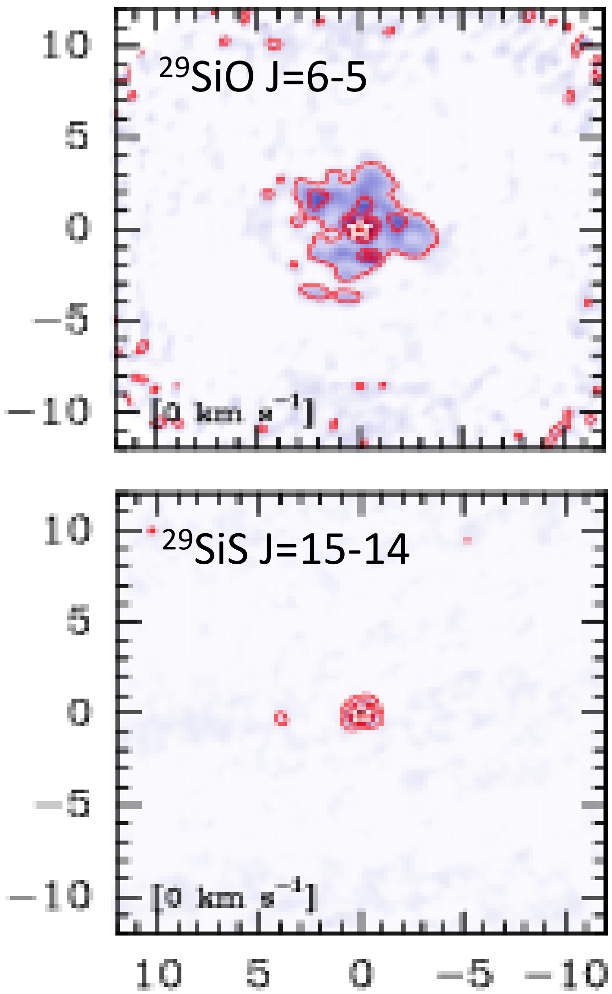
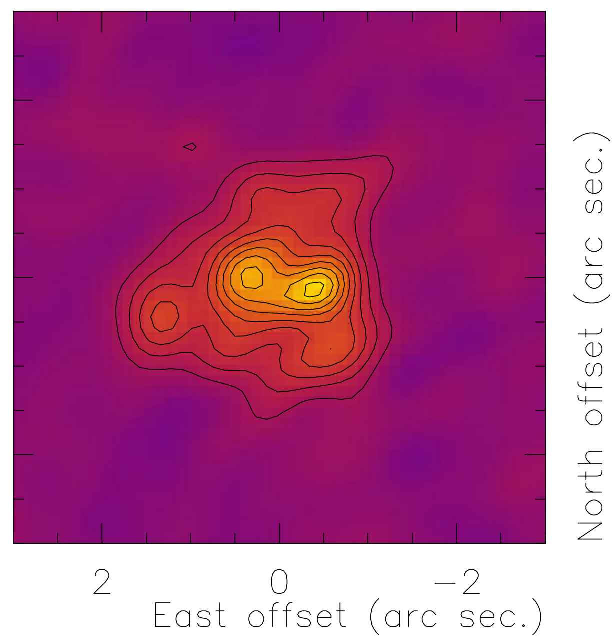
10^17
10^18
T[K]
3000
1000
100
20
n[cm^-3]
10^15
10^12
10^8
10^5
10^3
10

Small-scale distribution of parent species in IRC+10216



Velilla Prieto et al (2015)

NaCl J=21-20

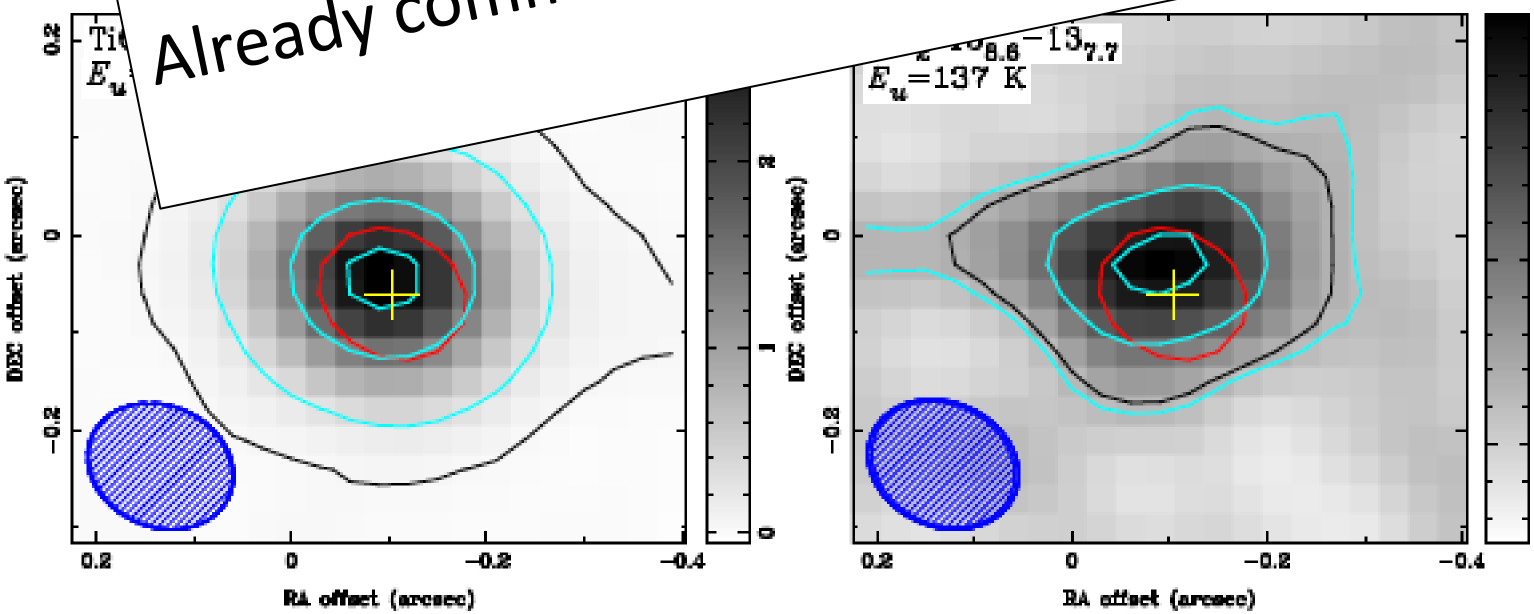


Quintana-Lacaci et al (2016)

