658 GHz Vibrationally-Excited Water Masers with the Submillimeter Array

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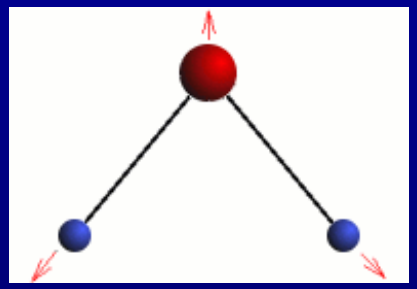
Vibrational states of water

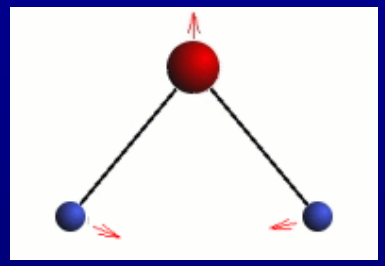
Water has 3 vibrational quantum numbers:

v_1



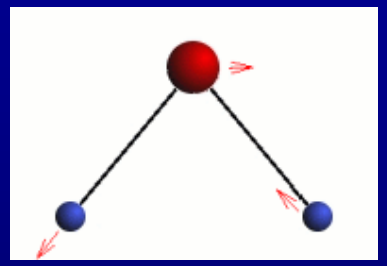
Symmetric stretching
3657 cm^{-1}

v_2



Bending mode
1595 cm^{-1}

v_3



Asymmetric stretching
3756 cm^{-1}

(Herzberg 1945)

Many of these lines involving these modes are in the mid- and near-IR

- Mira variables: e.g. R Leo (Hinkle & Barnes 1979)
- Comet Tempel1 after Deep Impact

Vibrationally-excited Water Lines

- predictions made by Deguchi & Nguyen-Q-Rieu (1990)
- observed mm/submm lines from the v_2=1 state = (0,1,0)

Frequency (GHz)	Transition $J_{Ka,Kc}$--$J'_{Ka'Kc'}$	E_{upper} (K)	Telescope	Reference
96.261	$4_{4,0}$ - $5_{3,3}$ (para)	3066	IRAM-30m	Menten & Melnick 1989
232.686	$5_{5,0}$ - $6_{4,3}$ (ortho)	3465	IRAM-30m	Menten & Melnick 1989
293.664	$6_{6,1}$ - $7_{5,2}$ (ortho)	2941	APEX-12m	Menten et al. 2006
336.227	$5_{2,3}$ - $6_{1,6}$ (ortho)	2958	APEX-12m	Menten et al. 2006
658.006	$1_{1,0}$ - $1_{0,1}$ (ortho)	2362	CSO	Menten & Young 1995

Non-detections:

12.008	$4_{2,3}$ - $3_{3,0}$ (ortho)	2748	140ft	Myers & Barrett 1982
67.704	$4_{1,4}$ - $3_{2,1}$ (ortho)	2623	12m	Petuchowski & Bennett 1991
297.439	$6_{6,0}$ - $7_{5,3}$ (para)	3938	APEX-12m	Menten et al. 2006

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strongly masing in O-rich stars (kJy)

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Known 658 GHz masers (as of 1995)

Original ten CSO detections (Menten & Young 1995):

1. Semi-regular pulsating stars:

R Crt	M7III	SRb
RT Vir	M8III	SRb
W Hya	M7e	SRa
RX Boo	M7.5	SRb

2. Cool hypergiants:

VX Sgr	M5/M6III	SRc
VY CMa	M3/M4II	$5 \times 10^5\ L_\odot$
NML Cyg	M6IIIe	$5 \times 10^5\ L_\odot$

3. Mira variable stars:

R Leo	M8IIIe
S CrB	M7e
U Her	M7III

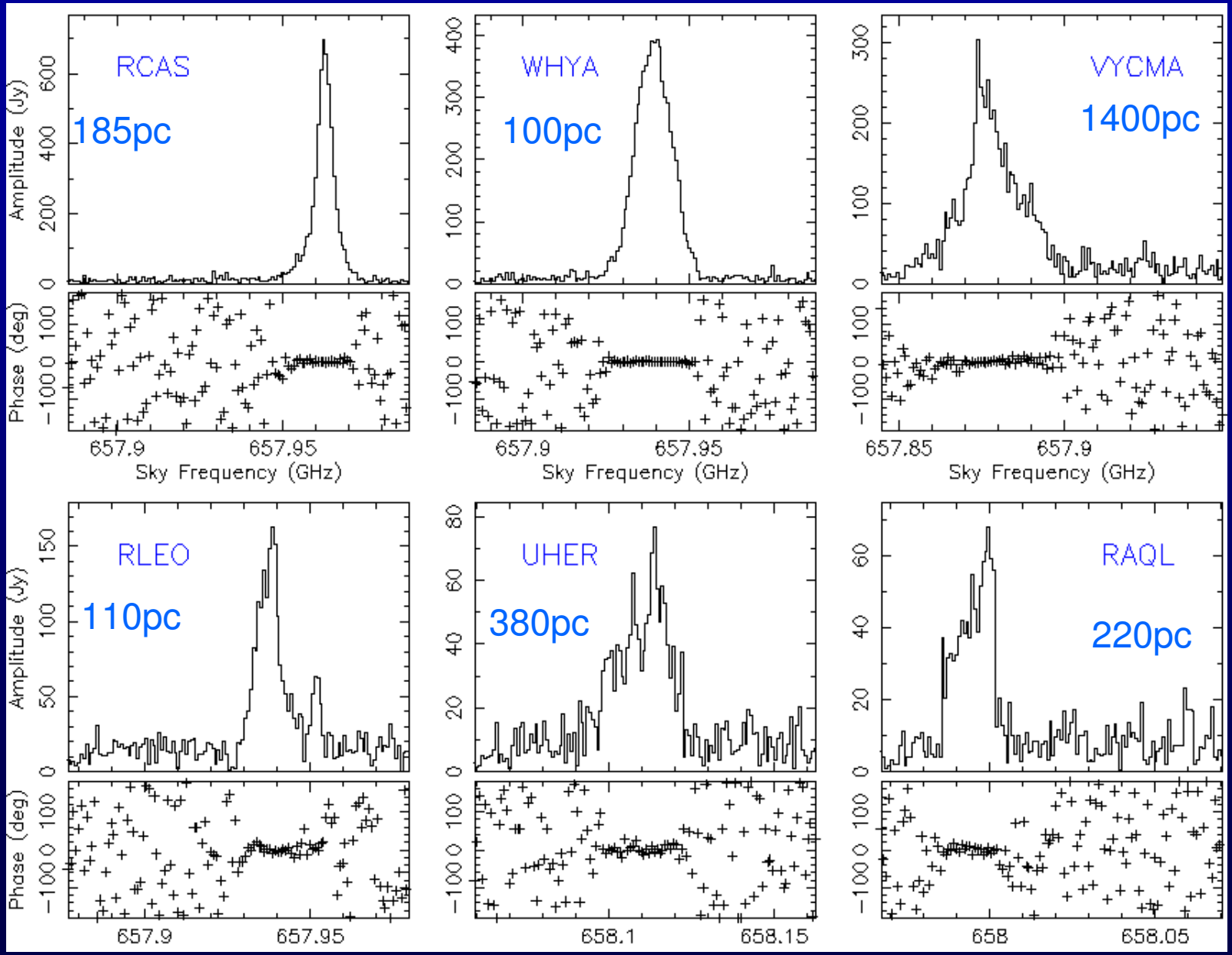
Not masing in SFRs (W49N, W51IRS2)
Detected as a thermal line in Orion KL line survey

658 GHz maser observations with SMA

- Compact configuration: 16m – 100m (1 arcsec)
- Taken mostly during commissioning time:
  - ✓ SMA began science operations in Dec 2003 at 230/345 GHz
  - ✓ 690 GHz system: needed something bright to detect for debugging
  - ✓ calibration was not a priority in these observations

Date	#Antennas	τ_{225GHz}	Detections
Dec 02, 2002	3	0.03 – 0.05	U Ori
Apr 08, 2004	4	0.07	R Cas, R Aql, VY CMa, U Her, R Leo
Jan 24, 2005	5	0.06	W Hya
Feb 16, 2005	6	0.03 – 0.06	VY CMa
Dec 14, 2005	7	0.028	NML Tau, TX Cam, R Cas
Jan 11, 2006	6	0.055	R Hya

