The Impact of Masers in Modern Astrophysics

by

James Moran

Harvard-Smithsonian Center for Astrophysics

Lo Memorial Lecture

Xinjiang Astronomical Observatory

September 19, 2018

Kwok-Yung (Fred) Lo

1947 - 2016

Jan Lo and Susan Moran, January 1983, Pasadena

Born in the year of the Dragon

Time Magazine, June 3, 1985

JIM BRITT

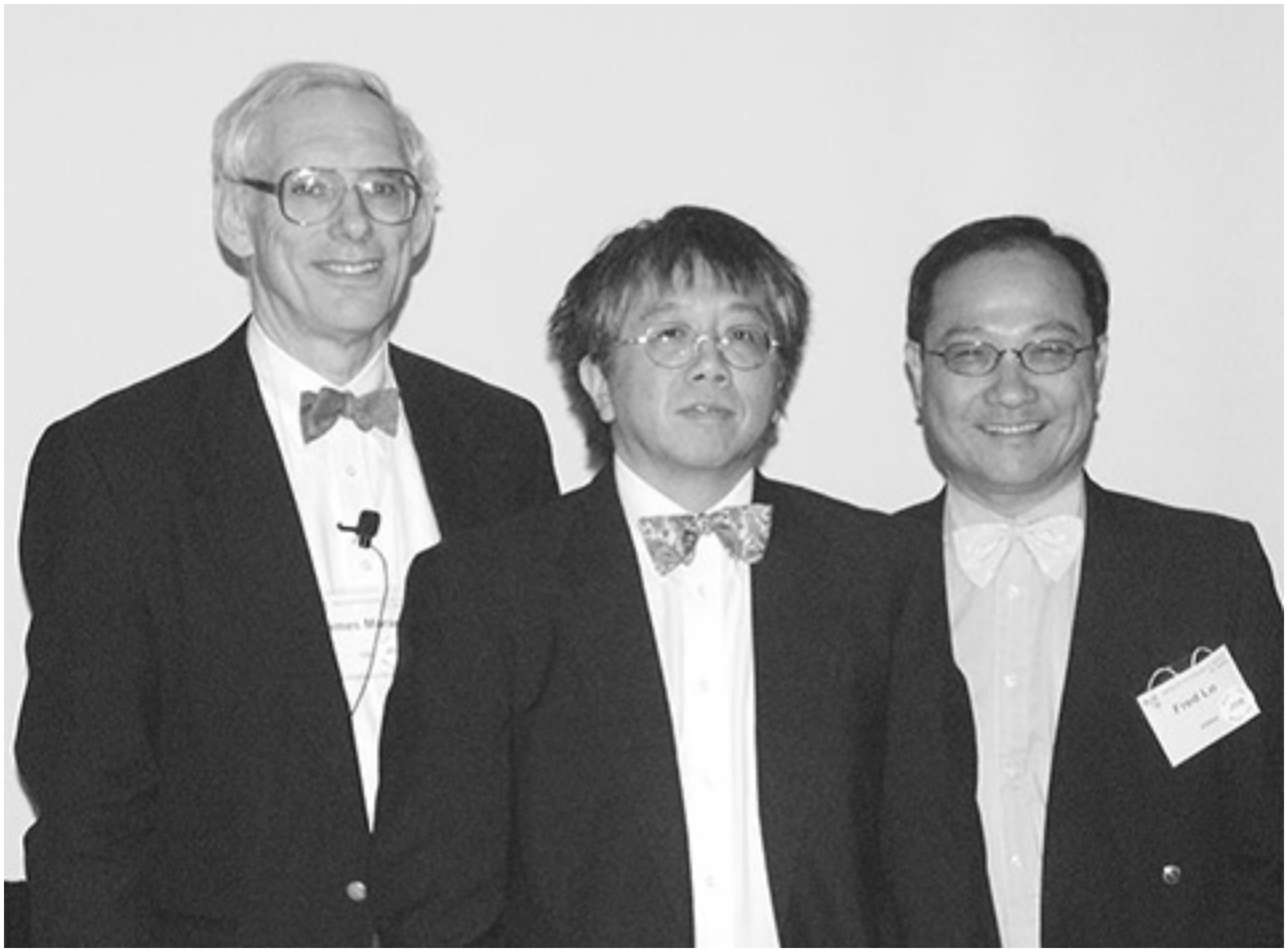
Radio Astronomer Lo of Caltech standing before a galactic swirl

The Milky Way's Hungry Black Hole

An astronomical discovery at the galactic center

Based on the article: On the Size of the Galactic Centre Compact Radio Source: Diameter < 20AU, by Lo, Backer, Ekers, Kellermann, Reid and Moran, Nature, 314, 124, May 9, 1985

SMA Press Conference 2002



Jim Moran Paul Ho Fred Lo

My First Attempt at Radio Astronomy

January 1959, with 400-MHz antenna

July 2013, with remains of 400-MHz antenna

Jim Moran (K1AKE), Then and Now

1958
Leominster,
Mass USA

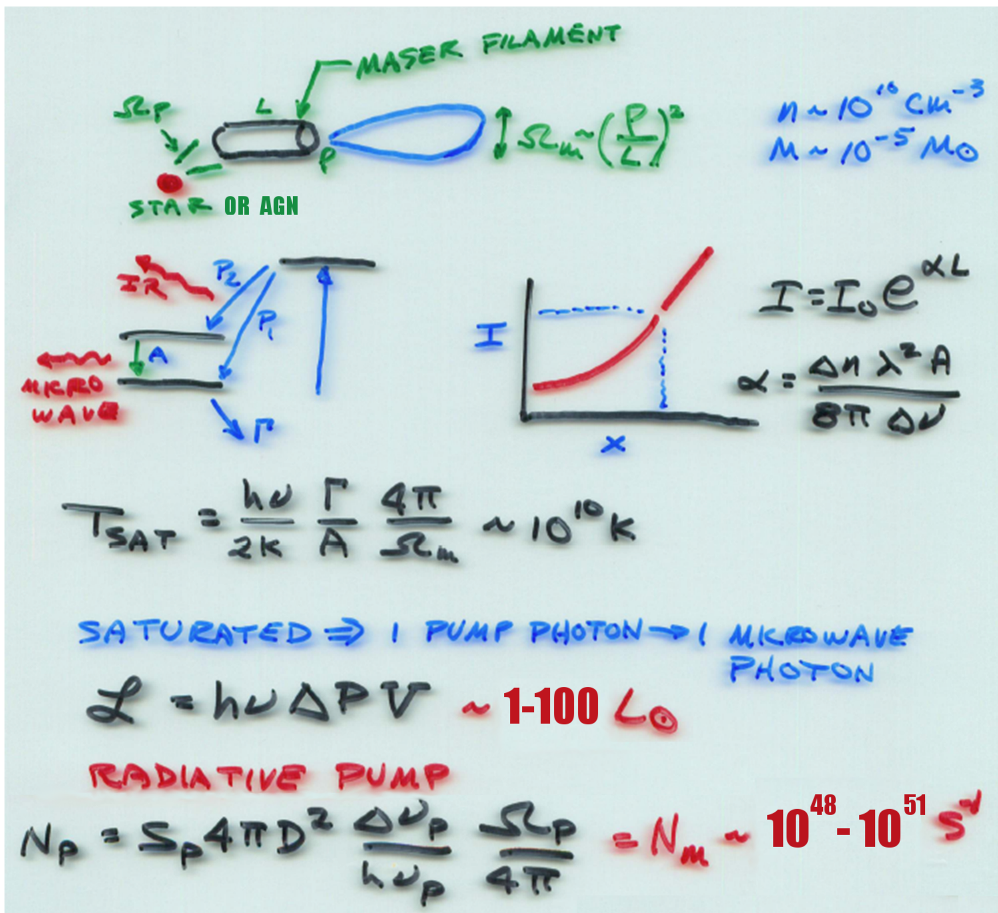
2008
Tsinghua
University,
Beijing, PRC

Today's Talk

- Short introduction to the physics of masers
- Discovery that masers trace dynamical motions
- How do interferometers work?
- The maser accretion disk in NGC4258
- "One of Nature's Most Beautiful Creations"
- Extreme resolution observations with Radioastron
- Measuring the Hubble constant

Cosmic Maser are Different from Lab Masers

One pass amplifiers
Little temporal coherence
Little spatial coherence
Gaussian noise – no noise pulses
Both have population inversion processes and high amplification



I Should Have Followed Up on That . . .

PHYSICAL PROCESSES IN GASEOUS NEBULAE

1. ABSORPTION AND EMISSION OF RADIATION

DONALD H. MENZEL

Ap.J. 1937, 85, 330

The total radiation, absorbed in the transition *n'– n*, including the effect of the "stimulated emissions," which must be counted as negative absorptions, is easily found to be . . . .

….. complicated equation …..

Outside of thermodynamic equilibrium, the condition may conceivably arise when the value of the integral [above] turns out to be negative. The physical significance of such a result is that energy is emitted rather than absorbed. This energy must be distinguished, however, from that arising in random emissions. The process merely puts energy back into the original beam, as if the atmosphere had a negative opacity. This extreme will probably never occur in practice.

NATURE October 2, 1965 VOL. 208

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

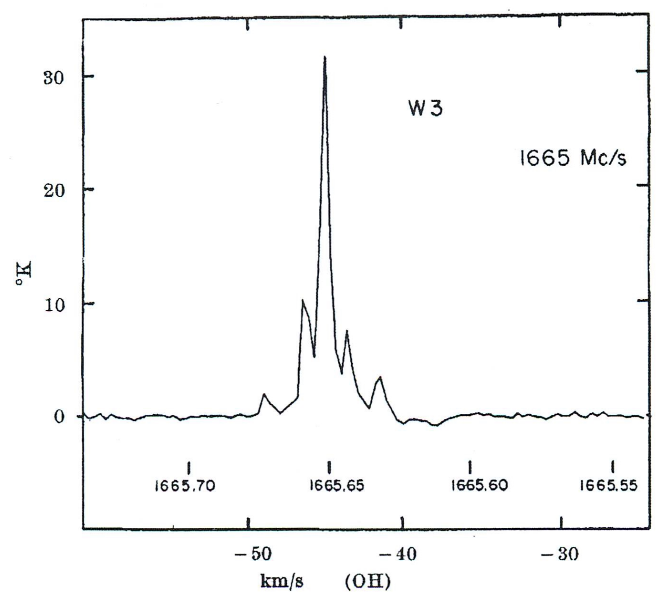
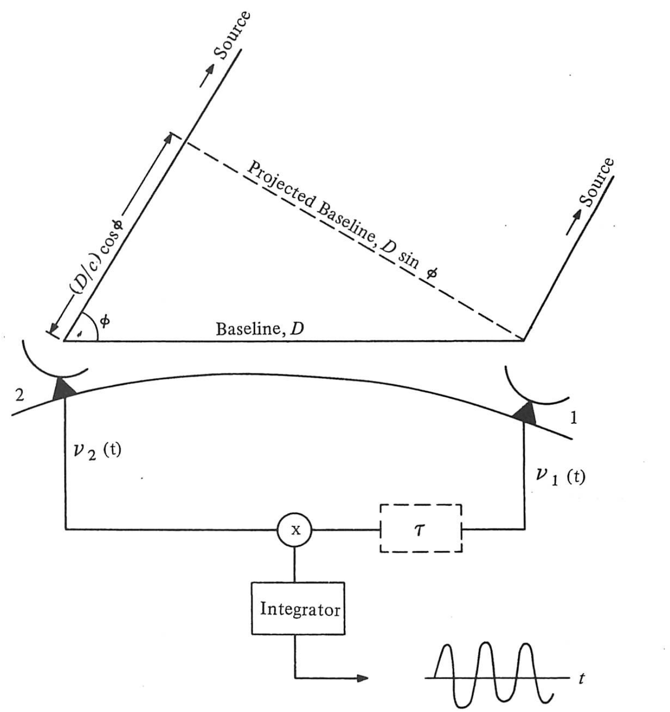
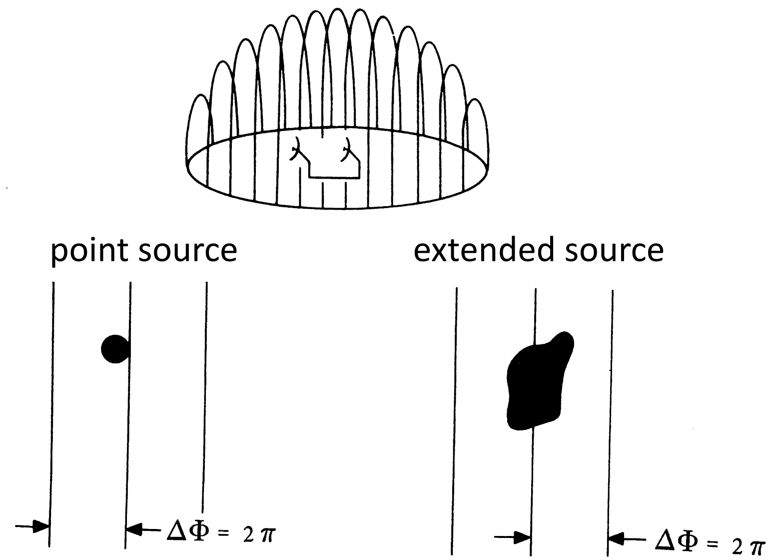


