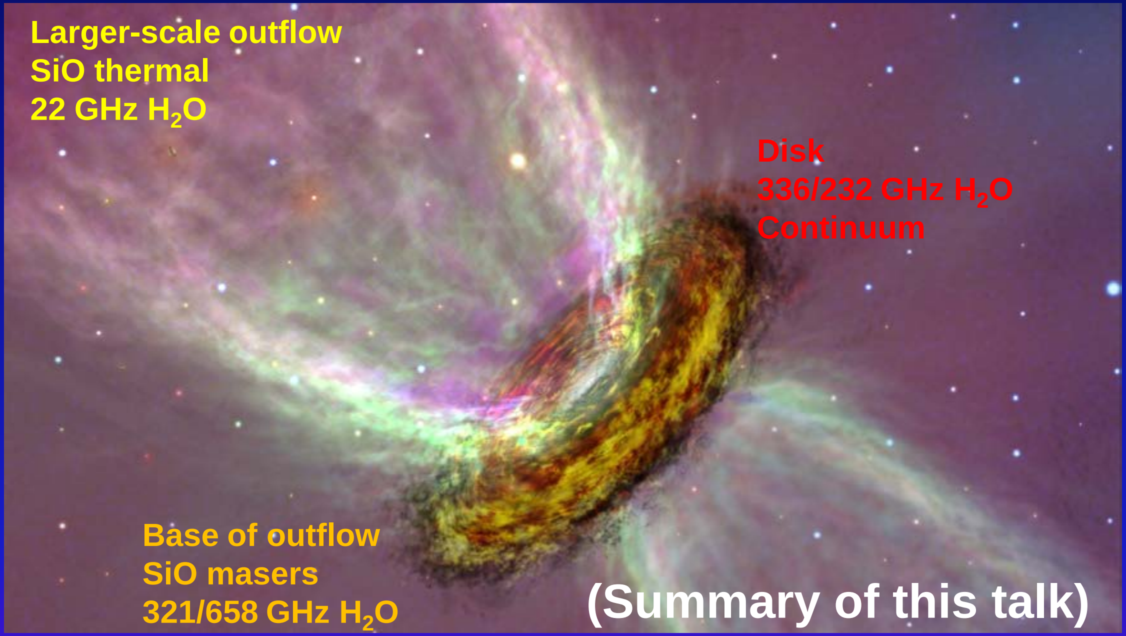
Hot water disk around Orion Source I



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  - High-mass star-formation
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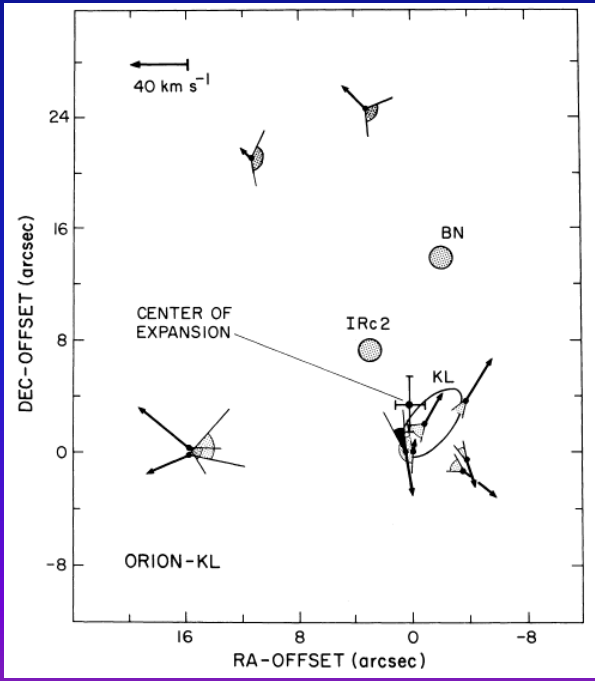
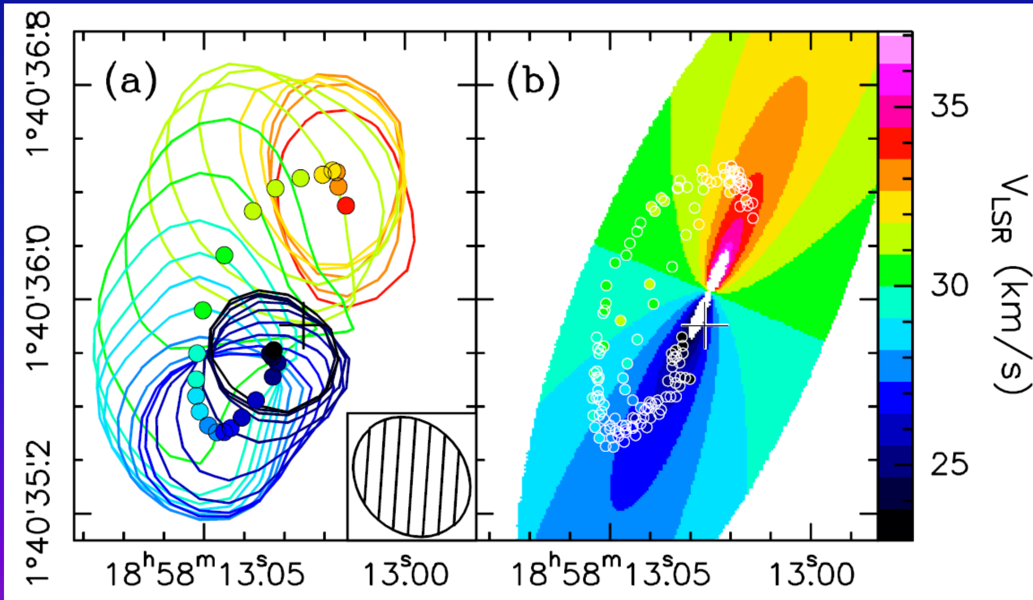
  - Physical properties of circumstellar disk around Source I
- Summary

Introduction

- **High-resolution study of high-mass star-formation**
  - ***How can high mass accretion rate be achieved?***
  - ***How do high-mass YSOs associated with disk/outflow evolve?***
  - ***What are differences from low-mass star-formation?***



