50+ Years of Maser Research

Karl M. Menten
MPI für Radioastronomie

IAU 336: Astrophysical Masers: Unlocking the Mysteries – Cagliari, 2017 September 4

Zur Quantentheorie der Strahlung.

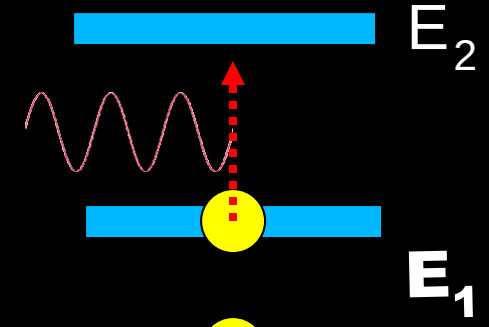
Von A. Einstein[1]).

Physik. Zeitschr. XVIII, 1917

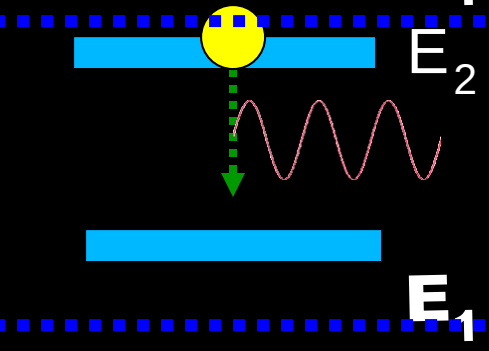
On the Quantum Theory of Radiation

Einstein's big realization:

There are different ways for a particle to get from state 1 to state 2 (or vice versa)

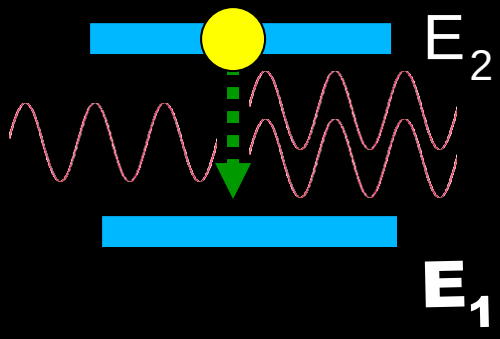


Stimulated Absorption



Spontaneous Emission

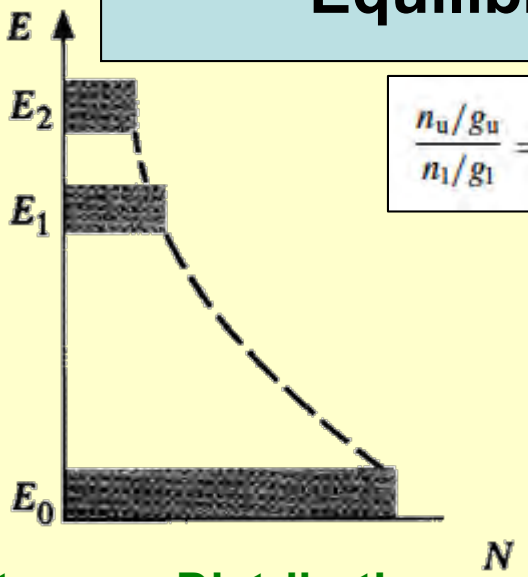
is a **random process:** the emitted photon is completely independent of the surrounding radiation field



Stimulated Emission

produces an **additional** photon that marches **in phase** with the incoming photon

Equilibrium



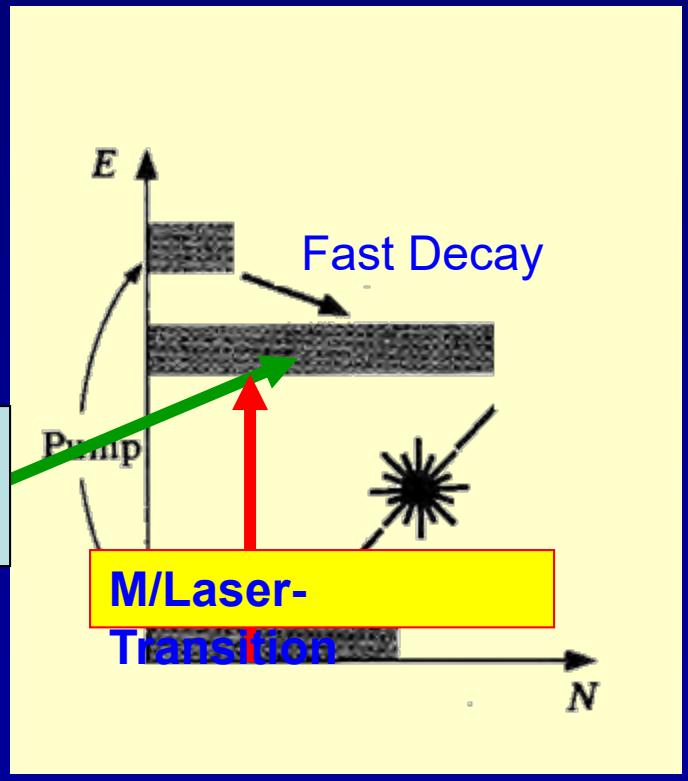
$$\frac{n_u/g_u}{n_l/g_l} = \exp\left(-\frac{h\nu}{kT}\right) < 1,$$

Boltzmann Distribution

feef

Overpopulation

Pumping



Pump processes: Radiation or collisions

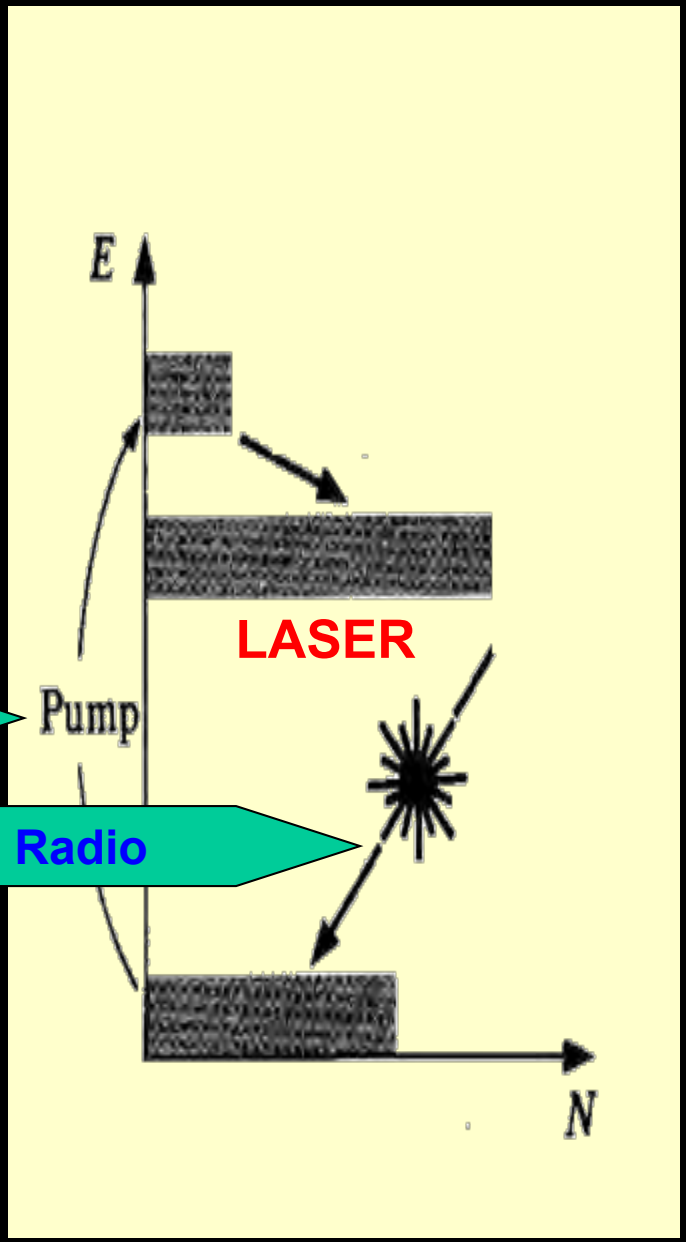
Radiative Pumping

- Pump radiation must have higher frequency than laser radiation

Infrared

Radio

Collisions between particles may move them to high energy levels



The First Maser
(Gordon, Zeiger, & Townes 1954)

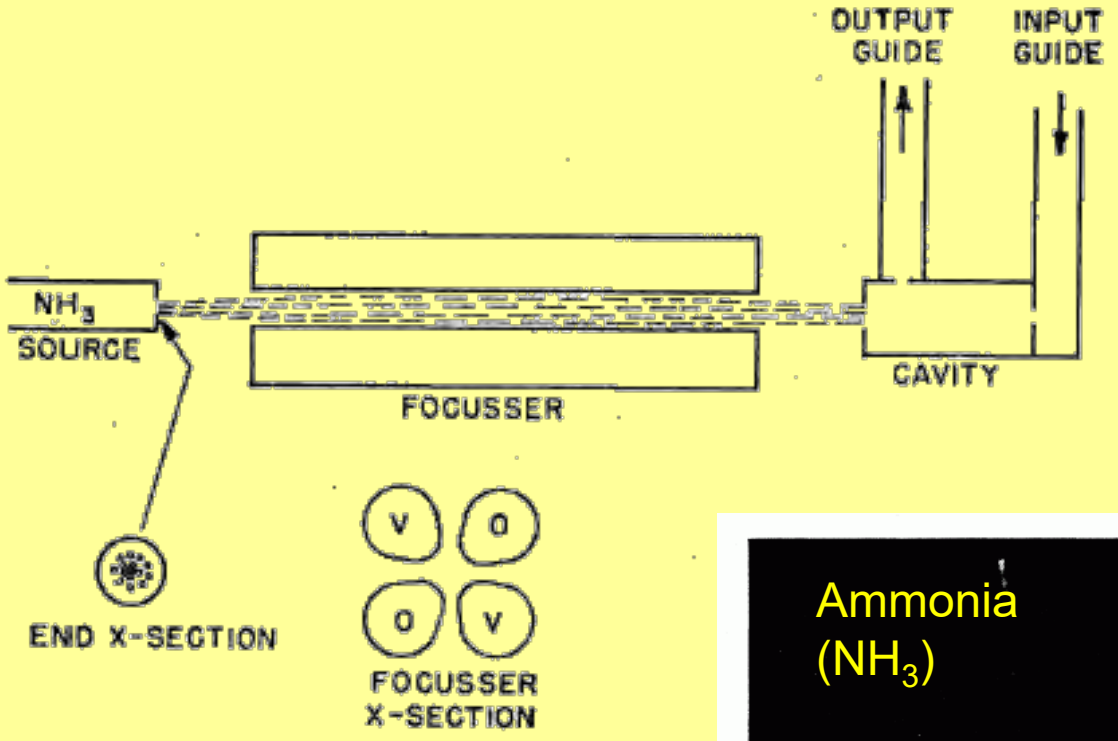
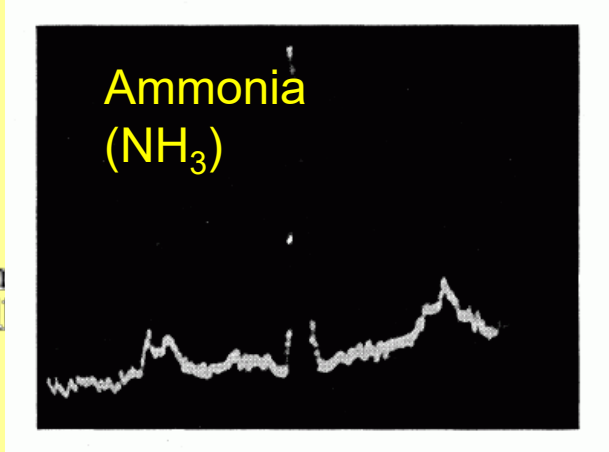
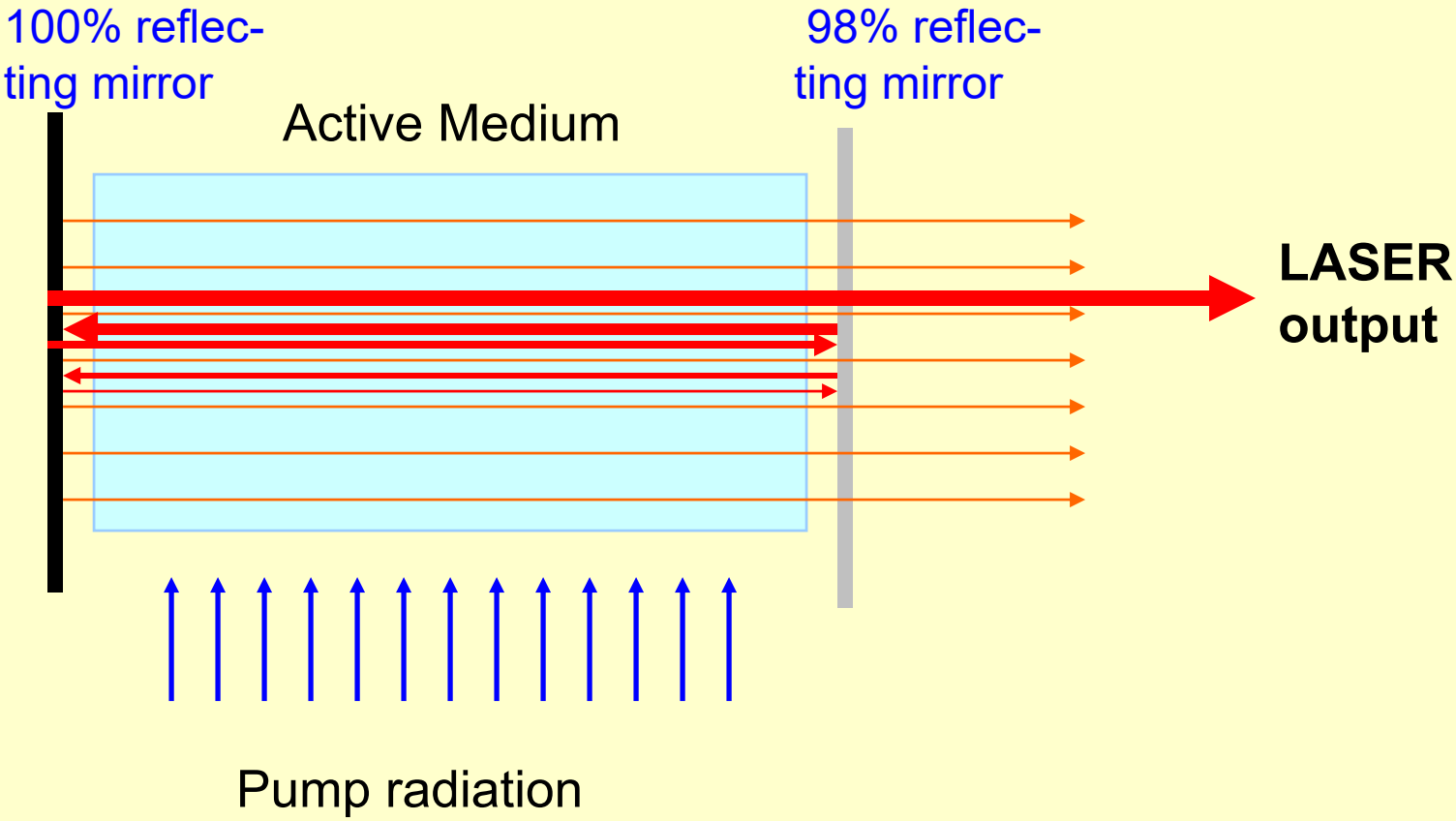


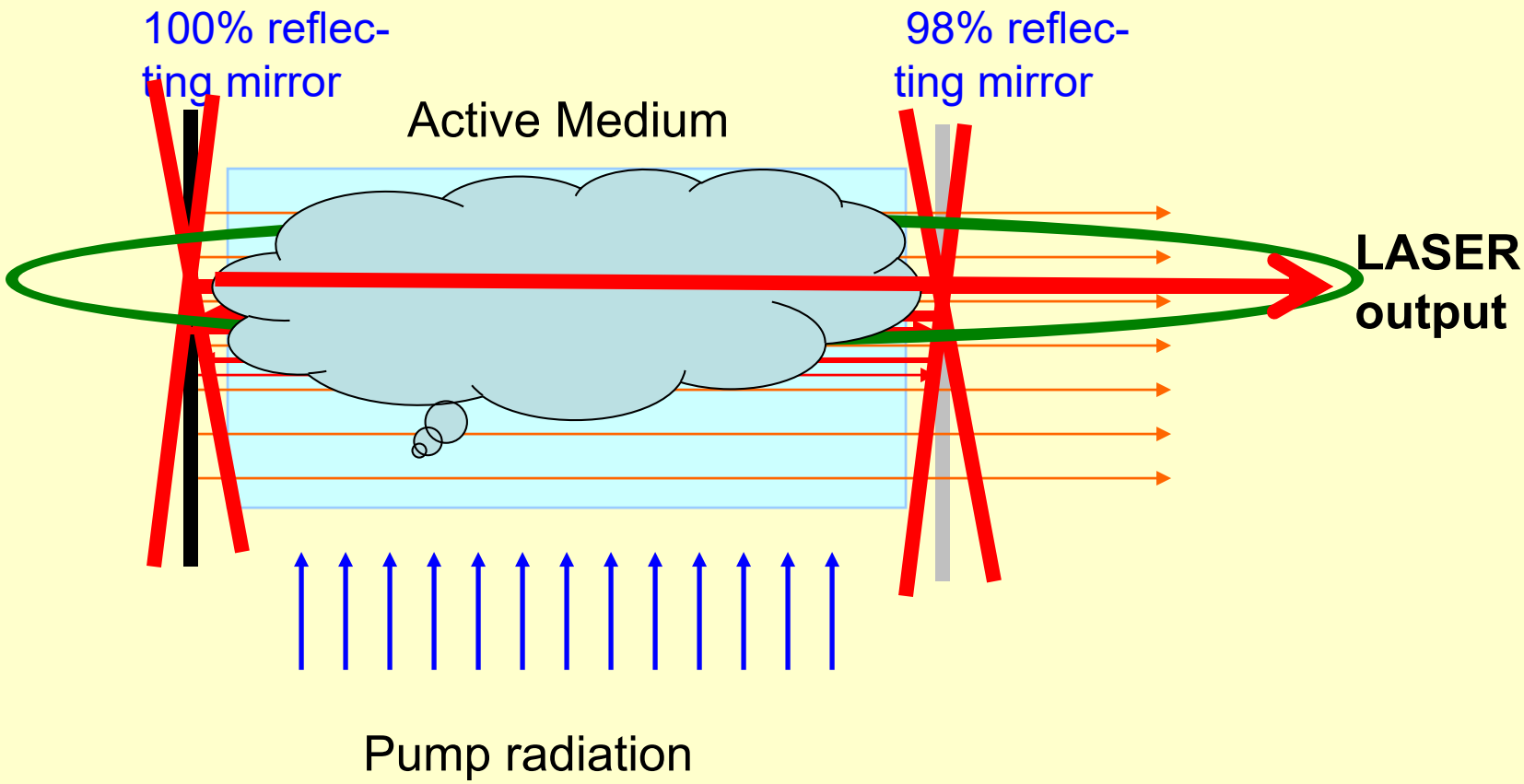
FIG. 1. Block diagram of the m
spectrometer and oscil



Realization of a M/LASER



Interstellar MASER





The Nobel Prize in Physics 1964

"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"



Charles Hard Townes

◐ 1/2 of the prize

USA

Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA

b. 1915



Nicolay Gennadiyevich Basov

◔ 1/4 of the prize

USSR

P.N. Lebedev Physical Institute
Moscow, USSR

b. 1922
d. 2001



Aleksandr Mikhailovich Prokhorov

◔ 1/4 of the prize

USSR

P.N. Lebedev Physical Institute
Moscow, USSR

b. 1916
d. 2002



Charles Hard Townes
1915–2015

PAPER 16

MICROWAVE AND RADIO-FREQUENCY RESONANCE LINES OF INTEREST TO RADIO ASTRONOMY

C. H. TOWNES

Physical Laboratory, Ecole Normale Supérieure, Paris

1957 Paris IAU Symposium

Table 1. *Some hyperfine structure transitions of interest to radio astronomy*

The approximate abundances of each nuclear species relative to H^1 for our Galaxy are given. These are not necessarily the relative abundance in interstellar gases, where H^1 has a density of 1 atom./cm.^{3}. The matrix element for each transition is due to a magnetic dipole, and is approximately one Bohr magneton ($|\mu''|=1$). The quantity F is the vector sum of electronic angular momentum J and nuclear spin I.

Nucleus	Abundance relative to H^1	Transition		Frequency (Mc./s.)	Comments
H^1	1	H I $^2S_{1/2}$,	$F=0$–1	1420·4051	Already detected in interstellar gases
H^2	2×10^{-4}	H I $^2S_{1/2}$,	$F=1/2$–$3/2$	327·3842	
He^3	10^{-5}	He II $^2S_{1/2}$,	$F=1$–0	8659·3*	Calculated frequency without allowance for finite nuclear size
He^3	10^{-5}	He I $^3S_{3/2}-{}^3S_{1/2}$		6739·71	Metastabile state
N^{14}	5×10^{-4}	N I $2^3p^4S_{3/2}$,	$F=3/2$–$5/2$	26·12	
			$F=1/2$–$3/2$	15·67	
		N II $2p^{2\,3}P_1$,	$F=1$–2	~ 500	Approx. 60 cm.$^{-1}$ above ground state
			$F=0$–1		
		N III $2p^2P_{1/2}$,	$F=1/2$–$3/2$	~ 800	
		N V $2s^2S_{1/2}$,	$F=1/2$–$3/2$	~3000	
		N VII $1S^2S_{1/2}$,	$F=1/2$–$3/2$	53·060	Calculated frequency without allowance for finite nuclear size
Na^{23}	1×10^{-6}	Na I $3s^{2\,2}S_{1/2}$,	$F=1$–2	1771·61	
Al^{27}	3×10^{6}	Al I $3p^2P_{1/2}$,	$F=2$–3	1450	
P^{31}	4×10^{-7}	P I $3^3p^4S_{3/2}$,	$F=2$–3	112	
Cl^{35}	4×10^{-7}	Cl I $3p^{5\,2}P_{3/2}$,	$F=3$–2	670·018	
			$F=2$–1	355·244	
			$F=1$–0	150·145	

Table 3

Some microwave transitions between molecular rotational levels of interest to radio astronomy. The inversion spectrum of NH_3 is also listed.

Molecule	Electronic state	Transition	Frequency (Mc./s.)	Matrix element in Debye units	Comments
CaH	$^2\Sigma$	$J=3/2-1/2$	254,080	Electric dipole unknown	
		$J=1/2-1/2$	252,650		
CO	$^1\Sigma$	$J=1-0$	115,270·6	0·10	
CO^+	$^2\Sigma$	$J=3/2-1/2$	117,980	Electric dipole unknown	
		$1/2-1/2$			
CS	$^1\Sigma$	$J=1-0$	48,991·0	2·0	
NO	$^2\Pi_{1/2}$	$J=3/1-1/2$	150,176·3	0·07	Also other nearby lines due to h.f.s.
H_2O	$^1\Sigma$	$6_{1,6}-5_{2,3}$	22,235·22	0·16	
N_2O	$^1\Sigma$	$J=1-0$	25,123·28	0·17	Other lines at multiples of the frequency given. Very small h.f.s. present
HCN	$^1\Sigma$	$J=1-0$, $F=1-1$	88,600·1	1·72	Also *l*-doublet transitions may occur
		$F=2-1$	88,601·5	2·22	
		$F=0-1$	88,603·6	0·99	
CH_2					Structure and spectrum unknown, but may produce some microwave lines
NH_2					Structure and spectrum not well known, but probably produces some microwave lines
NH_3	$^1\Sigma$	Inversion, $J=1$, $K=1$	23,694·48	1·0	Also other inversion transitions at nearby frequencies
O_2	$^1\Sigma$	$1_{11}-2_{02}$	42,832·62	0·17	Also other rotational transitions
		$1_{11}-0_{00}$	118,364·3	0·53	

Table 4. *Some molecular fine-structure transitions of interest to radio astronomy*

Transitions between Λ-doublets [electric dipole, $|\mu'| \sim 1$]

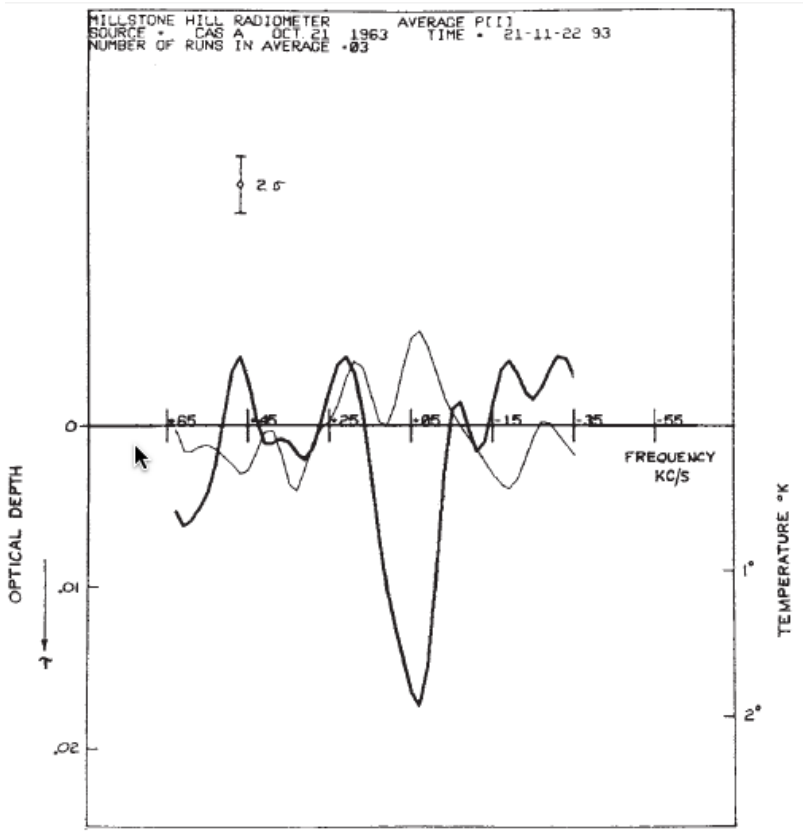
Molecule	Electronic state	Transition	Frequency (Mc./s.)	Comments
CH	$^2\Pi_{1/2}$	$J=1/2$	~1000	Also transitions at higher frequencies $\sim 1000N(N+1)$ in excited rotational states
	$^2\Pi_{3/2}$	$J=3/2$		
OH	$^2\Pi_{3/2}$	$J=3/2$, $F=2-2$	1665·0	Also, weak hyperfine satellites and higher frequencies in excited rotational states
		$F=1-1$	1667·0	
AlH	$^1\Pi$	$N=1$	380	Also higher frequencies in excited rotational states
SiH	$^2\Pi_{1/2}$	$J=1/2$	2400	Also higher frequencies in excited rotational states
SH	$^2\Pi_{3/2}$	$J=3/2$	114	Also higher frequencies in excited rotational states

Transitions between spin fine-structure levels [magnetic dipole, $|\mu''| \sim 1$]

H_2^+	$^2\Sigma$	$N=1$	~100	Approx. 60 cm.$^{-1}$ above ground state
NH	$^3\Sigma$	$N=1$, $J=0-1$	26,000	
		$J=1-2$	13,000	
OH^+	$^3\Sigma$	$N=1$, $J=0-1$	133,000	
		$J=1-2$	63,000	
MgH	$^2\Sigma$	$N=1$	1000	
CaH	$^2\Sigma$	$N=1$	1500	
CN	$^2\Sigma$	$N=1$	360	
CO^+	$^2\Sigma$	$N=1$	450	
O_2	$^3\Sigma$	$N=1$, $J=0-1$	118,750·5	Also known frequencies for other rotational levels
		$J=1-2$	56,265·6	
		$N=3$, $J=2-3$	62,487·4	

RADIO OBSERVATIONS OF OH IN THE INTERSTELLAR MEDIUM

By Dr. S. WEINREB
Lincoln Laboratory, Massachusetts Institute of Technology
Prof. A. H. BARRETT
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Mass.
AND
Dr. M. L. MEEKS and J. C. HENRY
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Mass.



OBSERVATIONS OF A STRONG UNIDENTIFIED MICROWAVE LINE AND OF EMISSION FROM THE OH MOLECULE

By Prof. HAROLD WEAVER, Dr. DAVID R. W. WILLIAMS, Dr. N. H. DIETER and W. T. LUM
Radio Astronomy Laboratory, University of California, Berkeley

(1965)

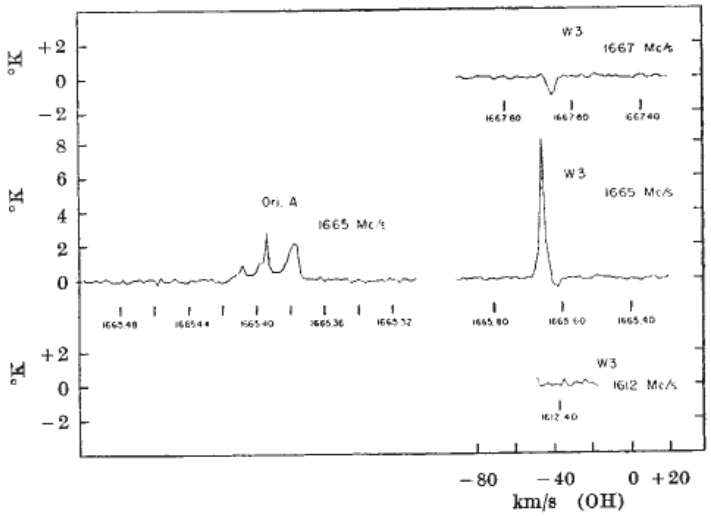


Fig. 1. Spectra of Ori *A* and *W*3 with a resolution of 10 kc/s (1·8 km/sec).

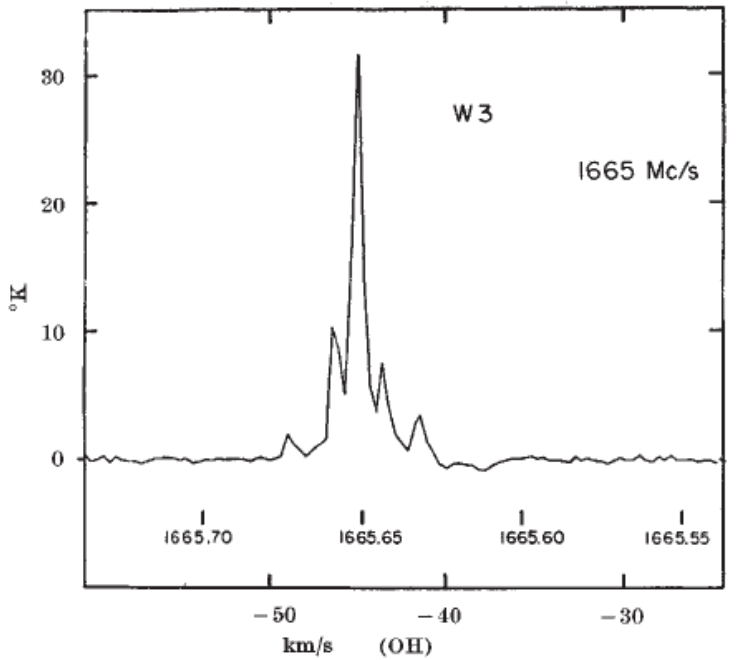


Fig. 2. Spectrum of *W*3 at 1,665 Mc/s with a resolution of 2 kc/s (0·4 km/sec)

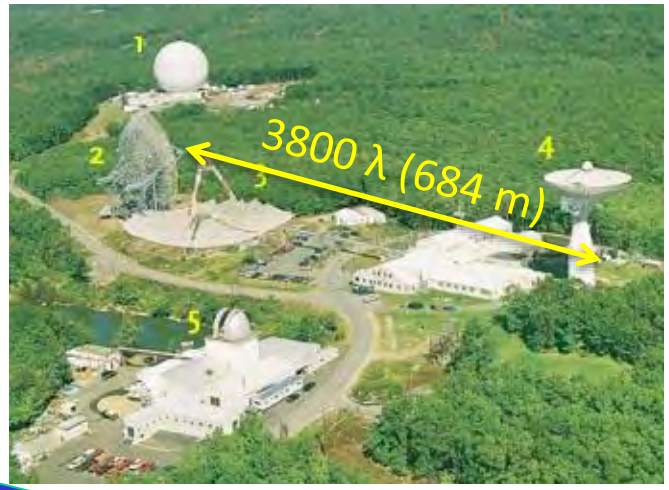
Mysterium

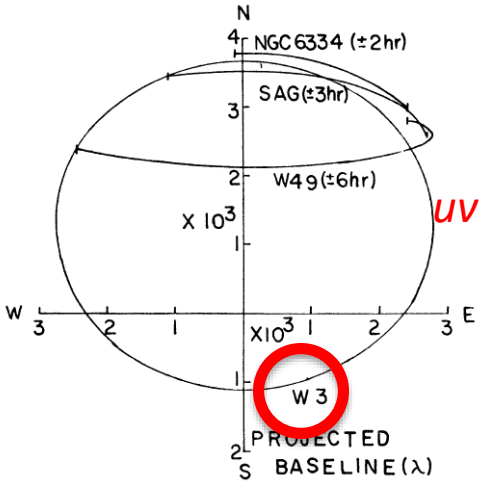
The Hat Creek 85 Foot (26 m) Radio Telescope



FWHM at 18 cm = 30’

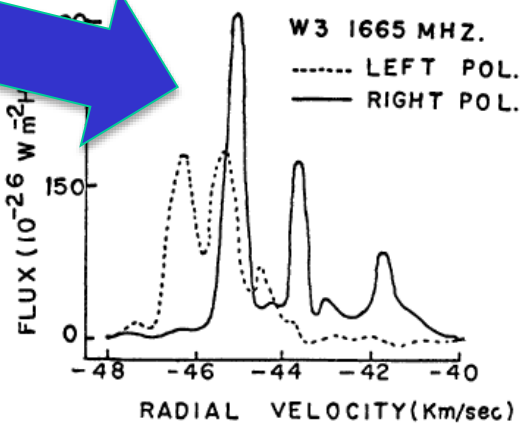
Hat Creek radio astronomy station
1964 from Original Negative by Ansel Adams
UCR/California Museum of Photography

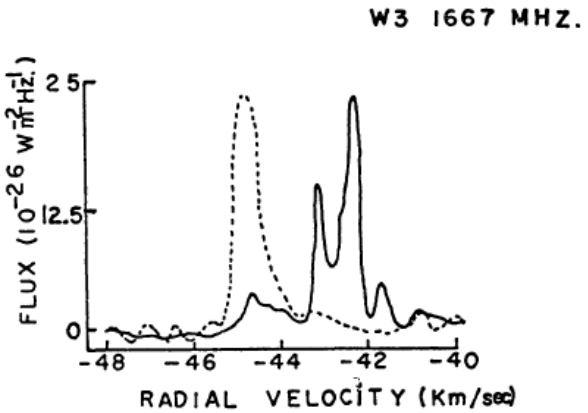


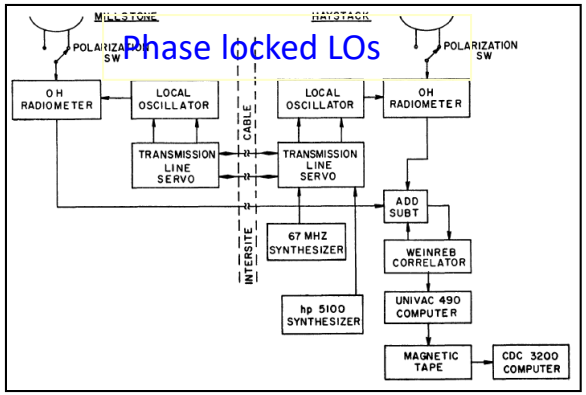


uv "coverage"

Zeeman







Phase locked LOs

October 18, 1966

RESEARCH LABORATORY OF ELECTRONICS*
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

A. E. E. ROGERS
J. M. MORAN
P. P. CROWTHER

DEPARTMENT OF PHYSICS AND RESEARCH LABORATORY OF ELECTRONICS†
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

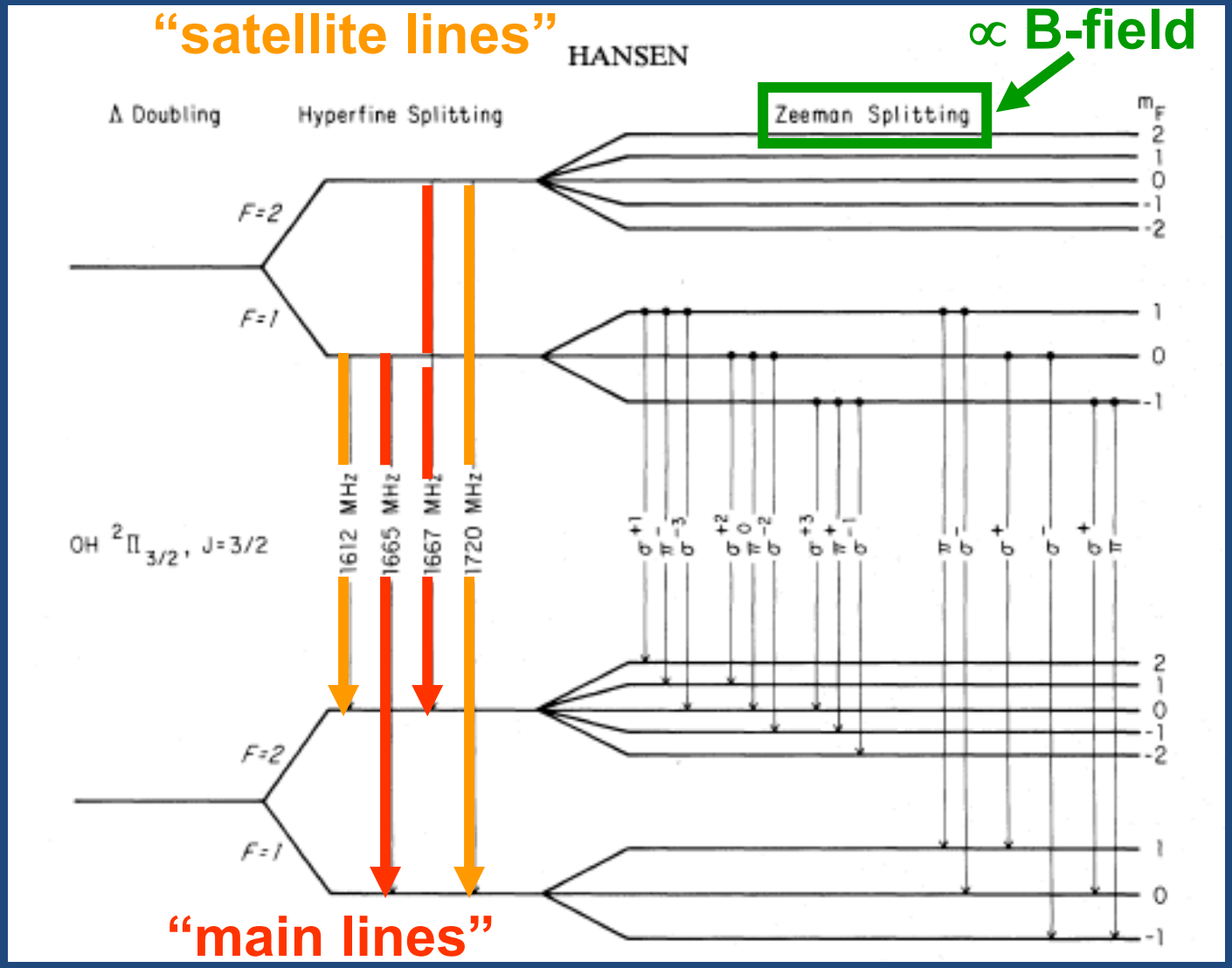
B. F. BURKE

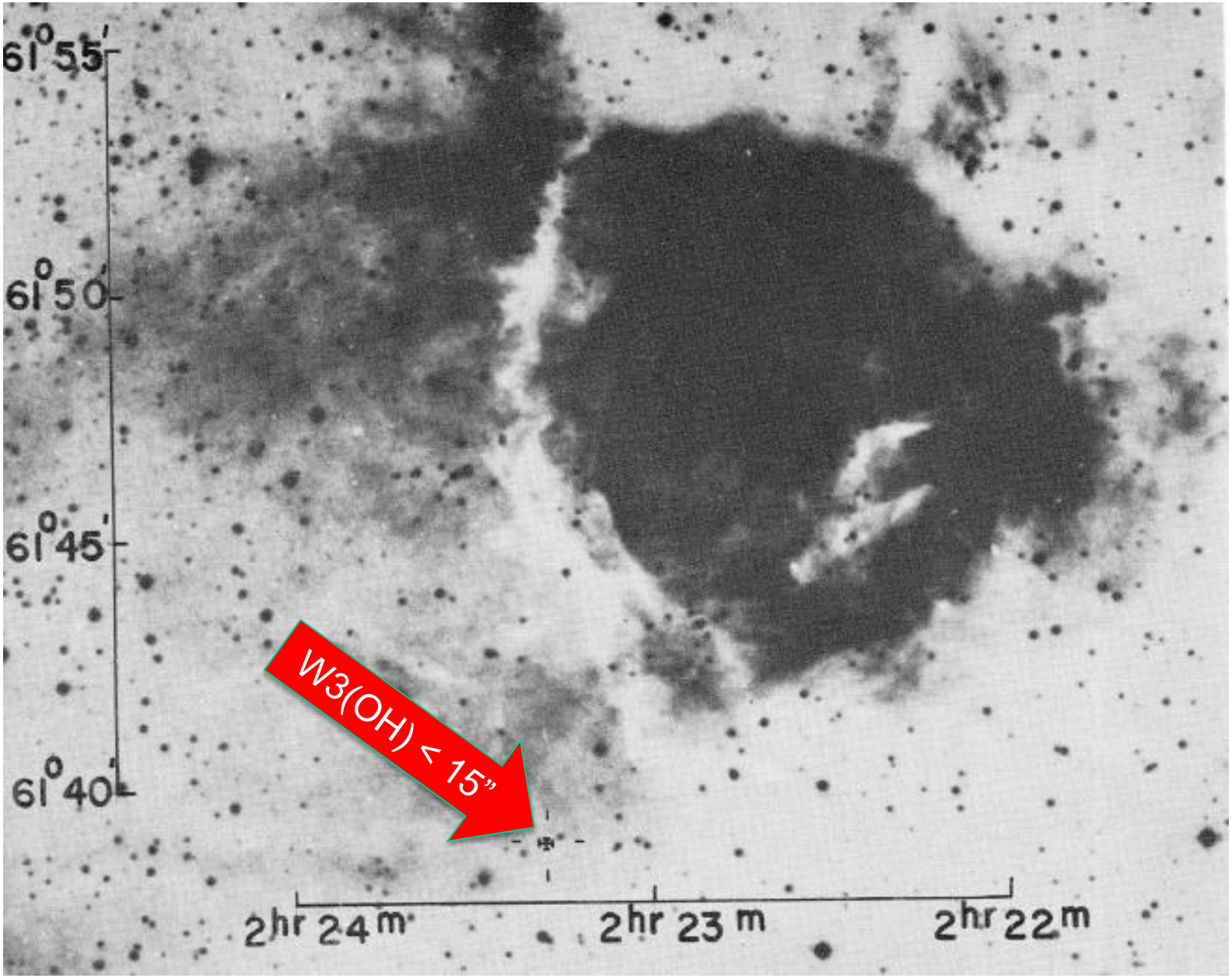
LINCOLN LABORATORY‡
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

M. L. MEEKS
J. A. BALL
G. M. HYDE

Phys. Rev. Letters 1966 + ApJ Letters 1967

Hydroxyl (OH) $^2\Pi_{3/2}$ ground-state transitions





Rogers+ 1967, ApJ
& Rogers+ 1966, Phys. Rev. Letters

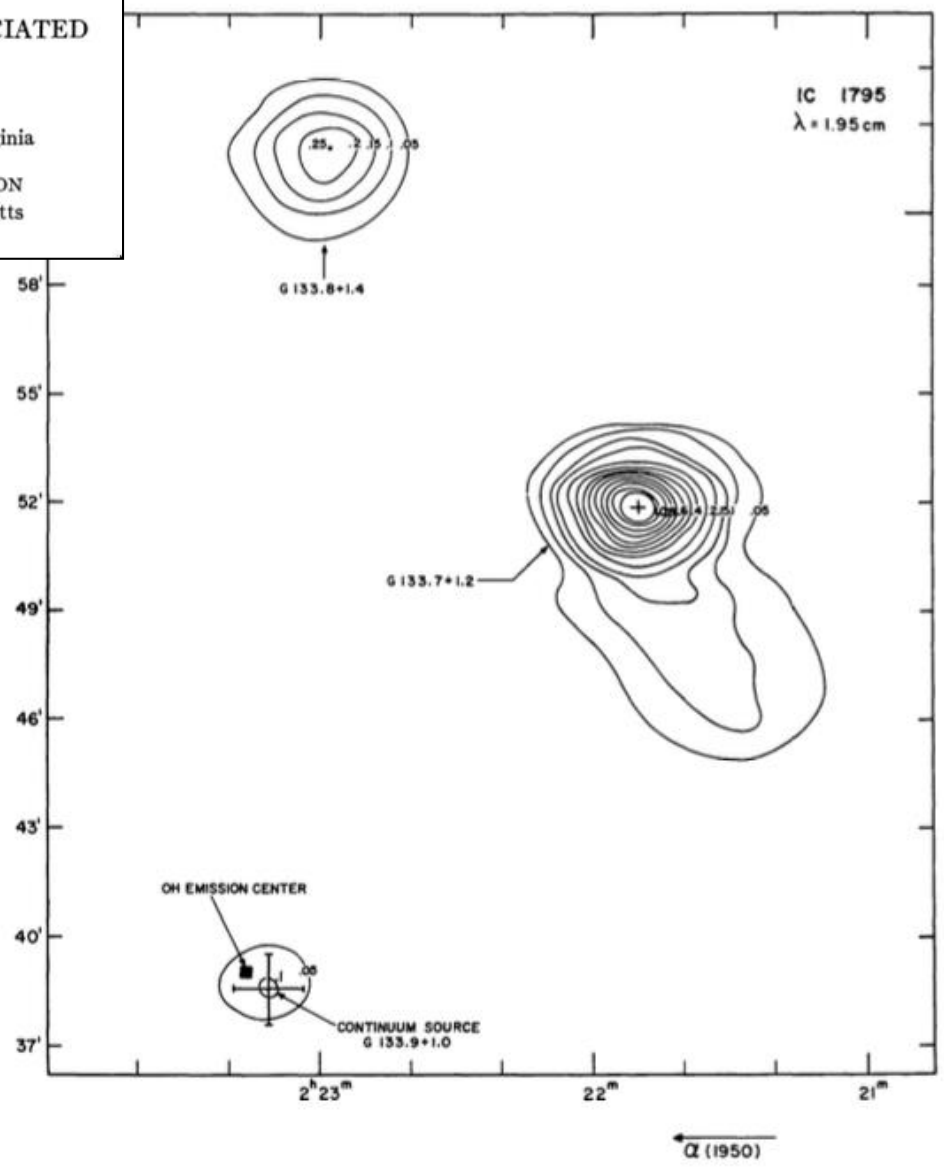
THE ASTROPHYSICAL JOURNAL, Vol. 150, December 1967

A NEW CLASS OF COMPACT H II REGIONS ASSOCIATED WITH OH EMISSION SOURCES

P. G. MEZGER, W. ALTENHOFF, J. SCHRAML
National Radio Astronomy Observatory,* Green Bank, West Virginia

B. F. BURKE, E. C. REIFENSTEIN III, AND T. L. WILSON
Massachusetts Institute of Technology,† Cambridge, Massachusetts

Received September 26, 1967

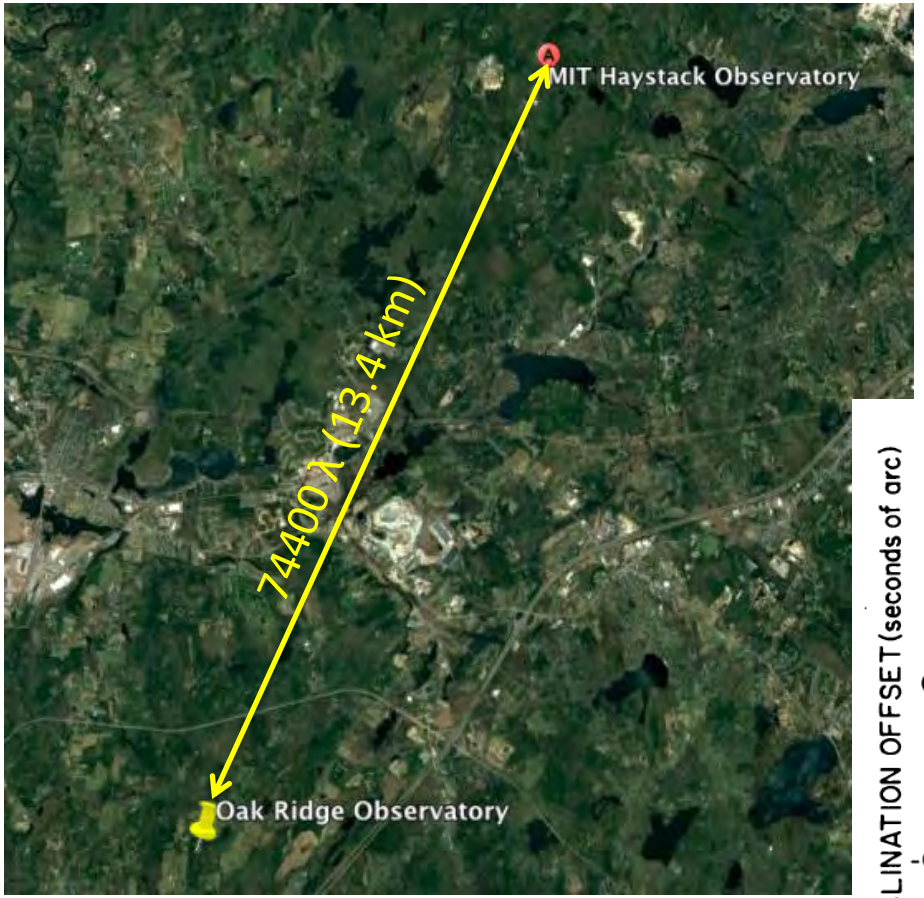


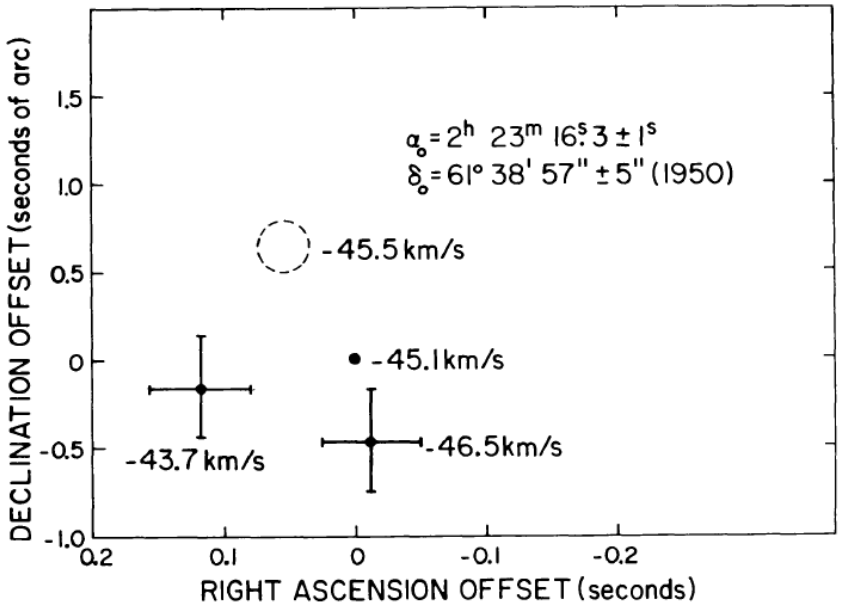
Masers and Interferometry



EVN/18 cm; http://www.evlbi.org/user_guide/coverage.html

OBSERVATIONS OF OH EMISSION IN THE H II REGION W3 WITH A 74400λ INTERFEROMETER





Moran+ 1967 ApJL (next issue)

Spectral Line Interferometry with Independent Time Standards at Stations Separated by 845 Kilometers

Moran+ 1967 Science

W3(OH): Source sizes < 20 mas

NATURE, MARCH 18, 1967

Measurements of OH Emission Sources with an Interferometer of High Resolution

127 km in UK

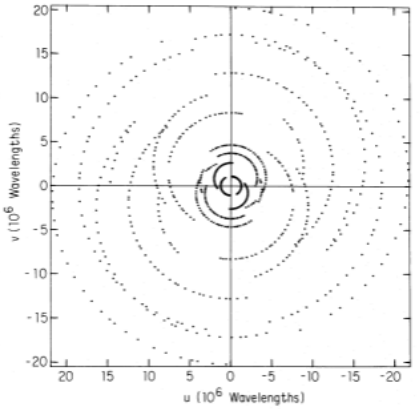
Davies+ 1967 Nature

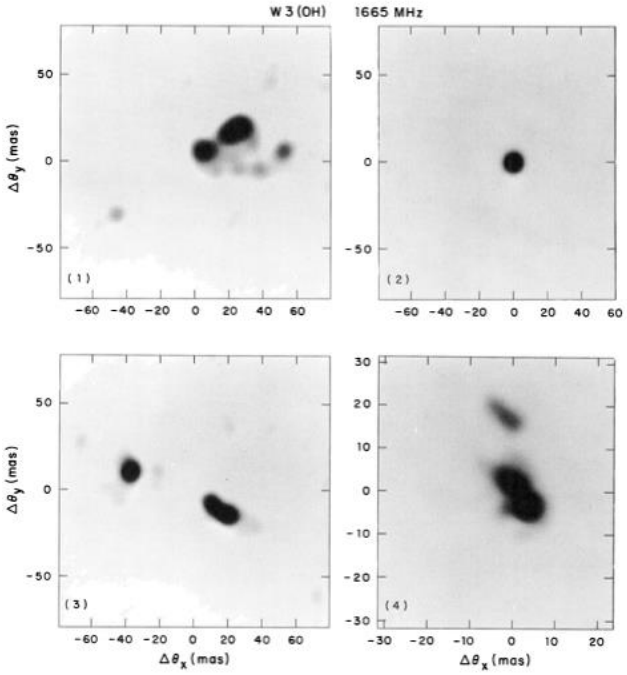
THE ASTROPHYSICAL JOURNAL, 239:89–111, 1980 July 1
© 1980. The American Astronomical Society. All rights reserved. Printed in U.S.A.