Fig. 2. Spectrum of *W*3 at 1,665 Mc/s with a resolution of 2 kc/s (0·4 km/sec)

There is no known identification of the strong emission line at 1,665 Mc/s shown in Fig. 1. In what follows, for brevity in writing and to emphasize the surprising nature of the observation just presented, we shall speak of this unidentified line as arising from 'mysterium'.

How Does an Interferometer Work ?

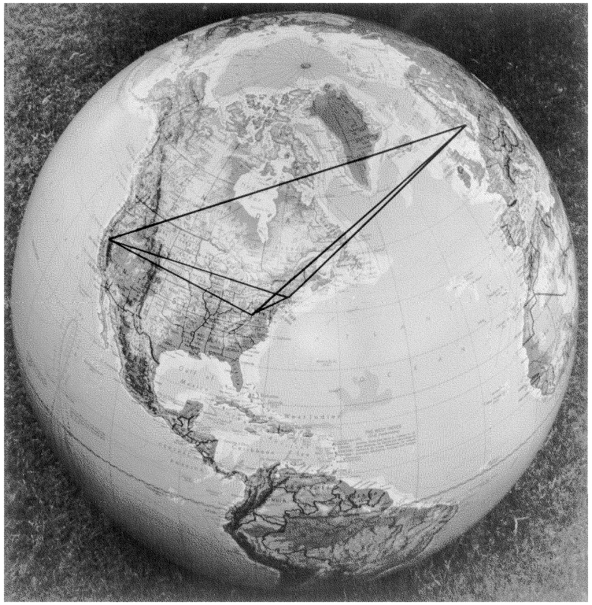


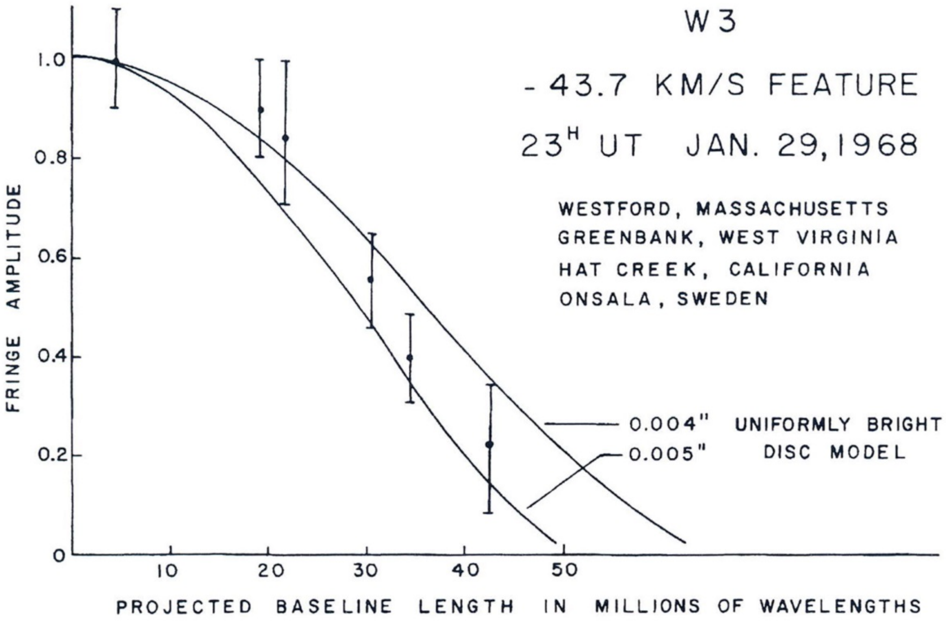


λ/D

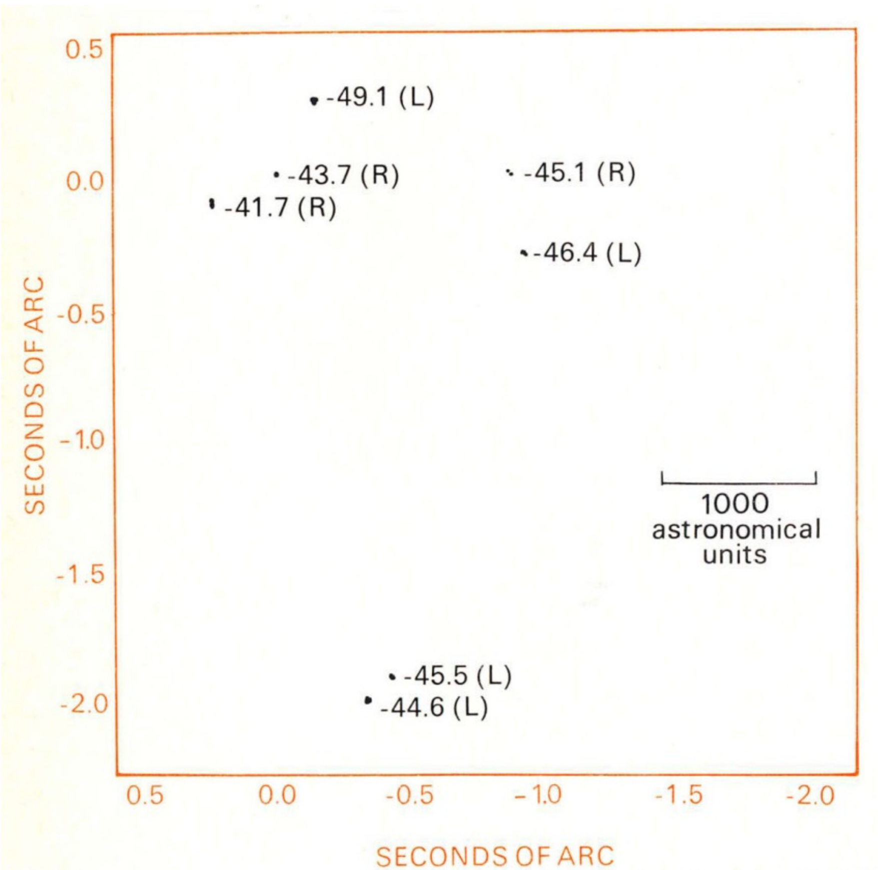
$$V(u,v) \overset{FT}{\rightleftarrows} I(x,y)$$

First Resolution of a Maser "Spot" (1968)

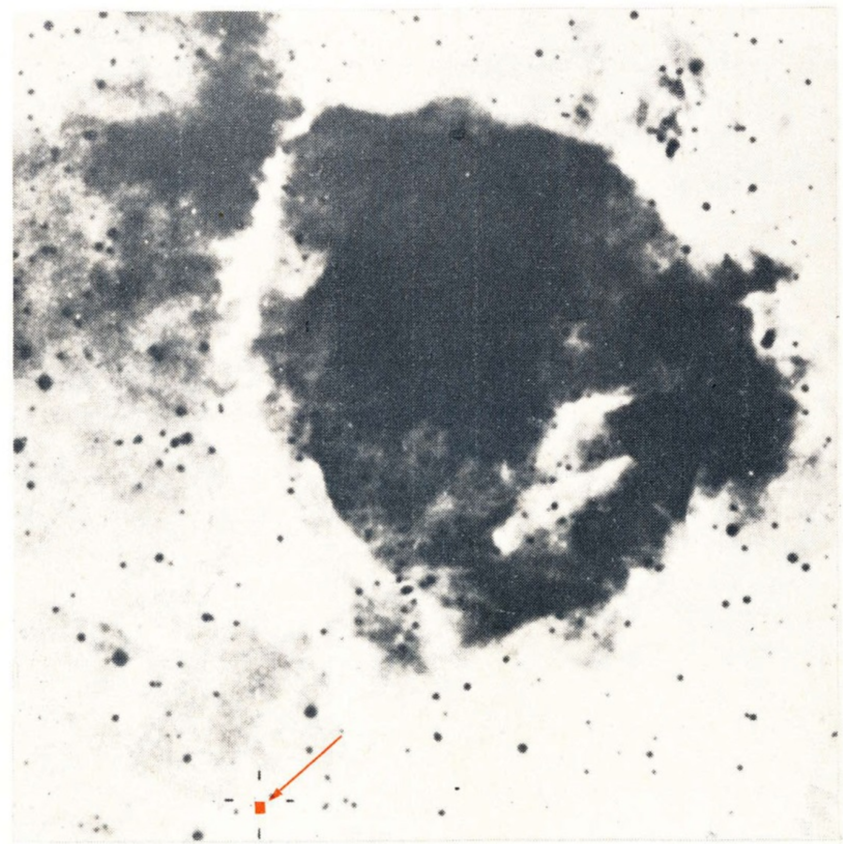




VLBI Image of W3 Maser

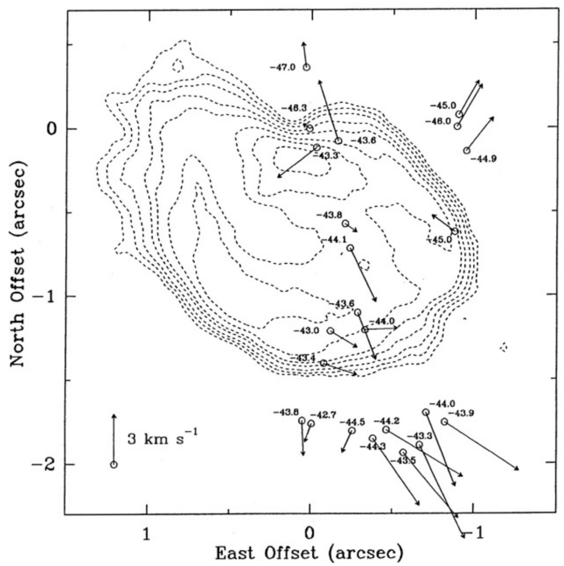


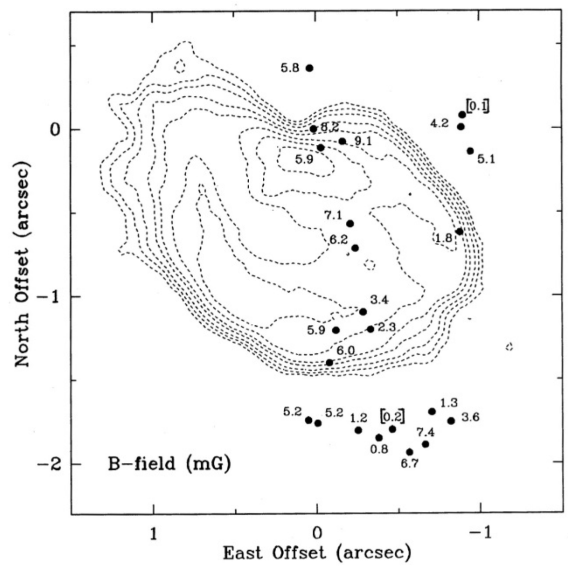
Palomar Sky Survey Image of W3 HII Region

