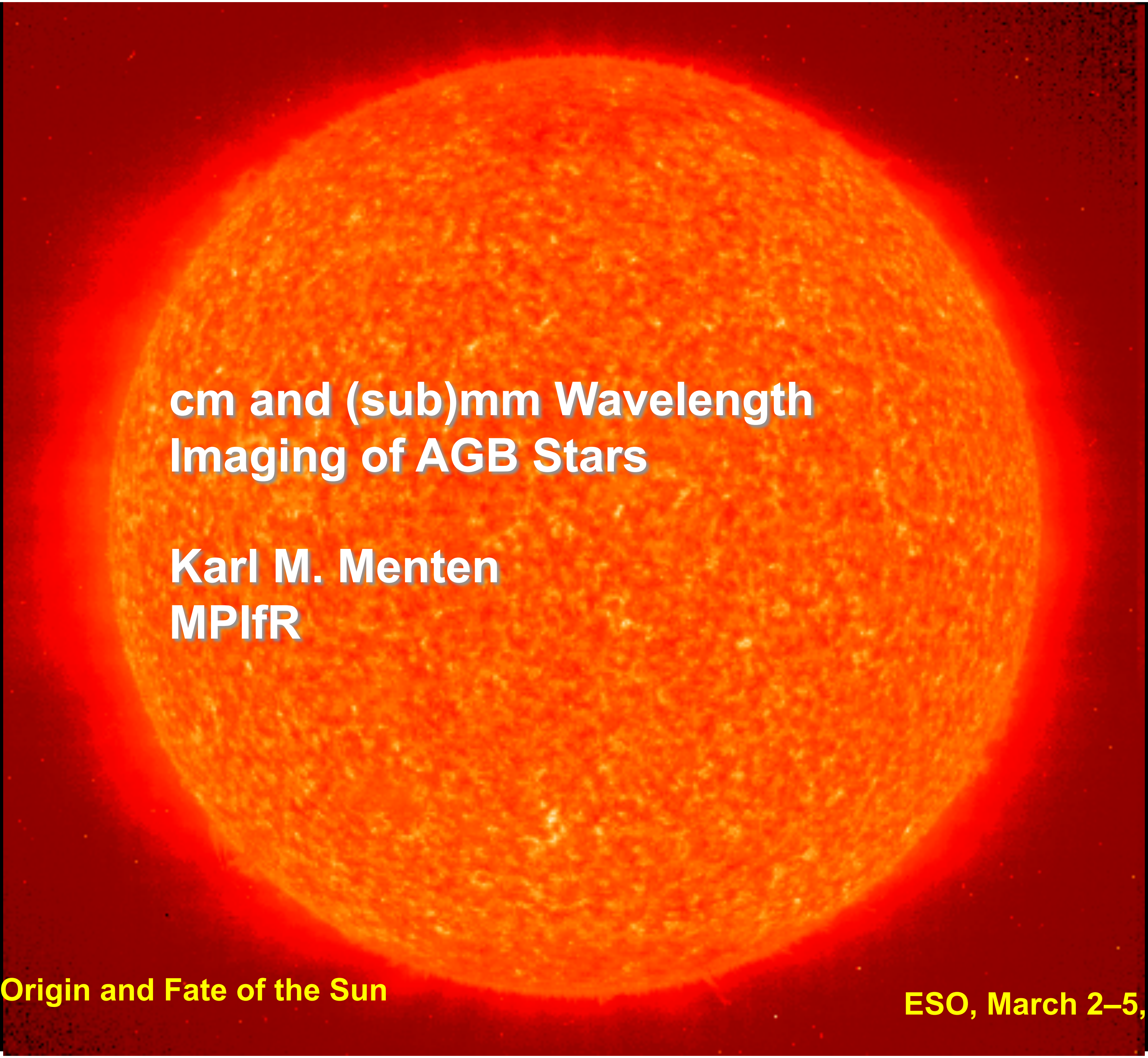


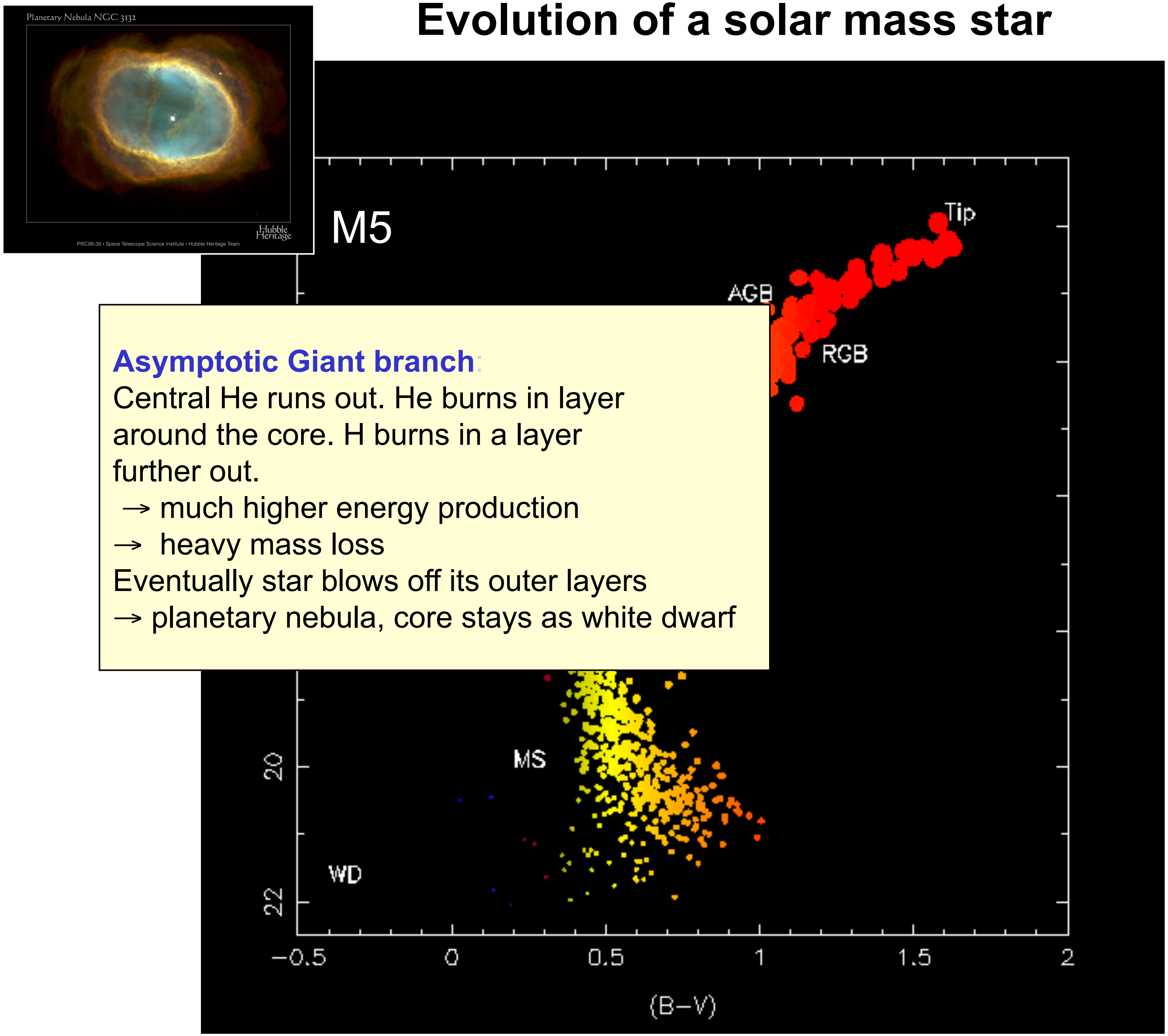
cm and (sub)mm Wavelength Imaging of AGB Stars

Karl M. Menten
MPIfR

The Origin and Fate of the Sun

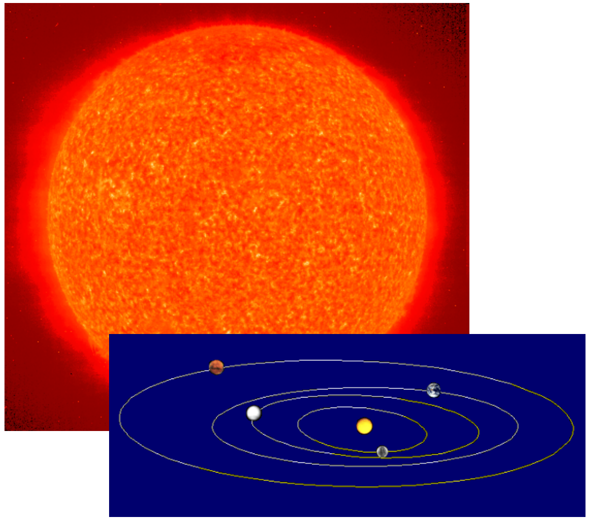
ESO, March 2–5, 2010

Evolution of a solar mass star



Asymptotic Giant branch:
Central He runs out. He burns in layer around the core. H burns in a layer further out.
→ much higher energy production
→ heavy mass loss
Eventually star blows off its outer layers
→ planetary nebula, core stays as white dwarf

AGB Red Giant stars – Basic facts



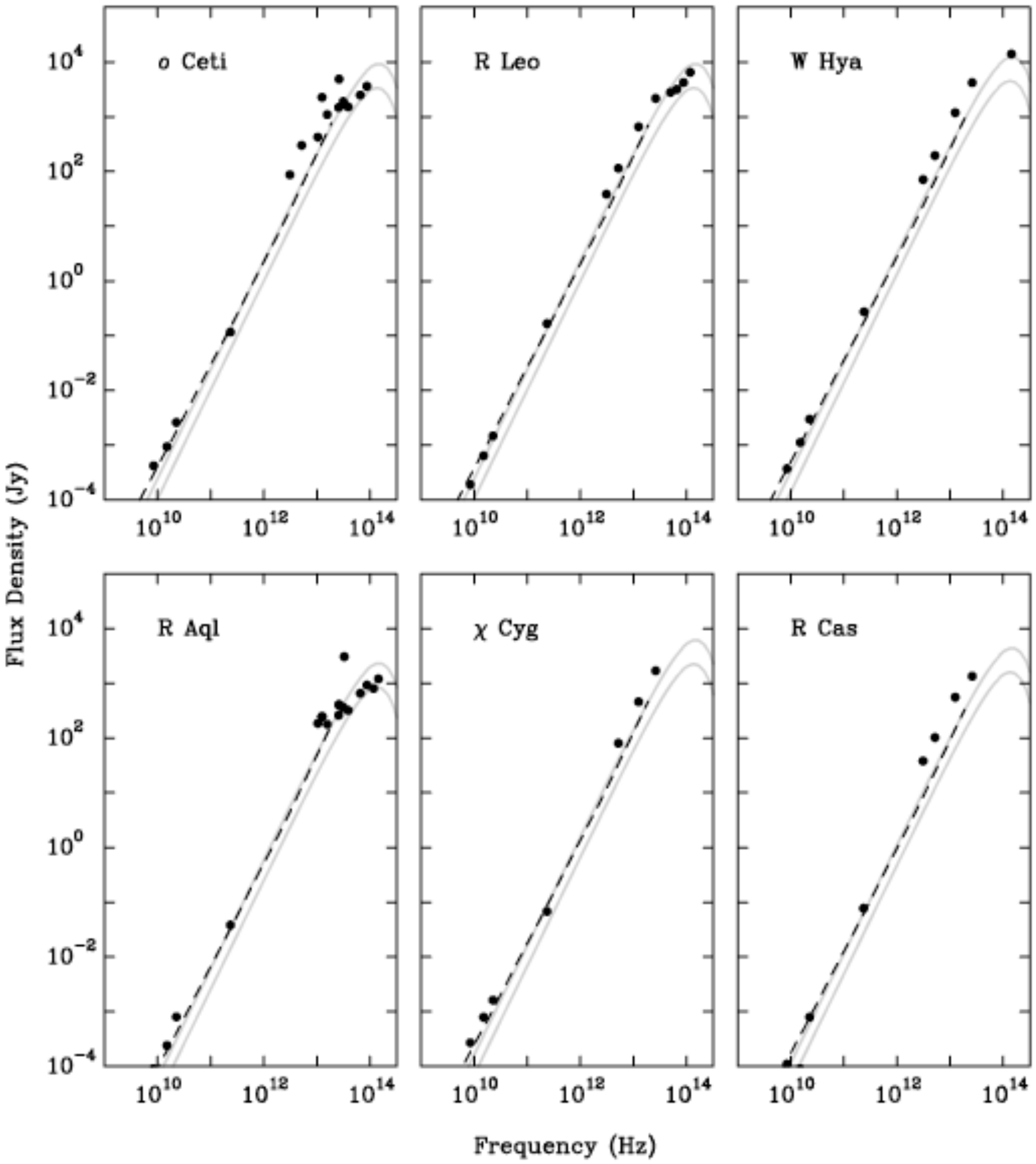
- Mass up to a few $M_\odot$
- Radii 100 – 1000 $R_\odot$ i.e. up to several AU!
- At tip of asymptotic giant branch
  - Star at the end of it’s life cycle
  - Small, hot core and large outer envelope
  - Fusion producing heavier elements; He, C, O
  - Shrouded in dust and gas, circumstellar shell
    - beginning of nebulae
  - Will finish it’s life as a white dwarf and planetary nebulae
- Stars pulsate with periods of 100s of days (“LPVs”)
- Luminosities many 1000s $L_\odot$

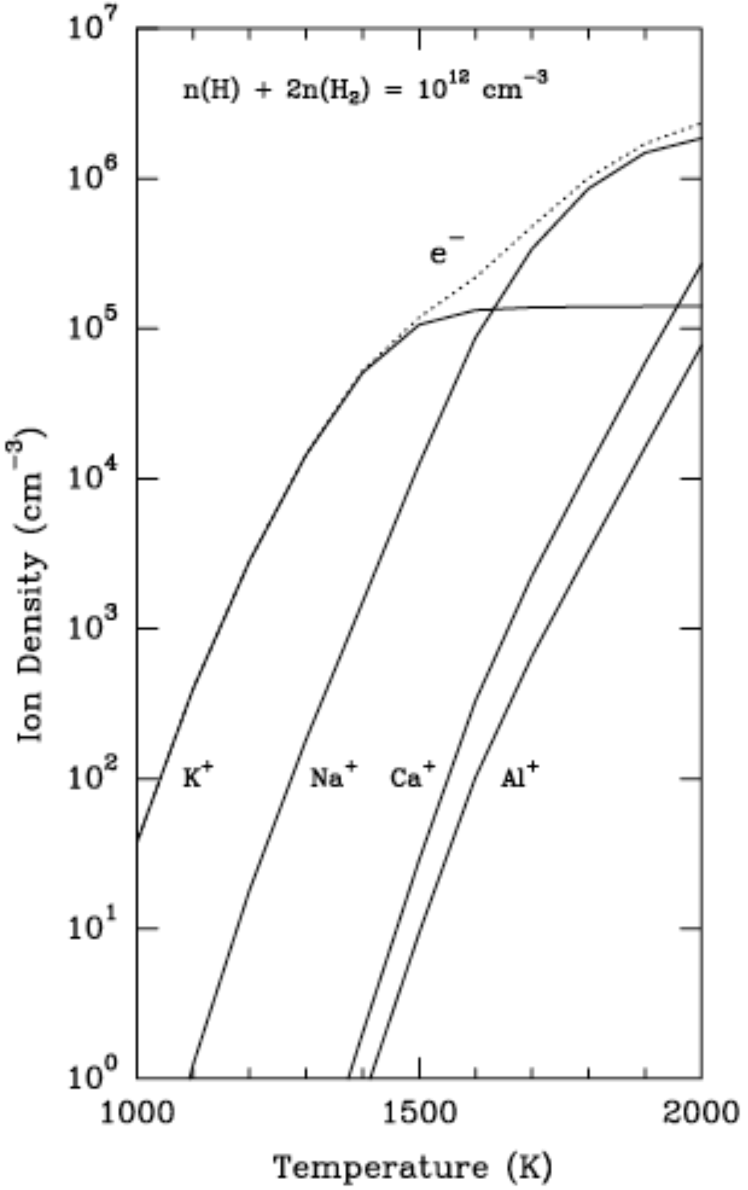
Why is it interesting to study AGB stars?

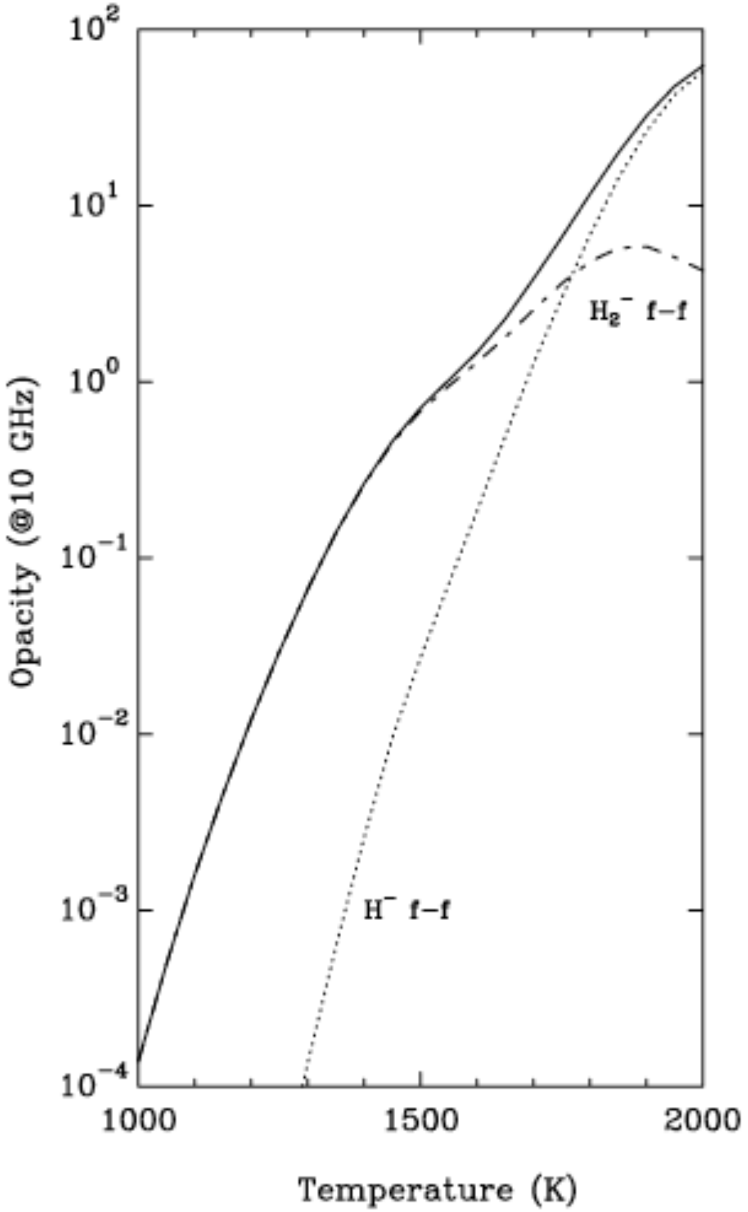
- mass return to the interstellar medium (> 50%???)
- element enrichment CNO+…
- study dust production
- stellar evolution
- precursors to supernovae (high mass only)
- (relatively) simple geometry (spherically symmetric to 1st order) makes meaningful modeling (e.g. of chemistry) possibe

Radio emission from AGB and red supergiant stars

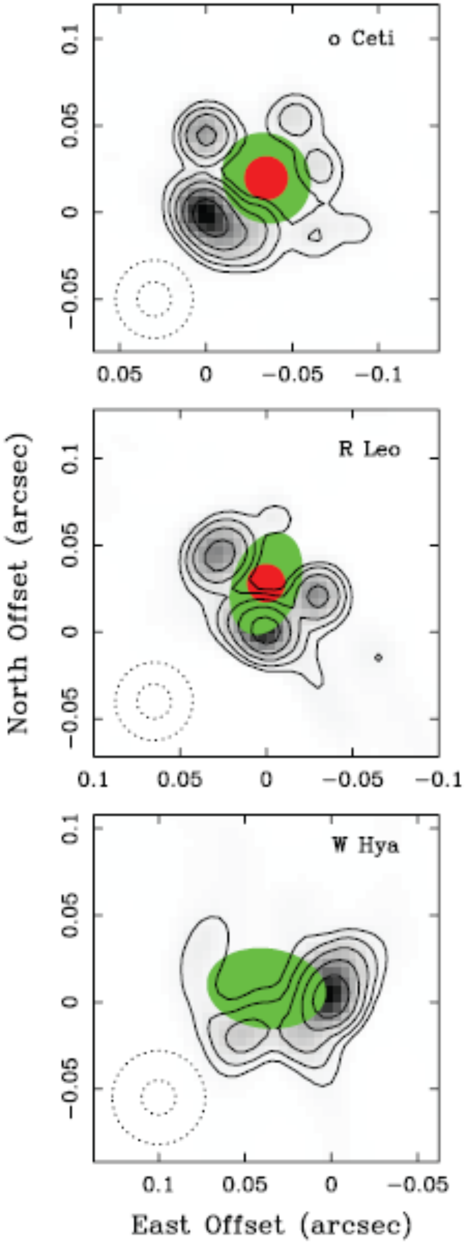
REID & MENTEN 1997

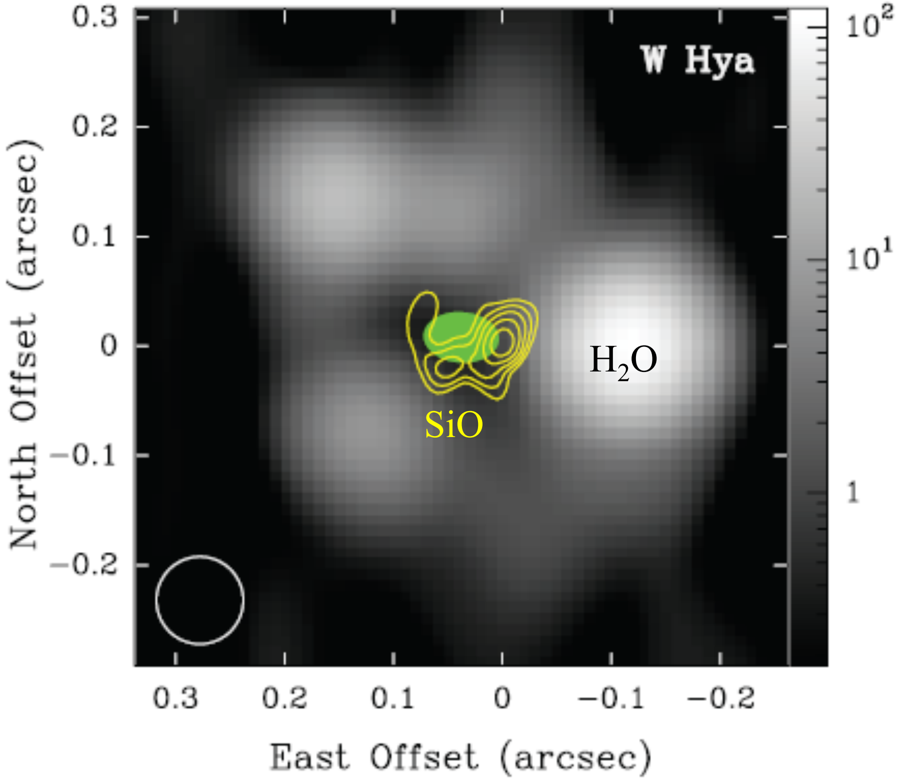




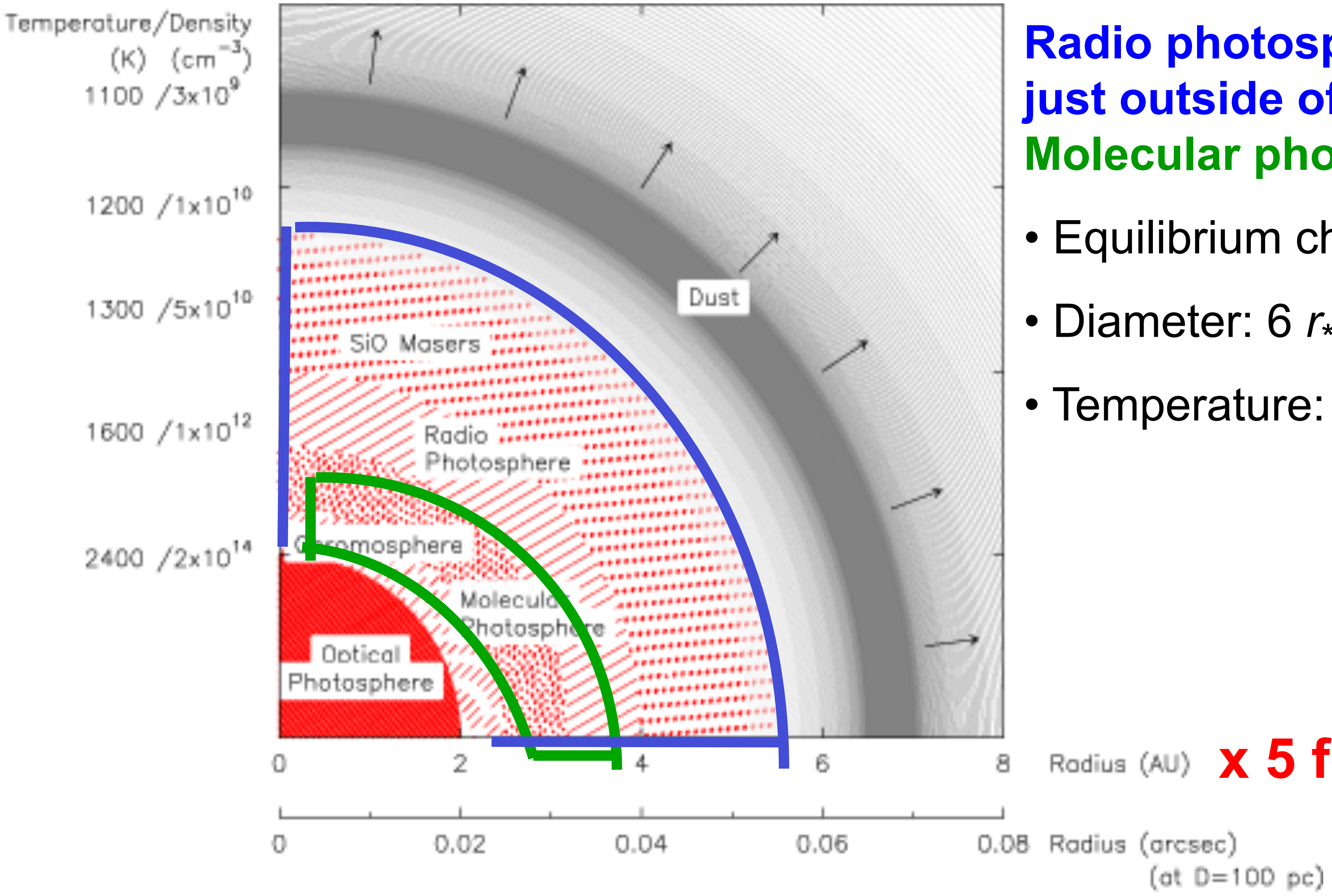


Reid & Menten 1997





Reid & Menten 1991, 2007



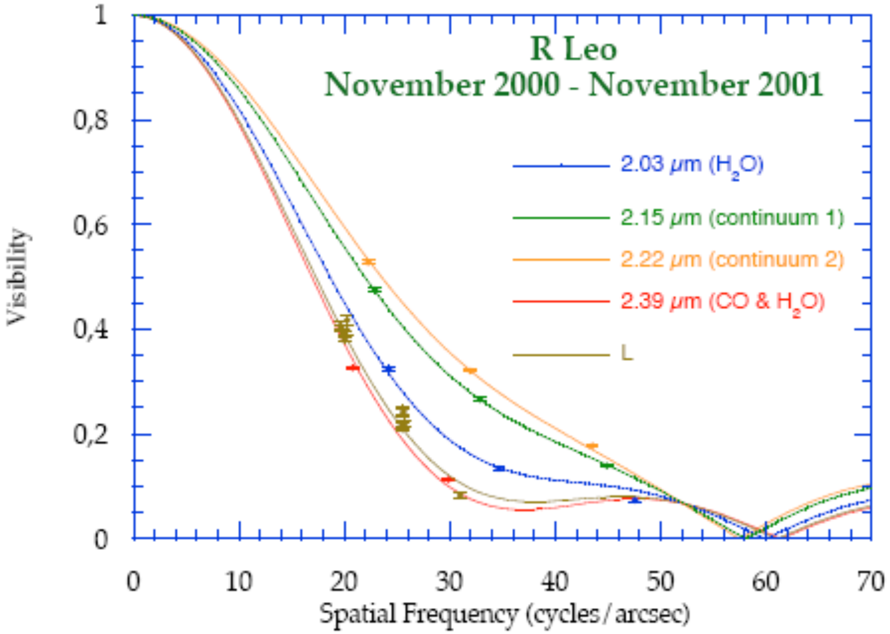
Radio photosphere is just outside of Molecular photosphere

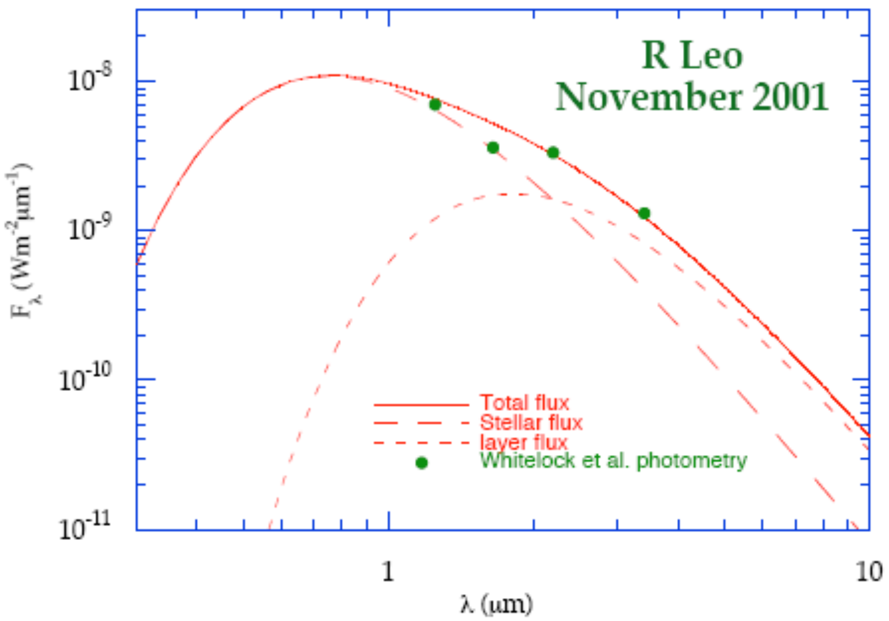
- Equilibrium chemistry
- Diameter: 6 r_*
- Temperature: 2000 K

x 5 for RSG

Reid & Menten 1997

G. Perrin et al.: Unveiling Mira stars behind the molecules **2004**





Talks by A. Chiavassa, I, Karovicova, K. Ohnaka

Thermal equilibrium chemistry close to stellar photosphere

T > 2000 K, n > 10^{12} cm^{-3}

M_1, M_2, Parent species (atoms, radicals, or molecules)

Dissociation equilibrium $M_1 + M_2 \leftrightarrow M_1M_2$

At the thermal equilibrium: $P_{M_1} \cdot P_{M_2} = K_D(T) P_{M_1M_2}$

P_{M1} partial pressure of species1

P_{M2} partial pressure of species 1

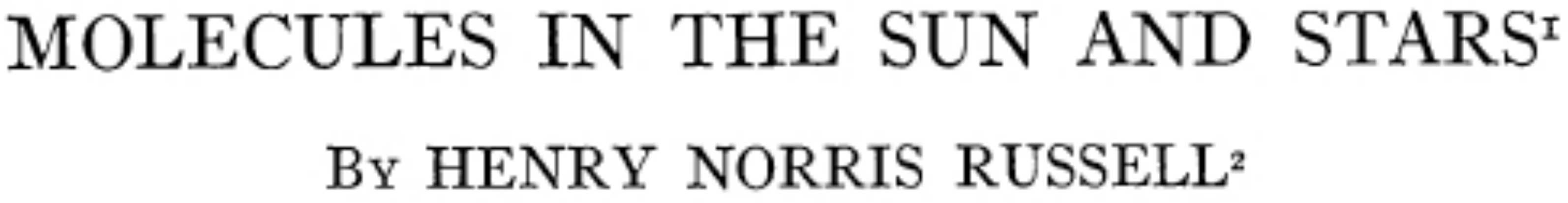
P_{M1M2} partial pressure of resulting molecule

K_D dissociation constant

$$K_D(T) = \frac{Q_{M_1} Q_{M_2}}{Q_{M1M1}} e^{-\frac{\Delta E_0^0}{kT}}$$

Q's partition functions

ΔE_0^0 Difference in zero point energy between state M_1+M_2 and M_1M_2 = “dissociation energy”



MOLECULES IN THE SUN AND STARS[1]

By HENRY NORRIS RUSSELL[2]

