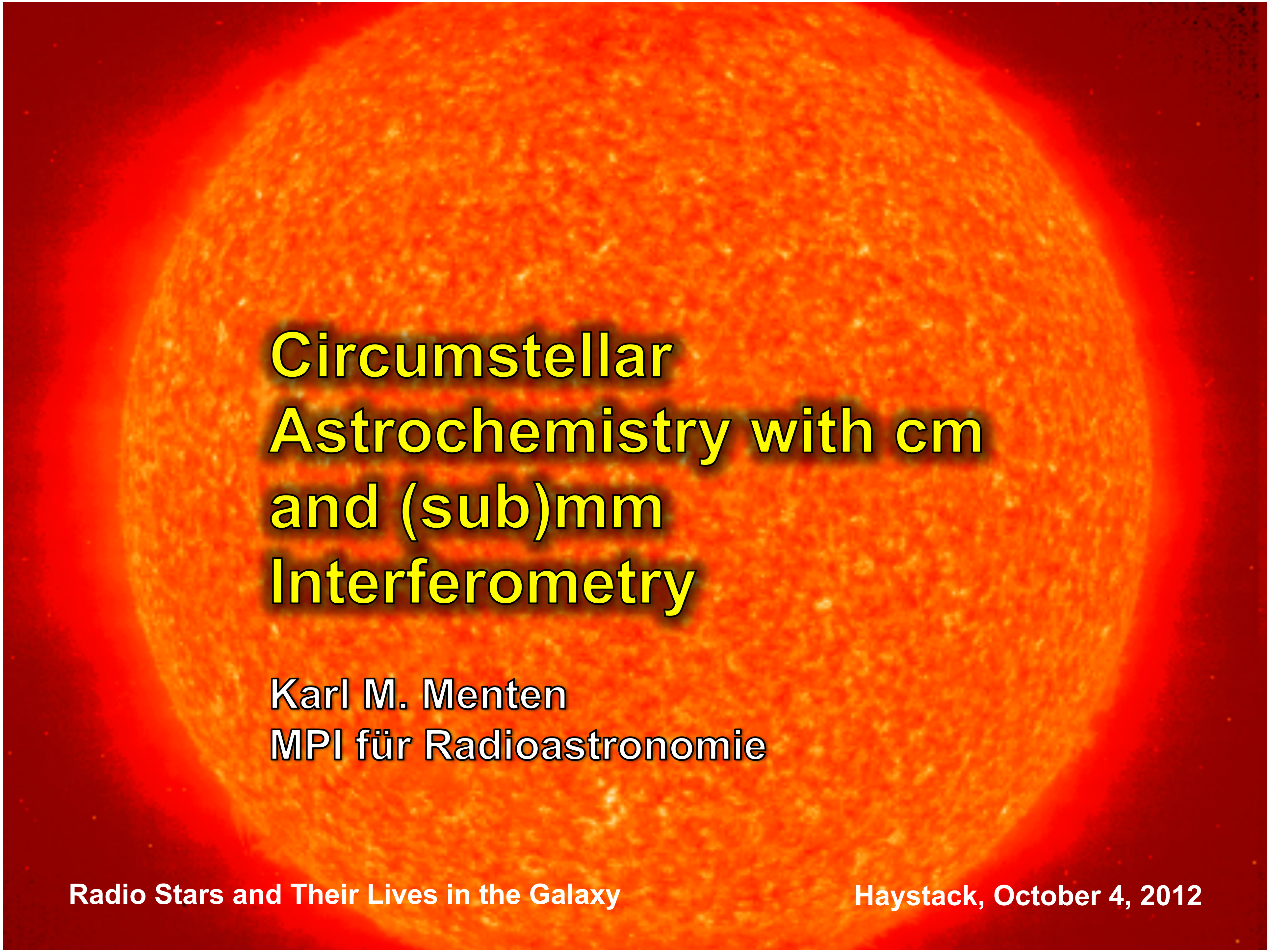


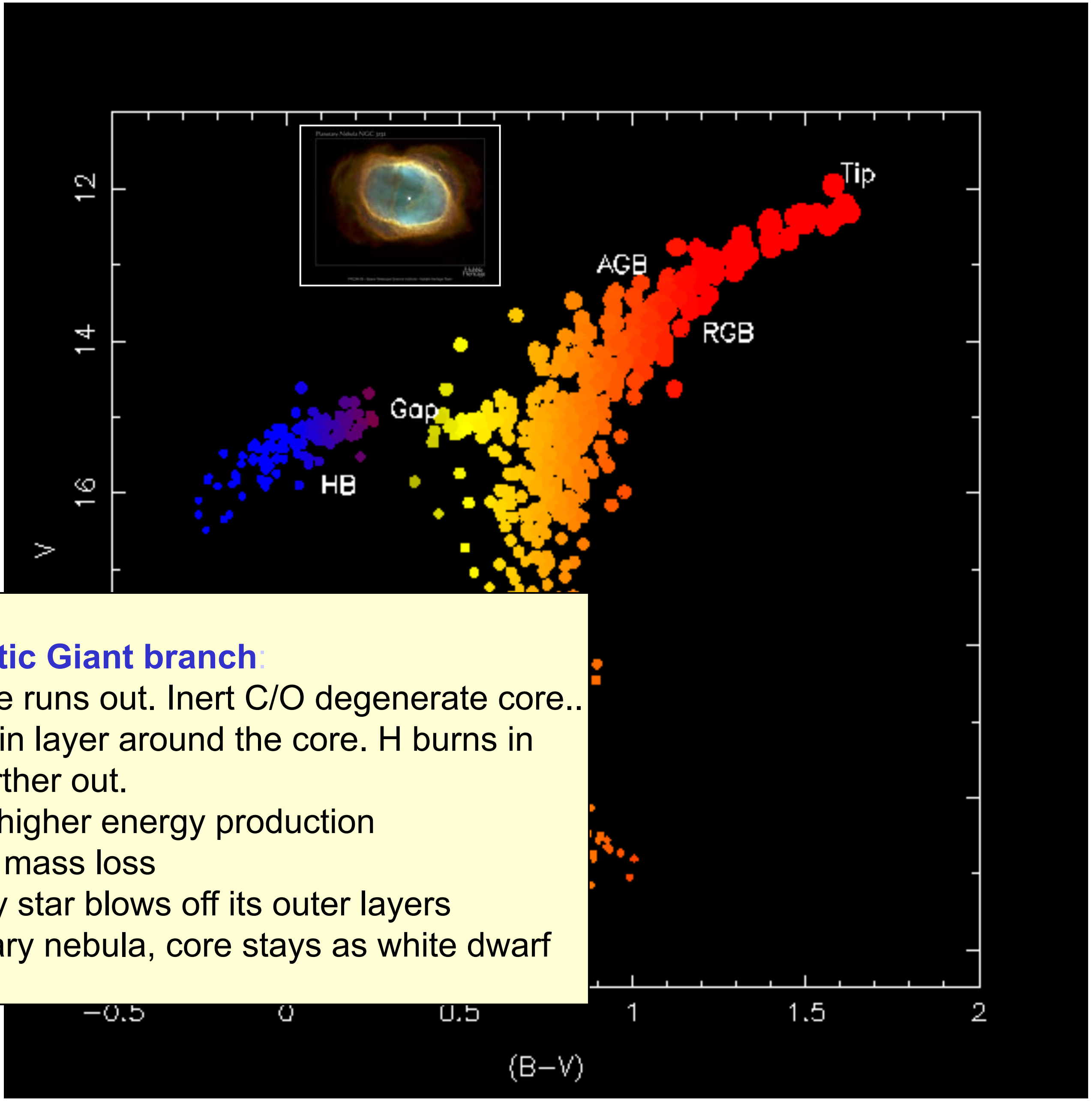
Circumstellar Astrochemistry with cm and (sub)mm Interferometry

Karl M. Menten
MPI für Radioastronomie

Radio Stars and Their Lives in the Galaxy

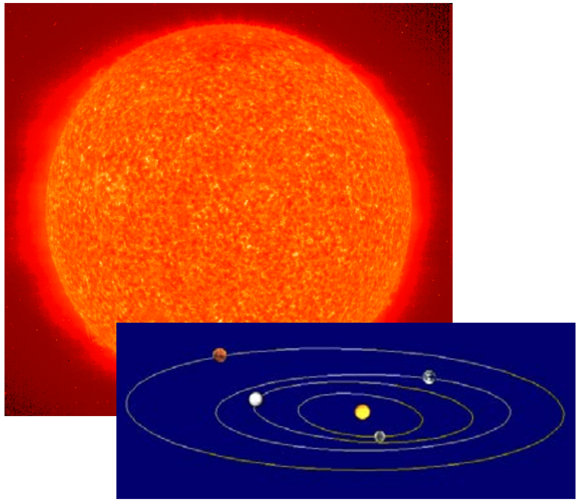
Haystack, October 4, 2012

Evolution of a solar mass star



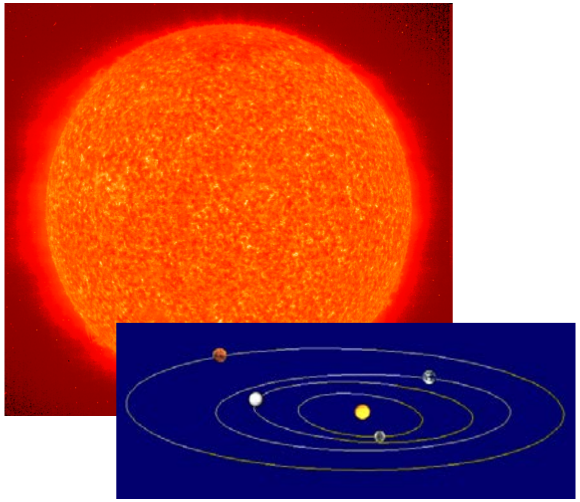
Asymptotic Giant branch:
Central He runs out. Inert C/O degenerate core..
He burns in layer around the core. H burns in
a layer further out.
→ much higher energy production
→ heavy mass loss
Eventually star blows off its outer layers
→ planetary nebula, core stays as white dwarf

AGB (= Red Giant) Stars – Basic Facts



- Mass ~0.8–8 $M_\odot$
- 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
  - Will finish it’s life as a white dwarf and planetary nebula
- Stars pulsate with periods of 100s of days (“LPVs”)
- Luminosities many 1000s $L_\odot$
  - Kinematic probes of Galactic structure, Inner Galaxy, Bar
    - Even 6 D (maser astrometry → distances motions)

AGB (= Red Giant) Stars – Basic Facts



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  nd of it' s life cycle
  ter envelope
  O
  ula
)
- Lu
  - Kinematic probe y, Bar
    - Even 6 D (maser astrometry → d

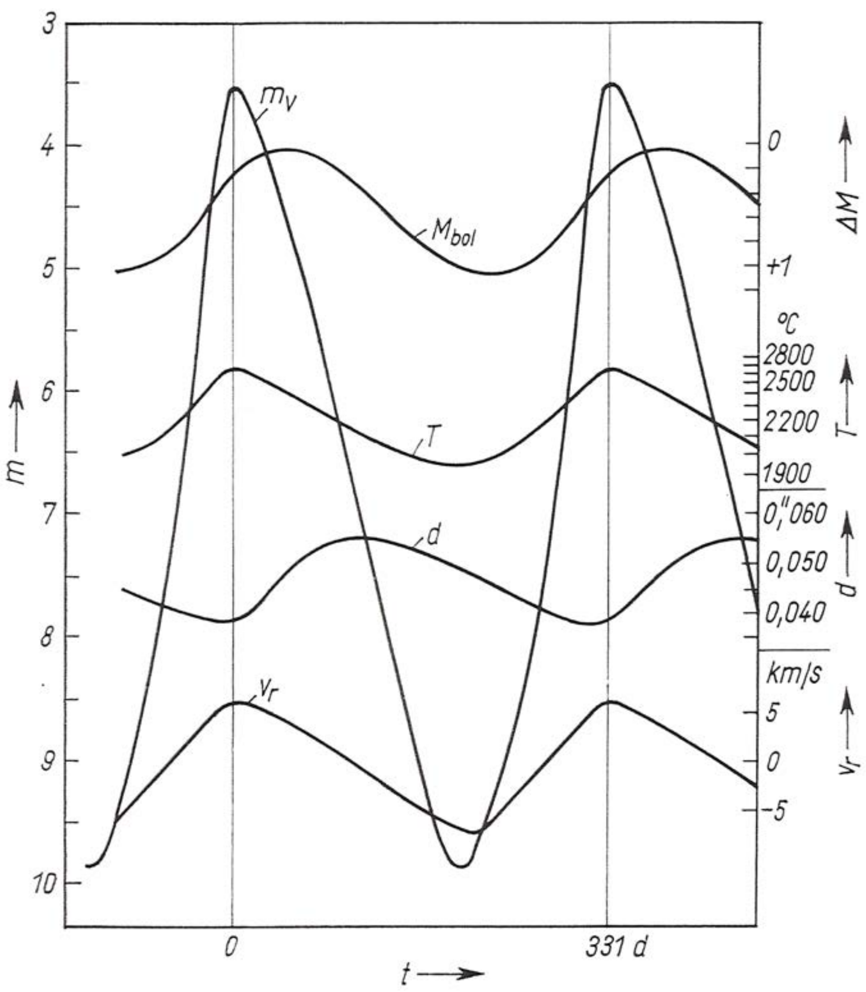
Red Supergiants:

- ~10 x more massive than AGBs
- ~10 x larger
- ~10–100 x higher mass-loss rates
- (most) much more distant
- young (~tens of millions y)

Talks by S. Deguchi, Y. K. Choi, B. Zhang

AGB Red Giant stars – Observational facts

- Varying visual magnitude
  - Magnitude can change by 6 magnitudes
  - Brightness can vary by a factor of 250
  - Changes in spectral type
- Changes in magnitude are the result of the pulsation of the star
  - Combination of temperature change, size change, and dust formation at temperature minimum



Why is it interesting to study AGB stars?

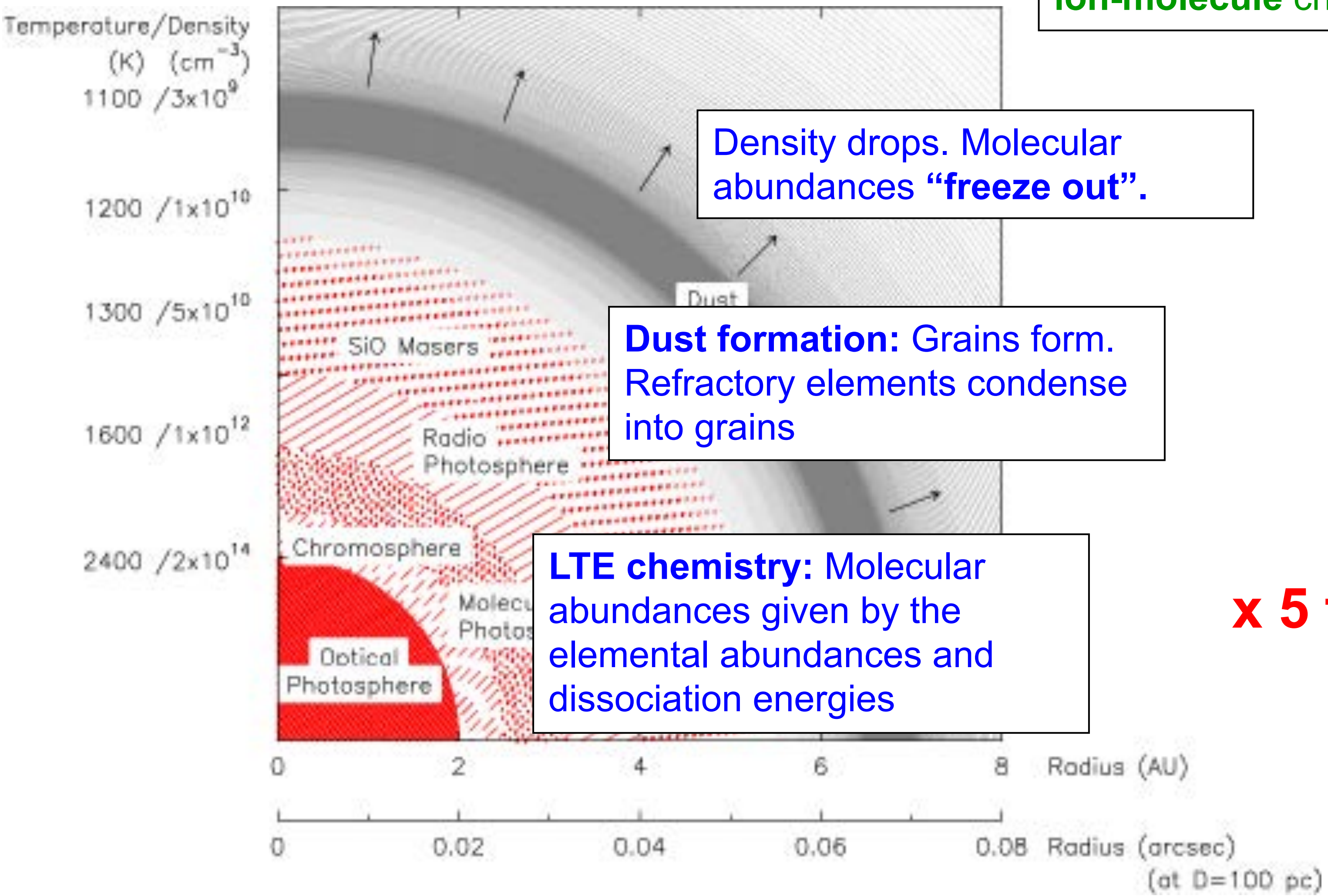
- stellar evolution
- mass return to the interstellar medium (> 50%???)
- heavy element enrichment CNO+…
  - complex molecules, fullerenes, PAHs
- dust production
- precursors to (P)PNe

Talk by R Sahai

  - or SNe (high mass only)
- (relatively) simple geometry (spherically symmetric to 1st order) makes meaningful modeling (e.g. of chemistry) possibe

Molecules in the dense circumstellar envelopes of red giant stars

Much further out (> 1000s of AU): Interstellar UV field drives **ion-molecule** chemistry



Density drops. Molecular abundances **“freeze out”.**

Dust formation: Grains form. Refractory elements condense into grains

LTE chemistry: Molecular abundances given by the elemental abundances and dissociation energies

x 5 for RSG

Reid & Menten 1997

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

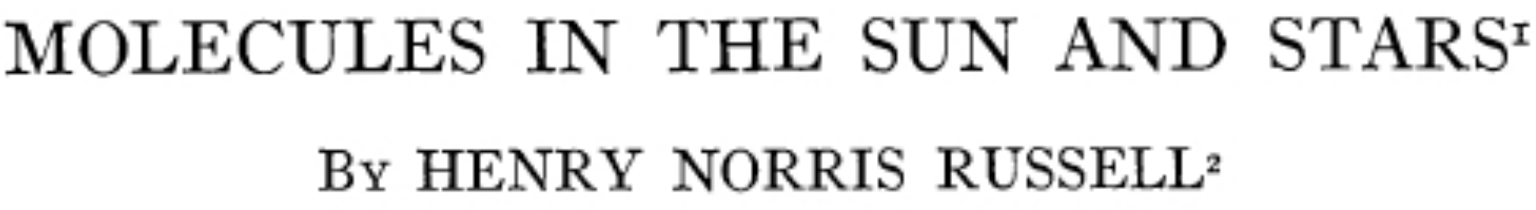
P_{M1M2} partial pressure of resulting molecule

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

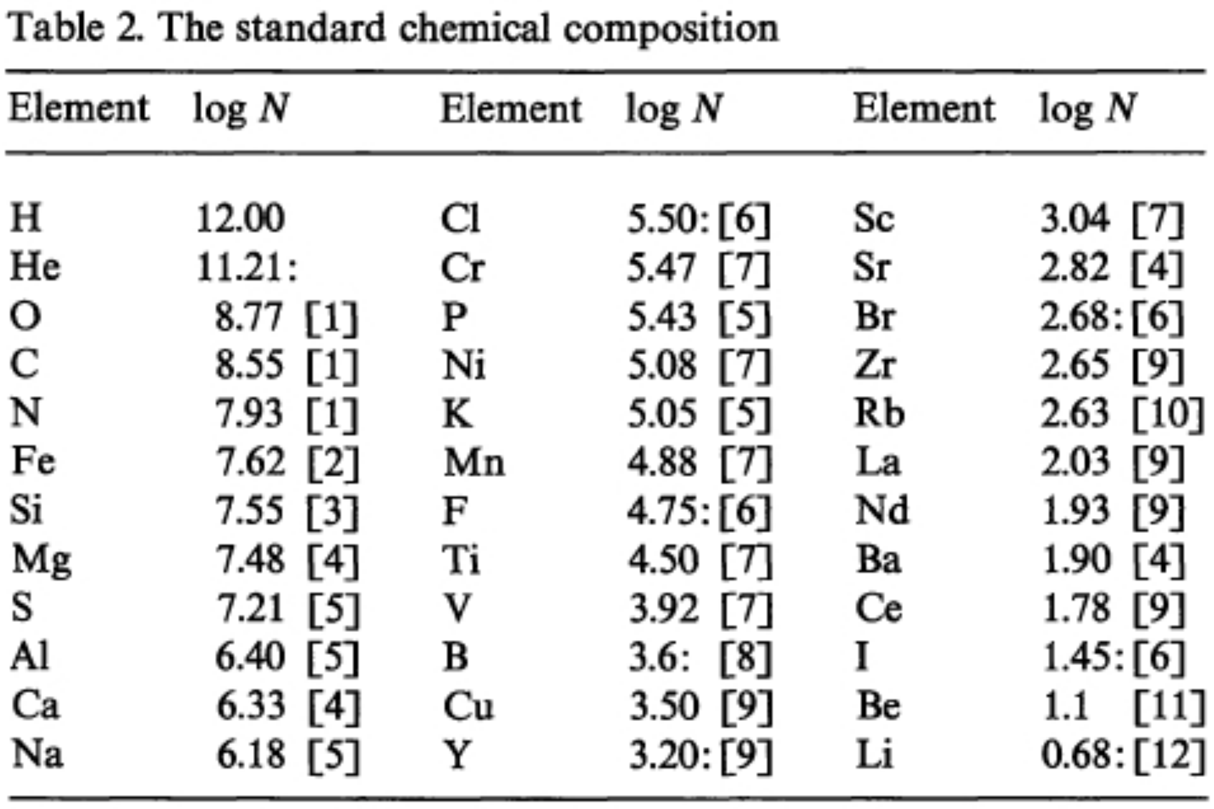
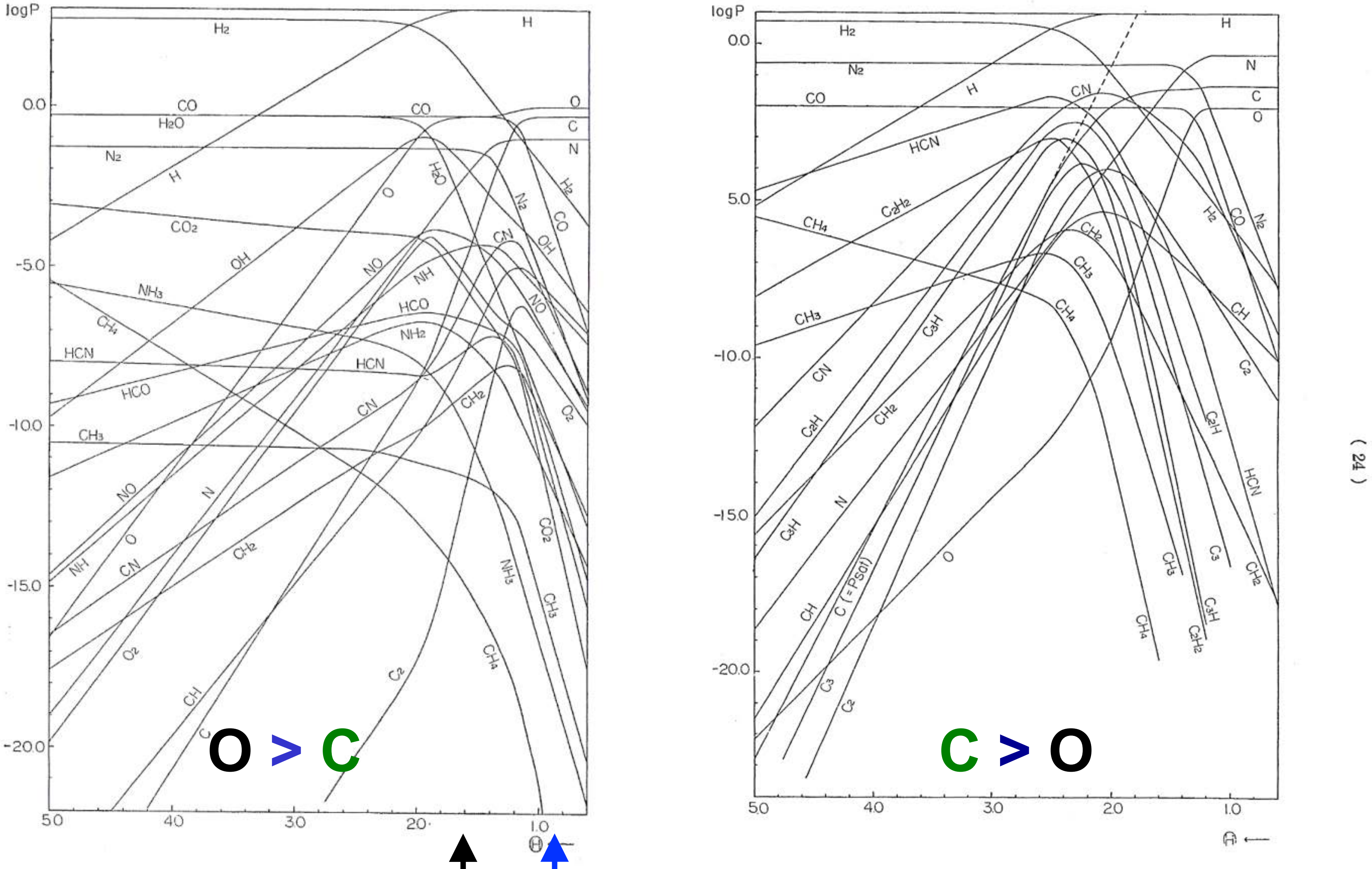