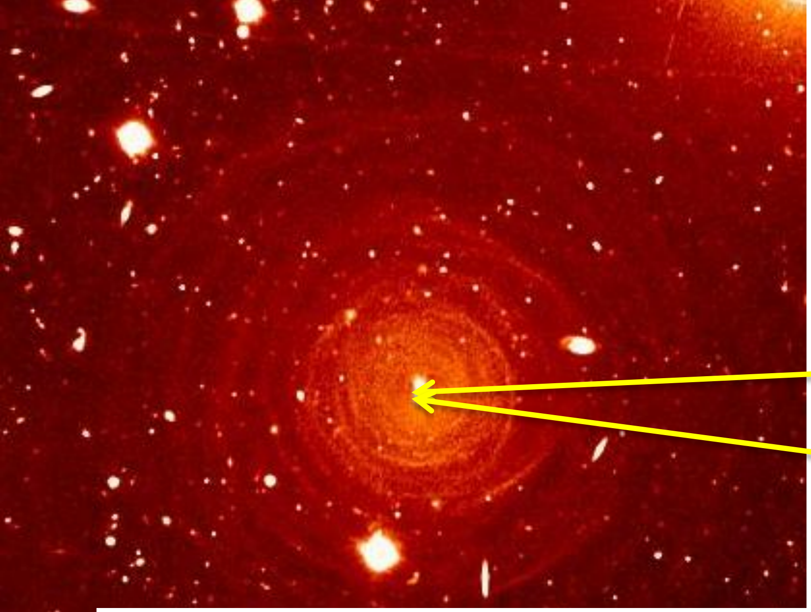
Small-scale distribution of Ti and Al oxides in O-rich stars

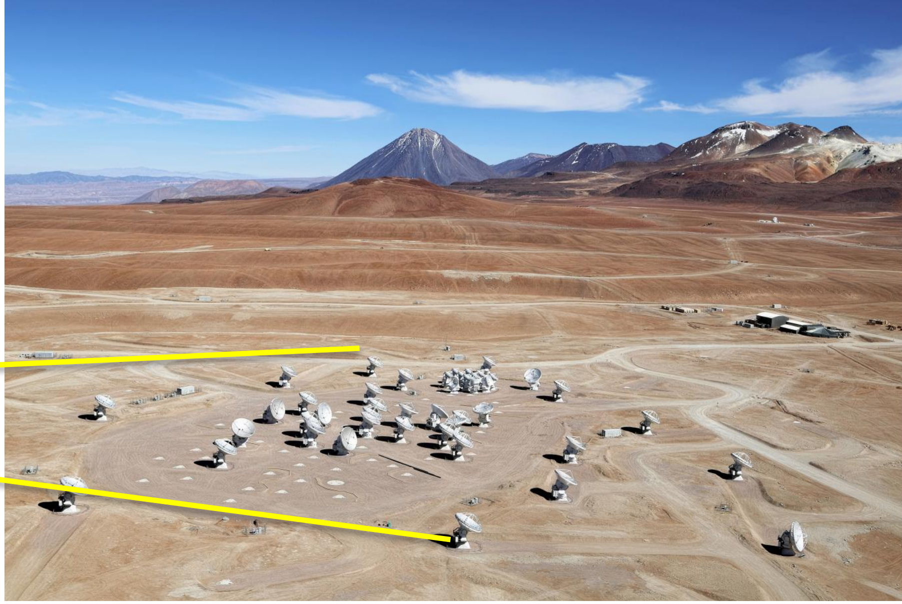
Evaluating the role of TiO, TiO_2, AlO
as gas-phase precurs

Already commented by Jean Martin Winters

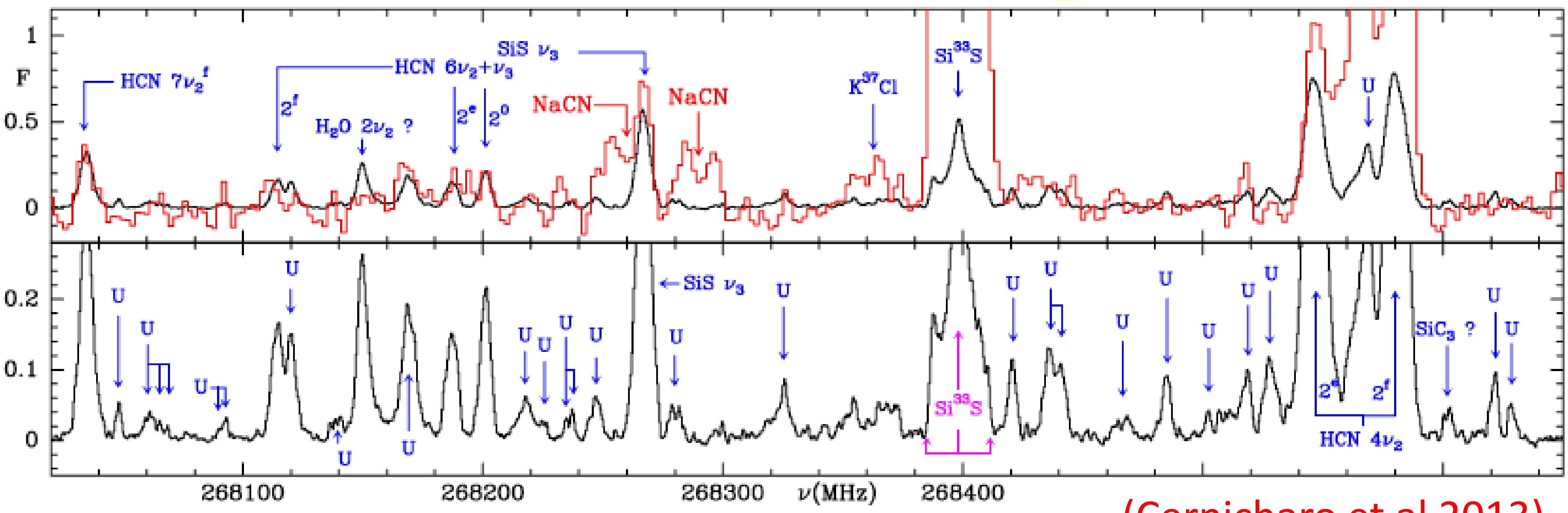


Kaminski et al (2017). See also Kaminski et al (2016), Decin et al (2017).