Astrophysical Journal, vol. 79, p.317, 1934

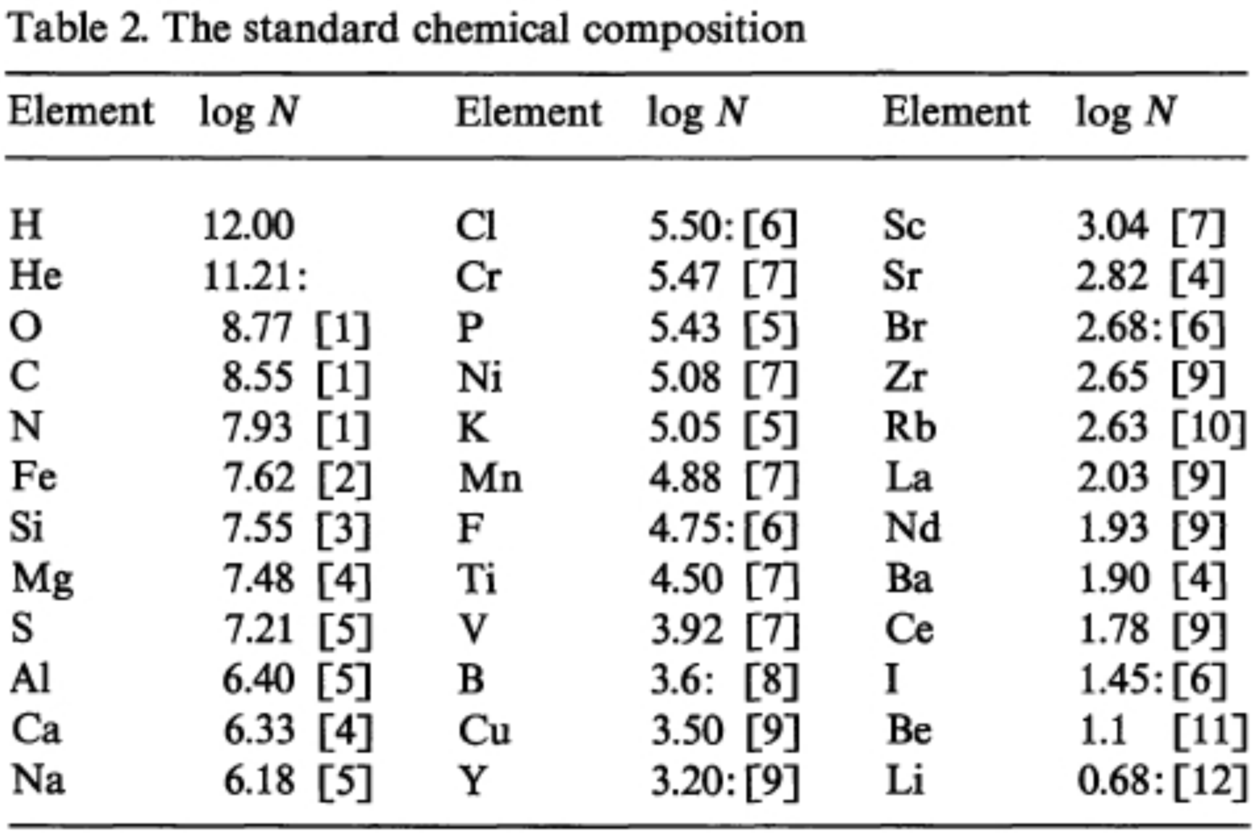
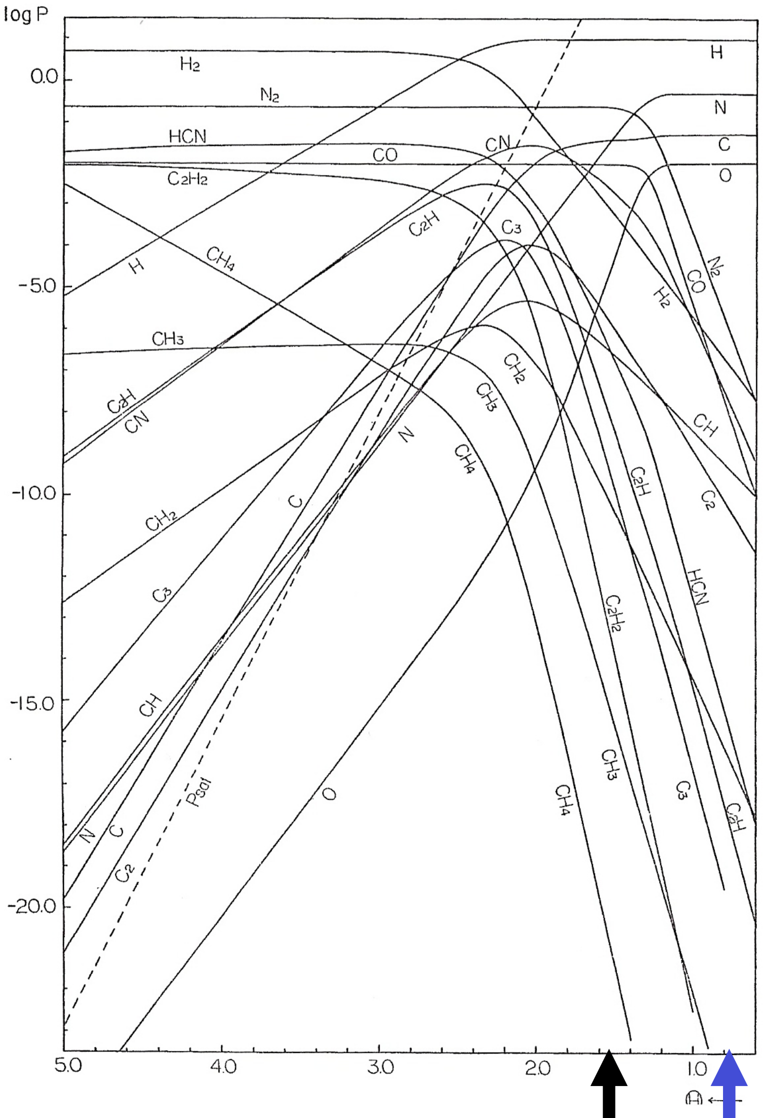
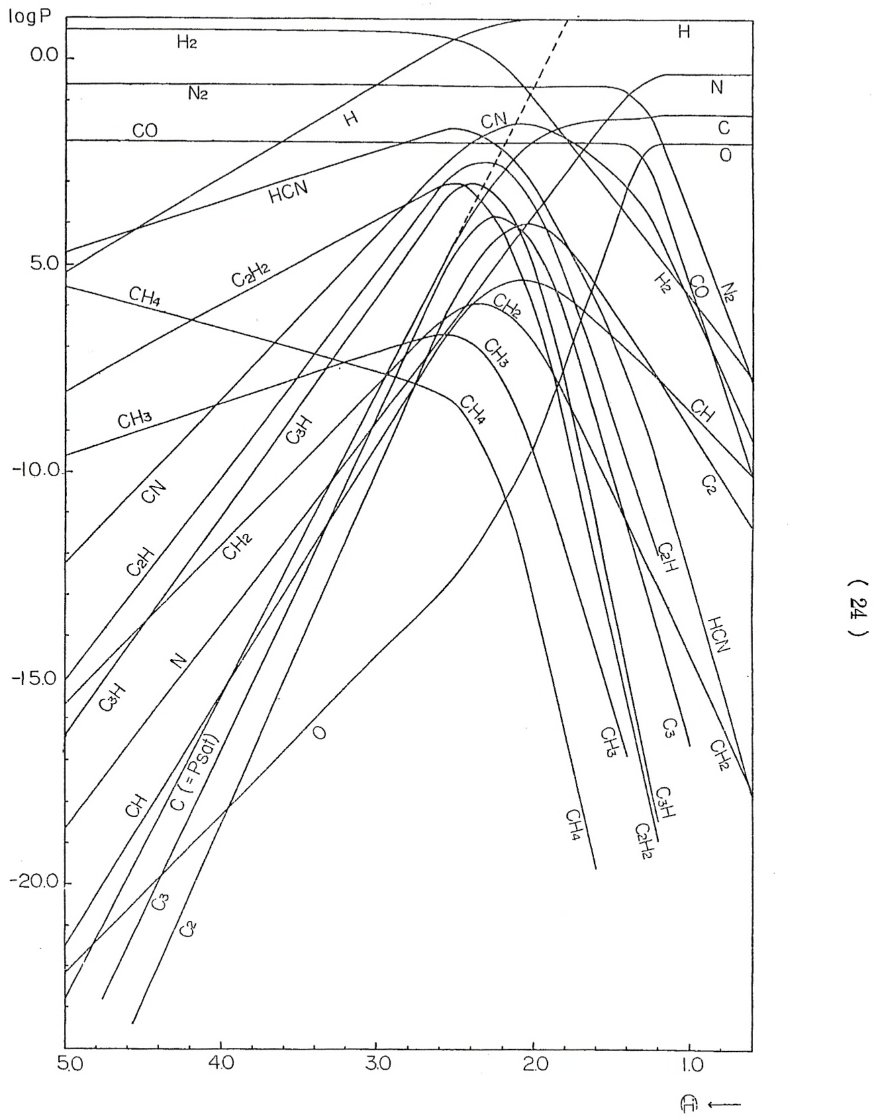


Table 2. The standard chemical composition

Element	log N	Element	log N	Element	log N
H	12.00	Cl	5.50: [6]	Sc	3.04 [7]
He	11.21:	Cr	5.47 [7]	Sr	2.82 [4]
O	8.77 [1]	P	5.43 [5]	Br	2.68: [6]
C	8.55 [1]	Ni	5.08 [7]	Zr	2.65 [9]
N	7.93 [1]	K	5.05 [5]	Rb	2.63 [10]
Fe	7.62 [2]	Mn	4.88 [7]	La	2.03 [9]
Si	7.55 [3]	F	4.75: [6]	Nd	1.93 [9]
Mg	7.48 [4]	Ti	4.50 [7]	Ba	1.90 [4]
S	7.21 [5]	V	3.92 [7]	Ce	1.78 [9]
Al	6.40 [5]	B	3.6: [8]	I	1.45: [6]
Ca	6.33 [4]	Cu	3.50 [9]	Be	1.1 [11]
Na	6.18 [5]	Y	3.20: [9]	Li	0.68: [12]





Sun (T_{eff} = 5770 K)

Sun spot (T_{eff} = < 4000 K)

Tsuji 1963

$\Theta = 5040/T = (\log e)/kT$

O-rich or C-rich?

[O]>[C]

→ CO and H_2O dominant molecules

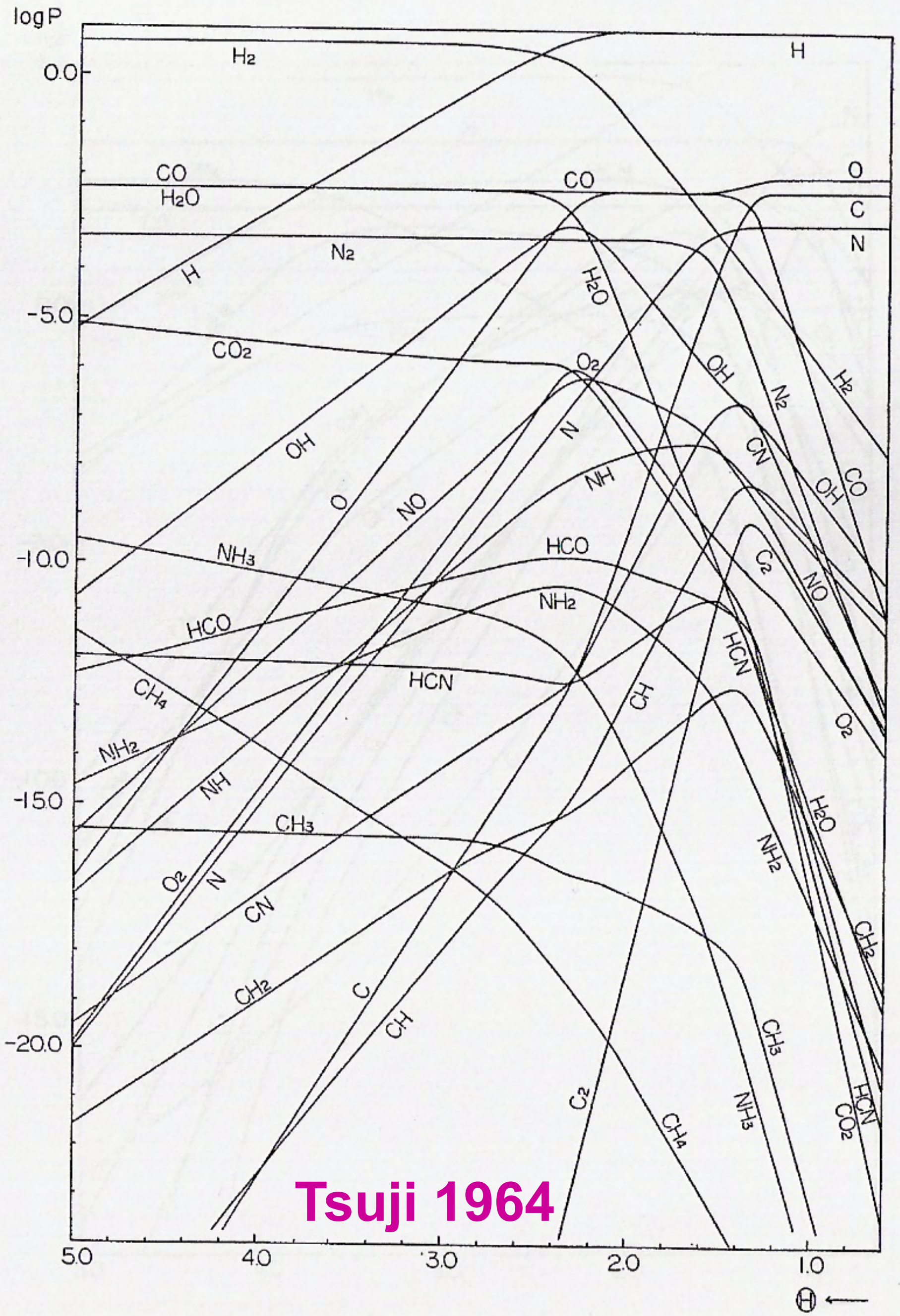
→ most oft the carbon goes into CO

[C]>[O]

→ CO dominant molecule

→ lots of C available to drive rich hydrocarbon chemistry

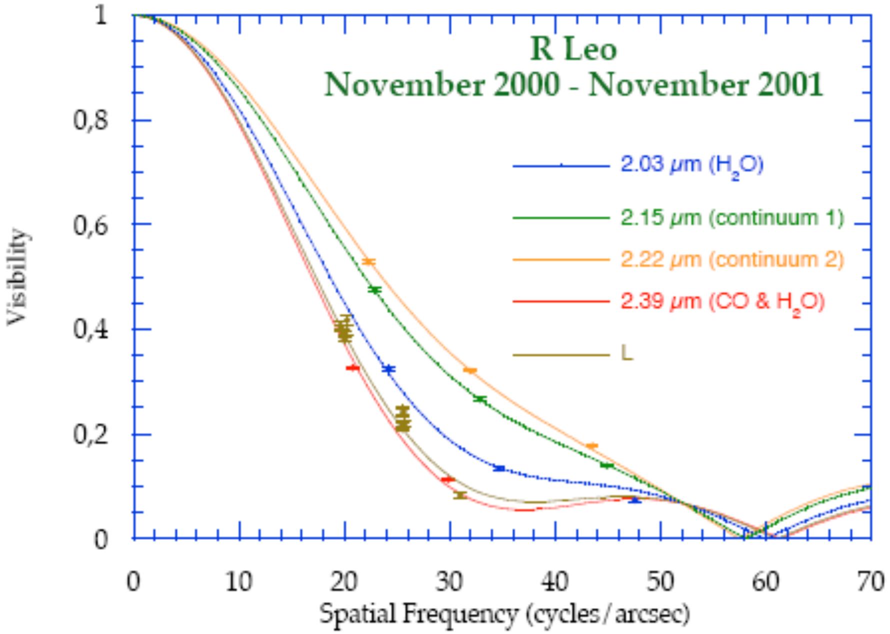
→ IRC+10216

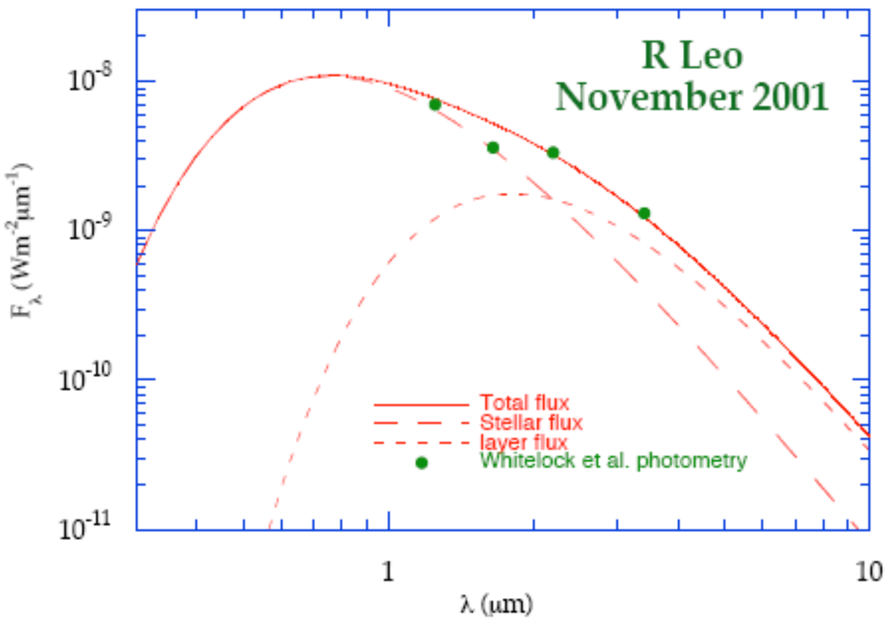


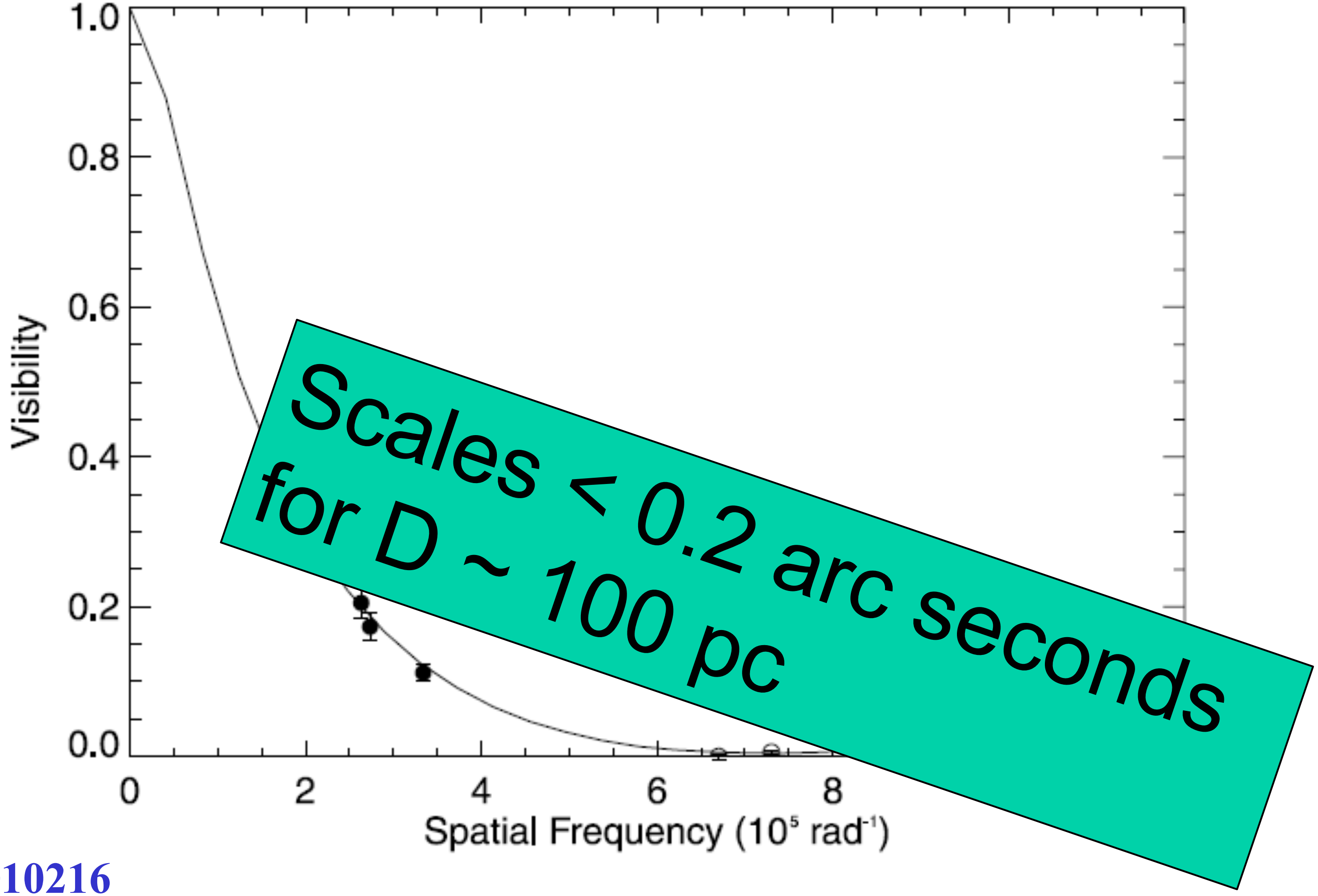
Tsuji 1964

Fig. 3. Most dominant molecular feature in oxygen rich stars of supergiant characteristics (case I; $H:C:N:O=1:5\cdot10^{-4}:10^{-4}:10^{-3}$, $\log P_g \sim \log P(H) = 1.0$). This figure may roughly correspond to the molecular feature in supergiant stars or in upper atmospheres of the giant stars of F~M spectral types.

G. Perrin et al.: Unveiling Mira stars behind the molecules **2004**







Scales < 0.2 arc seconds for D ~ 100 pc

IRC+10216

ISI 9–12 μm

Inner radius of dust shell ~150 mas (20 AU)

Monnier et al. 2000

Equilibrium chemistry produces molecules depending on

- temperature
- chemical nature of the star (O or C)

→ Parent molecules for chemistry of outer envelope

Abundances “freeze out” during dust formation

Further chemical processing by (interstellar) UV

Equilibrium chemistry produces molecules depending on

- temperature
- chemical nature of the star (O or C)

→ Parent molecules for chemistry of outer envelope

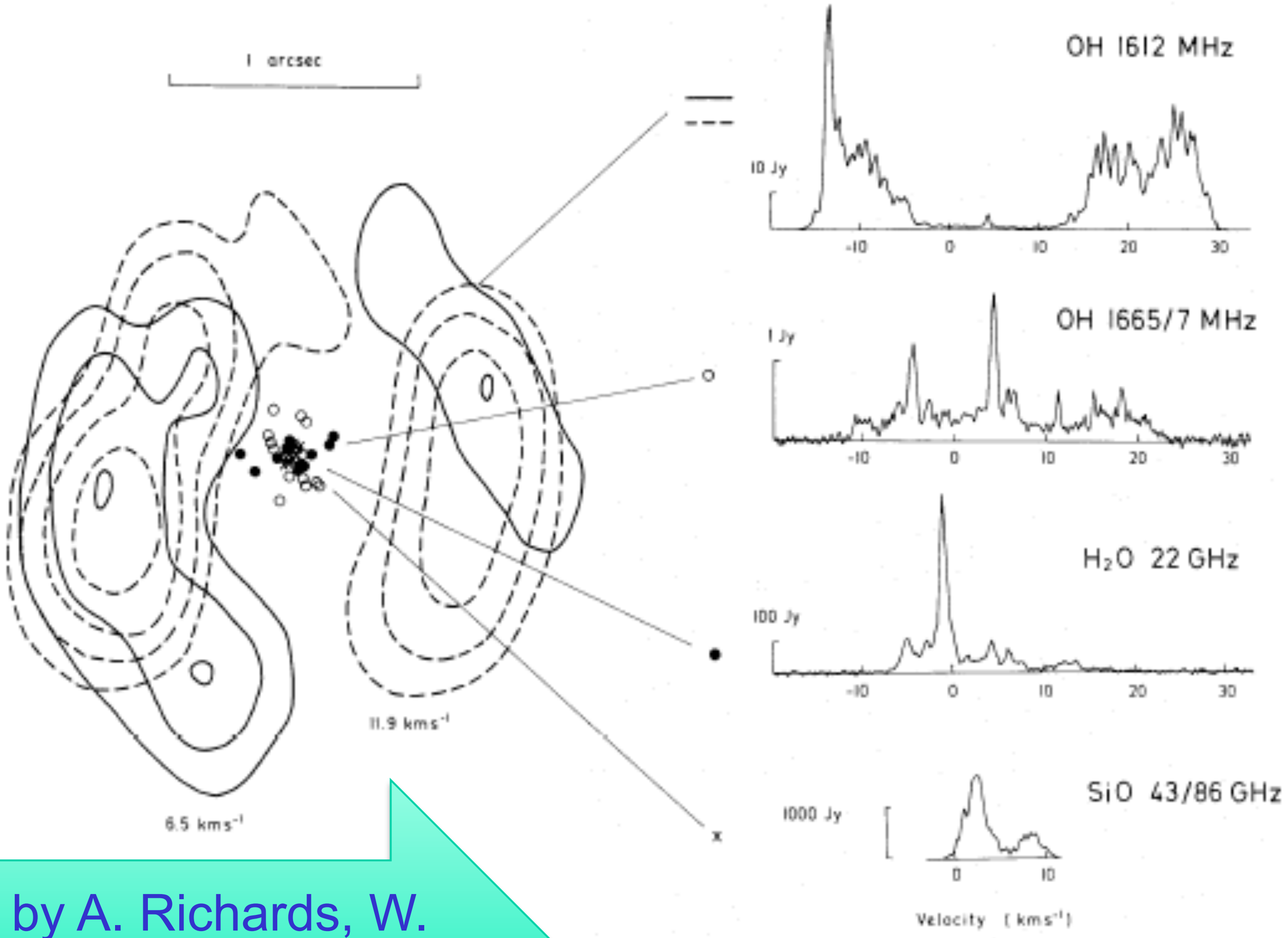
Abundances “freeze out” during dust formati

Further

Outer envelopes have angular sizes of several to several tens of arc seconds for nearby AGB stars

Inner envelopes have so far been almost exclusively been studied by optical and IR absorption spectroscopy (except for masers)

Masers in circumstellar envelopes around oxygen-rich, mass-losing evolved stars



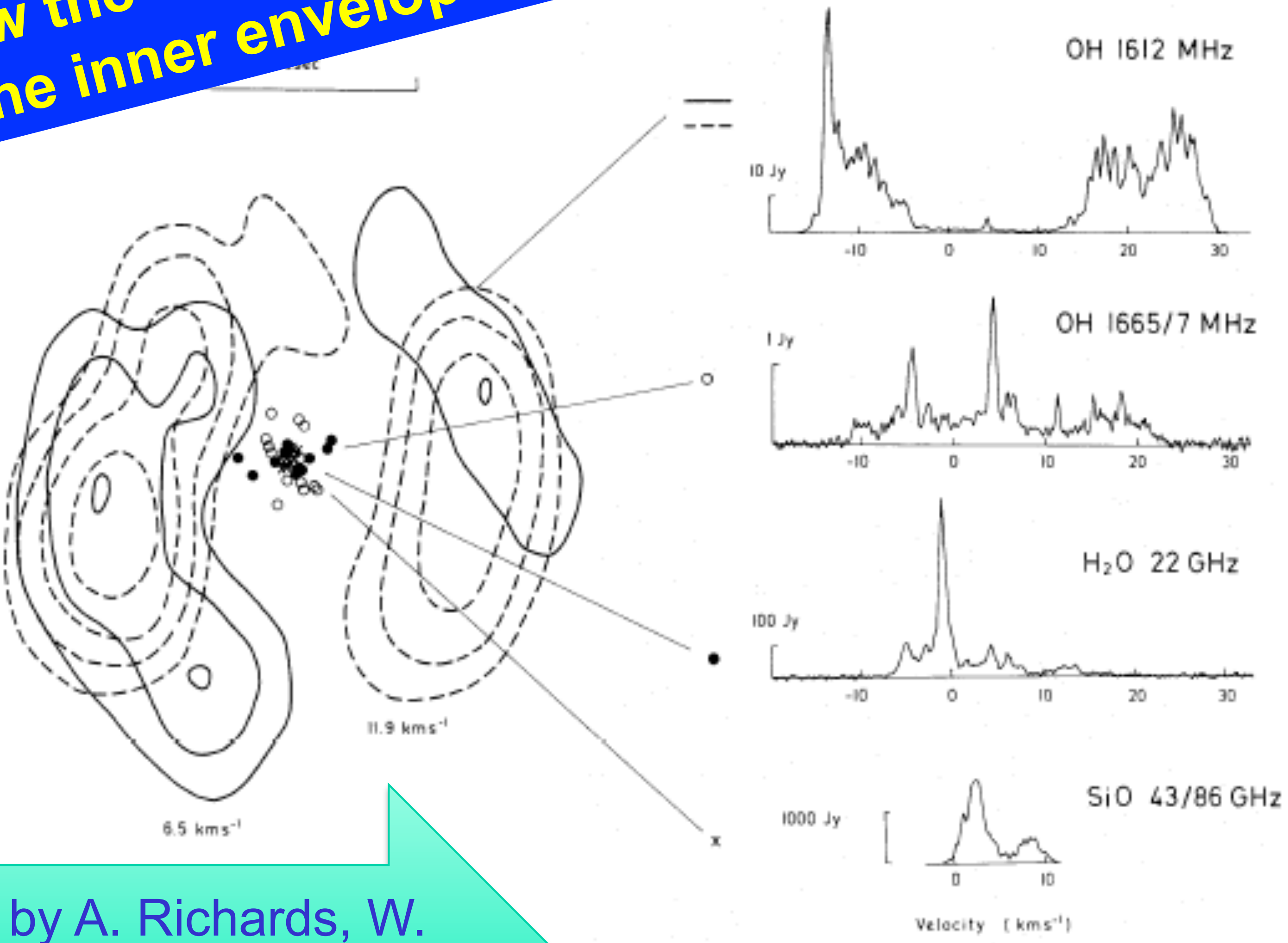
VX Sgr

Talks by A. Richards, W. Flemmings

Chapman & Cohen 1986

Masers in circumstellar envelopes around oxygen-rich, mass-losing evolved stars

Until now the only means to image the inner envelopes

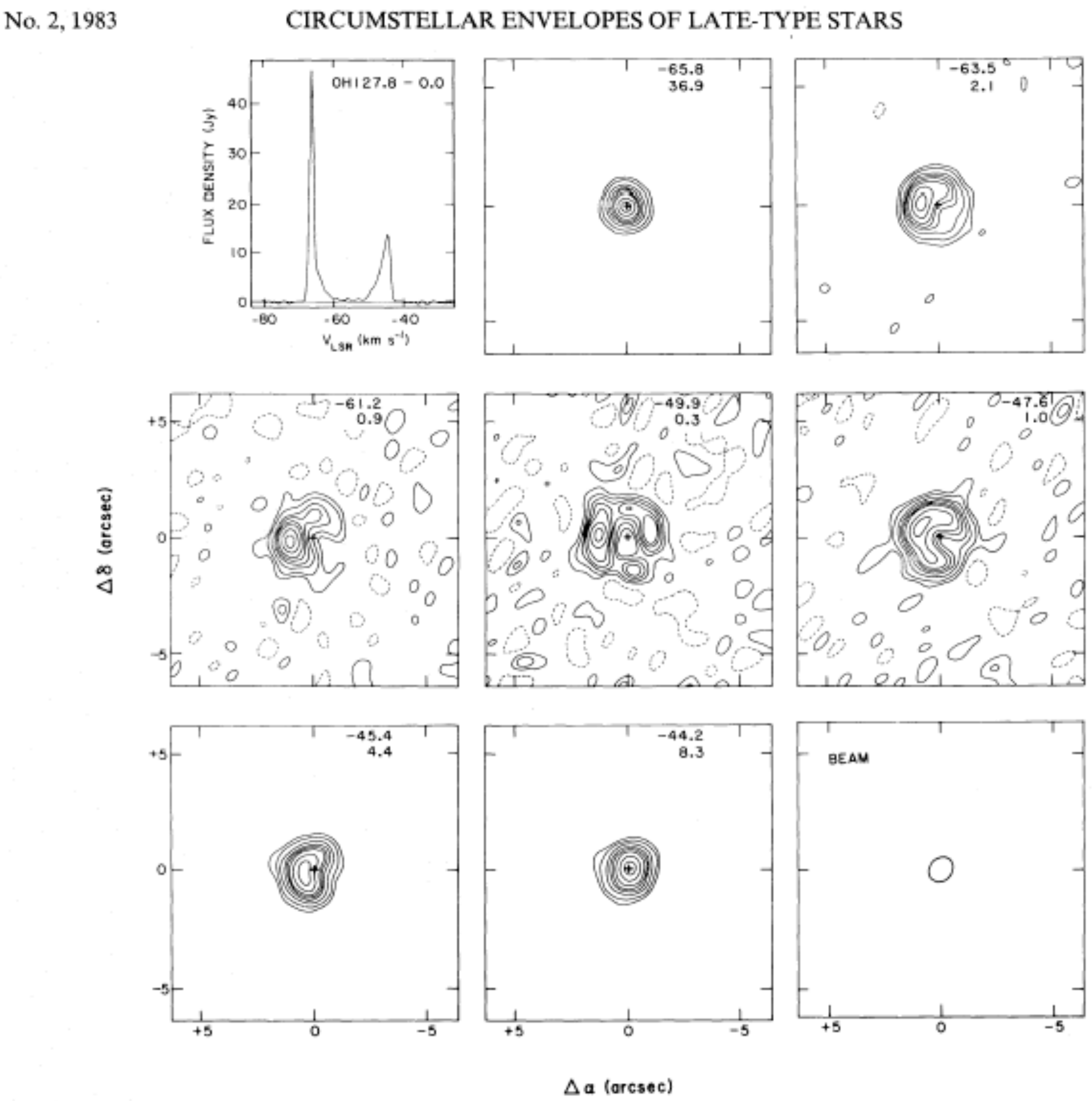


VX Sgr

Talks by A. Richards, W. Flemmings

Chapman & Cohen 1986

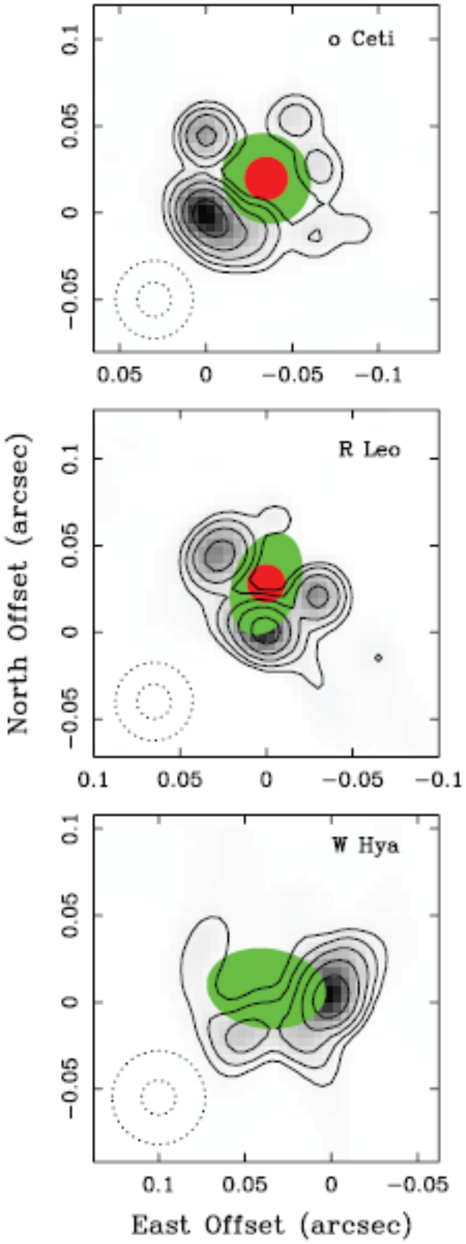
1612 MHz maser shell of a typical OH/IR star

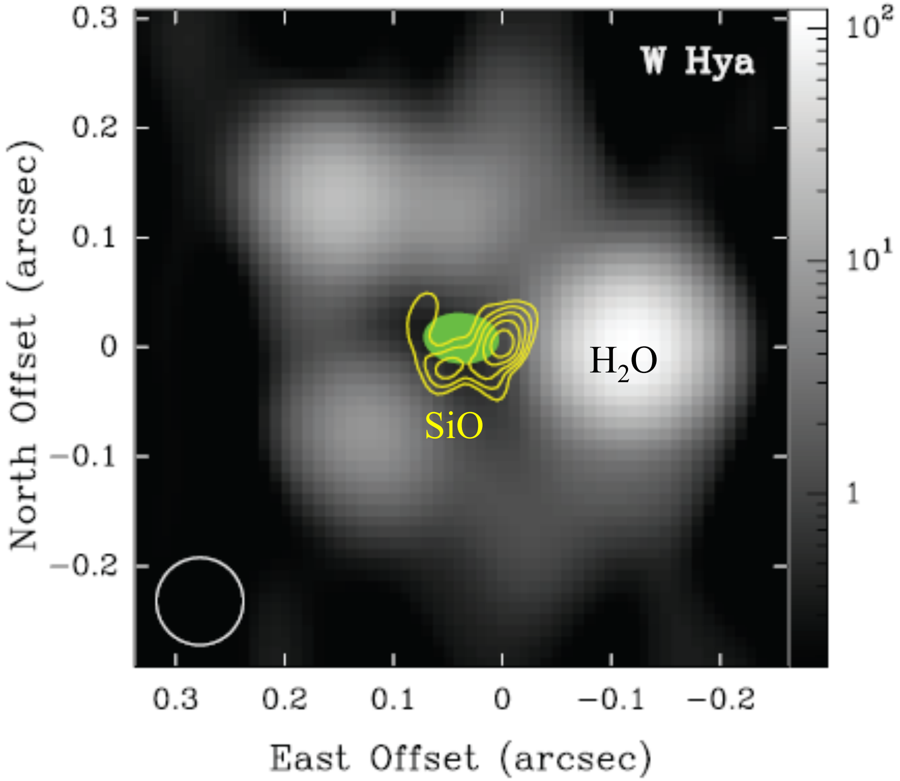


No. 2, 1983 CIRCUMSTELLAR ENVELOPES OF LATE-TYPE STARS

OH127.8-0.0

Bowers, Johnston, & Spencer (1983)





