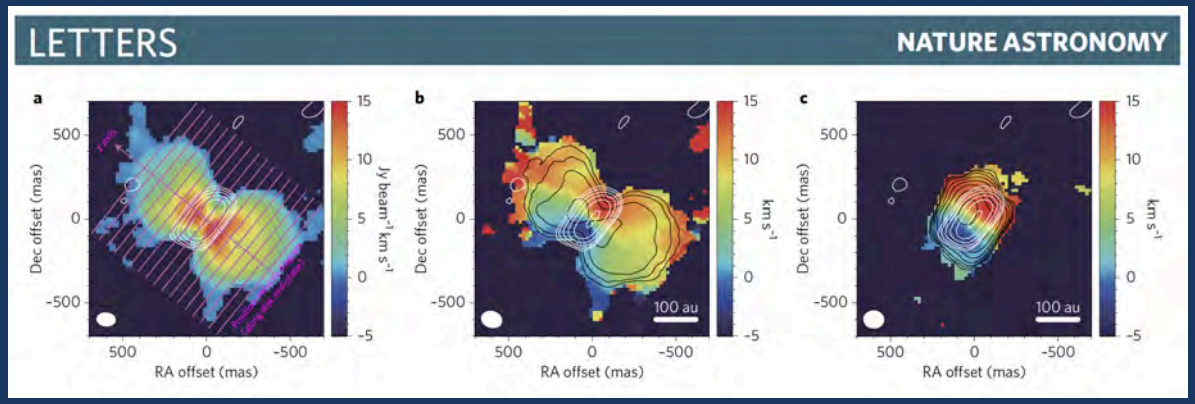
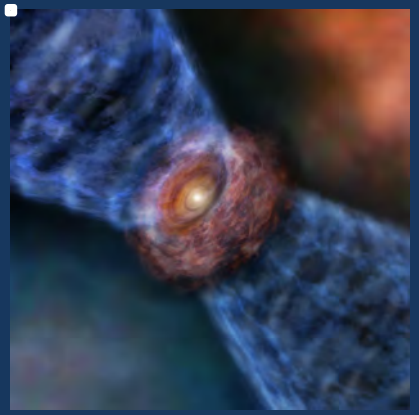
ALMA observations of submillimeter H_2O and SiO lines in Orion Source I





Tomoya Hirota (NAOJ)

M. N. Machida, Y. Matsushita (Kyushu Univ.)

K. Motogi, N. Matsumoto (Yamaguchi Univ./NAOJ)

M. K. Kim (KASI, Korea)

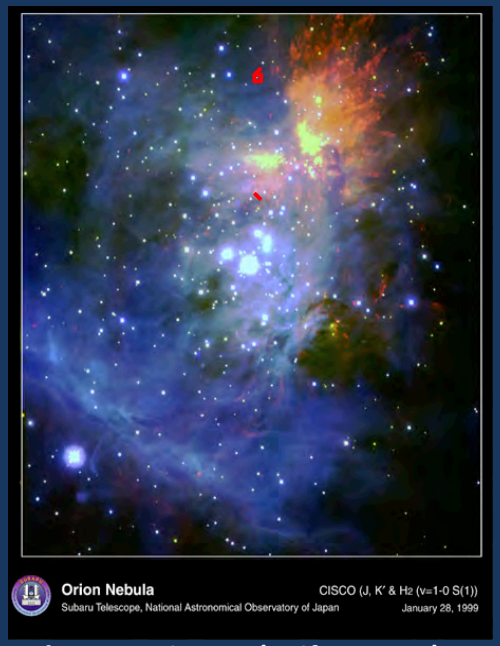
R. A. Burns (JIVE, Netherland)

M. Honma (NAOJ)

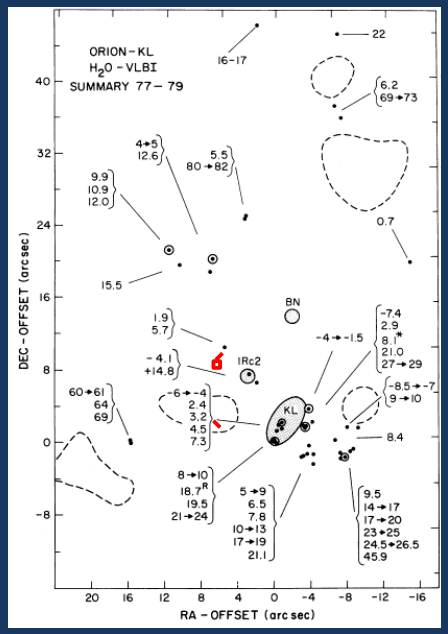
Our target; Orion KL

- One of the best laboratories for high-mass star-formation studies
  - Reviewed by Beltran, Moscadelli, and other talks/posters
  - **Parallax distance of 420 pc** (Hirota@IAUS 242, Menten+2007, Kim+2008)
  - **Strong H_2O masers** showing burst events (Genzel+1981, Hirota@IAU 287)
  - **Very rare SFR with SiO masers** (e.g. Zapata+2009, Cho+2016 for other YSOs)

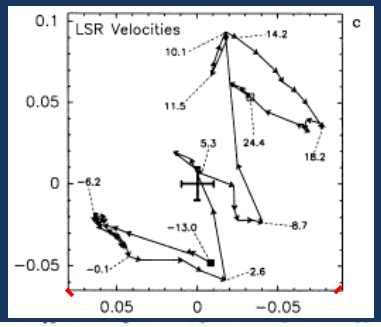


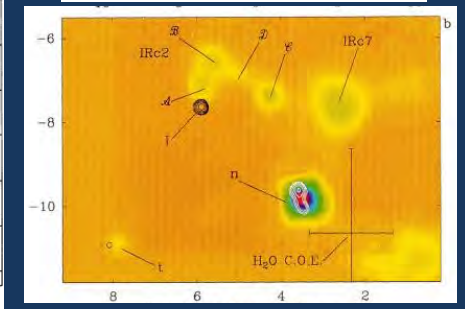


Subaru NIR image (Kaifu + 2000)



H_2O maser map (Genzel+1981)

