An Interferometric 270–355 GHz Spectral Line Survey of the Red Supergiant VY CMa

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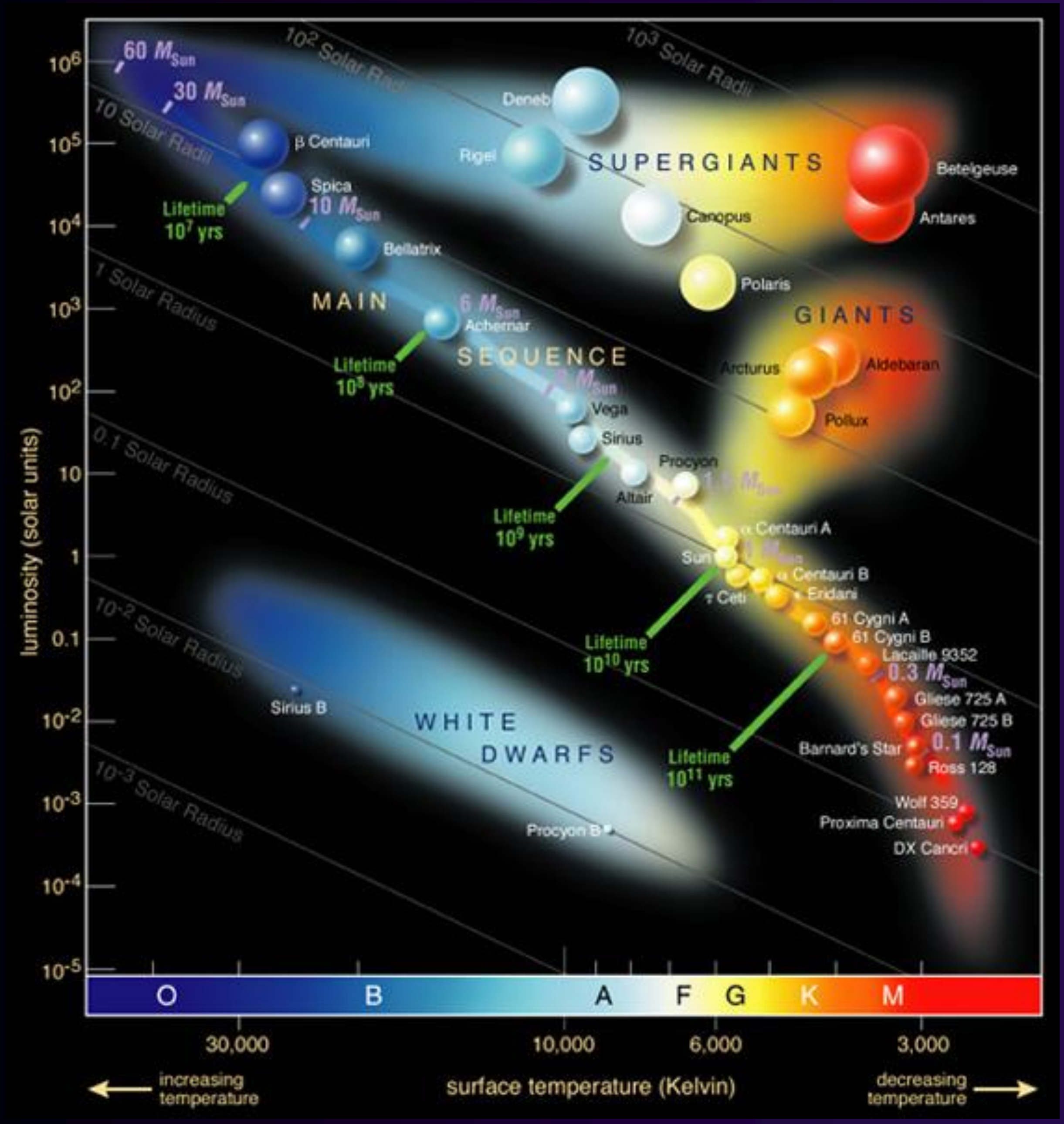
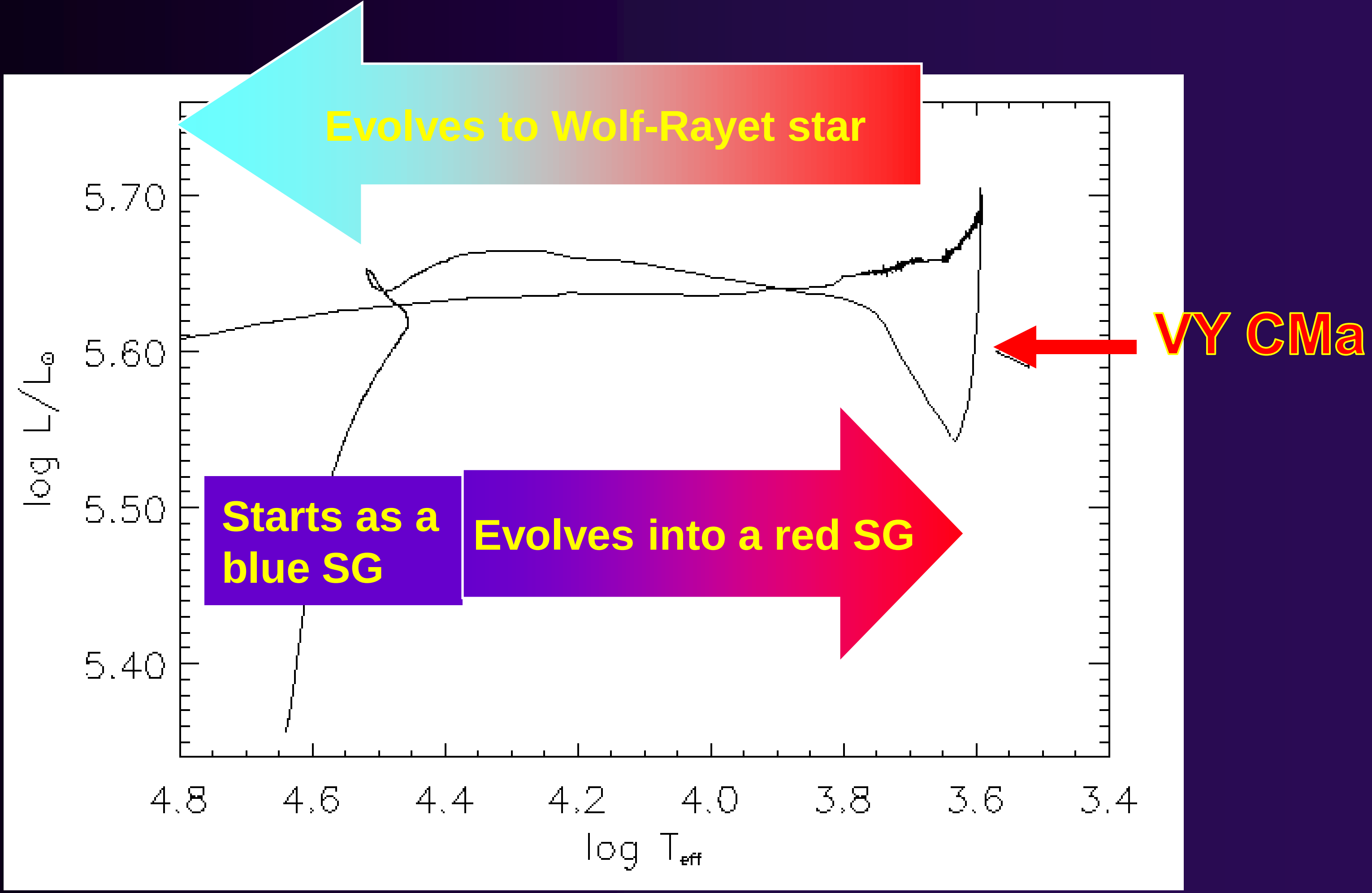
Toledo, ES/2011 May 31



SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Evolution of a 40 solar mass star



from Wittkowski, Weigelt, Langer 1998

VY CMa

- is fabulously luminous
  → 1 – 3 10^5 $L_\odot$
    - probably the most (near) IR luminous star known
    - one of the most largest and luminous stars known
- and massive
  → (peak) mass 40 $M_\odot$ (current mass 15 $M_\odot$)

  Wittkowski, Weigelt, & Langer 1998
- has an immense mass-loss rate
  → 1 – 2 10^{-4} $M_\odot$/yr

  Monnier et al. 1999; Harwit et al. 2001
- Is HUGE → ∅=25 mas (=23 mas) > ∅ Saturn orbit!!!
- will probably go supernova within next ~10^4 yr

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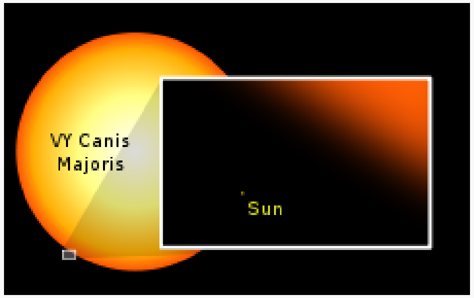
VY Canis Majoris

From Wikipedia, the free encyclopedia

Coordinates: 07h 22m 58.33s, −25° 46′ 03.17″

VY Canis Majoris (**VY CMa**) is currently the largest known star and also one of the most luminous. Located in the constellation Canis Major, it is a red hypergiant, between 1800 and 2100 solar radii, 8.4–9.8 astronomical units, 3.063 billion km or 1.7 billion miles in diameter, and about 1.5 kiloparsecs (4,900 light years, 4.6×10^{16} km or 2.9×10^{16} mi) away from Earth. Unlike most hypergiant stars, which occur in either binary or multiple star systems, VY CMa is a single star. It is categorized as a semiregular variable and has an estimated period of 2000 days. The actual size of VY Canis Majoris is 3,063,500,000,000m or 3.06 Tm (Terametre),[5] giving it an average density of 0.000005 to 0.000010 kg/m^3.

