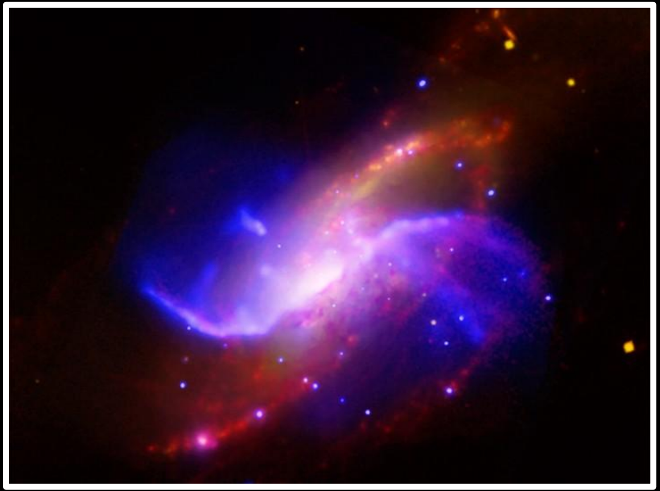
NGC 4258: “One of Nature’s Most Beautiful Dynamical Systems”

Maser Disk Discovery + BH Measurement: **Miyoshi+1995**

Geometry of Disk + Mass Accretion Rate: **Herrnstein+2008**

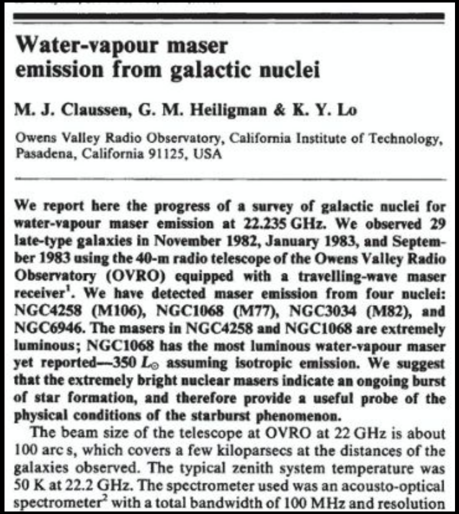
More Geometry + Distance Measurement: **Humphreys+2013**

The Context of NGC 4258



Red: IR
Blue: x-ray
Purple: Radio

- Type II Seyfert



Water-vapour maser emission from galactic nuclei

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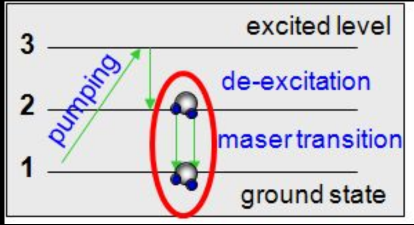
We report here the progress of a survey of galactic nuclei for water-vapour maser emission at 22.235 GHz. We observed 29 late-type galaxies in November 1982, January 1983, and September 1983 using the 40-m radio telescope of the Owens Valley Radio Observatory (OVRO) equipped with a travelling-wave maser receiver[1]. We have detected maser emission from four nuclei: NGC4258 (M106), NGC1068 (M77), NGC3034 (M82), and NGC6946. The masers in NGC4258 and NGC1068 are extremely luminous; NGC1068 has the most luminous water-vapour maser yet reported—350 $L_\odot$ assuming isotropic emission. We suggest that the extremely bright nuclear masers indicate an ongoing burst of star formation, and therefore provide a useful probe of the physical conditions of the starburst phenomenon.

The beam size of the telescope at OVRO at 22 GHz is about 100 arc s, which covers a few kiloparsecs at the distances of the galaxies observed. The typical zenith system temperature was 50 K at 22.2 GHz. The spectrometer used was an acousto-optical spectrometer[2] with a total bandwidth of 100 MHz and resolution

(Claussen+1984):
H_2O maser
discovery

MASERS:

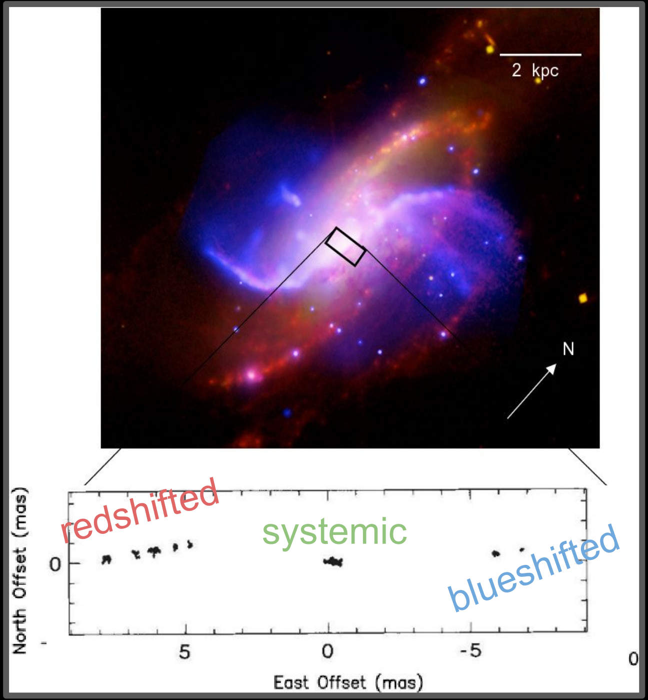
- Regions of intense microwave stimulated emission



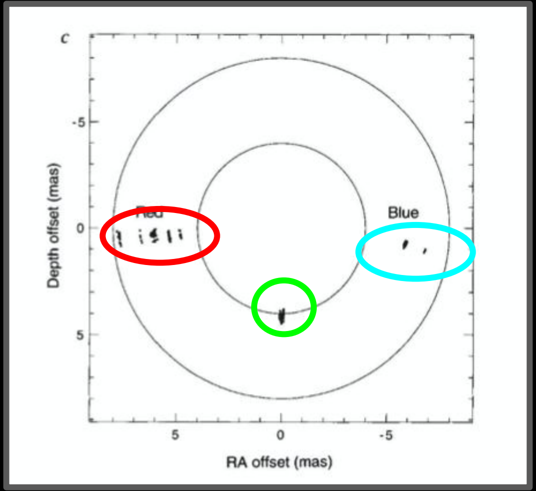
DETECTING MASERS:

(1) Coherent movement of gas.
(2) Long path lengths (called "gain lengths").