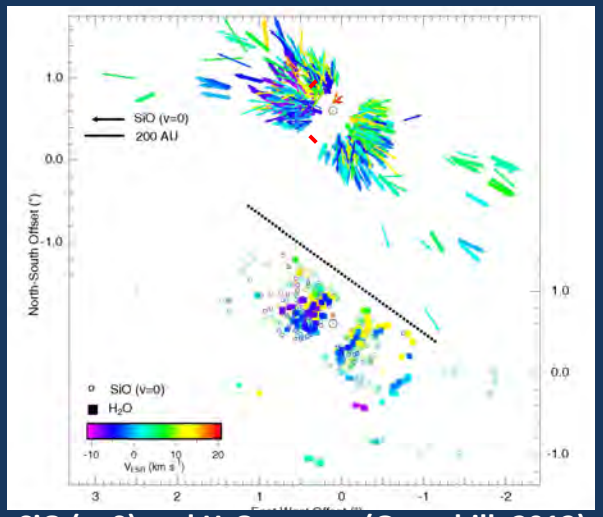




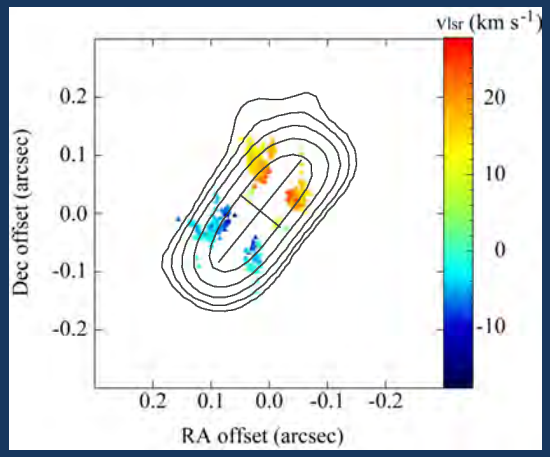
SiO maser at "Source I" (Menten+1995)

Radio source I in Orion KL (Source I)

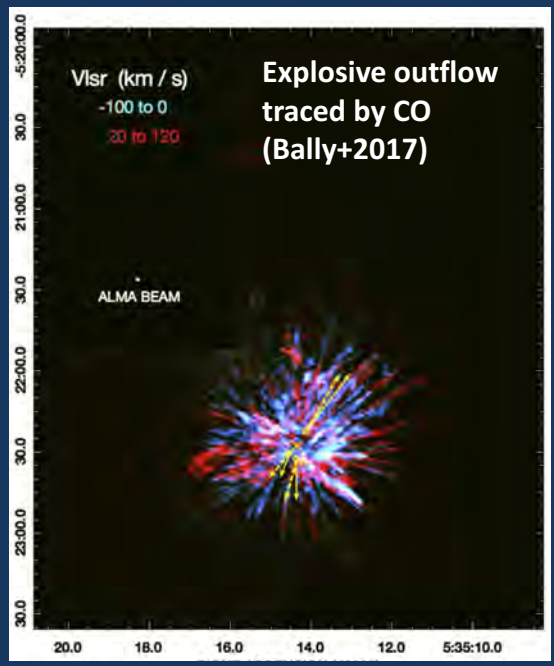
- YSO identified only at radio wavelength (Menten+1995)
  - SiO masers revealed by VLBI (Kim+2008, Matthews+2010, Issaoun+2017), with **enclosed mass of 5-8M_{Sun}** (e.g. Plambeck+2016)
  - **Close binary with 20M_{Sun}** formed in dynamical event (Gomez+2008, Goddi+2011, Bally+2011, 2017, Zapata+2017, etc.)
  - **Detailed properties traced by masers?**



SiO (v=0) and H_2O masers (Greenhill+2013)



43 GHz SiO maser (Kim+2008) and 460 GHz continuum (Hirota+2016)



ALMA observations

- Unique tool for H_2O and SiO maser lines
  - Achieving the highest resolution with ALMA longest baseline configurations
  - Less atmospheric opacity especially for H_2O lines
  - Comparable with VLBI data and multi-transition maser models

Band & Freq (GHz)	Cycle	On-src (min)	Beam (arcsec)	BL (m)	#Ant.
6 (232)	SV	20	1.7	270	16
6 (232)	1	50	0.18	1600	38
7 (321/336)	0	5*3 epochs	0.37	400	21-28
7 (321/336)	2	5	0.17	1600	35
8 (430)	2	30	0.08	2300	35
8 (460)	2	7	0.10	1600	40
8 (490)	2	5	0.09	1500	41
9 (658)	0	5	0.26	400	28

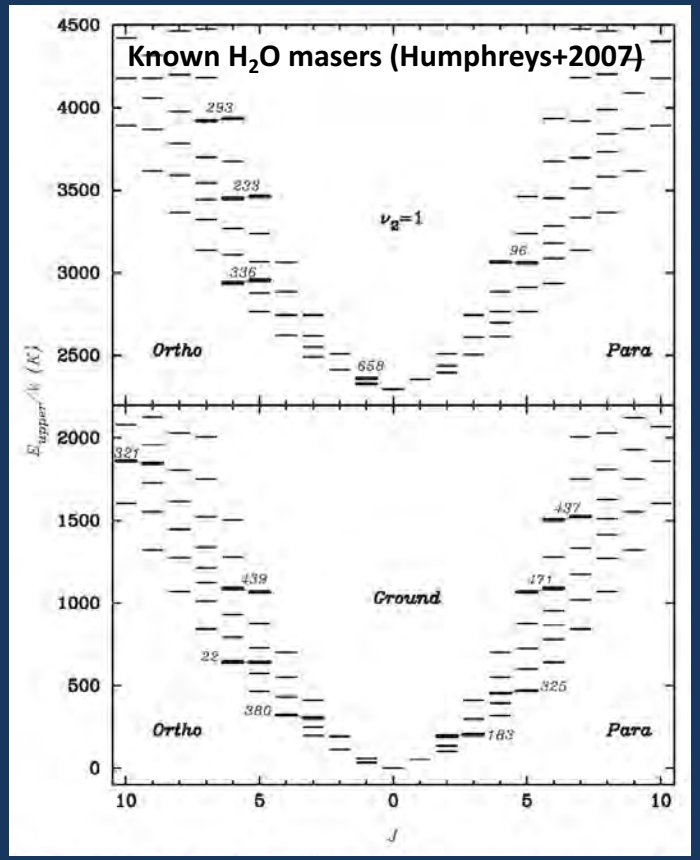
0.1”=42 au @Orion KL



Detected H_2O lines

- Including ν_2=1 transitions up to E_l~3500 K (Menten+1989,1990,1995,2006,2008,Humphreys+2007,Chen+1999)
  - First detection of 463 GHz and 498 GHz lines

