EUROPEAN ARC
ALMA Regional Centre

Masers and Betelgeuse

Liz Humphreys (ESO)

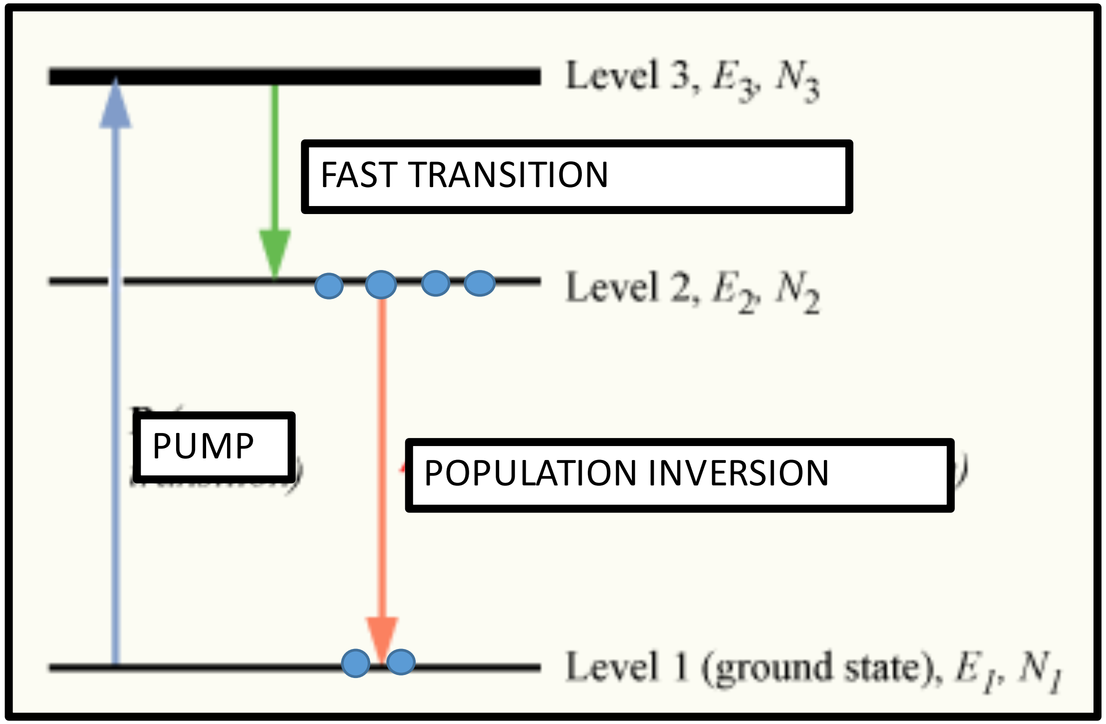
Thanks to Anita Richards, Malcolm Gray and many!

Masers (Microwave Amplification by Stimulated Emission of Radiation)

- **Compact, high brightness temperature masers enable study at high angular resolution (e.g. < 1 milliarcsecond)**
- **Present in:** Evolved Stars, AGN, Star Formation, Supernova Remnants, …
- **Species include:** SiO, H_2O, OH, HCN, CH_3OH, SiS, NH_3, H recombination masers
- **Uses include:**
  - Physical conditions (line ratios from >=2 transitions, simultaneous)
  - Dynamics (3D velocities from proper motions)
  - Magnetic fields
  - Clumping studies

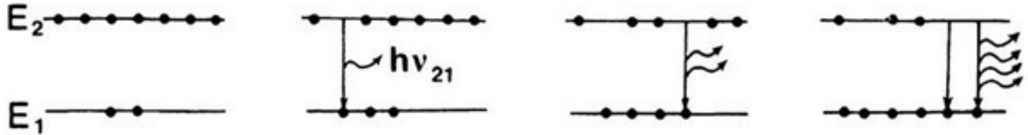
Maser Action: Population Inversion & More

①



②

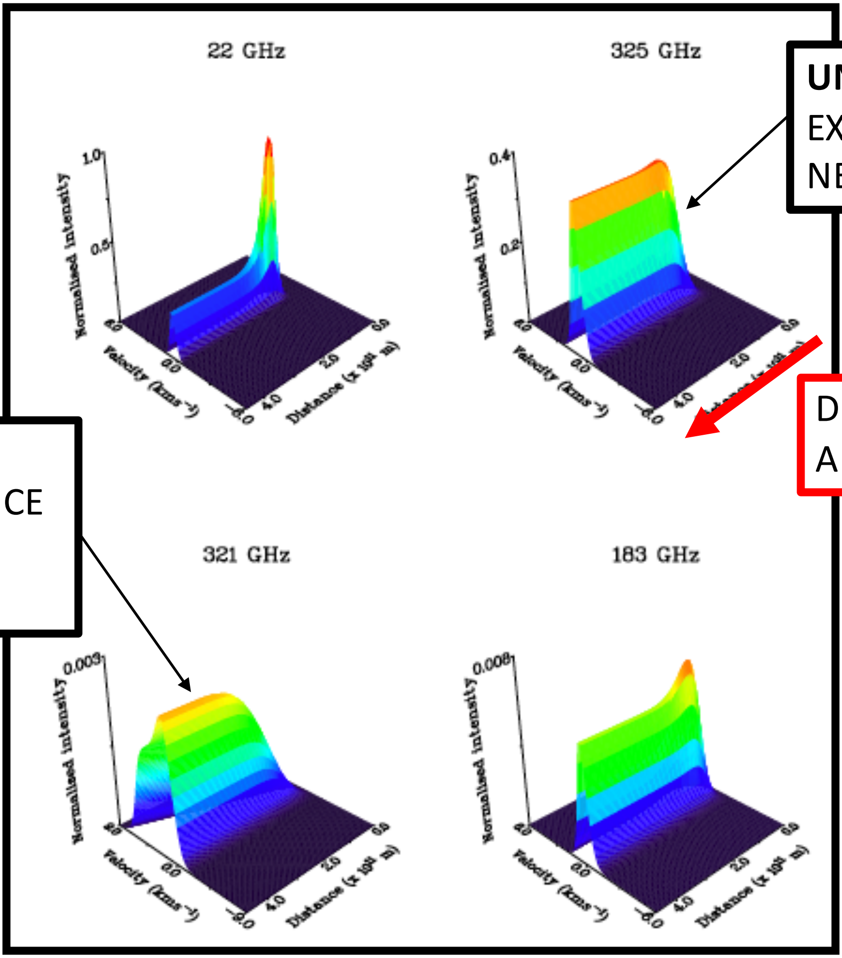
SEED



STIMULATED EMISSION

Maser Action: Amplification

3



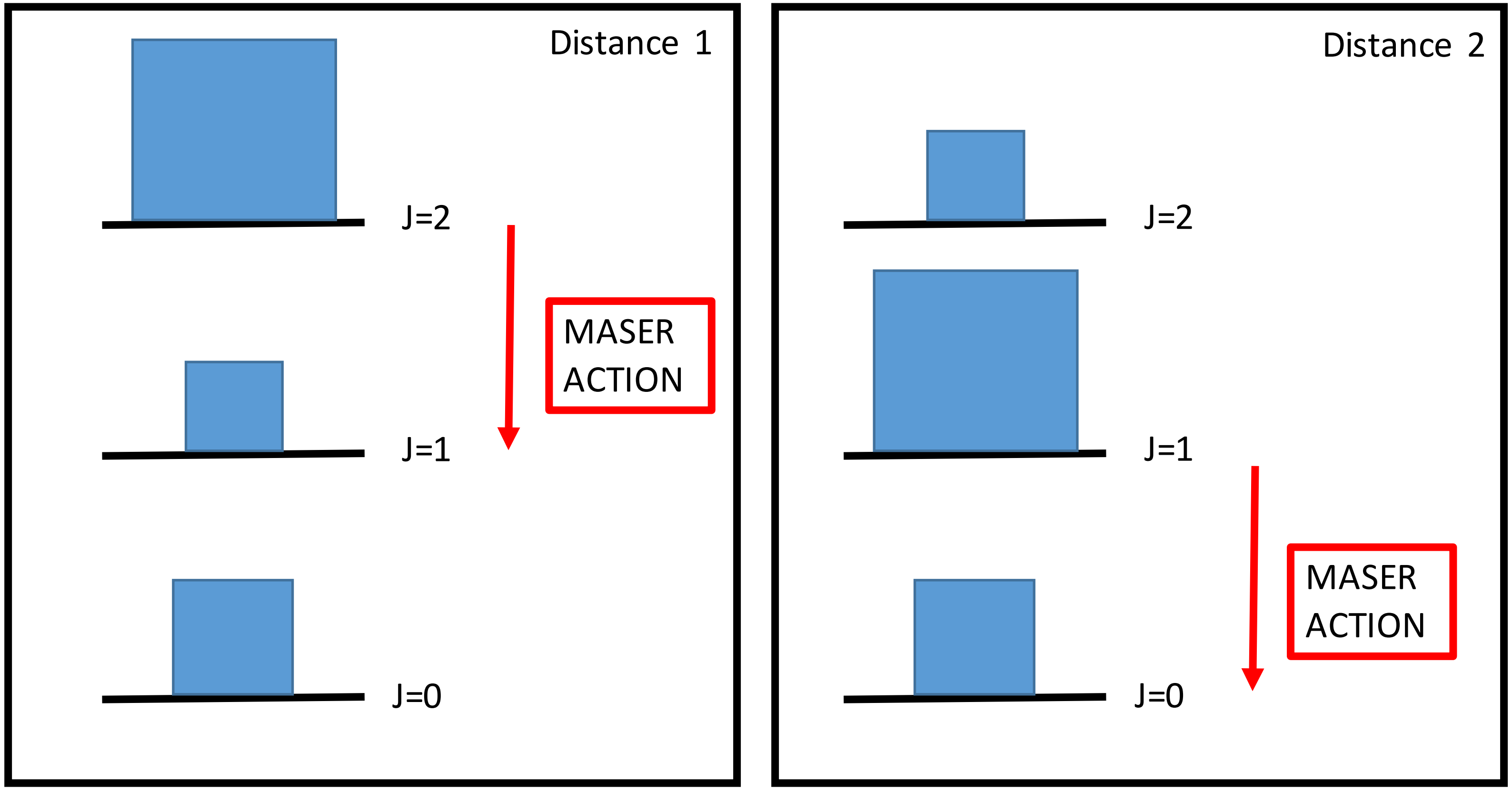
UNSATURATED REGIME
EXPONENTIAL GROWTH WITH DISTANCE
NEGLIGIBLE EFFECT ON POPULATIONS

DISTANCE ALONG MASER AMPLIFICATION PATH

SATURATED REGIME
LINEAR GROWTH WITH DISTANCE
POPULATIONS AFFECTED →
COMPETITIVE GAIN

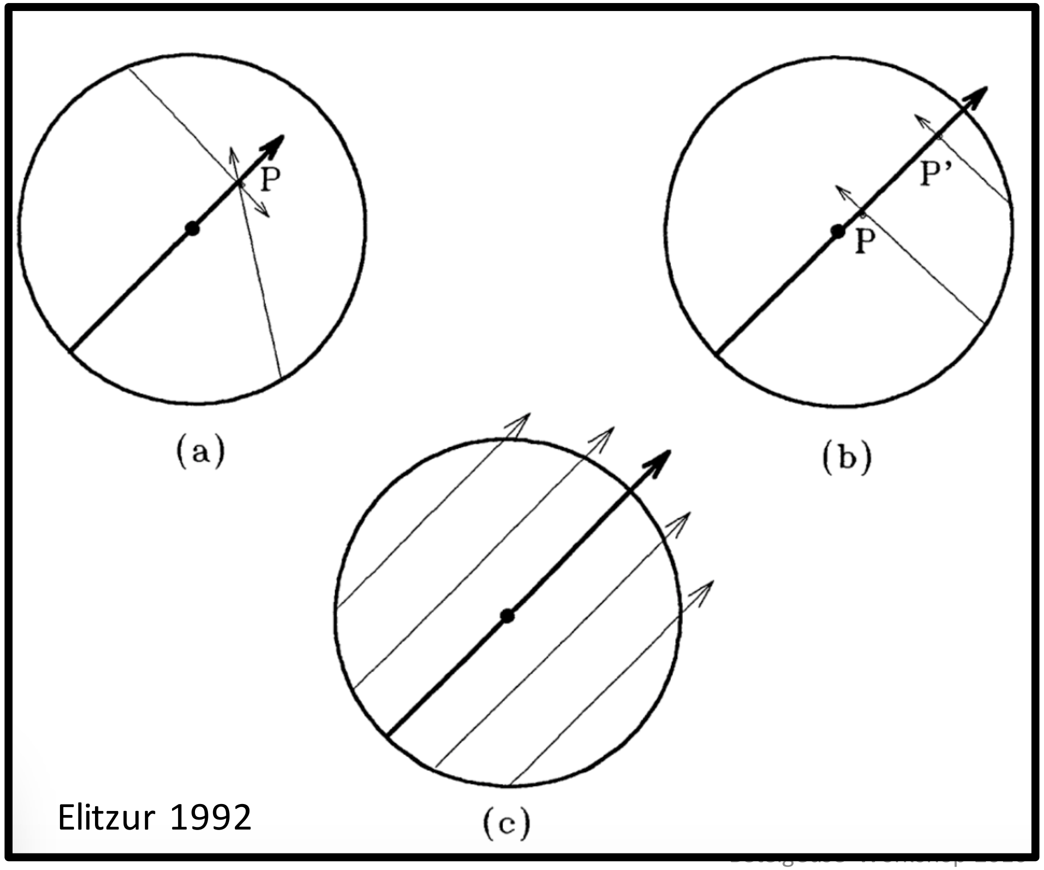
Humphreys et al. (2001)