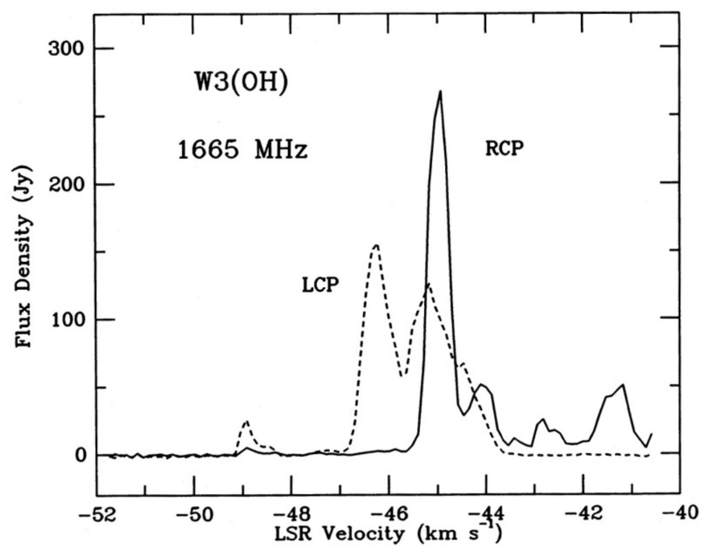


Proper Motions (left) and Magnetic Field Strength (right) in W3 OH Maser (1986) with US VLBI Network (NUG)

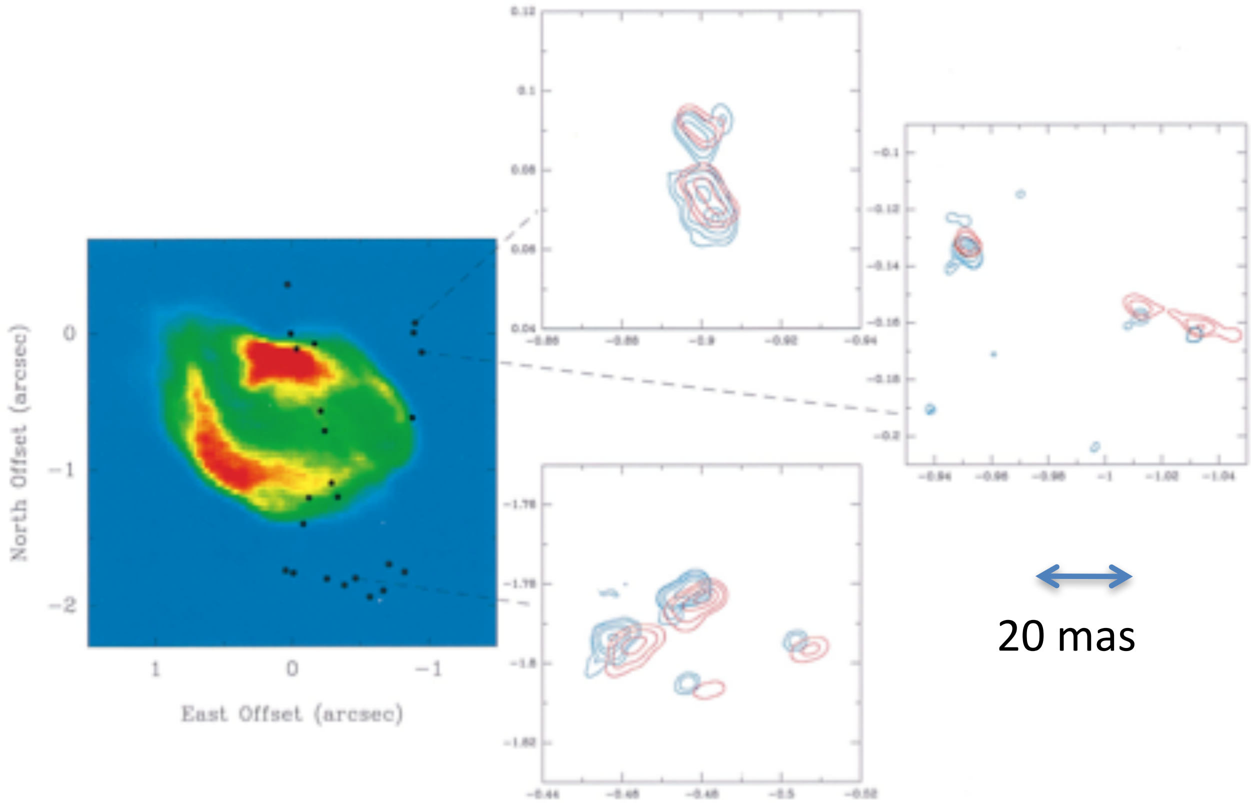
Contours
Trace
UCUII
Region
W3(OH)





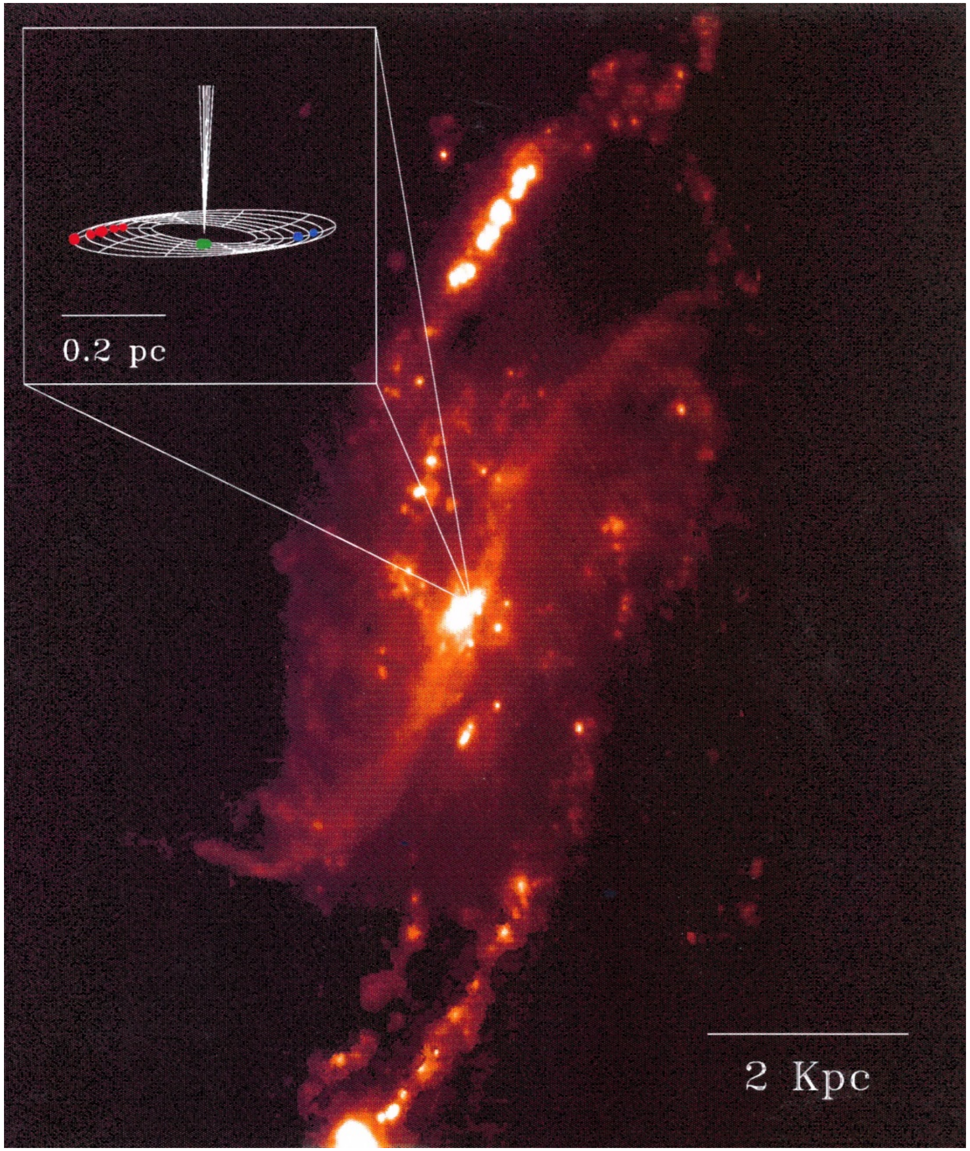


Motions of OH Masers in W3(OH): 1978-1986



Bloemhof, Reid, and Moran, 1996, Ap.J.(Lett.) 467, L117

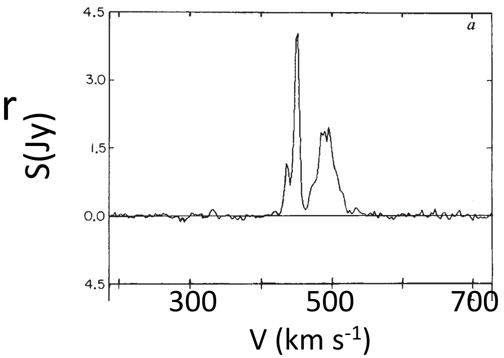
NGC4258 (M106)