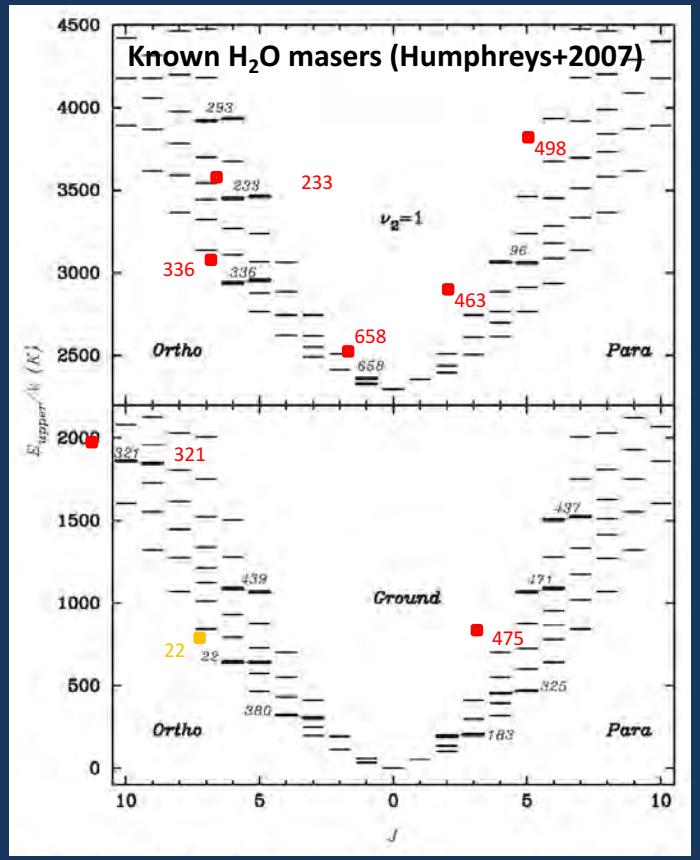
Freq (MHz)	Molecule	Transition	E_l (K)
22235	H_2O	6,1,6-5,2,3	643
474689	H_2O	5,3,3-4,4,0	702
321226	H_2O	10,2,9-9,3,6	1846
658007	H_2O	v=1, 1,1,0-1,0,1	2329
463171	H_2O	v=1, 4,2,2-3,3,1	2744
336228	H_2O	v=1, 5,2,3-6,1,6	2939
232687	H_2O	v=1, 5,5,0-6,4,3	3451
498502	H_2O	v=1, 7,4,4-6,5,1	3673



Detected H_2O lines

- Including ν_2=1 transitions up to E_l~3500 K (Menten+1989,1990,1995,2006,2008,Humphreys+2007,Chen+1999)
  - First detection of 463 GHz and 498 GHz lines

Freq (MHz)	Molecule	Transition	E_l (K)
22235	H_2O	6,1,6-5,2,3	643
474689	H_2O	5,3,3-4,4,0	702
321226	H_2O	10,2,9-9,3,6	1846
658007	H_2O	v=1, 1,1,0-1,0,1	2329
463171	H_2O	v=1, 4,2,2-3,3,1	2744
336228	H_2O	v=1, 5,2,3-6,1,6	2939
232687	H_2O	v=1, 5,5,0-6,4,3	3451
498502	H_2O	v=1, 7,4,4-6,5,1	3673

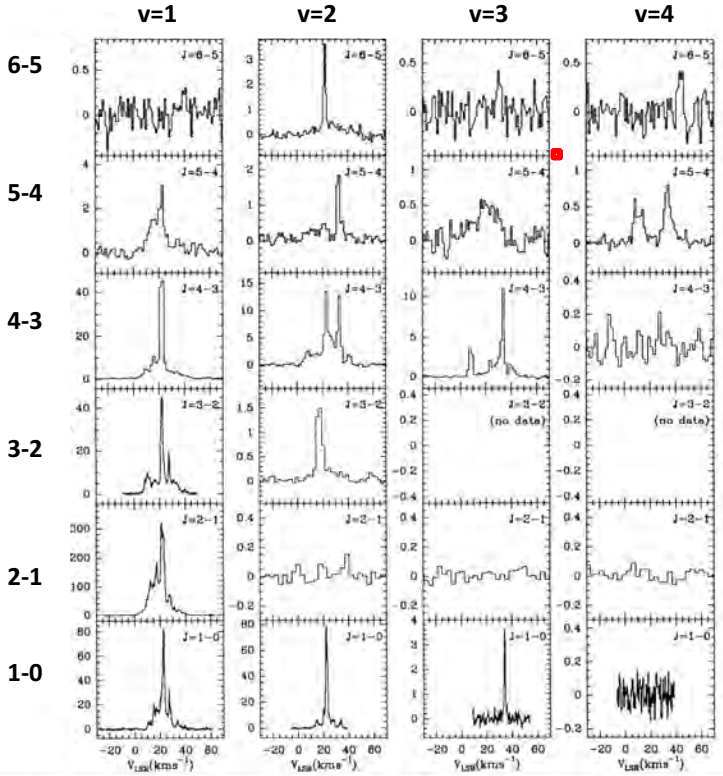


Detected SiO lines

- Including vibrationally excited transitions and rarer isotopologues (e.g. Baudry+1998, Cho+2005, Goddi+2011, Niederhofer+2012)
  - **Second detection of v=4 line** (Cernicharo+1993 for J=5-4 in VY-CMa)