Competitive Gain



IMPORTANCE OF INCLUDING SATURATION IN MASER RADIATIVE TRANSFER CODES

Maser Beaming



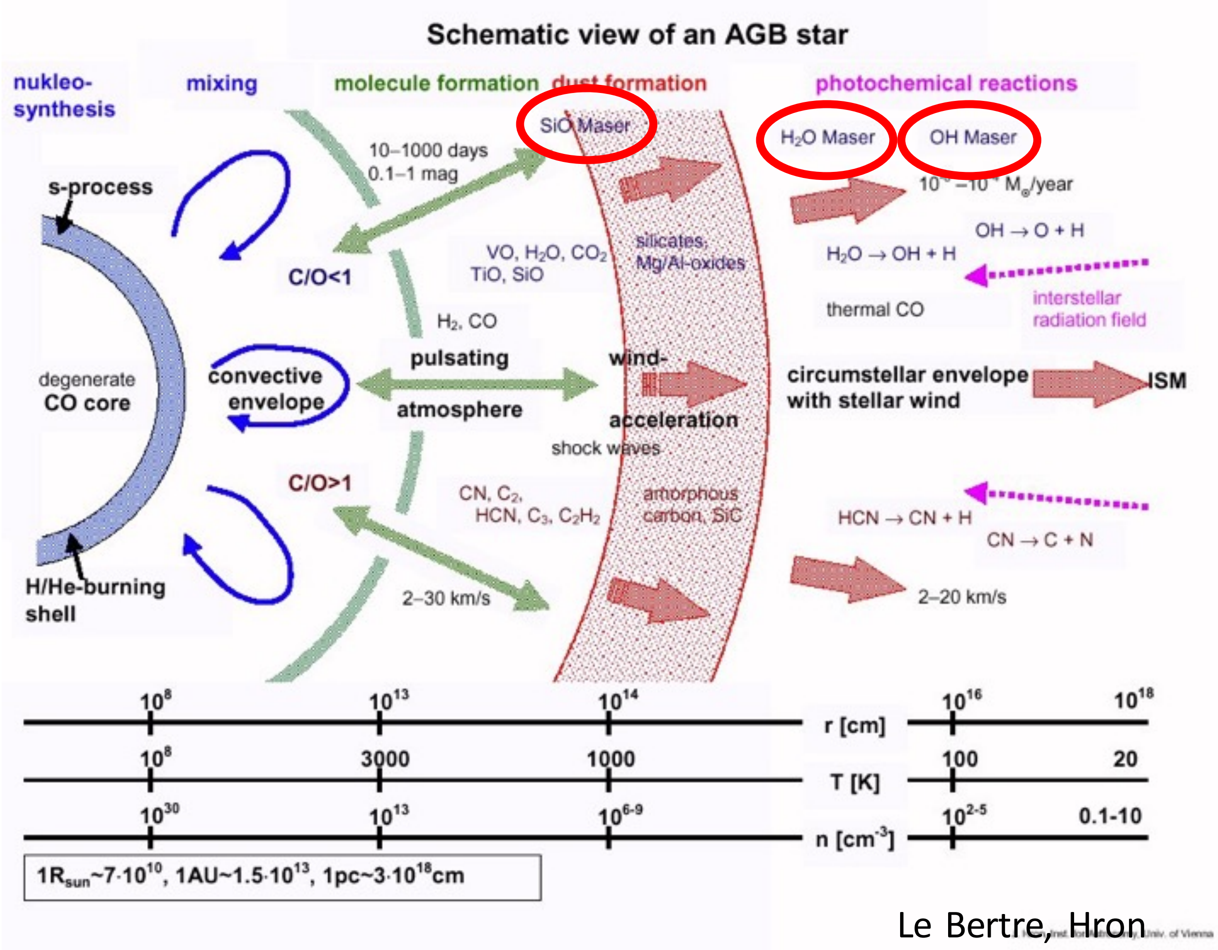
Elitzur 1992

DOMINANT RAY HAS FASTEST STIMULATED EMISSION RATE (LONGEST PATH LENGTH)

FOR CROSSING RAYS: DOMINANT RAY "STEALS" THE MAJORITY OF POPULATION INVERSION BEFORE THE WEAKER RAYS HAVE TIME

LEADS TO HIGHLY BEAMED EMISSION (MASERS STIMULATE INTO THE SAME DIRECTION)

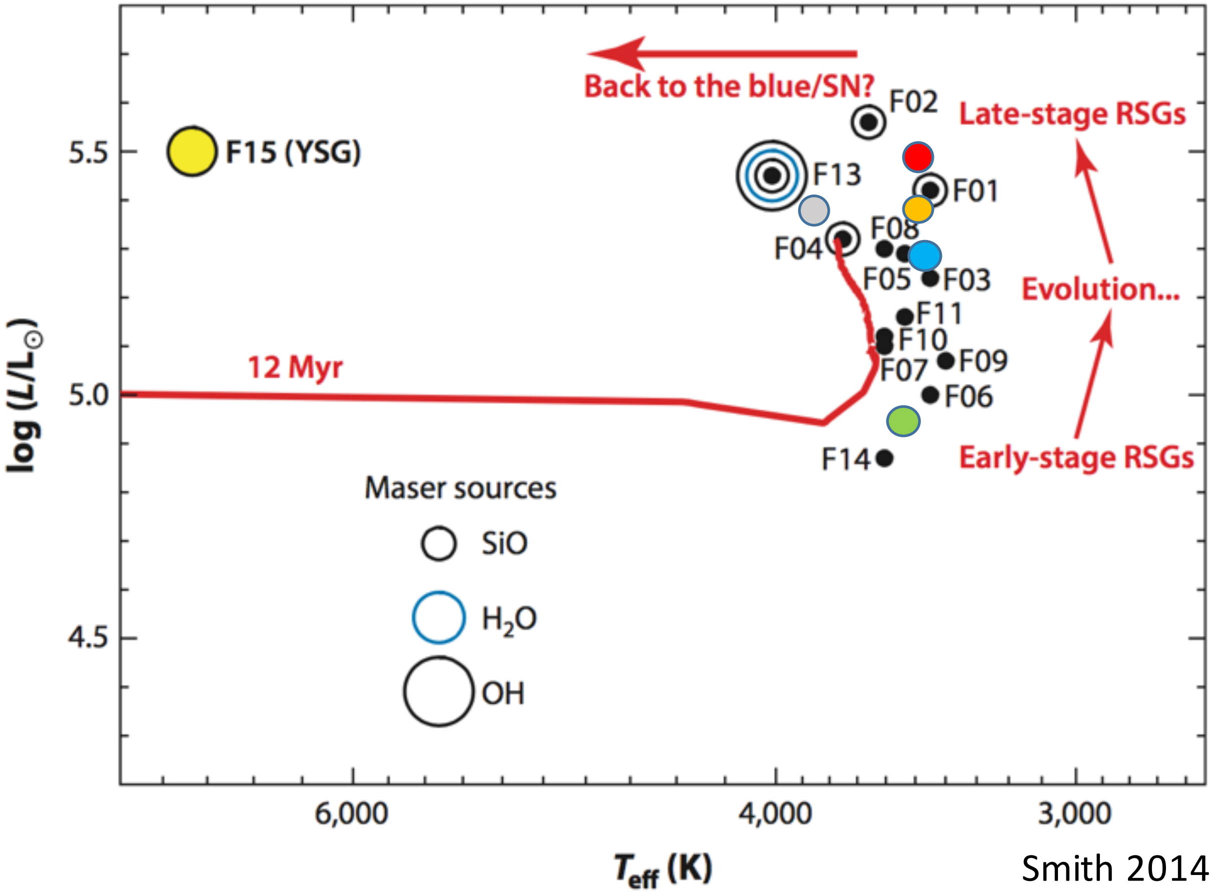
Masers in Evolved Stars



Le Bertre, Hron

- SiO masers: within a few R$_*$ of the photosphere
- Water masers: 10 to 100 R$_*$
- OH masers (mainline): 10 - 100 R$_*$
- OH masers (1612MHz): another order of magnitude from the star