658 GHz masers (April 2004), with 1” beam



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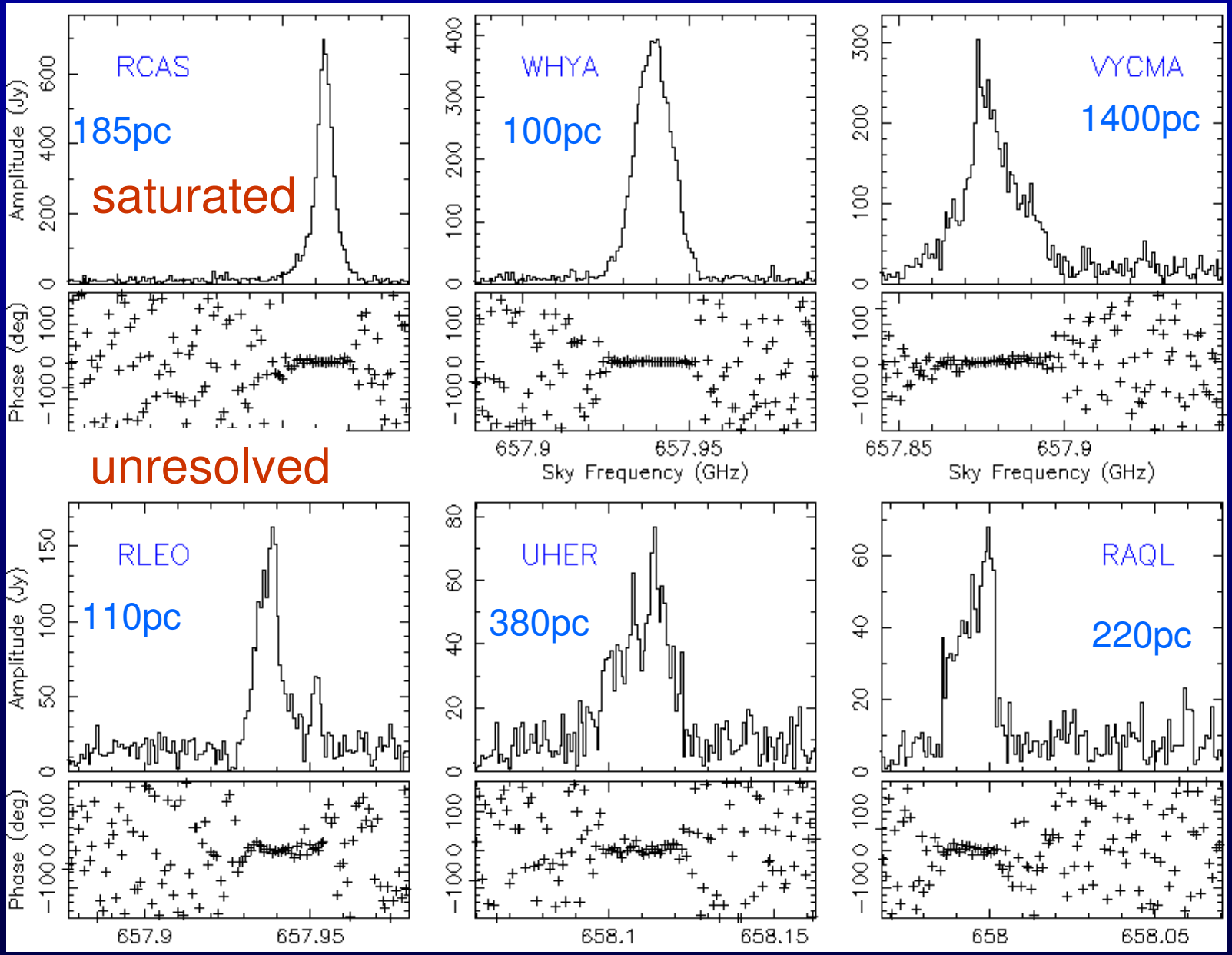
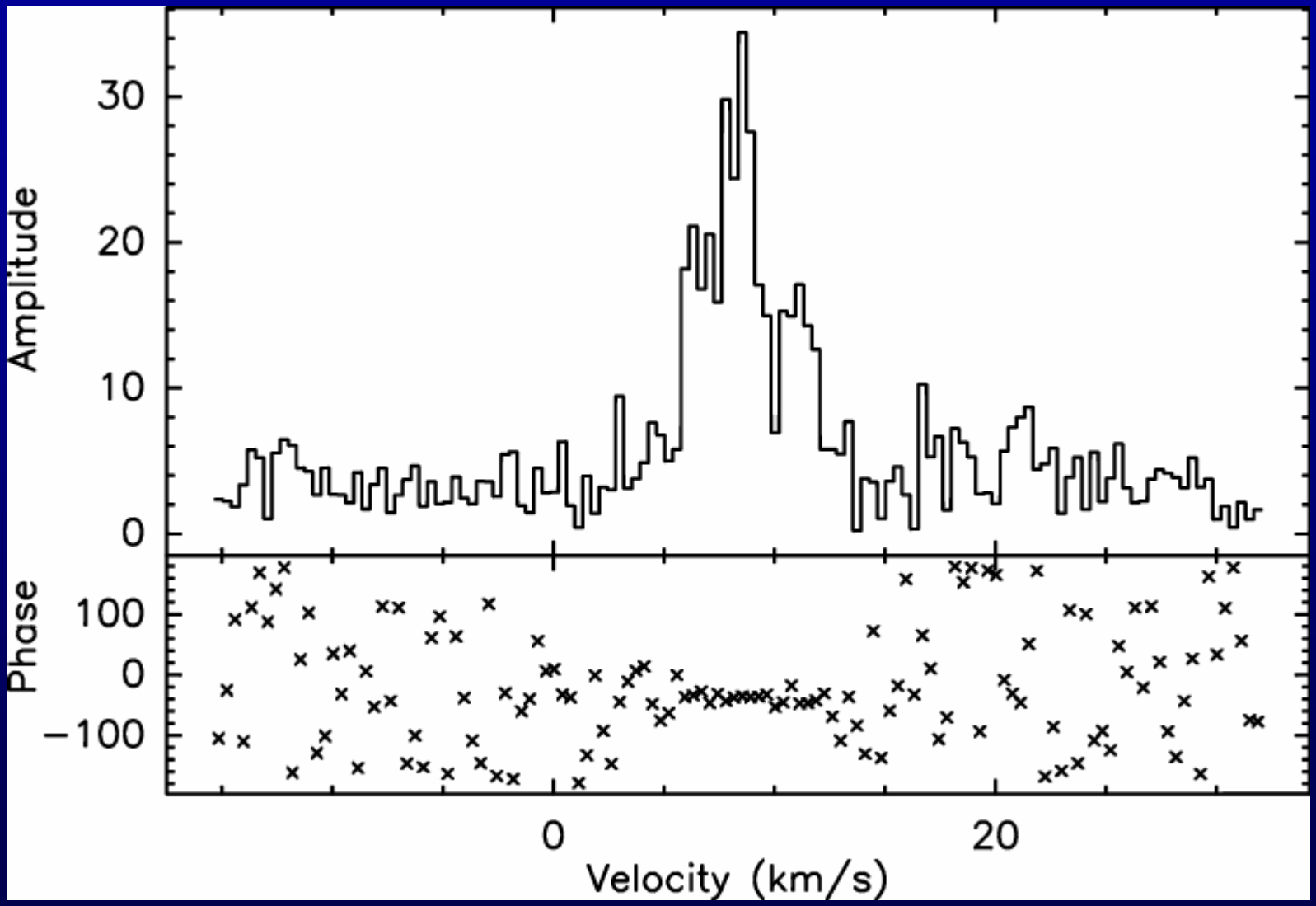
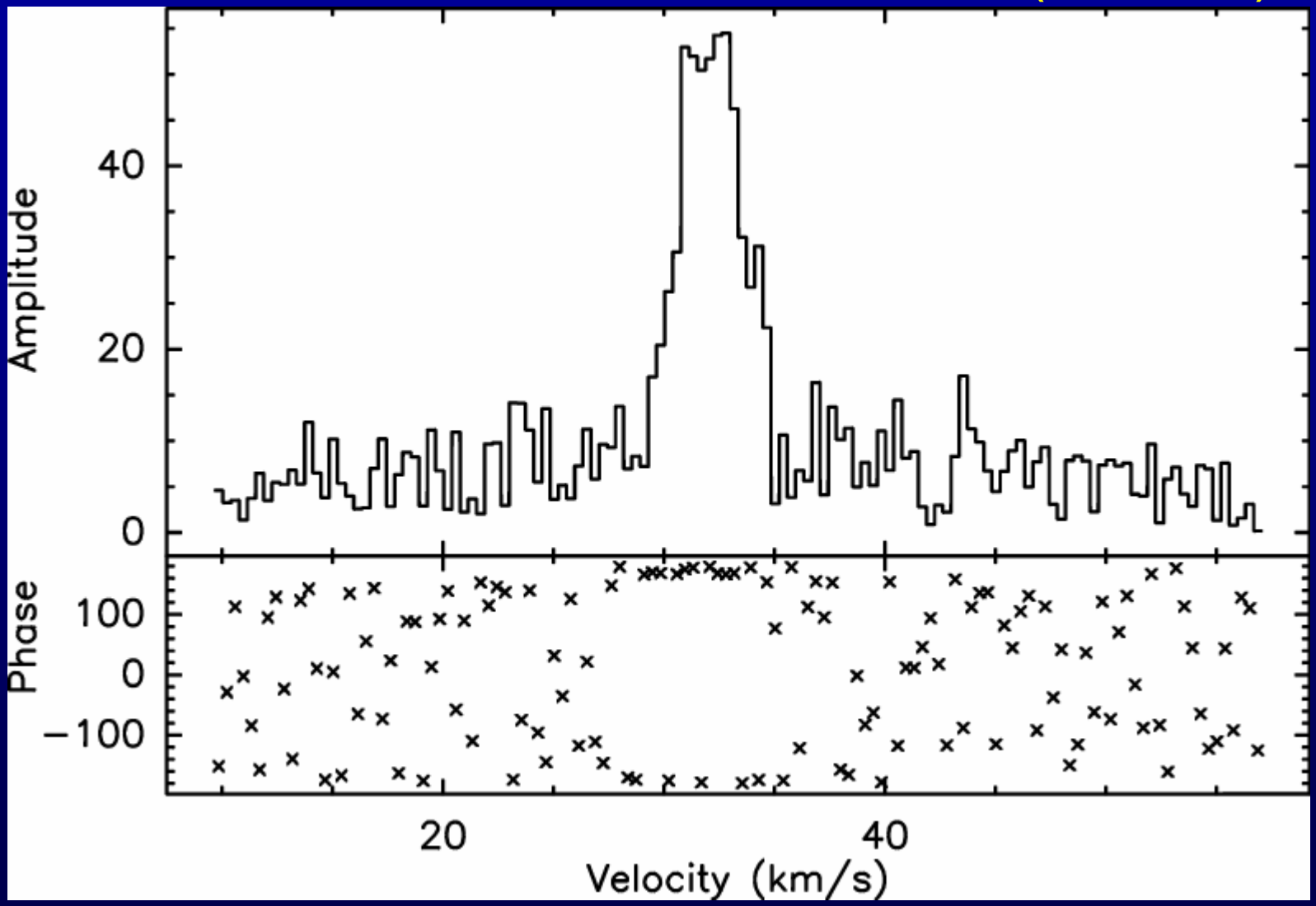


