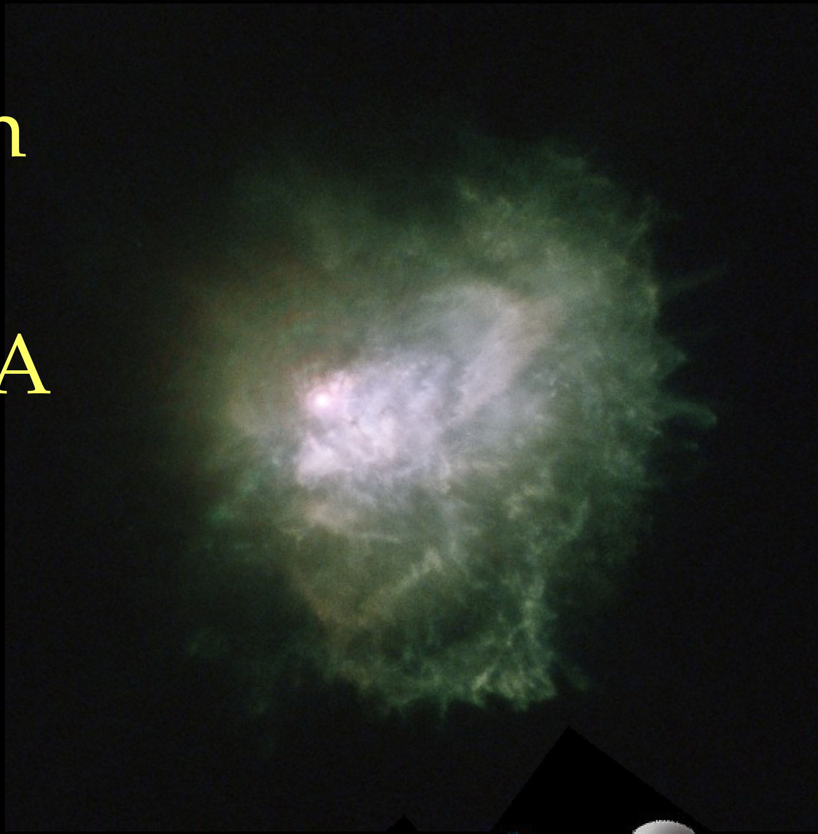
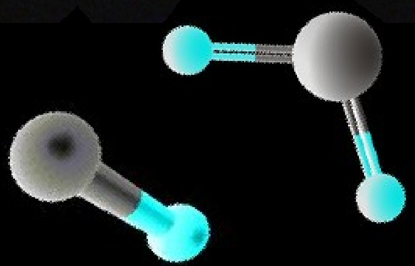
Investigating Dust Formation and Mass Loss in Evolved Stars with the SMA

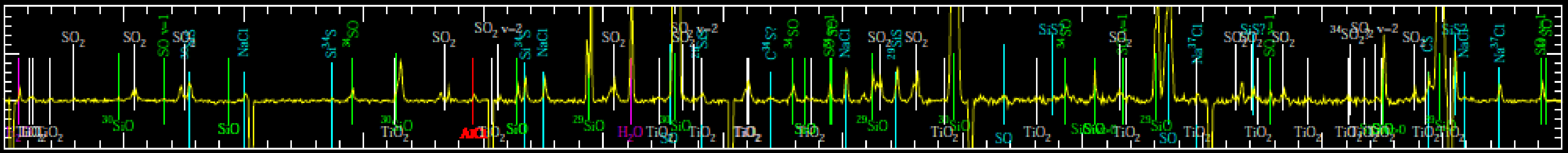




Tomek Kamiński & Karl Menten
Max-Planck-Institut für Radioastronomie

K. Young, N. Patel, C. Gottlieb
Harvard-Smithsonian Center for Astrophysics

et al.



SMA conference, Cambridge, 9 June 2014

Cycle of material in a galaxy

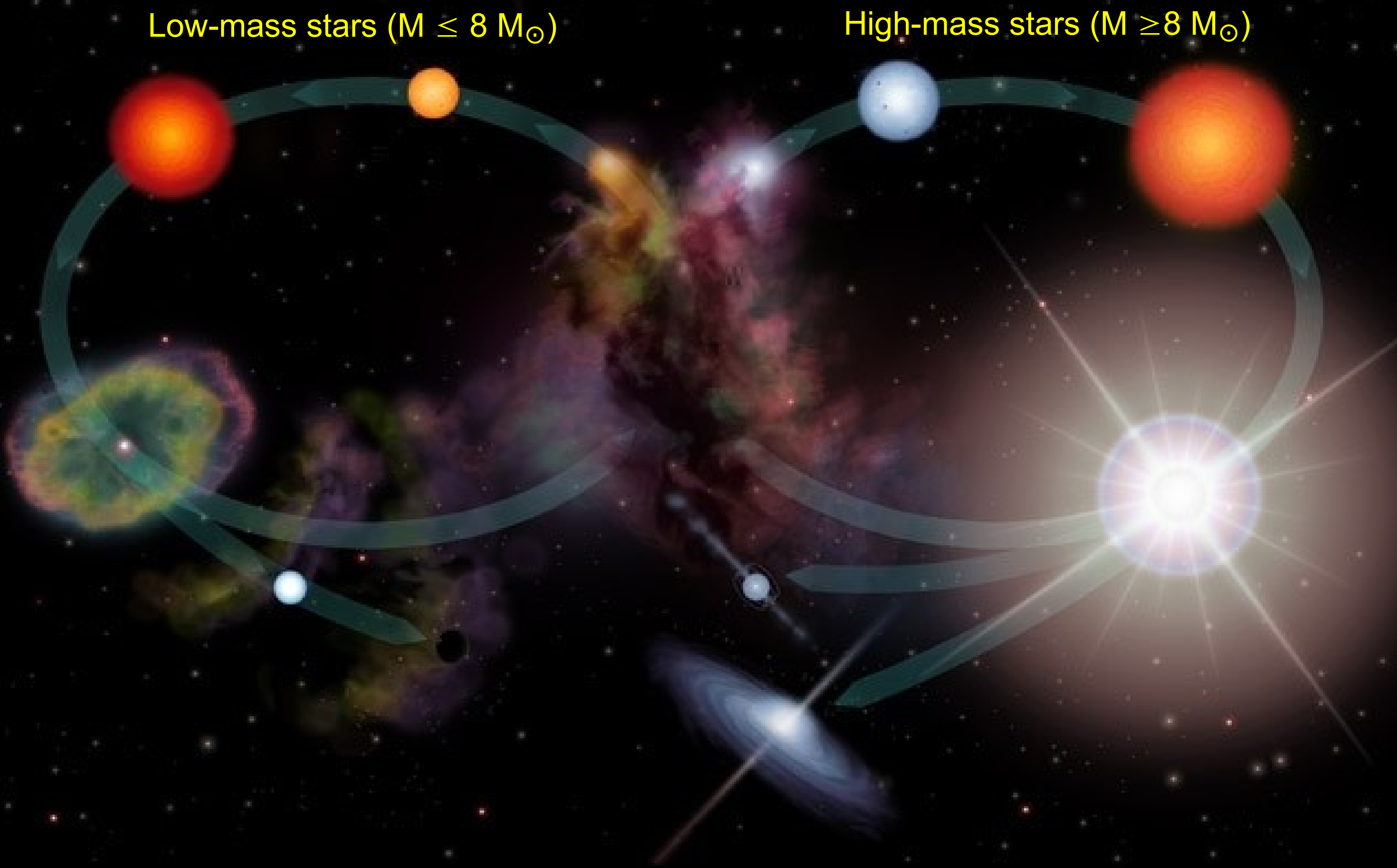


Image credit: F. Kemper

Key questions addressed with the SMA

- astrochemistry:
  - channels of formation of different molecules
  - and their link to elemental abundances (→nucleosynthesis→stellar evolution)

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- how dust is formed and processed in CSE ?

  - formation of seeds (=condensation cores) from the gas phase
  - how large can the grains grow ?
  - destructive (?) influence of shocks
  - what form of dust enters the ISM ?

–

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- astrochemistry:
  - channels of formation of different molecules
  - and their link to elemental abundances (→nucleosynthesis→stellar evolution)
- how dust is formed and processed in CSE ?
  - formation of seeds (=condensation cores) from the gas phase
  - how large can the grains grow ?
  - destructive (?) influence of shocks
  - what form of dust enters the ISM ?
- mass loss mechanism:
  - how is the material elevated in stellar atmospheres?
  - how are the outflows accelerated?
  - how are asymmetries introduced?
    - how are asymmetries in PN introduced between AGB and PN phases?
  - what is the role of magnetic fields in shaping the winds?
  - ....

Summary of the 10 years of SMA observations of evolved stars

- ~20 refereed papers + conf. proceedings

- favorite sources:

name	evolutionary stage	chemistry type	papers published
VY CMa	red supergiant	O-rich	5
IRC+10216	AGB	C-rich	8
IK Tau	AGB	O-rich	2
OH231.8 *Rotten Egg*	pre-planetary nebula	O-rich	1

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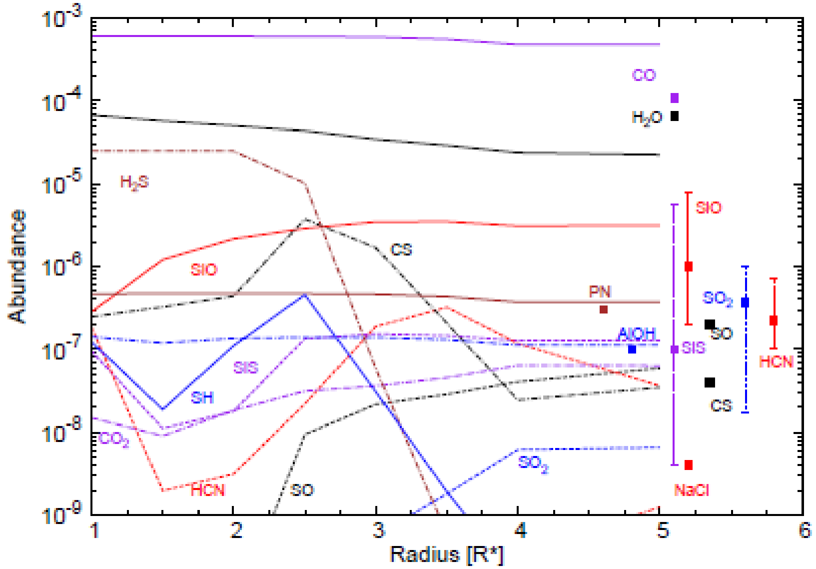
- special techniques used (highlights only):
  - first interferometric observations at 685 GHz (Young et al. 2004)
  - eSMA experiment with 0.22"x0.46" resolution (Shinnaga et al. 2009)
  - pioneering interferometric <u>spectro</u>-polarization studies
  - first interferometric line and imaging **surveys**

Science results I: Astrochemistry



Science results: Astrochemistry

Young, Hunter, Wilner, et al. 2004
origin of CS in the carbon star IRC+10216 through high-freq. imaging – CS is produced as a parent molecule very close to the photosphere

Schöier, Fong, Oloffson, et al. 2006
SiO in the wind of IRC+10216 must be formed in non-LTE conditions close to the photosphere and is depleted into dust in the outer wind

Schöier, Fong, Bieging, et al. 2007
HCN is formed in the photosphere of IRC+10216 under LTE conditions and provides radiative cooling of the inner envelope more effective than CO

Sahai, Young, Patel, et al. 2006
$^{12}CO/^{13}CO$ ratio in a PPN, IRAS 22036+5306, suggests the central object is enriched in products of hot-bottom burning, which constrains stellar mass to > 4 $M_\odot$

Fu, Molullet, Patel, et al. 2012
establishing the origin of sulfur oxides in VY CMa: shock chemistry

De Beck, Kamiński, Patel, et al. 2013
surprisingly rich phosphorous chemistry in AGB star IK Tau

See the poster by Elvire de Beck+ !

Patel, Young, Gottlieb, et al. 2011
Kamiński, Gottlieb, Young, et al. 2013
De Beck, et al. 2014 (in prep.)
chemical complexity of material around evolved stars

Spectral and imaging surveys

IRC+10216

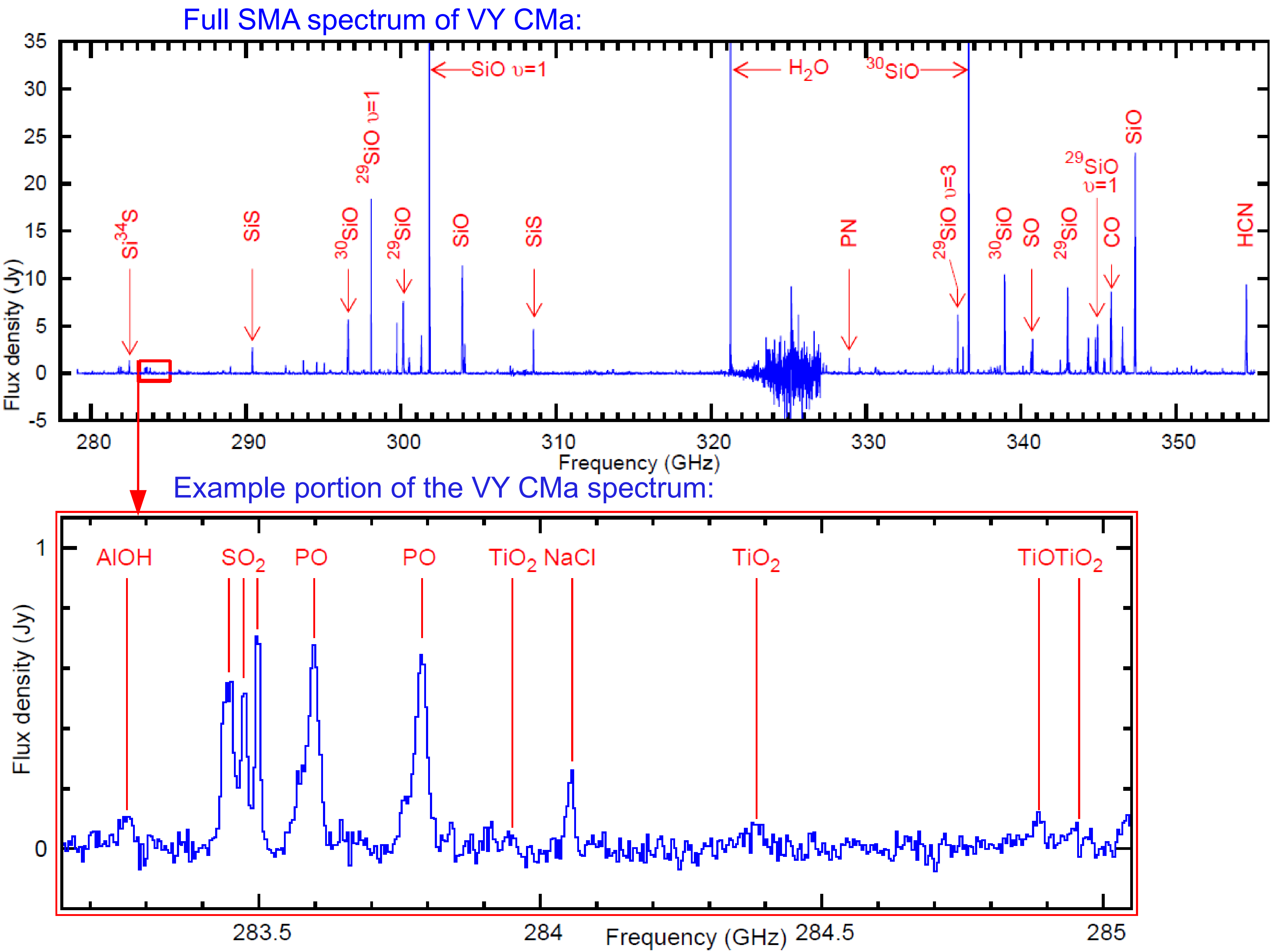
- (I) 294-355 + (II) 355-400 GHz
- nominal resolution 2.5" + limited mosaicking