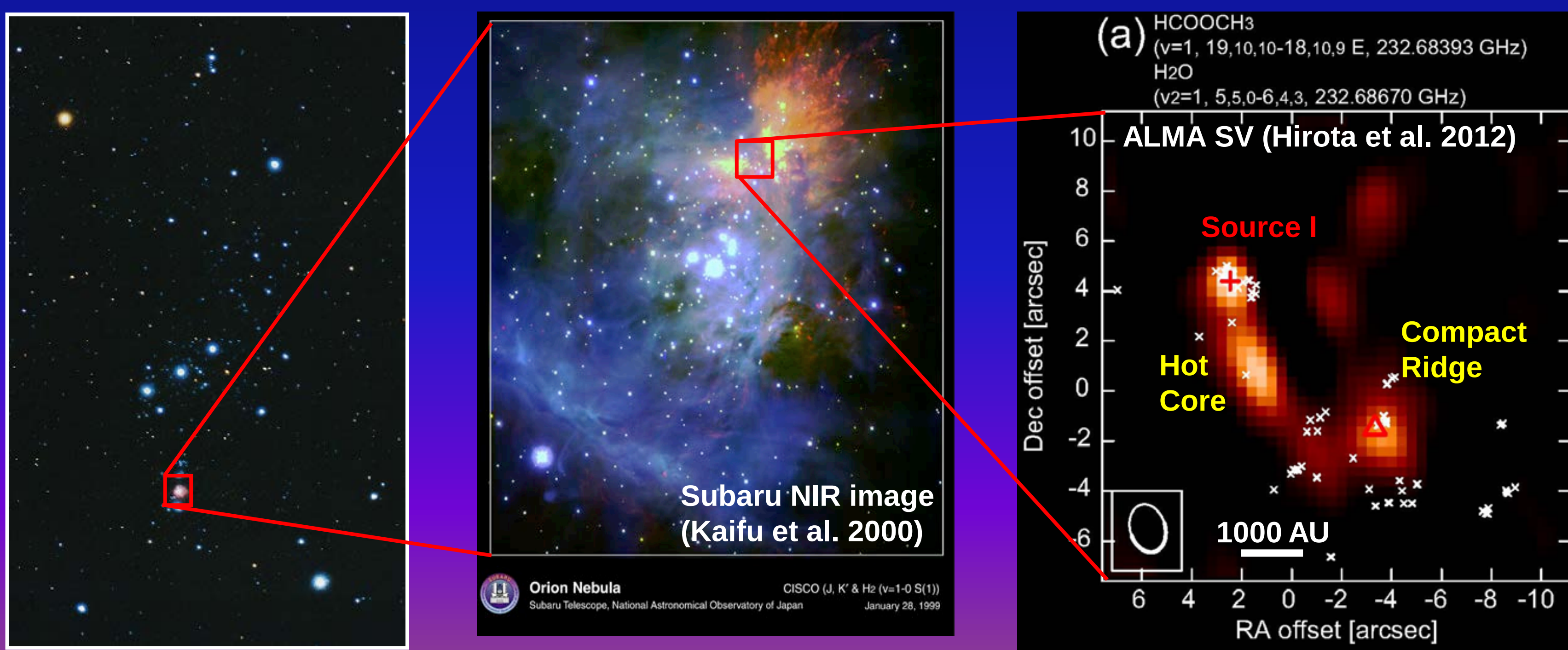
VLBI map of 22 GHz H_2O masers in Orion KL (Genzel et al. 1981)



ALMA image of circum-binary disk around G35.20-0.74N (Sanchez-Monge et al. 2013)

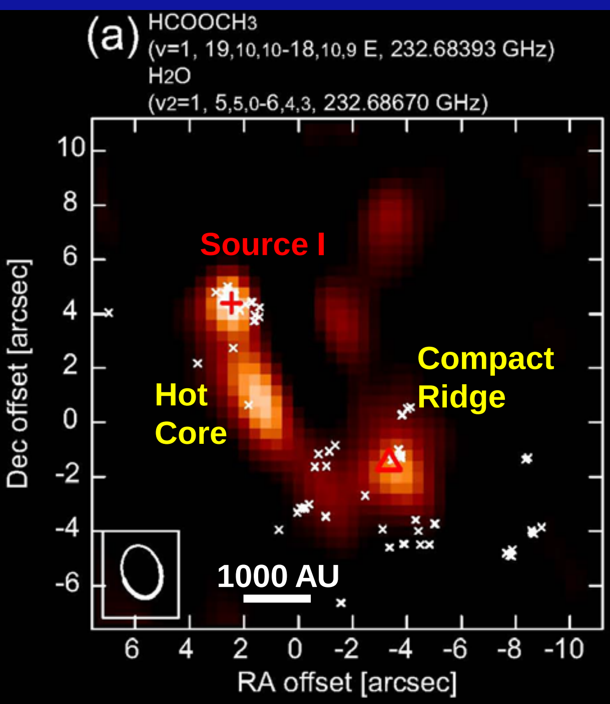
Orion KL

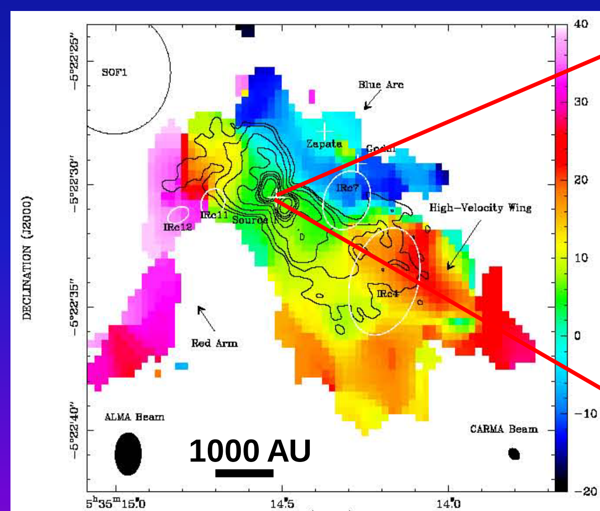
- Nearest high-mass star-forming region
  - 420 pc (Hirota et al. 2007, Menten et al. 2007, Kim et al. 2008)
  - One of the best targets for high-mass star-formation study
  - One of the most studied sources for astrochemistry