Water Vapor Maser Discoveries in NGC4258

$6_{16} - 5_{23}$ transition
λ = 1.35 cm

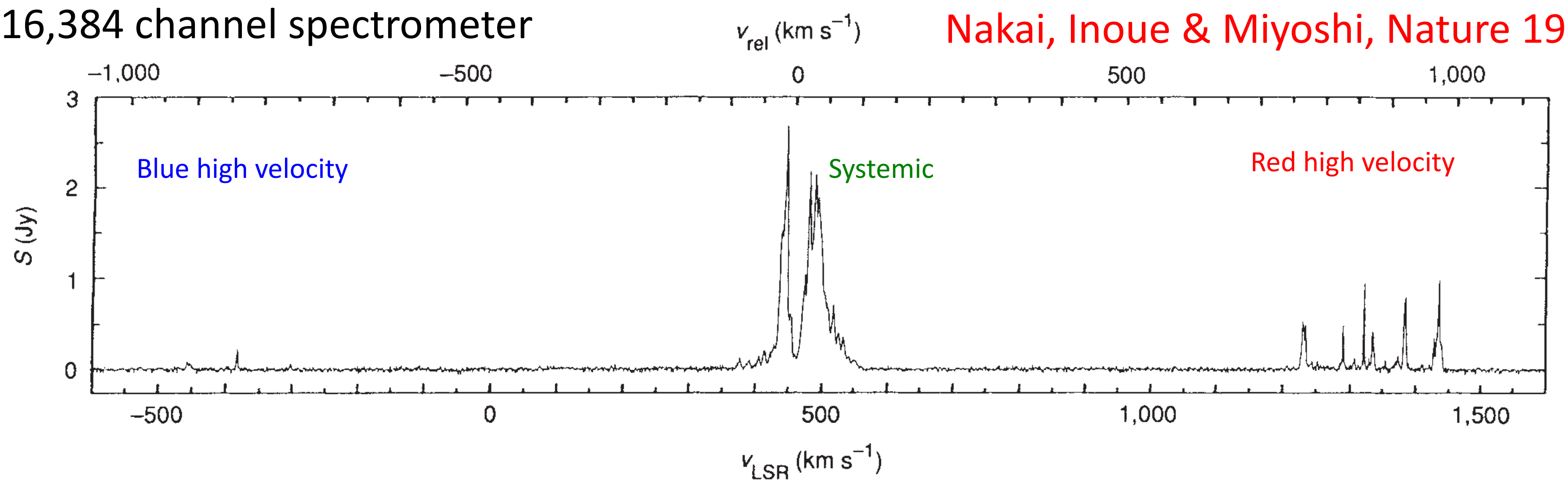
OVRO, 1024 channel spectrometer



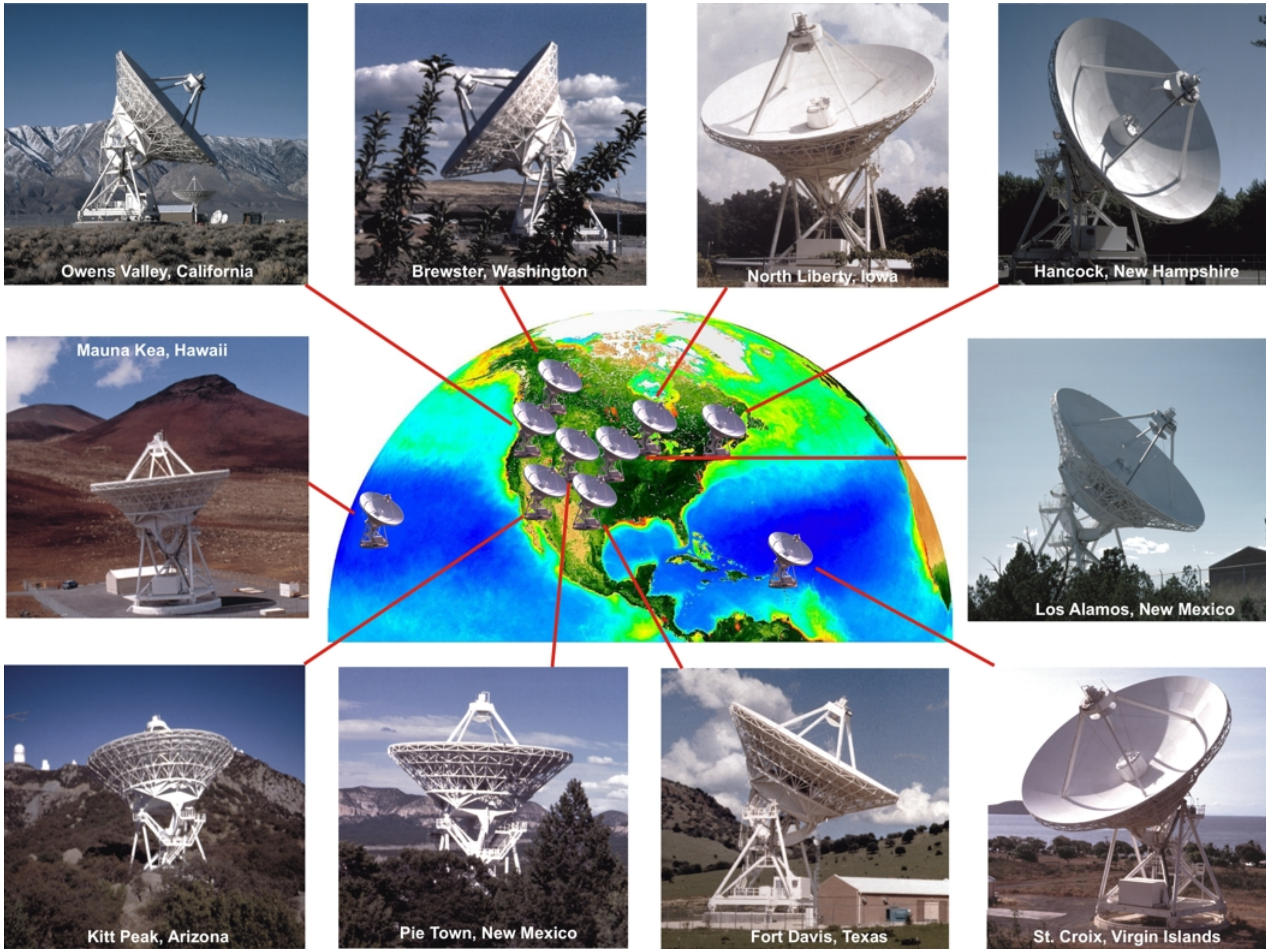
Claussen, Heiligman & Lo
Nature 1982

NRO, 16,384 channel spectrometer

Nakai, Inoue & Miyoshi, Nature 1993

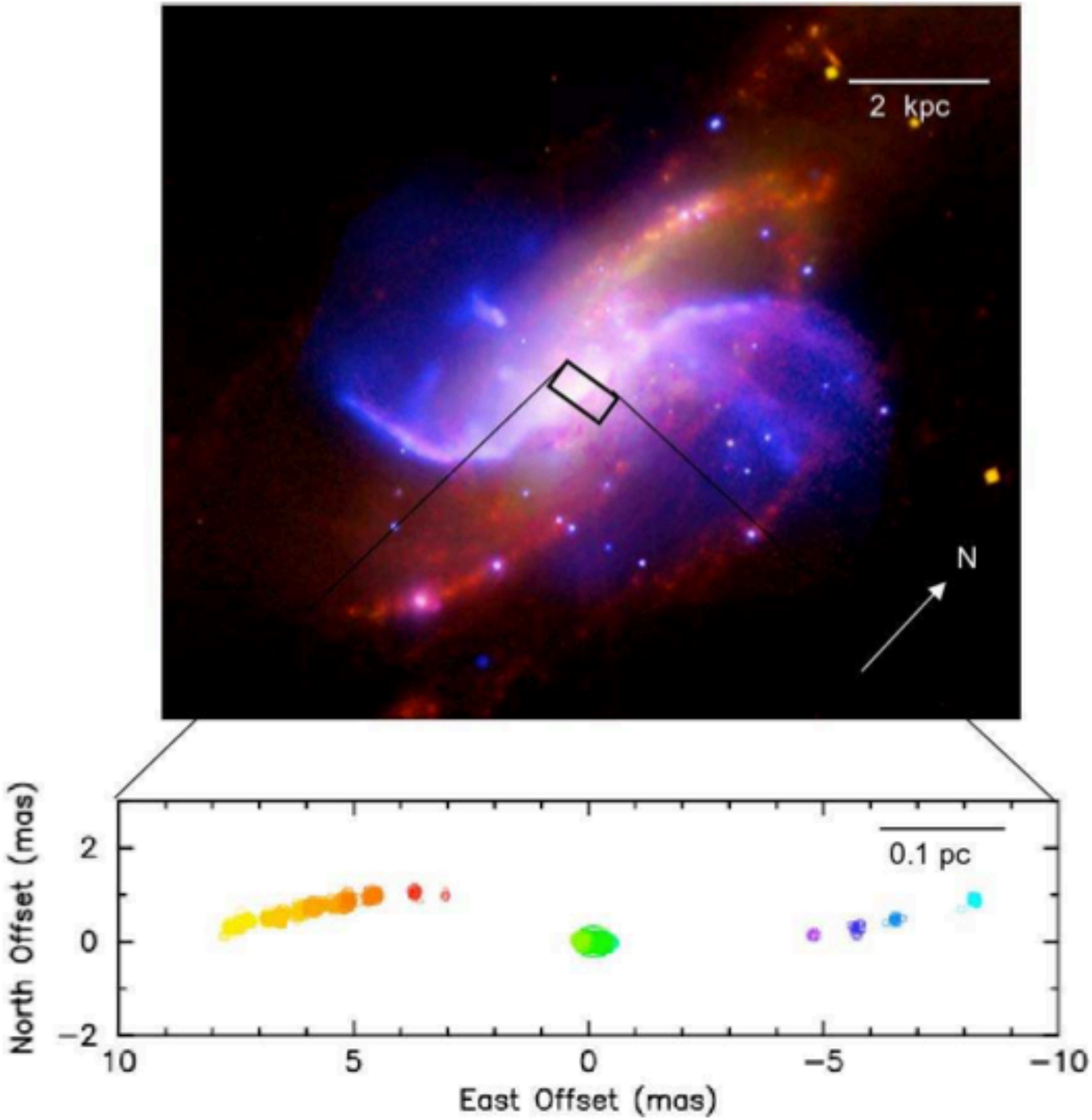


The NRAO Very Long Baseline Array (1994+)



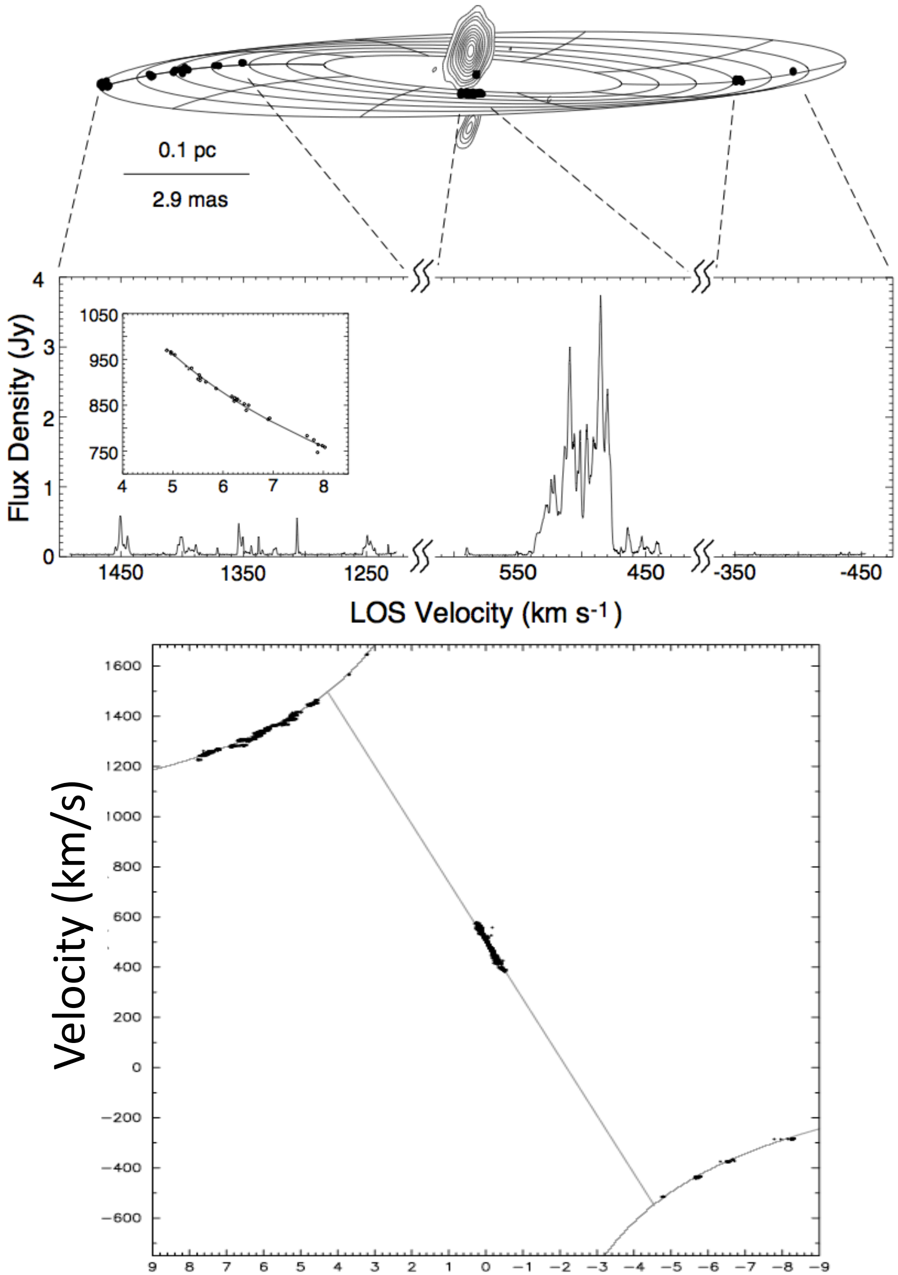
Maximum Baseline = 8000 km, Resolution = 200 microarcseconds at 1.3 cm wavelength