Miyoshi+1995: who can explain?



Maser emission embedded in a disk surrounding a region with largest density ever observed

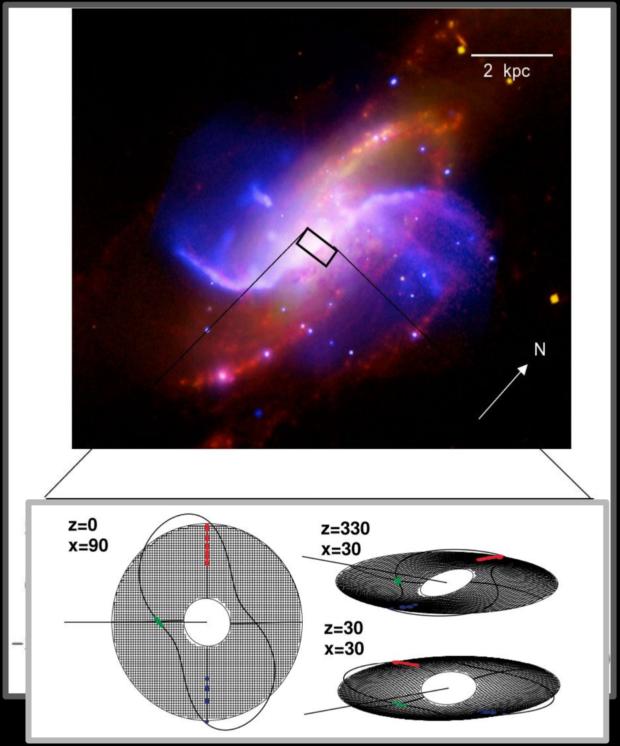


$M_{BH} = 3.6 \times 10^7\ M_\odot$,
$\rho_{central} > 4 \times 10^9\ M_\odot\ pc^{-3}$

Key Features:

- Locations of masers
- Velocity curve
- Central mass
- Inner to Outer spread in emission is ~0.14pc-0.28pc
- Systemic masers are below the center by 0.02 pc suggested warping but edge-on disk

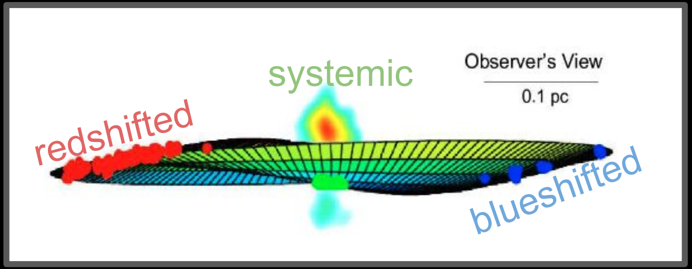
Herrnstein+2008: we can explain!

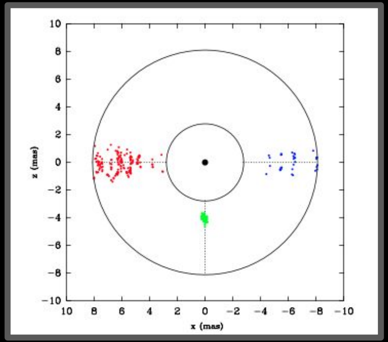


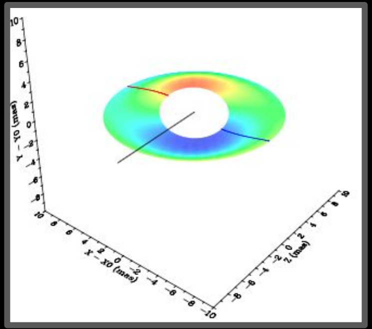
this disk geometry works and also makes predictions!

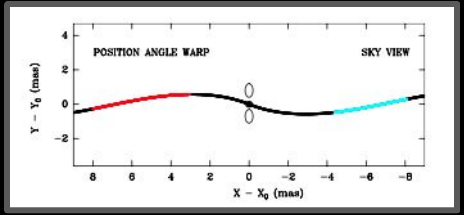
observed	suggests
high velocity maser rotation curve →	inclination warp in disk
narrow y-axis distribution of masers →	inclination warp in the disk leading to “bowl”
recurring flare from systemic masers →	inclination warp in the disk leading to “bowl”
X-axis distribution + considering temperature for maser emission →	accretion rate of $10^{-4}\alpha$ $M_{\odot}$ year^{-1}

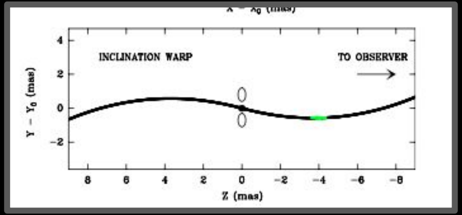
Humphreys+2013: what we know now











Key Features:

- 18 epochs of data, totalling more than 14,000 data points of (~1000 unique maser features)
- disk warping + differential precession in the disk
- new geometric distance measurement to the galaxy (with 3% error!!!!), and a new H_0 measurement by calibrating Cepheids