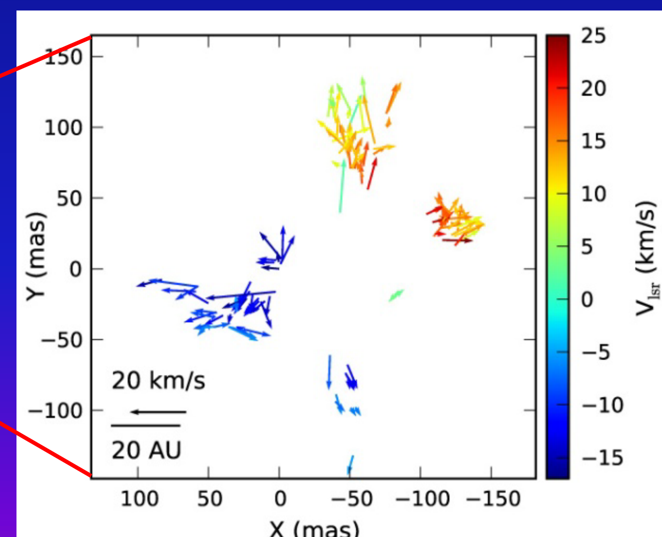
Orion KL; zoom-in

- Low-velocity (~18 km s^{-1}) NE-SW outflow
  - Traced by thermal SiO lines (Plambeck et al. 2009, Zapata et al. 2012, Niederhofer et al. 2012, etc.)
  - Perpendicular to high-velocity explosive outflow
  - SiO masers at the center (Kim et al. 2008, Matthews et al. 2010)





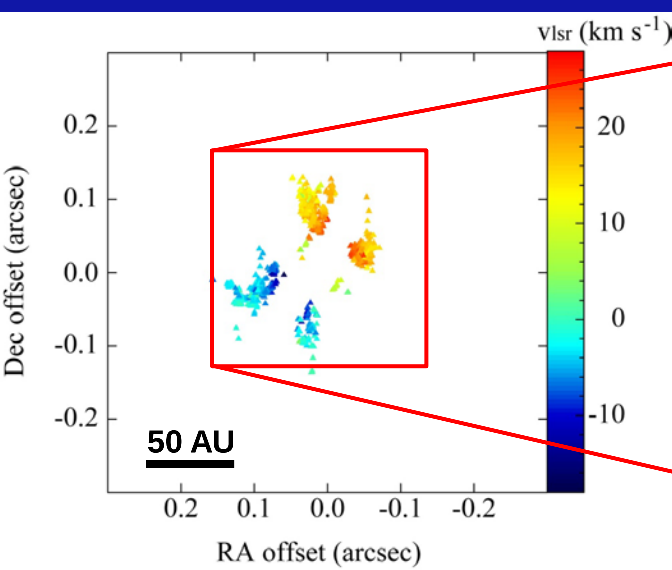
SiO thermal by ALMA SV (Niederhofer et al. 2012)



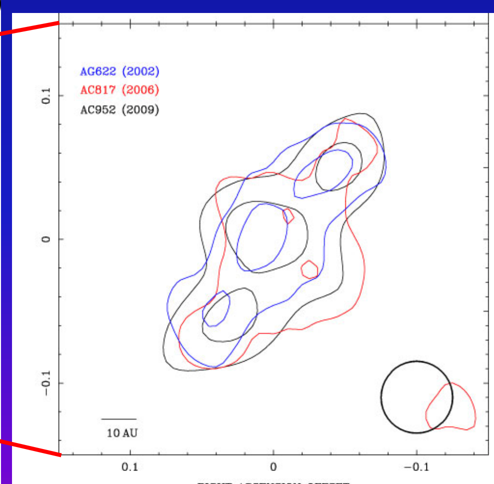
Position and proper motions of 43 GHz SiO maser map by VERA (Kim et al. 2008)

Radio Source I

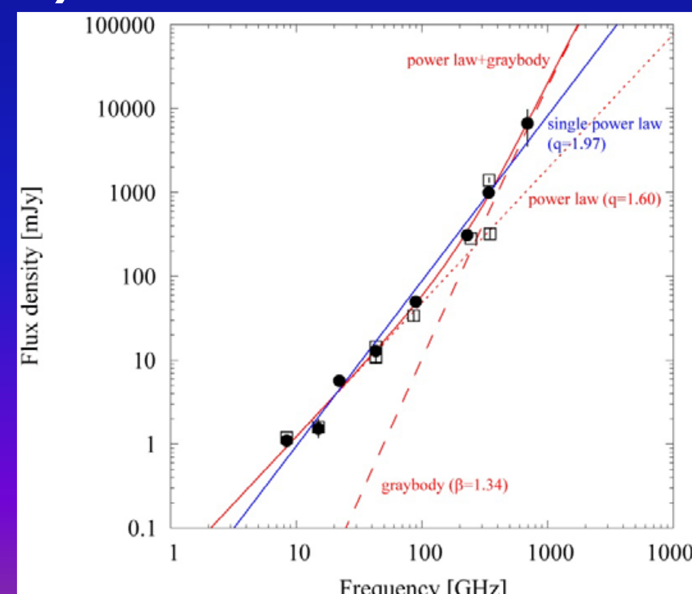
- Strong continuum source only visible in cm-submm
  - NW-SE elongation perpendicular to the NE-SW outflow
  - Coincident with SiO maser emission (Menten & Reid 1995)
  - Edge-on rotating disk with optically thick H^- free-free radiation *but still controversial* (Beuther et al. 2006, Reid et al. 2007, Goddi et al. 2011, Plambeck et al. 2013)



43 GHz SiO maser map by VERA (Kim et al. 2008)



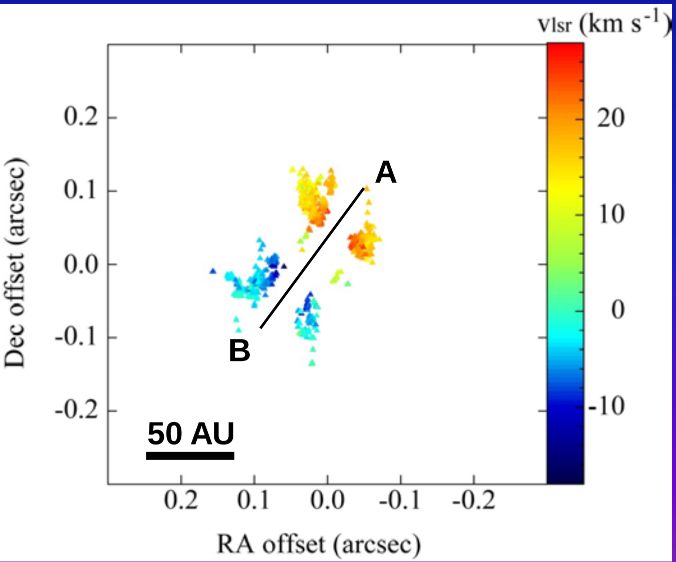
43 GHz continuum by VLA (Goddi et al. 2011)