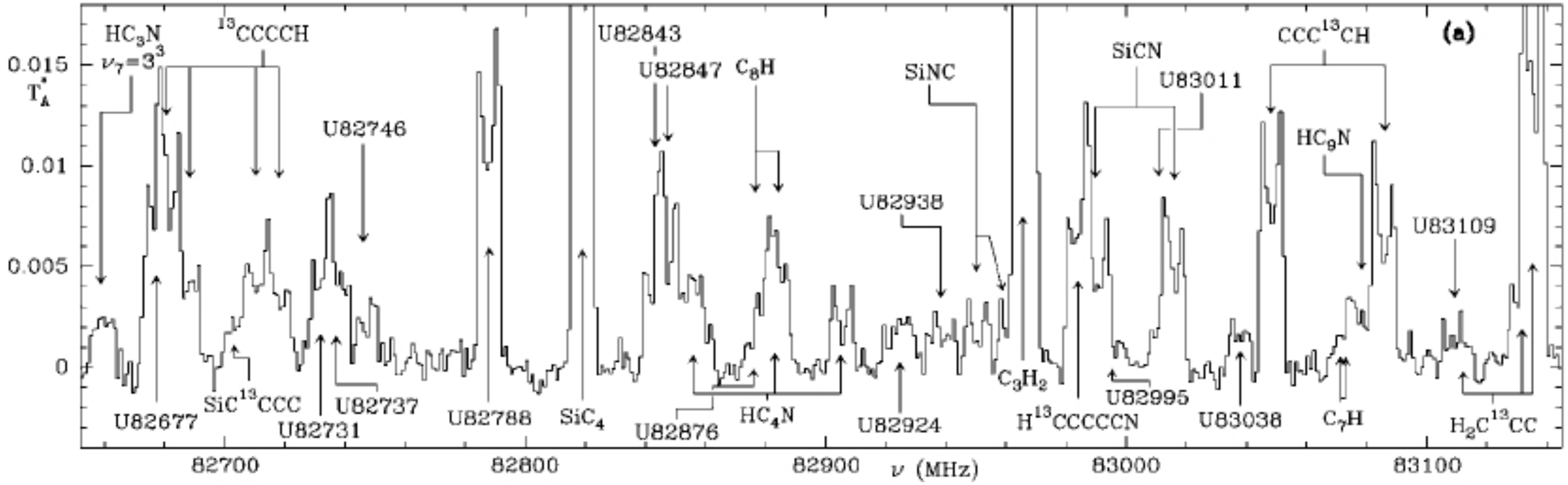
Reid & Menten 1991, 2007

IRC+10216 (= CW Leo) – extreme carbon star

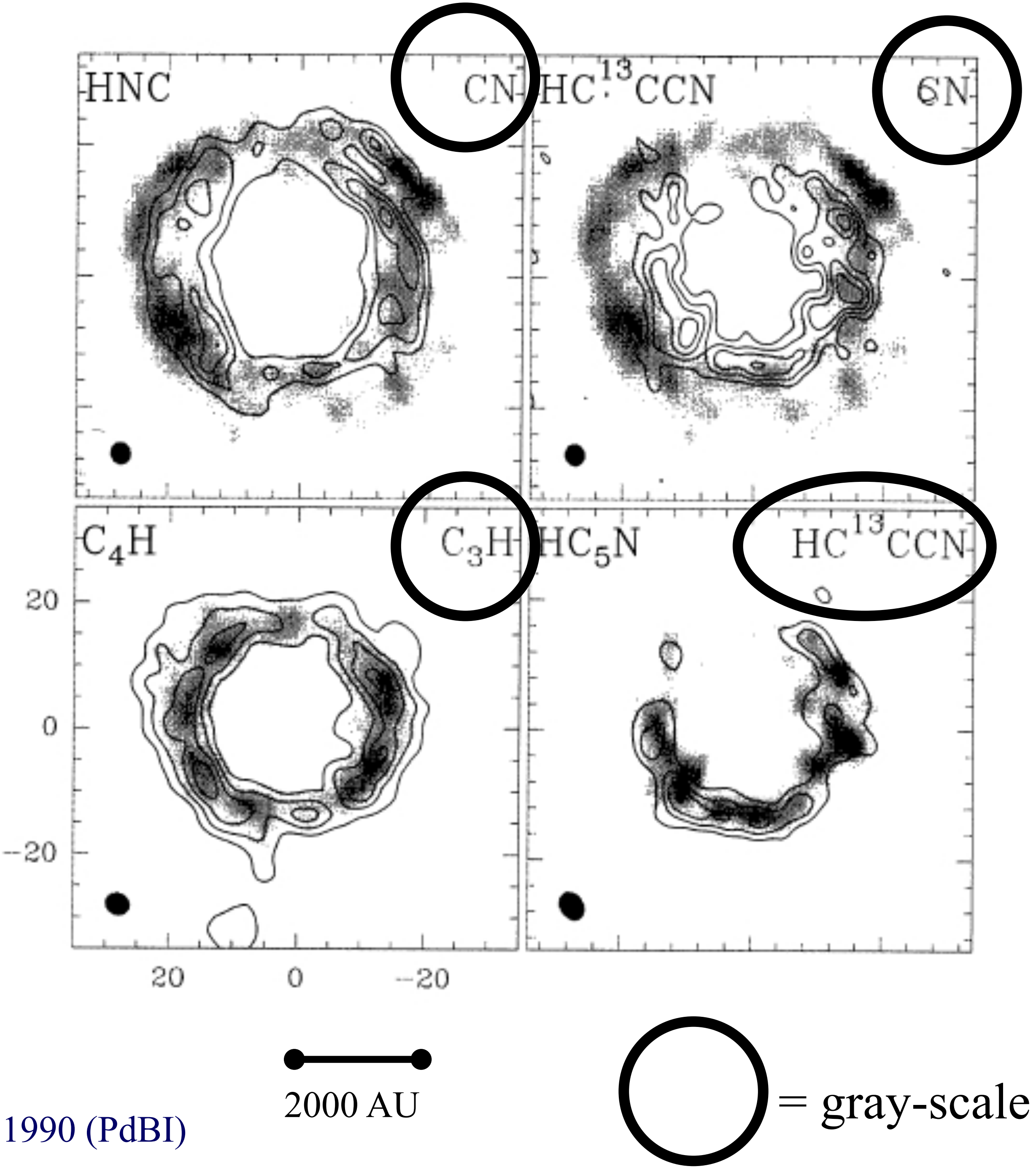
- Close (~100 pc)
- Very high mass-loss rate (3 10^{-5} $M_{\odot}$)

⇒ Exceedingly rich molecular spectrum

Many species ***only*** detected here



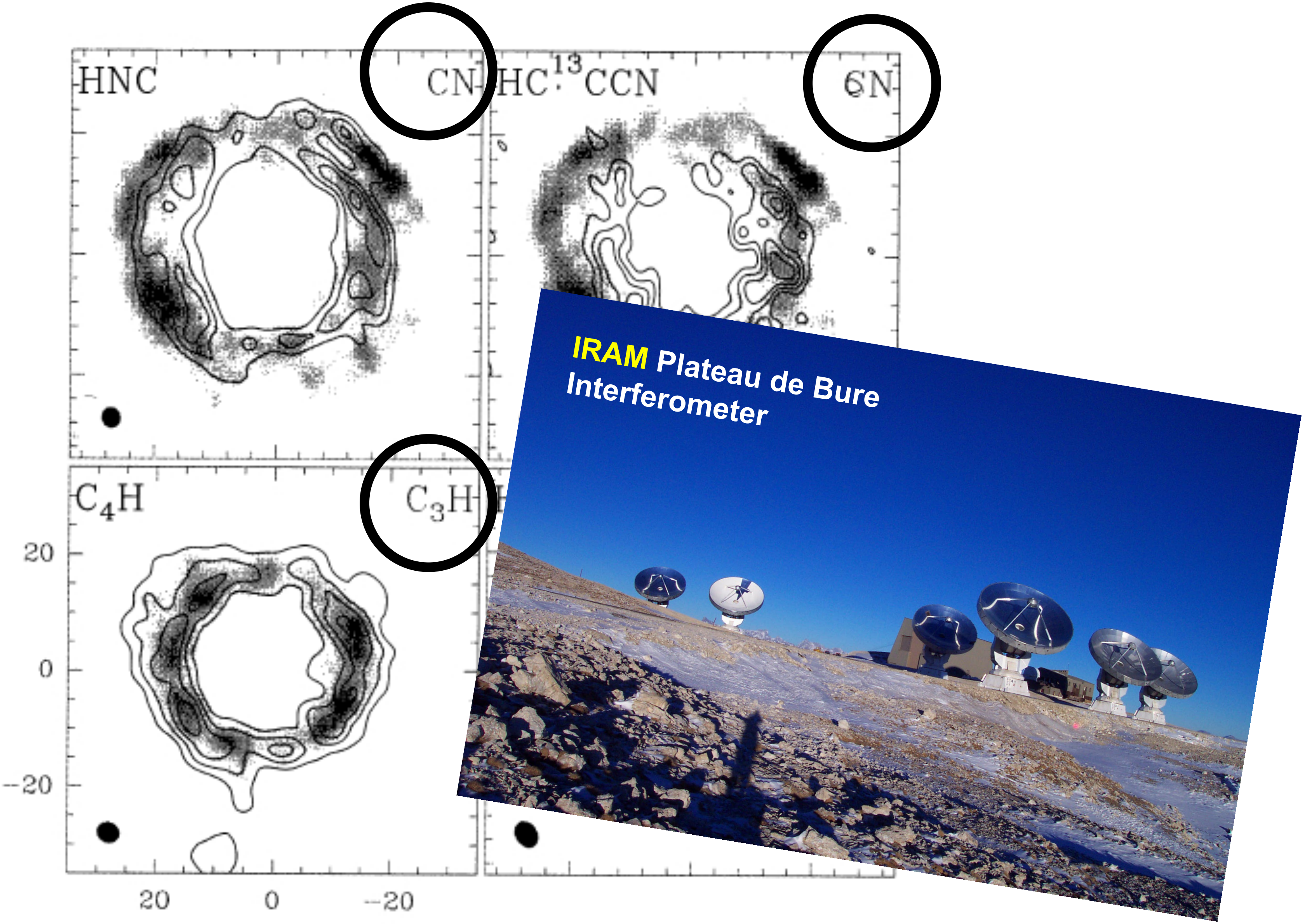
Cernicharo et al.



2000 AU

= gray-scale

Lucas & Guelin 1990 (PdBI)

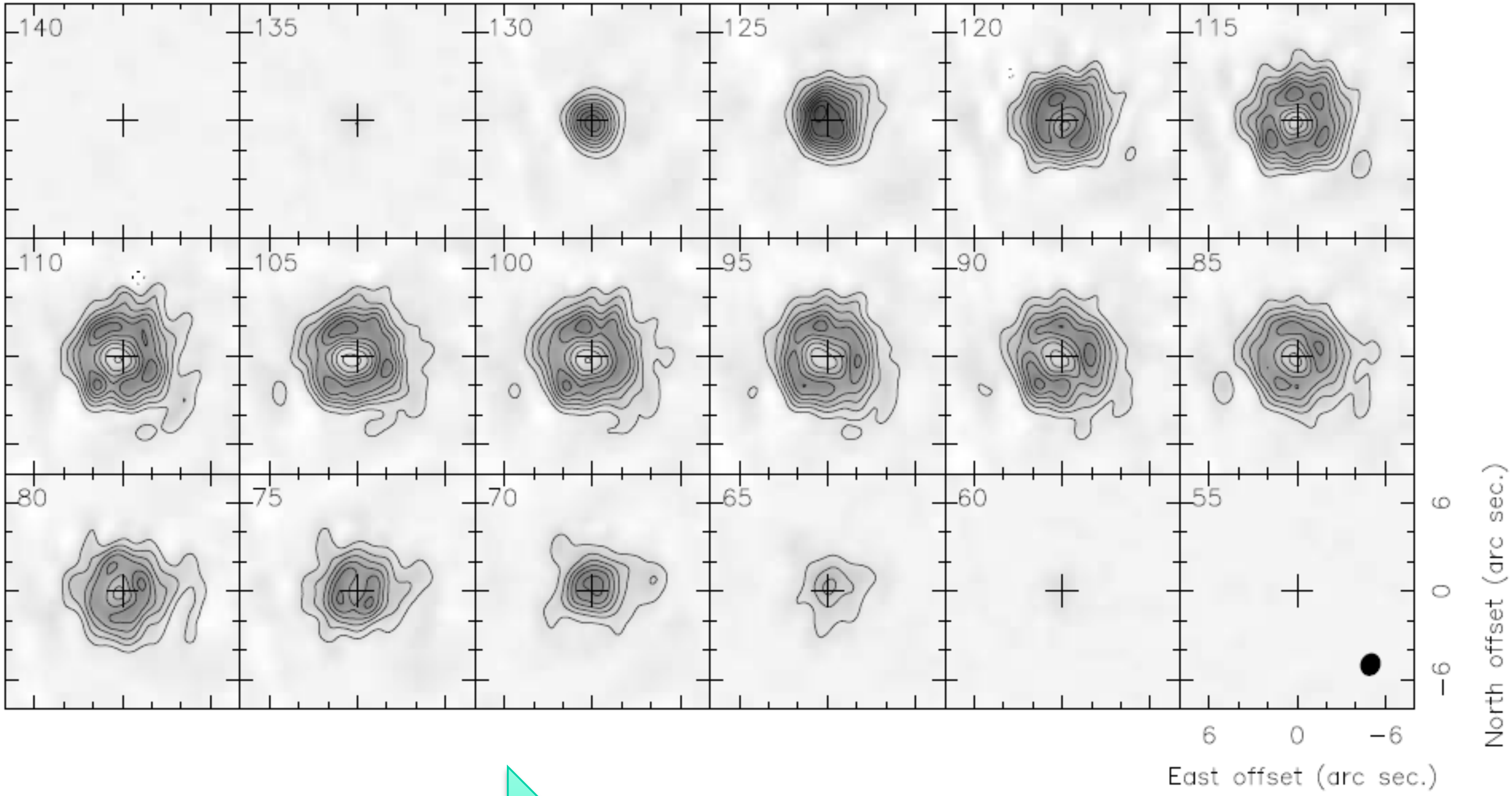


2000 AU

○ = gray-scale

Lucas & Guelin 1990 (PdBI)

A. Castro-Carrizo et al.: ^{12}CO mapping of the YHGs IRC +10420 & AFGL 2343

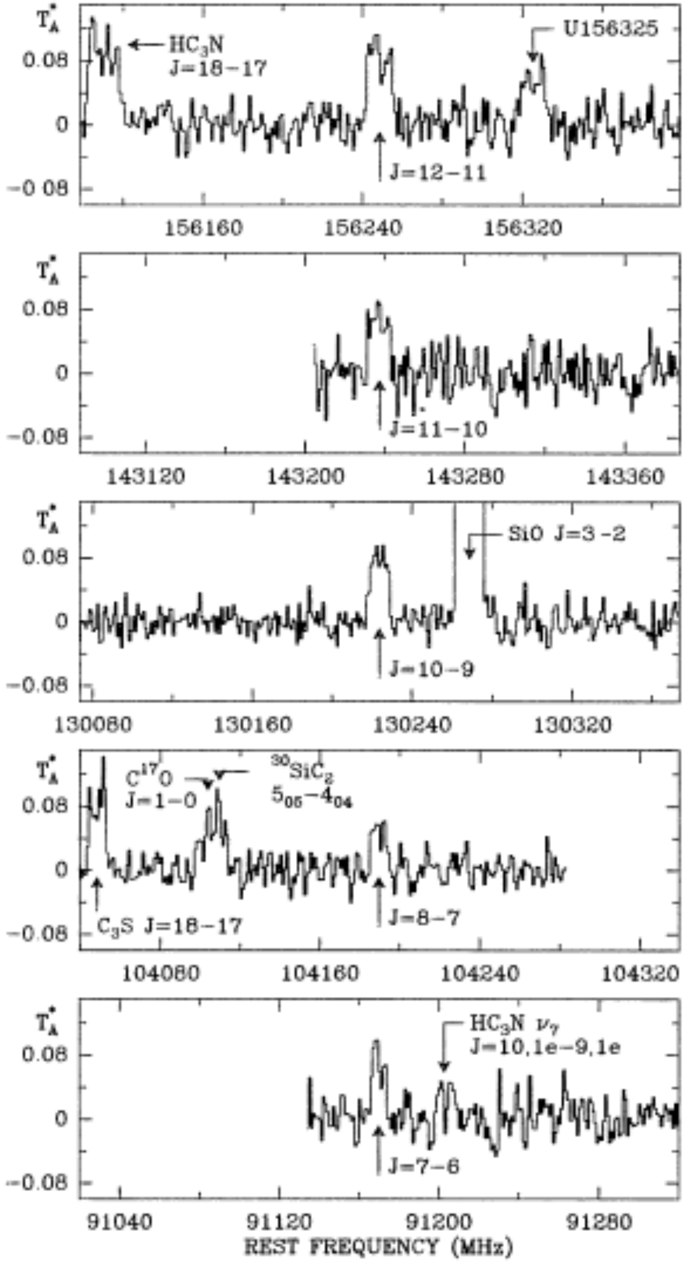


Talks by S. Ramstedt, M. Maercker

PdBI, 2007

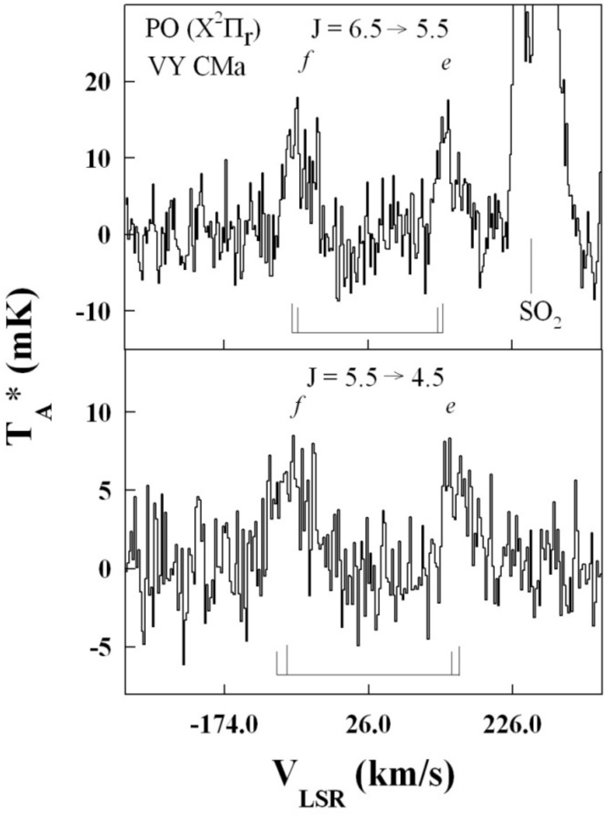
Metals in IRC+10216: detection of NaCl, AlCl, and KCl, and tentative detection of AlF

J. Cernicharo[1, 2] and M. Guélin[1] 1987

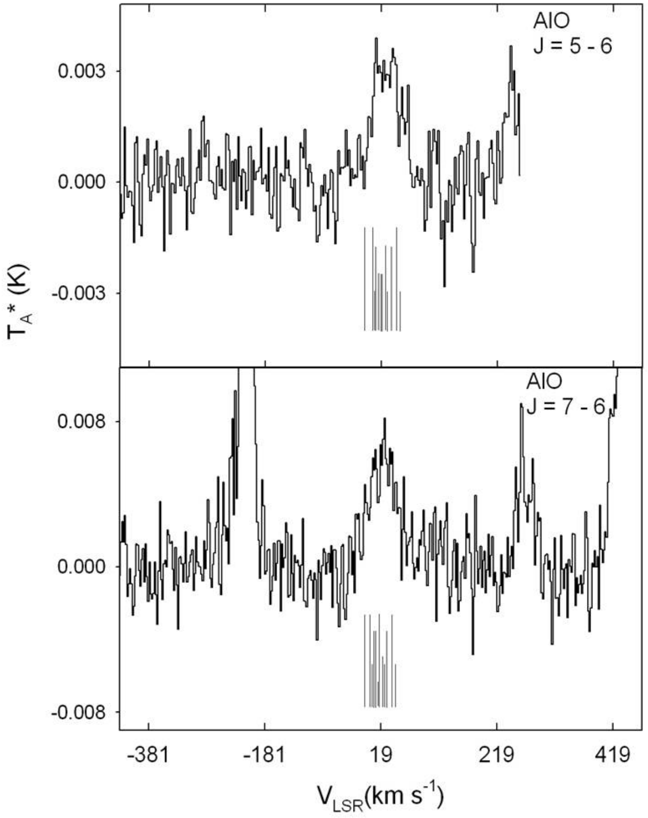


The amazing chemistry of the red supergiant VY CMa

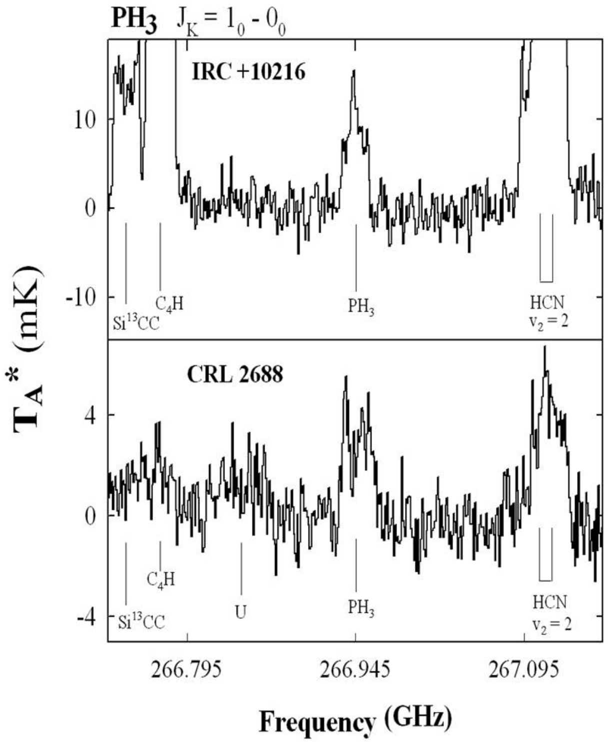
- Two new oxide species in VY CMa: **PO** and **AlO**
- Two phosphorus molecules in IRC+10216: **PH_3** and **HCP**



Tenenbaum et al 2007



Tenenbaum & Ziurys 2009

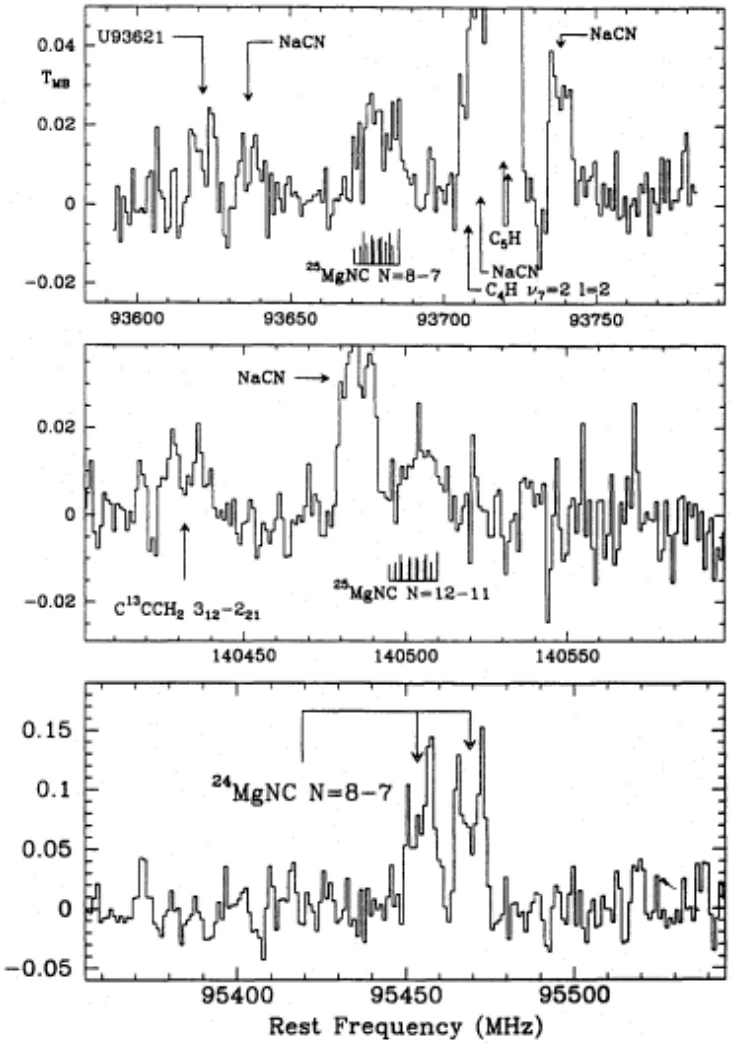


Tenenbaum & Ziurys 2008

Arizona Radio Observatory

Nucleosynthesis in AGB stars: observation of ^{25}Mg and ^{26}Mg in IRC+10216 and possible detection of ^{26}Al (1995)

M. Guélin[1], M. Forestini[2], P. Valiron[2], L. M. Ziurys[3], M.A. Anderson[3], J. Cernicharo[4], and C. Kahane[2]

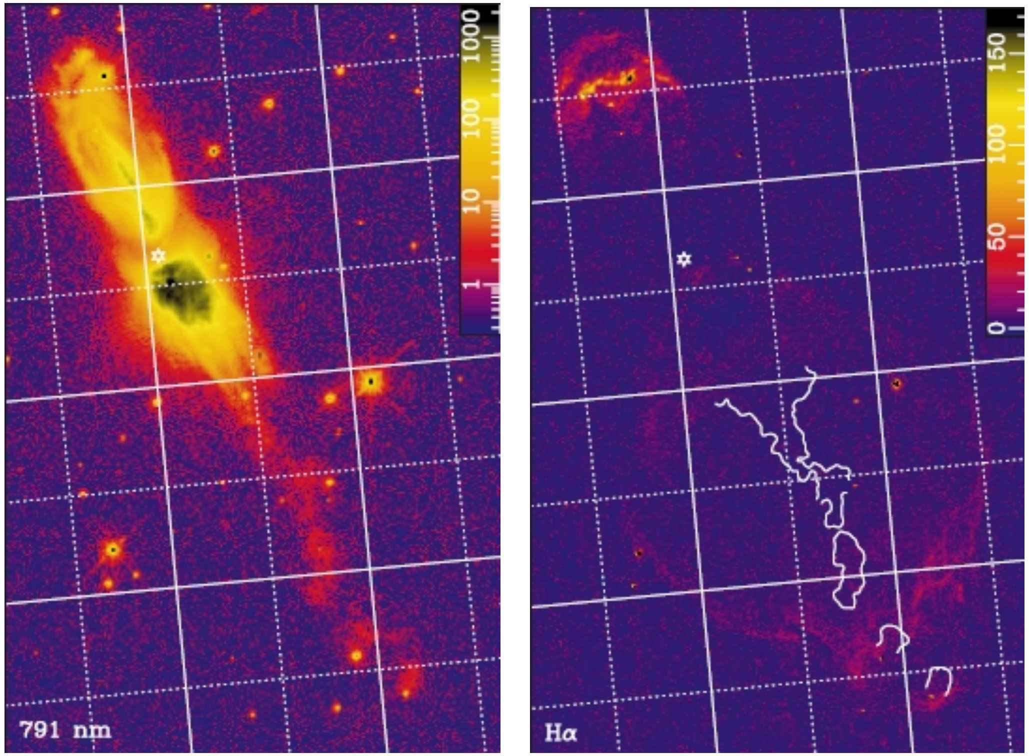


Protoplanetary Nebulae

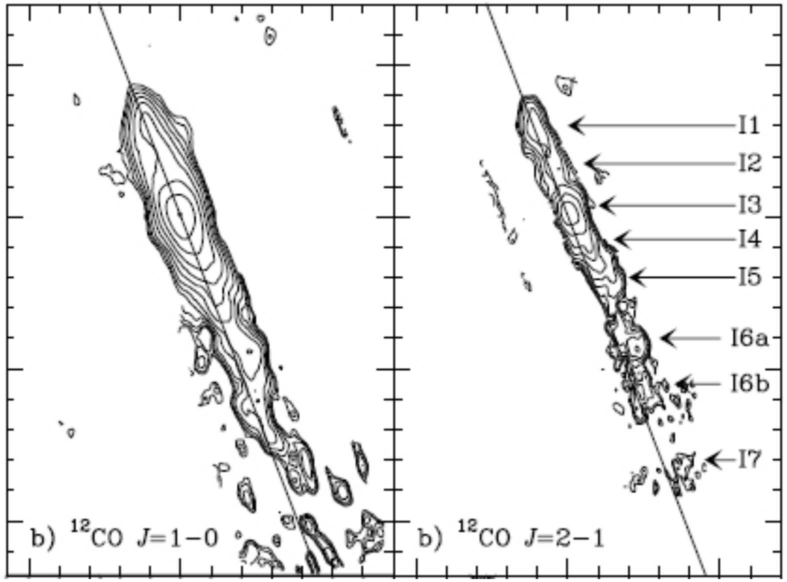
OH231.8+4.2

Talks by A. Zijlstra, W. Flemmings

HST

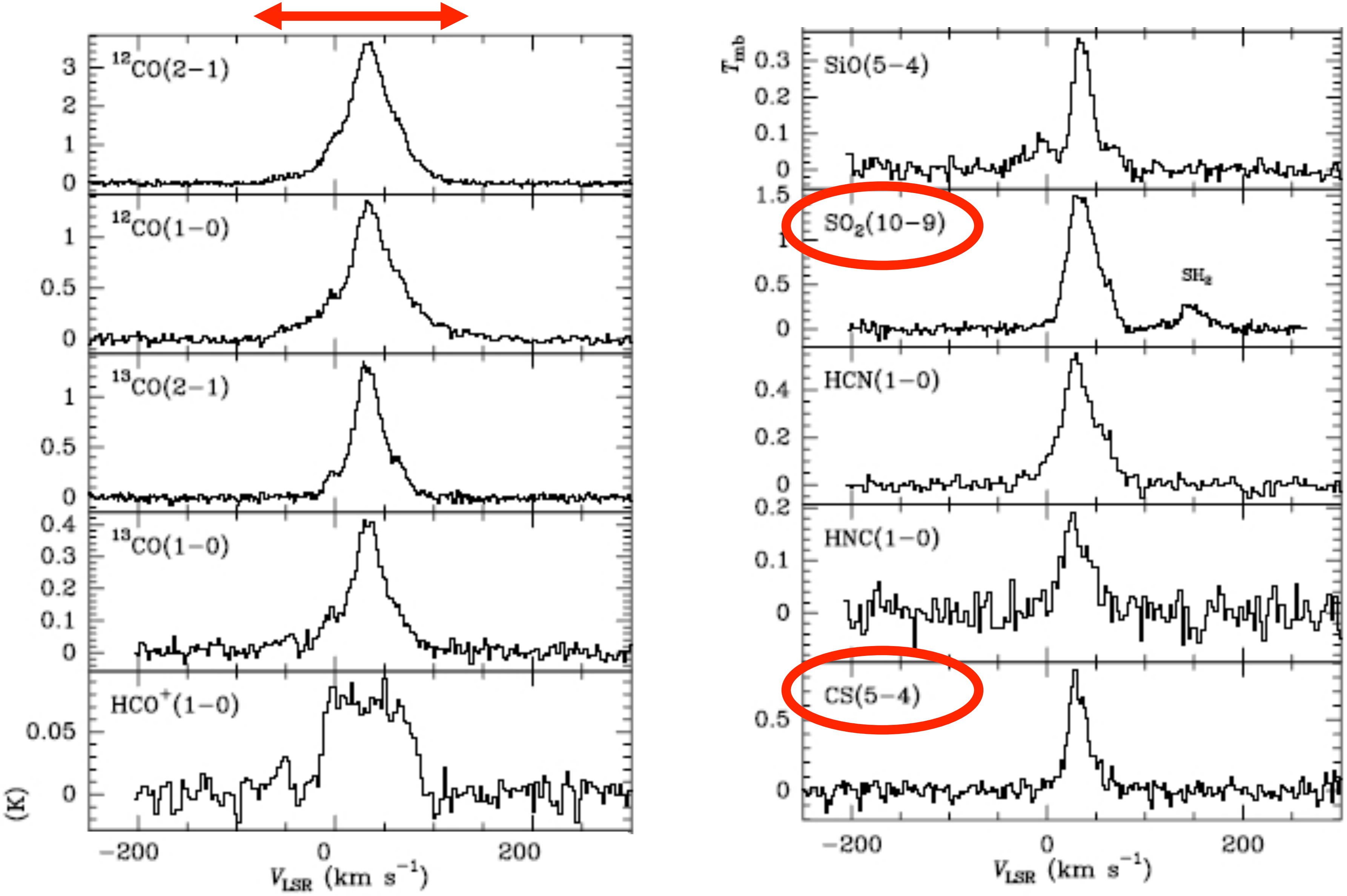


CO/PdBI



Bujarrabal, Alcolea, Sanchez-Contreras…

Very large Δv > 250 km/s

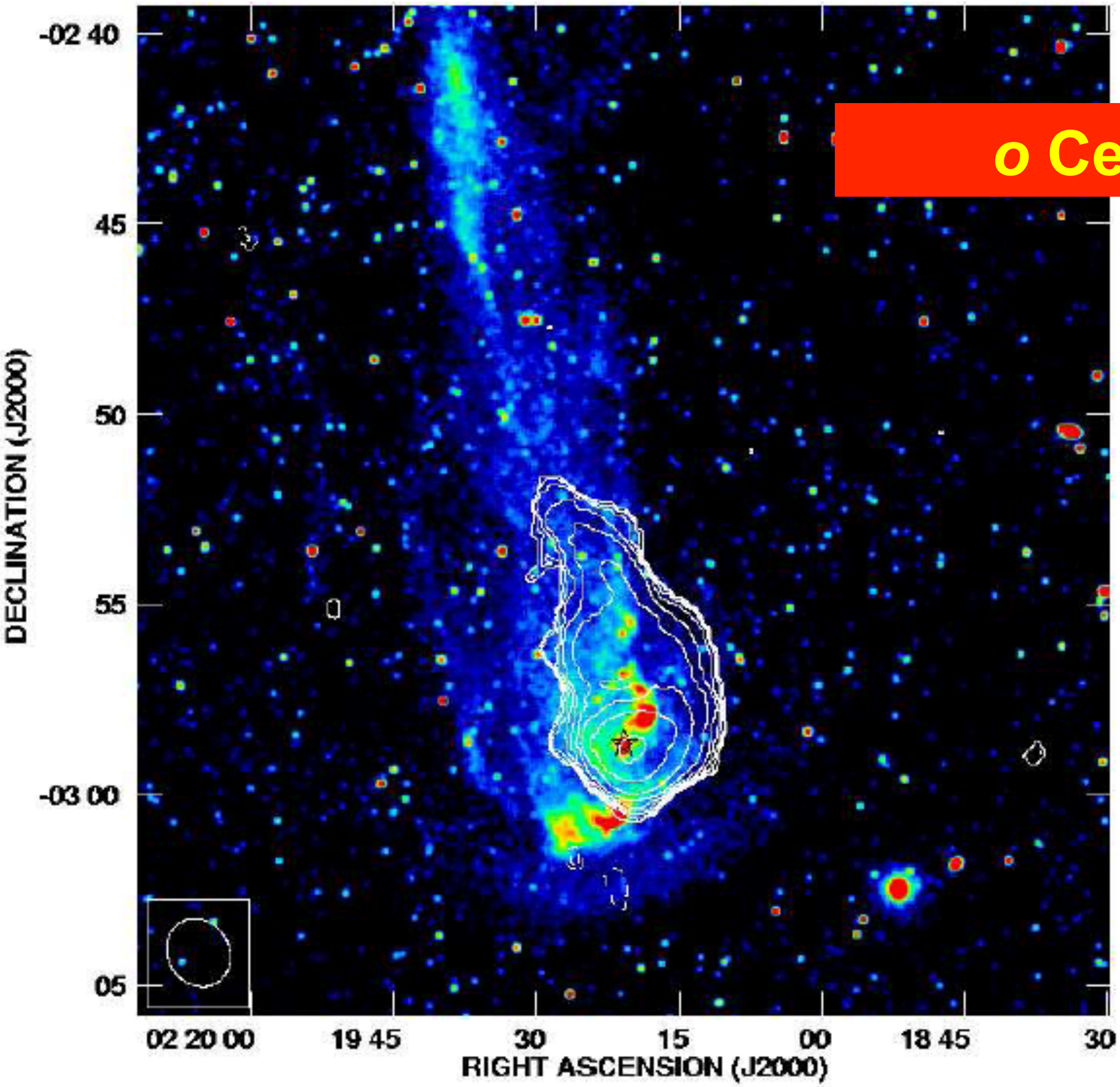


OH231.8+4.2

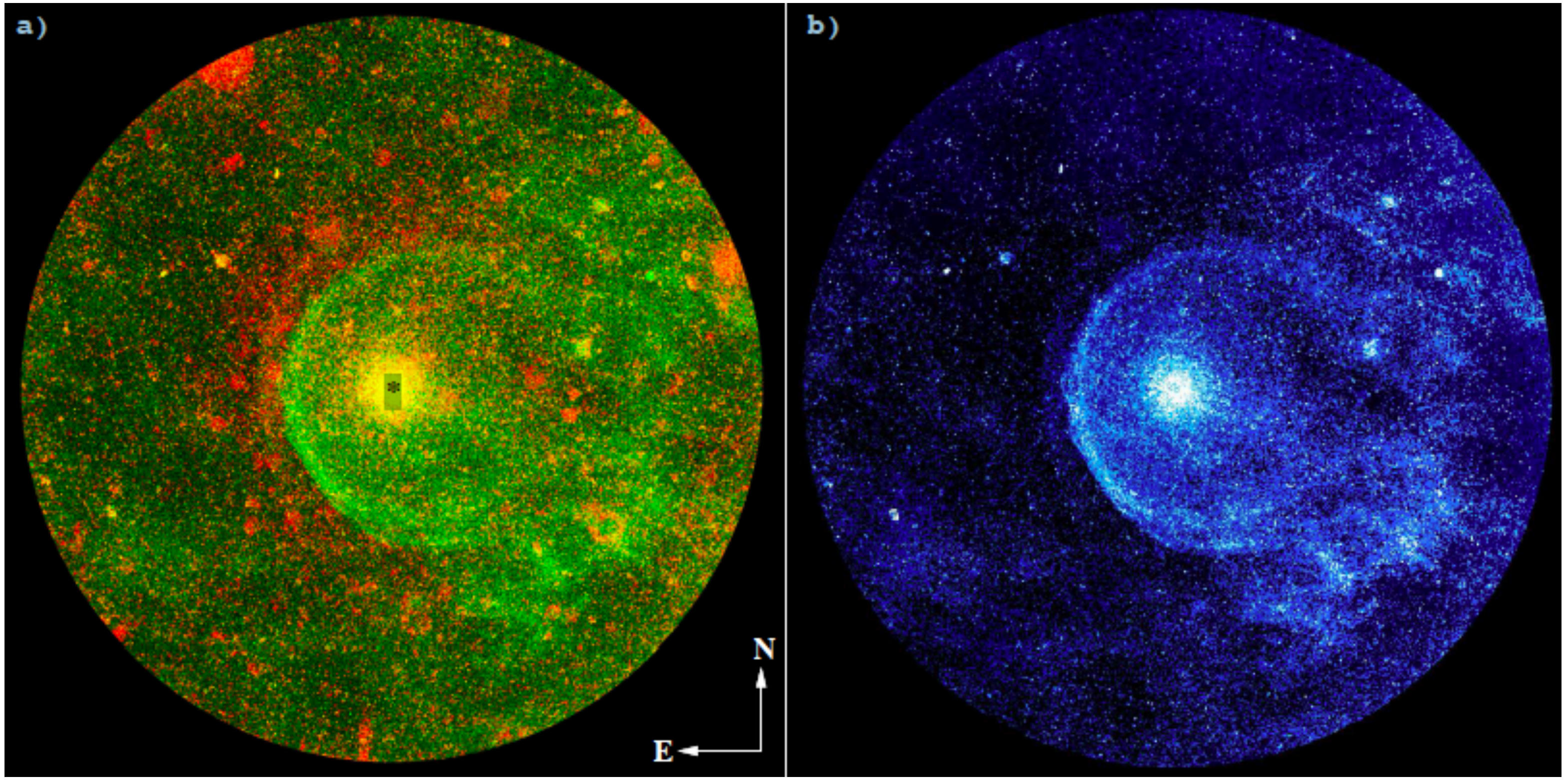
“Rotten egg nebula”