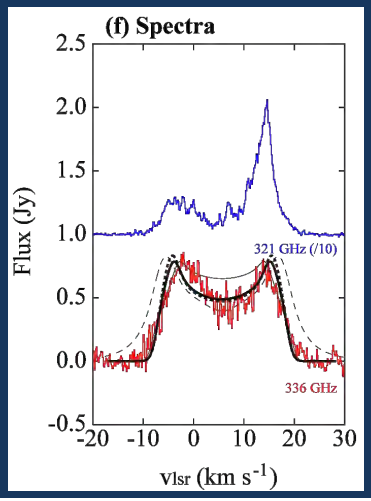
Freq (MHz)	Molecule	Transition	E_l (K)	Isotope ratio (Tercero+2011)
428684	^{29}SiO	10-9	93	^{28}Si/^{29}Si=26
477505	SiO	11-10	115	
484056	Si^{18}O	12-11	128	^{16}O/^{18}O>239
462757	^{30}SiO	v=1, 11-10	1859	^{28}Si/^{30}Si=44
474185	SiO	v=1, 11-10	1883	
465014	^{29}SiO	v=2, 11-10	3611	^{28}Si/^{29}Si=26
428087	SiO	v=2, 10-9	3614	
464245	SiO	v=4, 11-10	7085	

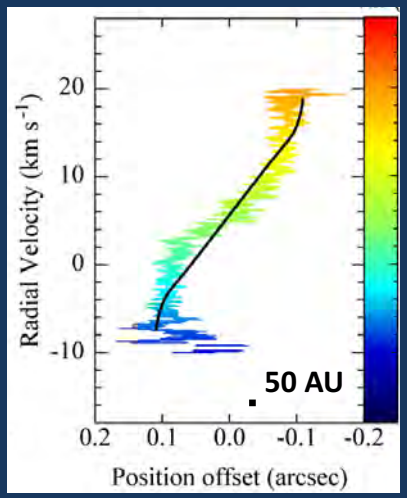
SiO masers toward VY-CMa (Cernicharo+1993)

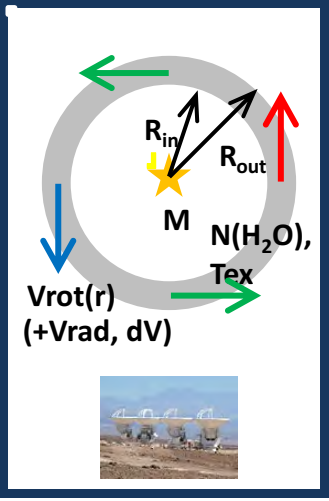


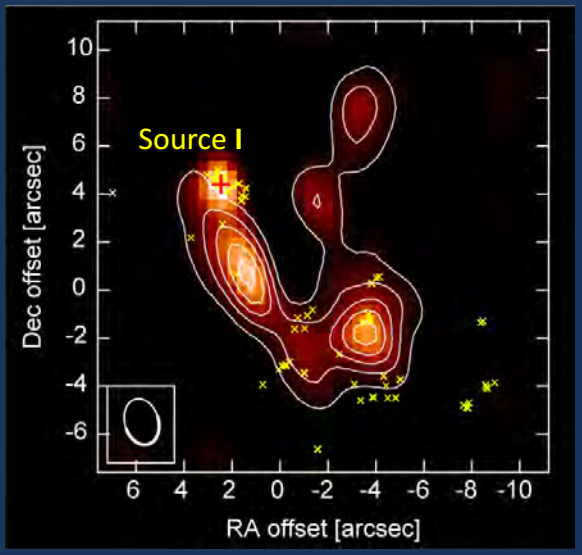
SV and cycle 0 results

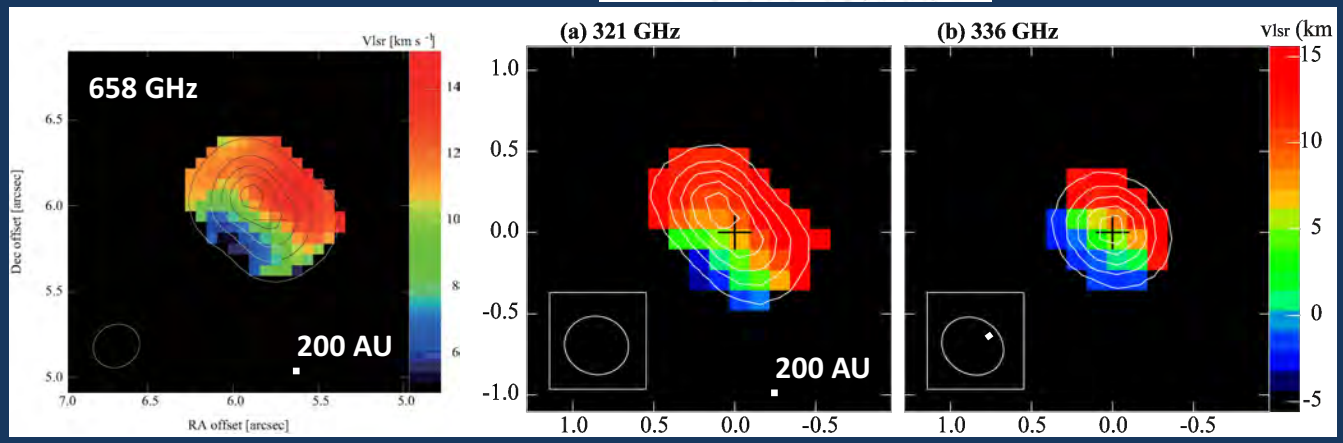
- 232, 321, 336, and 658 GHz H_2O (Hirota+2012,Hirota+2014, 2016)
  - Velocity gradient consistent with edge-on rotating ring with R_{in}~45 AU, R_{out}~50 AU, and M~7M_{Sun}
  - Thermal excitation at 336 GHz (Alcolea+1993)