First 658 detection of TX Cam



First 658 detection of NML Tau (IK Tau)



Known 658 GHz masers (March 2007)

10 CSO detections (Menten & Young 1995)

1. Semi-regular pulsating stars:

R Crt	M7III	SRb
RT Vir	M8III	SRb, 220 pc
W Hya	M7e	SRa, 98 pc
RX Boo	M7.5	SRb

2. Cool hypergiants with high-mass loss rates:

VX Sgr	M5/M6III	SRc, 1.4 kpc
VY CMa	M3/M4II	1.5 kpc, 5 x 10^5 $L_\odot$
NML Cyg	M6IIIe	2.0 kpc, 5 x 10^5 $L_\odot$

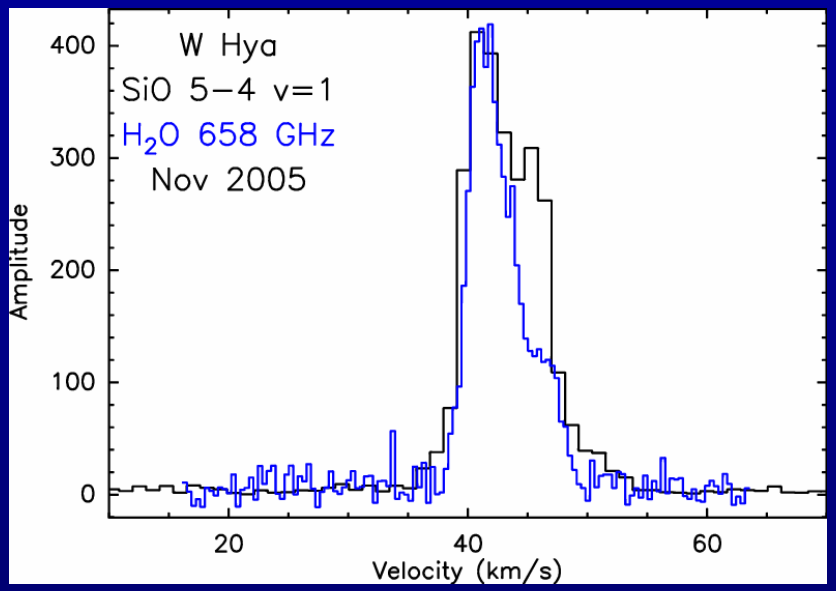
3. Mira variables

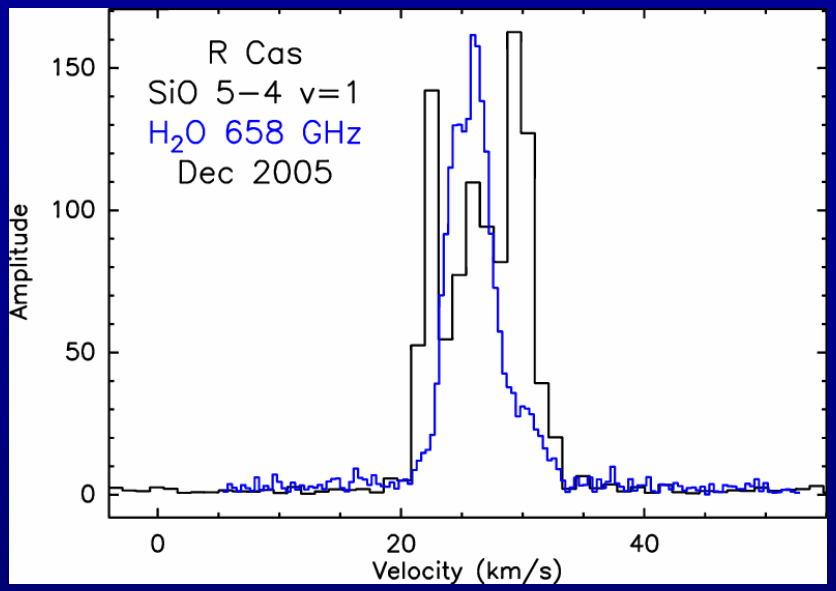
6 new SMA detections

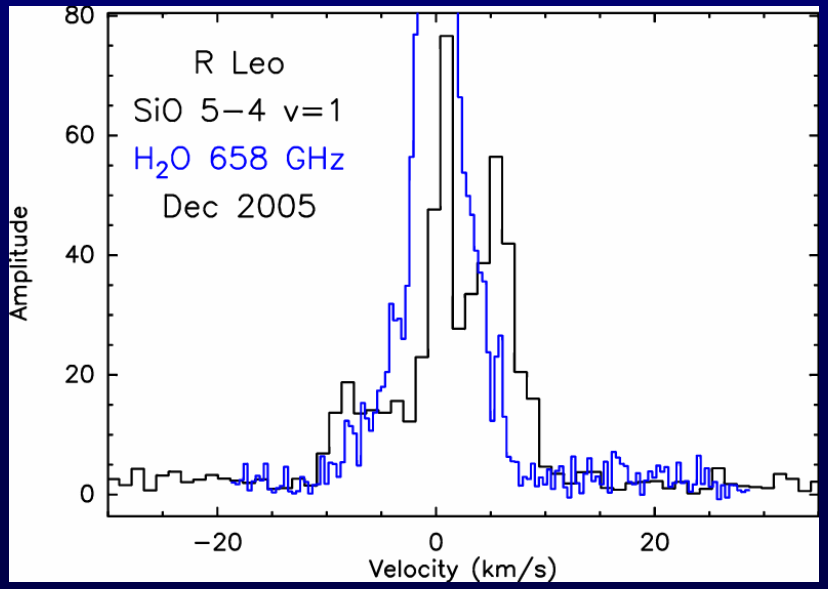
R Leo	M8IIIe	110 pc
S CrB	M7e	430 pc
U Her	M7III	380 pc 8200$L_\odot$
R Hya	M7IIIe	125 pc
R Cas	M7IIIe	180 pc, 8700$L_\odot$
TX Cam	M8.5	380 pc
NML (IK) Tau	M6me	270 pc
R Aql	M7IIIev	220 pc
U Ori	M8III	265 pc

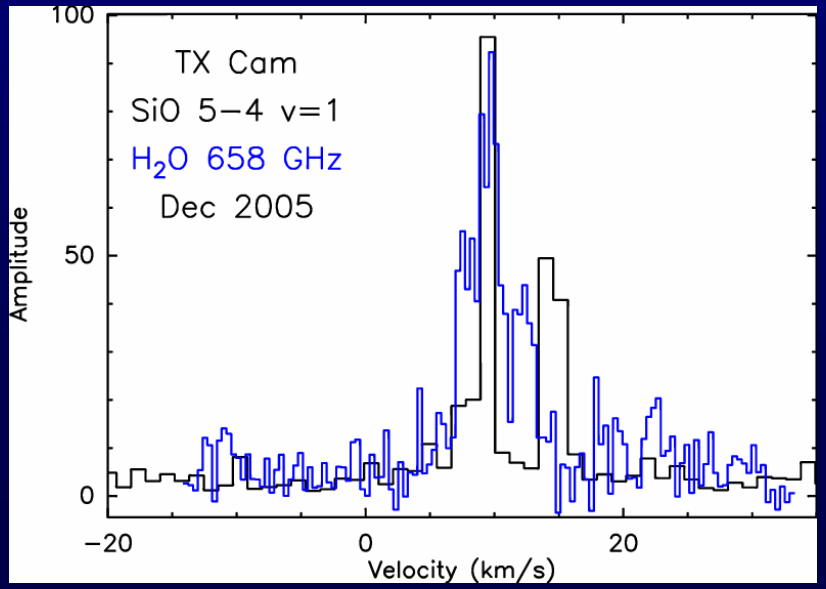
Non-detections: IRC+10011, IRC+70066, Betelgeuse, GX Mon, RS Cnc, Chi Cyg, OH231.8

