MESS
Mass loss of Evolved StarS

Early spectroscopic results

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on behalf of the MESS Consortium

Scientific Goals:

To obtain complete spectral coverage from 55-685um at resolving powers ranging up R=3500 (PACS) and R=1200 (SPIRE), in order to:

(a) Characterise the atomic and molecular chemistry in the outflows from O-rich and C-rich evolved stars.

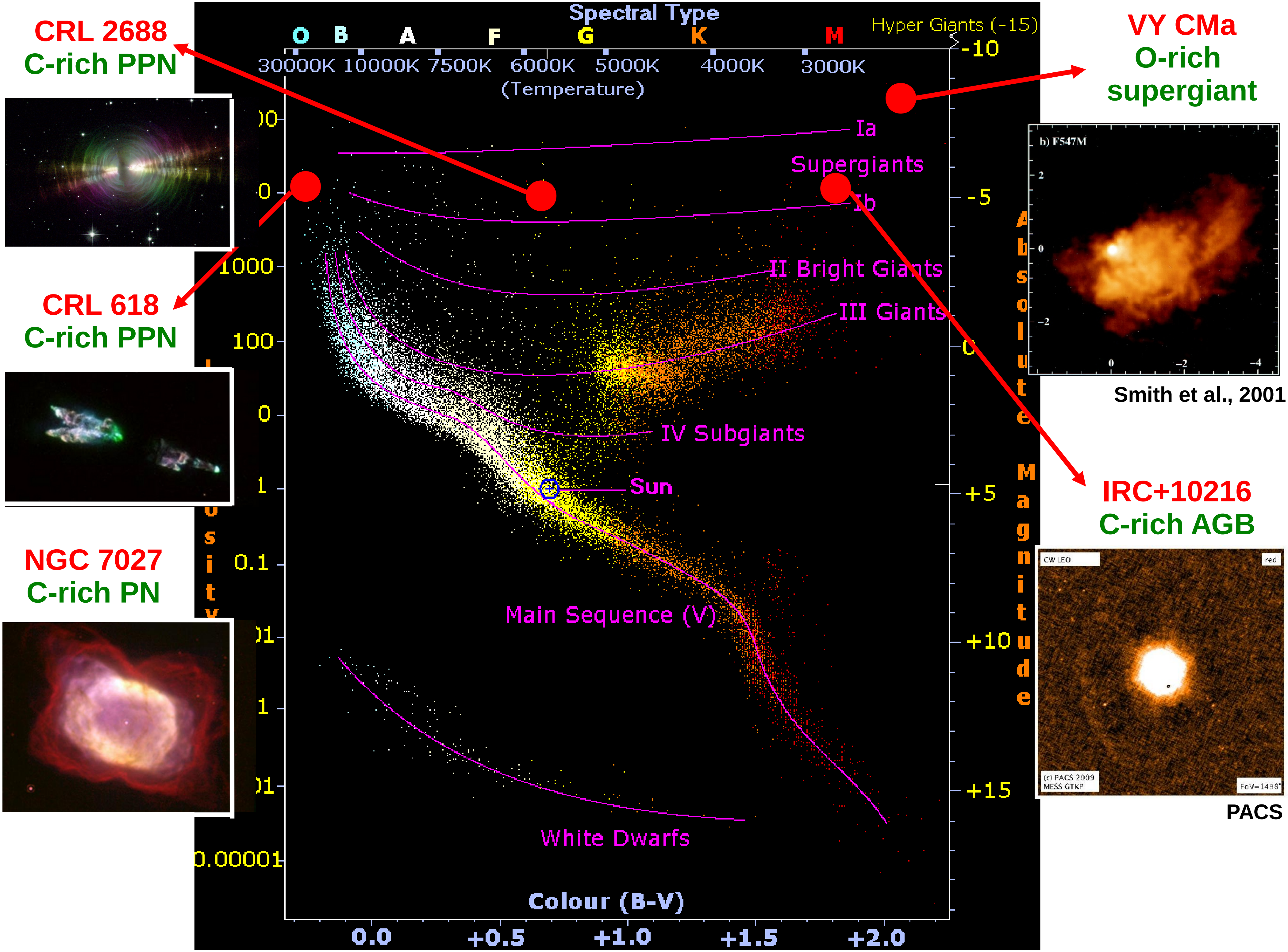
(b) Determine the dominant coolants, the temperature structures and the mass loss rates of the outflows.

(c) Characterise dust spectral features, where found, as well as dust continuum emissivity laws, for sources that have known chemistries (e.g. known C/O ratios)

SPIRE FTS Spectra of MESS Evolved Objects

SPIRE SAG 6 members and consultants:

M. Agundez, M. Barlow, J. Cernicharo, F. Daniel, L. Dunne, W. Gear, H. Gomez, P. Hargrave, P. Imhof, R. Ivison, S. Leeks, T. Lim, M. Matsuura, G. Olofsson, E. Polehampton, G. Savini, B. Sibthorpe, B. Swinyard, R. Wesson, J. Yates.


CRL 2688
C-rich PPN
CRL 618
C-rich PPN
NGC 7027
C-rich PN
Spectral Type
O B A F G K M
Hyper Giants (-15)
30000K 10000K 7500K 6000K 5000K 4000K 3000K
(Temperature)
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
Sun
Main Sequence (V)
White Dwarfs
1000
100
1
0.1
0.00001
-10
-5
0
+5
+10
+15
Absolute Magnitude
Colour (B-V)
0.0 +0.5 +1.0 +1.5 +2.0
VY CMa
O-rich
supergiant
b) F547M
Smith et al., 2001
IRC+10216
C-rich AGB
CW LEO
red
(c) PACS 2009
MESS GTKP
PACS

Five luminous evolved MESS targets were observed with the SPIRE FTS during SDP:

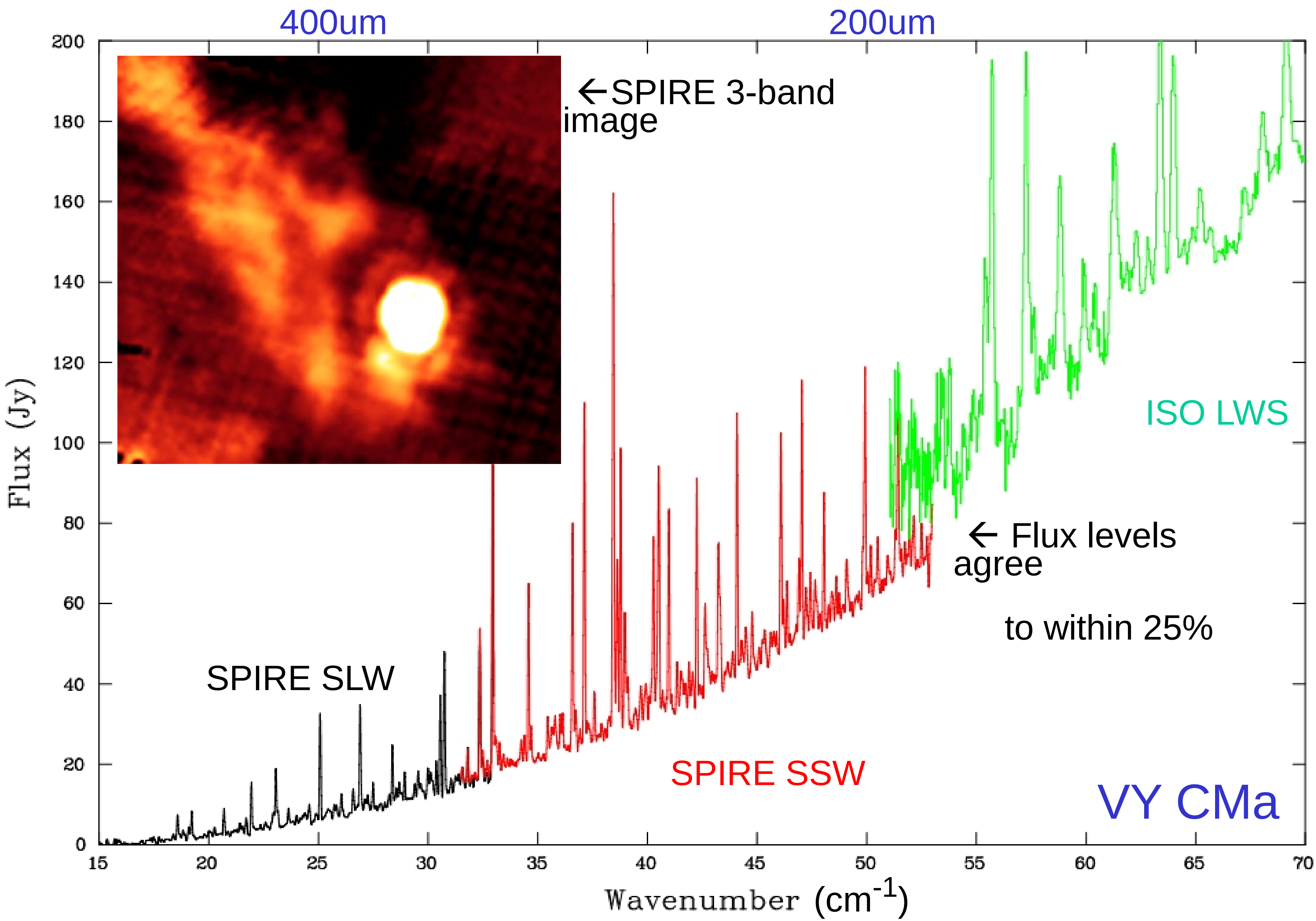
VY CMa: O-rich self-obscured M supergiant (Teff~2800 K)

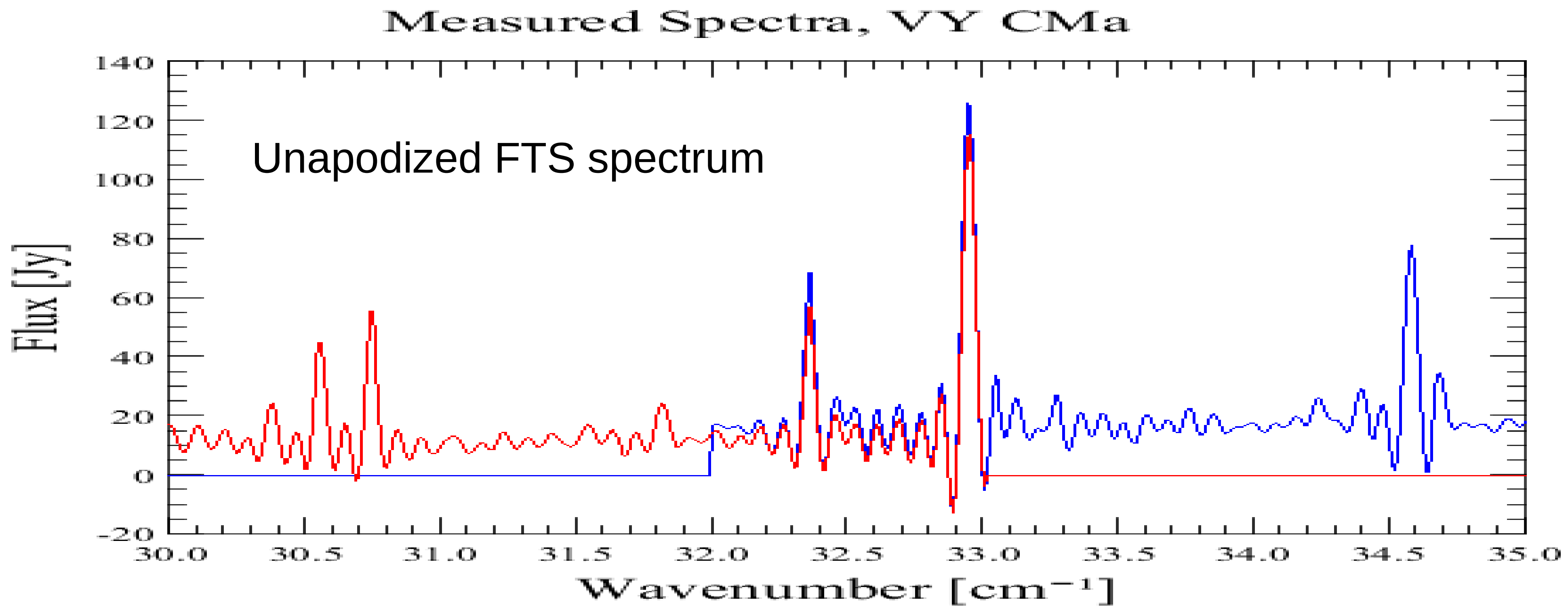
IRC+10216 (CW Leo): self-obscured carbon star

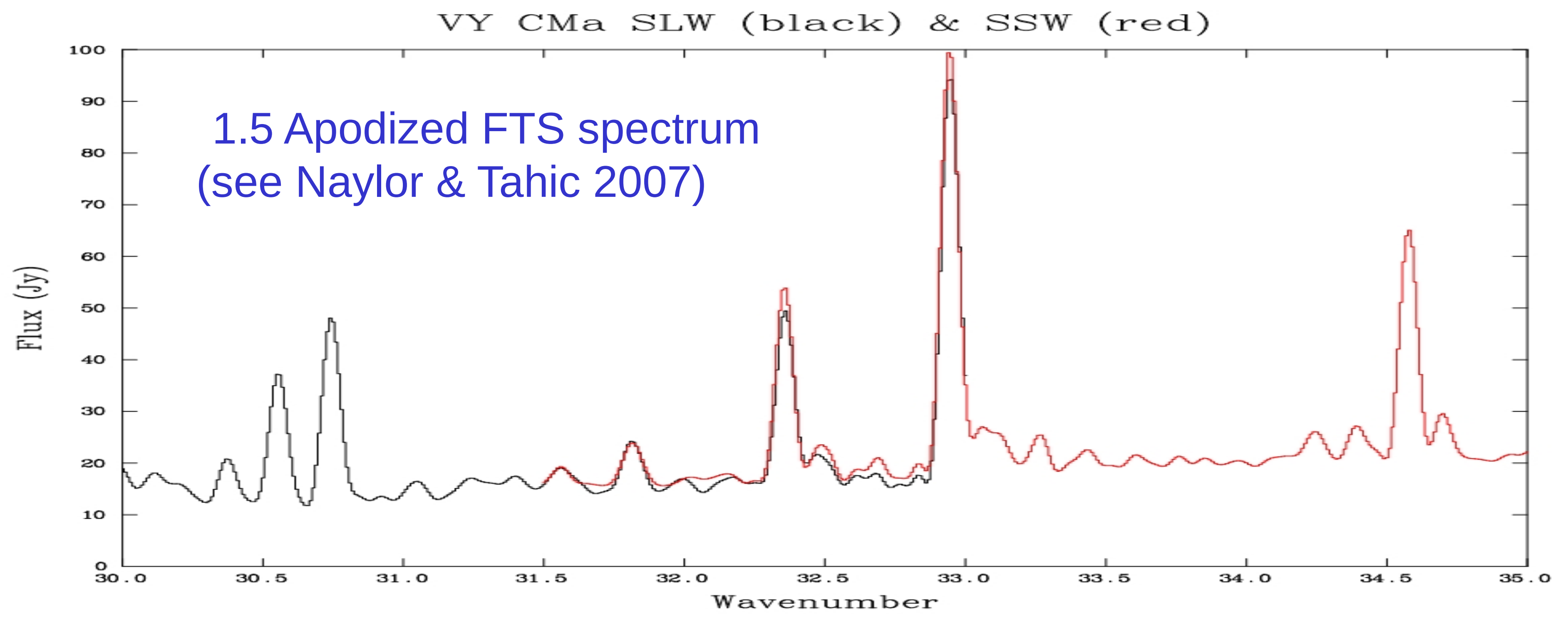
AFGL 2688: C-rich bipolar post-AGB object (A/F-type star)

AFGL 618: C-rich bipolar post-AGB object (early B-type star)

NGC 7027: C-rich planetary nebula (150,000 K central star)

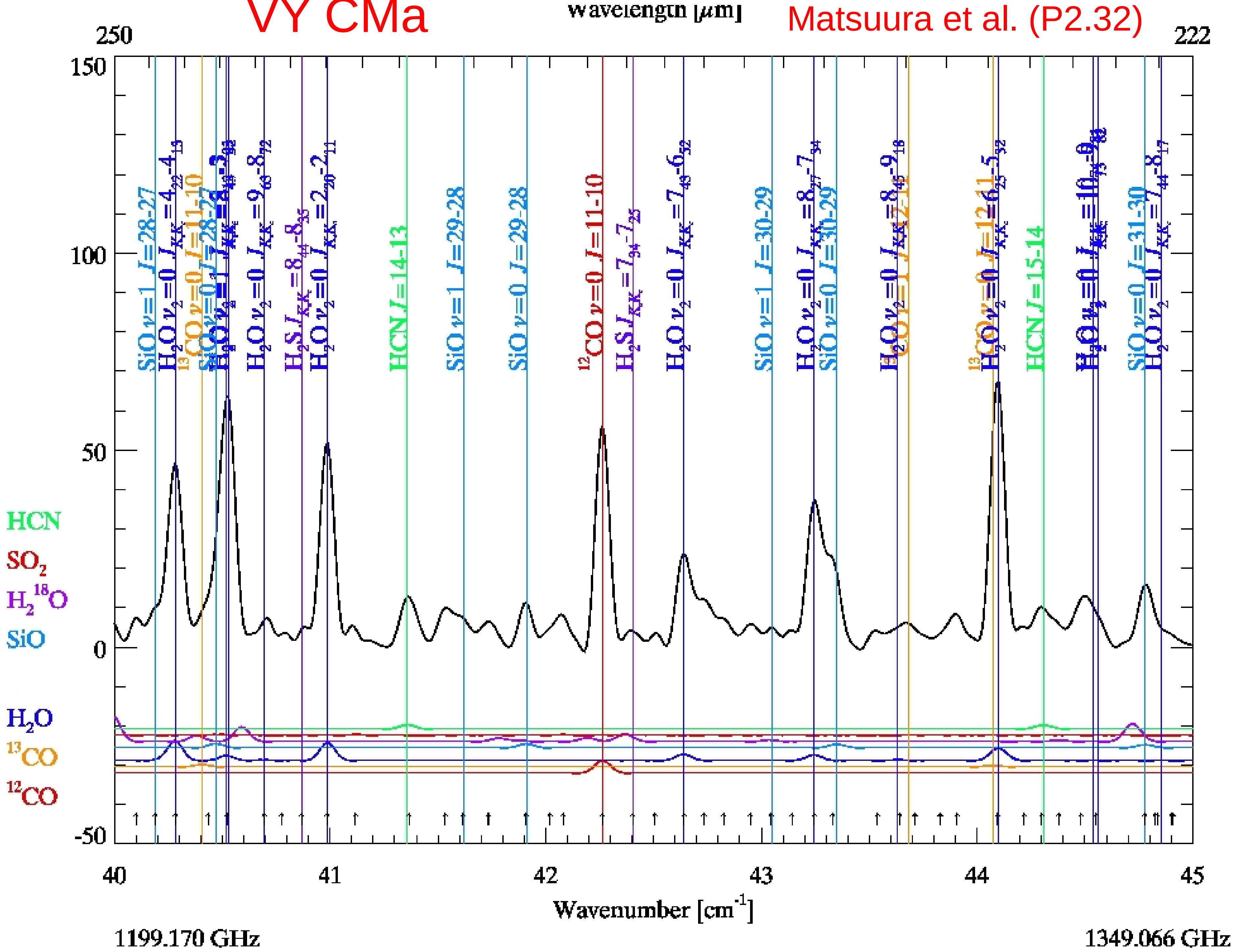

400um
200um
←SPIRE 3-band image
Flux (Jy)
SPIRE SLW
SPIRE SSW
ISO LWS
← Flux levels agree
to within 25%
VY CMa
Wavenumber (cm-1)
200
180
160
140
120
100
80
60
40
20
0
15
20
25
30
35
40
45
50
55
60
65
70


Measured Spectra, VY CMa
Unapodized FTS spectrum
Flux [Jy]
140
120
100
80
60
40
20
0
-20
30.0
30.5
31.0
31.5
32.0
32.5
33.0
33.5
34.0
34.5
35.0
Wavenumber [cm⁻¹]


VY CMa SLW (black) & SSW (red)
1.5 Apodized FTS spectrum
(see Naylor & Tahic 2007)
Flux (Jy)
100
90
80
70
60
50
40
30
20
10
0
30.0
30.5
31.0
31.5
32.0
32.5
33.0
33.5
34.0
34.5
35.0
Wavenumber

VY CMa

Royer et al. (P2.30)
Matsuura et al. (P2.32)



VY CMa: species detected in the SPIRE FTS range:

(~300 emission lines from 14.6 – 52 cm^{-1}; 192-685μm)

o-H_2O

p-H_2O

$^{18}H_2O$

^{12}CO

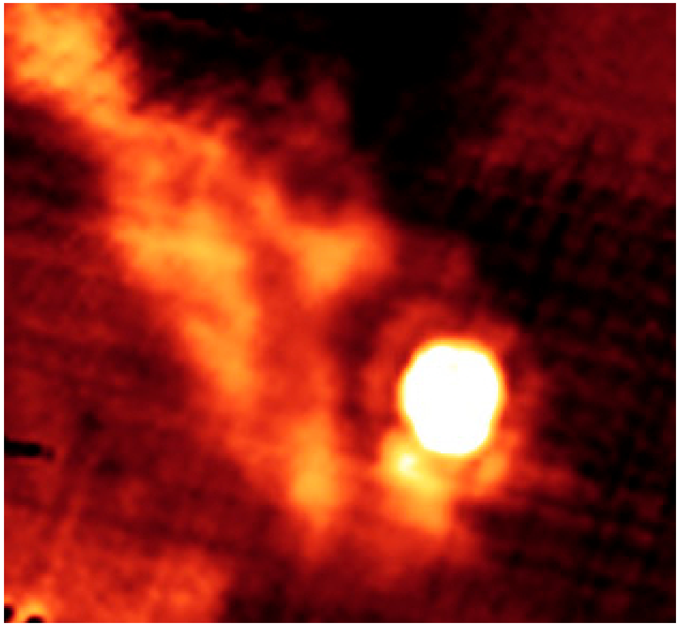
^{13}CO

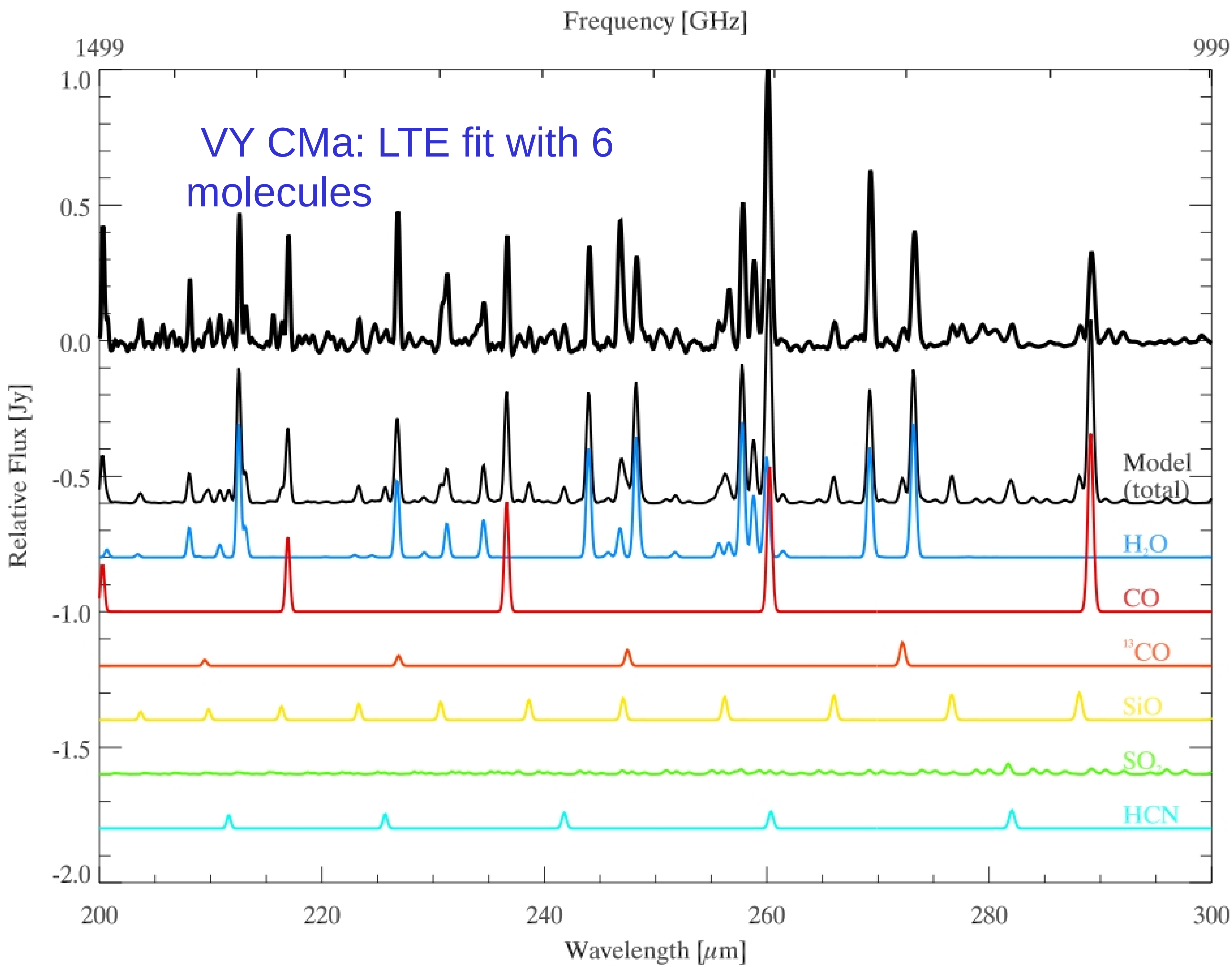
SiO

HCN

CN

NH_3



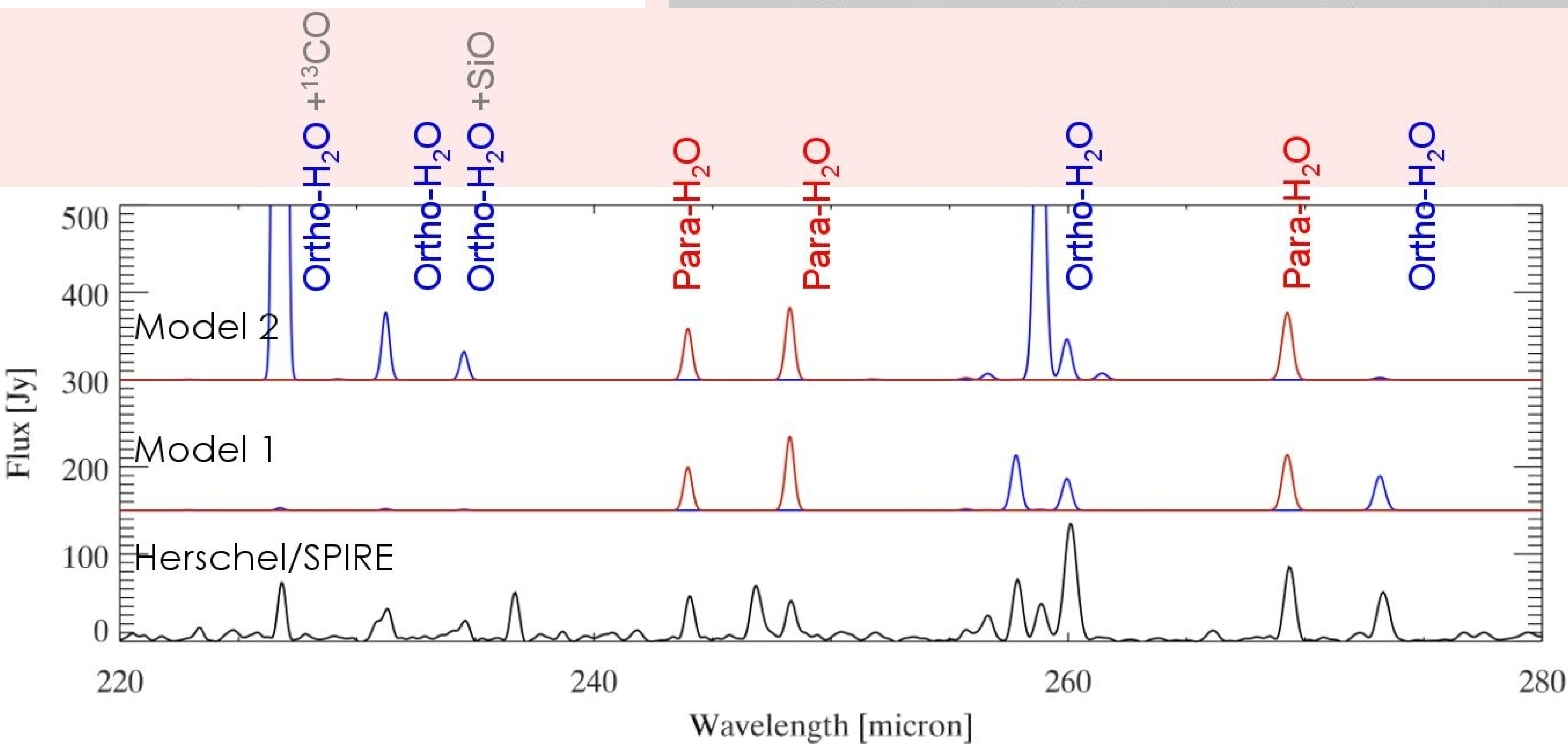

VY CMa: LTE fit with 6 molecules
Frequency [GHz]
1499
999
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Relative Flux [Jy]
Model (total)
H2O
CO
13CO
SiO
SO2
HCN
200
220
240
260
280
300
Wavelength [μm]

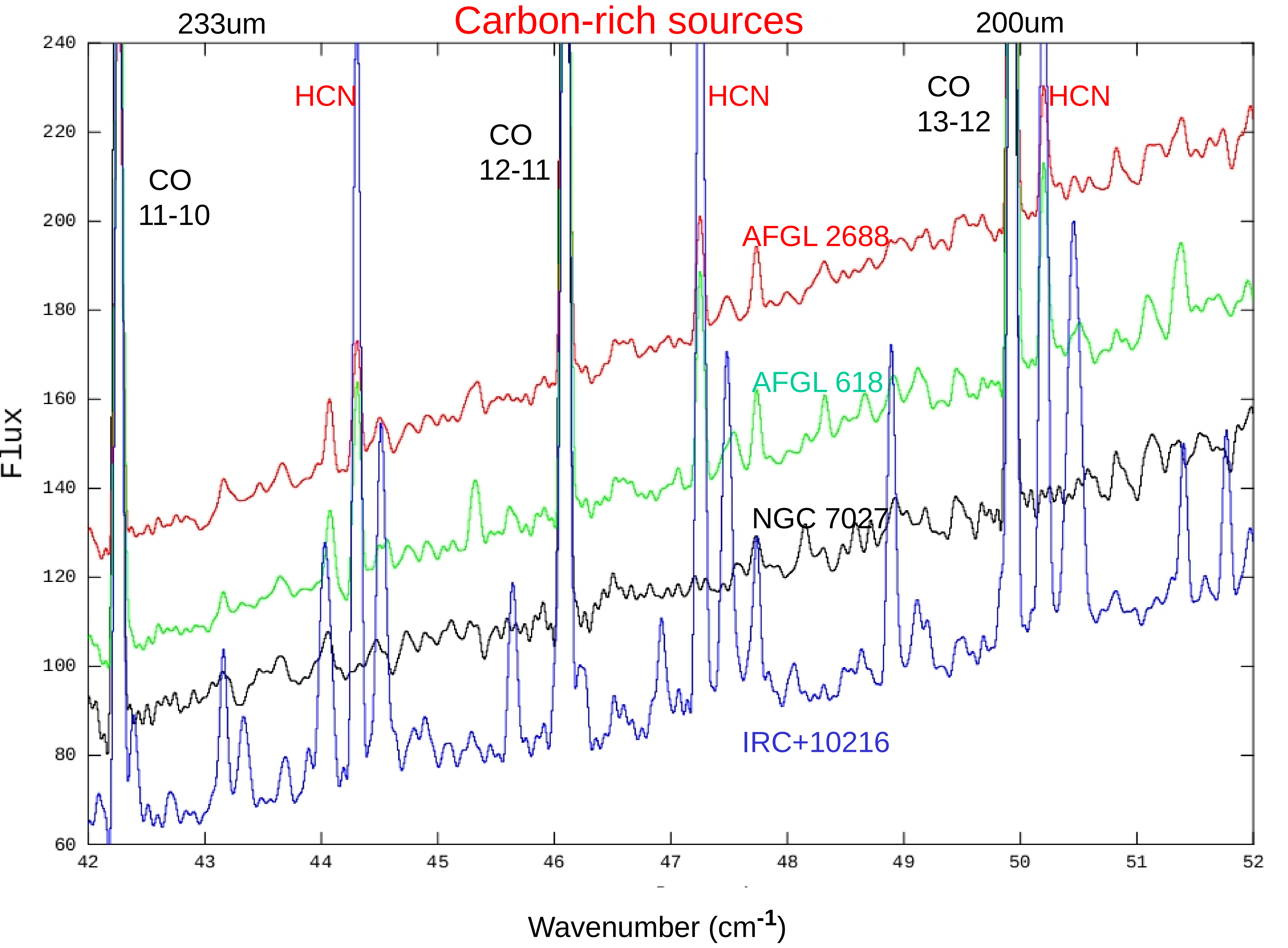
NLTE water line models for VY CMa. 3 codes:

SMMOL; GASTRoNOoM; 1DART

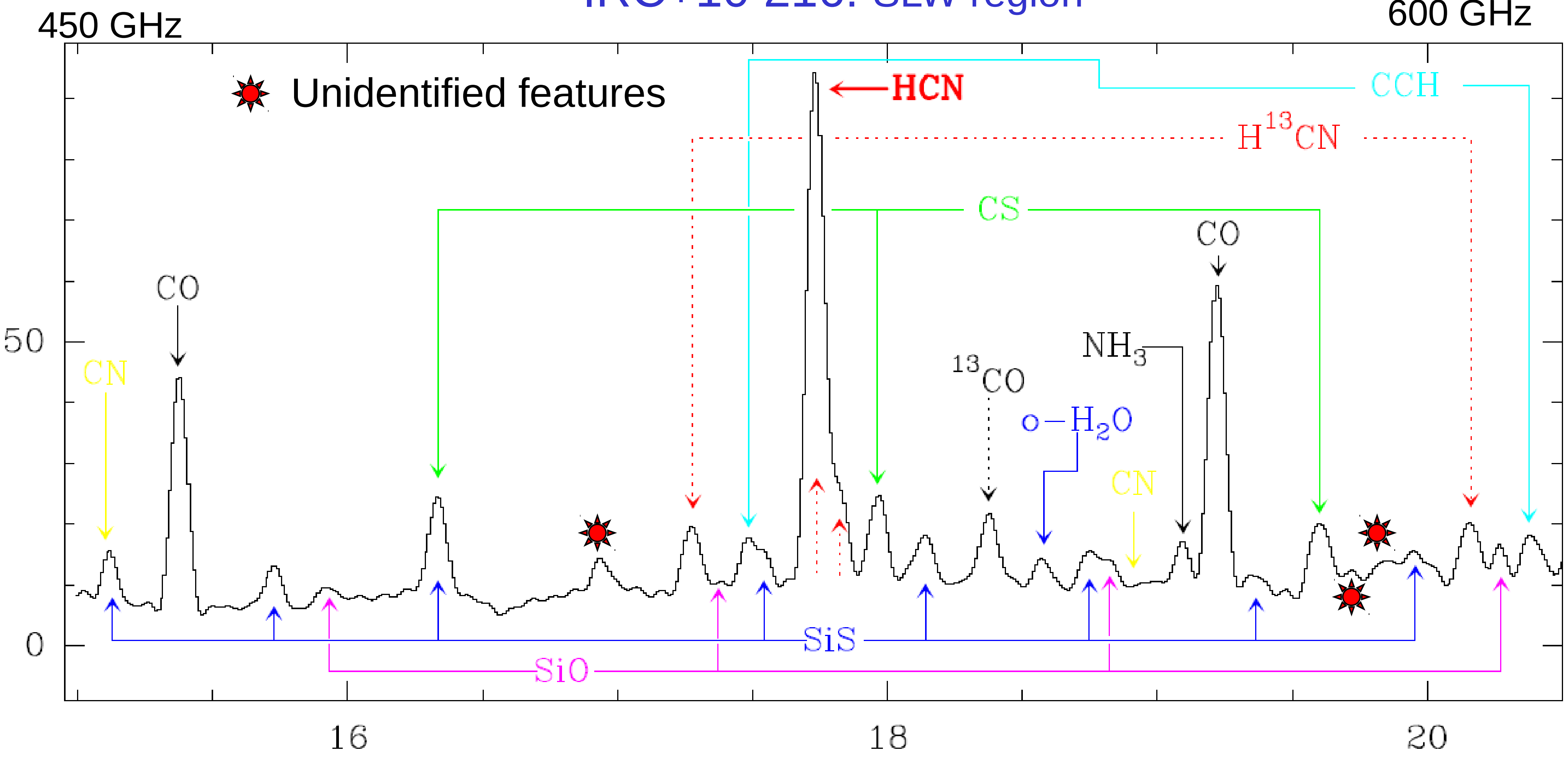
See Matsuura et al. (P2.32)

- Model parameters (SMMOL)
  - Distance: 1500 pc $T_* = 2800$ K $\tau(UV)=50$
  - $dM/dt = 2\times10^{-4} M_\odot\ yr^{-1}$
  - R_{in}: 2×10^{14} cm (gas) R_{in} : 1.3×10^{15} cm (dust)
  - T_{in}: 2000 K
  - R_{out}: 6.8 $\times10^{17}$ cm
  - ρ: $(r/R_{in})^{-2}$
  - T : $T_{in}*(r/R_{in})^{-0.5}$ (model 1) $T_{in}*(r/R_{in})^{-0.4}$ (model 2)
  - T_{sub} (H_2O): 100 K
  - $H_2O/H = 10^{-4}$
  - Ortho : para = 3: 1

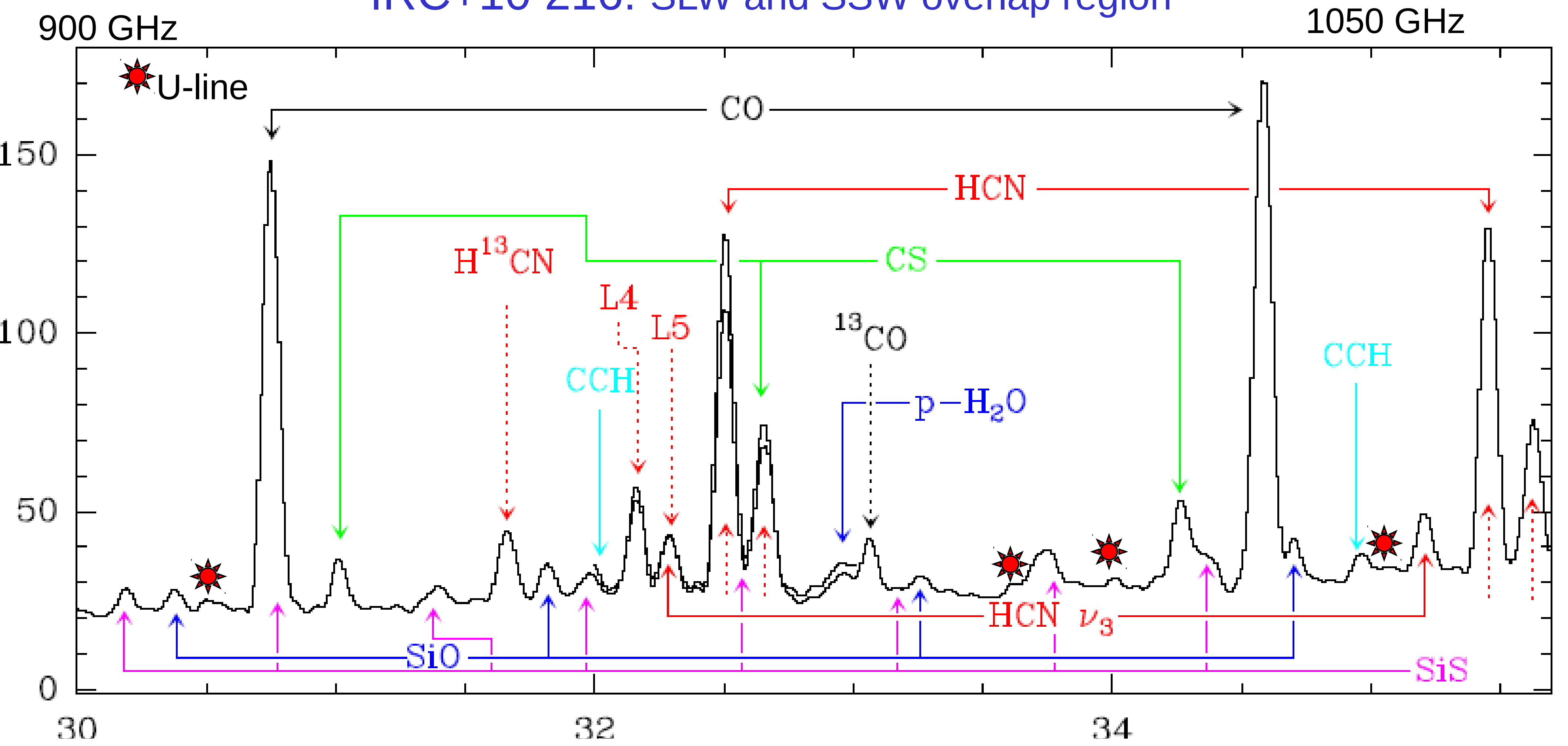



Carbon-rich sources
233um
200um
HCN
HCN
HCN
CO
11-10
CO
12-11
CO
13-12
AFGL 2688
AFGL 618
NGC 7027
IRC+10216
Flux
Wavenumber (cm-1)
240
220
200
180
160
140
120
100
80
60
42
43
44
45
46
47
48
49
50
51
52