VY Canis Majoris



Size comparison between the Sun and VY Canis Majoris

Contents [hide]

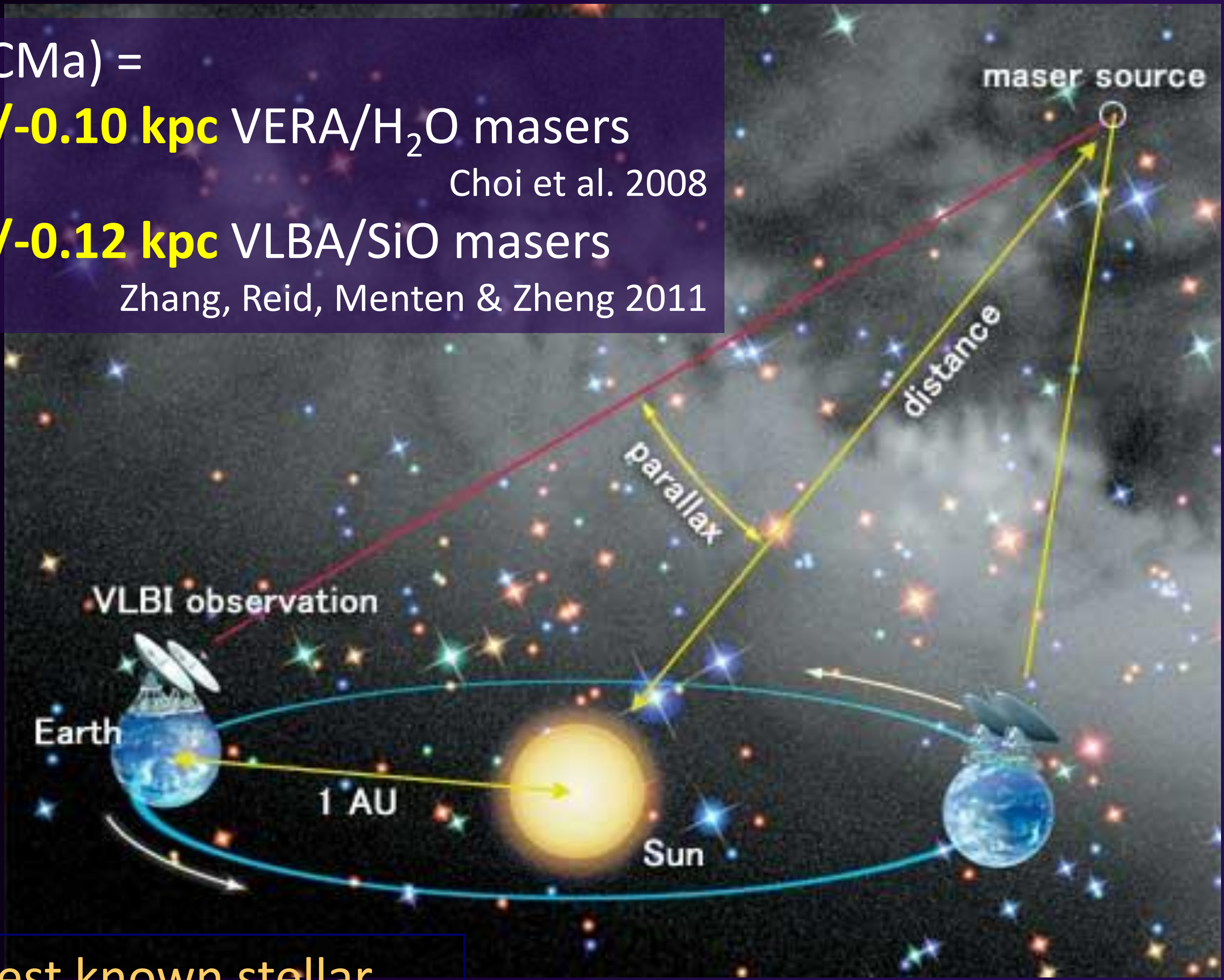
D(VY CMa) =

1.14+/-0.10 kpc VERA/H_2O masers

Choi et al. 2008

1.20+/-0.12 kpc VLBA/SiO masers

Zhang, Reid, Menten & Zheng 2011



Strongest known stellar OH, H_2O and SiO masers

http://veraserver.mtk.nao.ac.jp/outline/vera2-e.html

Why study VY CMa?

- Mass return into interstellar medium
- Study stellar birth and death in the same molecular cloud
- Stellar evolution: Study precursor of
  - Wolf-Rayet star
  - core-collapse supernova (asymmetries in envelope)

Why study VY CMa (II)?

- Great source for molecular and solid-state spectroscopy
$\rightarrow$ high quality circumstellar chemistry and mineralogy

- VY CMa is for O-rich stars what IRC+10216 is for C-rich stars and has a
    - > 10 x higher luminosity and a
    - 10 x higher mass-loss rate

BUT

- it is 10 x farther away and
- is has more O than C (which drives IRC+10216's extremely rich chemistry)

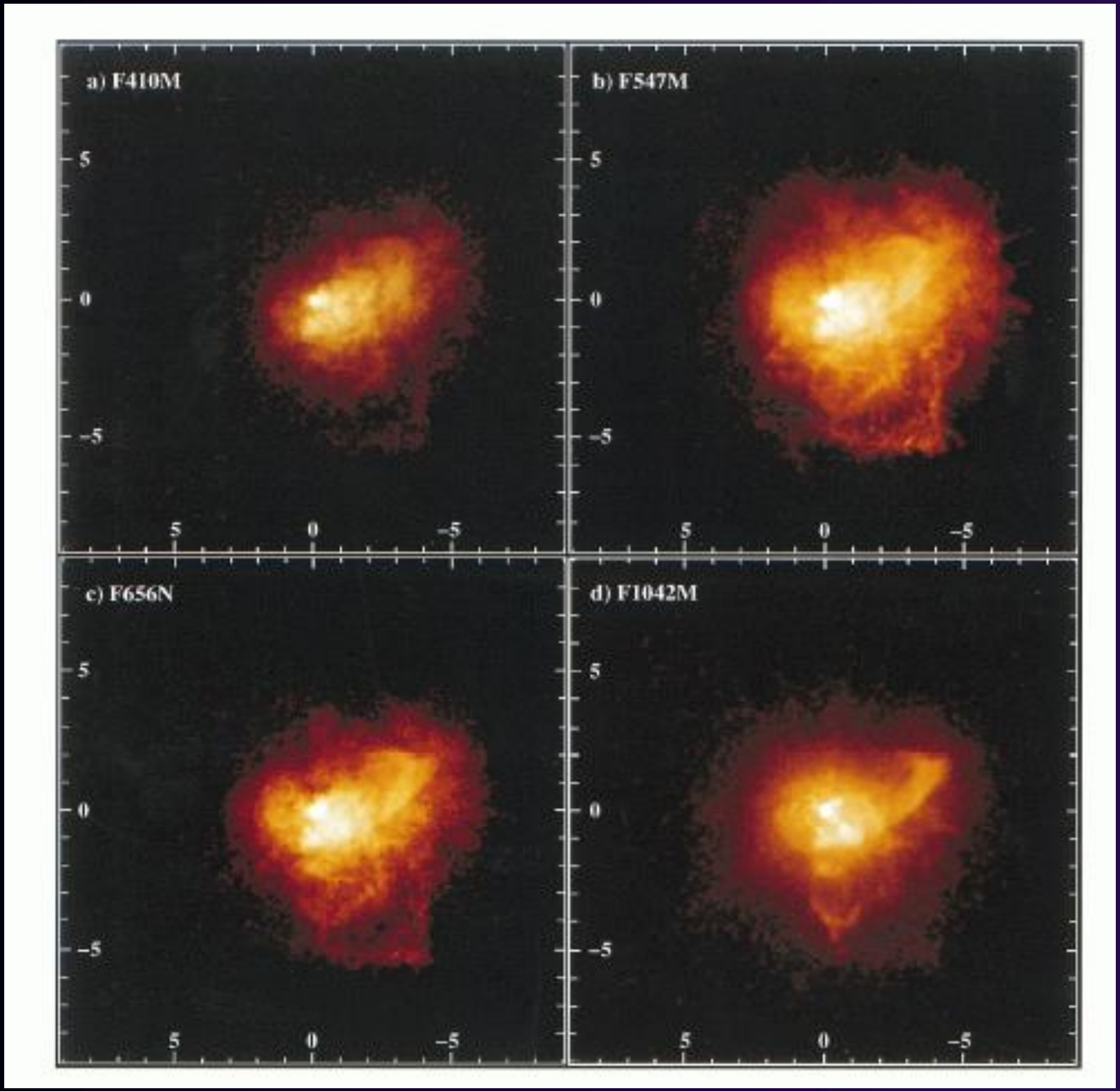
Peculiarities…

- Metal and metal oxide lines are seen in **emission:** Na I, K I, Ca I and TiO, ScO, VO bandheads