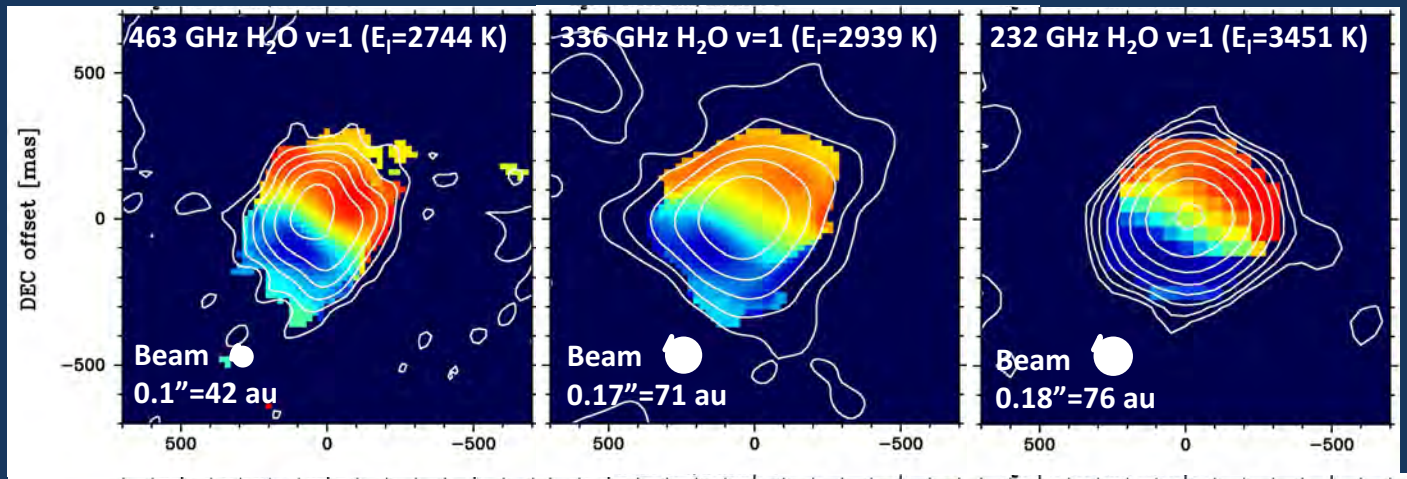




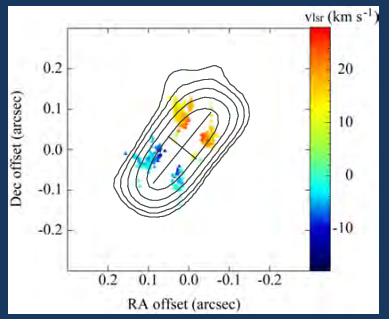
[Left] Moment 0 maps of H_2O+$HCOOCH_3$ (color) and $HCOOCH_3$ lines at 232 GHz (Hirota+2012)
[Right] Moment 0 and 1 maps of 321/336 GHz (Hirota+2014) and 658 GHz (Hirota+2016) lines

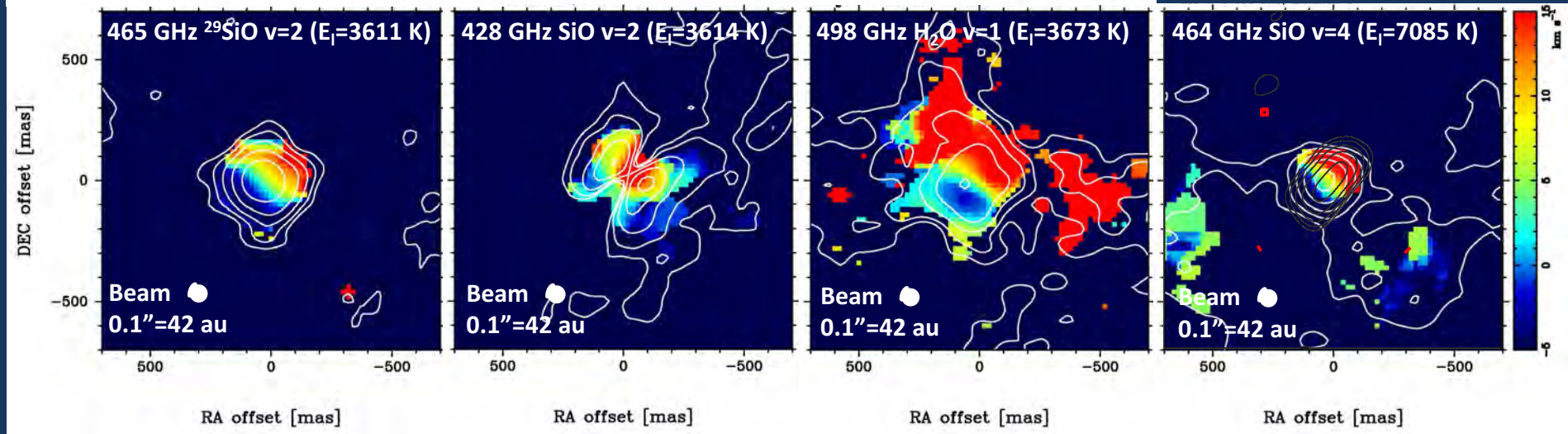
Maps of higher excitation lines

- Slightly extended toward NE-SW direction with rotation
  - **Velocity gradients** consistent with J=2-1/1-0 SiO masers revealed by VLBI