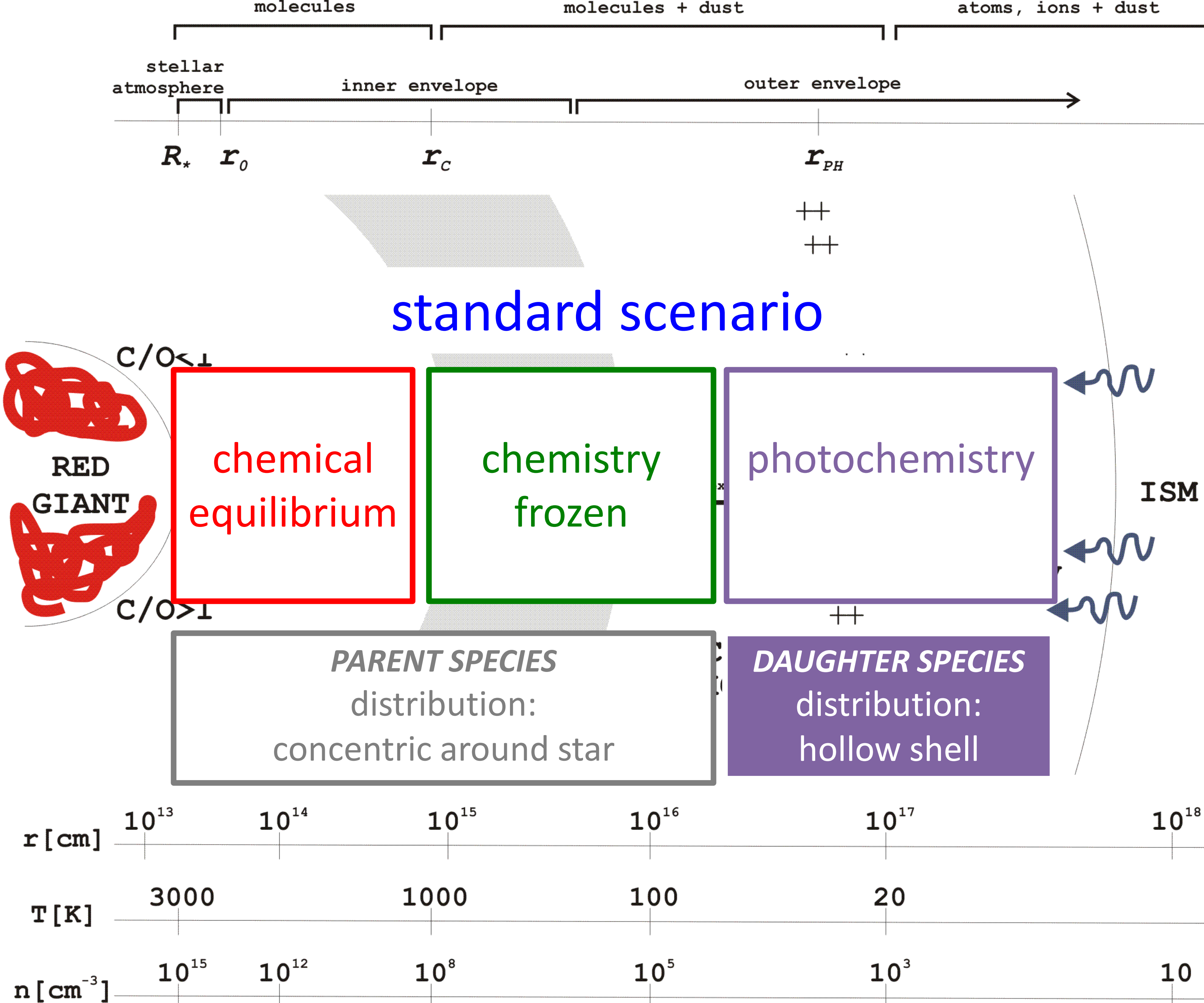


The ALMA view of IRC+10216: a forest of U lines arises from the surroundings of the star



(Cernicharo et al 2013)

The outer circumstellar envelope



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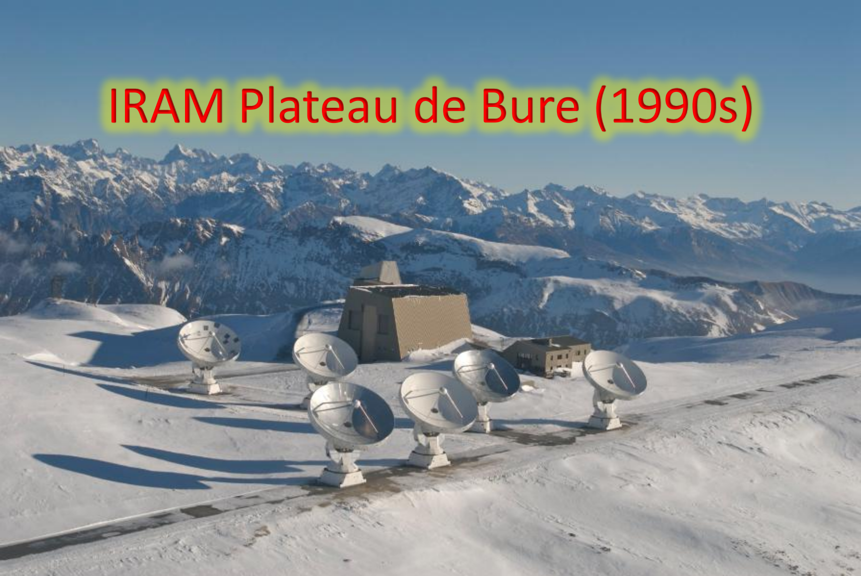
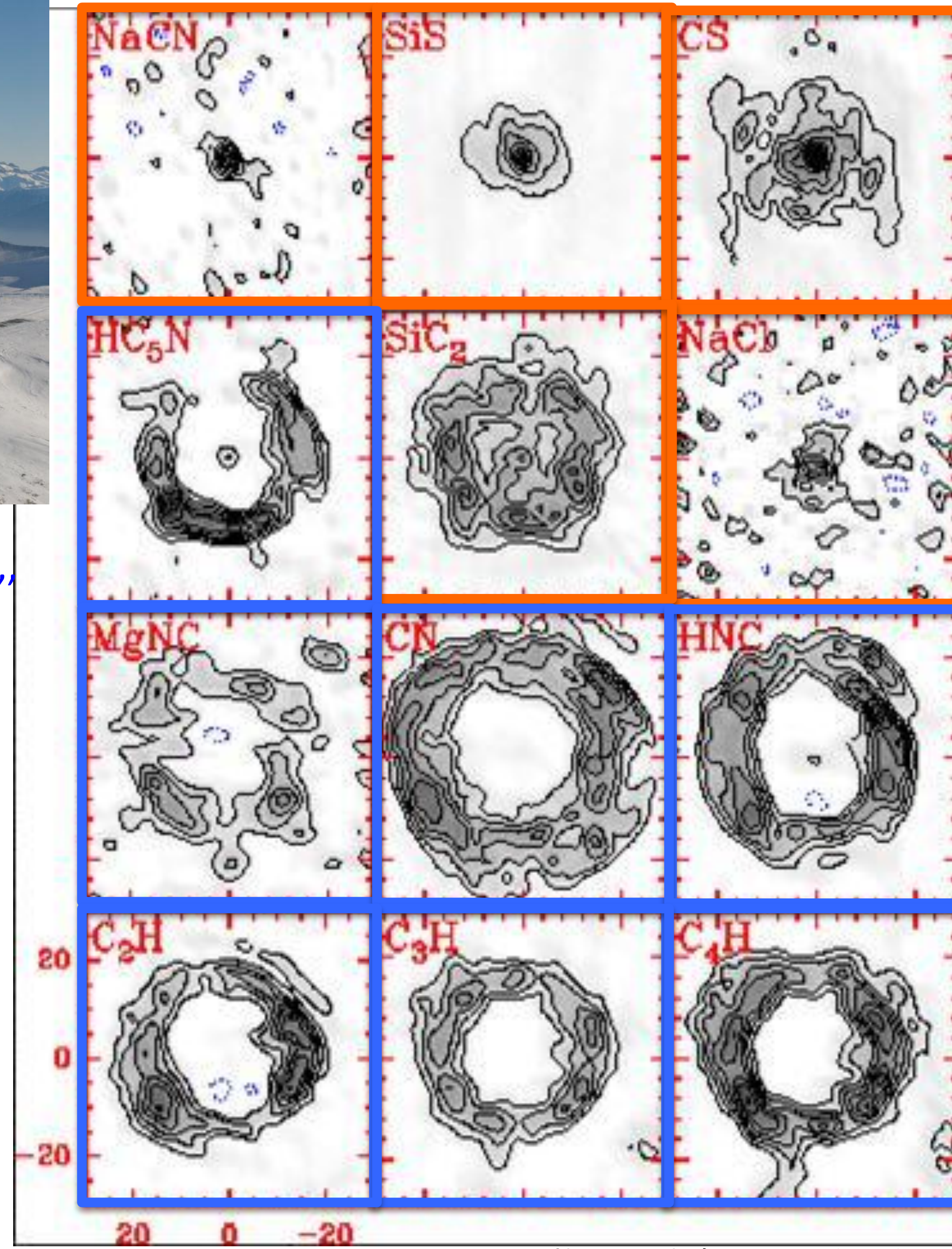