Herbig 1970

⇒ dense, warm and extended circumstellar region

VY CMa – High Resolution Optical/IR Imaging

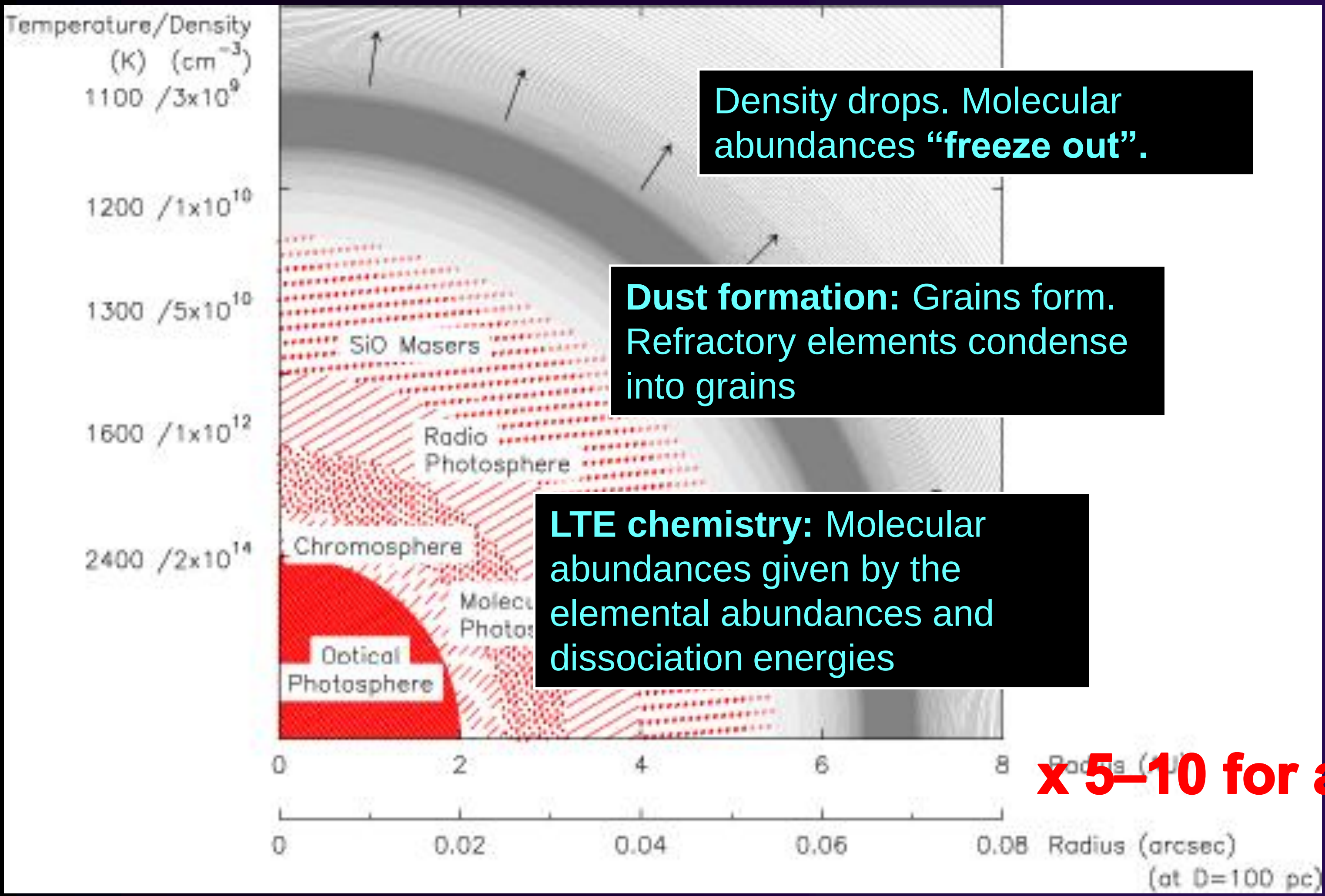


HST/WFPC2

N. Smith et al. 2001

Molecules in the dense circumstellar envelopes of red giant AGB stars

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

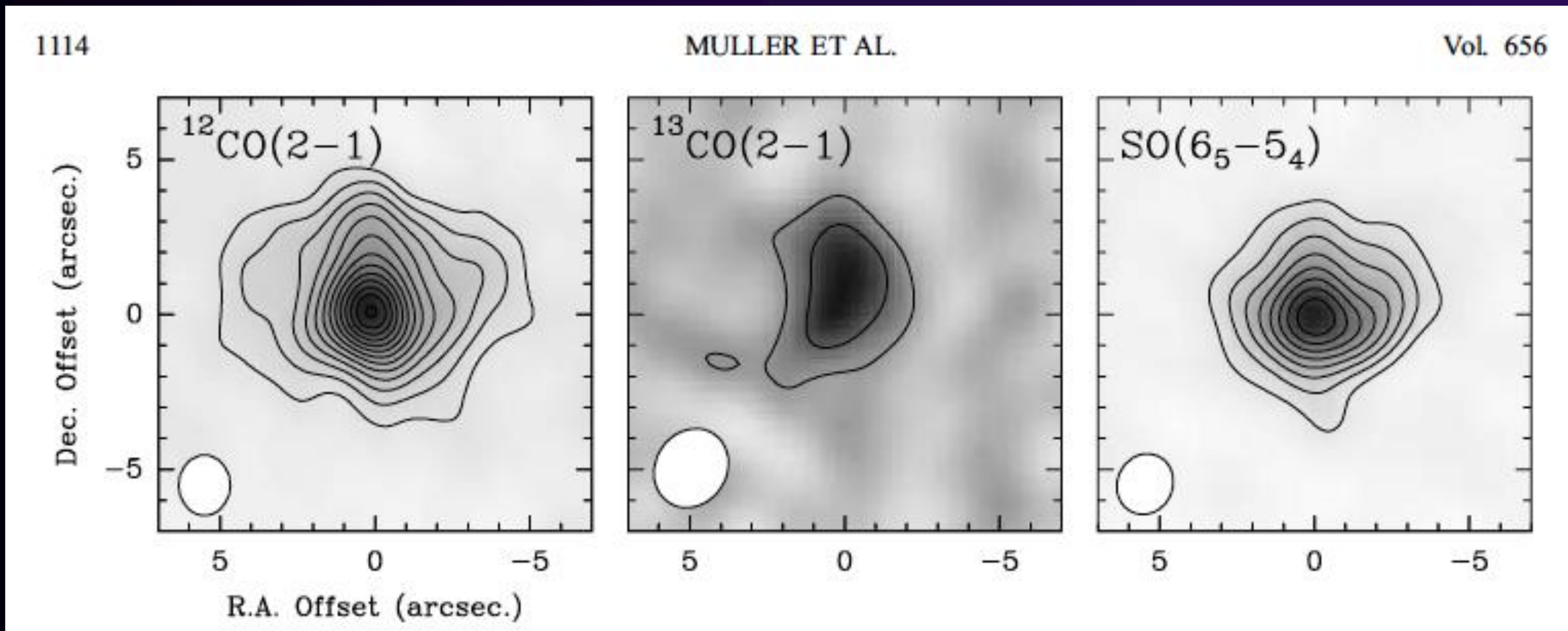


Density drops. Molecular abundances **"freeze out".**

Dust formation: Grains form. Refractory elements condense into grains

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

x 5–10 for a RSG



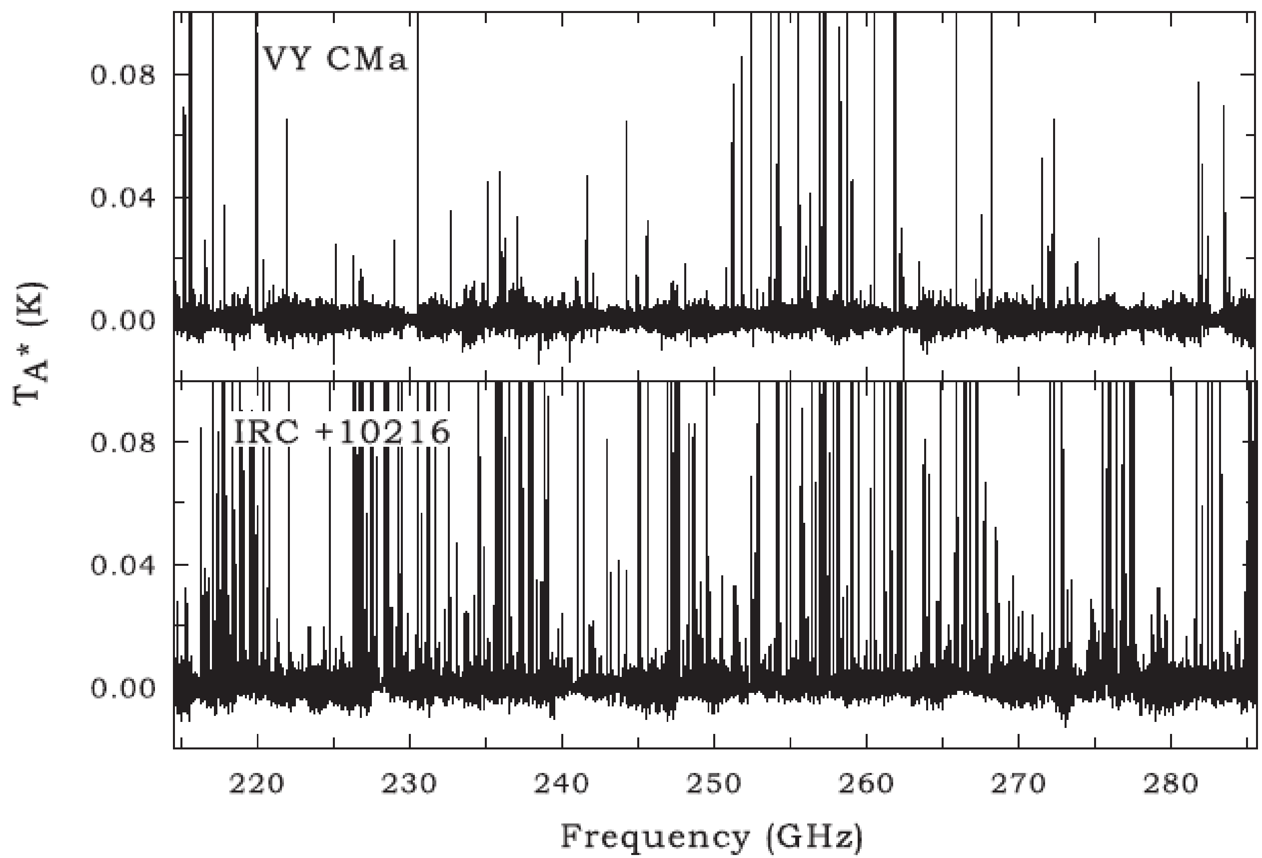
SMA/Muller et al. 2007

The Astrophysical Journal Supplement Series, 190:348–417, 2010 October doi:10.1088/0067-0049/190/2/348

THE ARIZONA RADIO OBSERVATORY 1 mm SPECTRAL SURVEY OF IRC +10216 AND VY CANIS MAJORIS (215–285 GHz)

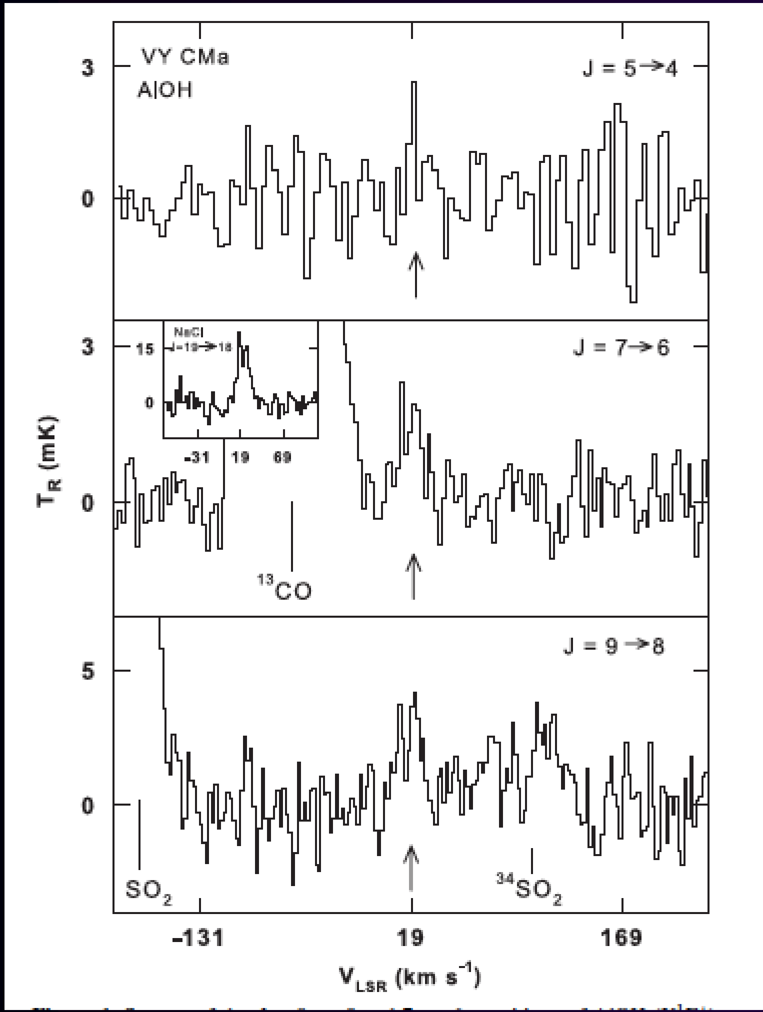
E. D. Tenenbaum[1,2,5], J. L. Dodd[1,2], S. N. Milam[3], N. J. Woolf[1], and L. M. Ziurys[1,2,4]