Simultaneous SiO J=5-4 v=1 & 658 H_2O spectra





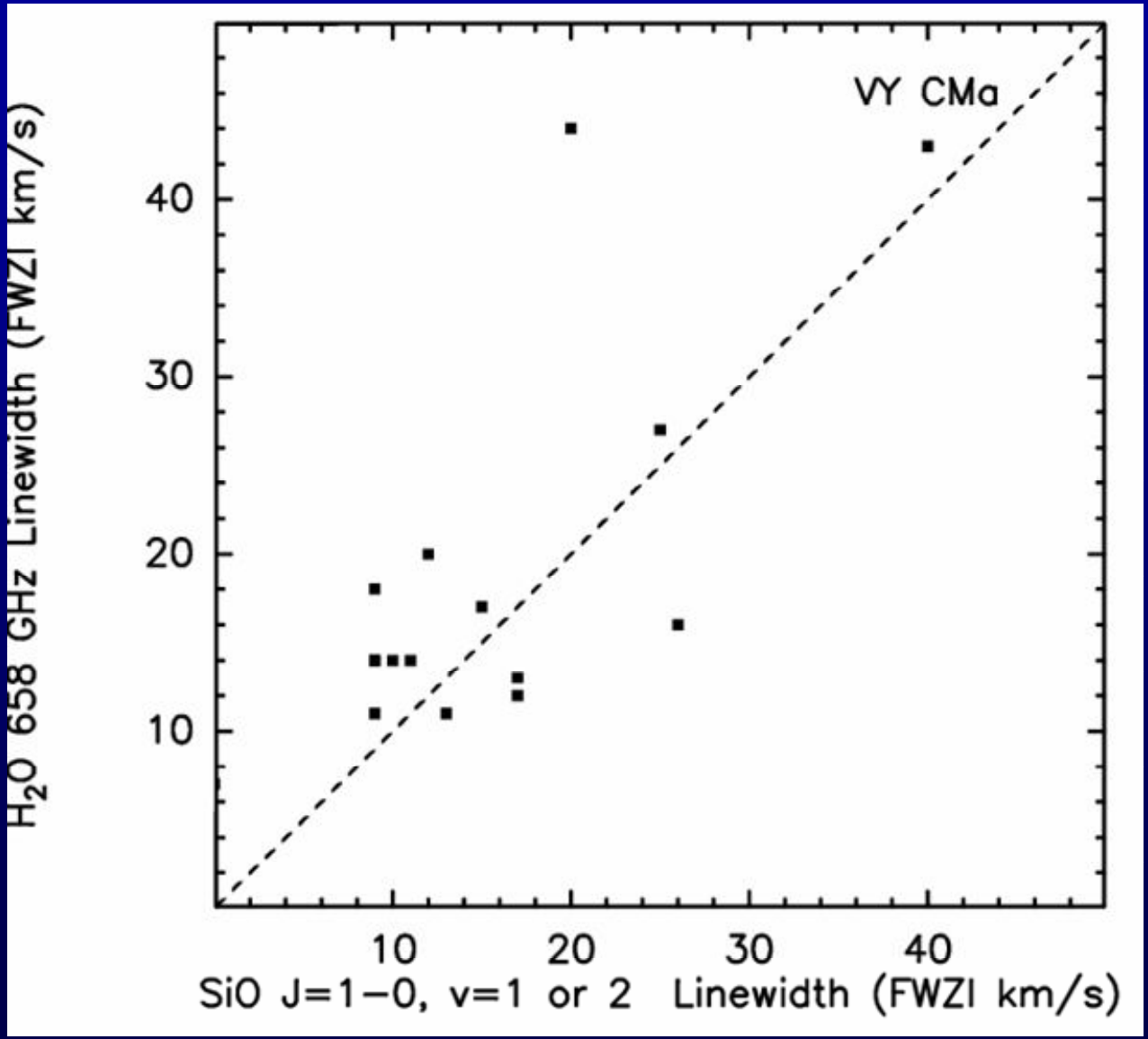




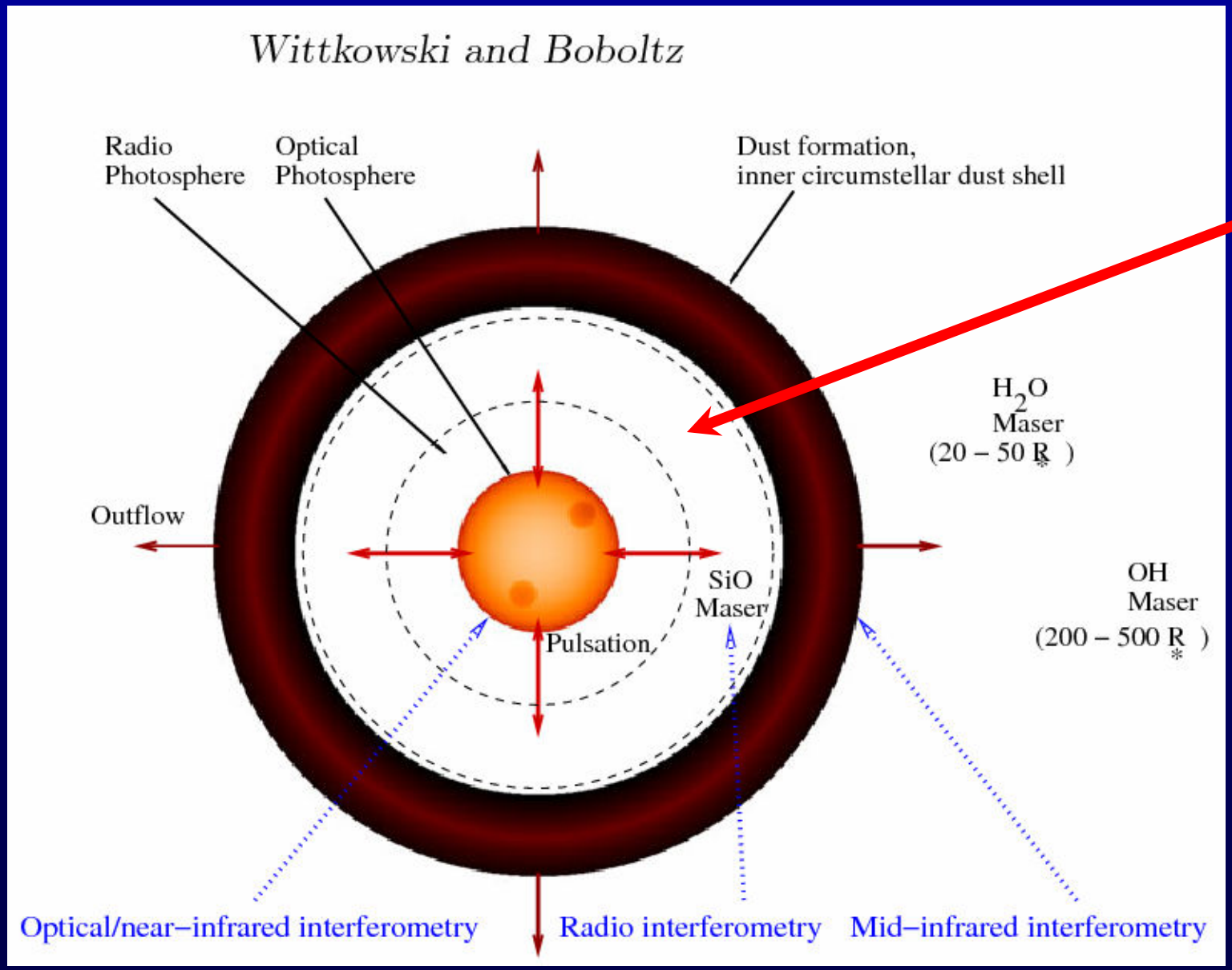
Maser linewidths: H_2O vs SiO

Source	H_2O	SiO v=2, J=1-0 (km/s)	
VYCMa	40	43	(Cho et al. 1996)
NML Cyg	26	16	(Cho et al. 1996)
VX Sgr	25	27	(Chen et al. 2006)
R Crt	20	44	(Alcolea et al. 1990)
RT Vir	17	13	(Cho et al. 1996)
RX Boo	17	12	(Cho et al. 1996)
W Hya	15	17	(Cho et al. 1996)