Parent species: concentric around star

Daughter species: hollow shell at ≈15-20''

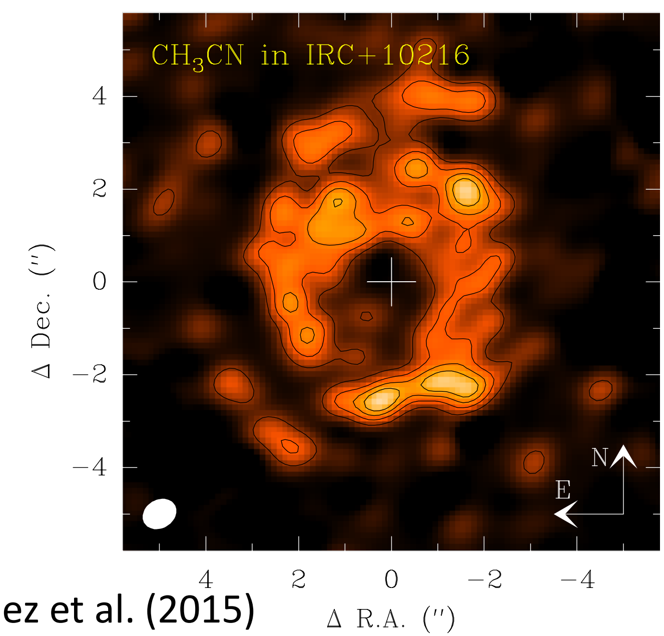


Guélin et al. (IRAM PdBI data)