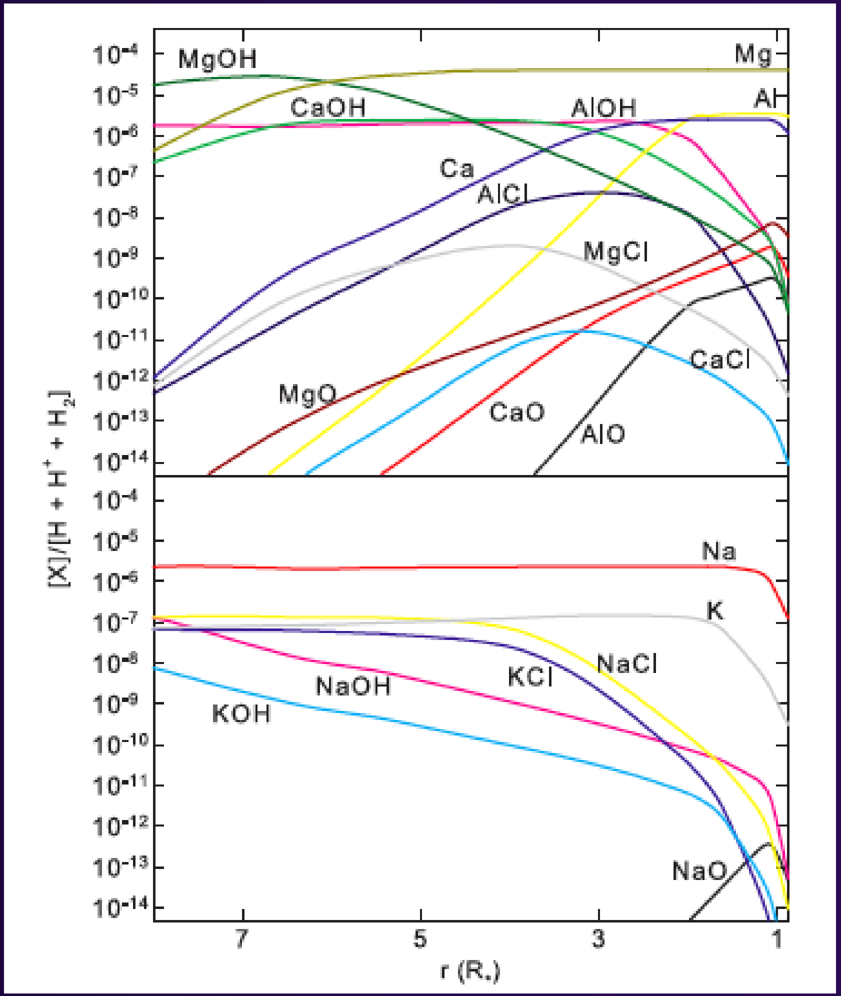
THE ARO 1 mm SPECTRAL SURVEY OF IRC +10216 AND VY CANIS MAJORIS