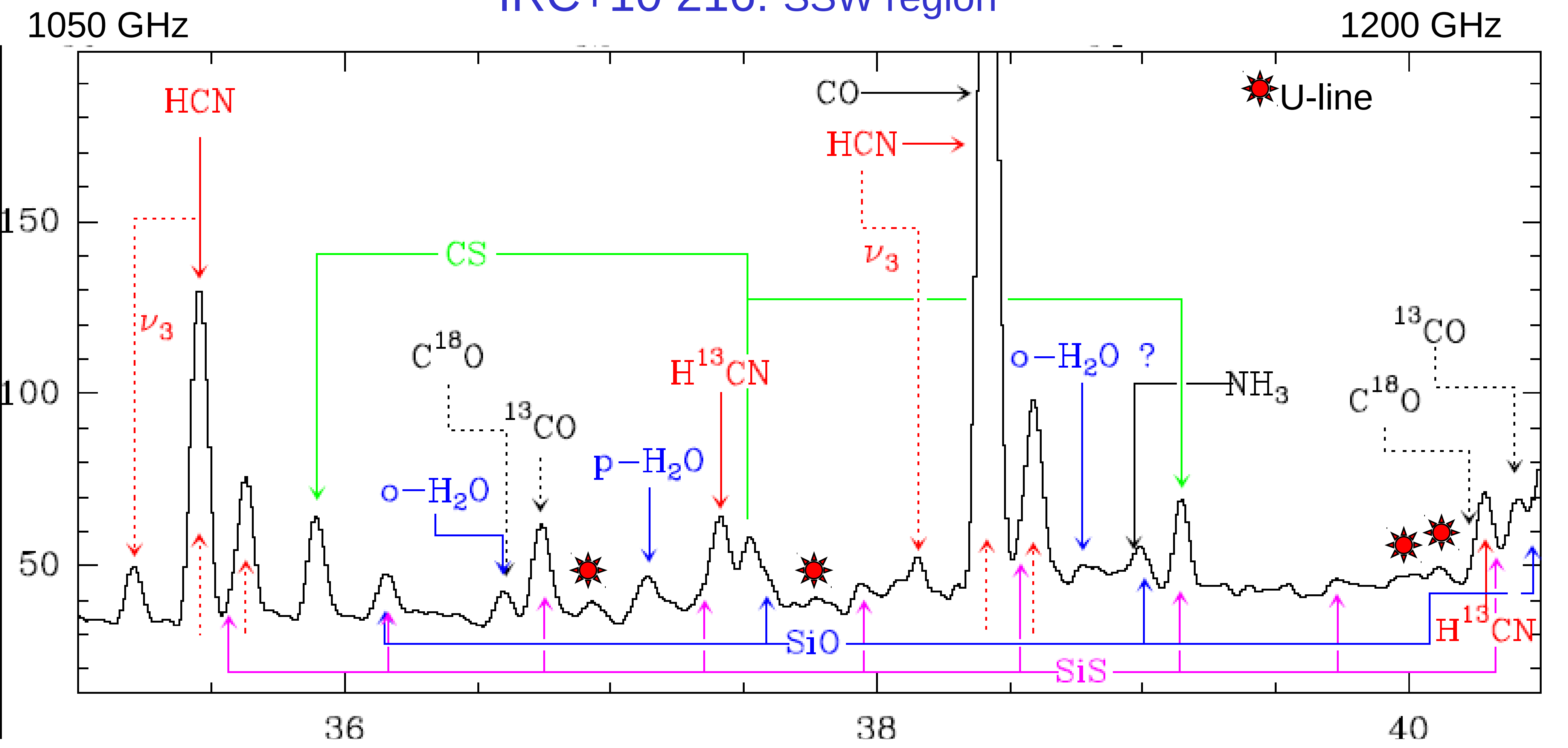
IRC+10 216: SLW region



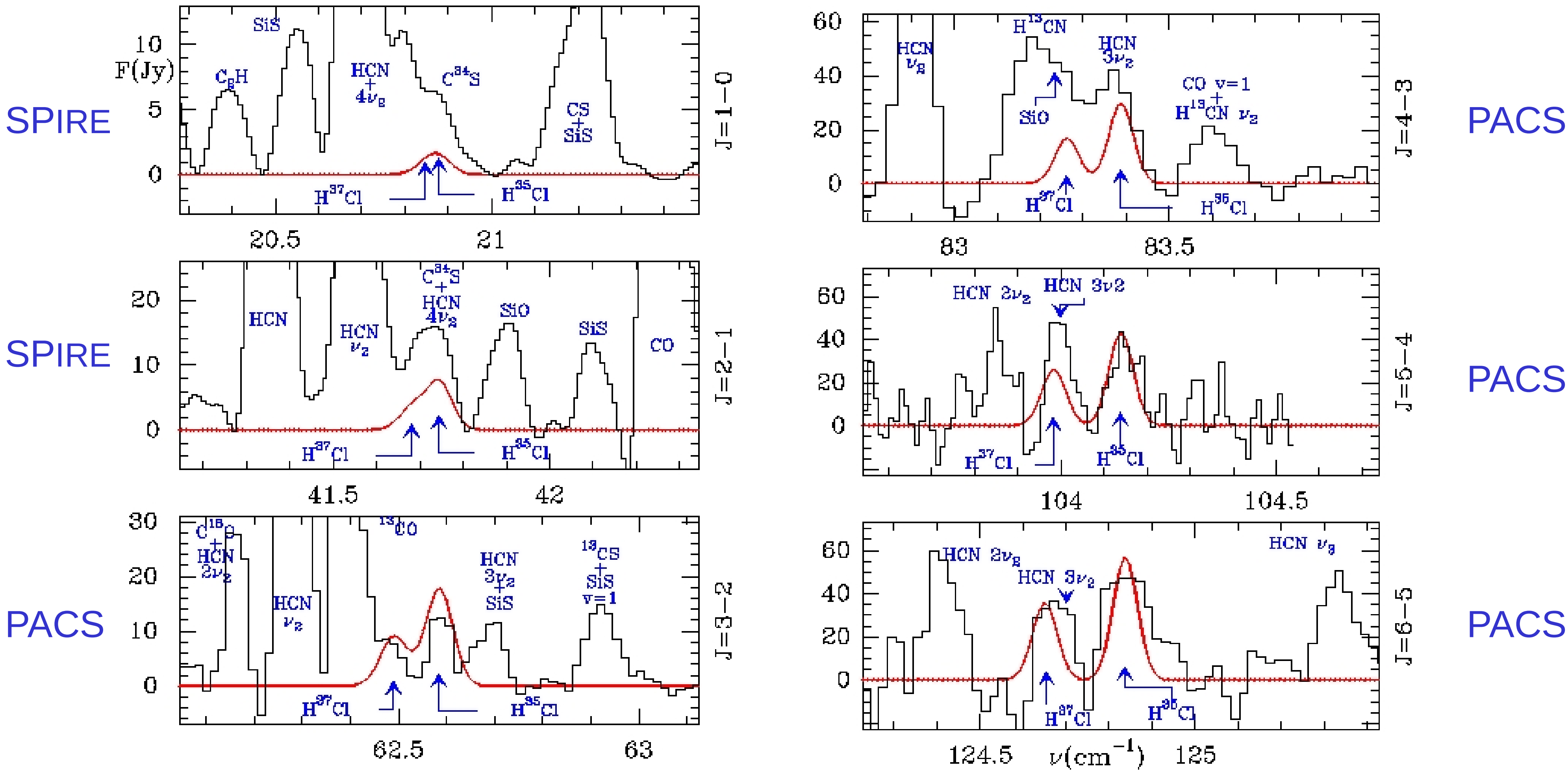
IRC+10 216: SLW and SSW overlap region



IRC+10 216: SSW region



IRC+10216 = CW Leo



First detection of HCl in an evolved star outflow
(Cernicharo et al. 2010, A&A; P1.34)

$HCl/H_2 \sim 5\times10^{-8}$

Model fits use $^{35}Cl/^{37}Cl = 3.1$
(from other CW Leo chlorides)

Species detected so far in the FTS spectrum of IRC+10216 (~250 emission lines):

^{12}CO, ^{13}CO, $C^{18}O$

HCN, $H^{13}CN$

SiS

SiO

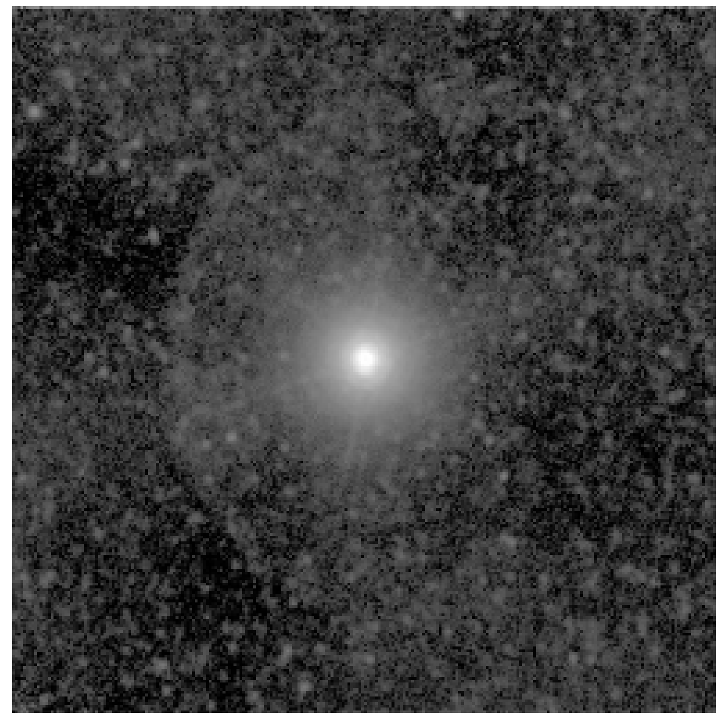
o-H2O, p-H2O

NH_3

CCH

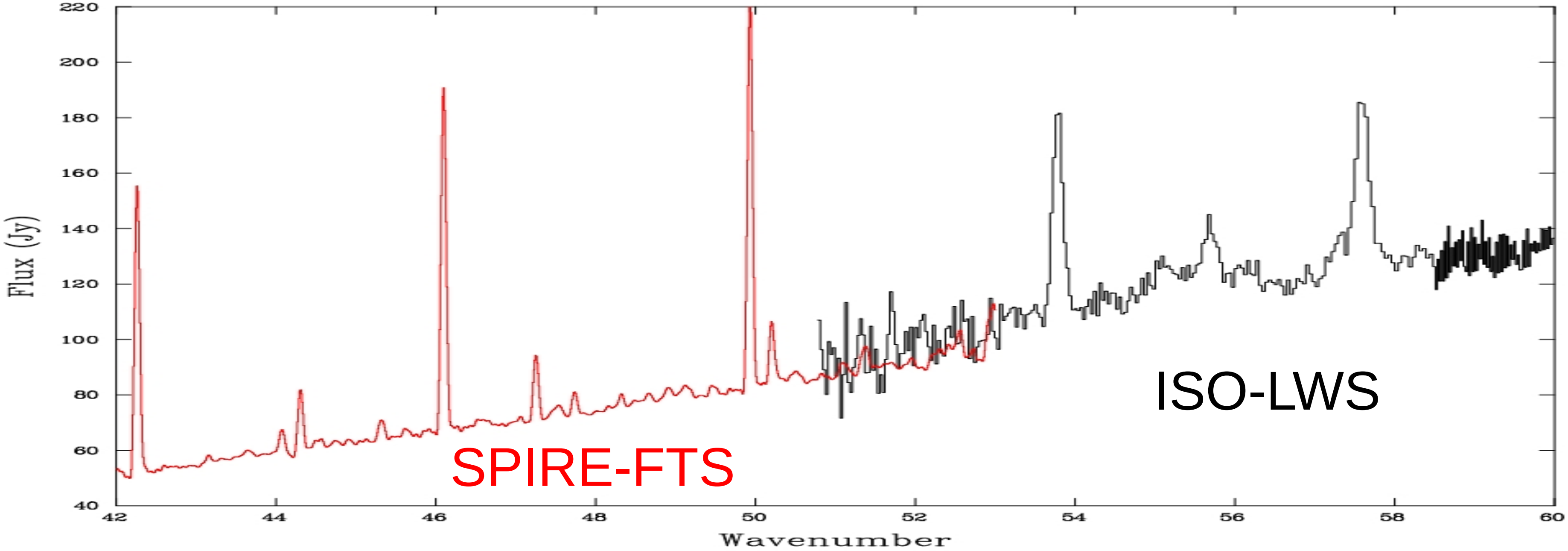
CS

HCl

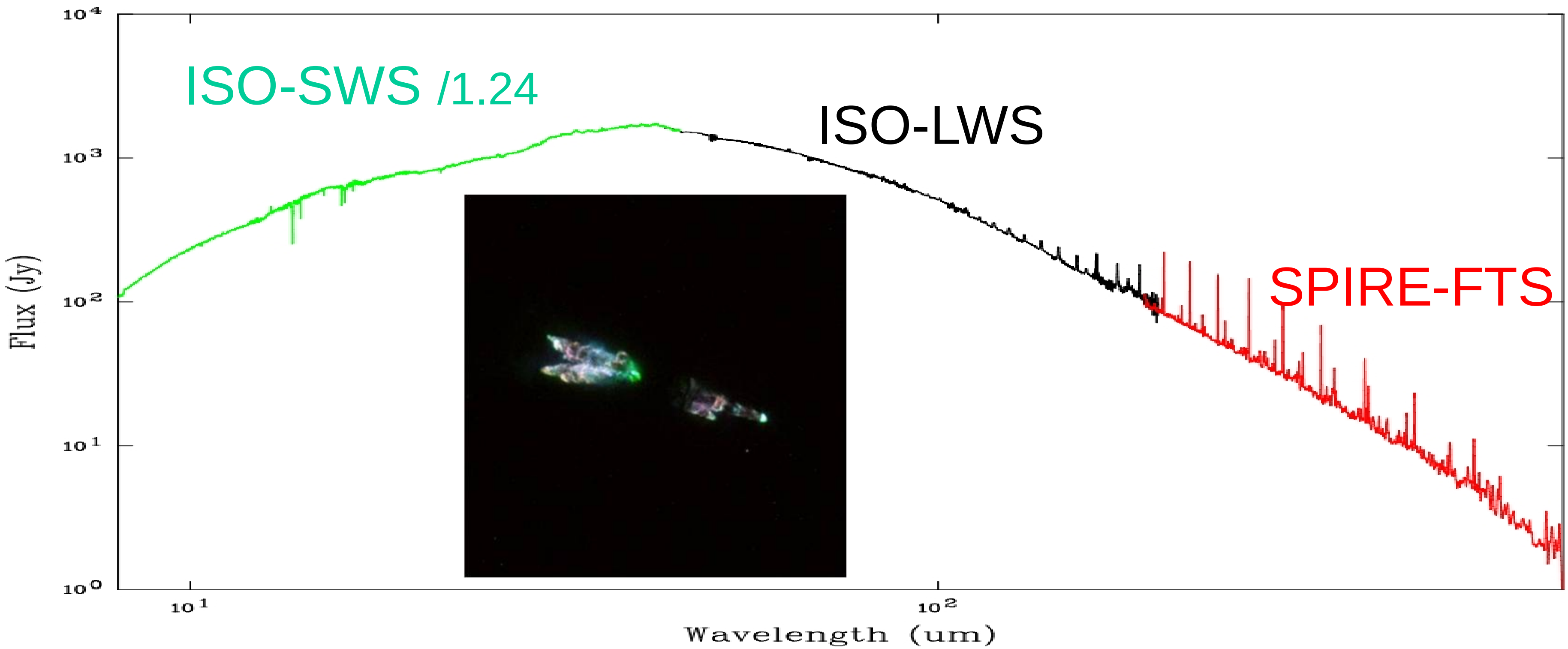


SPIRE
250um

AFGL 618



220
200
180
160
140
120
100
80
60
40
Flux (Jy)
42
44
46
48
50
52
54
56
58
60
Wavenumber
ISO-LWS
SPIRE-FTS

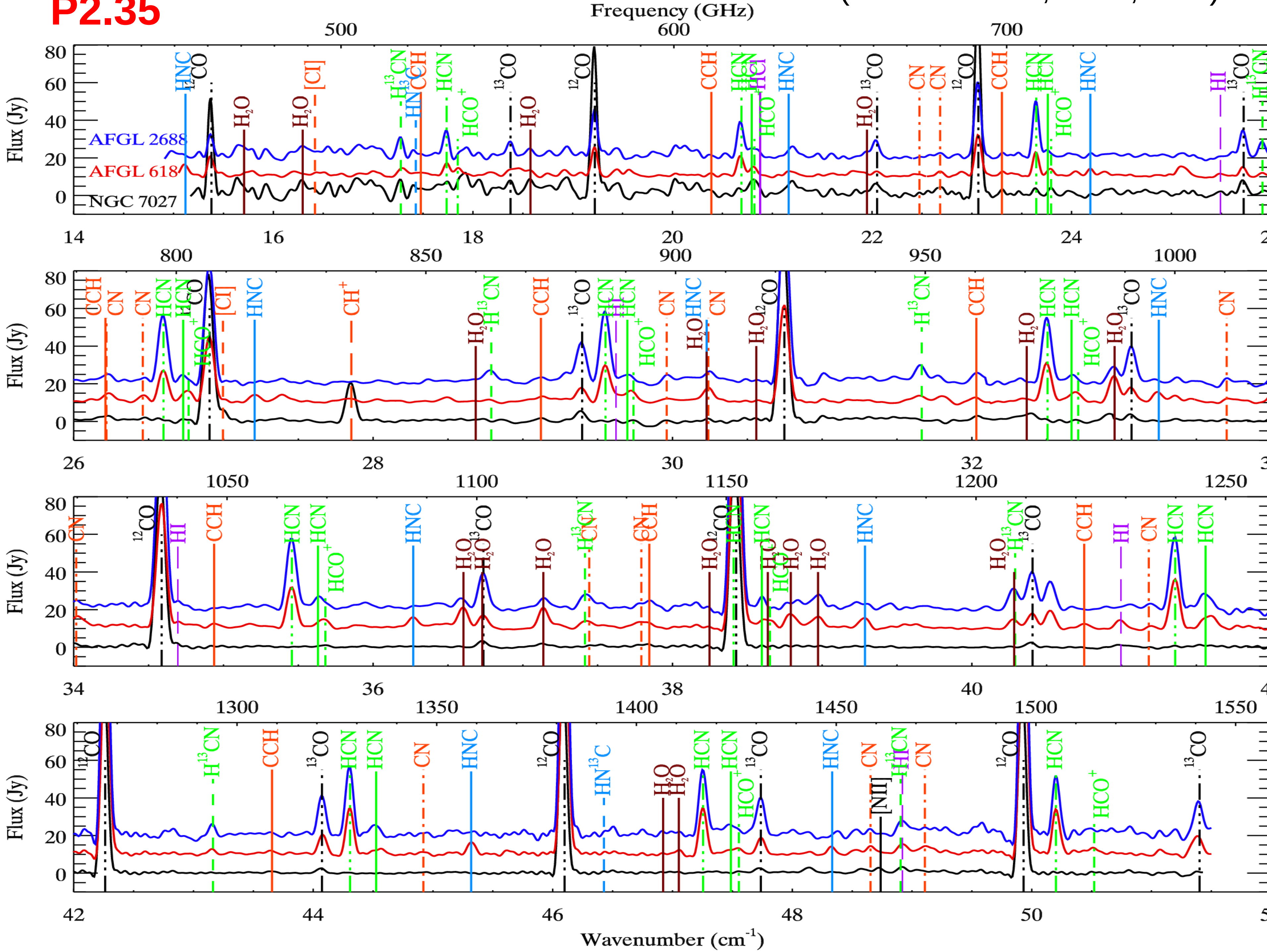


10^4
10^3
10^2
10^1
10^0
Flux (Jy)
10^1
10^2
Wavelength (um)
ISO-SWS /1.24
ISO-LWS
SPIRE-FTS

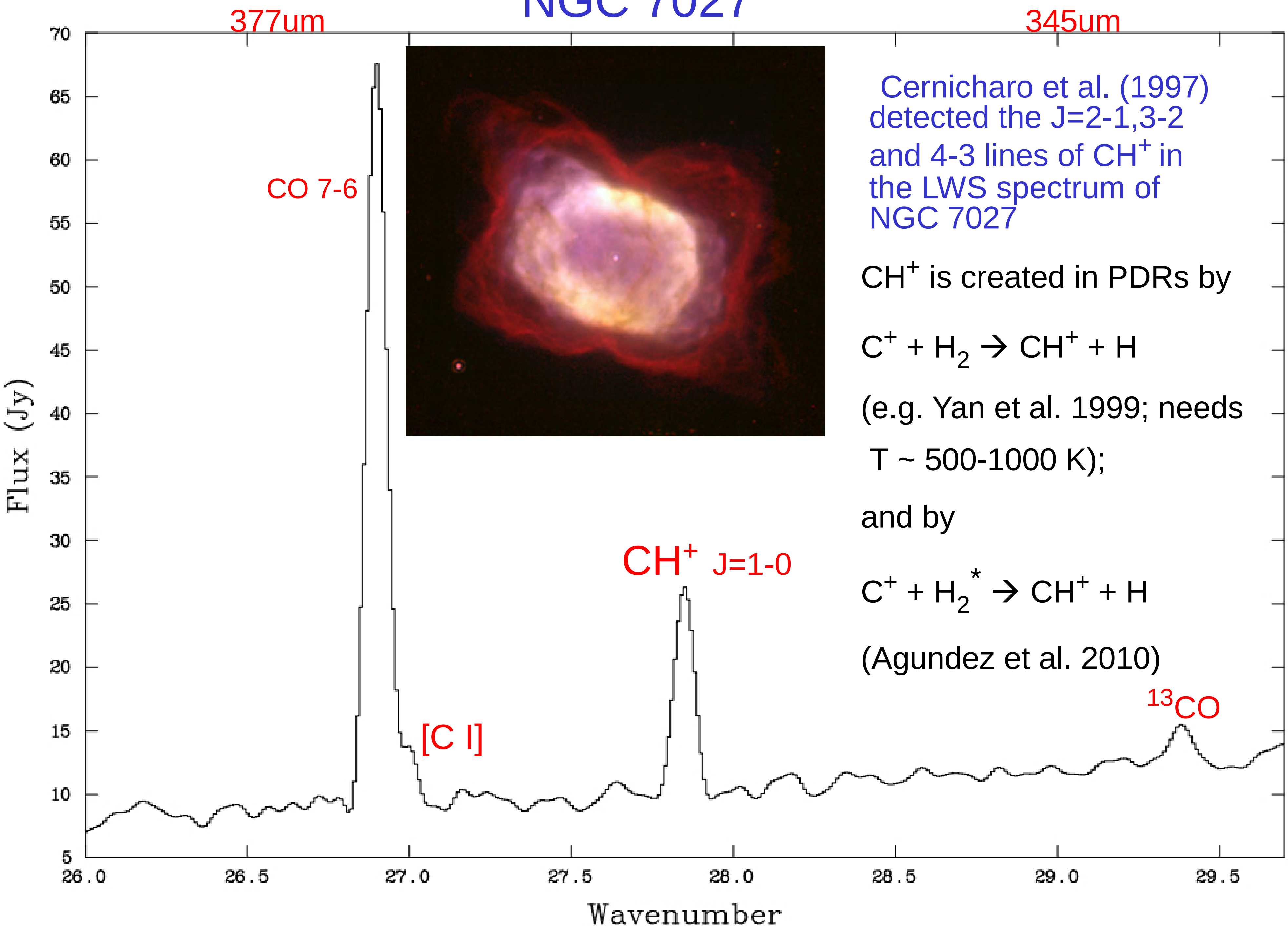
Continuum-subtracted FTS spectra of AFGL 2688, AFGL 618 and NGC 7027