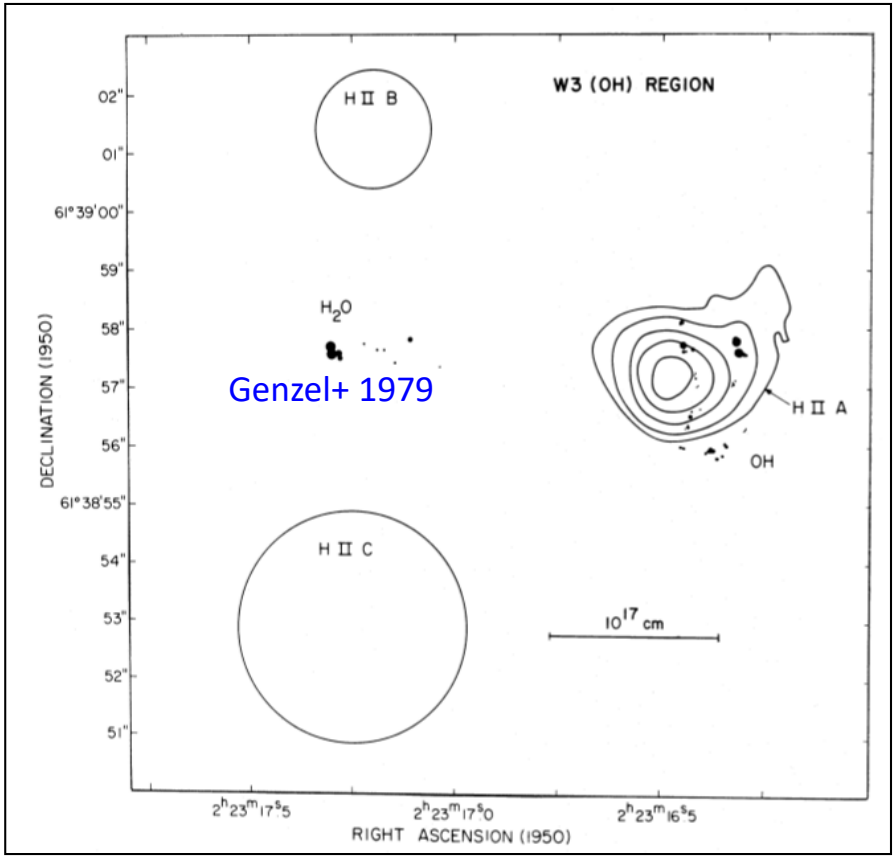
THE STRUCTURE OF INTERSTELLAR HYDROXYL MASERS: VLBI SYNTHESIS OBSERVATIONS OF W3(OH)

M. J. REID
Harvard-Smithsonian Center for Astrophysics; and National Radio Astronomy Observatory[1]
A. D. HASCHICK AND B. F. BURKE
Research Laboratory of Electronics, Massachusetts Institute of Technology
J. M. MORAN
Harvard-Smithsonian Center for Astrophysics
K. J. JOHNSTON
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C.
AND
G. W. SWENSON, JR.
Vermilion River Observatory, University of Illinois
Received 1979 October 22; accepted 1979 December 27



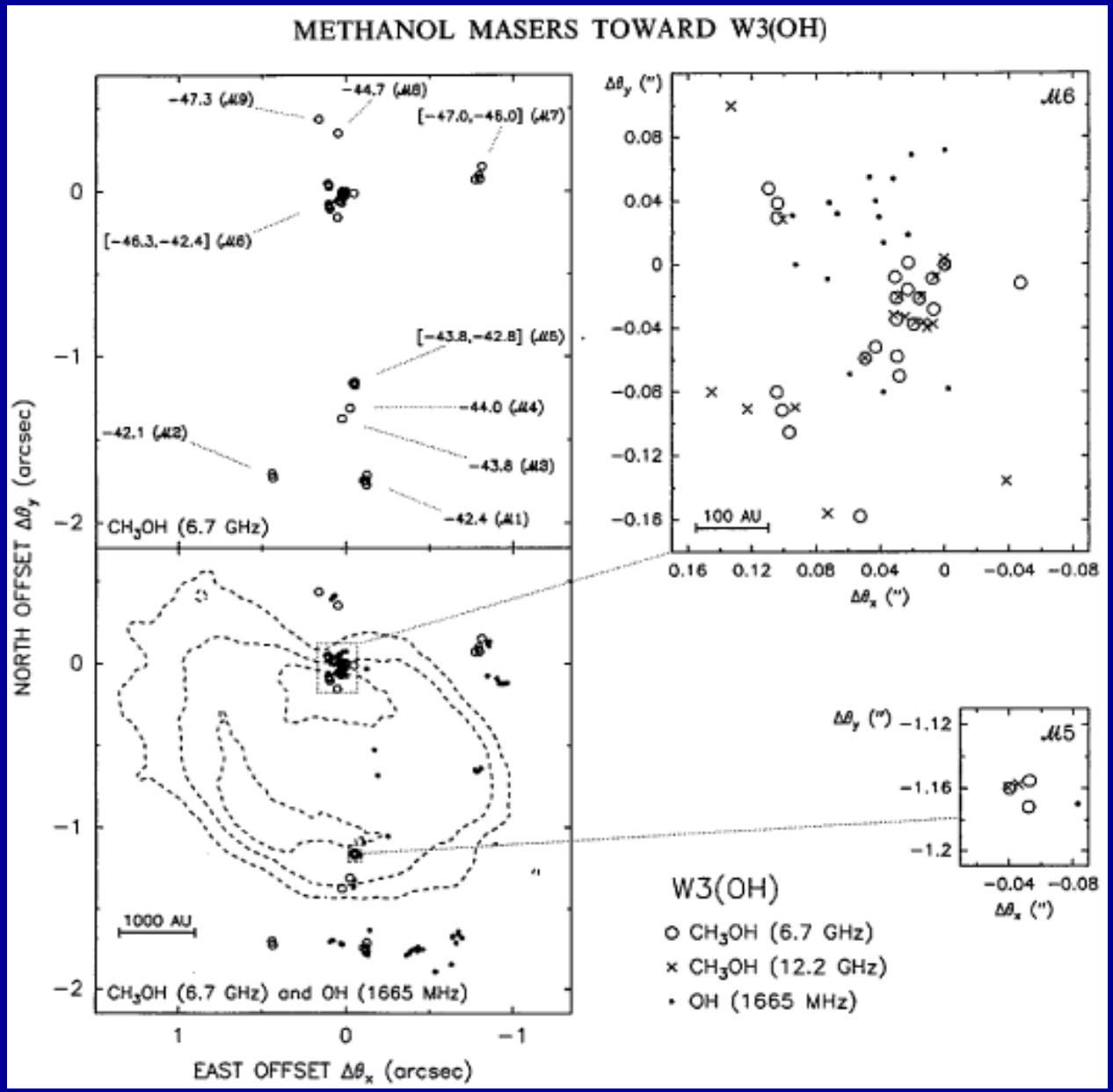






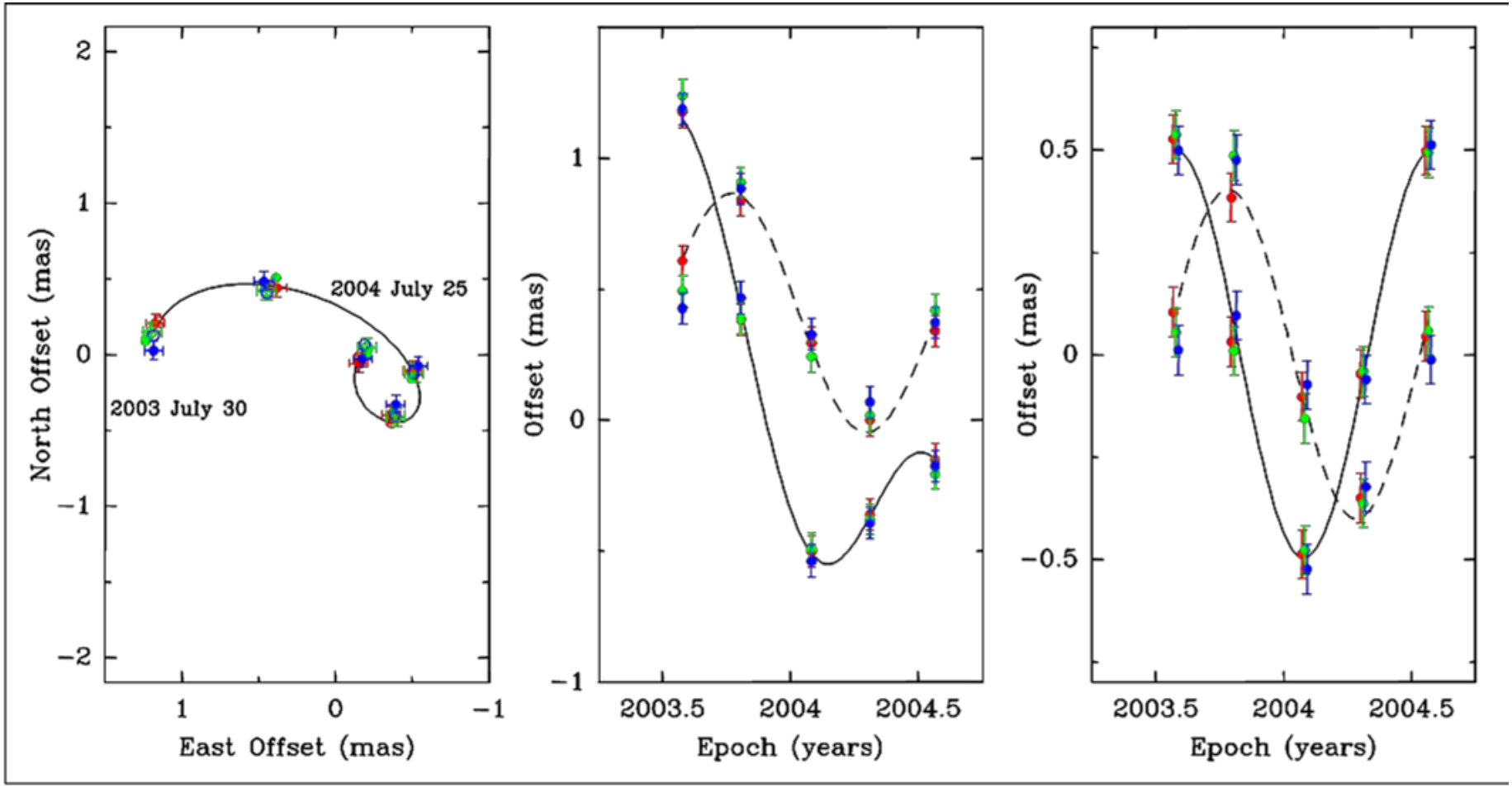
Reid+ 1980

W3OH



Menten+ 1988,1992

W3OH CH_3OH Maser Parallax

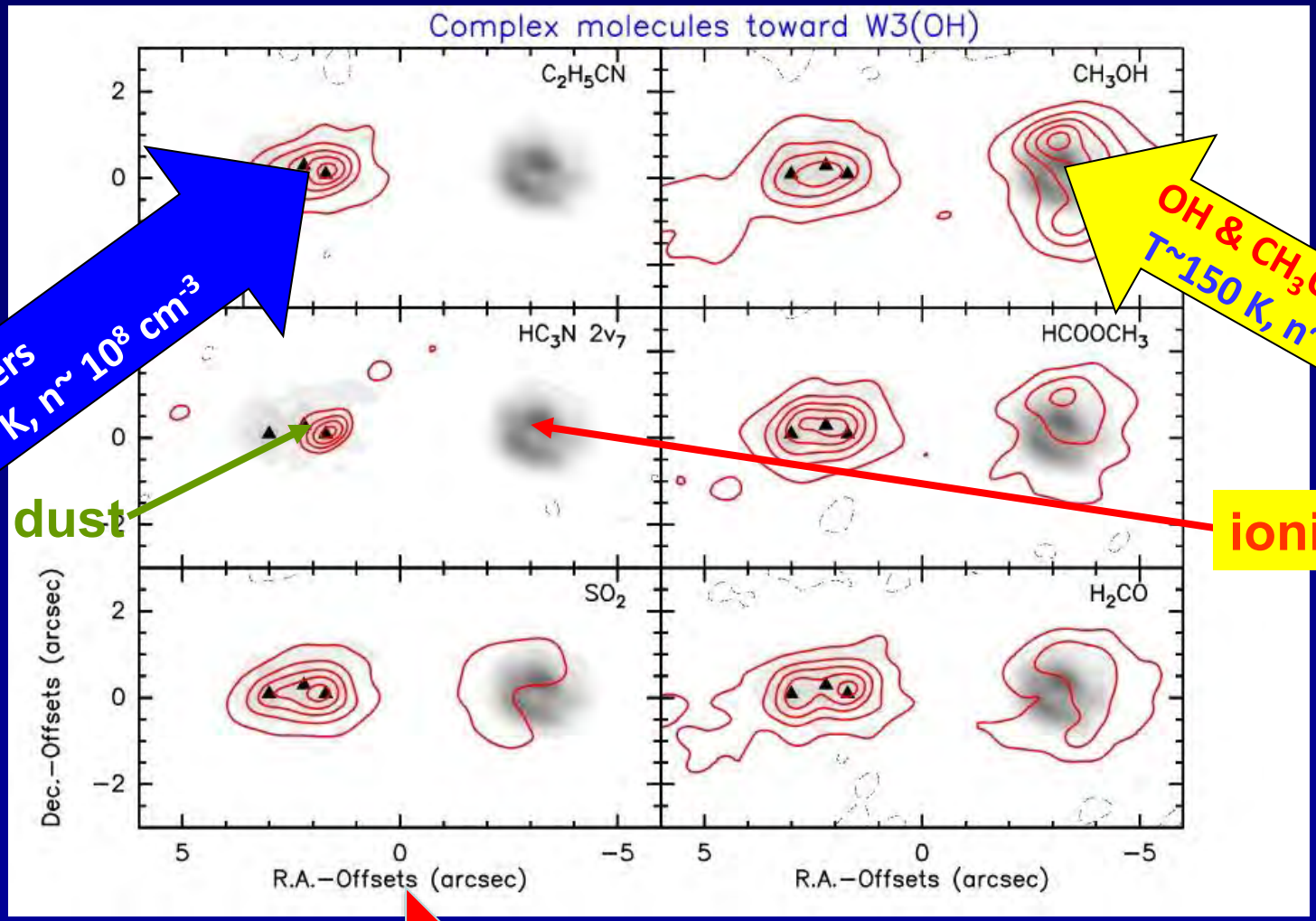


Xu, Reid, Zheng & Menten
Science, 2006

π = 0.512 +/- 0.010 mas

D = 1.95 +/- 0.04 kpc

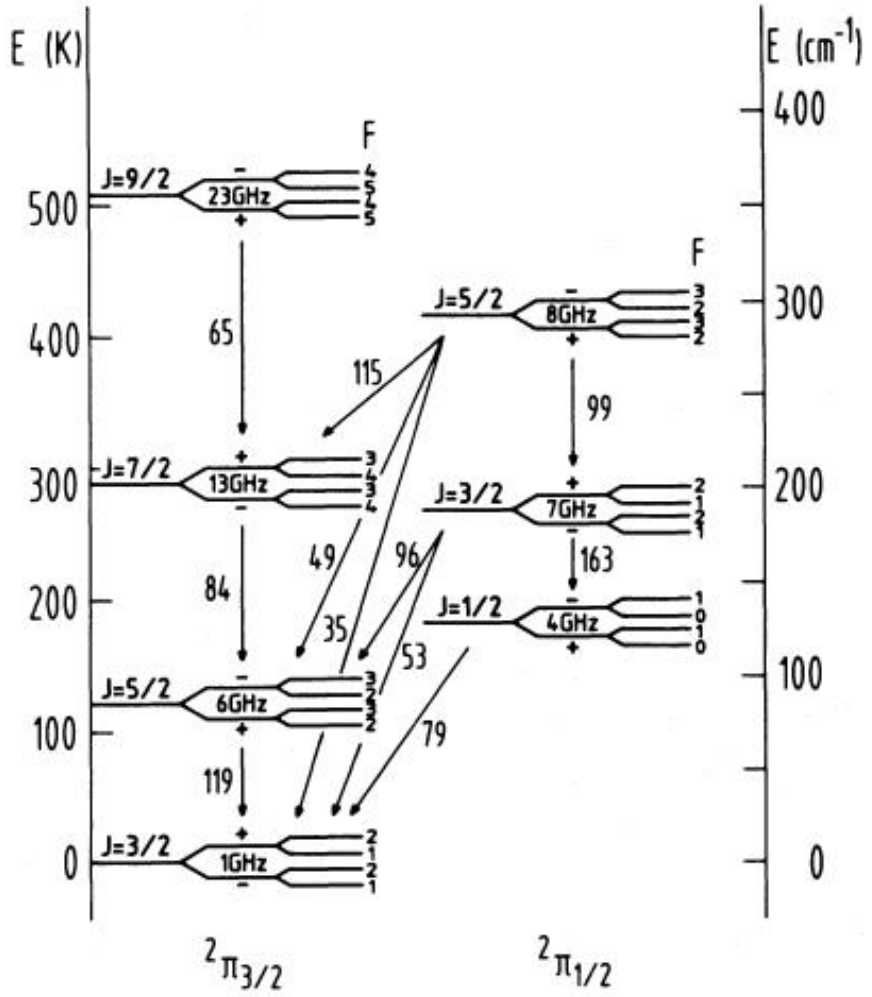
Chemical (and evolutionary) diversity in the W3OH region

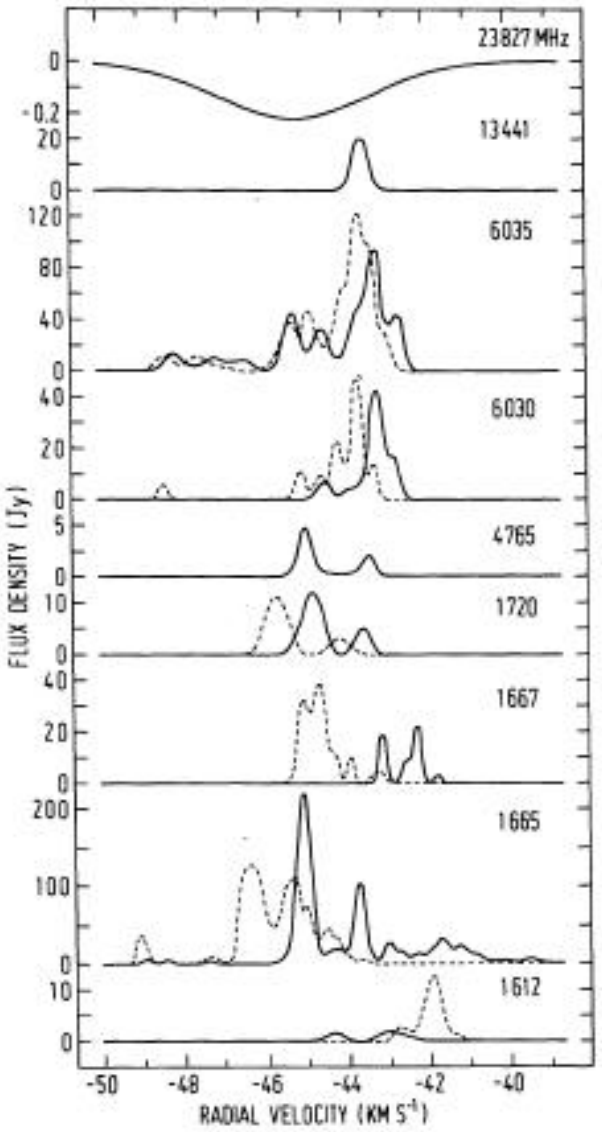


Talk by C. Goddi

Wyrowski et al. 1999

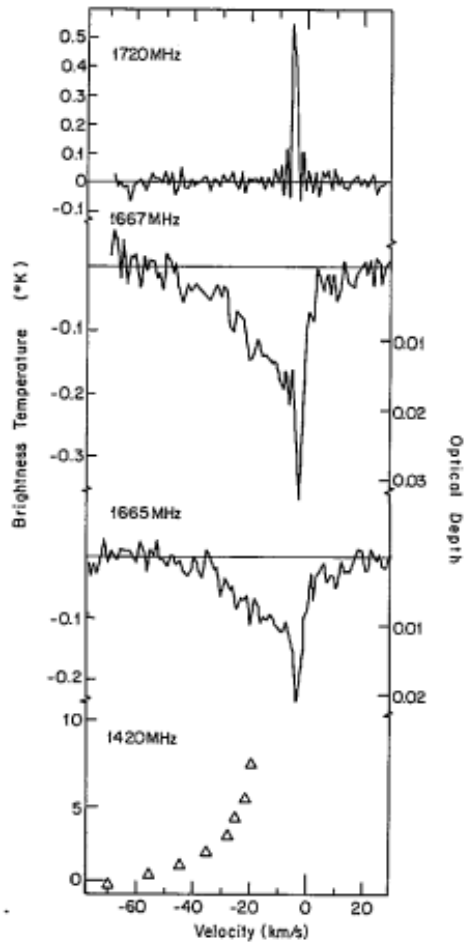
Hydroxyl maser emission and absorption:

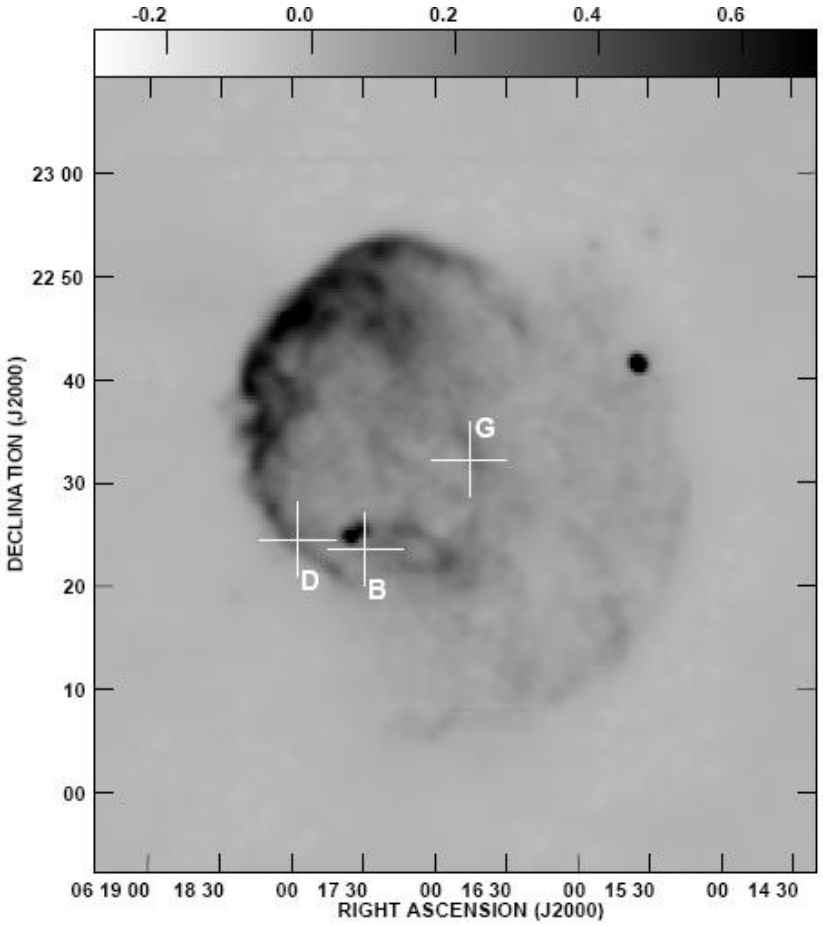




Baudry, Guilloteau, Walmsley, Wilson, Winnberg, …

1720 MHz OH Maser Emission toward IC 443

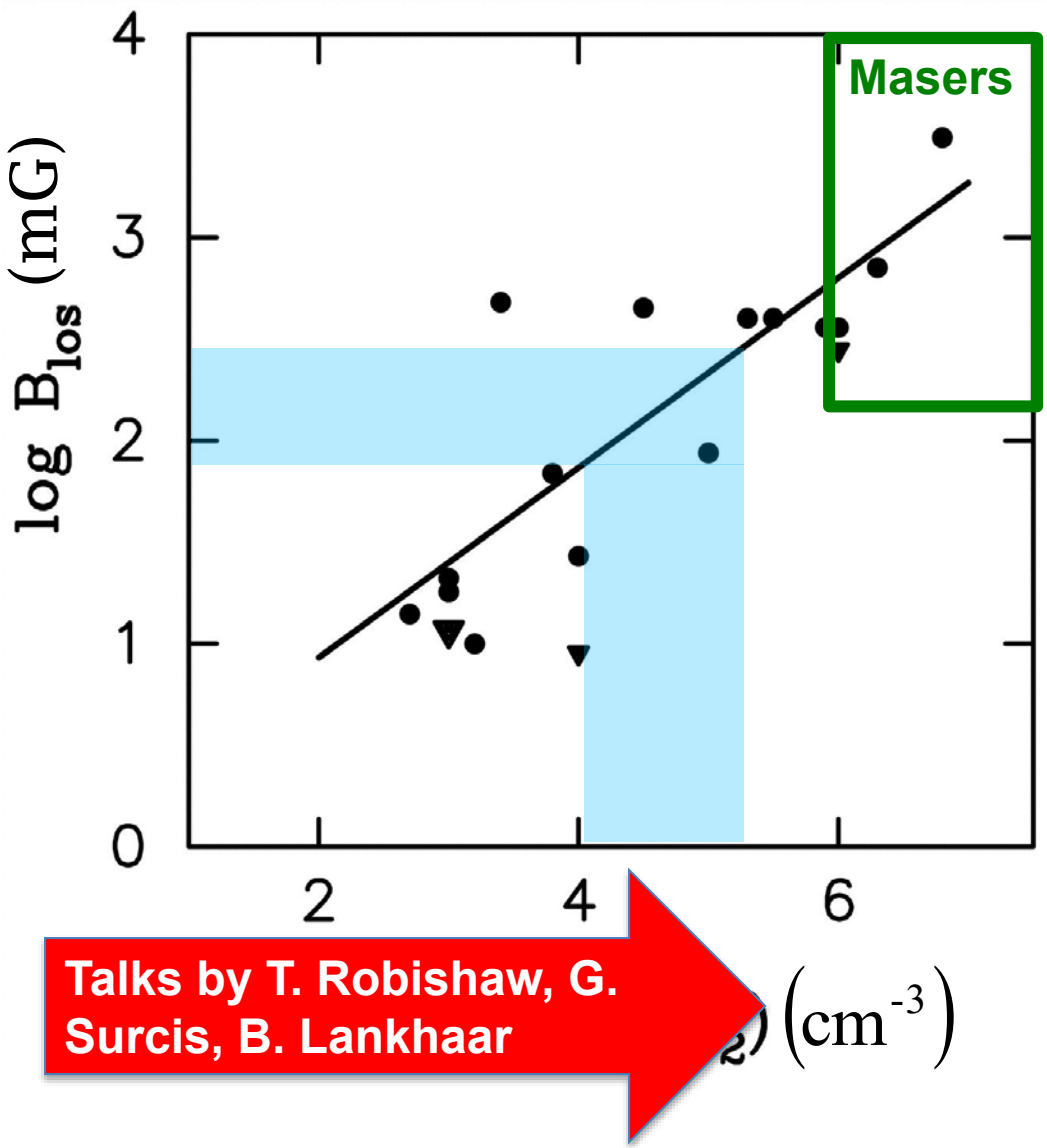




Denoyer 1979

Hewitt+ 2006
Claussen+ 1997

Masers and B fields



$$B_{los} \propto n^{0.47\pm0.08}$$

Talks by T. Robishaw, G. Surcis, B. Lankhaar

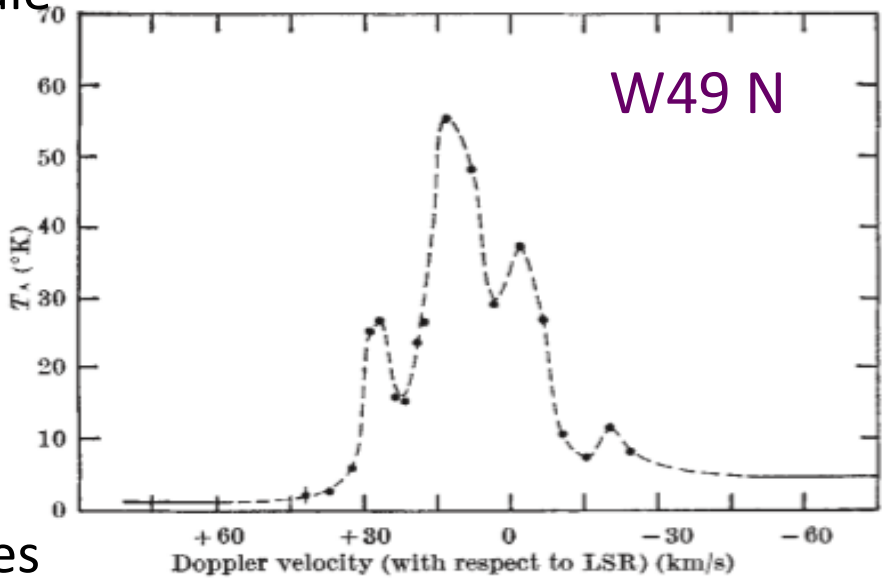
Crutcher 1999

The 22.2 GHz H_2O line

- Discovered 1969 by Cheung … Townes …
  - First triatomic interstellar molecule
  - In Orion, Sgr B2, W49 N
  - Very intense emission/ strongest radio line: W 49 N ~ 1 $L_\odot$
- Level energies 643 K above ground
- Very wide velocity spread
- **VLBI:**
  - Very compact, variable emission
  - Very high brightness temperatures

  → Maser
  - Collisonally pumped in post-J shock gas

    Neufeld & Melnick 1991, Hollenbach+ 2013, Gray+ 2017

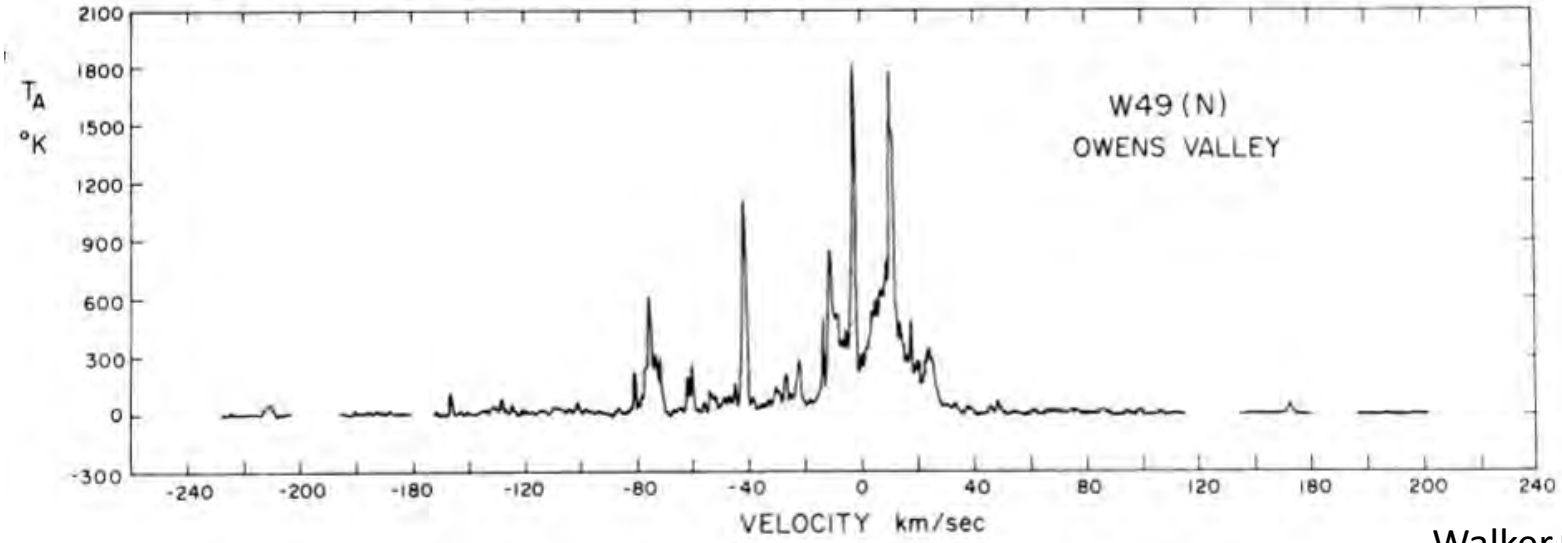


Cheung+ 1969

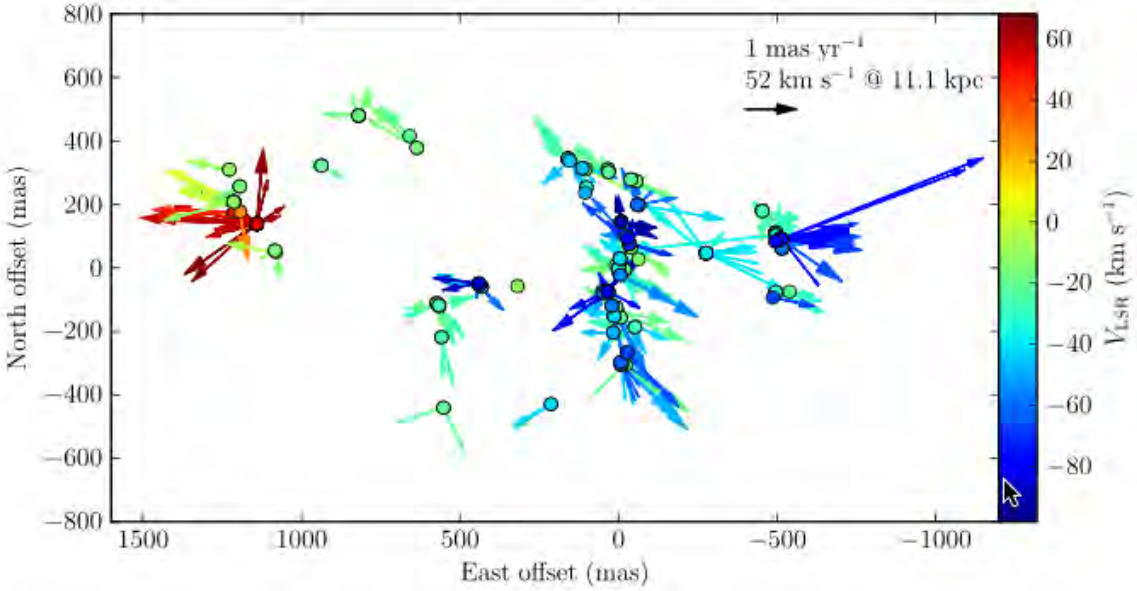
Interstellar H_2O Masers

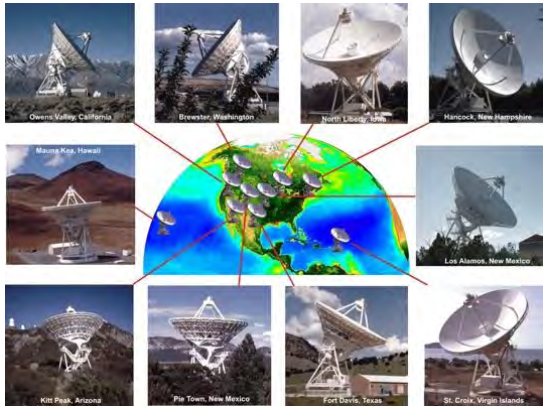
- are always associated with outflows → trace accretion
- are signposts for energy sources
- Variability marks energetic events

H_2O Maser motions in W49 N



Walker+ 1977

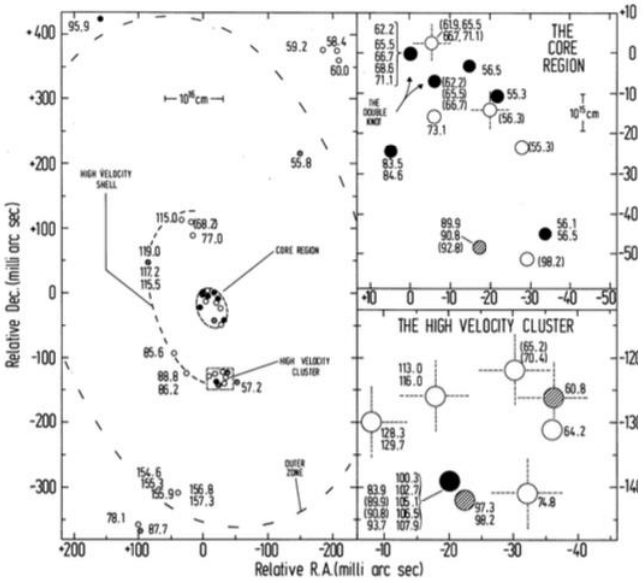




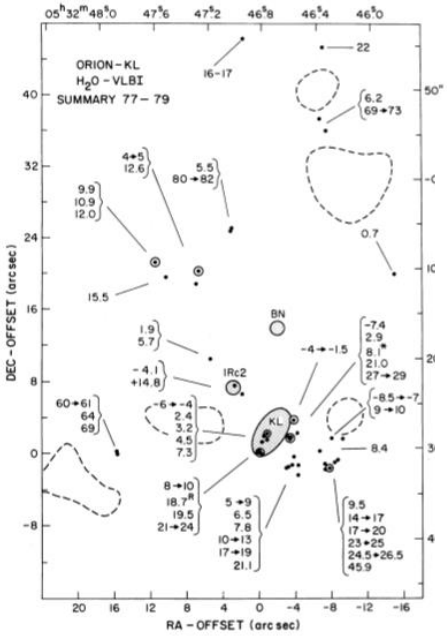
Luminosity in 22.2 GHz H_2O line ~1 $L_\odot$

Zhang+ 2013/
BeSSeL survey

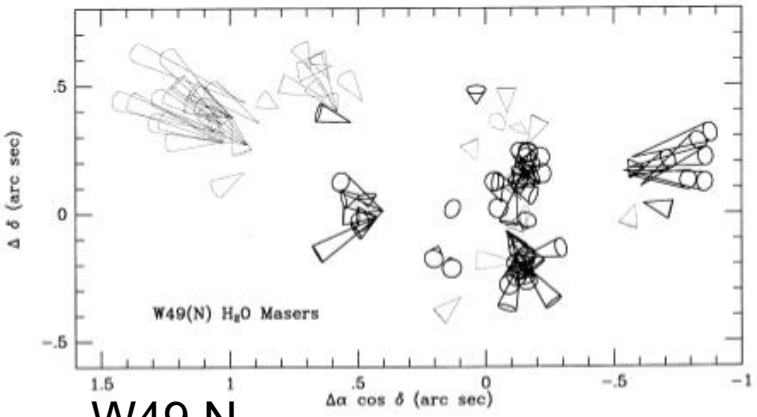
Global H_2O maser VLBI ~1980: Genzel, Reid, Moran, Downes,...



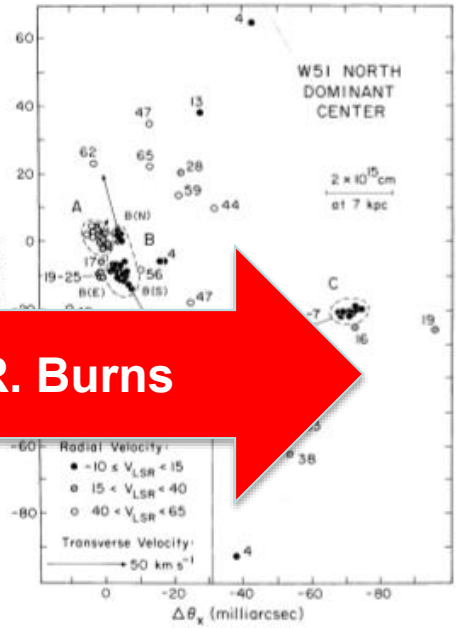
W51 M
Genzel+ 1979



Orion-KL
Genzel+ 1981

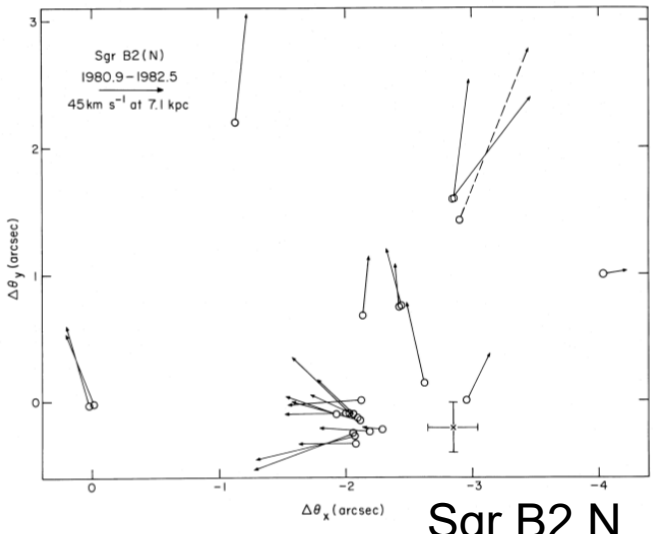


W49 N
Gwinn+ 1992

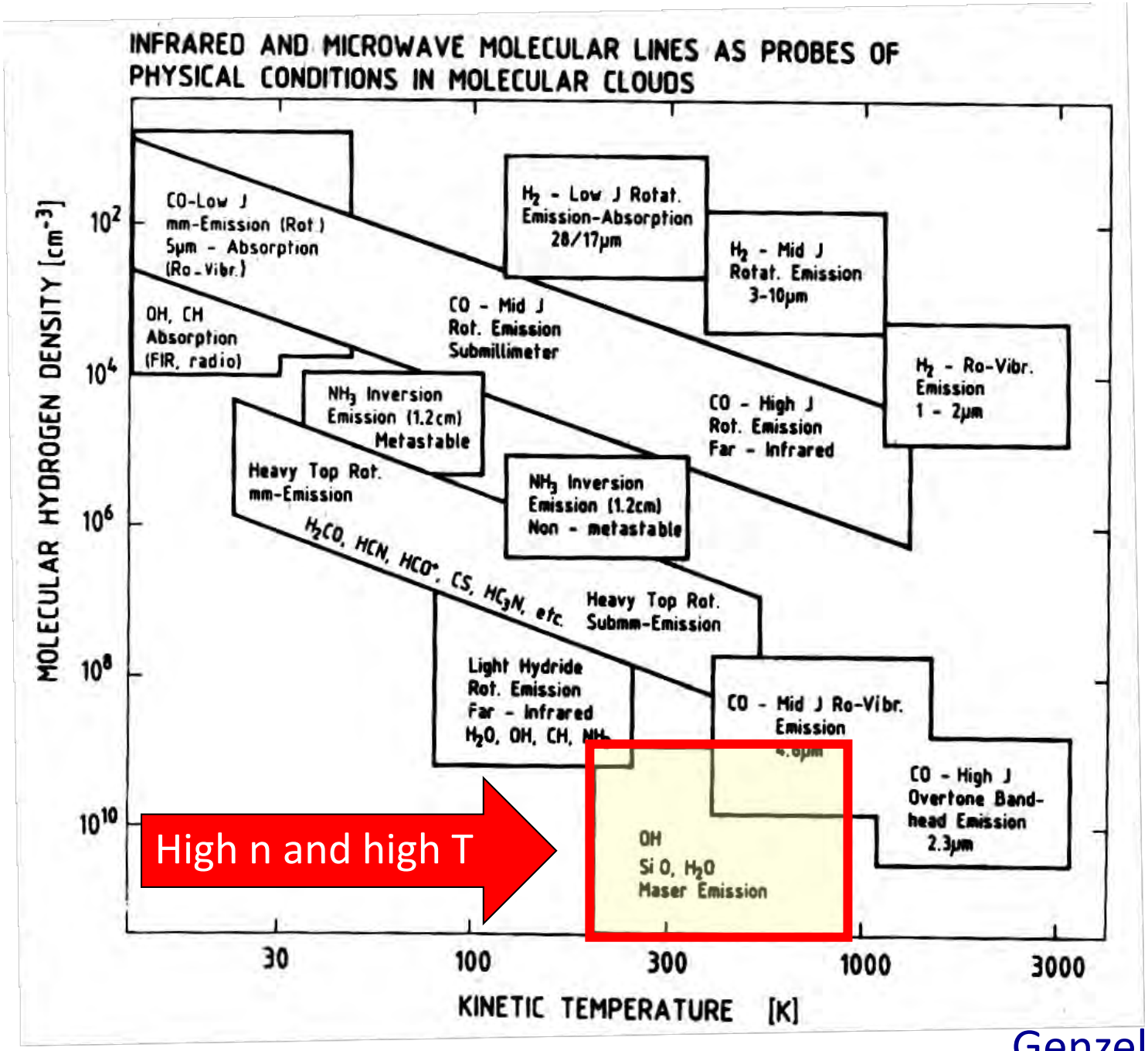


W51 N
Sc

Talk by R. Burns



Sgr B2 N
Reid+ 1988


INFRARED AND MICROWAVE MOLECULAR LINES AS PROBES OF PHYSICAL CONDITIONS IN MOLECULAR CLOUDS
MOLECULAR HYDROGEN DENSITY [cm⁻³]
10²
10⁴
10⁶
10⁸
10¹⁰
CO-Low J mm-Emission (Rot.) 5μm - Absorption (Ro.-Vibr.)
OH, CH Absorption (FIR, radio)
H₂ - Low J Rotat. Emission-Absorption 28/17μm
H₂ - Mid J Rotat. Emission 3-10μm
CO - Mid J Rot. Emission Submillimeter
H₂ - Ro-Vibr. Emission 1 - 2μm
NH₃ Inversion Emission (1.2cm) Metastable
CO - High J Rot. Emission Far - Infrared
Heavy Top Rot. mm-Emission
NH₃ Inversion Emission (1.2cm) Non - metastable
H₂CO, HCN, HCO⁺, CS, HC₃N, etc.
Heavy Top Rot. Submm-Emission
Light Hydride Rot. Emission Far - Infrared H₂O, OH, CH, NH
CO - Mid J Ro-Vibr. Emission
CO - High J Overtone Band-head Emission 2.3μm
High n and high T
OH
Si O, H₂O
Maser Emission
30
100
300
1000
3000
KINETIC TEMPERATURE [K]

Genzel 1988

The recipe for strong masers

$$S \propto |t|$$

$$t \propto N(X) \propto XN(H_2) = Xn(H_2)l$$

Strong masers require:

- High molecular abundance **(chemistry)**
- High density (environment)
- long enough l (geometry)

+ pumping: F/IR field, shocks, …

THE ASTROPHYSICAL JOURNAL, 162:L203–L210, December 1970
© 1970. The University of Chicago. All rights reserved. Printed in U.S.A.