Morris et al. 1987

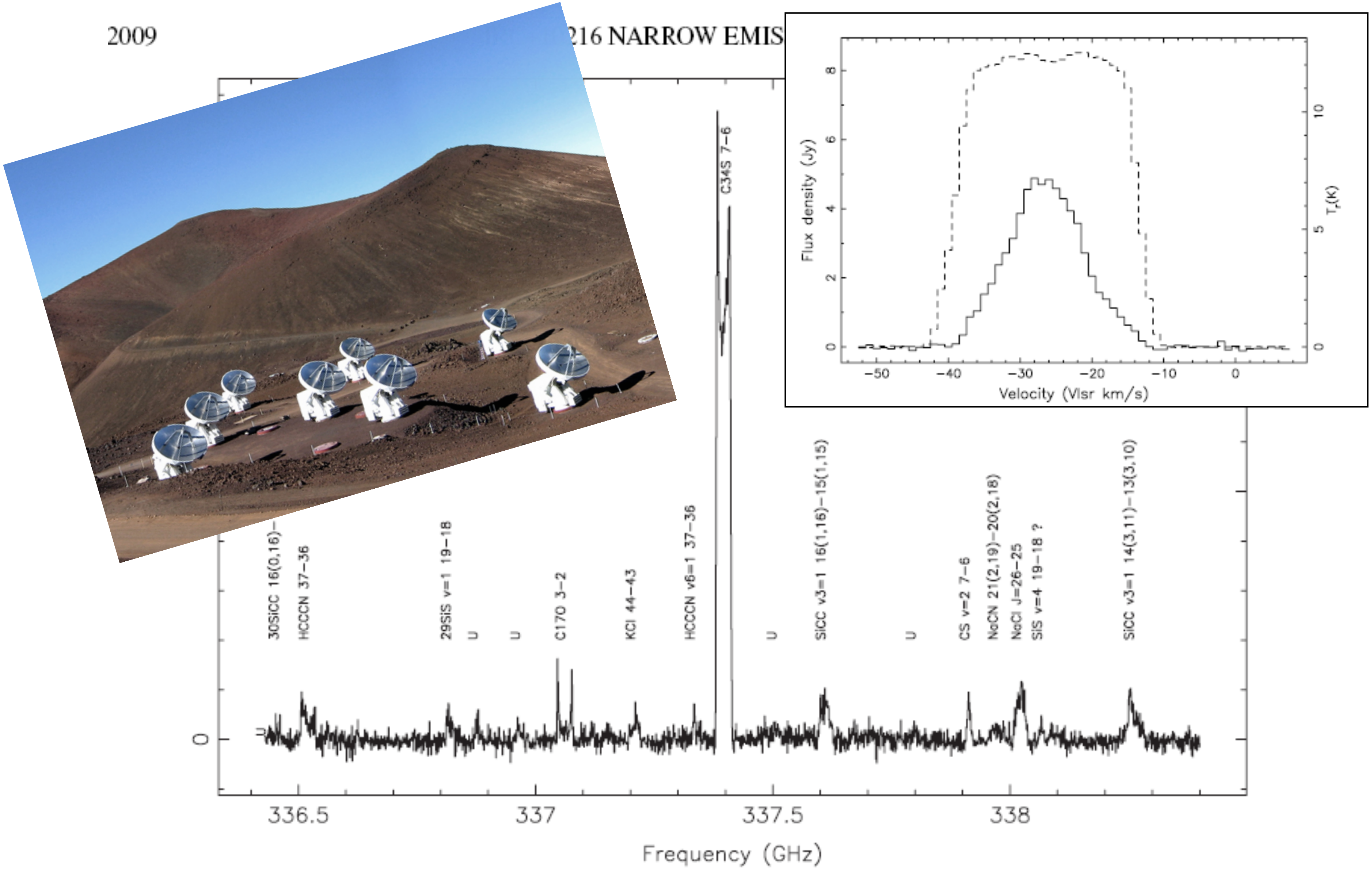
o Cet (Mira)



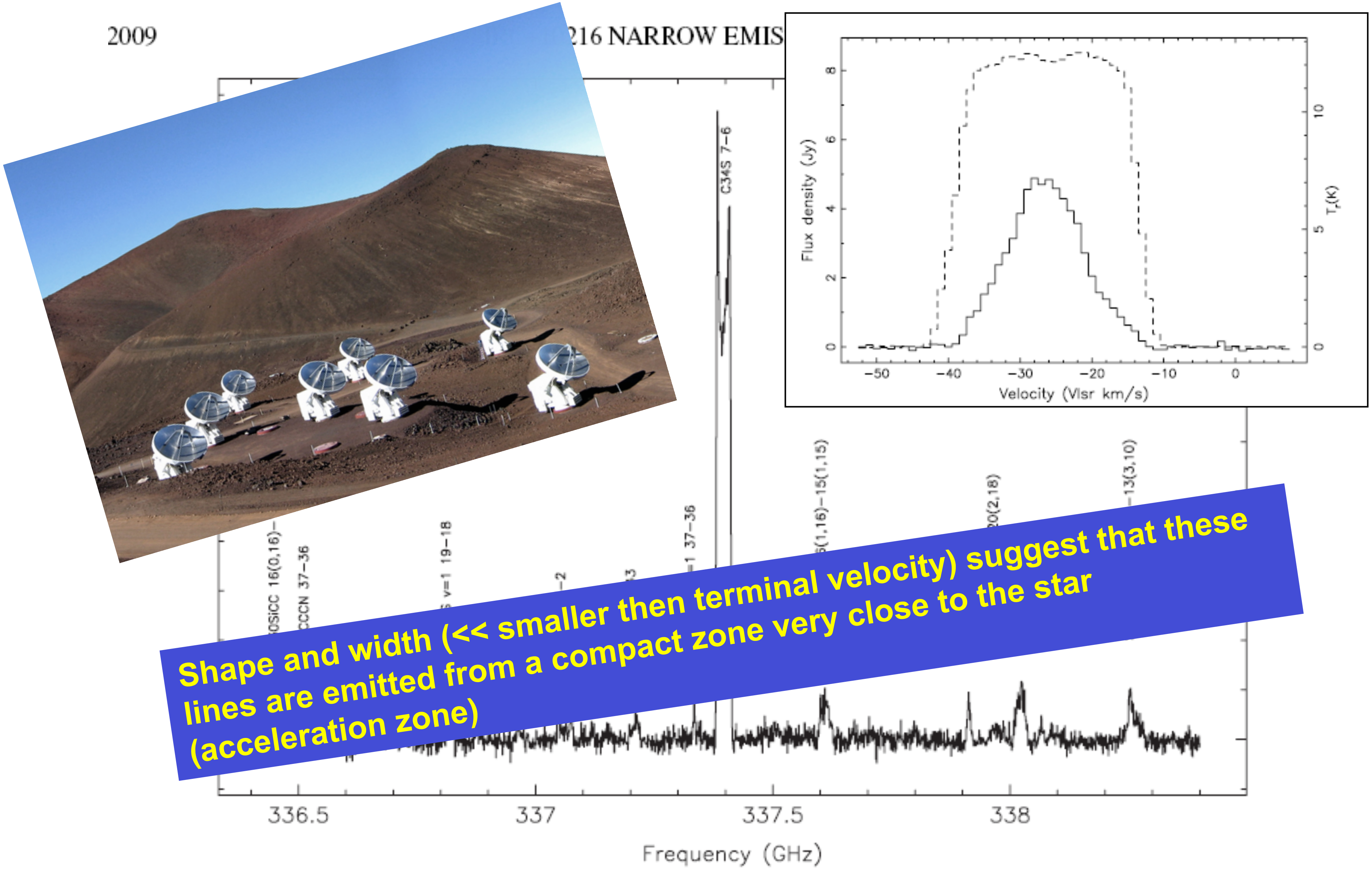
Matthews et al. 2008



IRC+10216: Sahai & Chronopoulos 2010

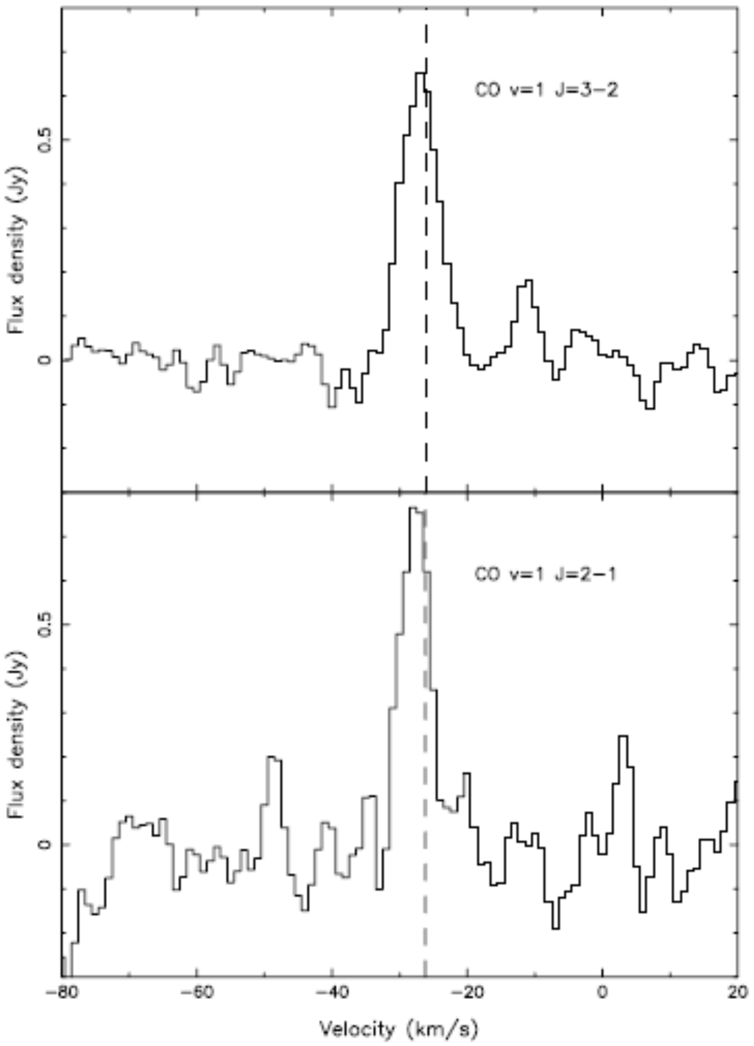


Patel et al. 2009 – SMA



Shape and width (<< smaller then terminal velocity) suggest that these lines are emitted from a compact zone very close to the star (acceleration zone)

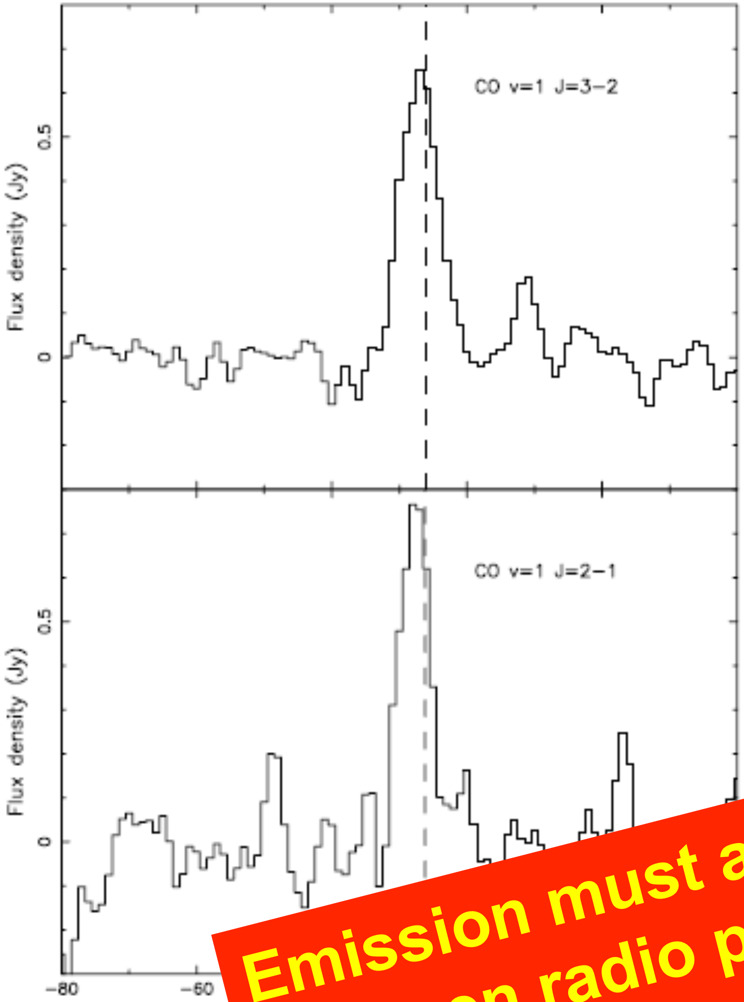
Patel et al. 2009 – SMA



Vibrationally excited CO

From energy levels ~3100 K above ground

Patel et al. 2009 – SMA

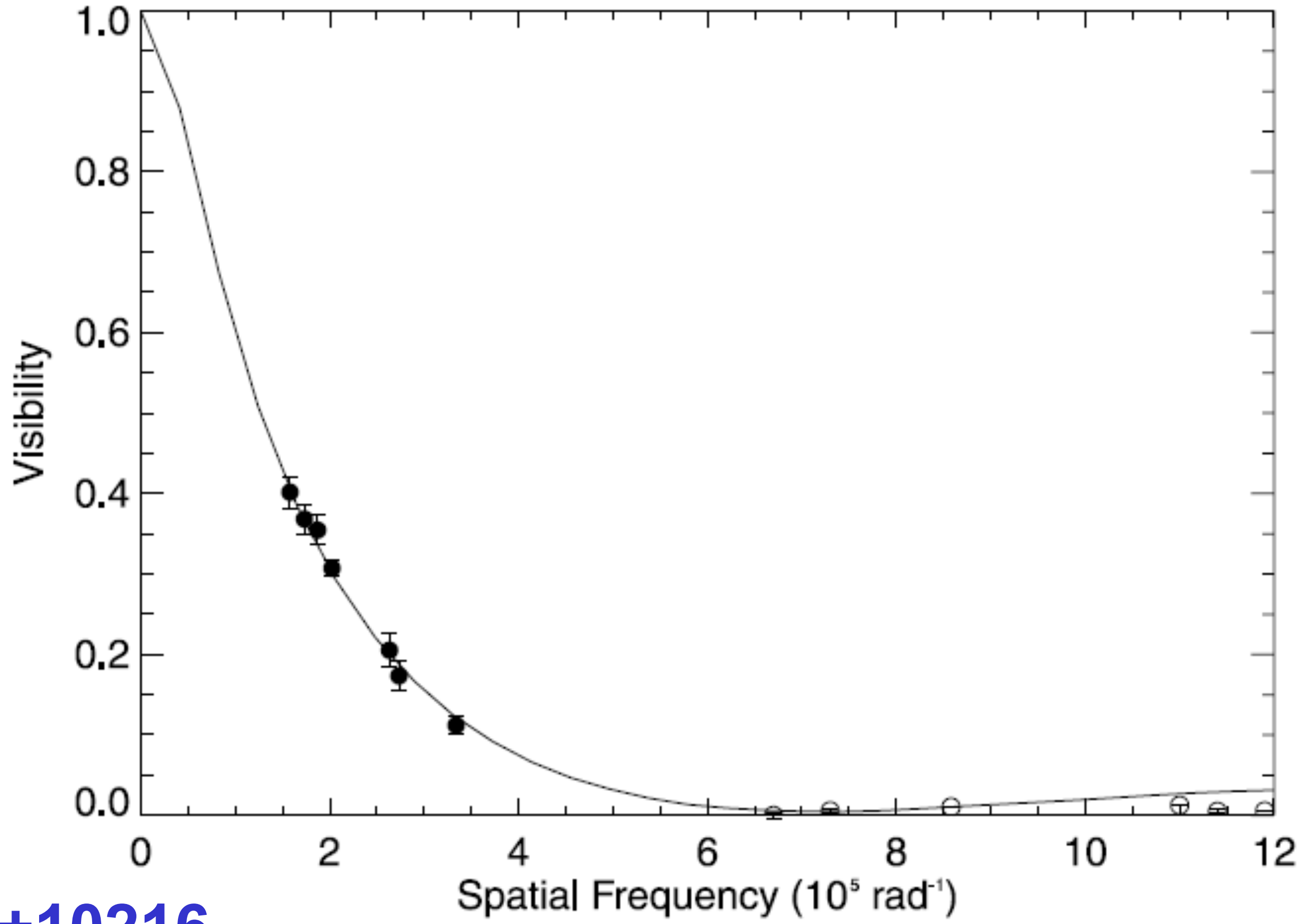


Vibrationally excited CO

From energy levels ~3100 K above ground

Emission must arise from region between radio photosphere and dust formation zone (size < 40 AU)

Patel et al. 2009 – SMA

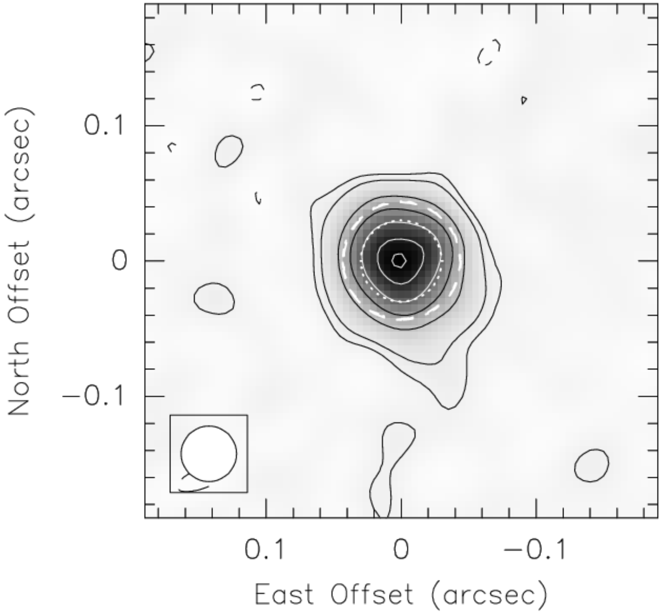


IRC+10216

ISI 9–12 µm

Inner radius of dust shell ~150 mas (20 AU)

Monnier et al. 2000

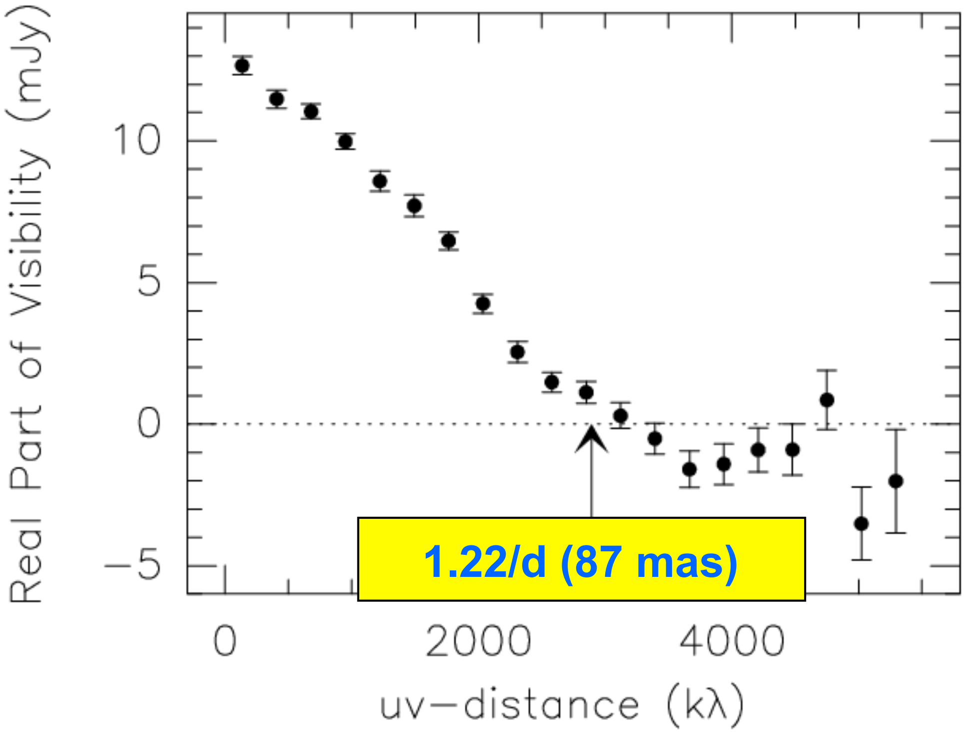


IRC+10216 (= CW Leo)

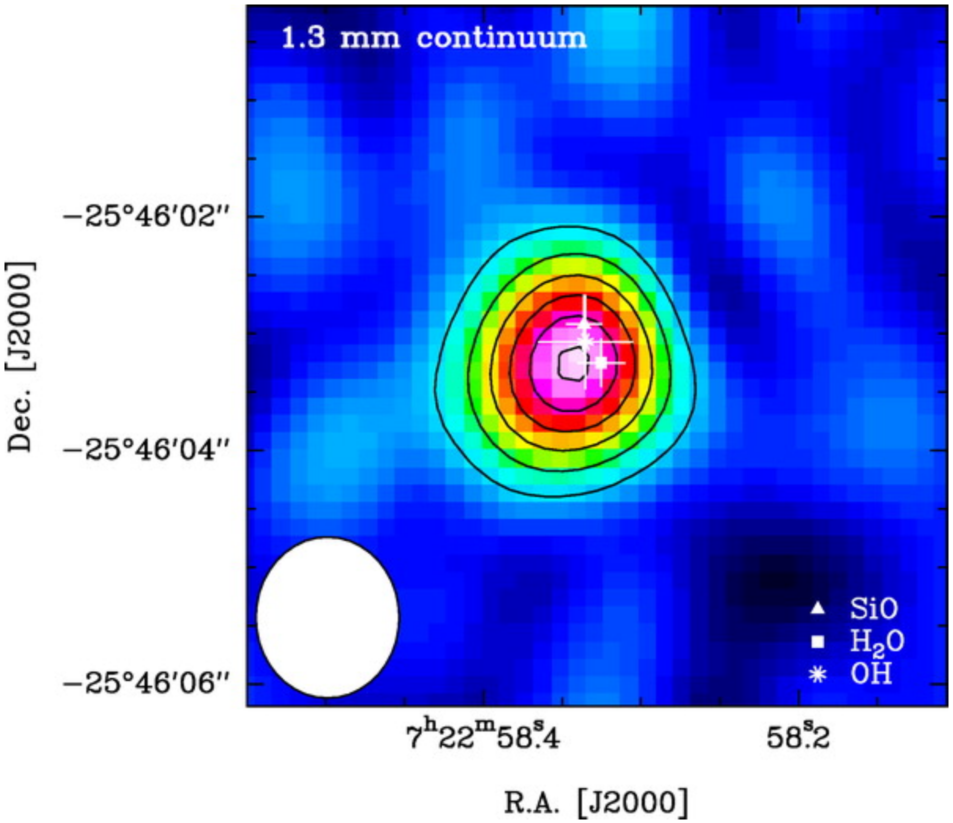
VLA A-array

T_B = 1640 K

L = 8.8 10^3 $L_\odot$



Menten, Reid, & Claussen 2010

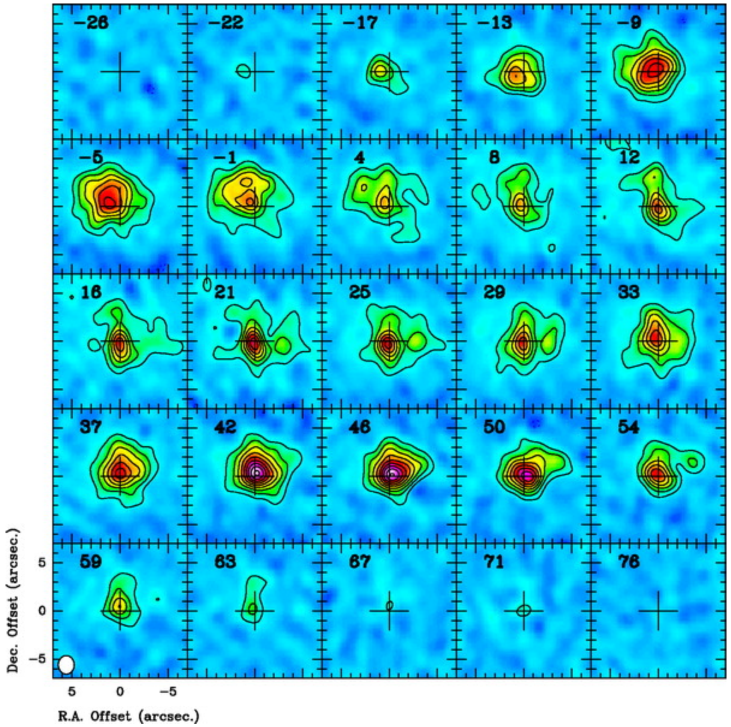


VY CMa

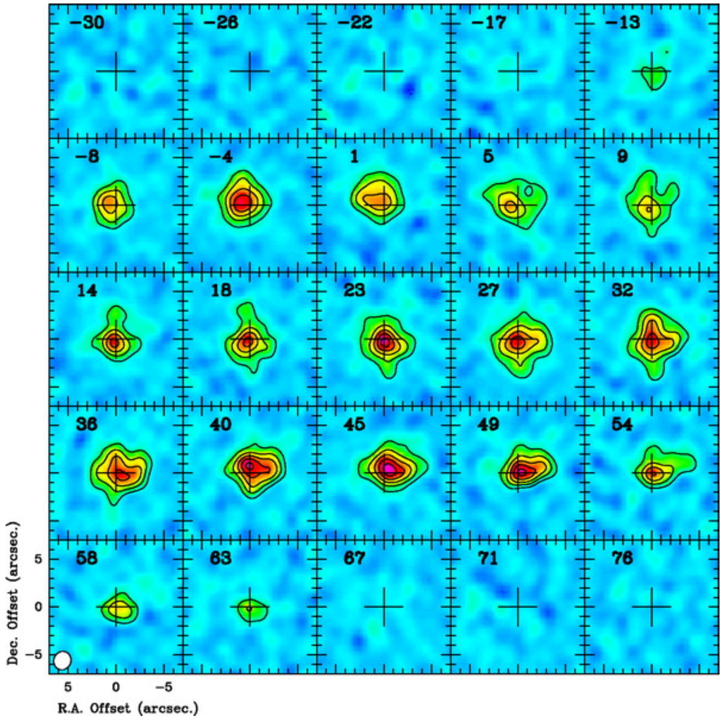
- Submillimeter Array
- 230 GHz/1.3 mm
- ≈ 2” resolution