(Wesson et al., 2010, A&A)

P2.35



NGC 7027



Cernicharo et al. (1997) detected the J=2-1,3-2 and 4-3 lines of CH^+ in the LWS spectrum of NGC 7027

CH^+ is created in PDRs by

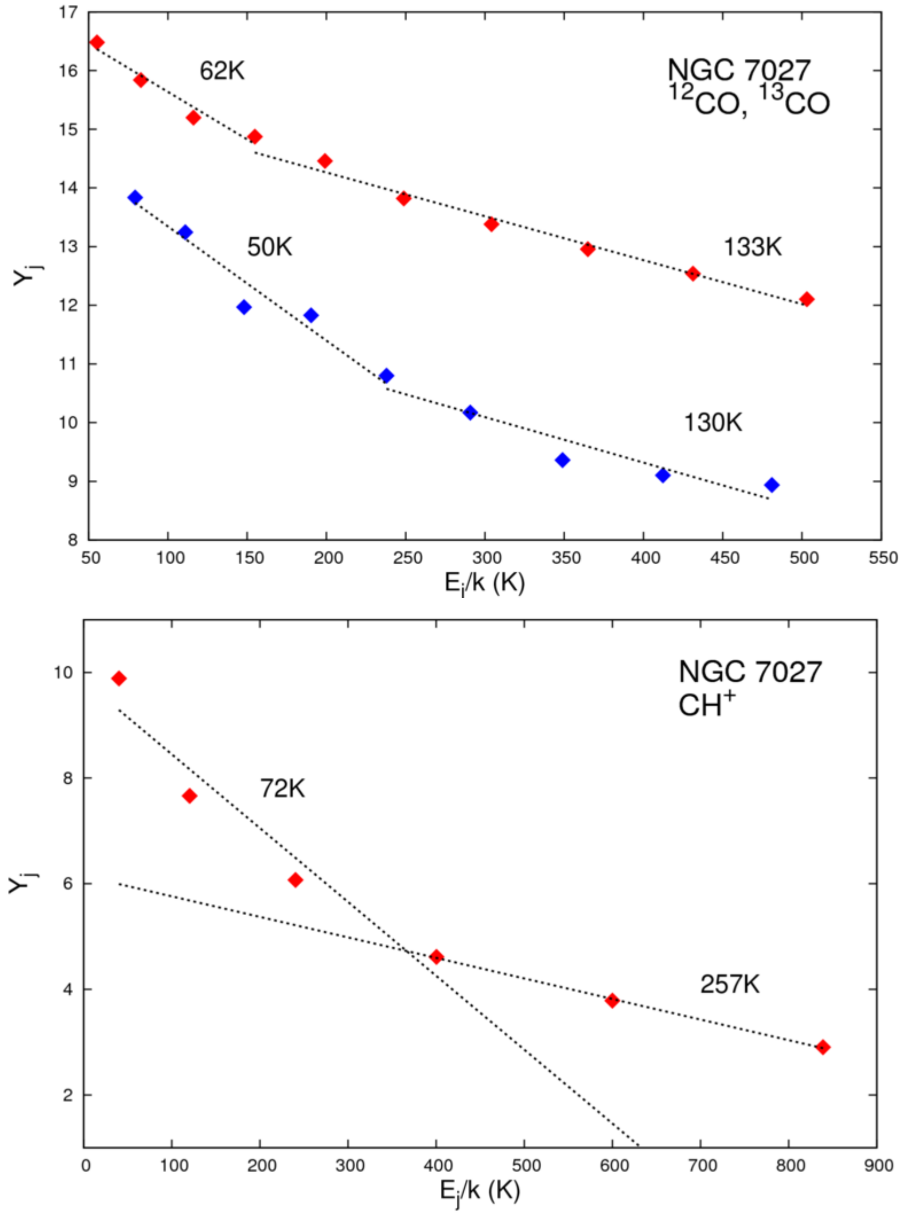
$C^+ + H_2 \rightarrow CH^+ + H$

(e.g. Yan et al. 1999; needs T ~ 500-1000 K);

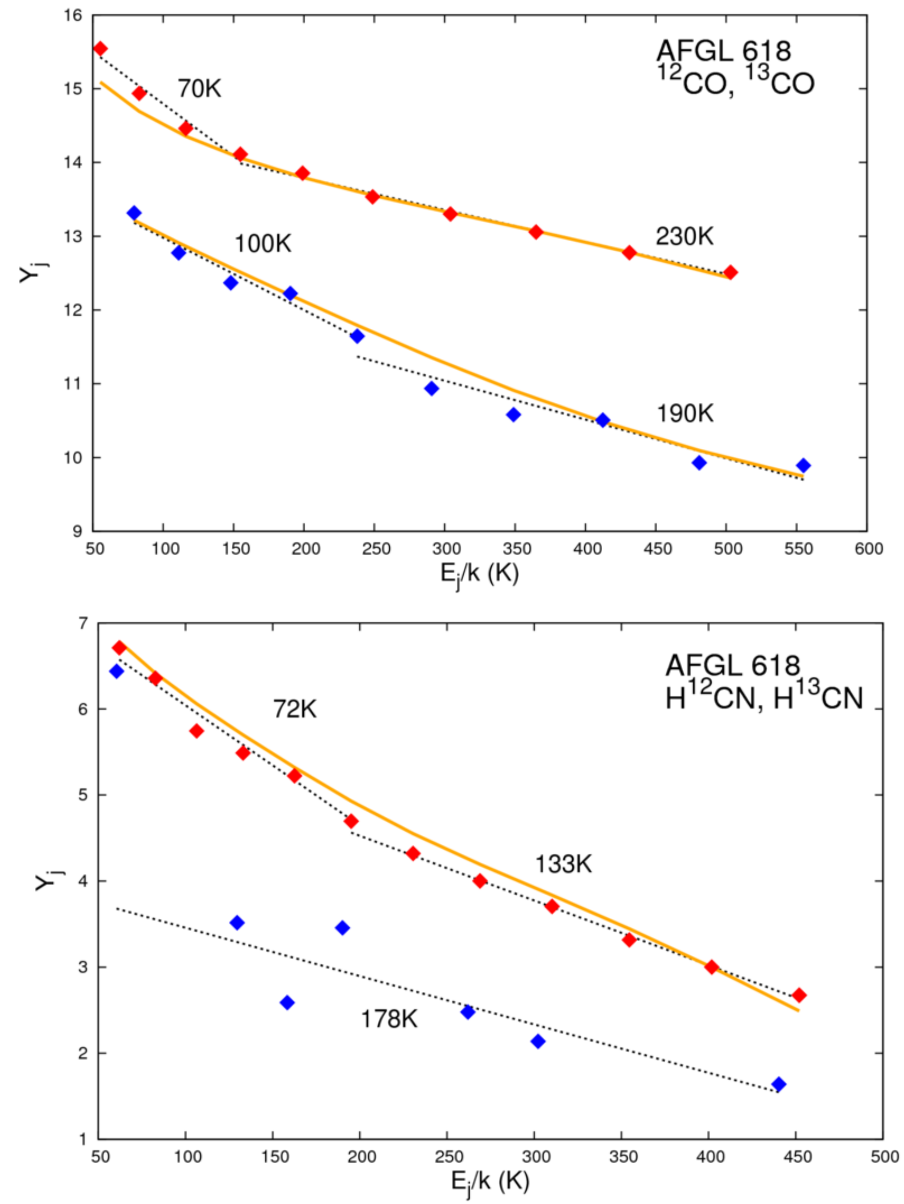
and by

$C^+ + H_2^* \rightarrow CH^+ + H$

(Agundez et al. 2010)



NGC 7027: fairly low rotational T_x's derived from CO and CH^+



AFGL 618: Orange curves: LVG models of Herpin & Cernicharo (2000) for $^{12}C/^{13}C$ =21

P2.35

MESS
Mass loss of Evolved StarS

PACS MESS team:

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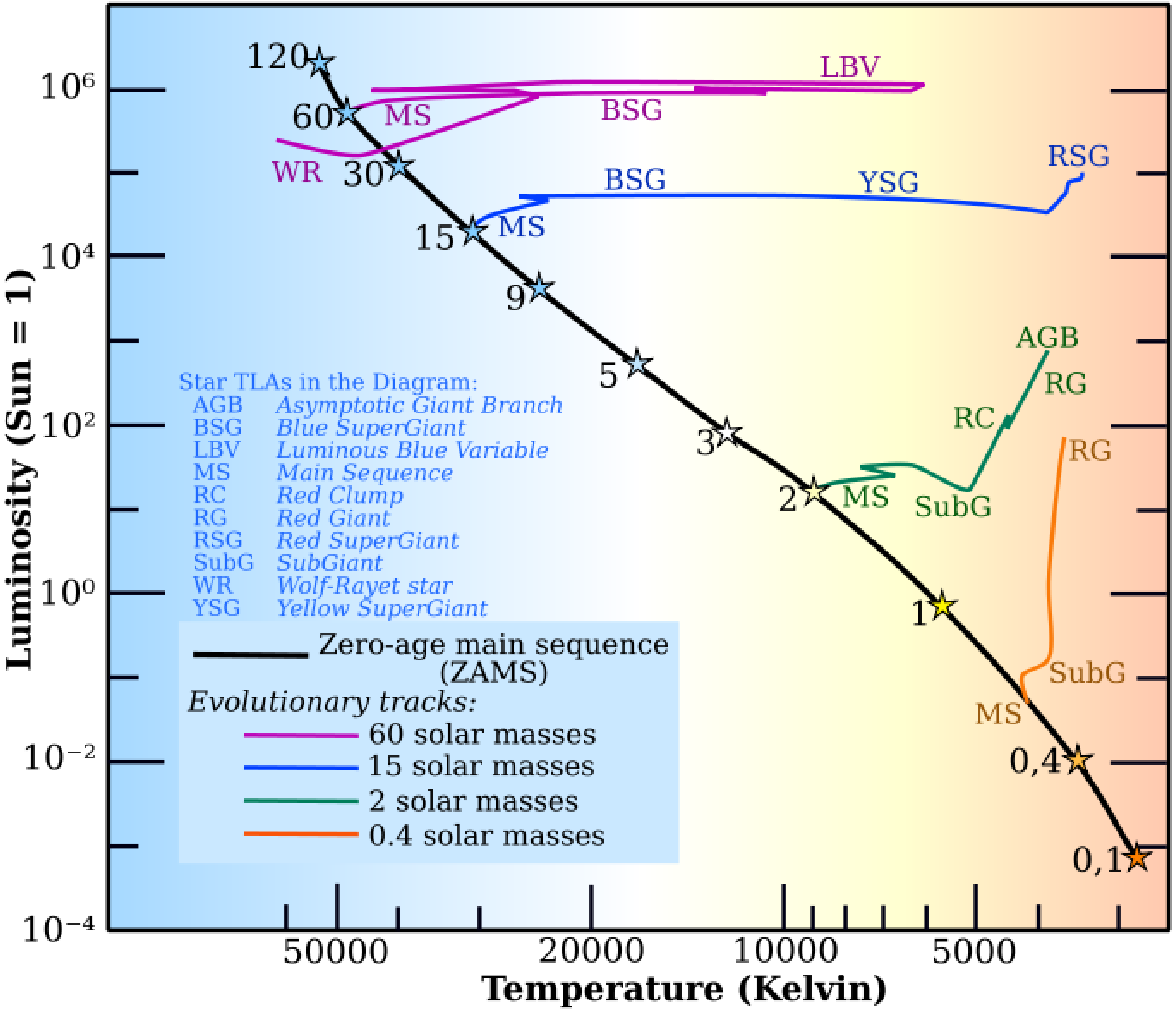
Hans Van Winckel
Oliver Krause
Angela Baier
Jeroen Bouwman
Thomas Henning
Damien Hutsemekers
Goeran Olofsson
Thomas Posch
Gregor Rauw
Eva Verdugo

PACS spectroscopy of evolved stars (55-210 µm)



*** 27 AGB/RSG**
*** 26 Post-AGB/PN**
*** 2 WR/LBV**

↓

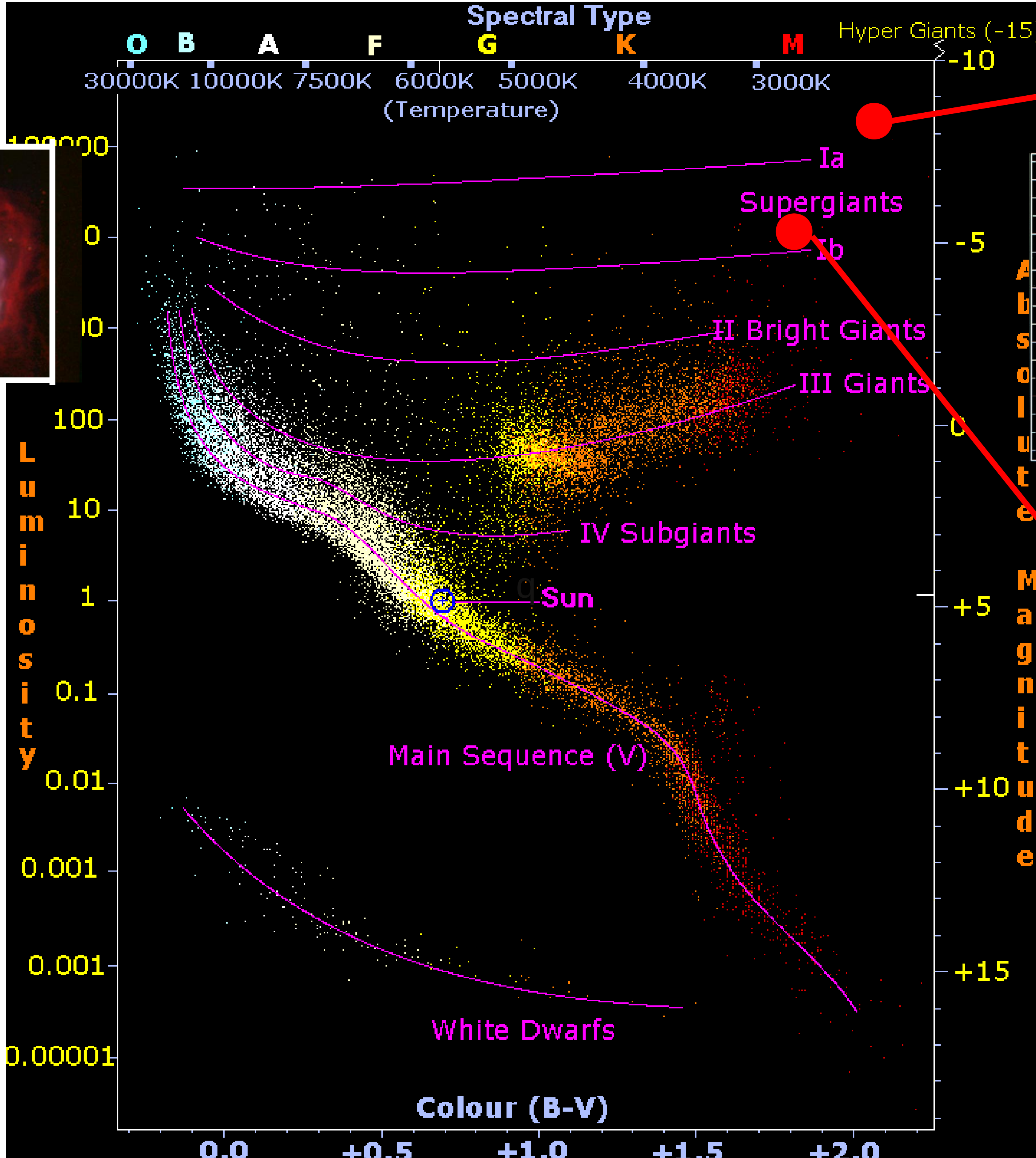
121 hours

*** different evolutionary phase**
*** different temperature, luminosity, mass**
*** different chemistry type**

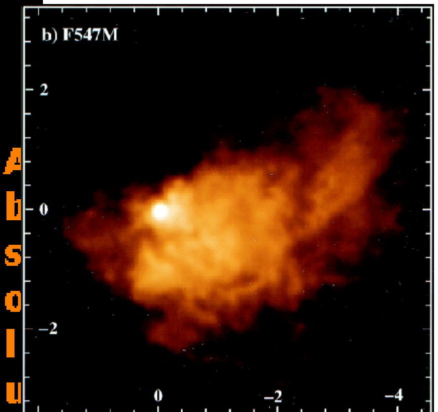
GOALS:

study mass-loss history, chemical processes, dust formation, ...

NGC 7027
C-rich PN
T_{eff}~140000K

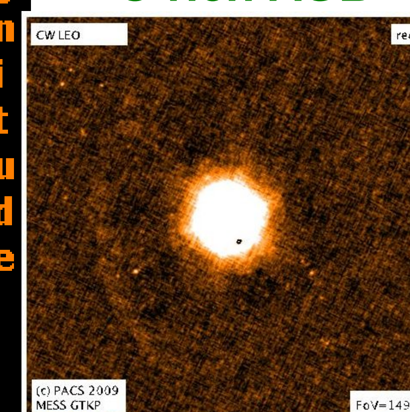


VY CMa
O-rich
supergiant



Smith et al., 2001

IRC+10216
C-rich AGB



PACS

PACS MESS spectroscopic A&A special issue papers

1. PACS and SPIRE Spectroscopy of the Red Supergiant VY CMa
   Royer et al.

2. Detection of Anhydrous Hydrochloric Acid, HCl, in IRC+10216 with the Herschel SPIRE and PACS spectrometers
   Cernicharo et al.

3. Silicon in the dust formation zone of IRC+10216
   Decin et al.

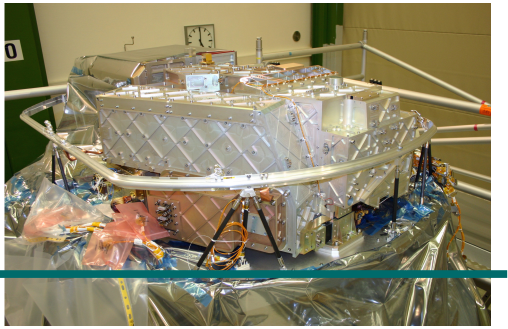
PACS MESS ESLAB posters

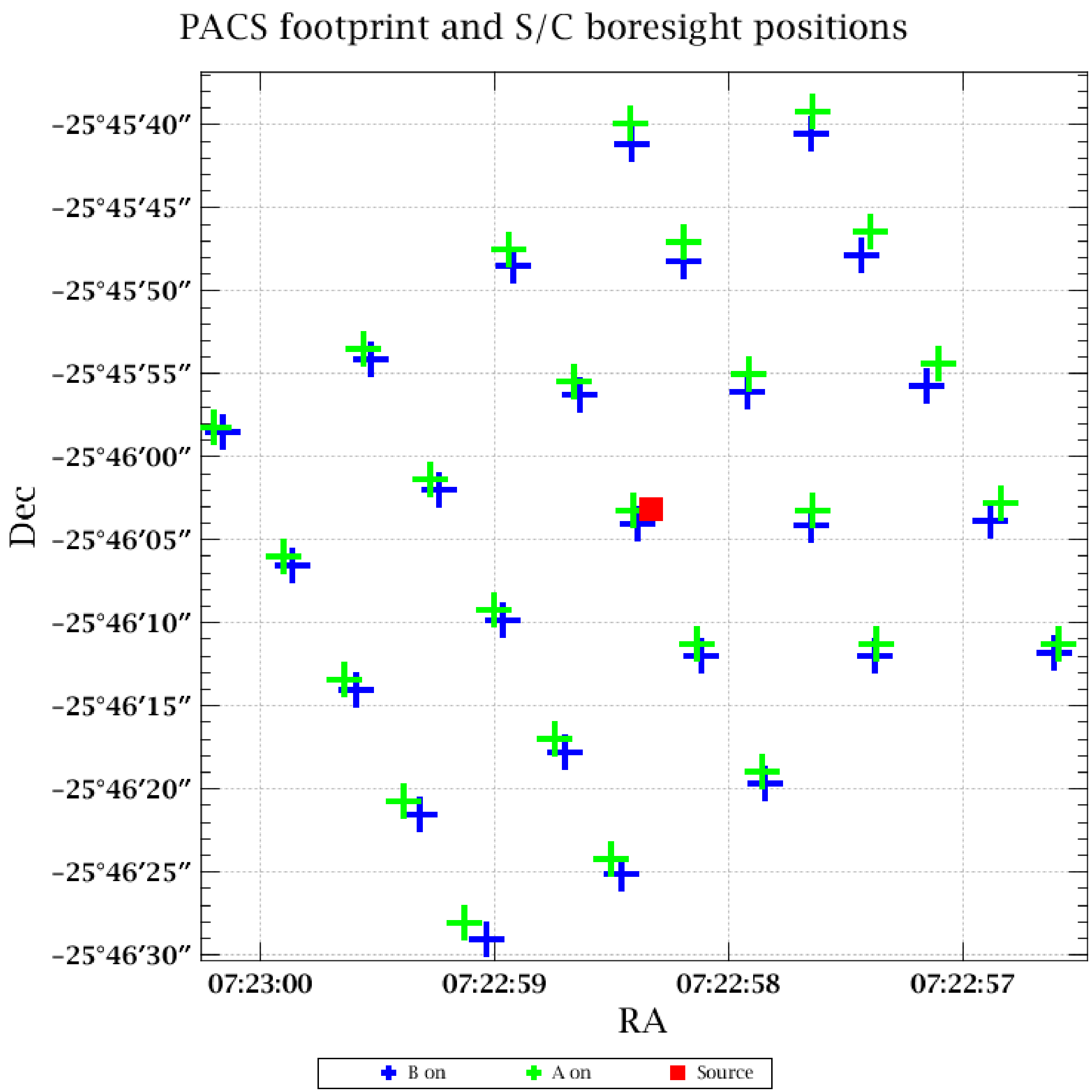
P 1.34 Hydrides in IRC+10216. Detectin of HCl with PACS and SPIRE
Cernicharo et al.