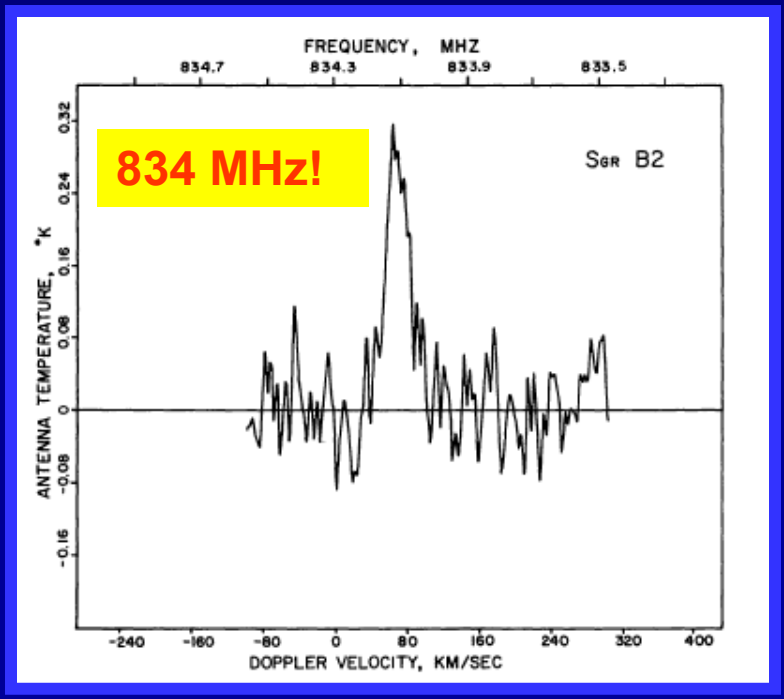
DETECTION OF METHYL ALCOHOL IN SAGITTARIUS

JOHN A. BALL, CARL A. GOTTLIEB, AND A. E. LILLEY
Harvard College Observatory, Cambridge, Massachusetts

AND

H. E. RADFORD
Smithsonian Astrophysical Observatory, Cambridge, Massachusetts





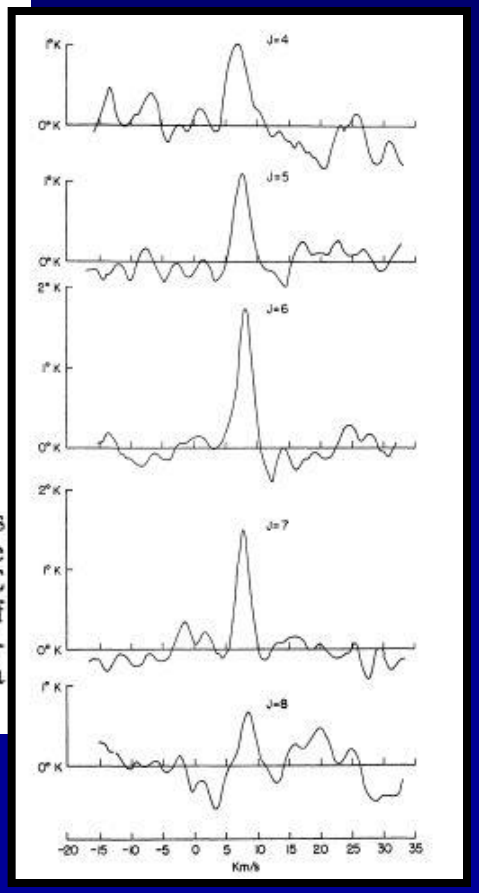
THE ASTROPHYSICAL JOURNAL, 168:L101–L106, 1971 September 15
© 1971. The University of Chicago. All rights reserved. Printed in U.S.A.

DETECTION OF METHYL ALCOHOL IN ORION AT A WAVELENGTH OF ~1 CENTIMETER

A. H. BARRETT, P. R. SCHWARTZ, AND J. W. WATERS
Departments of Physics and Electrical Engineering and Research Laboratory of Electronics, Massachusetts Institute of Technology
Received 1971 June 14

ABSTRACT

Five transitions of CH_3OH, corresponding to the $J = 4, 5, 6, 7$, and 8 rotational levels, at frequencies of approximately 25 GHz, have been detected in Orion A. The source of emission is less than 1 arc minute in angular size and appears to be coincident with the infrared nebula. Although departures from LTE are evident in the line intensities, if the emission originates in the infrared nebula then a temperature of ~90° K, a column density of $\sim 5 \times 10^{16}$ CH_3OH molecules per cm^2, and a CH_3OH density of 0.25 molecules per cm^3 are indicated. Collisional excitation requires a total gas density of $\sim 2 \times 10^6$ cm^{-3} and a total mass of gas in excess of 20 $M_\odot$.



THE ASTRONOMICAL JOURNAL VOLUME 82, NUMBER 12 DECEMBER 1977

Search for methanol masers

R. B. Buxton, A. H. Barrett, P. T. P. Ho, and M. H. Schneps

TABLE I. Maser sources searched for methanol emission.

Source name	(1950) R.A.	(1950) Dec.	Center Vel. (km sec^{-1})	$J=6$ (K) rms	$J=6$ (K) Lim.	$J=2,4$ (K) rms	$J=2,4$ (K) Lim.	Dist. (kpc)	Refs.
Y Cas	00^h 00^m 45^s	55° 24′ 21″	+2	0.23	0.8	0.29	0.8	...	4
CIT−3	01 03 49	12 18 42	+6	0.21	0.6	0.26	0.5	...	1,4
o Ceti	02 16 49	−03 12 12	+47	0.44	0.8	0.23	0.5	0.25	4,6
S Per	02 19 16	58 21 30	−36	0.36	1.1	0.16	0.5	...	4,5
W3 (1)	02 21 41	61 53 26	−49	0.12	0.3	0.21	0.6	3	1,20
W3 (2)	02 21 53	61 52 20	−38	0.16	0.4	0.20	0.5	3	17,20
W3 (3)	02 22 06	61 50 40	−54	0.12	0.3	0.21	0.7	3	20
W3 (OH)	02 23 17	61 38 57	−47	0.13	0.3	0.27	0.7	3	17,20
CRL 490	03 23 39	58 36 39	−11	0.18	0.3	...	...	...	13,14
near H–H 9/11	03 25 58	31 05 46	−20	0.25	0.6	0.22	0.5	...	11,12
NML Tau	03 50 46	11 15 42	+20	0.42	1.2	0.21	0.5	0.27	1,4,6
T Tau	04 19 04	19 25 05	+2	0.15	0.5	...	...	0.2	10,20
R Tau	04 25 36	10 03 30	+11	0.15	0.4	...	...	...	4
CRL 712	05 13 07	45 30 50	−75	0.19	0.5	...	...	...	13,14
OMC−2	05 33 00	−05 11 57	+12	0.35	1.0	0.23	0.7	...	15
H–H 1	05 33 52	−06 47 09	+4	0.33	1.1	0.24	0.6	...	12
S 235	05 37 32	35 40 18	−21	0.33	0.8	0.20	0.6	2	12,20
Ori B	05 39 14	−01 57 30	+14	0.43	1.3	0.24	0.6	...	19,20
OH 205.1 −14.1	05 44 30	00 20 18	+14	0.23	0.6	...	...	...	3
U Ori	05 52 51	20 10 24	−39	0.33	0.8	0.20	0.5	...	2,4,5
Mon R2	06 05 17	−06 22 40	+10	0.50	1.5	0.27	0.8	0.8	15,1
S 255	06 09 59	18 00 16	+8	0.31	0.8	0.20	0.6	1.3	1
S 269	06 11 47	18 50 39	+18	0.31	0.5	0.20	0.5	...	1
CRL 989	06 38 25	09 32 29	+16	0.18	0.5	...	...	...	13,14
VY CMa	07 20 54	−25 40 14	−5	...	...	0.50	...	...	13,14
OH 231.8 +4.2	07 39 59	−14 35 38	+25	0.36	1.0	...	...	...	3
X Hya	09 33 07	−14 28 00	0	0.29	0.4	...	...	...	1,4,6
R LMi	09 42 35	34 44 18	+2	0.20	0.6	...	...	...	1,4
RLeo	09 44 52	11 39 48	+2	0.42	...	...	...	...	17,18,20
RCrt	10 58 09	−18 03 36	0	0.29	...	...	...	...	12,20
UCVn	12 44 57	38 38 24	−23	0.18	...	...	...	...	3,7
RT Vir	13 00 05	05 27 06	+15	0.26	...	...	...	...	13,14
R Hya	13 26 59	−23 01 30	−9	0.36	...	...	...	...	13,14
W Hya	13 46 13	−28 07 06	+38	0.21	...	...	...	...	1,4,6
RU Hya	14 08 42	−28 38 24	−1	0.26	...	...	...	...	1,4
RX Boo	14 21 58	25 55 54	+2	0.22	...	...	...	...	4
RS Vir	14 24 45	04 53 54	−13	0.23	...	...	...	...	4
S CrB	15 19 19	31 32 36	+5	0.33	...	...	...	...	1,4,6
WX Ser	15 25 32	19 44 06	+3	0.35	...	...	...	...	1,4,6
CRL 1822	16 03 00	−30 41 25	0	0.60	1.3	...	...	...	13,14
U Her	16 23 35	19 00 24	−13	0.18	0.3	...	...	...	2,4,5,6
CRL 1992	17 36 03	−30 12 46	0	0.46	1.3	...	...	...	13,14
Sgr B2(N)	17 44 10	−28 21 14	+100	0.29	0.8	...	...	10	20
Sgr B2(M)	17 44 10	−28 22 00	+26	0.21	0.6	0.61	1.5	10	20
Sgr B2(S)	17 44 11	−28 22 39	+66	0.30	0.7	0.44	1.3	10	20
CRL 2019	17 50 11	−26 55 57	−5	0.35	0.8	...	...	...	13,14
W28 A2	17 57 27	−24 04 00	+14	0.54	1.4	0.39	0.8	2.5	19,20
G 7.5 +0.06	17 59 12	−22 28 13	−16	0.44	1.3	0.44	1.4	...	20
G 8.1 +0.2	18 00 00	−21 48 29	+14	0.22	0.7	0.43	1.1	...	20
IRC −20424	18 00 58	−20 19 12	+10	0.31	1.0	...	...	...	2,4
CRL 2059	18 01 49	−24 27 00	−2	0.32	0.7	...	...	...	13,14
W31(1)	18 05 41	−19 52 23	+64	0.22	0.4	0.40	0.7	12	20
W31(2)	18 07 30	−19 56 38	−1	0.22	0.5	0.34	0.6	6	20
CRL 2086	18 08 20	−26 30 15	0	0.35	0.8	...	...	...	13,14
W33 B	18 10 59	−18 02 39	+58	0.21	0.6	0.35	0.9	4.5	19,20
W33 (CON)	18 11 38	−17 56 21	+20	0.22	0.5	0.31	0.6	4.5	20
G 13.9 +0.3	18 11 42	−16 46 34	−21	0.38	0.9	0.31	0.7	...	20
W33 A	18 11 44	−17 53 08	+40	0.38	1.3	0.35	0.9	4.5	20
G 14.6 +0.0	18 14 08	−16 15 46	+31	0.22	0.4	0.33	0.8	4	20
M17 (1)	18 17 30	−16 16 03	+4	0.53	1.2	0.28	1.0	2.5	20
M17 (2)	18 17 30	−16 13 06	+19	0.19	0.6	0.30	1.0	2.5	19,20
CRL 2136	18 19 37	−13 31 40	+28	0.24	0.6	...	...	...	13,14
OH 1821 −12	18 21 17	−12 28 00	+14	0.26	0.6	...	...	...	1
G 19.6 −0.2	18 24 30	−11 58 22	+36	0.24	0.6	...	...	4	20
OH 21.5 +0.5	18 25 44	−10 00 08	+116	0.27	0.8	...	...	...	3,7
OH 19.1 −1.0	18 26 40	−12 43 44	+58	0.30	0.8	...	...	...	3,7
W 41	18 31 27	−09 00 54	+35	0.18	0.4	0.37	1.0	...	1,9
G 24.8 +0.1	18 33 31	−07 13 11	+113	0.38	1.0	...	...	8	20
OH 26.5 +0.6	18 34 51	−05 26 31	+27	0.50	1.0	...	...	...	3,7
IRC 10365	18 34 59	10 23 00	−47	0.22	0.6	...	...	...	1,4
OH 1837 −05	18 37 42	−05 00 36	+51	0.53	1.5	...	...	...	1
W43(S)	18 43 27	−02 42 40	+100	0.38	0.9	0.29	0.7	8.5	10,20
OH 30.1 −0.2	18 44 33	−02 38 57	+51	0.24	0.6	...	...	...	3,7

TABLE I (continued)

Source name	(1950) R.A.	(1950) Dec.	Center Vel. (km sec^{-1})	$J=6$ (K) rms	$J=6$ (K) Lim.	$J=2,4$ (K) rms	$J=2,4$ (K) Lim.	Dist. (kpc)	Refs.
G 31.4 +0.3	18 44 59	−01 16 07	+101	0.20	0.5	...	...	...	20
W 43 Main (1)	18 45 03	−02 00 45	+90	0.21	0.6	0.27	0.8	7.5	20
W 43 Main (2)	18 45 03	−02 01 50	+51	0.43	1.0	0.28	0.8	...	20
W43 (OH)	18 45 06	−01 48 39	+35	0.22	0.7	0.27	0.7	...	1,20
W 43 Main (3)	18 45 11	−01 [illegible] 57	+103	0.24	0.6	0.30	0.8	8	20
W 43 Main (4)	18 45 33	[illegible] 01	+97	0.45	1.0	0.31	0.8	7.5	20
OH 31.1 −0.2	18 46 2[illegible]	[illegible] 0	−28	0.25	0.4	...	...	...	3,7
OH 30.4 −0.7	18 46 [illegible]		+61	0.43	1.3	...	...	...	3,7
OH 33.2 −0.1			+77	0.21	0.5	...	...	...	3,20
OH 32.8 −0.2			+60	0.37	0.9	...	...	...	3,4,7
G 34.3 +0.2			+58	0.47	1.3	...	...	4	20
[illegible]			+58	0.46	1.2	0.26	0.9	...	19,20
[illegible]			+78	0.29	0.7	...	...	...	1
[illegible]			+46	0.45	0.8	0.31	0.8	3	20
[illegible]			0	0.27	0.5	...	...	...	13,14
[illegible]			+50	0.34	1.0	0.38	0.8	0.3	1,4,6
[illegible]			+5	0.39	0.8	...	...	...	1,4
[illegible]			+10	0.34	1.0	0.44	1.2	14	17,18,20
[illegible]			+10	0.35	0.9	0.37	1.0	14	19,20
[illegible]			+64	0.38	1.4	0.38	0.8	10	12,20
[illegible]			+58	0.34	1.0	0.37	0.8	9.5	12,20
[illegible]		21 05 25	+35	0.37	1.0	...	...	...	3,7
[illegible]		23 43 53	+16	0.23	0.7	...	...	...	13,14
[illegible]		−26 20 18	−5	0.34	0.9	...	...	...	13,14
[illegible]	18 13	13 49 43	+38	0.32	1.0	0.36	1.3	12	19,20
[illegible]	19 20 53	14 20 47	+52	0.32	0.8	0.41	1.1	7	20
[illegible]	19 21 22	14 25 19	+33	0.36	0.9	0.40	0.8	8	20
[illegible] (S)*	19 21 26	14 24 30	+72	0.18	0.5	0.29	0.9	8	17,19,20
RT Aql	19 35 36	11 36 16	−30	0.34	0.6	...	...	...	4
CRL 2445	19 42 16	35 06 52	−49	0.24	0.5	...	...	...	13,14
CRL 825-2650	19 49 33	08 35 08	0	0.37	1.1	...	...	...	13,14
RR Aql	19 54 58	−02 01 12	+30	0.42	1.2	0.33	1.0	0.4	1,4,6
K-350	19 59 50	33 24 17	−19	0.23	0.7	...	...	9	20
ON–3	19 59 58	33 25 47	−19	0.27	0.6	...	...	9	20
Z Cyg	20 00 00	49 54 06	+1	0.24	0.7	0.88	2.0	...	4
SY Aql	20 04 43	12 48 10	−49	0.32	1.0	...	...	...	4
ON–1	20 08 10	31 22 44	+13	0.19	0.6	0.27	0.7	6	20
ON–2(1)	20 19 49	37 15 58	−8	0.31	0.8	0.29	0.5	5.5	20
ON–2 (2)	20 19 52	37 17 00	−8	0.31	0.6	0.24	0.6	5.5	20
OH 2026 +38	20 26 40	38 57 00	−39	0.33	0.9	...	...	...	1
CRL 809 −2992	20 27 36	40 01 25	−30	0.33	1.3	0.62	1.7	...	12
W75N(OH)	20 36 50	42 27 01	+15	0.33	0.8	0.26	0.7	3	7,19,20
W75S(1)	20 37 13	42 13 57	−3	0.42	0.9	0.26	0.7	3	20
DR 21	20 37 14	42 08 52	−6	0.16	0.4	0.25	0.8	3	20
W75S (2)	20 37 14	42 12 11	0	0.42	0.9	0.25	0.7	3	20
W75S (3)	20 37 17	42 15 15	−20	0.13	0.2	...	...	3	20
NML Cyg	20 44 13	39 56 06	+1	...	...	0.45	1.4	0.5	4,5,6
UX Cyg	20 53 00	30 13 24	+4	0.24	0.7	1.14	3.0	...	1,4
TW Peg	22 01 41	28 06 30	−8	0.21	0.7	0.52	1.0	...	4
SV Peg	22 14 31	35 06 39	+2	0.23	0.4	...	...	...	4
S140–IR	22 17 41	63 03 00	−15	0.16	0.4	0.39	.9	...	15
S 152	22 55 38	58 33 02	−52	0.12	0.3	0.26	0.7	...	12
CRL 3022	23 03 52	59 58 45	−29	0.17	0.4	...	...	...	13,14
R Peg	23 04 08	10 16 22	+25	0.34	1.0	0.67	1.5	...	4
NGC 7538 S	23 11 36	61 10 30	−55	0.27	0.5	0.25	0.7	3.5	19,20
NGC 7538 IR	23 11 36	61 11 50	−59	0.26	0.6	0.26	0.6	3.5	20
S 157	23 13 53	59 45 18	−46	0.12	0.3	0.30	0.6	3.5	20
PZ Cas	23 41 41	61 31 00	−43	0.17	0.5	...	...	...	4
R Cas	23 55 53	51 06 36	+28	0.16	0.3	0.29	0.8	0.2	2,4,5,6

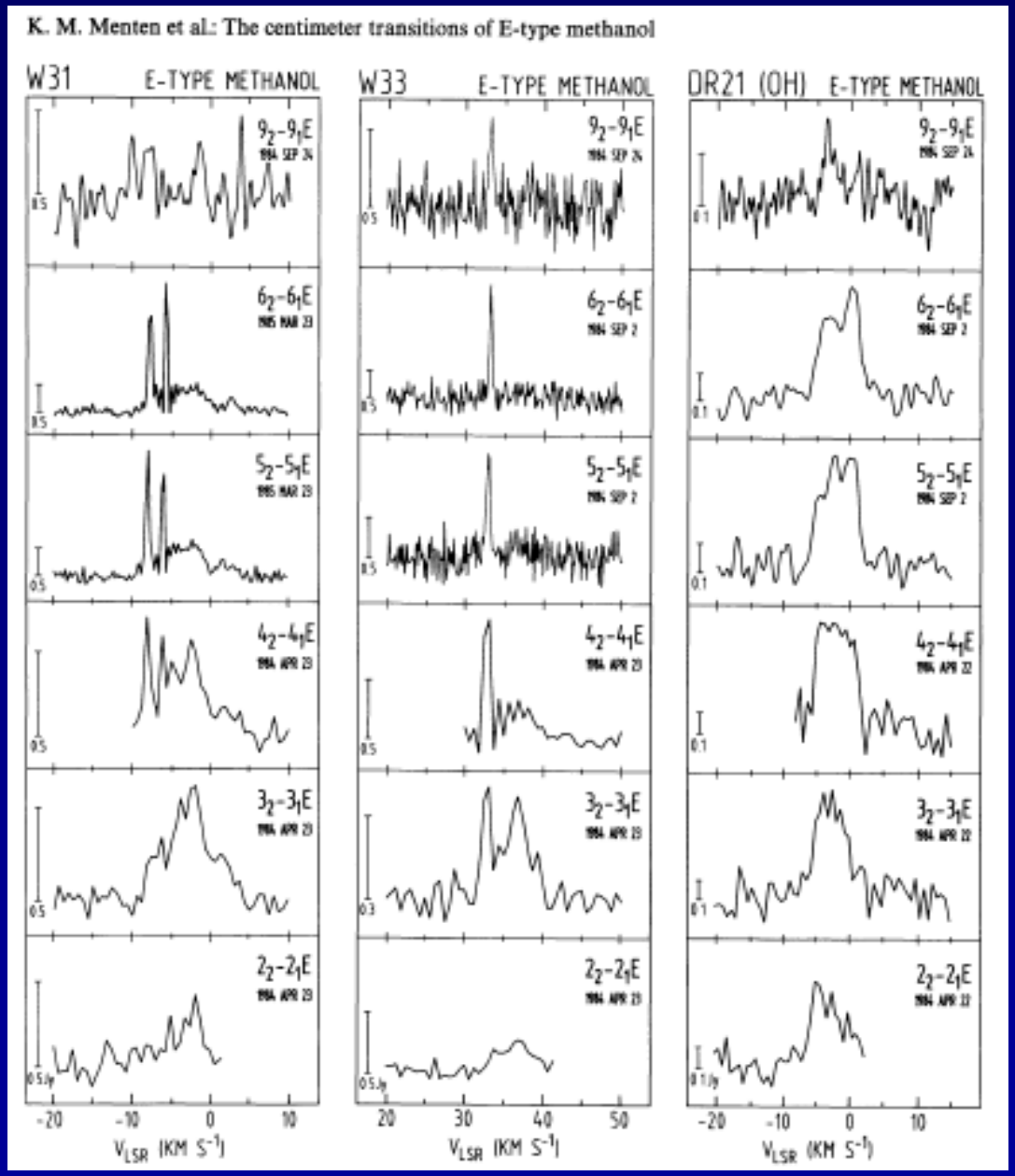
* W 51 (Main) was also within the beam [see Ref. (20)].

References:

(1) Wilson and Barrett (1972)
(2) Wilson *et al.* (1972)
(3) Winnberg *et al.* (1975)
(4) Dickinson (1976)
(5) Kaifu, Buhl, and Snyder (1975)
(6) Snyder and Buhl (1975)
(7) Evans, Crutcher, and Wilson (1976)
(8) Lépine, Paes de Barros, and Gammon (1976)
(9) Hardebeck (1972)
(10) Knapp and Morris (1976)
(11) Lo *et al.* (1976)
(12) Lo, Burke, and Haschick (1975)
(13) Joyce *et al.* (1977)
(14) Kleinmann (1977)
(15) Morris and Knapp (1976)
(16) Knapp and Brown (1976)
(17) Hills *et al.* (1972)
(18) Moran *et al.* (1973)
(19) Johnston, Sloanaker, and Bologna (1973)
(20) Genzel and Downes (1977)

132 duds! ☹

Meet AI story



Other Barrett-type CH_3OH masers were found:

They were much weaker (= more distant) than Orion and offset from known sources

Menten+1986

Astron. Astrophys. 134, L7–L10 (1984)

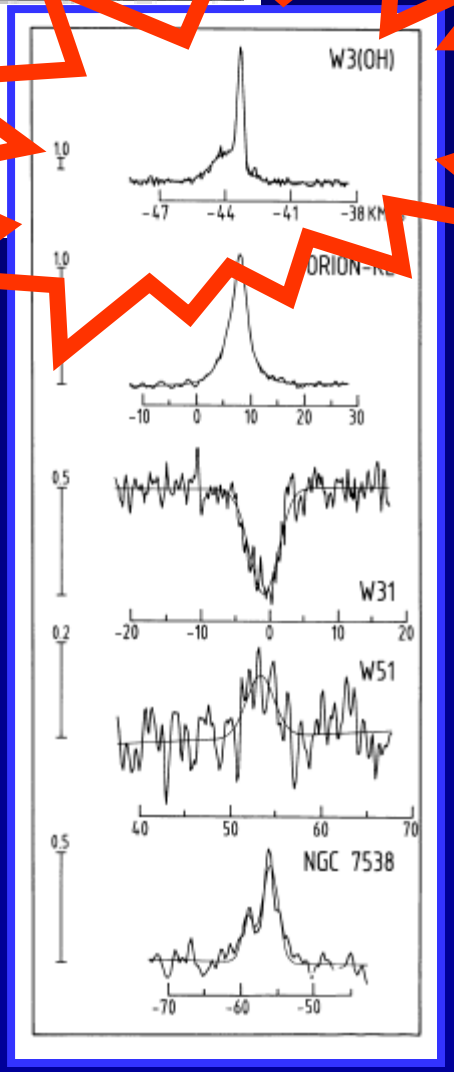
ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Detection of a new type of methanol maser

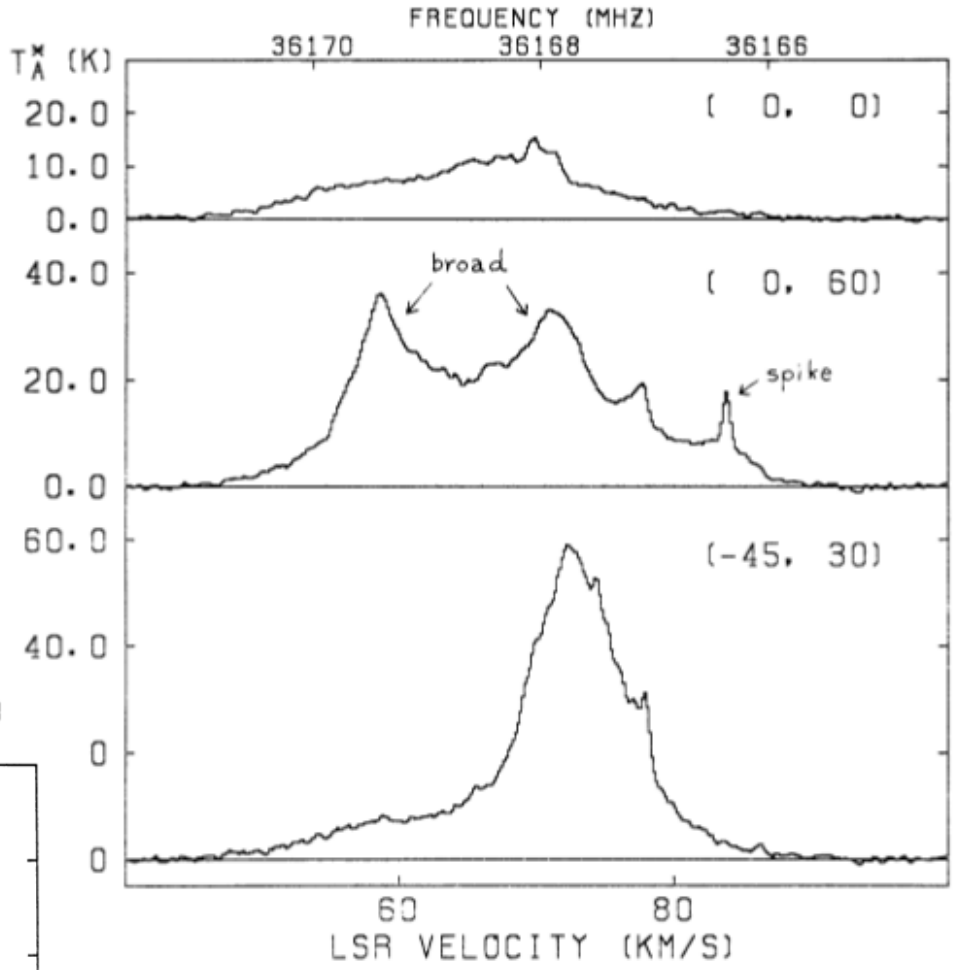
T. L. Wilson[1], C. M. Walmsley[1], L. E. Snyder[1,2], and P. R. Jewell[1]

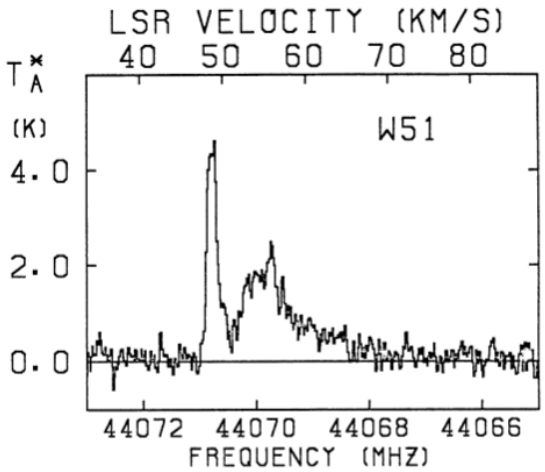






MORIMOTO, OHISHI, AND KANZAWA 1985





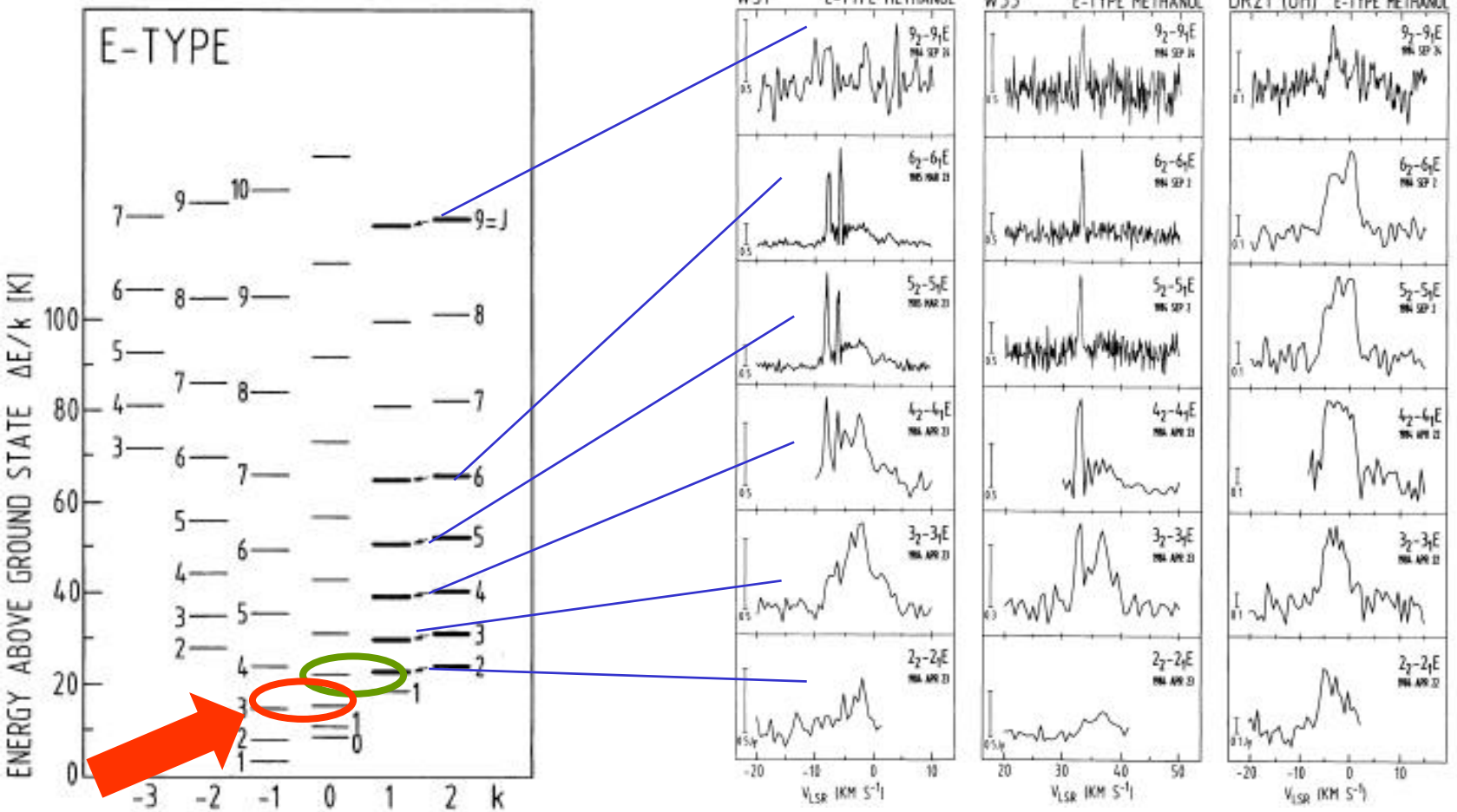
Sgr B2 CH_3OH 4_{-1}–3_0 *E*

Astron. Astrophys. 157, 318–328 (1986)

The centimeter transitions of *E*-type methanol

K.M. Menten, C.M. Walmsley, C. Henkel, and T.L. Wilson

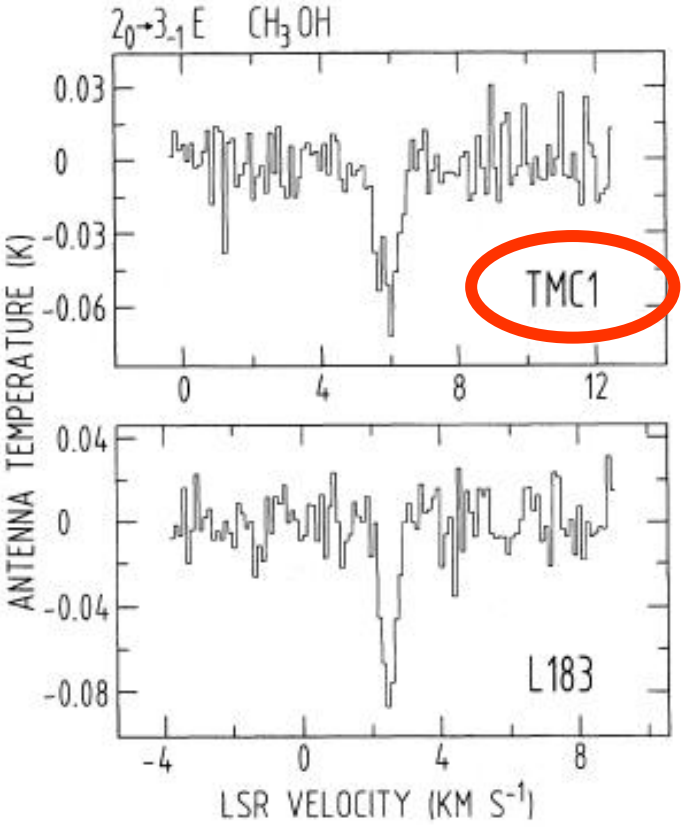
Max-Planck-Institut für Radioastronomie, D-5300 Bonn 1, Auf dem Hügel 69, Federal Republic of Germany



Astron. Astrophys. 197, 271–273 (1988)

Anti-inversion of the 12.1 GHz methanol line towards dark clouds

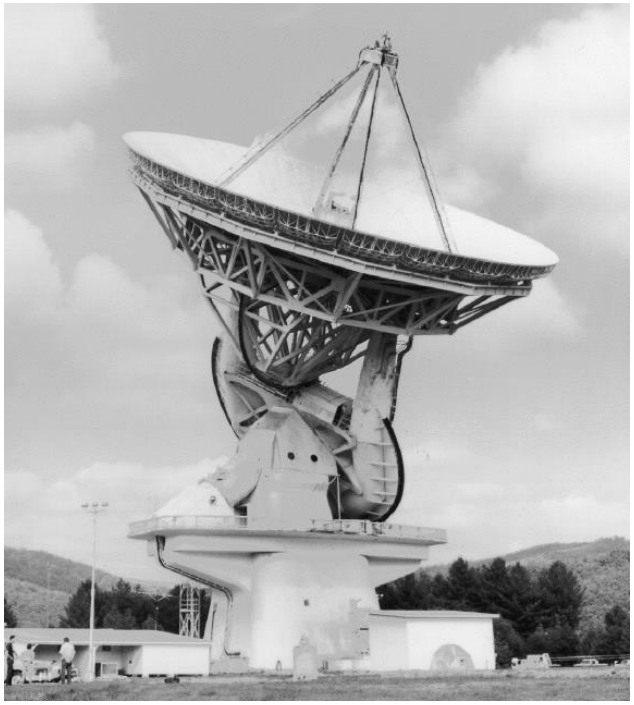
C. M. Walmsley [1], W. Batrla [2], H. E. Matthews [3,**] and K. M. Menten [1,*]

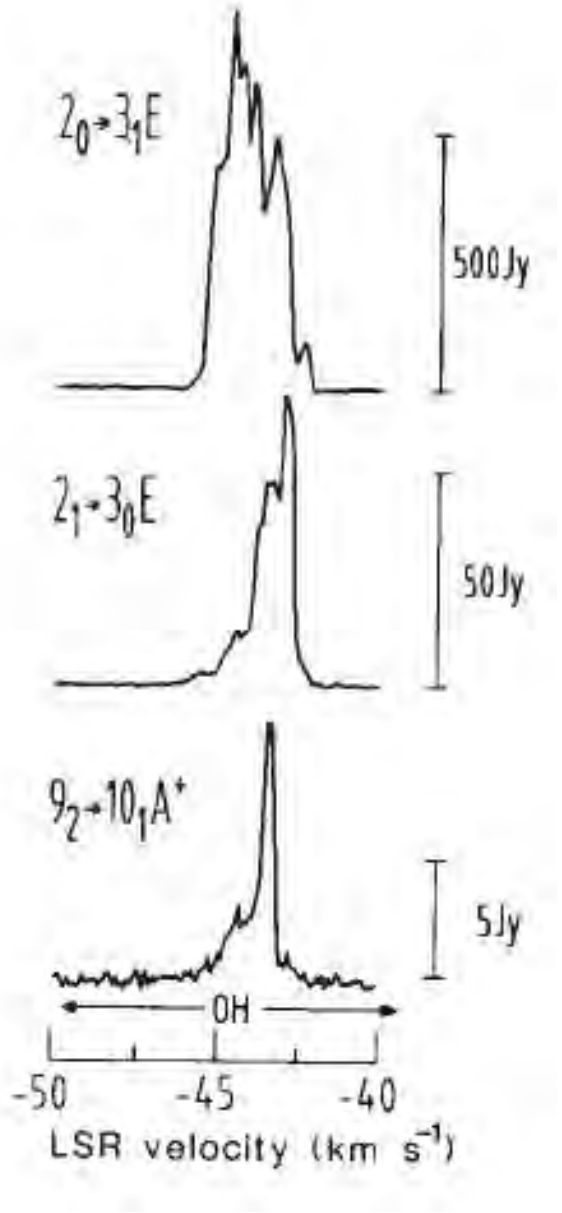


"DASAR"

Detection of strong methanol masers towards galactic H II regions

W. Batrla*, H. E. Matthews†, K. M. Menten‡ & C. M. Walmsley‡

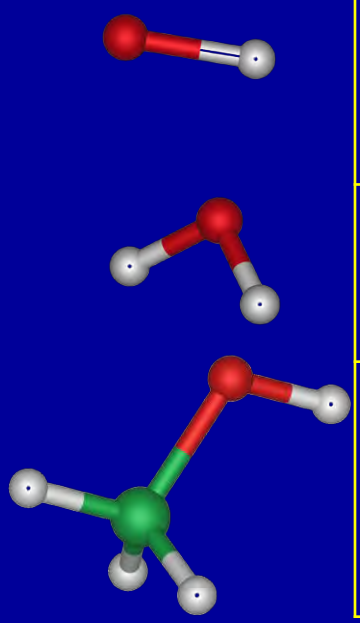






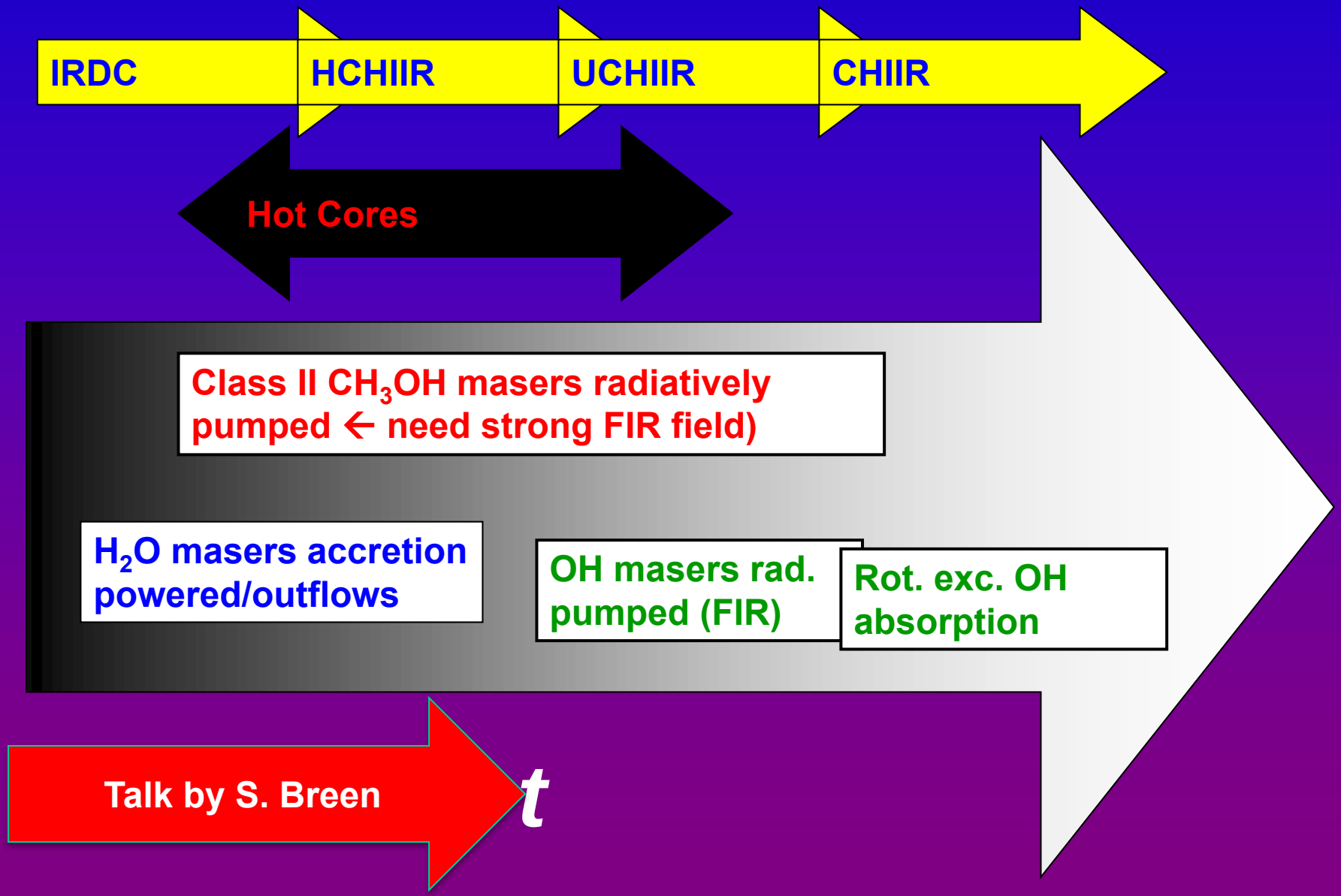
Charles Malcolm Walmsley
1941–2017

Common Strong Interstellar Masers:



		First found	Where	Pump	# known
OH	Hydroxyl	1965	UCHIIRs	R (FIR)	many
H_2O	Water vapor	1969	L+HM YSOs	C	very many
CH_3OH	Methanol	1971 (I) 1984 (II)	Class I outflows Class II HMYSOs	Cl. I: C Cl. II: R (FIR)	Class I: many Class II: very many

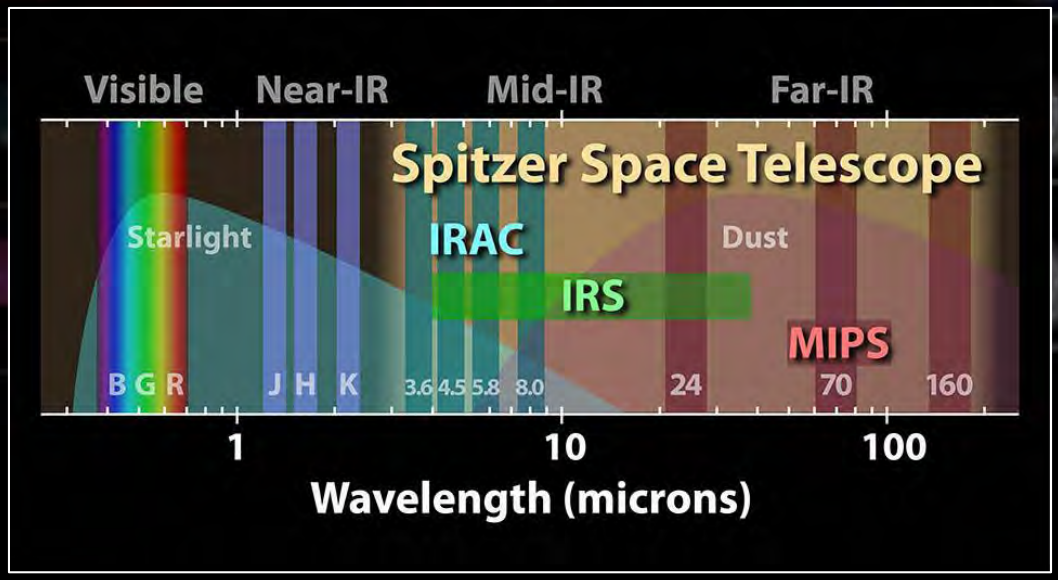
Masers in Regions of High Mass Star Formation



INFRARED MILKY WAY

The Complete 360° GLIMPSE Survey





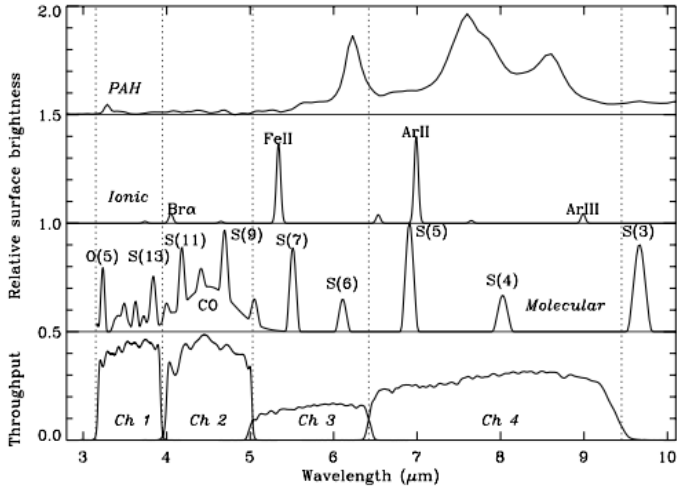
PI: Ed Churchwell

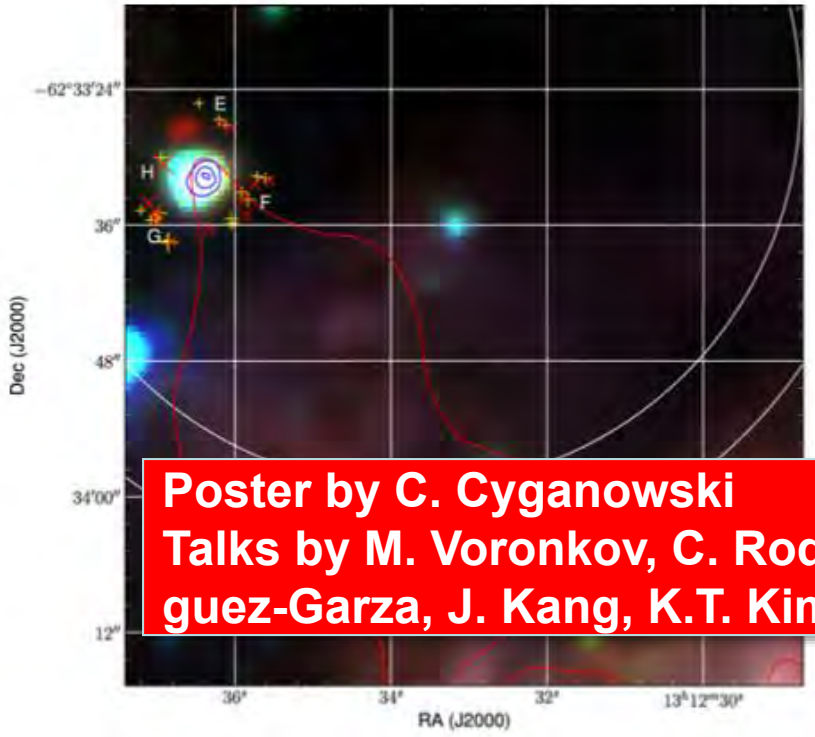


Spitzer/IRAC 4.5 μm band covers emission from rotationally excited H_2
→ traces shocks/outflows
Like Class I CH OH masers!