Water Masers in NGC4258



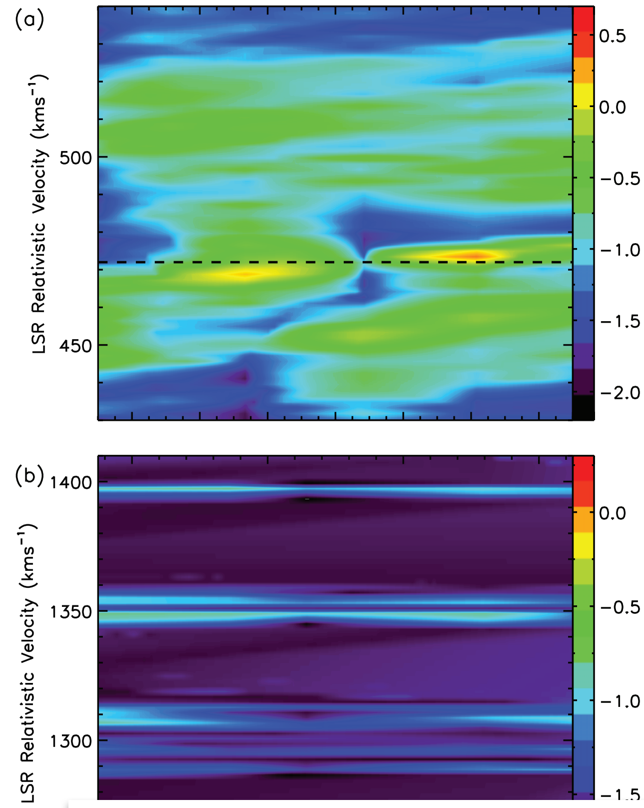
Myoshi et at, 1995, Nature; Herrnstein et al, 2005, Humphreys, et al., 2013

Maser Spot Distribution in NGC4258



Impact parameter (mas)

Line of Sight Accelerations (top) systemic features (bottom) red high velocity



1998.8 2000

time (year)

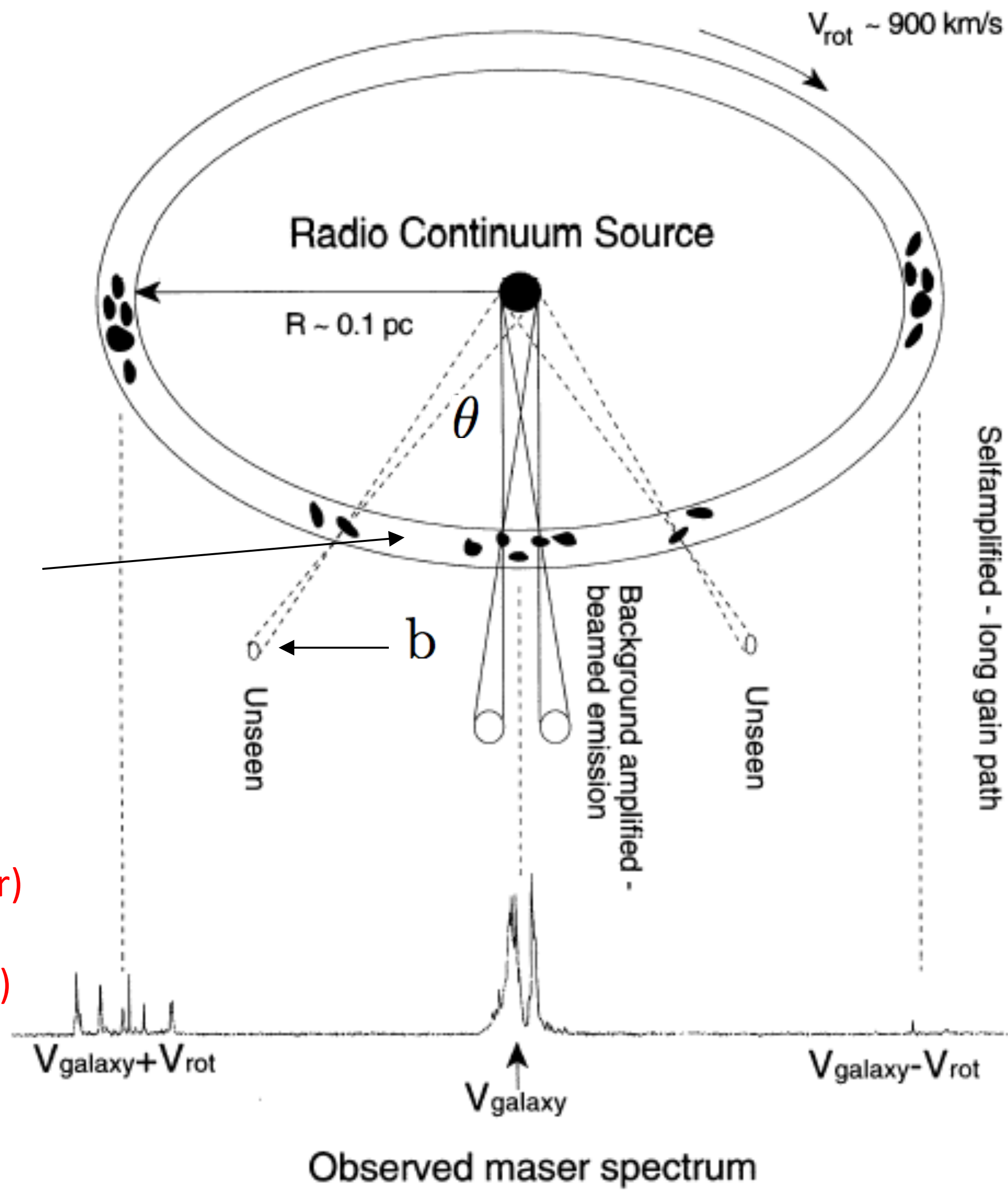
Systemic feature velocity drift originally discovered by Haschick, Baan & Peng, ApJ 1994