P 2.30 PACS and SPIRE Spectroscopy of the Red Supergiant VY CMa
Royer et al.

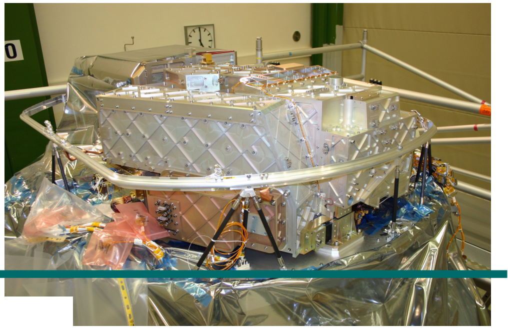
P 2.32 Unraveling the Chemical Complexity of VY CMa with the PACS and SPIRE Spectrometers
Matsuura et al.

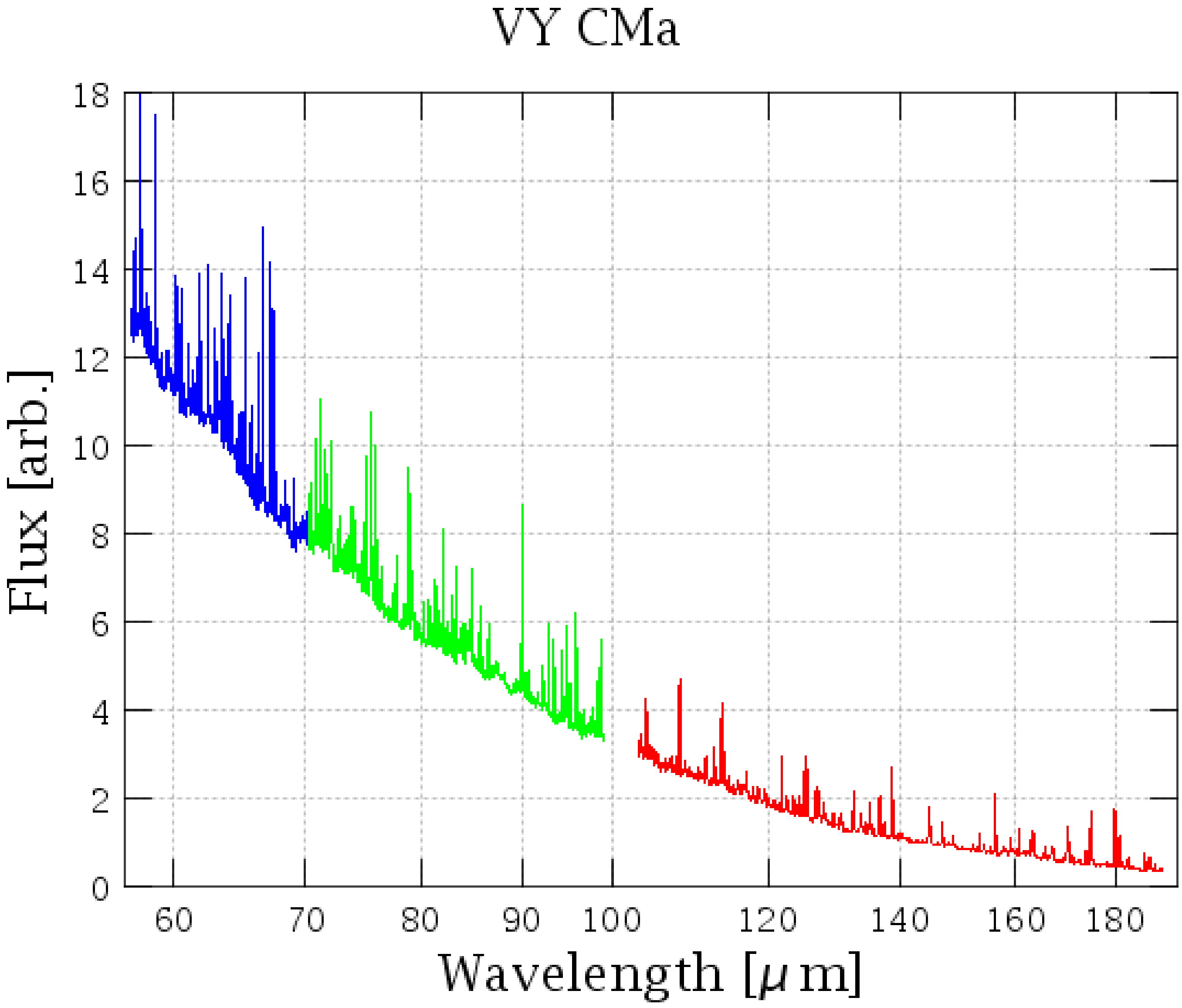
PACS observations

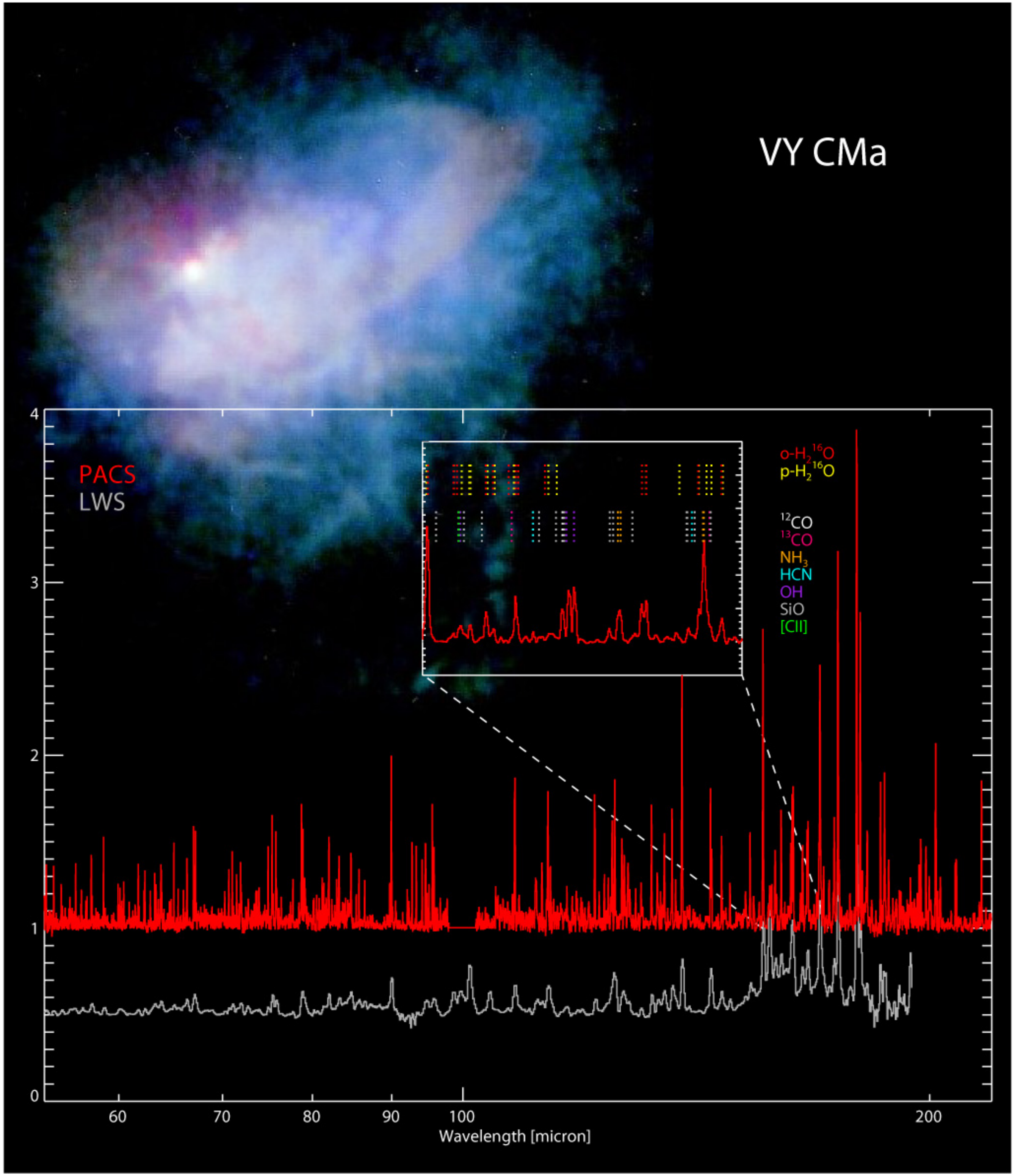




PACS observations







ESA-PR
27/11/2009

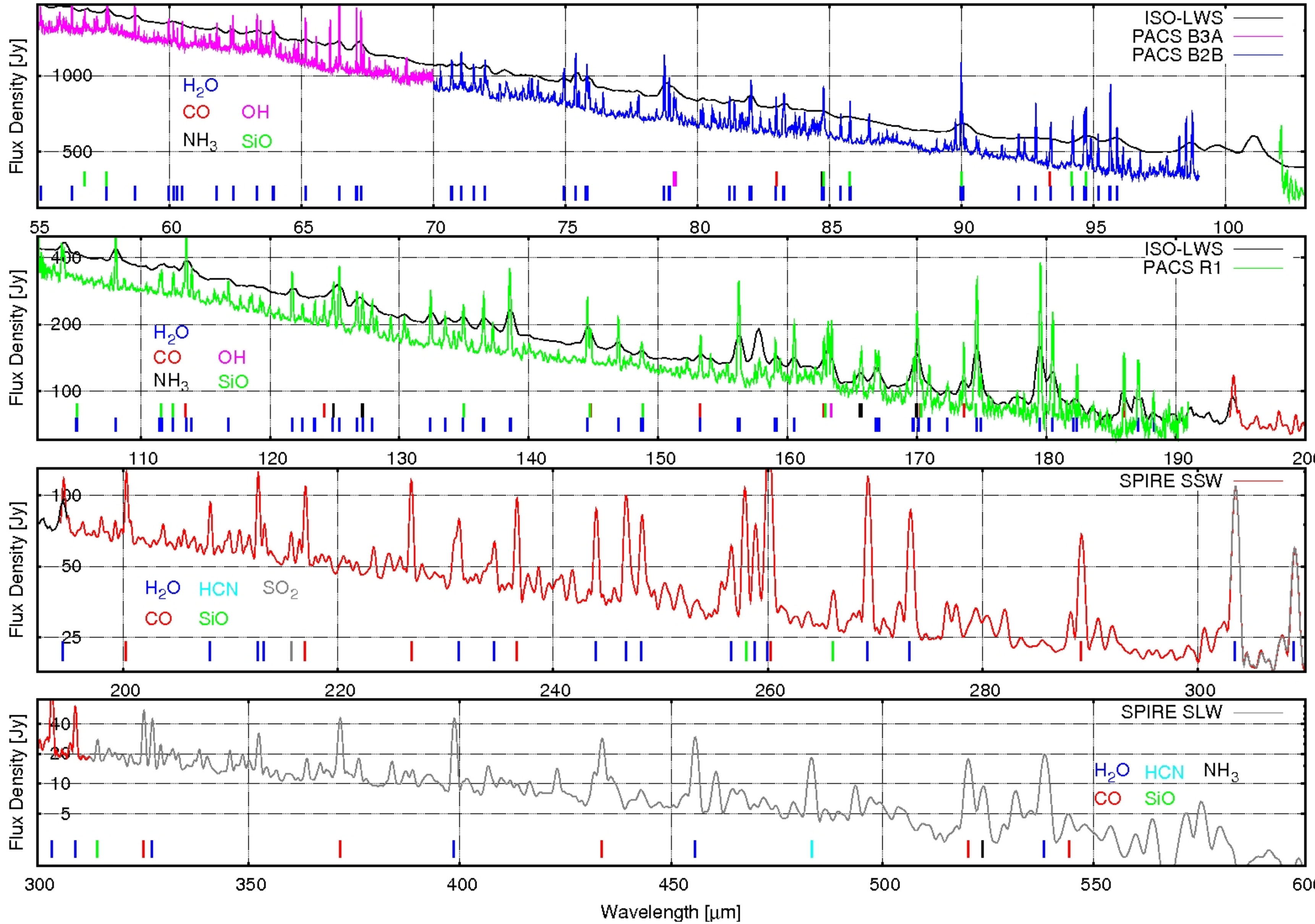
Spectral movie VY CMa

First spectroscopic results

Molecular inventory

VY CMa	IRC+10216
TOTAL: ~250 unblended	
o-H_2O, p-H_2O } 2/3 of all lines	
^{12}CO, ^{13}CO, $C^{17}O$, $C^{18}O$	
NH_3	
OH	
SiO	
HCN	
CN	
CS	
SO	
SiS	
H_3O^+?	
[C II]	
[O I] + unidentified lines	

First modeling results of VY CMa Royer et al. (2010)



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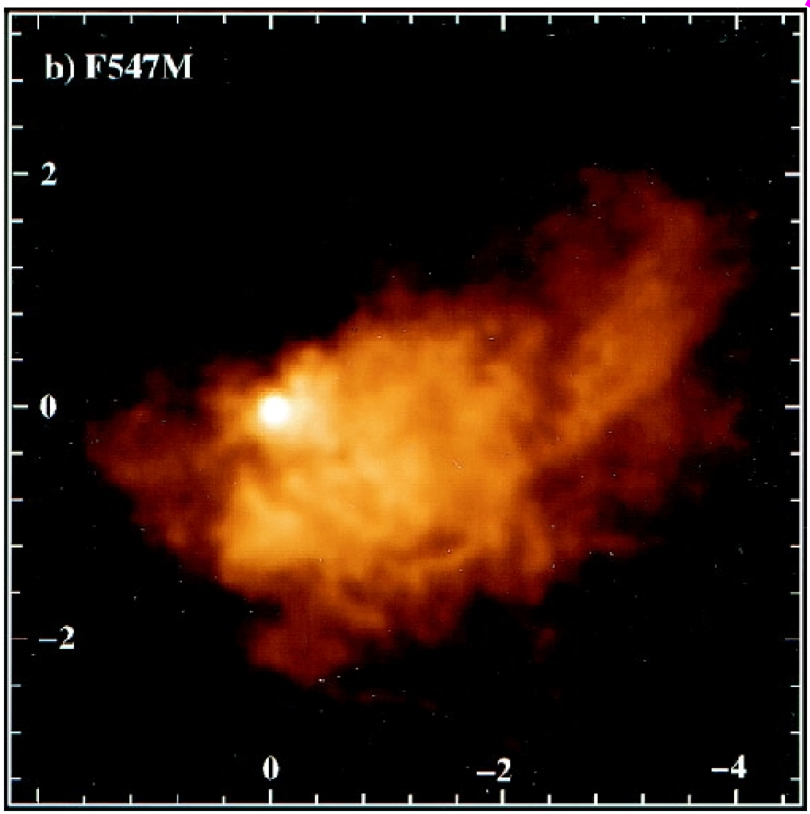
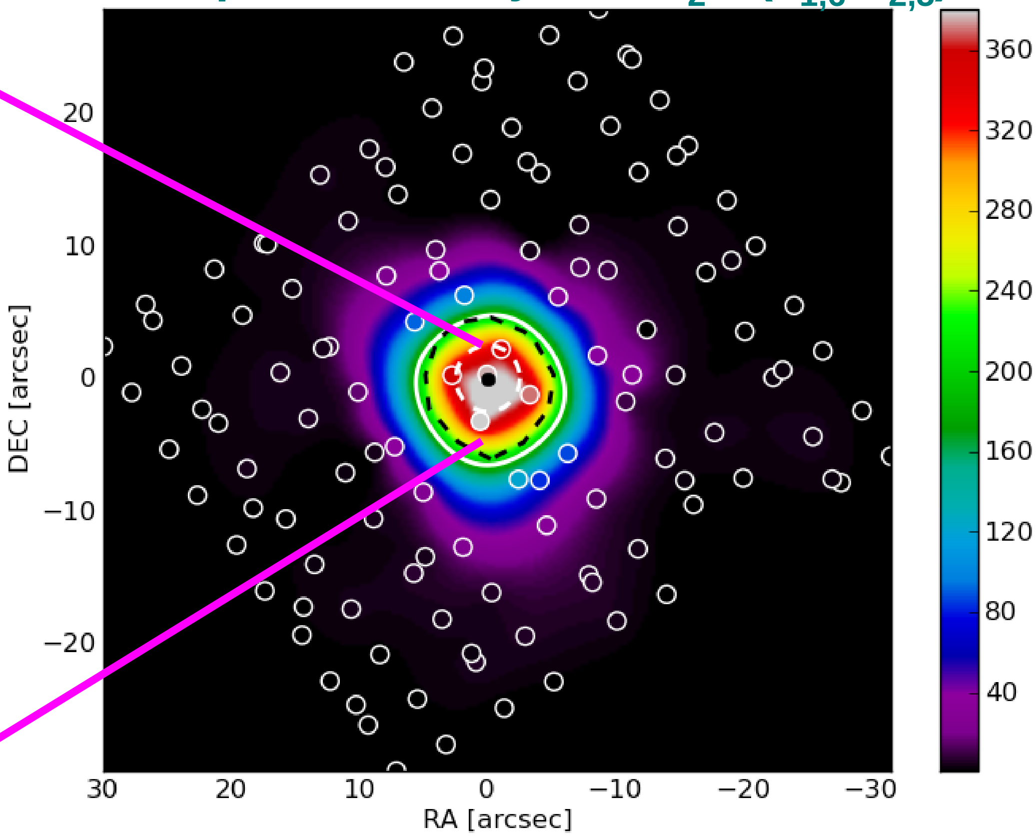


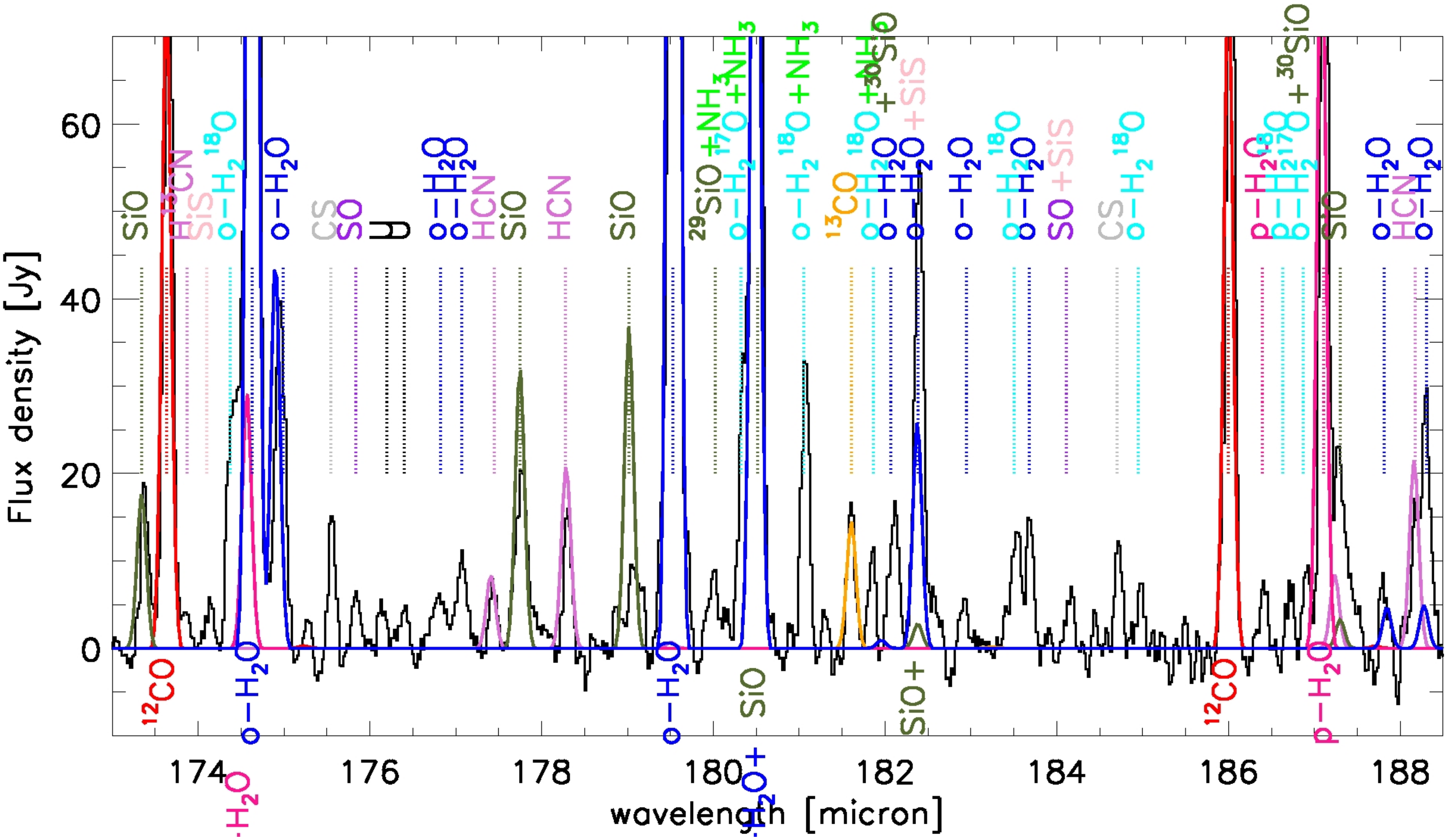
Smith et al. 2001

Line peak intensity of o-H_2O ($7_{1,6}$-$6_{2,5}$)