VY CMa & IK Tau

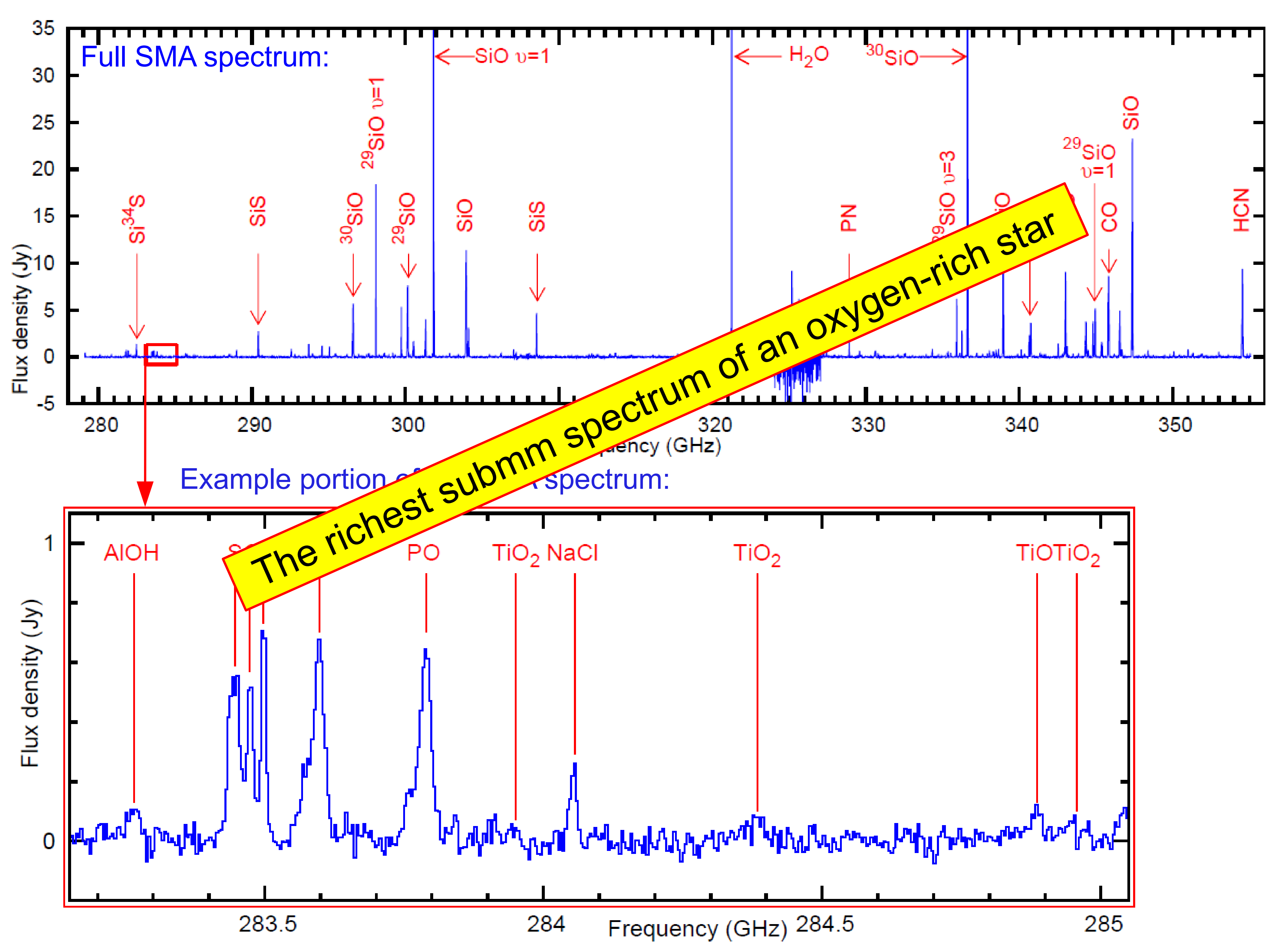
- 279-355 GHz
- 0.9" resolution

See the poster
by Elvire de Beck+ !

most comprehensive submm observations of evolved stars to date



Full SMA spectrum of VY CMa:
Flux density (Jy)
Frequency (GHz)
SiO υ=1
H2O
30SiO
Si34S
SiS
30SiO
29SiO υ=1
29SiO
SiO
SiS
PN
29SiO υ=3
30SiO
SO
29SiO
29SiO υ=1
CO
SiO
HCN
Example portion of the VY CMa spectrum:
AlOH
SO2
PO
PO
TiO2
NaCl
TiO2
TiO
TiO2
Flux density (Jy)
Frequency (GHz)



Full SMA spectrum:
SiO υ=1
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SiO
SiS
PN
29SiO υ=3
29SiO υ=1
CO
SiO
HCN
Flux density (Jy)
Frequency (GHz)
Example portion of
spectrum:
AlOH
PO
TiO2
NaCl
TiO2
TiO
TiO2
Flux density (Jy)
Frequency (GHz)
The richest submm spectrum of an oxygen-rich star

$E_u \sim 6000$ K

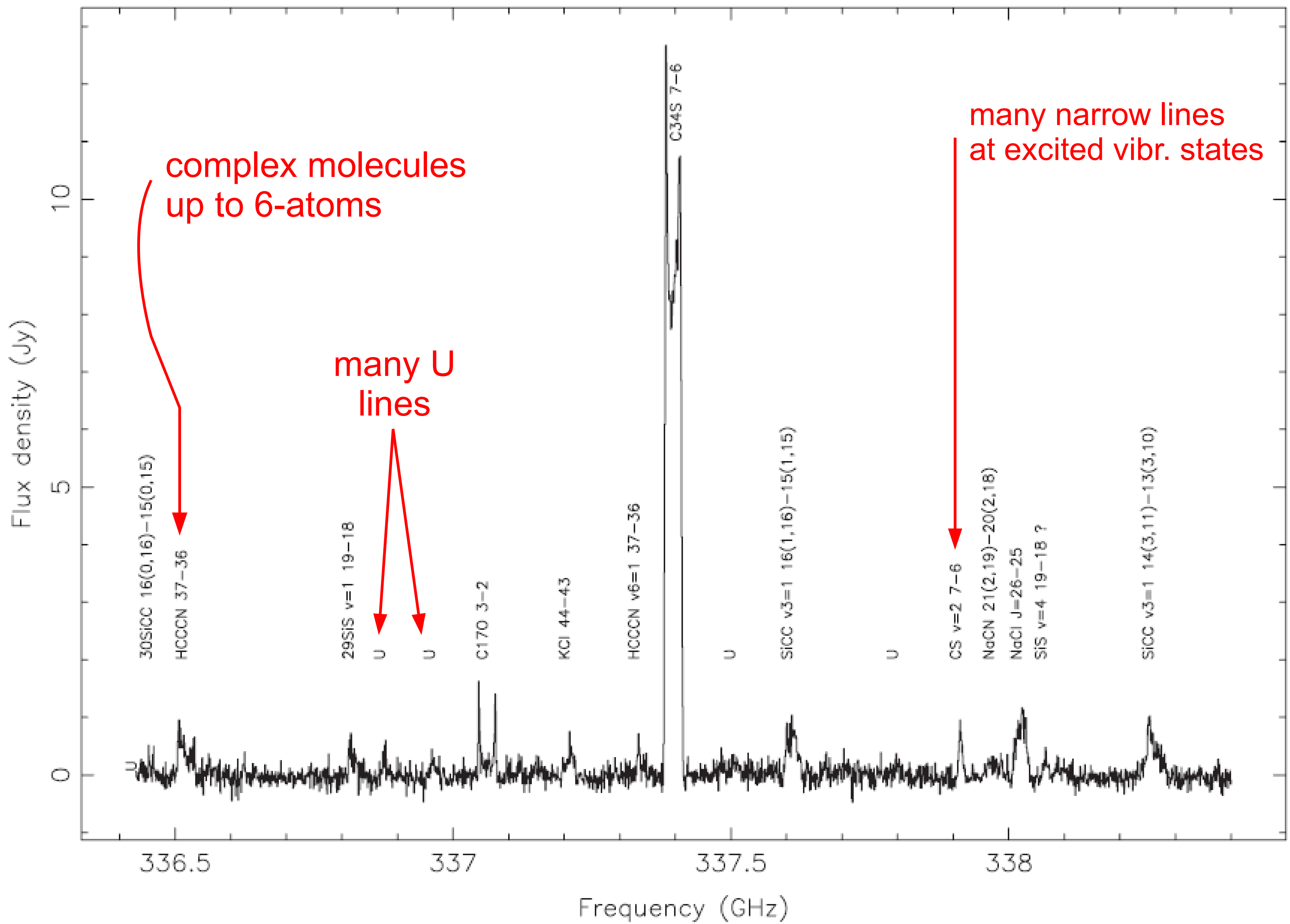
Some highlights from the VY CMa survey

Di-atomic molecules	Number of lines	Tri-atomic molecules	Number of lines
CO, ^{13}CO	1, 1	HCN, H^{13}CN	1, 3
SiO, ^{29}SiO, ^{30}SiO, Si^{18}O, $v \leq 5$!	$\Sigma=29$	HN^{13}C	1
SO $v \leq 1$, ^{34}SO	17, 9	SO_2 $\nu_2 \leq 1$, $^{34}SO_2$	$\Sigma=53$!
CS, C^{34}S	2, 1	H_2O $\nu_2 \leq 2$	7
SiS $v \leq 2$, ^{29}SiS $v \leq 2$, ^{30}SiS	$\Sigma=26$	H_2S	1
NaCl $v \leq 3$, Na^{37}Cl $v \leq 1$	21, 12		
AlCl	5		
AlO	2	AlOH	2
PO	6		
PN	2		
NS	1		
CN	2		
TiO	7	TiO_2, $^{50}TiO_2$	34+

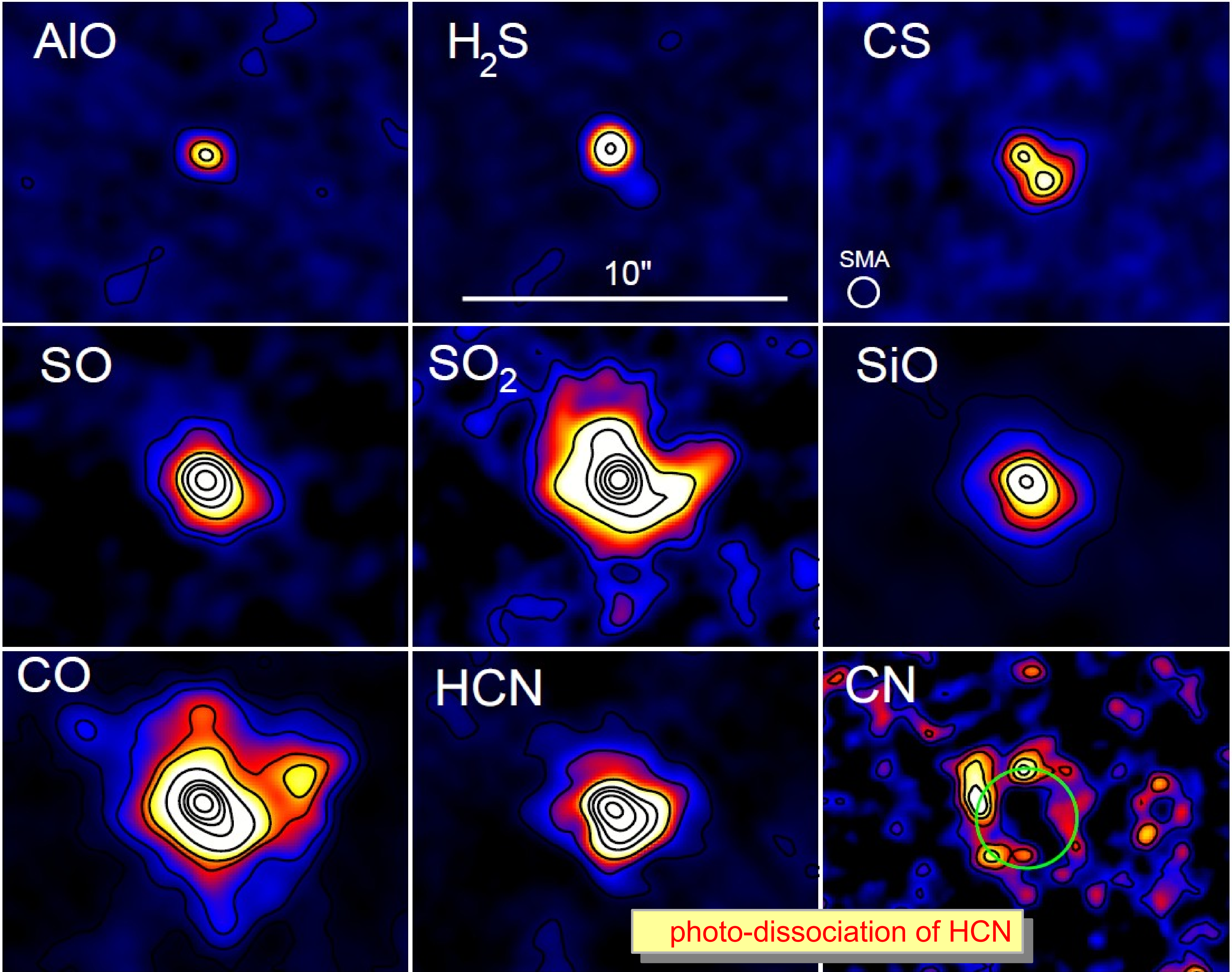
- ~224 features detected
    - only ~12 unidentified
- 19 (33iso) molecular species
    - many exotic
    - 3 new
- many transitions at high vibrational levels
    - SiO up to v=5

Kamiński et al. 2013

Portion of the SMA spectrum of IRC+10216:

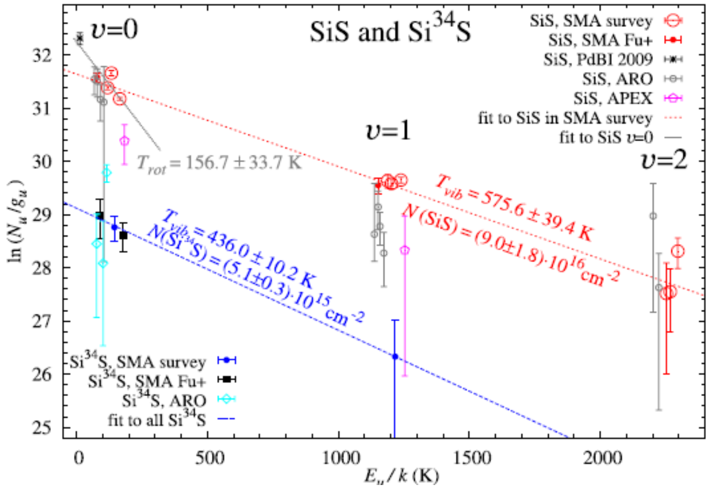


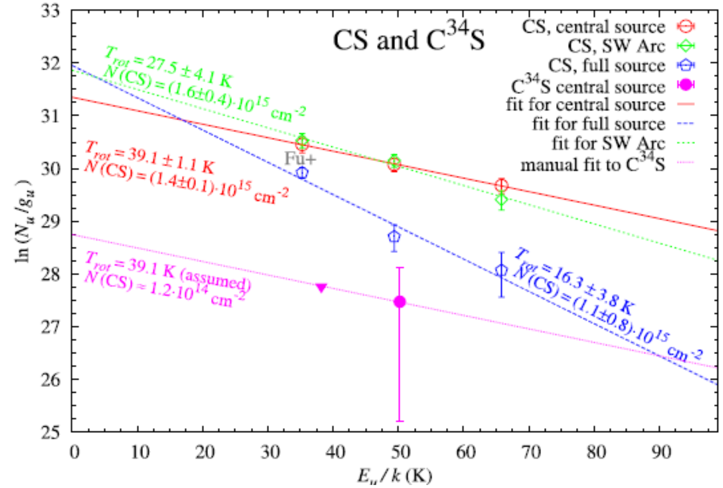
Patel et al. 2009, 2011

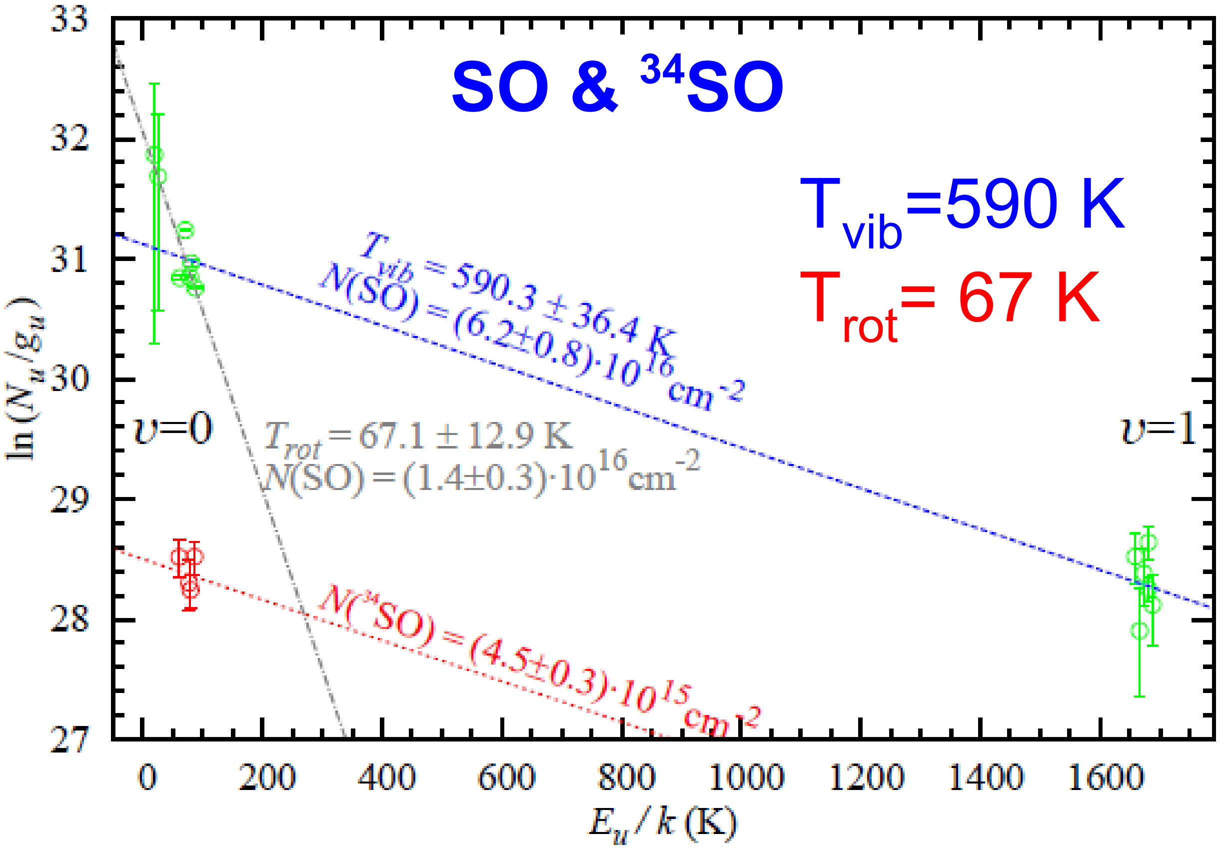


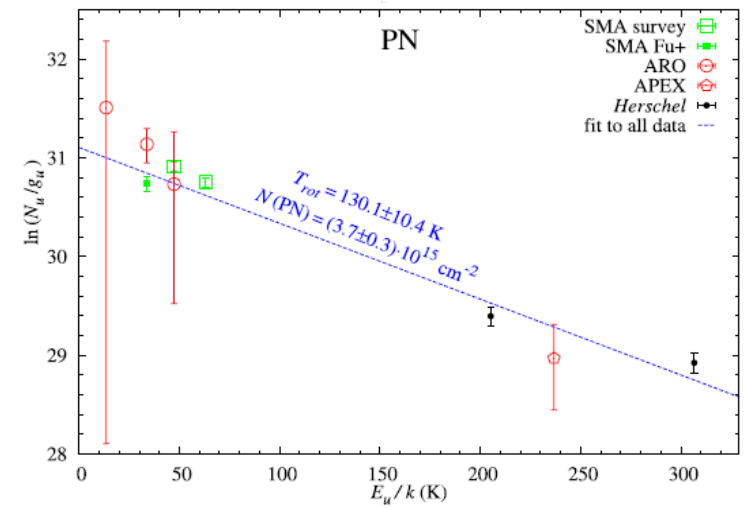
AlO
H2S
CS
10"
SMA
SO
SO2
SiO
CO
HCN
CN
photo-dissociation of HCN

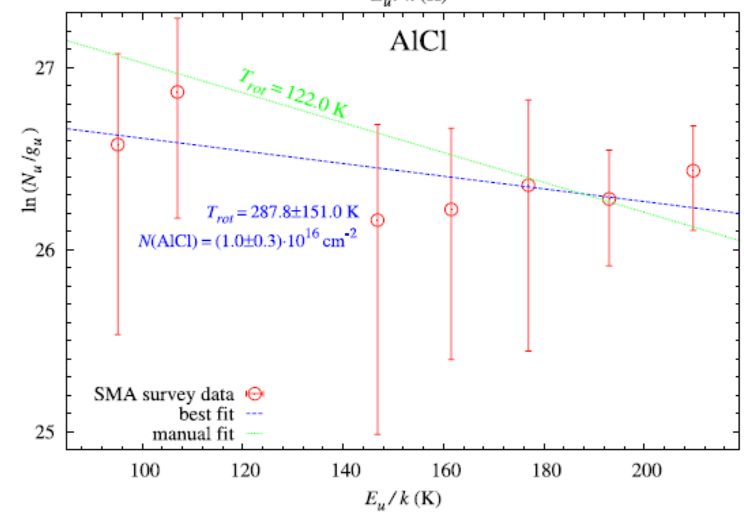
Excitation analysis

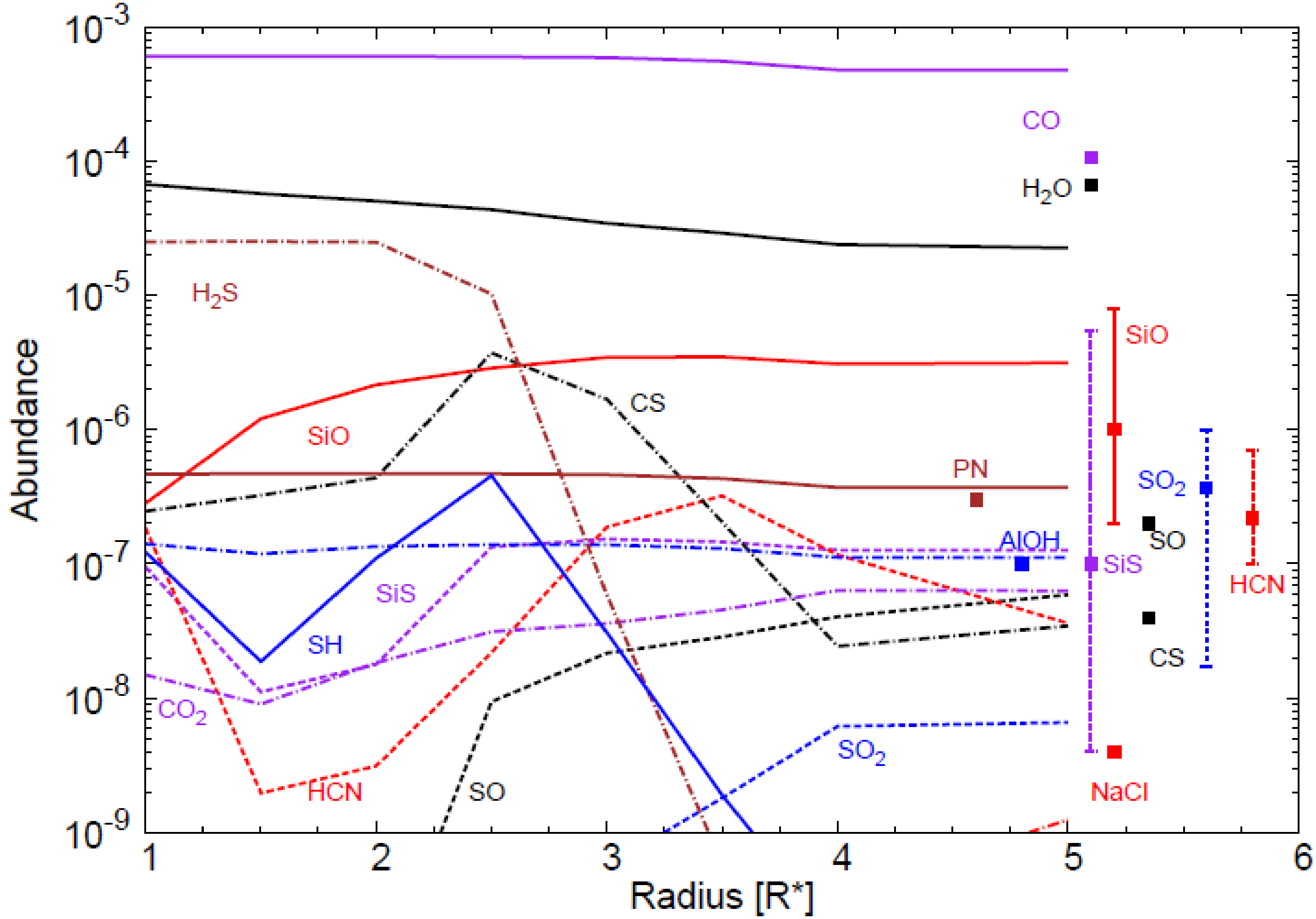










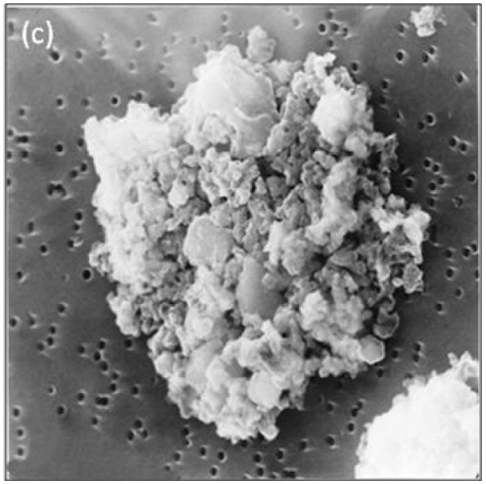


results from the SMA observations have already influenced theoretical work on the topic (e.g. Gobrecht & Cherchneff 2013 + priv. comm.)

Science results II:

Dust

formation & processing



Science results: Dust

Sahai, Young, Patel, et al. 2006
claim a substantial mass (0.03 $M_\odot$) of large grains with radius ≥1mm in a tori around a PPN, IRAS 22036+5306

Patel, Young, Gottlieb, et al. 2011
Patel, Gottlieb, Young 2013
IRC+10216 survey: high angular-resolution observations of SiC, SiN, and SiCC which are thought to condense into dust in carbon-rich envelopes. While SiC is seen only in spatially resolved outer envelope, SiCC is present in the outer parts as well as in the inner regions where the outflow is accelerated

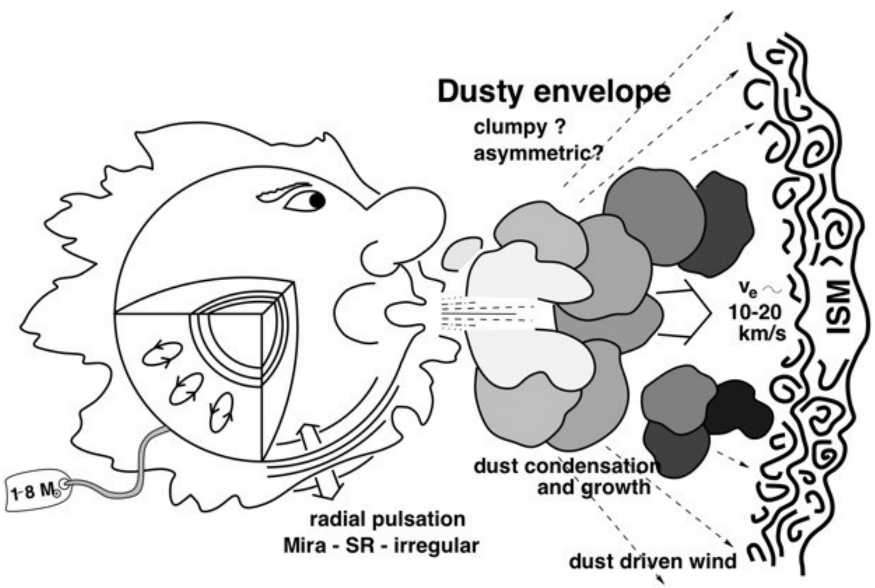
See the poster by Nimesh+ !

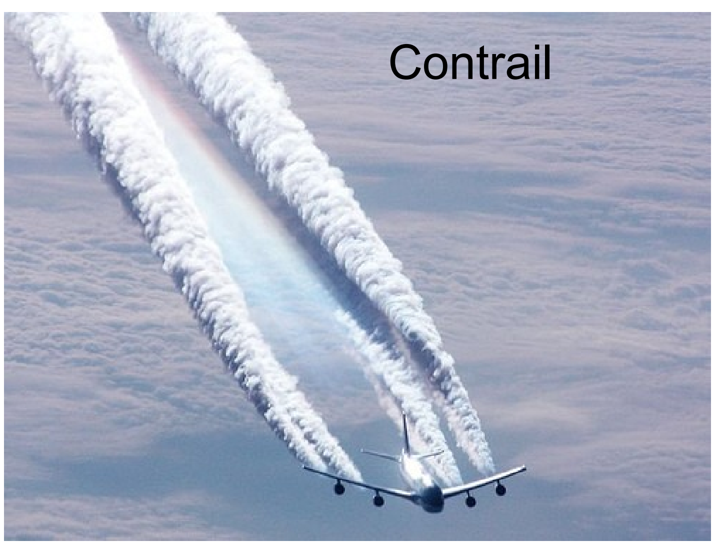
Kamiński, Gottlieb, Menten, et al. 2013
Kamiński, Gottlieb, Young, et al. 2013
VY CMa survey: first (sub-)millimeter detection of TiO & TiO_2 – molecules long suspected to produce condensation cores initiating formation of inorganic dust in oxygen-rich environments...