D = 7.60 +/- 0.17 +/- 0.15 Mpc
H_0 = 72.0 +/- 3.0 km s^{-1} Mpc^{-1}

Miyoshi+1995

Evidence for a black hole from high rotation velocities in a sub-parsec region of NGC4258

Makoto Miyoshi*, **James Moran**†, **James Herrnstein**†, **Lincoln Greenhill**†, **Naomasa Nakai**‡, **Philip Diamond**§ **& Makoto Inoue**‡

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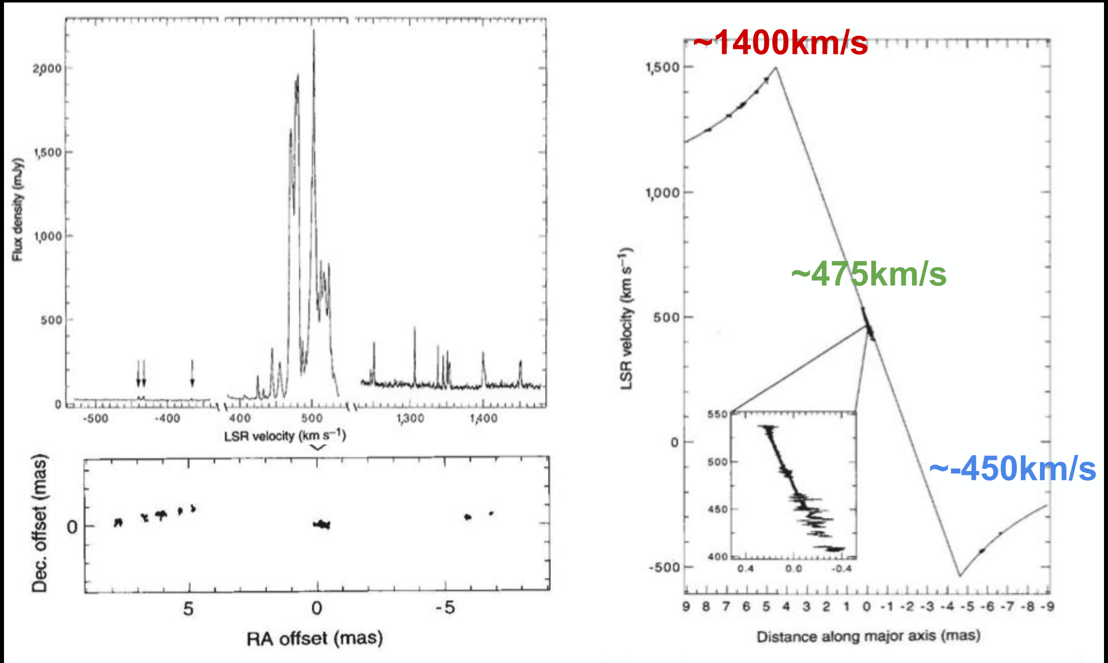
§ National Radio Astronomy Observatory, PO Box 0, Socorro, New Mexico 87801, USA

MANY galaxies are thought to contain massive black holes—exceeding ten million solar masses—at their centres[1,2], but firm observational evidence has proved to be surprisingly elusive. The best evidence comes from observing gas or stars rotating rapidly within a small region around a central body. If the observed velocities are due solely to the gravitational force of the central body—as in the Solar System—then the mass of the central body can be readily calculated. Here we present observations of rotating gas near the centre of the galaxy NGC4258 (M106), which indicate the presence of a mass of 3.6×10^7 solar masses in a region less than 0.13 pc in radius. The volume-averaged mass density in this region exceeds by a factor of at least 40 that for any other black-hole candidate observed previously. These observations provide compelling evidence that a massive black hole exists at the centre of NGC4258.



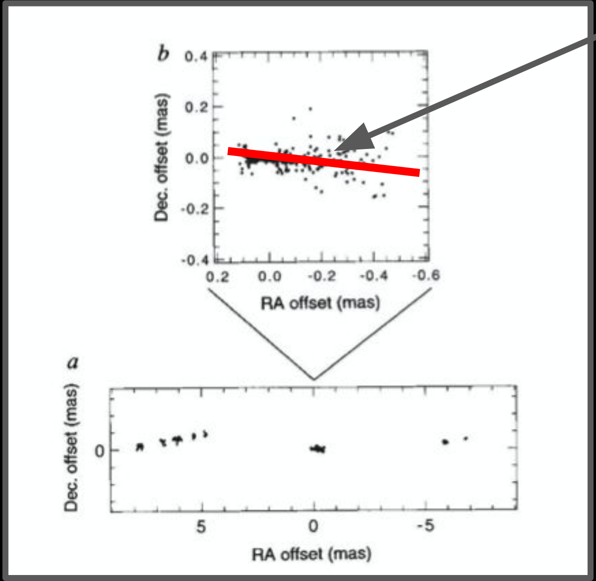
VLBA + VLA Observations of f_0 = 22 GHz (1.35cm) transition of H_2O

- velocity resolution: 0.2 km s^{-1}
- microarcsecond position certainty

→

- Edge-on Keplerian Disk ($v(r) \sim r^{-1/2}$)
- Disk stretching from 4mas-8mas
- height/radius < 0.02