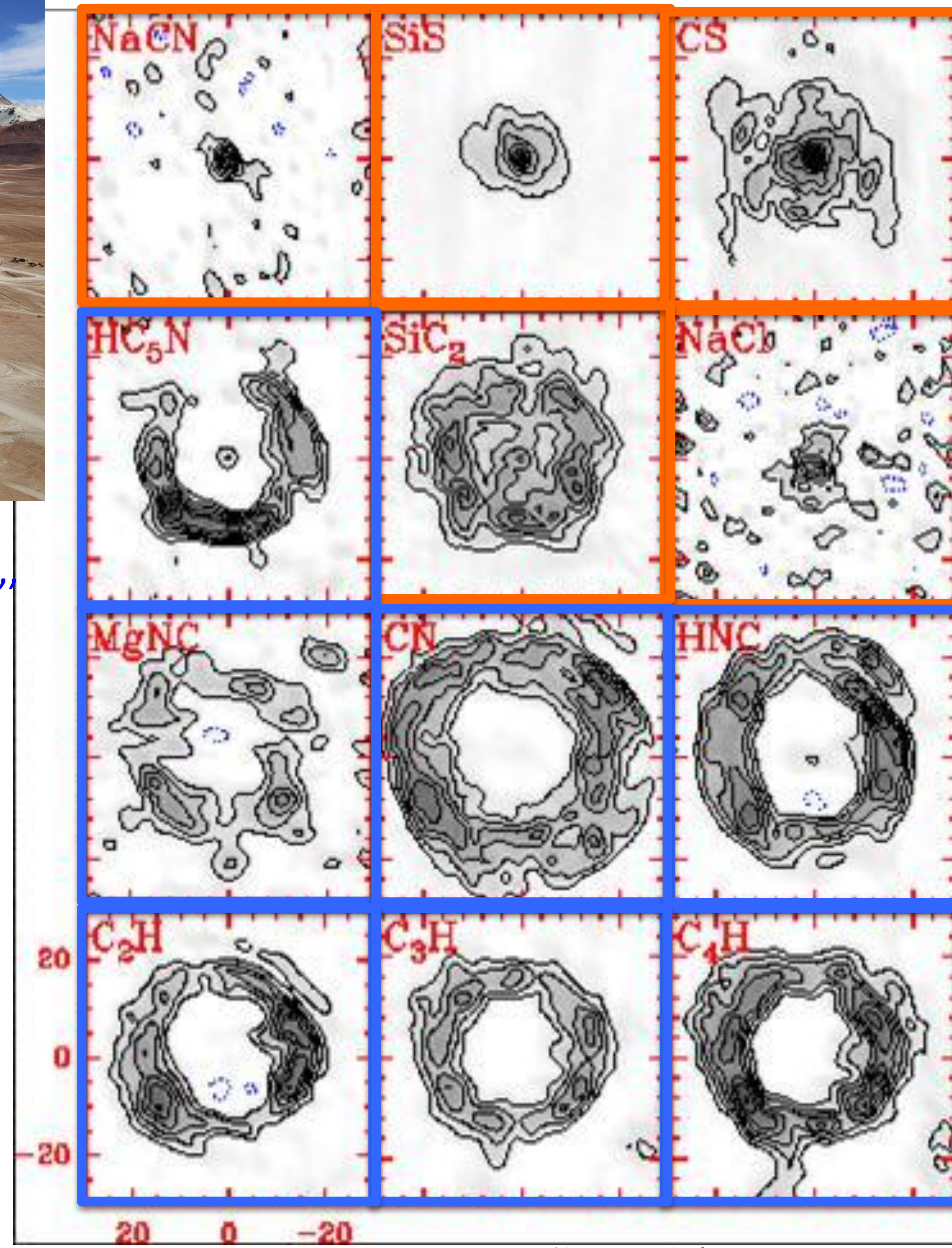
Parent species: concentric around star

Daughter species: hollow shell at ≈15-20''

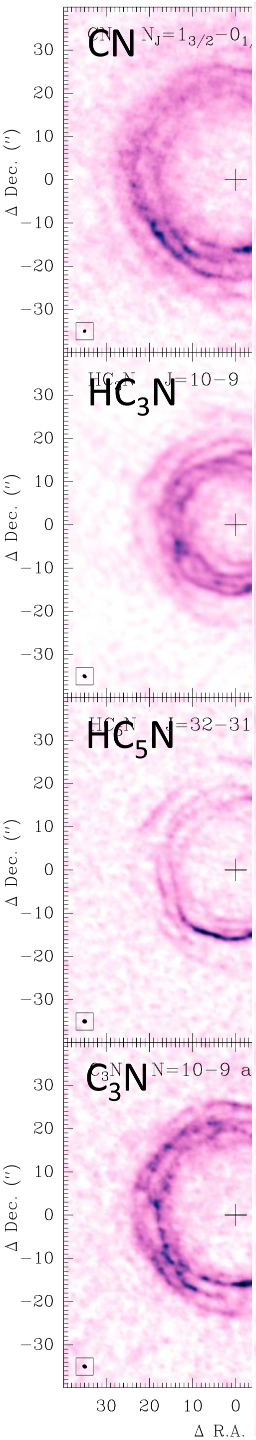
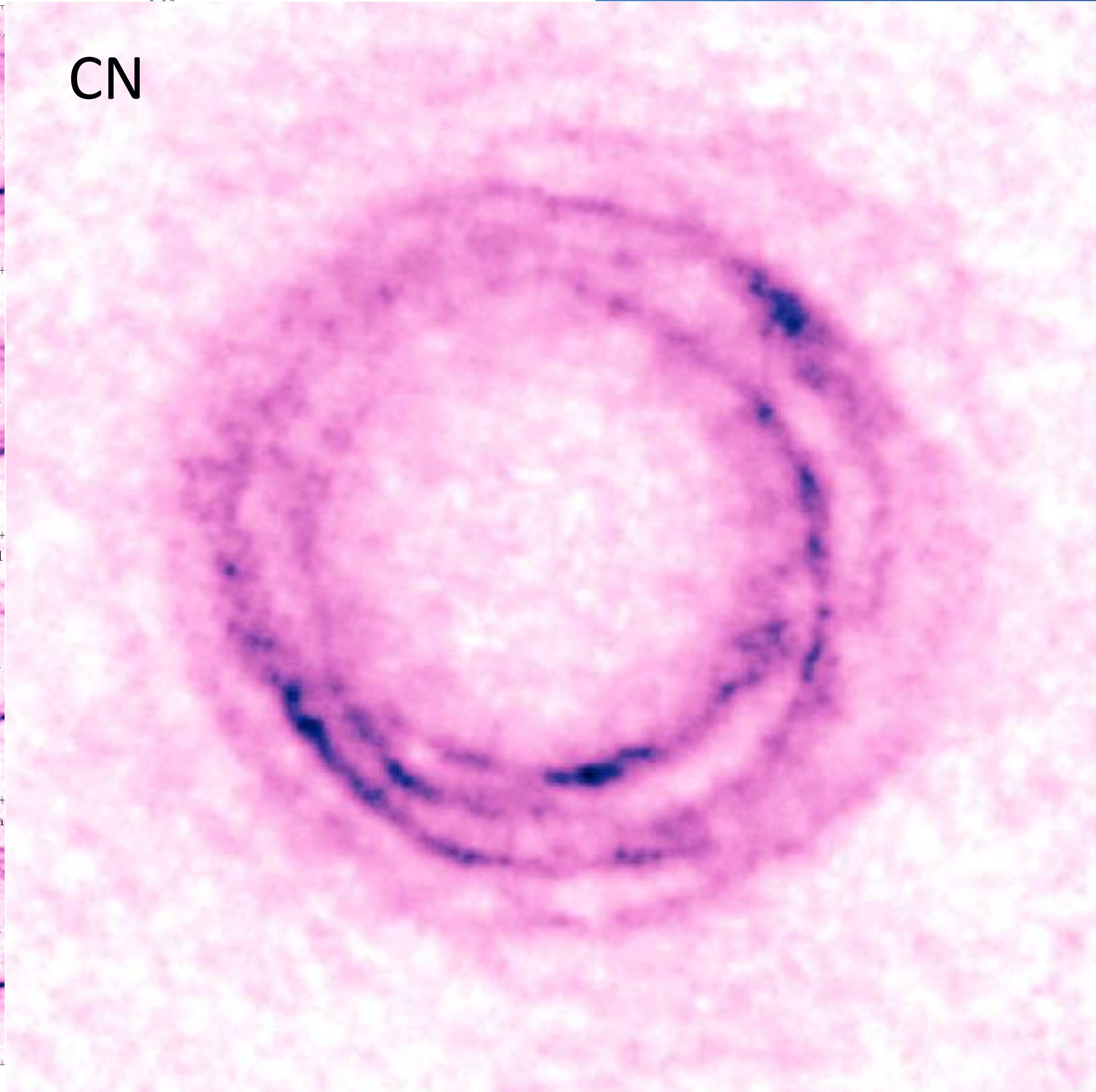
CH_3CN shows a peculiar distribution