Table 2. The standard chemical composition

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]



O > C

C > O

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] Throughout most of AGB phase

→ CO and H_2O dominant molecules

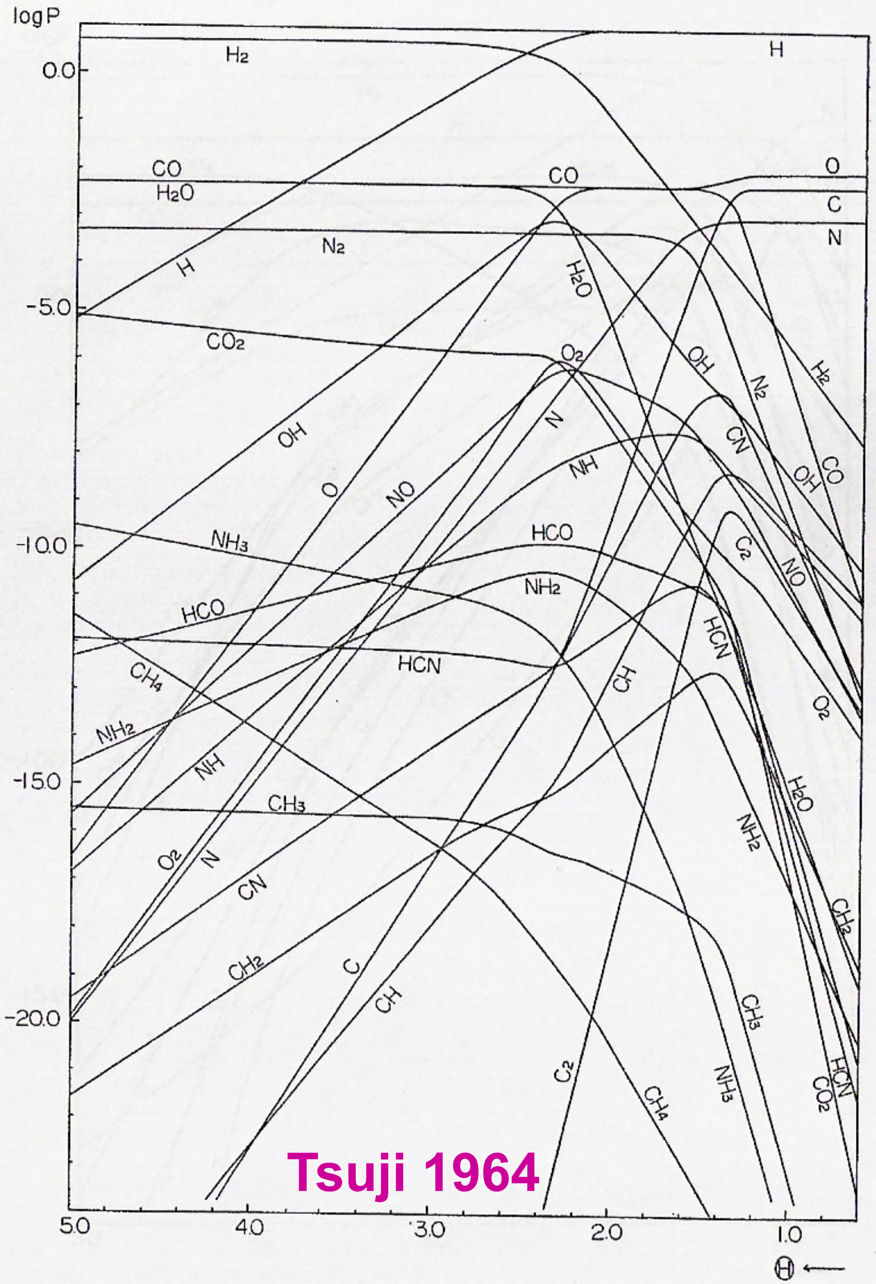
→ most oft the carbon goes into CO

[C]>[O] Final phase: C from core convects to surface

→ CO dominant molecule

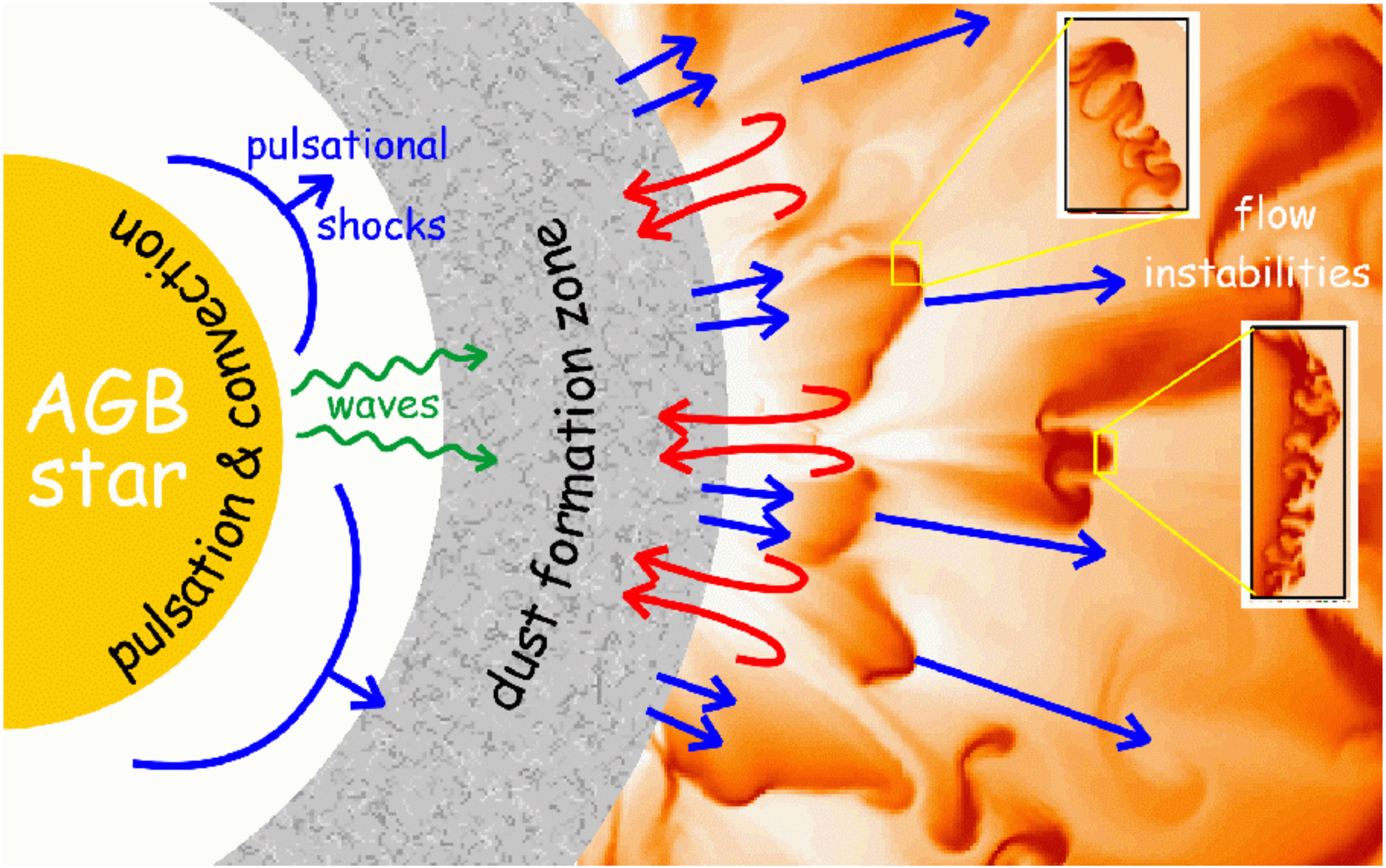
→ lots of C available to drive rich hydrocarbon chemistry

→ IRC+10216

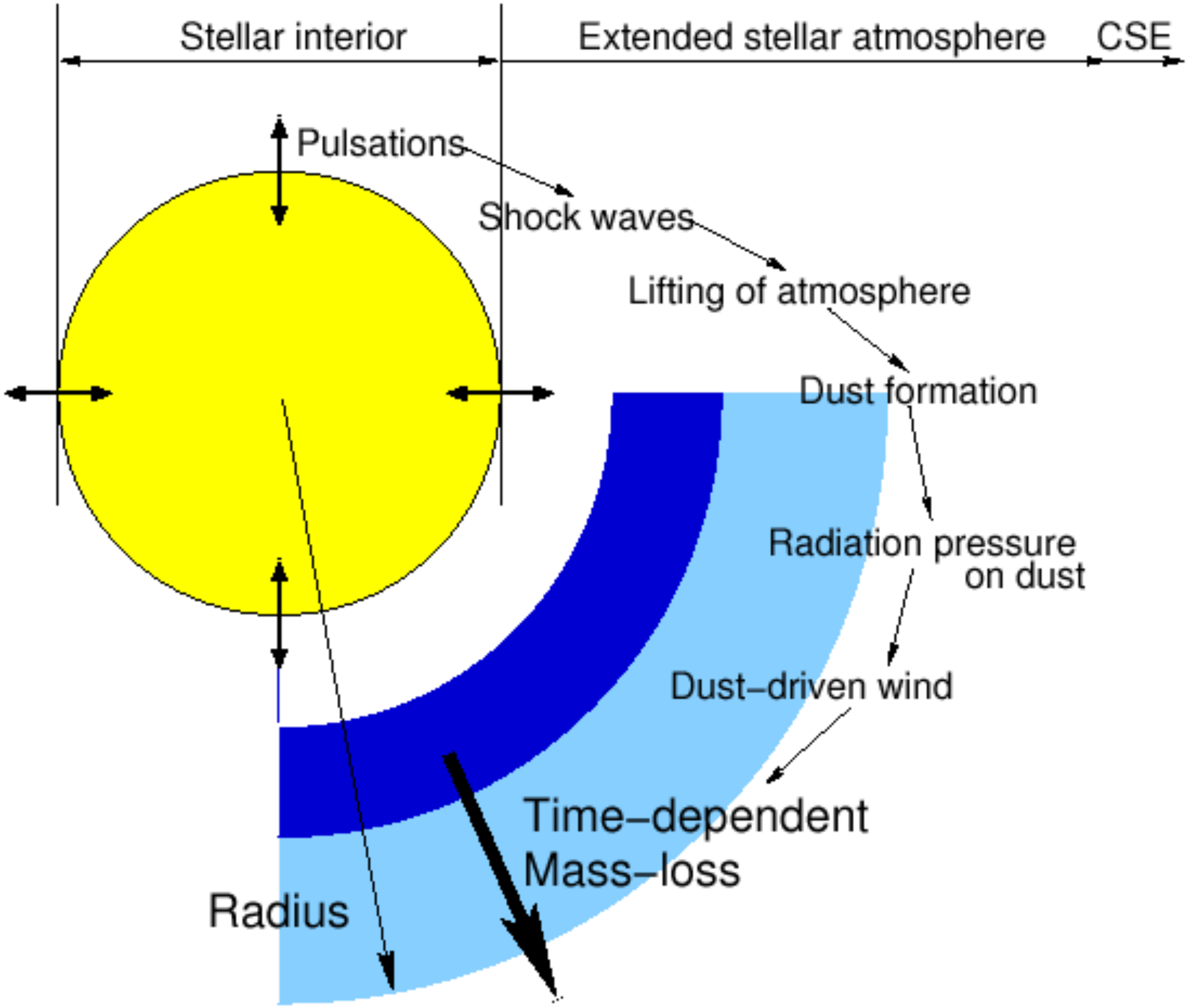


Tsuji 1964

Fig. 3. Most dominant molecular feature in oxygen rich stars of super-giant 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 super-giant stars or in upper atmospheres of the giant stars of F~M spectral types.

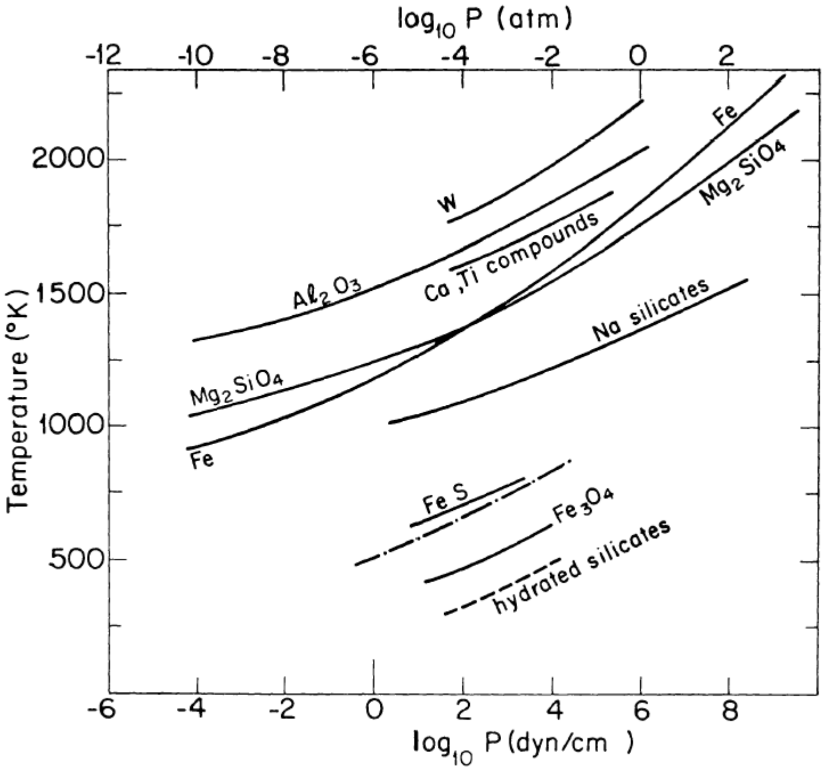


P. Woitke (2006)

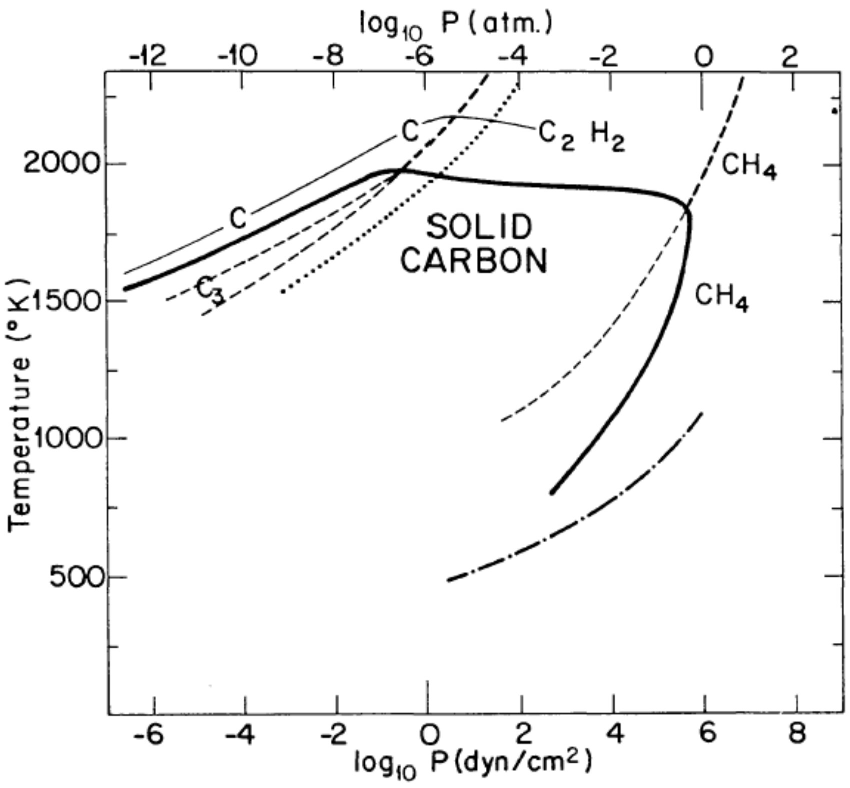


- Pulsation creates a shocked atmosphere
  - Shockwaves liberate outer atmosphere resulting in high mass loss rates and wind: $dM/dt = 10^{-7}$ (RGB) to about 10^{-4} (AGB) solar masses/year

Condensation of substance X depends on *T* and *p* (i.e. on radial distance from star)



Oxygen-rich star
(solar composition)



Carbon-rich star

Equilibrium chemistry produces molecules depending on

- temperature
- chemical natu

→ Parent molec

Abundances “fr ormation

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

- Further chemical processing by (interstellar) UV field
  drives a rich ion molecule chemistry
- (except for densest envelopes) much l ion than
  in dense i
- “norm s star
  fo

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

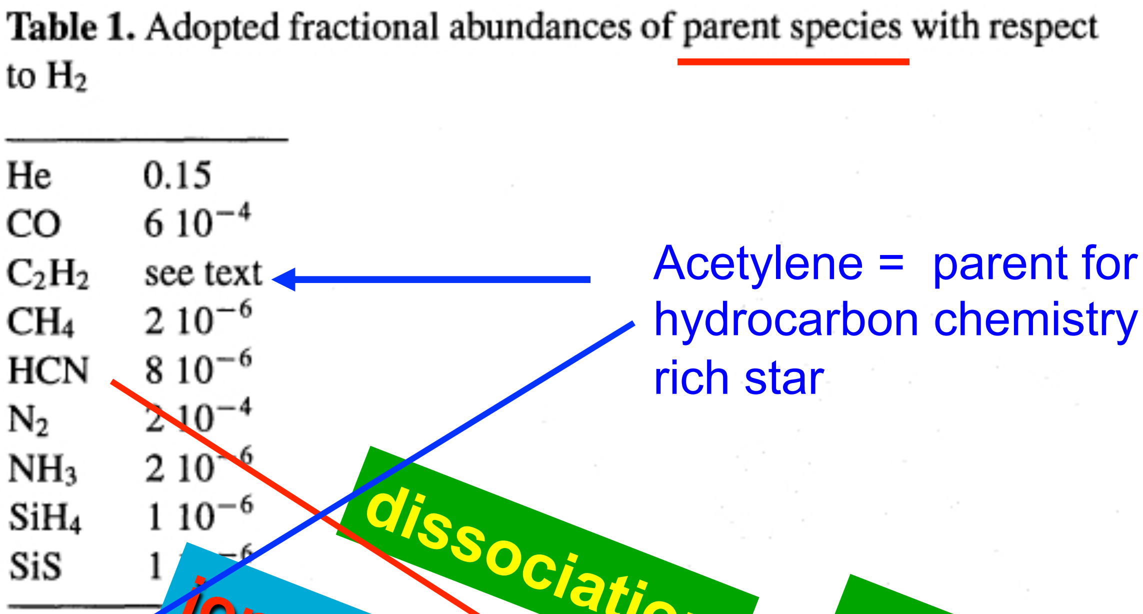
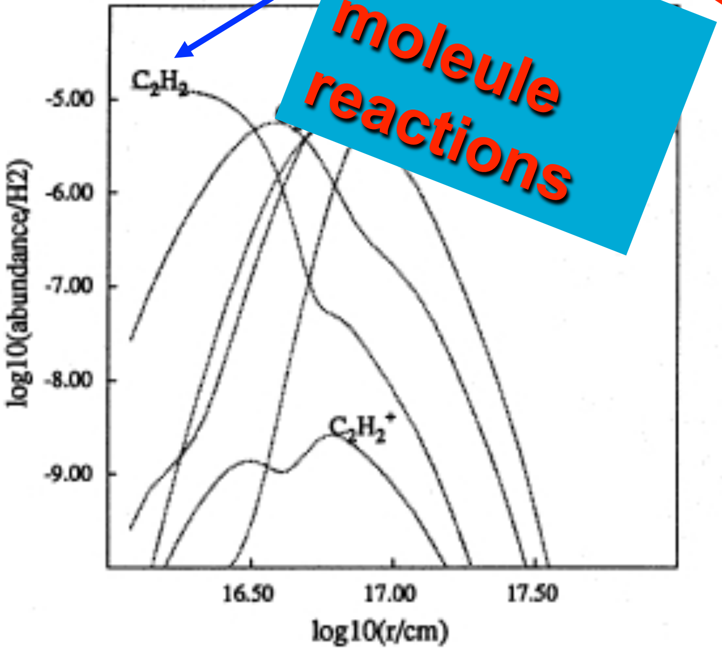


Table 1. Adopted fractional abundances of parent species with respect to H_2

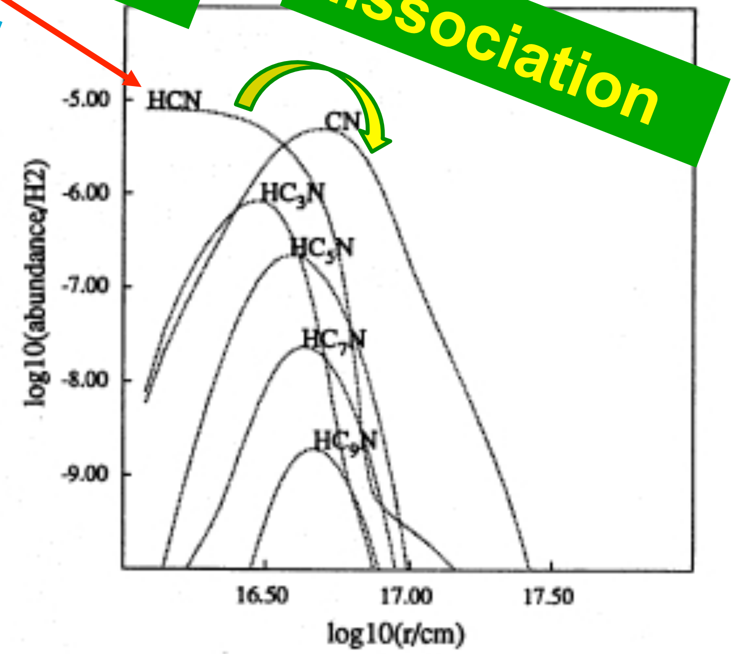
He	0.15
CO	6 10^{-4}
C_2H_2	see text
CH_4	2 10^{-6}
HCN	8 10^{-6}
N_2	2 10^{-4}
NH_3	2 10^{-6}
SiH_4	1 10^{-6}
SiS	1 [illegible]

Acetylene = parent for hydrocarbon chemistry in C-rich star



ion-moleule reactions

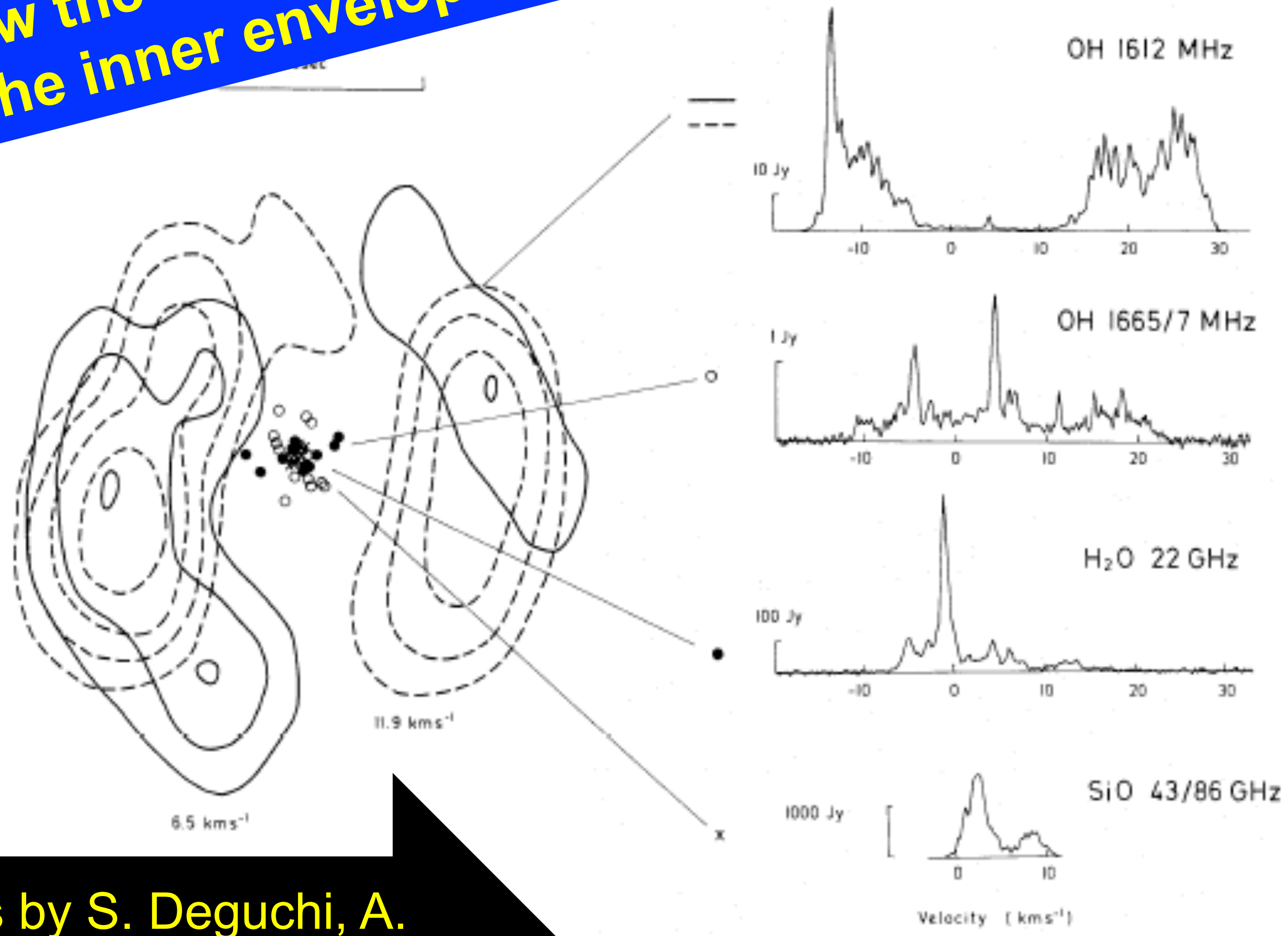
dissociation



dissociation

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

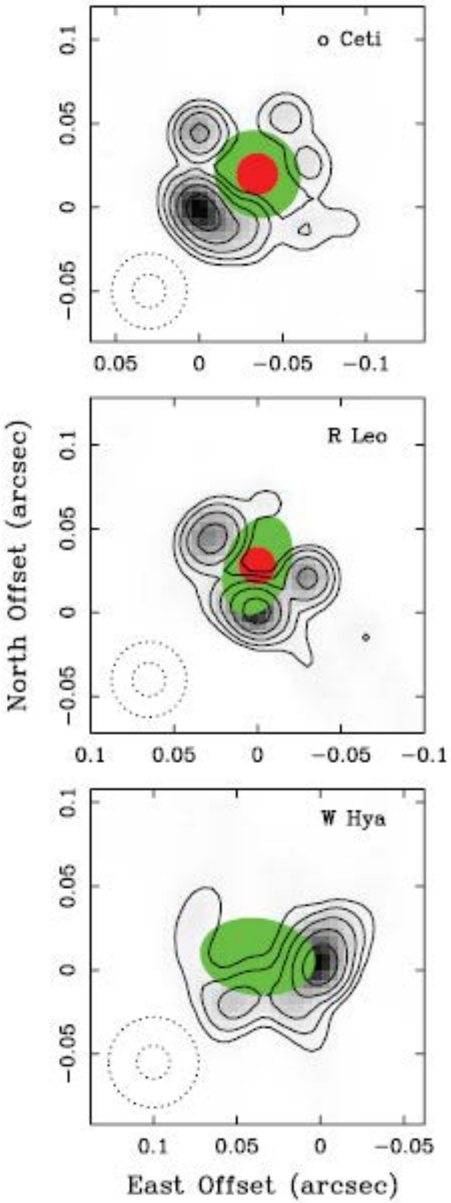
Until now the only means to image the inner envelopes