Masers in Red Supergiants



🟢 Betelgeuse

🟡 VY CMa

🔵 S Per

⚪ NML Cyg

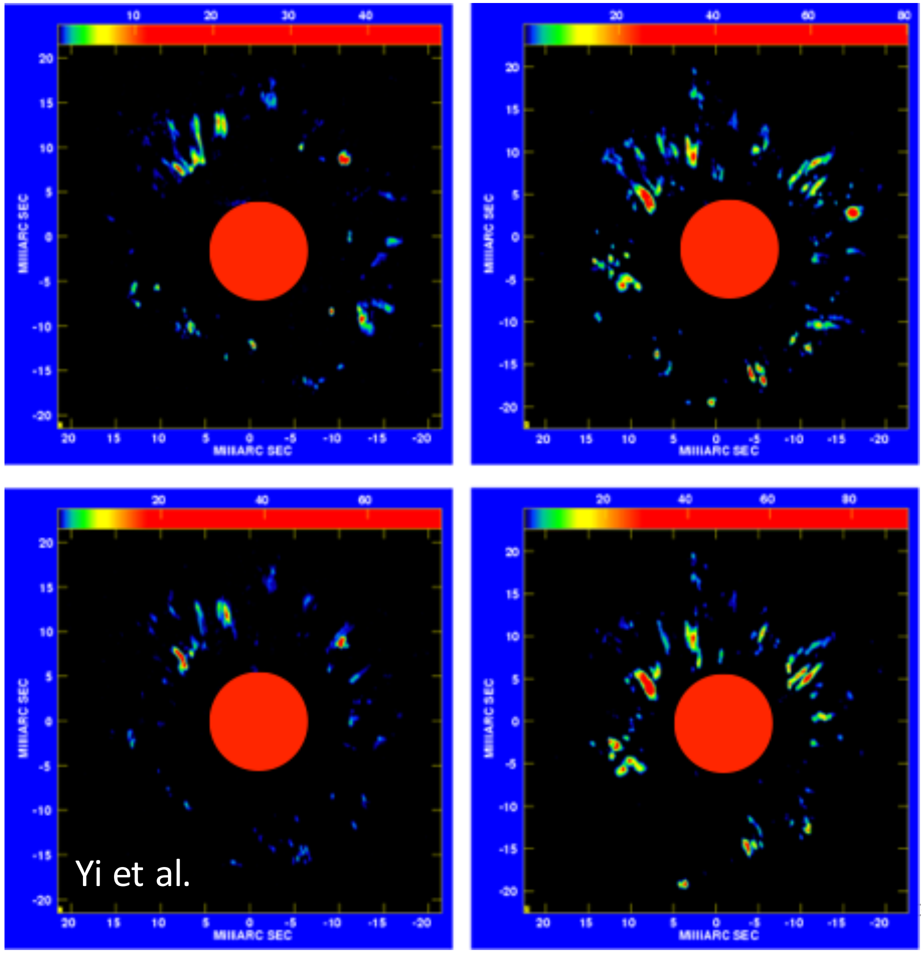
🔴 VX Sgr

SiO,
H_2O
OH masers

Smith 2014, adapted from Davies 2008

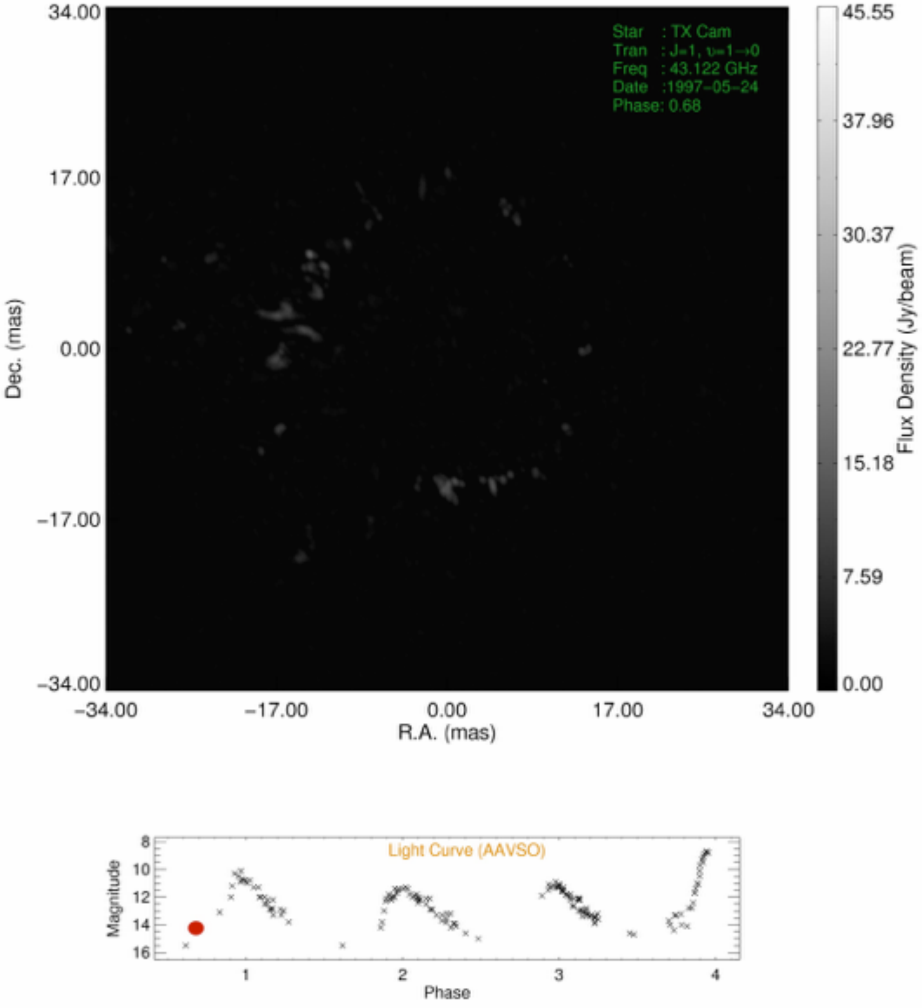
SiO Masers

v=1 J=1-0 43 GHz



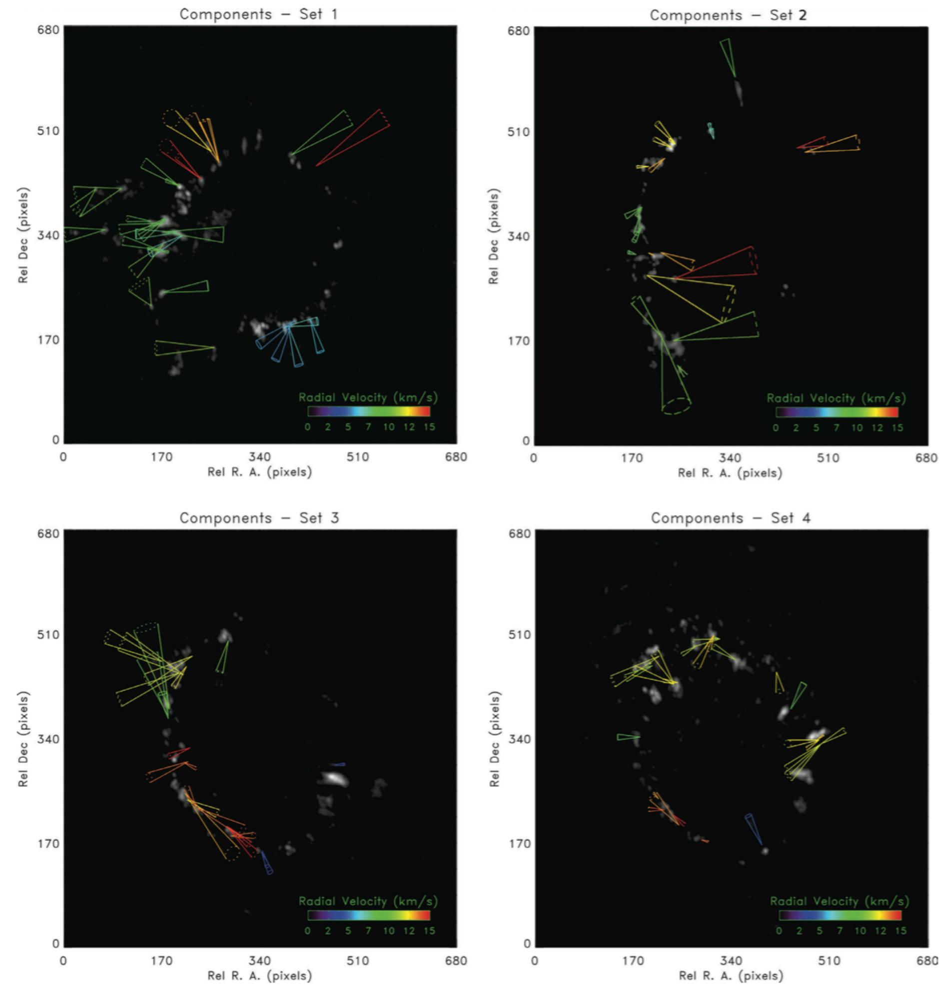
Yi et al.

TX Cam



Gonidakis et al. (2013)

3D Component Kinematics

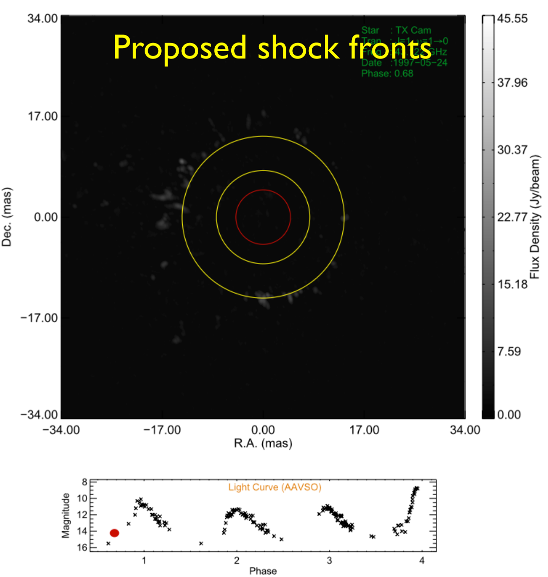


Gonidakis et al. 2013; VLBA 43 GHz

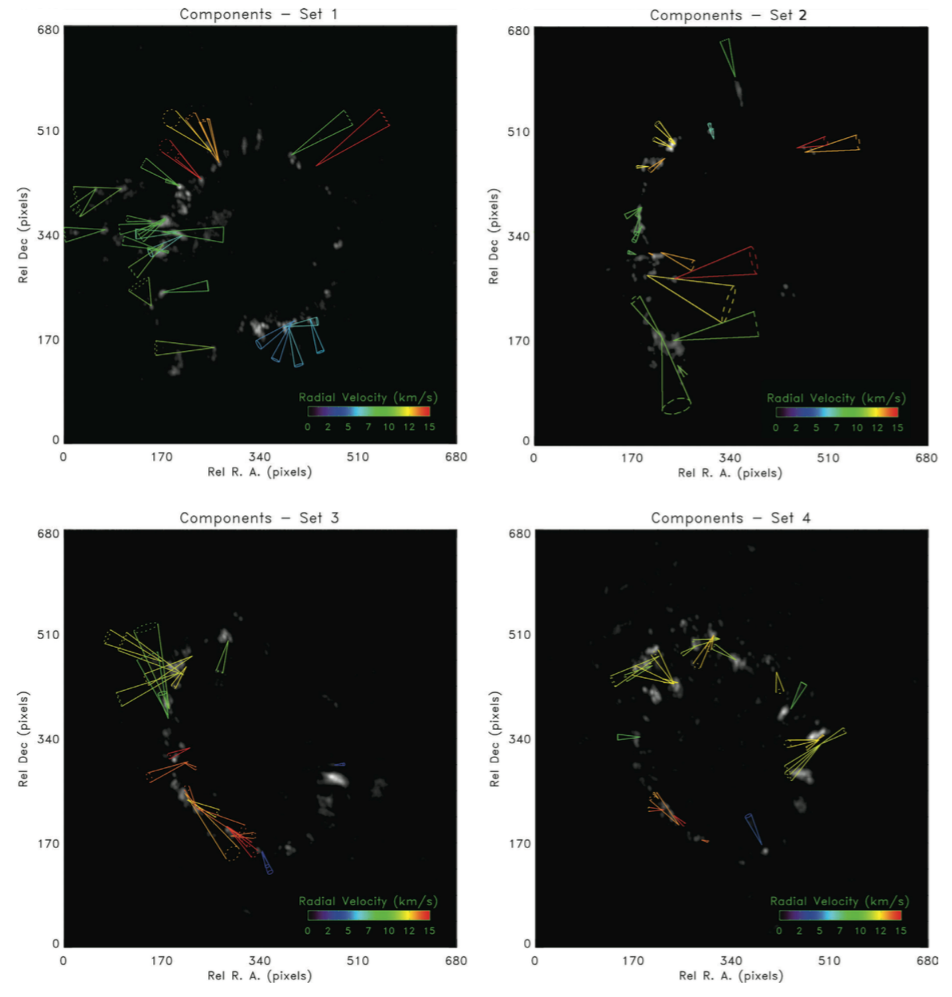
Outflow and infall detected, complex non-radial motions

Shock velocity ~7 km/s, broadly consistent with radio photosphere constraints

Evidence for bipolar outflow

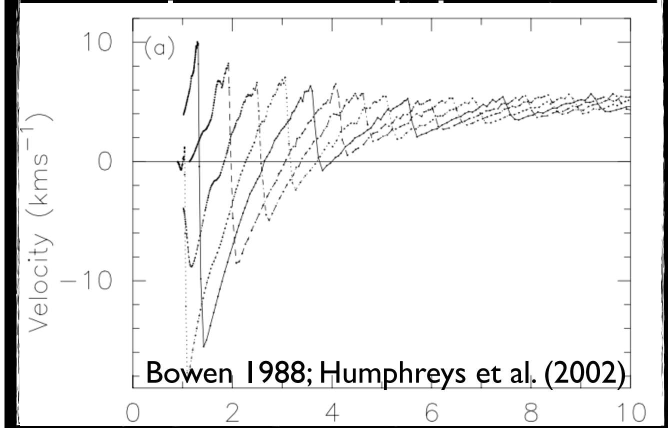

Proposed shock fronts

3D Component Kinematics

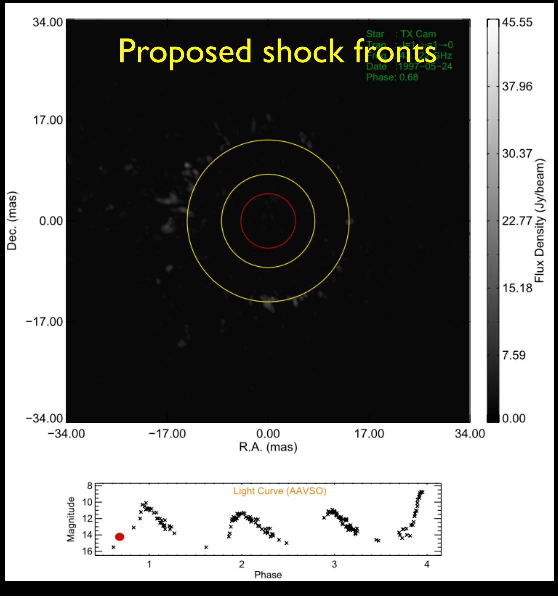


Gonidakis et al. 2013; VLBA 43 GHz

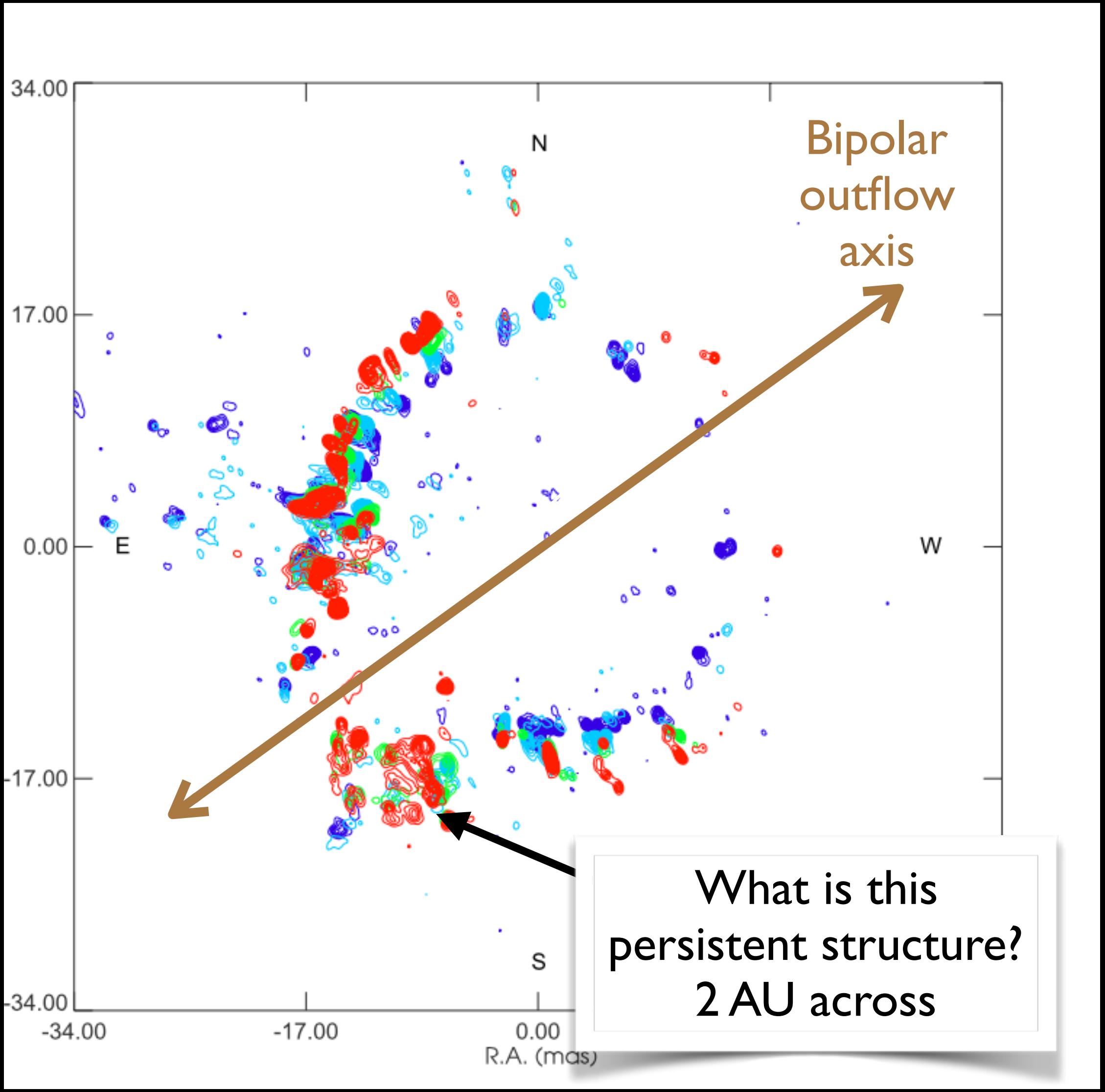
Outflow and infall detected,



Bowen 1988; Humphreys et al. (2002)