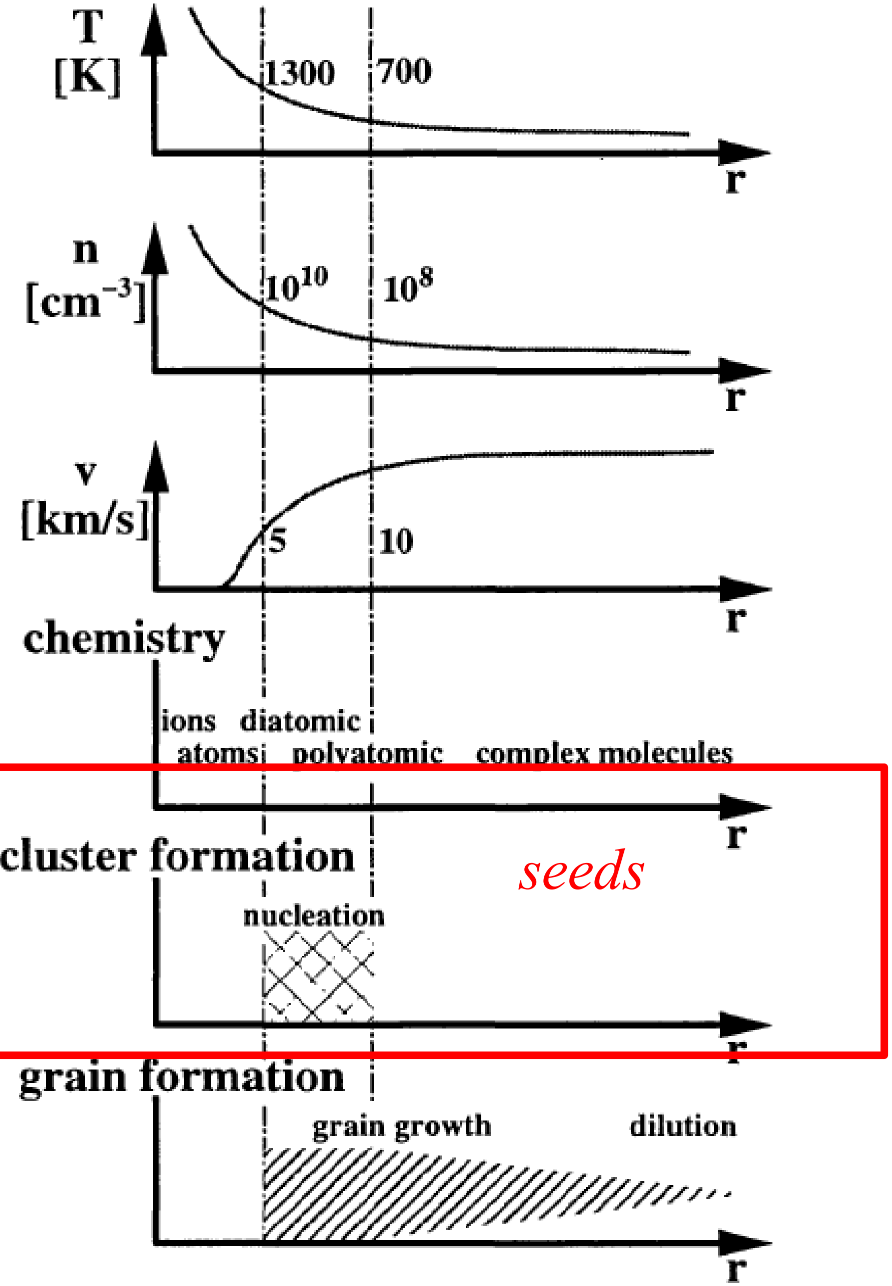
Good quality spectra of AlO and other Al-bearing species (AlOH, AlCl)

Sabin, Zhang, Zijlstra, et al. 2014
Inorganic (silicon) dust produces higher dust polarization due to grain alignment than carbonaceous dust

Formation of inorganic dust in oxygen-rich stars







Sedlmayr & Winters 2000

TiO and TiO_2 as seeds

Nucleation rates

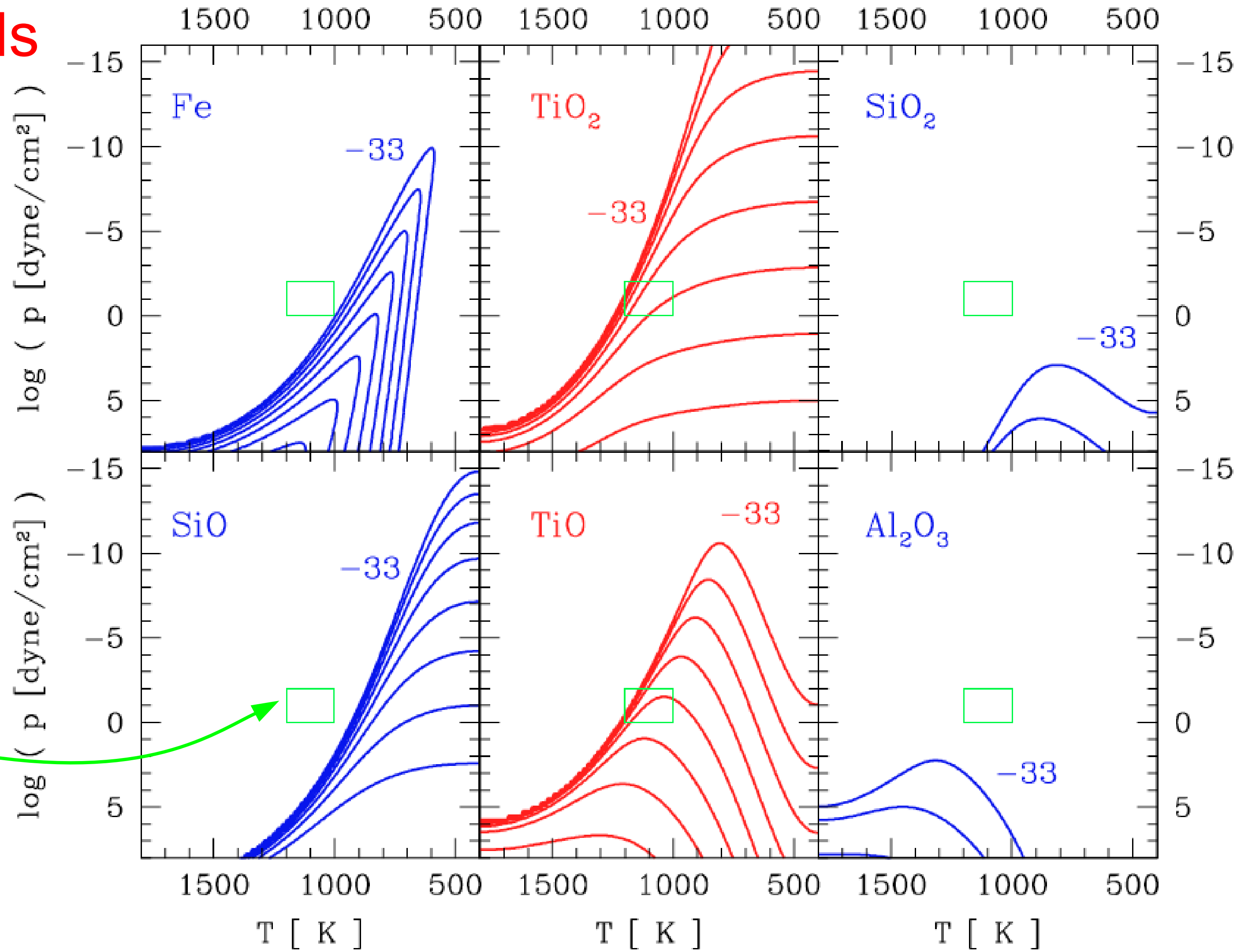
(in range

log J / n = -33 : -5, every 4)

for nucleating species

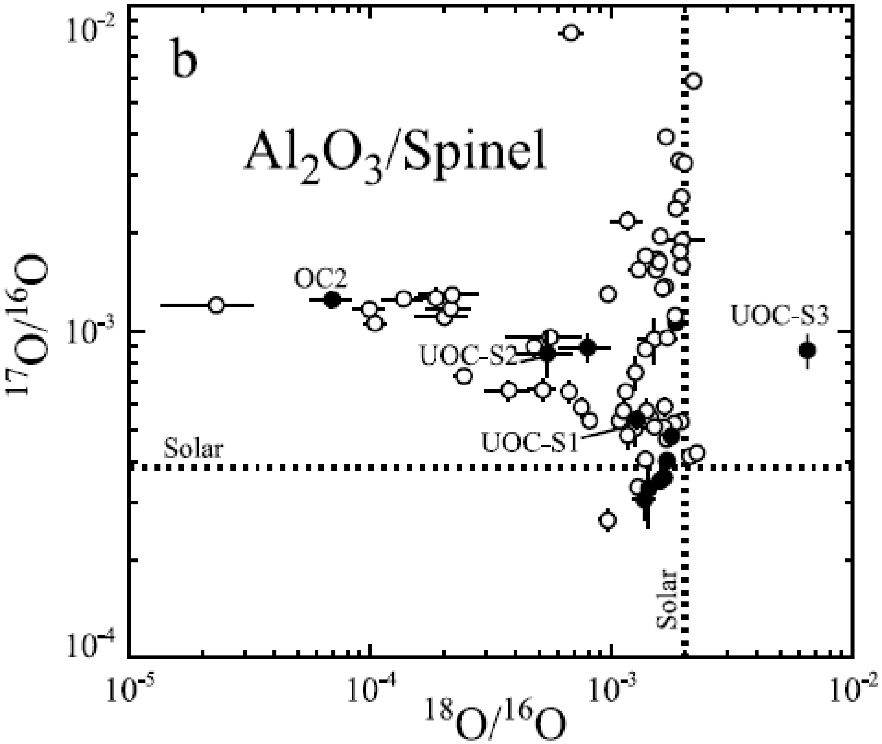
(from Jeong et al. 2003)

temperature and pressure expected in seed-formation zone



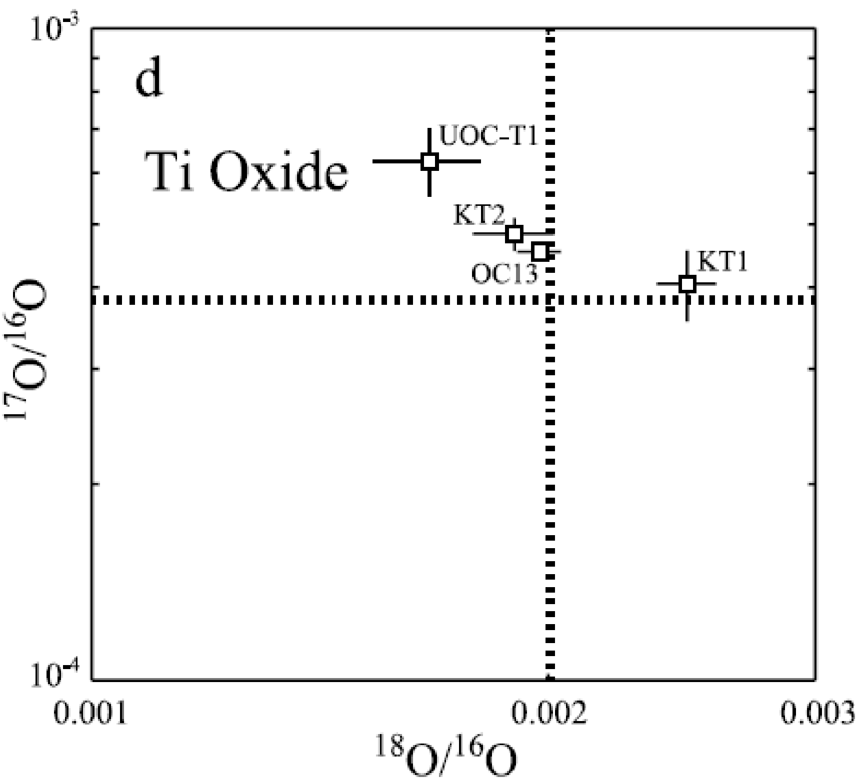
solids:

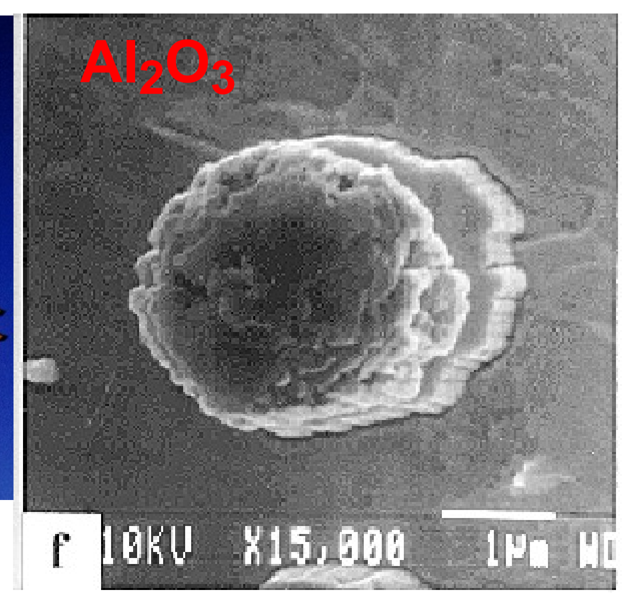
$$TiO \xrightarrow{H_2O} TiO_2 \longrightarrow \begin{matrix} Ti_2O_3 \\ Ti_3O_5 \\ Ti_4O_7 \\ \dots \\ CaTiO_3 \\ MgTiO_3 \end{matrix} \longrightarrow \textbf{DUST}$$



Ti & Al oxides in presolar grains

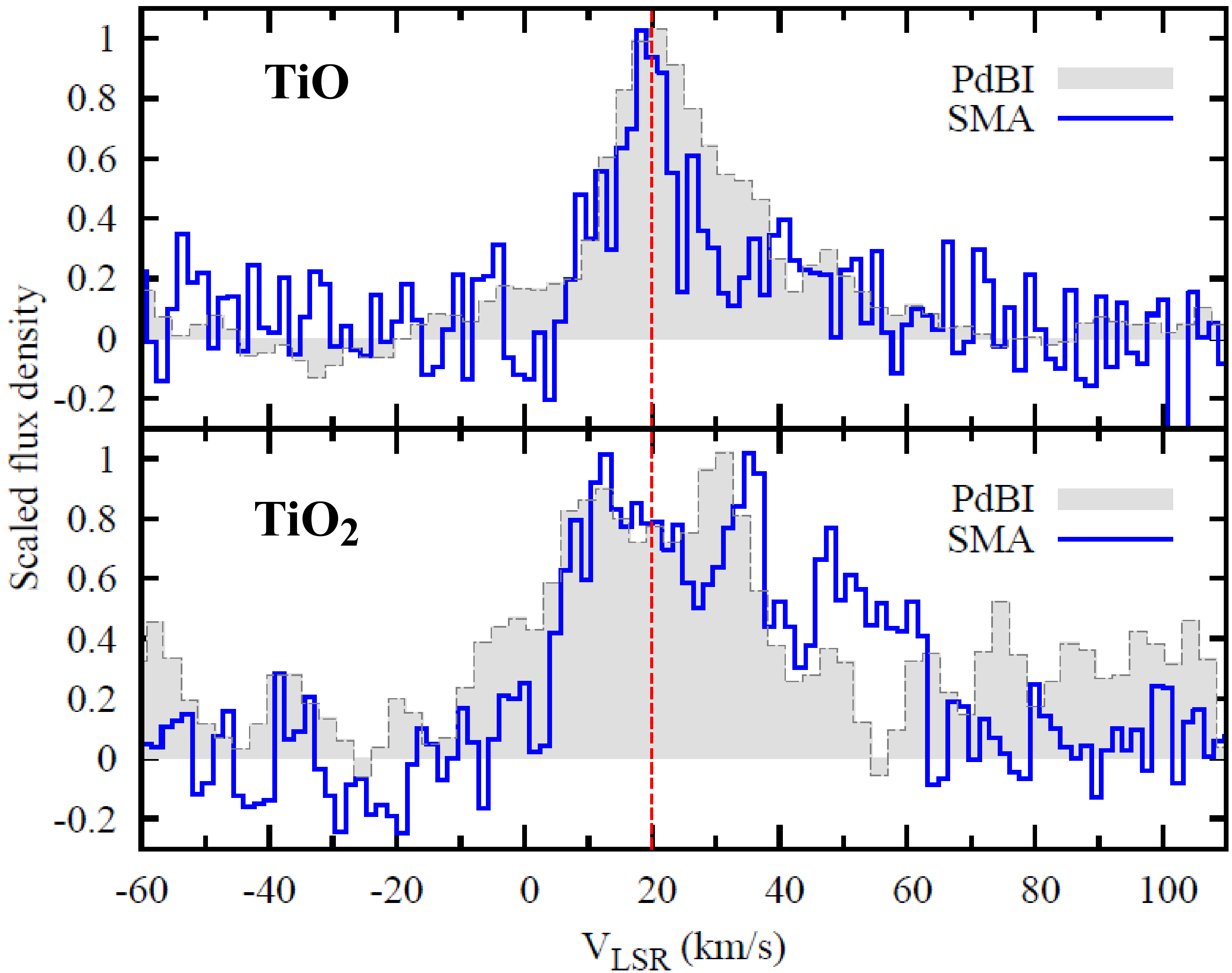
- Pristine stardust
- Both types of oxides present in presolar grains
- Only AlO is found in dust cores
- Bias – only large grains analyzed so far