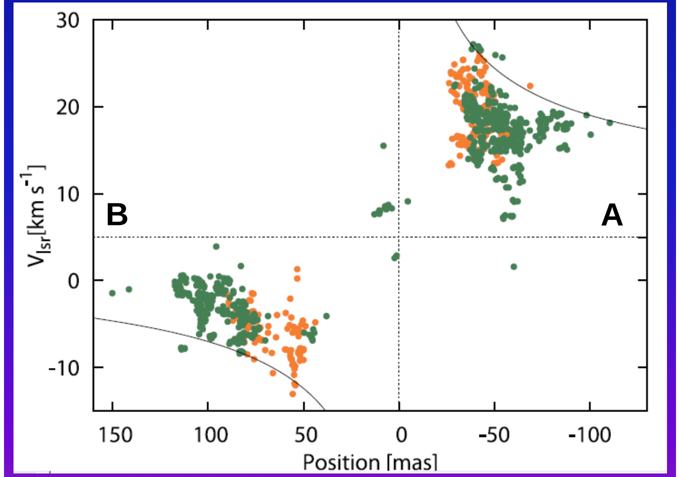


SED of source I (Hirota et al. 2015)

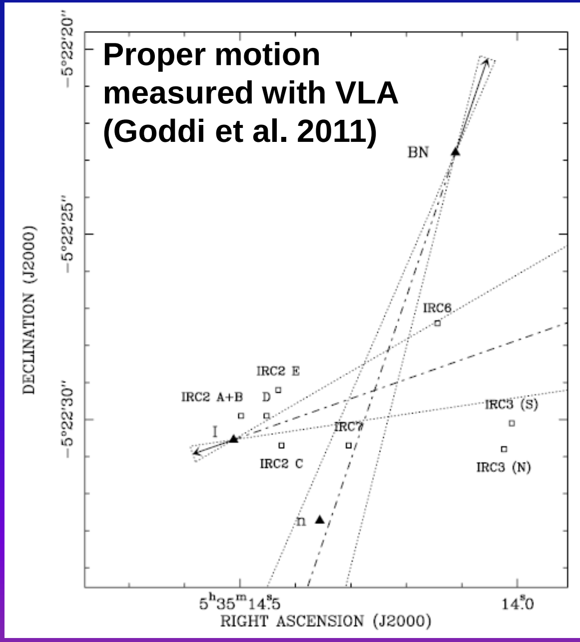
Radio Source I

- **Massive protostar candidate in accretion phase**
  - **SiO maser; >8 M_{Sun} (Kim et al. 2008, Matthews et al. 2010)**
  - **NIR spectroscopy; 10M_{Sun} disk (Testi et al. 2010)**
  - **Proper motion; 20M_{Sun} binary proposed by a dynamical interaction scenario (Goddi et al. 2011, Bally et al. 2011)**
    --- *What is the nature of Source I?*





43 GHz SiO maser map and PV diagram along the disk major axis (Kim et al. 2008)



ALMA observations

- Band 7 in cycle 0
  - Sum of 3 epochs, 5 min on-source for each
  - 0.37” resolution (maximum baseline length of 400 m)
- Band 9 in cycle 0
  - Best data from 5 epochs, 5 min. on-source
  - 0.26” resolution (maximum baseline length of 400 m)
- Band 6 in cycle 1
  - Transferred to cycle 2, 50 min. on-source
  - 0.18” resolution (maximum baseline length of 1600 m)

0.1” resolution = 42 AU at Orion KL

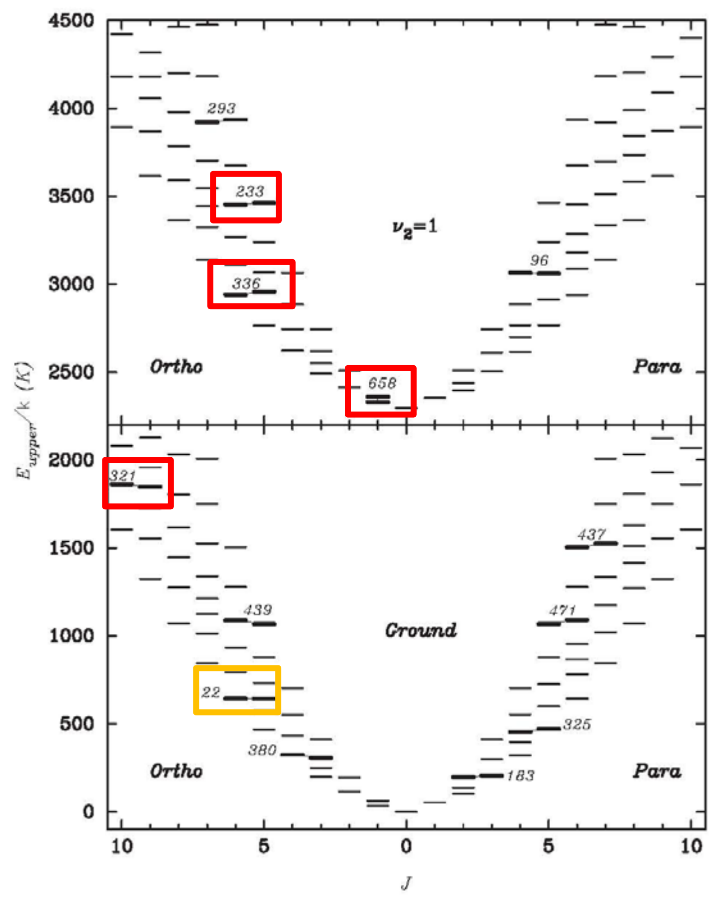
Observed lines

- **Multi-transitions of H_2O as useful probes for high-resolution studies**
  - **Including strong maser lines (Humphreys 2007, Gray et al. 2016)**
  - **Manly focus on o-H_2O in cycle 0/1 (p-H_2O observed in cycle 2)**