Cartoon of Accretion Disk Megamaser

$$V_z = \sqrt{\frac{GM}{R}}\sin\theta$$

$$V_z = \sqrt{\frac{GM}{R}}$$

$$V_z = \sqrt{\frac{GM}{R}}\,\frac{b}{R} = \sqrt{\frac{GM}{R^3}}\;b$$



Measuring Distance

1. Proper motions (8 μas/year)
2. Accelerations (9 km/s/year)

$D = R/\theta$

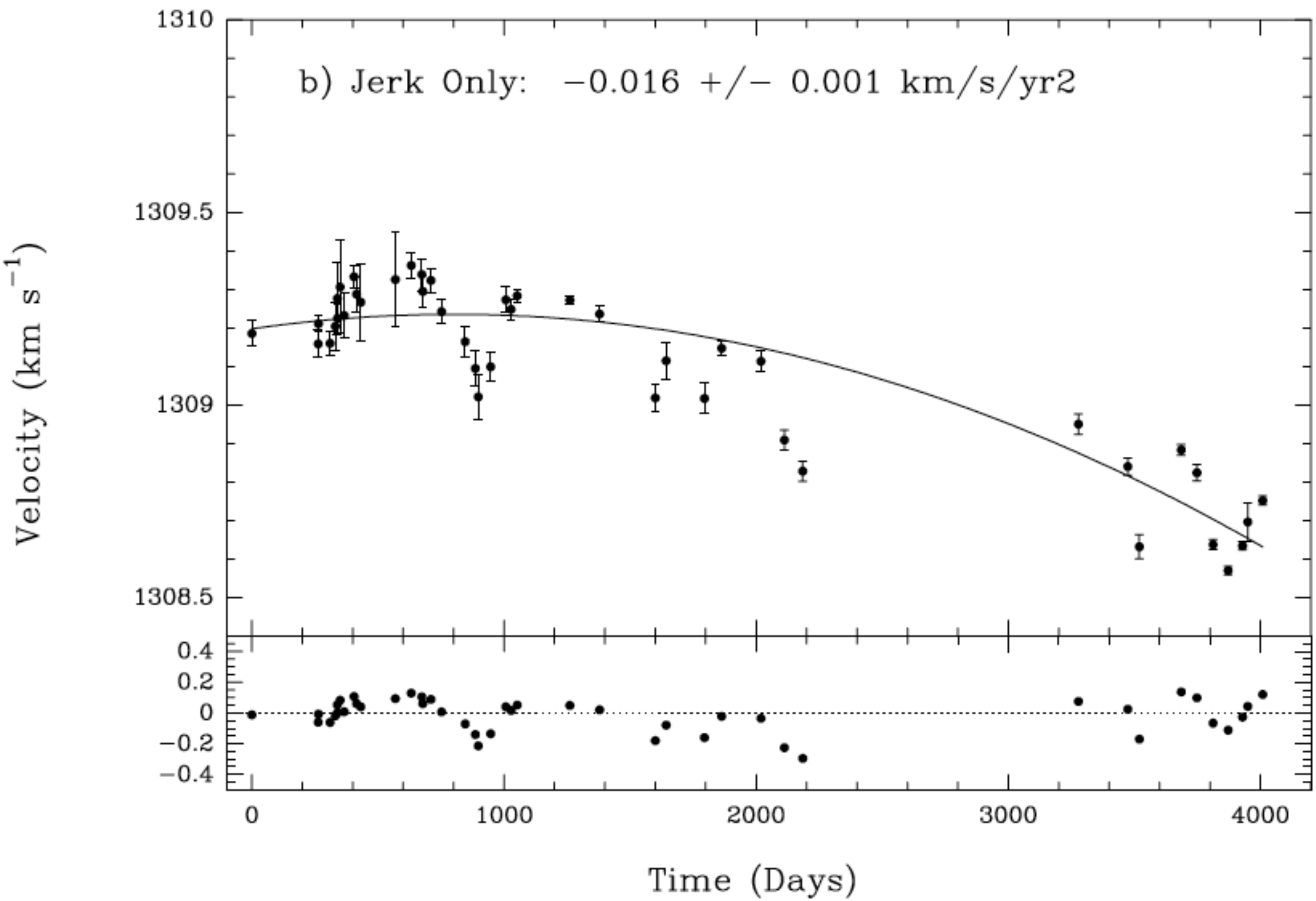
$a = V_r^2/R$

$D = V_r^2/a\theta$

D = 7.54 +/- 0.20 (3%) Mpc

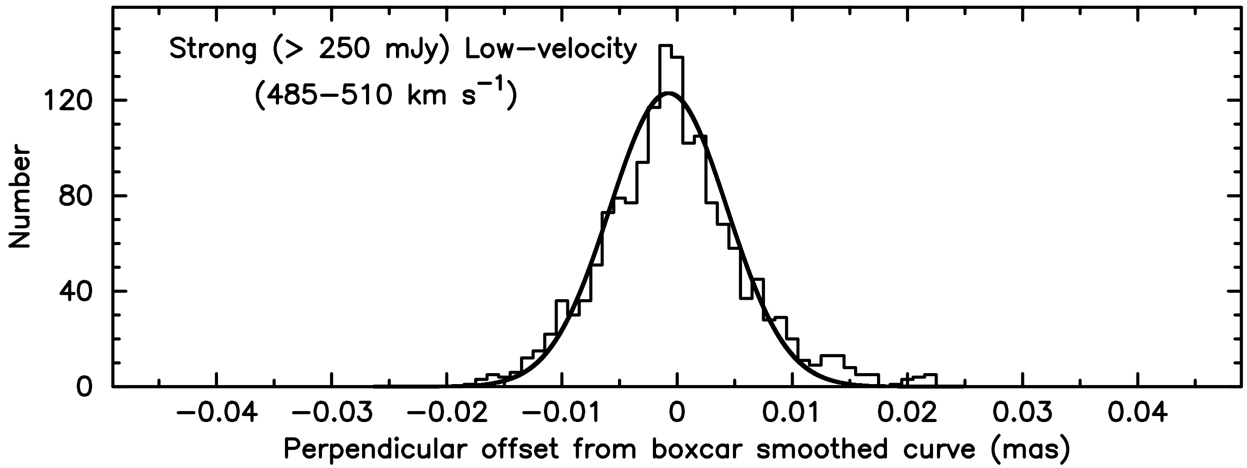
Riess et al., 2016; Humphreys et al., 2013

Acceleration of the "1306" kms^{-1} Feature



Humphreys et al. 2013

Measurement of the Thickness of the Accretion Disk in the Vicinity of the Systemic Features



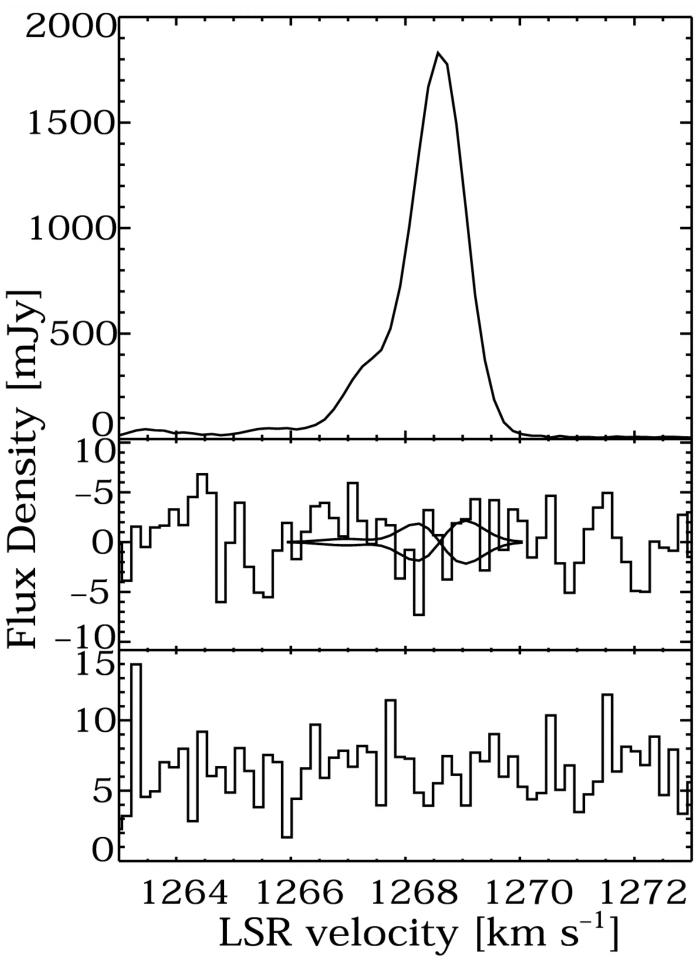
$$\sigma = 5.1\ \mu as$$

$$\rho = \rho_0 e^{-z^2/2\sigma^2} \qquad \sigma = Rc_s/v$$

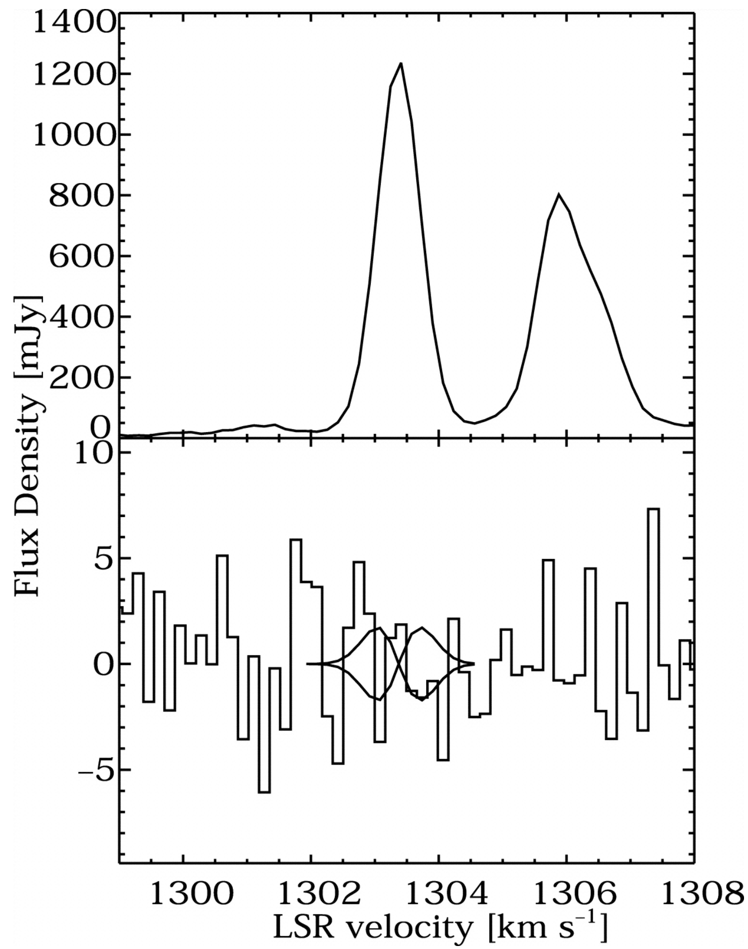
$$c_s = 1.5\ \mathrm{km/s} \quad \mathrm{T} = 600\mathrm{K} \quad \sigma/\mathrm{R} = 1.3 \times 10^{-3}$$

Argon, et al., Ap.J., 659, 1040, 2007

Search for Zeeman Splitting of Maser Features in NGC 4258 (B < 30 mG)



VLA Spectrum



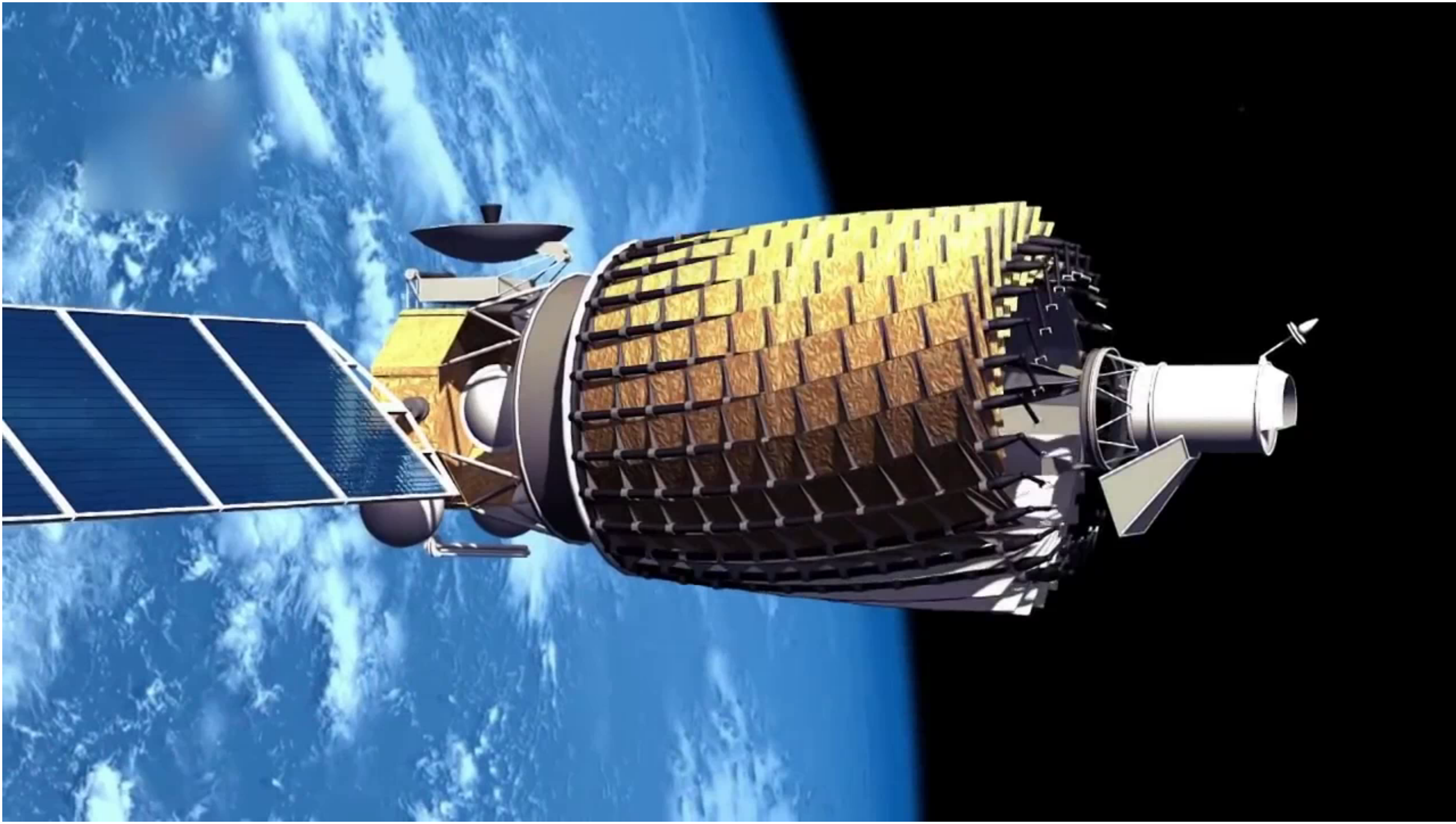
GBT Spectrum

Modjaz, Moran, Kondratko, & Greenhill, ApJ 2005

RadioAstron MegaMaser Team

Alexi Alakoz
Tao An (SHAO)
Willem Baan
Simon Ellingsen
Chris Henkel
Hiroshi Imai
Vladimir Kostenko
Ivan Litovchenko
Jim Moran
Andrej Sobolev
Alexander Tolmachev

RadioAstron Satellite (launched 2011)