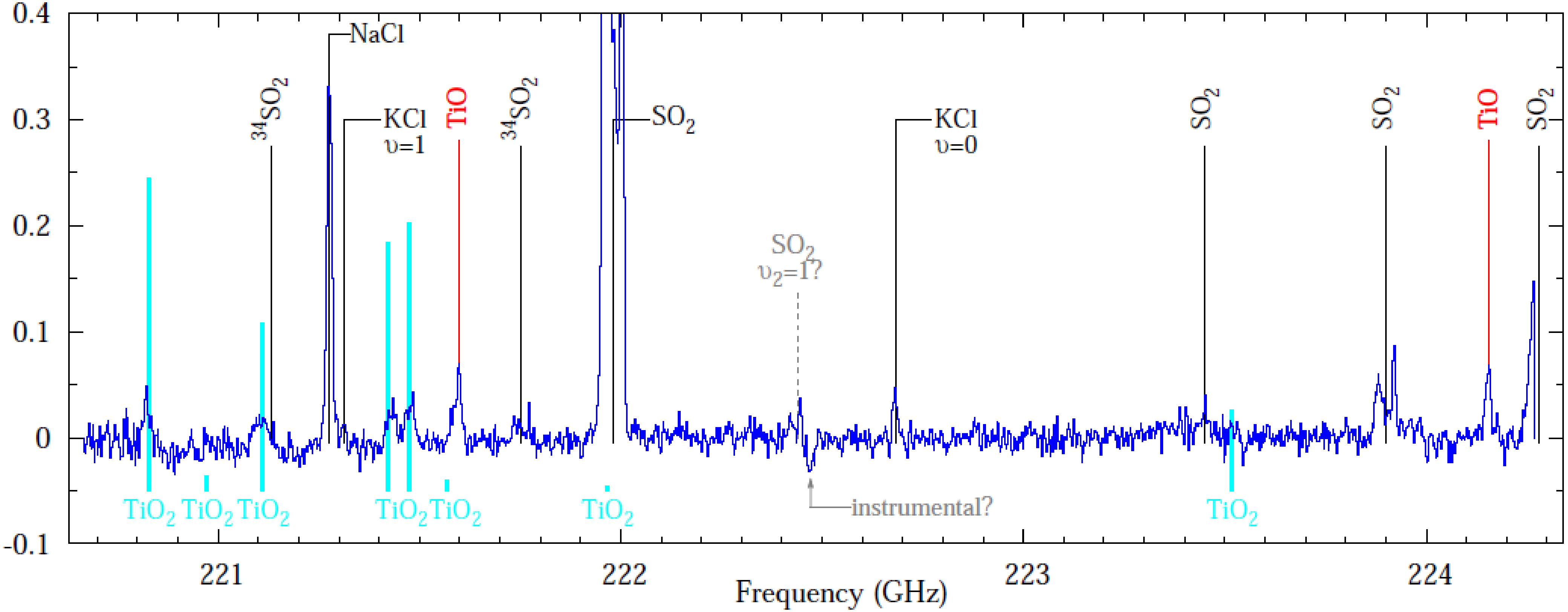


First detection of pure rotational transitions of TiO and TiO_2

(average profiles:)



Plateau de Bure Interferometer confirmation

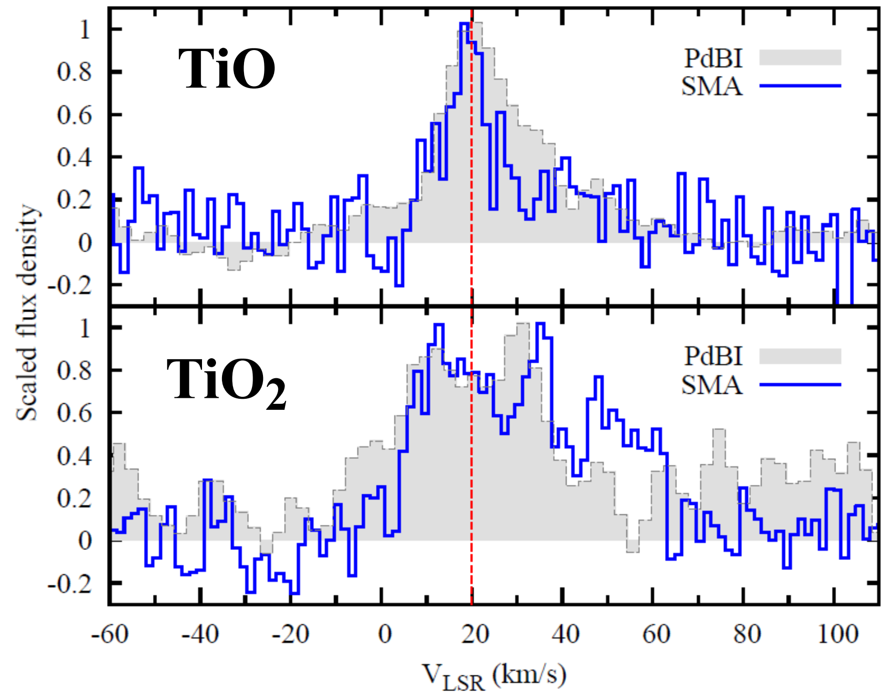


Observations of TiO and TiO_2

First detection of pure rotational transitions of TiO and TiO_2

<u>TiO observed at optical wavelengths</u>

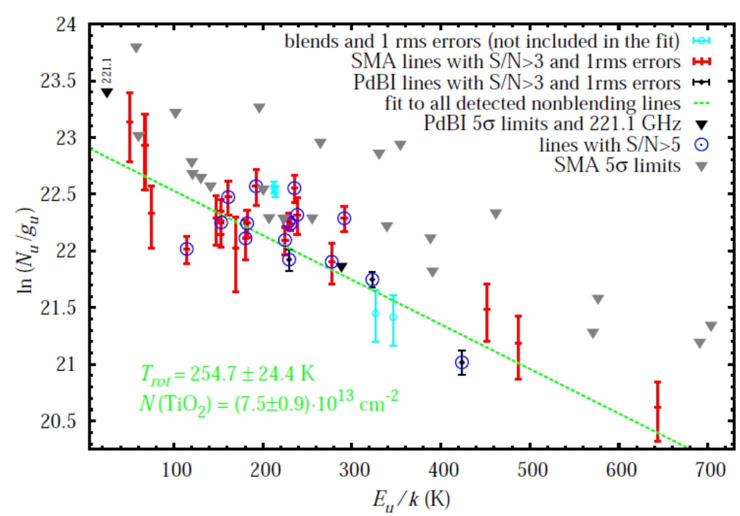
- In photospheres of late type stars
- In circumstellar envelopes – very rare: only a few objects known, all very bizarre
- TiO_2 never observed



- The extend of the emission:
  - TiO_2 $r \leq 50\ R_*$ (resolved)
  - TiO $r \leq 30\ R_*$

- Line profiles:
  - TiO_2: multiple line components
  - TiO: single, narrow component →already accelerated?

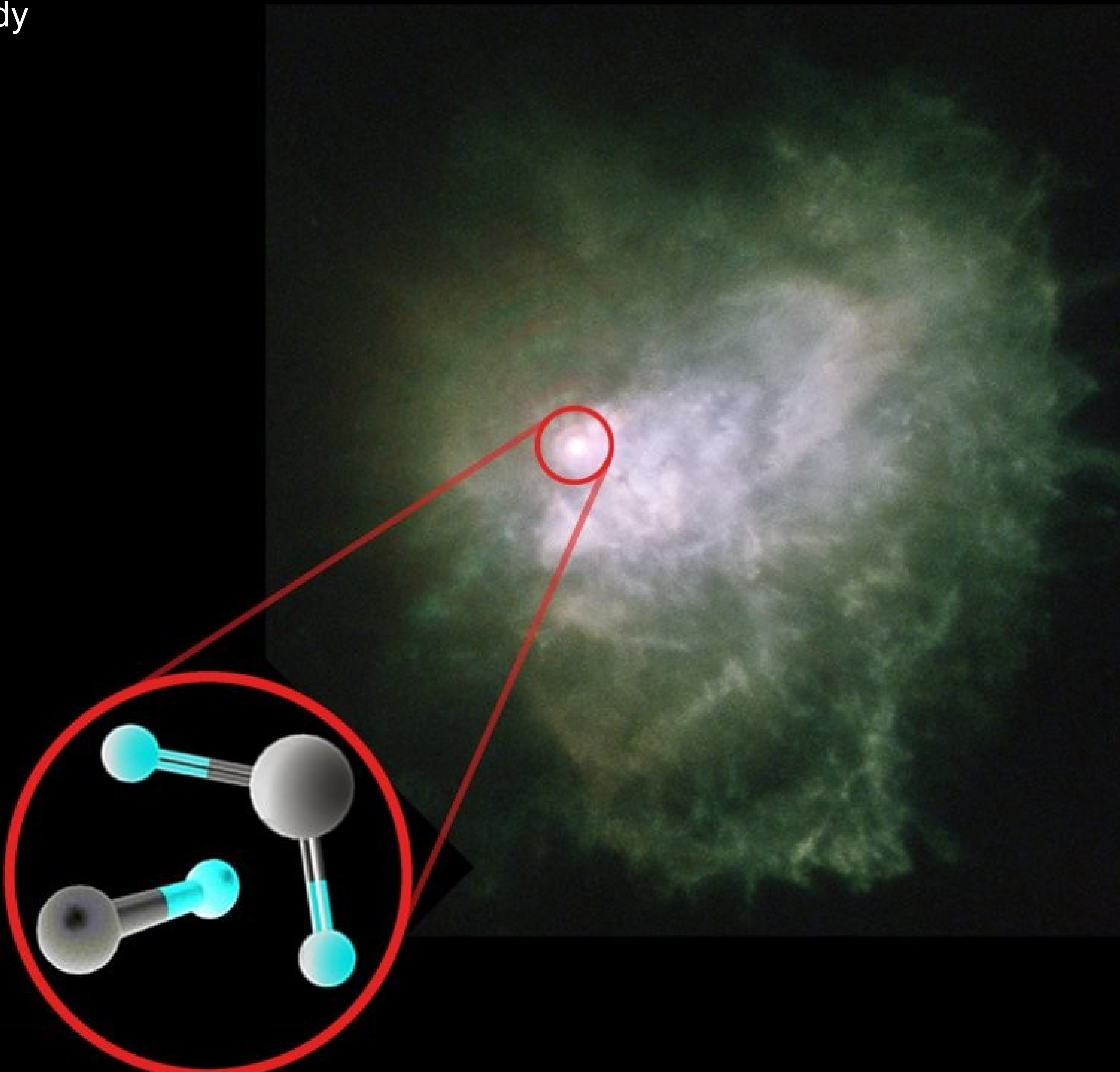
- Temperatures and column densities: some problems



TiO_2

T_{rot}=255 K

TiO & TiO_2 as tools to study
dust formation
or
dust destruction ?

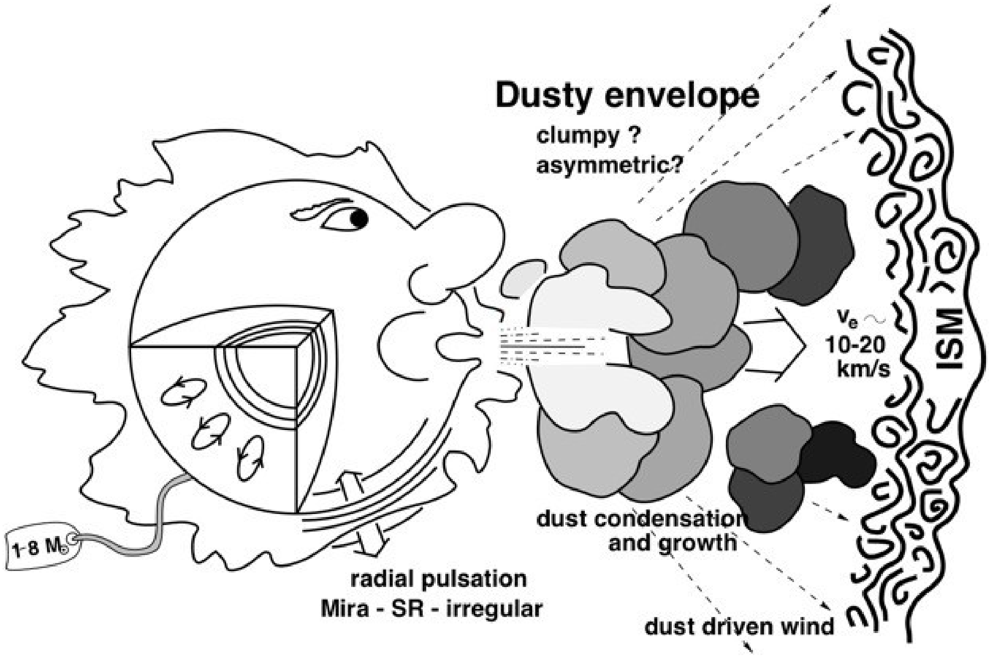


Science results III:

Mass loss

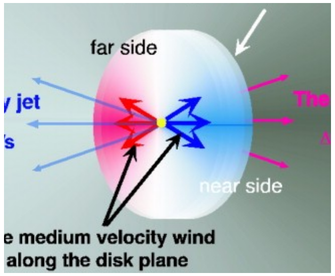
outflow mechanism(s)

& formation of asymmetries

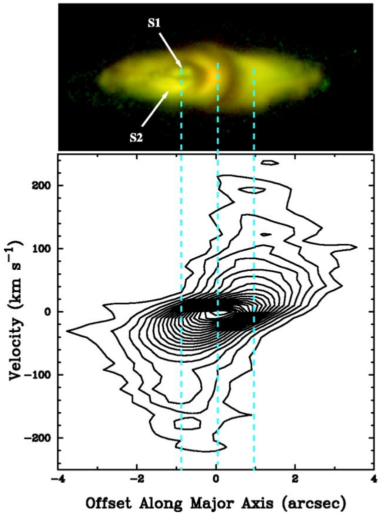


Science results: Outflows

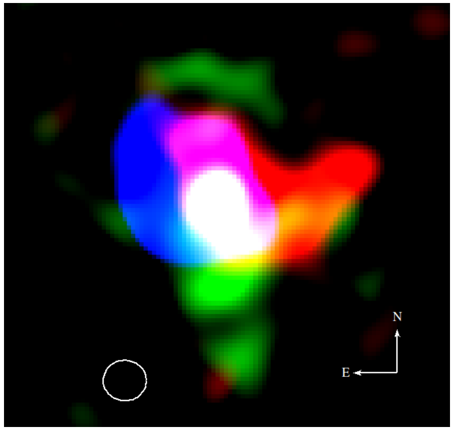
Hirano, Shinnaga, Dinh-V-Trung, et al. 2004
Hirano, Chiu, Muller, et al. 2005
detailed description of a wind-jets structure in a transitional objects (AGB→pre-planetary nebula) V Hydrae & π^1 Gru