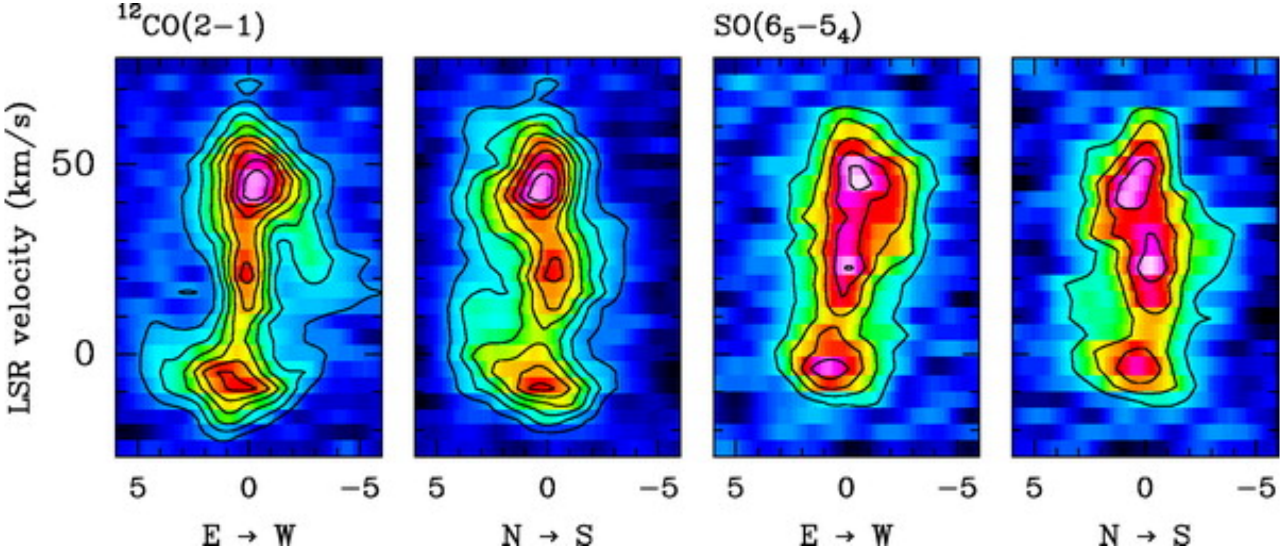
Muller et al. 2007

CO J = 2–1



SO $J_k = 6_5–5_4$

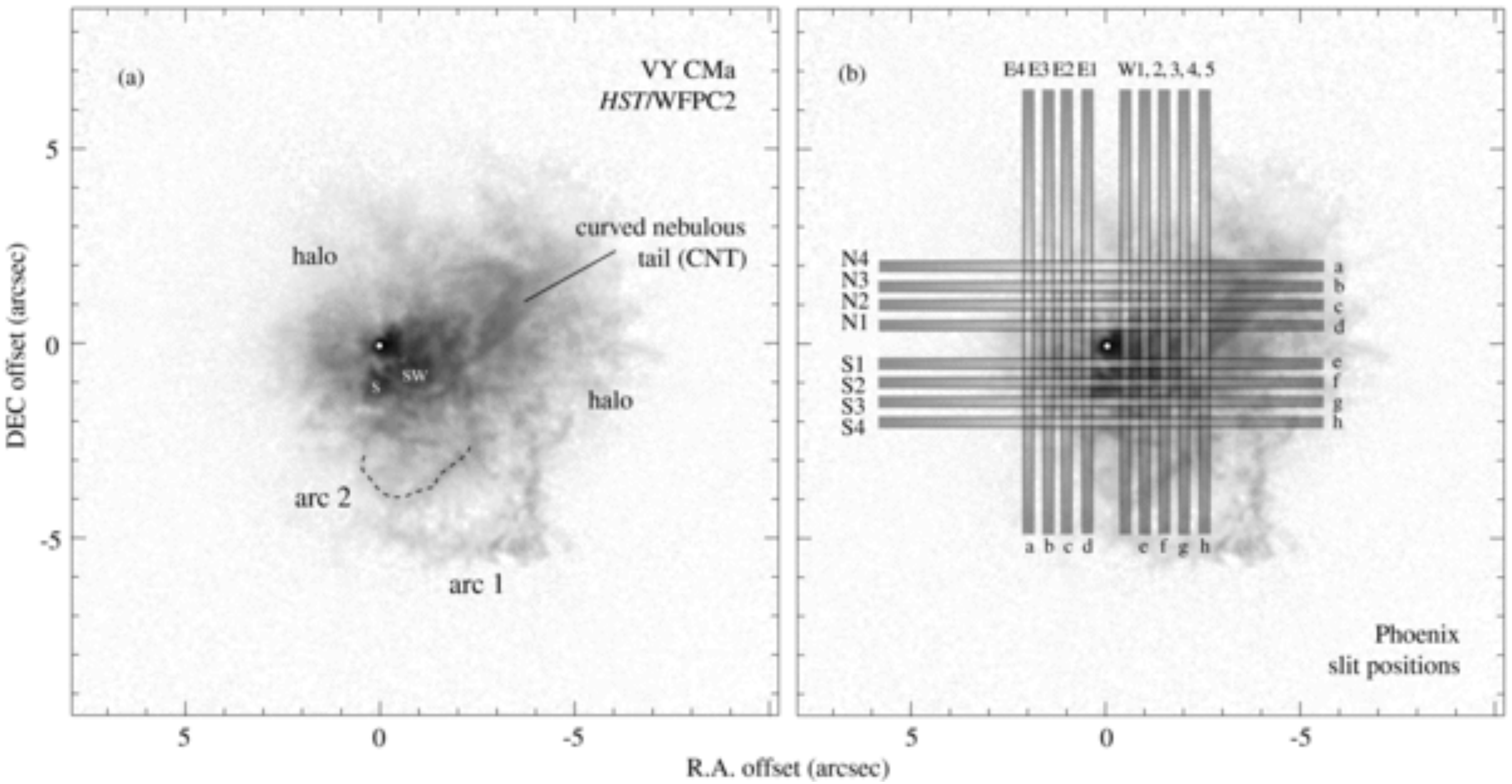




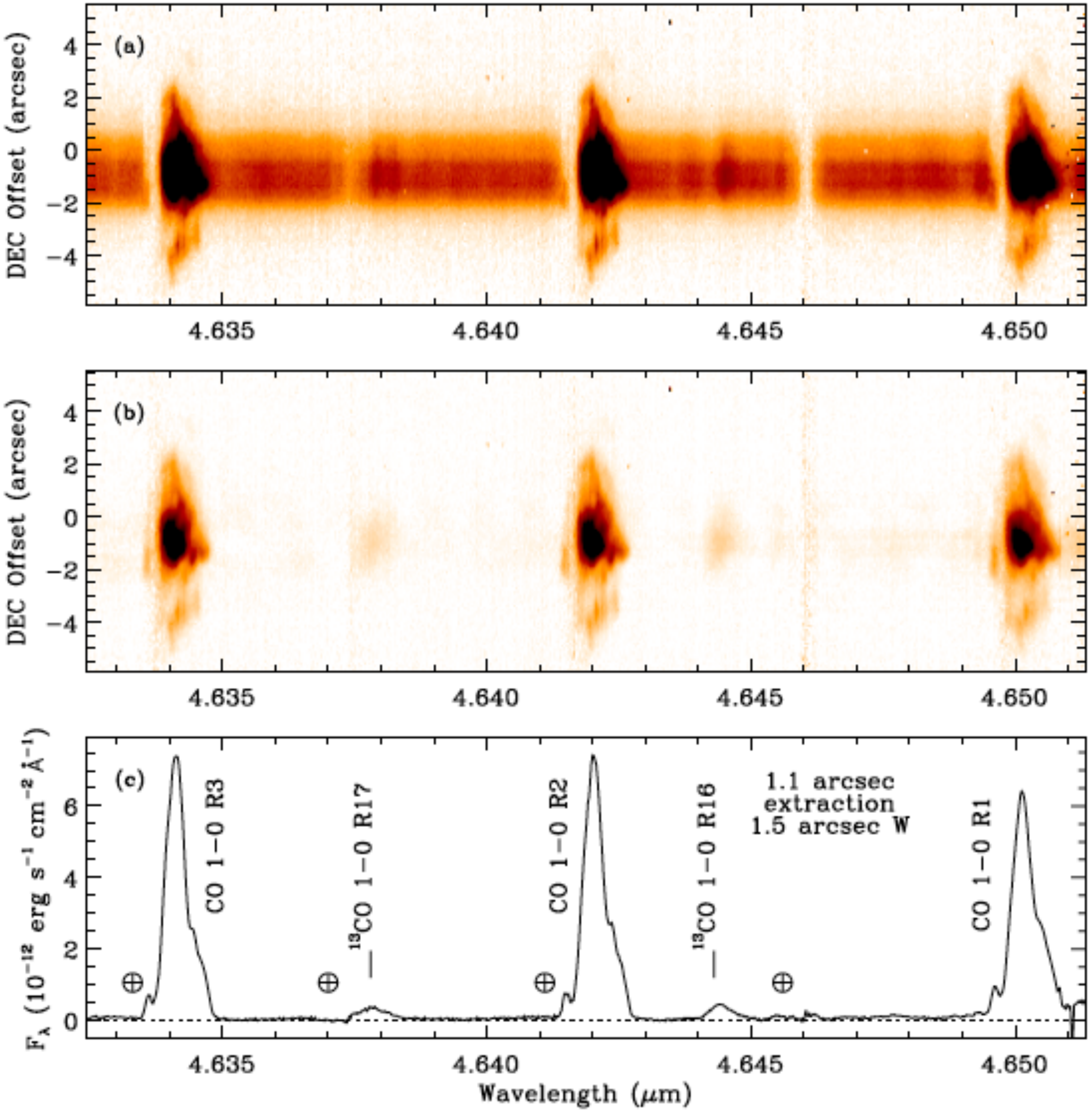
$^{12}CO(2-1)$

$SO(6_5-5_4)$

Muller et al. 2007



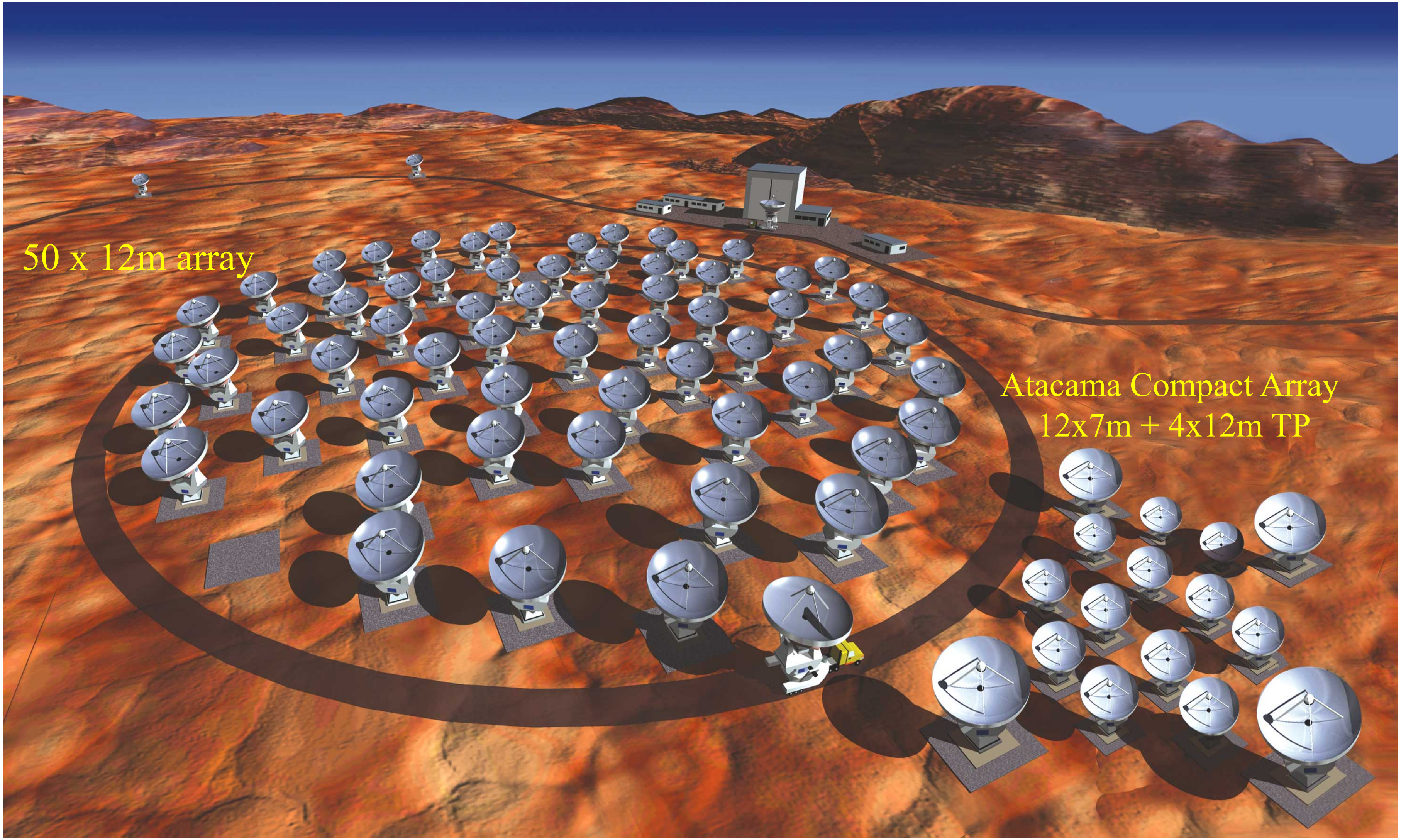
N. Smith et al. 2009


(a)
(b)
(c)
DEC Offset (arcsec)
4
2
0
−2
−4
4.635
4.640
4.645
4.650
F_λ (10^{-12} erg s^{-1} cm^{-2} Å^{-1})
6
4
2
0
⊕
CO 1−0 R3
^{13}CO 1−0 R17
CO 1−0 R2
^{13}CO 1−0 R16
1.1 arcsec extraction 1.5 arcsec W
CO 1−0 R1
Wavelength (μm)

What is ALMA?

North American, European, Japanese, and Chilean collaboration to build & operate a large millimeter/submm array at high altitude site (5000m) in northern Chile

➔ order of magnitude, or more, improvement in *all* areas of (sub)mm astronomy, including resolution, sensitivity, and frequency coverage.



ALMA: Technical Specifications

- 50 12-m antennas, 12 7-m antennas, 4 12-m with nutators (TP)
- Chajnantor 5000 m altitude site.
- Surface accuracy ±25 μm, 0.6” reference pointing in 9m/s wind, 2” absolute pointing all-sky.
- Array configurations between 150m to 18km (+ACA)
- 10 bands in 31-950 GHz + 183 GHz WVR. Initially:

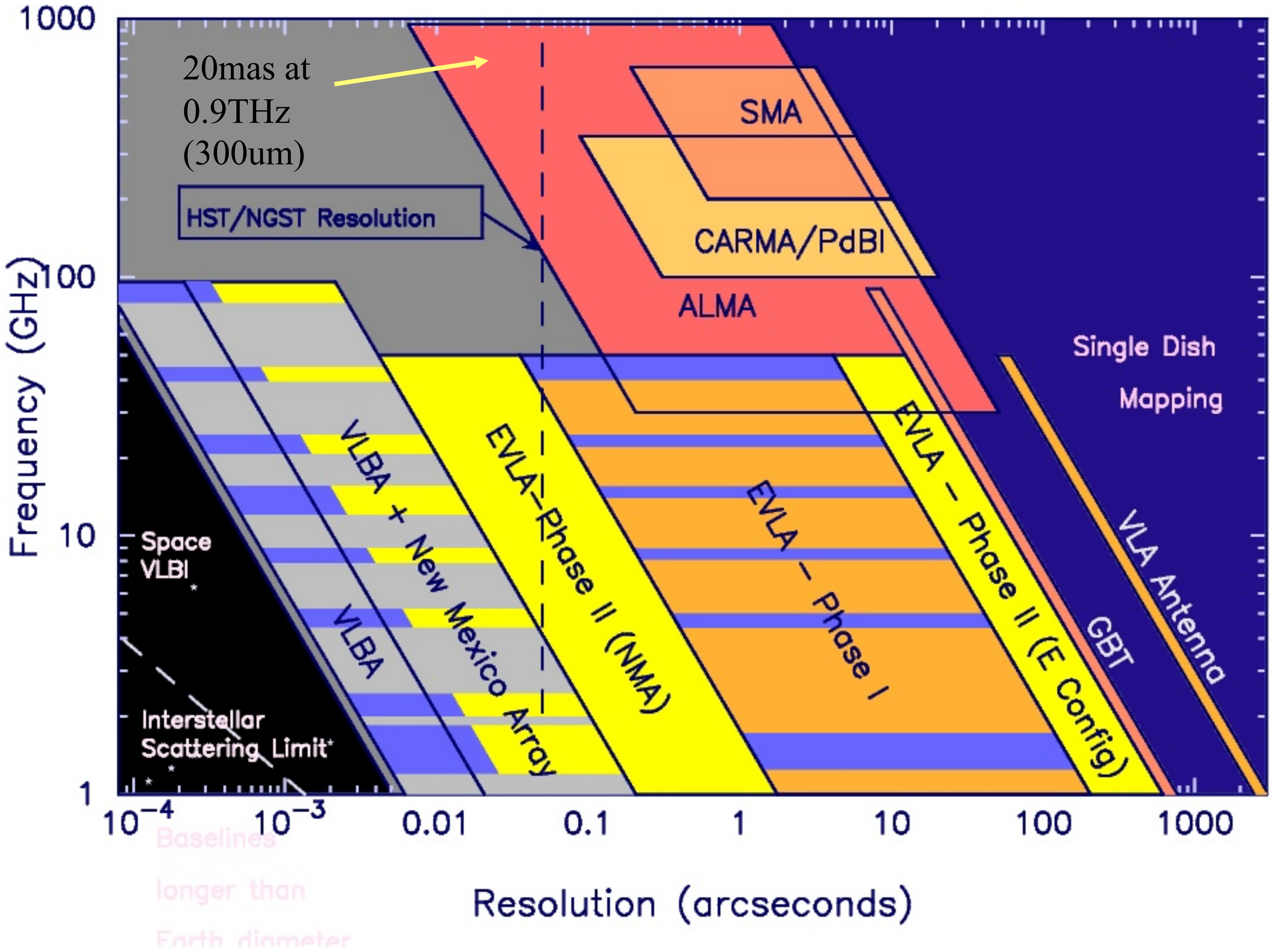
86-119 GHz	“3”	125-169 GHz	“4”
211-275 GHz	“6”	275-370 GHz	“7”
385-500 GHz	“8”	602-720 GHz	“9”

- 8 GHz BW, dual polarization.
- Flux sensitivity 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/2GHz IF, full Stokes.
- Data rate: 6MB/s average; peak 60-150 MB/s.
- All data archived (raw + images), pipeline processing.

ALMA Science Requirements

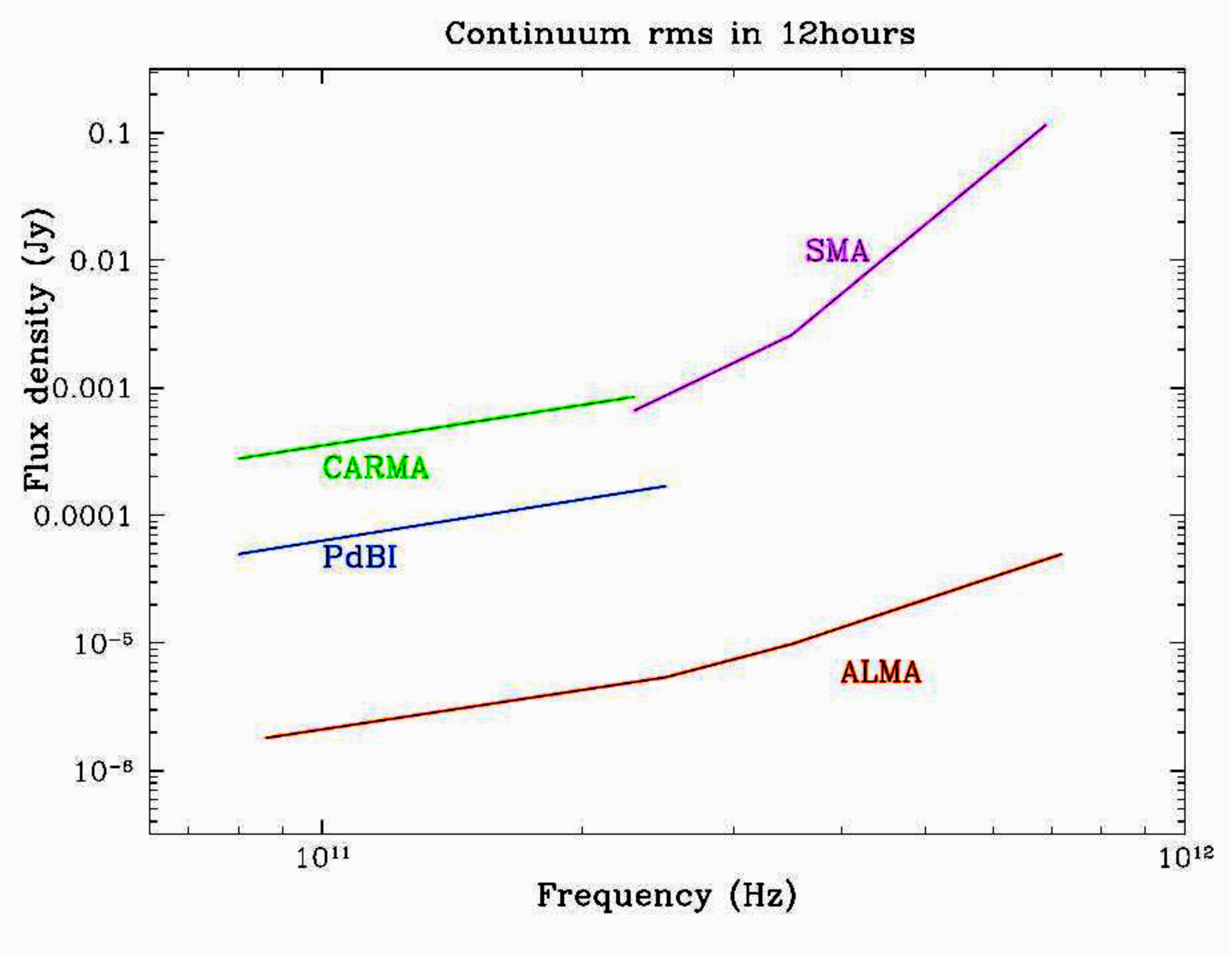
- High Fidelity Imaging.
- Precise Imaging at 0.1” Resolution.
- Routine sub-mJy Continuum Sensitivity.
- Routine mK Spectral Sensitivity.
- Wideband Frequency Coverage.
- Wide Field Imaging Mosaicing.
- Submillimeter Receiver System.
- Full Polarization Capability.
- System Flexibility.

Giant Steps I: Frequency and resolution



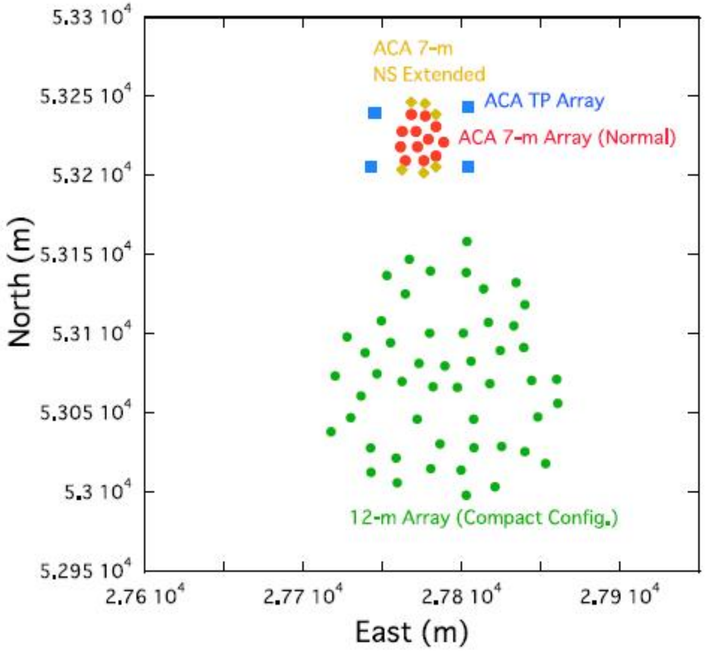
20mas at
0.9THz
(300um)

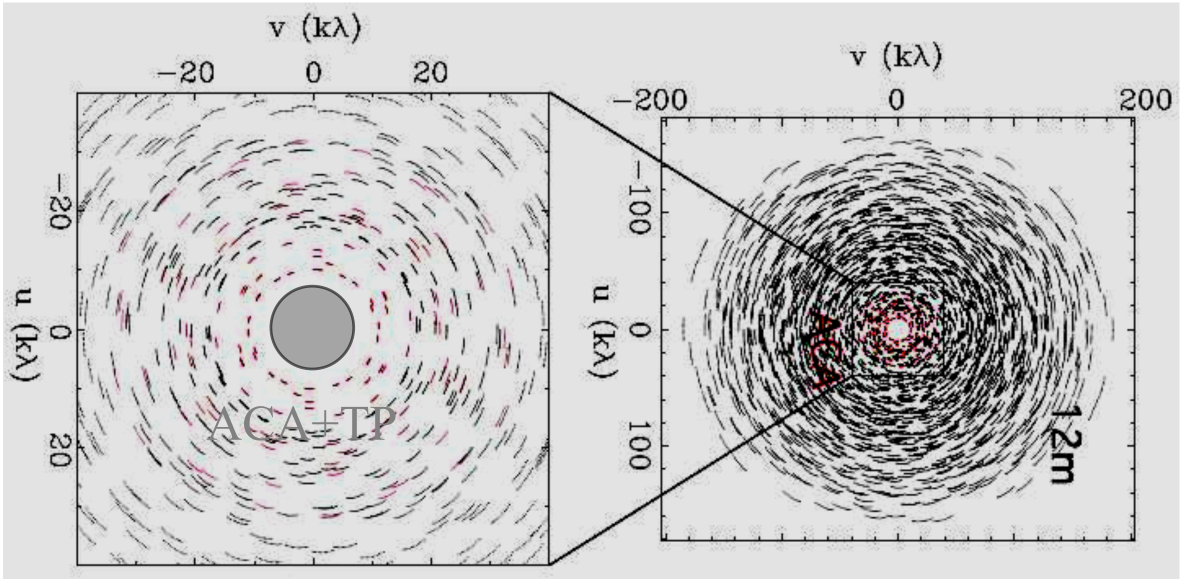
Giant Steps II: Sensitivity

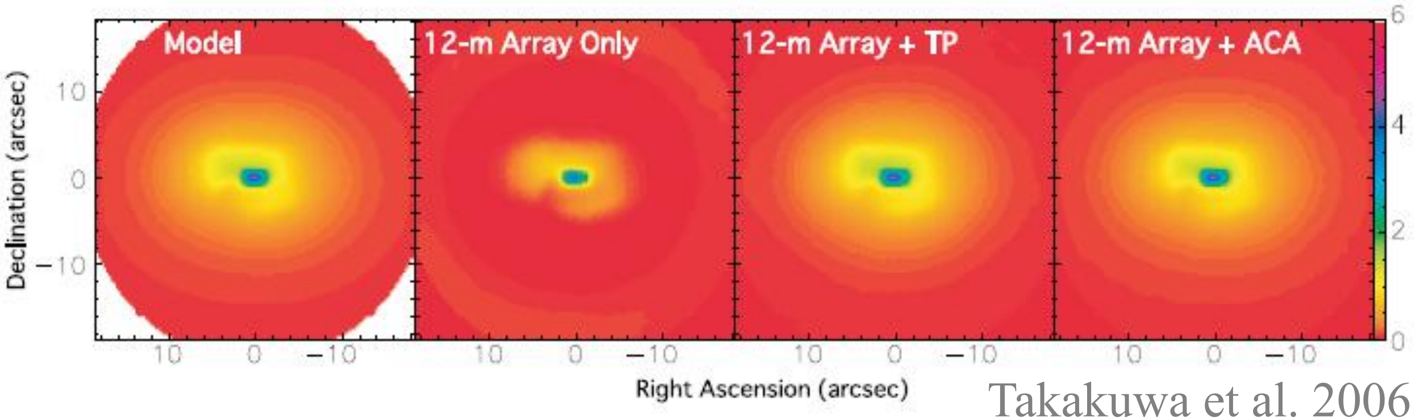


Giant Steps III: Image quality w. 50 x12m, 12x7m, 4x12m w/ TP

HST quality imaging through with dense sampling of *uv* plane

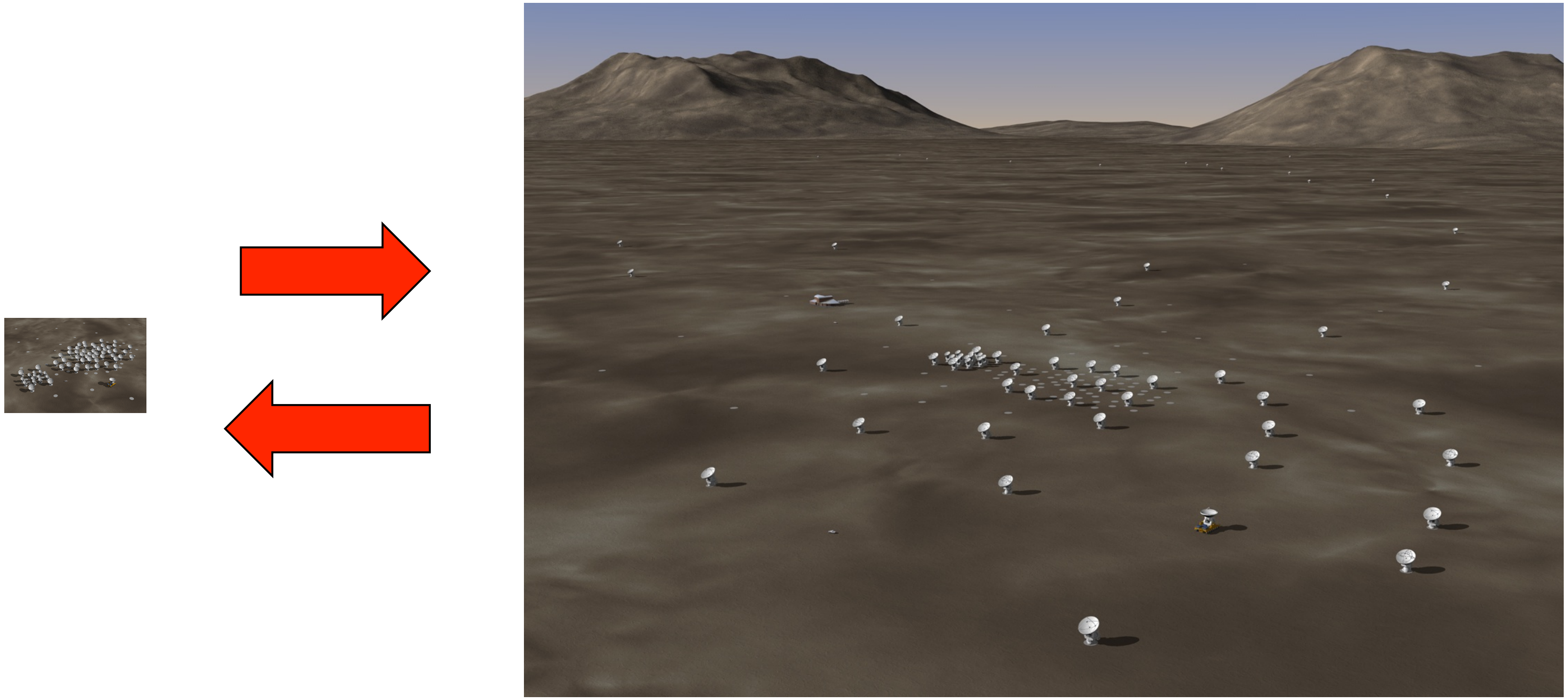






Takakuwa et al. 2006

A giant zoom lens



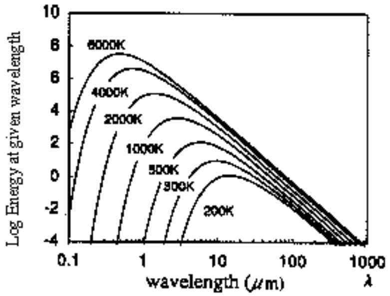
$$\Delta S_\nu \propto \frac{T_{sys}}{A_{eff}\sqrt{N(N-1)t_{\text{int}}\Delta\nu}}$$

$$\begin{aligned}
S_\nu(\text{mJy}) &= \frac{2k}{\lambda^2}\int T_B\, d\Omega \\
&\approx 10^{-9}\theta^2(\text{mas})\nu^2(\text{GHz})T(\text{K}) \\
\Rightarrow \Delta T_B(K) &\approx 20\Delta S(\text{mJy}) \text{ for } \theta = 20 \text{ mas}, \;\; \nu = 345 \text{ GHz} \\
&\approx 8\ 10^{-3}\Delta S(\text{mJy}) \text{ for } \theta = 1 \;\; \text{arcsec}
\end{aligned}$$

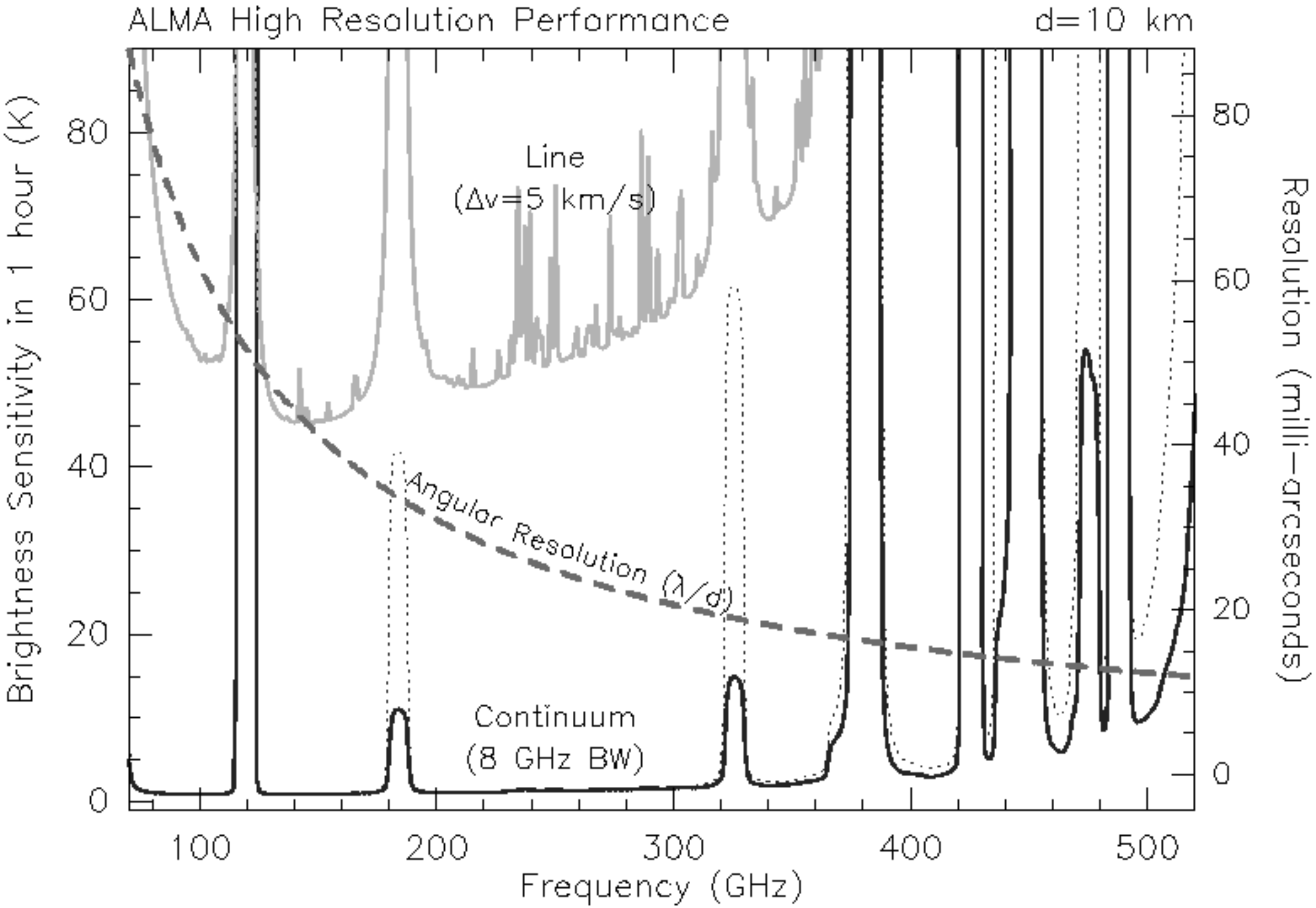
ALMA at 345 GHz in 1 h:

ΔS = 3 mJy at $\Delta\nu$ = 1 MHz

= 0.022 mJy at $\Delta\nu$ = 16 GHz



Black Body Radiation


ALMA High Resolution Performance
d=10 km
Line
(Δv=5 km/s)
Angular Resolution (λ/d)
Continuum
(8 GHz BW)
Brightness Sensitivity in 1 hour (K)
0
20
40
60
80
Resolution (milli-arcseconds)
0
20
40
60
80
100
200
300
400
500
Frequency (GHz)

With ALMA it will be possible to probe the whole molecular envelope of an AGB star

ALMA’s superb sensitivity and zoom capability will allow continuum and multi-molecule/multi-isotopologic imaging of

- the star itself
- the composition of its its molecular photosphere
- element depletion during dust formation
- the acceleration of the envelope
- the complex photochemistry of the outer envelope

The Very Large Array (VLA)

- Built 1970’s, dedicated 1980
- 27 x 25m diameter antennas
- Two-dimensional 3-armed array design
- Four scaled configurations, maximum baselines 35, 10, 3.5, 1.0 Km.
- Eight bands centered at 0.074, 0.327, 1.4, 4.6, 8.4, 15, 23, 45 GHz
- 100 MHz total IF bandwidth per polarization
- Full polarization in continuum modes.
- Digital correlator provides up to 512 total channels – but only 16 at maximum bandwidth.

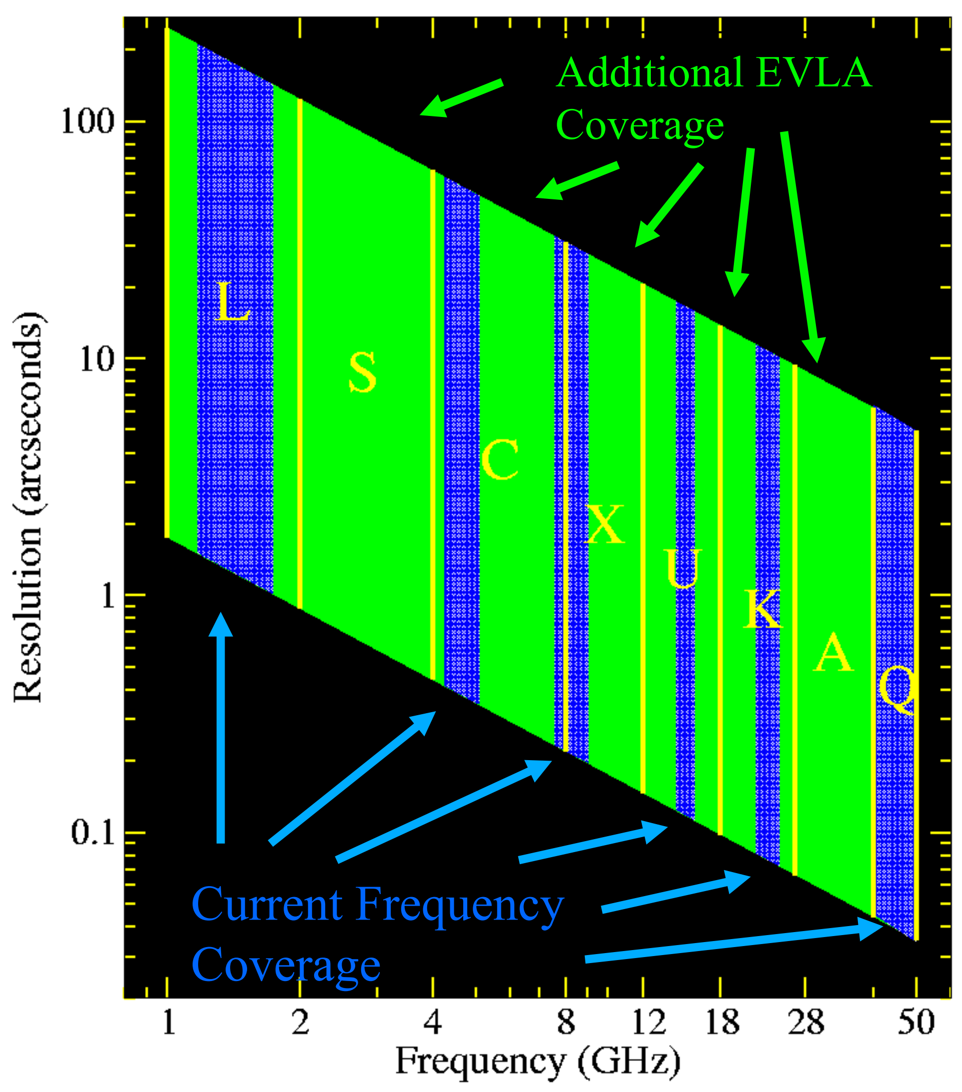
VLA in D-configuration
(1 km maximum baseline)

The Expanded Very Large Array

- **The EVLA Project:**
  - builds on the existing infrastructure - antennas, array, buildings, people - and,
  - implements new technologies to produce a new array whose top-level goal is to provide
- **Ten Times the Astronomical Capability of the VLA.**
  - Sensitivity, Frequency Access, Image Fidelity, Spectral Capabilities, Spectral Fidelity, Spatial Resolution, User Access
  - With a timescale and cost far less than that required to design, build, and implement a new facility.