x 47 -> Jy

Tenenbaum et al. 2008 –2010





PO, AlO, AlOH
PN, AlCl

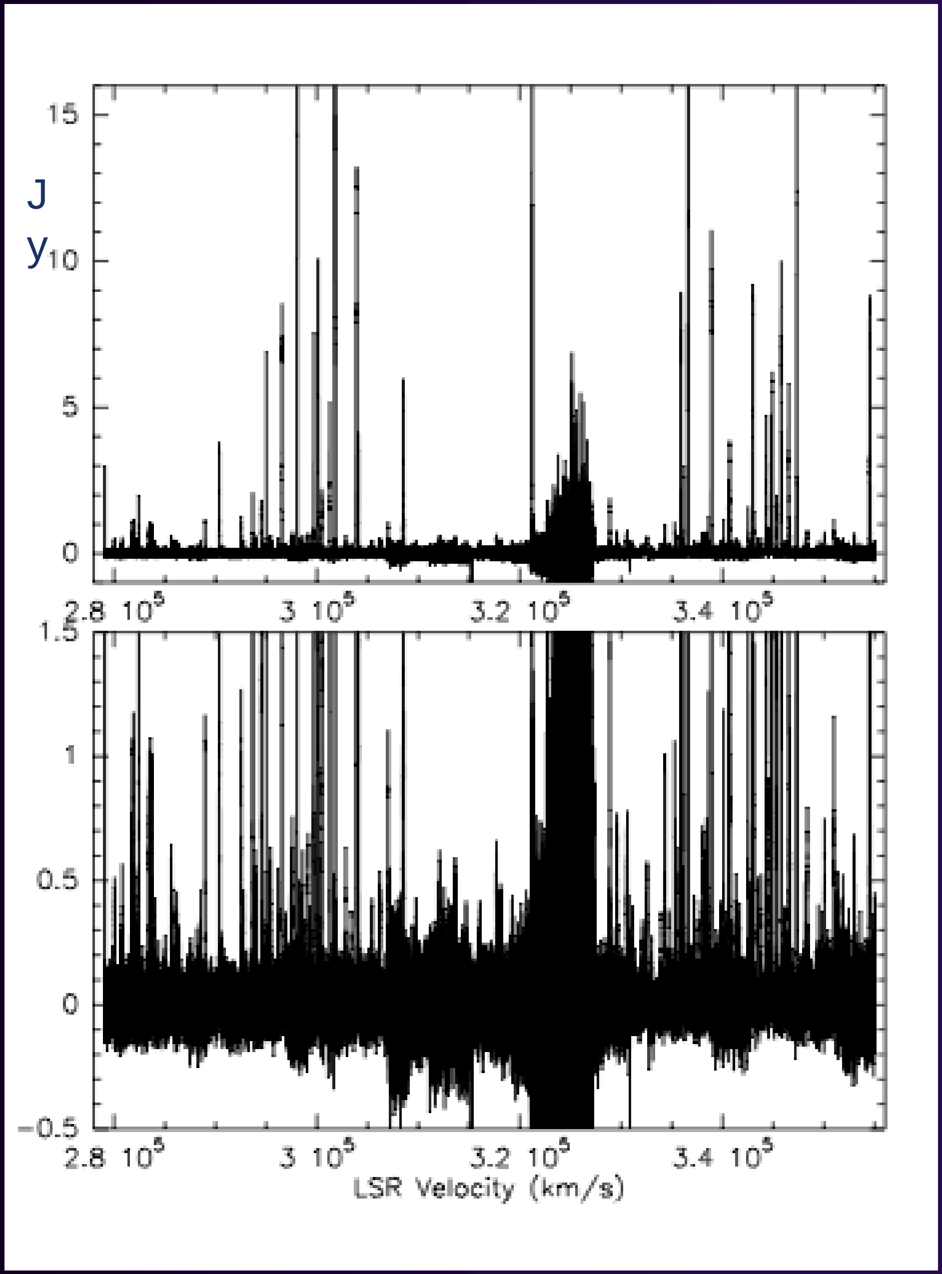
Tenenbaum & Ziurys 2010

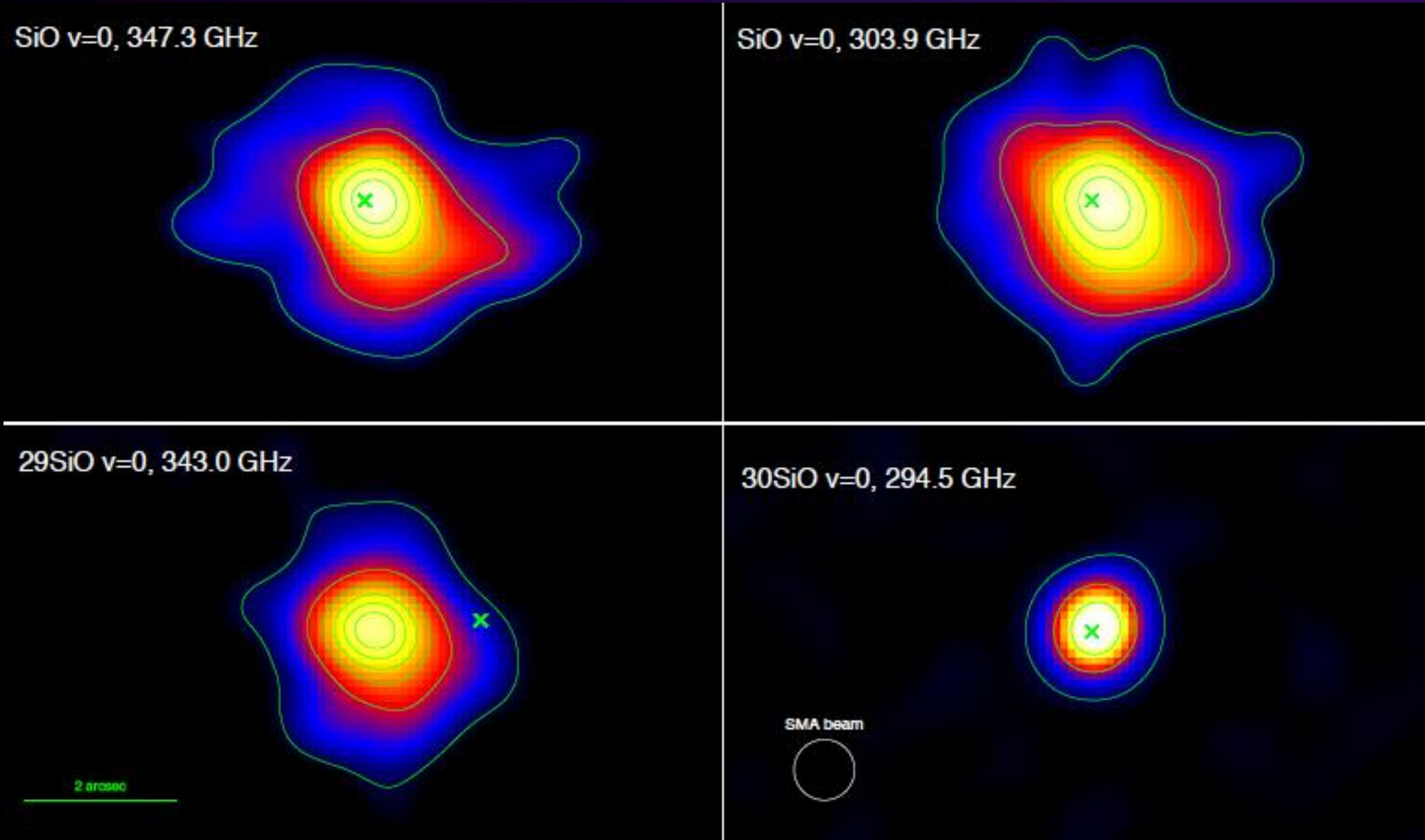
A Submillimeter Array Legacy Program

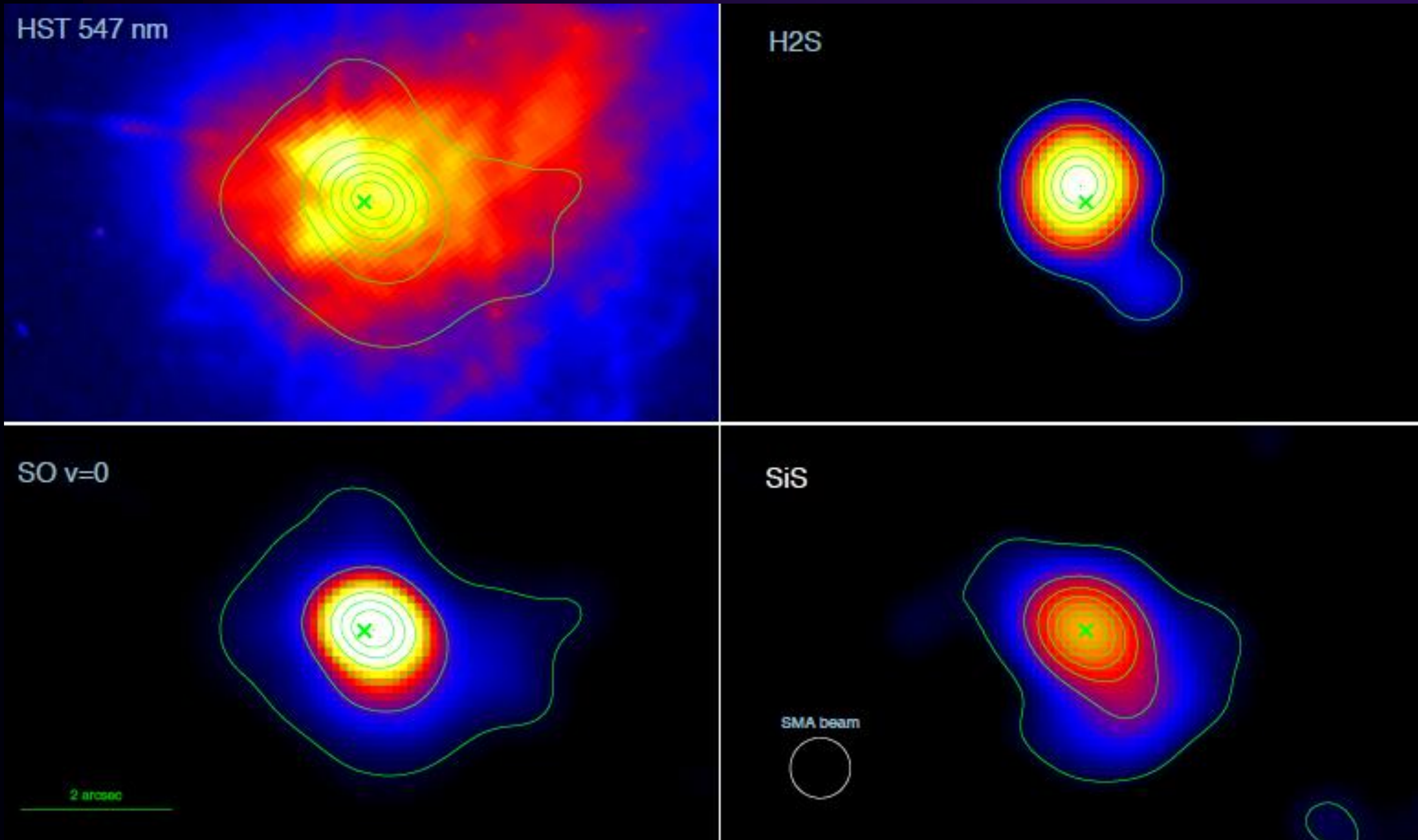
- **CfA/Harvard U.:**
  K. H. ("T.") Young, N. A. Patel, C. A. Gottlieb, P. Thaddeus, M. C. McCarthy, & M. A. Gurwell
- **MPI für Radioastronomie:**
  K. M. Menten, T. Kaminski, A. Belloche & L. Verheyen
- **K. U. Leuven:**
  L. Decin
- **U. of Cologne:**
  S. Brünken, S. & H. S. P. M. Müller

SMA Observations