NGC4258 VLBI Observations

Stations: Radioastron, GBT

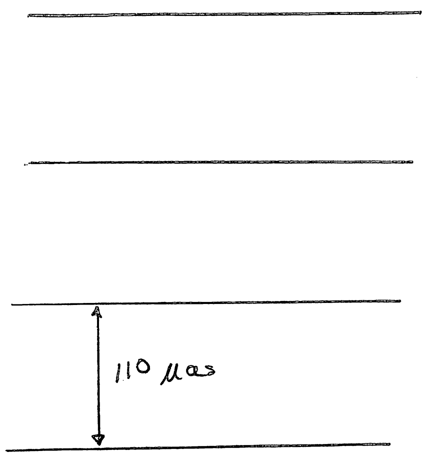
Observations: 18 December 2014 (fringe spacing = 110 μas (1.9 ED)
(fringes parallel to maser disk) duration 60 minutes

16 March 2016 (fringe spacing = 11 μas (19.5 ED)
(fringes perpendicular to maser disk) duration 74 minutes

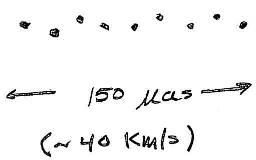
Spectroscopy: Systemic features only (no high velocity)
resolution 7.8 kHz (0.1 km/s; smoothed to 0.3 km/s)

Observations of NGC4258 with Fringes Parallel and Perpendicular to Accretion Disk

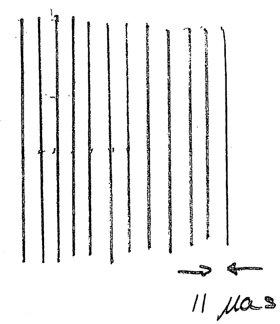
Fringe orientation
18 December 2014
parallel



Systemic
velocity maser
in accretion disk

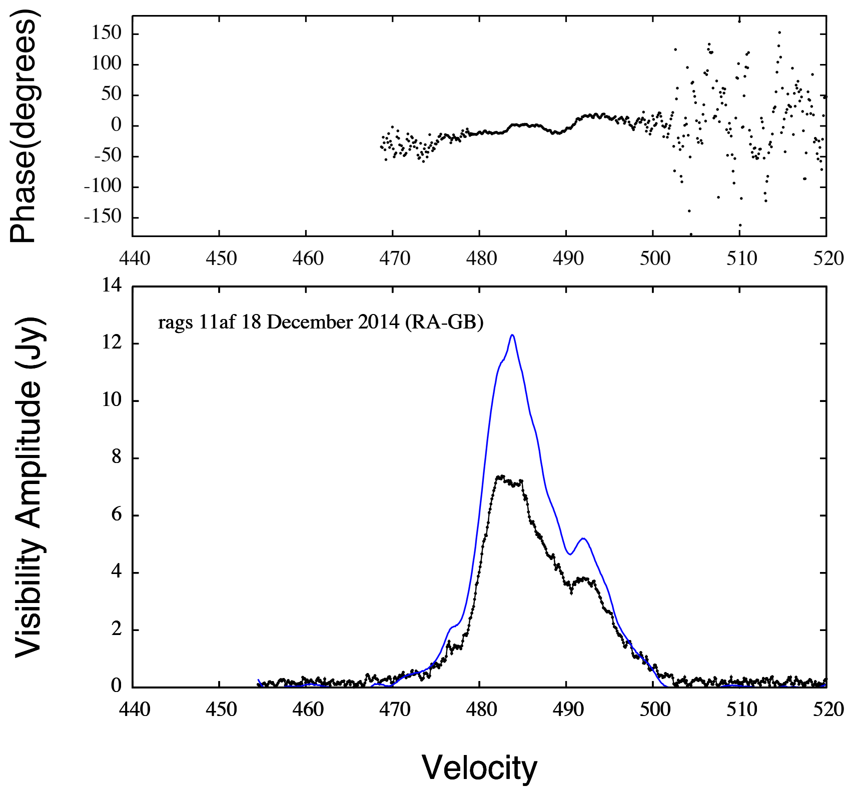


Fringe orientation
16 March 2016
perpendicular

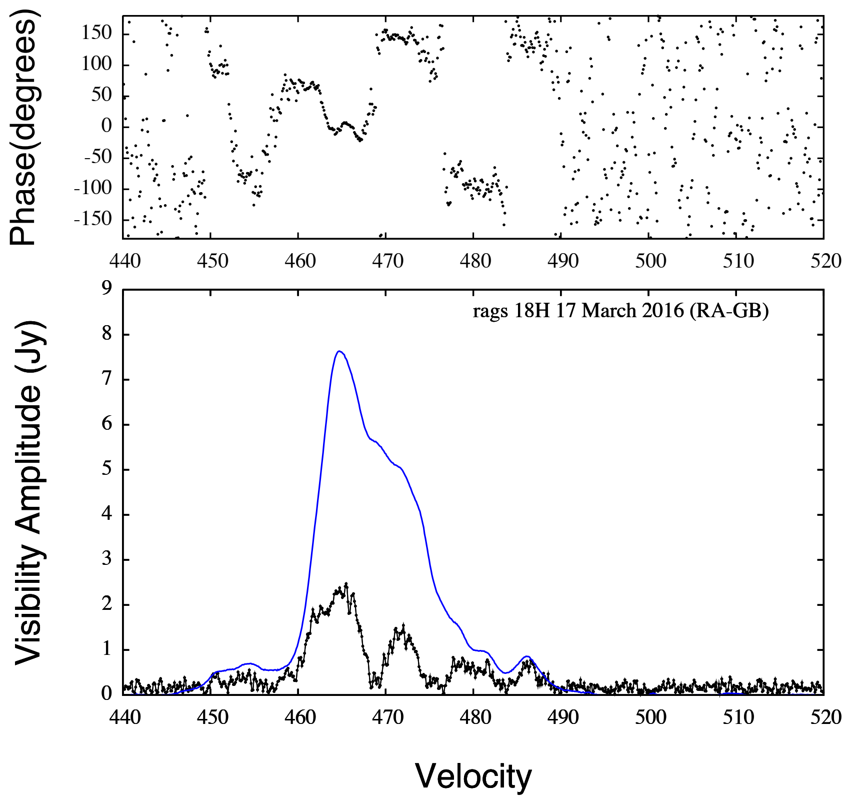


RadioAstron – GBT Visibility Spectrum of Systemic Velocity Group of Masers

18 December 2014 (110 μas parallel)

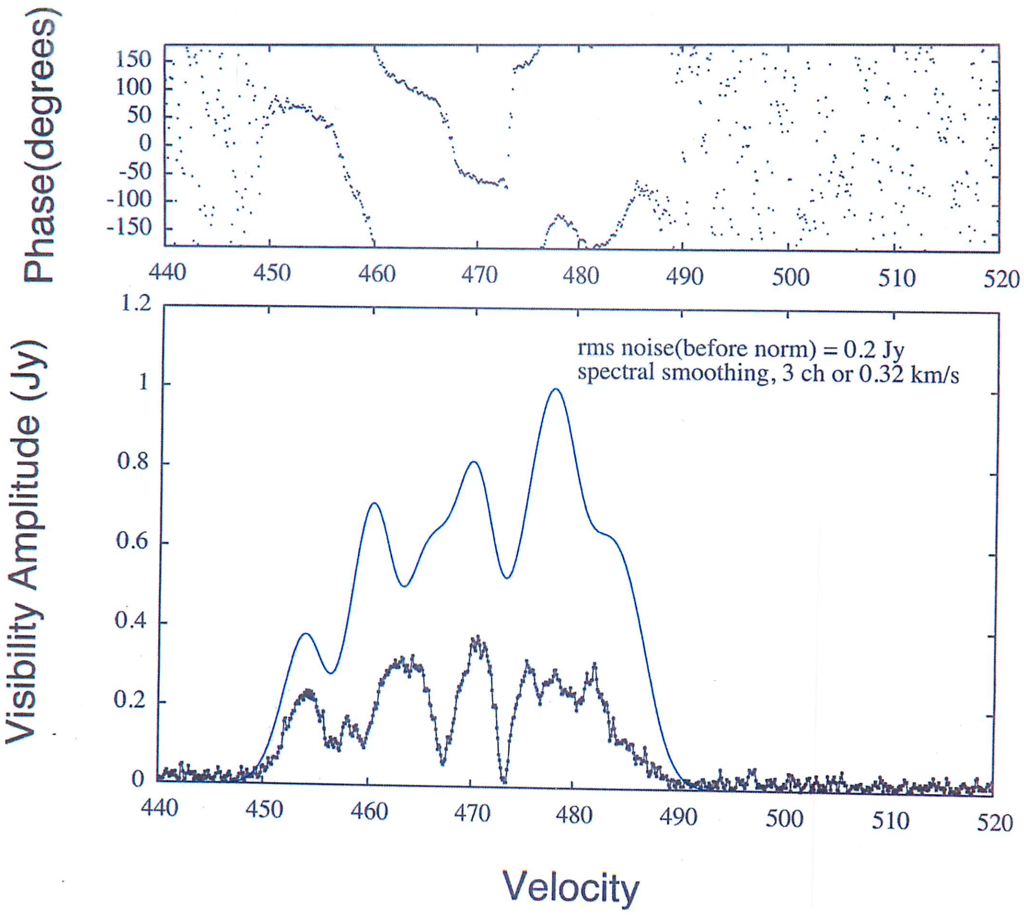


17 March 2016 (11 μas perpendicular)



Simulation Fringe Pattern (11 μas perpendicular) of UNRESOLVED Maser Spots in NGC4258

50 3-km/s components at random positions



$T_B \geq 4 \times 10^{15}$ K

Spots smaller than 3 μas (2×10^{15} cm)

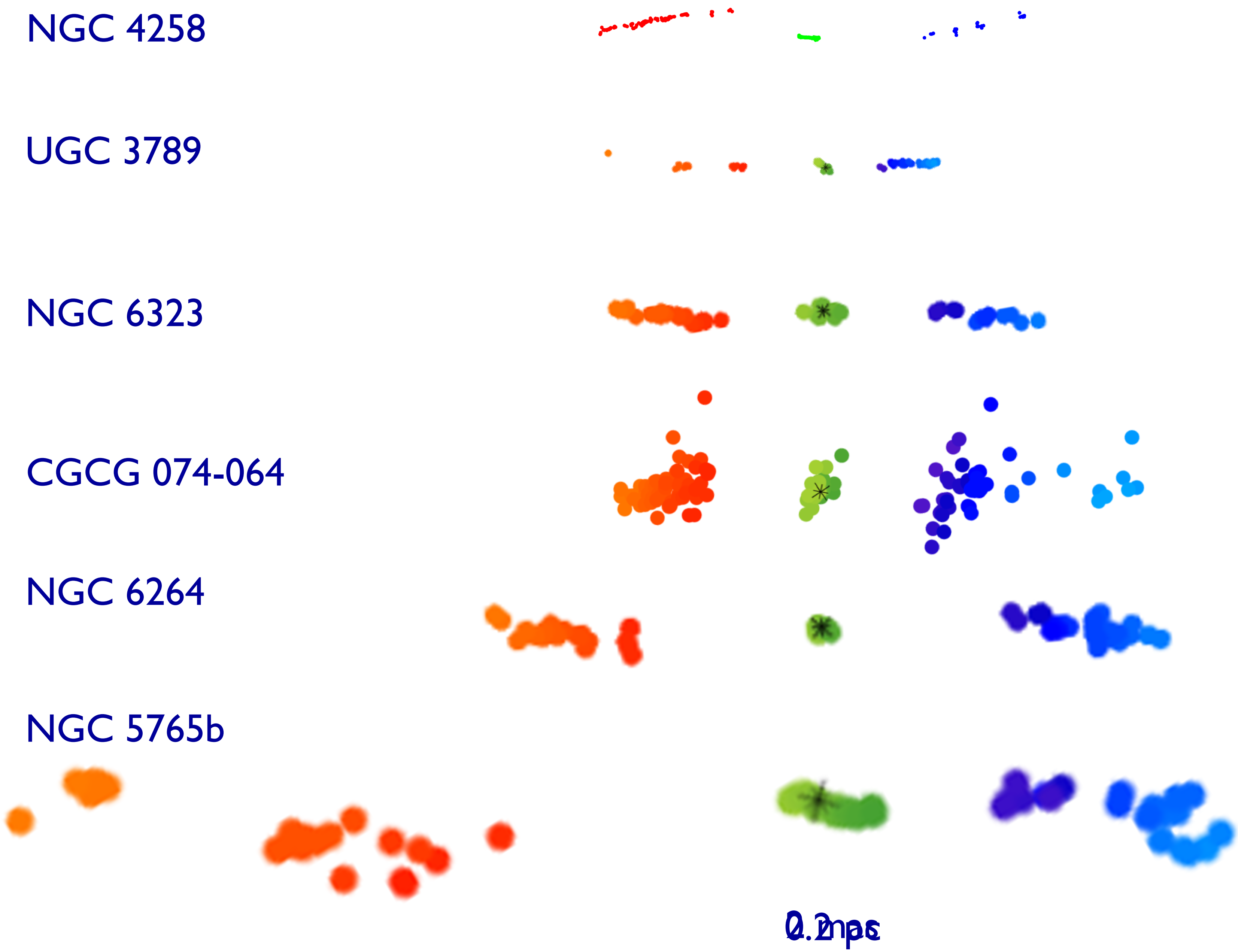
Megamaser Cosmology Project (MCP)