Sahai, Young, Patel, et al. 2006
Wind-jets system in PPN, IRAS 22036

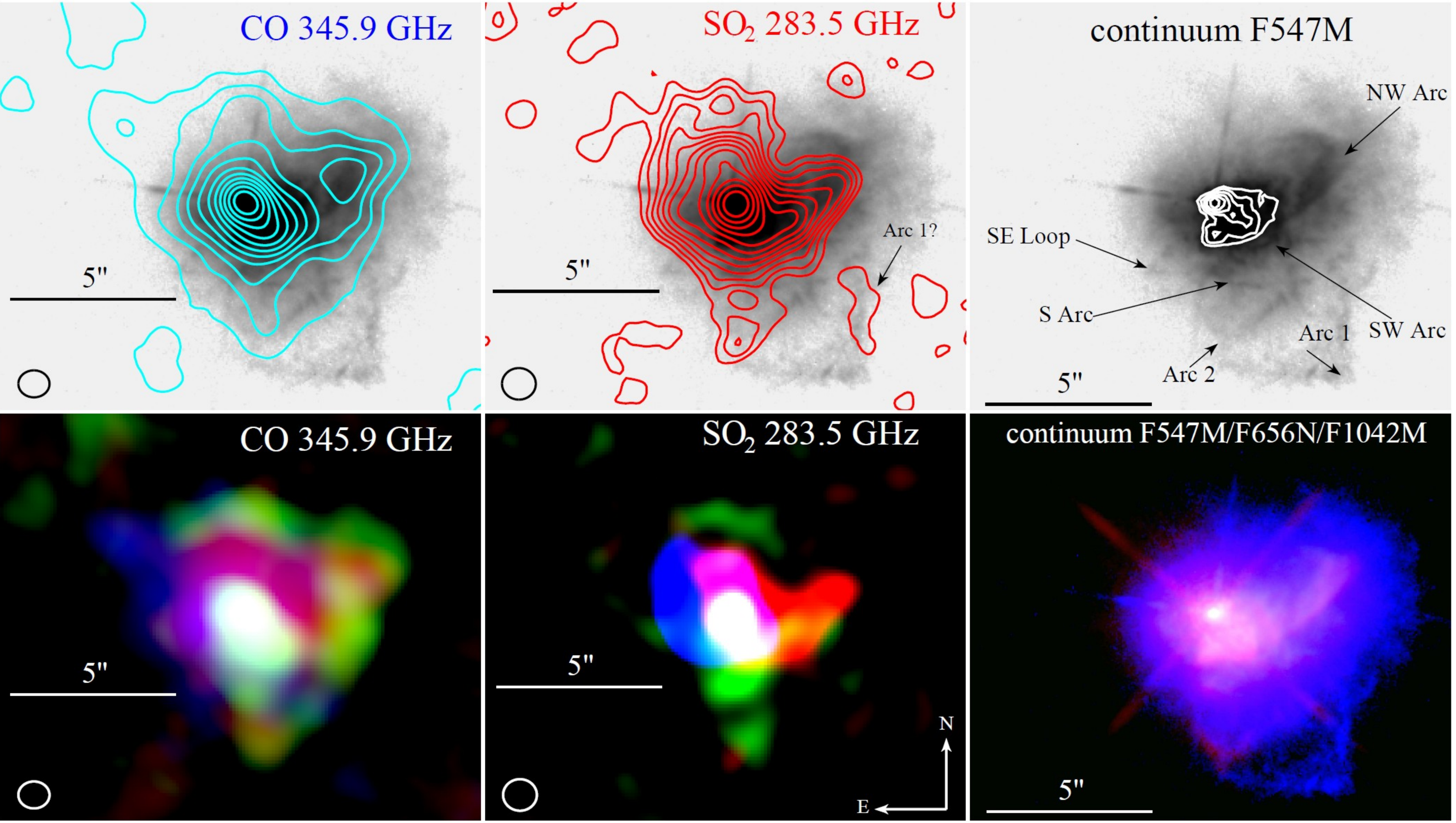


Hirano, Chiu, Muller,et al. 2005
Muller, Dinh-V-Trung, Hirano,et al. 2007
Fu, Molullet, Patel,et al. 2012
Kamiński, Gottlieb, Young, et al. 2013
spatiokinematical structure of the complex outflow around red supergiant VY CMa



Shinnaga, Young, Tilanus, et al. 2009
Patel, Young, Gottlieb, et al. 2011
Patel, Gottlieb, & Young 2013
direct observations of the wind acceleration zone in IRC+10216, the role of lines from vibrationally excited states

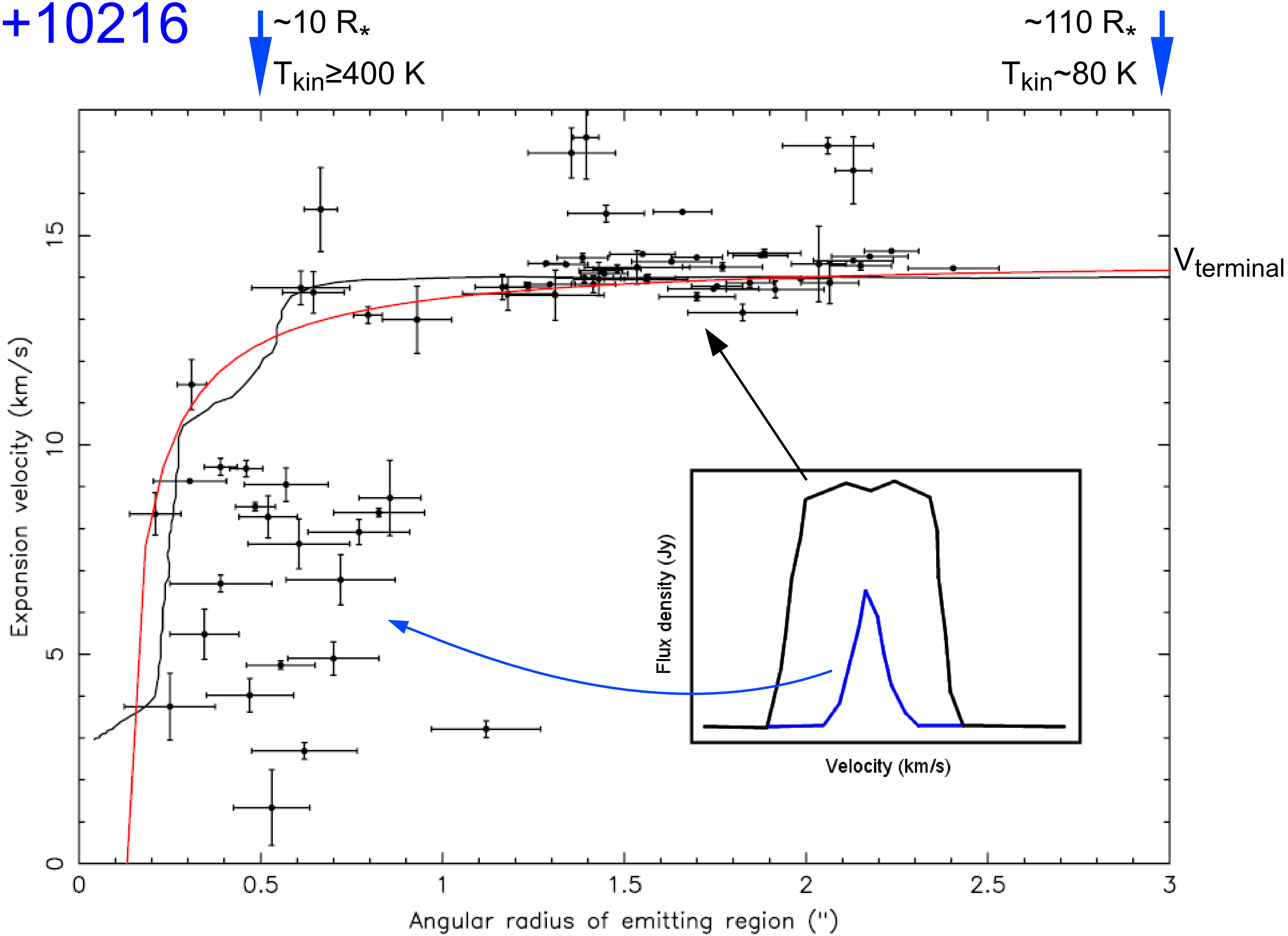
The magnificent VY CMa



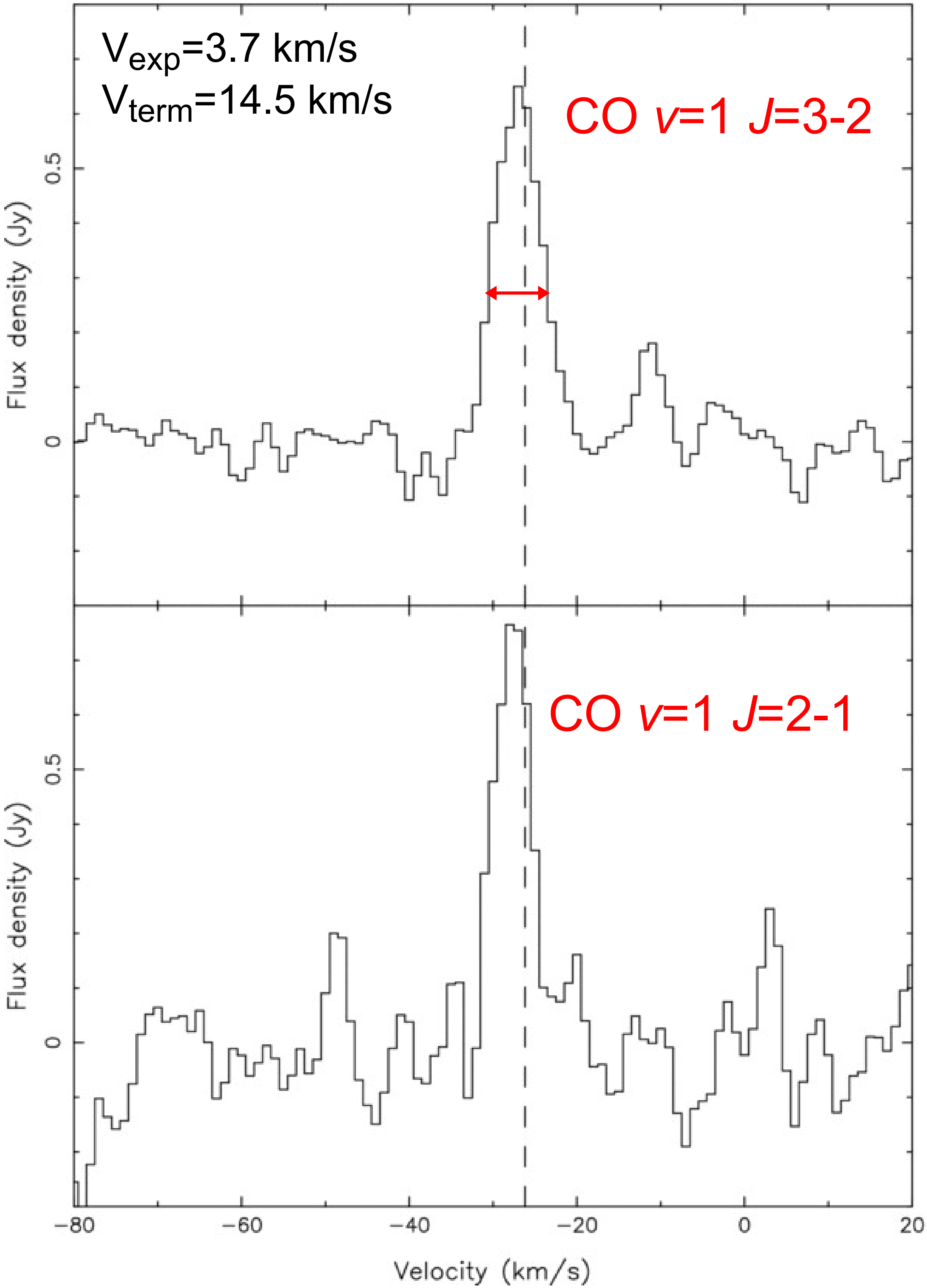
SMA beats Hubble, yeah!

Kamiński et al. 2013

IRC+10216



Patel *et al.* 2009, 2011, 2013

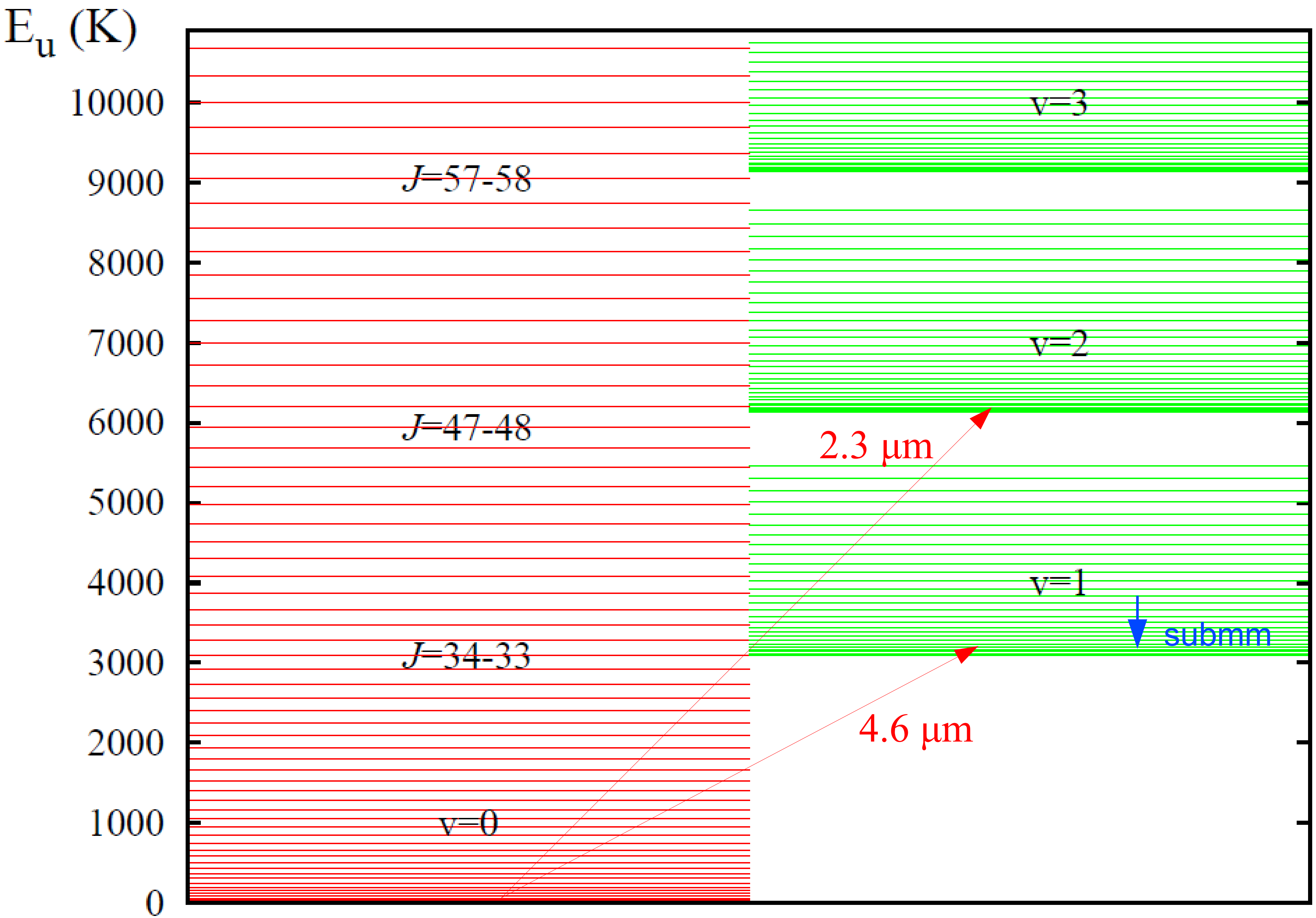


CO v=1 lines in IRC+10216

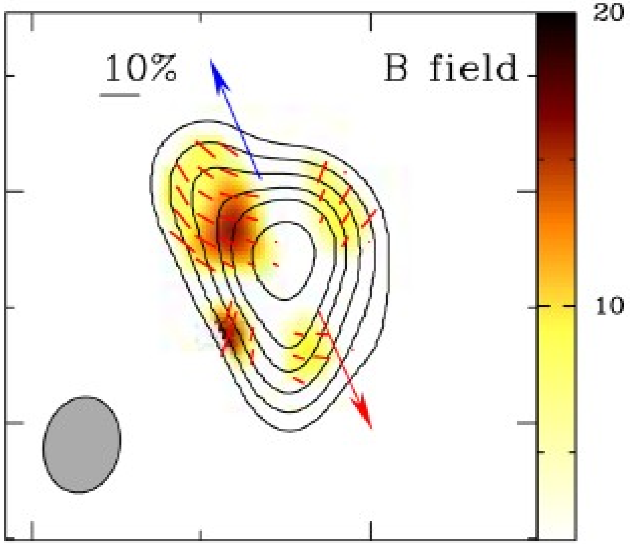
(Patel *et al.* 2009, 2011)

- first detections of CO v=1 with SMA
  - unresolved spatially
  - observations at different epochs
  - ^{13}CO v=1 *J*=3-2
- unsolved problems:
  - collisionally or radiatively excited?
  - time variability
  - maser action ?