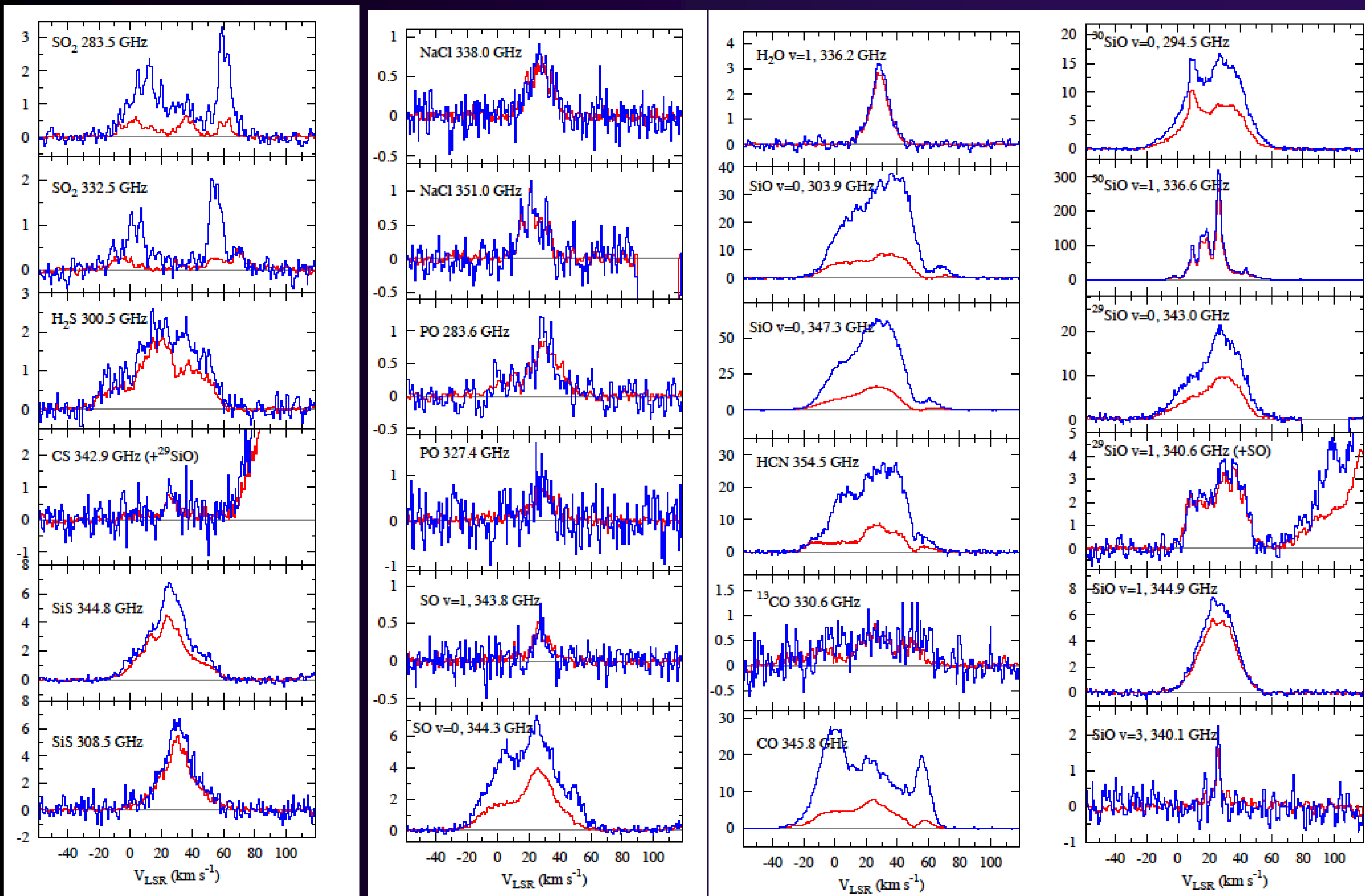
- 10 tracks in compact configuration
  - each 2 x 4 GHz LSB and USB separated by 12 GHz
- Spectral resolution 812.5 kHz/channel (0.71 kms@ 345 GHz)
- Typical resolution 0.8 arcsec FWHM


Jy
15
10
5
0
2.8 10^5
3 10^5
3.2 10^5
3.4 10^5
1.5
1
0.5
0
-0.5
2.8 10^5
3 10^5
3.2 10^5
3.4 10^5
LSR Velocity (km/s)


SiO v=0, 347.3 GHz
SiO v=0, 303.9 GHz
29SiO v=0, 343.0 GHz
2 arcsec
30SiO v=0, 294.5 GHz
SMA beam


HST 547 nm
H2S
SO v=0
SiS
2 arcsec
SMA beam

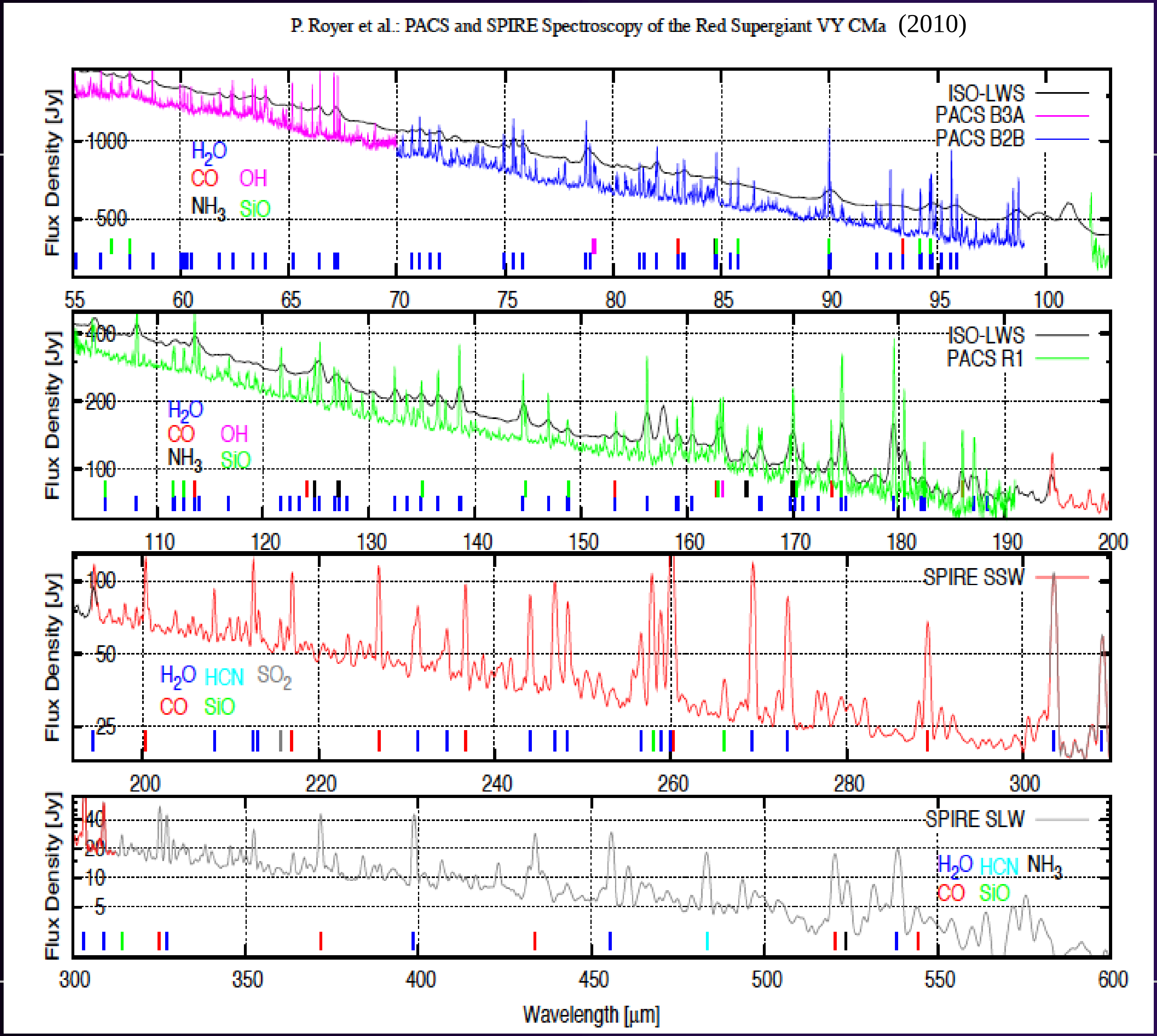
---- 0.8” FWHM --- 8” FWHM “aperture”