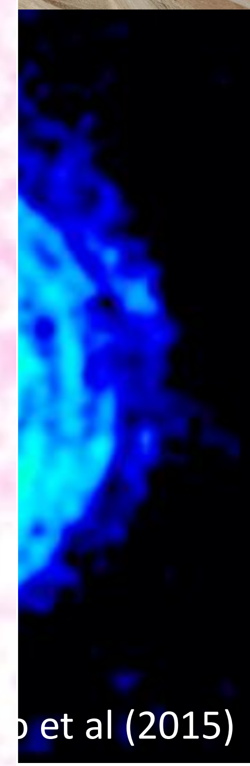


Agúndez et al. (2015)



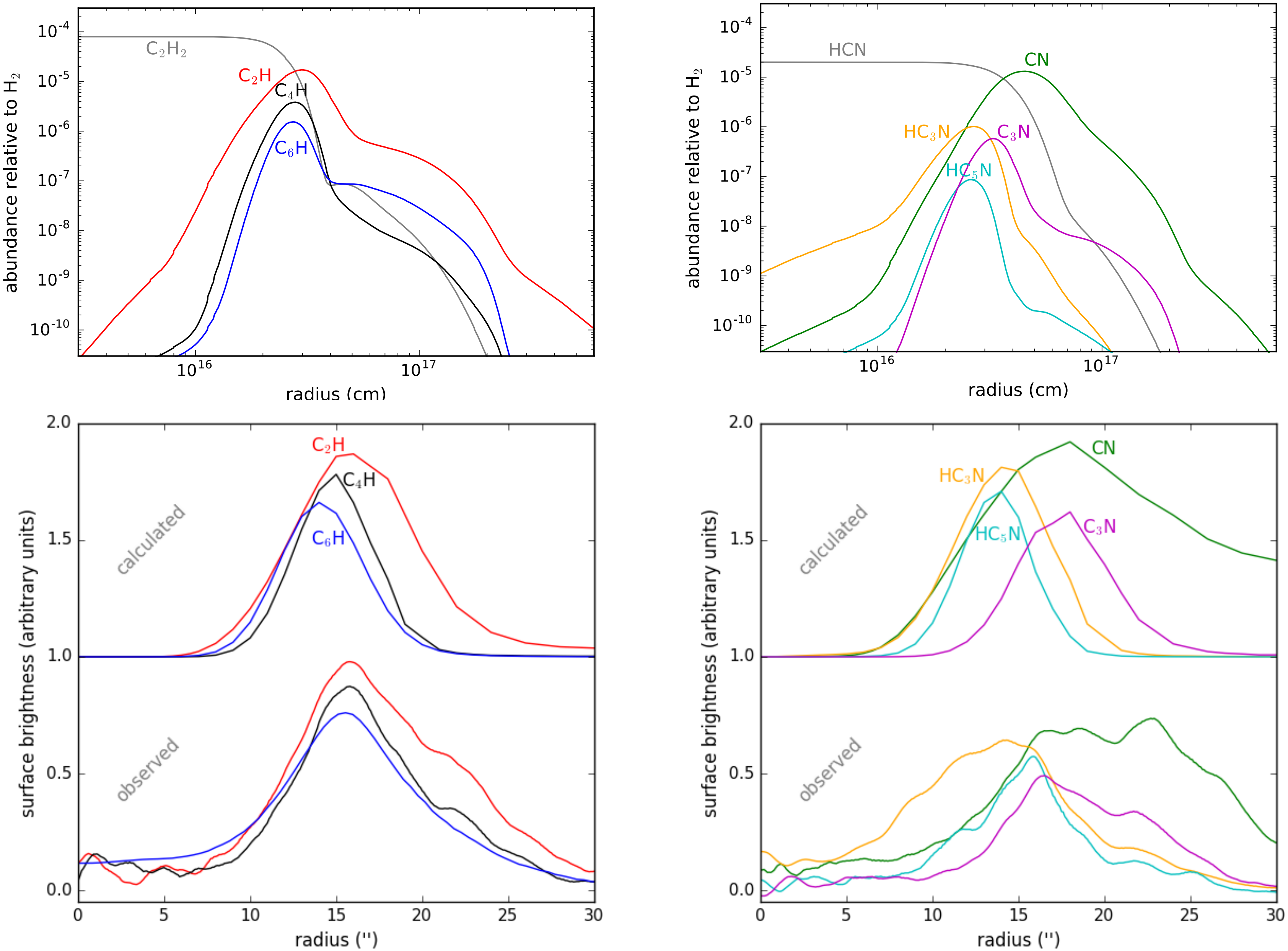
Guélin et al. (IRAM PdBI data)


CN
HC3N
J=10-9
HC5N
J=32-31
C3N
N=10-9
Δ Dec. (″)
Δ R.A.

CN


et al (2015)

Carbon chain growth in IRC+10216

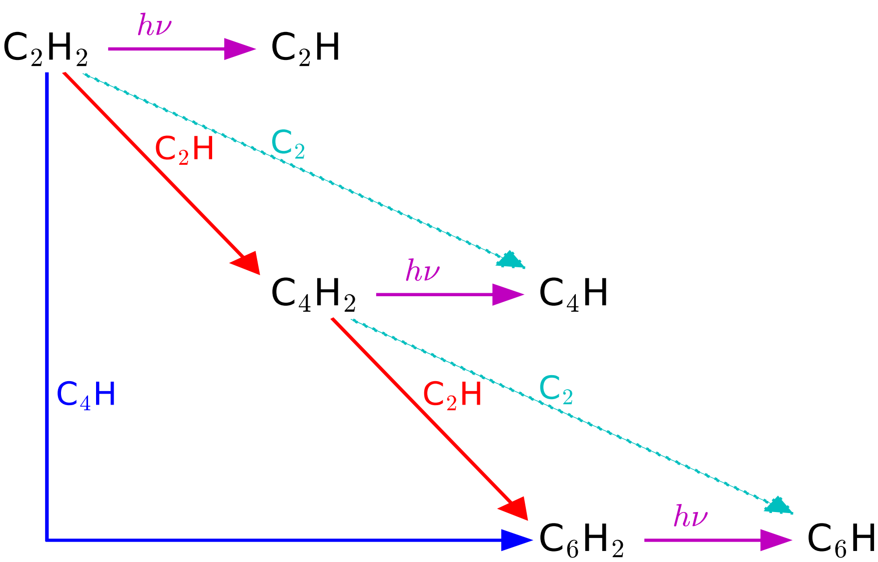
(Agúndez et al 2017)