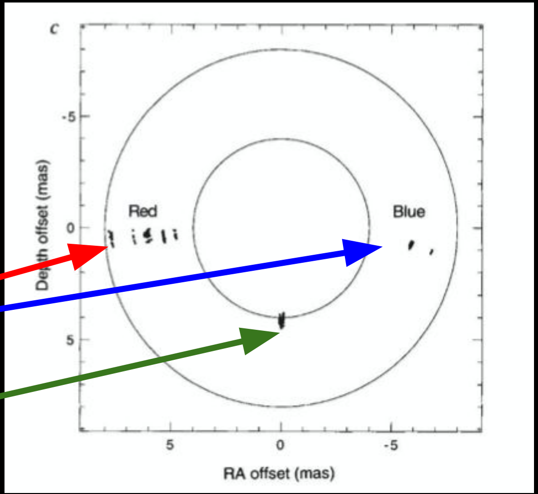
Miyoshi+1995



systemic masers

- can tell us position angle (~83°) inclination (~86°) of disk, distance from center

$$M_{BH} = 3.6 \times 10^7 M_\odot,$$
$$\rho_{central} > 4 \times 10^9 M_\odot pc^{-3}$$



→

- high velocity masers allow us to calculate binding mass and central density

$v_{l\text{-}o\text{-}s} = (GM/R)^{1/2}\cos(\theta)$

$dv/d\theta = 0$ at $\theta = 0°, 90°$

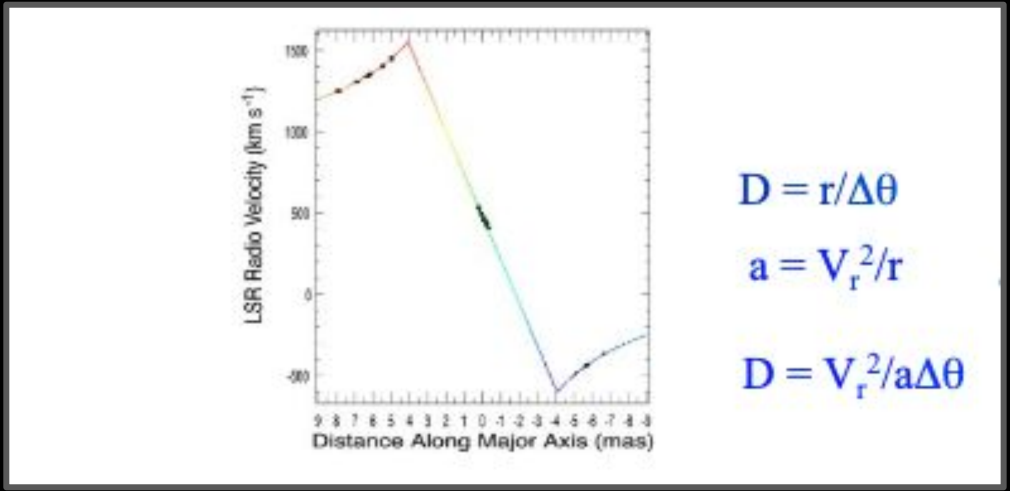
No doppler shift

REMEMBER:

(1) Coherent movement of gas.

(2) Long path lengths (called "gain lengths").

Miyoshi+1995: precision distance!



inner-most systemic velocity maser:

- 1,080 +/- 0.5 km/s rotational velocity
- velocity drift of 9.5 +/- 1.1 km/s/year