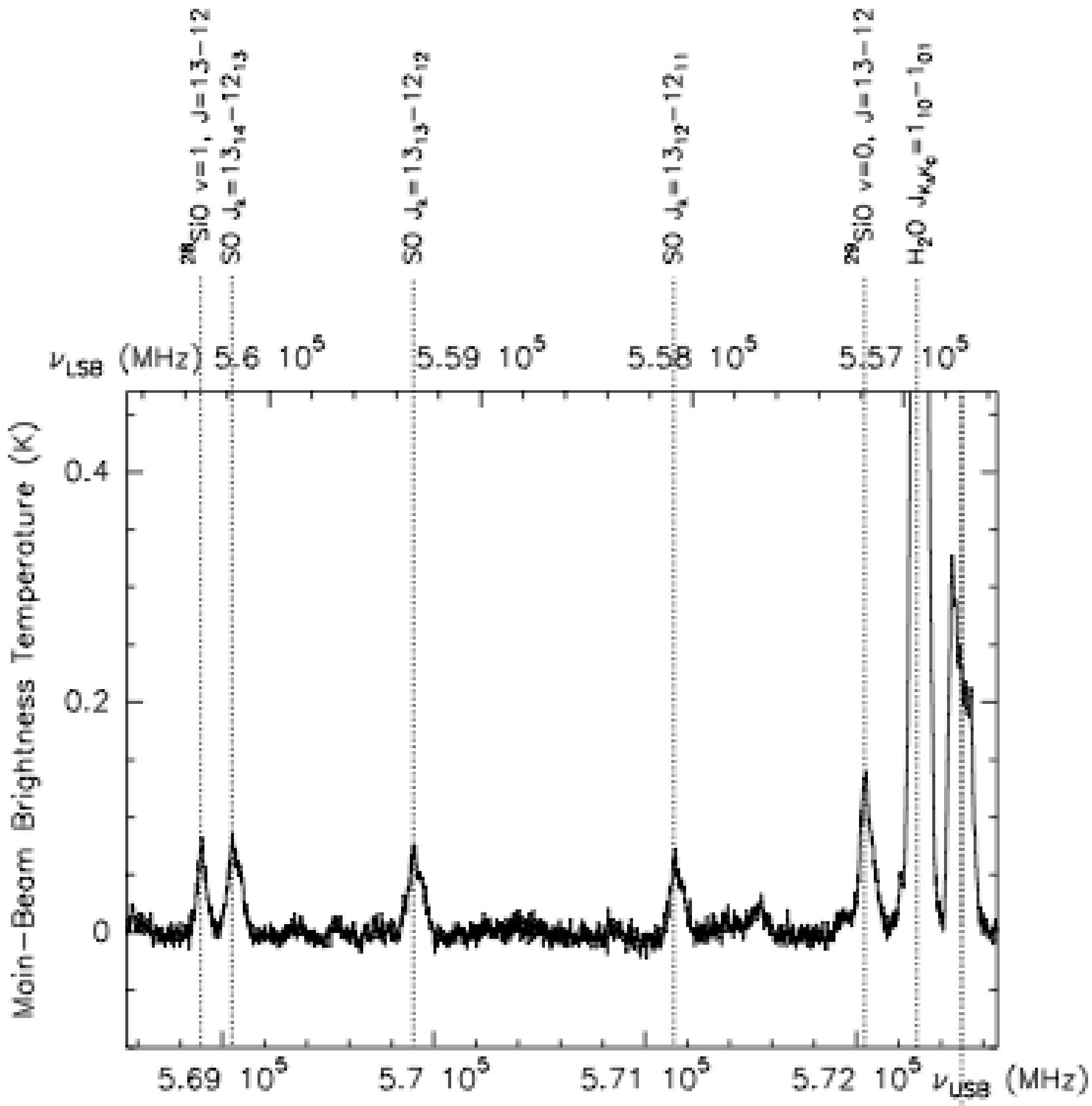


Diatomic molecules	Number of lines	Triatomic molecules	Number of lines
CO, ^{13}CO	2	HCN,$H^{13}CN$	2 (+1?)
SiO, ^{29}SiO, ^{30}SiO, $Si^{18}O$	26	$HN^{13}C$	(1?)
SO, ^{34}SO	17 (+6?)	SO_2, $^{34}SO_2$	31 (+3?)
SiS, ^{29}SiS, ^{30}SiS, $Si^{34}S$	14 (+8?)	H_2O	5 (+1?)
$NaCl$, $Na^{37}Cl$	21 (+3?)	H_2S	1
CS	2	AlOH	(1?)
AlO	2		
PO	6		
PN	(2?)		
NS	(2?)	Unidentified (>0.1 Jy/beam)	~7

- numbers in brackets are for lines only tentatively detected
- table includes lines for v=1 and v=2, if spectroscopic data available

VY CMa is a spectacular source of H_2O emission





VY CMa with Herschel/HIFI

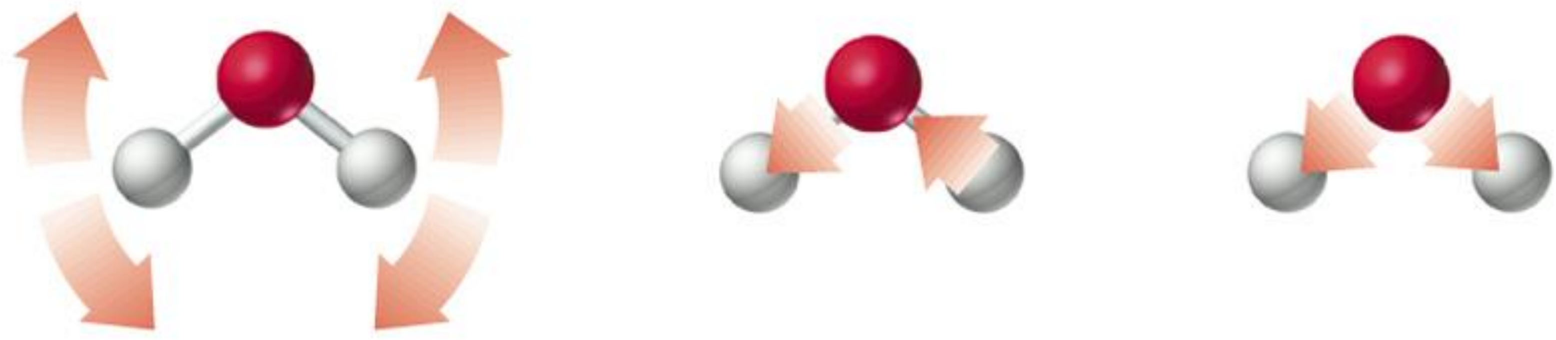
J. Alcolea et al. (in prep.)

In the following:

We are interested in VY CMa’s innermost circumstellar envelope. Why is this interesting?

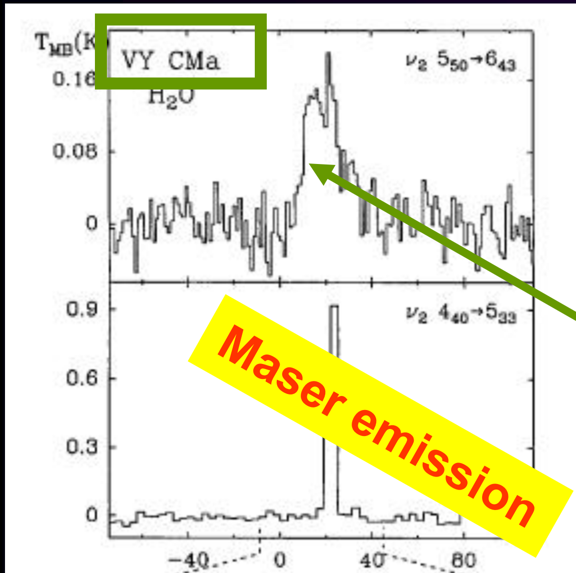
- **Dust formation zone**
- **Acceleration of the outflow**
- **Geometry**
- **H_2O is the most abundant molecule (apart from H_2)**

Observing hot water toward VY CMa



H_2O Vibrational Modes

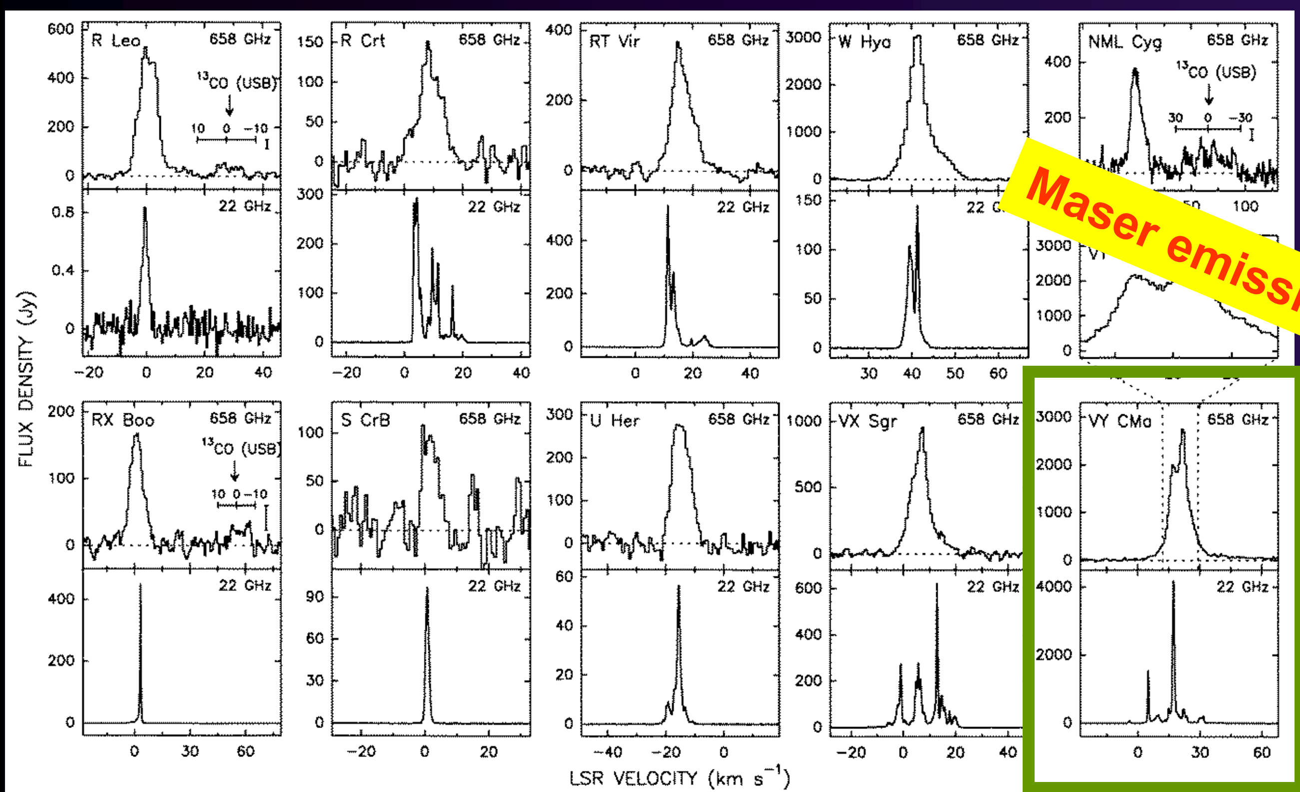
Bending ν_2	Asymmetric stretch ν_3	Symmetric stretch ν_1
2295 K	5404 K	5262 K
6.27 μm	2.66 μm	2.73 μm