Proposed shock fronts

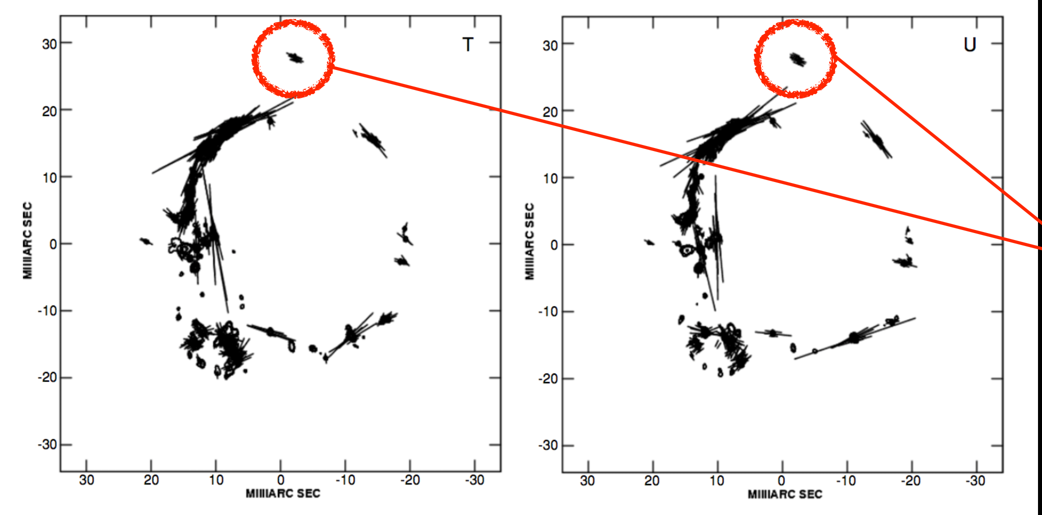


Bipolar outflow axis

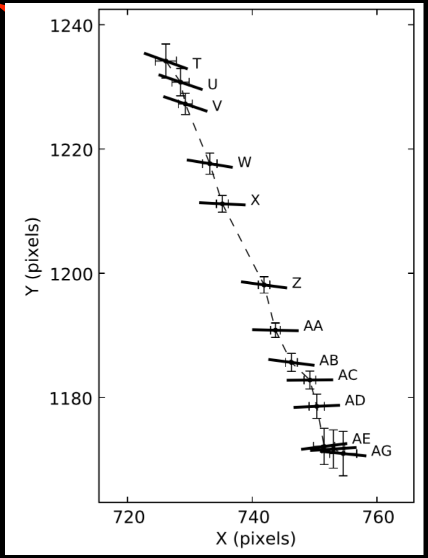
What is this persistent structure? 2 AU across

Gonidakis et al. 2013; VLBA 43 GHz

Are B-fields dynamically-significant in the extended atmosphere?

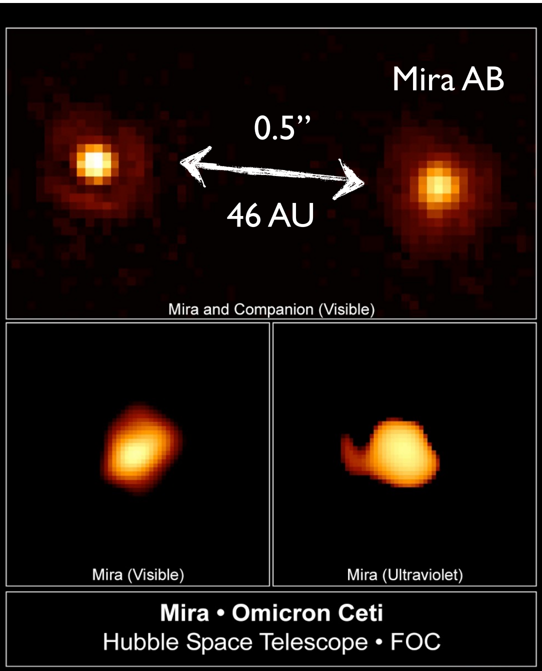


TX Cam
Kemball et al. (2009)

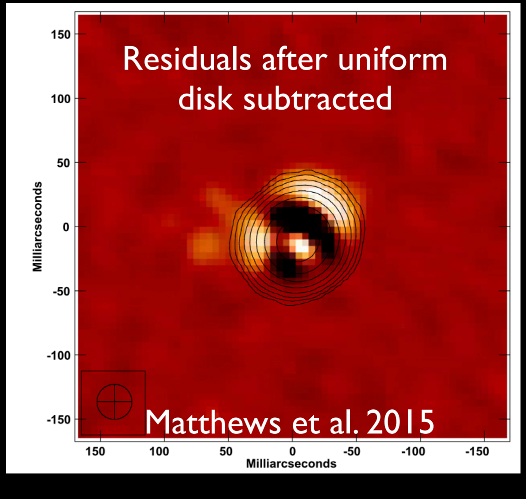


TX Cam: trajectories of isolated features consistent with component motion along magnetic field lines
IK Tau: consistent with ballistic motion (Matsumoto et al. 2008)

Hotspot on Mira A? (ALMA Continuum)

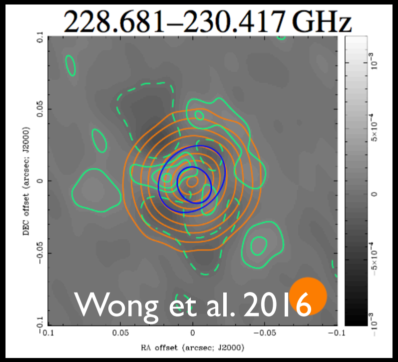


Mira • Omicron Ceti
Hubble Space Telescope • FOC

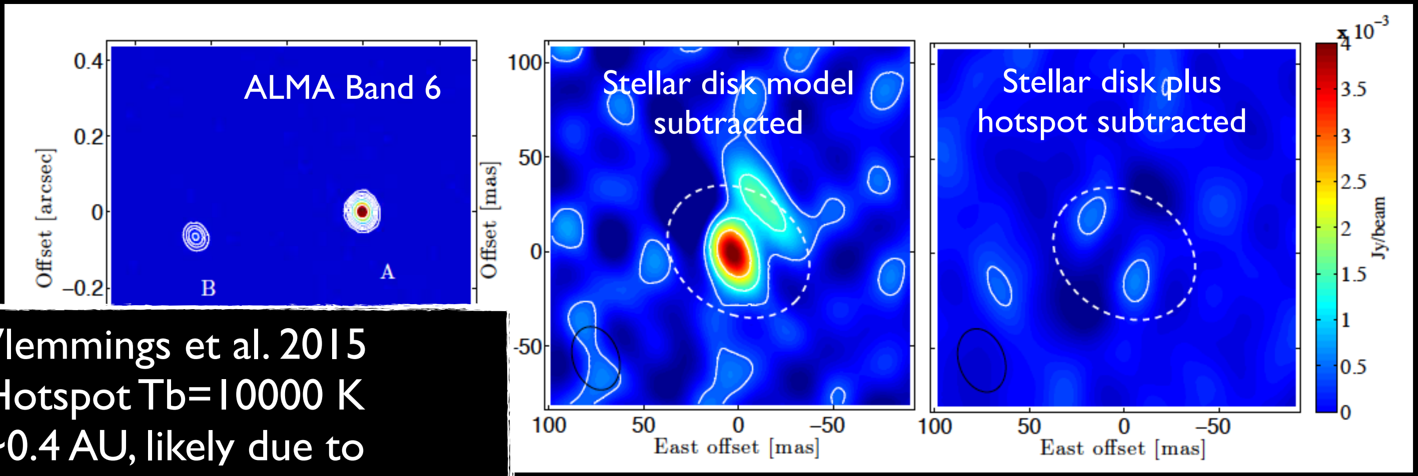


Residuals after uniform disk subtracted

Matthews et al. 2015



Wong et al. 2016



ALMA Band 6

Stellar disk model subtracted

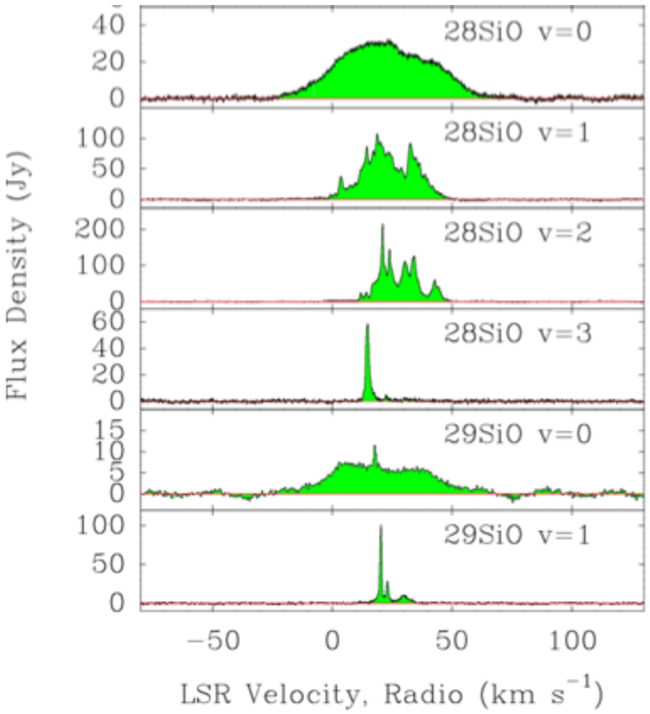
Stellar disk plus hotspot subtracted

Vlemmings et al. 2015
Hotspot Tb=10000 K
~0.4 AU, likely due to magnetic activity .