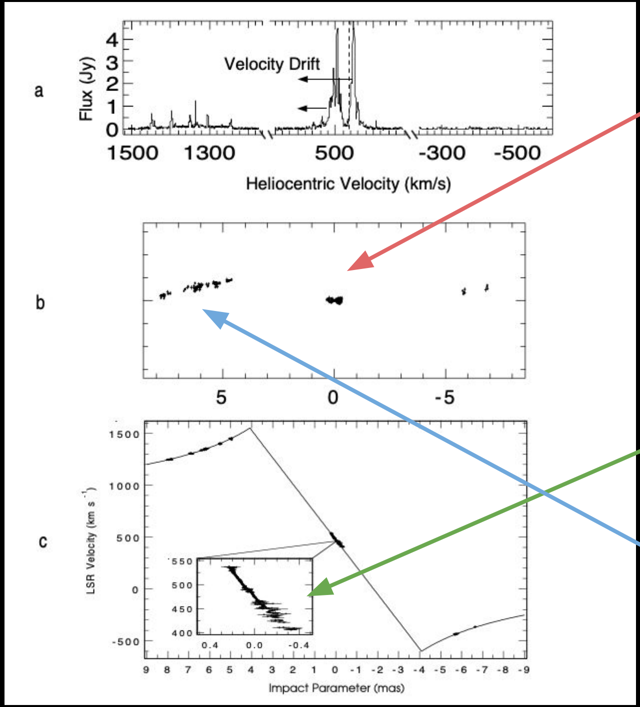
+

- 4.1 mas angular disk size

↓

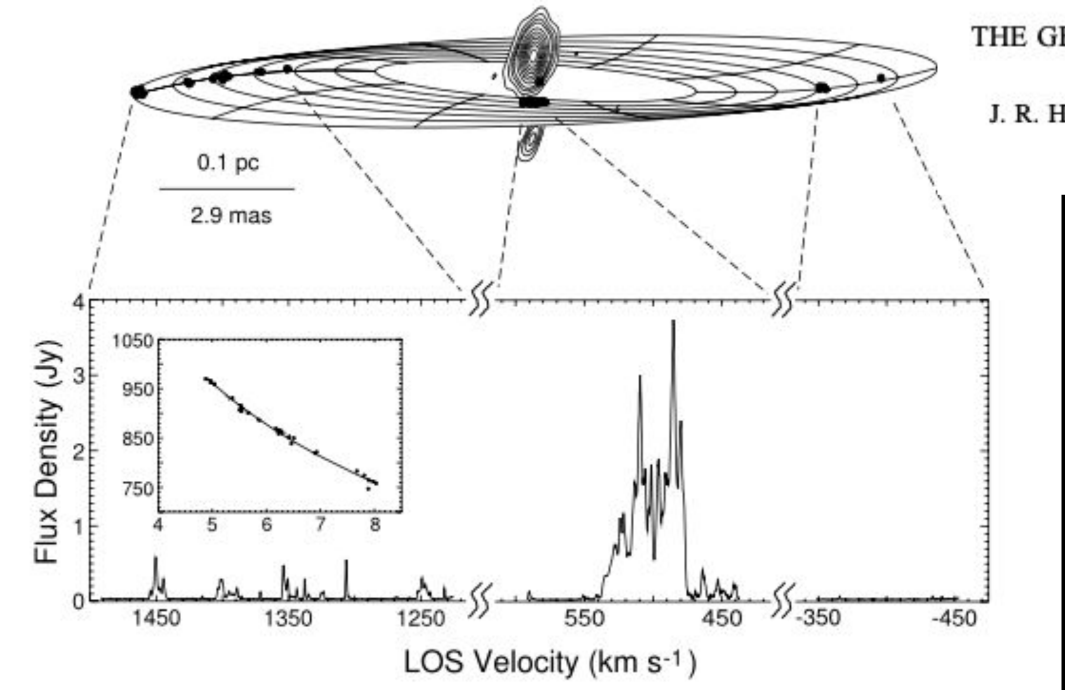
D = 6.4 +/- 0.9 Mpc

Miyoshi+1995: what's left to do? lots...



- clustering of systemic masers?
- is the explanation for midline distribution accurate?
- background being mased is completely absent?
- systematic deviation from linear dependence on systemic feature?
- deviations of high velocity masers from planar geometry?

"velocity drift of high velocity masers could be readily measured in order to improve the definition of the disk and to estimate the distance more accurately"



THE GEOMETRY OF AND MASS ACCRETION RATE THROUGH THE MASER ACCRETION DISK IN NGC 4258

J. R. Herrnstein,[1] J. M. Moran,[2] L. J. Greenhill,[2] and Adam S. Trotter[3]

Received 2004 December 17; accepted 2005 April 17

Maximum likelihood analysis of multi-epoch data sets.

↓

Geometry
(inclination warped disk)
+
Accretion Rate
($\dot{M} < 10^{-4}\alpha\ M_{\odot}\ yr^{-1}$)

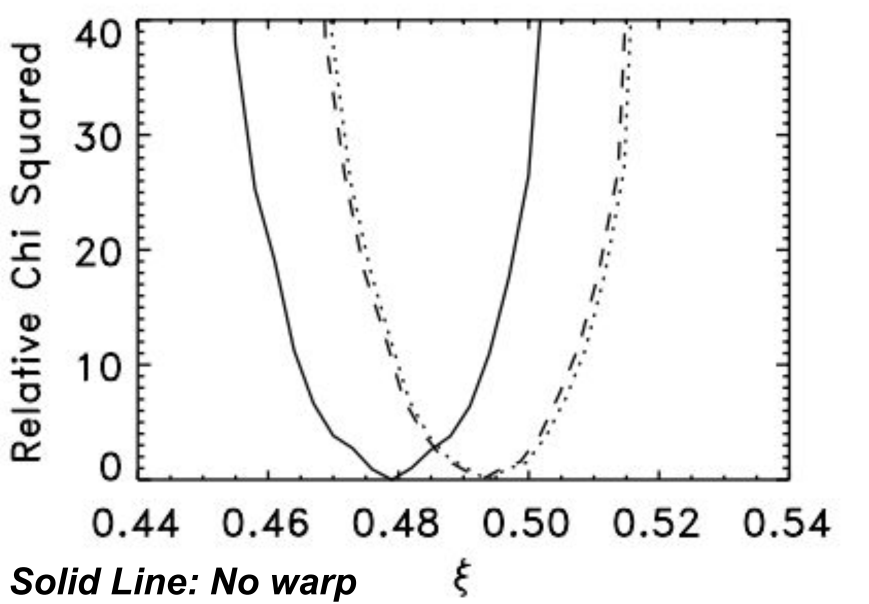
Herrnstein+2005

1. What is the accretion rate?
2. What is the true geometry to explain the maser feature distribution?

Question: Velocity Curve Fit of High Velocity Masers

$$v_{\mathrm{rot}_i} = \frac{\sqrt{GM}}{[(x_i - x_0)^2 + (y_i - y_0)^2]^{\xi}}$$

deviations from a Keplerian orbit

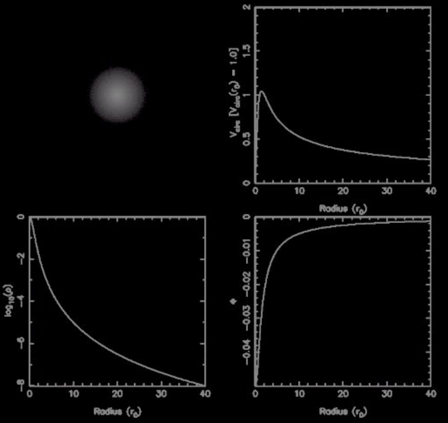


Solid Line: No warp
(Dashed lines: With a warp)

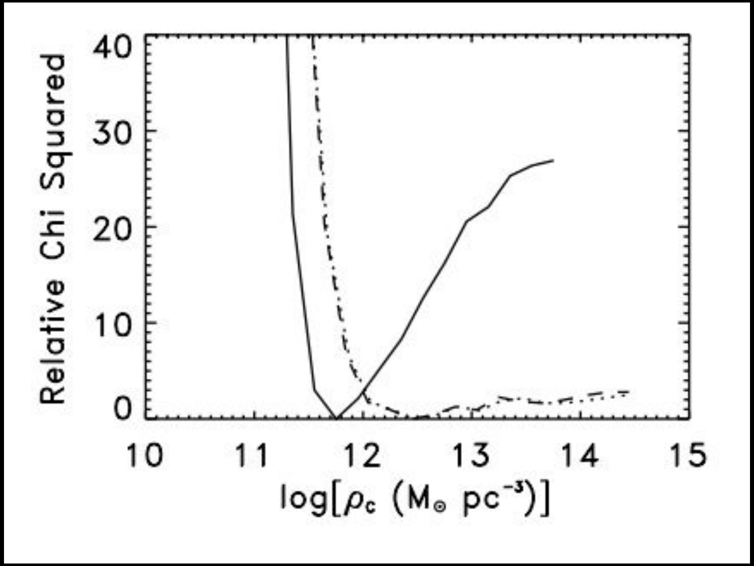
Question: Velocity Curve Fit of High Velocity Masers