Table 1. H_2O masers

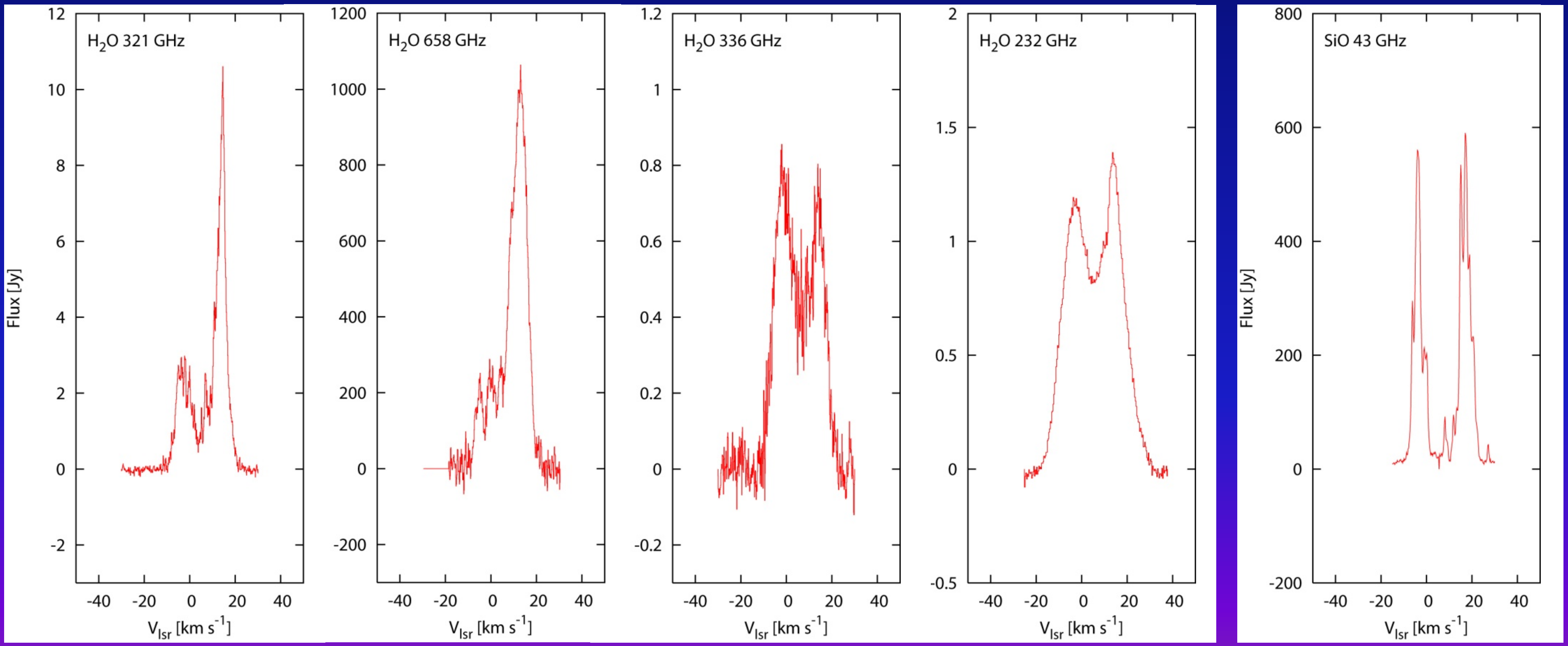
Freq. (GHz)	Transition J_{k_a,k_c} - J_{k_a,k_c}	Vib. State	Species[1]	E_u/k (K)	CSE[2]	SFR[2]	EXG[2]	Primary Reference
22.235	6_{16} - 5_{23}	G	O	644	Y	Y	Y	Cheung *et al.* (1969)
96.261	4_{40} - 5_{33}	ν_2=1	P	3065	Y			Menten & Melnick (1989)
183.308	3_{13} - 2_{20}	G	P	205	Y	Y	Y	Waters *et al.* (1980)
232.687	5_{50} - 6_{43}	ν_2=1	O	3463	Y			Menten & Melnick (1989)
293.439	6_{61} - 7_{52}	ν_2=1	O	3935	Y			Menten *et al.* (2006)
321.226	10_{29} - 9_{36}	G	O	1862	Y	Y		Menten *et al.* (1990a)
325.153	5_{15} - 4_{22}	G	P	470	Y	Y		Menten *et al.* (1990b
[3]336.228	5_{23} - 6_{16}	ν_2=1	O	2956	Y			Feldman *et al.* (1993)
354.885	17_{412} - 16_{710}	G	O	5782	Y			Feldman *et al.* (1991)
380.194	4_{14} - 3_{21}	G	O	324		Y		Phillips *et al.* (1980)
437.347	7_{53} - 6_{60}	G	P	1525	Y			Melnick *et al.* (1993)
439.151	6_{43} - 5_{50}	G	O	1089	Y	Y		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=1	O	2361	Y			Menten & Young (1995)

List of known H_2O masers (Humphreys 2007)



Spectra of H_2O lines

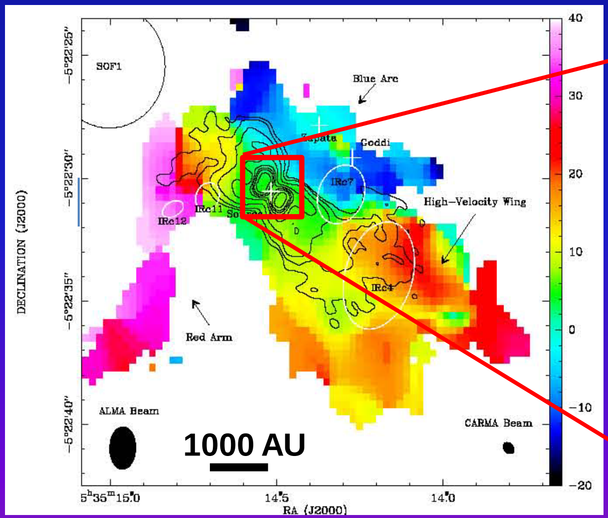
- **Double-peaked profiles similar to the SiO masers**
  - **Suggesting a common origin or close relation with each other**