U Her	13	11	(Cho et al. 1996)
TX Cam	11	20	(Yi et al. 2005)
R Leo	11	14	(Cho et al. 1996)
R Cas	10	14	(Cho et al. 1996)
S CrB	9	11	(Herpin et al. 2006)
R Aql	9	14	(Cho et al. 1996)
U Ori	9	18	(Cho et al. 1996)
NML Tau	9	14	(Boboltz & Diamond 2005)
R Hya		7	(Cho et al. 1996)

Maser linewidths: H_2O vs SiO



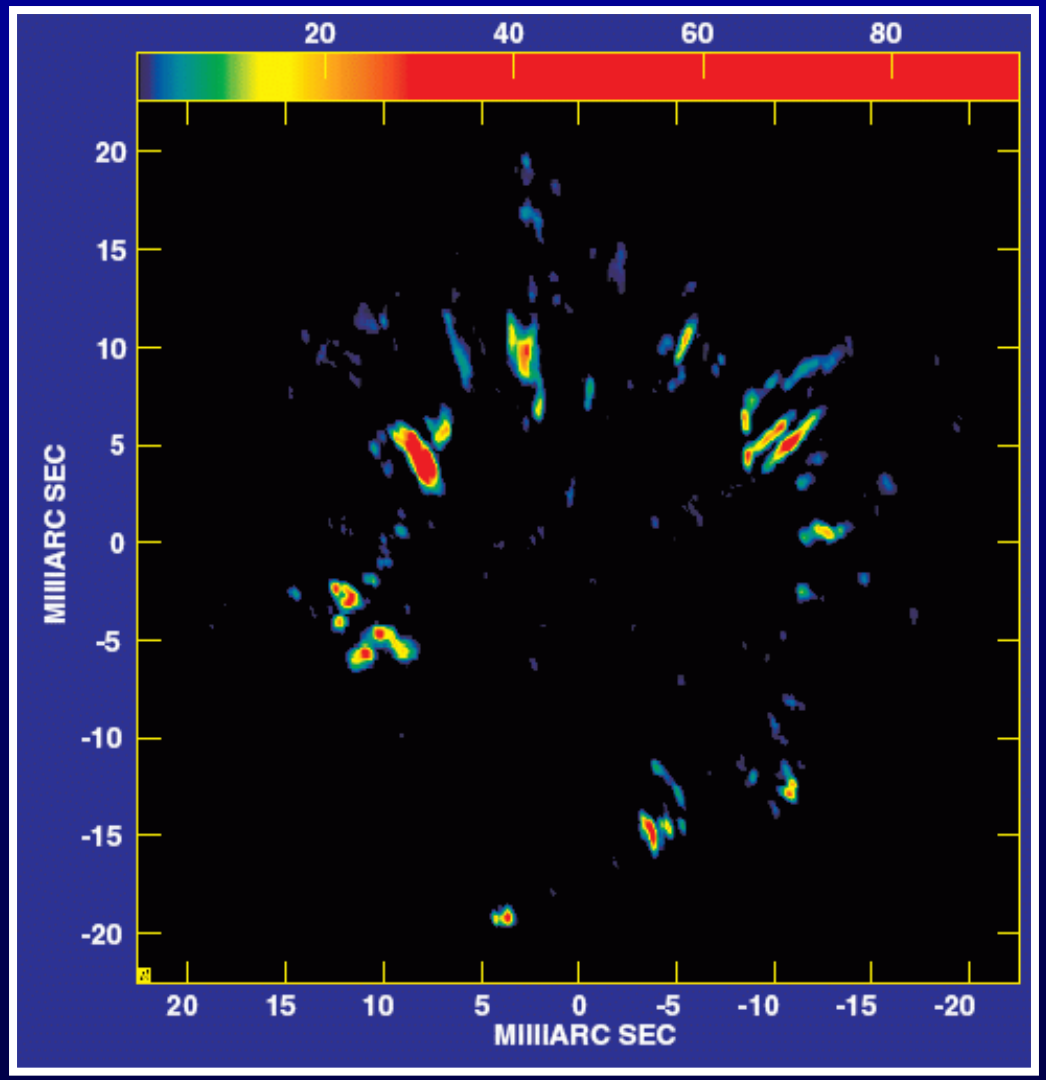
Velocity extent of 658 H_2O maser similar to SiO masers