Is it...a cluster of stars?

$$M(<r) = \frac{4\pi\rho_c}{3} r^3 \left(1 + \frac{r^2}{r_c^2}\right)^{-3/2}.$$



schematic; density, velocity, and potential for a plummer model



- *ρ_c ~ 6 x 10^{11} $M_\odot$ pc^{-3}*
- *r_c ~ 0.78 mas*
- *large rotation curve flattening of 10.9 km s^{-1} compared to observed ~ 8 km/s*

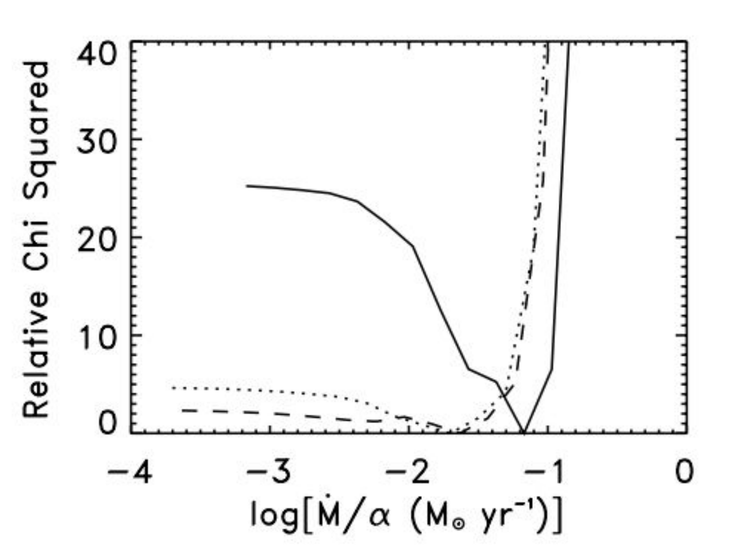
Question: Velocity Curve Fit of High Velocity Masers

Is it...a massive disk?

$$\rho_{\rm mid} = \frac{G M_0 \dot{M}}{3\pi (2\pi)^{1/2} \alpha r^3 c_s^3},$$

(Neufield+1995)

$$M_D = 8.3 \times 10^4 \frac{\dot{M}}{\alpha} \frac{M_0^{1/2}\left(r_2^{1/2} - r_1^{1/2}\right)}{c_s^2} M_\odot,$$

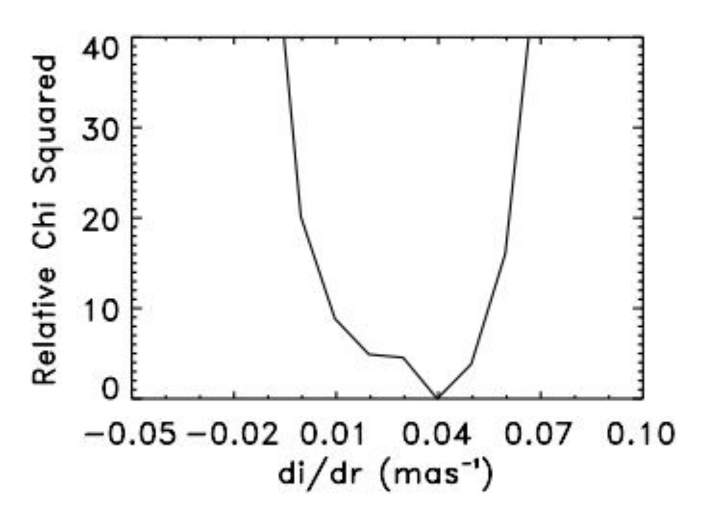


- ***can calculate disk mass + accretion rate***
- ***result is unphysical for masing***

Question: Velocity Curve Fit of High Velocity Masers

Is it...an inclination warp?

$$i_i = i_0 + \frac{di}{dr}(r_i - r_0),$$



- *For di/dr = 0.04+/-0.01 mas^{-1}, we get a flattening of ~9 km/s compared to observed 8 km/s*
- *Non-keplerian rotation is thus a projection effect*

Question: Velocity Curve Fit of High Velocity Masers

what is the most likely explanation?

Inclination warp with
di/dr = 0.04 mas^{-1}

star cluster at the center

massive disk

Question: Velocity Curve Fit of High Velocity Masers

what is the most likely explanation?