Frequency – Resolution Coverage

- A key EVLA requirement is continuous frequency coverage from 1 to 50 GHz.
- This will be met with 8 frequency bands:
  - Two existing (K, Q)
  - Four replaced (L, C, X, U)
  - Two new (S, A)
- Existing meter-wavelength bands (P, 4) retained with no changes.
- Blue areas show existing coverage.
- Green areas show new coverage.

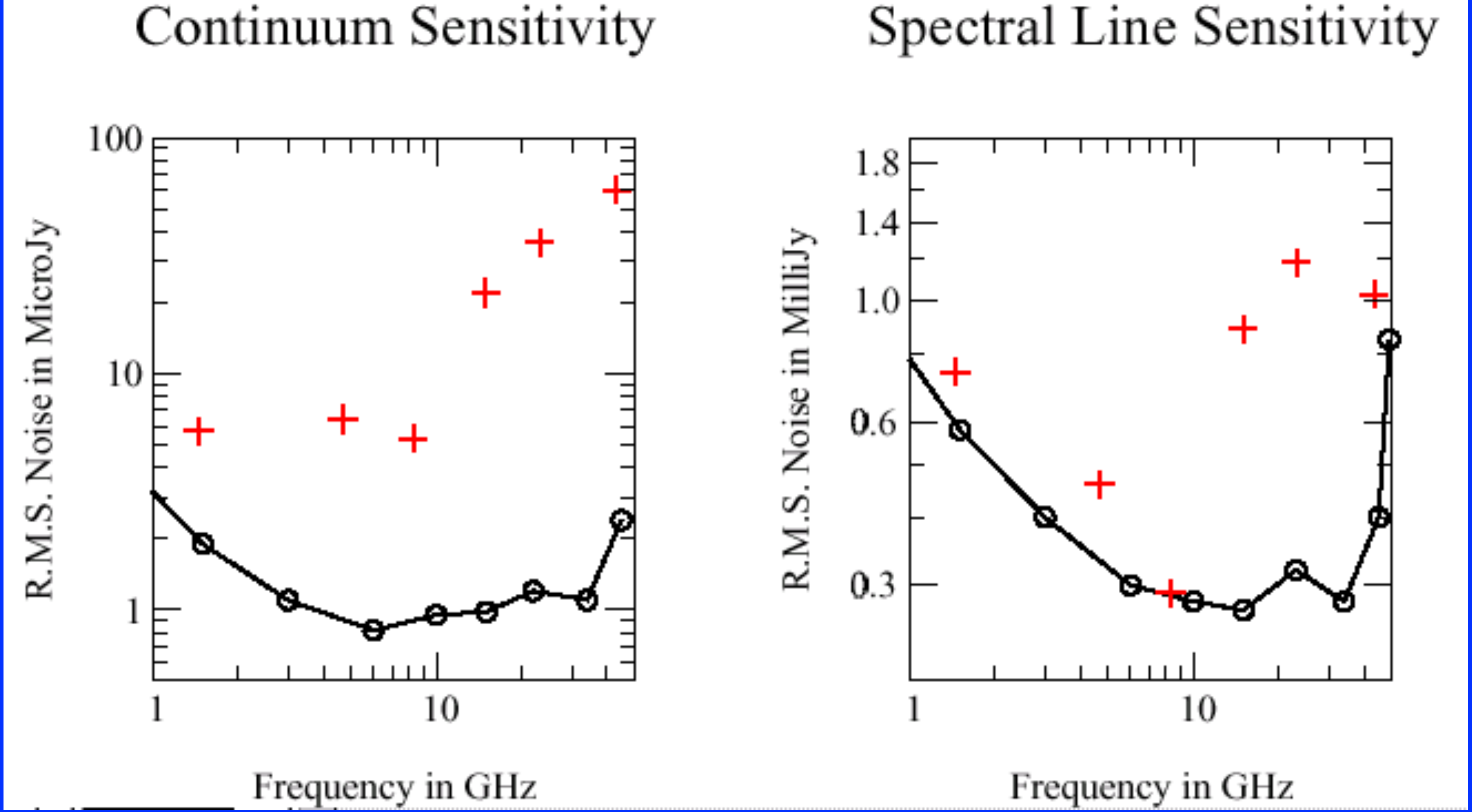


EVLA-I Performance Goals

The EVLA’s performance is vastly better than the VLA’s:

Parameter	VLA	EVLA-I	Factor
Point Source Sensitivity (1-s, 12 hours)	10 mJy	1 mJy	10
Maximum BW in each polarization	0.1 GHz	8 GHz	80
# of frequency channels at max. bandwidth	16	16,384	1024
Maximum number of frequency channels	512	4,194,304	8192
Coarsest frequency resolution	50 MHz	2 MHz	25
Finest frequency resolution	381 Hz	0.12 Hz	3180
(Log) Frequency Coverage (1 – 50 GHz)	22%	100%	5

Sensitivity Improvement (1σ, 12 hours)



Red: Current VLA, **Black:** EVLA Goals

©Rick Perley@NRAO

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left[\exp(h\nu/kT)-1\right]^{-1} \text{ (Planck's law)}$$

$$= \frac{2kT}{c^2}\nu^2 \text{ if } h\nu << kT \text{ (Rayleigh - Jeans law)}$$

$$S_\nu(T) = \Omega_s B_\nu(T) = \Omega_s \frac{2k}{c^2}\nu^2 T$$

$$S_\nu(\text{mJy}) \approx 10^{-9}\theta^2(\text{mas})\nu^2(\text{GHz})T(\text{K})$$

$$S_\nu(\text{mJy}) \approx 10^{-9}\theta^2(\text{mas})\nu^2(\text{GHz})T(\text{K})$$

$$\approx 3\times10^{-3}T(K) \text{ for } \theta = 40 \text{ mas, } \nu = 43 \text{ GHz}$$

Q-band sensitivity ~0.5 mJy/9 h/Δv= 2 km/s

⇒ Can image 100s of K hot gas at hundreds of 100 mas resolution

⇒ non-maser emission from innermost CSEs

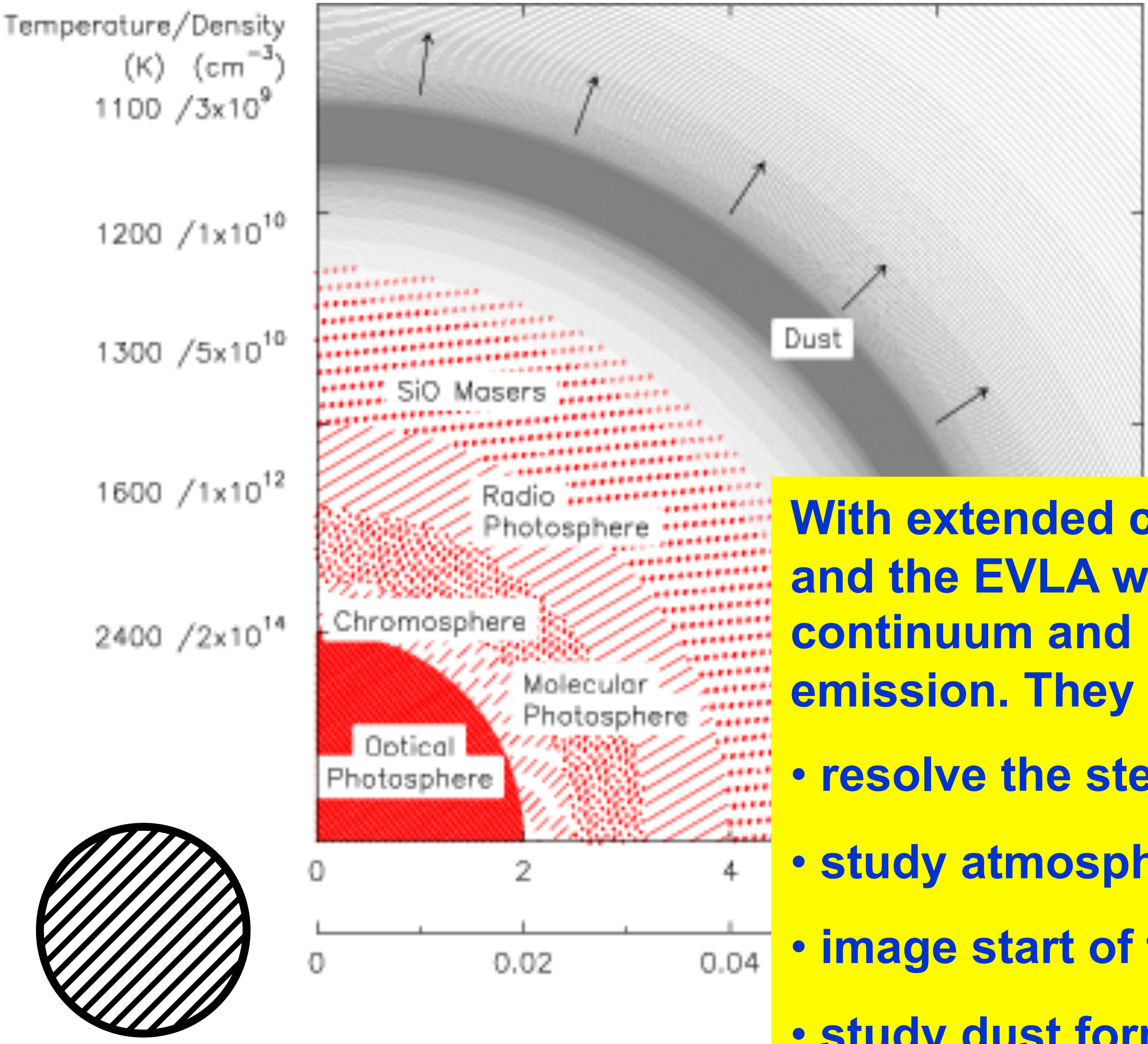
$$
\begin{aligned}
S_\nu(\text{mJy}) &\approx 10^{-9}\,\theta^2(\text{mas})\,\nu^2(\text{GHz})\,T(\text{K}) \\
&\approx 3\times10^{-3}\,T(K)\ \text{for } \theta = 40\ \text{mas},\ \nu = 43\ \text{GHz} \\
&\approx 0.08\,T(K)\ \text{for } \theta = 1\ \text{arcsec}
\end{aligned}
$$

If all lines of a species are optically thick, their flux densities scale as ν^2.

$\Rightarrow$ cm lines weaker than (sub)mm lines

$\rightarrow$ need for spectral multiplexing

High resolution continuum and *thermal* line imaging

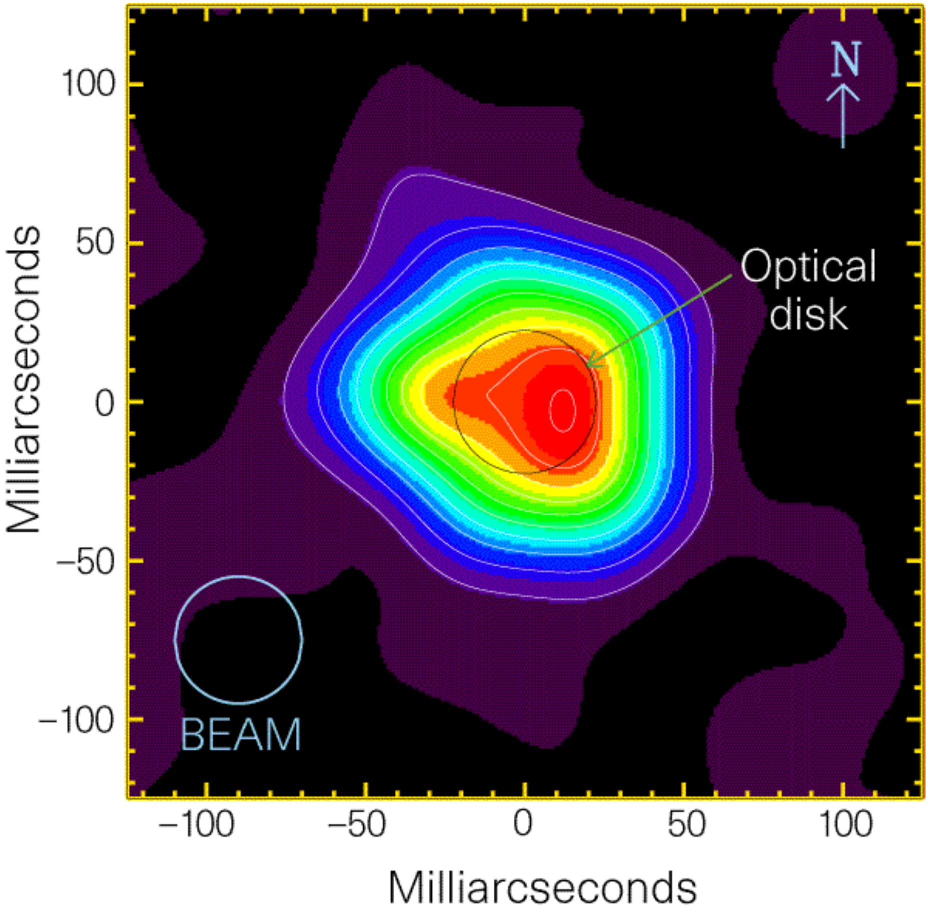


With extended configurations, ALMA and the EVLA will be able image continuum and *thermal* line emission. They will:

- **resolve the stellar photosphere**
- **study atmospheric chemistry**
- **image start of the outflow**
- **study dust formation and depletion**

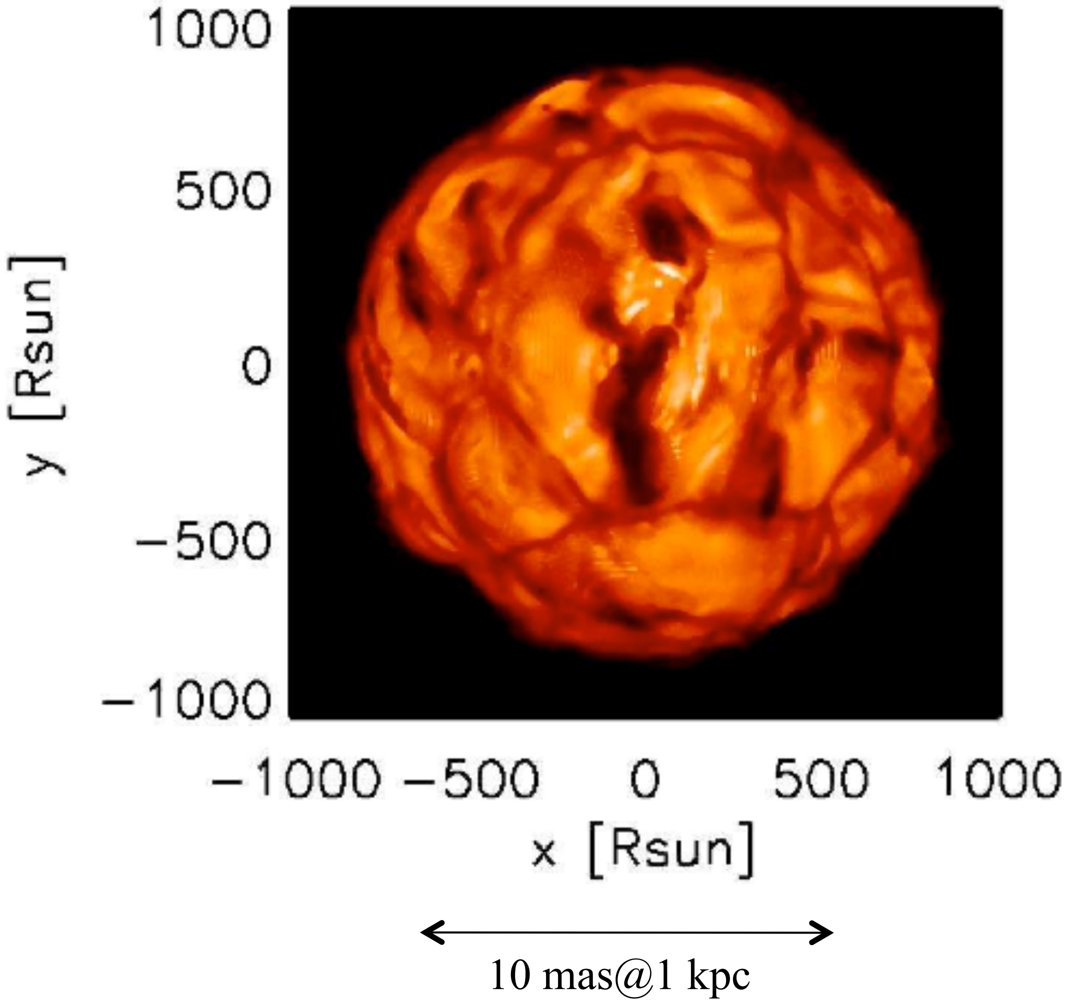
Large convection cells as the source of Betelgeuse's extended atmosphere

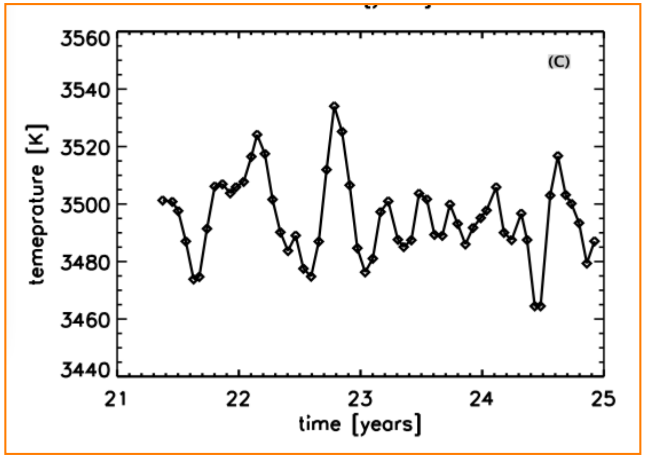
Lim et al. 1998



α Orionis (Betelgeuse)
VLA 7 mm (43 GHz)

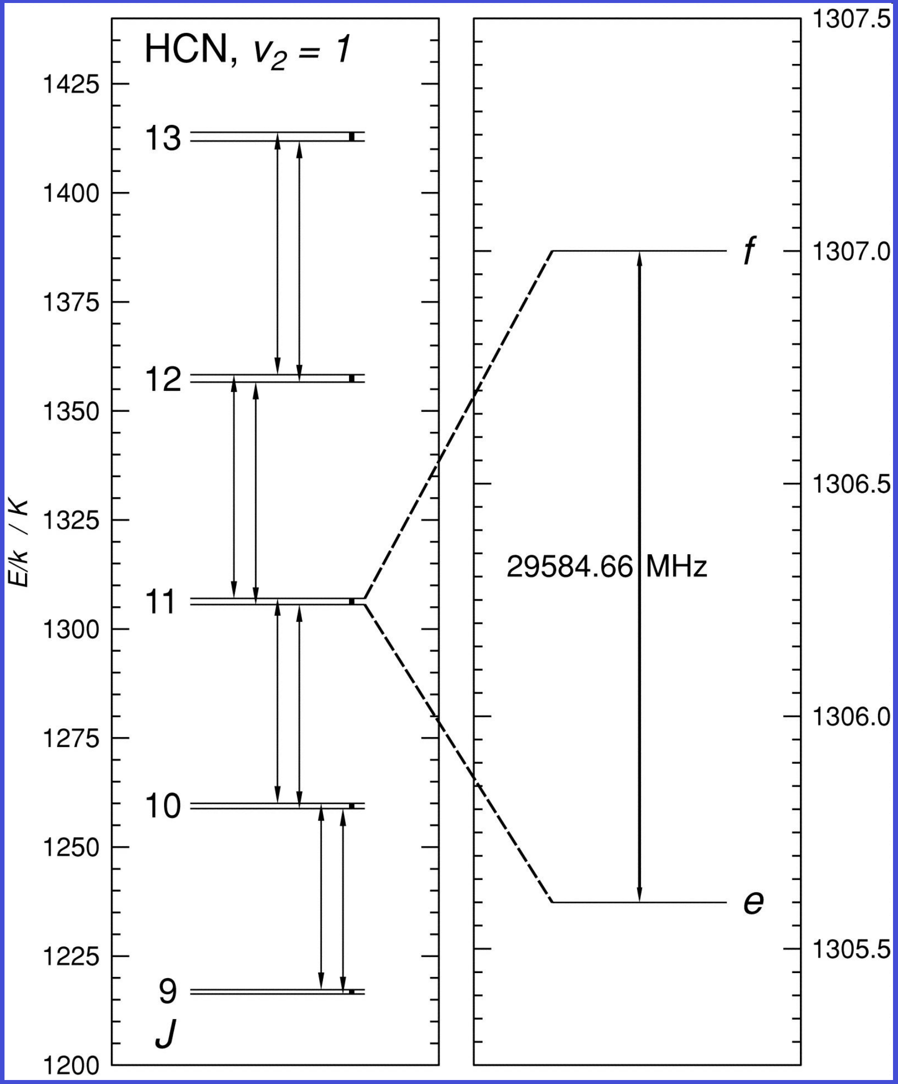
Talk by S. Höfner





Chiavassa, Plez, Josselin, & Freytag 2009

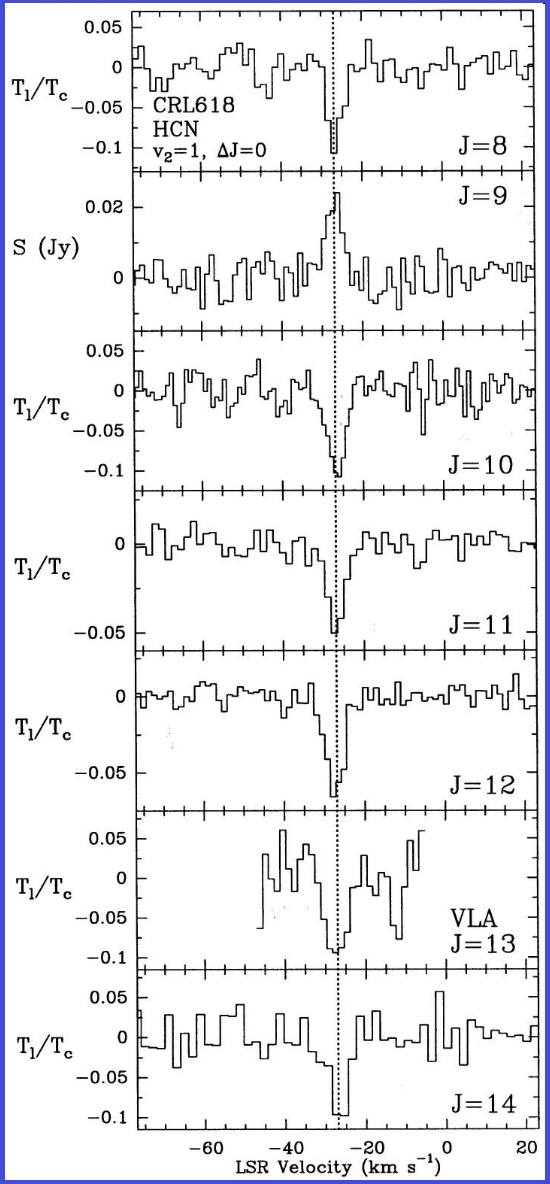
Non-maser observations of circumstellar chemistry with the EVLA – Some examples

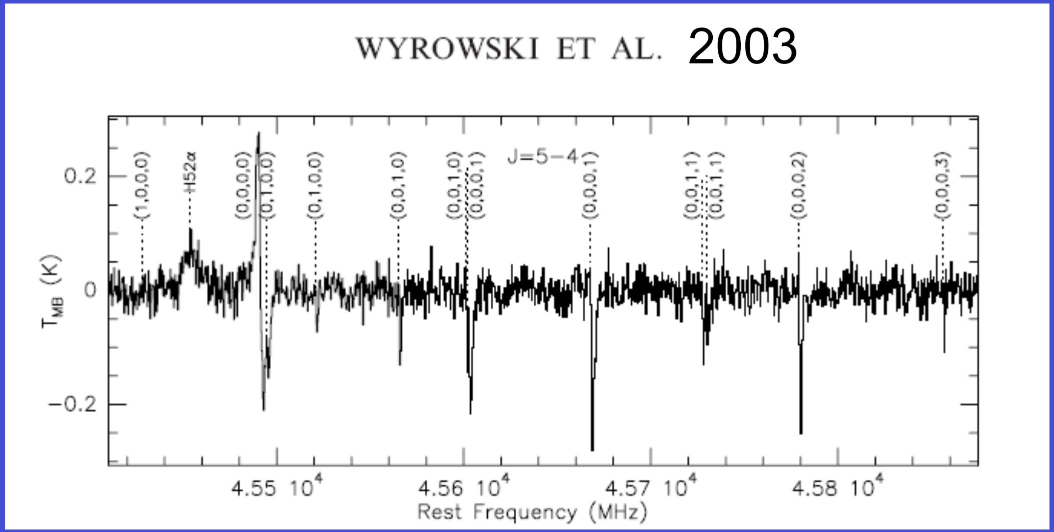


HCN *l*-type transitions

ν(GHz)	E(K)/1.44	*J*
1346.7652	720.8477	2
2693.3388	729.7156	3
4488.4723	741.5391	4
6731.9105	756.3180	5
9423.3348	774.0518	6
12562.3629	794.7403	7
16148.5495	818.3829	8
20181.3862	844.9789	9
24660.3100	874.5279	10
29584.6600	907.0291	11
34953.7600	942.4816	12
40766.9000	980.8848	13
47023.2000	1022.2376	14

CRL 618



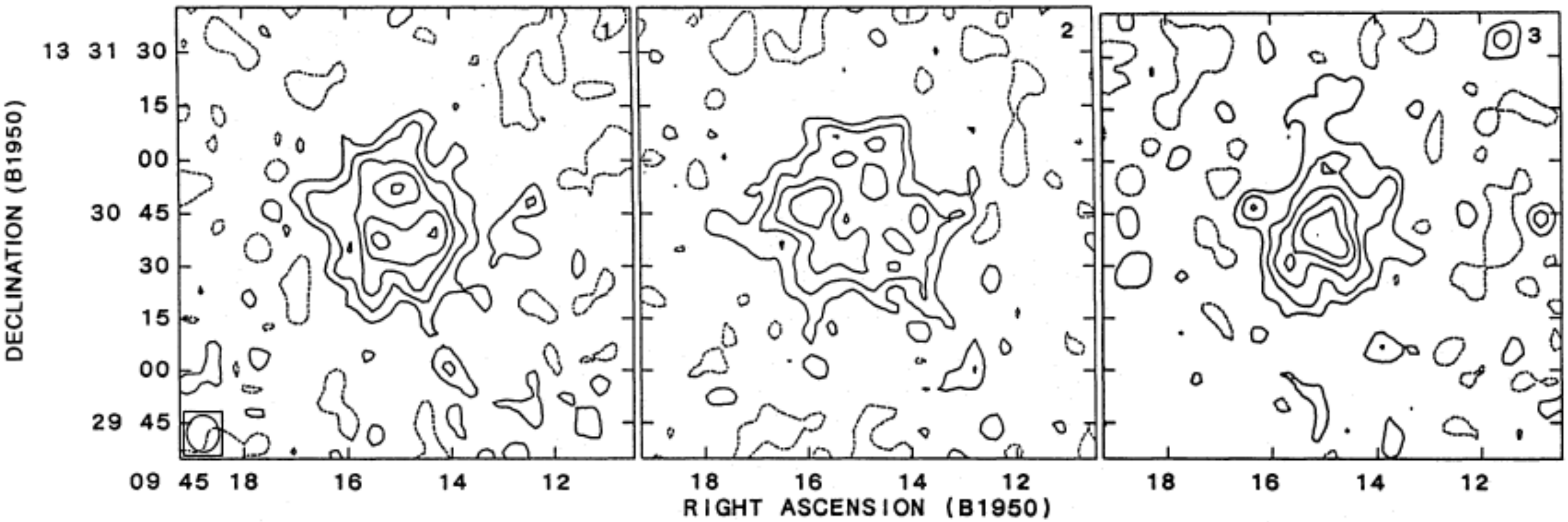


HC_3N

HCN

Thorwirth et al. 2003

A. Wootten et al.: Images of low excitation HC_3N emission from IRC+10°216 1994 201



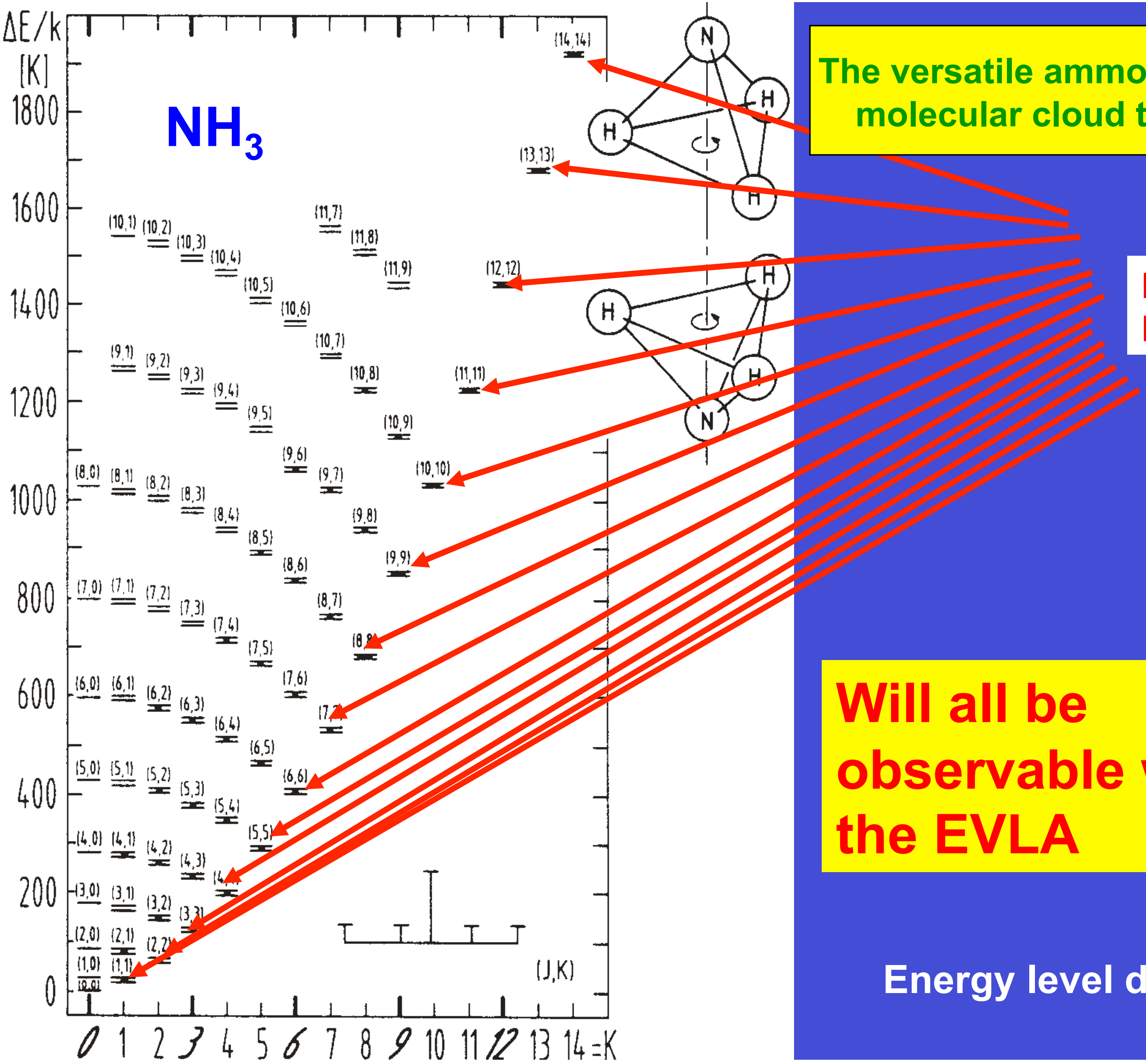
HC_3N J = 1 – 0

9.0 GHz

l-type doublet vibrationally excited HCN lines need

- 14 μm radiation for their excitation and, thus
- probe mid-IR radiation field unaccessible by other means (due to high opactity)

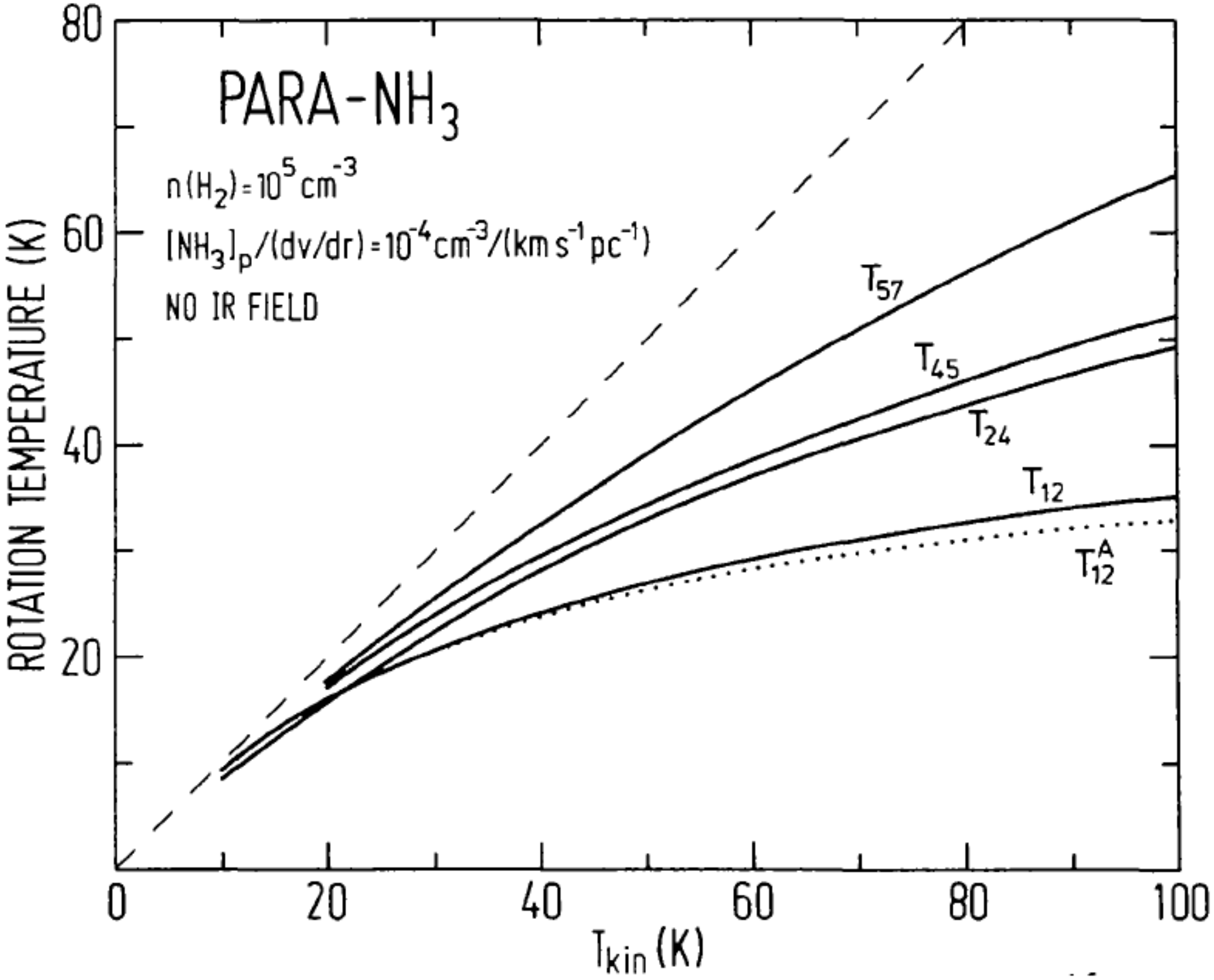
The versatile ammonia molecule – molecular cloud thermometer



Metastable levels (*J* = *K*)