658 GHz H_2O masers?

$n \sim 10^9$
$T = 1000K$
$r < 20R_*$

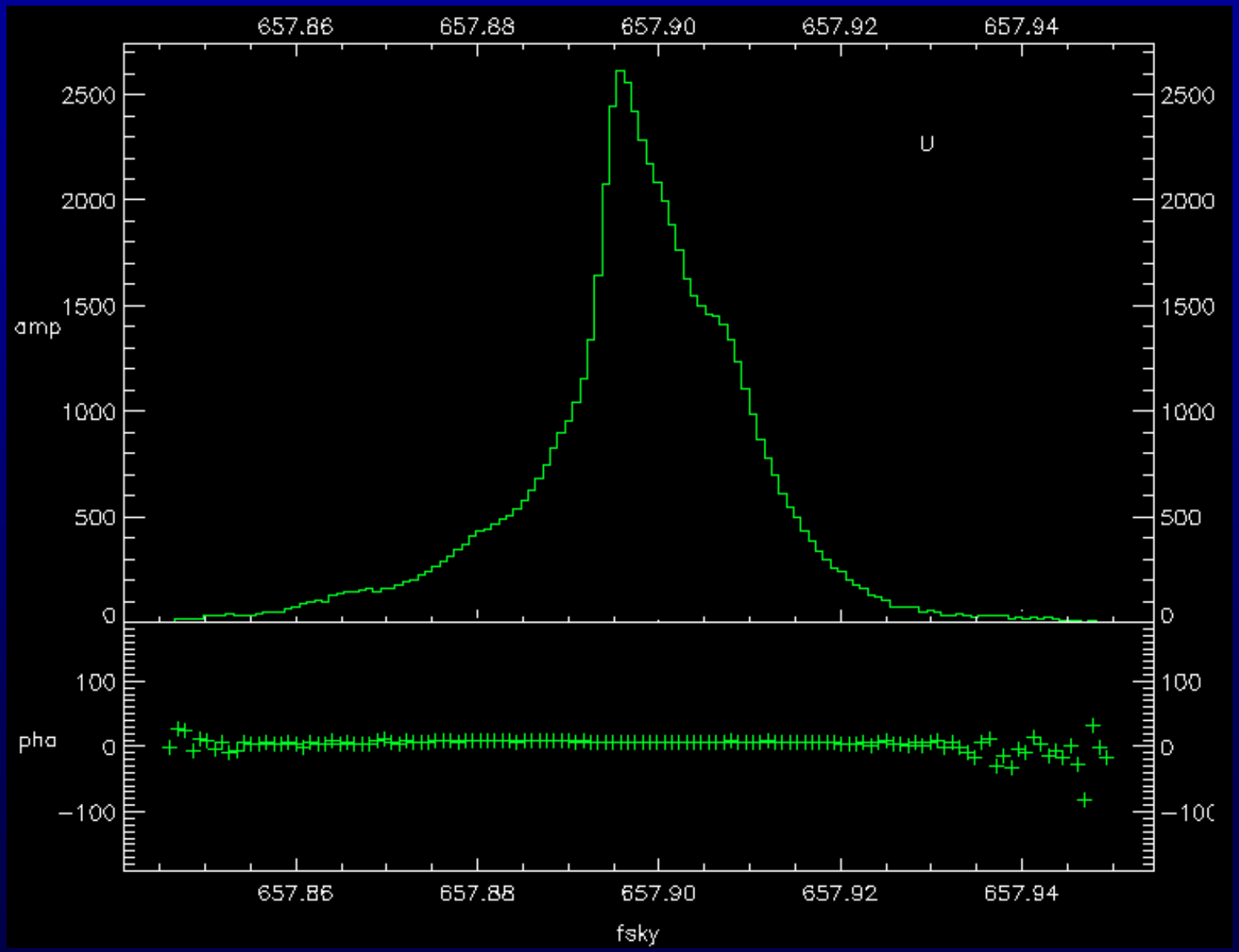
VLBI image of SiO J=1-0 v=2 in TX Cam (Yi et al. 2005)



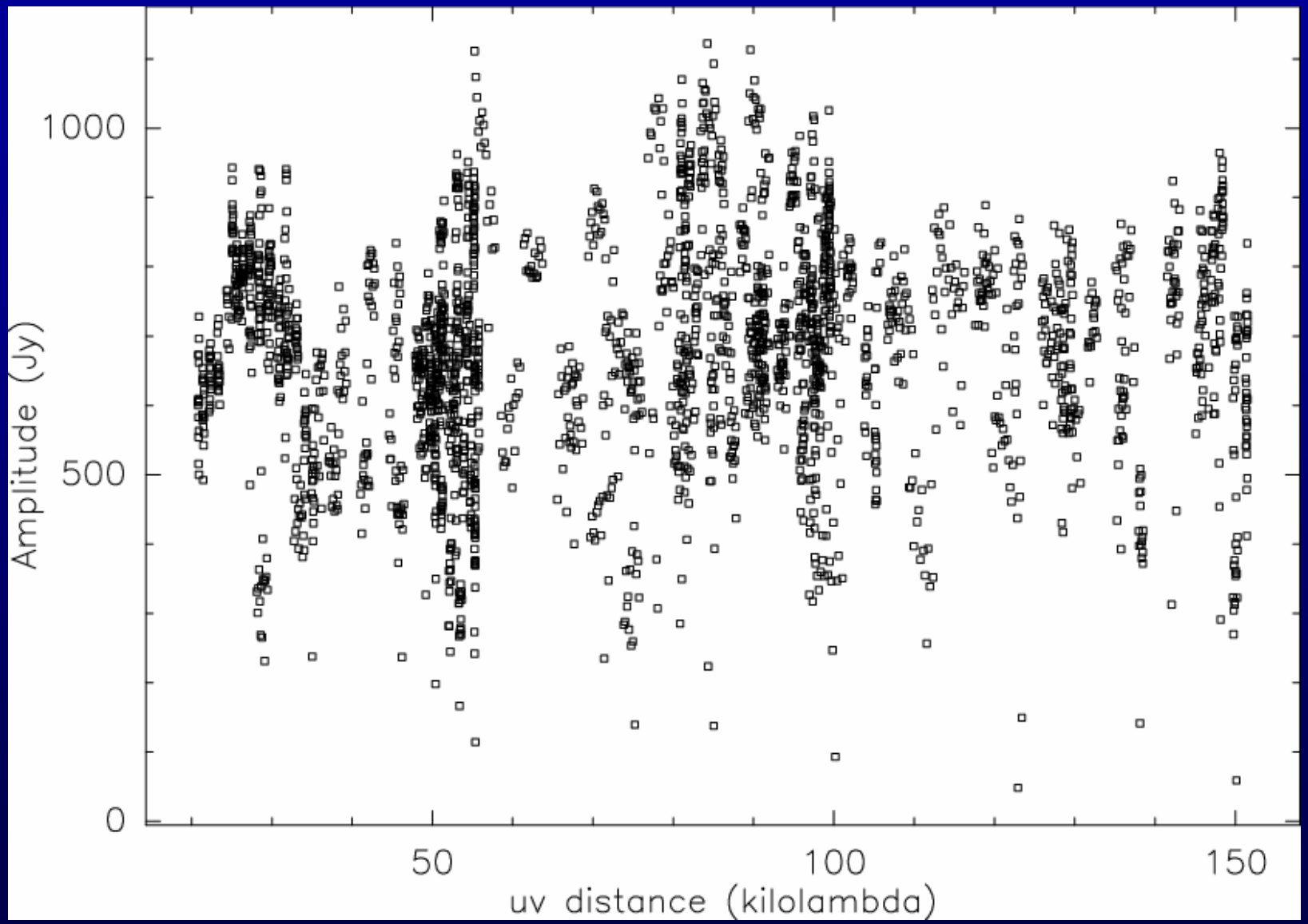
0.03” = 12 AU

If the 658 masers come from here, they should be unresolved with the SMA beam.

VY CMa: 87 minutes, 6 antennas



VY CMa maser: unresolved



Practical use of 658 GHz masers: Phase calibrators?

- Interferometry requires calibration of antenna-based phase and amplitude introduced by instrumental and atmospheric effects.