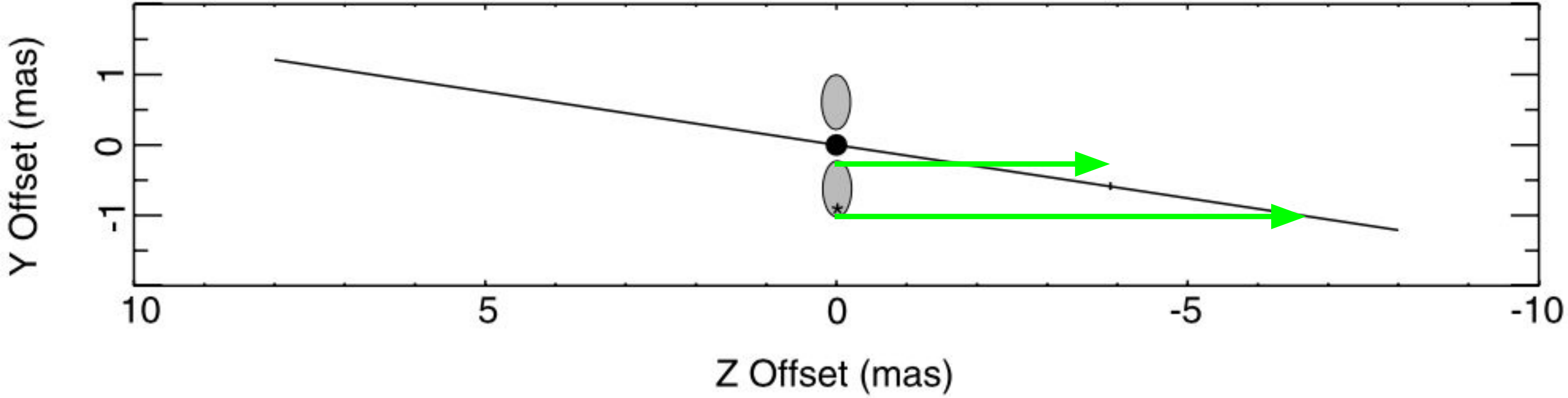
Inclination warp with
di/dr = 0.04 mas^{-1}

"there are substantial unanswered questions surrounding the geometry of the systemic features. We then show that the inclination warp answers these questions convincingly."

Question: Narrow y distribution of systemic masers

consider no warp (constant inclination)

note that this view is a cross section in the z-direction (along line of sight)

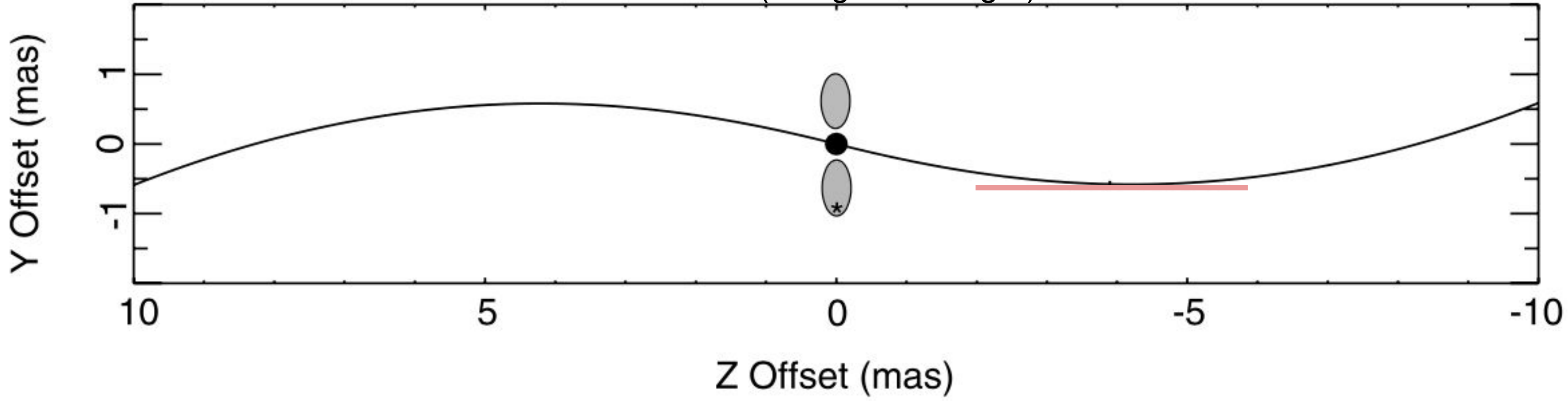


systemic masers amplify the background emission!

Question: Narrow y distribution of systemic masers

consider with a warp! (a revised warp of 0.034 mas^{-1} as opposed to the calculated 0.04+/-0.01 mas^{-1})

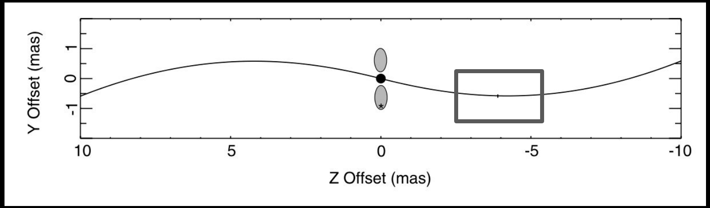
note that this view is a cross section in the z-direction (along line of sight)



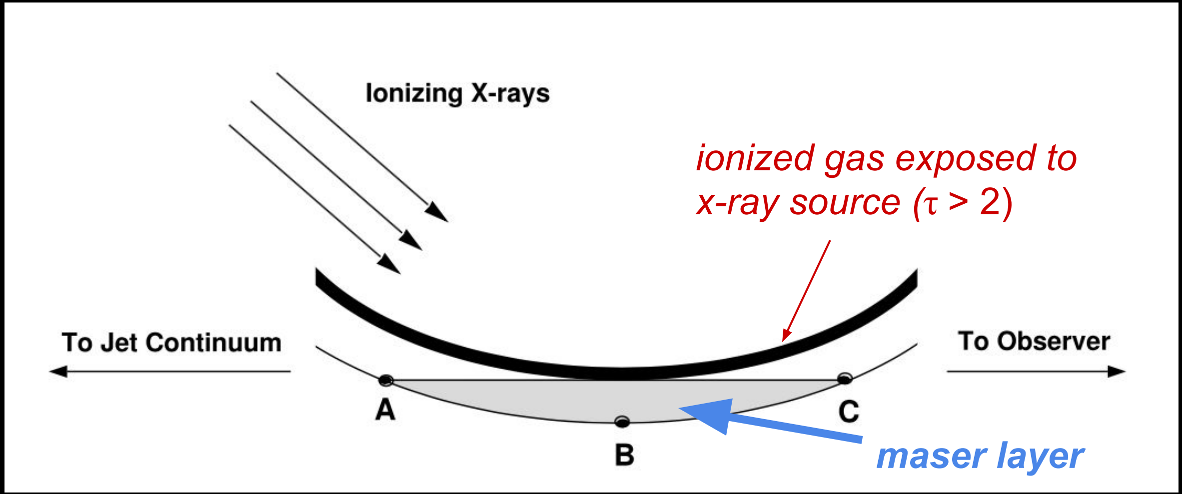
“however, the fact that the high velocity fits lead to a geometry in which they systemic masers lie at a tangent point to the disk is either a ***remarkable coincidence or of physical significance****”*