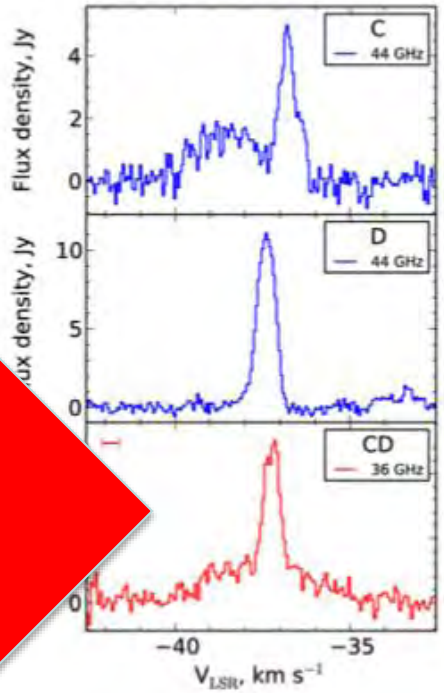
- Extended Green Objects (EGOs) "Green fuzzies" (**RGB** coding)

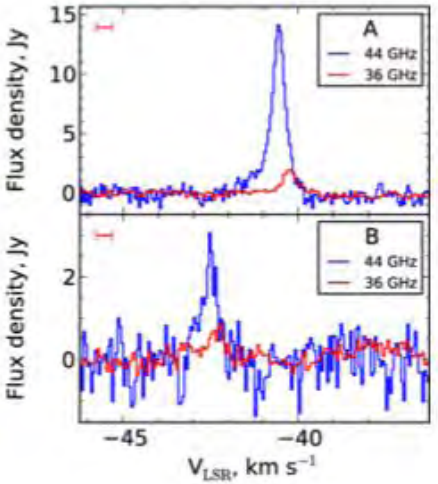
Cyganowski+ 2008





Poster by C. Cyganowski
Talks by M. Voronkov, C. Rodríguez-Garza, J. Kang, K.T. Kim





Voronkov+ 2014

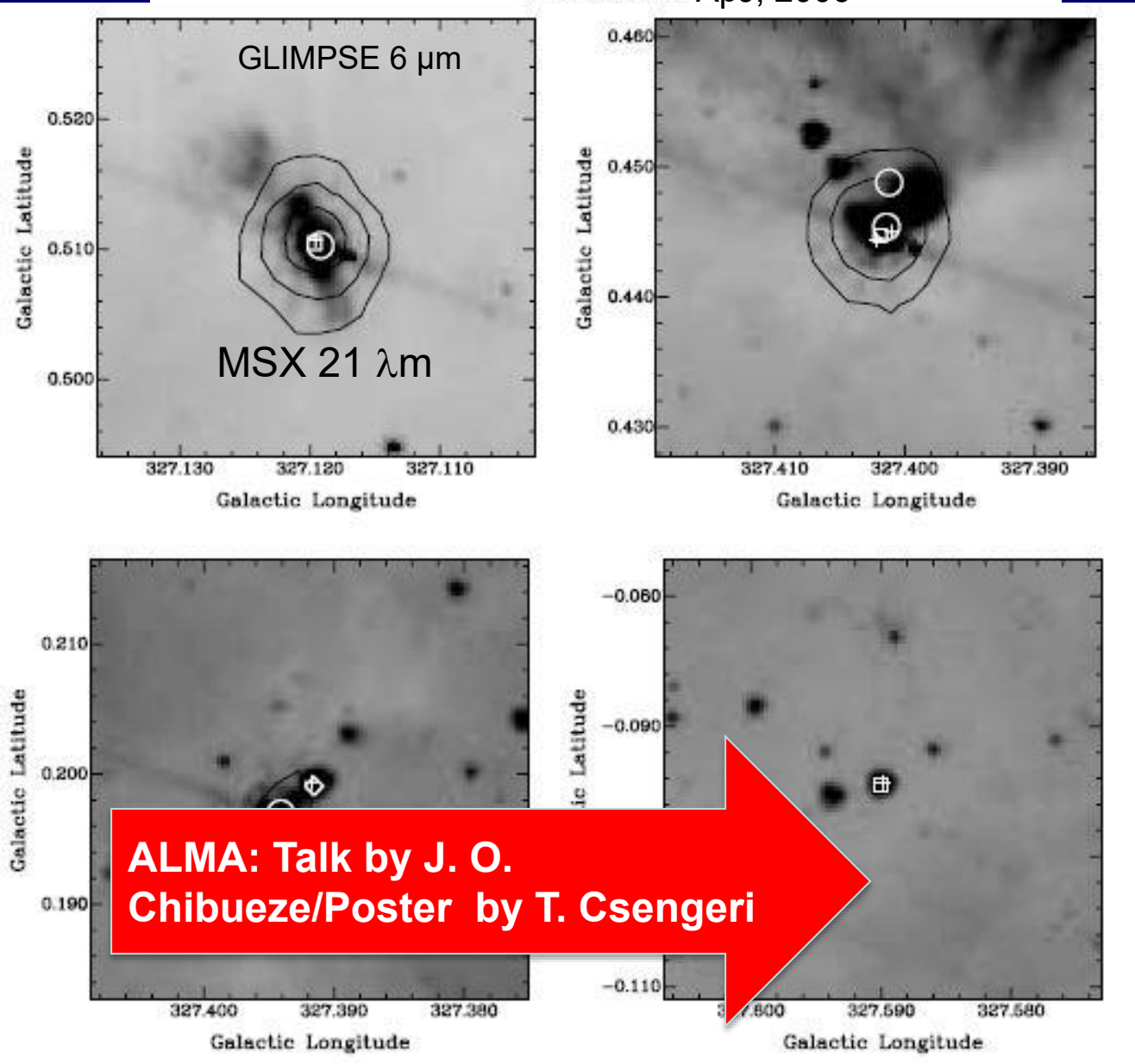


APEX 870 + Planck µm emission (ATLASGAL) + GLIMPSE

ESO/APEX/ATLASGAL consortium/NASA/GLIMPSE consortium/ESA/Planck

METHANOL MASERS: RELIABLE TRACERS OF THE EARLY STAGES OF HIGH-MASS STAR FORMATION

S. P. Ellingsen ApJ, 2006



GLIMPSE 5.8 μm

+ = 6.7 GHz CH_3OH

ALMA: Talk by J. O. Chibueze/Poster by T. Csengeri

Ellingsen 2006

Table 1. Known interstellar Class I methanol maser transitions.

Transition	Frequency (MHz)	Lab. Ref.	Astronomical reference
$9_{-1} \rightarrow 8_{-2}$-$E$	9936	L2	A28
$10_1 \rightarrow 9_2$-A^-	23 445	L5	A48
$3_2 \rightarrow 3_1$-E	24 929	L3	A12, A20
$4_2 \rightarrow 4_1$-E	24 933	L1	A1, A6, A8, A12, A20
$2_2 \rightarrow 2_1$-E	24 934	L1	A7, A12, A17, A20
$5_2 \rightarrow 5_1$-E	24 959	L4	A1, A6, A12, A17, A20, *A24*
$6_2 \rightarrow 6_1$-E	25 018	L4	A1, A2, A3, A17, A20, **A4***, A5, A6, A7, *A8*, **A9**, A12, **A13**, A17, A20, *A24*, **A26***, *A36*, **A38***
$7_2 \rightarrow 7_1$-E	25 125	L4	A1, A2, A3, A17, A20
$8_2 \rightarrow 8_1$-E	25 294	L4	A1, A6, A17
$9_2 \rightarrow 9_1$-E	25 541	L4	A12, A32
$10_2 \rightarrow 10_1$-E	25 878	L4	A39
$12_2 \rightarrow 12_1$-E	26 847	L5	A32
$13_2 \rightarrow 13_1$-E	27 473	L5	A32
$14_2 \rightarrow 14_1$-E	28 169	L5	A32
$15_2 \rightarrow 15_1$-E	28 906	L5	A32
$16_2 \rightarrow 16_1$-E	29 637	L5	A32
$17_2 \rightarrow 17_1$-E	30 308	L5	A32
$4_{-1} \rightarrow 3_0$-E	36 169	L5	**A4**, **A9**, A10, **A13**, A19, A25, **A26**, A27, A33, *A51*
$7_0 \rightarrow 6_1$-A^+	44 069	L5	**A4**, **A9**, A10, A21, A22, **A26**, A30, A34, A37, *A44*, *A46*, A47, *A51*
$5_{-1} \rightarrow 4_0$-E	84 521	L3	*A14*, **A13**, **A26**, A42
$8_0 \rightarrow 7_1$-A^+	95 169	L3	A11, A18, *A23*, **A26**, A29, A31, A49, A50
$11_{-1} \rightarrow 10_{-2}$-$E$	104 300	L3	A43
$6_{-1} \rightarrow 5_0$-E	132 891	L5	**A26**, A35, A40
$9_0 \rightarrow 8_1$-A^+	146 618	L5	**A26**
$4_2 \rightarrow 3_1$-E	218 440	L6	*A52*
$8_{-1} \rightarrow 7_0$-E	229 758	L6	A43
$9_{-1} \rightarrow 8_0$-E	278 305	L6	*A53*

Leurini+ 2016

References. References are in chronological order. Laboratory references for higher accuracy frequencies are: L1: Gaines et al. (1974); L2: Breckenridge & Kukolich (1995); L3: Müller et al. (2004); L4: Tsunekawa et al. (1995); L5: Mehrotra et al. (1985); L6: Sastry et al. (1984). Astronomical references presenting interferometric observations are given in italics, theoretical papers in boldface. Theoretical references discussing various of the $J_2 \rightarrow J_1$-E transitions are only listed for the $6_2 \rightarrow 6_1$-E transition and are marked by an asterisk. Astronomical references are: A1: Barrett et al. (1971); A2: Chui et al. (1974); A3: Hills et al. (1975); A4*: Pelling (1975); A5: Barrett et al. (1976) (VLBI); A6: Barrett et al. (1975); A7: Buxton et al. (1977); A8: Matsakis et al. (1980); A9: Sobolev & Strelnitskii (1983); A10: Morimoto et al. (1985); A11: Nakano & Yoshida (1986); A12: Menten et al. (1986); A13: Zeng et al. (1987); A14: Batrla & Menten (1988); A17: Menten et al. (1988d,c); A18: Plambeck & Wright (1988); A19: Haschick & Baan (1989); A20: Menten & Batrla (1989); A21: Haschick et al. (1990); A22: Bachiller et al. (1990); A23: Plambeck & Menten (1990); A24: Johnston et al. (1992); A25: Kalenskii et al. (1992); A26*: Cragg et al. (1992); A27: Haschick & Baan (1989); A28: Slysh et al. (1993); A29: Kalenskii et al. (1994); A30: Slysh et al. (1994); A31: Val'tts et al. (1995); A32: Wilson et al. (1996); A33: Liechti & Wilson (1996); A34: Mehringer & Menten (1997); A35: Slysh et al. (1997); A36: Johnston et al. (1997); A37: Kogan & Slysh (1998); A38*: Matsakis et al. (1980); A39: Sobolev et al. (1998); A40: Slysh et al. (1999); A41: Val'tts et al. (2000); A42: Kalenskii et al. (2001); A43: Slysh et al. (2002); A44: Kurtz et al. (2004); A45: Voronkov et al. (2005); A46: Cyganowski et al. (2009); A47: Fontani et al. (2010); A48: Voronkov et al. (2011); A49: Chen et al. (2011); A50: Gan et al. (2013); A51: Voronkov et al. (2014); A52: Hunter et al. (2014); A53: Yanagida et al. (2014).

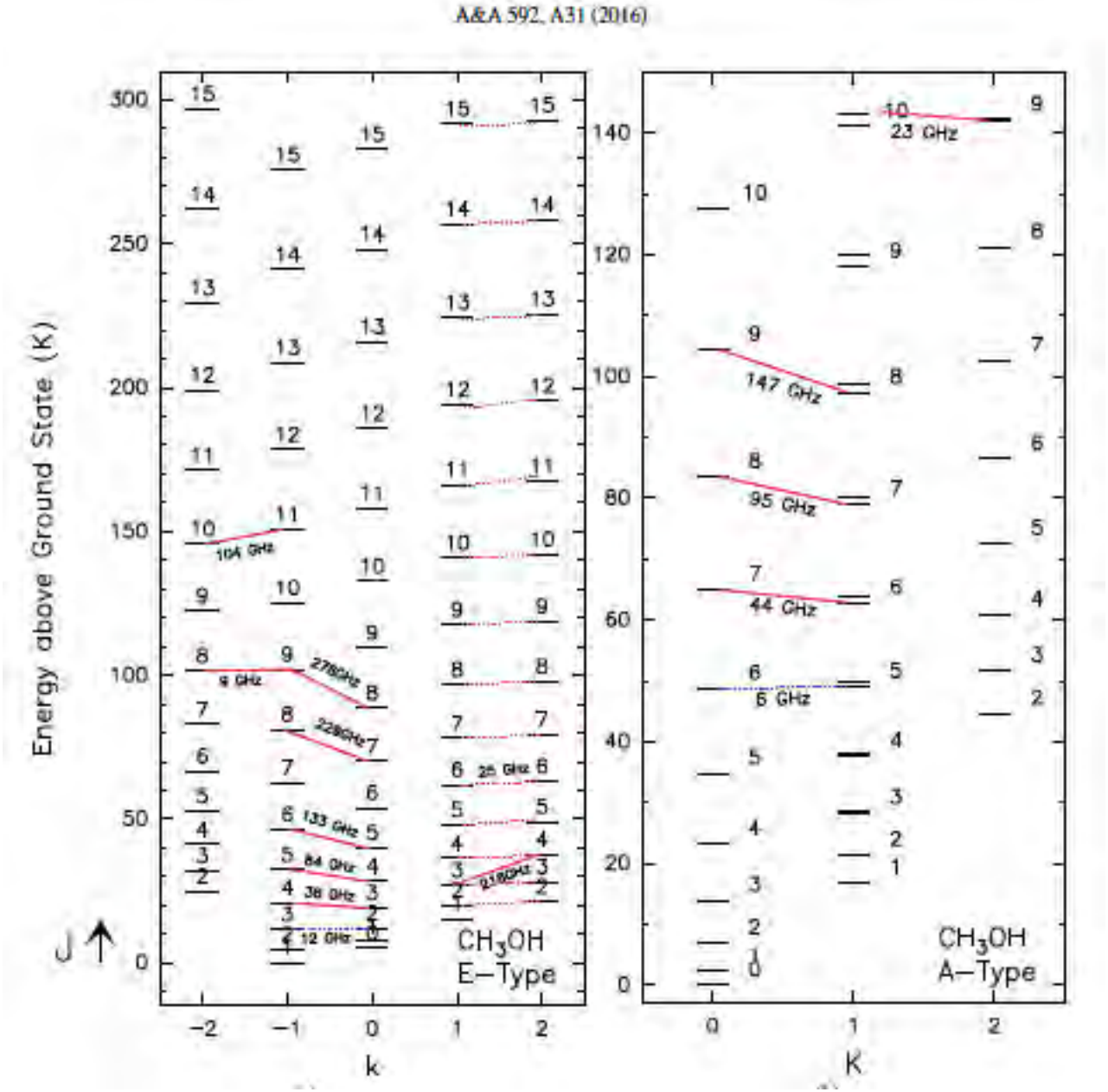
Table 1. Known interstellar Class I methanol maser transitions.

Transition	Frequency (MHz)	Lab. Ref.	Astronomical reference
$9_{-1} \rightarrow 8_{-2}$-$E$	9936	L2	A28
$10_1 \rightarrow 9_2$-A^-	23 445	L5	A48
$3_2 \rightarrow 3_1$-E	24 929	L3	A12, A20
$4_2 \rightarrow 4_1$-E	24 933	L1	A1, A6, A8, A12, A20
$2_2 \rightarrow 2_1$-E	24 934	L1	A7, A12, A17, A20
$5_2 \rightarrow 5_1$-E	24 959	L4	A1, A6, A12, A17, A20, *A24*
$6_2 \rightarrow 6_1$-E	25 018	L4	A1, A2, A3, A17, A20, **A4***, A5, A6, A7, *A8*, **A9**, A12, **A13**, A17, A20, *A24*, **A26***, *A36*, **A38***
$7_2 \rightarrow 7_1$-E	25 125	L4	A1, A2, A3, A17, A20
$8_2 \rightarrow 8_1$-E	25 294	L4	A1, A6, A17
$9_2 \rightarrow 9_1$-E	25 541	L4	A12, A32
$10_2 \rightarrow 10_1$-E	25 878	L4	A39
$12_2 \rightarrow 12_1$-E	26 847	L5	A32
$13_2 \rightarrow 13_1$-E	27 473	L5	A32
$14_2 \rightarrow 14_1$-E	28 169	L5	A32
$15_2 \rightarrow 15_1$-E	28 906	L5	A32
$16_2 \rightarrow 16_1$-E	29 637	L5	A32
$17_2 \rightarrow 17_1$-E	30 308	L5	A32
$4_{-1} \rightarrow 3_0$-E	36 169	L5	**A4**, **A9**, A10, **A13**, A19, A25, **A26**, A27, A33, *A51*
$7_0 \rightarrow 6_1$-A^+	44 069	L5	**A4**, **A9**,A10, A21, A22, **A26**, A30, A34, A37, *A44*, *A46*, A47, *A51*
$5_{-1} \rightarrow 4_0$-E	84 521	L3	*A14*, **A13**, **A26**,A42
$8_0 \rightarrow 7_1$-A^+	95 169	L3	A11, A18, *A23*, **A26**, A29, A31, A49, A50
$11_{-1} \rightarrow 10_{-2}$-$E$	104 300	L3	A43
$6_{-1} \rightarrow 5_0$-E	132 891	L5	**A26**, A35, A40
$9_0 \rightarrow 8_1$-A^+	146 618	L5	**A26**
$4_2 \rightarrow 3_1$-E	218 440	L6	*A52*
$8_{-1} \rightarrow 7_0$$E$	229 758	L6	A43
$9_{-1} \rightarrow 8_0$-E	278 305	L6	*A53*

References. References are in chronological order. Laboratory references for higher accuracy frequencies are: L1: Gaines et al. (1974); L2: Breckenridge & Kukolich (1995); L3: Müller et al. (2004); L4: Tsunekawa et al. (1995); L5: Mehrotra et al. (1985); L6: Sastry et al. (1984). Astronomical references presenting interferometric observations are given in italics, theoretical papers in boldface. Theoretical references discussing various of the $J_2 \rightarrow J_1$-E transitions are only listed for the $6_2 \rightarrow 6_1$-E transition and are marked by an asterisk. Astronomical references are: A1: Barrett et al. (1971); A2: Chui et al. (1974); A3: Hills et al. (1975); A4*: Pelling (1975); A5: Barrett et al. (1976) (VLBI); A6: Barrett et al. (1975); A7: Buxton et al. (1977); A8: Matsakis et al. (1980); A9: Sobolev & Strelnitskii (1983); A10: Morimoto et al. (1985); A11: Nakano & Yoshida (1986); A12: Menten et al. (1986); A13: Zeng et al. (1987); A14: Batrla & Menten (1988); A17: Menten et al. (1988d,c); A18: Plambeck & Wright (1988); A19: Haschick & Baan (1989); A20: Menten & Batrla (1989); A21: Haschick et al. (1990); A22: Bachiller et al. (1990); A23: Plambeck & Menten (1990); A24: Johnston et al. (1992); A25: Kalenskii et al. (1992); A26*: Cragg et al. (1992); A27: Haschick & Baan (1989); A28: Slysh et al. (1993); A29: Kalenskii et al. (1994); A30: Slysh et al. (1994); A31: Val'tts et al. (1995); A32: Wilson et al. (1996); A33: Liechti & Wilson (1996); A34: Mehringer & Menten (1997); A35: Slysh et al. (1997); A36: Johnston et al. (1997); A37: Kogan & Slysh (1998); A38*: Matsakis et al. (1980); A39: Sobolev et al. (1998); A40: Slysh et al. (1999); A41: Val'tts et al. (2000); A42: Kalenskii et al. (2001); A43: Slysh et al. (2002); A44: Kurtz et al. (2004); A45: Voronkov et al. (2005); A46: Cyganowski et al. (2009); A47: Fontani et al. (2010); A48: Voronkov et al. (2011); A49: Chen et al. (2011); A50: Gan et al. (2013); A51: Voronkov et al. (2014); A52: Hunter et al. (2014); A53: Yanagida et al. (2014).



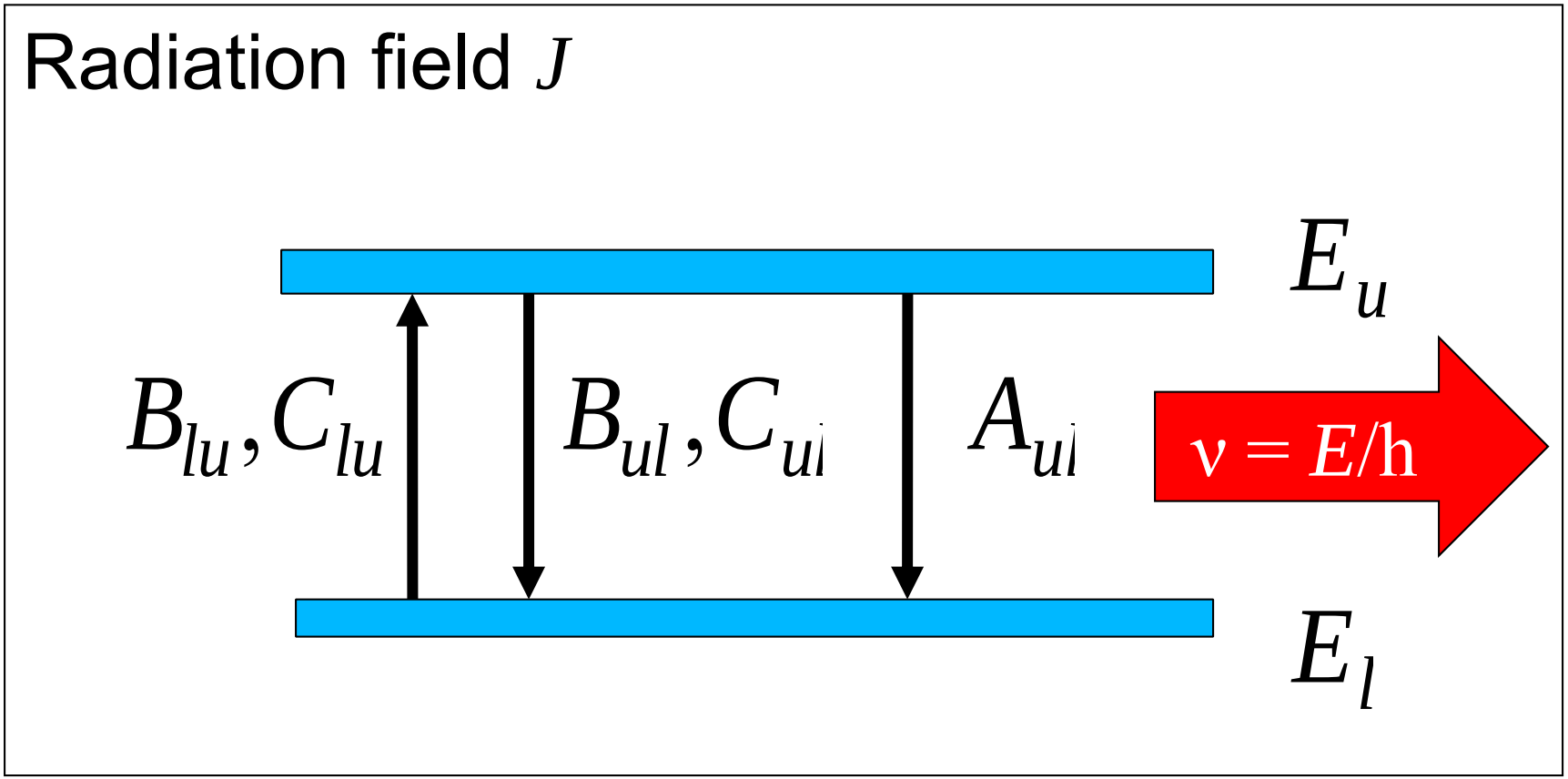
Vyacheslav Ivanovich (Slava) Slysh
1935–2008



- **Class I CH 3 OH masers are collisionally excited**
- **Switch FIR field on → Class II CH_3OH masers**

All class I CH_3OH maser transitions (as of 2017)
Leurini, Menten & Walmsley 2016

Molecular Transitions



$$n_u B_{ul} + n_u C_{ul} n_{tot} - n_u A_{ul} = n_l B_{lu} J + n_l C_{lu} n_{tot}$$

Molecular Transitions

Radiation field J

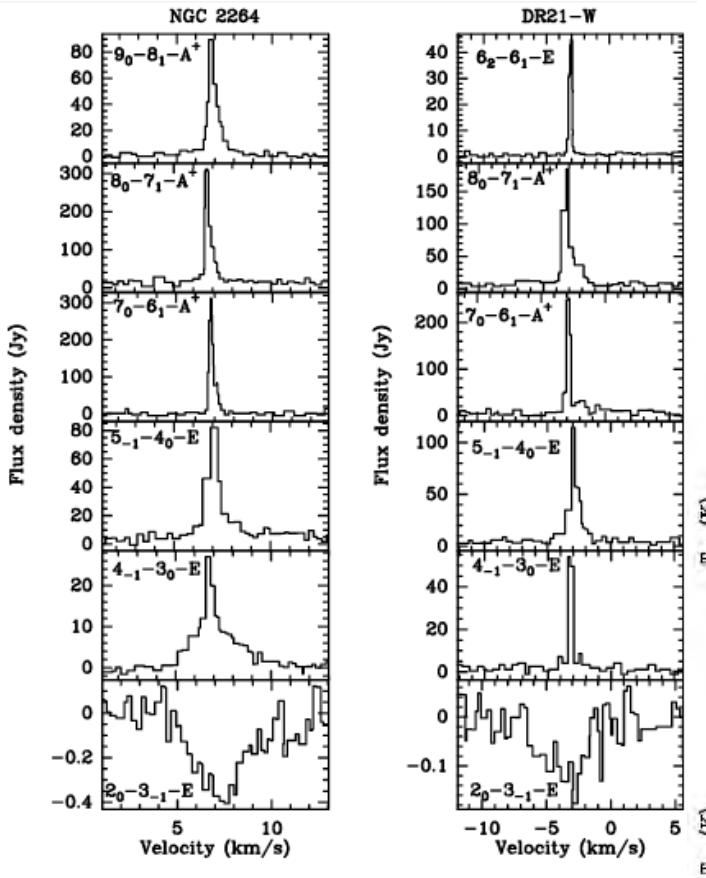
Multilevel radiative transfer calculations model the intensities of many maser lines as a function of physical parameters: *n*, *N*, *T*

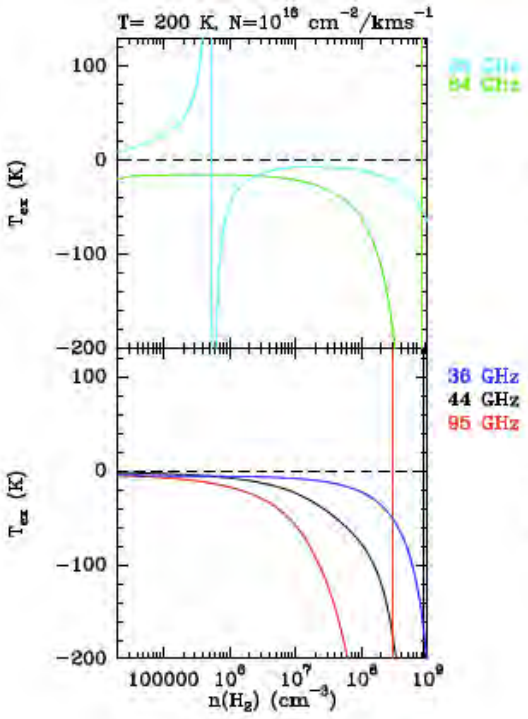
The more lines are observed, the better the masing regions can be constrained

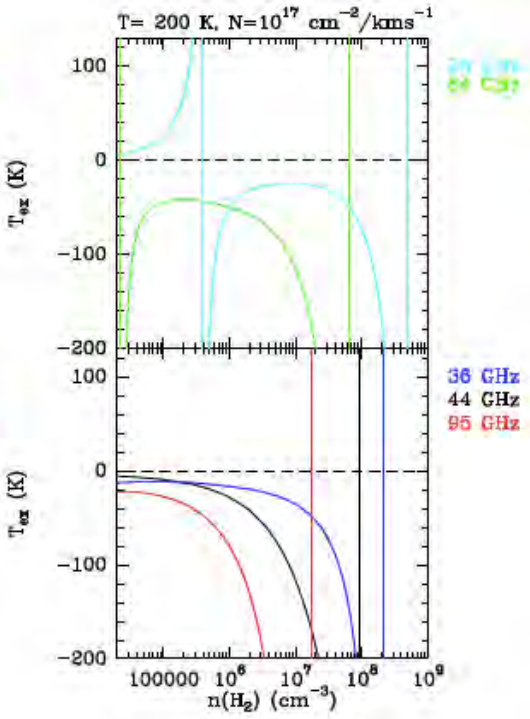
Talks b M. Gray, R. van Rooyen, S. Leurini

$$n_u A_{ul} = n_l B_{lu} J + n_l C_{lu} n_{tot}$$

Class I CH_3OH maser modeling

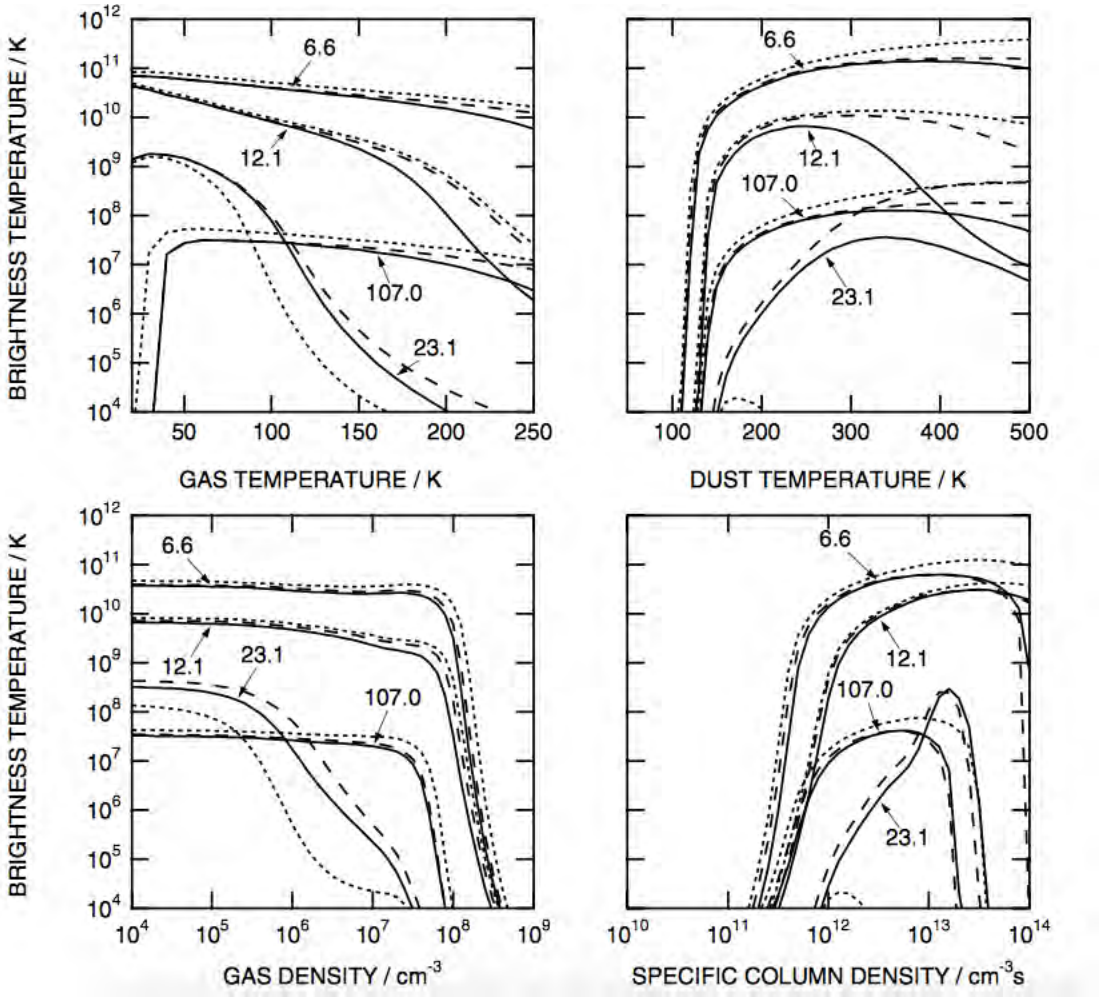






Leurini, Menten & Walmsley 2016

Class II CH_3OH maser modeling



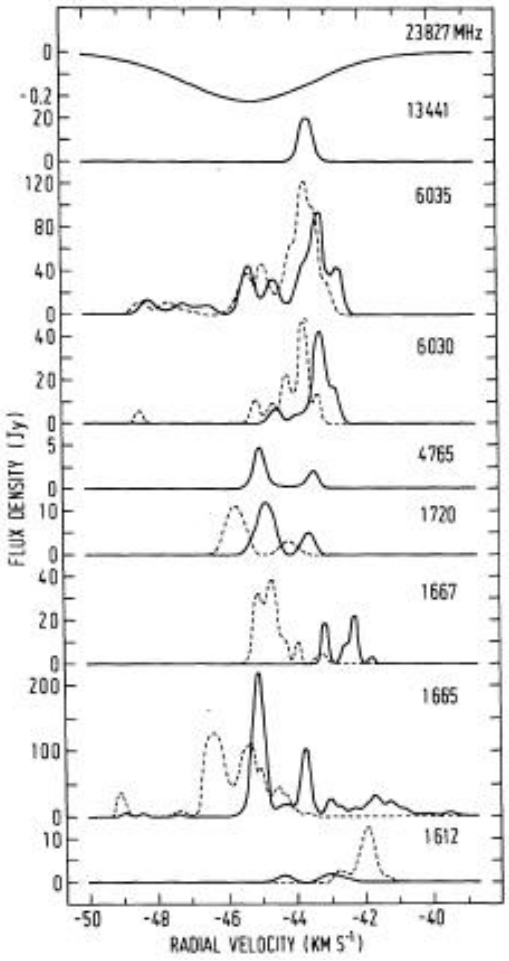
Sobolev & Deguchi 1994,Sobolev+ 1997, Cragg+2005

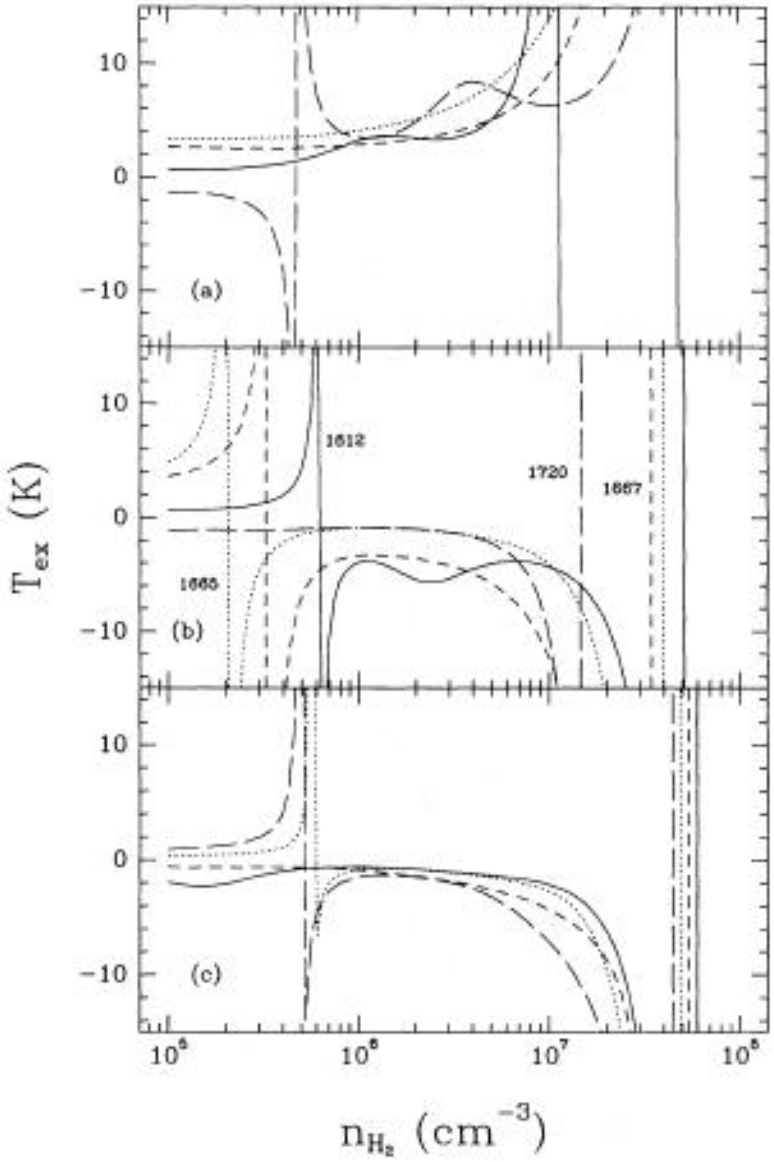
Astron. Astrophys. 241, 537–550 (1991)

OH maser models revisited

R. Cesaroni and C.M. Walmsley

Max-Planck-Institut für Radioastronomie, Auf dem

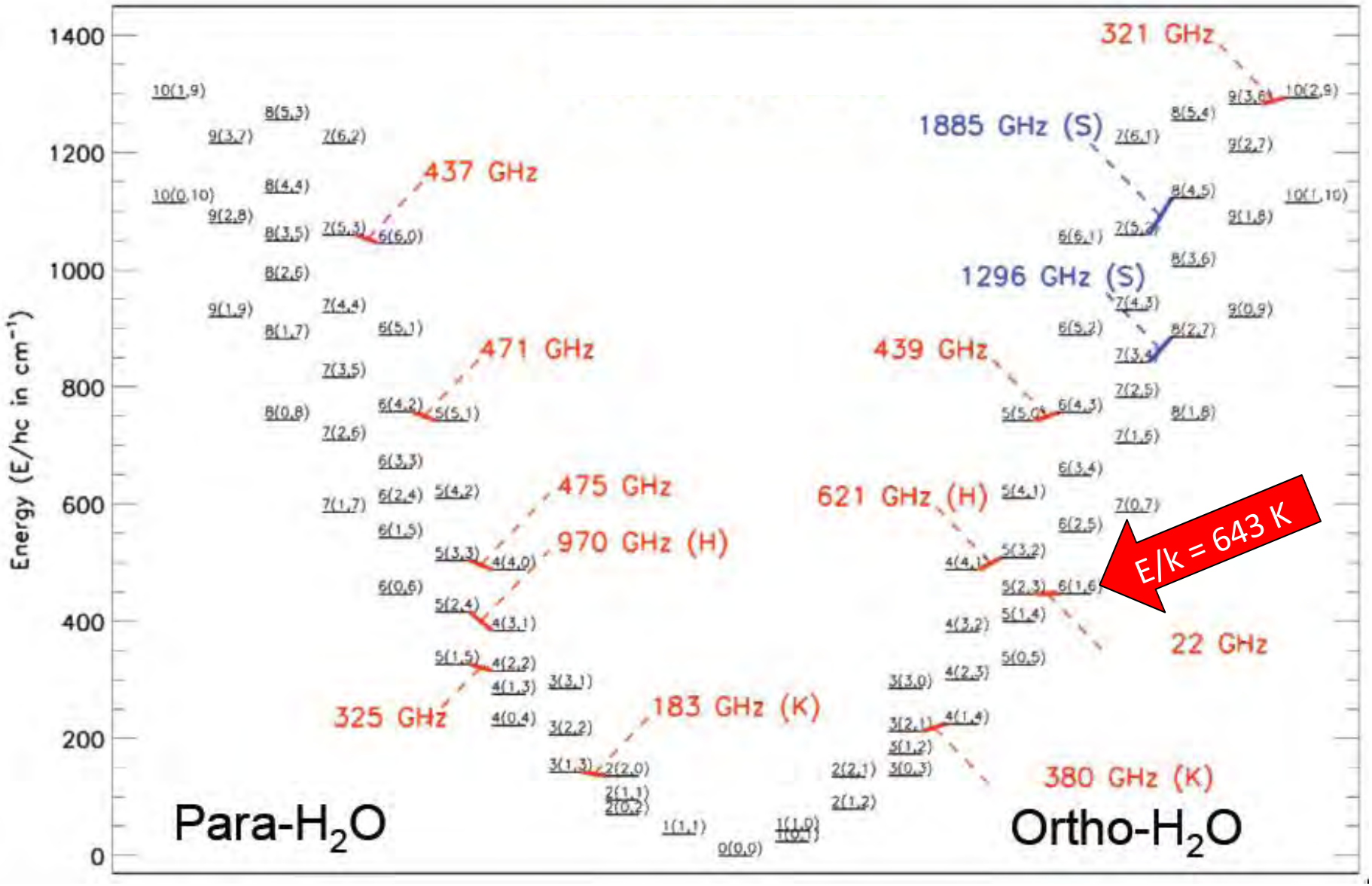




no overlap

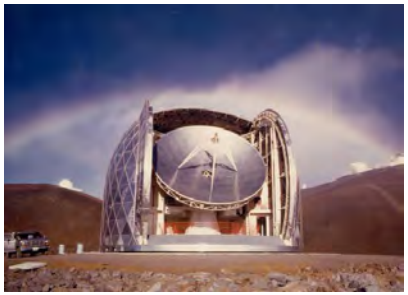
local overlap

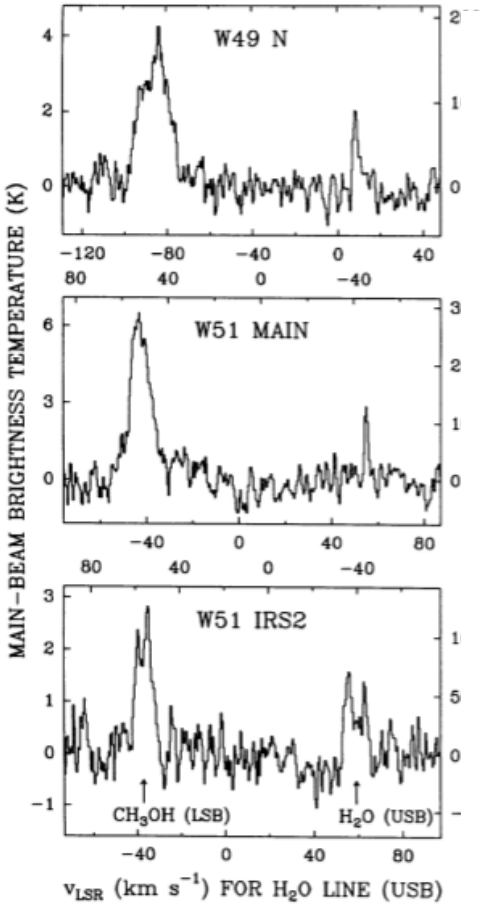
local and non-local overlap



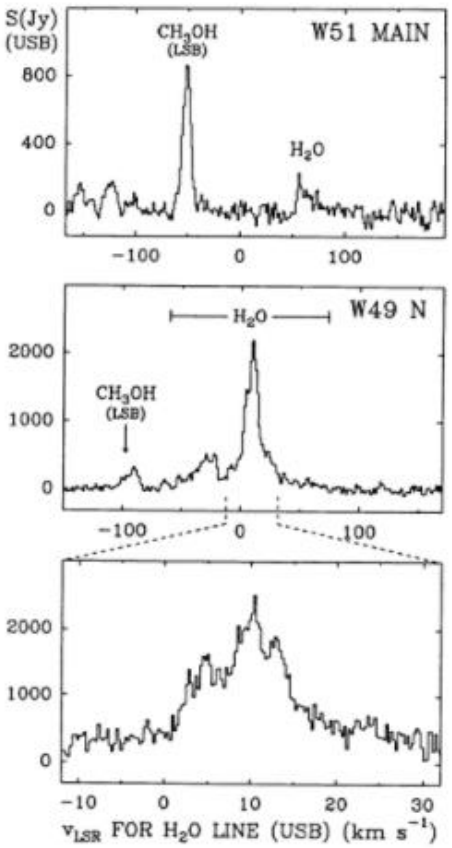
Observed H_2O maser transitions (as of 2017) D. Neufeld

Submillimeter H_2O Masers

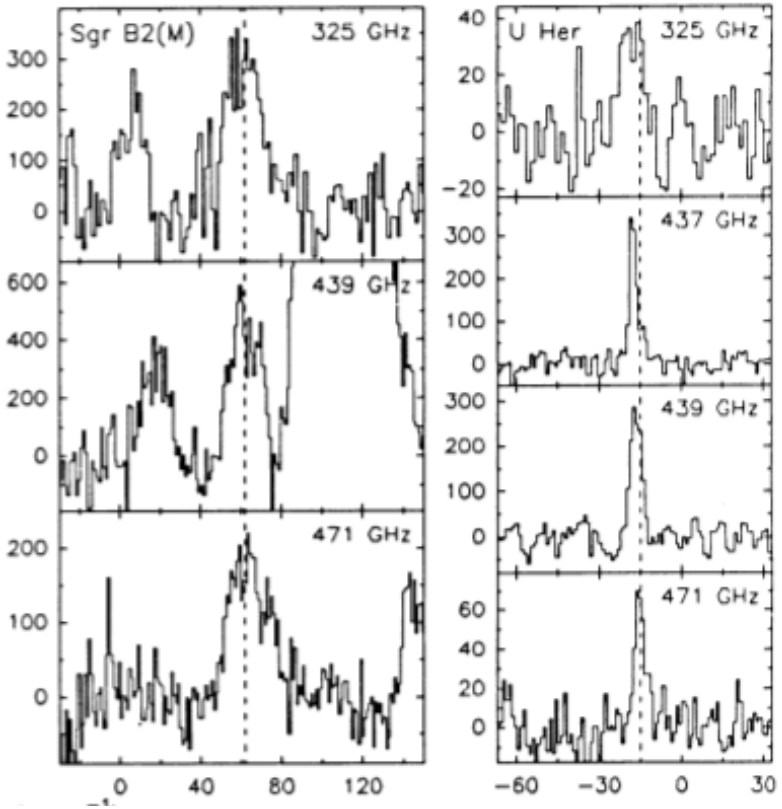




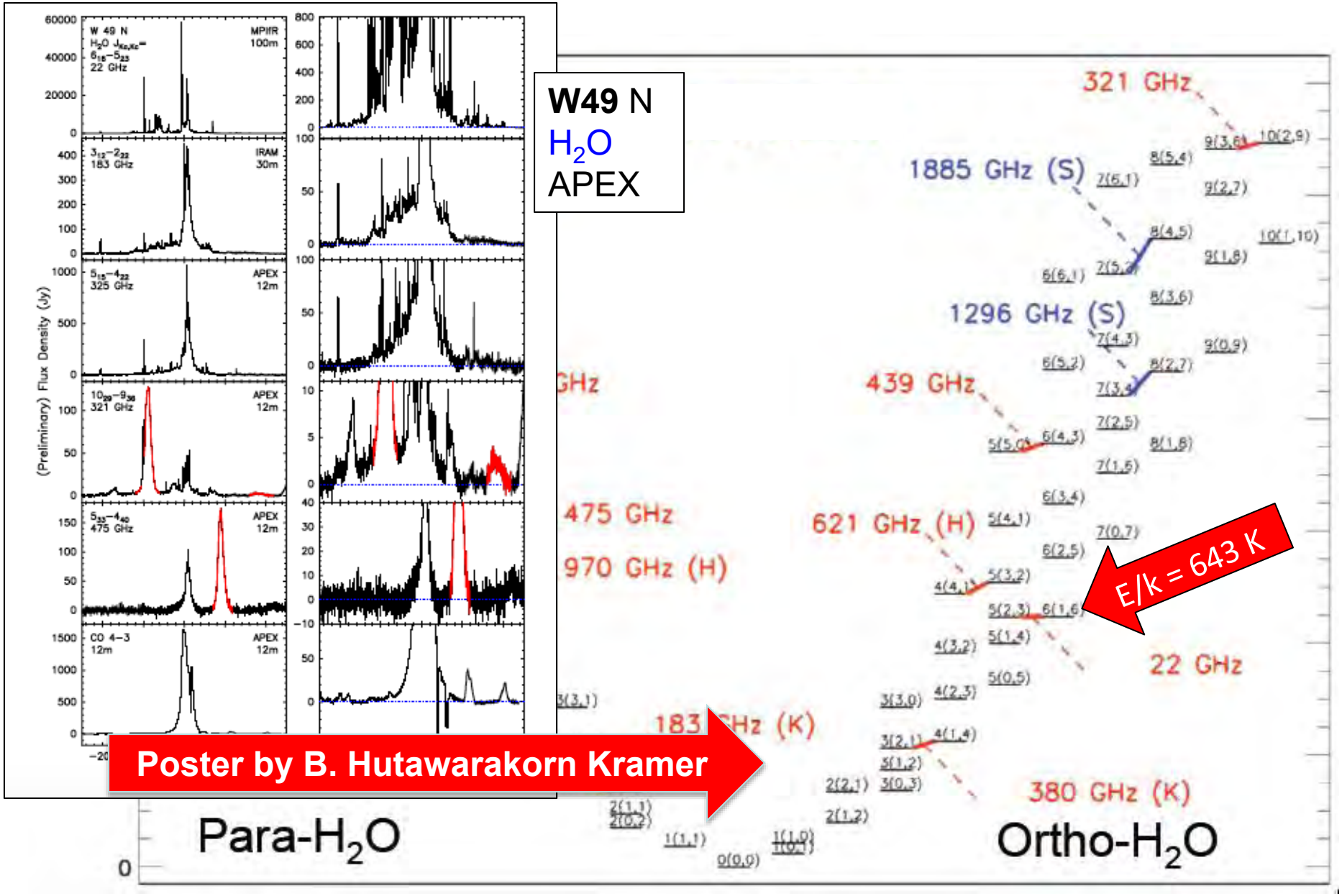
Menten, Melnick & Phillips 1990



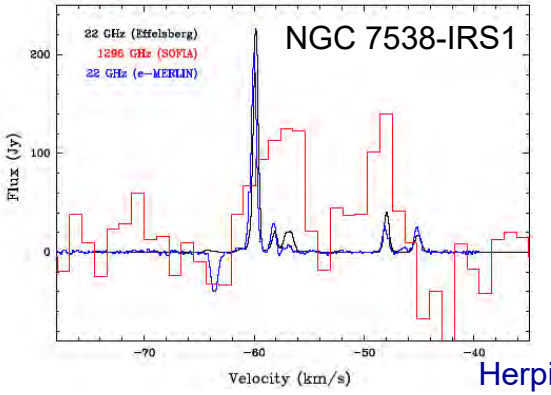
Menten+ 1990



Melnick+ 1993

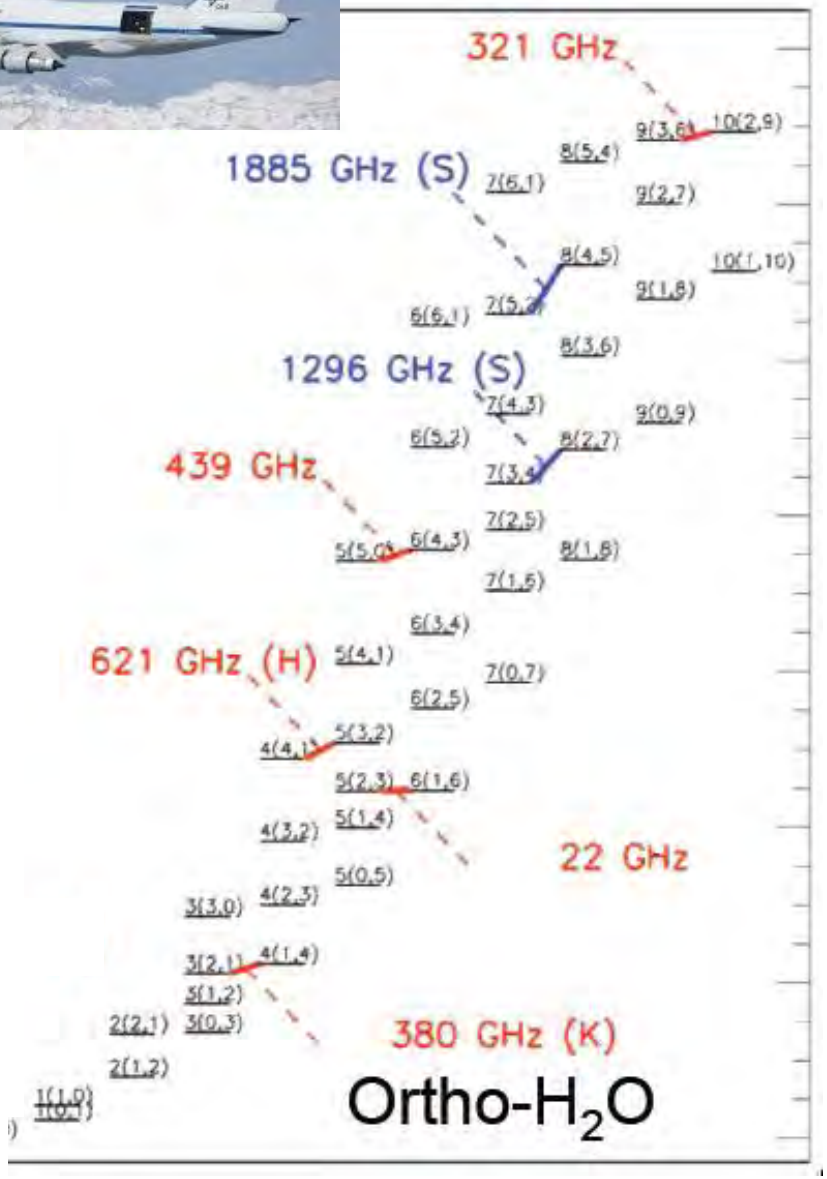


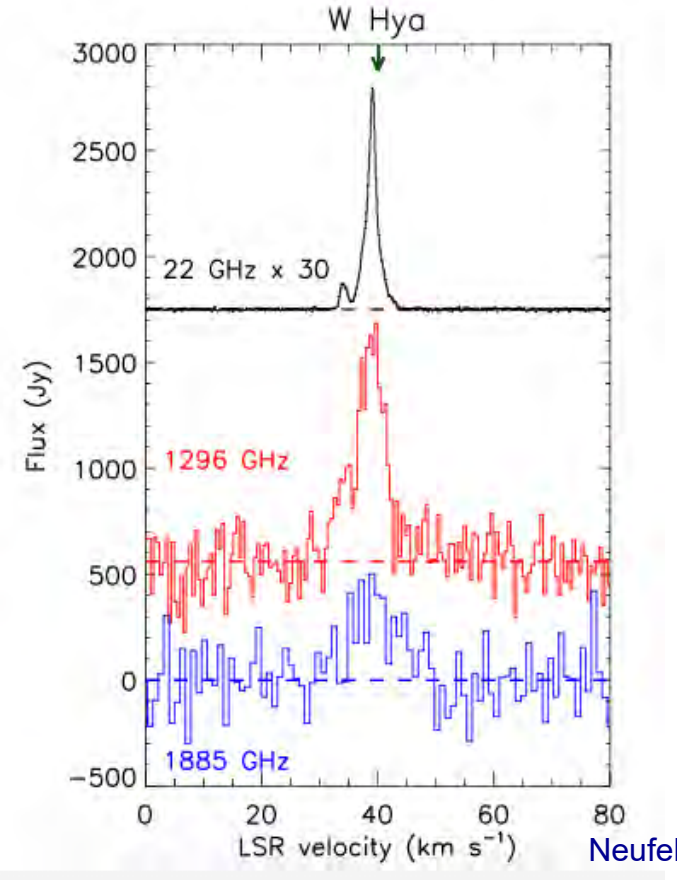
Observed H_2O maser transitions (as of 2017) D. Neufeld