IRAM 30m

Menten & Melnick 1989

Thermal component?

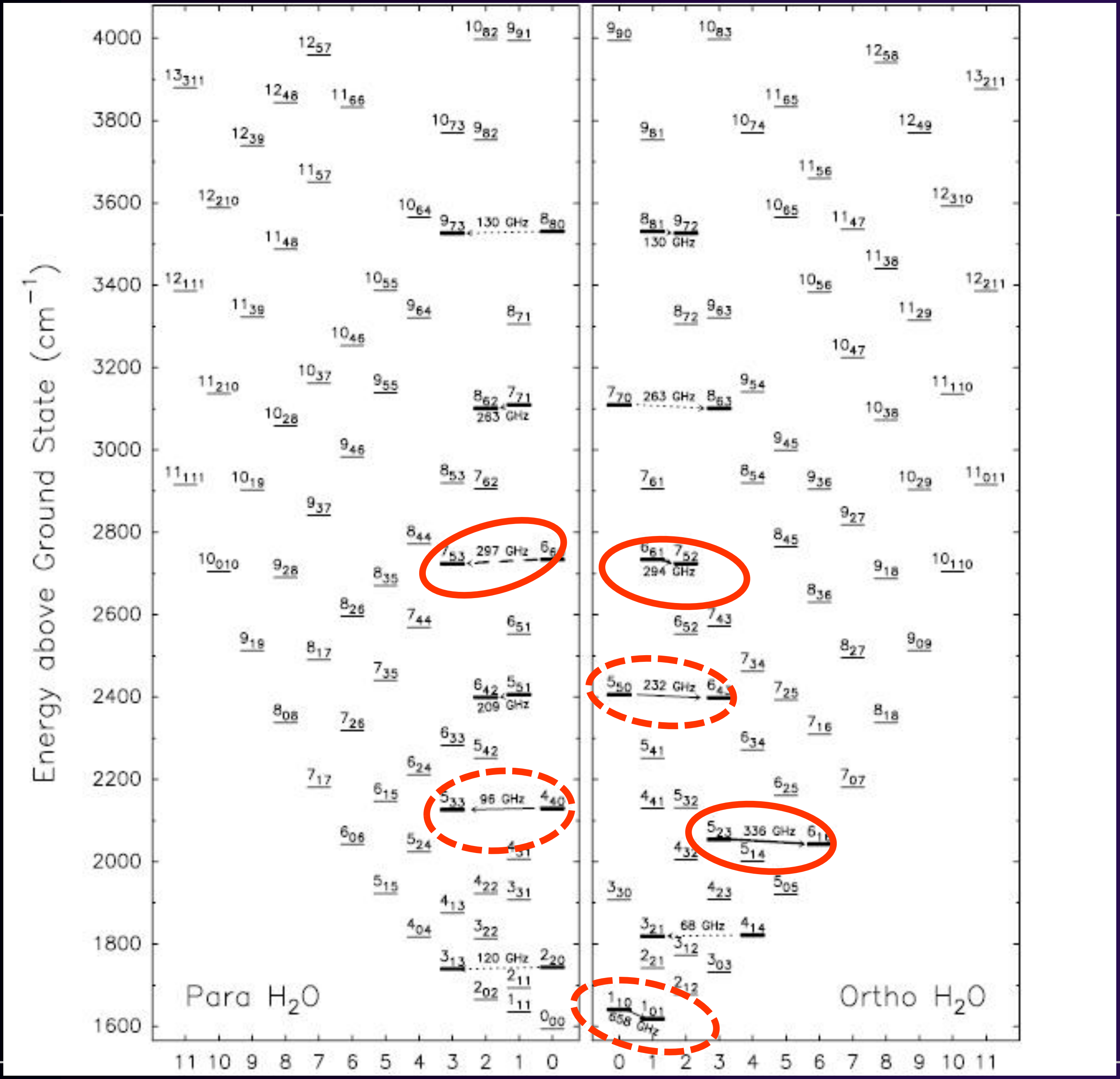


ν_2=1, $1_{10} - 1_{01}$ ortho ground-state line

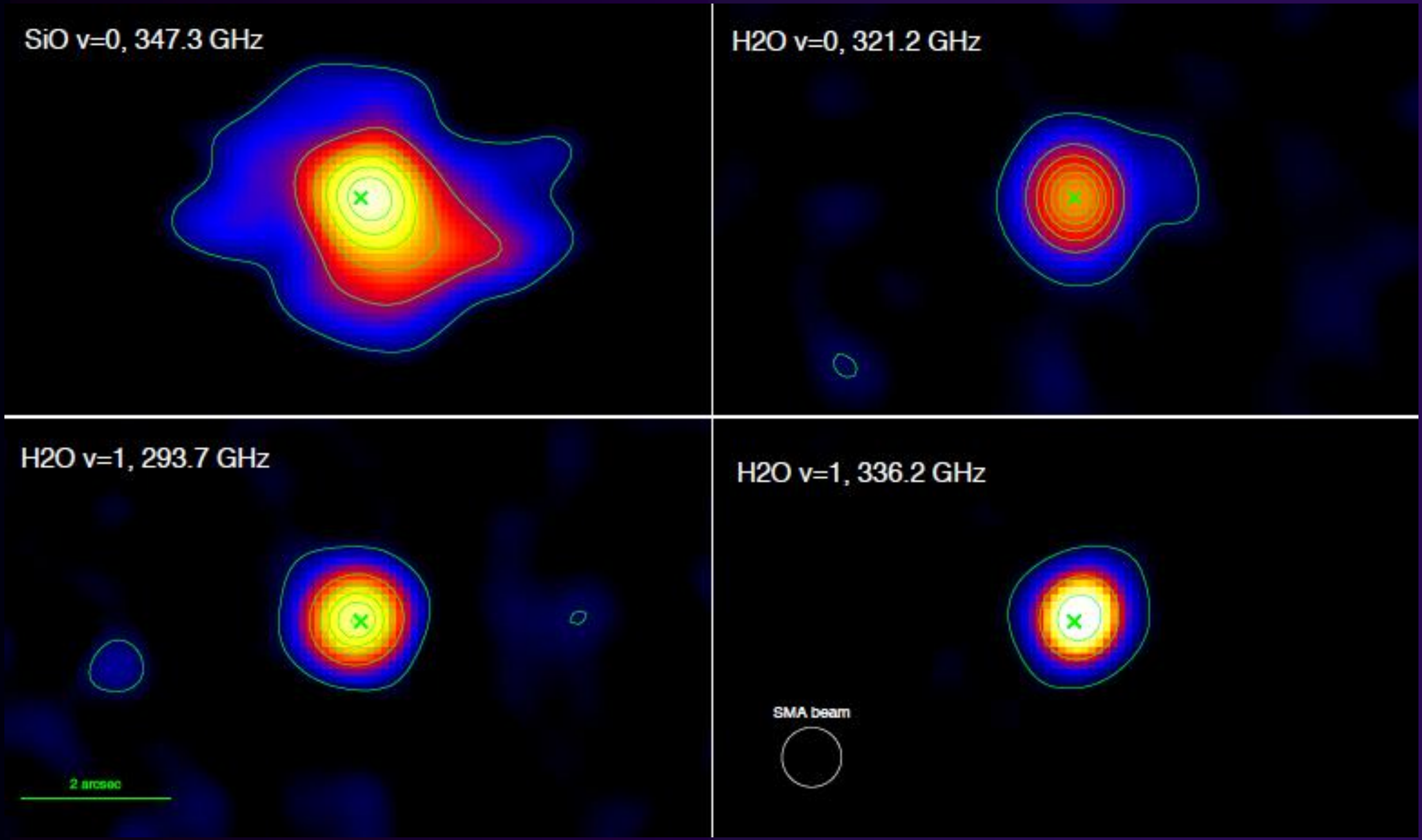
Menten & Young 1995/CSO

H_2O

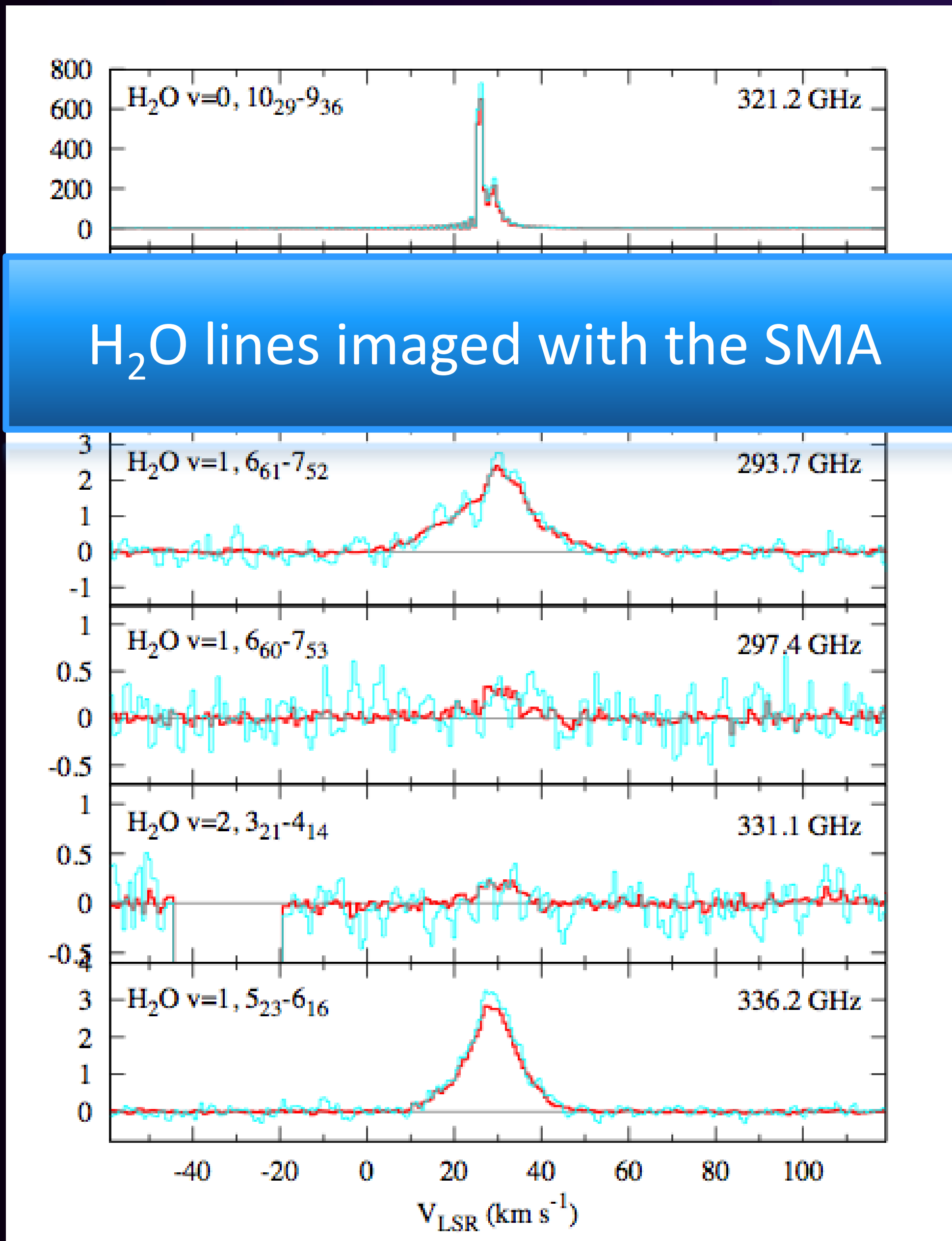
$\nu_2 = 1$



Energy above Ground State (cm⁻¹)
Para H2O
Ortho H2O
130 GHz
297 GHz
96 GHz
120 GHz
263 GHz
209 GHz
294 GHz
232 GHz
336 GHz
68 GHz
658 GHz


SiO v=0, 347.3 GHz
H2O v=0, 321.2 GHz
H2O v=1, 293.7 GHz
H2O v=1, 336.2 GHz
2 arcsec
SMA beam

H_2O lines imaged with the SMA



E_{lower}

1846 K

3920 K

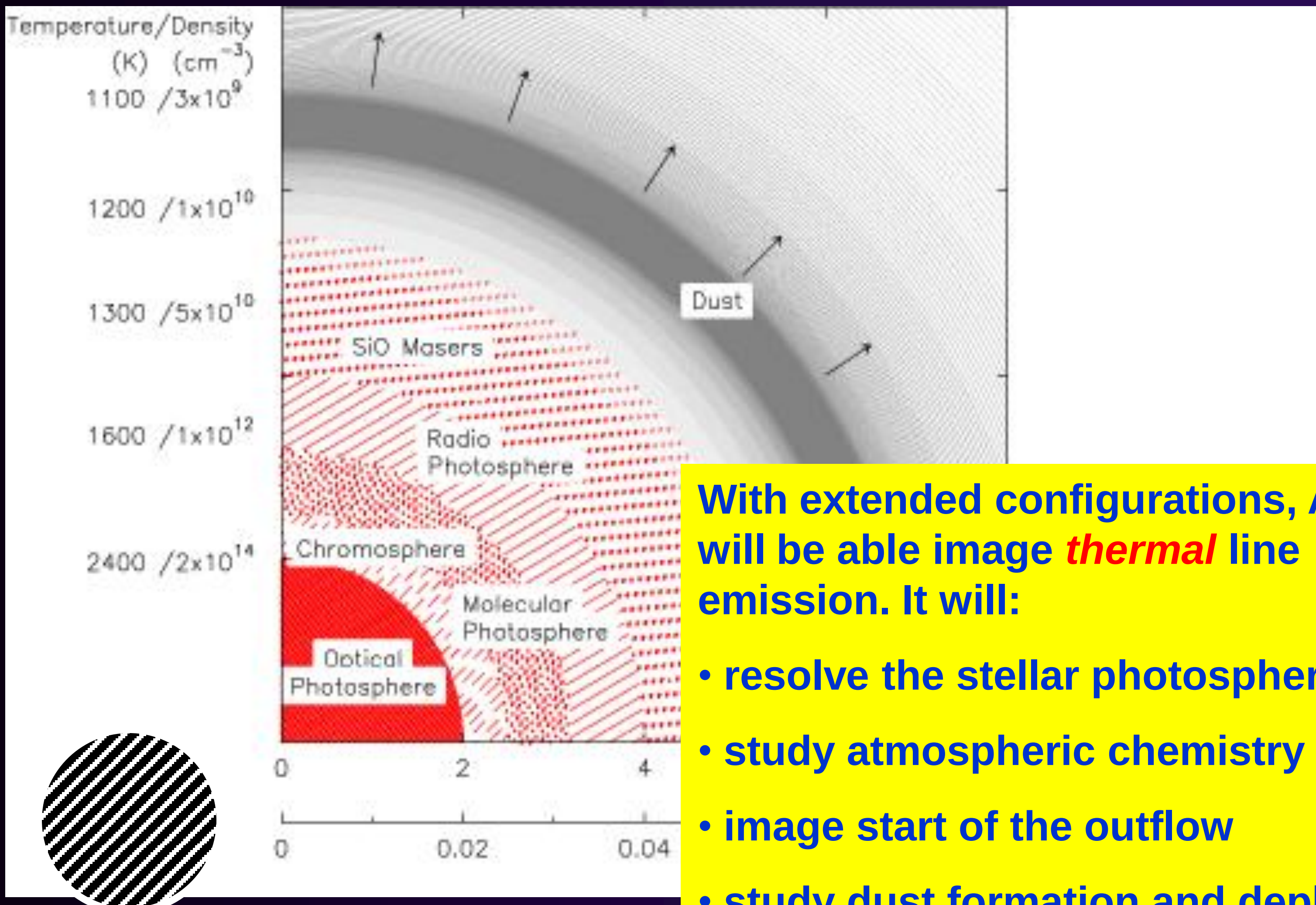
3920 K

4866 K

2939 K

"Can't" be more than 3 x stronger!

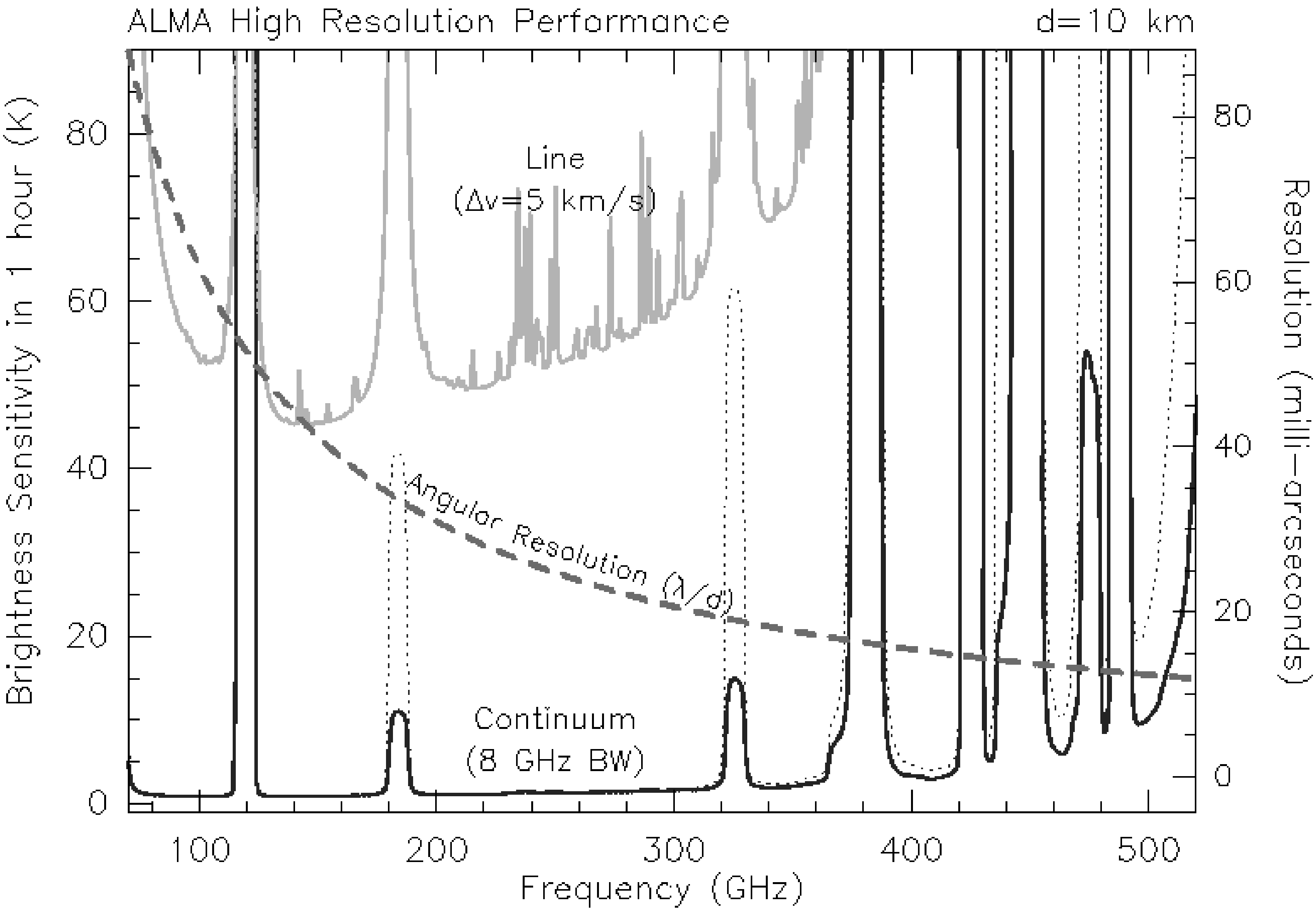
If you can detect something the SMA, you can image it with ALMA



With extended configurations, ALMA will be able image *thermal* line emission. It will:

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

ALMA: The high resolution imaging machine



ALMA will resolve the stellar photosphere of nearby red (super)giants

It will image molecule formation, depletion, and photochemistry (of many isotopologues) – the whole (gas phase) picture

VY CMa and IRC+10216 are the keystone AGB and RSG stars

Thanks for your attention!

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

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

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

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

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

$$\approx 3\times 10^{-3}T\left(K\right) \text{ for } \theta = 40 \text{ mas}, \ \nu = 43 \text{ GHz}$$

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