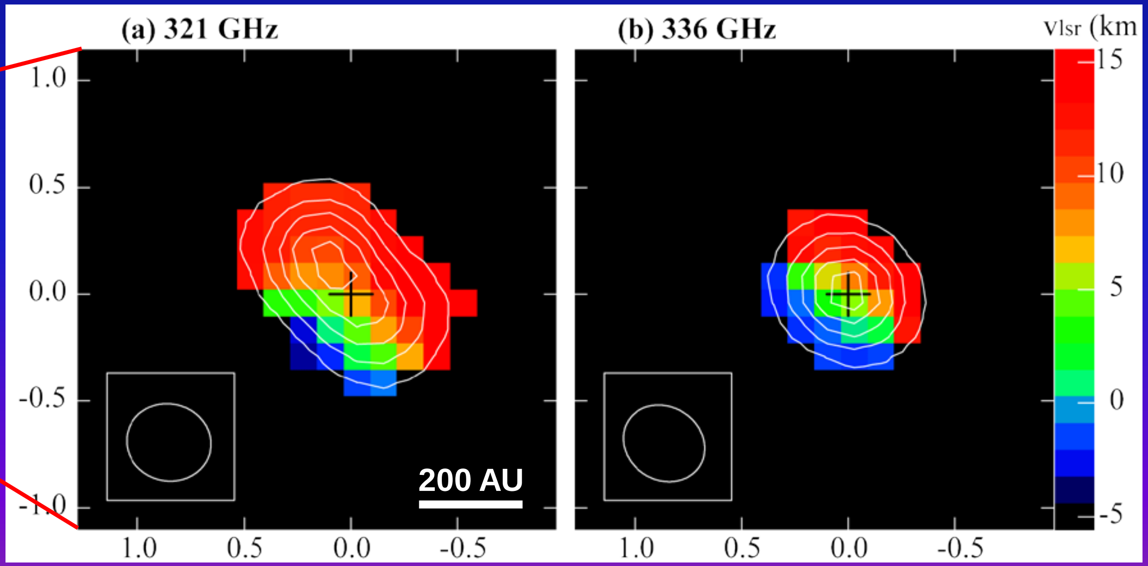
Spectra of H_2O lines of 321 GHz and 336 GHz (Hirota et al. 2014), 658 GHz (Hirota et al. 2016), 232 GHz (Hirota et al. in prep), and 43 GHz SiO maser with VERA (Kim et al. 2008)

Moment maps

- Common velocity gradient perpendicular to outflow
- 321 GHz ($10_{2,9}$-$9_{3,1}$, E_l=1846 K)
  - NE-SW elongation possibly tracing base of the outflow
- 336 GHz (v=1, $5_{2,3}$-$6_{1,6}$, E_l=2939 K); unresolved structure
  - Unresolved structure suggesting rotating disk



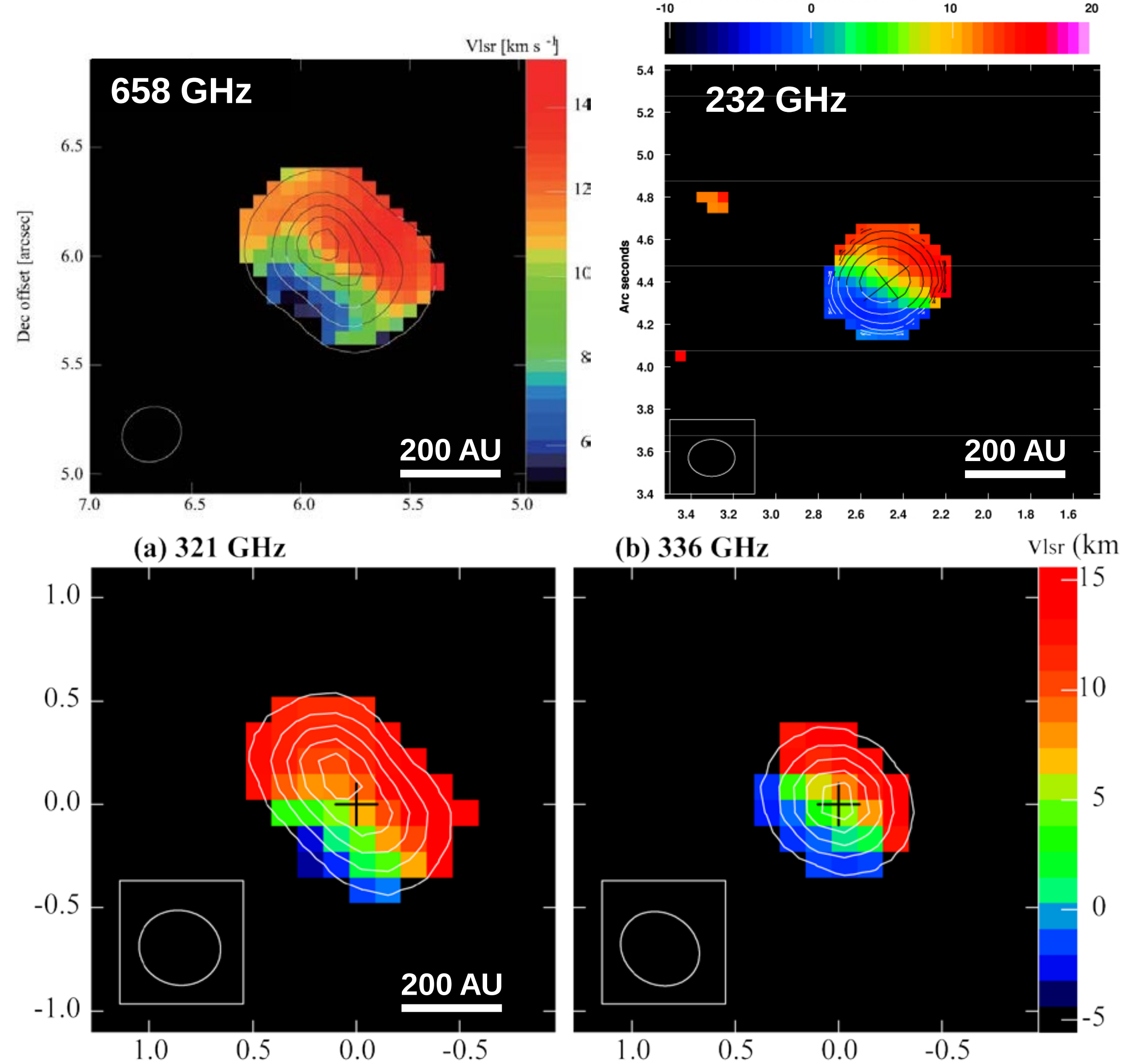
SiO thermal by ALMA SV
(Niederhofer et al. 2012)