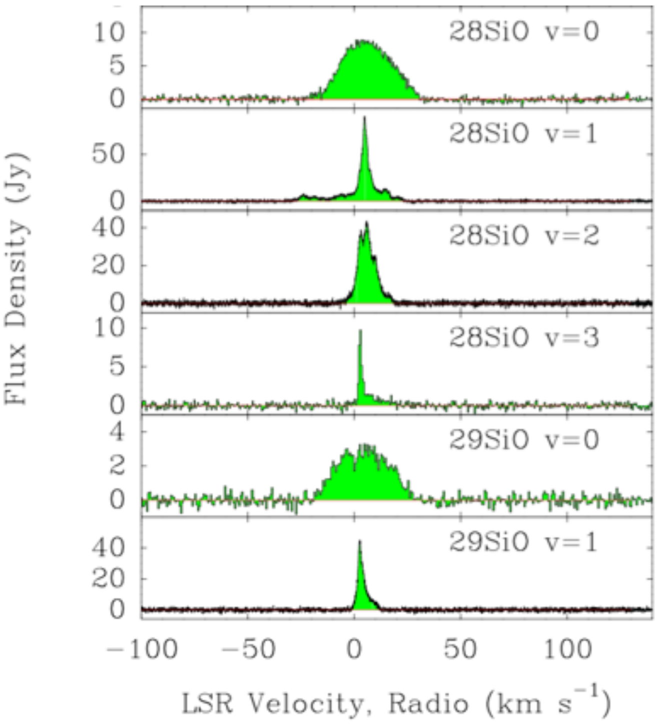
TX Cam

SiO Masers: throughout ALMA/APEX Bands

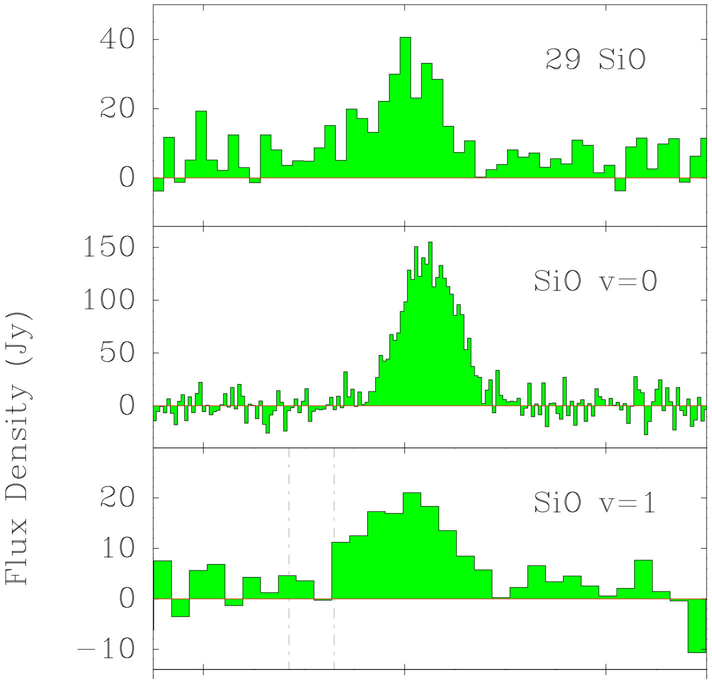
VY CMa J=4-3; 172 GHz



VX Sgr J=4-3; 172 GHz



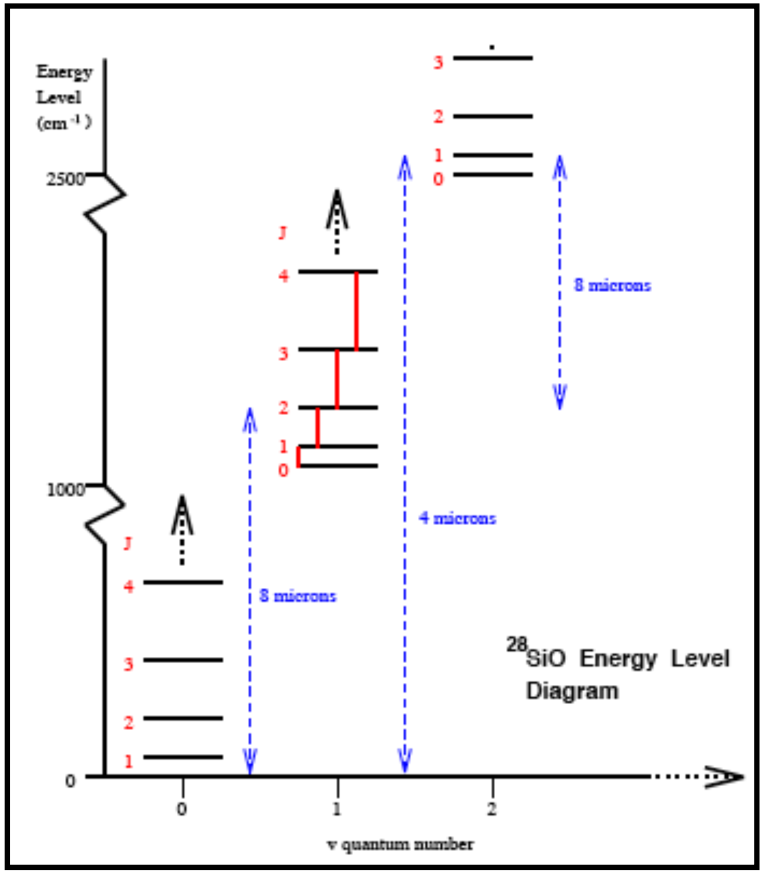
W Hya J=15-14; 650 GHz

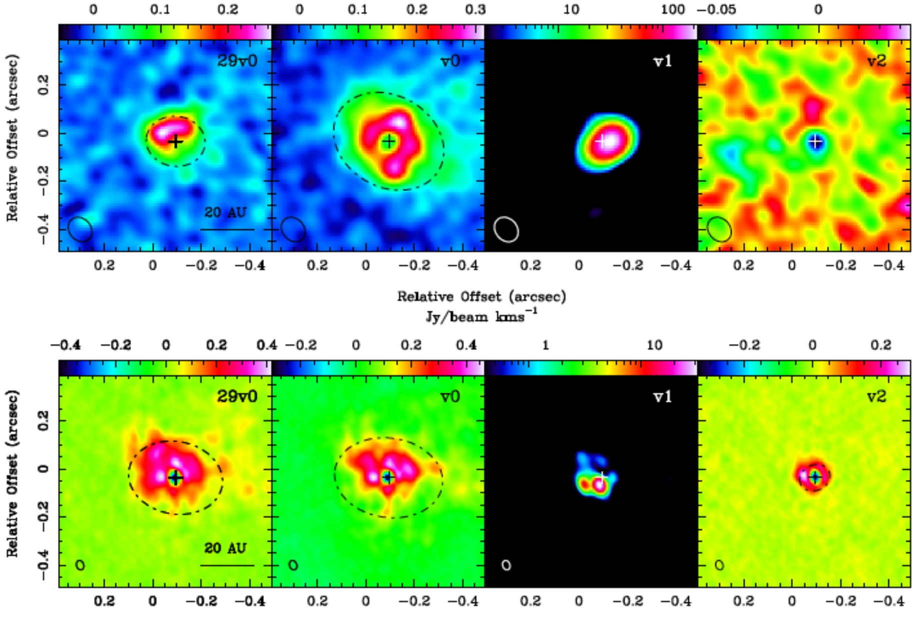


Humphreys et al. (in prep)

SiO Masers

- SiO masers probe the extended atmosphere
- Masers typically thought to arise from vibrationally excited states (>1800 K)
- These require high densities and temperatures
- $T_k \sim 1500$ K, $n(H_2) \sim 10^{10+/-1}$ cm^{-3}

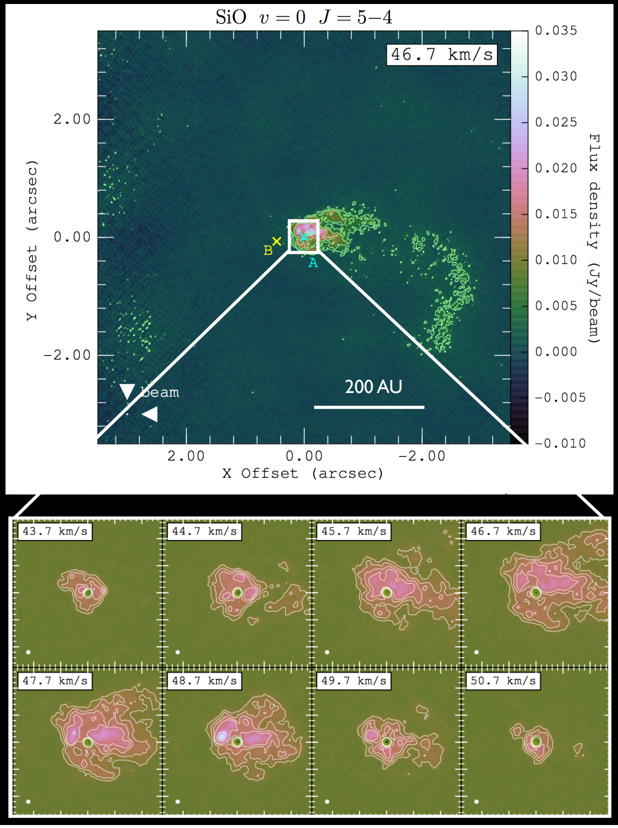




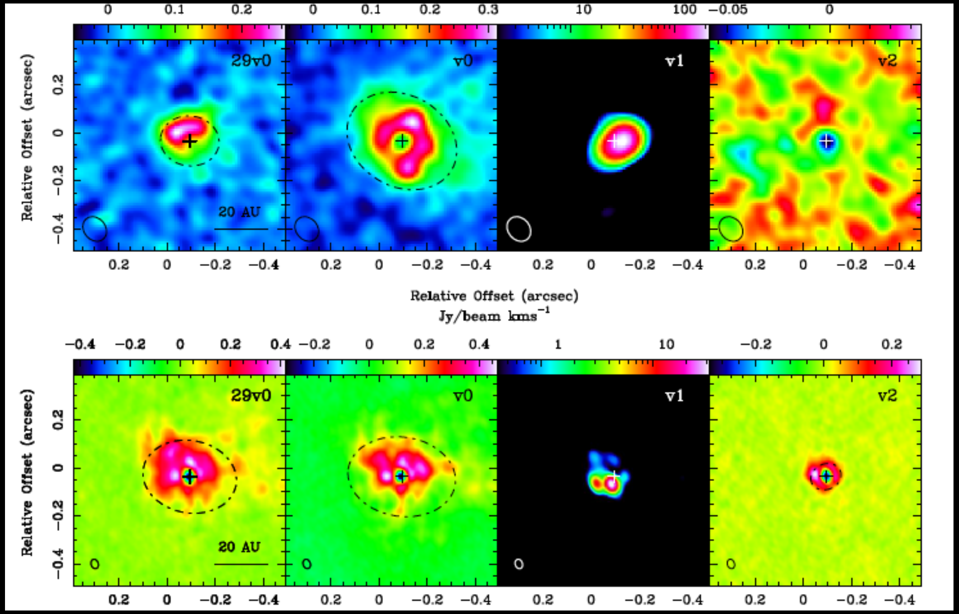
ALMA SV Long Baseline data: J=2-1 and J=5-4 lines

ALMA Observations of the Extended Atmosphere: Mira AB

Plume of SiO v=0 emission



ALMA 15 km Bands 3 and 6: SiO and H_2O lines



Wong et al. 2016; Wittkowski, Humphreys et al.

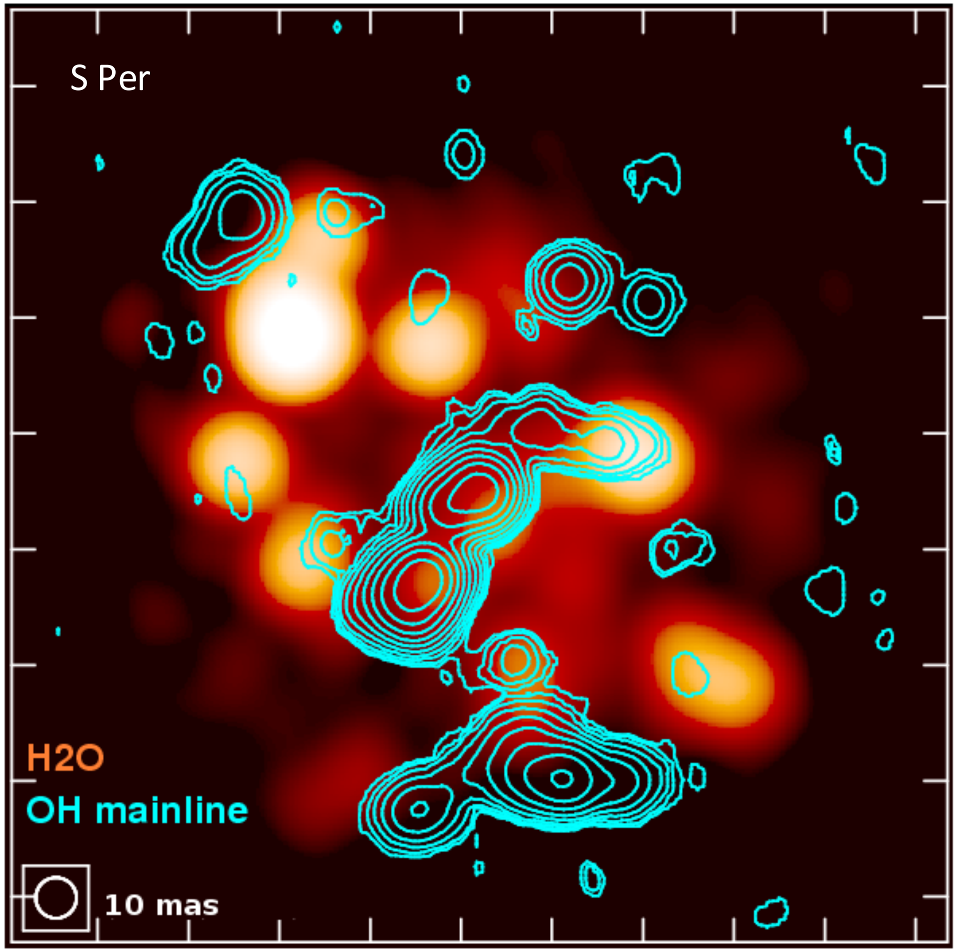
ALMA Observations of the Extended Atmosphere: Mira AB

- Key Findings:
- At this epoch, mixed infall (7 km/s) and outflow (4 km/s)
- Molecular absorption towards the stellar continuum is detected
- SiO depletes at about 4 R*, and at temperatures < 600 K, so dust interior to this radius is not likely to be purely silicate based
- Clear evidence for maser emission in several transitions - future constraints on the magnetic field