- For good phase solutions, we need S/N > 5 per baseline (in 2 min)

- SMA sensitivity: Tsys ~ 150 K at 230 GHz
  Tsys ~ 2500 K at 690 GHz

This requires a strong source! { 0.5 Jy at 230 GHz (70 quasars with F > 1Jy)
8 Jy at 690 GHz (maybe 1 or 2 quasars)

Quasars are inadequate for the SMA at 690 GHz

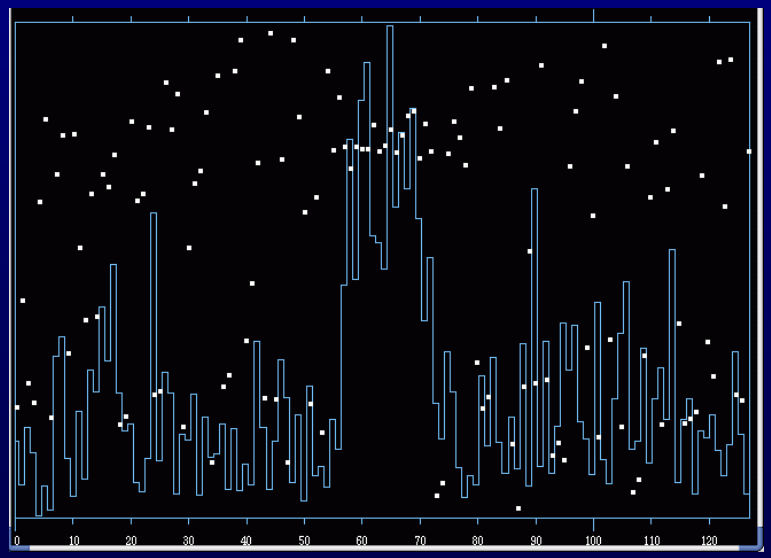
Minor planets are usable, but only in compact config.

Practical use of 658 GHz masers: Phase calibrators?

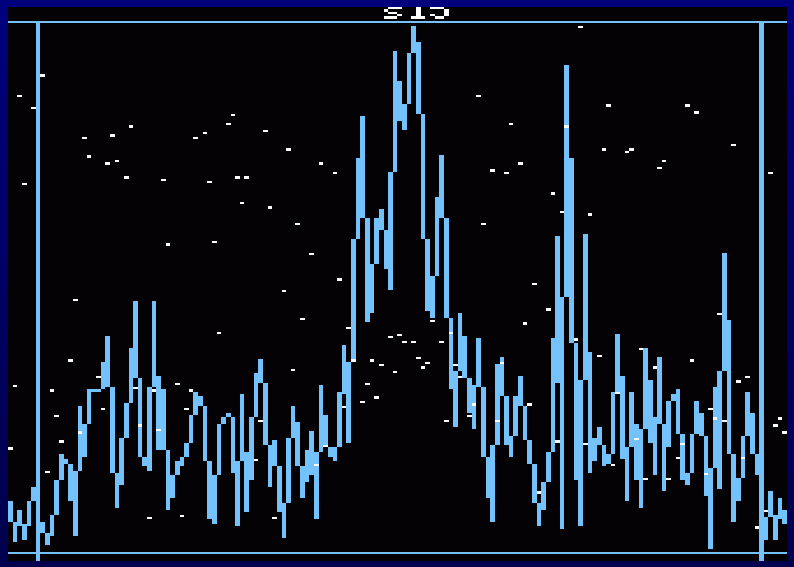
- Easily detectable on long baselines (pointlike to < 1”)

Raw 5 second integration on W Hya:

123-meter baseline



226-meter baseline



Practical use of 658 GHz masers: Phase calibrators?

- Easily detectable on long baselines (pointlike to < 1”)
- Decent sky coverage

Source	R.A.	Dec
NML Tau	03:53	+11
TX Cam	05:00	+56
U Ori	05:55	+20
VY CMa	07:22	- 25
R Leo	09:47	+11
R Crt	11:00	- 18
RT Vir	13:02	+ 5
R Hya	13:29	- 23
W Hya	13:49	- 28
RX Boo	14:21	+25
S CrB	15:21	+31
U Her	16:23	+19
VX Sgr	18:08	- 22
R Aql	19:06	+ 8
NML Cyg	20:44	+39
R Cas	23:58	+51

Practical use of 658 GHz masers: Phase calibrators?

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- Decent sky coverage

Caveats:

- Excess phase path due to terrestrial atmosphere
- not good amplitude calibrators (variable & polarized)
- however, the stellar continuum may be useful for amplitude calibration and flux calibration (Reid, Gurwell, Menten)
  VY CMa ~ 9 Jy

Example of using maser as phase calibrator: G240.31+0.07

UCHII within 5° of VY CMa

Chen et al. ApJ (Jan 1, 2007)