Herpin+ 2017







Neufeld+ 2017

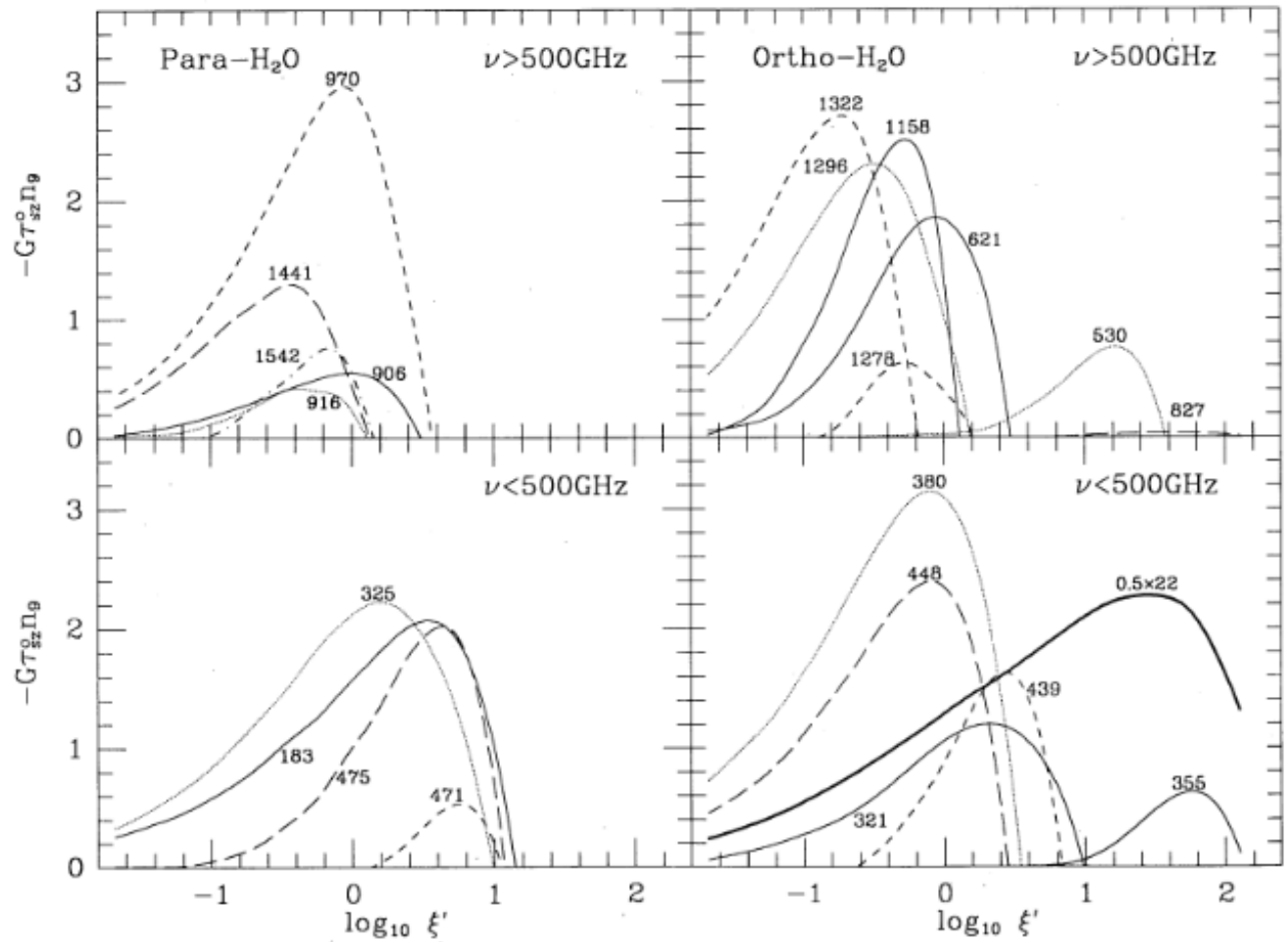
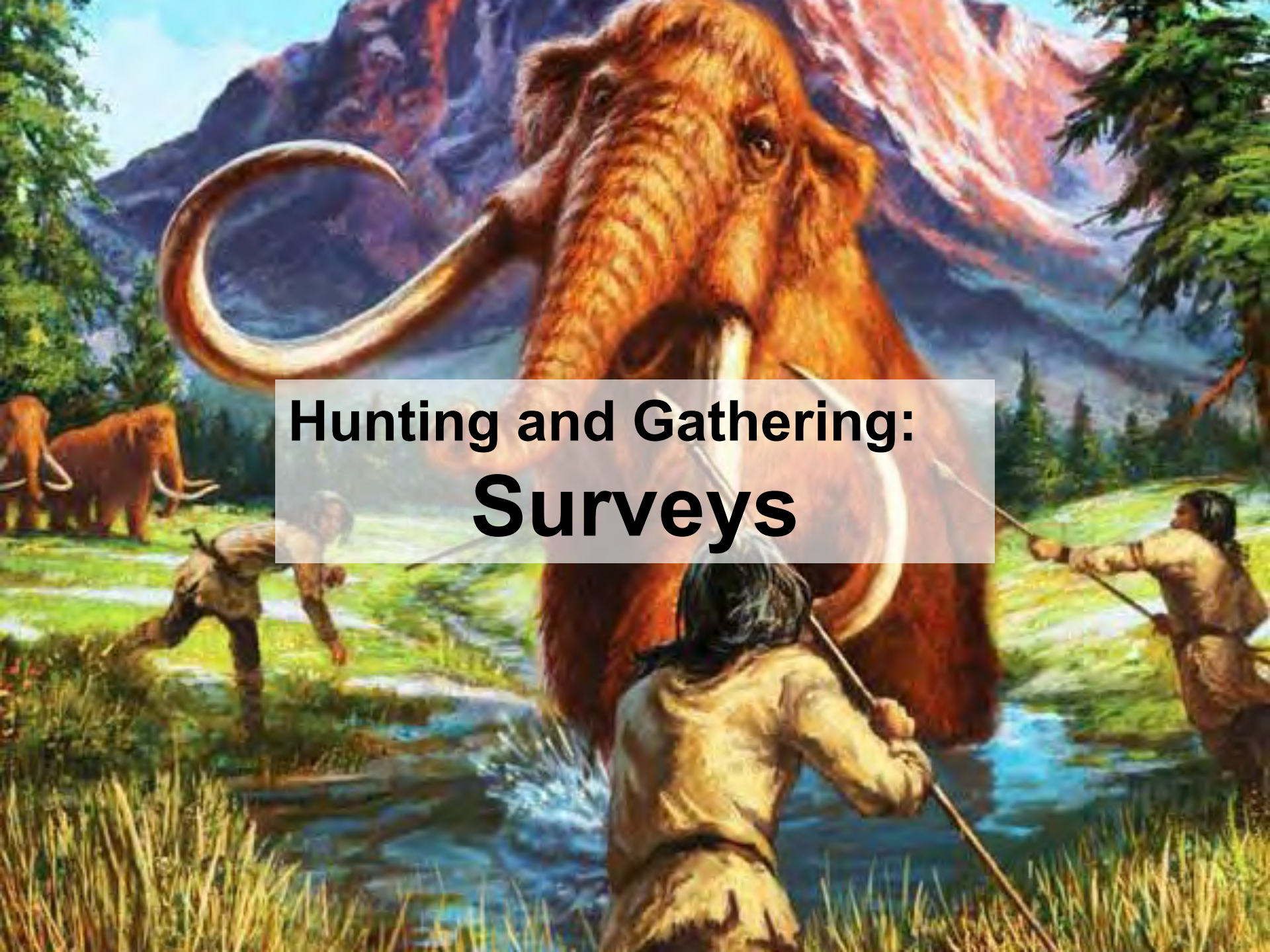


FIG. 5.—Maser optical depths at 1000 K, as a function of the variable ξ' (see text). Each curve is labeled with the transition frequency in GHz, and is scaled by Gn_9—where G is a geometric factor (see text) and $10^9 n_9$ cm^{-3} is the density of H nuclei—so as to be independent both of the geometry and the density.

Neufeld & Melnick 1991
Gray+ 2016


Hunting and Gathering:
Surveys

Two types of maser surveys:

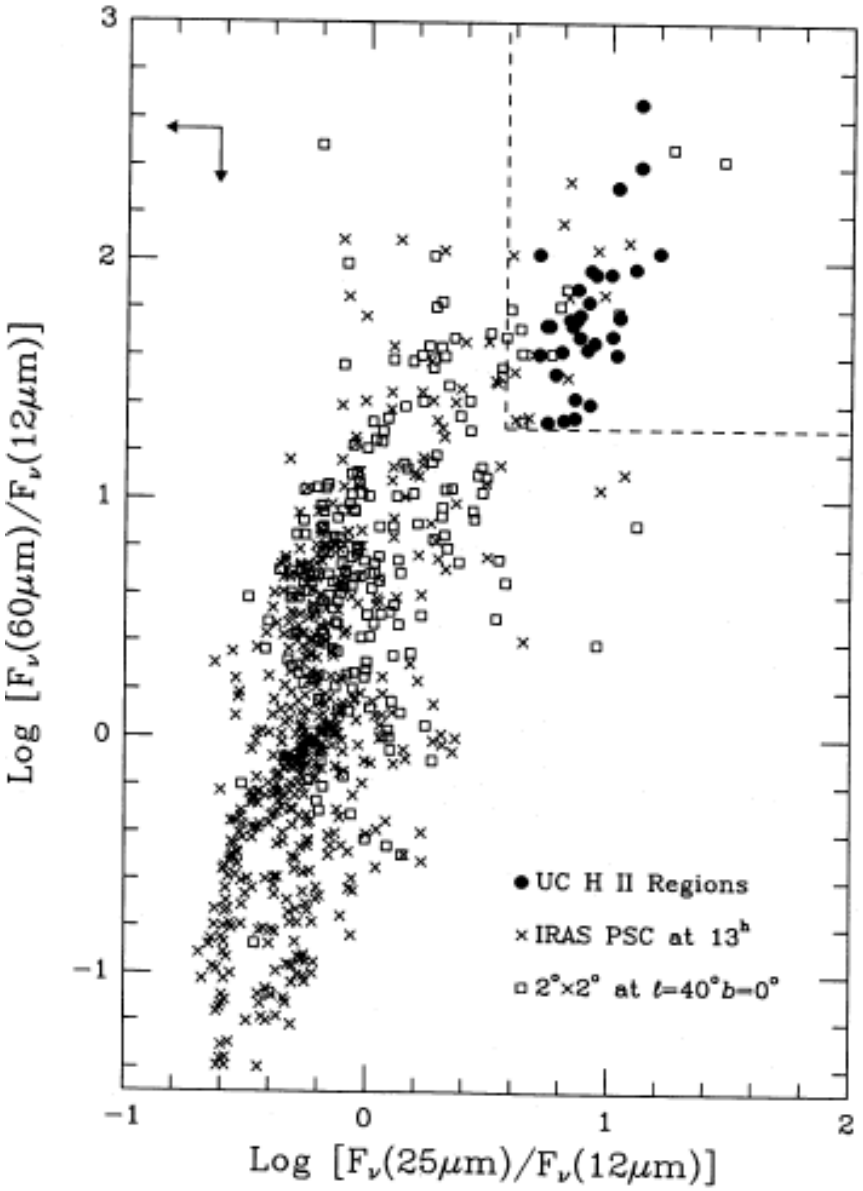
- **Blind surveys: Cover large area uniformly with multiple pointings (e.g. NVSS) or fast scanning, for masers often in the Galactic plane**
  - **Caswell et al. H_2O, OH**
  - **several class II CH_3OH maser (Ellingsen, Szymczak, Pandian)**
  - **Pks/JB 6 GHz multibeam**
  - **JVLA surveys**
- **Targeted observations: Source sel g., based on:**
  - **Regions with other species toward OH/H_2O (Hartebeesthoek, Caswell e**
  - **(F)IR color criteria (IRAS, MSX)**
    - **LPV stars (Habing et al., Deguchi et al.)**
    - **Young stellar objects (Brand & Wouterloot, Hartebees**
    - **OH megamasers**
  - **AGN: H_2O megamasers**

Serendipity happens for both types!



IRAS 100 µm all-sky image

Schlegel+ 1998



Finding embedded high mass young stellar objects



Wood & Churchwell 1989

The basis of many Southern maser surveys

Australian Journal of Physics Astrophysical Supplement

Number 45 August 1978

A southern hemisphere survey of the galactic plane at 5 GHz. *R. F. Haynes, J. L. Caswell and L. W. J. Simons*

Abstract. Seventy five maps are presented showing the 5 GHz emission from the galactic plane in the range $l = 190° \rightarrow 360° \rightarrow 40°$ for $-2° < b < 2°$ (an area of approximately 600 square degrees). The method of observing and the computer reduction of the data are discussed. The telescope resolution is $4'{\cdot}1$ arc to half-power points and the detection limit for point sources is better than $0{\cdot}5$ Jy.

1 ☐	1987AuJPh..40..215C	1.000	00/1987	A		F	G		T	R	C	S	O U
	Caswell, J. L.; Haynes, R. F.	Survey of OH masers at 1665 MHz. III - Galactic longitudes 233 to 326 deg											
2 ☐	1983AuJPh..36..417C	1.000	00/1983	A		F	G			R	C	S	U
	Caswell, J. L.; Haynes, R. F.	Atlas of main-line OH masers in the galactic longitude range 3 to 60 deg											
3 ☐	1983AuJPh..36..361C	1.000	00/1983	A		F	G			R	C	S	O U
	Caswell, J. L.; Haynes, R. F.	Survey of OH masers at 1665 MHz. II - Galactic longitude 340 deg to the galactic centre											
4 ☐	1980AuJPh..33..639C	1.000	09/1980	A		F	G				C	S	O U
	Caswell, J. L.; Haynes, R. F.; Goss, W. M.	Survey of OH masers at 1665 and 1667 MHz. I - Galactic longitudes 326 deg to 340 deg											

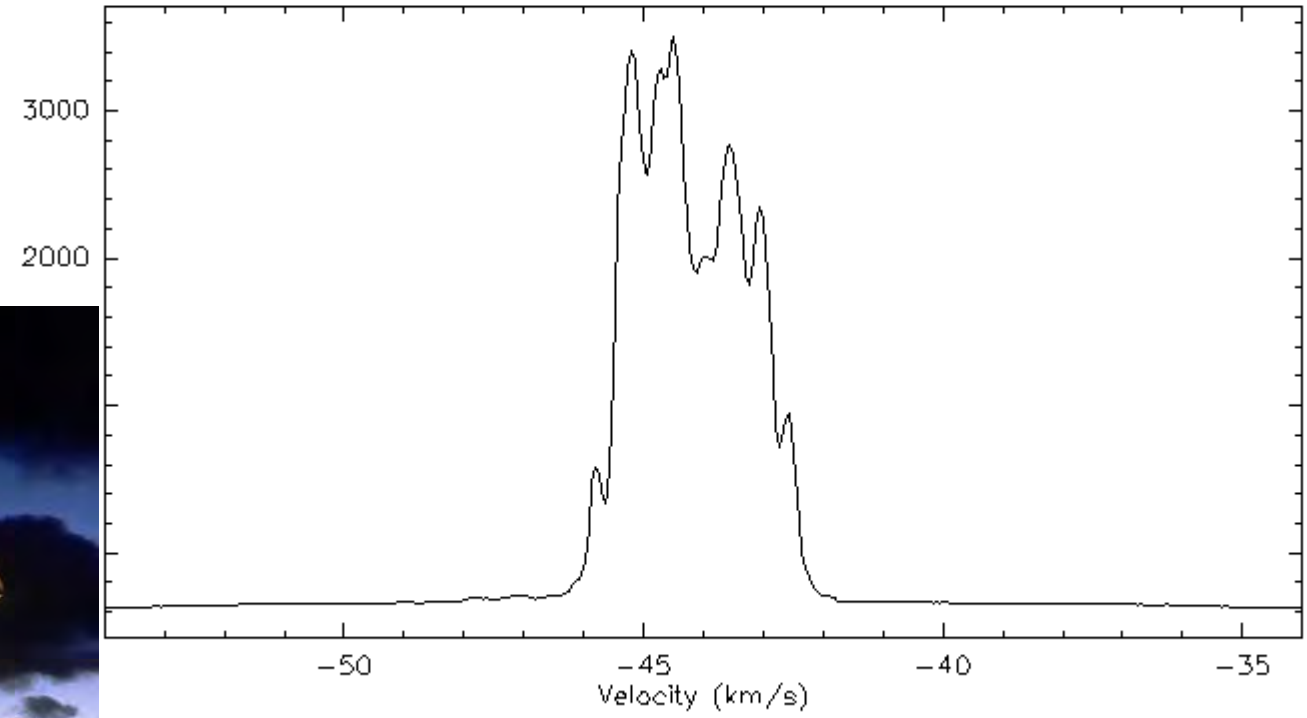
same for H_2O

and, later, for CH_3OH



James Leslie (Jim) Caswell
1940–2015

6921; 6 W3(OH) NRAO NRAO 140ft O: 01-JUN-1991 R: 12-JUN-1991
RA: 02:23:16.400 DEC: 61:38:57.00 (1950.0) Offs: +0.103 +0.048 Eq
Unknown Tau: 0.000 Tsys: 607.8 Time: 1.000 El: 57.19
N: 512 I0: 258.2 V0: -43.61 Dv: 5.4878E-02 Unkn
F0: 6668.51800 Df: -1.2207E-03 Fi: 2.019531250E-03






Green Bank Observatory

THE ASTROPHYSICAL JOURNAL, 380:L75–L78, 1991 October 20
© 1991. The American Astronomical Society. All rights reserved. Printed in U.S.A.

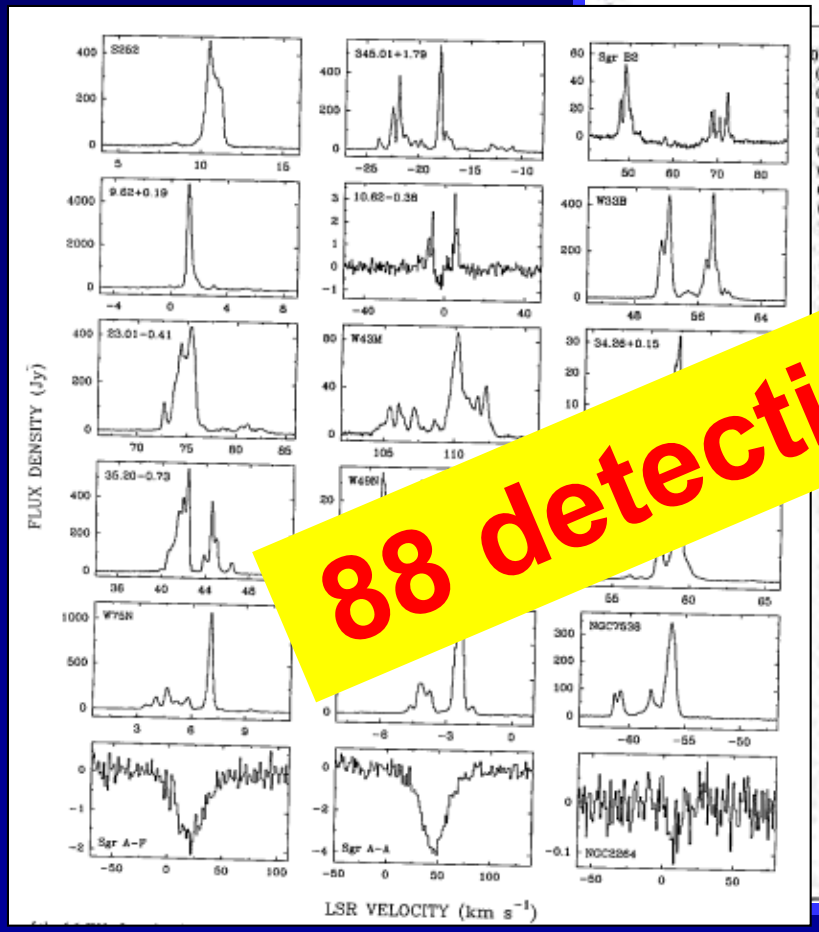
THE DISCOVERY OF A NEW, VERY STRONG METHANOL MAS

KARL M. ME
Harvard-Smithsonian Center for Astrophysics, 60
Received 1991 July 2; accep

TABLE 1

SOURCES DETECTED IN THE $5_1 \rightarrow 6_0 A^+$ TRANSITION OF CH_3OH

Source	α_{1950}	δ_{1950}	S_{peak} (Jy)	v_{LSR}-range (km s^{-1})
M17[a,b]	18^{h}17^{m}31^s.8	−16°13′07″	49	21,24
16.59−0.06	18 18 20.3	−14 33 18	22	56,65
18.46−0.01	18 21 48.0	−12 53 02	28	46,50
19.48+0.16	18 23 10.3	−11 54 31	24	13,28
20.24+0.08	18 24 55.8	−11 16 24	112	69,76
20.08−0.13	18 25 23.0	−11 30 40	4	43,54
21.88+0.02[b]	18 28 16.1	−09 51 01	14	20,22
22.44−0.18	18 30 01.0	−09 27 00	24	24,39
23.43−0.19	18 31 55.8	−08 34 17	85	95,108
23.01−0.41	18 31 56.7	−09 03 15	439	70,84
24.33+0.11	18 32 32.3	−07 38 24	3[c]	107,120
W42[c]	18 33 30.6	−07 15 07	89	106,115
27.35−0.20	18 39 16.0	−05 06 35	12[c]	96,103
28.21−0.06	18 40 21.6	−04 16 26	2[d]	95,105
28.83−0.25	18 42 12.4	−03 49 08	85	80,93
29.95−0.02[a,b]	18 43 27.1	−02 42 35	329	95,105
30.82+0.28	18 44 00.3	−01 48 39	4[d]	82,109
30.22−0.15	18 44 24.0	−02 32 00	11	103,114
30.60−0.06	18 44 45.0	−02 09 15	5[d]	40,90
30.70−0.06	18 44 58.9	−02 04 27	125	85,92
30.79−0.06	18 45 05.8	−01 59 12	25[d]	88,110
30.82−0.06[a,b]	18 45 11.0	−01 57 57	21	93,110
W43M[a]	18 45 35.8	−01 29 12	57	104,114
32.74−0.07	18 48 46.0	−00 10 28	46	28,40
33.13−0.09	18 49 33.6	00 04 25	10	72,110?
34.26+0.15	18 50 46.2	01 11 12	32	55,62
35.03+0.35[a]	18 51 50.3	01 57 30	50	44,46
35.19−0.74[c]	18 55 40.8	01 38 30	207	27,34
35.20−0.73[a]	18 59 13.8	01 09 20	556	39,47
40.62−0.14	19 06 34.9	06 41 55	14	30,37
W49N[a]	19 07 49.9	09 01 14	28	−2,23
43.80−0.13	19 09 30.8	09 30 47	152	39,44
45.07+0.13	19 11 00.4	10 45 43	42	57,59
45.47+0.13	19 11 47.5	11 07 14	15[d]	57,72
45.47+0.05	19 12 01.4	11 04 11	3[d]	55,60
W51[a,c]	19 21 24.8	14 24 48	979	48,76
Vac Cyg	19 41 04.2	23 36 42	103	15,28
ON1[c]	20 08 10.0	31 22 40	91	−1,16
ON2[c]	20 19 50.6	37 16 30	54	−11,3
W75N[c]	20 36 50.4	42 27 23	1080	0,13
DR21(OH)[c]	20 37 13.8	42 12 18	13	−7,8
W75S(3)[c]	20 37 16.7	42 15 15	39	−7,0
Cep A[a]	22 54 19.2	61 45 47	1420	−6,−1
NGC7538[a,c]	23 11 36.6	61 11 50	366	−62,−54



88 detections!



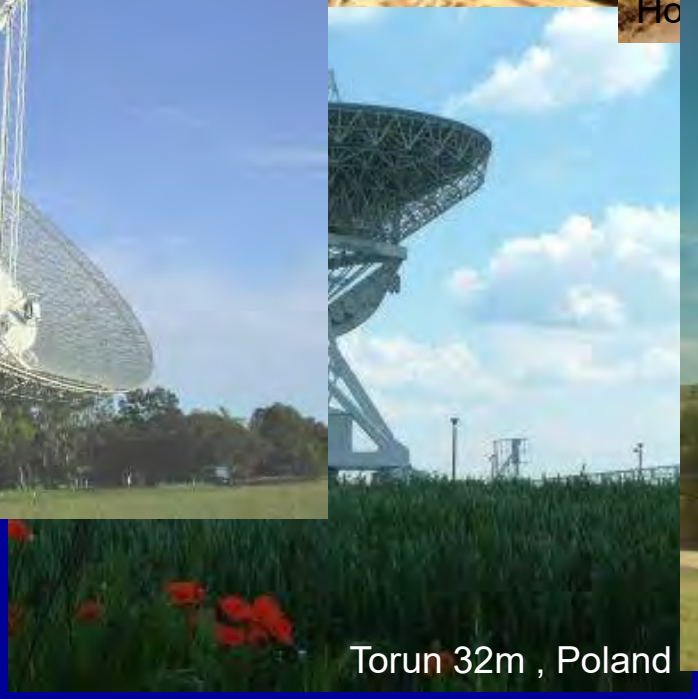
enticton, CA



Mt
Ho

Parkes 64 m,
Australia



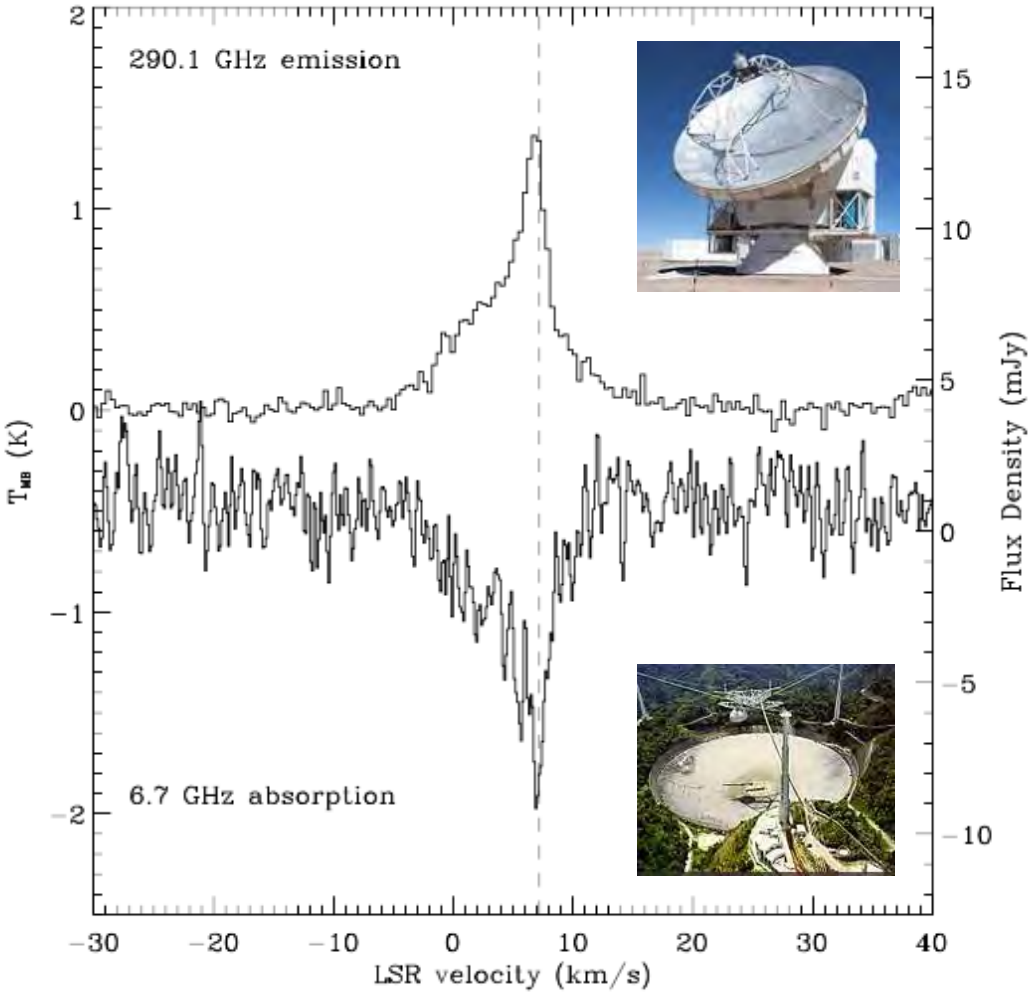


Torun 32m , Poland



Hartebeesthoek 26m, South Africa

BTW:The 6.7 GHz CH_3OH line was eventually found in absorption against the CMB!



Pandian+ 2008

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

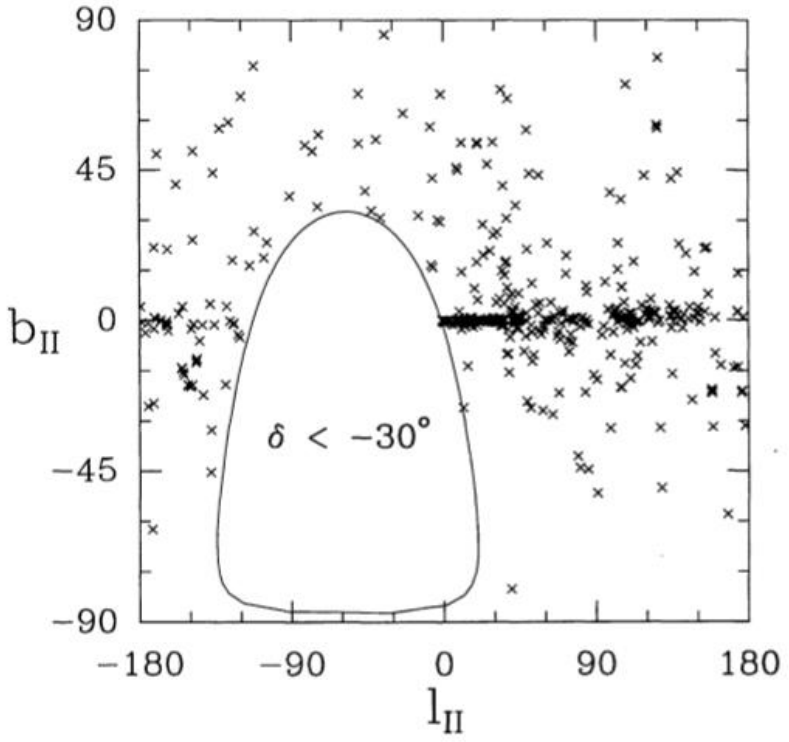
DECEMBER **1988,** PAGE 445

Astron. Astrophys. Suppl. Ser. **76,** 445-458 (1988)

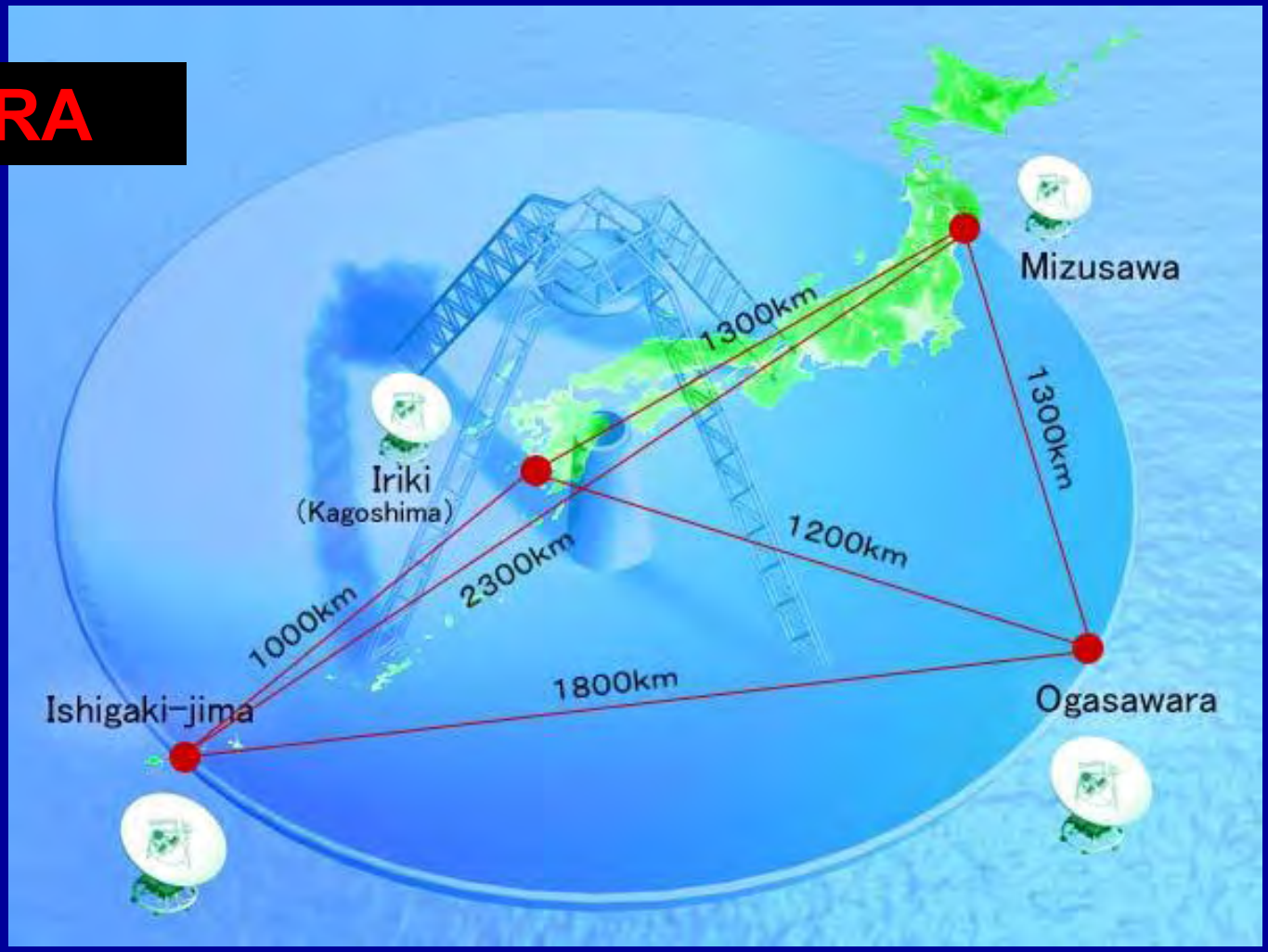
A catalogue of H_2O maser sources north of $\delta = -30^\circ$

R. Cesaroni (1), F. Palagi (2), M. Felli (3), M. Catarzi (3), G. Comoretto (3), S. Di Franco (1), C. Giovanardi (3) and F. Palla (3)

(1) Istituto di Astronomia, largo E. Fermi 5, 50125, Florence, Italy
(2) C.N.R., Gruppo Nazionale Astronomia, U.d.R. Arcetri, largo E. Fermi 5, 50125, Florence, Italy
(3) Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125, Florence, Italy



VERA



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

VLBA Legacy Programme
5296 h observing time

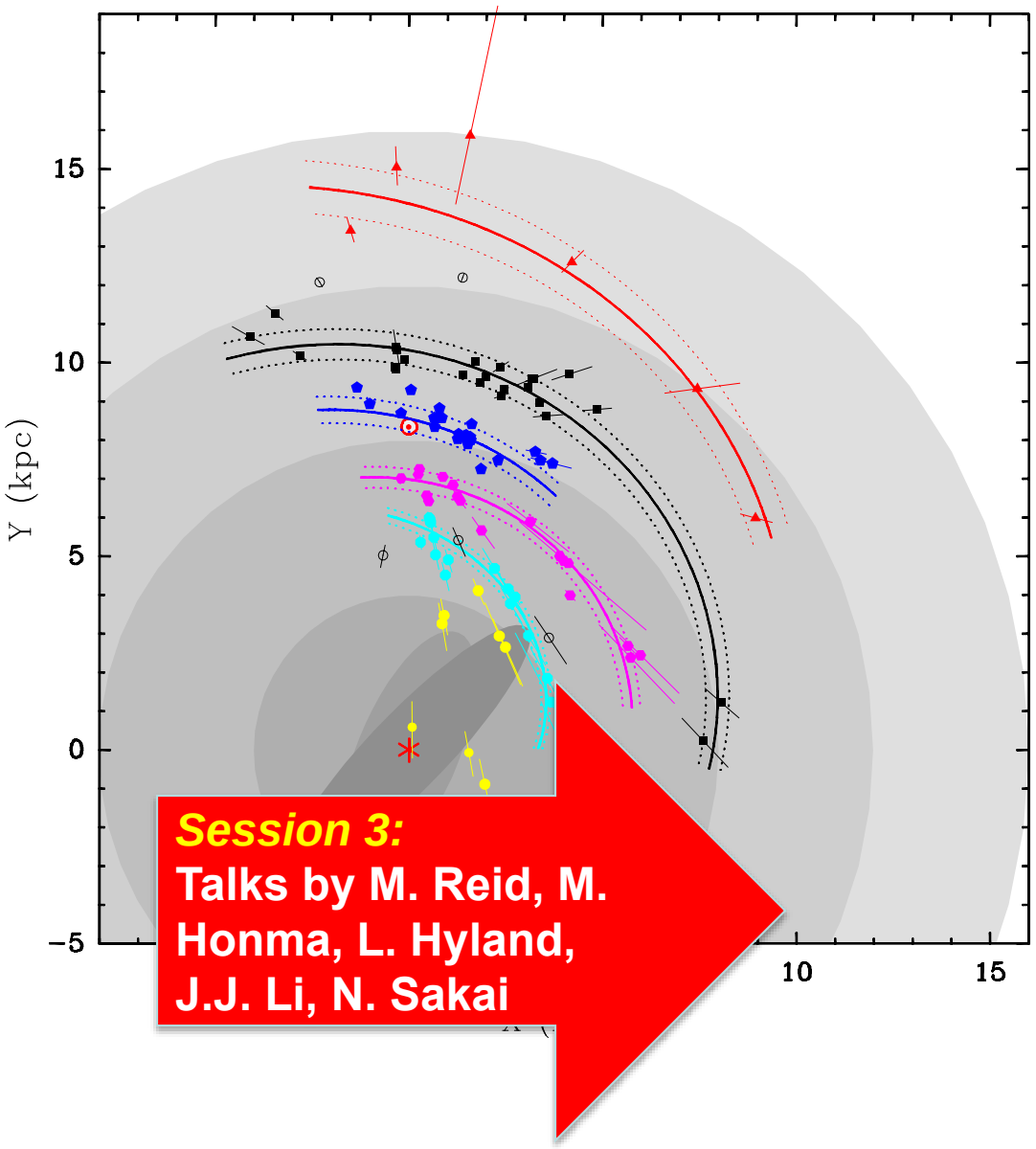


Friedrich Wilhelm Bessel
(1748 –1846)

BESSEL

Bar and Spiral Structure Legacy Survey,
a VLBA Key Science Project

Mapping Spiral Structure



- Parallaxes: VLBA, EVN & VERA
- ~100 parallaxes for massive young stars
- Arms assigned by CO l-v plot
- Tracing most spiral arms, eg…
  - Outer arm traced
  - Perseus arm “gap”
  - Local arm significant
- Inner, bar-region is complicated

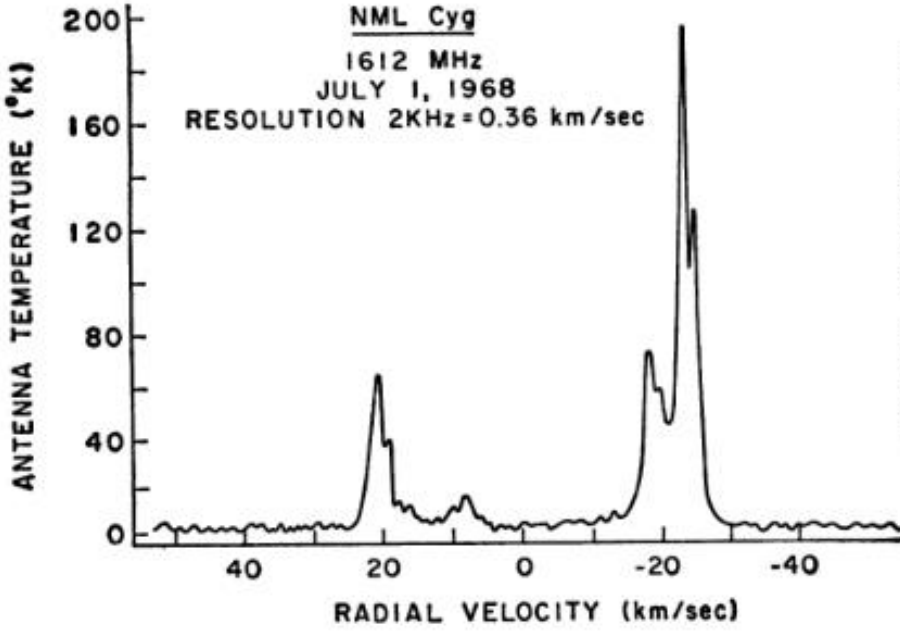
Reid et al. 2014

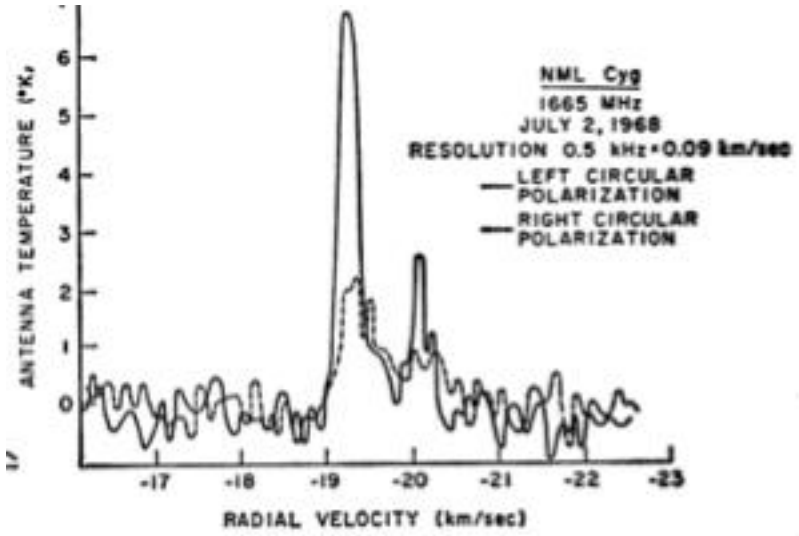
Finding stellar masers

Two-micron sky survey. A preliminary catalogue

G. Neugebauer & R. B. Leighton
NASA SP, Washington: NASA, 1969

The IRC catalog contains about 5000 objects between declinations +15 and -15 degrees.
Most of the sources are M-type stars
Some of the brightest could not (or only faintly) be detected at visual wavelength; e.g., IRC+10216, IRC+10420, NML Cygnus





NML Cyg
Wilson & Barrett 1968, Science

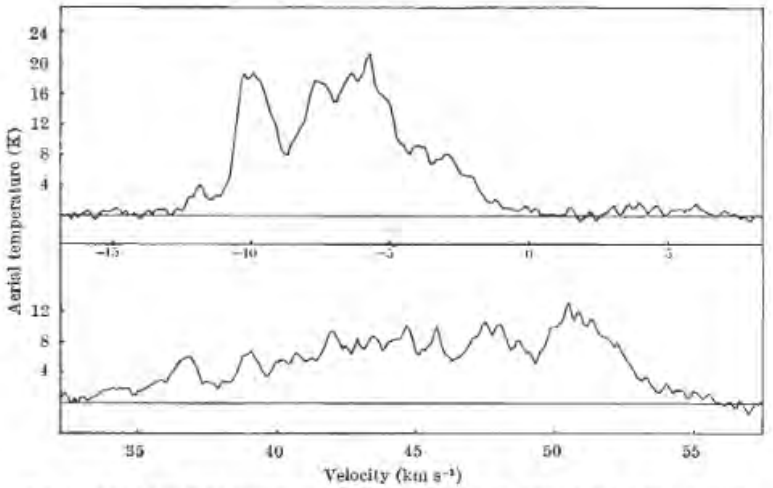


Fig. 2. The 1,612 MHz spectrum of VY CMa (August 25, 1969) taken with a linearly polarized aerial. The emission is concentrated in two velocity regions and no emission > 1·0 K is observed between 10 km s⁻¹ and 30 km s⁻¹. Resolution = 1·1 kHz.

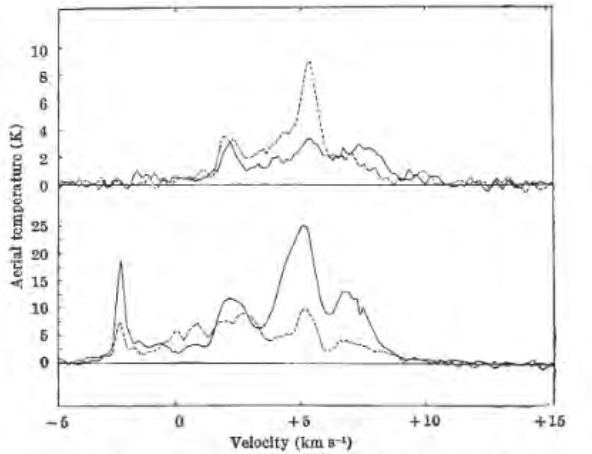
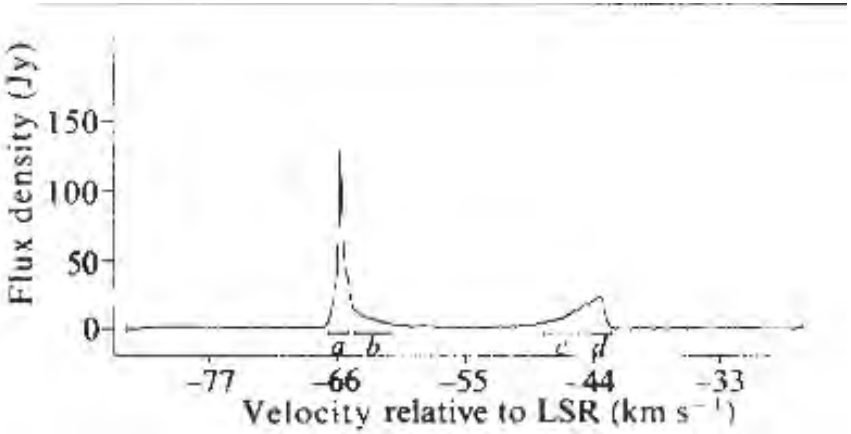


Fig. 1. Main line OH spectra of VY CMa in both senses of circular polarization with a resolution of 1·1 kHz (0·2 km s⁻¹). Top, 1,665 MHz, May 16, 1969; bottom, 1,667 MHz, May 14, 1969. ——, RH; - - - -, LH.