Fred Lo, Founder
Jim Braatz, Principal Investigator

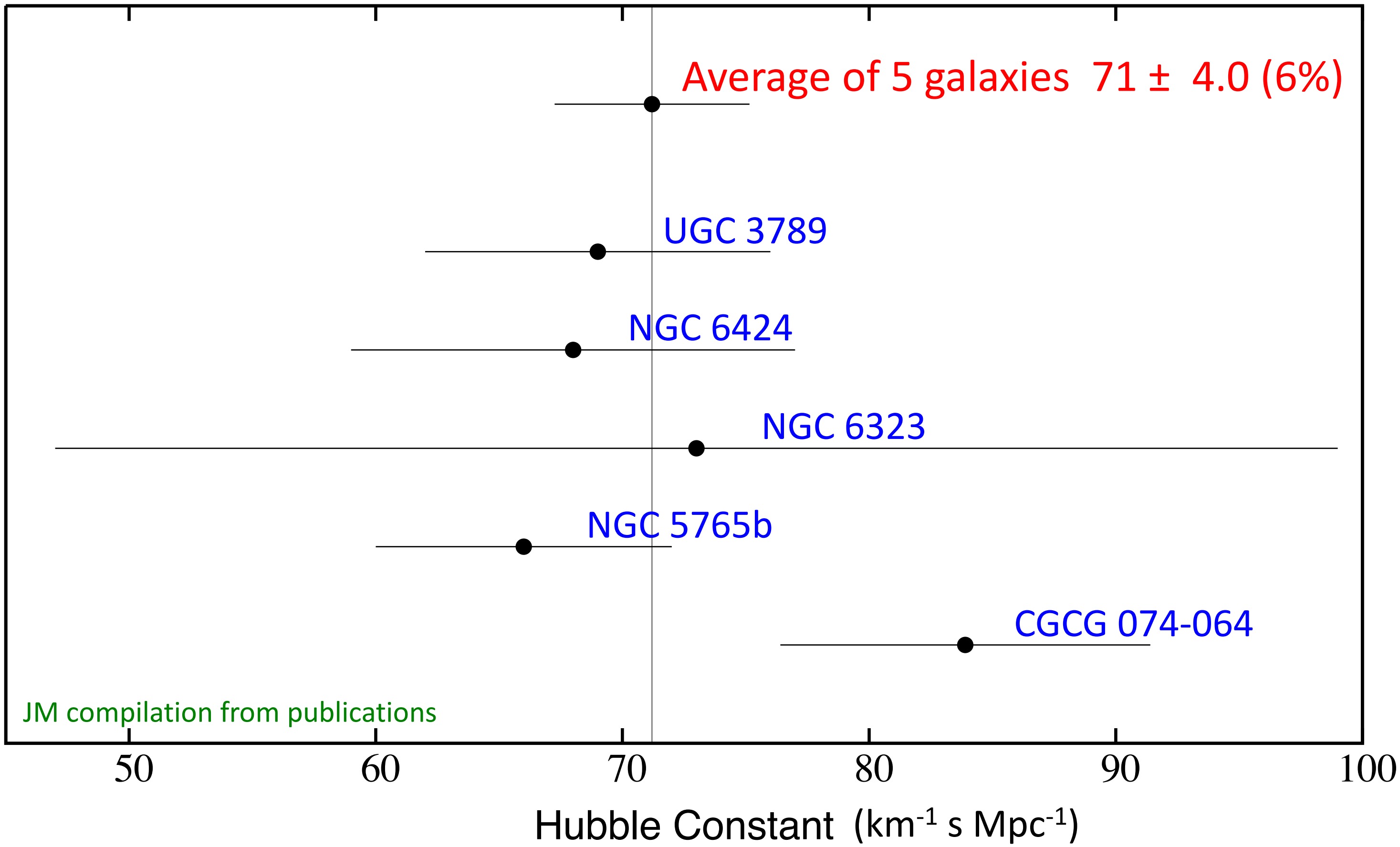
Mark Reid
Jim Condon
Christian Henkel
Jenny Greene

Dom Pesce
Feng Gao
Violetta Impellizzeri
Cheng-Yu Kuo

Anca Constantin
Lei Hao
Wei Zhao

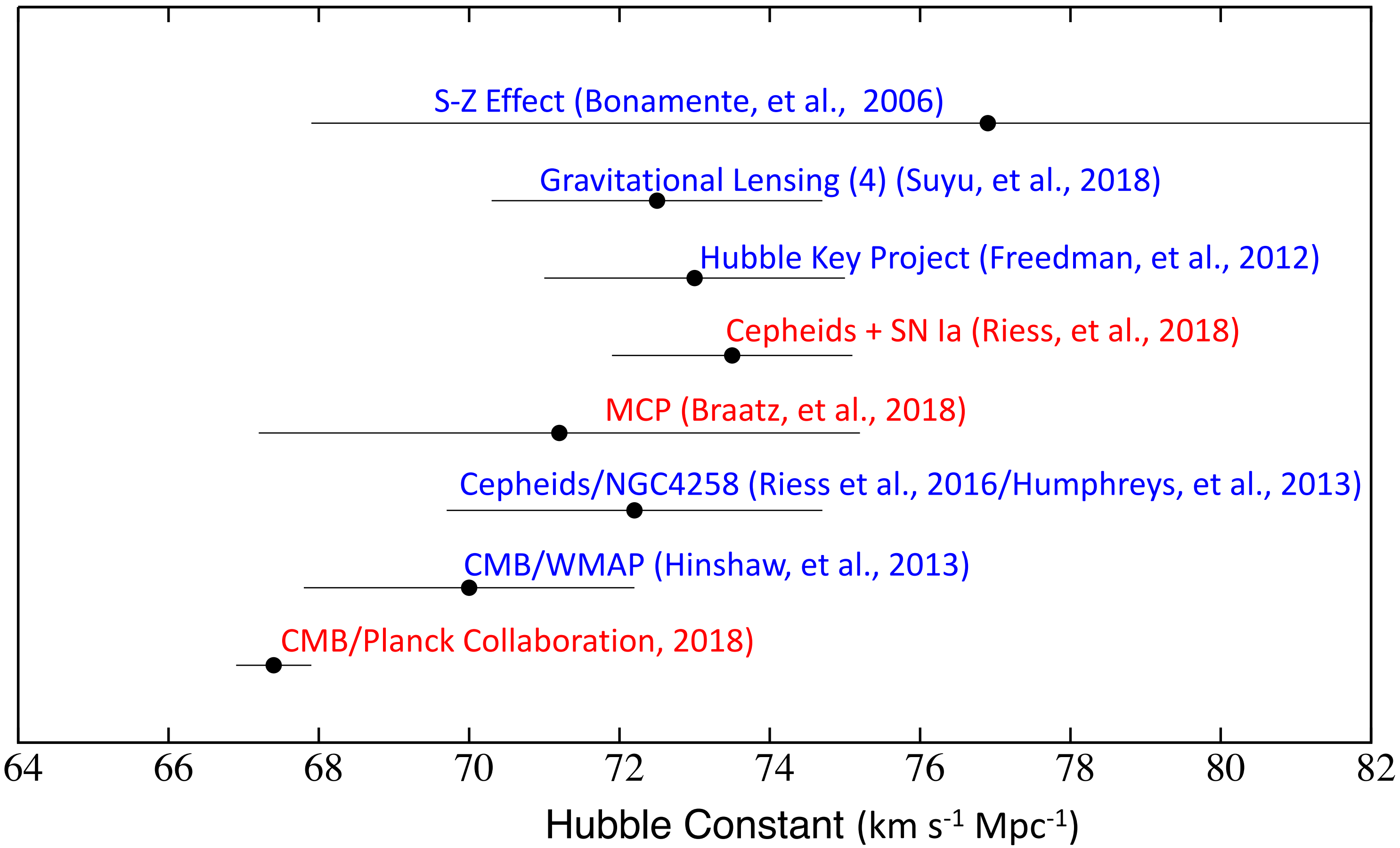

NGC 4258
UGC 3789
NGC 6323
CGCG 074-064
NGC 6264
NGC 5765b

Hubble Constant Estimates from Maser Cosmology Project (MCP)



UGC 3789 (49.6 +/- 5.1 Mpc) Reid et al., 2013
NGC 6264 (137 +/- 19 Mpc) Kuo et al., 2013
NGC 6323 (107 +/- 42 Mpc) Kuo et al., 2015
NGC 5765b (126 +/- 11 Mpc) Gao et al., 2016
CGCG 074-064 (83.9 +/- 7.4 Mpc) Pesce (thesis) 2018

Some Recent Hubble Constant Determinations



Summary

- Maser trace the dynamics of stellar outflows and AGN accretion disks
- NGC4258 is an ideal test bed for accretion dynamics
- Some properties of the accretion disk
- Accretion disk is very thin: h/R ~ 0.0002
- Masers spots very small: < 3 μas or 2 x 10^{15} cm
- Distance is known extremely well: 7.5 +/- 0.2 Mpc
- NGC4258 anchors the Cepheid distance scale
- H_o = 71 +/- 4.0 km/s/Mpc (5 megamasers)

Kwok-Yung (Fred) Lo

1947 - 2016

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Lo Memorial Lecture

Shanghai Astronomical Observatory

September 12, 2018

The Impact of Masers in Modern Astrophysics

by

James Moran

Harvard-Smithsonian Center for Astrophysics

Lo Memorial Lecture

National Astronomical Observatory of China

September 17, 2018

The Impact of Masers in Modern Astrophysics

by

James Moran

Harvard-Smithsonian Center for Astrophysics

Lo Memorial Lecture

Kavli Institute for Astronomy and Astrophysics

at Peking University

September 18, 2018