Water Masers: mostly studied at 22 GHz so far

Freq. (GHz)	**Transition $J_{ka,kc}$ ->$J_{ka,kc}$**	**Vib. State**	**Ortho/ Para**	**E_u/k (K)**	**CSE**	**SFR**	**EXG**	**Primary Reference**
22.235	6_{16}-5_{23}	G	O	644	Y	Y	Y	Cheung et al. (1969)
96.261	4_{40}-5_{33}	ν_2	P	3065	Y			Menten & Melnick (1989)
183.308	3_{13}-2_{20}	G	P	205	Y	Y	Y	Waters et al. (1980)
232.687	5_{50}-6_{43}	ν_2	O	3463	Y			Menten et al. (1989)
293.439	6_{61}-7_{52}	ν_2	O	3935	Y			Menten et al. (2006)
321.226	10_{29}-9_{36}	G	O	1862	Y	Y		Menten & Melnick (1991)
325.153	5_{15}-4_{22}	G	P	470	Y	Y		Menten & Melnick (1991)
336.228	5_{23}-6_{16}	ν_2	O	2956	Y			Feldman et al. (1992)
354.885	$17_{4\,13}$-$16_{7\,10}$	G	O	5782	Y			Feldman et al. (1992)
380.194	4_{14}-3_{21}	G	O	324		Y		Phillips et al. (1980)
437.347	7_{53}-6_{60}	G	P	1525	Y	Y		Melnick et al. (1993)
439.151	6_{43}-5_{50}	G	O	1089	Y	Y	T	Melnick et al. (1993)
470.889	6_{42}-5_{51}	G	P	1091	Y	Y		Melnick et al. (1993)
658.007	1_{10}-1_{01}	ν_2	O	2361	Y			Menten & Melnick (1989)

22 GHz Water Masers in RSGs: Probing Wind Acceleration



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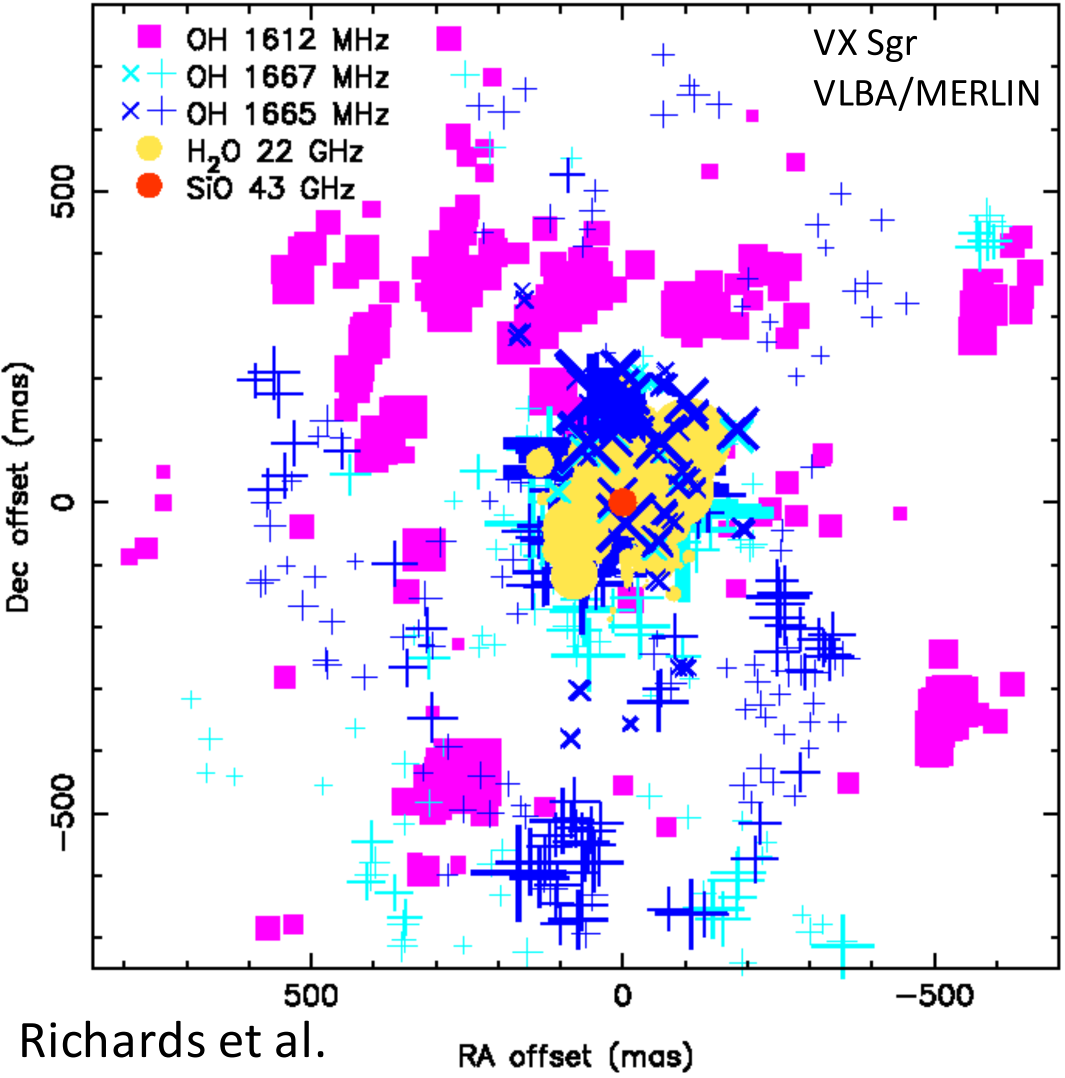
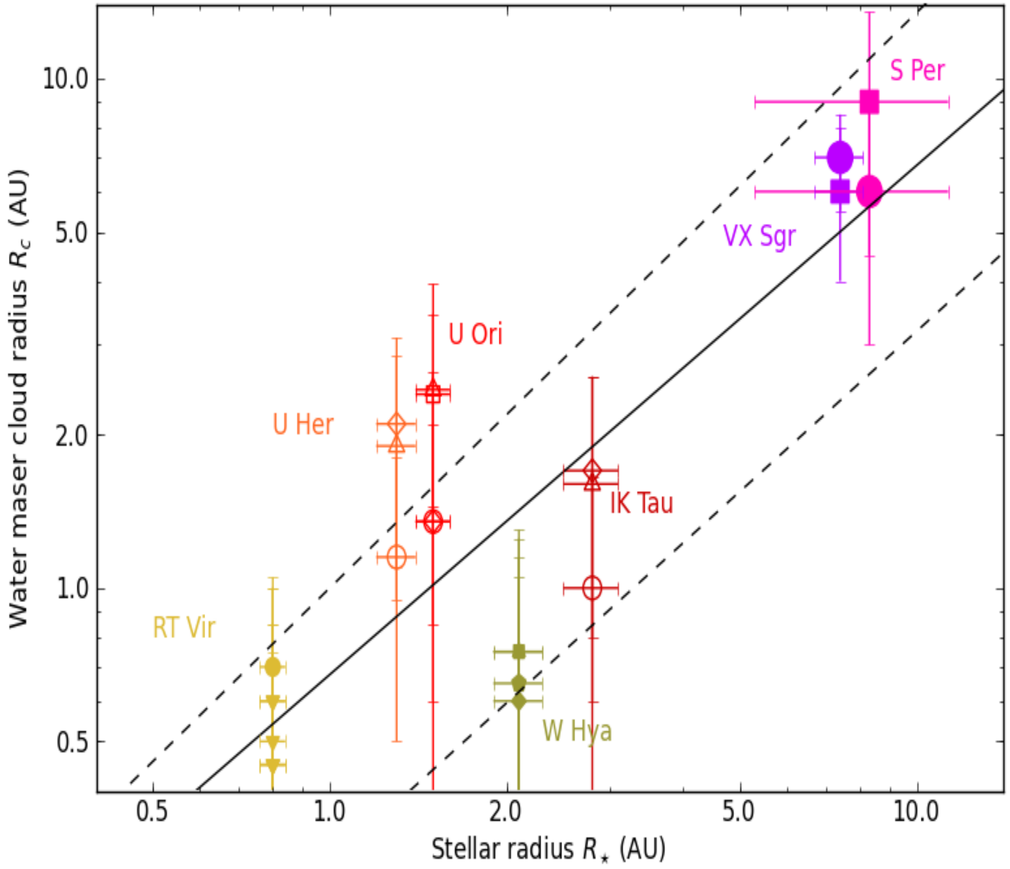


Richards et al.

Slide courtesy of Anita Richards

Cloud size depends on star size

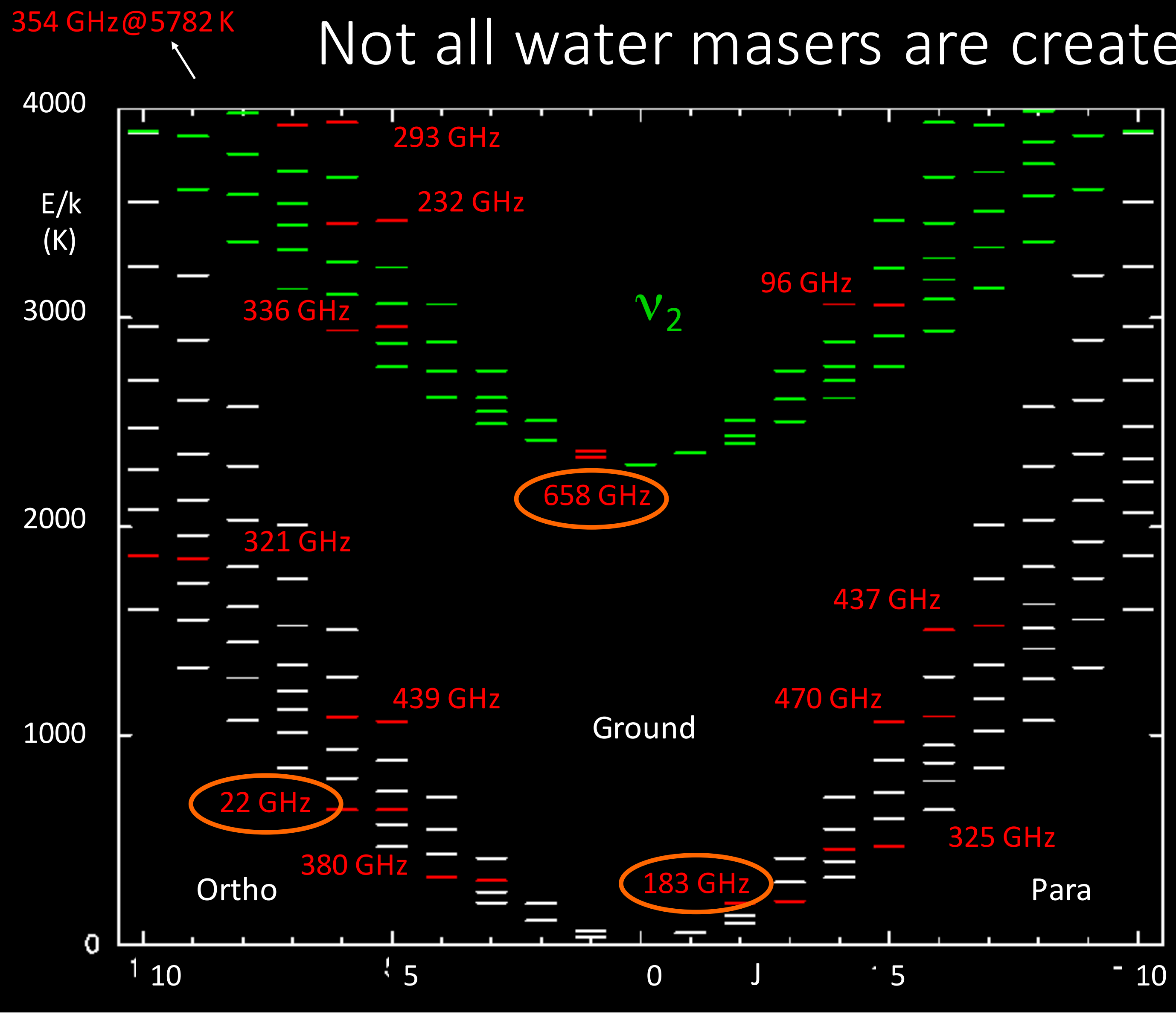
- Cloud radius ~1$R_{\mathbf{H}}$
  - Ten-fold range of $R_{\mathbf{H}}$
  - Assuming radial expansion, birth radius 5%–10% $R_{\mathbf{H}}$
- Must be determined by stellar properties
  - Not dust cooling/ microphysics
    - Would be same scale for all **H**'s
  - Star spots?
  - Convection cells?
    - *Chiavassa* models