Rotational lines from vibrationally excited states of CO



Science results IV: circumstellar polarimetry



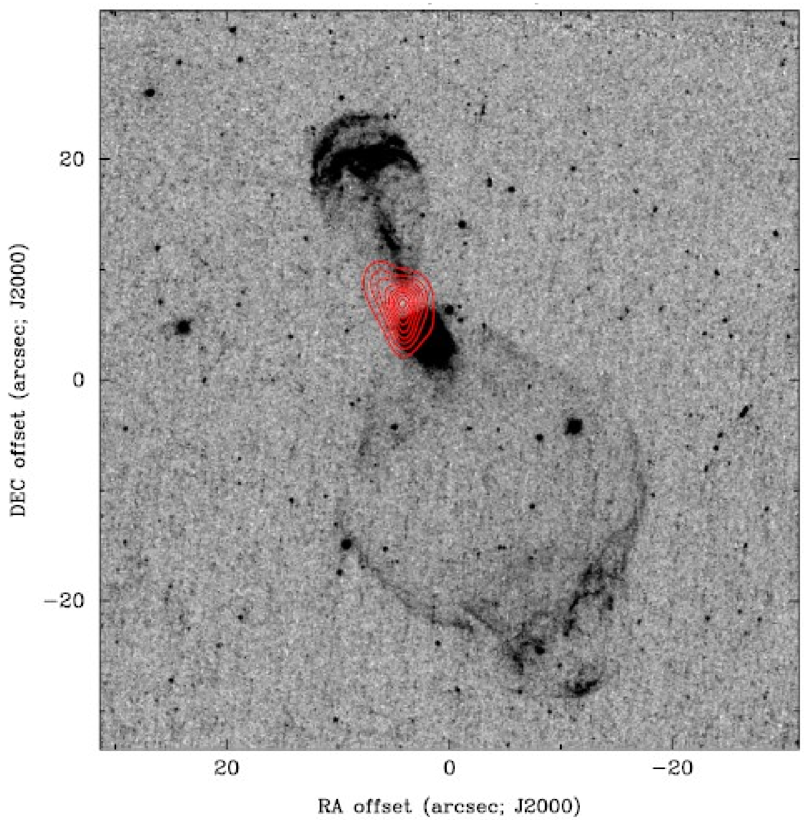
Science results: Polarimetry

Shinnaga, Moran, Young, Ho 2004
SiO(5-4) at v=1 linear polarization in VY CMa reveals maser spots which are 60% polarized. This supports radiative process as the pumping mechanism of SiO masers.

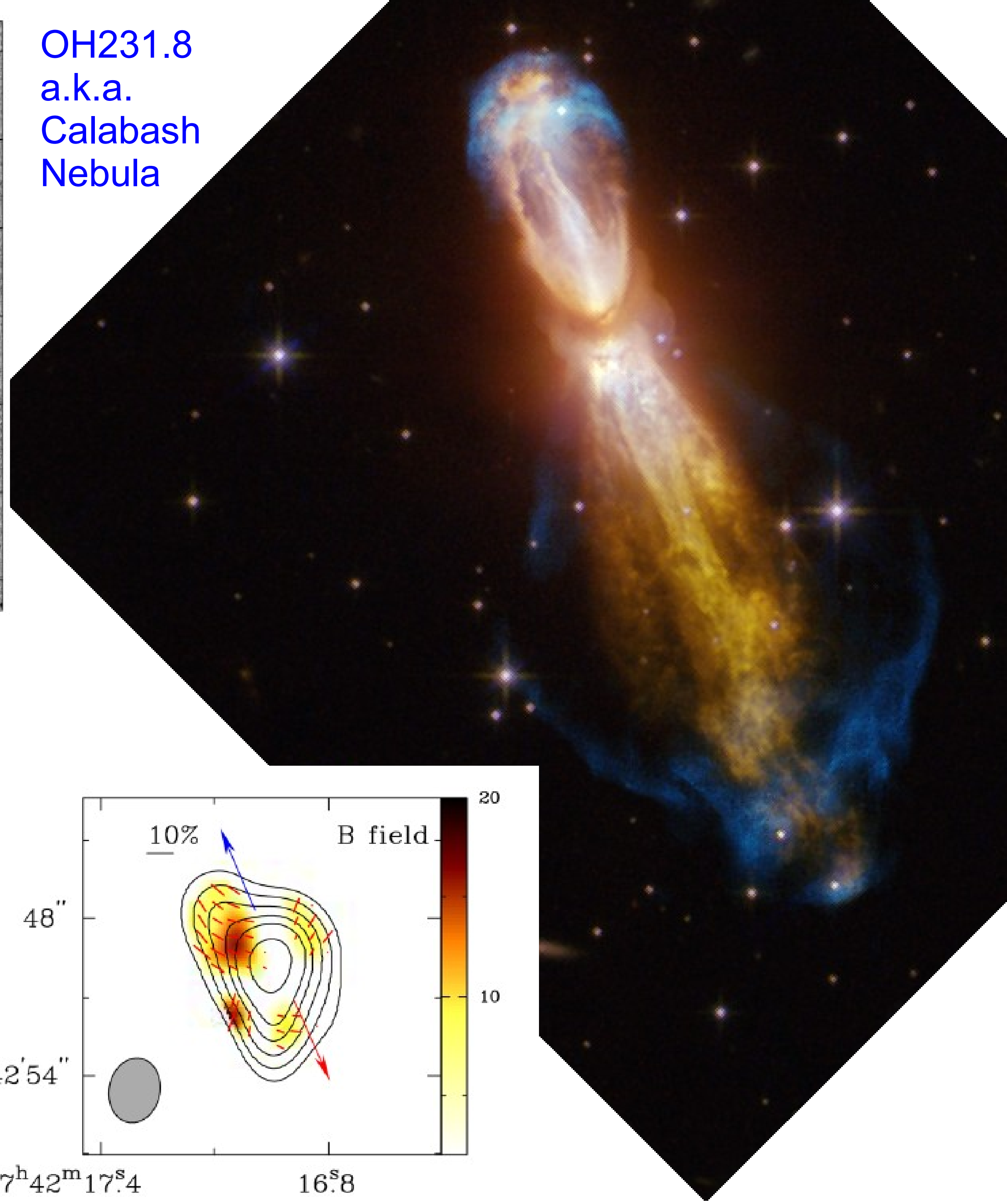
Vlemmings, Ramstedt, Rao, Maercker 2012
line polarization study of IK Tau and observations of the Goldreich-Kylafis effect in CO(2-1) and SiO(5-4) → constraints on the magnetic field geometry in IK Tau

Girart, Patel, Vlemmings, Rao 2012
line polarization study of IRC+10216. Linear polarization detected in CO(3-2), SiS(19-18),CS(7-6) reveals a complex magnetic field configuration (through the Goldreich-Kylafis effect)

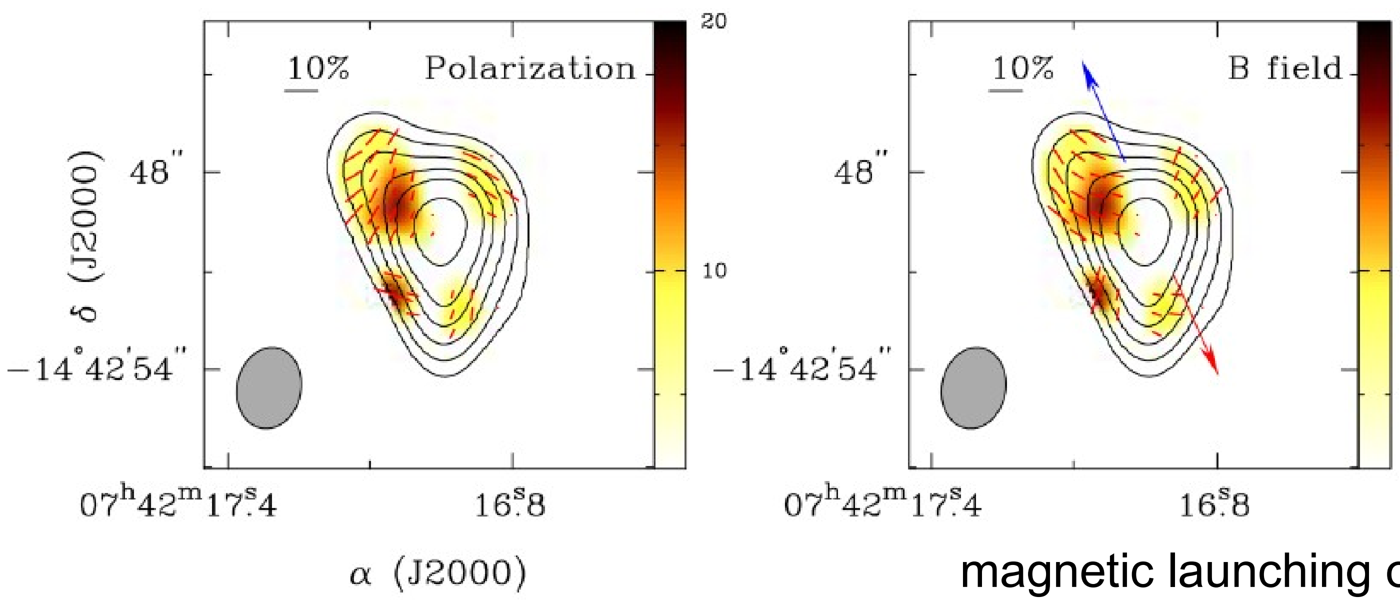
Sabin, Zhang, Zijlstra, et al. 2014
continuum polarization measurements in two PPNs at 345 GHz. Well organized nearly polar magnetic fields present in both objects.