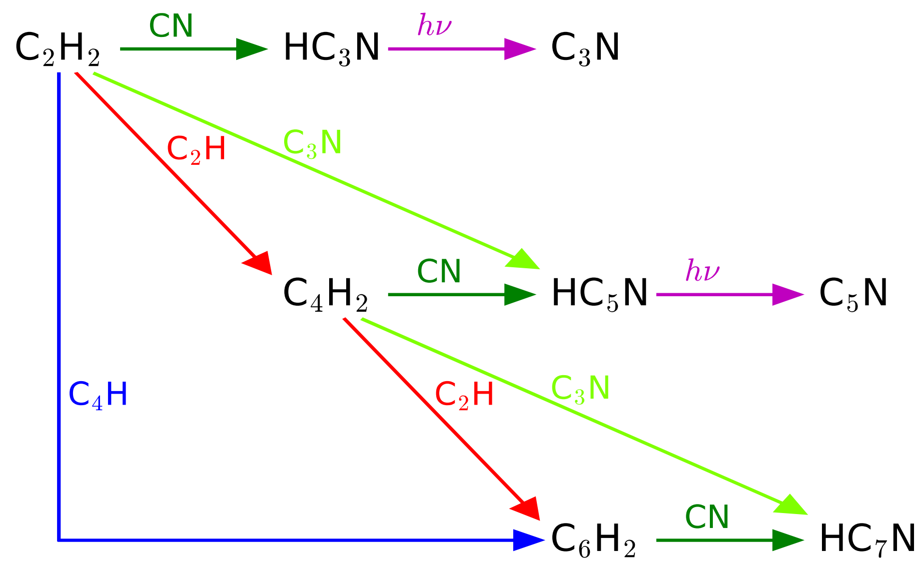
Carbon chain growth in IRC+10216
(schemes according to chemical model)

(Agúndez et al 2017)

Polyynes



Cyanopolyynes



The growth of polyynes is driven by reactions involving C_2H and C_4H radicals

The growth of cyanopolyynes is driven by reactions involving CN and C_3N radicals

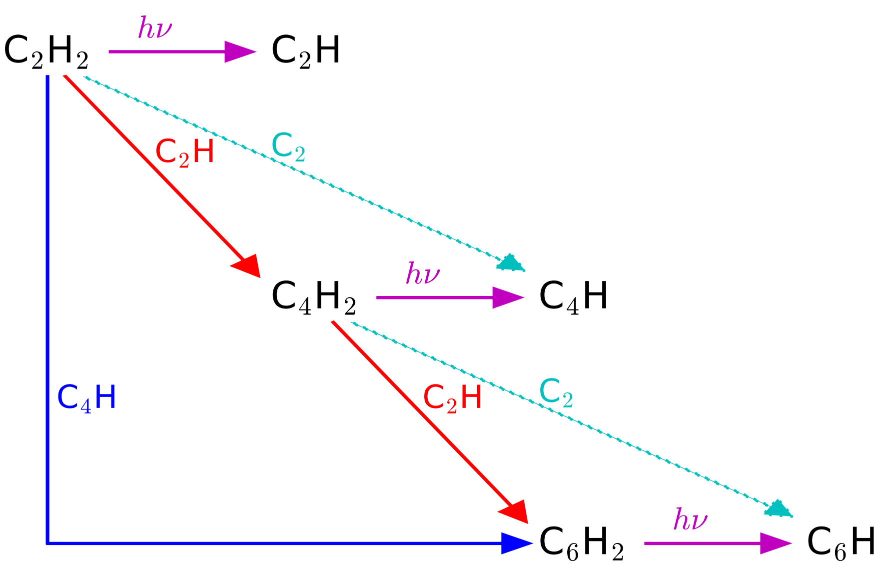
Low-temperature kinetics of these reactions studied with CRESU machines

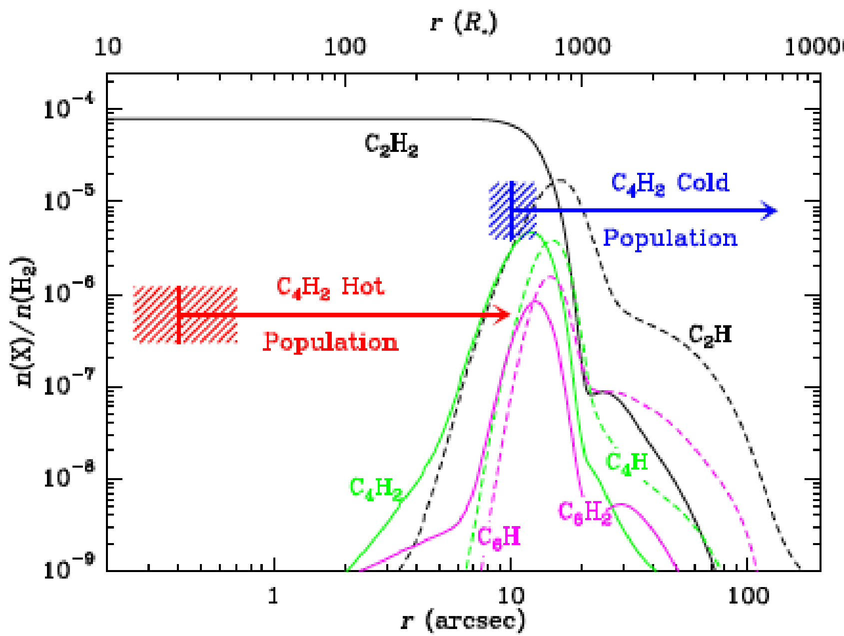
Infrared detection of diacetylene (C_4H_2) in IRC+10216 (Fonfría et al 2018)