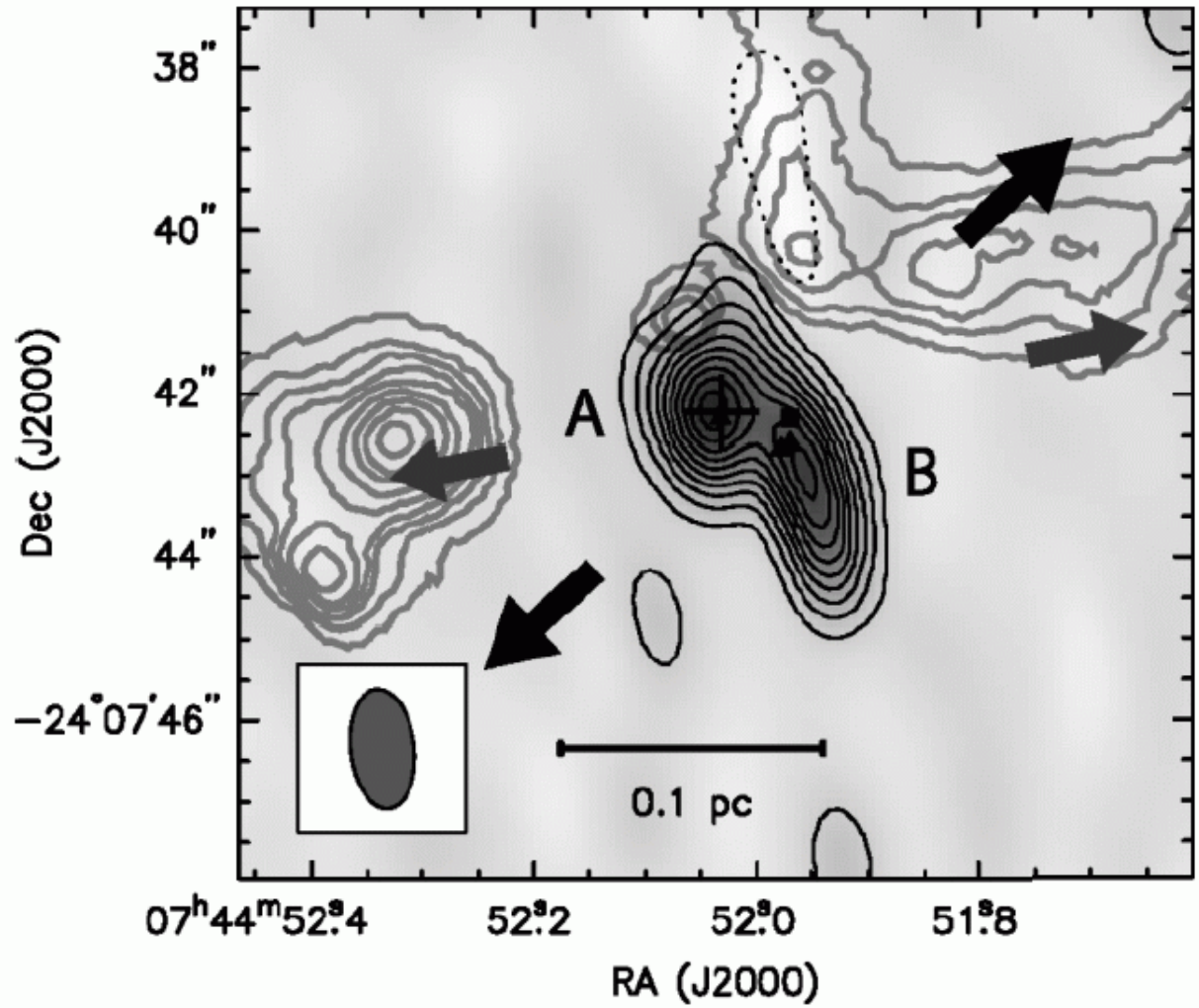


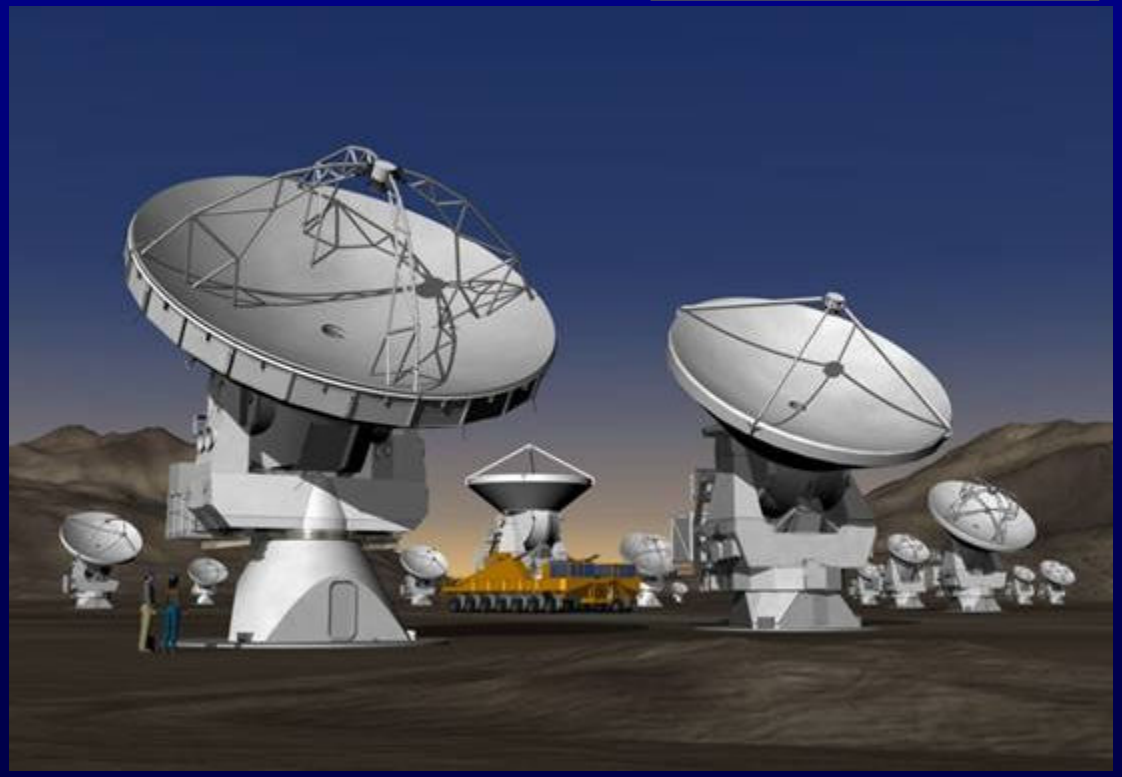
FIG. 1.—SMA 654 GHz line-free continuum map (*thin lines*) toward G240 with the H_2 emission features (*gray thick lines*; Kumar et al. 2003). The continuum emission is resolved into two clumps, with clump A well coincident with a VLA 6 cm point source (*cross*; Hughes & MacLeod 1993). The triangles represent the locations of H_2O masers (0.1″ positional error; Migenes et al. 1999), while the square indicates an OH maser spot (0.4″ positional error; Caswell 2003). Two

Future Prospects

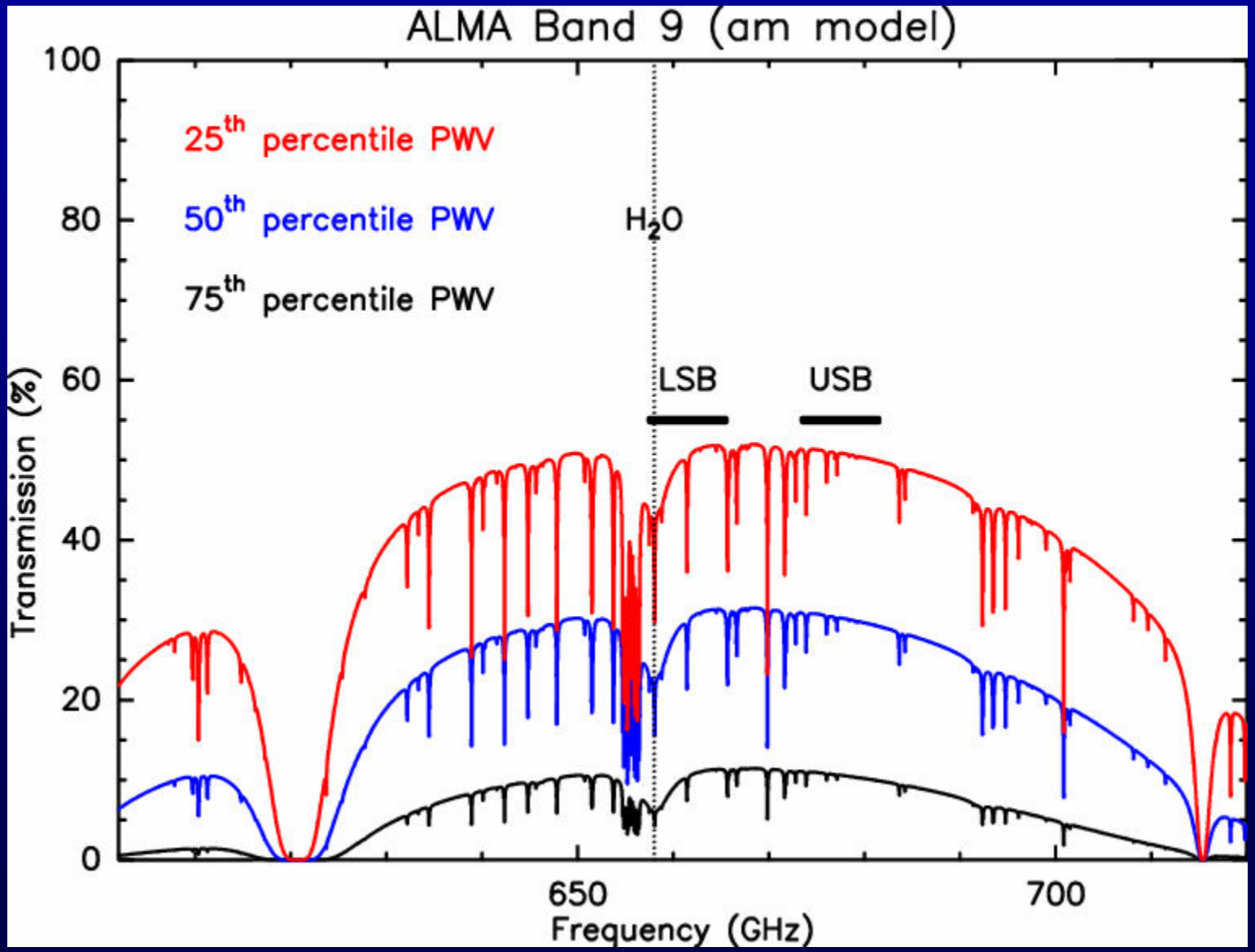
- SMA may begin to resolve 658 emission with 500m array (0.15”)

- ALMA will be the first telescope that can observe all the known vibrationally-excited H_2O rotational transitions:

Band 3: 96 GHz
Band 6: 232 GHz
Band 7: 294 & 336 GHz
Band 9: 658 GHz



Suggested ALMA band 9 tuning setup



Summary

- SMA observations have expanded the list of stars with 658 GHz water masers to 16, with typical flux densities of 100's to 1000's Jy

- Emission is compact (<1") and time variable

- Linewidth is similar to SiO vibrationally-excited masers

- As natural beacons, they will be useful as phase calibrators on baselines up to a few hundred meters for SMA and ALMA

- As objects for study, ALMA will be able to detect and resolve the emission in at least five different vibrationally-excited water lines. Probably the best way to probe the high density, high temp. regions.

- However, collisional rate coefficients in the v_2=1 level are unknown: Much work remains to be done on all fronts (lab, observation, theory)