VY CMa
Booth 1969, Nature

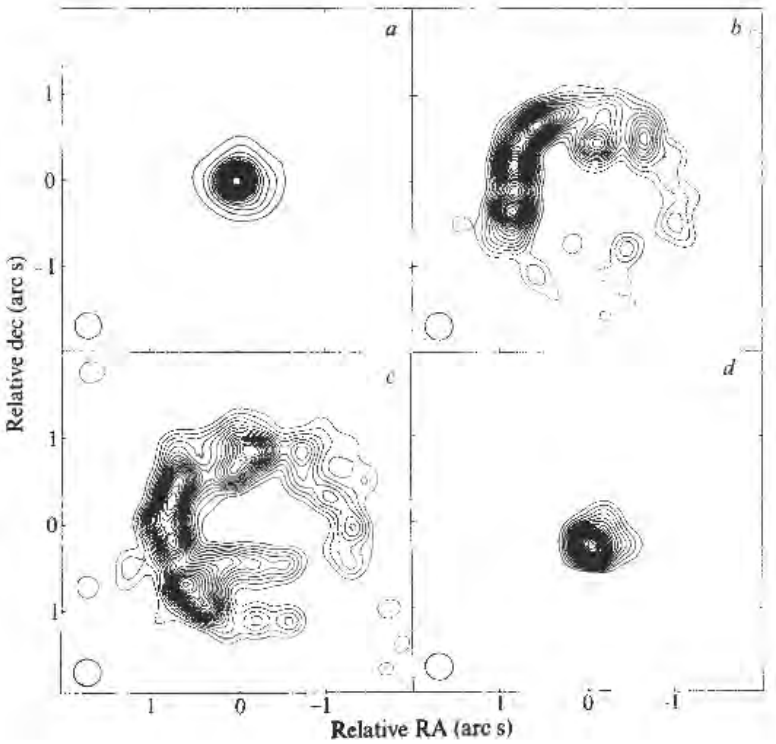


Observations of a circumstellar shell around the OH/IR star OH127.8−0.0

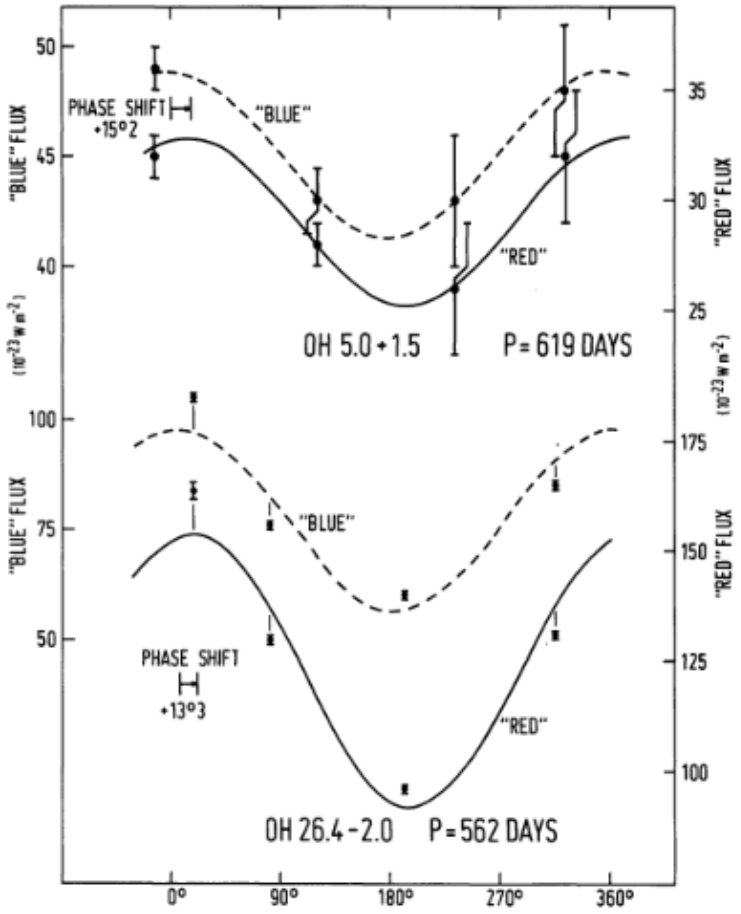
1981

R. S. Booth, A. J. Kus*, R. P. Norris & N. D. Porter

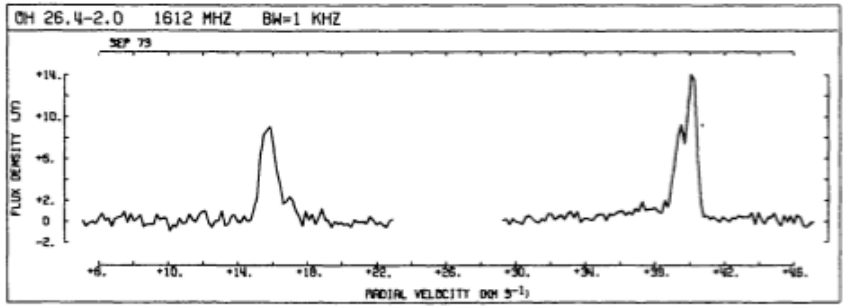
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK



MTRLI = Proto-MERLIN



Schultz+ 1978



Johansson+ 1977

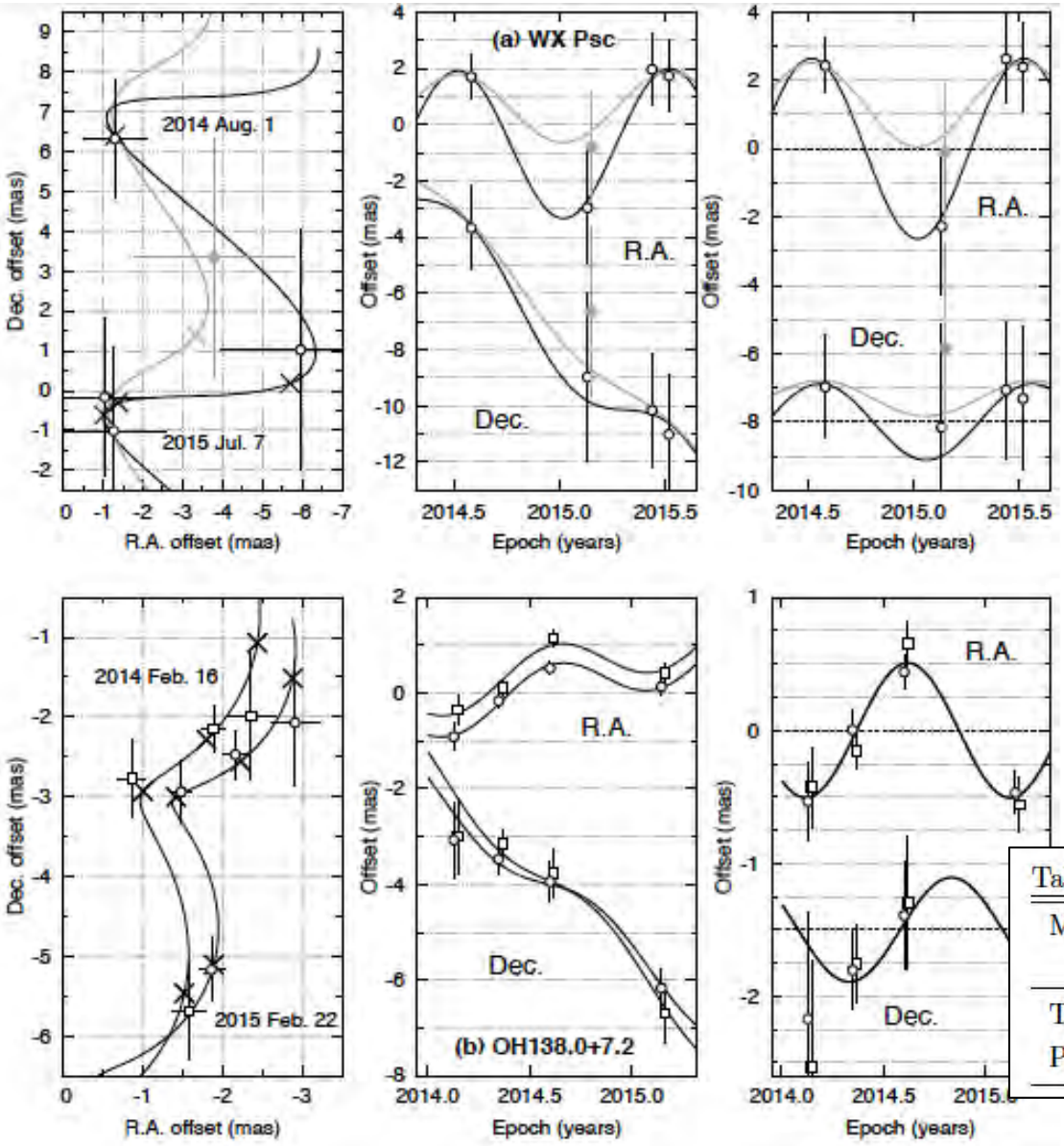
Linear shell diameter:
a few x 10^{16} cm

Talk by S. Etoka

distance

van Langevelde+ 1990

Name	D (kpc)	σ_D	L ($10^3\ L_\odot$)	σ_L
WX PSC	0.74	0.15	39.4	16.0
20.7+0.1	5.06	1.38	5.9	3.2
21.5+0.5	8.51	1.41	96.9	32.1
21.5+0.5	7.34	1.38	72.1	27.1
26.5+0.6	1.44	0.27	21.6	8.1
26.5+0.6	1.30	0.35	17.6	9.5
28.7−0.6	1.45	0.49	6.1	4.1
32.0−0.5	11.87	2.70	67.2	30.6
32.8−0.3	5.02	0.25	23.1	2.3
35.6−0.3	4.21	1.70	5.8	4.7
39.7+1.5	2.04	0.50	36.3	17.8
39.7+1.5	0.98	0.34	8.4	5.8
44.8−2.3	1.13	0.34	4.3	2.6
104.9+2.4	2.30	0.40	11.7	4.1
127.9−0.0	2.90	0.60	56.8	23.5



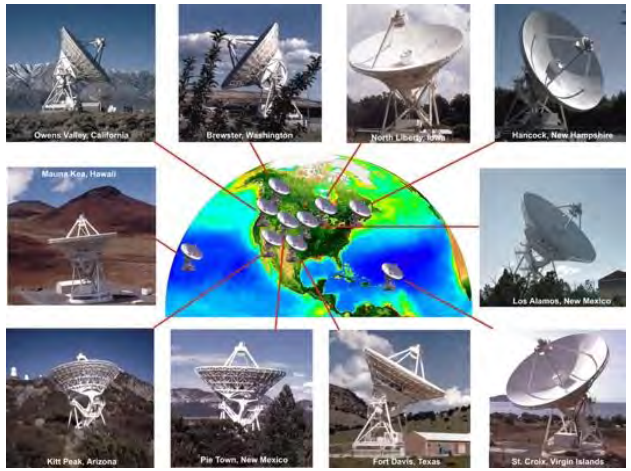


Table 5: Comparison of distance estimates.

Method	WX Psc distance (kpc)	OH138.0+7.2 distance (kpc)
Trigonometric	$\gtrsim 0.2$	$1.9\ ^{+0.4}_{-0.3}$
Phase–lag	0.5 ± 0.1	2.2 ± 0.5

Orosz+ 2017

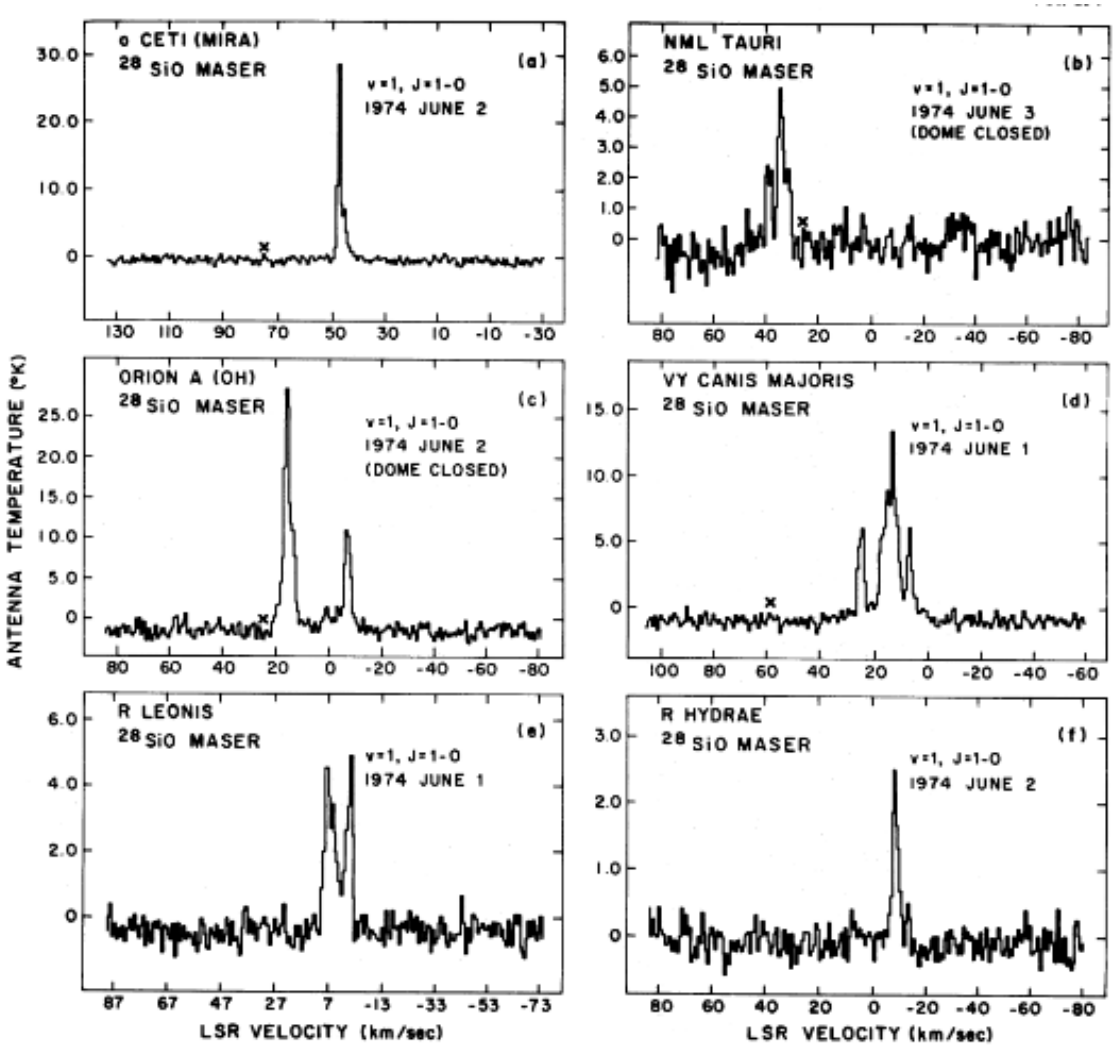


FIG. 1.—SiO $v = 1, J = 1 \rightarrow 0$ emission spectra for (*a*) o Cet, (*b*) NML Tau, (*c*) Ori A, (*d*) VY CMa, (*e*) R Leo, and (*f*) R Hya.

SiO maser emission from Mira stars

Snyder & Buhl 1975
Thaddeus+ 1974

Deguchi and his collaborators used (IRAS, and later MSX) color criteria to search (not only) in our galaxy for

- (mostly the) 43 GHz J=1-0, v=1 and 2 SiO masers in Mira stars; also 22.2 GHz H_2O line
- using the Nobeyama 45 m telescope (40″ FWHM). Typical sensitivity ~0.1 – 0.2 Jy

They systematically searched in:

- the Galactic bulge
- the Inner and Outer Galactic disk
- toward and near the Galactic center
- North Galactic cap
- cold IRAS sources
- globular clusters

… and found > 1000 SiO (and H_2O) masers

Other extensive stellar surveys for OH 1612 MHz line with VLA+ATCA by H. Habing + his students (M. Sevenster) + collaborators → > 1000 OH/IR stars

86 GHz SiO maser survey of late-type stars in the Inner Galaxy⋆,⋆⋆,⋆⋆⋆,†

I. Observational data

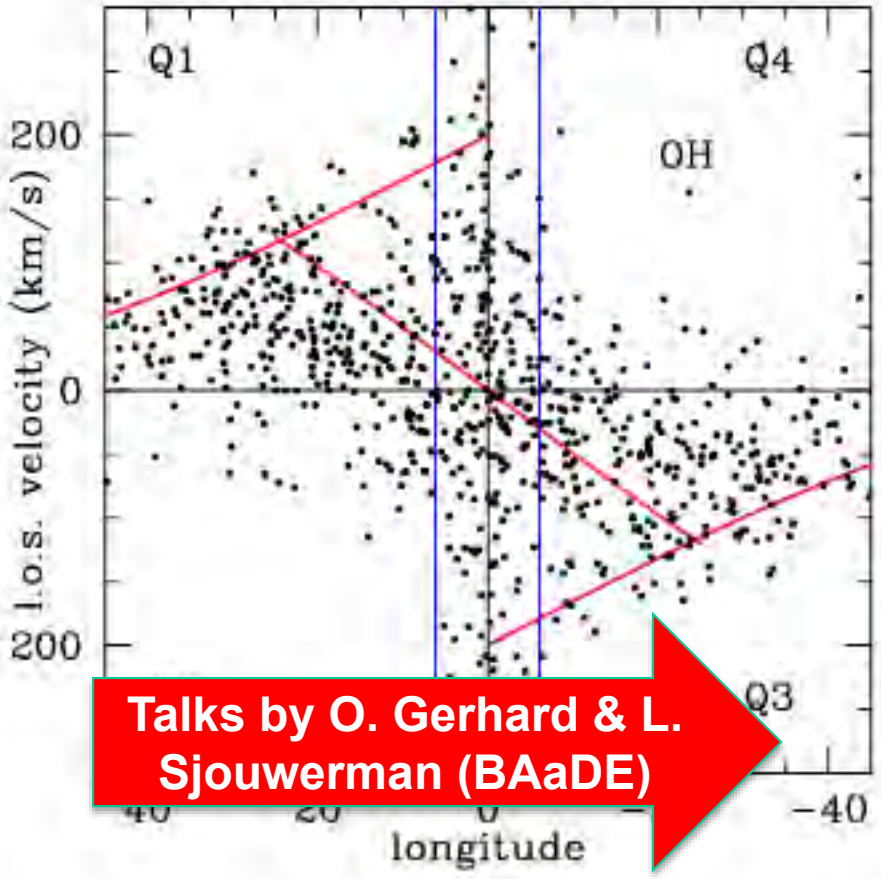
M. Messineo[1], H. J. Habing[1], L. O. Sjouwerman[2], A. Omont[3], and K. M. Menten[4]



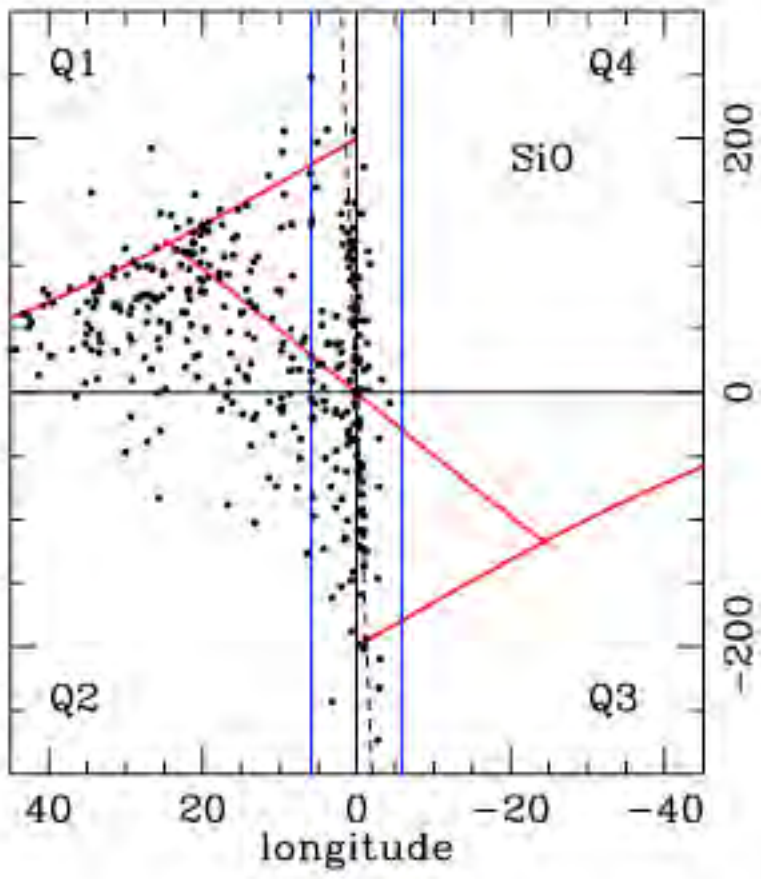
- Searched for v=1, J=2-1 SiO line toward stars in -4° < l < 30°
- based on ISOGAL and MSX colors
- Detect 271 out of 441

The distribution of maser stars in the inner Milky Way: the effect of a weak, rotating bar

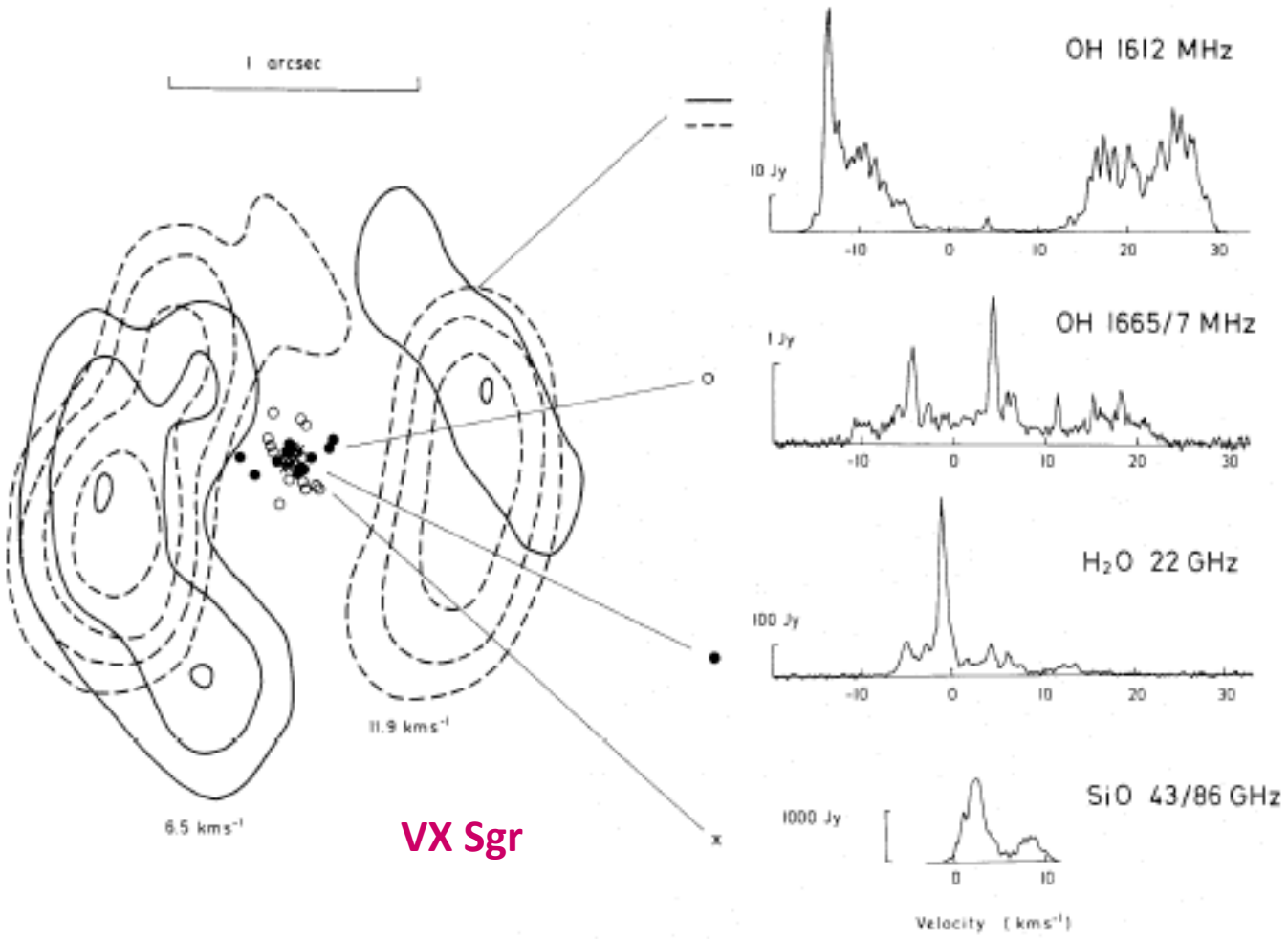
H. J. Habing, M. N. Sevenster, M. Messineo, G. van de Ven, and K. Kuijken 2006



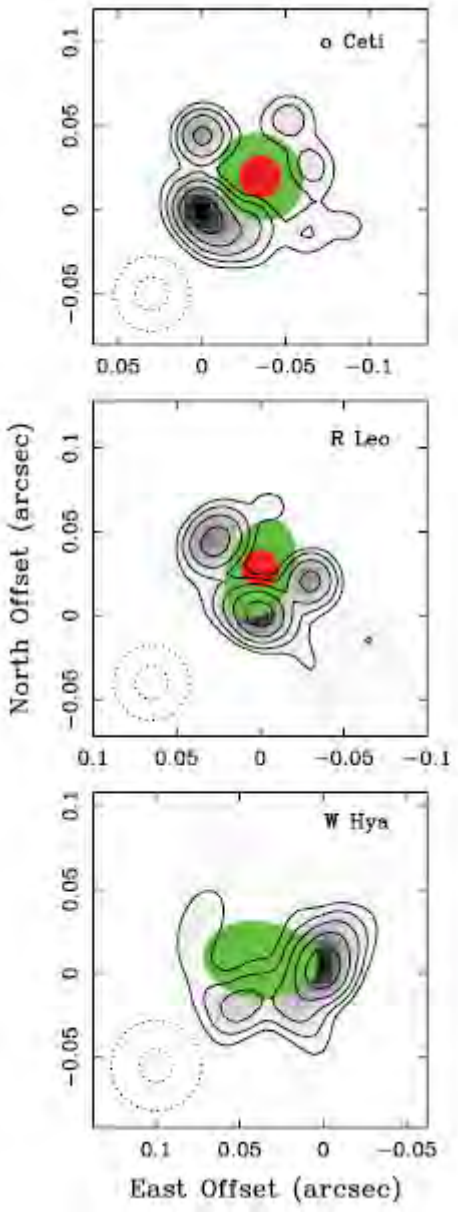
Talks by O. Gerhard & L. Sjouwerman (BAaDE)

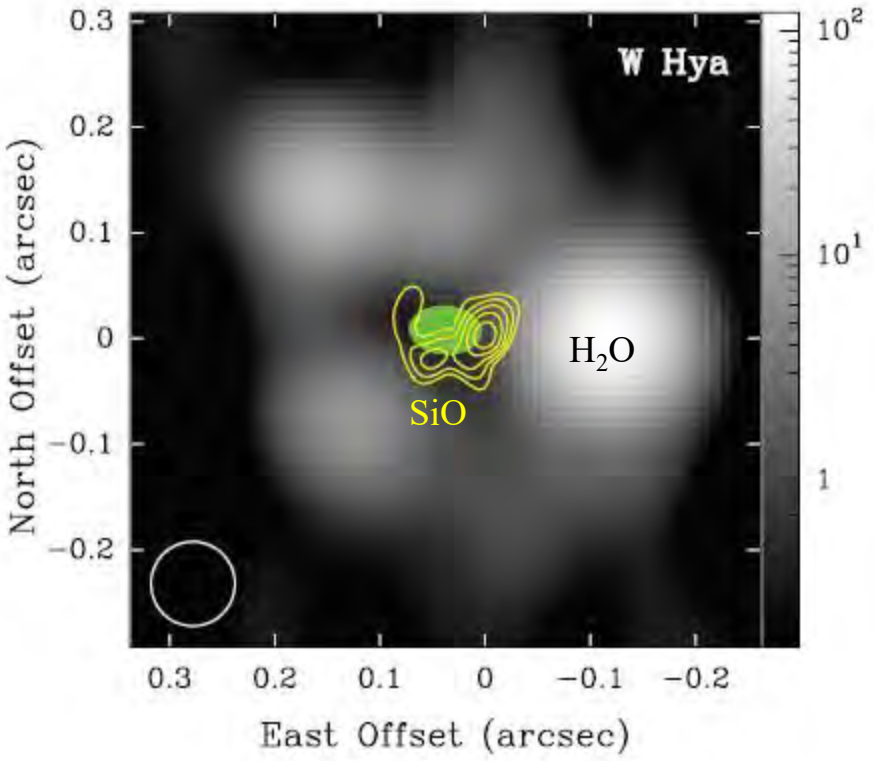


Masers in circumstellar envelopes around oxygen-rich, mass-losing evolved stars



Chapman & Cohen 1986

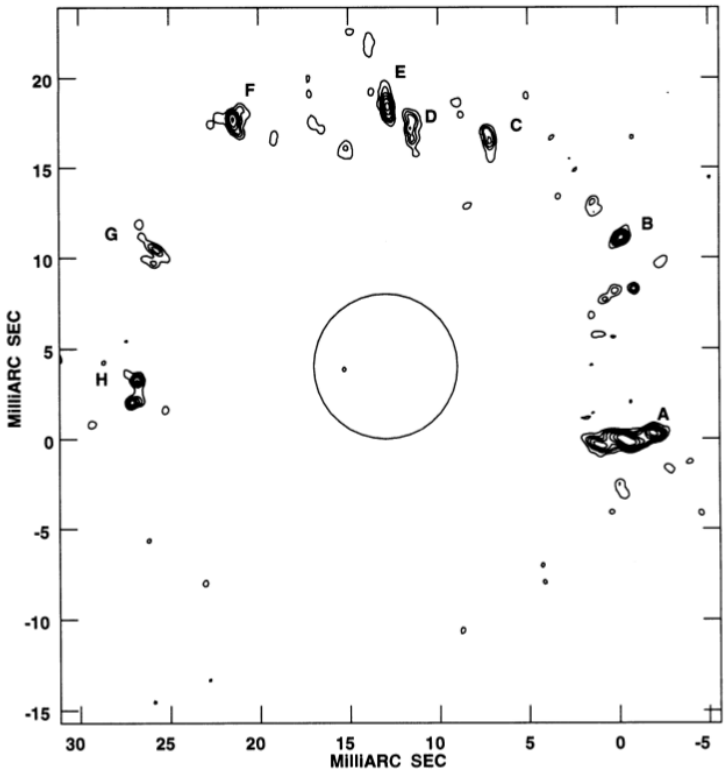


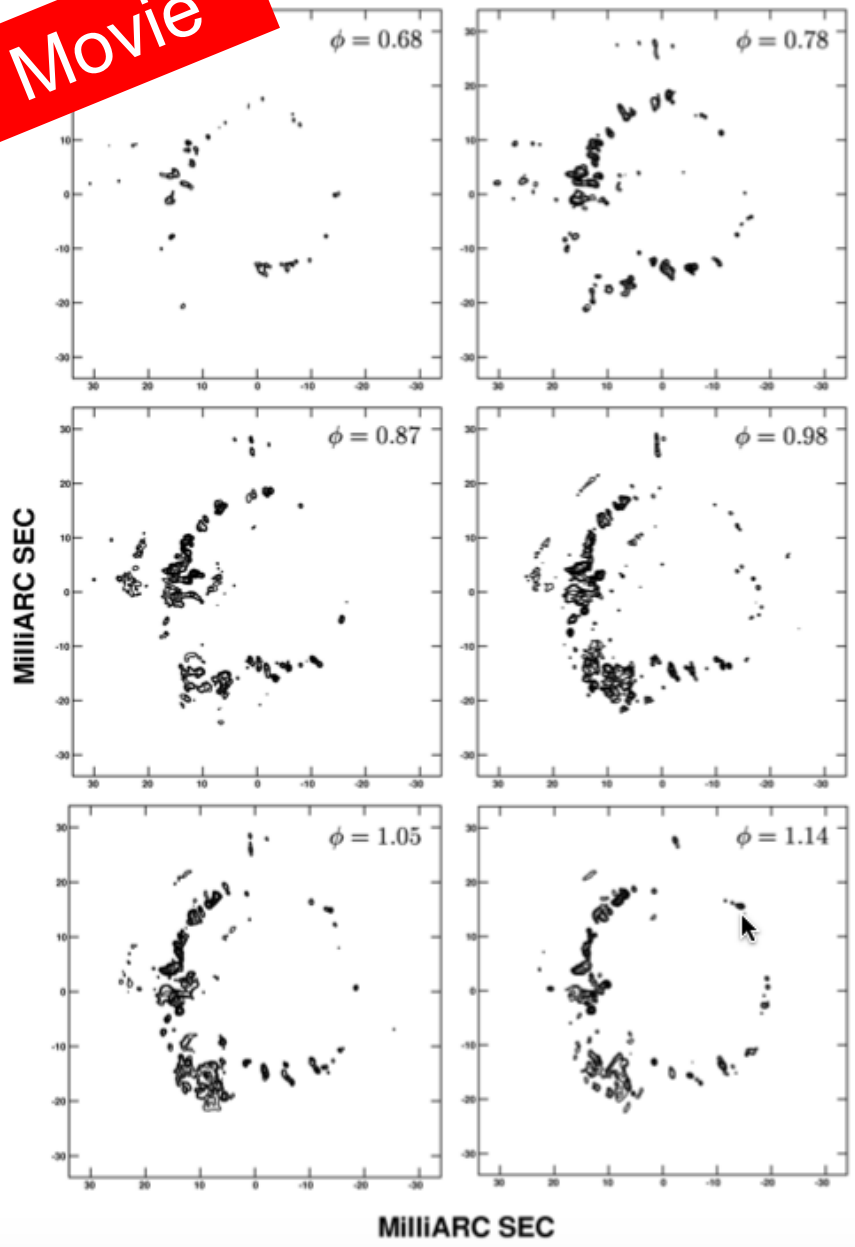


Reid & Menten 1991, 2007

TX Cam

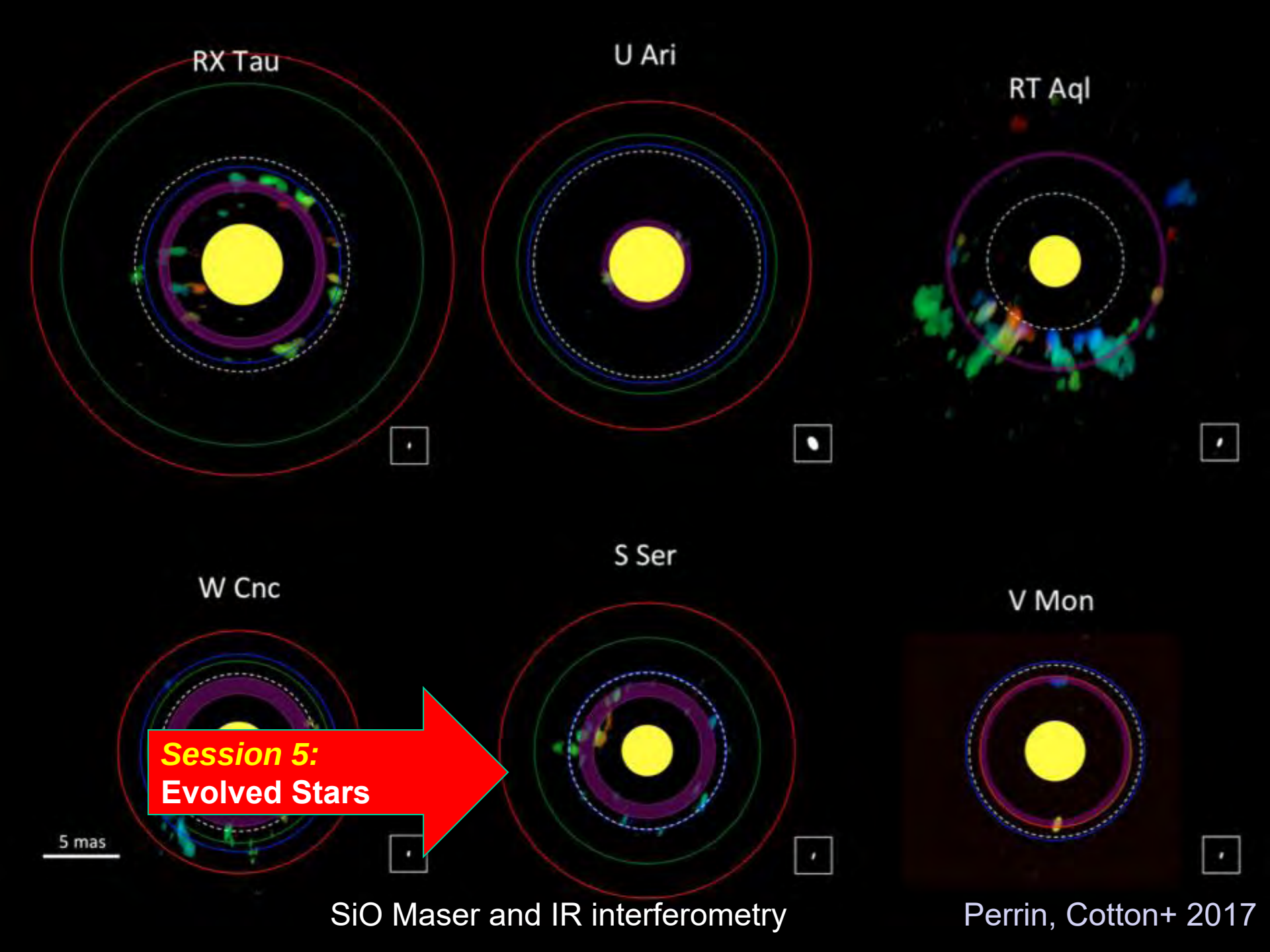
The Movie





Diamond+ 1994

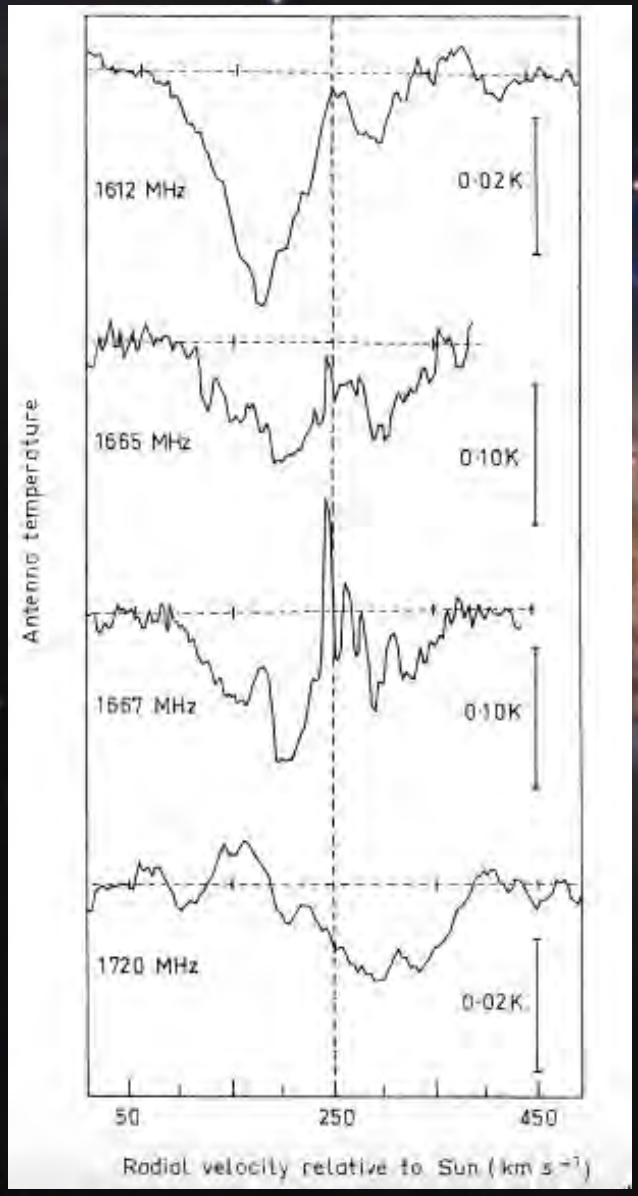
Kemball+ 2003



SiO Maser and IR interferometry

Perrin, Cotton+ 2017

OH in NGC 253



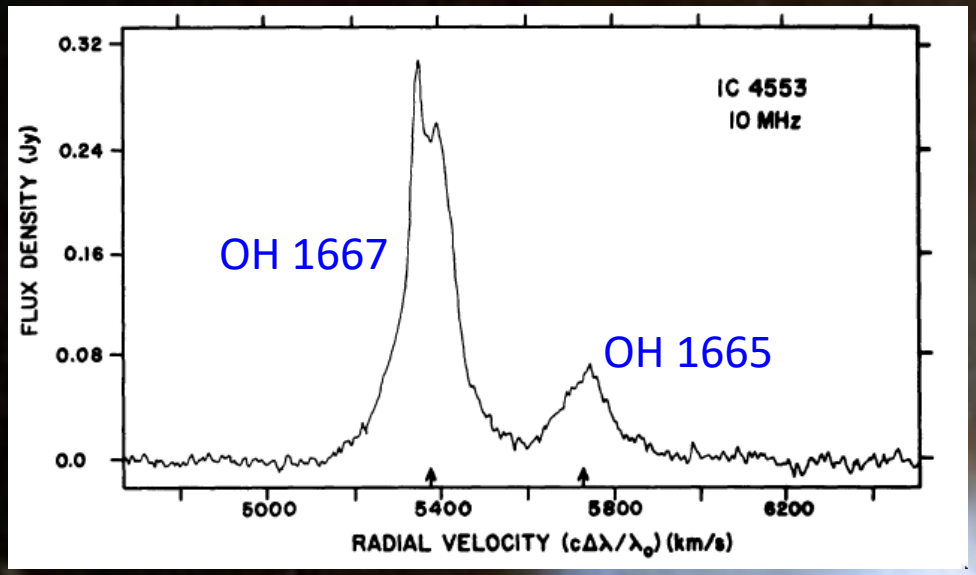
Gardner & Whiteoak 1975

Talk by S. Ellingsen

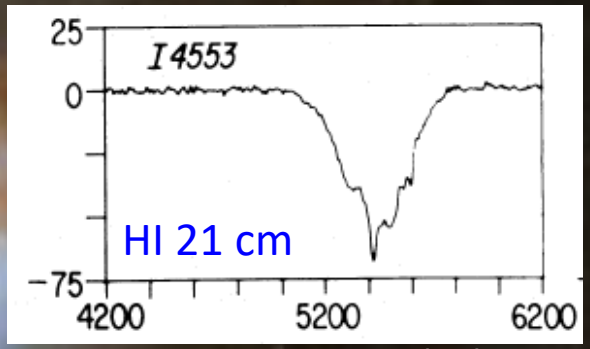
OH in Arp 220

D = 75 Mpc!





Baan, Wood & Haschick 1982



Mirabel1982

ABSTRACT

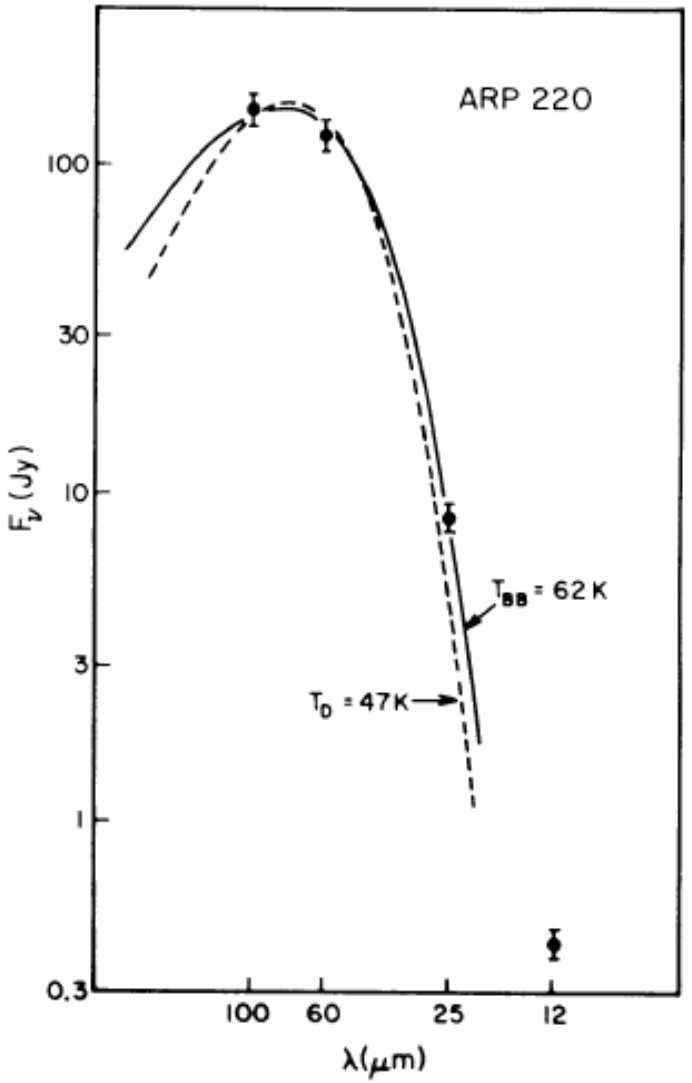
The main line transitions of hydroxyl (OH) have been detected in emission in the peculiar galaxy IC 4553. The 1667 and 1665 MHz transitions appear in a ratio of 4.2:1, and both have a radial velocity of 5375 km s^{-1} and a full width at half-maximum of 108 km s^{-1}. This is the first detection of broad OH emission in an external galaxy. The features probably are due to stimulated emission from many H II/OH masers in the active nuclear region of the galaxy. It is suggested that IC 4553 is a starburst galaxy.