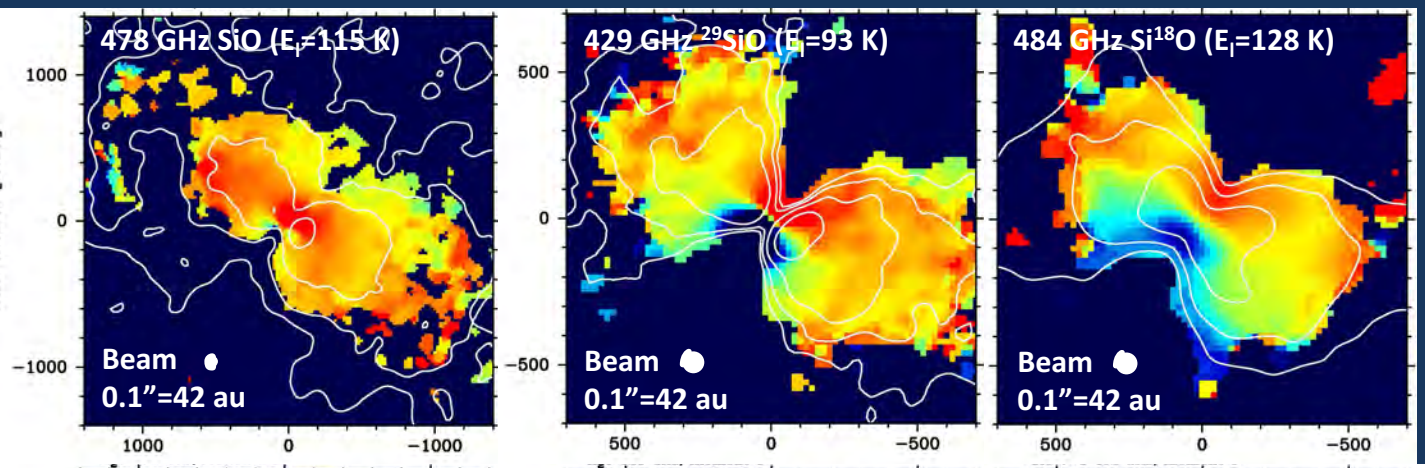
SiO maser (Kim+2008) and continuum (Hirota+2016)



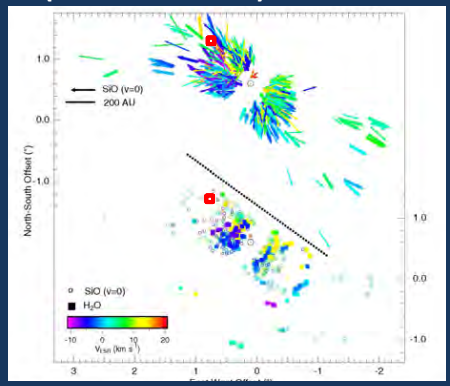


Maps of lower excitation lines

- Velocity gradient suggesting rotating outflow (e.g. talk by Burns)
  - M=8.7+/-0.6 M_{sun}, centrifugal radii=21-47 au; magneto-centrifugal disk wind