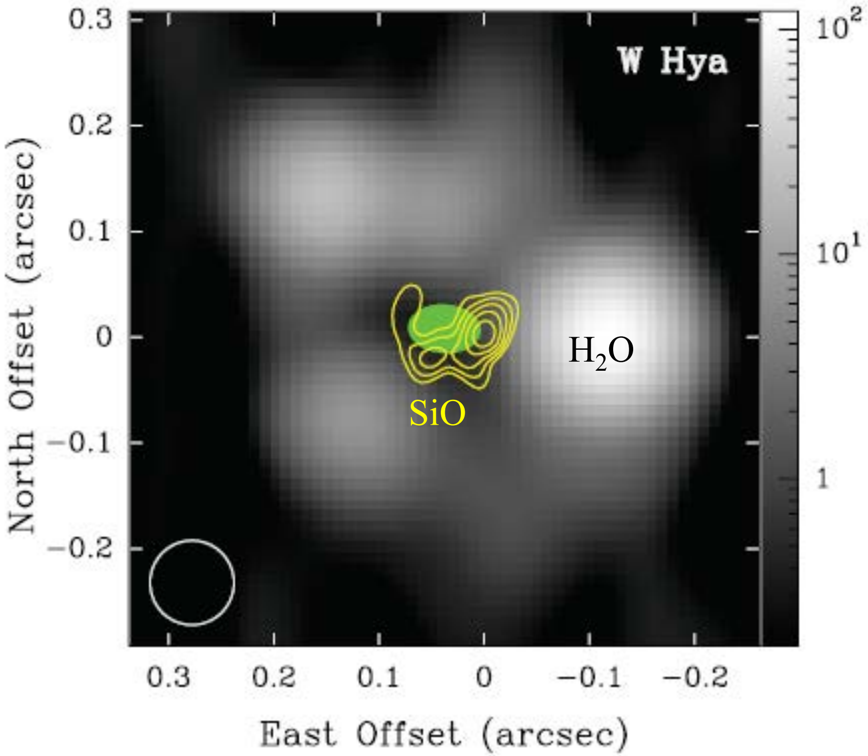


VX Sgr

Talks by S. Deguchi, A. Richards, W. Flemmings

Chapman & Cohen 1986

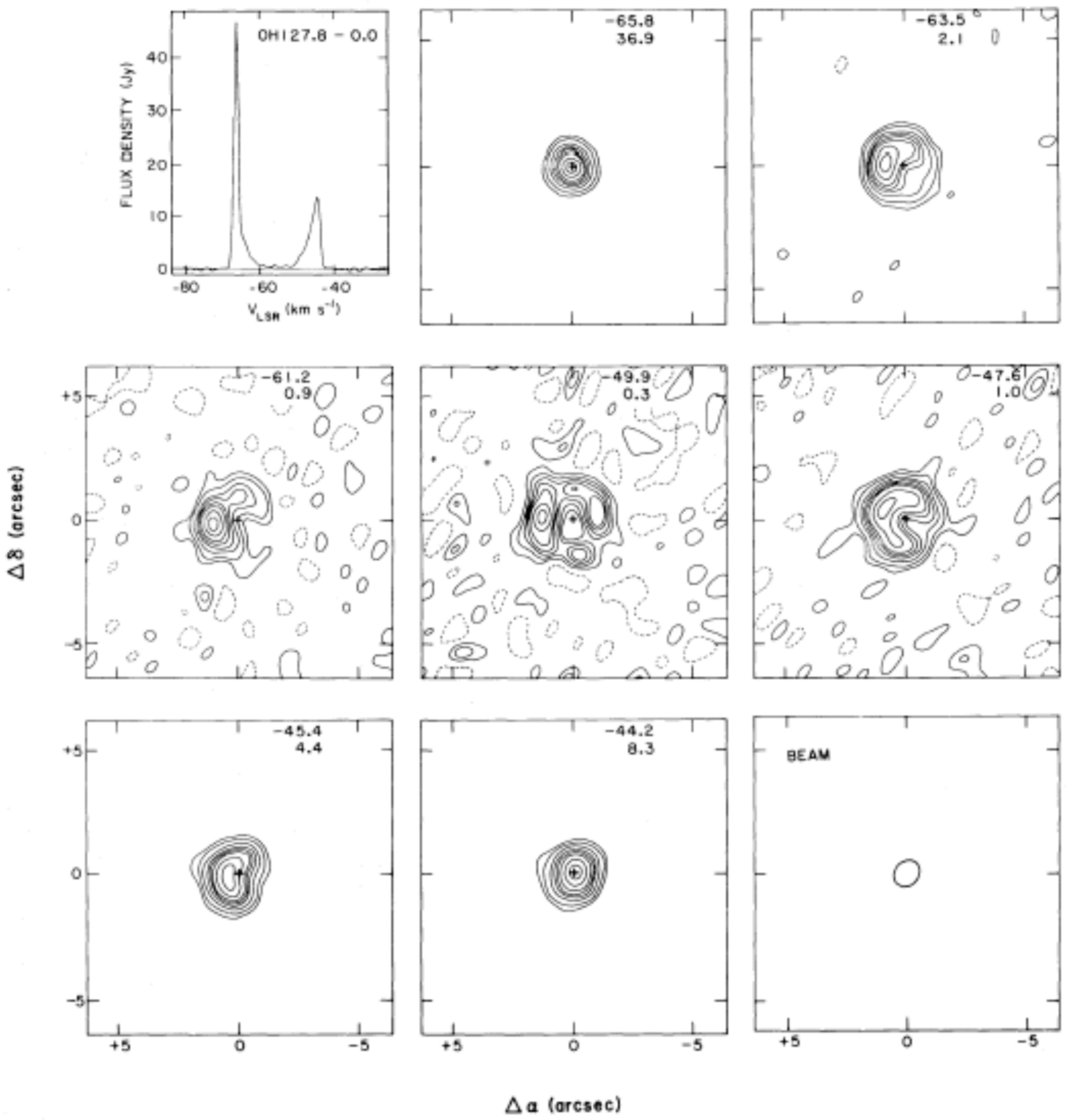




Reid & Menten 1991, 2007

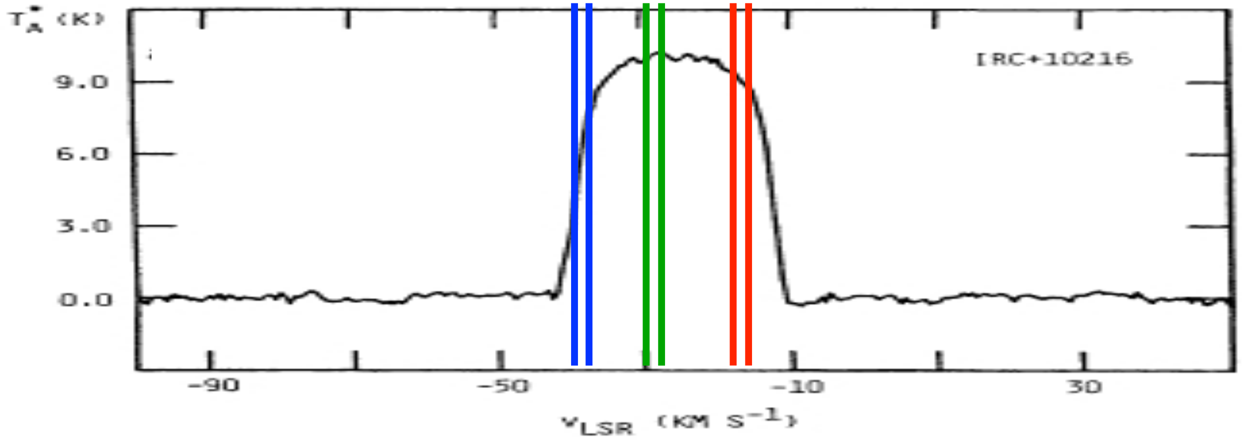
1612 MHz maser shell of a typical OH/IR star

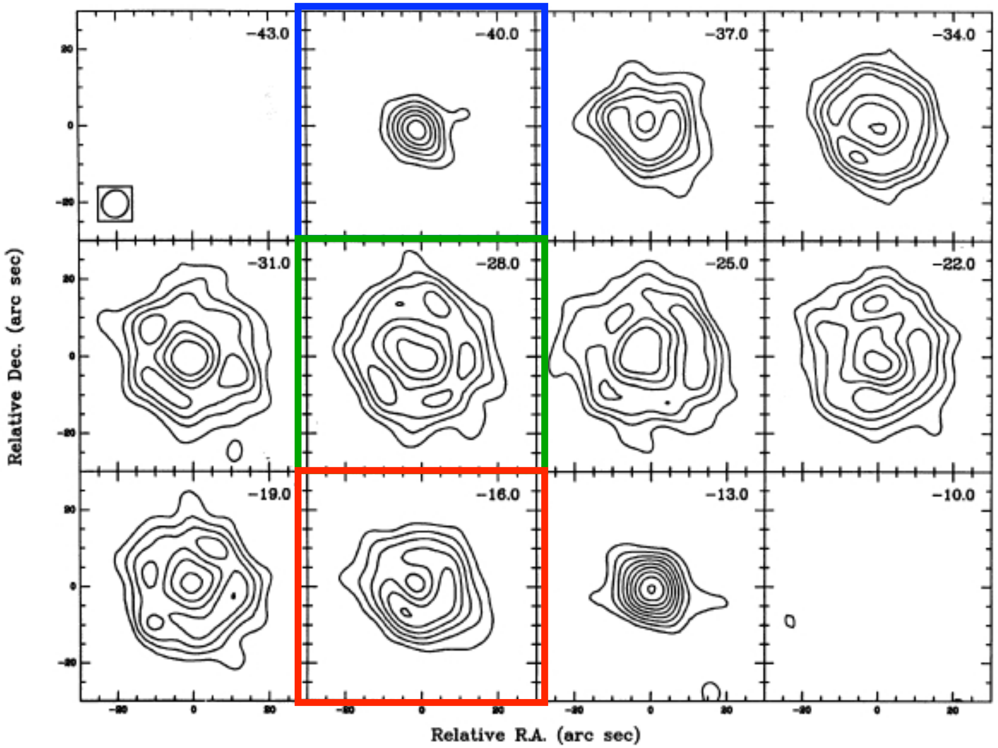
No. 2, 1983 CIRCUMSTELLAR ENVELOPES OF LATE-TYPE STARS

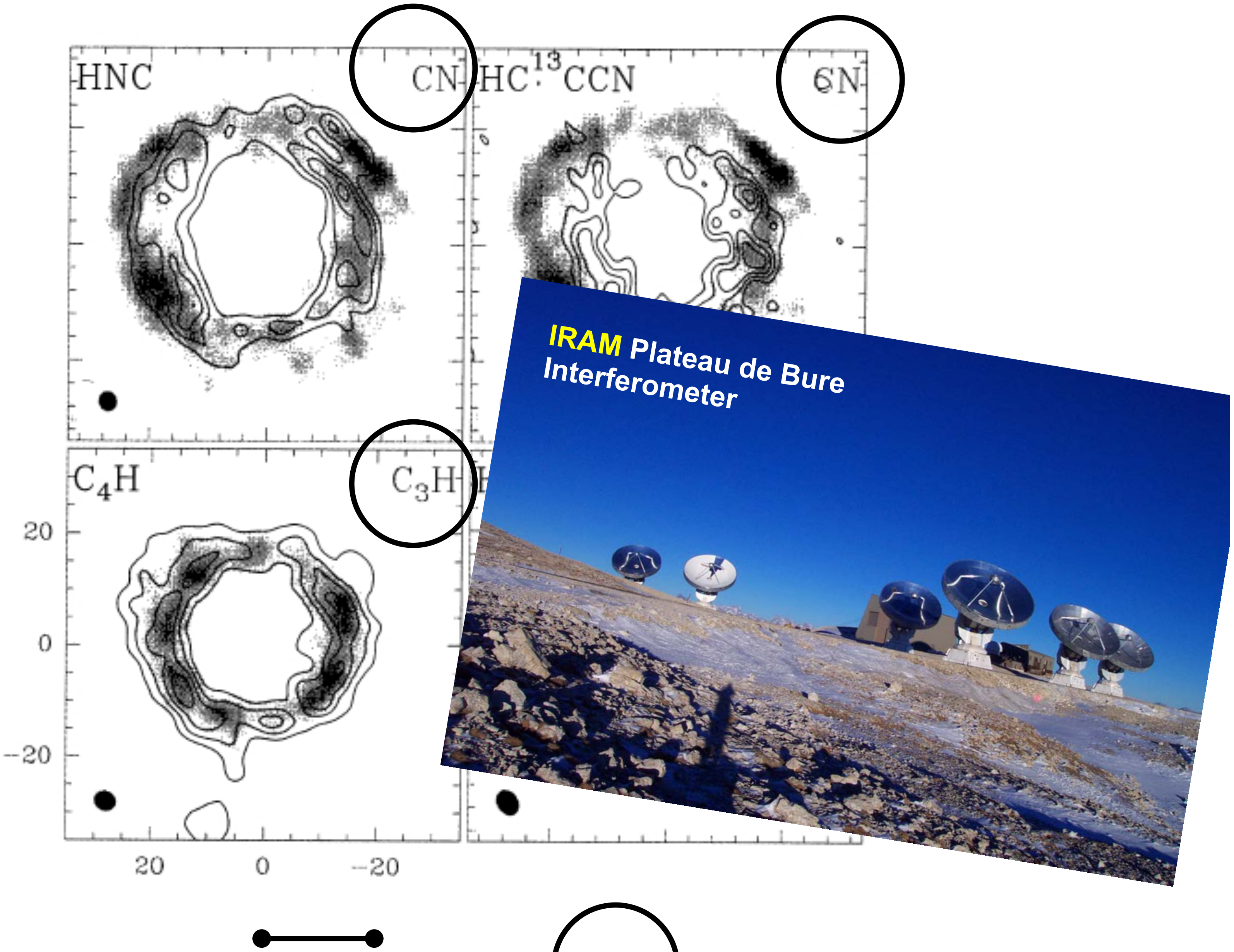


OH127.8-0.0

Bowers, Johnston, & Spencer (1983)


T_A^* (K)
9.0
6.0
3.0
0.0
IRC+10216
-90
-50
-10
30
V_{LSR} (KM S^{-1})

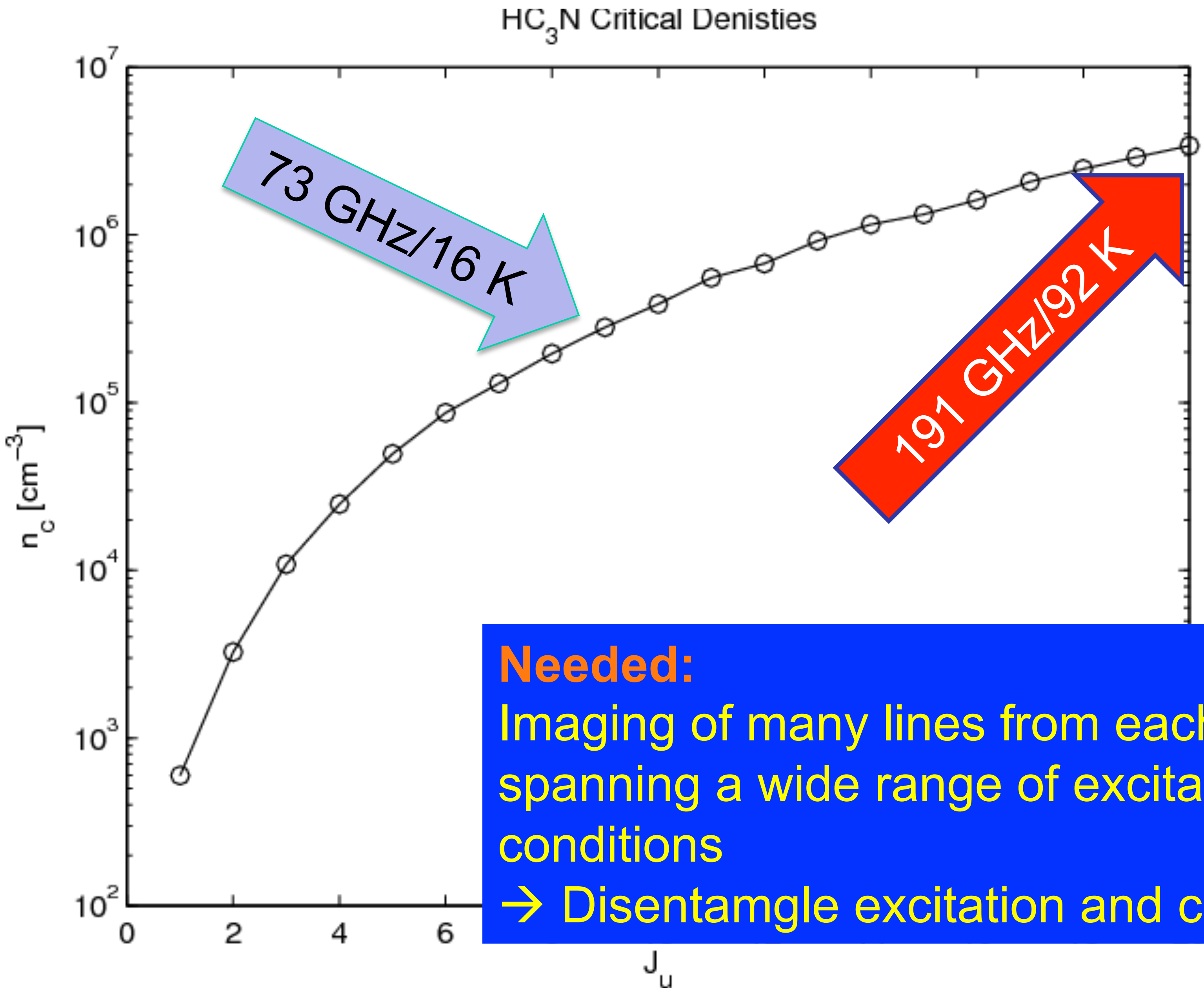

-43.0
-40.0
-37.0
-34.0
-31.0
-28.0
-25.0
-22.0
-19.0
-16.0
-13.0
-10.0
20
0
-20
Relative Dec. (arc sec)
Relative R.A. (arc sec)



2000 AU

Lucas & Guelin 1990 (PdBI)

○ = gray-scale



Needed:

Imaging of many lines from each species spanning a wide range of excitation conditions

→ Disentamgle excitation and chemistry

Costagliola & Aalto 2010

Thermodynamics of the Envelope (*T* vs. *r*) determined by Thermal Balance

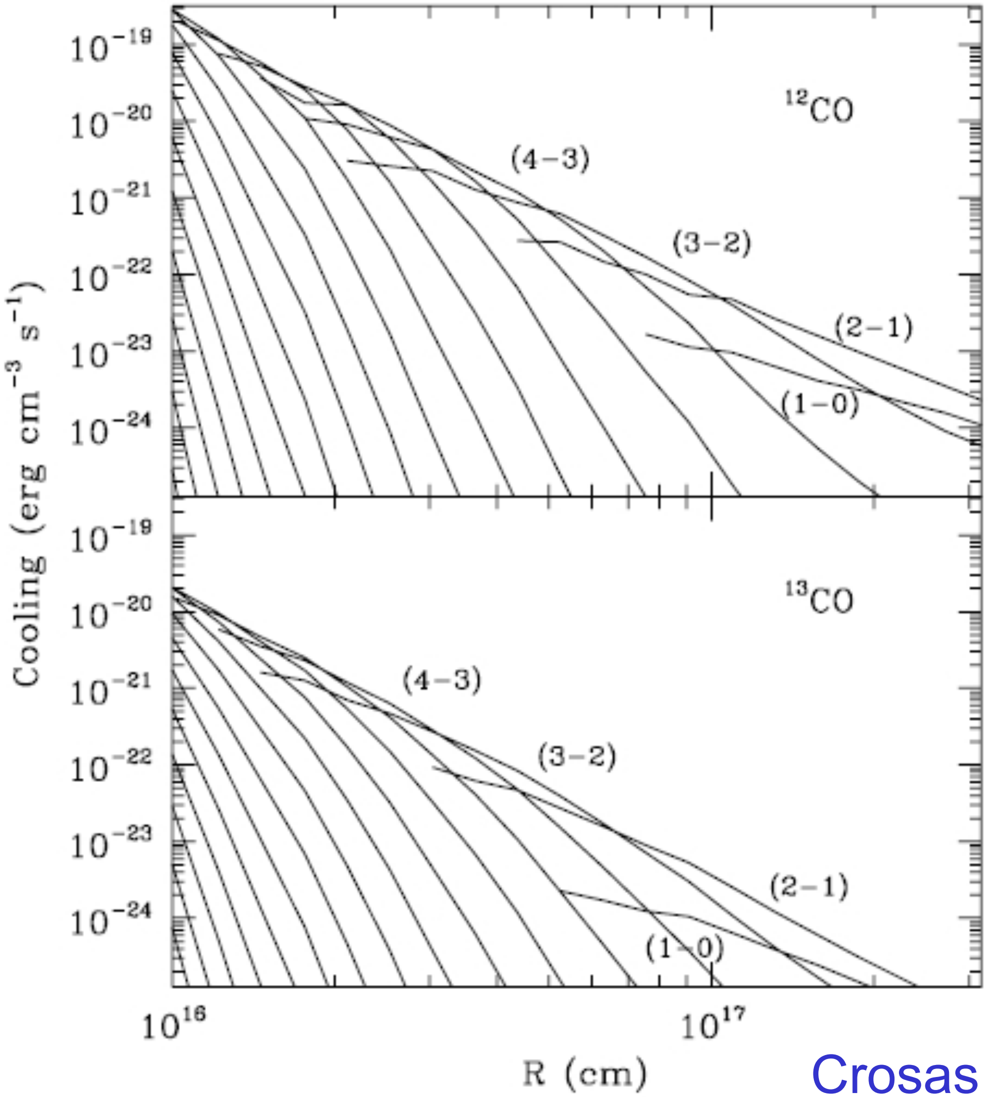
$$\frac{1}{T}\frac{dT}{dr} = -\frac{4}{3r}\left(1+\frac{1}{2}\frac{d\ln \mathrm{v}}{d\ln r}\right)+\frac{2}{3}\frac{H-C}{k\mathrm{v}Tn_{H_2}}$$

e.g., Goldreich & Scoville 1978

- Heating implicitly contains mass-loss rate: $H \propto \mathrm{v}_{\mathrm{d}}^2 \propto \dot{M}^{-1}$