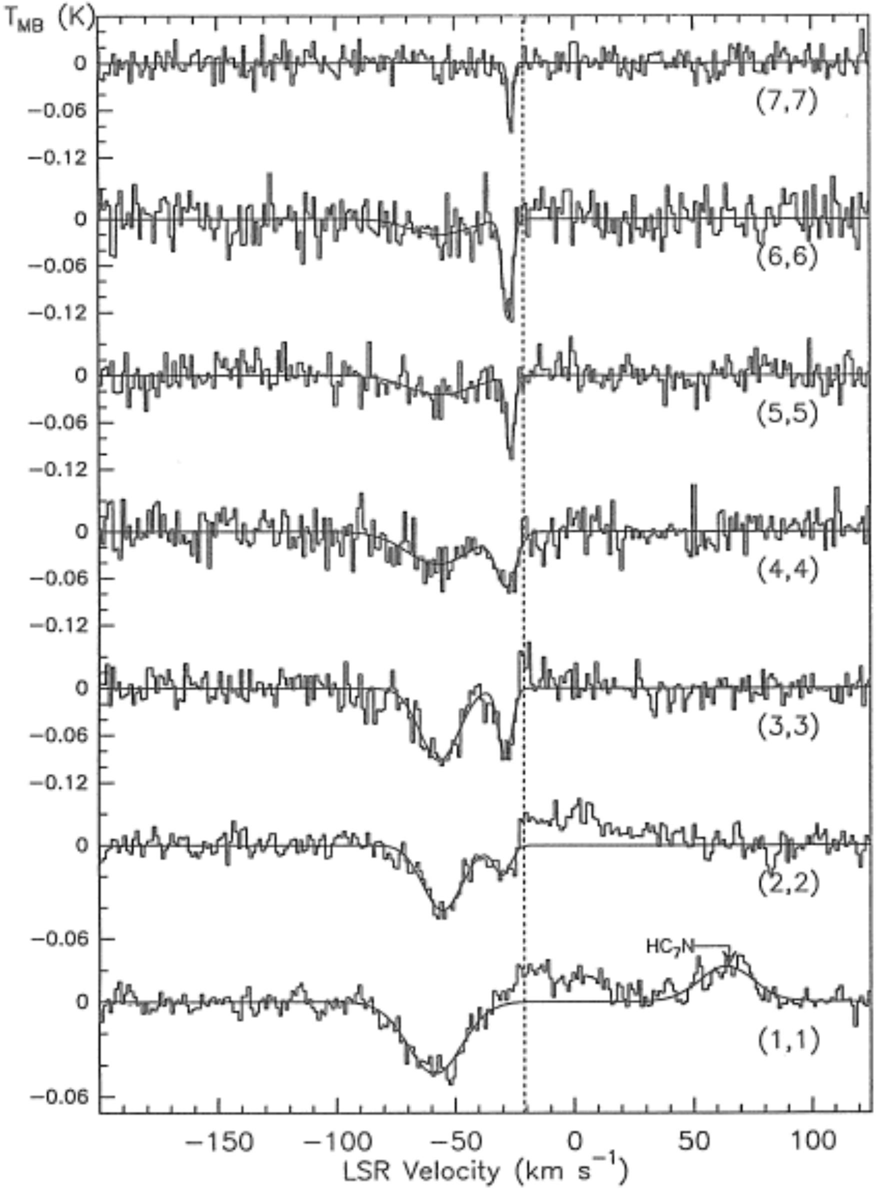
Will all be observable with the EVLA

Energy level diagram



Ungerechts & Walmsley 1983

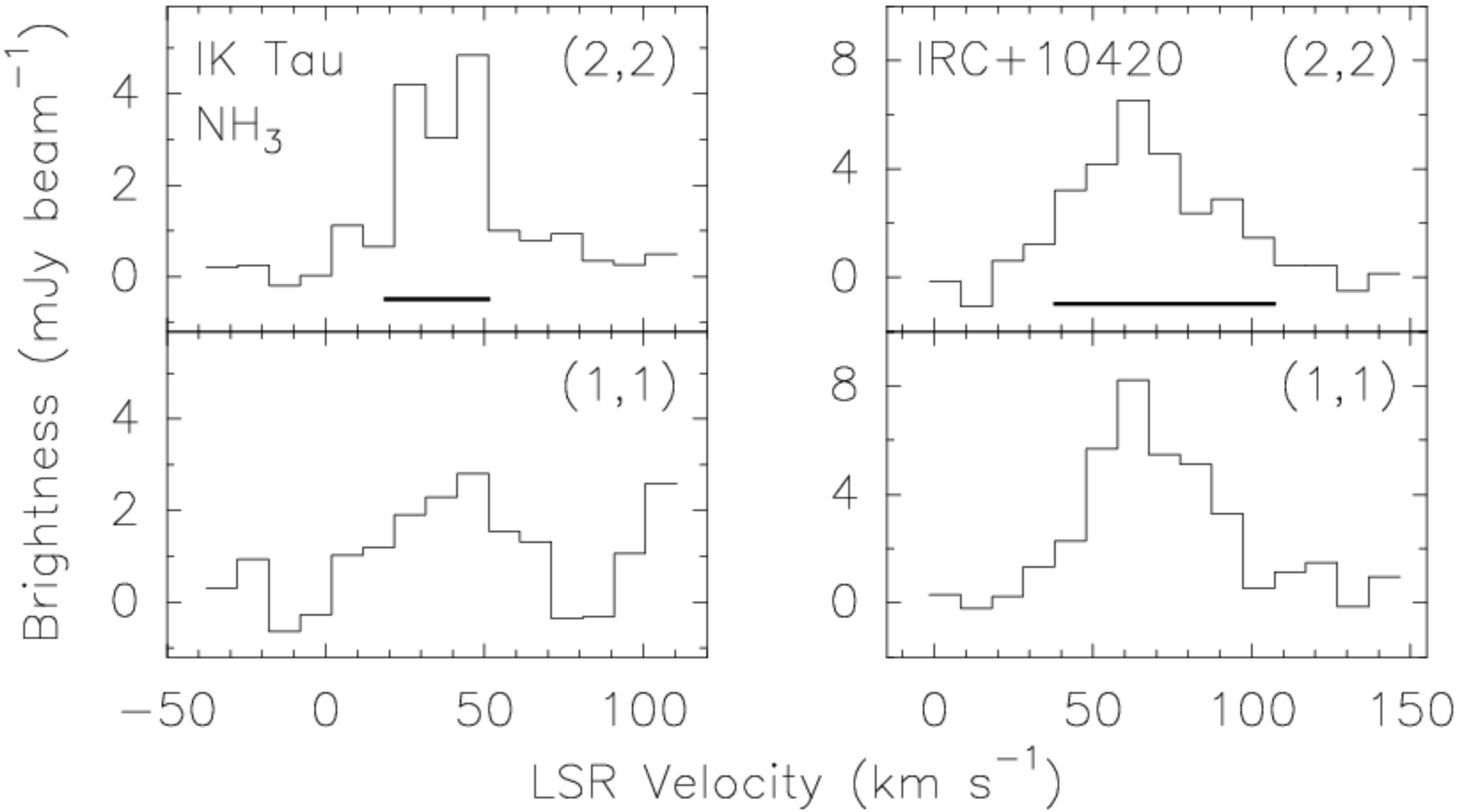
PPN CRL 618



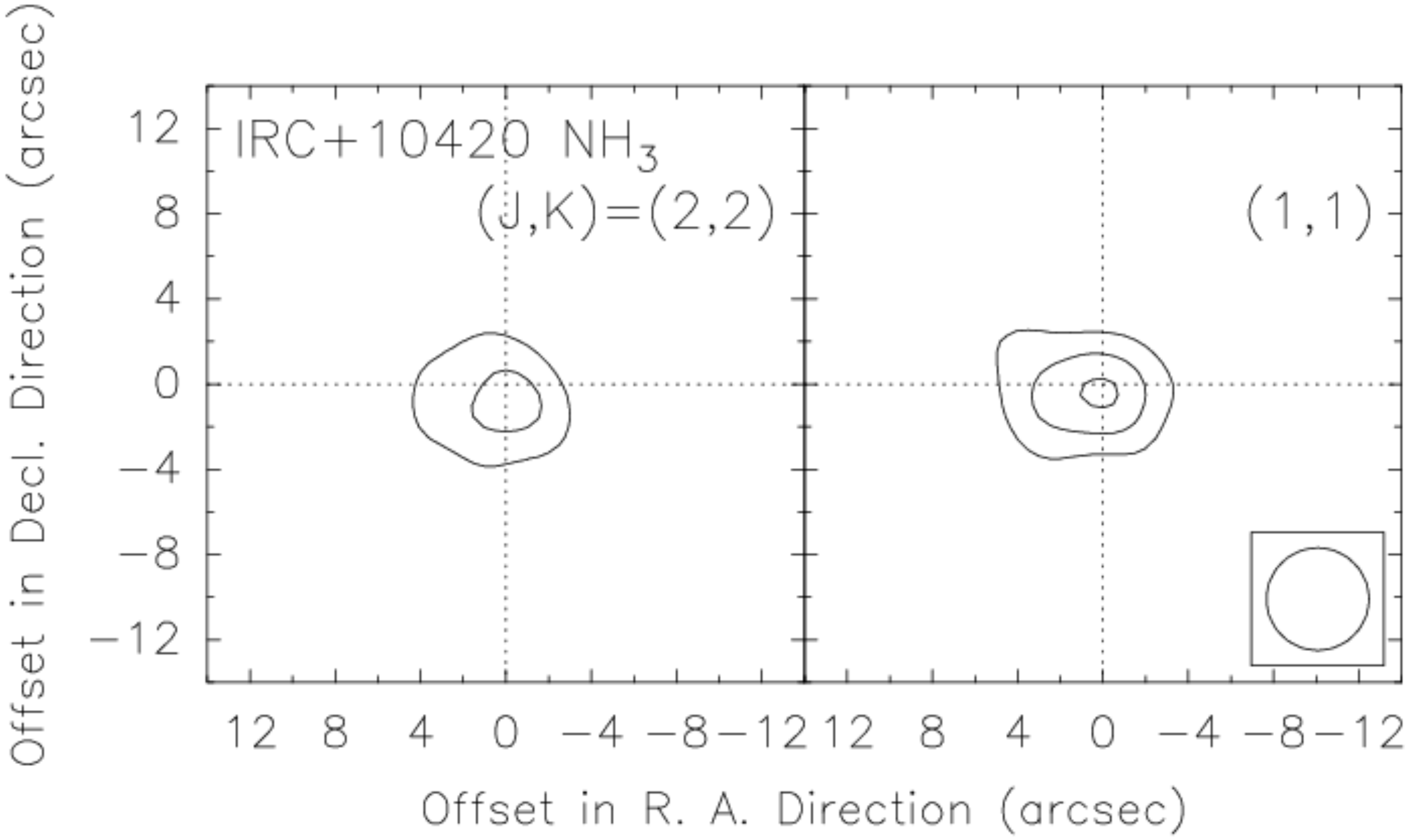
$T_{kin} > 100$ K

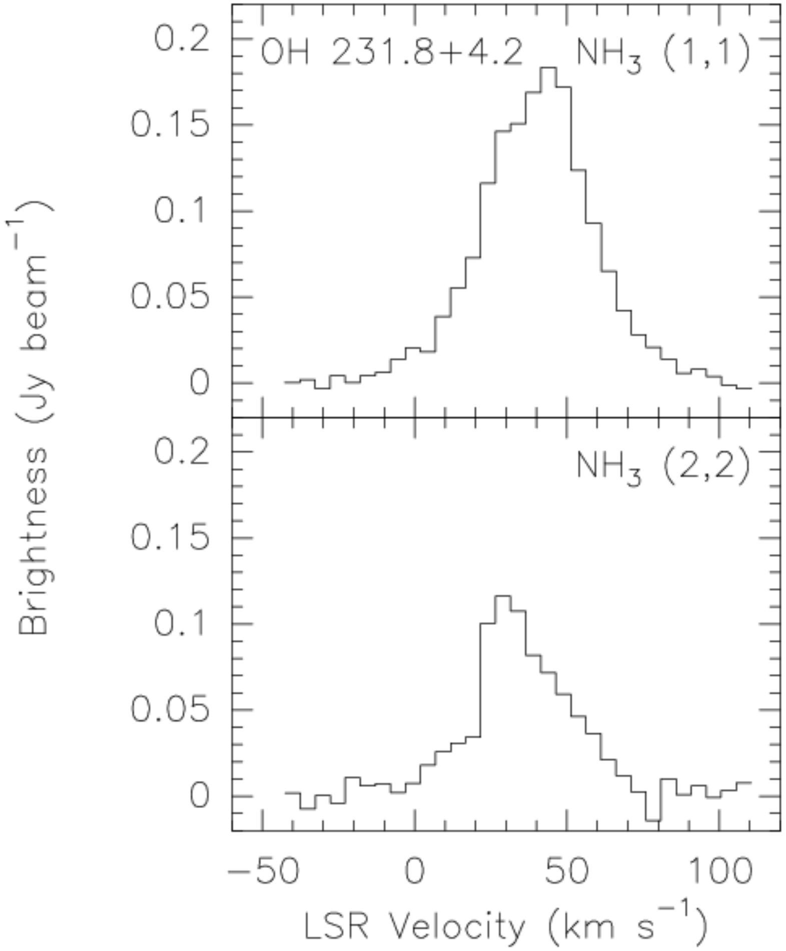
Martin-Pintado & Bachiller 1992

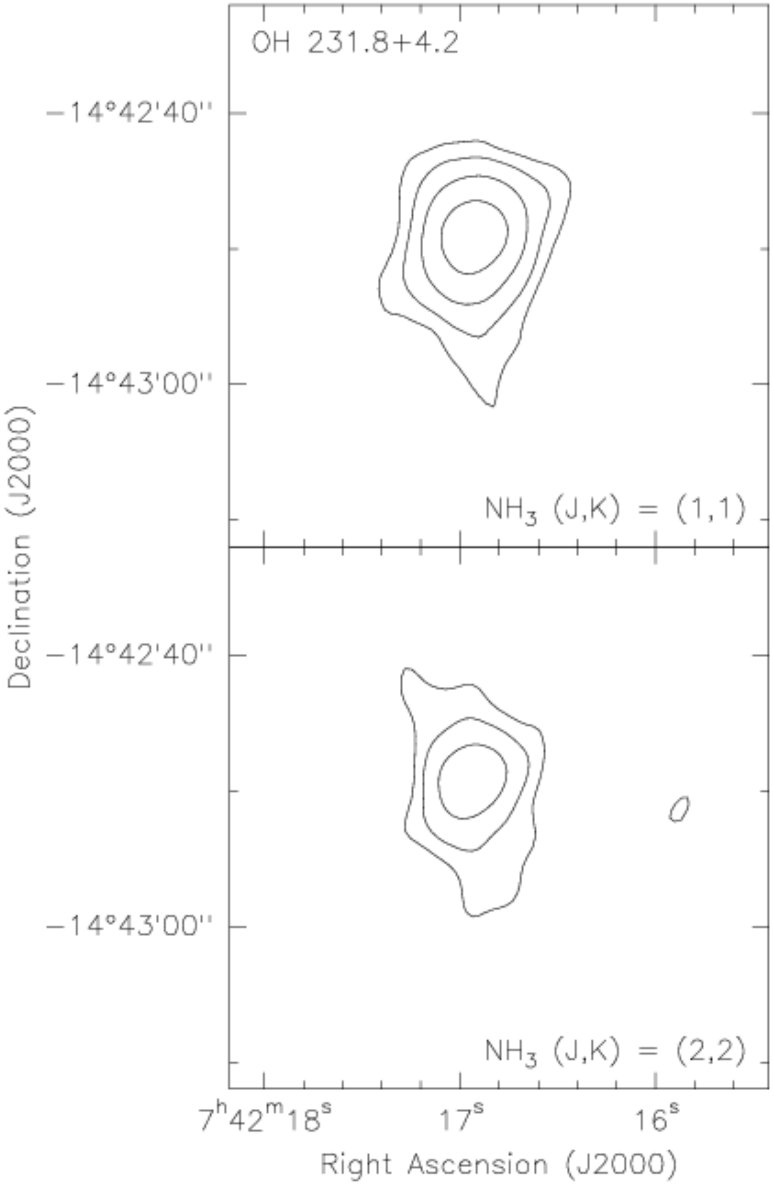
T_{kin} > 50 K



Menten et al. in prep.

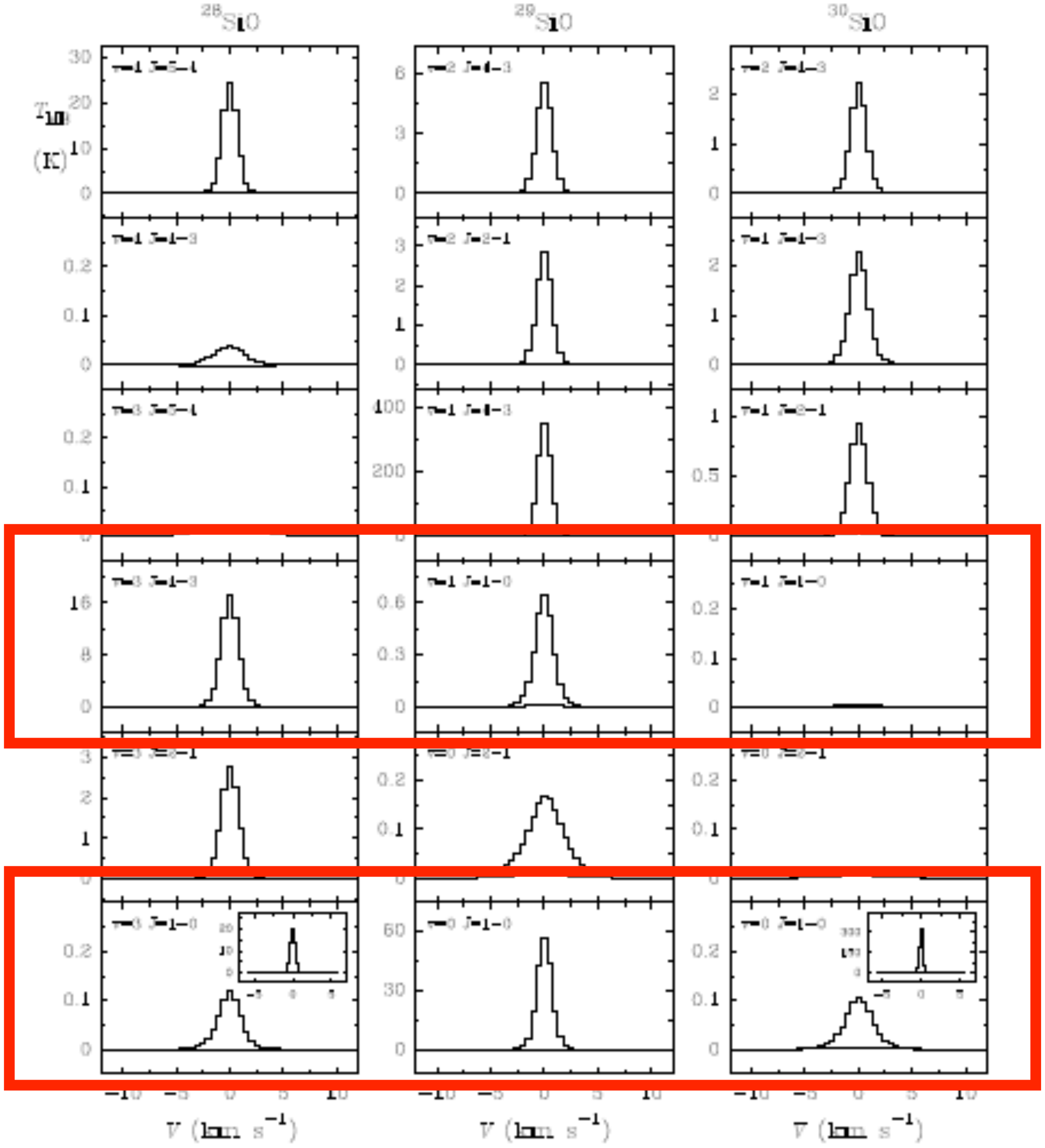

IRC+10420 NH$_3$
(J,K)=(2,2)
(1,1)
Offset in Decl. Direction (arcsec)
12
8
4
0
−4
−8
−12
Offset in R. A. Direction (arcsec)
12 8 4 0 −4 −8 −12
12 8 4 0 −4 −8 −12


OH 231.8+4.2
NH$_3$ (1,1)
NH$_3$ (2,2)
Brightness (Jy beam^{-1})
0.2
0.15
0.1
0.05
0
−50
0
50
100
LSR Velocity (km s^{-1})


OH 231.8+4.2
NH$_3$ (J,K) = (1,1)
NH$_3$ (J,K) = (2,2)
−14°42'40''
−14°43'00''
Declination (J2000)
7^{h}42^{m}18^s
17^s
16^s
Right Ascension (J2000)

SiO J=1-0, vib. exc. states, and isotopomers

```
41791.9439 2417.9288  1 2          0 2                 Si-30-O, v=0-3
42082.5464 1214.7678  1 1          0 1                 Si-30-O, v=0-3
42287.9951 2432.1545  1 2          0 2                 Si-29-O, v=0-3
42373.3400    0.0000  1 0          0 0                 Si-30-O, v=0-3
42583.8300 1221.9500  1 1          0 1                 Si-29-O, v=0-3
42820.4800 2447.3345  1 2          0 2                 SiO, v=0-6
42879.8200    0.0000  1 0          0 0                 Si-29-O, v=0-3
43122.0300 1229.6145  1 1          0 1                 SiO, v=0-6
43423.7600    0.0000  1 0          0 0                 SiO, v=0-6
```

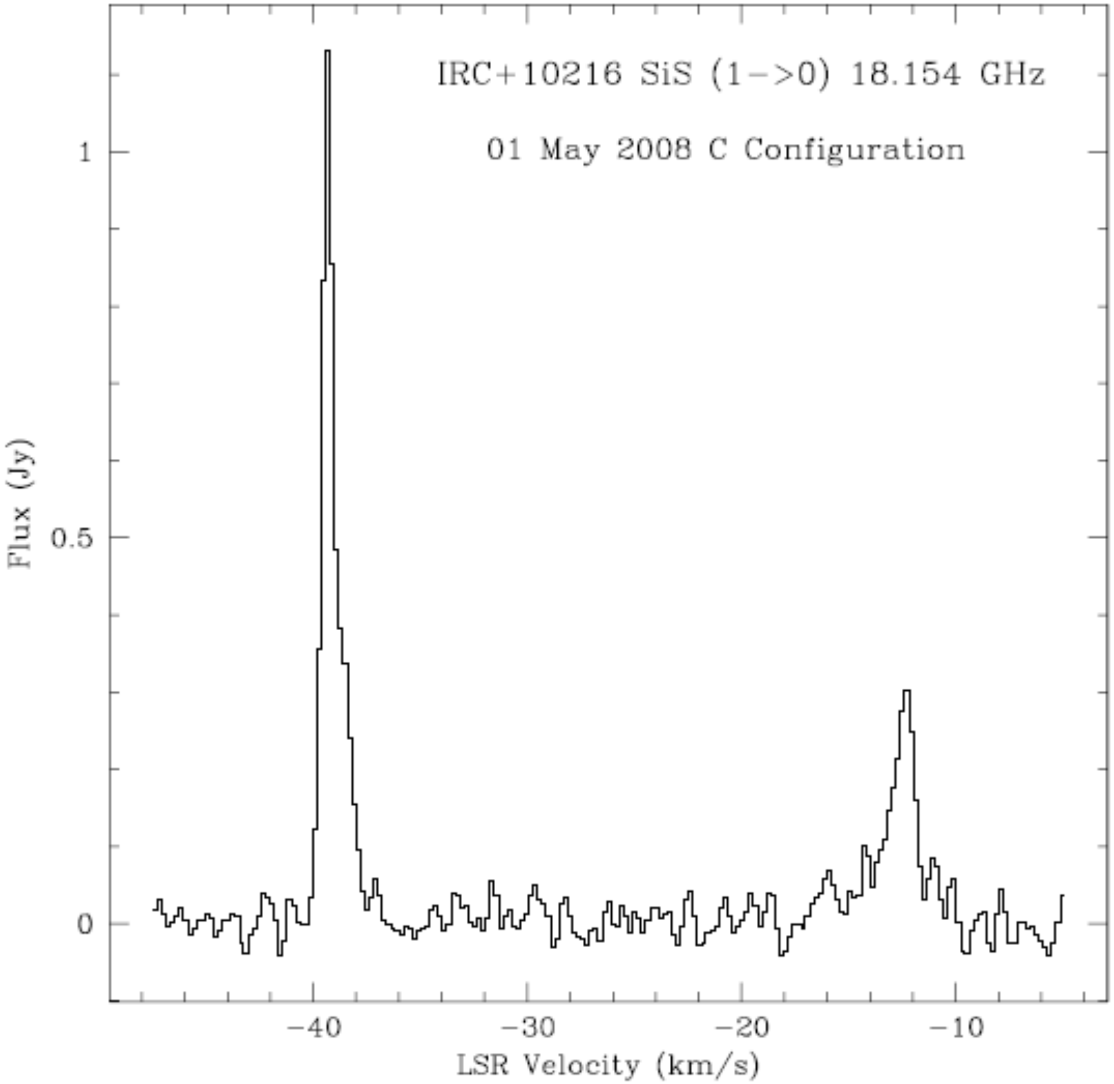

28SiO
29SiO
30SiO
T_{MB} (K)
v=1 J=5-4
v=2 J=4-3
v=2 J=4-3
v=1 J=4-3
v=2 J=2-1
v=1 J=4-3
v=3 J=5-4
v=1 J=4-3
v=1 J=2-1
v=3 J=4-3
v=1 J=1-0
v=1 J=1-0
v=3 J=2-1
v=0 J=2-1
v=0 J=2-1
v=3 J=1-0
v=0 J=1-0
v=0 J=1-0
V (km s^{-1})
V (km s^{-1})
V (km s^{-1})

SiS J=1-0, vib. exc. states, and isotopomers

```
17343.2990 1457.4630  1 2         0 2              Si-30-S, v=0-2
17426.9750  731.2215  1 1         0 1              Si-30-S, v=0-2
17488.2470 1463.5169  1 2         0 2              SiS-34, v=0-2
17510.6470    0.0000  1 0         0 0              Si-30-S, v=0-2
17564.8123    0.0000  1           0                Si-29-S-33
17572.9820  734.2693  1 1         0 1              SiS-34, v=0-2
17649.4786 1470.2185  1 2         0 2              Si-29-S, v=0-2
17657.7070    0.0000  1 0         0 0              SiS-34, v=0-2
17735.3942  737.6434  1 1         0 1              Si-29-S, v=0-2
17811.9389  739.2288  1 1         0 1              SiS-33, v=0,1
17821.3020    0.0000  1 0         0 0              Si-29-S, v=0-2
17889.8550 2217.9457  1 3         0 3              SiS, v=0-5
17898.4055   -0.0000  1 0         0 0              SiS-33, v=0,1
17978.2090 1483.7898  1 2         0 2              SiS, v=0-5
18066.5520  744.4766  1 1         0 1              SiS, v=0-5
18154.8880    0.0000  1 0         0 0              SiS, v=0-5
```

SiS J=2-1, vib. exc. states, and isotopomers

35623.7384	739.8230	2	1	1	1	SiS-33, v=0,1
35642.4659	0.5945	2	0	1	0	Si-29-S, v=0-2
35779.5670	2218.5424	2	3	1	3	SiS, v=0-5
34976.3590	1464.1002	2	2	1	2	SiS-34, v=0-2
35021.1560	0.5841	2	0	1	0	Si-30-S, v=0-2
35129.4904	0.5859	2		1		Si-29-S-33
35145.8260	734.8555	2	1	1	1	SiS-34, v=0-2
35298.8188	1470.8072	2	2	1	2	Si-29-S, v=0-2
35315.2810	0.5890	2	0	1	0	SiS-34, v=0-2
35470.6502	738.2350	2	1	1	1	Si-29-S, v=0-2
35796.6718	0.5970	2	0	1	0	SiS-33, v=0,1
35956.2740	1484.3895	2	2	1	2	SiS, v=0-5
36132.9590	745.0792	2	1	1	1	SiS, v=0-5
36309.6270	0.6056	2	0	1	0	SiS, v=0-5
34686.4670	1458.0416	2	2	1	2	Si-30-S, v=0-2
34853.8160	731.8028	2	1	1	1	Si-30-S, v=0-2

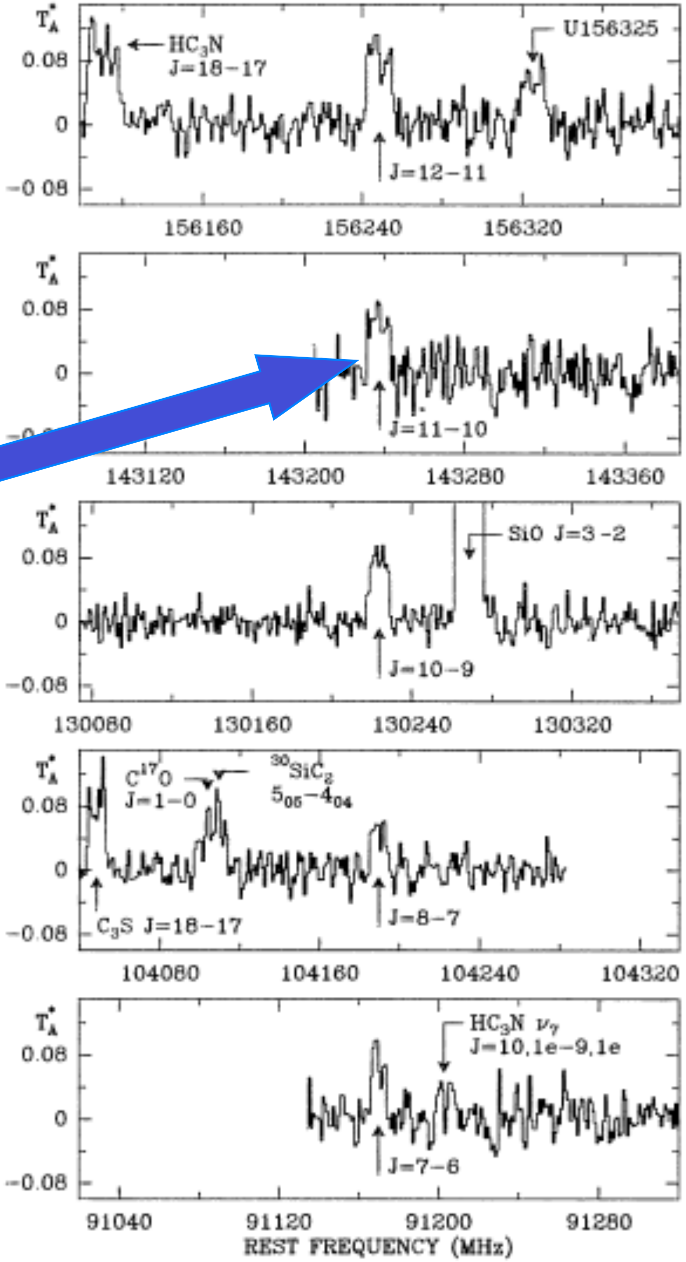


Claussen et al. – EVLA

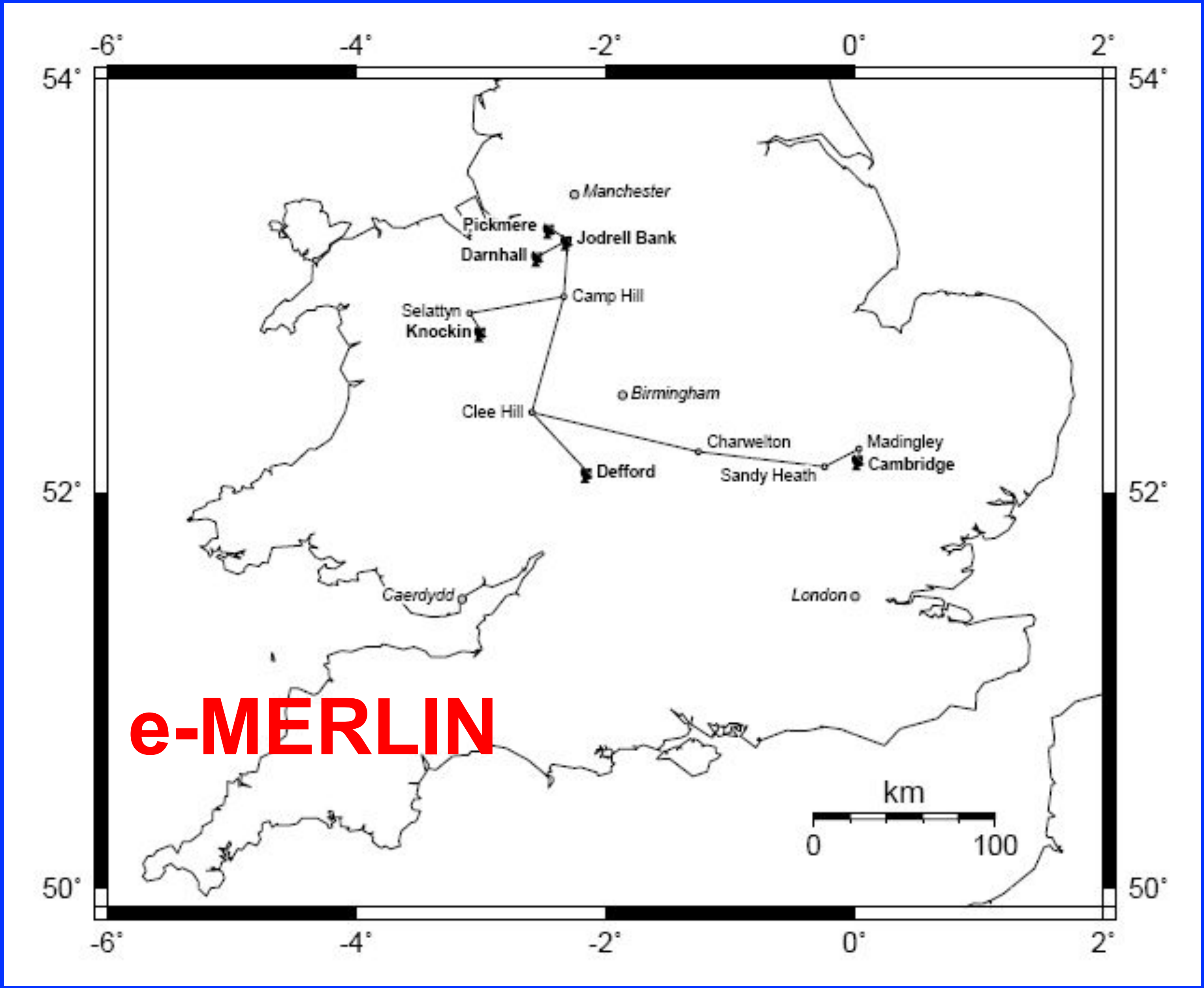
Metals in IRC+10216: detection of NaCl, AlCl, and KCl, and tentative detection of AlF