Moment 0 (contour) and 1 (color) maps
for 321/336 GHz lines (Hirota et al. 2014)

Moment maps

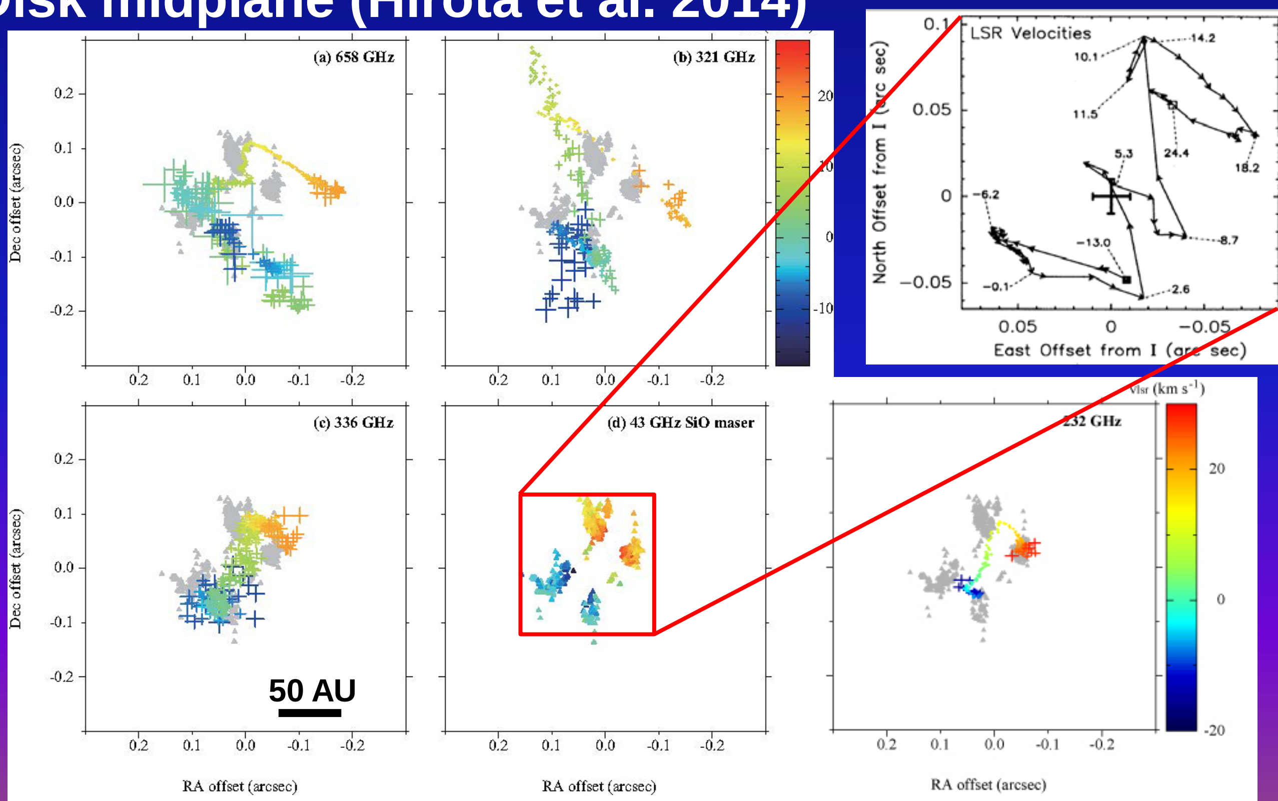
- 658 GHz ($v=1$, $1_{1,0}$-$1_{0,1}$, E_l=2329 K)
  - Similar to 321 GHz
- 232 GHz ($v=1$, $5_{5,0}$-$6_{4,3}$, E_l=3451 K)
  - Similar to 336 GHz



Moment 0 (contour) and 1 (color) maps;
658 GHz line (Hirota et al. 2016)
232 GHz line (Hirota et al. in prep)

Velocity centroid maps

- **Similarity of 658/321 GHz H_2O and SiO lines**
  - Disk wind traced by SiO masers (Matthews et al. 2010)
- **Anti-correlation between 336/232 GHz H_2O and SiO lines**
  - Disk midplane (Hirota et al. 2014)

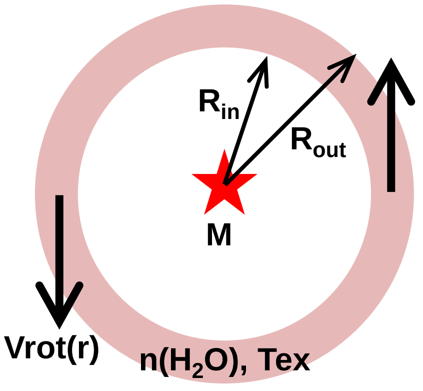


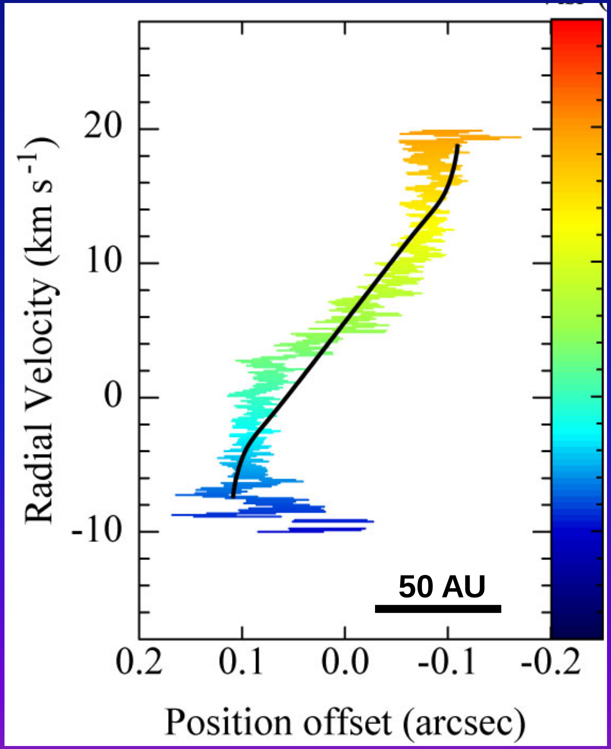
43 GHz SiO by VLA (Menten & Reid 1995)