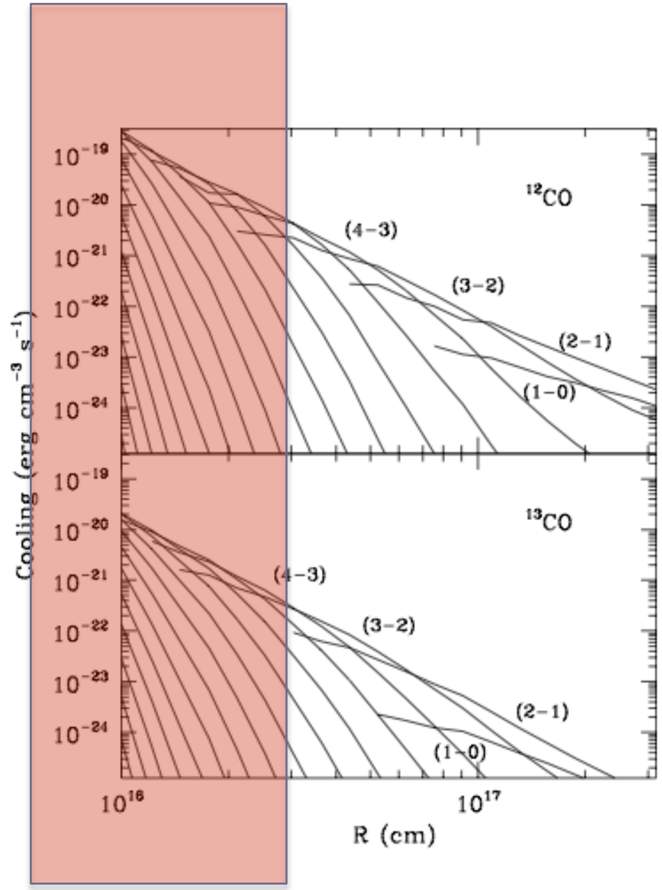
$\Rightarrow \dot{M}$ is a fittable parameter

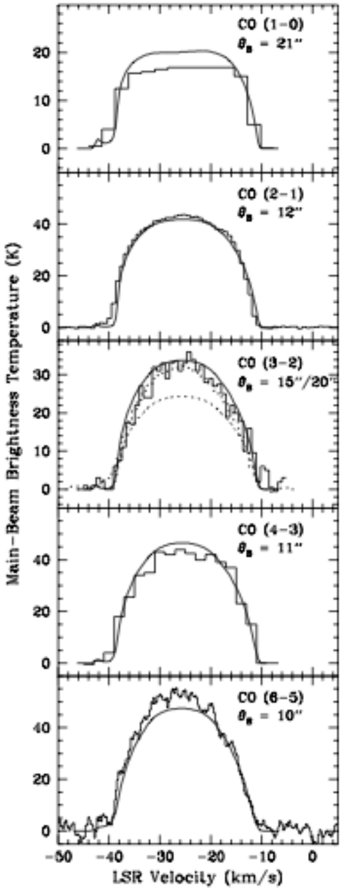
CO line emission provides most of the cooling for C-(O-)rich stars

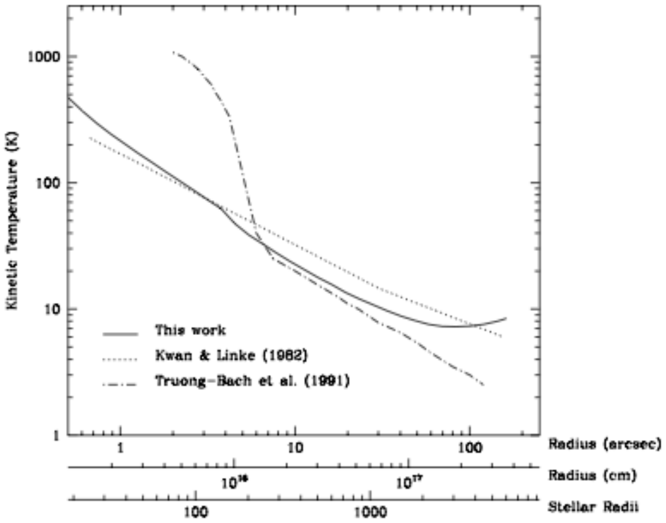


Crosas & Menten 1995

CO line emission provides most of the cooling for C- (O-)rich stars

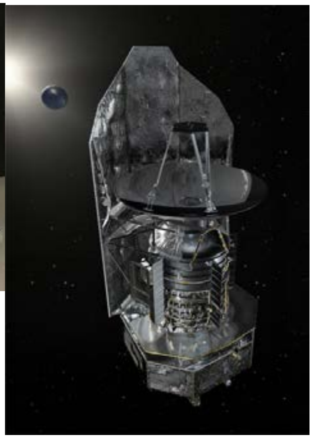




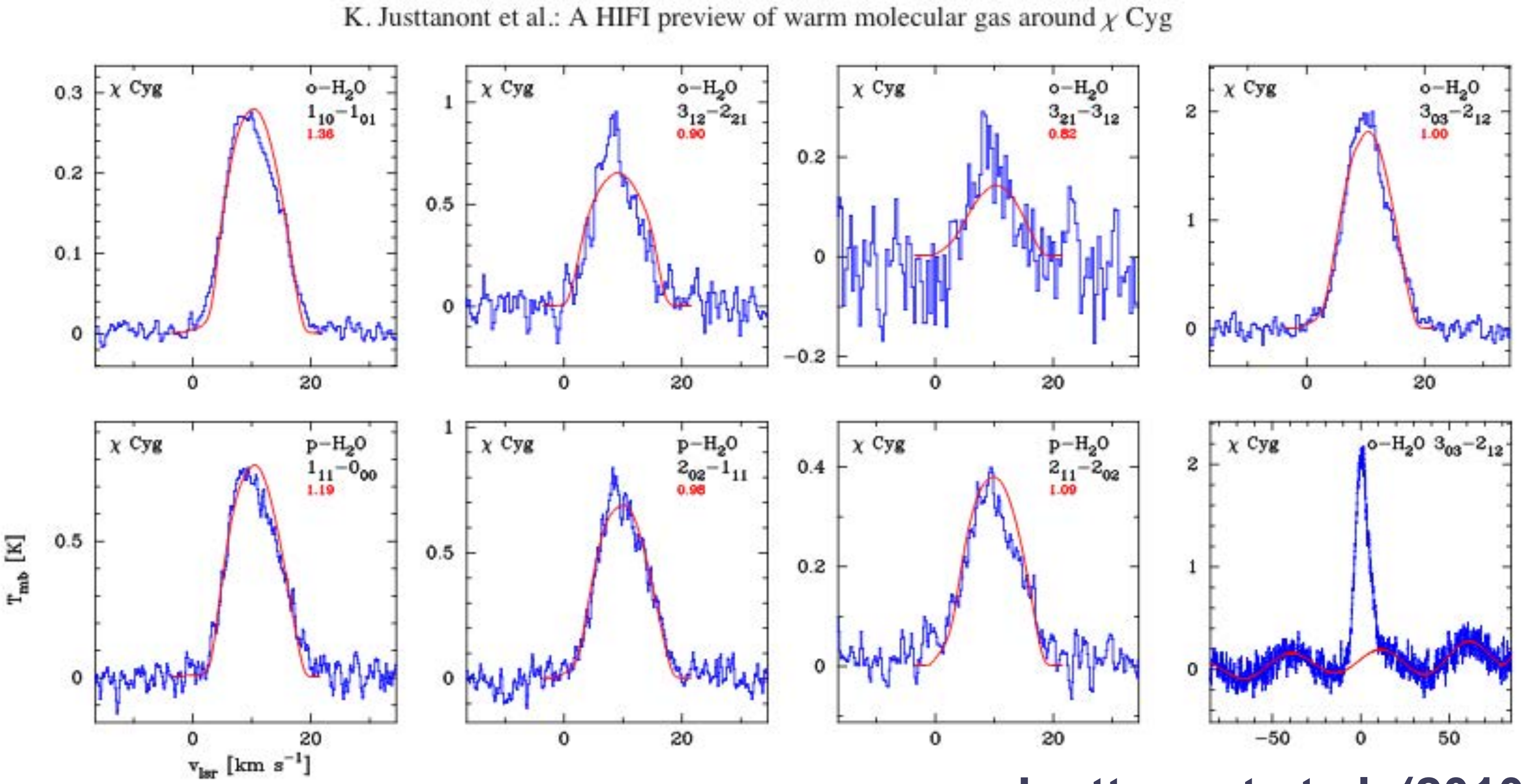


Crosas & Menten 1995

Now, for the first time: High Spectral Resolution Observations of Thermal H_2O emission



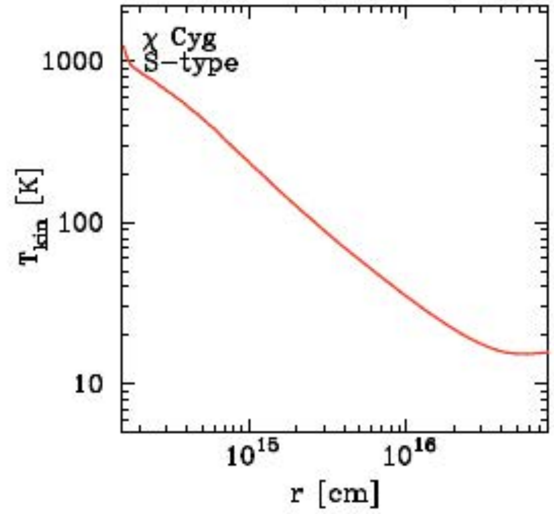
Herschel/HIFI

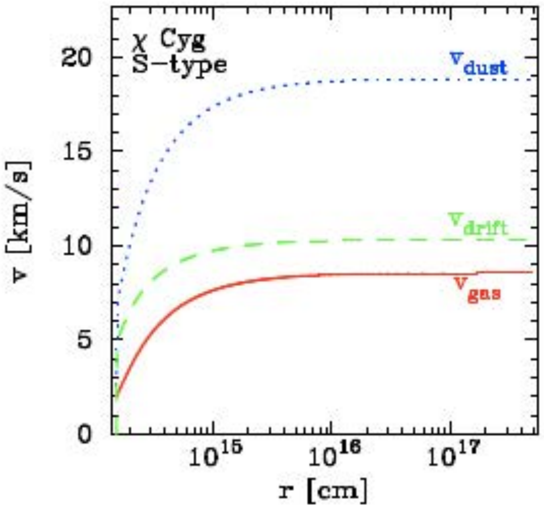


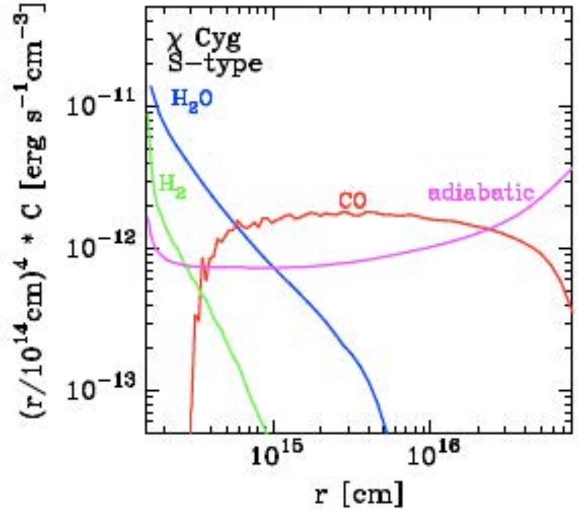
K. Justtanont et al.: A HIFI preview of warm molecular gas around χ Cyg

Justtanont et al. (2010)

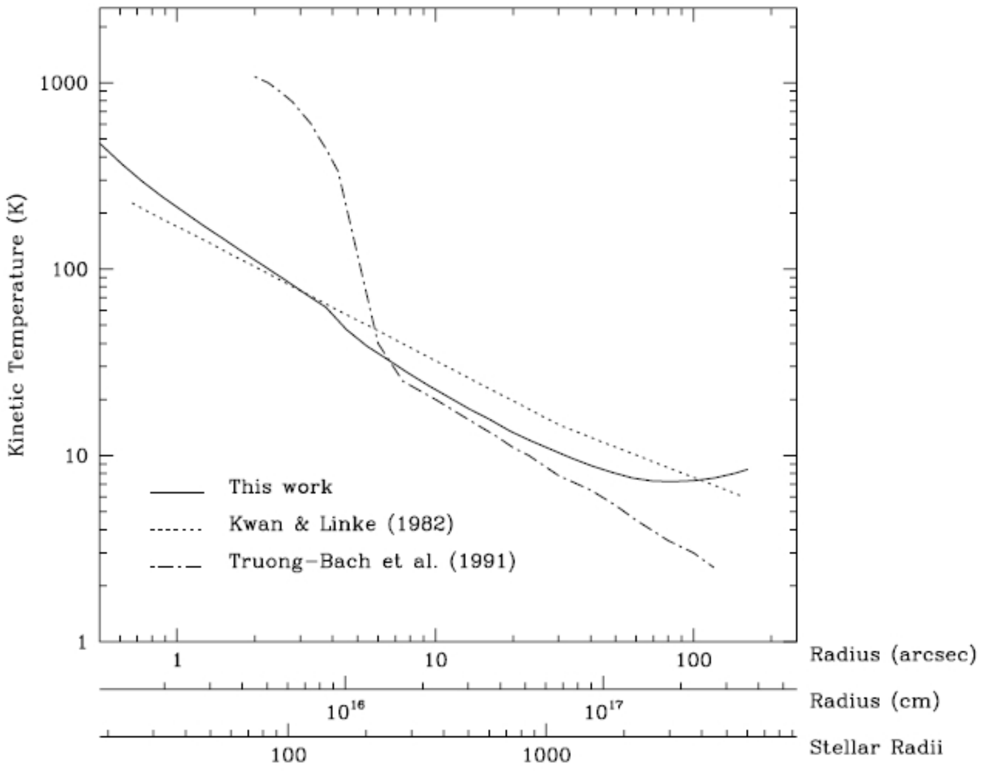
χ Cyg: results from models







Justtanont et al. (2010)



Using this temperature profile and abundance profiles from theoretical chemical models we can calculate model spectra for various molecules.

These spectra, in turn, are used to constrain the chemical models

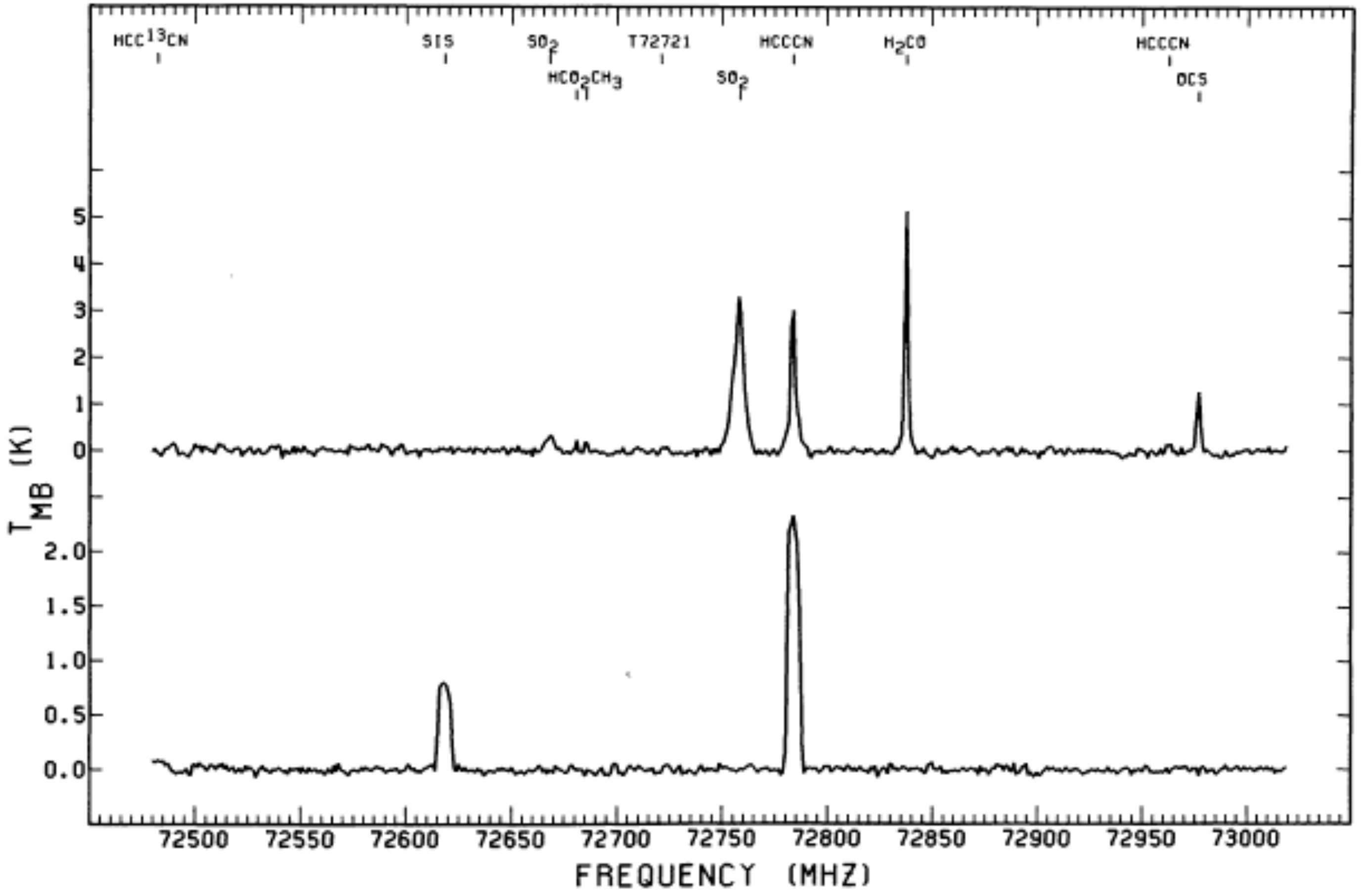
Astron. Astrophys. 130, 227–256 (1984)

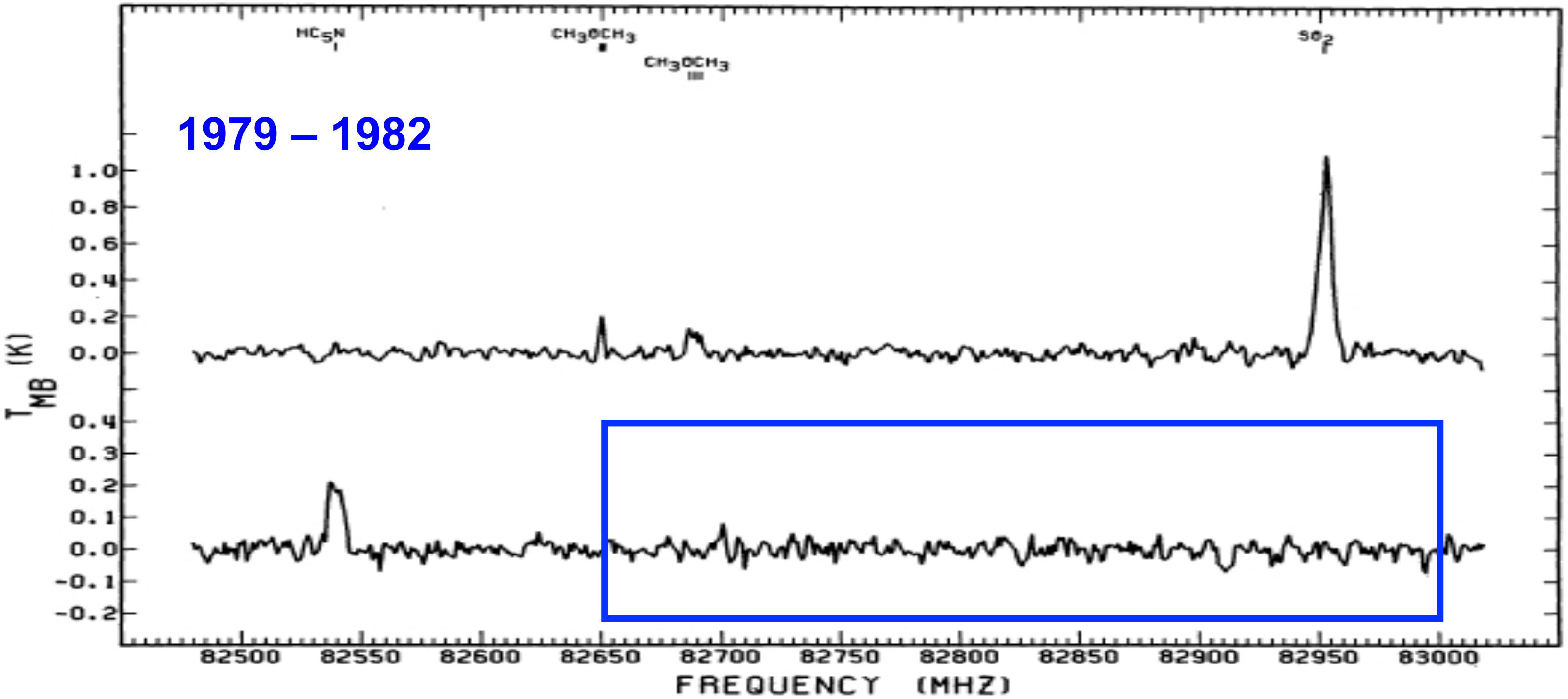
ASTRONOMY
AND
ASTROPHYSICS

Spectral scan of Orion A and IRC + 10216 from 72 to 91 GHz

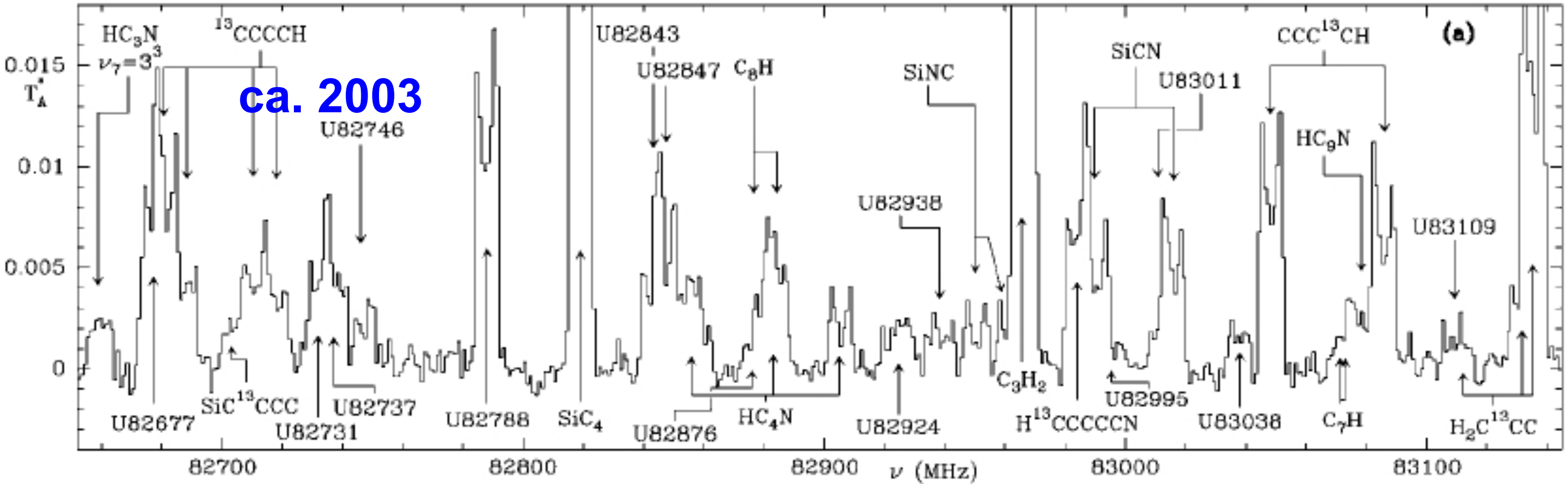
L. E. B. Johansson, C. Andersson, J. Elldér, P. Friberg, Å. Hjalmarson, B. Höglund, W.M. Irvine*, H. Olofsson, and G. Rydbeck
Onsala Space Observatory, S-439 00 Onsala, Sweden