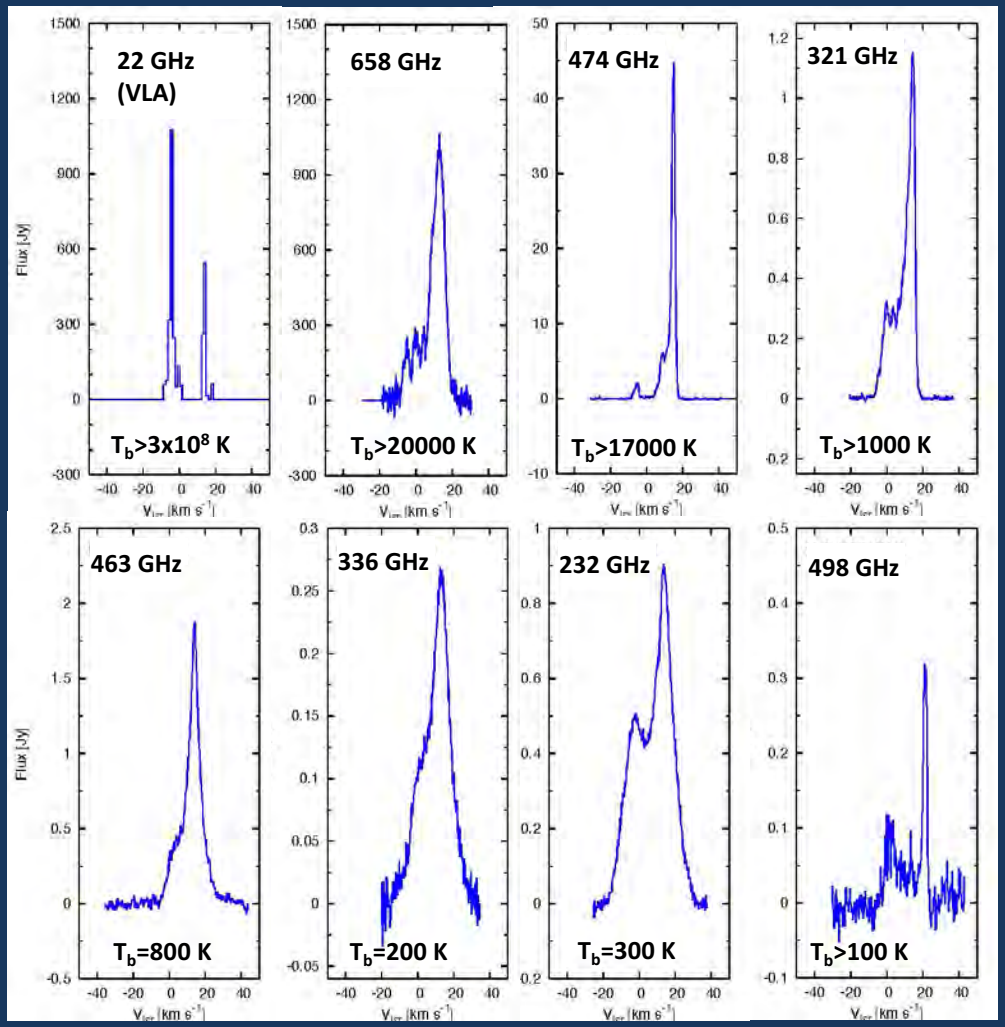


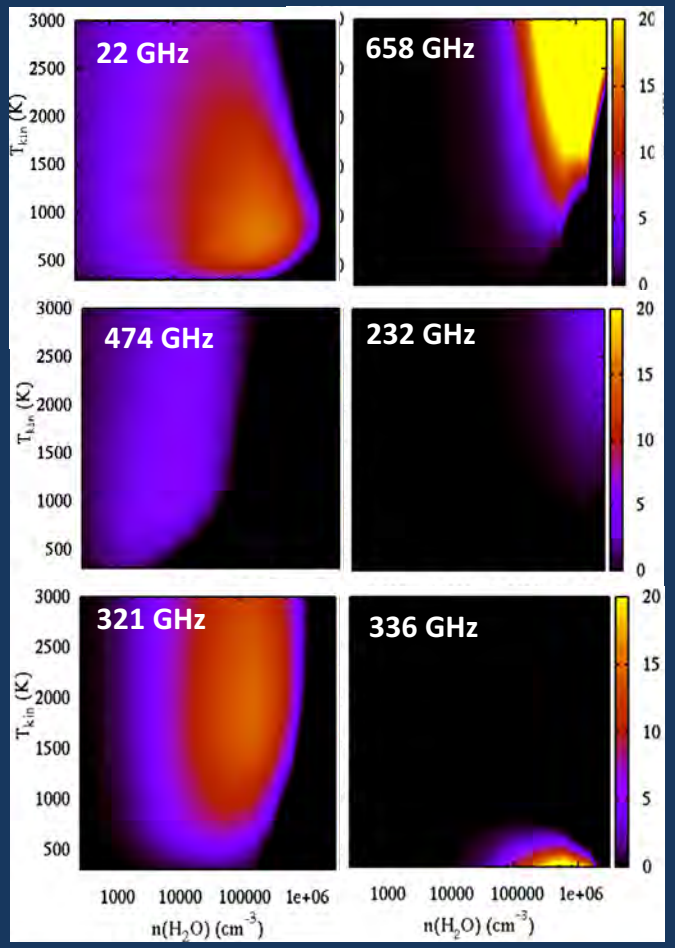
SiO (v=0) and H_2O masers (Greenhill+2013)



H_2O masers?