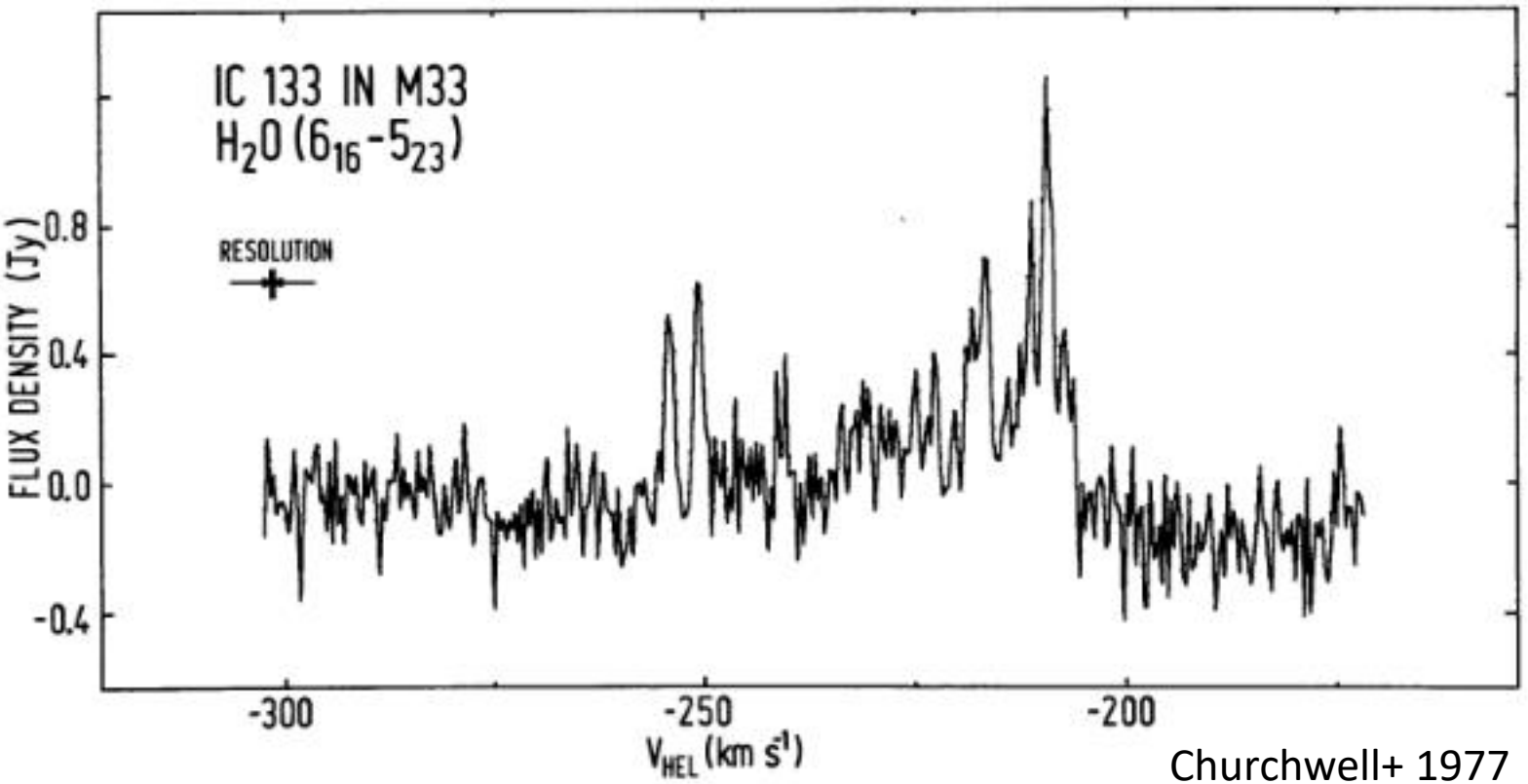
THE REMARKABLE INFRARED GALAXY ARP 220 = IC 4553

B. T. SOIFER,[1] GEORGE HELOU,[2] CAROL J. LONSDALE,[2] G. NEUGEBAUER,[1] P. HACKING,[2] J. R. HOUCK,[3]
F. J. LOW,[4] W. RICE,[2] AND M. ROWAN-ROBINSON[5] 1984

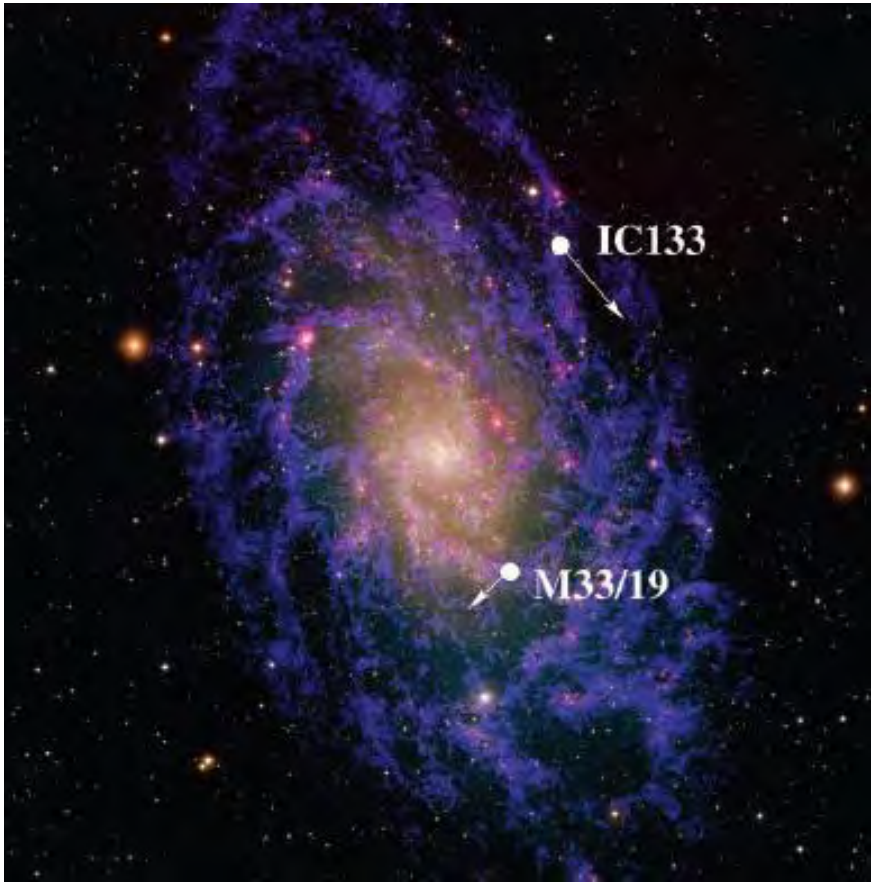
The first ULIRG:

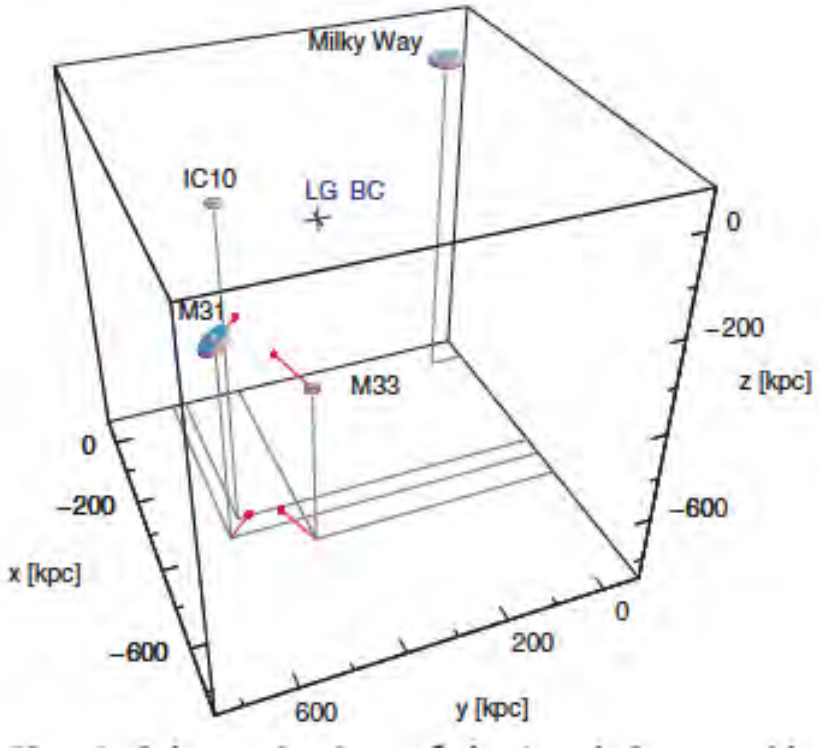
$$L = 2 \acute{} \ 10^{12} L_{Sun}$$





Churchwell+ 1977





Brunthaler+ 2005 Science

$L \sim 10L$(W49N)

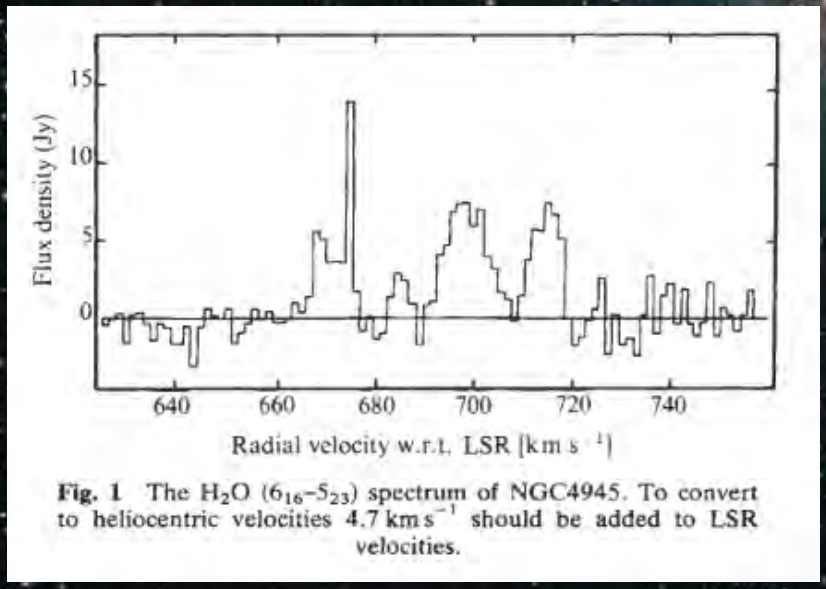
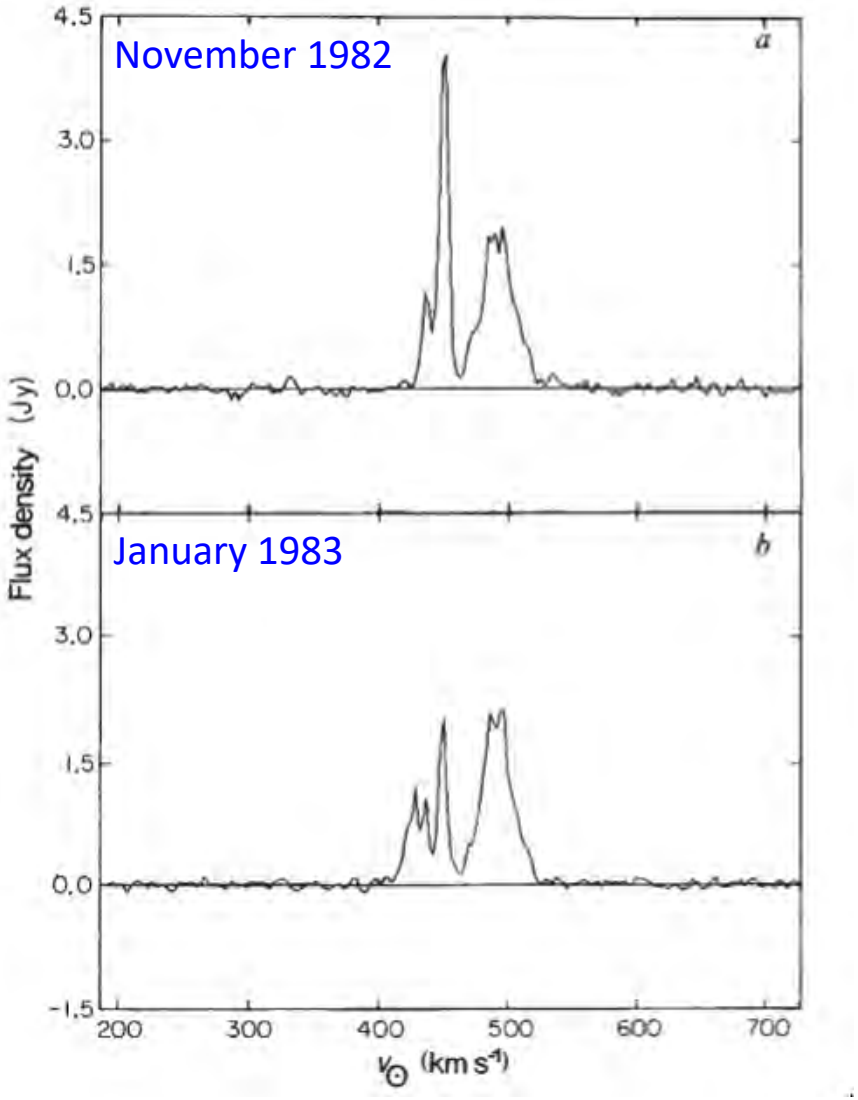


Fig. 1 The H_2O (6_{16}–5_{23}) spectrum of NGC4945. To convert to heliocentric velocities 4.7 km s^{-1} should be added to LSR velocities.

Dos Santos & Lepine 1979

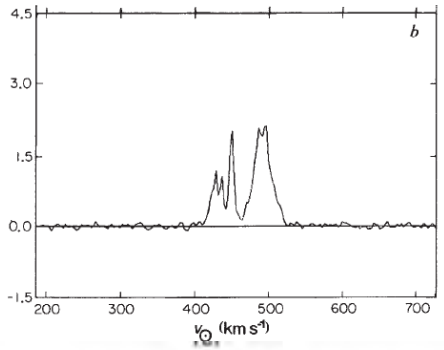
Masers in AGN

The 22.2 GHz H_2O line in NGC 4258

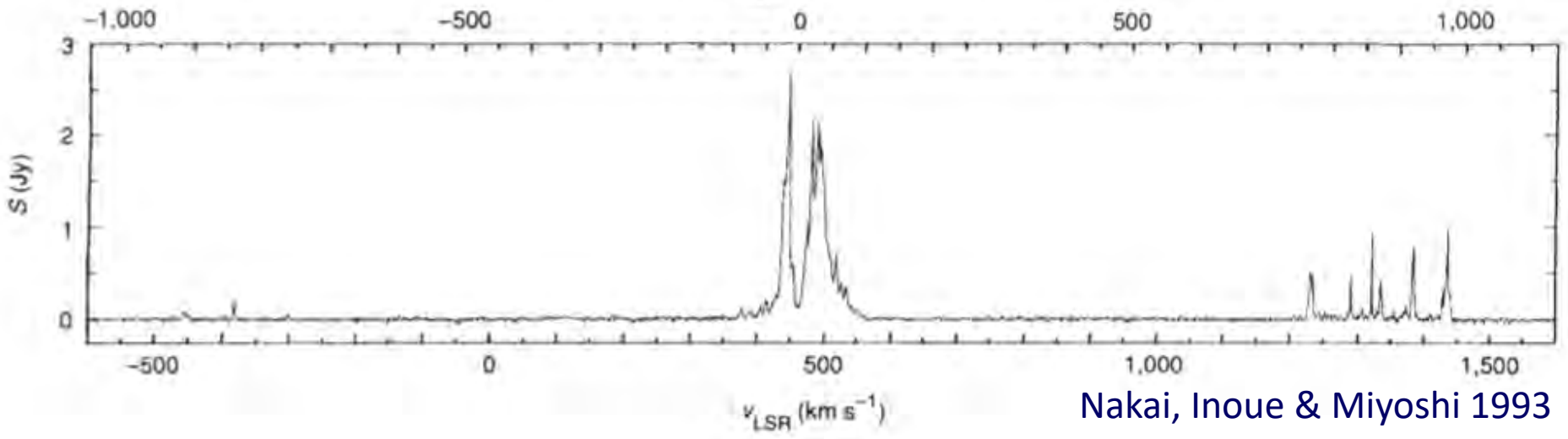


Claussen, Heiligman & Lo 1984

The 22.2 GHz H_2O line in NGC 4258



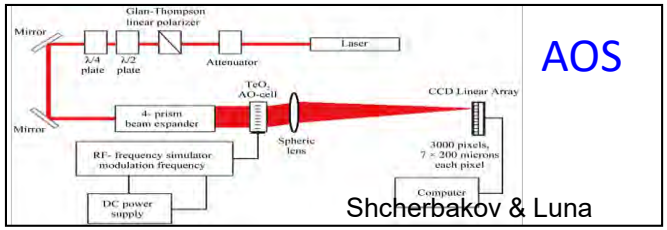
Claussen, Heiligman & Lo 1984



Nakai, Inoue & Miyoshi 1993

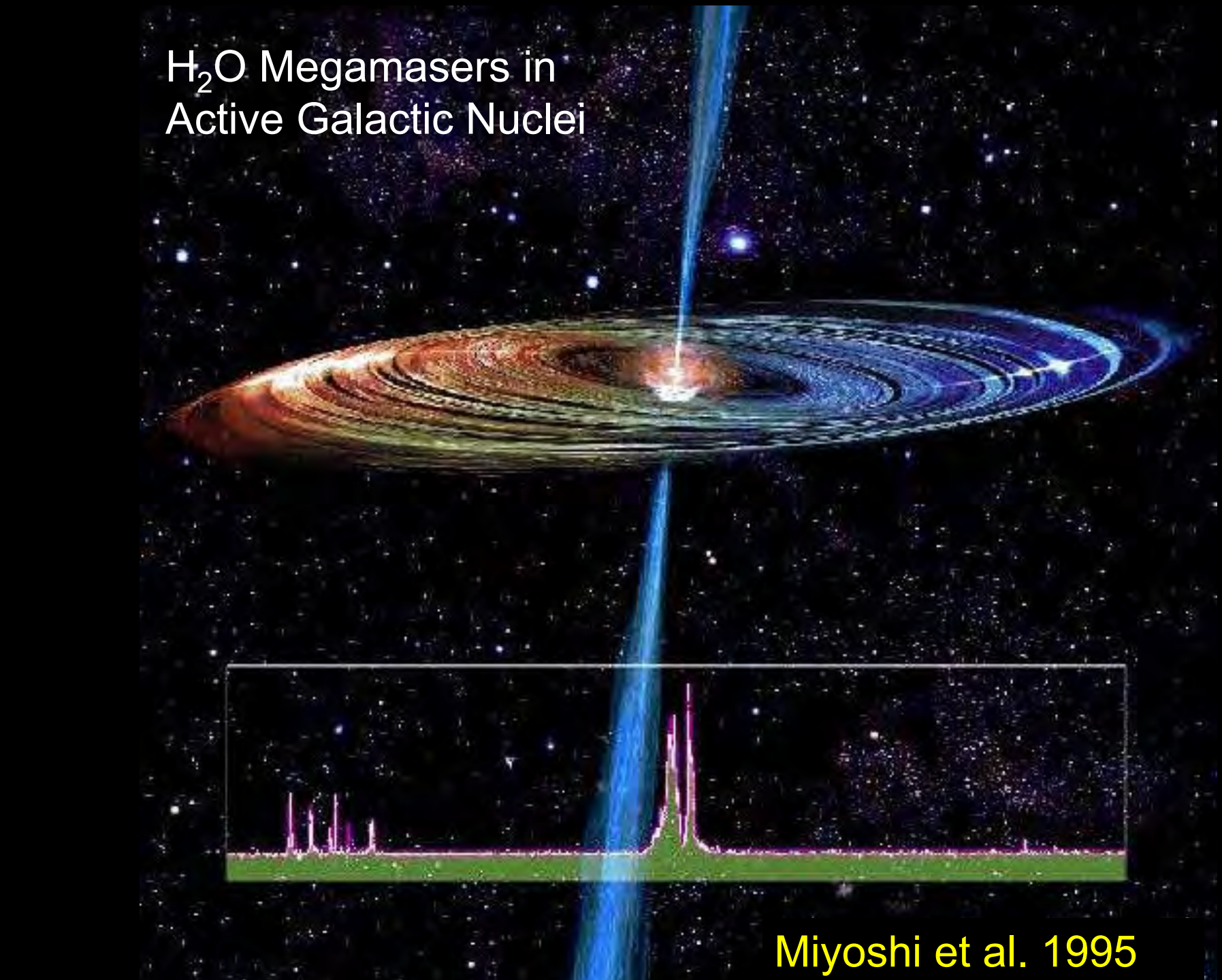


+

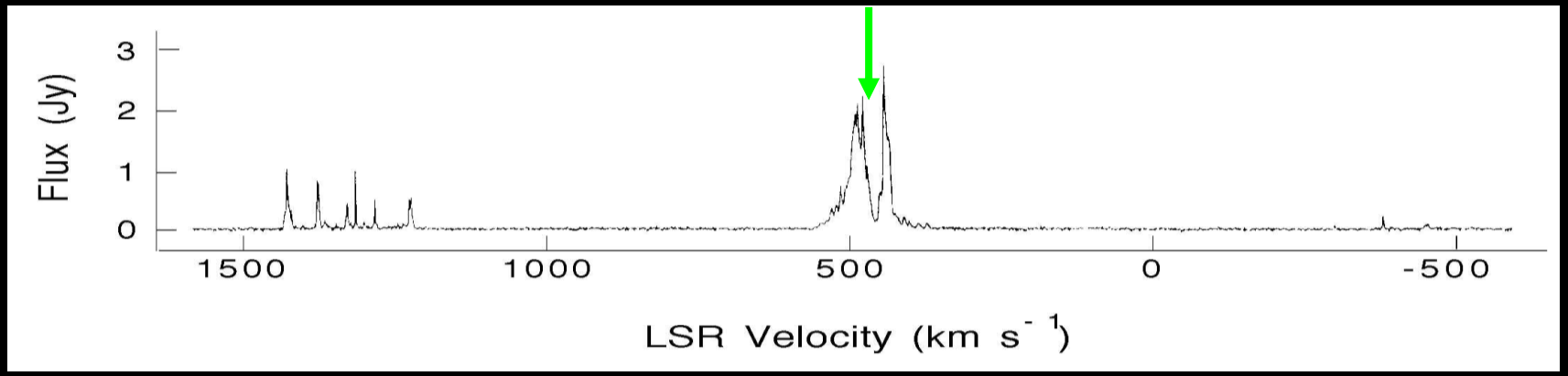


AOS

Shcherbakov & Luna


H_2O Megamasers in
Active Galactic Nuclei
Miyoshi et al. 1995

Very high velocities indicate rotation around a massive body



VLBI imaging determines positions of maser components

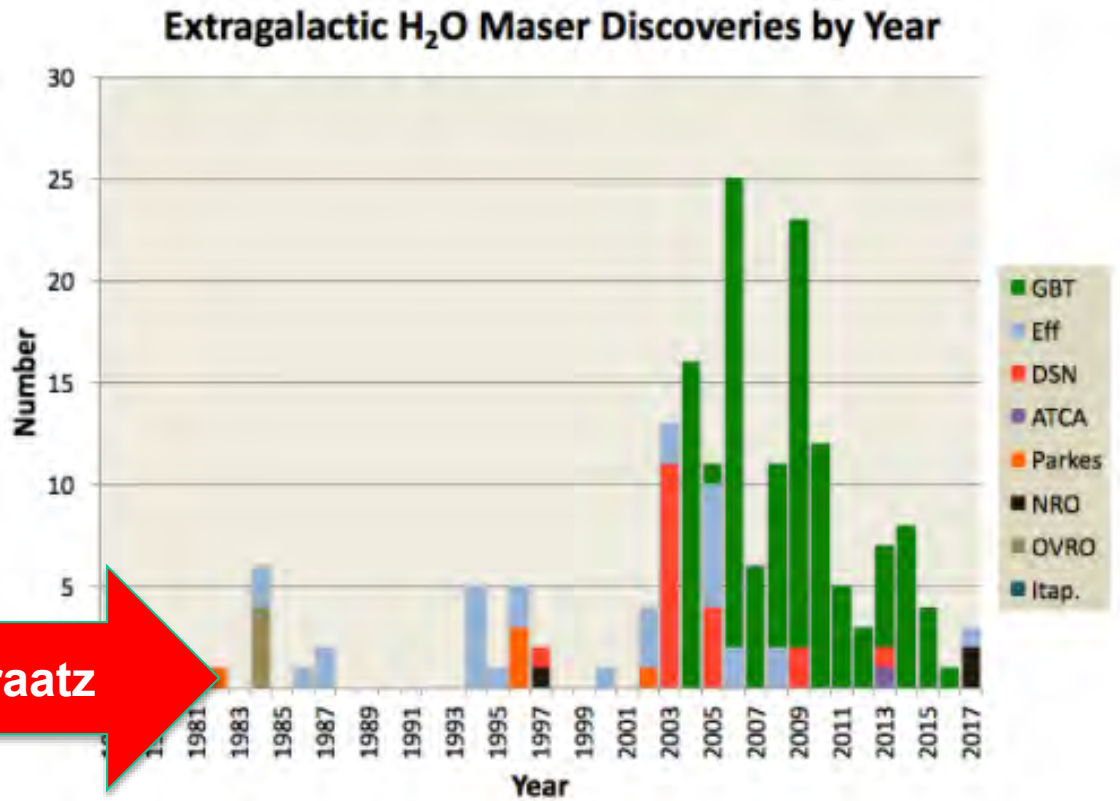


Greenhill+ 1997, Herrnstein+ 1977



Kwok-Yung (Fred) Lo
1947–2016

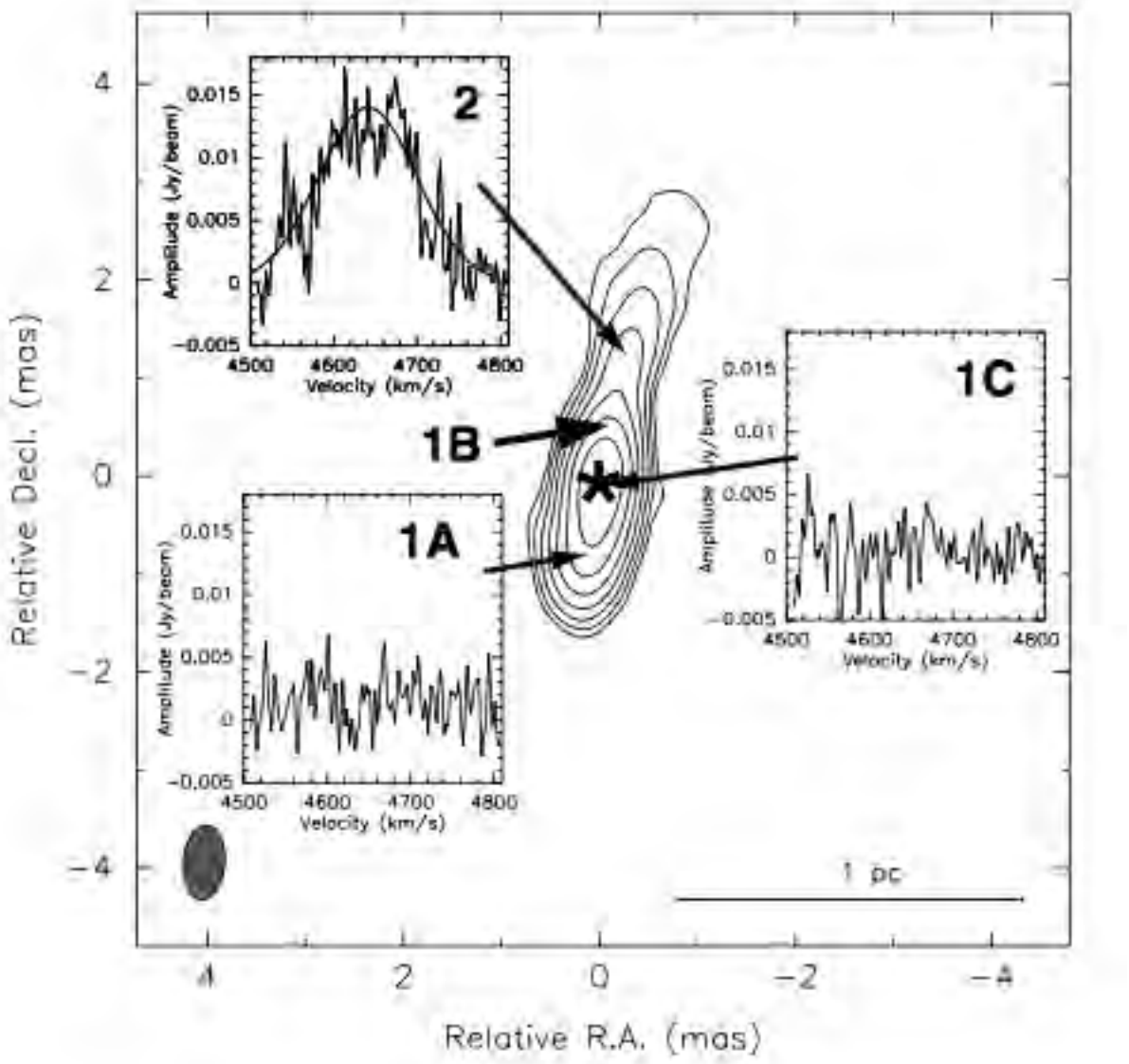
The Megamaser Cosmology Project



Talk by J. Braatz

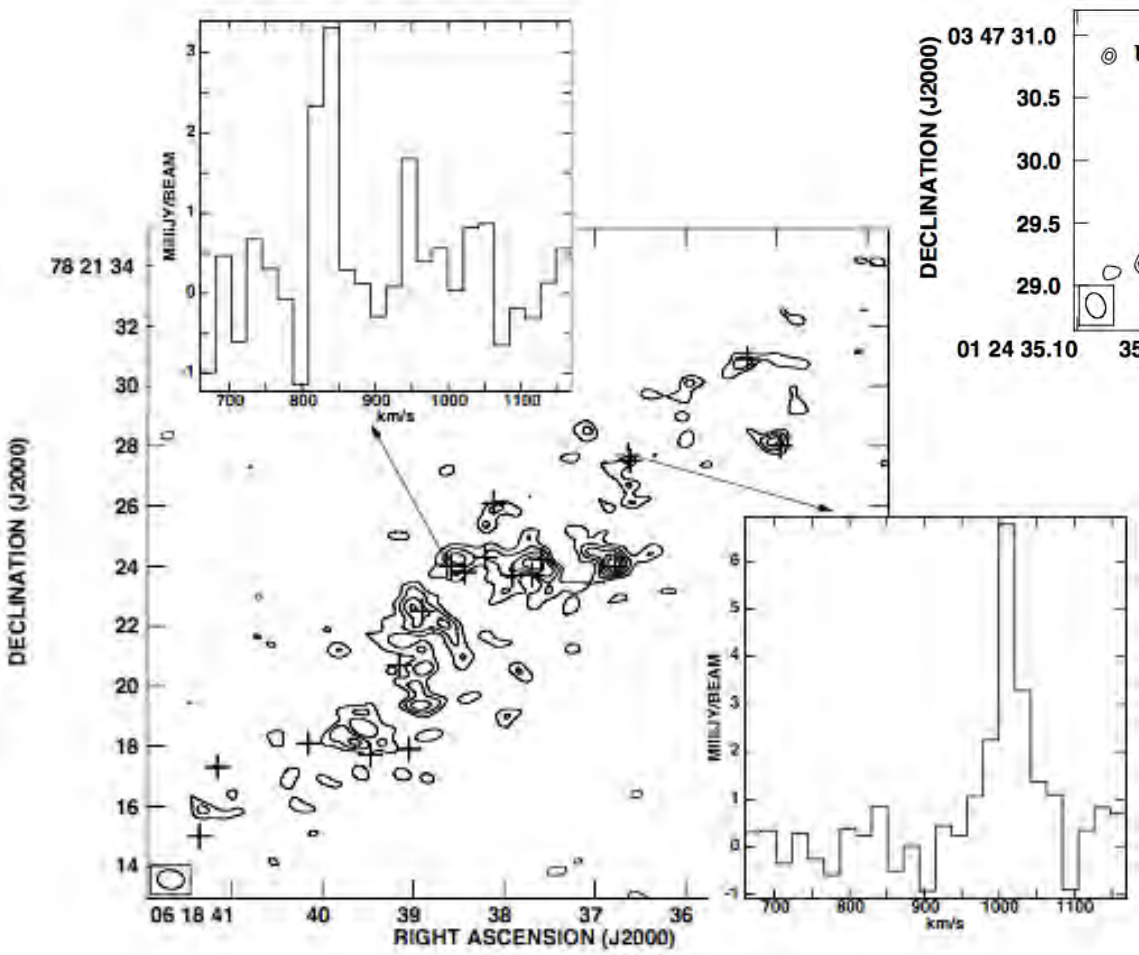
https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

Jet-driven H_2O Megamasers

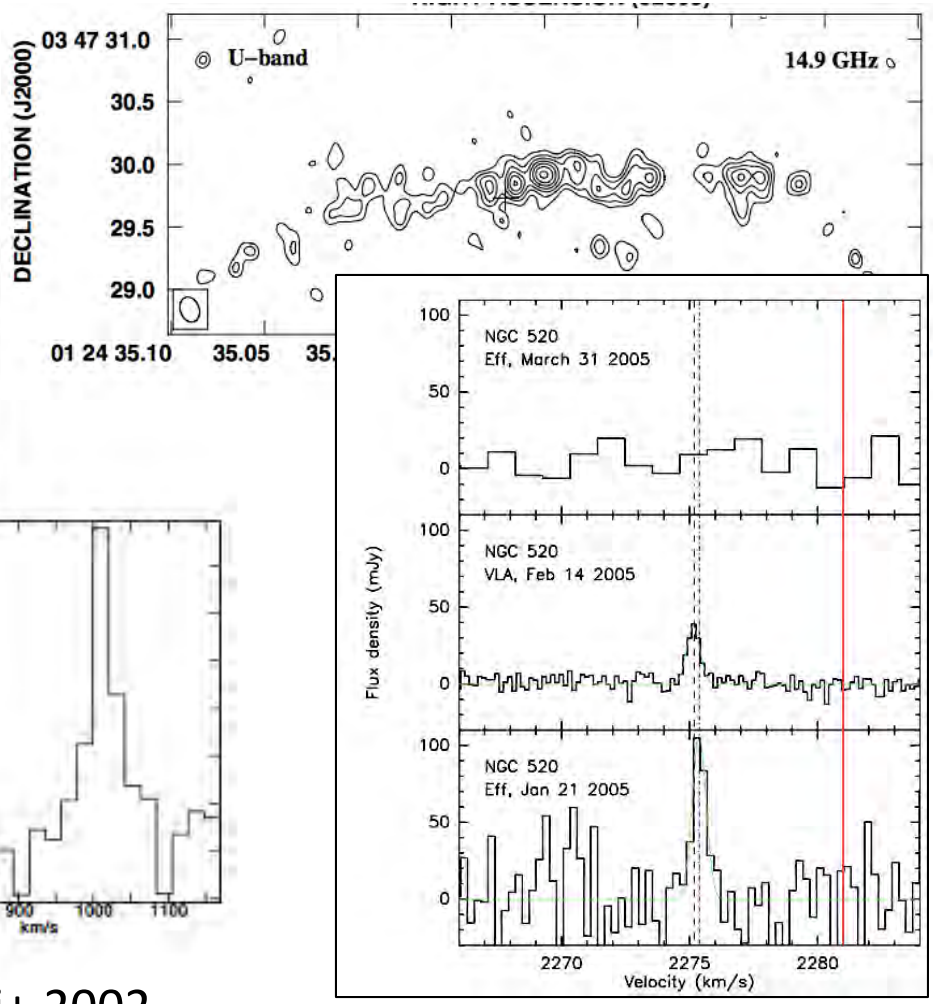


Peck+ 2003

H_2O Kilomasers in starburst galaxies



Tarchi+ 2002



Castangia+ 2008

Time Domain Maser Astronomy

Periodic Class II CH_3OH Masers

First discovered with **Hartebeesthoek 26 meter telescope**

- S. Goedhart (2005 PhD thesis) + collaborators (M. Gaylard, J. van der Walt…)
- 8 year time series:
  - 6 periodic sources
  - periods ~133 d–504 d

Many more now, periods down to ~20 d

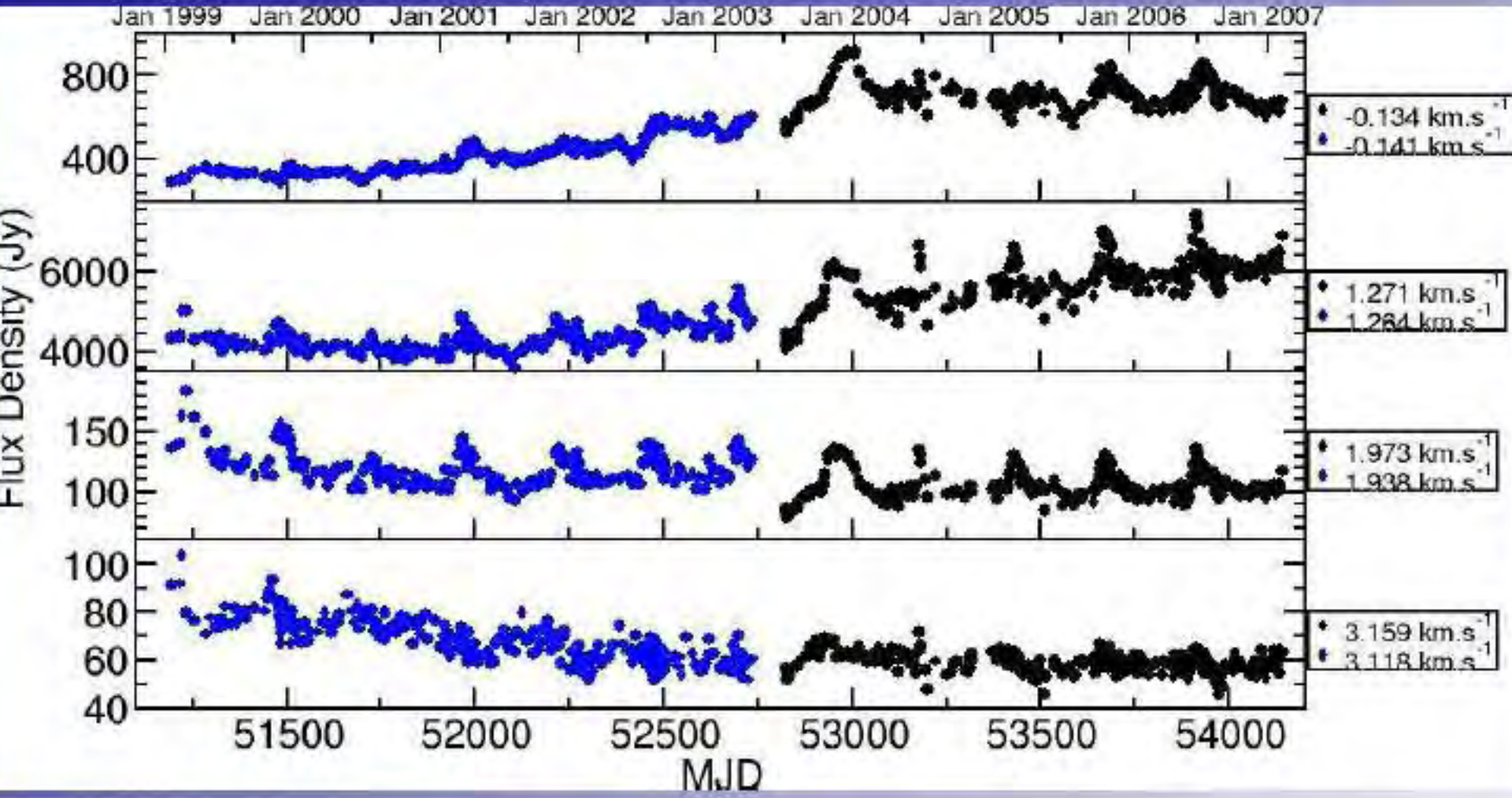


Methanol Maser Sources with Periodic Variability

Source	P_{met}	D_{src}	L_{IRAS}	References	
				P	*D*
(Galactic Name)	(days)	(kpc)	($10^4\ L_\odot$)		
009.621+0.196	244	5.2	30.0	1	6
012.681−0.182	307	4.5	4.2	2	7
012.889+0.489	29.5	2.34	2.0	3	8
022.357+0.066	179.2	4.6	2.4	4	9
037.550+0.200	237	5.0	4.5	5	9
188.946+0.886	404	2.10	1.2	1	10
196.454−1.677	668	5.28	10.2	2	11
328.237−0.547	220	12.0	117.2	1	9
331.132−0.244	504	4.7	6.2	1	7
338.935−0.062	133	2.9	3.8	1	9
339.622−0.121	201	2.6	1.6	1	9

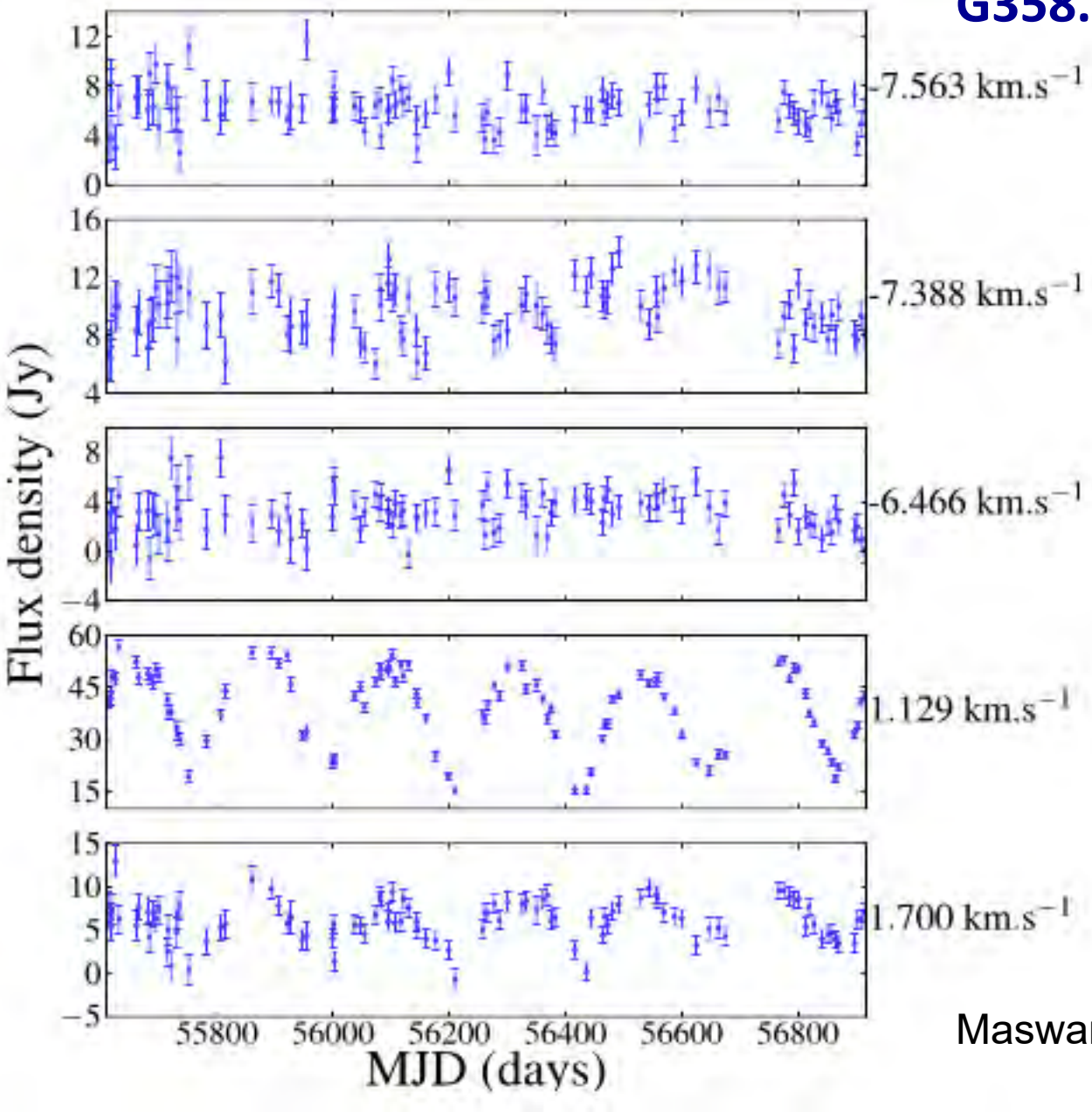
Compilation:
Inayoshi et al. 2013

G9.62+0.20: Time Series



S. Goedhart

G358.460-0.391

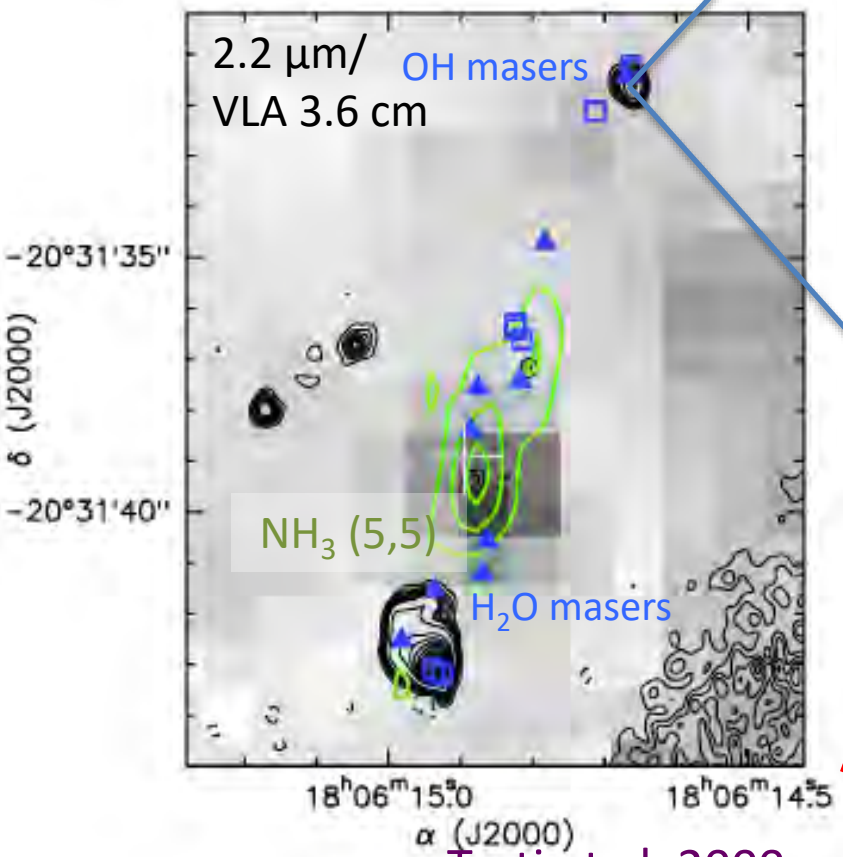


Maswanganye+ 2015

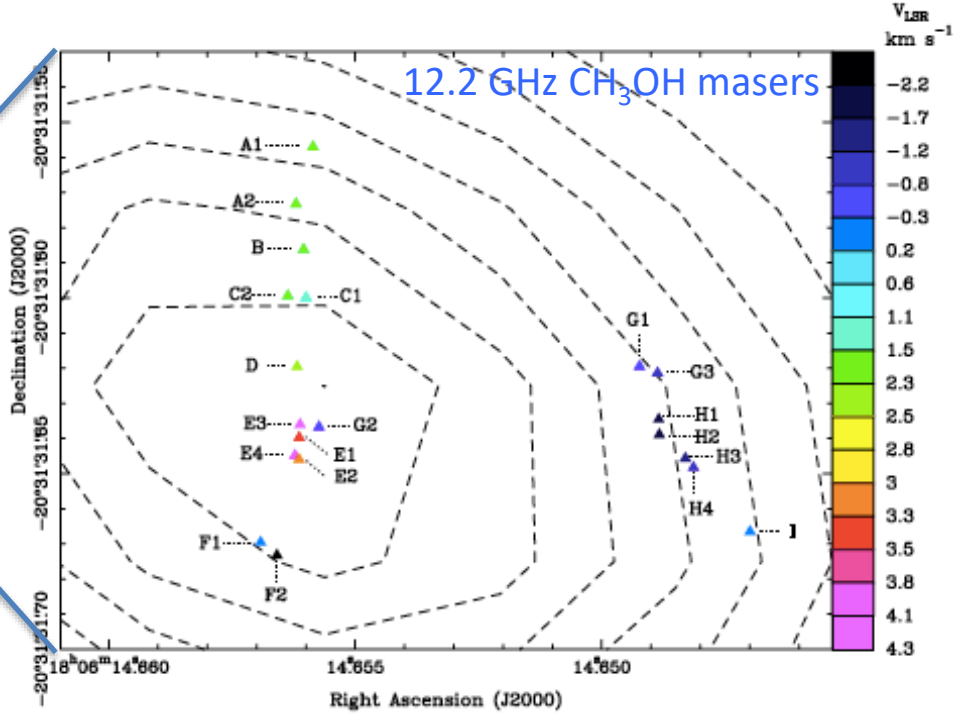
Goedhart et al. (2005) VLBA multi-epoch imaging:

maser components. It was found that while existing maser spots increased in flux density, no new spots developed and no changes in morphology were observed. This rules out any mechanism which disturbs the masing region itself, implying that the flares are caused by a change in either the seed or pump photon levels. A time delay of one to two weeks was observed

G9.62+0.19

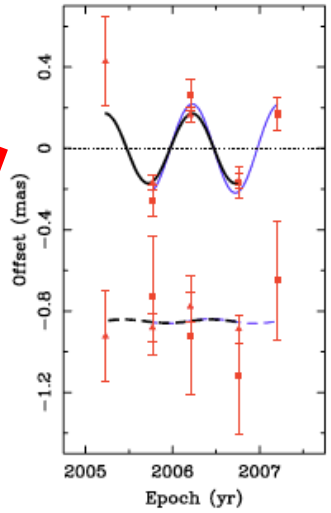


Testi et al. 2000



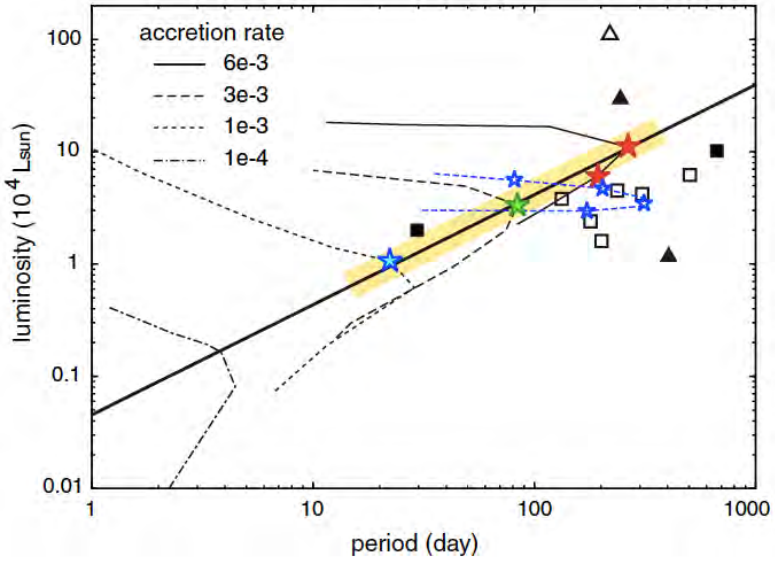
Sanna et al. 2013

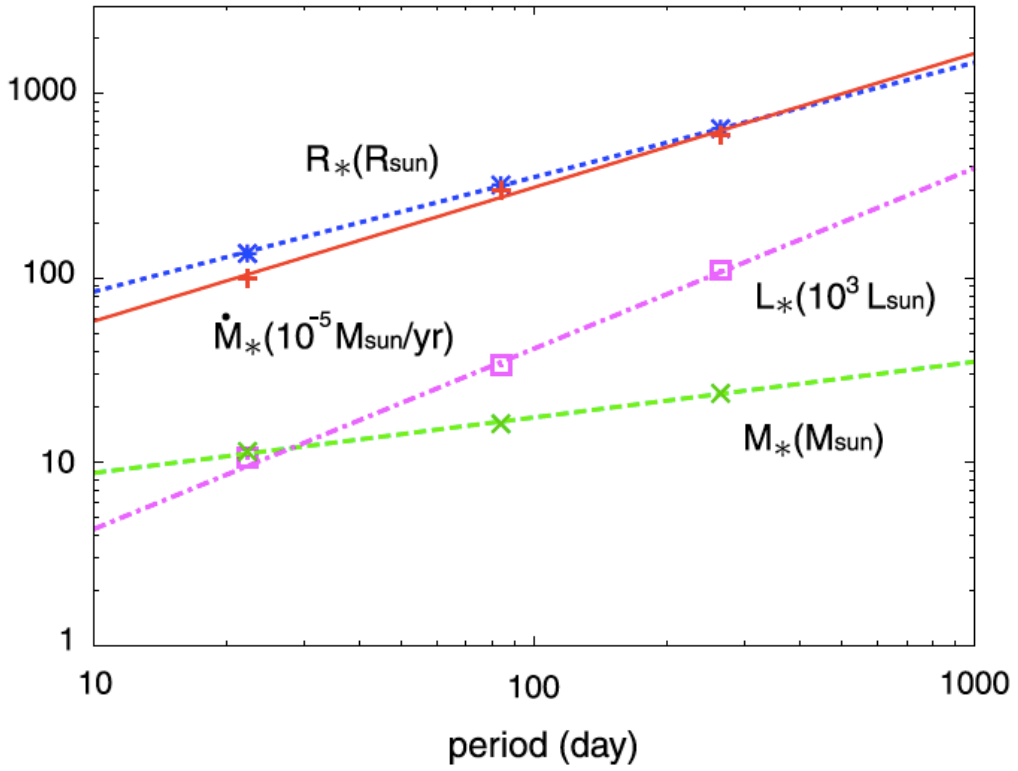
BeSSeL
D = 5.2 +/-0.6 kpc
Sanna et al. 2009



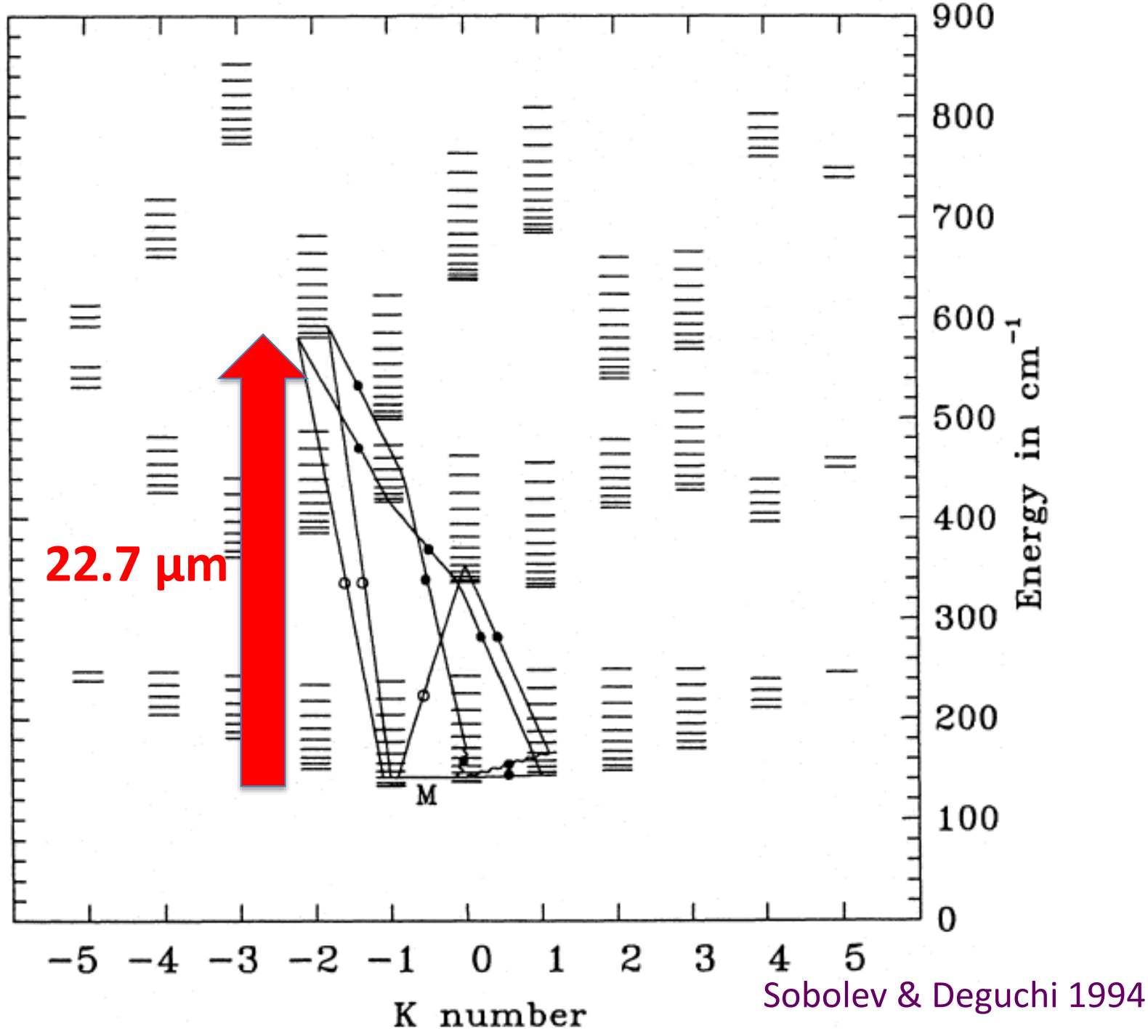
Earlier VLBI:
Minier, Booth, Conway et al. 2001–2002
Goedhart et al. 2003

Recently, **Inayoshi et al. (2013)** proposed that periodic variations of cIIMMs could be explained by the pulsation of massive protostars growing under rapid mass accretion with rates of $dM/dt > 10^{-3}\ M_{\odot}\ yr^{-1}$

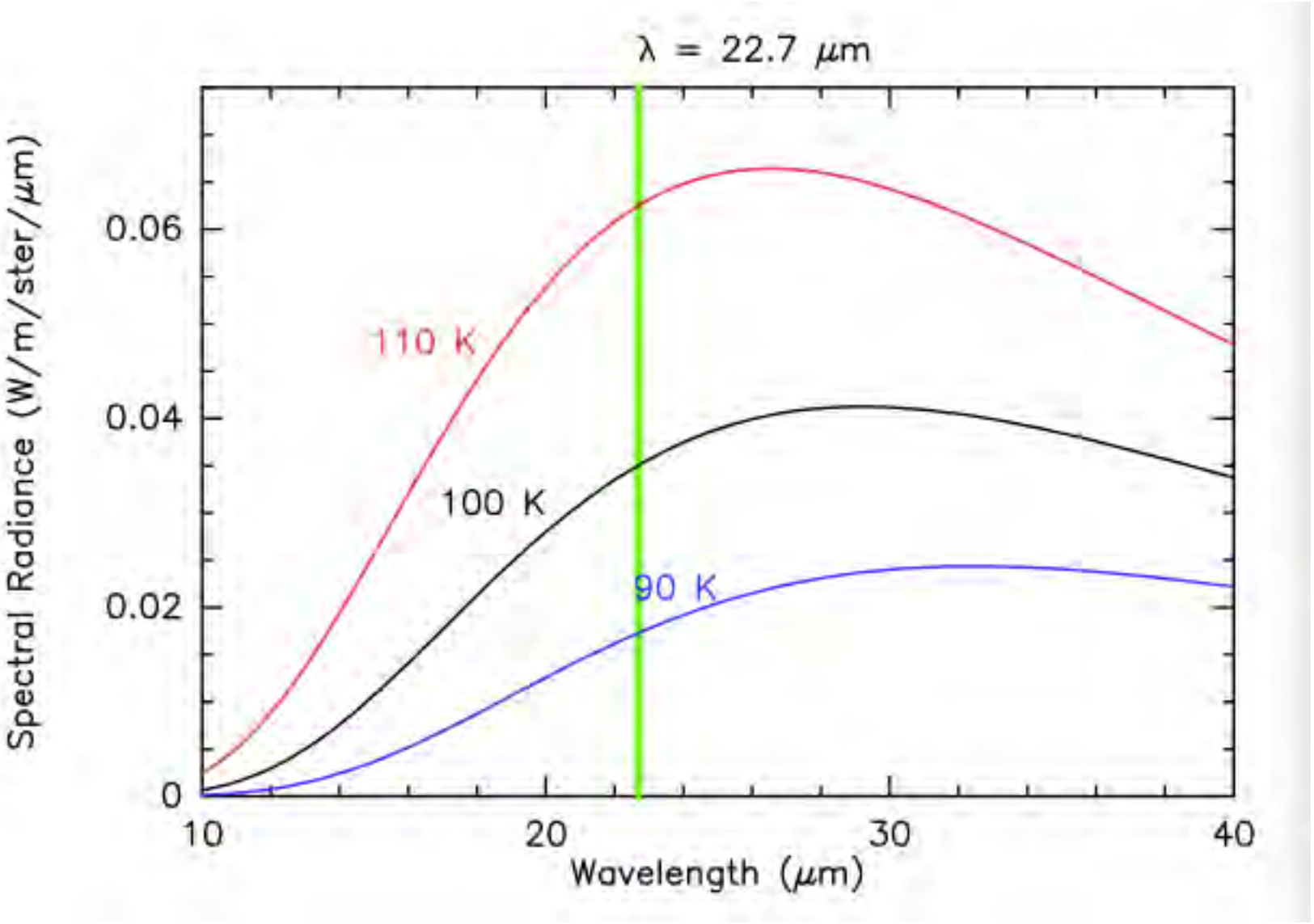




Periodic temperature and size change could be cause perio-dic change of pump *and* seed photons



Sobolev & Deguchi 1994


λ = 22.7 μm
Spectral Radiance (W/m/ster/μm)
0.06
0.04
0.02
0
110 K
100 K
90 K
10
20
30
40
Wavelength (μm)

Goedhart et al. (2005) VLBA multi-epoch imaging:

maser components. It was found that while existing maser spots increased in flux density, no new spots developed and no changes in morphology were observed. This rules out any mechanism which disturbs the masing region itself, implying that the flares are caused by a change in either the seed or pump photon levels. A time delay of one to two weeks was observed

Maybe both!