OH231.8
a.k.a.
Calabash
Nebula

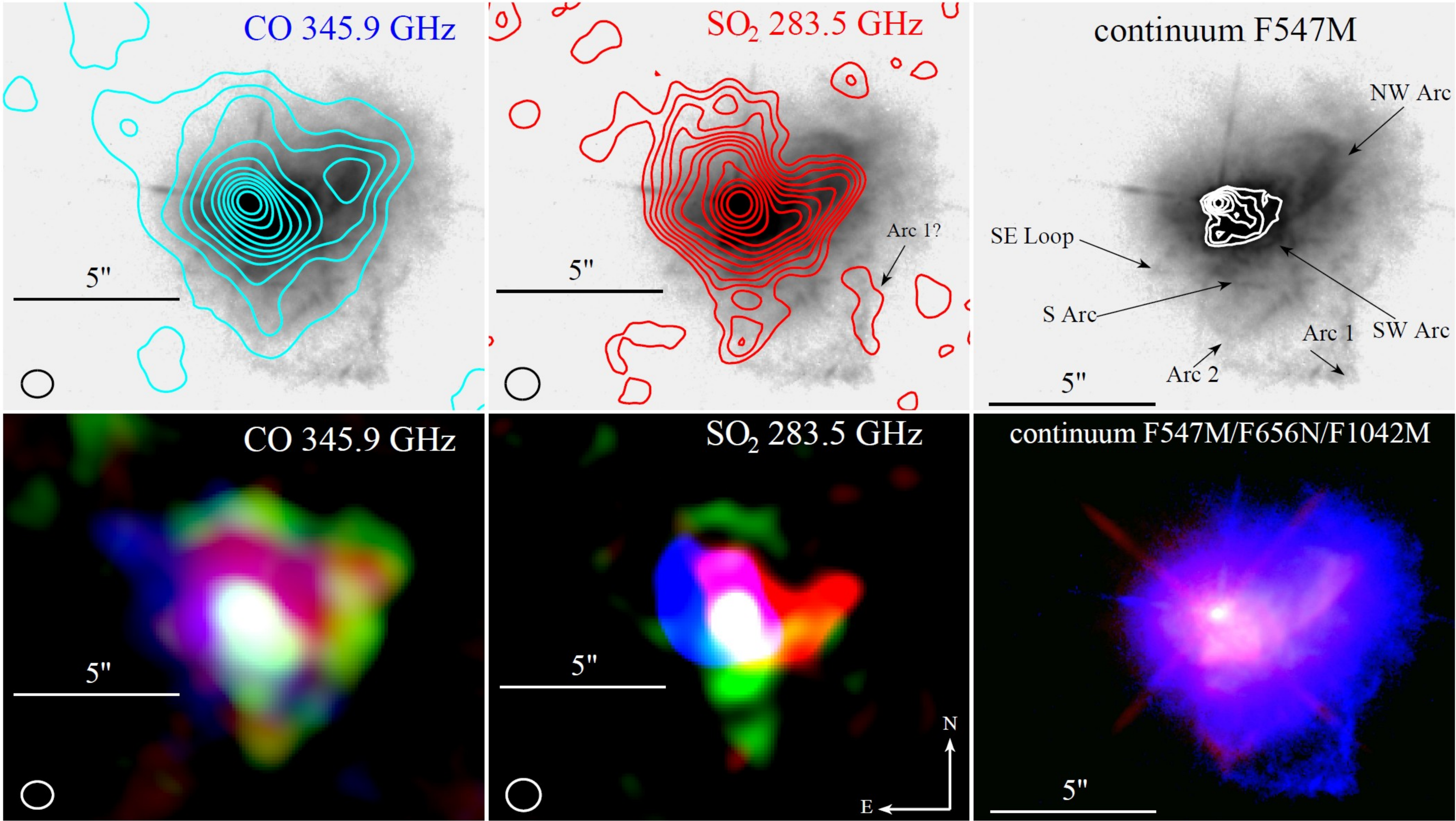


Sabin, Zhang, Zijlstra, et al. 2014



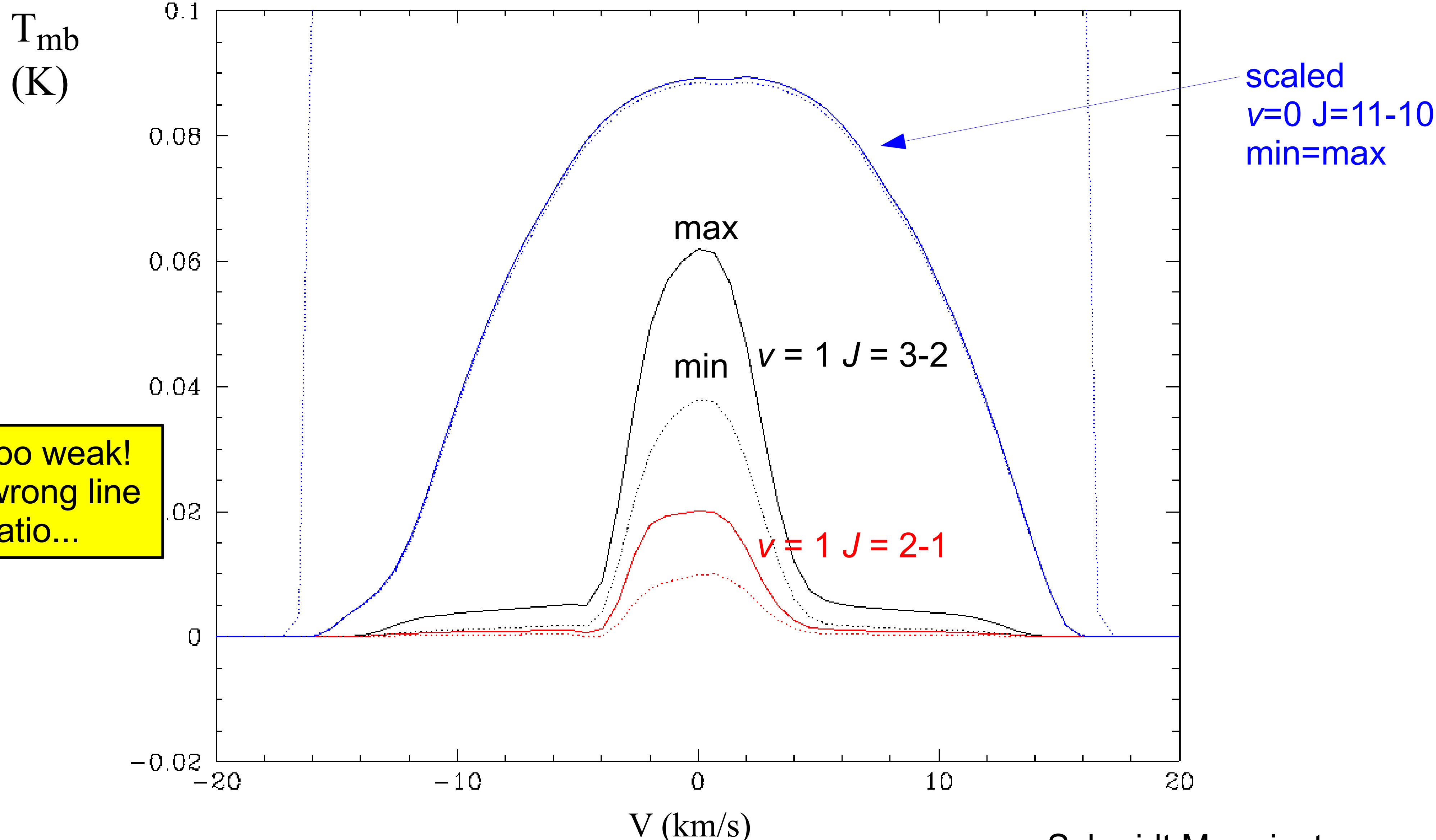
magnetic launching of the outflow?

Thank you


CO 345.9 GHz
5"
SO_2 283.5 GHz
Arc 1?
5"
continuum F547M
NW Arc
SE Loop
S Arc
Arc 1
SW Arc
Arc 2
5"
CO 345.9 GHz
5"
SO_2 283.5 GHz
5"
N
E
continuum F547M/F656N/F1042M
5"

Would the v=1 lines change if only collisionally induced (due to gas-dust thermal coupling & size effect)? YES!

A test for IRC+10216

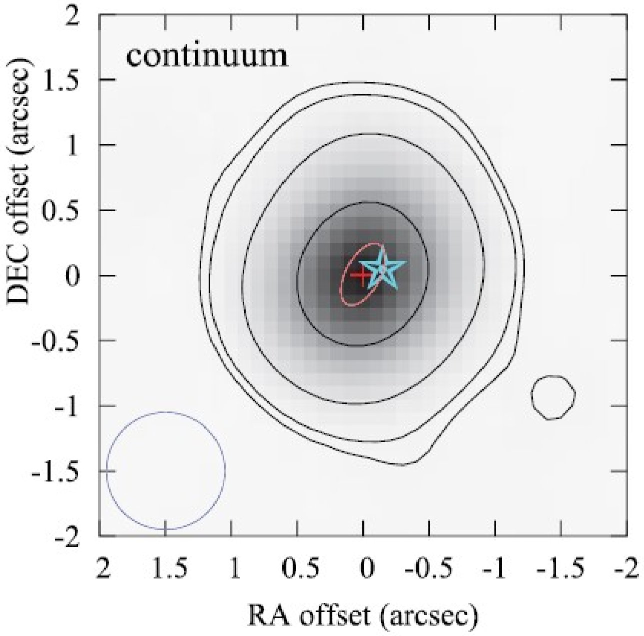


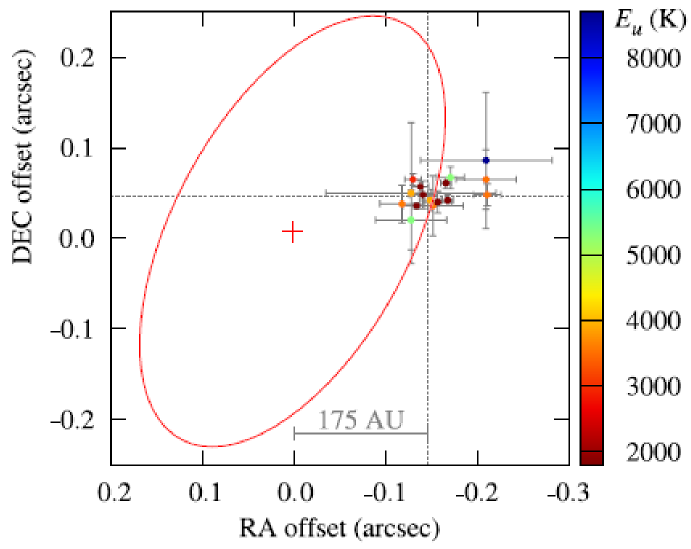
too weak!
wrong line ratio...

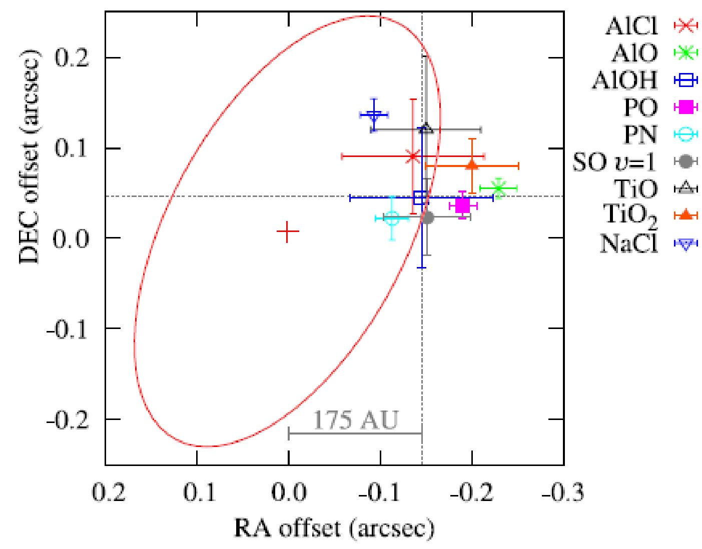
Schmidt M., privat comm.

Subarcsec structures in VY CMa...

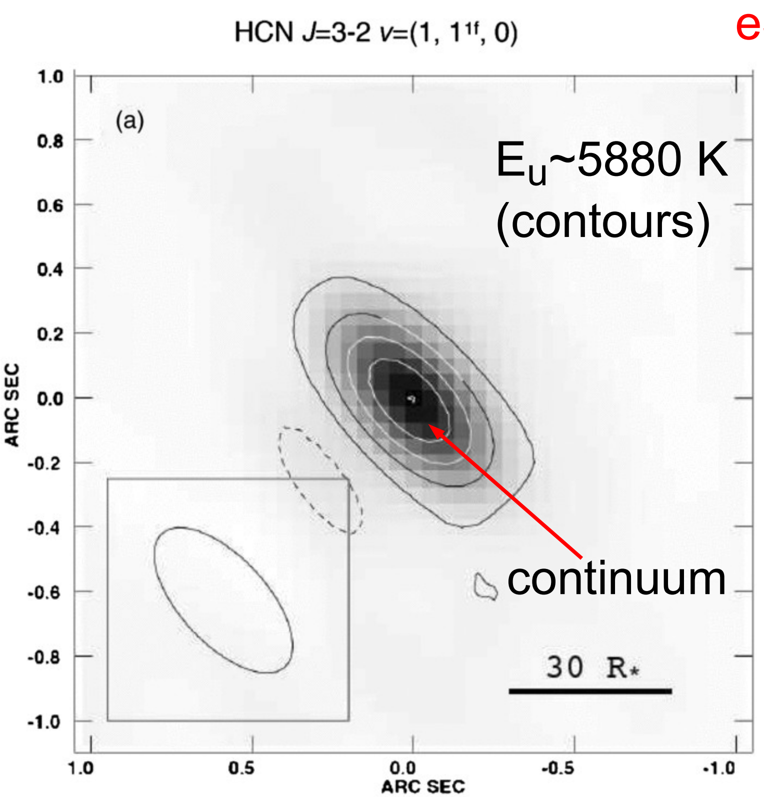
(Kamiński et al. 2013)

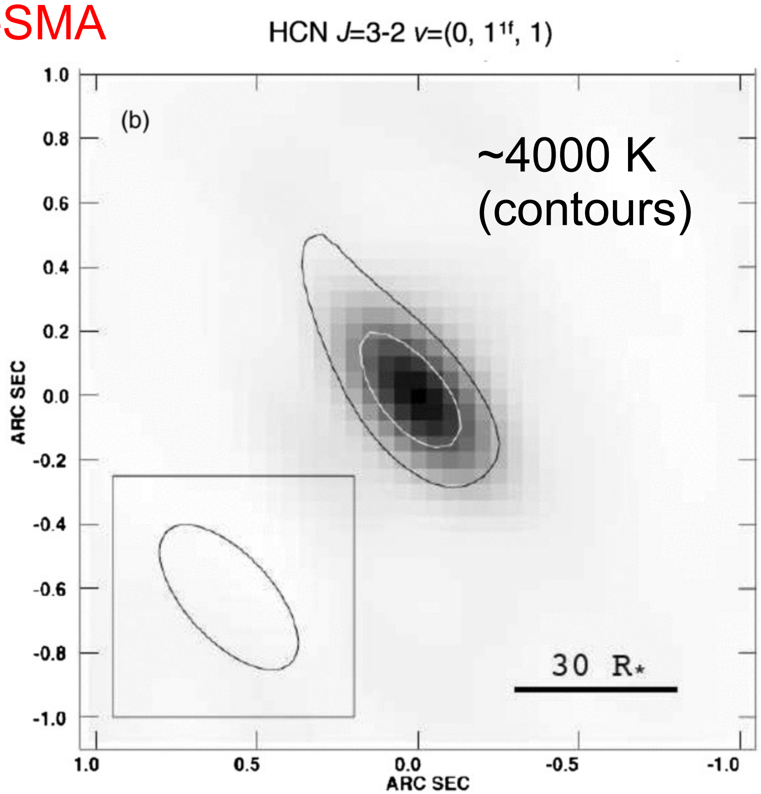






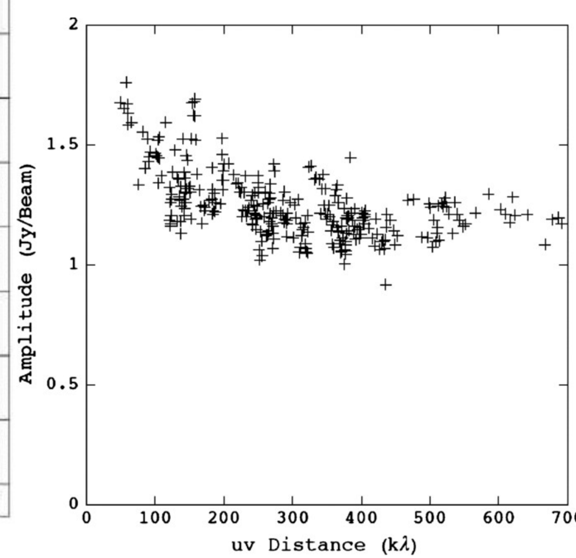
eSMA





... and IRC+10216

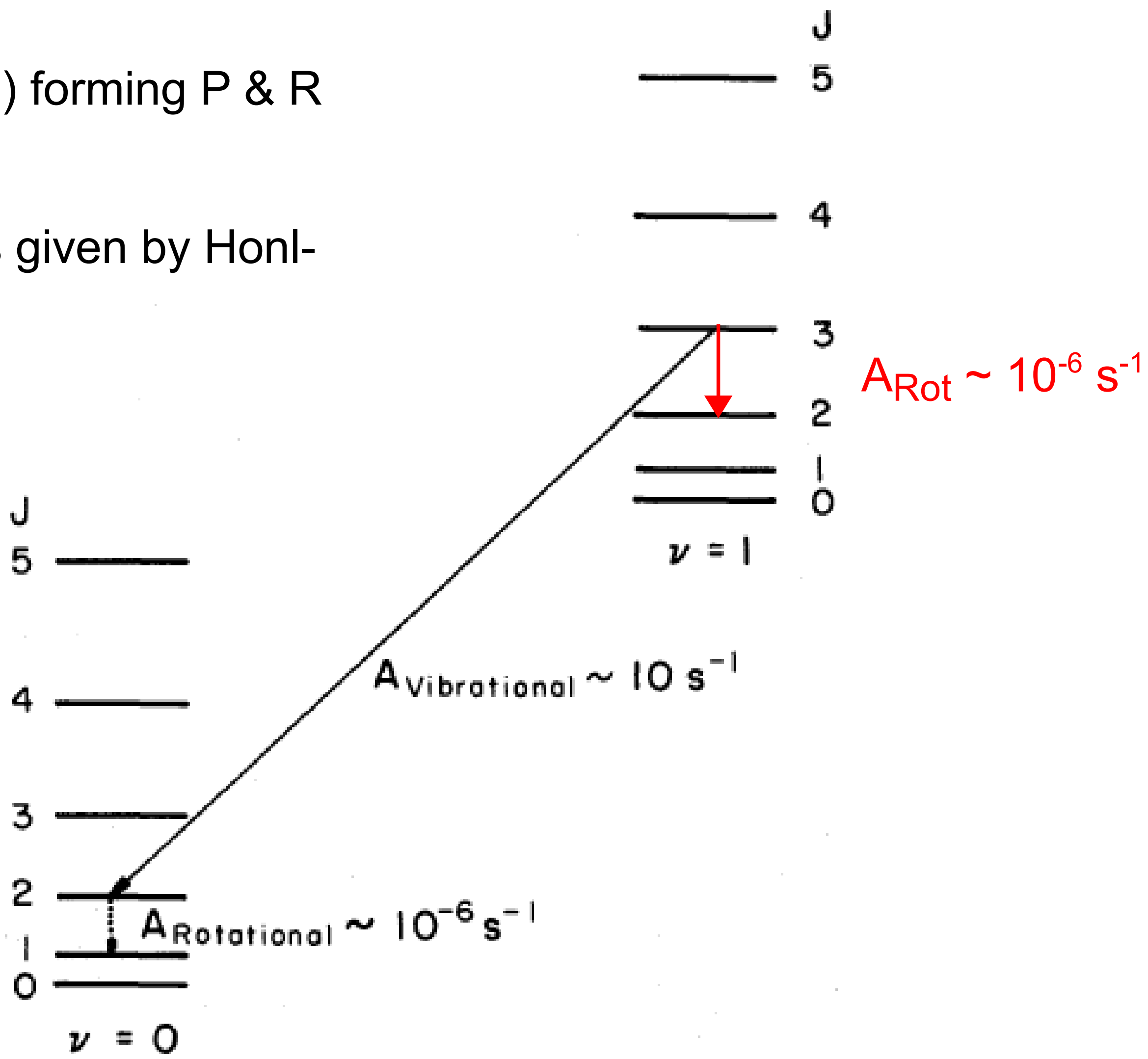
(Shinnaga et al. 2009)



Redistribution of populations at v=1 by radiation:

Selection rules (J=±1) forming P & R (no Q) branches

Rovib. line intensities given by Honl-London factors



needs detailed modelling