Received April 28, accepted June 28, 1983





1979 – 1982



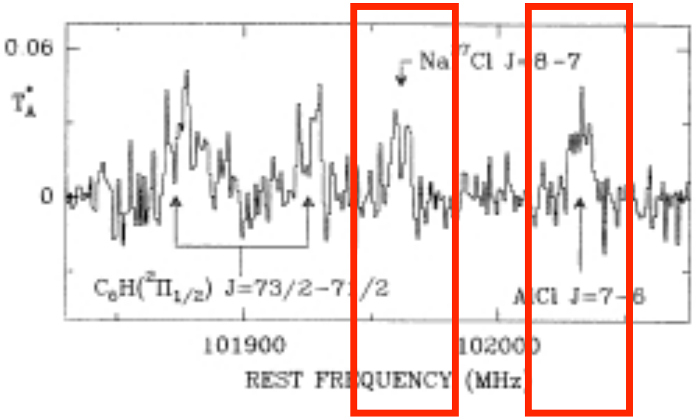
ca. 2003

IRC+10216 – extreme carbon star

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

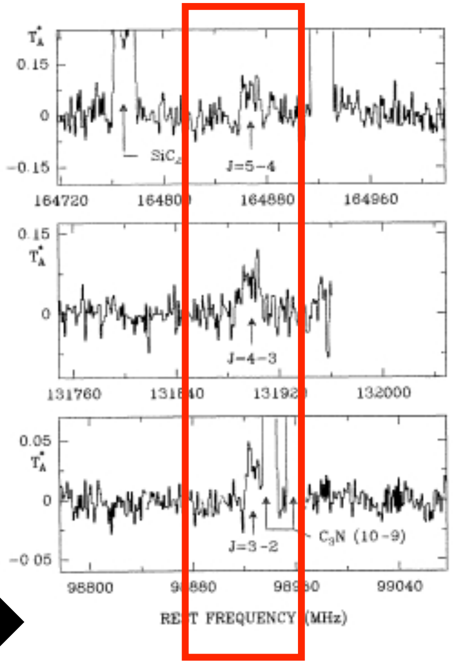
⇒ Exceedingly rich molecular spectrum

Many species ***only*** detected here

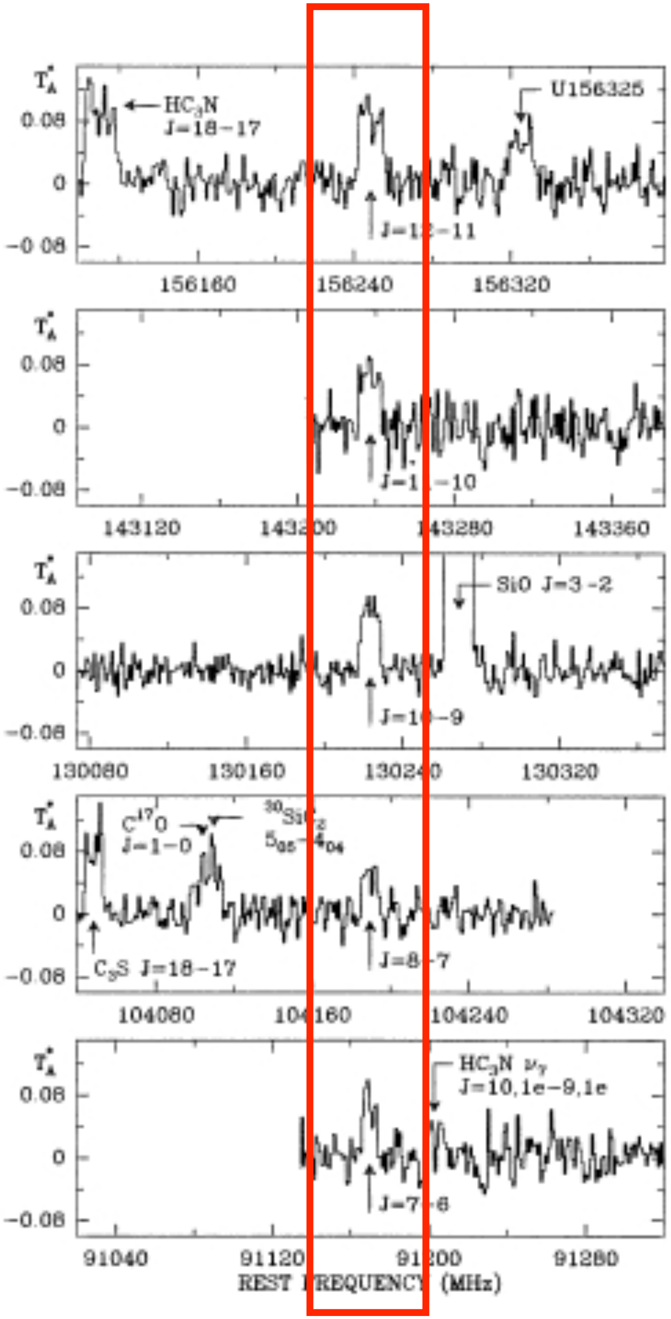


$Na^{37}Cl$ **AlCl**

Talk by M. Claussen



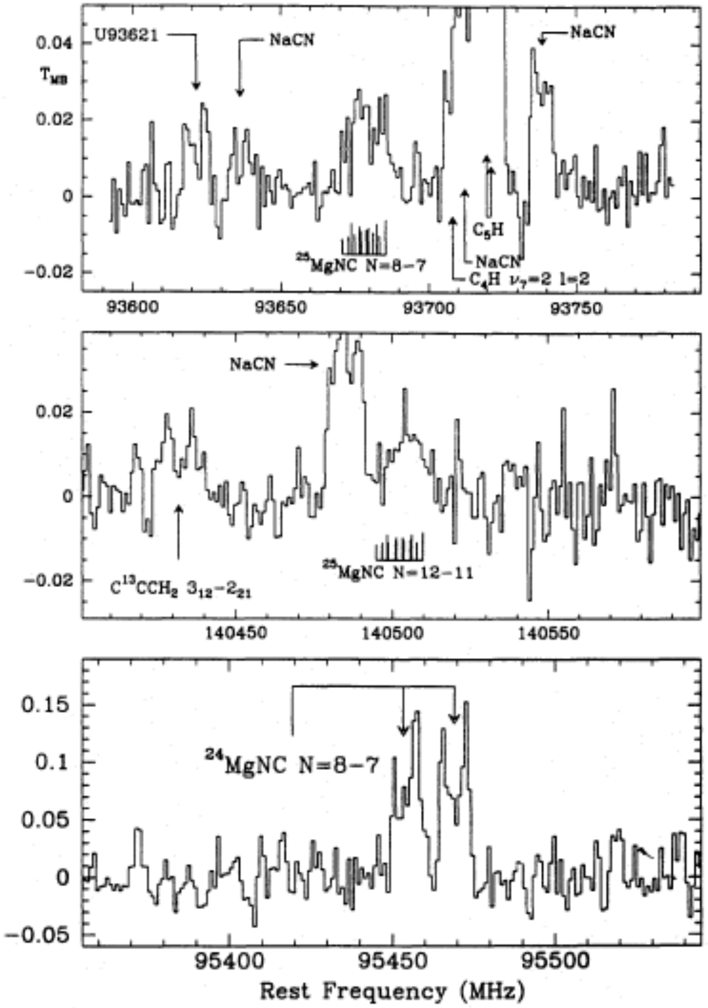
AlF

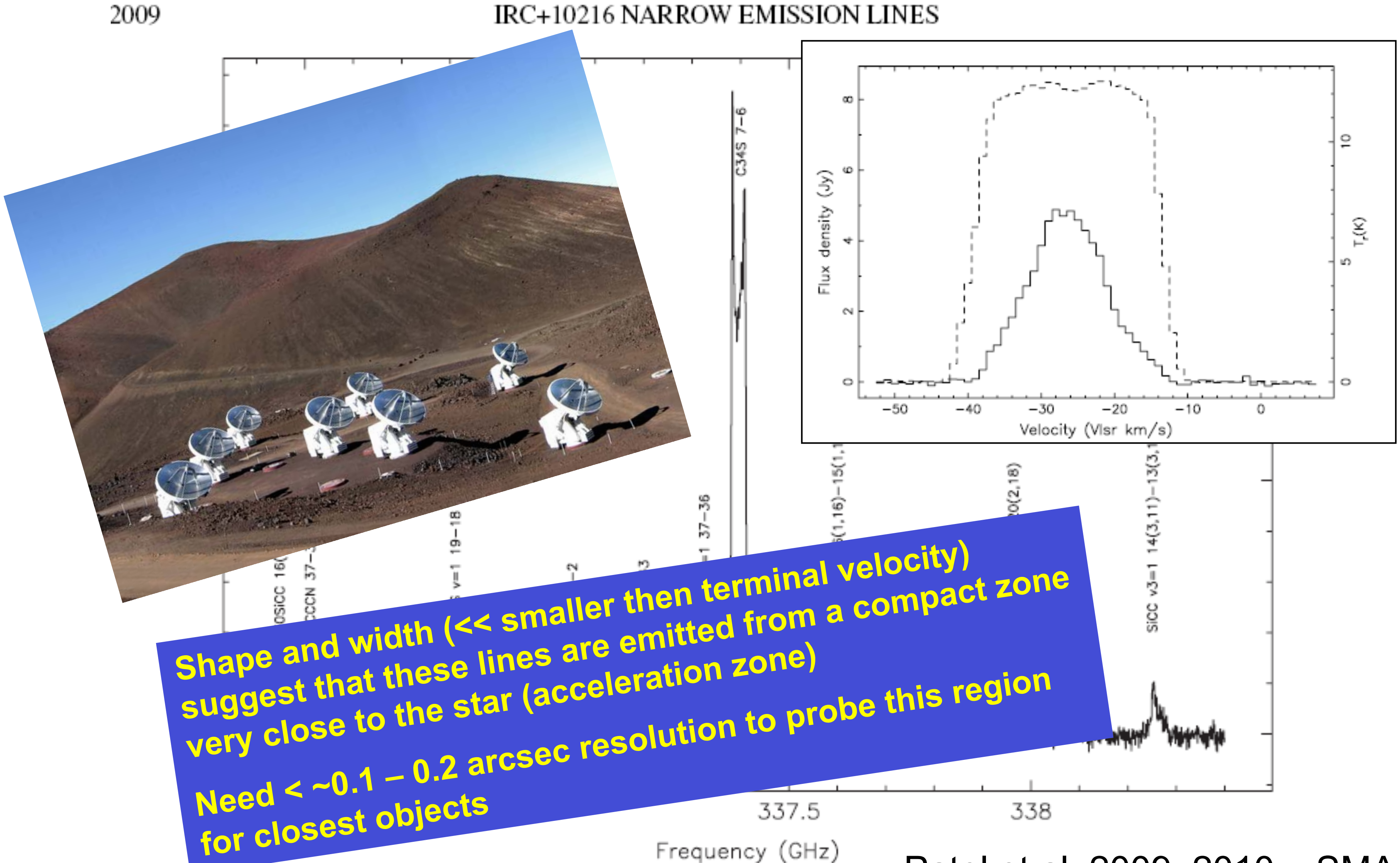


NaCl

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]





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

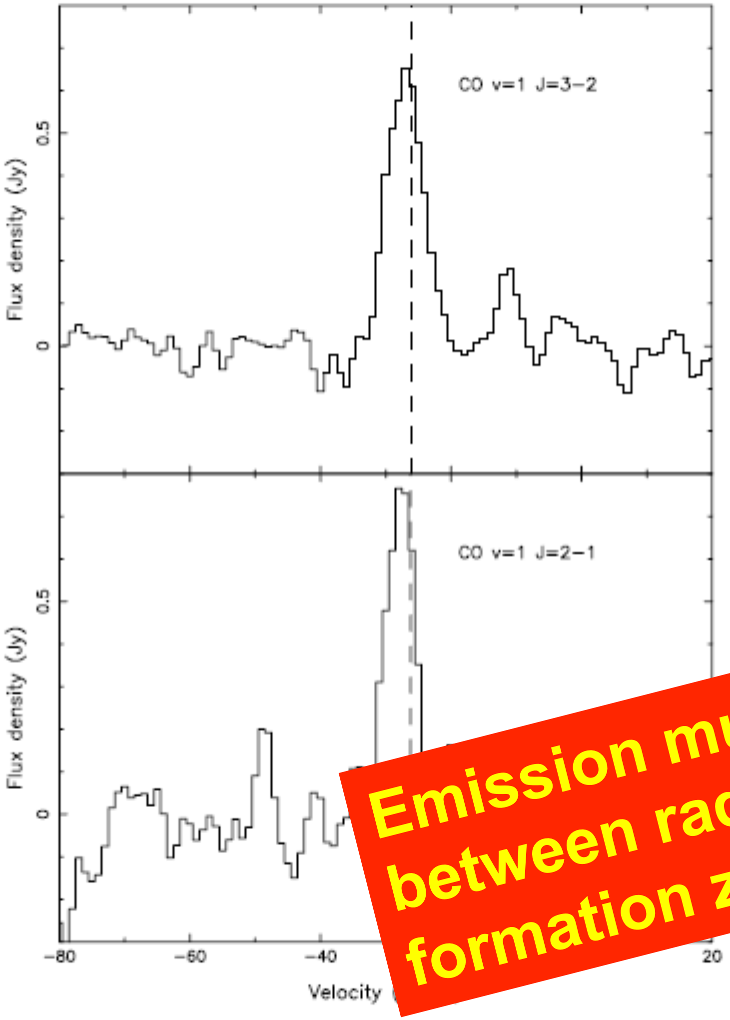
Need < ~0.1 – 0.2 arcsec resolution to probe this region for closest objects

Patel et al. 2009, 2010 – SMA

Talk by K. Young

Vibrationally excited CO

From energy levels ~3100 K above ground

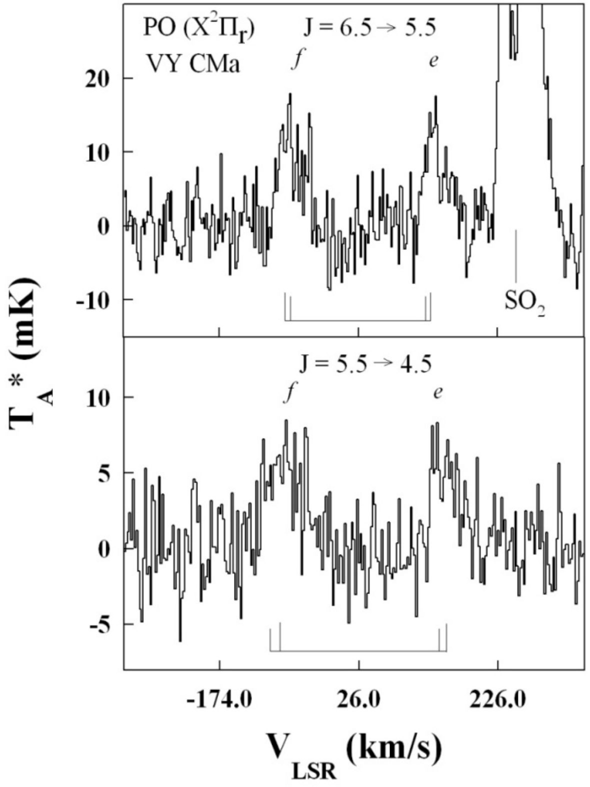


Emission must arise from region between radio photosphere and dust formation zone (size > 40 AU)

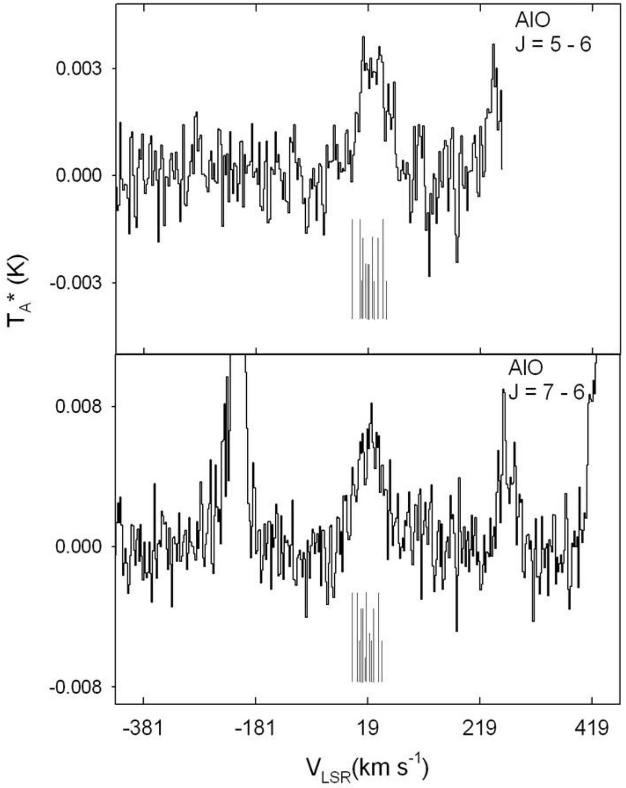
Patel et al. 2009 – SMA

The amazing chemistry of the red supergiant VY CMa

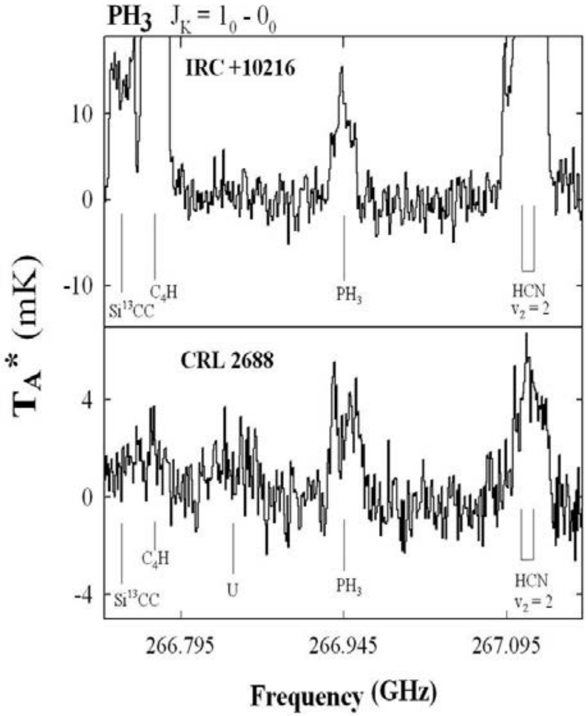
- Two new oxide species in VY CMa: **PO** and **AlO**
- Two phosphorus molecules in IRC+10216: **PH_3** and **HCP**



Tenenbaum et al 2007



Tenenbaum & Ziurys 2009

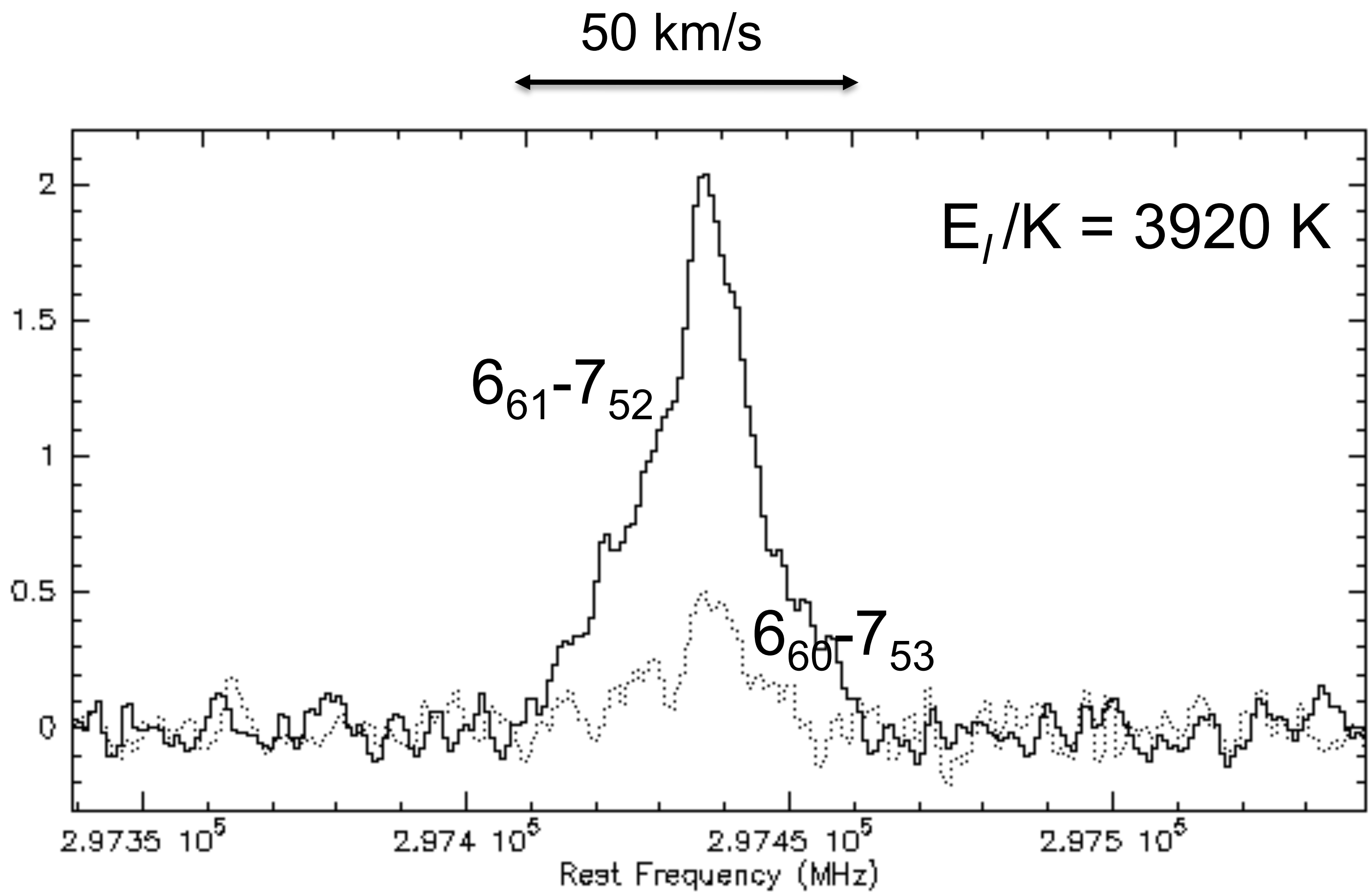


Tenenbaum & Ziurys 2008

Arizona Radio Observatory

VY CMa: SMA ~1 arcsec resolution imaging survey 280–355 GHz

Example: Vibrationally excited o/p H_2O ($v_2 = 1$)

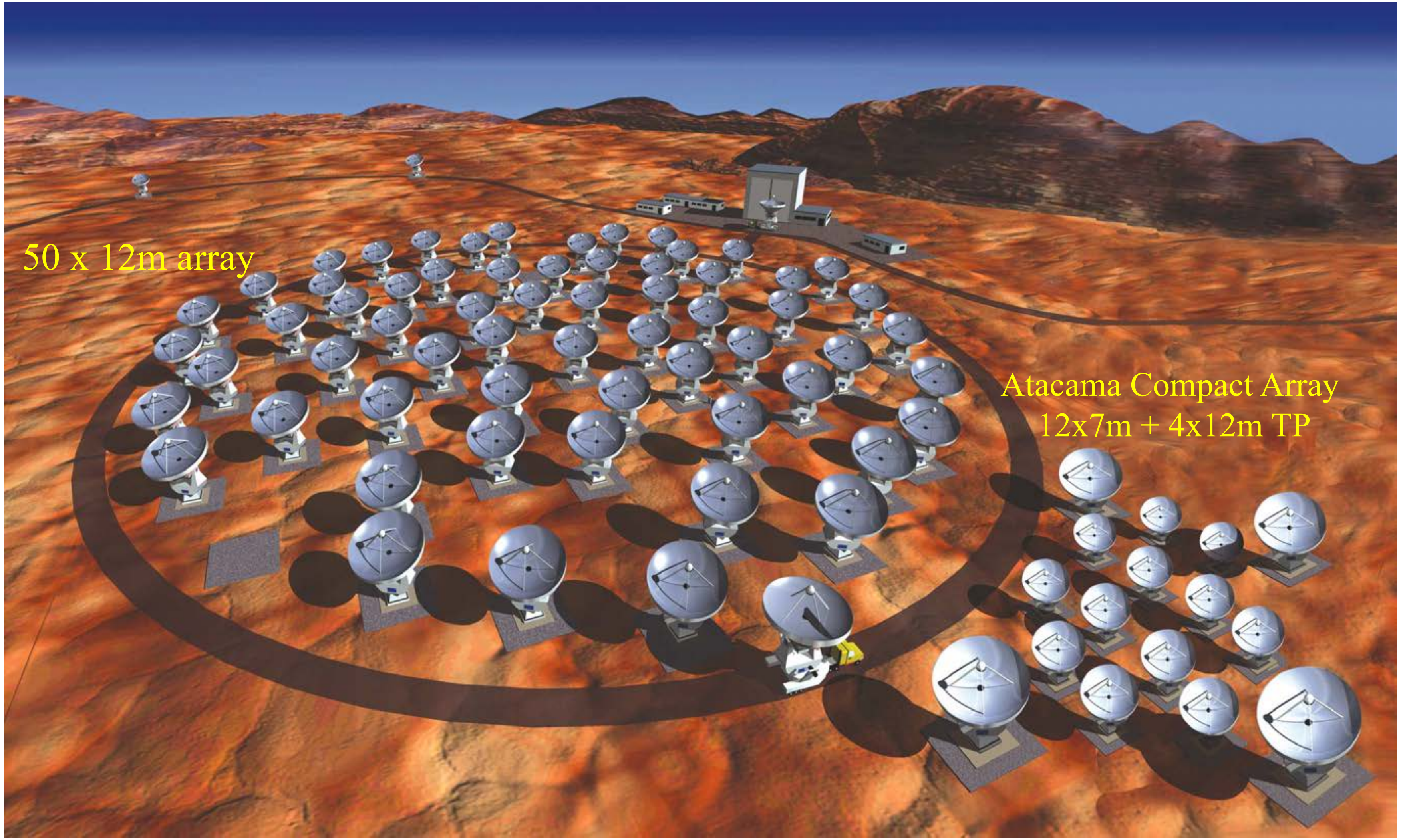


$E_l/K = 3920$ K

Talks by T. Kaminski
(IK Tau) E. de Beck/M.Maercker

The Atacama Large Millimeter/submillimeter Array

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:

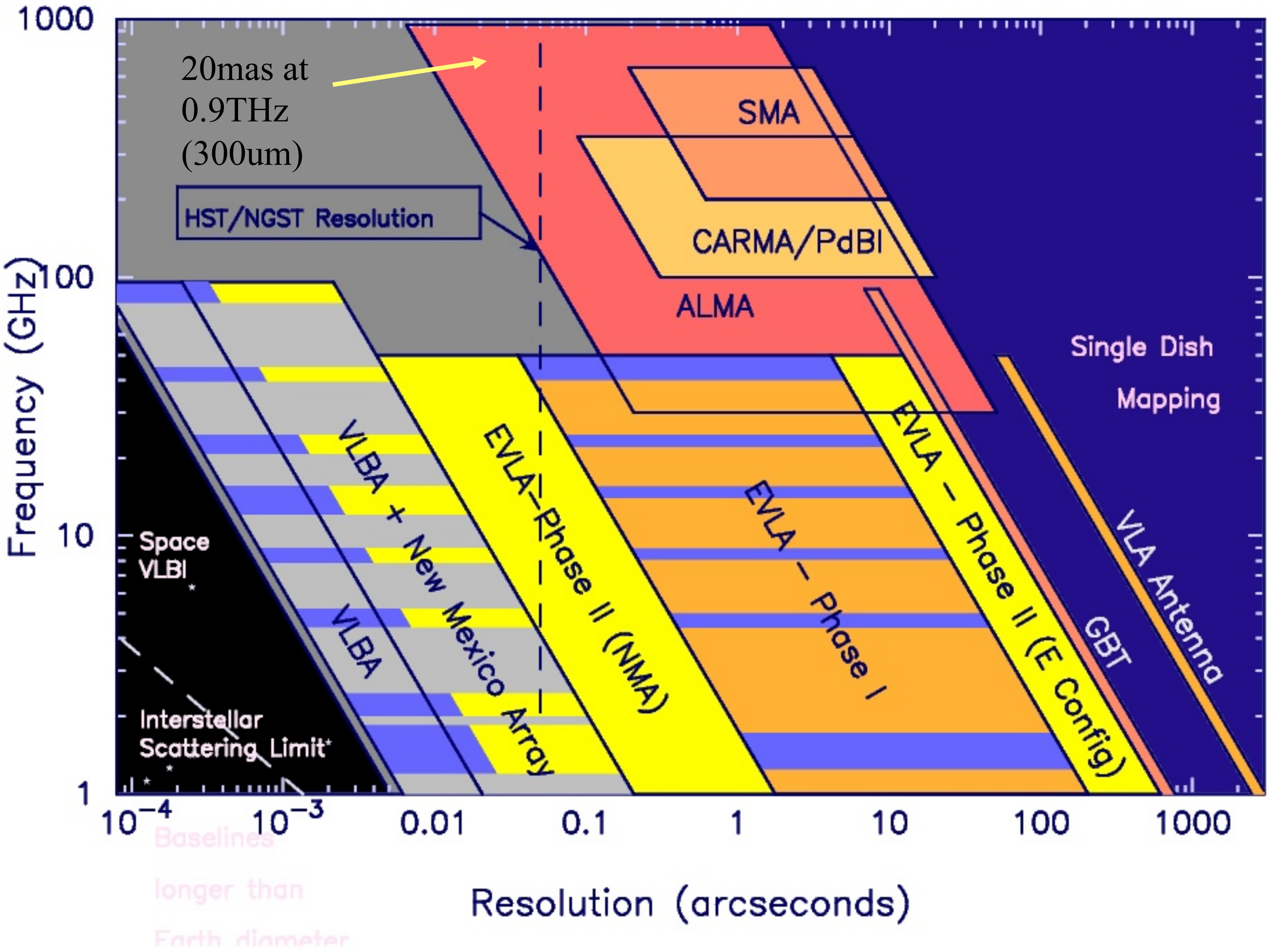
86–119 GHz	“3”	211–275 GHz	“6”
275–370 GHz	“7”	602–720 GHz	“9”

- 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

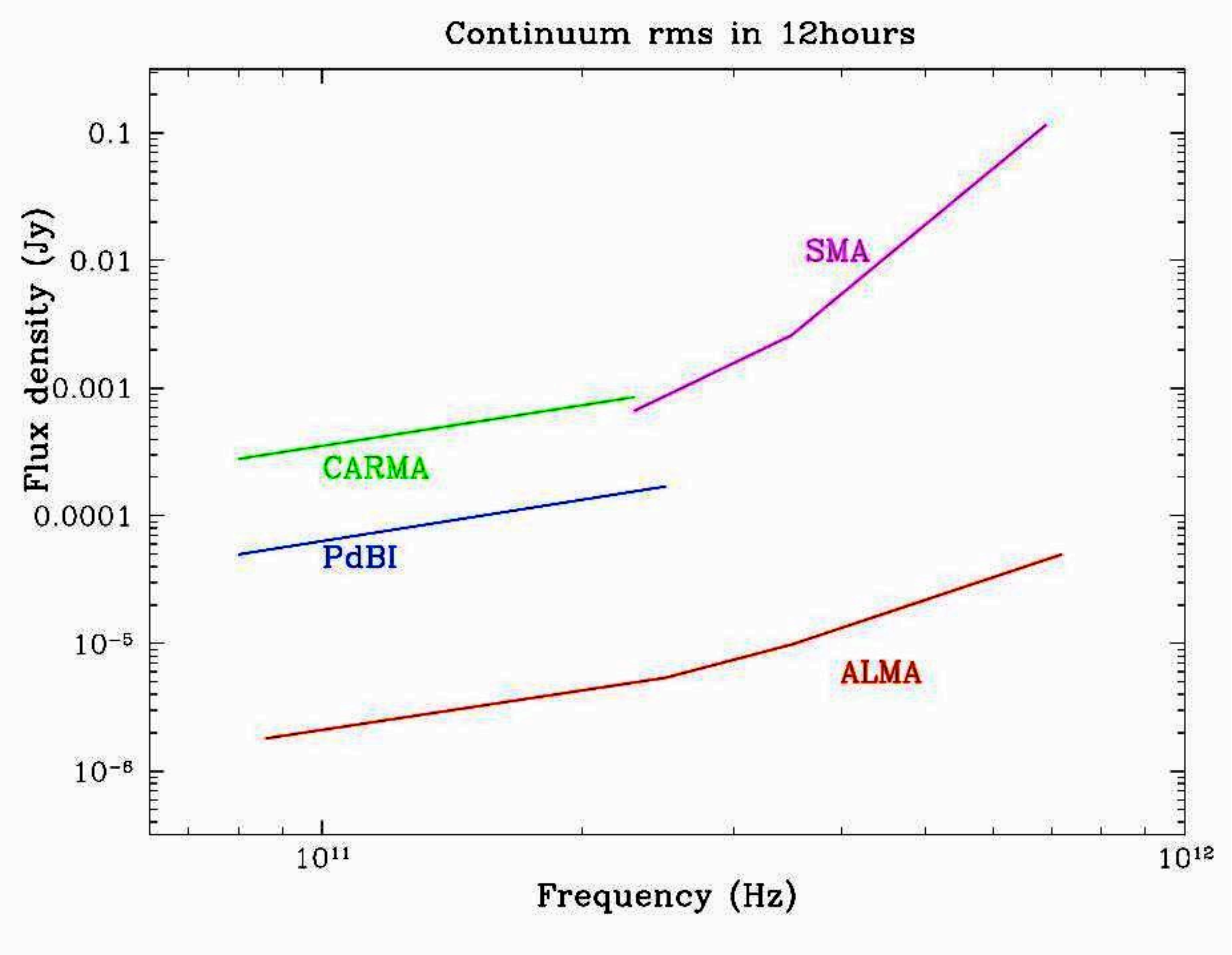
- High Fidelity Imaging.
- Precise Imaging at 0.1” Resolution.
- Routine sub-mJy Continuum Sensitivity.
- Routine mK Spectral Sensitivity.
- Wideband Frequency Coverage.
- Wide Field Imaging Mosaicing.
- Full Polarization Capability.
- System Flexibility.

Giant Steps I: Frequency and resolution



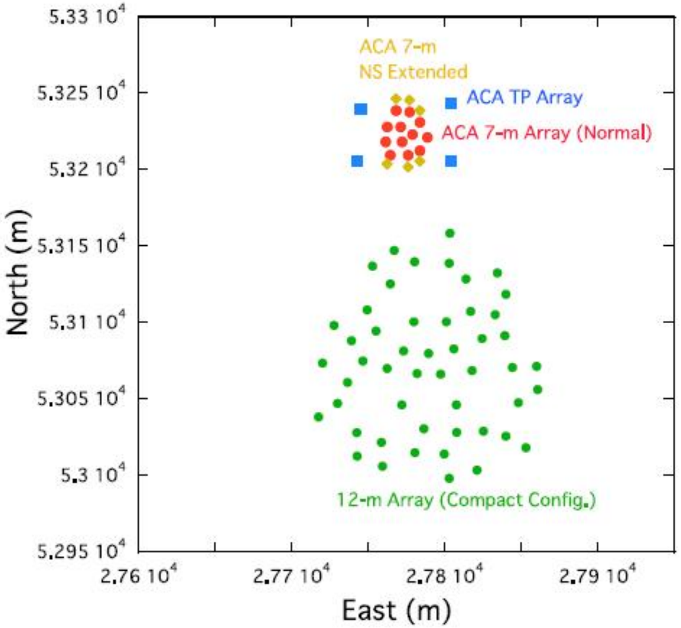
20mas at
0.9THz
(300um)

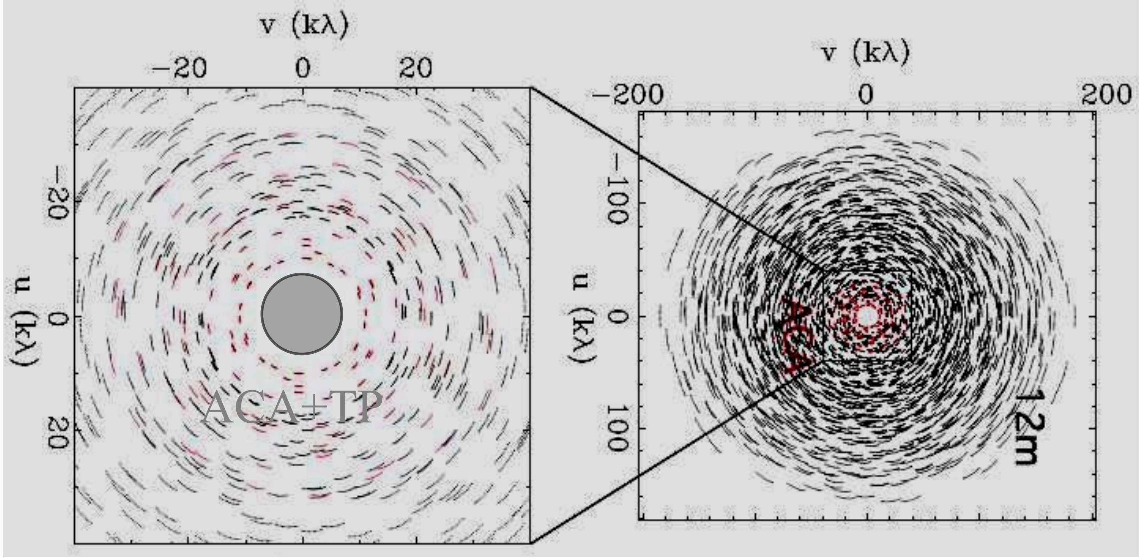
Giant Steps II: Sensitivity

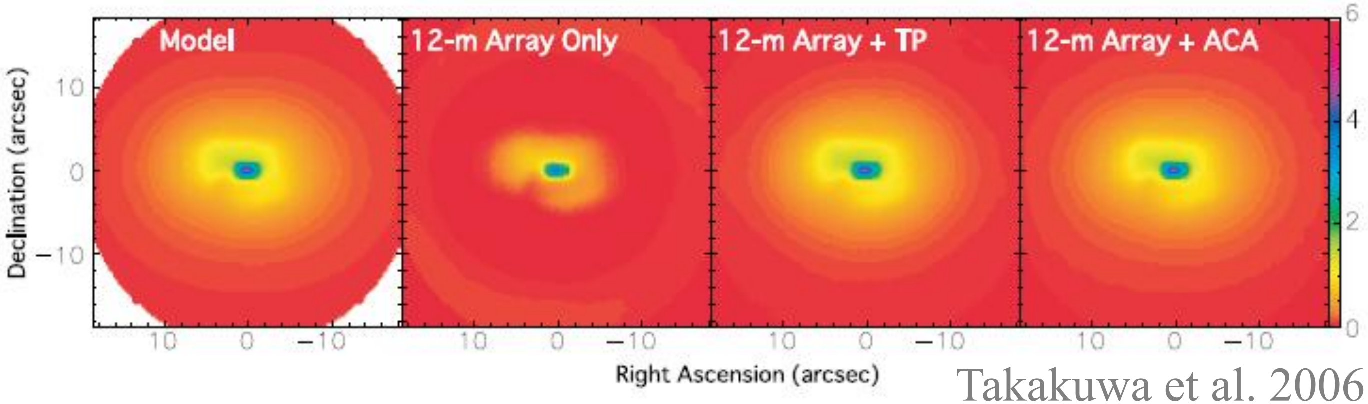


Giant Steps III: Image quality w. 50 x12m, 12x7m, 4x12m w/ TP

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

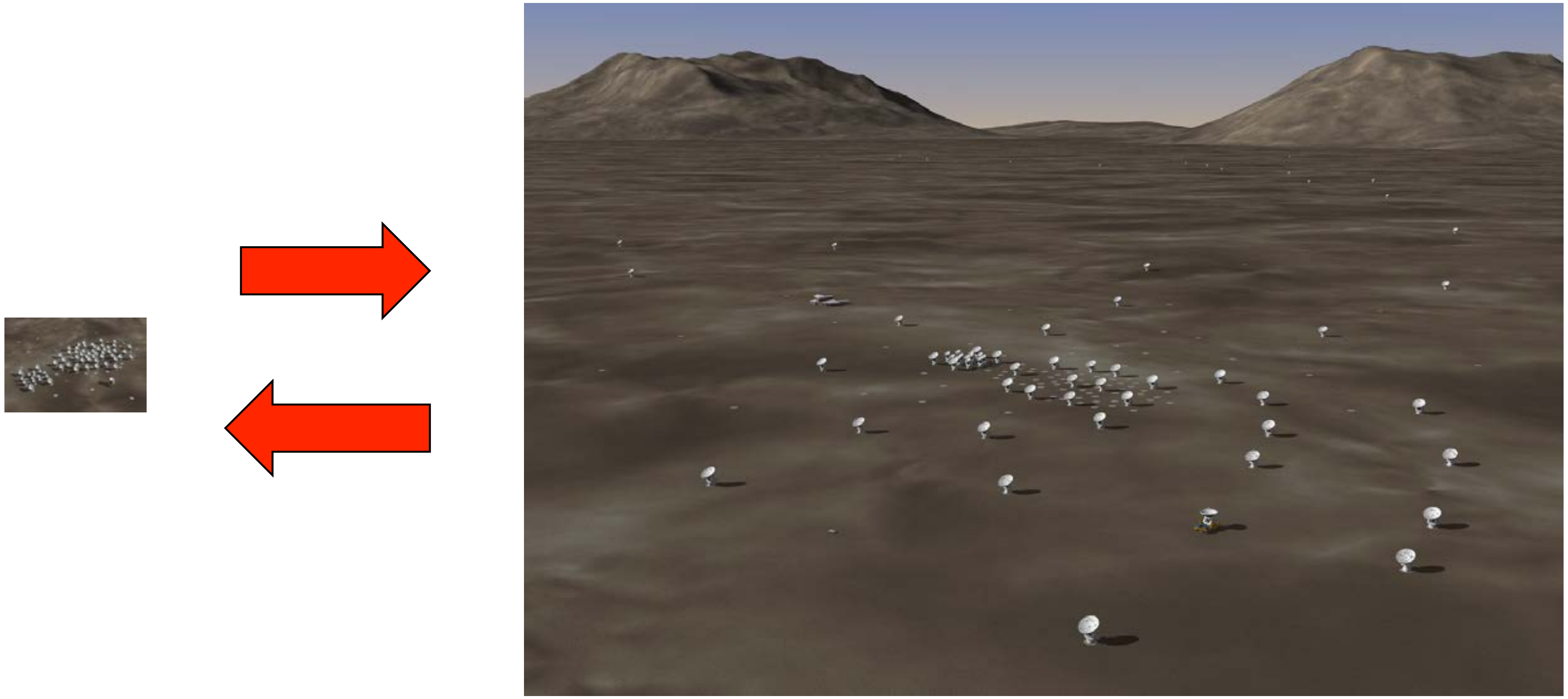


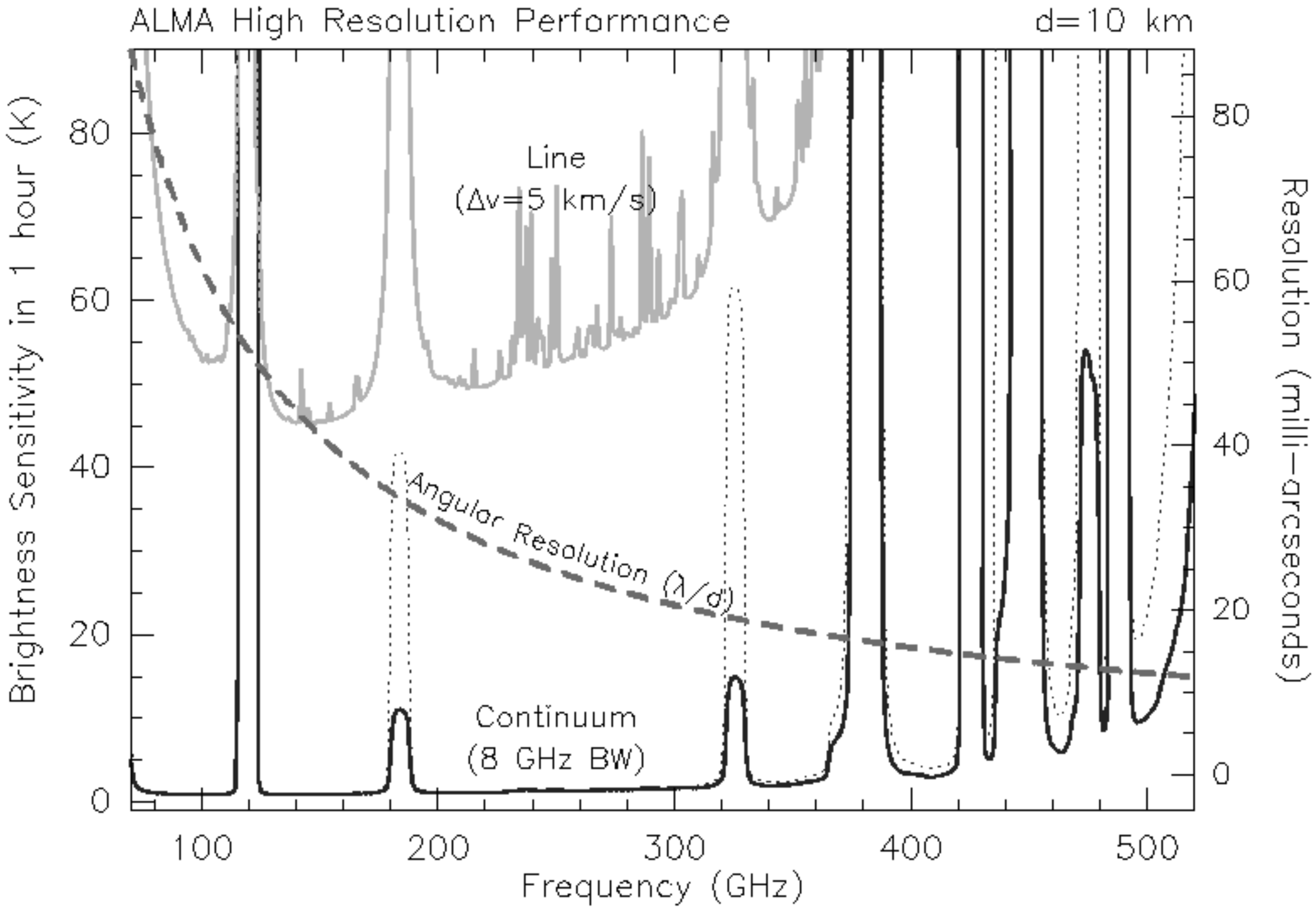




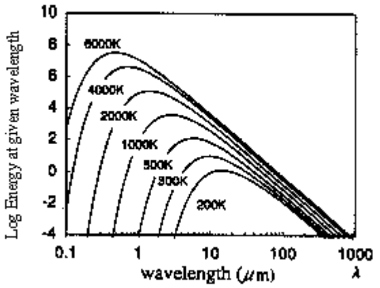
Takakuwa et al. 2006

A giant zoom lens




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)

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



Black Body Radiation

$$S_\nu(\mathrm{mJy}) = \frac{2k}{\lambda^2}\int T_B\, d\Omega$$

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

$$\Rightarrow \Delta T_B(K) \approx 20\Delta S(\mathrm{mJy}) \text{ for } \theta = 20 \text{ mas}, \ \ \nu = 345 \text{ GHz}$$

$$\approx 8\ 10^{-3}\Delta S(\mathrm{mJy}) \text{ for } \theta = 1 \ \text{ arcsec}$$

ALMA at 345 GHz in 1 h:

ΔS = 3 mJy at $\Delta\nu$ = 1 MHz (0.87 km/s)

→ ΔT = 60 K (20 mas FWHM)

= 0.022 mJy at $\Delta\nu$ = 16 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 (incl. adaptive calibration)**
- **the composition of its its molecular photosphere**
- **element depletion during dust formation**
- **the acceleration of the envelope**
- **the complex photochemistry of the outer envelope**

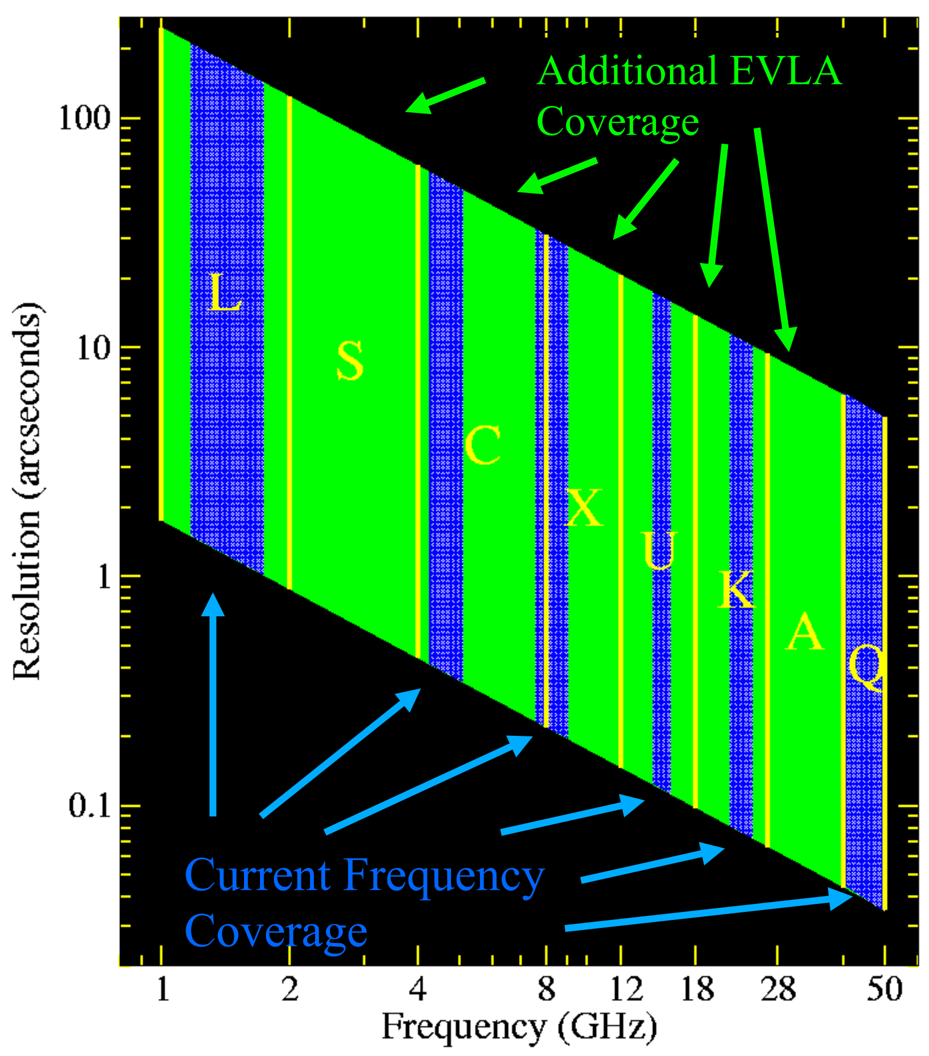
The Very Large Array (VLA)

- **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)

JVLA 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.