Richards et al. 2012

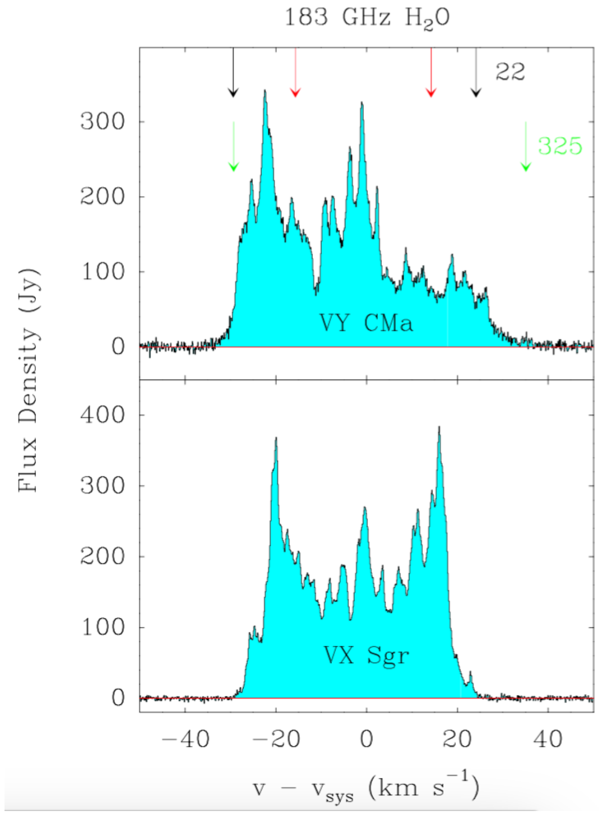
Tk ~ 400 K
n(H_2)=10^8-10^{10}cm-3

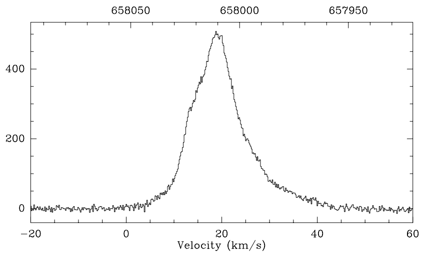
Not all water masers are created equal…



Data
from
Tennyson
(UCL)

Mm and submm water masers in evolved stars: first mapping by Richards et al. (2014; ALMA)

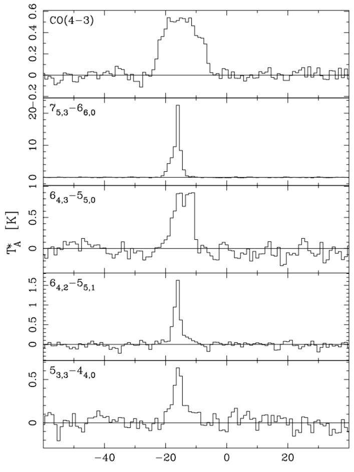


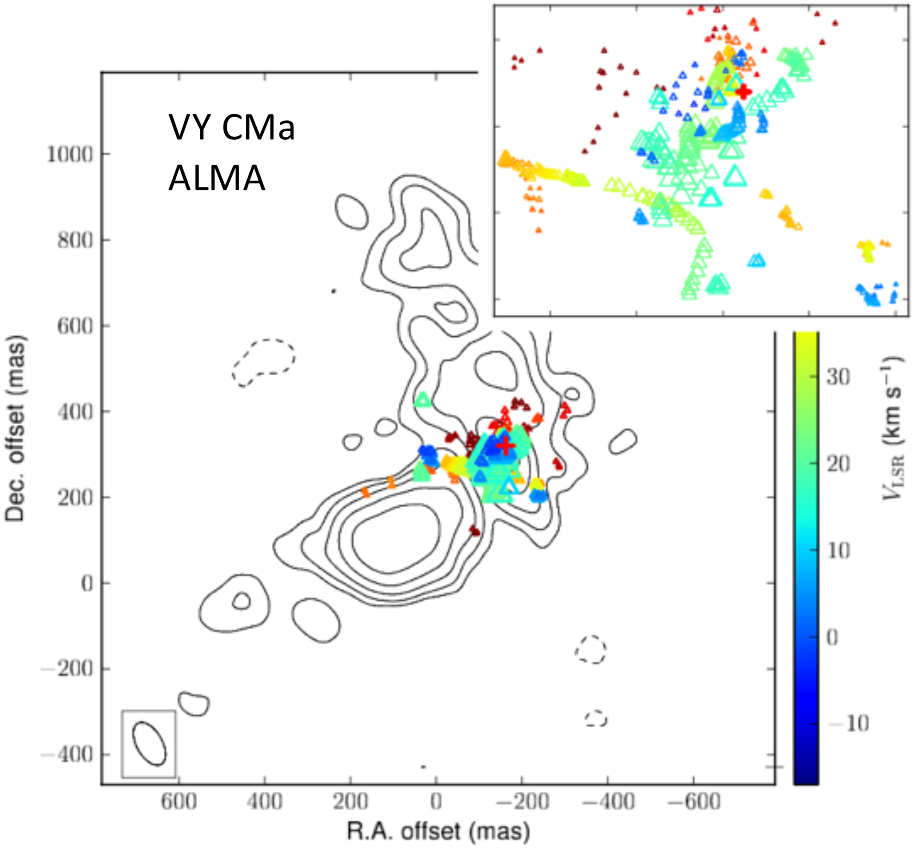


658 GHz VY CMa

Several hundred Jy

U Her: 437, 439, 471, 475 GHz





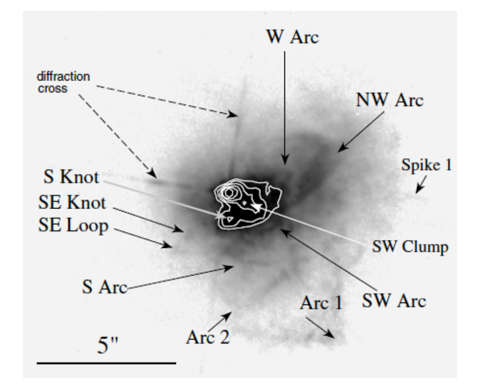
VY CMa

ALMA

321, 325 and 658 GHz (Richards et al. 2014)

Humphreys et al. (in prep); Baudry et al. (in prep)

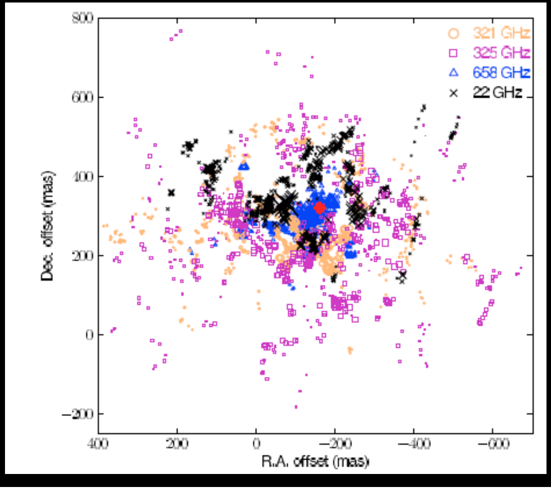
Wind acceleration: H_2O Masers

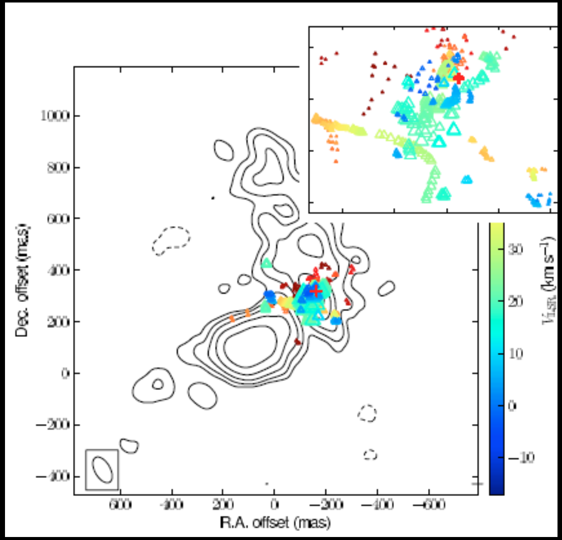


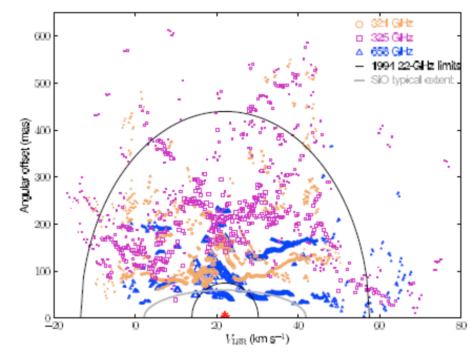
VY CMa (RSG)

Richards et al. (2014)

ALMA 2.7 km baseline, 0.1 to 0.2”
Relative position uncertainties B9
maser spots: << 0.1”





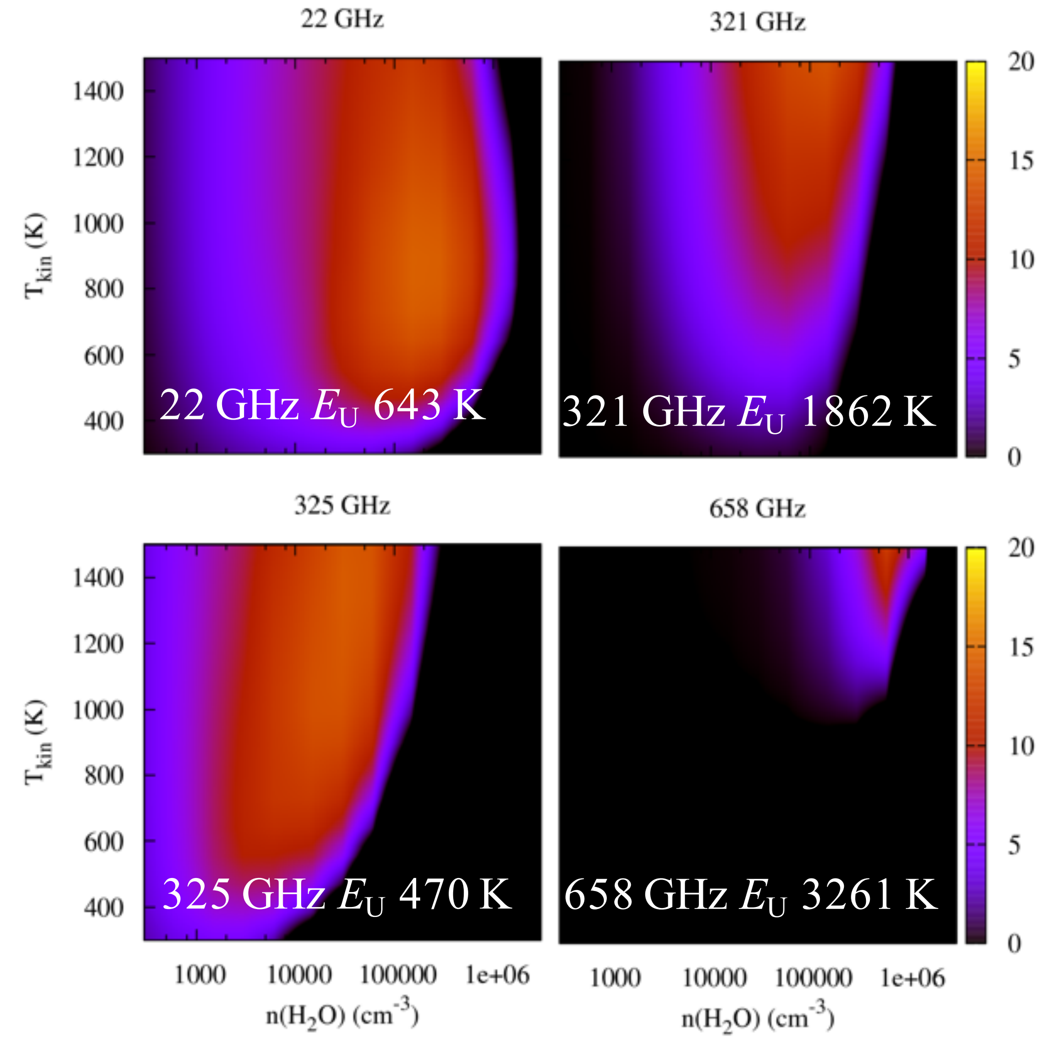


H_2O masers straddle the dust formation zone

Proper motions, physical conditions, B-field

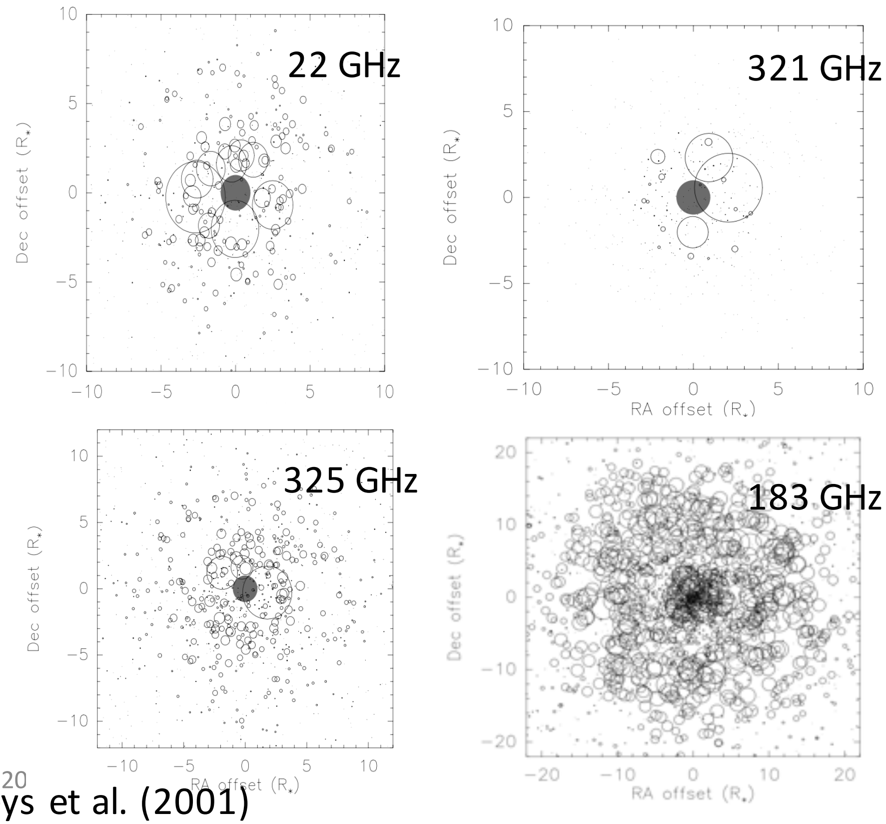
Throughout the ALMA Bands

Water Maser Models/ Predictions



Gray et al. (2016)