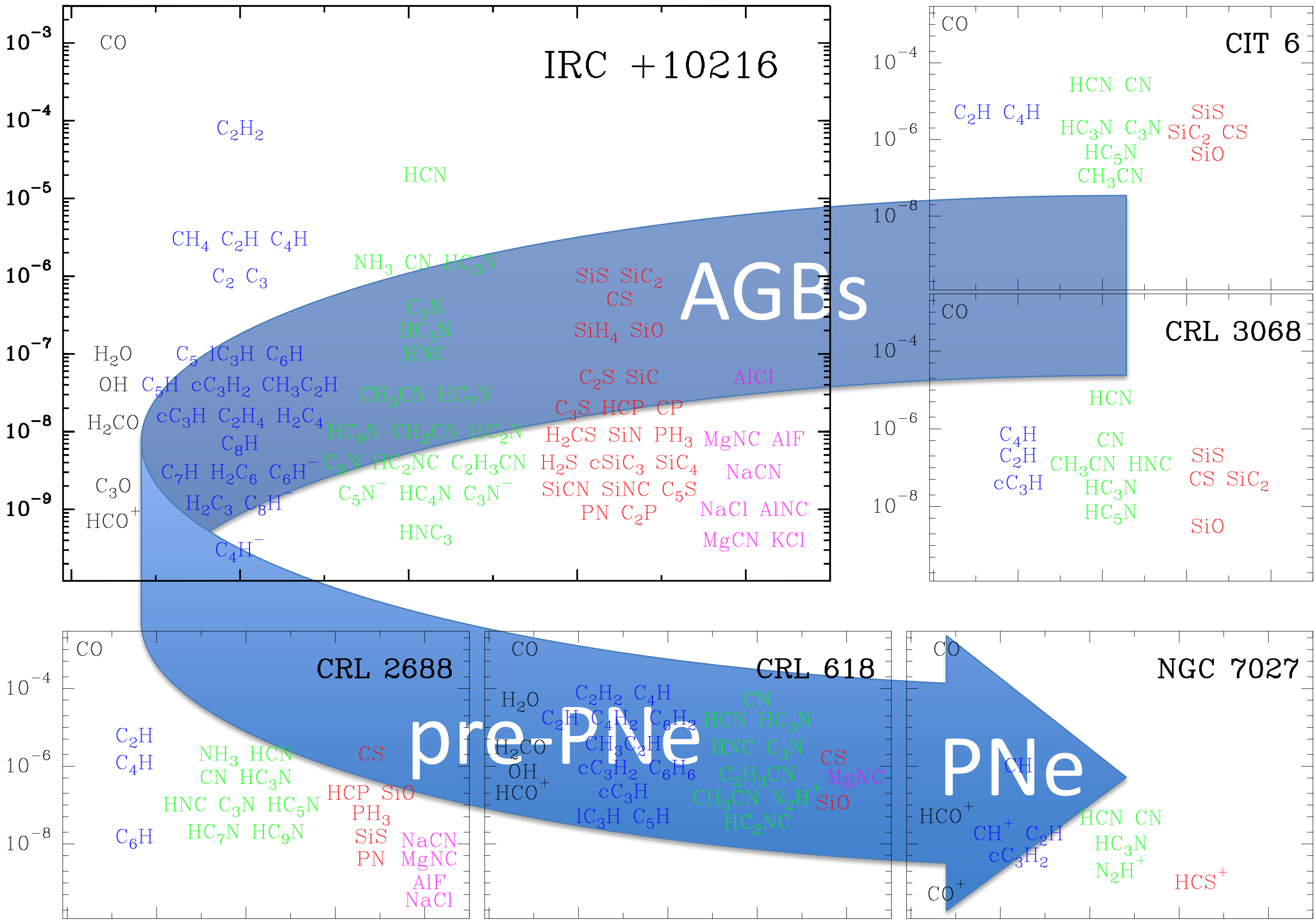
NASA InfraRed Telescope Facility INSTITUTE FOR ASTRONOMY, UNIVERSITY OF HAWAI'I

C_4H_2 is a non polar molecule, predicted to form abundantly in the outer envelope. Important observation because it allows to put constraints on the chemical model.

Derived abundance of cold (outer) C_4H_2 in good agreement with chemical model. Presence of hot (inner) C_4H_2 is puzzling.







IRC +10216
CIT 6
CRL 3068
CRL 2688
CRL 618
NGC 7027
AGBs
pre-PNe
PNe
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
CO
C_2H_2
HCN
CH_4 C_2H C_4H
NH_3 CN HC_3N
C_2 C_3
SiS SiC_2
CS
C_3N
HC_5N
HNC
SiH_4 SiO
H_2O
C_5 lC_3H C_6H
OH C_5H cC_3H_2 CH_3C_2H
CH_3CN HC_7N
C_2S SiC
AlCl
H_2CO
cC_3H C_2H_4 H_2C_4
HC_9N CH_2CN HC_2N
C_3S HCP CP
C_8H
H_2CS SiN PH_3
MgNC AlF
C_7H H_2C_6 C_6H^-
C_5N HC_2NC C_2H_3CN
H_2S $cSiC_3$ SiC_4
NaCN
C_3O
C_5N^- HC_4N C_3N^-
SiCN SiNC C_5S
HCO^+
H_2C_3 C_8H^-
PN C_2P
NaCl AlNC
HNC_3
MgCN KCl
C_4H^-
HCN CN
C_2H C_4H
HC_3N C_3N
SiS
SiC_2 CS
SiO
CH_3CN
C_4H
C_2H
cC_3H
CH_3CN HNC
HC_3N
HC_5N
CS SiC_2
NH3 HCN
CN HC_3N
HNC C_3N HC_5N
HC_7N HC_9N
C_6H
HCP SiO
PH_3
PN MgNC
AlF
NaCl
C_2H_2 C_4H
C_2H C_4H_2 C_6H_2
HCN HC_3N
CH_3C_2H
cC_3H_2 C_6H_6
C_2H_3CN
MgNC
CH_3CN N_2H^+
lC_3H C_5H
HC_2NC
CH
CH^+
cC_3H_2
N_2H^+
HCS^+
CO^+

Concluding remarks:

\# Overall picture of the circumstellar chemistry around AGB stars well understood

> parent molecules formed under LTE close to the star
> daughter species formed by photochemistry in outer envelope

\# Observations are revealing a growing number of aspects not well understood yet

> Formation of H_2O in C-rich objects and other hydrides (NH_3, PH_3)
> Relevance of non-equilibrium chemistry in the inner envelope
  different small-scale distribution of molecules: (NaCl, KCl) vs (SiS, SiO) in IRC+10216
  role of refractory molecules as precursors of dust grains
  distribution of CH_3CN in IRC+10216
  existence of hot C_4H_2 in IRC+10216
  carriers of unidentified lines arising just close to the star
> Discontinuous and non-isotropic mass loss

\# Need to revise the current paradigm of circumstellar chemistry

> Dust formation
> Shocks driven by the stellar pulsation
> Clumpiness
> Spiral-like structures caused by binarity

The evolved stars team at IFF, Madrid

José Cernicharo

Luis Velilla Prieto

José Pablo Fonfría

Guillermo Quintana-Lacaci

Sarah Massalkhi

Jason Champion