©Rick Perley@NRAO

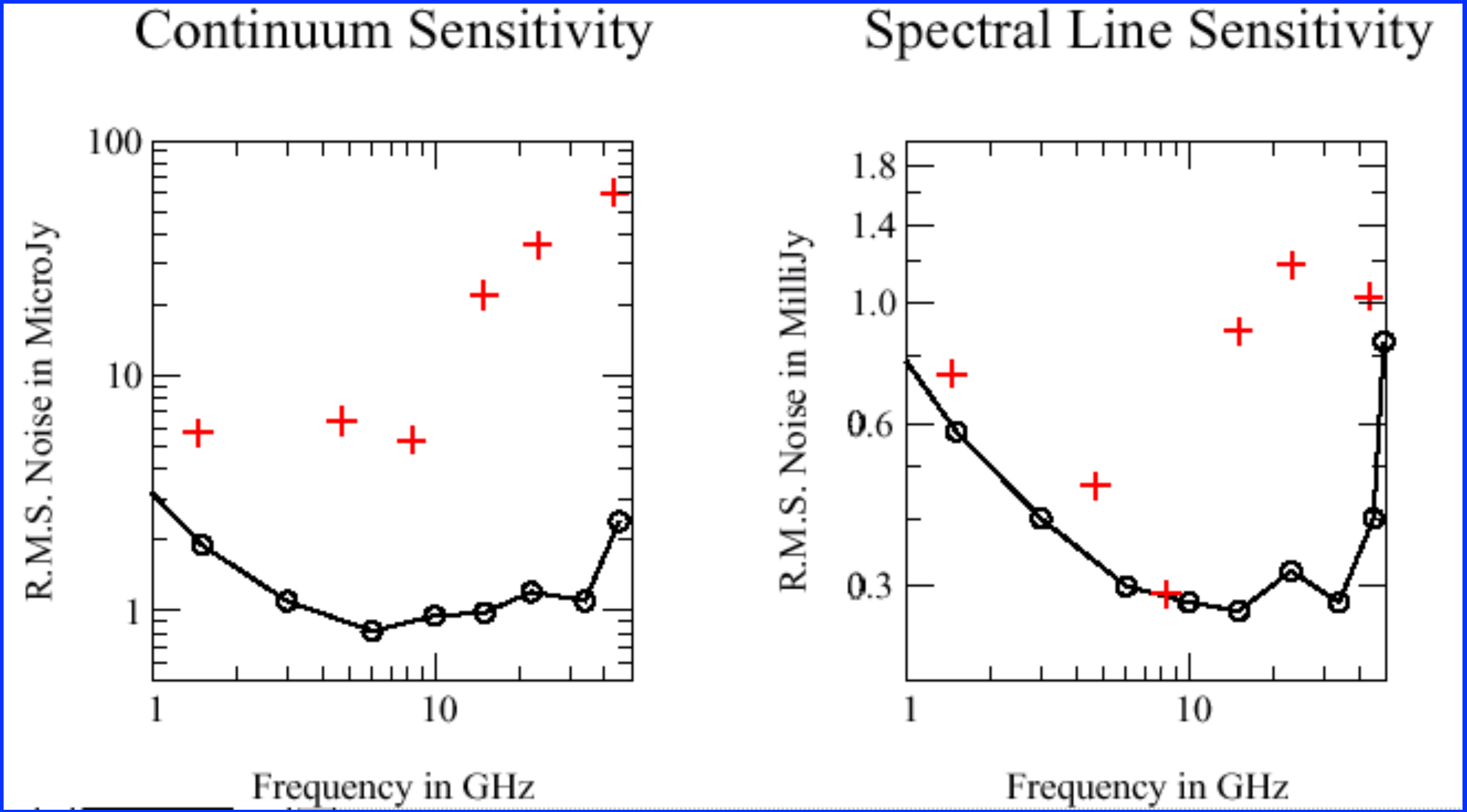
JVLA-I Performance Goals

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

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

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

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

$$\Rightarrow \Delta T(K) = 330\ S_\nu(\mathrm{mJy}) \text{ for } \theta = 40 \text{ mas}, \ \nu = 43 \text{ GHz}$$

$$= 1.8 S_\nu(\mathrm{mJy}) \text{ for } \theta = 1 \text{ arcsec}, \ \nu = 43 \text{ GHz}$$

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

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

⇒ non-maser emission from innermost CSEs

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

$$\Rightarrow \Delta T(K) = 330\ S_\nu(\mathrm{mJy})\ \text{ for } \theta = 40\ \text{mas},\ \ \nu = 43\ \text{GHz}$$

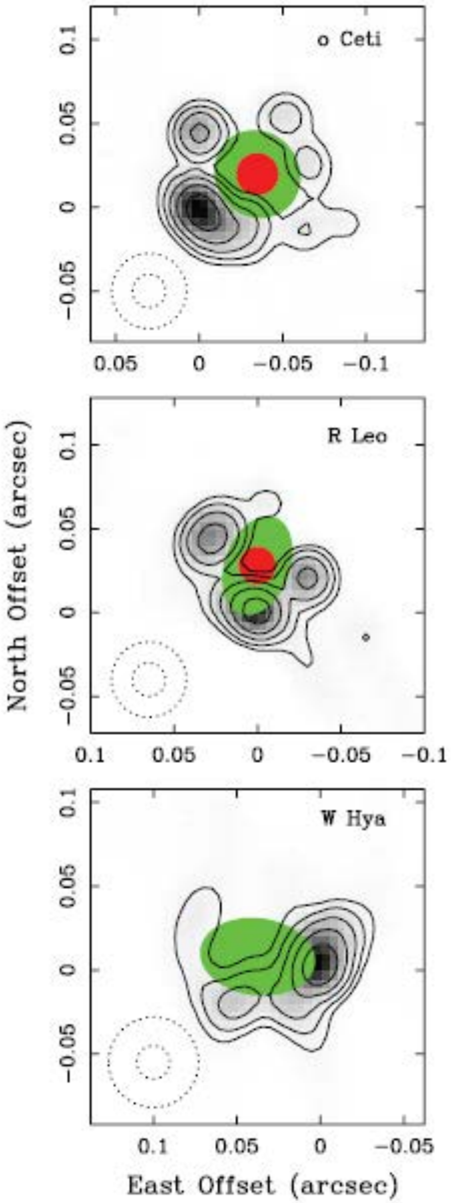
$$= 1.8 S_\nu(\mathrm{mJy})\ \text{ for } \theta = 1\ \text{arcsec},\ \ \nu = 43\ \text{GHz}$$

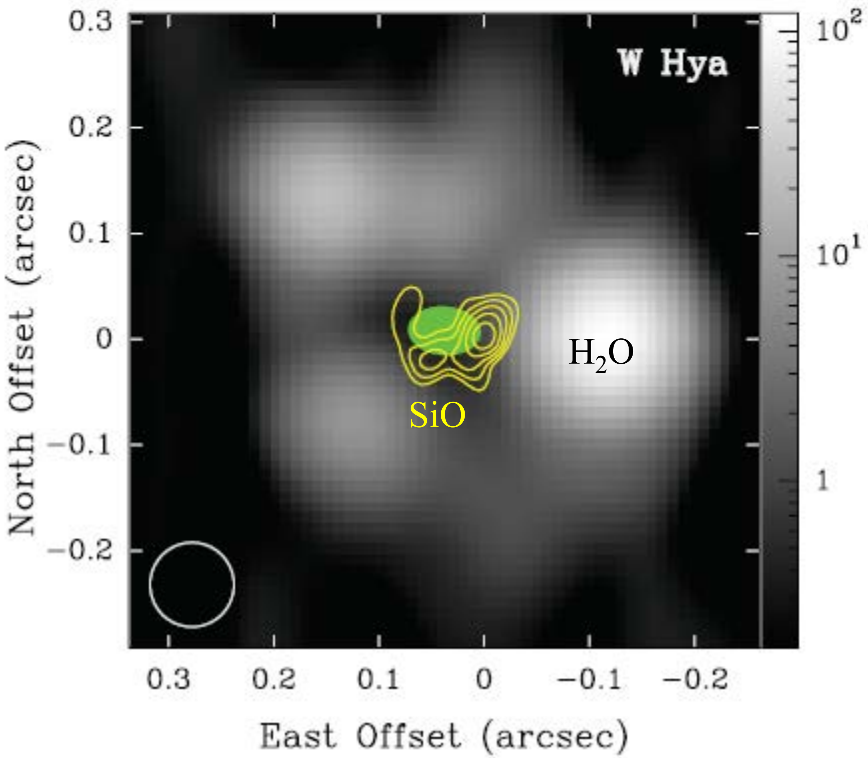
If all lines of a species are optically thick, their flux densities scale as ν^2.

⇒ cm lines weaker than (sub)mm lines

→ need for spectral multiplexing

EVLA resolution inadequate for detailed imaging of (radio) photopheres

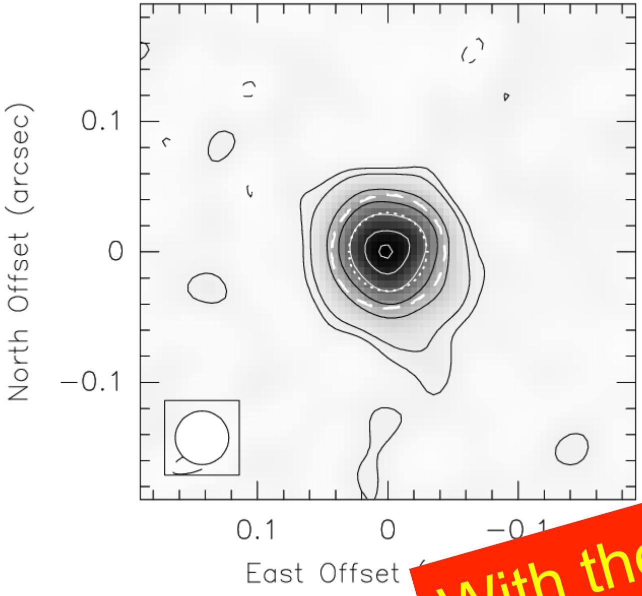




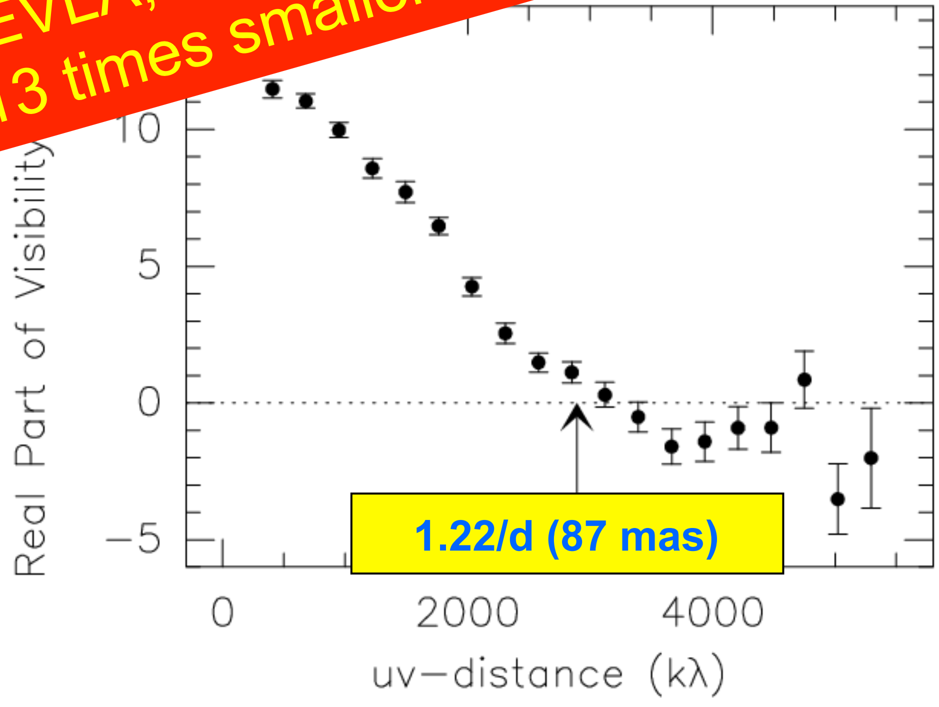
Reid & Menten 1991, 2007

IRC+10216 (= CW Leo)

VLA A-array



With the EVLA, error bars will be ≈13 times smaller

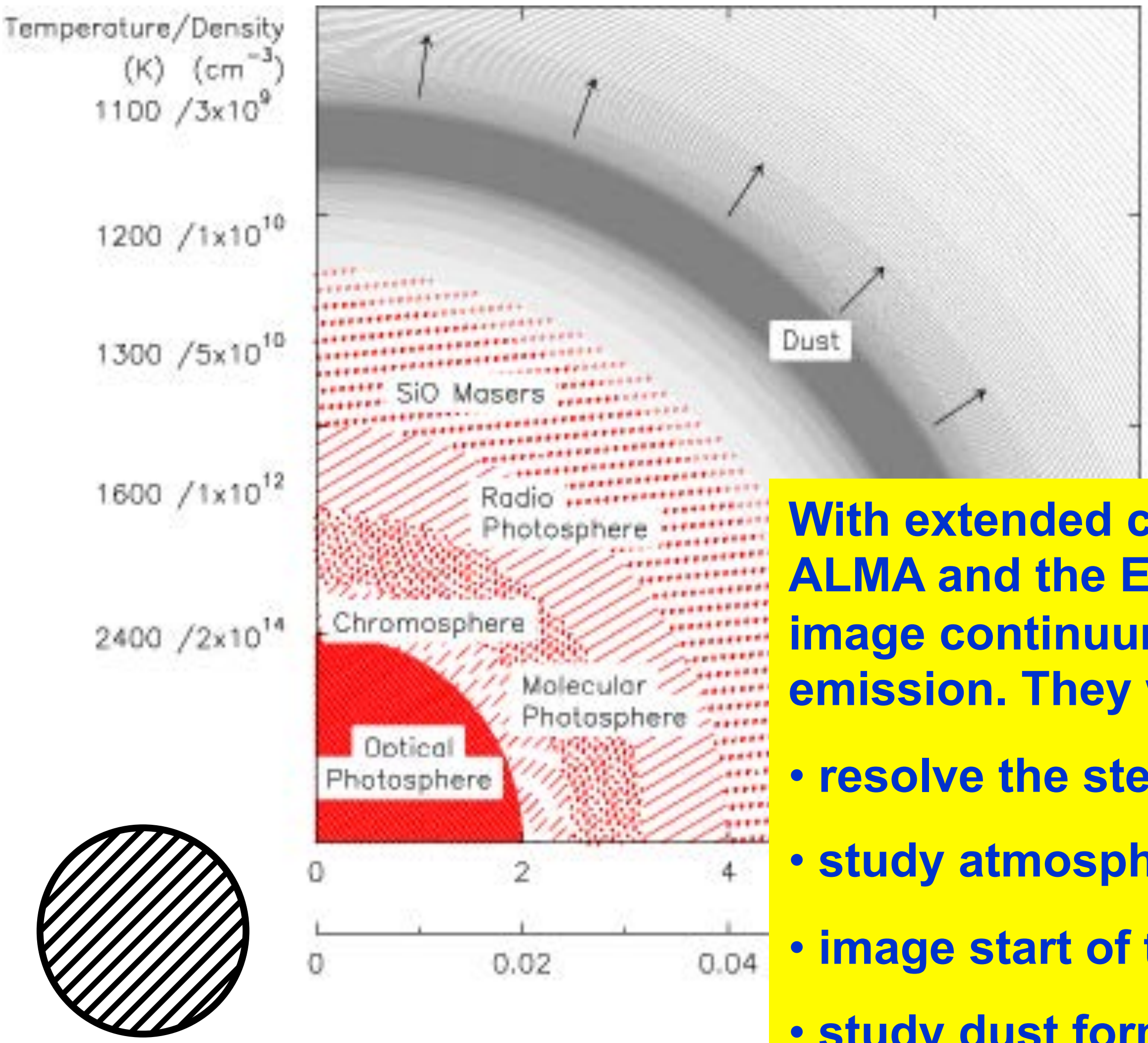


T_B = 1640 K

L = 8.8 10^3 $L_\odot$

Menten, Reid, Kaminski & Claussen 2012

High resolution continuum and *thermal* line imaging

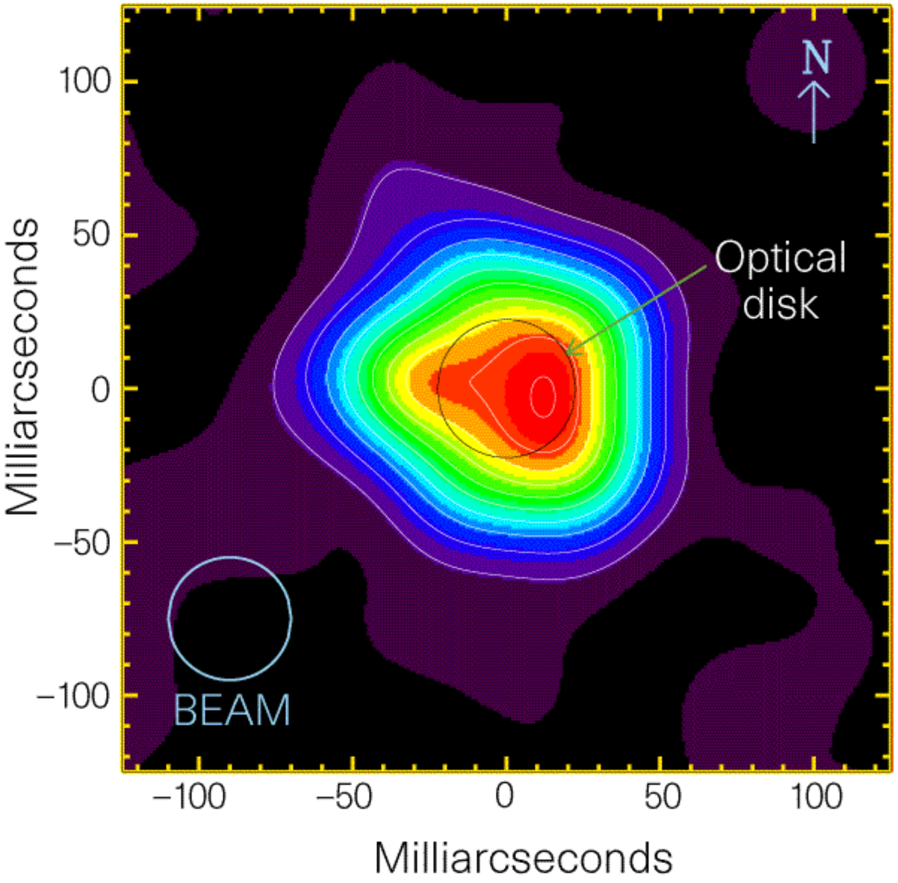


With extended configurations, ALMA and the EVLA will be able image continuum and *thermal* line emission. They will:

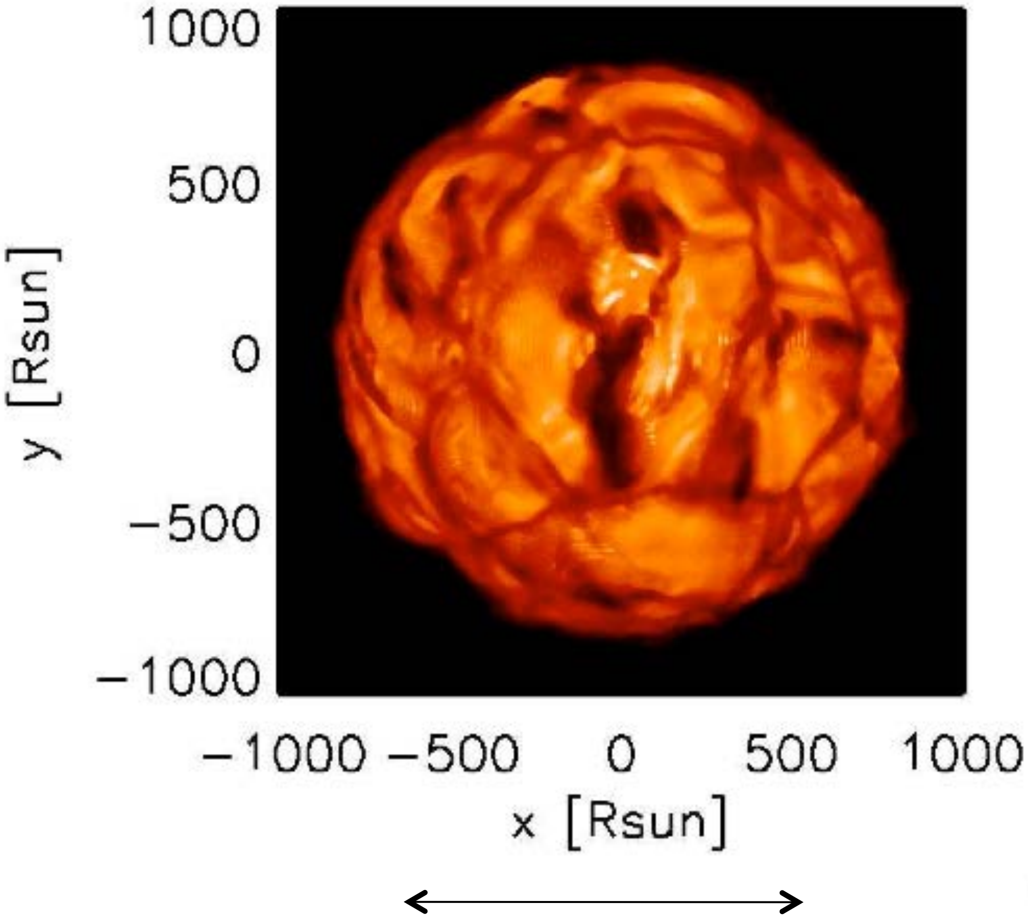
- **resolve the stellar photosphere**
- **study atmospheric chemistry**
- **image start of the outflow**
- **study dust formation and depletion**

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

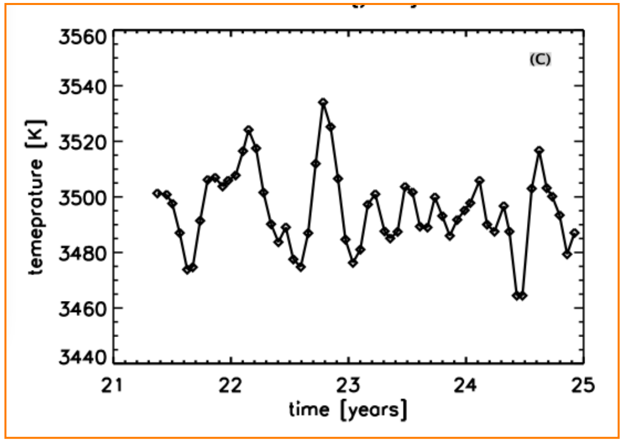
Lim et al. 1998



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

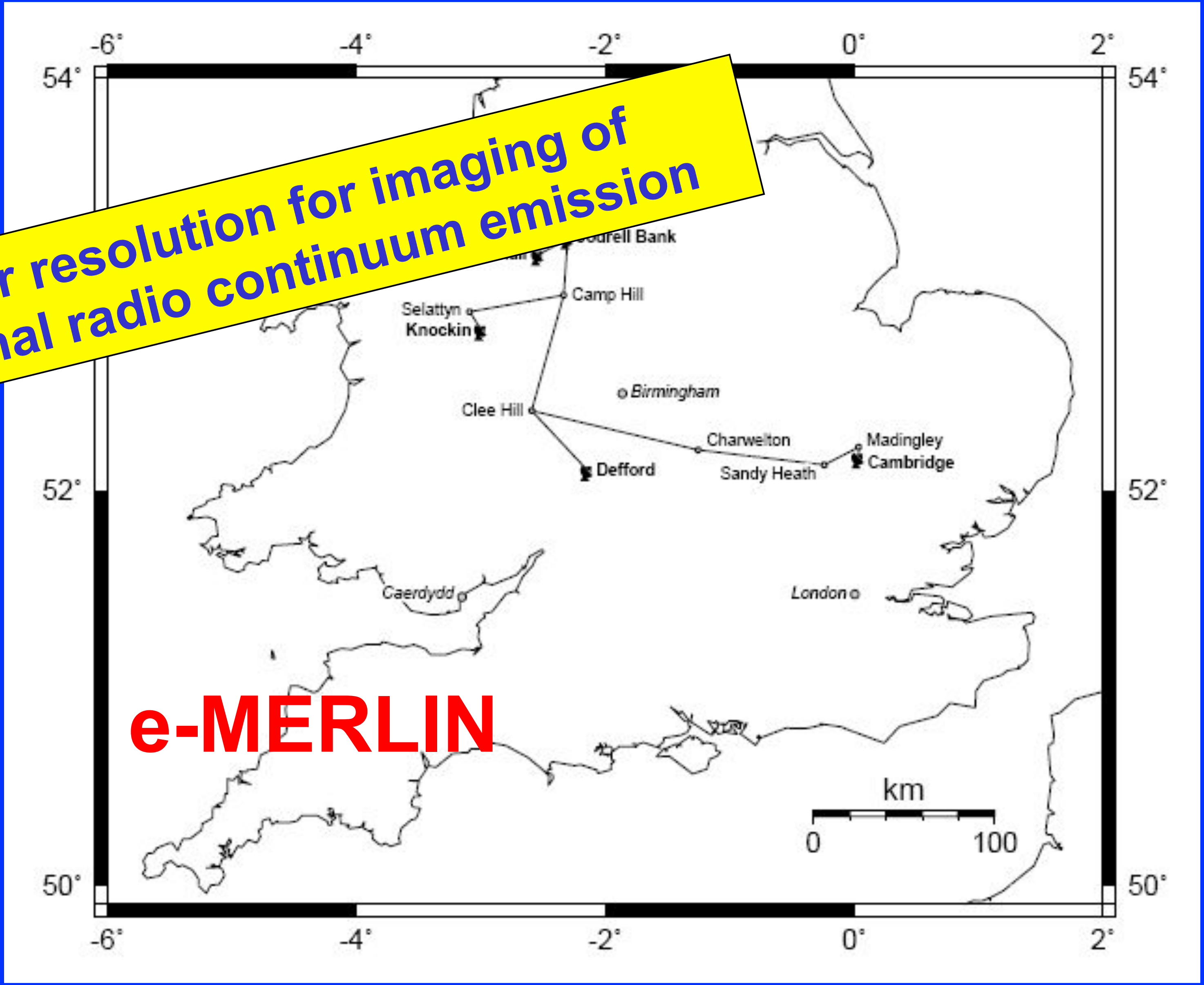


10 mas@1 kpc



Chiavassa, Plez, Josselin, & Freytag 2009

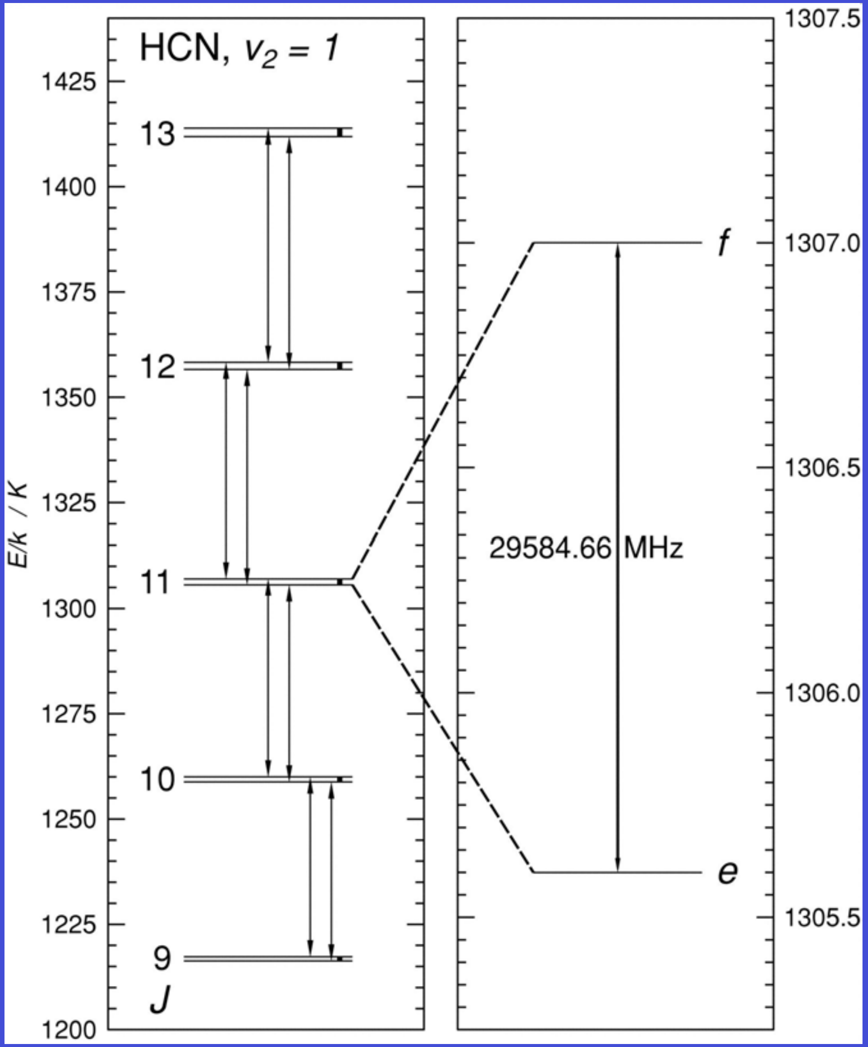
Higher resolution for imaging of thermal radio continuum emission



e-MERLIN

Longest baseline: 217 km (= 6 x VLA)