Black bullet: central target
White dashed contour: diffraction limited beam size at 66 μm (5")
Black dashed contour: instrumental PSF at half Maximum
Outer white contour: 50% of max. H_2O intensity

First modeling results of VY CMa
Royer et al. (2010)



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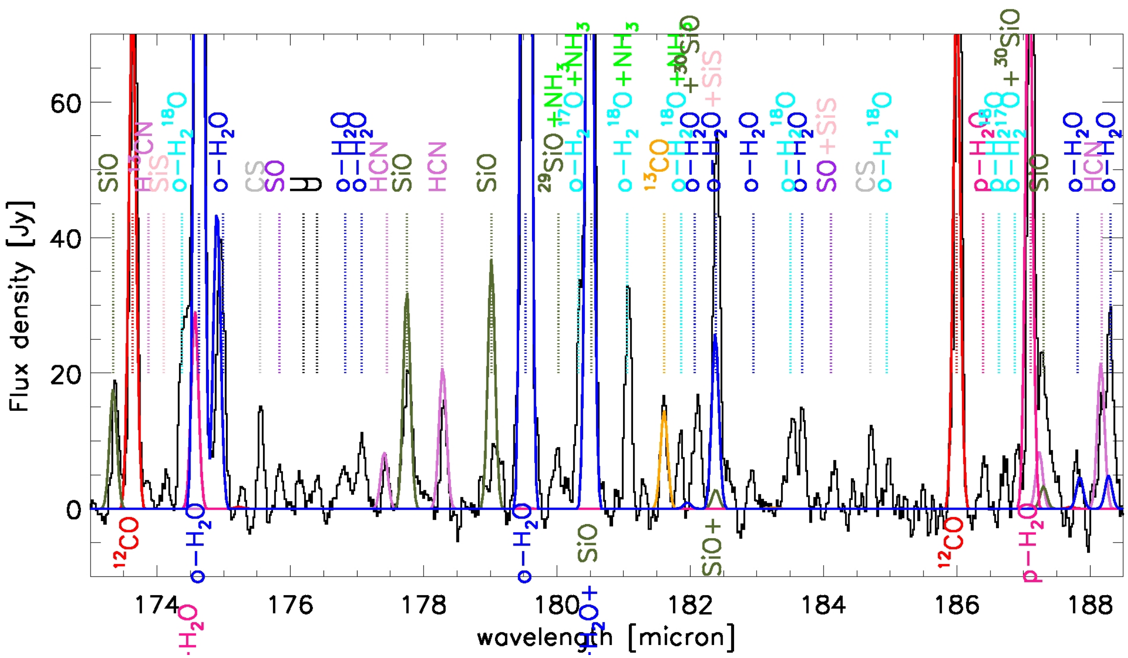


1D-non-LTE modeling

$T_* = 2800K$

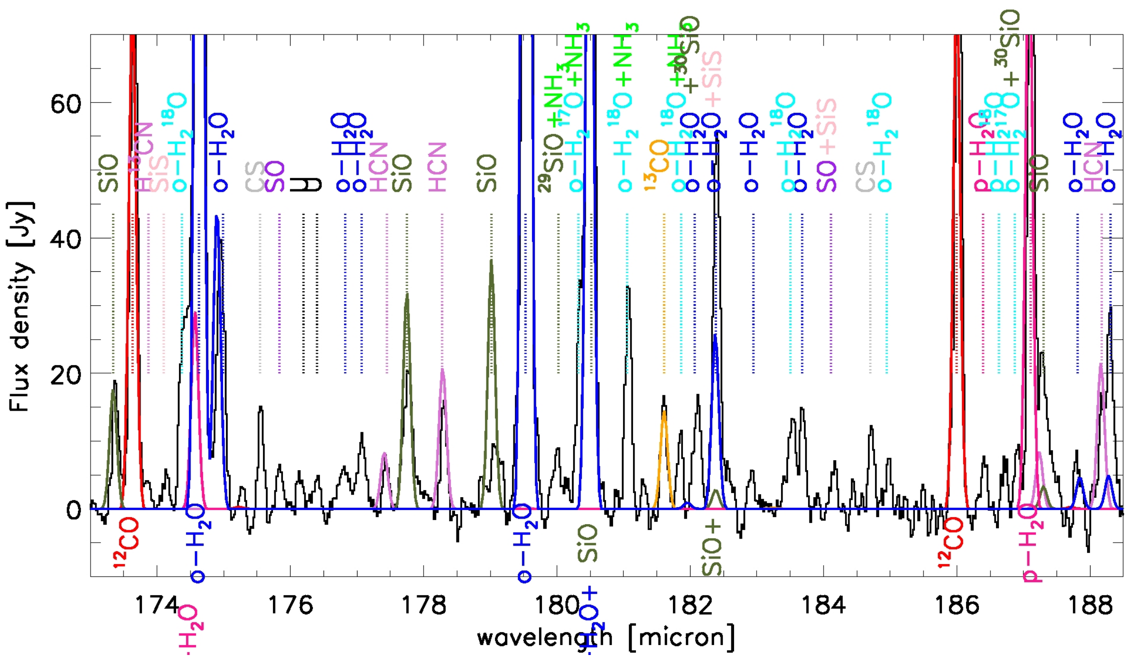
$M_* = 15\ M_{sun}$

$L_* = 3 \cdot 10^5\ L_{sun}$

D = 1140 pc

$[CO/H_2] = 3 \cdot 10^{-4}$

First modeling results of VY CMa
Royer et al. (2010)



1D-non-LTE modeling

$T_* = 2800K$

$M_* = 15\ M_{sun}$

$L_* = 3 \cdot 10^5\ L_{sun}$

D = 1140 pc

$[CO/H_2] = 3 \cdot 10^{-4}$

$\dot{M} = 1.5 \cdot 10^{-4}\ M_{sun}/yr$

$^{12}C/^{13}C = 60$

$[SiO/H_2] = 4.5 \cdot 10^{-5}$

$[H_2O/H_2] \approx 3 \cdot 10^{-4}$

$[HCN/H_2] = 4.5 \cdot 10^{-6}$

First modeling results of VY CMa
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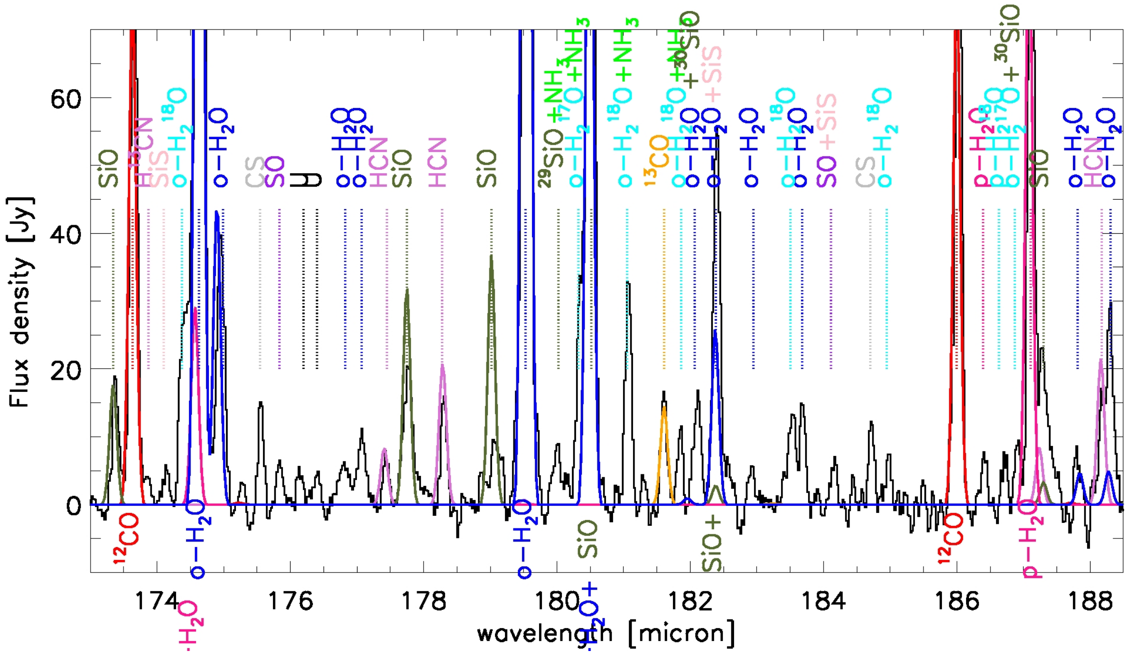

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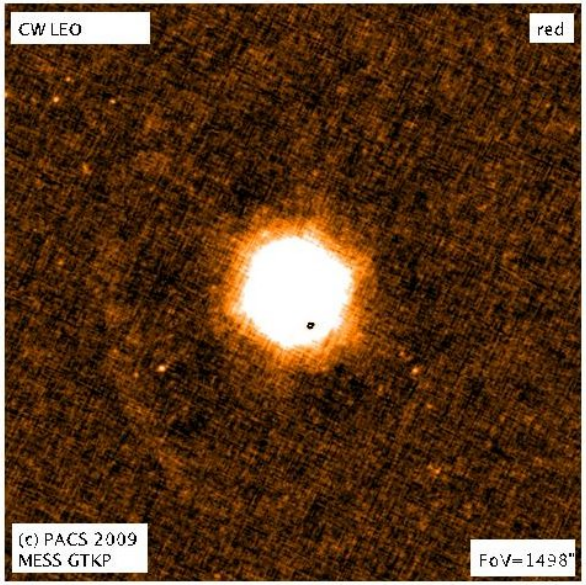
$[H_2O/H_2] \approx 3 \cdot 10^{-4}$

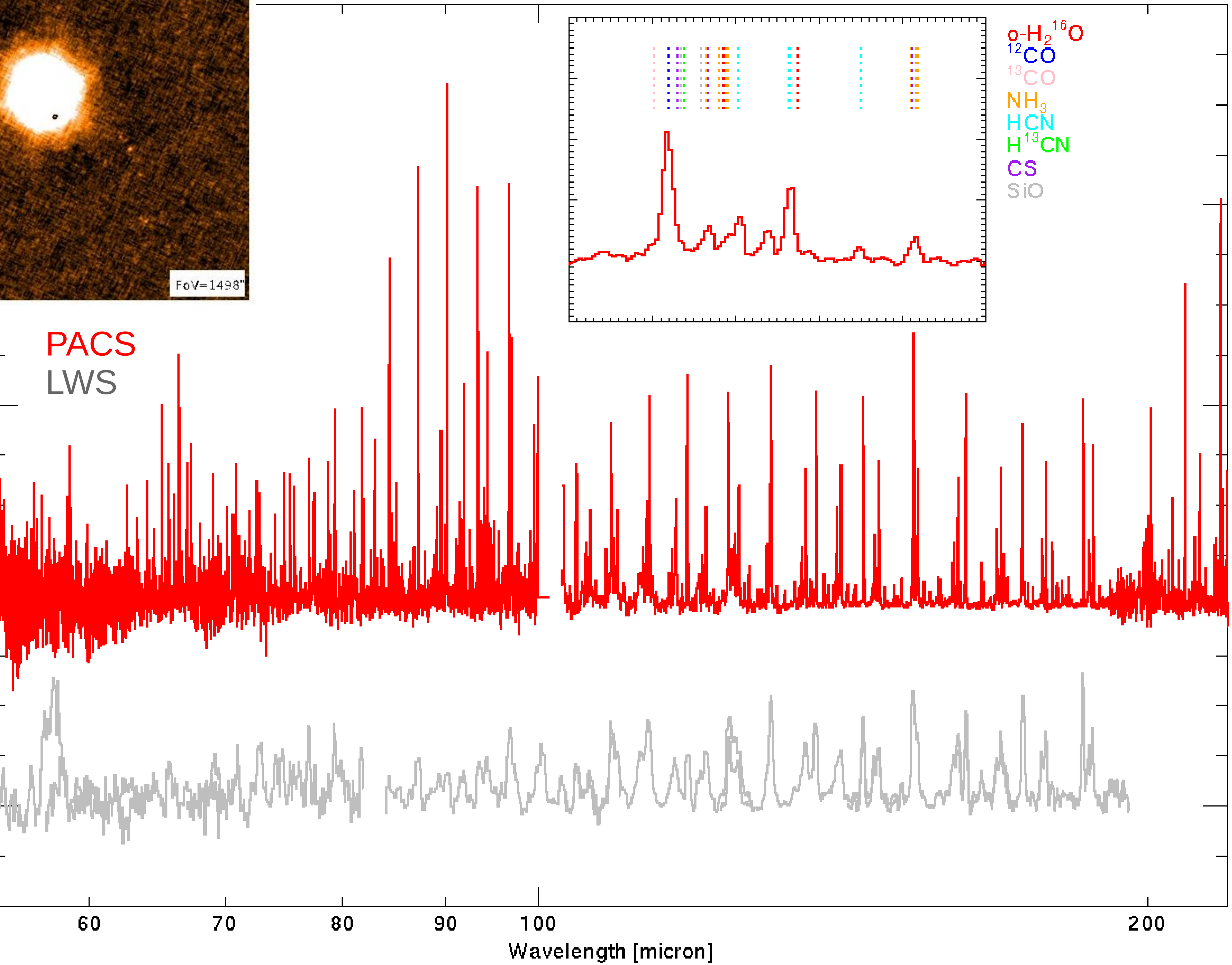
$[HCN/H_2] = 4.5 \cdot 10^{-6}$

ortho-to-para ratio 1.27:1

non-equilibrium chemistry

IRC+10216


CW LEO
red
(c) PACS 2009
MESS GTKP
FoV=1498"


o-H2 16O
12CO
13CO
NH3
HCN
H13CN
CS
SiO
PACS
LWS
200
0
-200
Flux [Jy]
60
70
80
90
100
200
Wavelength [micron]

First spectroscopic results

Molecular inventory

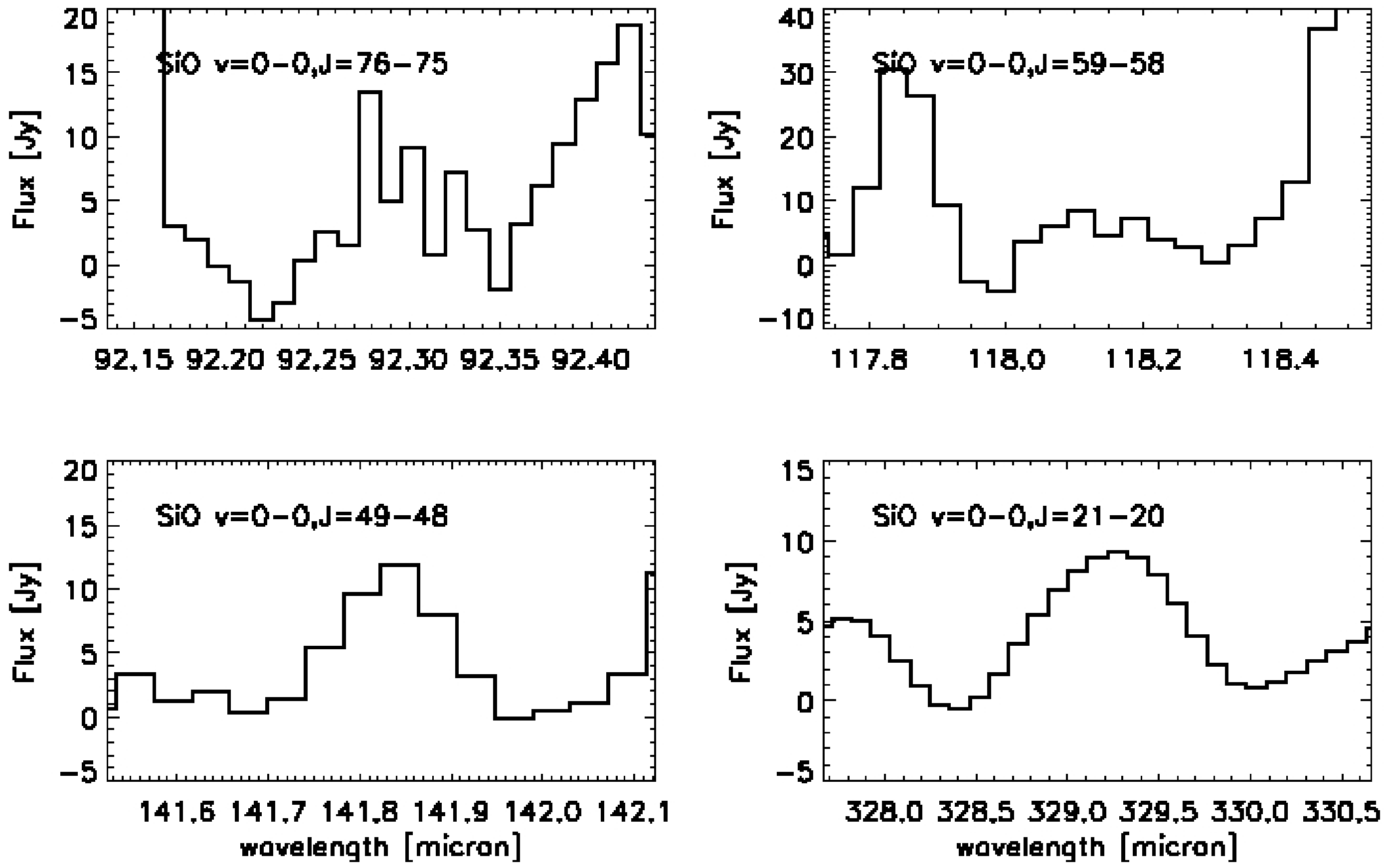
VY CMa	IRC+10216
TOTAL: ~250 unblended	TOTAL: ~250 unblended
o-H_2O, p-H_2O } 2/3 of all lines	$H^{12}CN$, $H^{13}CN$ } 1/2 of all lines
^{12}CO, ^{13}CO, $C^{17}O$, $C^{18}O$	^{12}CO, ^{13}CO, $C^{18}O$
NH_3	o-H_2O
OH	p-H_2O
SiO	NH_3
HCN	SiS
CN	SiO
CS	CS
SO	C_3
SiS	C_2H
H_3O^+?	HCl
[C II]	
[O I]	
+ unidentified lines	+ unidentified lines

First spectroscopic results

Molecular inventory

VY CMa	IRC+10216
TOTAL: ~250 unblended	TOTAL: ~250 unblended
o-H_2O } 2/3 of all lines	$H^{12}CN$ } 1/2 of all lines
p-H_2O }	$H^{13}CN$ }
^{12}CO, ^{13}CO, $C^{17}O$, $C^{18}O$	^{12}CO, ^{13}CO, $C^{18}O$
NH_3	o-H_2O
OH	p-H_2O
SiO	NH_3
HCN	SiS
CN	SiO
CS	CS
SO	C_3
SiS	C_2H
H_3O^+?	HCl
[C II]	
[O I]	
+ unidentified lines	+ unidentified lines

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)