Simulated Distributions



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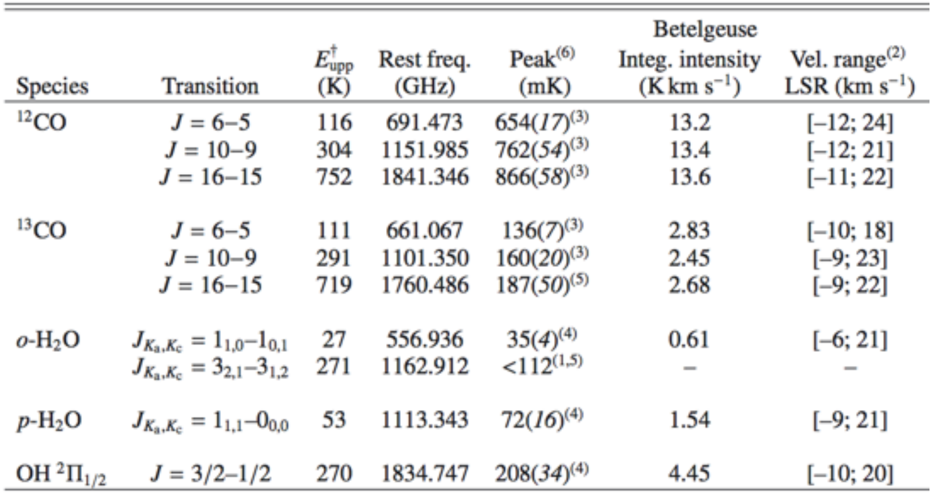
Humphreys et al. (2001)

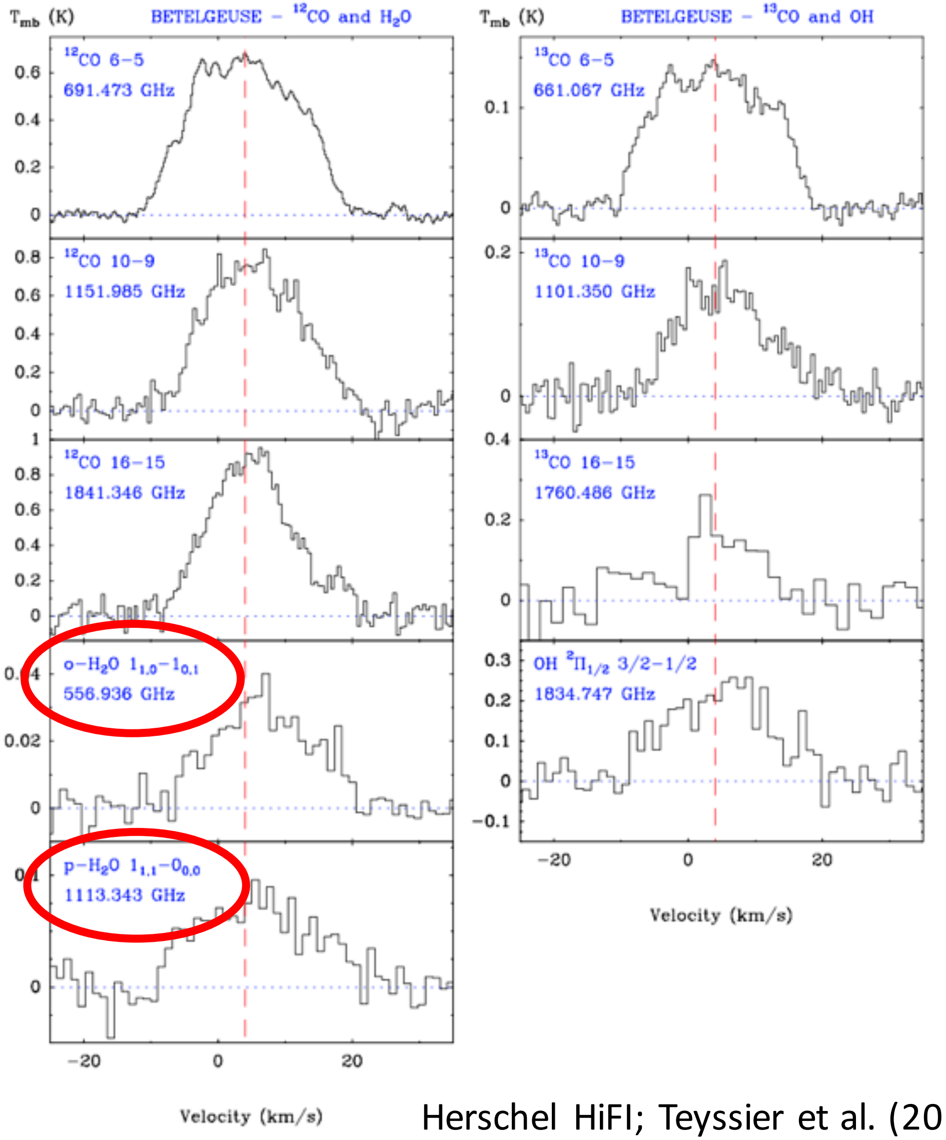
HIFI Water & OH in Betelgeuse



Species	Transition	$E^\dagger_{\rm upp}$ (K)	Rest freq. (GHz)	Peak[6] (mK)	Betelgeuse Integ. intensity (K km s^{-1})	Vel. range[2] LSR (km s^{-1})
^{12}CO	$J = 6–5$	116	691.473	654(*17*)[3]	13.2	[–12; 24]
	$J = 10–9$	304	1151.985	762(*54*)[3]	13.4	[–12; 21]
	$J = 16–15$	752	1841.346	866(*58*)[3]	13.6	[–11; 22]
^{13}CO	$J = 6–5$	111	661.067	136(*7*)[3]	2.83	[–10; 18]
	$J = 10–9$	291	1101.350	160(*20*)[3]	2.45	[–9; 23]
	$J = 16–15$	719	1760.486	187(*50*)[5]	2.68	[–9; 22]
o-H_2O	$J_{K_a,K_c} = 1_{1,0}–1_{0,1}$	27	556.936	35(*4*)[4]	0.61	[–6; 21]
	$J_{K_a,K_c} = 3_{2,1}–3_{1,2}$	271	1162.912	<112[1,5]	–	–
p-H_2O	$J_{K_a,K_c} = 1_{1,1}–0_{0,0}$	53	1113.343	72(*16*)[4]	1.54	[–9; 21]
OH $^2\Pi_{1/2}$	$J = 3/2–1/2$	270	1834.747	208(*34*)[4]	4.45	[–10; 20]

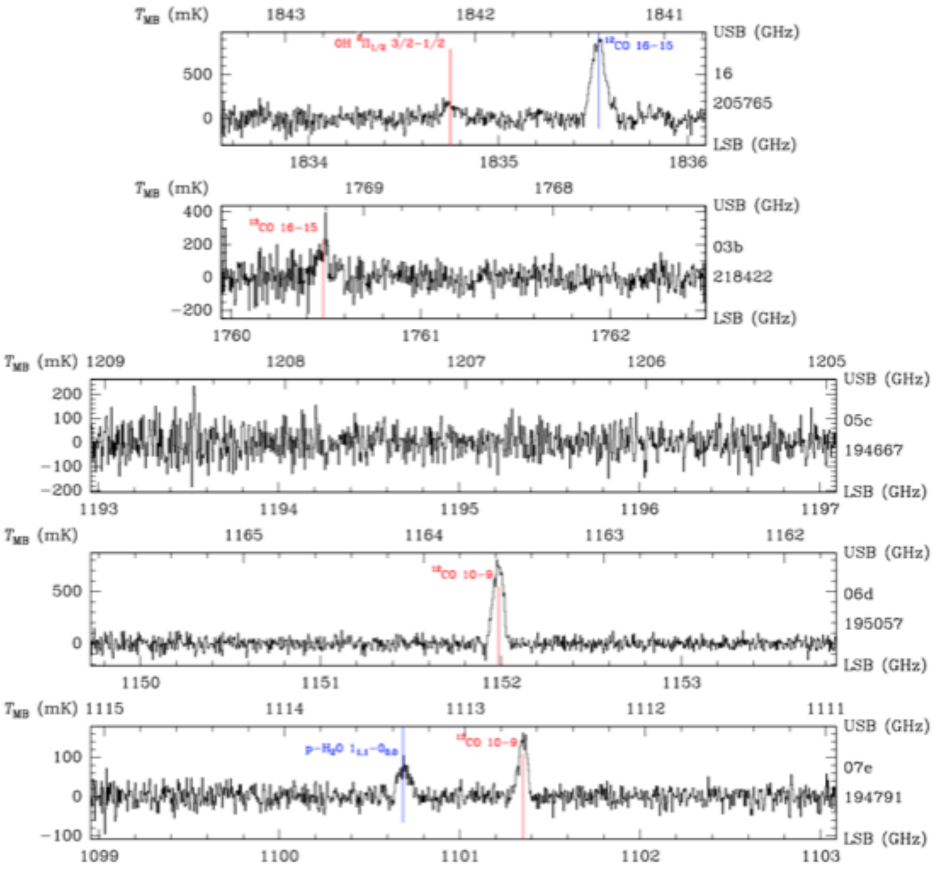
The 556 GHz line is predicted to be a maser by Gray et al. (2016)

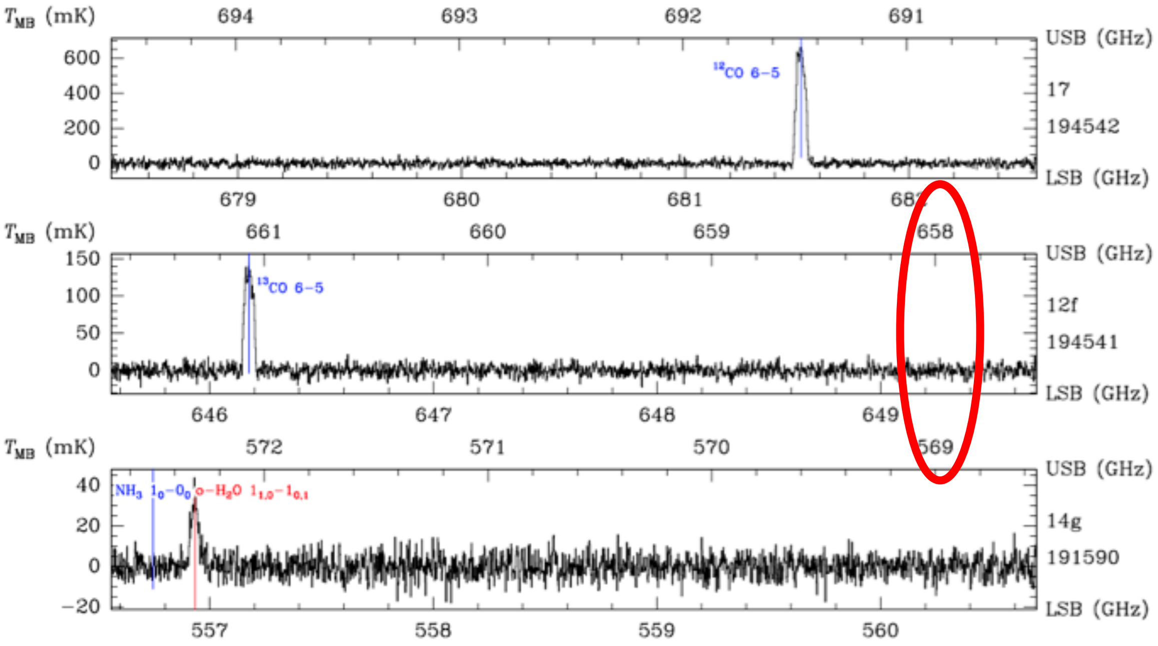
Eu = 27 K, 16 Jy



Herschel HiFI; Teyssier et al. (2012)

Betelgeuse Lines
Teyssier et al. (2012)
Herschel HIFI





Non-detection at 658 GHz

Be