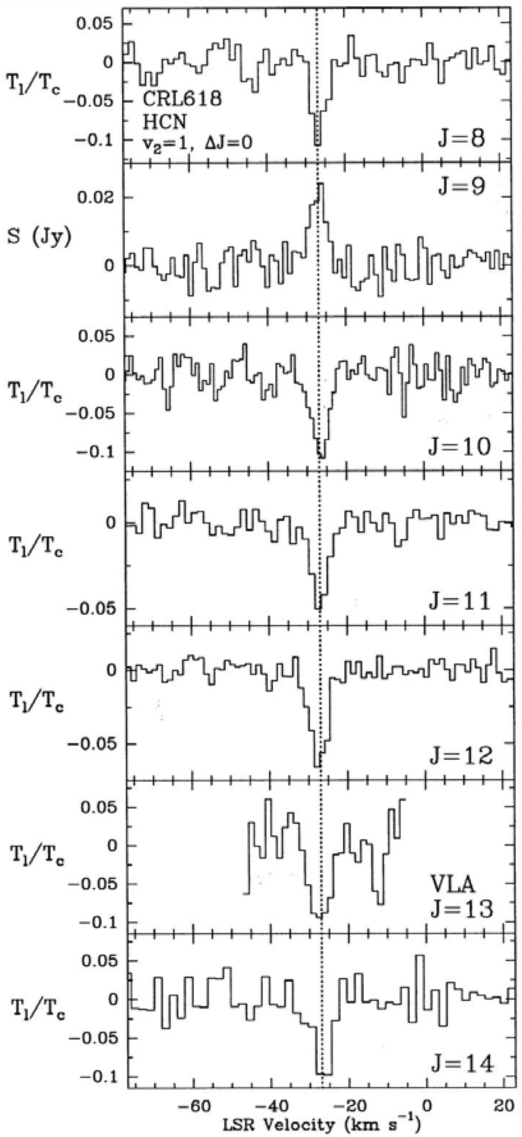
Non-maser observations of circumstellar chemistry with the JVLA –
Some examples



HCN *l*-type transitions

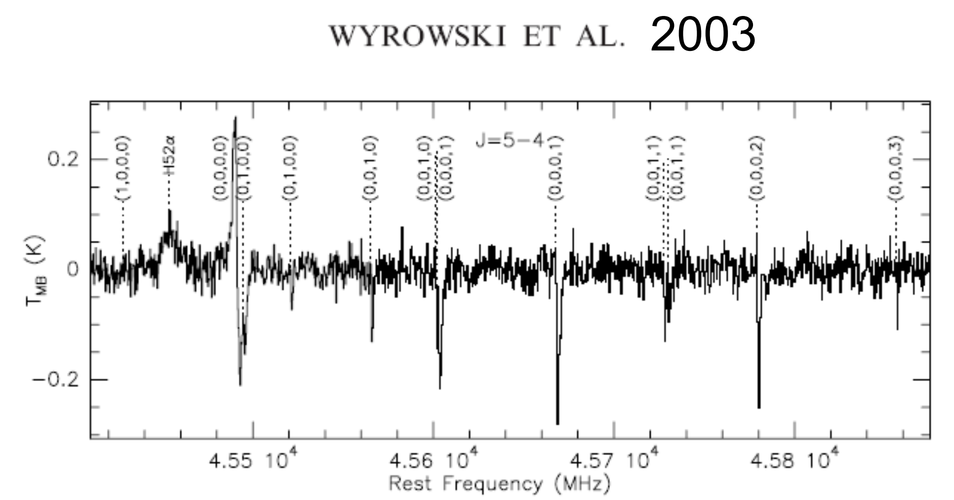
ν(GHz)	E(K)/1.44	*J*
1346.7652	720.8477	2
2693.3388	729.7156	3
4488.4723	741.5391	4
6731.9105	756.3180	5
9423.3348	774.0518	6
12562.3629	794.7403	7
16148.5495	818.3829	8
20181.3862	844.9789	9
24660.3100	874.5279	10
29584.6600	907.0291	11
34953.7600	942.4816	12
40766.9000	980.8848	13
47023.2000	1022.2376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

CRL 618

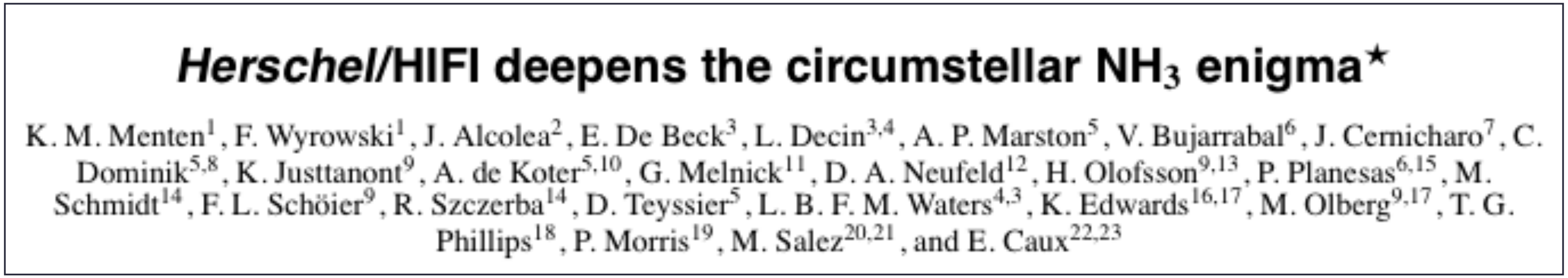


HCN

Thorwirth et al. 2003



HC_3N

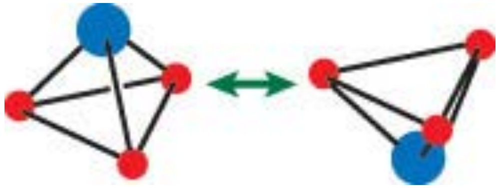


Herschel/HIFI deepens the circumstellar NH$_3$ enigma★

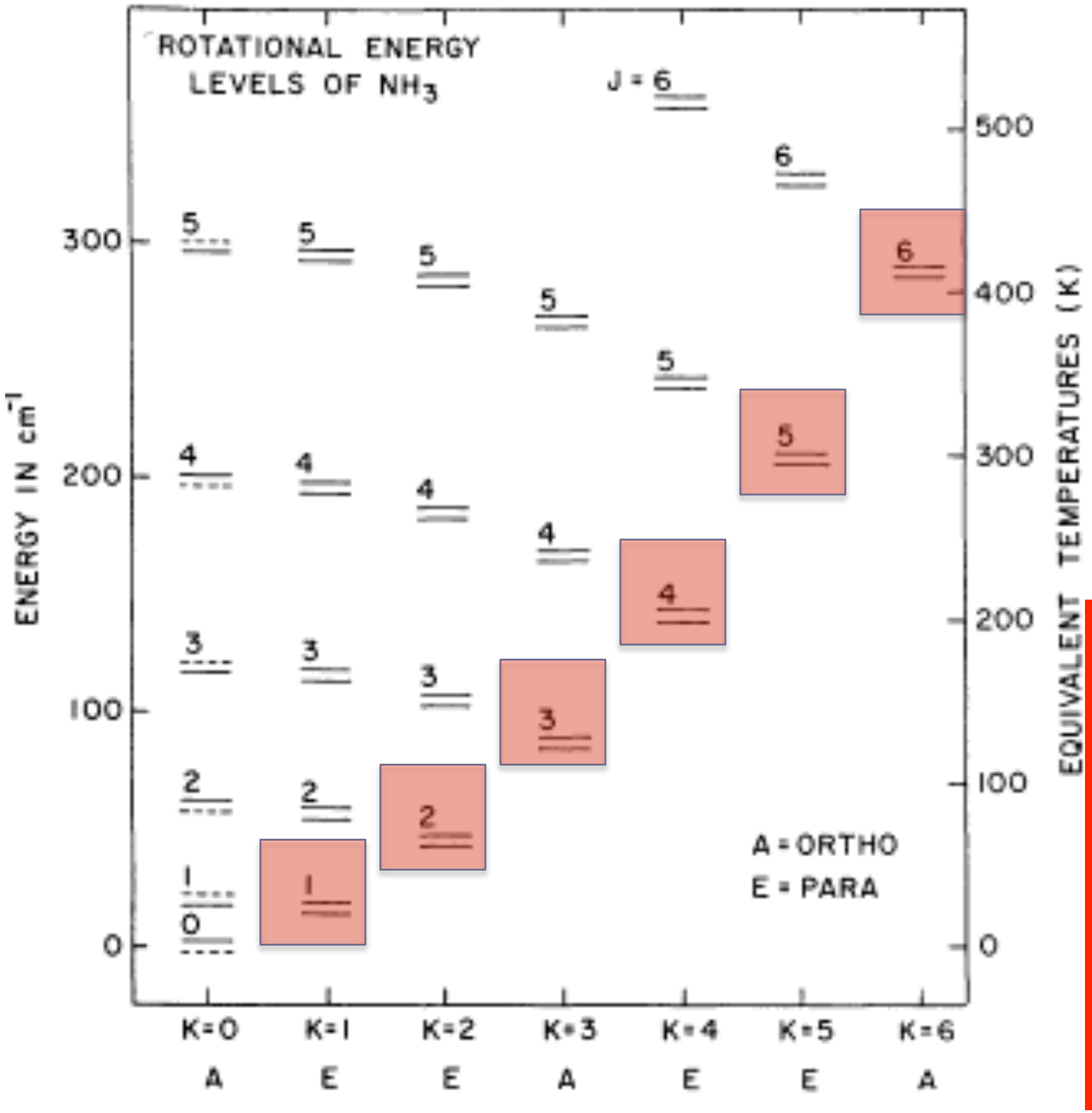
K. M. Menten[1], F. Wyrowski[1], J. Alcolea[2], E. De Beck[3], L. Decin[3,4], A. P. Marston[5], V. Bujarrabal[6], J. Cernicharo[7], C. Dominik[5,8], K. Justtanont[9], A. de Koter[5,10], G. Melnick[11], D. A. Neufeld[12], H. Olofsson[9,13], P. Planesas[6,15], M. Schmidt[14], F. L. Schöier[9], R. Szczerba[14], D. Teyssier[5], L. B. F. M. Waters[4,3], K. Edwards[16,17], M. Olberg[9,17], T. G. Phillips[18], P. Morris[19], M. Salez[20,21], and E. Caux[22,23]

Only negligible amounts of ammonia should be formed in the atmospheres of evolved stars

Nevertheless, significant amounts of NH$_3$ have been found in AGB stars, RSGs, PPNe with
- IR heterodyne spectroscopy
- Radio spectroscopy of inversion lines

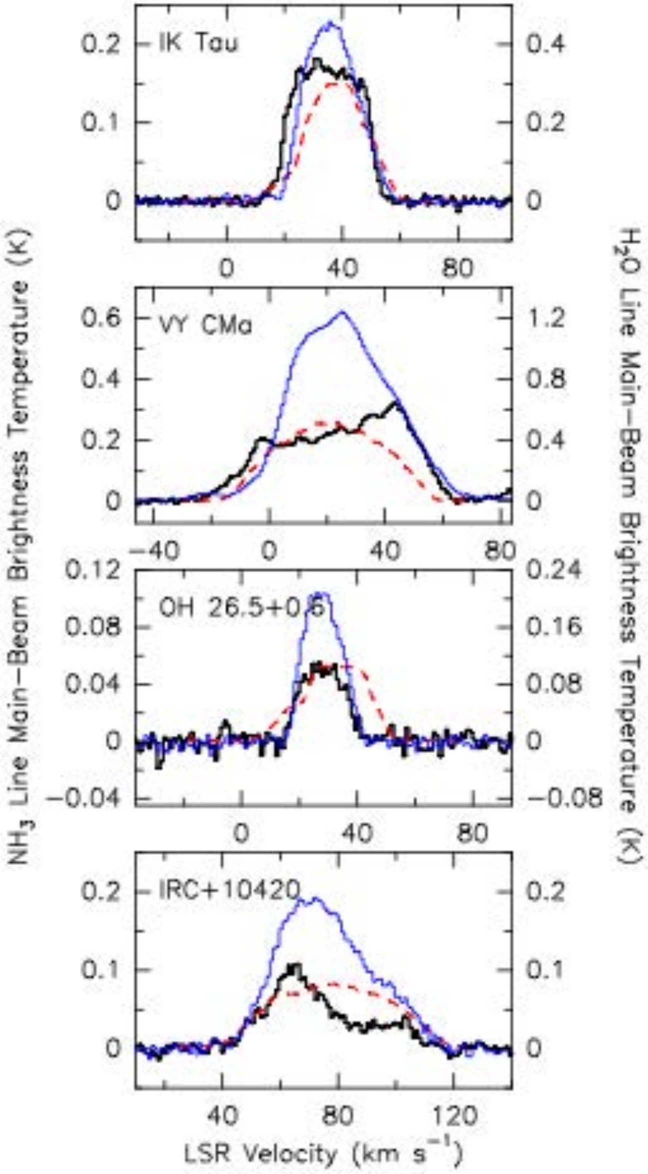


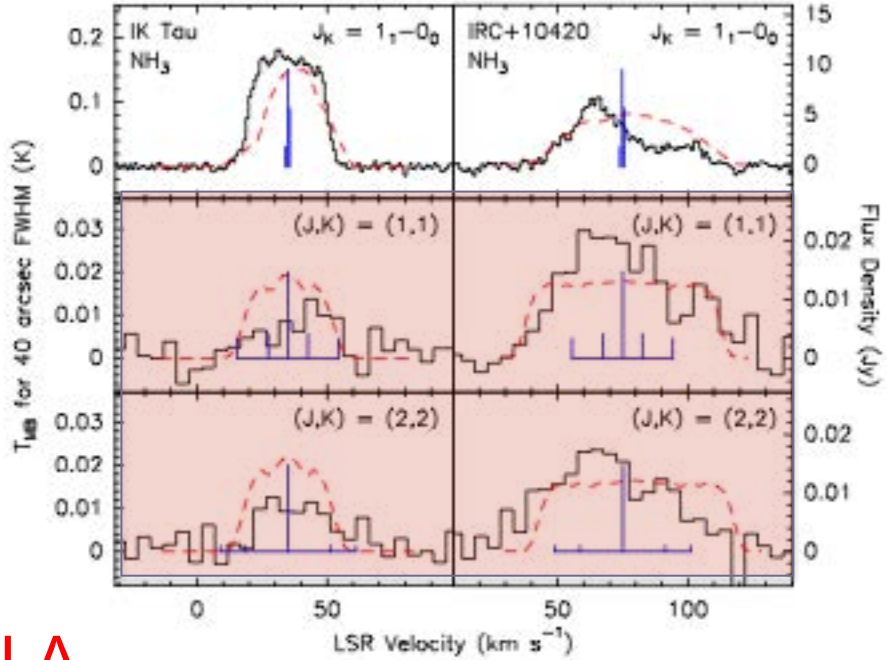
★Part of HIFISTARS GTKP



J = *K* levels

- are metastable
- are thermalized at $T_{rot} \rightarrow T_{kin}$ (Molecular cloud “thermometer”)
- Inversion lines all at similar frequency (23.7 to > 26 GHz)



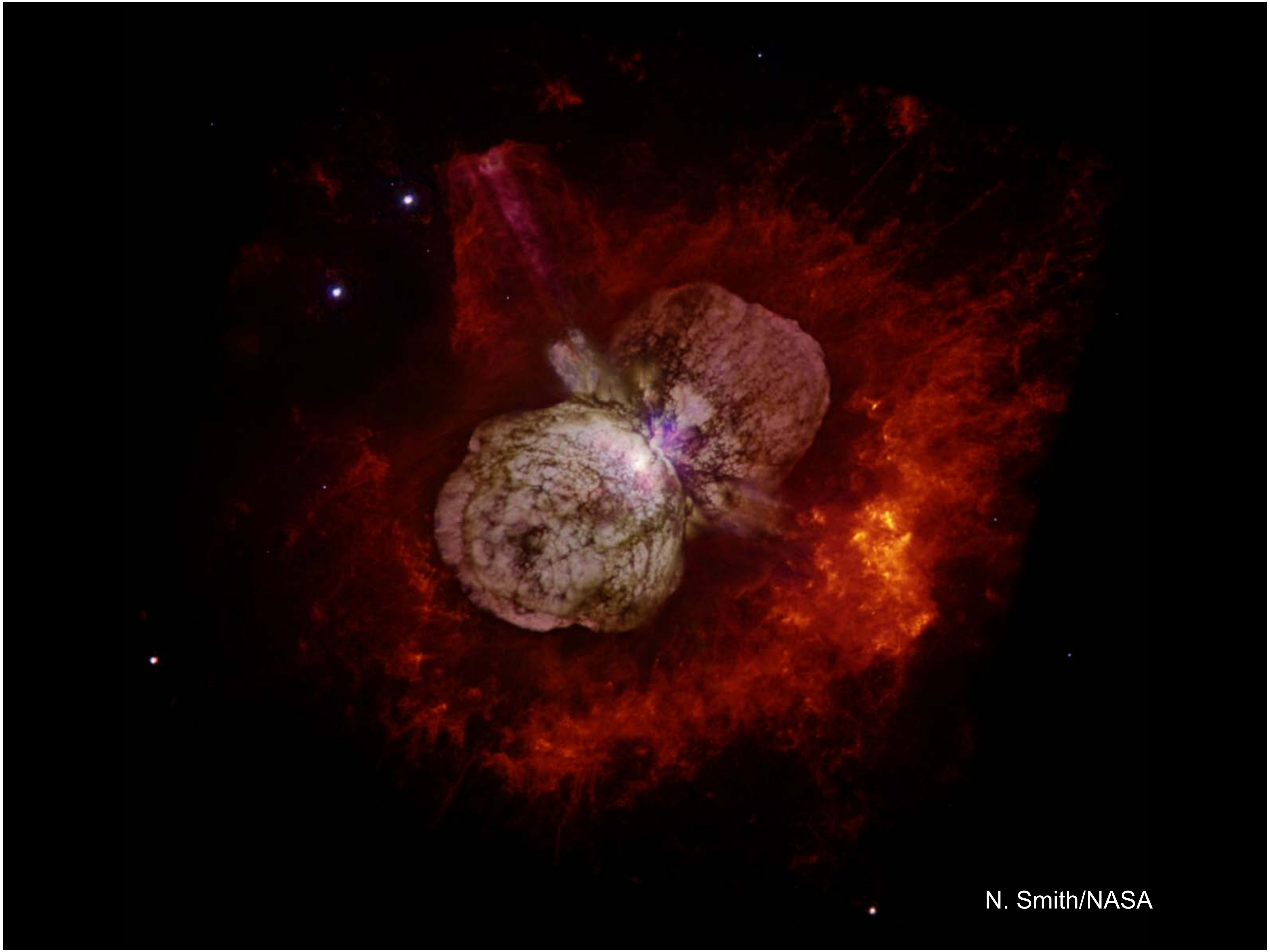


VLA

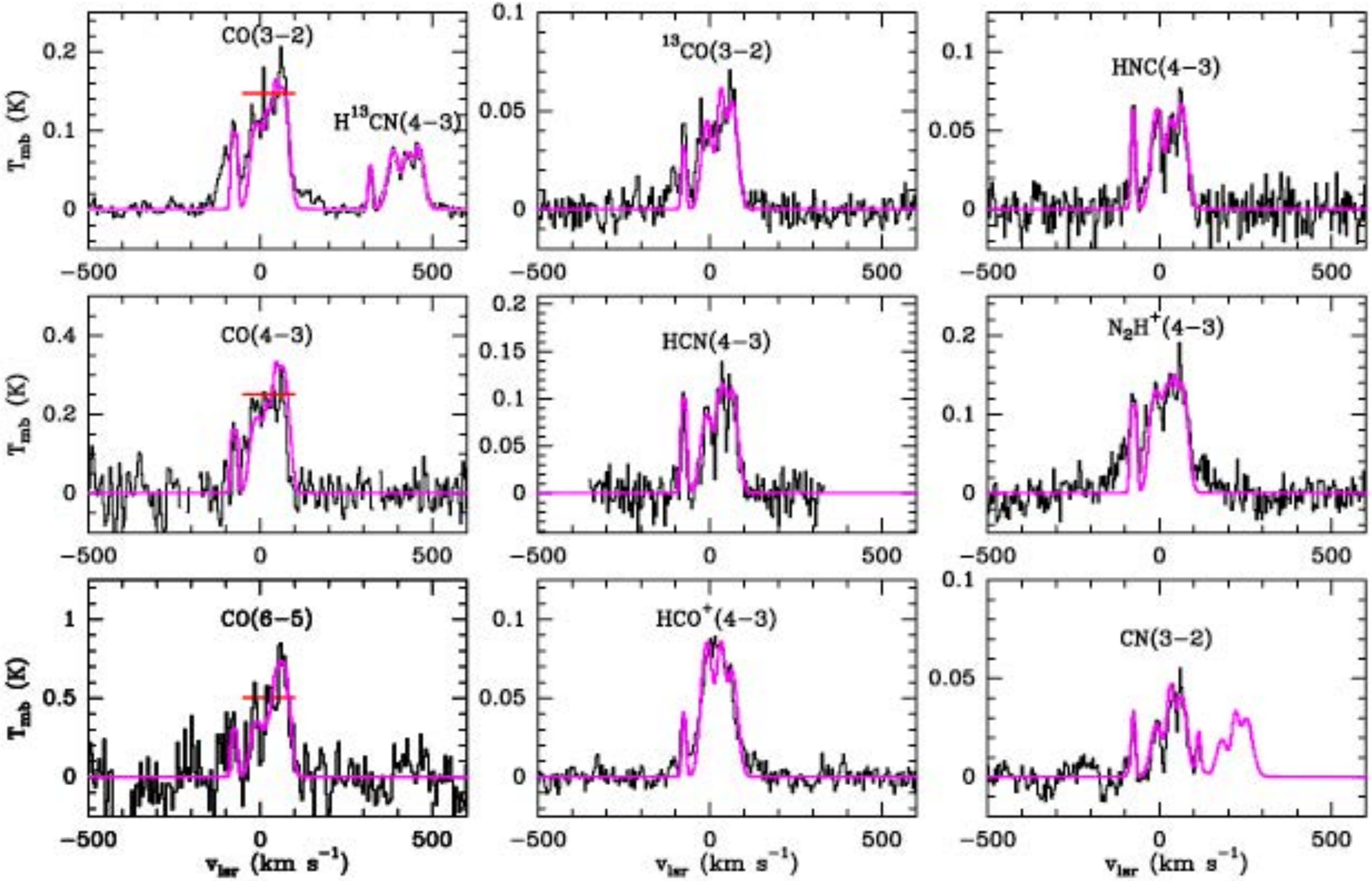
n_{crit} (inv. lines) ~ 10^4 cm^{-3}
n_{crit} (rot. line) ~ 10^8 cm^{-3}

$[NH_3/H_2] = 2\ 10^{-7} – 3\ 10^{-6}$

Menten et al. 2010



N. Smith/NASA



[HCN/H^{13}CN] = 2,
[CO/^{13}CO] = 5

Loinard et al. 2012

Their wide bandwidth and advanced spectroscopic capability will make allow ALMA and the EVLA to image the radio photospheres of nearby stars and make important contributions to circumsteller astrochemistry

Their adequate (JVLA) 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