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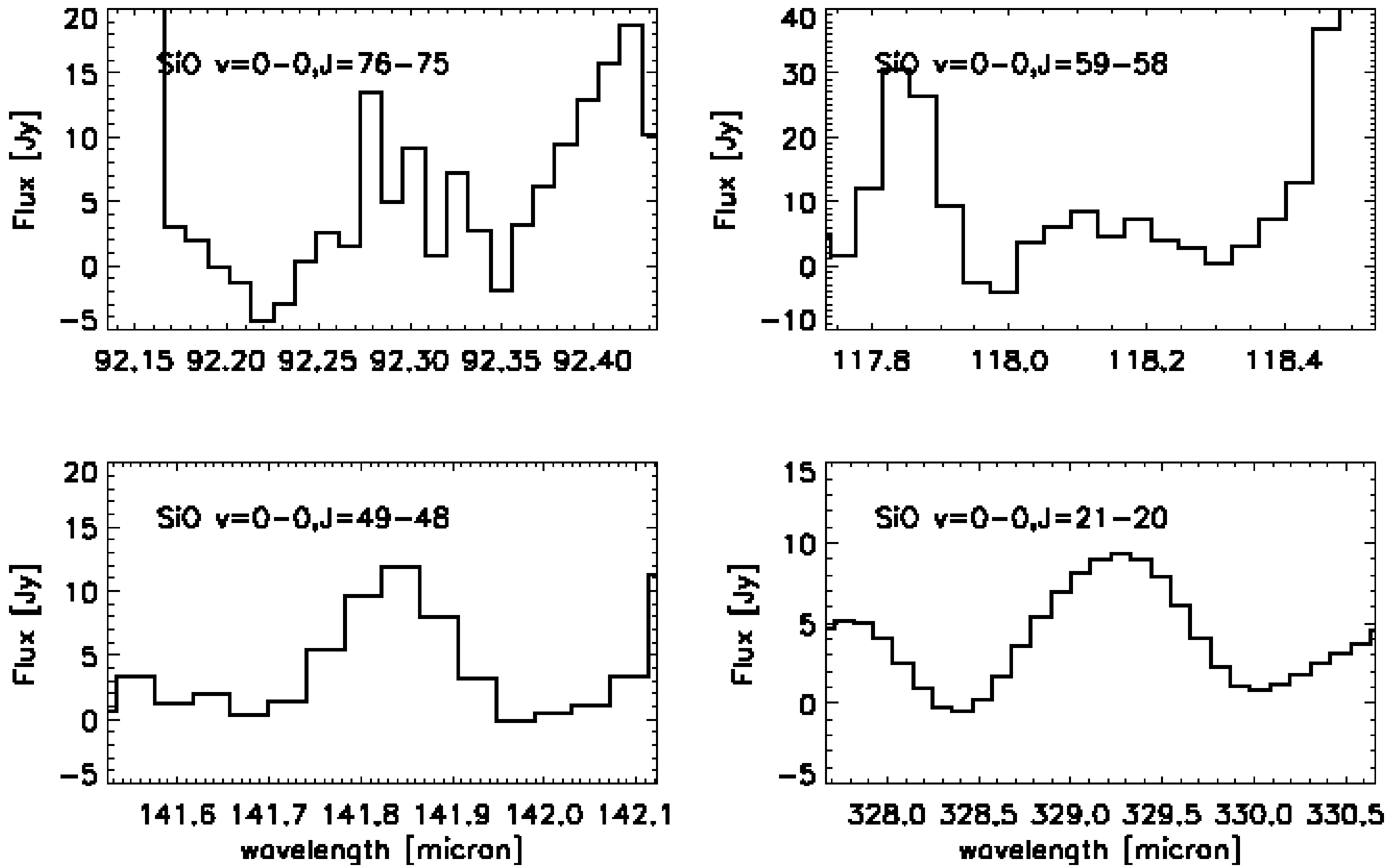
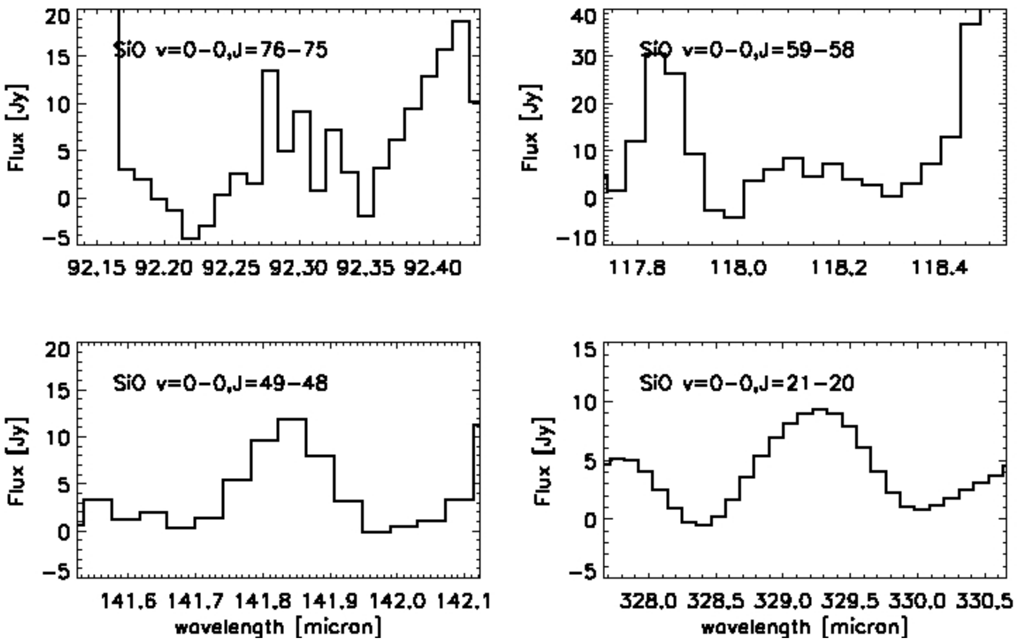


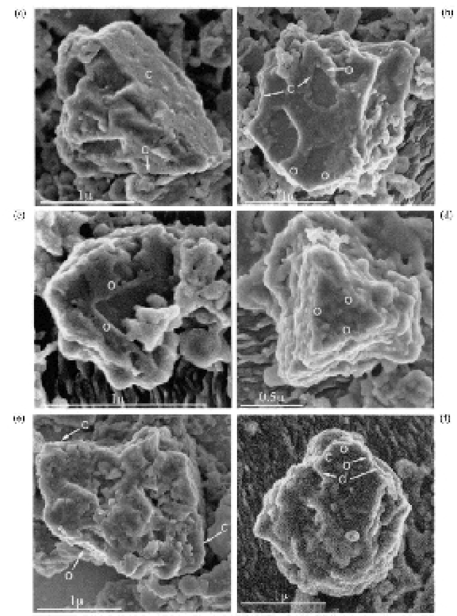
High J lines of SiO and SiS: trace dust formation zone

SiO : J=11-10 to J=90-89 (E_{up} = 8432 K)

SiS: J=26-25 to J = 124-123 (E_{up} = 6678 K)

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)





Role in AGB dust formation?

High J lines of SiO and SiS: trace dust formation zone

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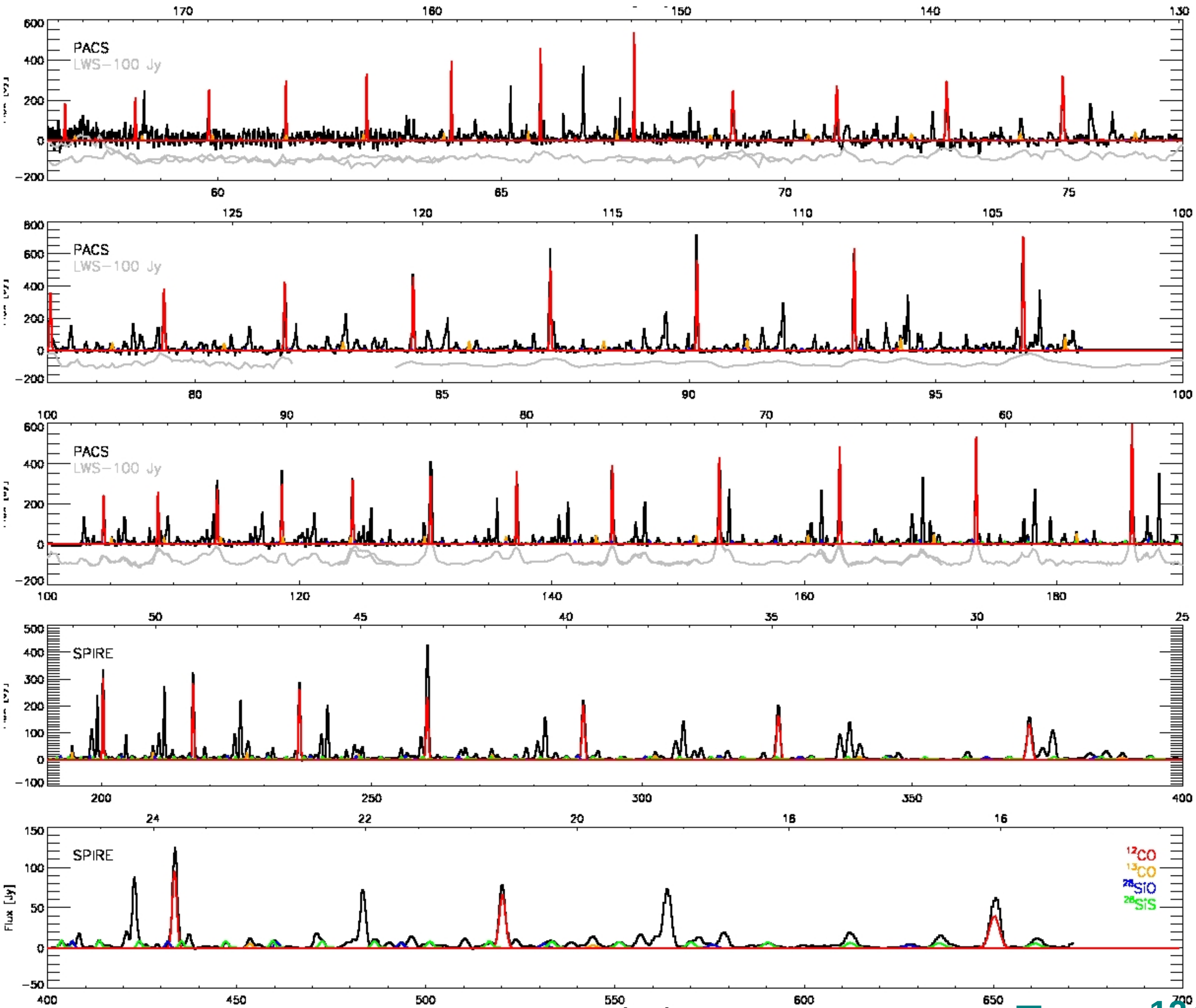

1D non-LTE modeling

$T_* = 2050K$

$M_* = 1\ M_{sun}$

$L_* = 8.1\ 10^3\ L_{sun}$

$D = 150$ pc

$[CO/H_2] = 1 \cdot 10^{-3}$

From ^{12}CO and ^{13}CO lines:
J=3 (at 31 K) to J=47 (at 5853 K)
determine thermophysical structure in envelope

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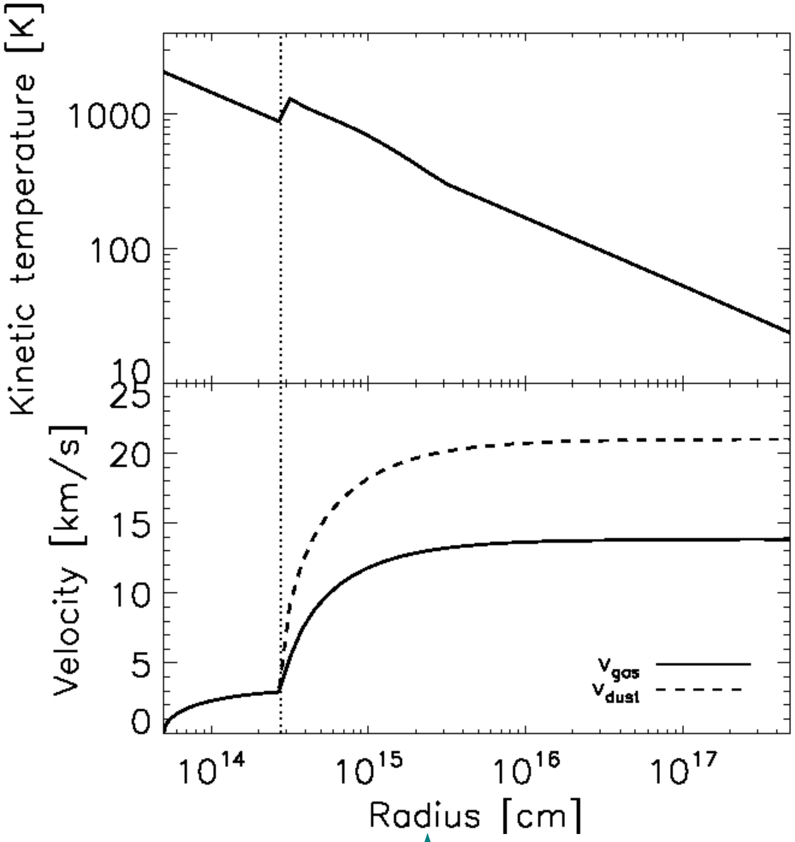

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determine thermophysical structure in envelope

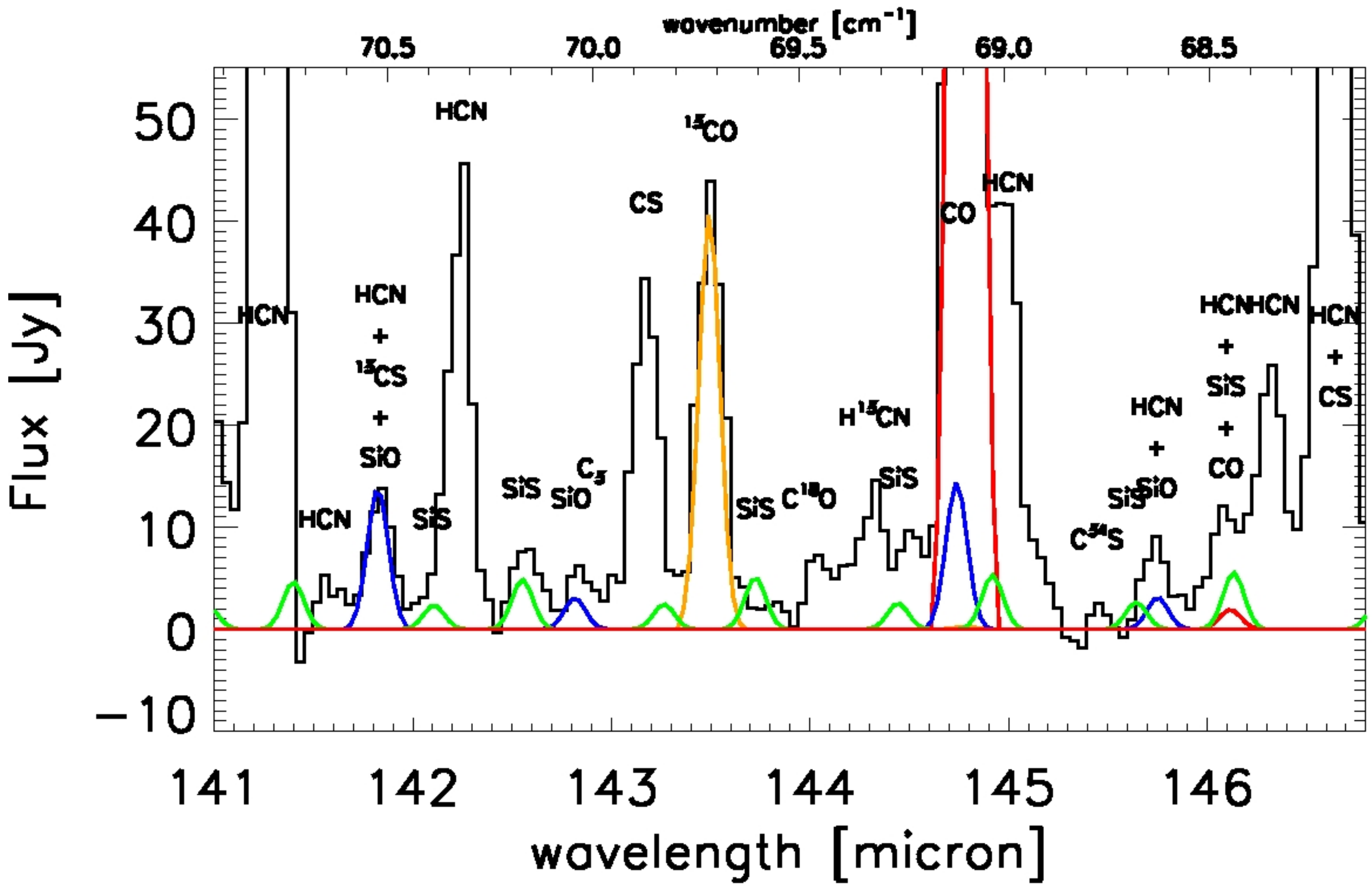
$\dot{M} = 1 \times 10^{-5}\ M_{sun}/yr$
$^{12}CO/^{13}CO=30$

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

$[SiO/H_2] = 1 \times 10^{-7}$

$[SiS/H_2] = 4 \times 10^{-6}$



Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

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Schoier et al. (2006): from SiO J=2-1 to J=5-4 + interferometric map of SiO J=5-4:

$R<3R_*$: $[SiO/H_2] = 3 \times 10^{-8}$ → TE-value

$3<R<8R_*$: $[SiO/H_2] = 1.5 \times 10^{-6}$ → Grain surfaces act as catalyst and/or pulsationally induced non-TE chemistry

$R>8R_*$: $[SiO/H_2] = 1.7 \times 10^{-7}$ → Freeze out onto dust-grains

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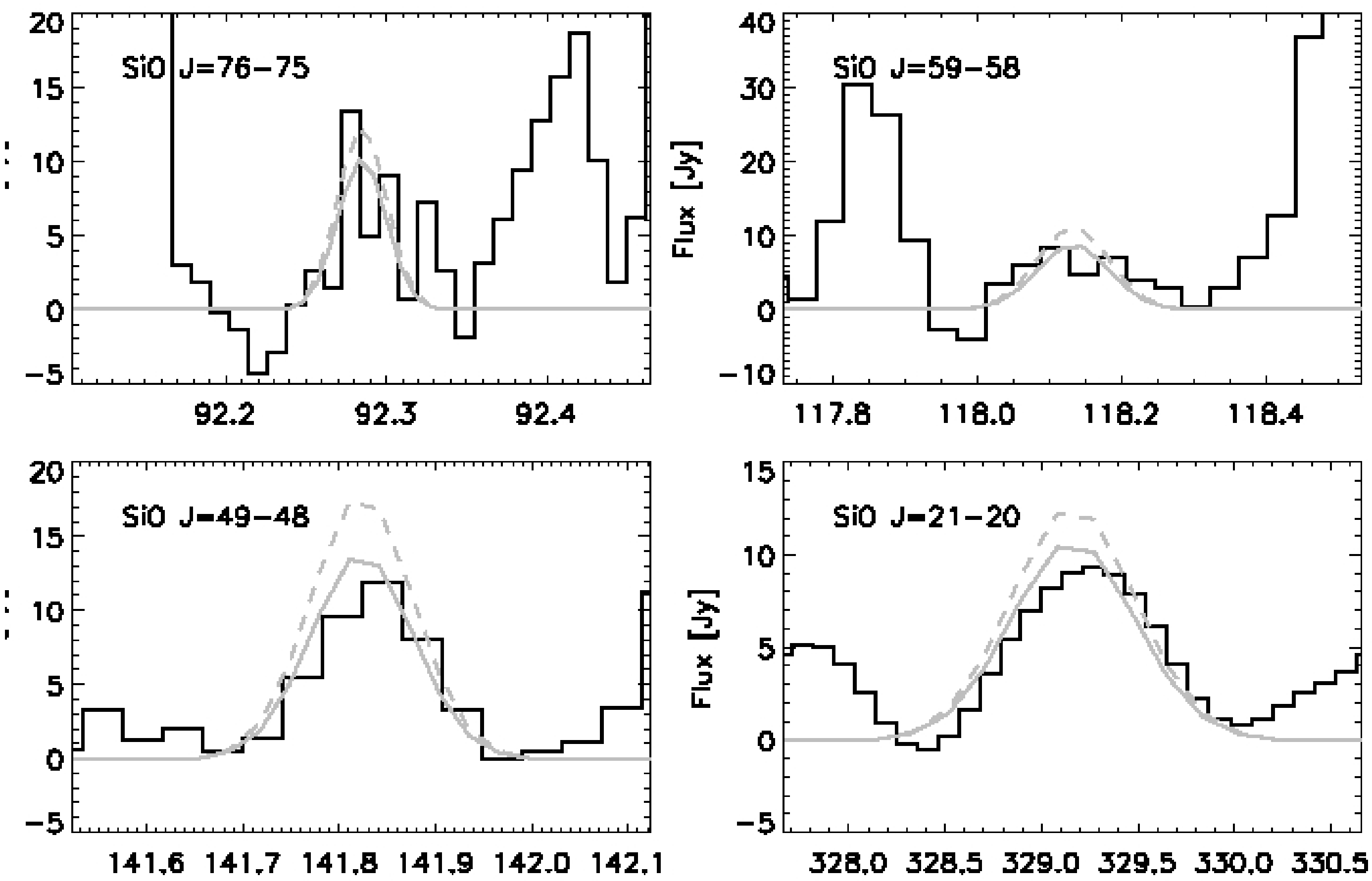