- **High brightness, narrow components, compact features**

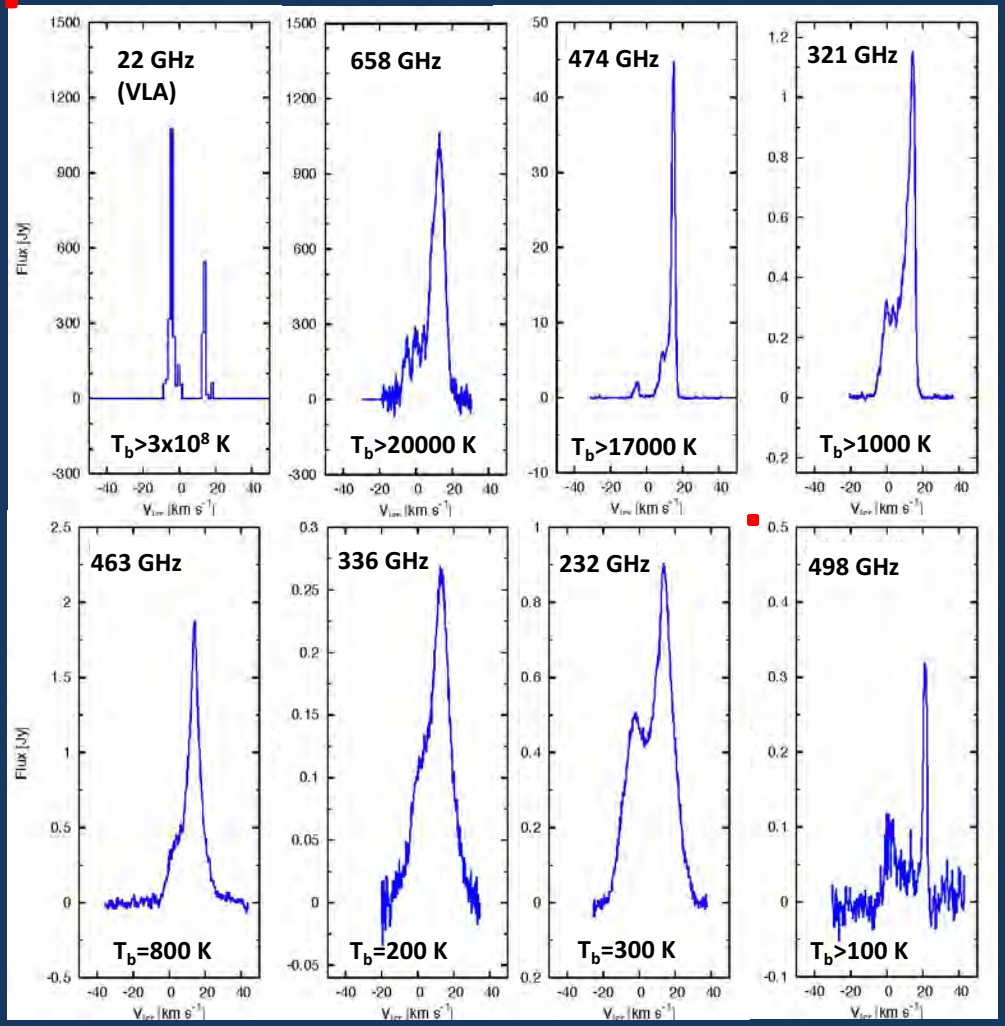


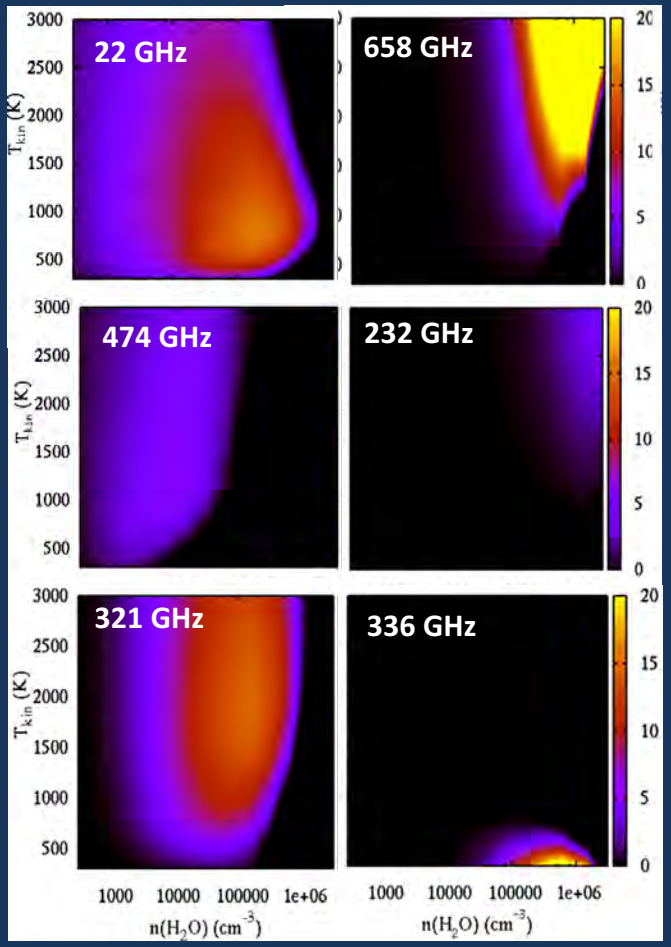


Negative optical depth as function of H_2O density and temperature (Gray+2016)

H_2O masers?

- **High brightness, narrow components, compact features --- Masers!**

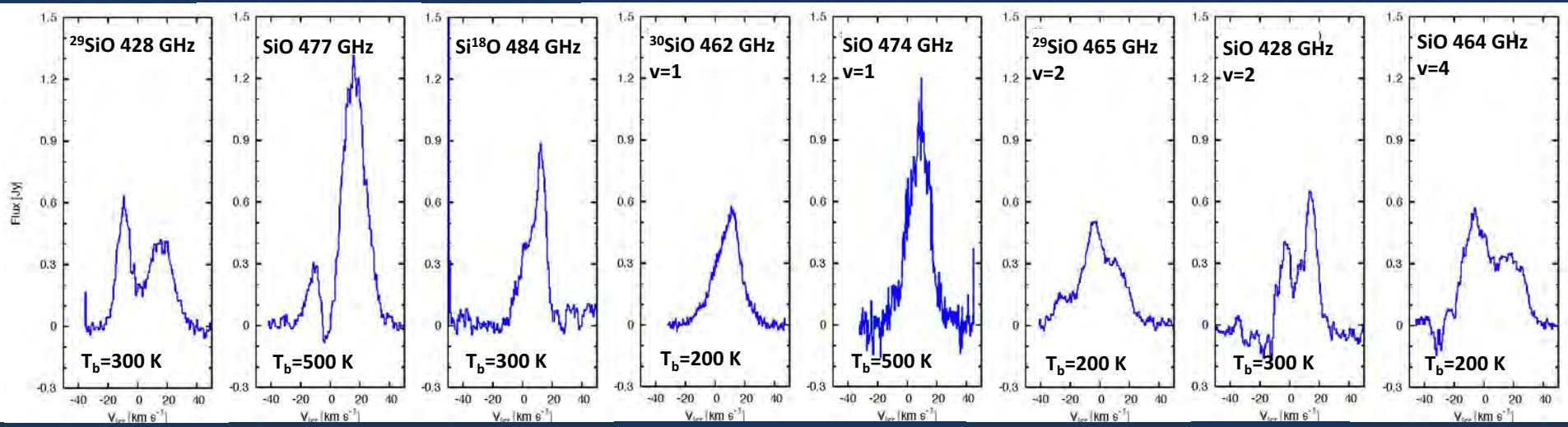




Negative optical depth as function of H_2O density and temperature (Gray+2016)

SiO masers?

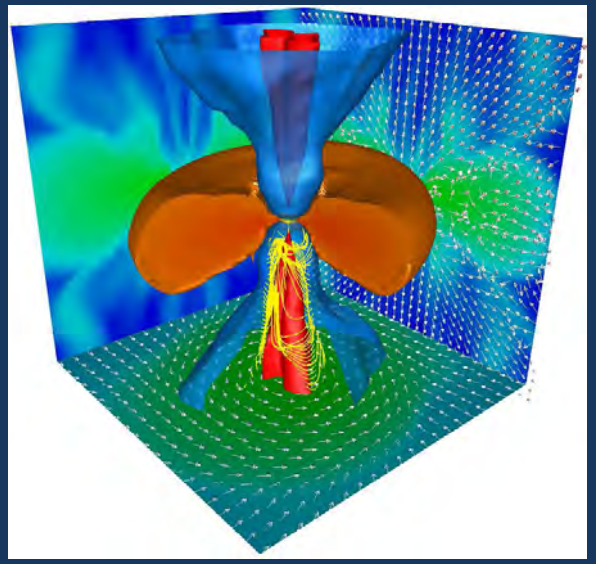
- **Broad profiles, spatially more extended than J=1-0/2-1 masers, even at v=1 transitions (E_l~1800 K)**
  - **Inconsistent with isotope ratios of $^{28}Si/^{29}Si=26$, $^{28}Si/^{30}Si=44$, $^{16}O/^{18}O>239$ (Tercero+2011)**
  - **Optically thick thermal emission at higher-J (e.g. Beuther+2005 for J=8-7)?**
  - **Masers with unresolved structure due to insufficient resolution (0.1")?**
  - **Mixture of masers and thermal components (e.g. Goddi+2011 for J=1-0)?**



Summary

- High-excitation H_2O and SiO lines trace hot molecular gas associated with either disk (E_l>2000 K) or outflow (E_l<2000 K) around Source I
- Evidences of H_2O masers are detected at 658, 474, 321, and 498 GHz
- Excitation condition of SiO transitions are still inconclusive

- Future works
  - Higher resolution at band 10 (cycle 4 Grade A)
  - More sub-mm maser sources (cycle 5 Grade C)
  - Polarization measurements (cycle 5 Grade B)
  - Multi-transition analysis (on-going)
  - Simulation of high-mass YSO (Matsushita+2017)
  - Maser theory; welcome collaboration!



Model of low-mass protostar outflow (Machida 2014)