HMPOs: Critical Questions:

- Is radio emission from an HMPO thermal or non-thermal (or both)?
- If thermal:
  - Is it HII region-like free-free emission? → T ~10000K
  - Is it (late-type) stellar (radio- photosphere-like emission? → T ~ 3000K

Answer: Only(!) from VLBI+SKA-mid

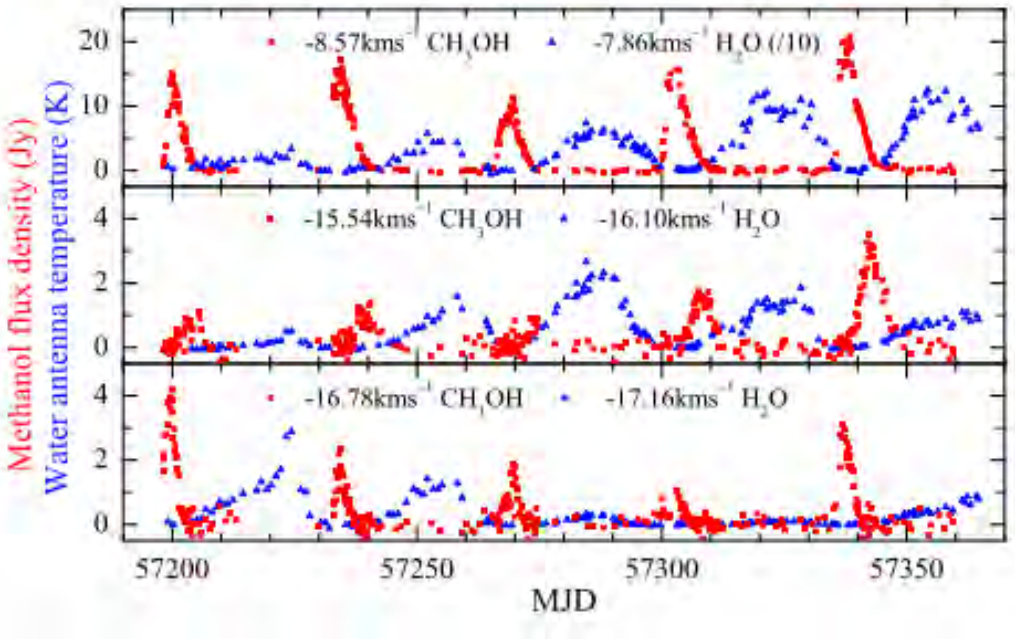
S_{rms} (μjy)	f (GHz)	θ_{FWHM} (mas)	ΔT_B (K)	B (km)
0.72	3	10	979	2061
0.72	15	10	39	412
0.72	15	2	979	2062

Discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639

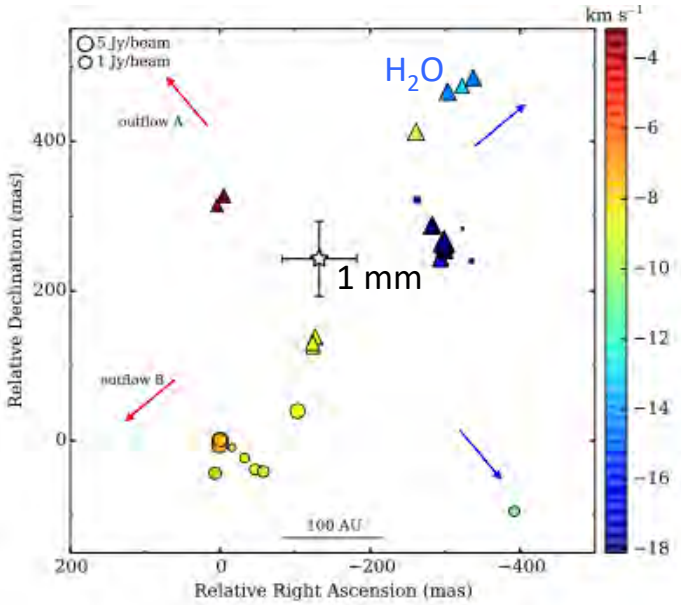
M. Szymczak,* M. Olech, P. Wolak, A. Bartkiewicz and M. Gawroński

Centre for Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, PL-87-100 Torun, Poland

MNRAS 2016



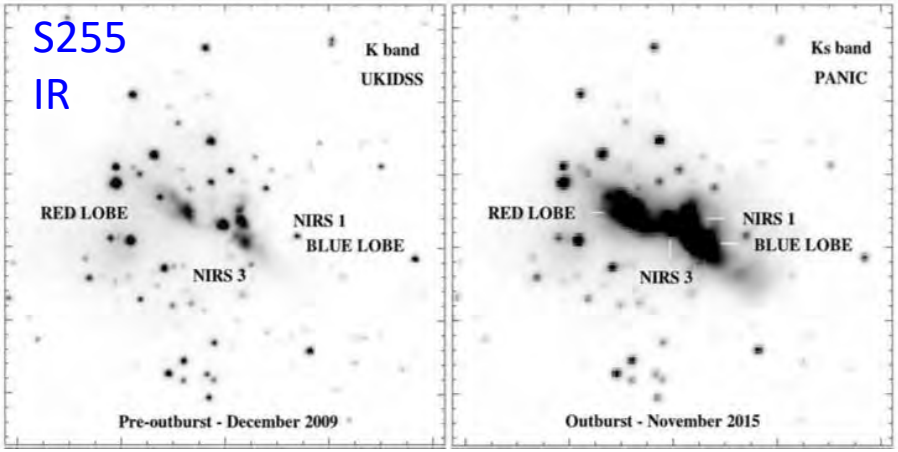
Talk by M. Szymczak

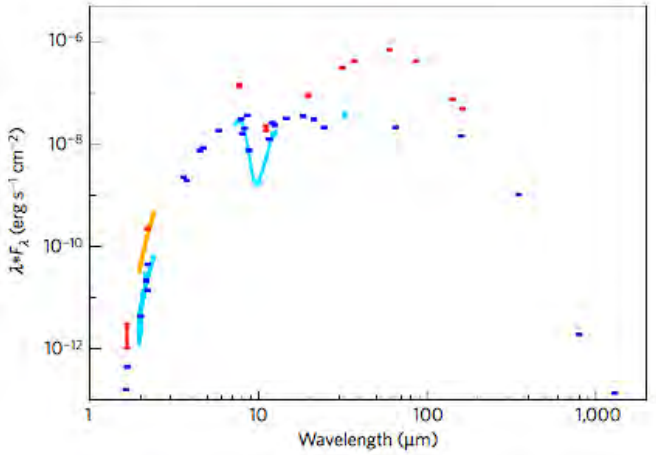


Maser monitoring can have big pay-off!!

Recently discovered strong outburst of high mass YSO were accompanied (even preempted?) by very strong maser outbursts

Factor ~10 increase in L_{bol}



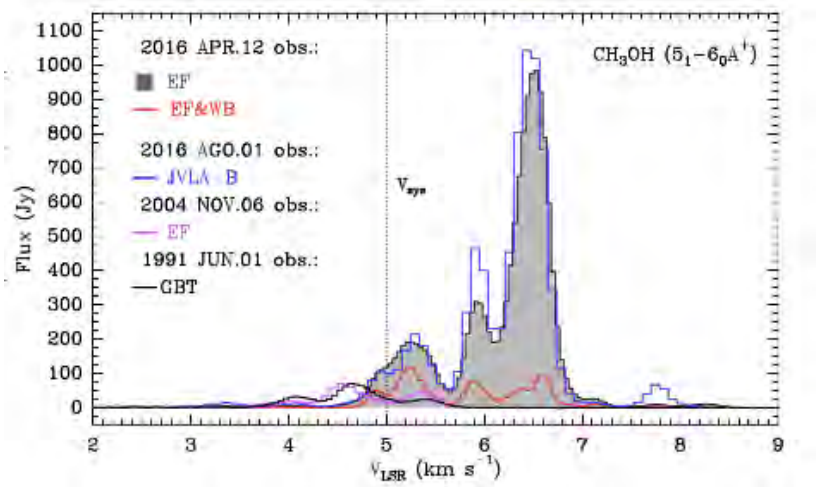


Caratti o Garatti+ 2017

Nature Physics 2917 March

Talk by B. Stecklum

Moscadelli+ 2017

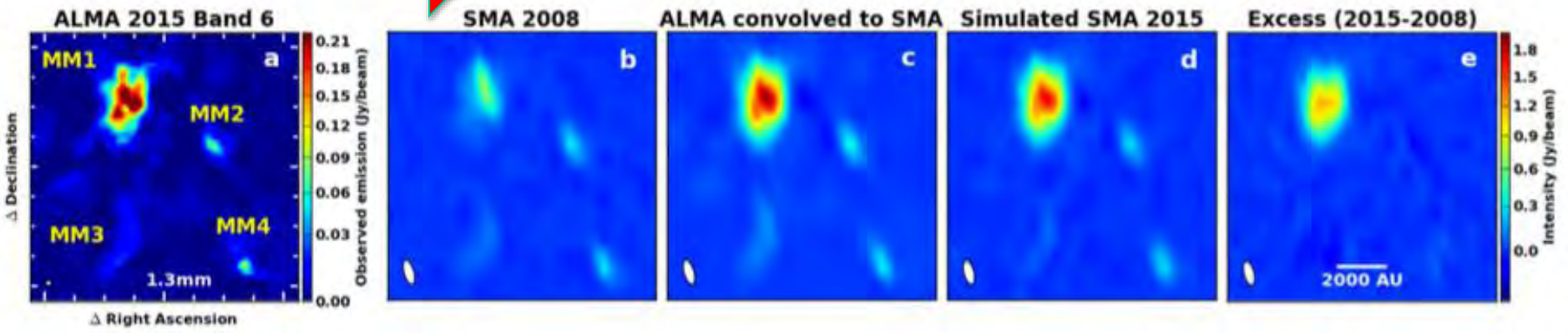


An Extraordinary Outburst in the Massive Protostellar System NGC 6334I-MM1: Quadrupling of the Millimeter Continuum

T. R. Hunter[1], C. Brogan[1], G. MacLeod[2], C. J. Cyganowski[3], C. J. Chandler[4], J. O. Chibueze[5,6,7], R. Friesen[8], R. Indebetouw[1,9], C. Thesner[7], and K. H. Young[10]

Talks by T. Hunter & C. Brogan

ApJ 2017 March

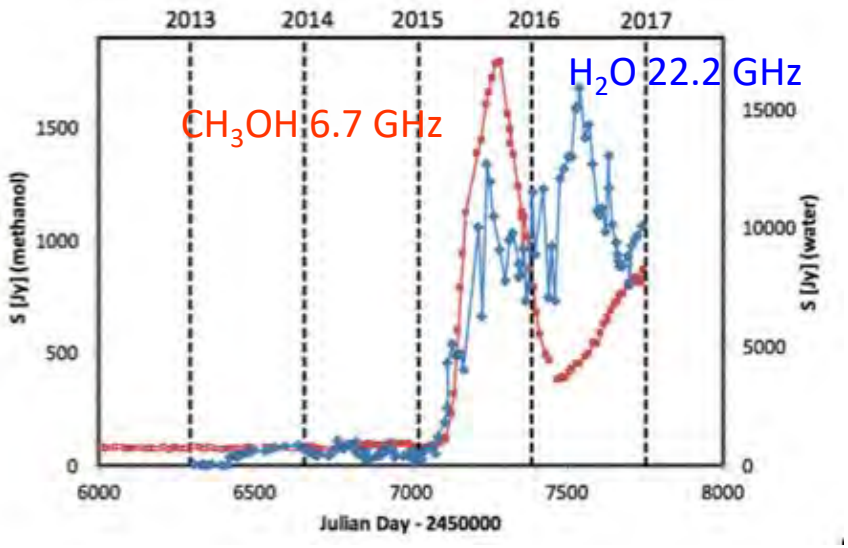


Luminosity surge by a factor ~70
← Sudden accretion event?

Persistent, long-term monitoring



Hartebeesthoek Radio Observatory 26m telescope



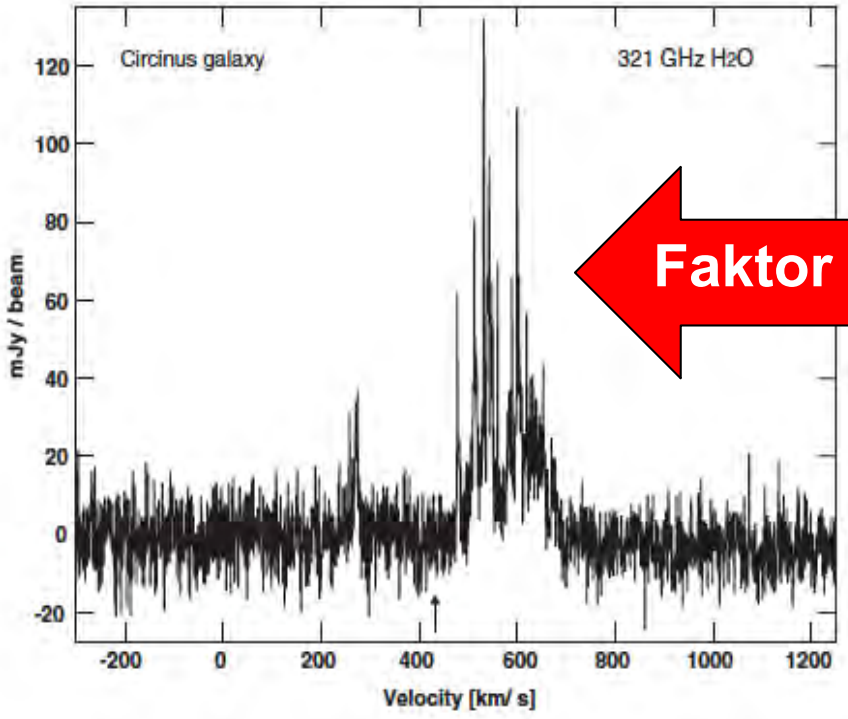




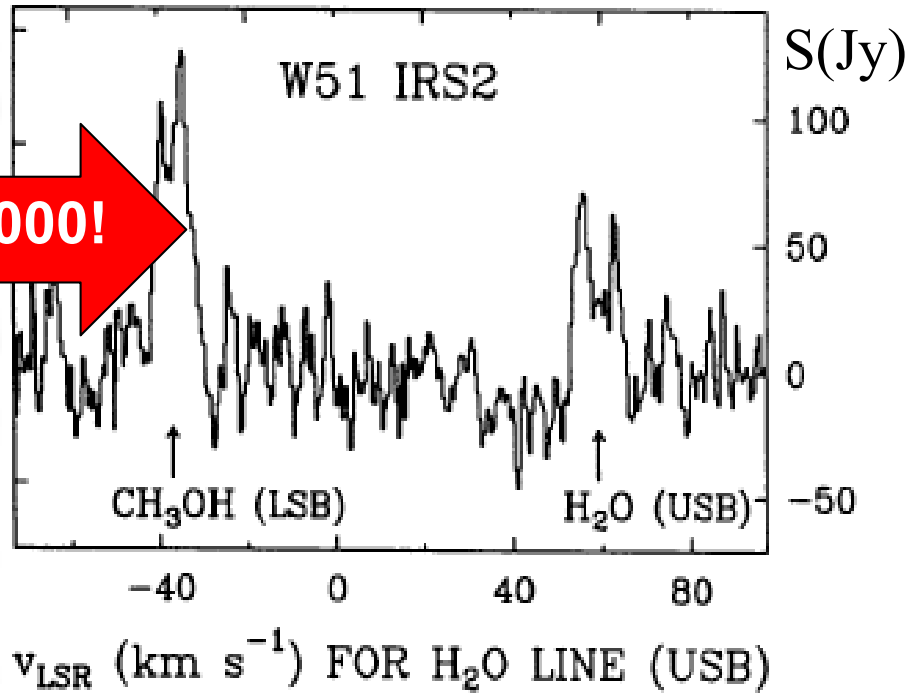
ALMA



Caltech Submillimeter Observatory 10.4 m (Mauna Kea)



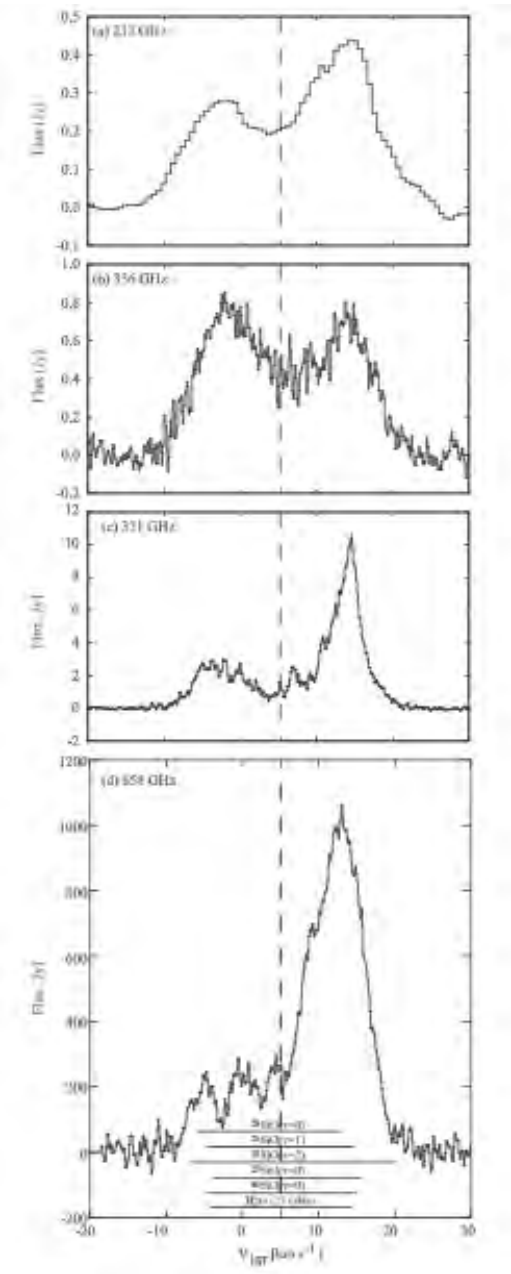
Faktor 1000!

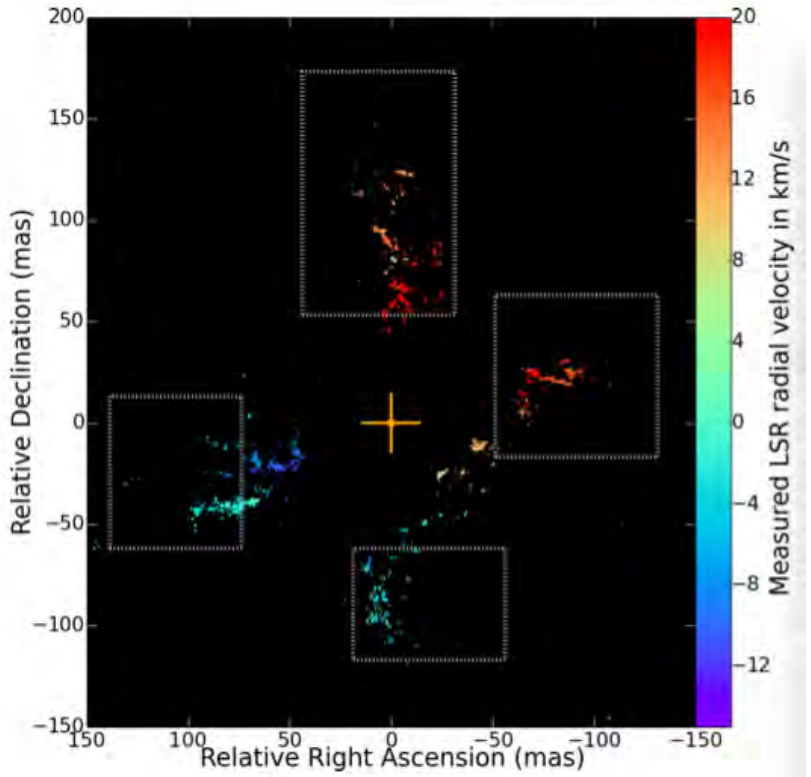


Hagiwara et al. 2013

Menten et al. 1990

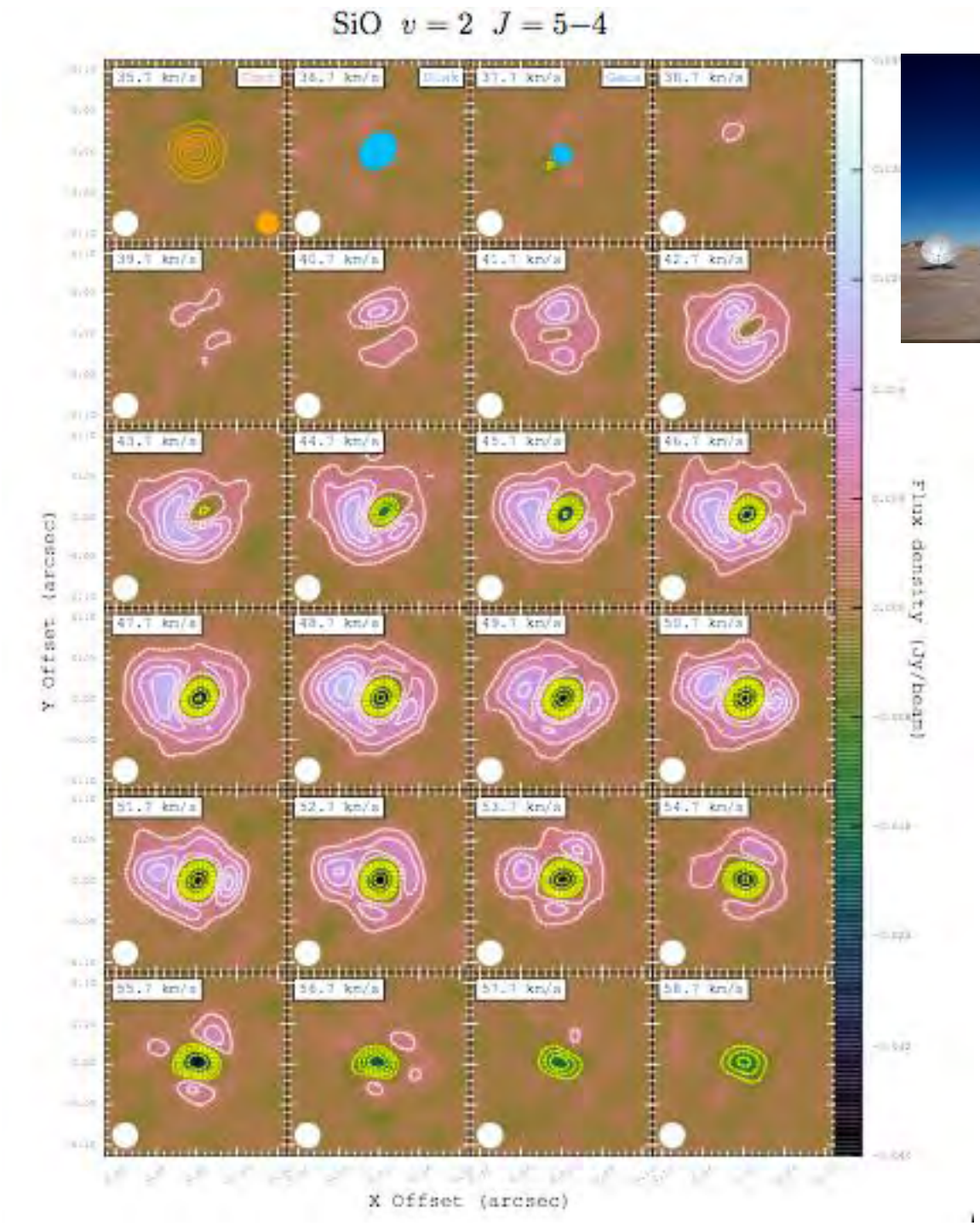
Orion-I





VLBA 3 mm SiO v=1,
J =1-0 imaging
Issaoun+ 2017

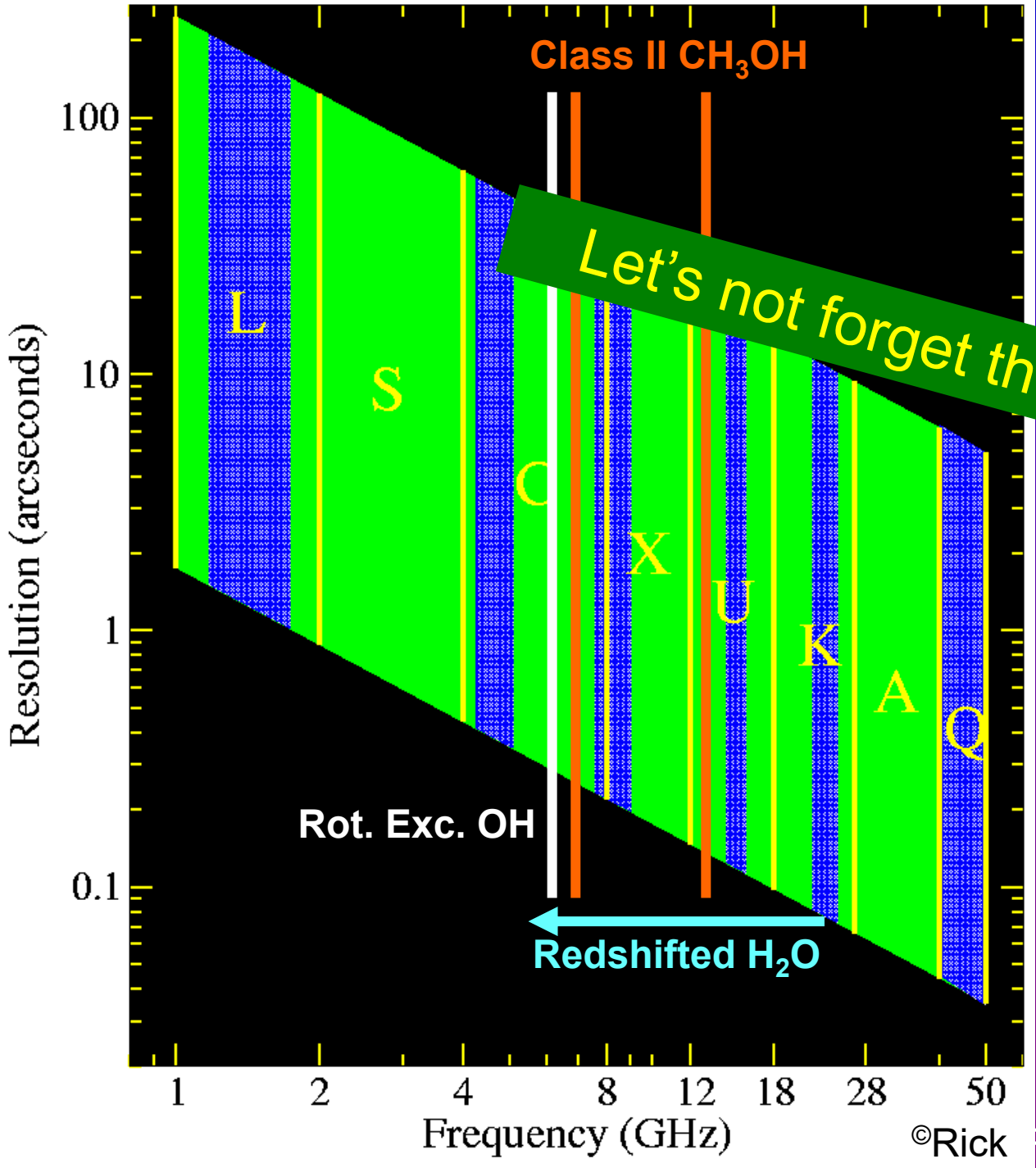
Submillimeter H_2O
maser lines
Hirota+ 2016



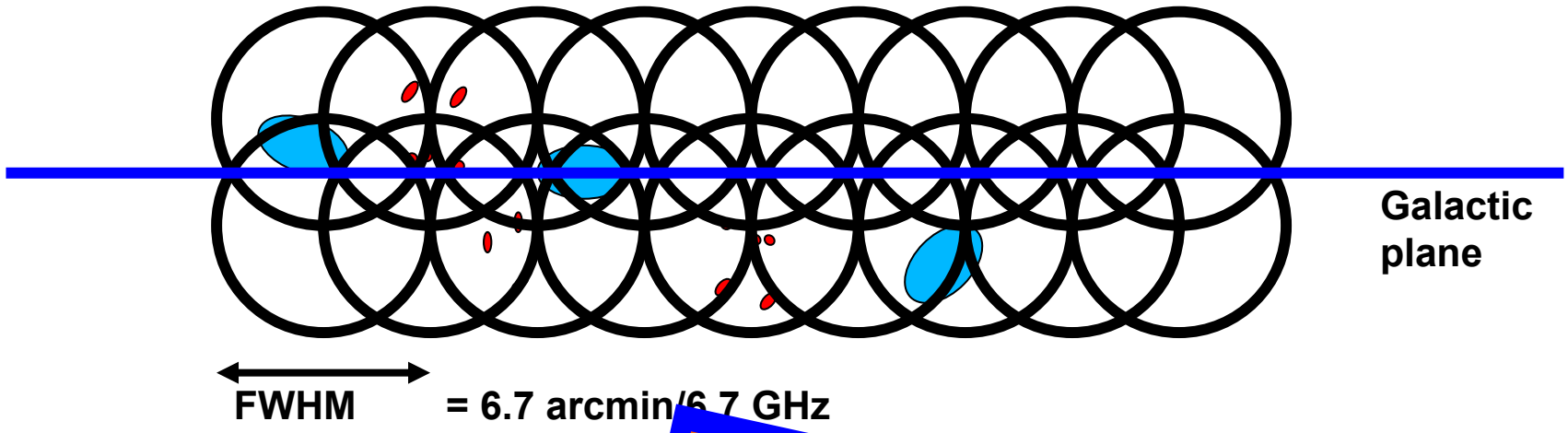


Mira (*o* Ceti)
Vibrationally excited SiO at 30 mas resolution
E/k ~3500 K

Wong+ 2016


Class II CH3OH
Let's not forget the JVLA!
L
S
C
X
U
K
A
Q
Rot. Exc. OH
Redshifted H2O
Resolution (arcseconds)
100
10
1
0.1
1
2
4
8
12
18
28
50
Frequency (GHz)
©Rick Perley@NRAO

A comprehensive star formation survey of the Galactic plane



rms (Δv = 0.1 km/s in 10 sec) = … blind survey)

rms (BW= 1 GHz in 10 sec) = …

Band 4 … 8 GHz → determine S…

JVLA B + D array + Effelsberg: θ_B~ 2 arcsec

PLUS: Do 6.7 GHz CH_3OH maser, RRLs, 4.8 GHz H_2CO absorption (+ emission) … SIMULTANEOUSLY!

GLOSTAR

A Global View of Star Formation in the Galaxy

4–8 GHz K. G. Jansky VLA Survey

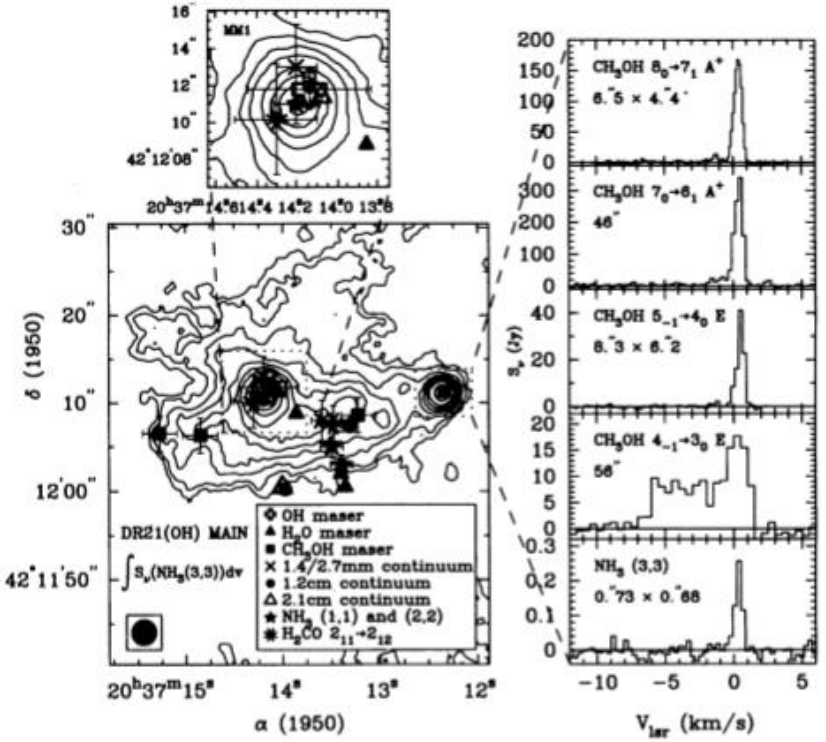
http://glostar.vlbi-astrometry.org

What's next?

- Keep the VLBA (LBO) going!
- BeSSeL South (Southern Milky Way CH_3OH maser trigonometric parallaxes)
- Monitoring with "real time" trigger
- High precision H_0 from Megamaser Cosmology Project
- Monitoring with "real time" trigger
- ALMA imaging of multiple H_2O lines
- …
- …

Curiosum: Only two known transitions have found to show maser action in space as well as in the laboratory

I. The NH_3 (J,K) = (3,3) inversion line



DISCOVERY OF $^{14}NH_3(3, 3)$ MASER EMISSION IN THE INTERSTELLAR MEDIUM

JEFFREY G. MANGUM
Submillimeter Telescope Observatory, Steward Observatory, University of Arizona, Tucson, AZ 85721
AND
ALWYN WOOTTEN
National Radio Astronomy Observatory,[1] 520 Edgemont Road, Charlottesville, VA 22903

Mangum & Wootten 1994

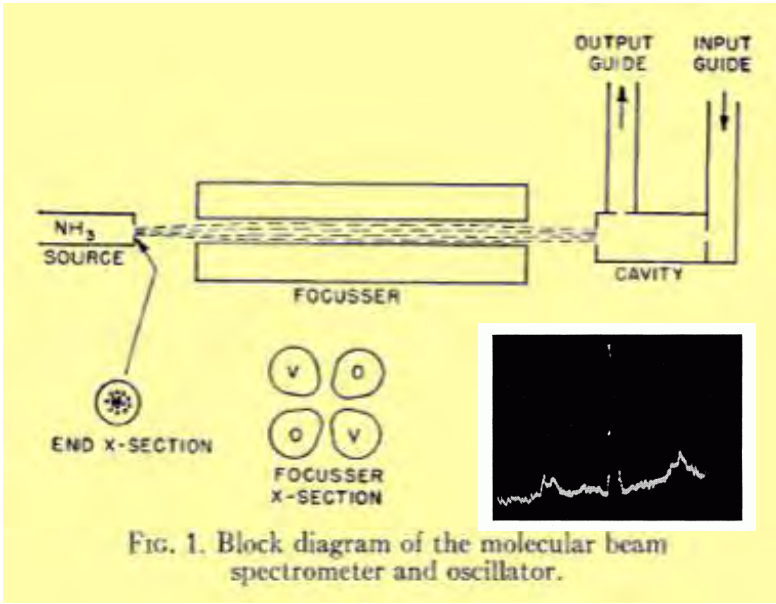
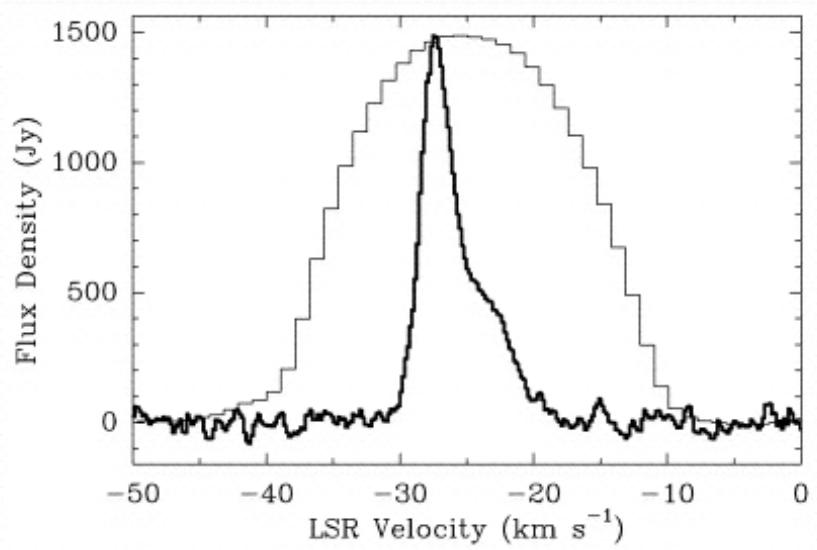


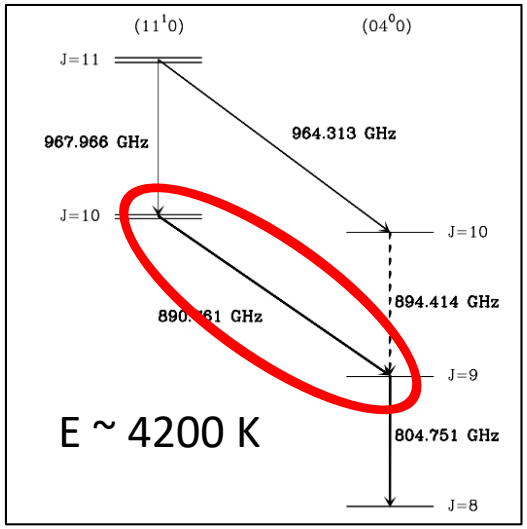
FIG. 1. Block diagram of the molecular beam spectrometer and oscillator.

Gordon, Zeiger & Townes 1954

Curiosum: Only two known transitions have found to show maser action in space as well as in the laboratory

II. A HCN laser line in IRC+10216





Schilke, Mehringer & Menten 2000

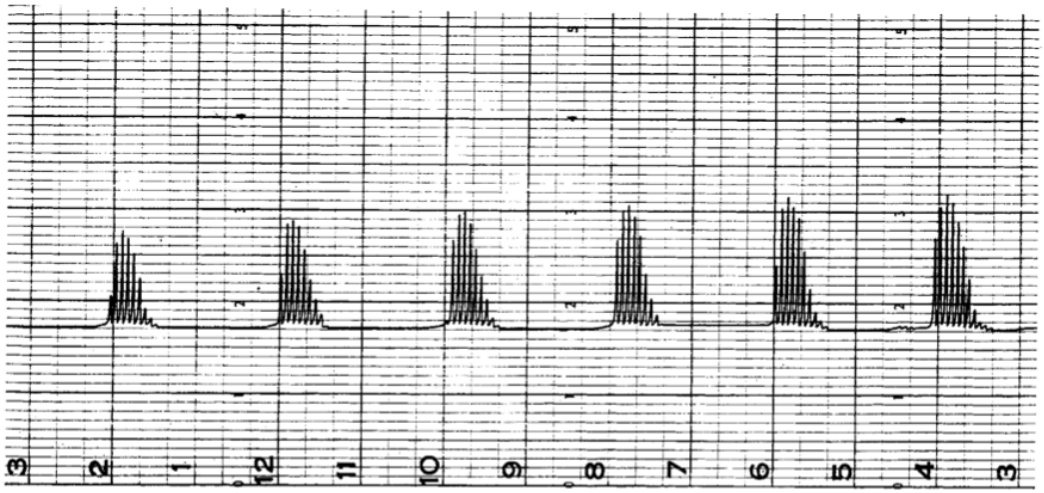
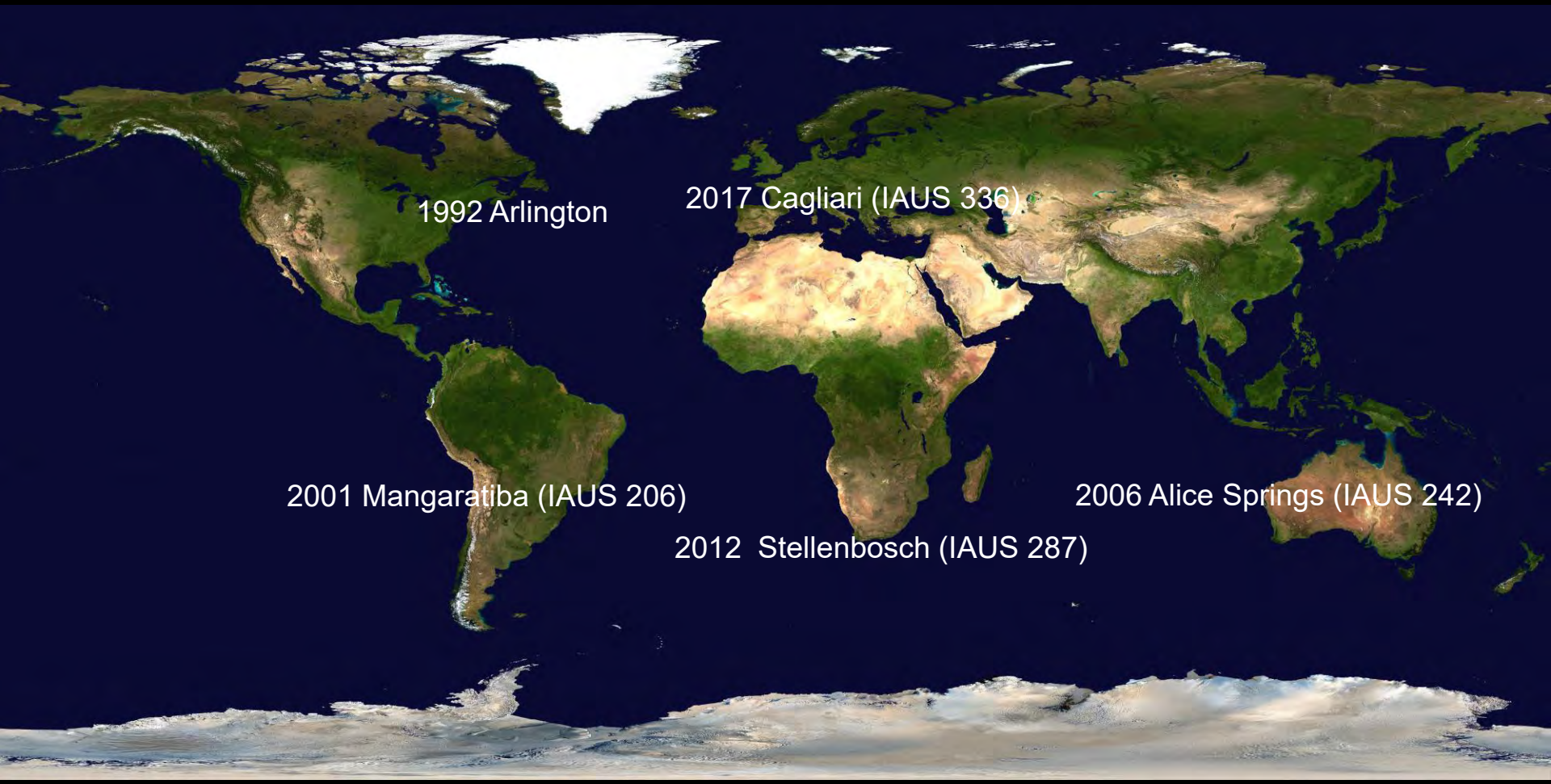


Fig. 1. Fabry–Perot interferogram made with a line of wave-length 0·337 mm. Each group of pulses is one interference fringe

A Stimulated Emission Source at 0·34 Millimetre Wave-length

Gebbie+ 1968 (Nature)

Maser Conferences



50+ Years of Maser Research

Karl M. Menten
MPI für Radioastronomie

IAU 336: Astrophysical Masers: Unlocking the Mysteries – Cagliari, 2017 September 4

50+ Years of Maser Research ...and counting!

Karl M. Menten
MPI für Radioastronomie

IAU 336: Astrophysical Masers: Unlocking the Mysteries – Cagliari, 2017 September 4

Hot cores