$R<8R_*$: $[SiO/H_2]=3 \times 10^{-7}$

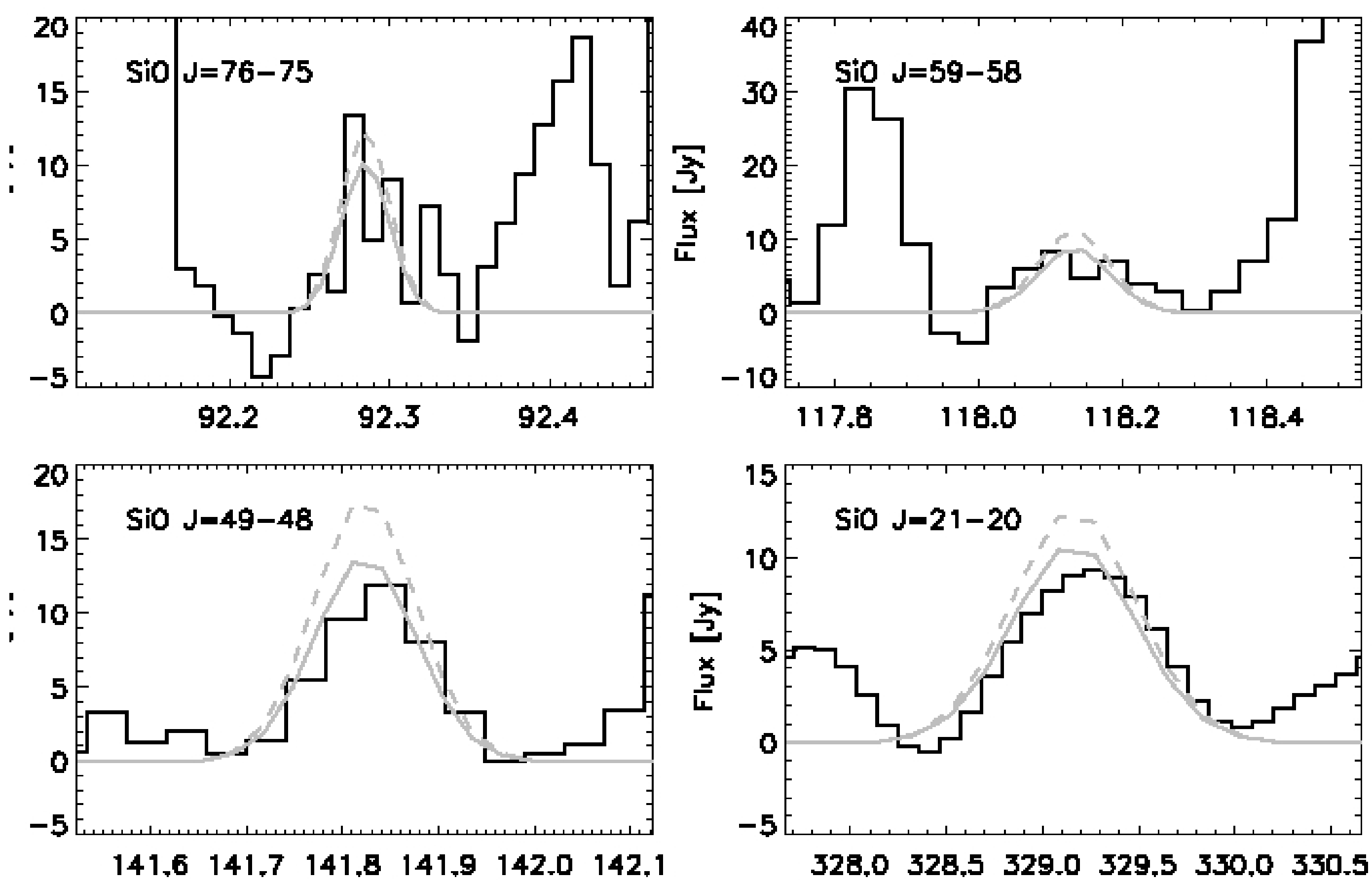
$R>8R_*$: $[SiO/H_2]=1 \times 10^{-7}$

$[SiO/H_2] = 1 \times 10^{-7}$

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS <u>CONSTANT</u> fractional abundance in the envelope

$[SiO/H_2] = 1 \times 10^{-7}$



$R<8R_*$: $[SiO/H2]=3 \times 10^{-7}$

$R>8R_*$: $[SiO/H2]=1 \times 10^{-7}$

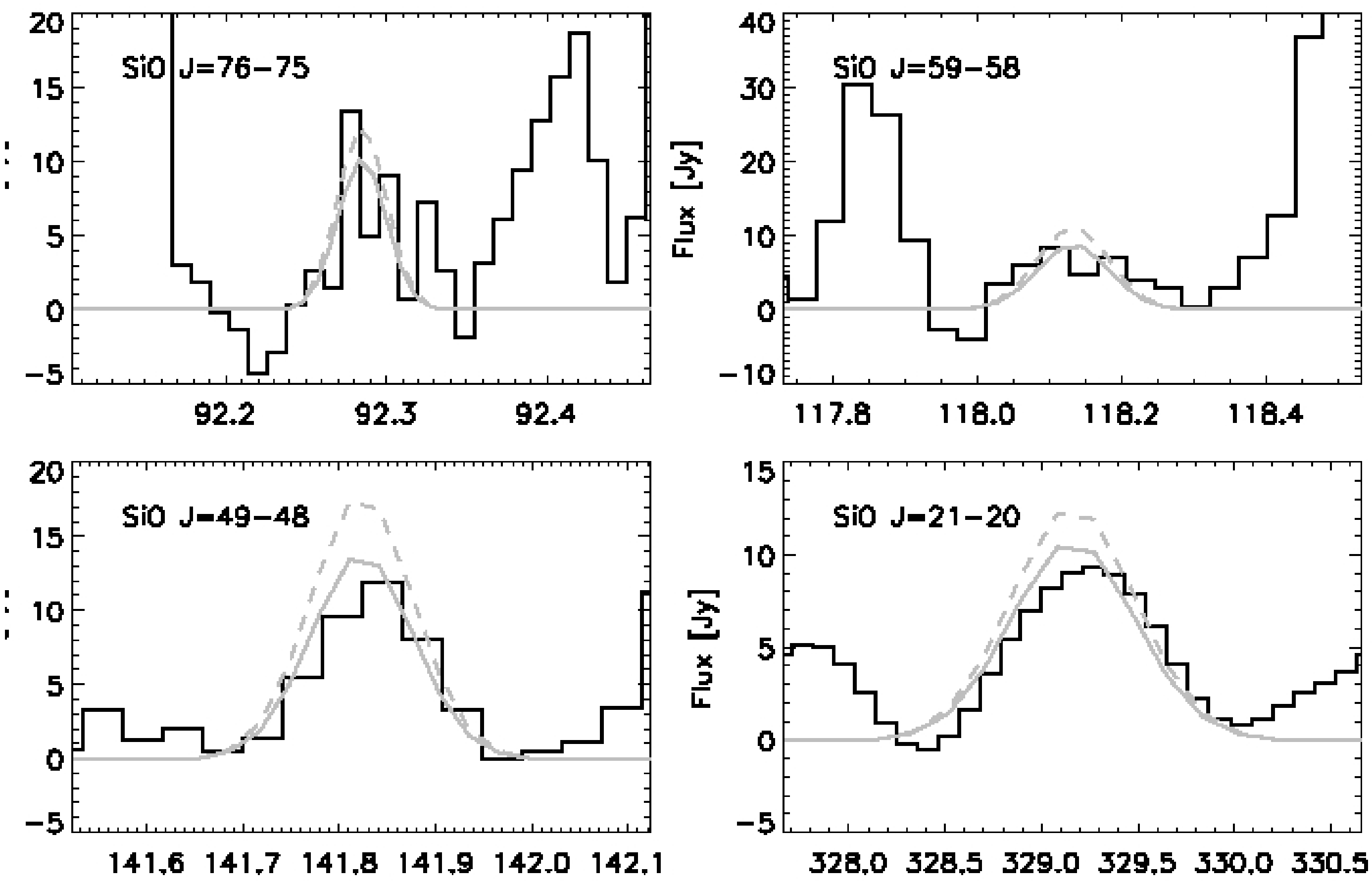
$0.2\text{-}3 \times 10^{-7}$

At maximum
30% takes part
in dust formation

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

$[SiO/H_2] = 1 \times 10^{-7}$



R<8R$_*$: [SiO/H2]=3 x 10^{-7}

R>8R$_*$: [SiO/H2]=1 x 10^{-7}

0.2-3 x 10^{-7}

* lowest SiO J=11-10
* low S/N high J-lines
* velocity field unknown
  → HIFI

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

$[SiS/H_2] = 4 \times 10^{-6}$ → At maximum 50% takes part in dust formation

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

$[SiS/H_2] = 4 \times 10^{-6}$

TE chemistry: $[SiS/H_2] = 1.5 \times 10^{-5}$ (Willacy & Cherchneff, 1998)

non-TE chemistry: $[SiS/H_2] = 3.4 \times 10^{-5}$

Formation of SiS

$S + H_2 \rightarrow HS + H$

$S + C_2H_2 \rightarrow C_2H + HS$

$HS + Si \rightarrow SiS + H$

Activation energy barriers:
occur in hot `fast chemistry' zone of
excursions induced by fast shocks

$SiS + S + M \rightarrow SiS + M$

Slow shock strengths

Silicon in the dust formation zone of IRC+10216 (Decin et al. 2010)

SiO and SiS CONSTANT fractional abundance in the envelope

$[SiS/H_2] = 4 \times 10^{-6}$

TE chemistry: $[SiS/H_2] = 1.5 \times 10^{-5}$ (Willacy & Cherchneff, 1998)
non-TE chemistry: $[SiS/H_2] = 3.4 \times 10^{-5}$

Formation of SiS

$S + H_2 \rightarrow HS + H$
$S + C_2H_2 \rightarrow C_2H + HS$ *
$HS + Si \rightarrow SiS + H$ *

Activation energy barriers:
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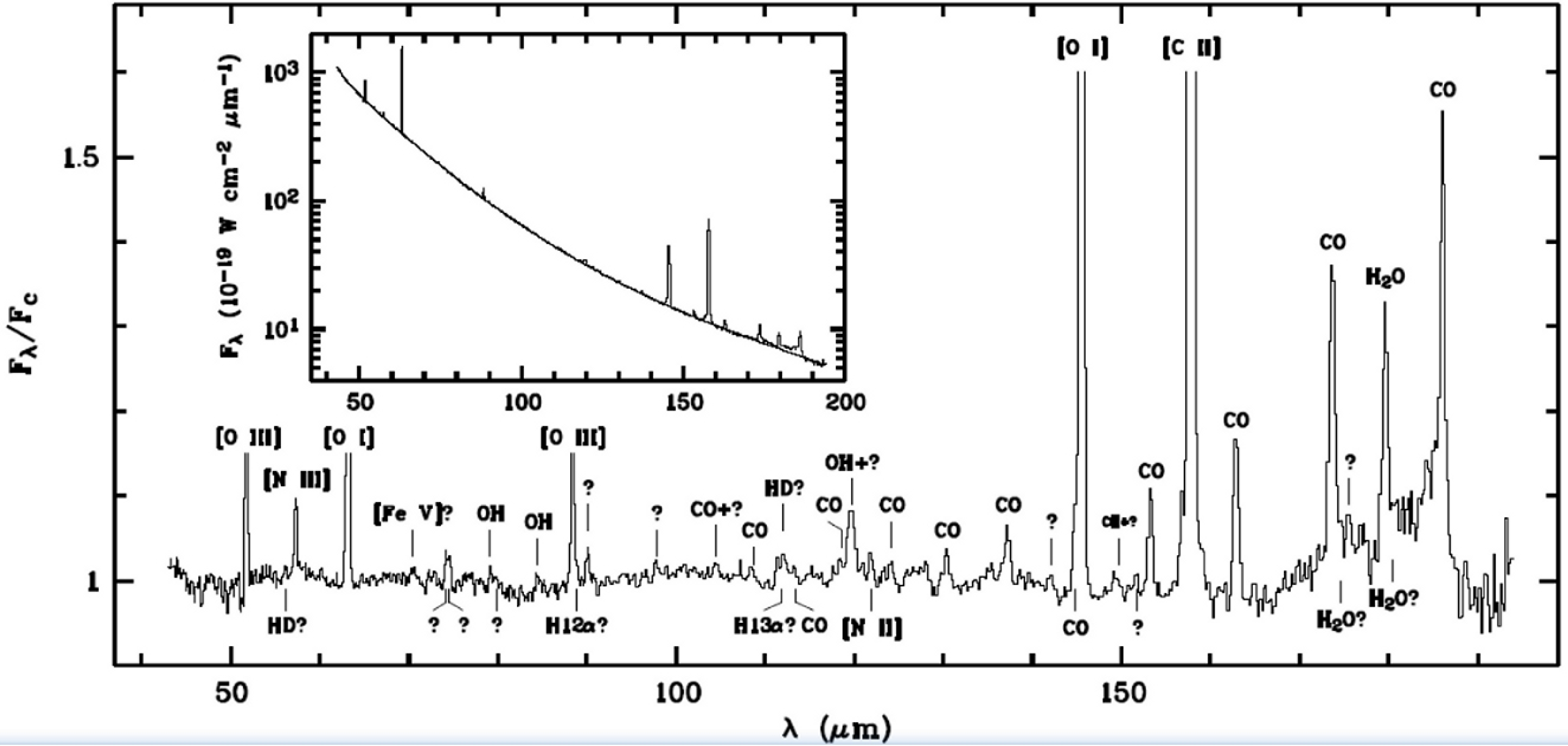
$SiS + S + M \rightarrow SiS + M$ *

Slow shock strengths

* =estimated rates

NGC 7027

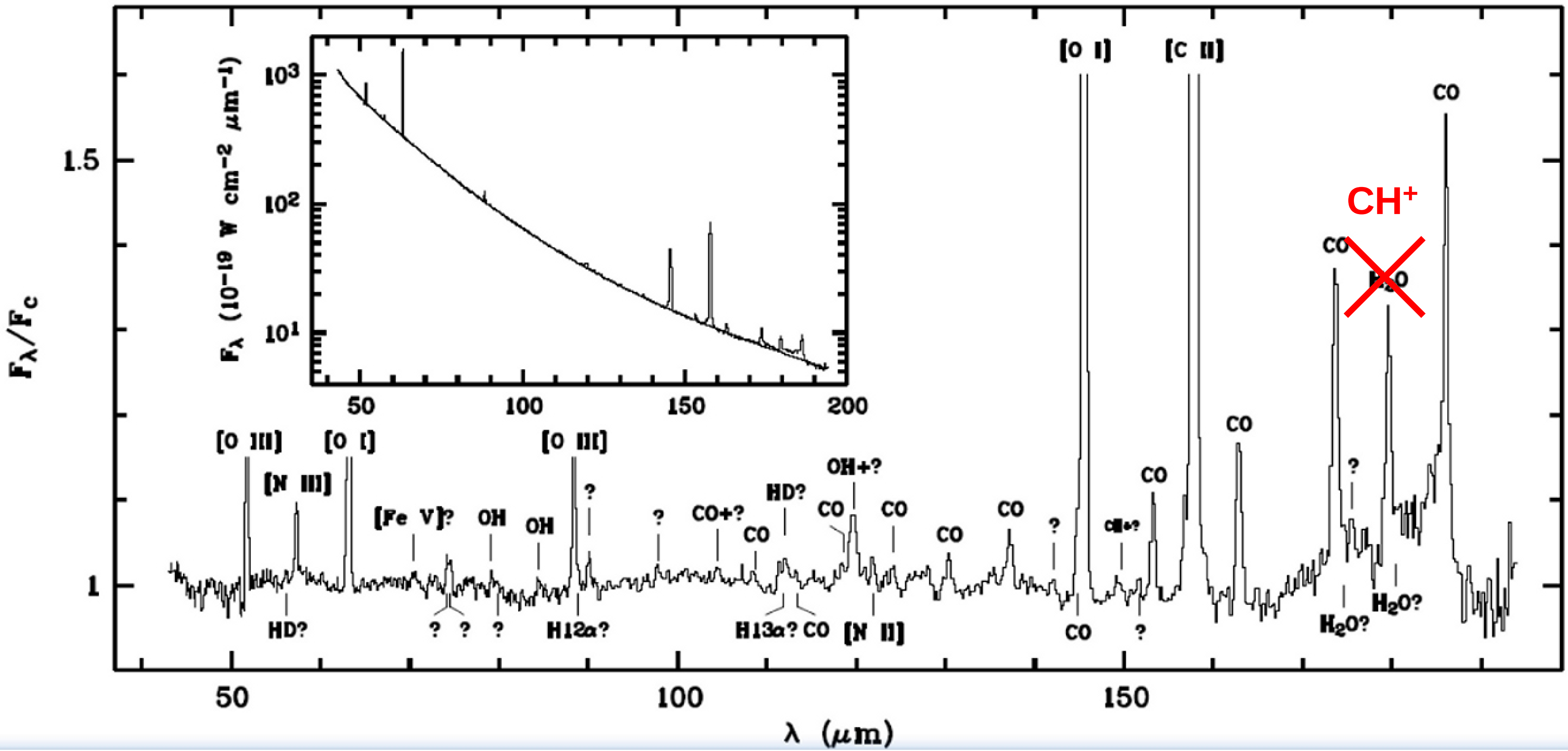
ISO-LWS



Liu et al. 1996

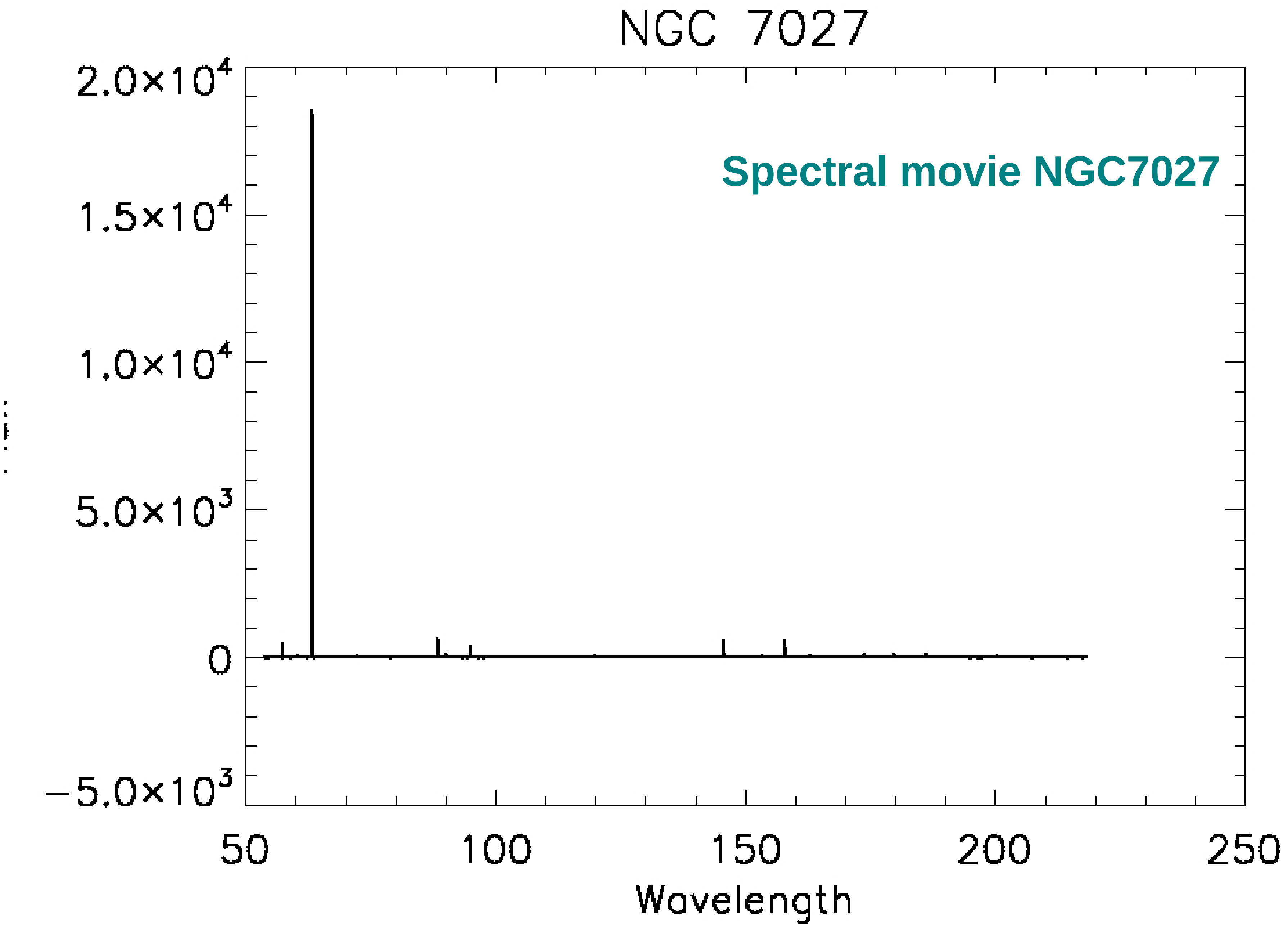
NGC 7027

ISO-LWS



Liu et al. 1996
Cernicharo et al. 1997

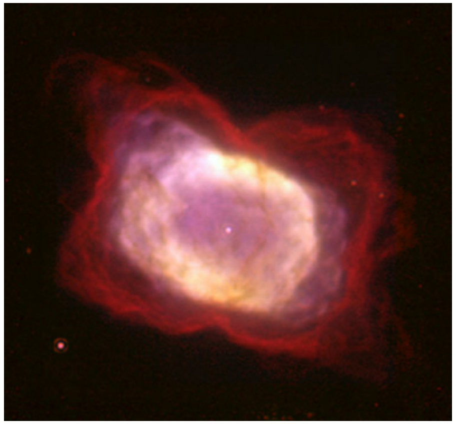
NGC 7027



NGC 7027
Spectral movie NGC7027
2.0×10⁴
1.5×10⁴
1.0×10⁴
5.0×10³
0
−5.0×10³
50
100
150
200
250
Wavelength

NGC 7027

Detection of
* ^{12}CO
* ^{13}CO
* OH
* CH
* CH^+
* [O I]
* [O III]
* [C II]
* [N II]
* ....



Tracing the ionized region which is surrounded by a massive molecular envelope

* HD(0,0) R(0) @112.07 µm: NOT detected
* o-H_2O $2_{2,1}$-$1_{1,0}$ and $3_{2,1}$-$2_{1,2}$ suggested by LWS not detected with PACS
* H_2O tentatively detected o-H_2O $2_{1,2}$-$1_{0,1}$, $2_{2,1}$-$2_{1,2}$, $3_{0,3}$-$2_{1,2}$, and $1_{1,0}$-$1_{0,1}$

PLANS:
PACS + SPIRE + UV, optical and near-IR data: will be analysed with Cloudy

Conclusions

* PACS and SPIRE spectroscopic data:
  wealth of molecular line diagnostics: trace mass-loss history, chemical processes,excitation mechanisms, temperature structure, dust-gas coupling, ...
* only few molecules analyzed so far; already 3 articles published, few in prep.
* dust features → requires accurate RSRF
* combine with HIFI, ground-based data, interferometric maps

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Questions?

Spectral movie VY CMa

Spectral movie IRC+10216

Spectral movie NGC7027