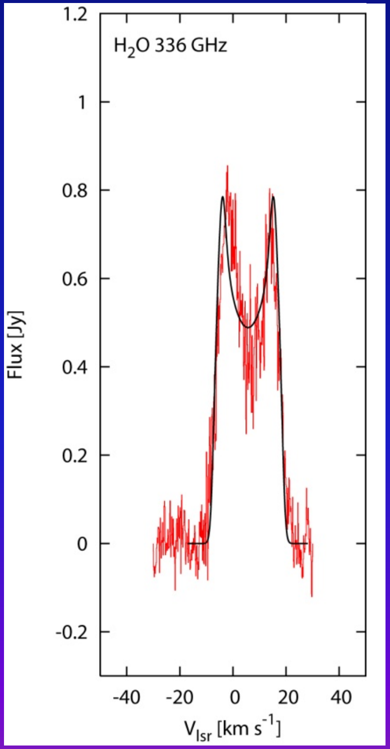
H_2O and SiO (VLBI) maps (Hirota et al. 2014, 2016, in preparation)

Position-velocity diagram

- **Quasi-linear velocity gradient found in 336/232 GHz**
  - **Simple model of edge-on rotating ring-like structure**
  - **T_{ex}>3000 K, thermal excitation (e.g. Alcorea & Menten 1993)**
  - **$n(H_2O)$~5 X10^5 cm^{-3}**
  - **R_{in}~45 AU, R_{out}~50 AU**
  - **M ~ $7M_{Sun}$**



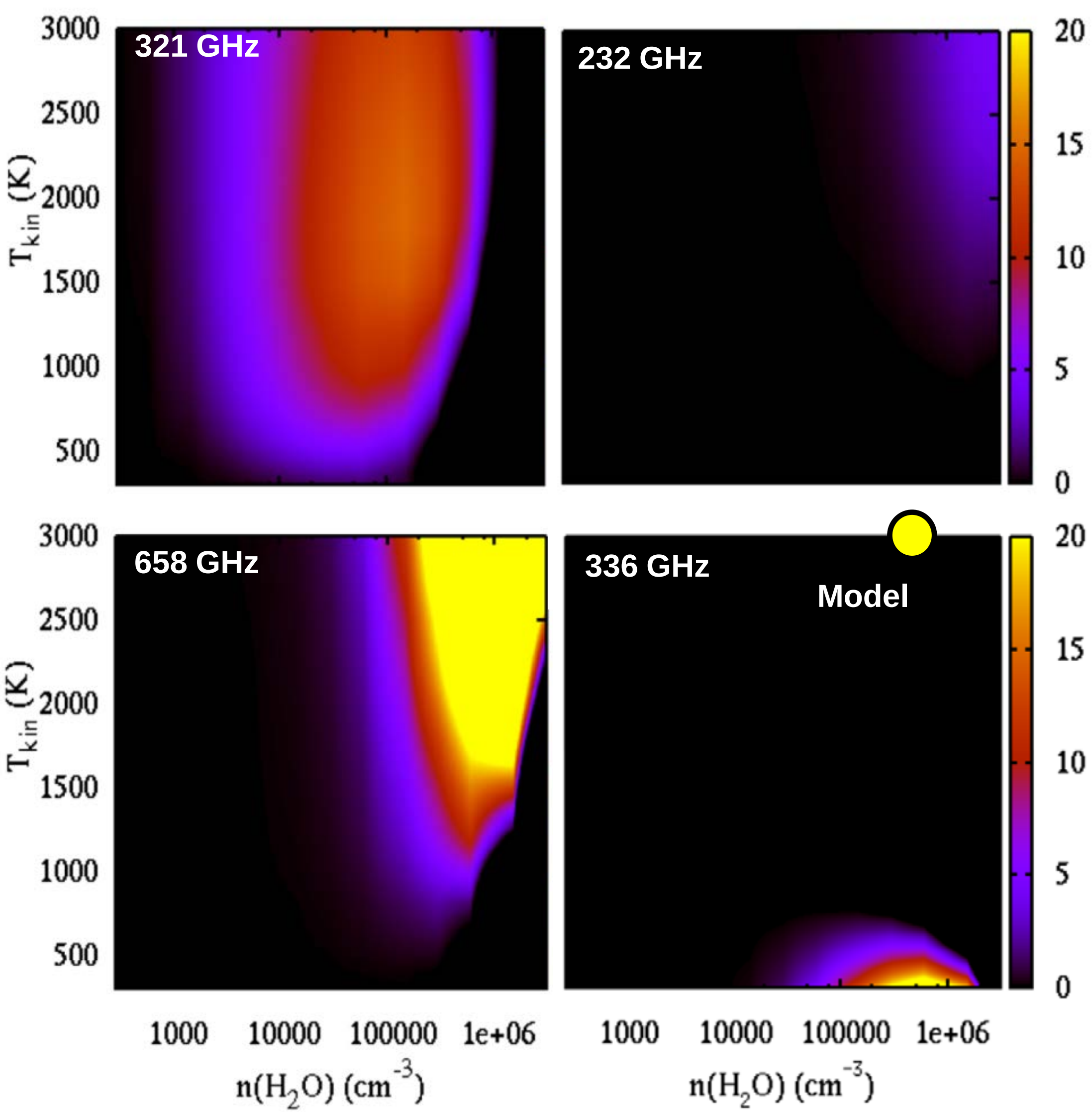




PV diagram and spectrum of 336 GHz H_2O line (Hirota et al. 2014)

Excitation condition

- **Model prediction for late-type stars (Gray et al. 2016)**
  - **Radiative transfer and level population of all H_2O transitions**
  - **Only 336 GHz could be thermal excitation**



Negative optical depth as function of H_2O density and temperature (Gray et al. 2016)

Summary

- Sub-mm H_2O lines/continuum in Source I reveal that
  - 321 and 658 GHz lines trace base of outflow similar to SiO masers
  - 336 (and possibly 232) GHz line traces rotating ring-like structure with R_{in}~45 AU and R_{out}~50 AU
  - enclosed mass of the ring is >7M_{sun}
  - 336 GHz line is excited thermally with T_{ex} >3000 K

- Higher frequency data with higher spatial resolution and detailed radiative transfer/maser pumping model will be crucial to constrain above parameters