J. Cernicharo[1,2] and M. Guélin[1]

1987

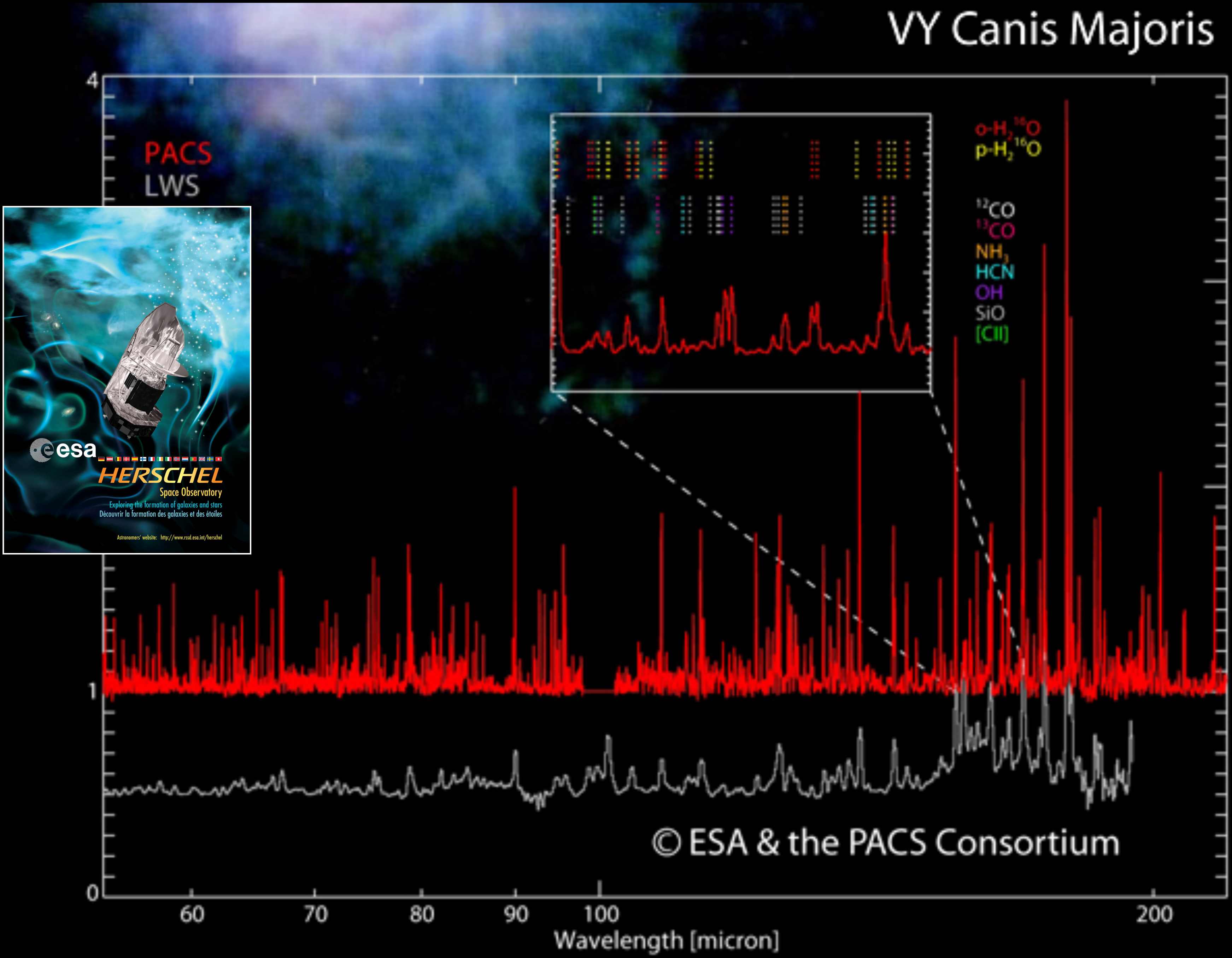


High-*J* lines, lower *J* lines are in EVLA range



Longest baseline: 217 km (= 6 x VLA)

VY Canis Majoris



Their wide bandwidth and advanced spectroscopic capability will make allow ALMA and the EVLA to make important contributions to circumsteller astrochemistry

Their adequate (EVLA) and superb (ALMA) brightness sensitivities even at the highest angular resolution will allow

- determination of the diameters and molecular atmospheres of many nearby AGB stars
- unique studies of element depletion in the dust forming process

Due to the zooming capability, if will be possible to image all the different physical and chemical regimes of envelopes

Circumstellar maser surveys with the EVLA

Deguchi and his collaborators used (IRAS, and later MSX) color criteria to search (not only) in our galaxy for

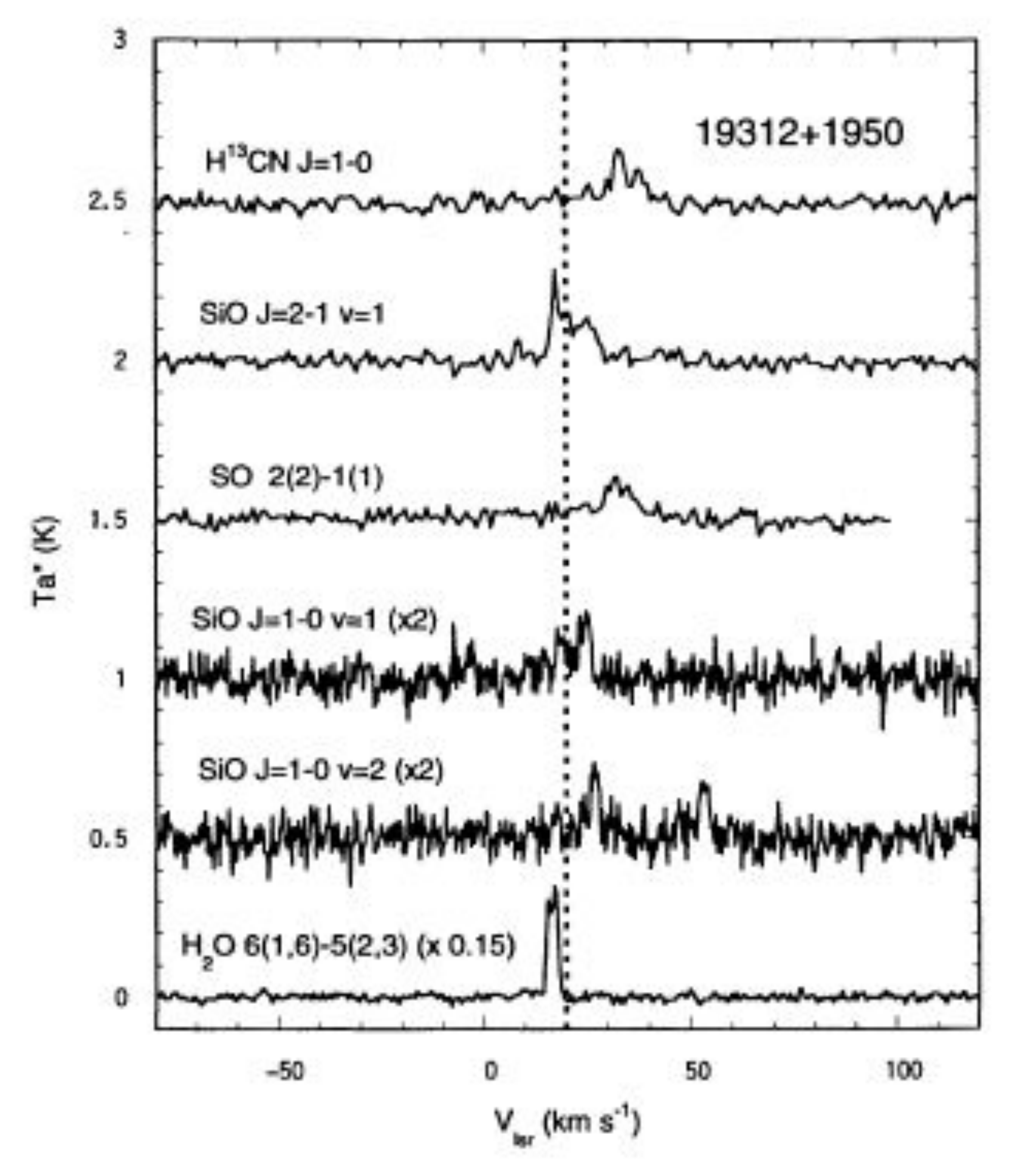
- (mostly the) 43 GHz J=1-0, v=1 and 2 SiO masers in Mira stars; also 22.2 GHz H2O line
- using the Nobeyama 45 m telescope (40″ FWHM).
  Typical sensitivity ~0.1–0.2 Jy@Δv = 0.3 km/s

They systematically searched in:

- the Galactic bulge
- the Inner and Outer Galactic disk
- toward and near the Galactic center
- North Galactic cap
- cold IRAS sources
- globular clusters

… and found many hundreds of SiO (and H_2O) masers

Serendipity strikes! IRAS 19312+1950



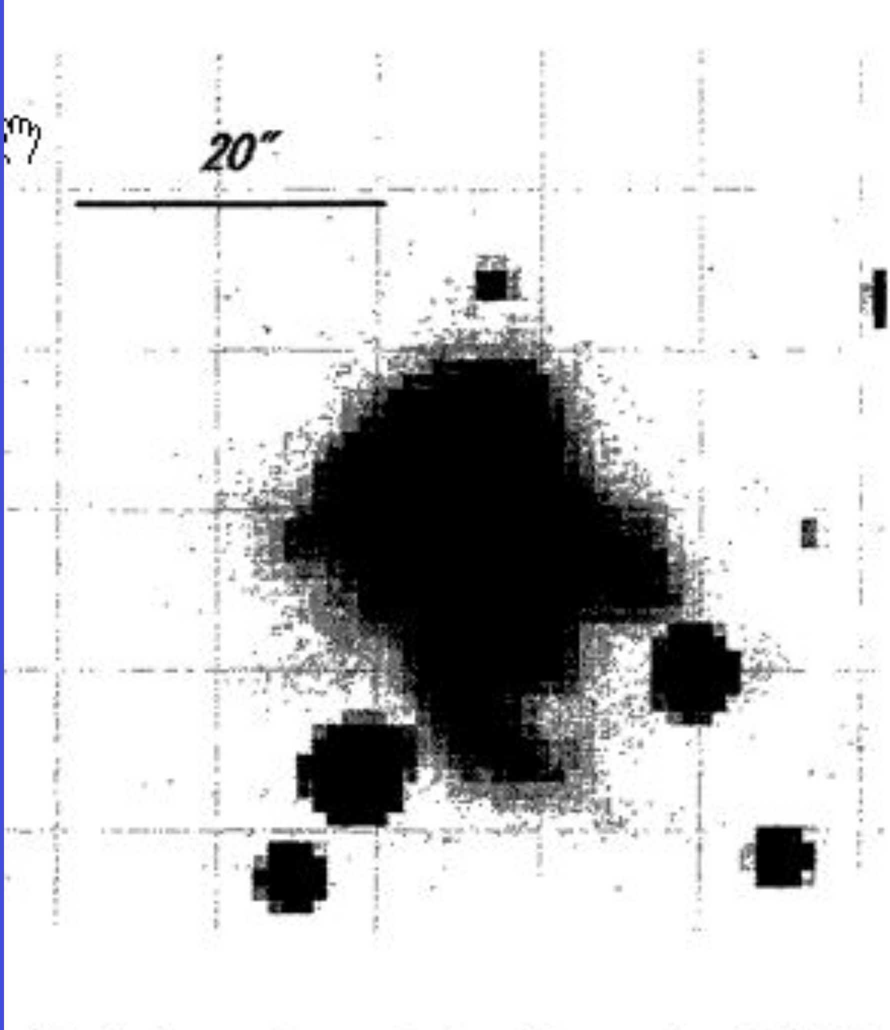
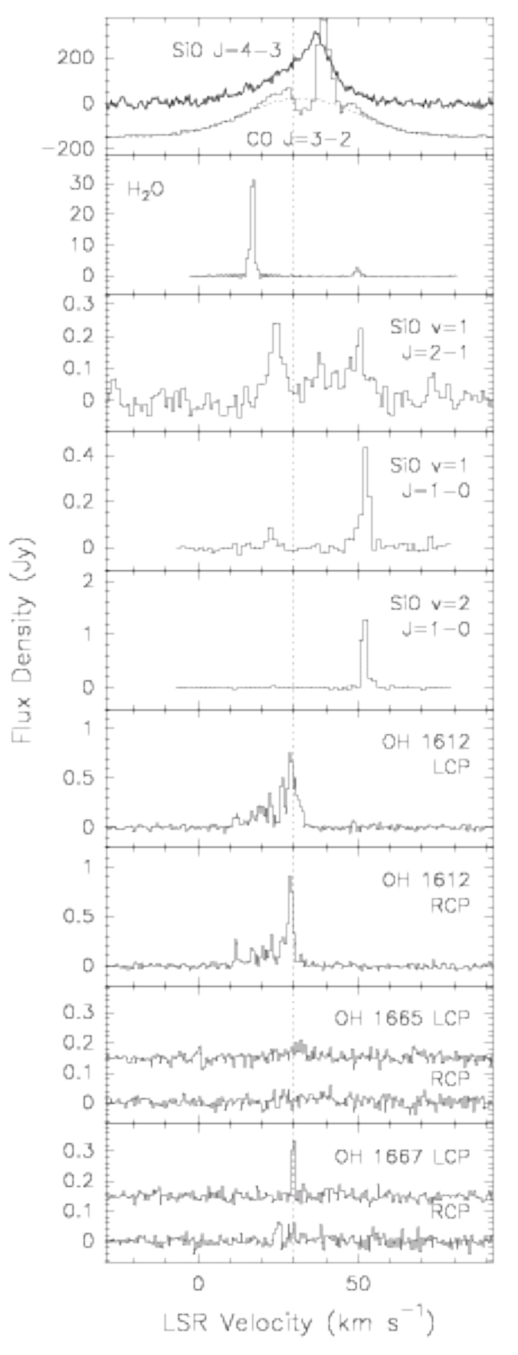


Fig. 2. Composite near-infrared image from 2MASS

Nakashima & Deguchi 2000, 2004, 2005



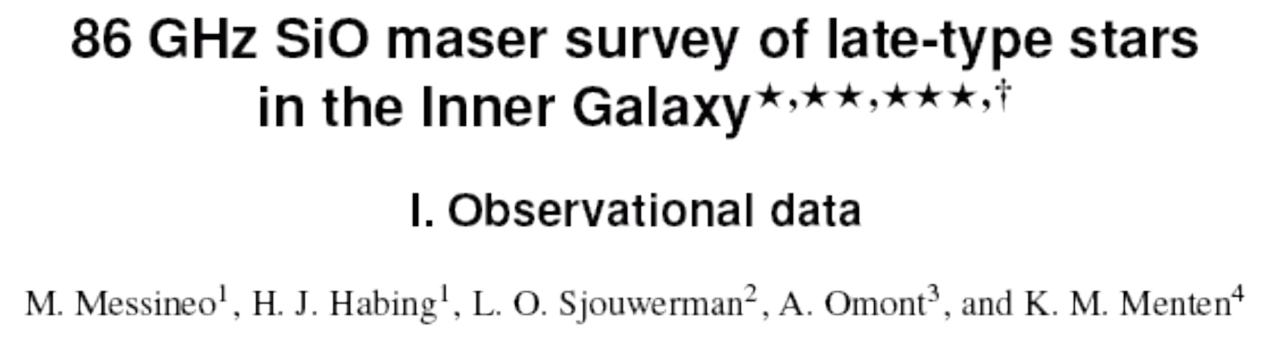
IRAS 19312+1950

Checked more than 1000 SiO spectra published by Deguchi et al. The *only* other SiO source with $\Delta v > 30$ km/s was W43A

Bipolar SiO maser emission is extremely interesting as it proves that the transition to bipolarity happens already near the stellar photosphere!

APEX+VLA: Menten et al. 2010

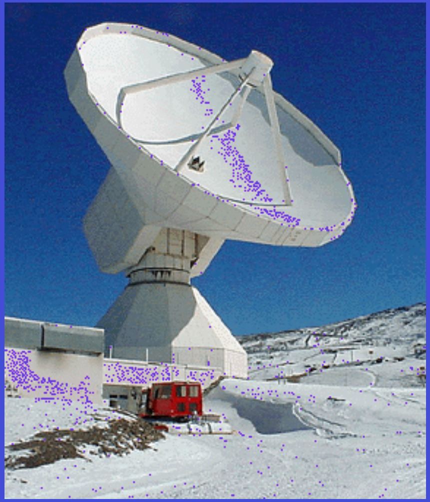
Other extensive stellar surveys for OH 1612 MHz line with VLA+ATCA by H. Habing + his students (M. Sevenster) + collaborators → > 1000 OH/IR stars



86 GHz SiO maser survey of late-type stars in the Inner Galaxy⋆,⋆⋆,⋆⋆⋆,†

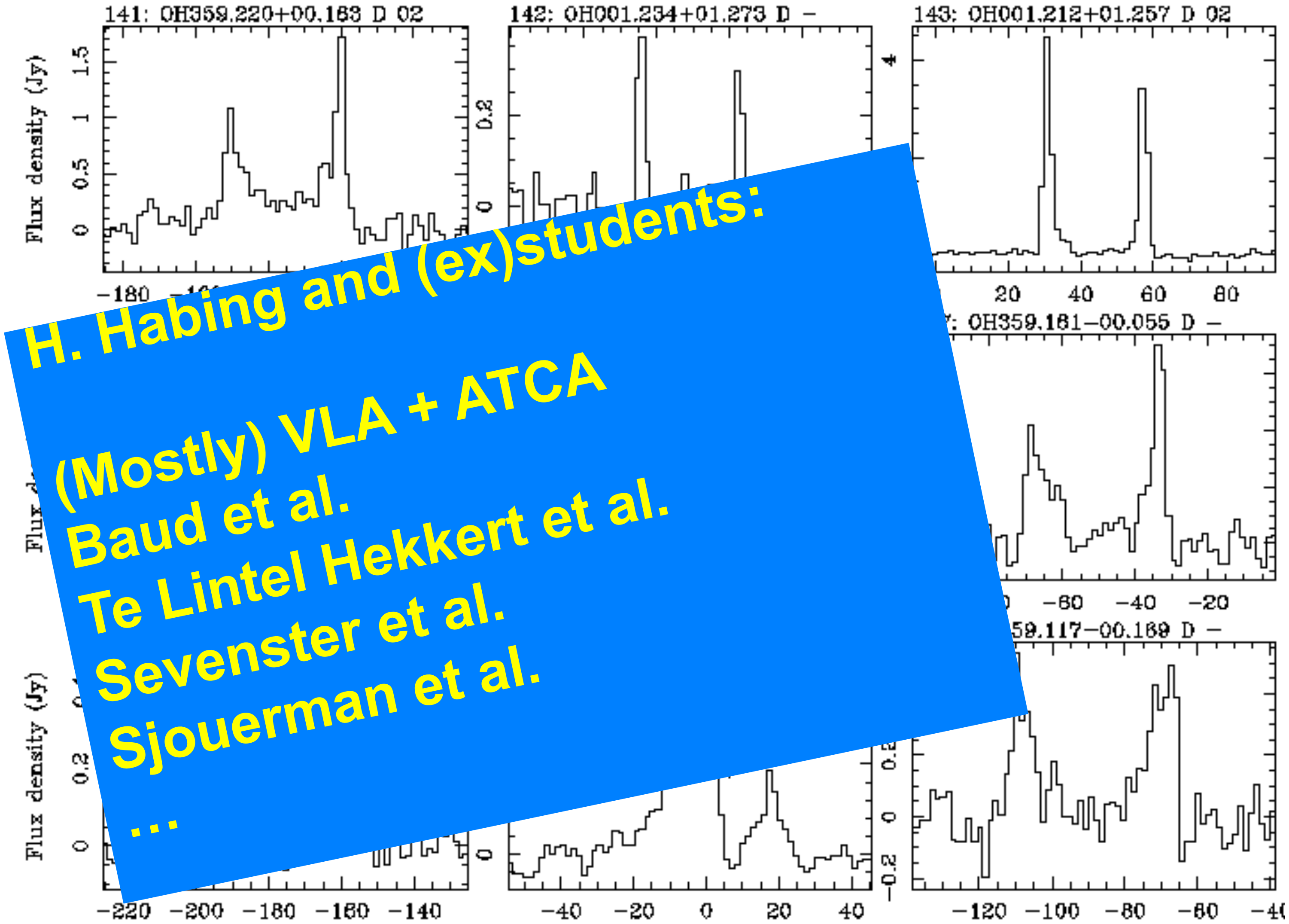
I. Observational data

M. Messineo[1], H. J. Habing[1], L. O. Sjouwerman[2], A. Omont[3], and K. M. Menten[4]



- Searched for v=1, J=2-1 SiO line toward stars in -4° < l < 30°
- based on ISOGAL and MSX colors
- Detect 271 out of 441

OH 1612 MHz “satellite” line



H. Habing and (ex)students:

(Mostly) VLA + ATCA

Baud et al.

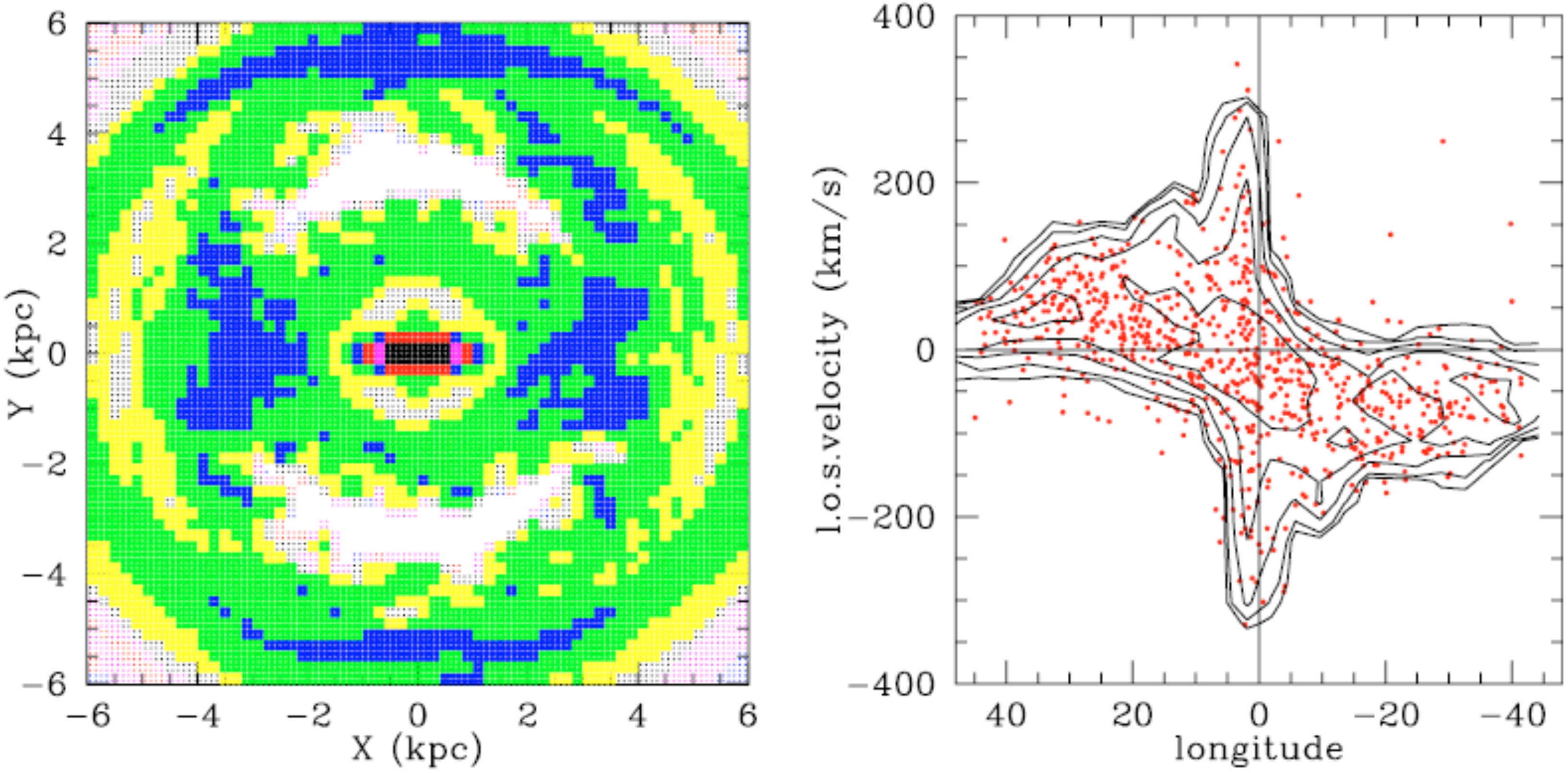
Te Lintel Hekkert et al.

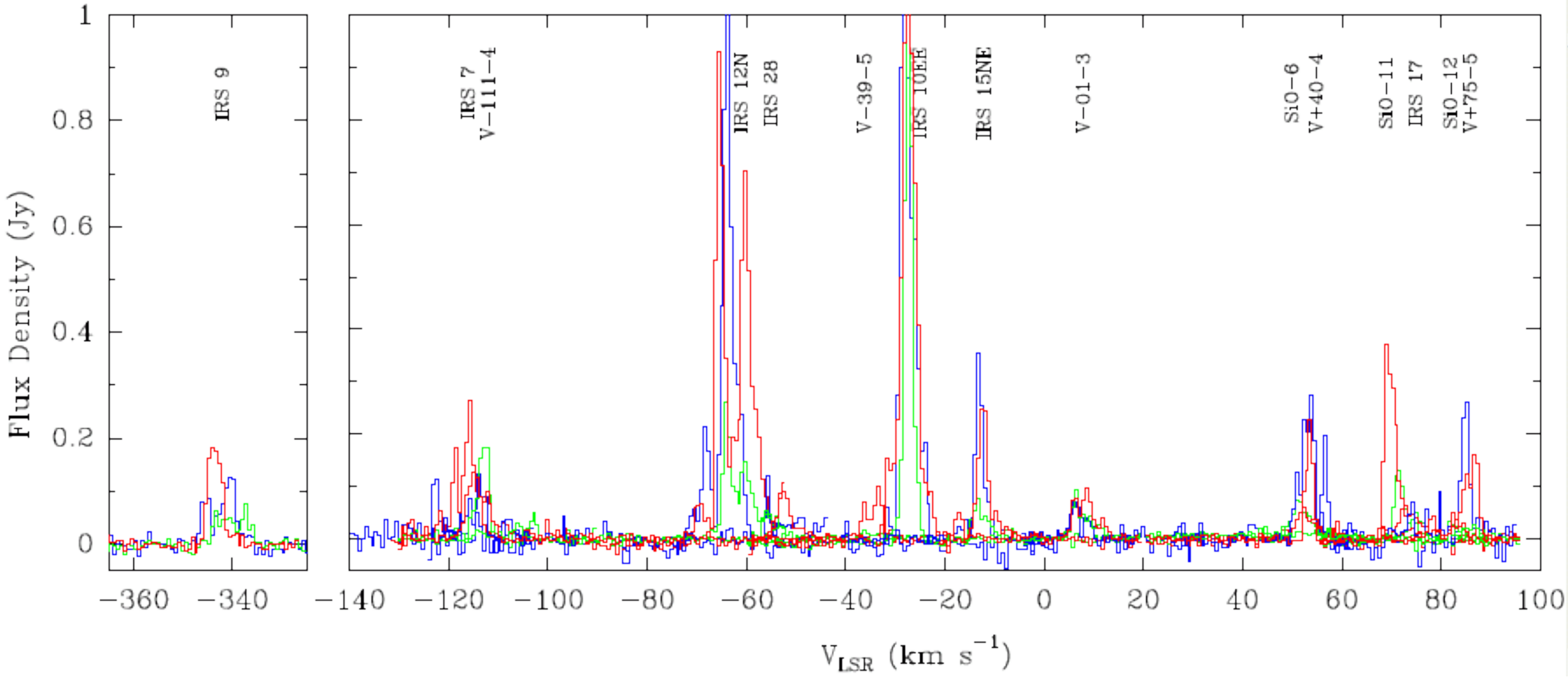
Sevenster et al.

Sjouerman et al.

…

H. J. Habing et al.: Maser stars and a rotating Galactic bar

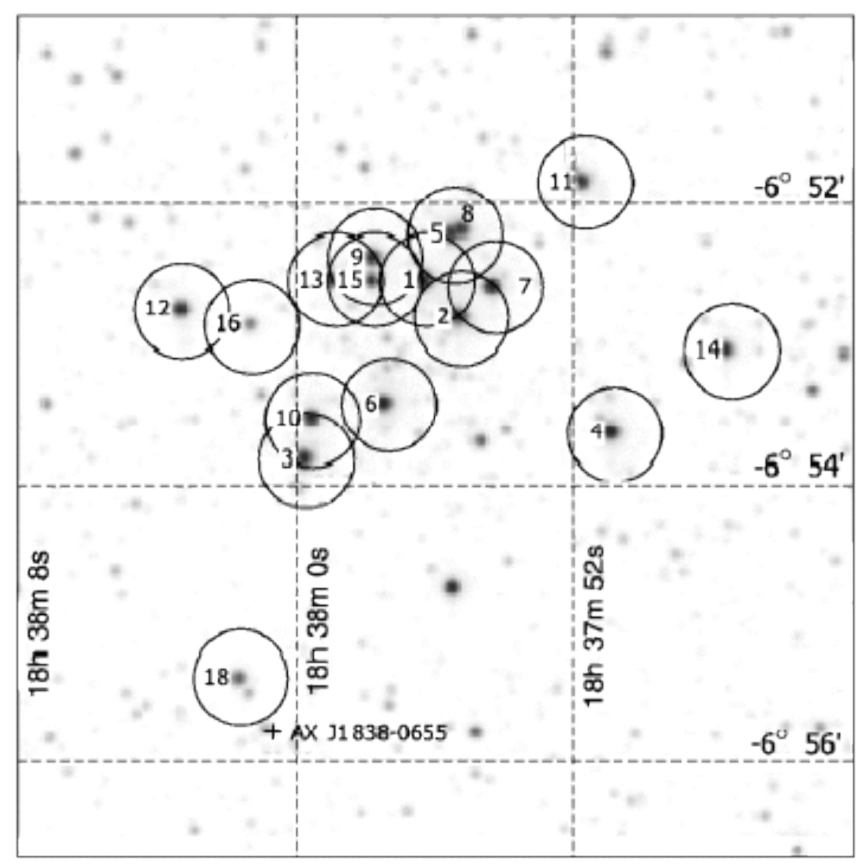


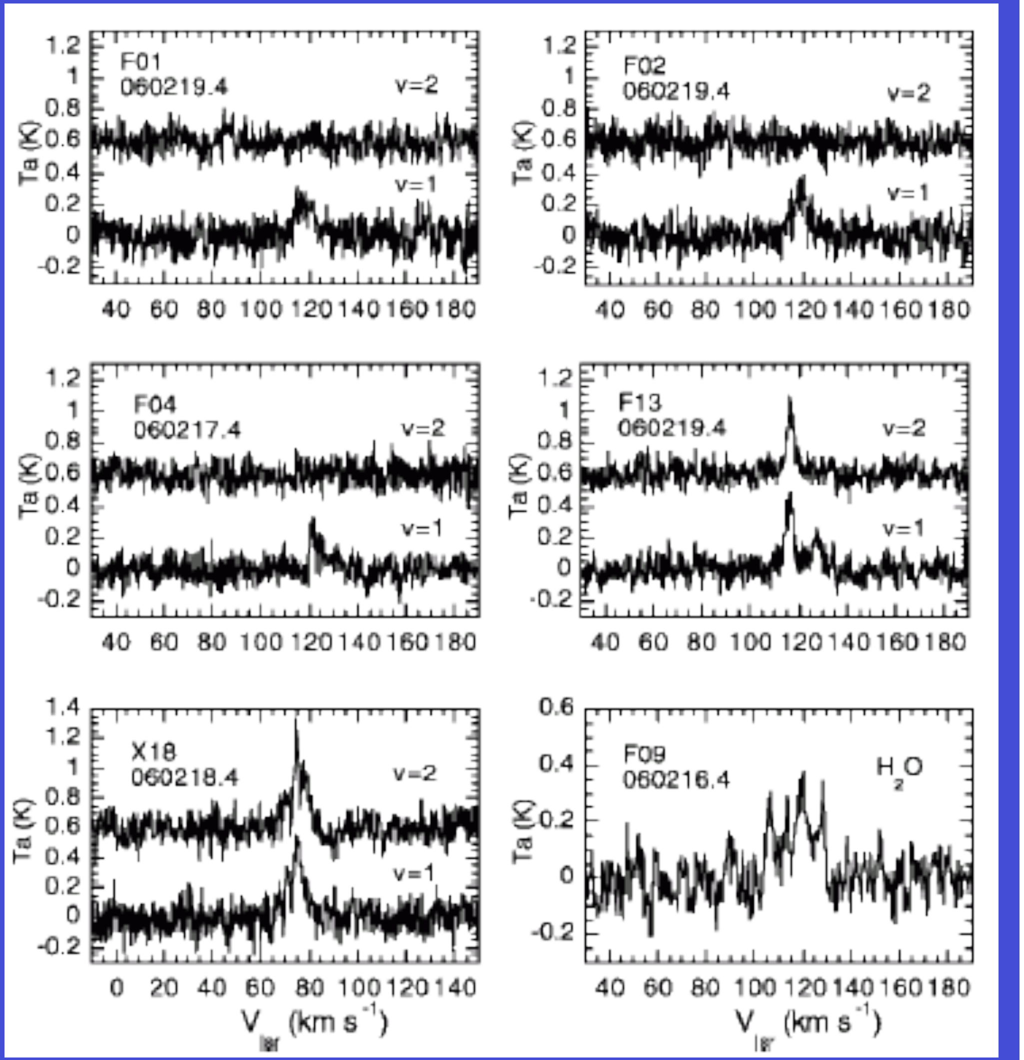


SiO maser emission from stars within the central parsec of our Galaxy (Reid et al. 2007)

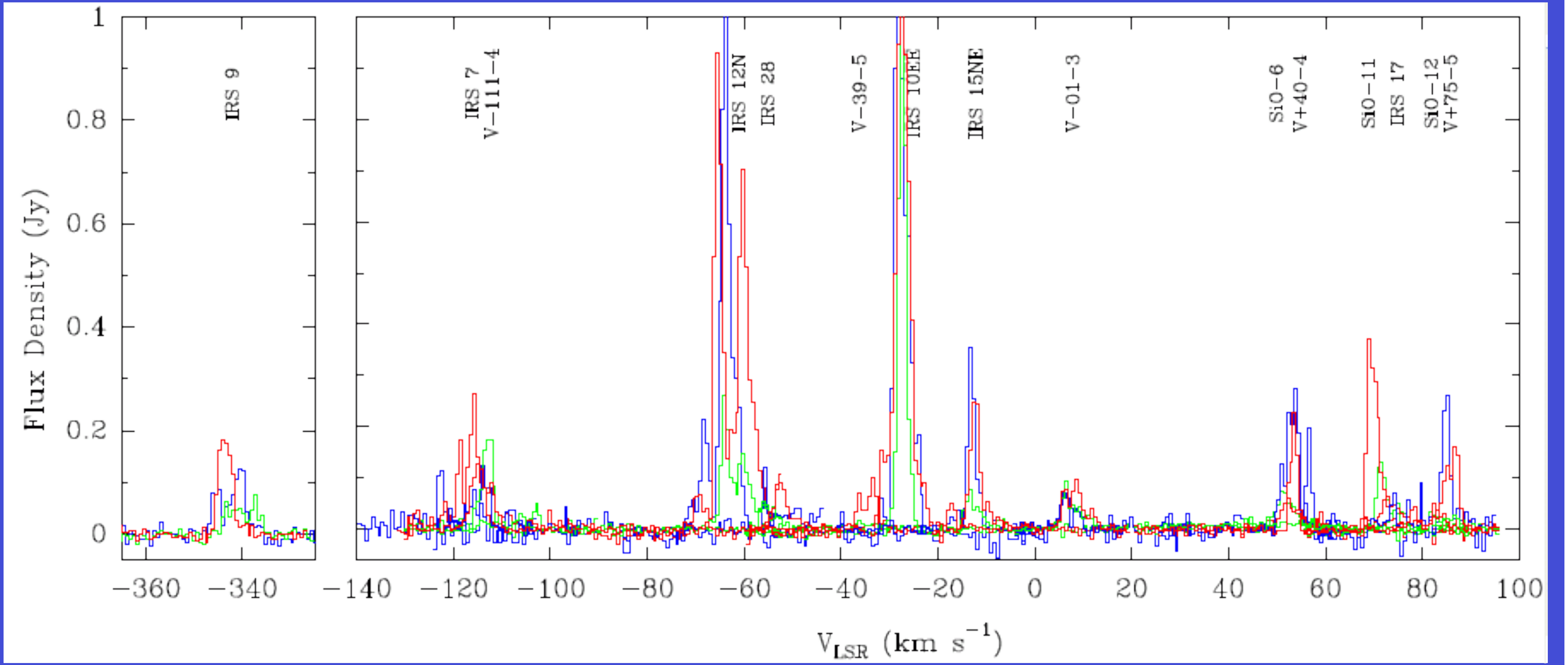
“Scutum Cluster” (Bica 122)

- **Figer et al. (2006) detect 14 RSGs within 8 pc**





Nakashima & Deguchi (2006) find SiO masers in 4 of them



SiO maser emission from stars within the central parsec of our Galaxy (Reid et al. 2007)

With the EVLA it would be possible to detect SiO (and other) masers anywhere in the Galaxy and even in the Magellanic Clouds with very little observing time

Provide source lists for VLBA and VERA parallax studies