Question: Narrow y distribution of systemic masers

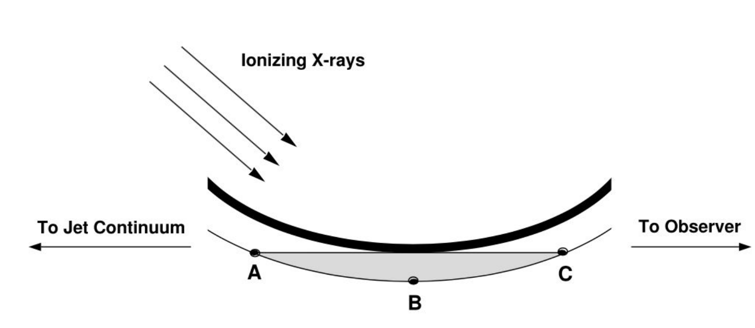
*“however, the fact that the high velocity fits lead to a geometry in which they systemic masers lie at a tangent point to the disk is either a **remarkable coincidence or of physical significance**”*

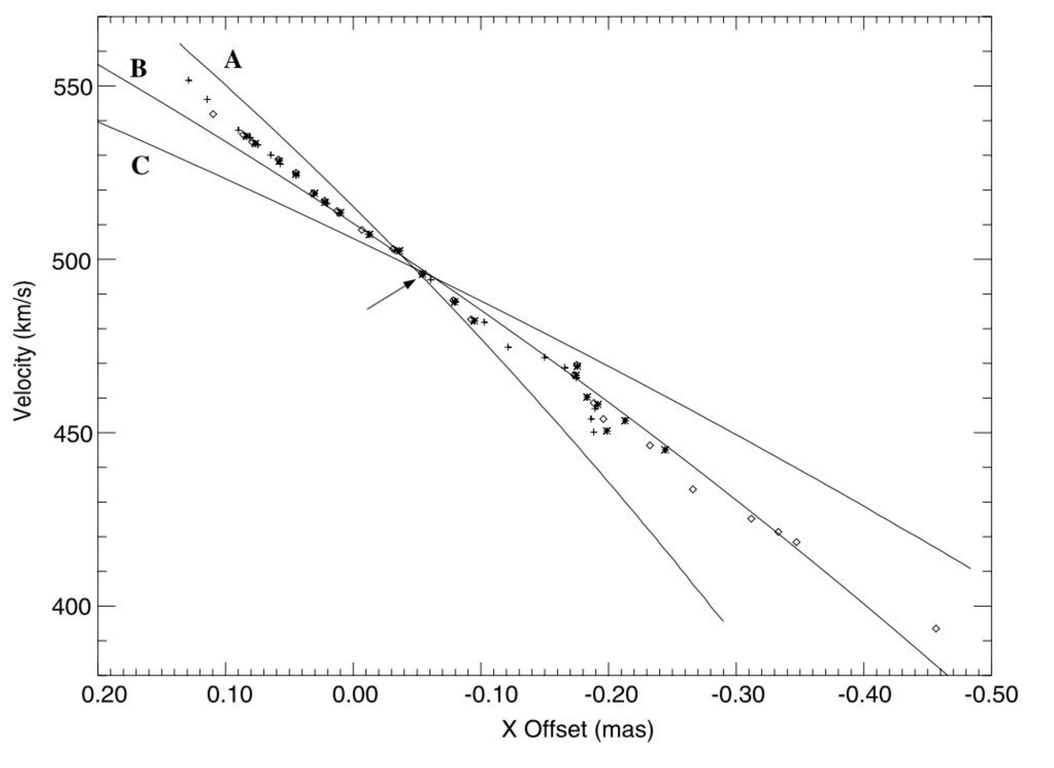


- ***Internal to A: has to traverse two layers of ionized gas***
- ***External to C: background is attenuated so no amplification (20x weaker signal)***



Question: Narrow y distribution of systemic masers





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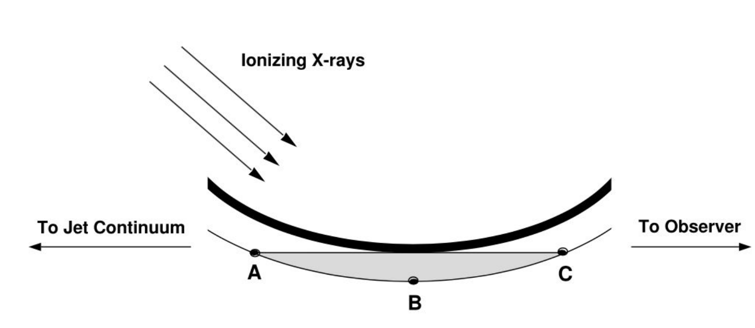
Question: Narrow y distribution of systemic masers



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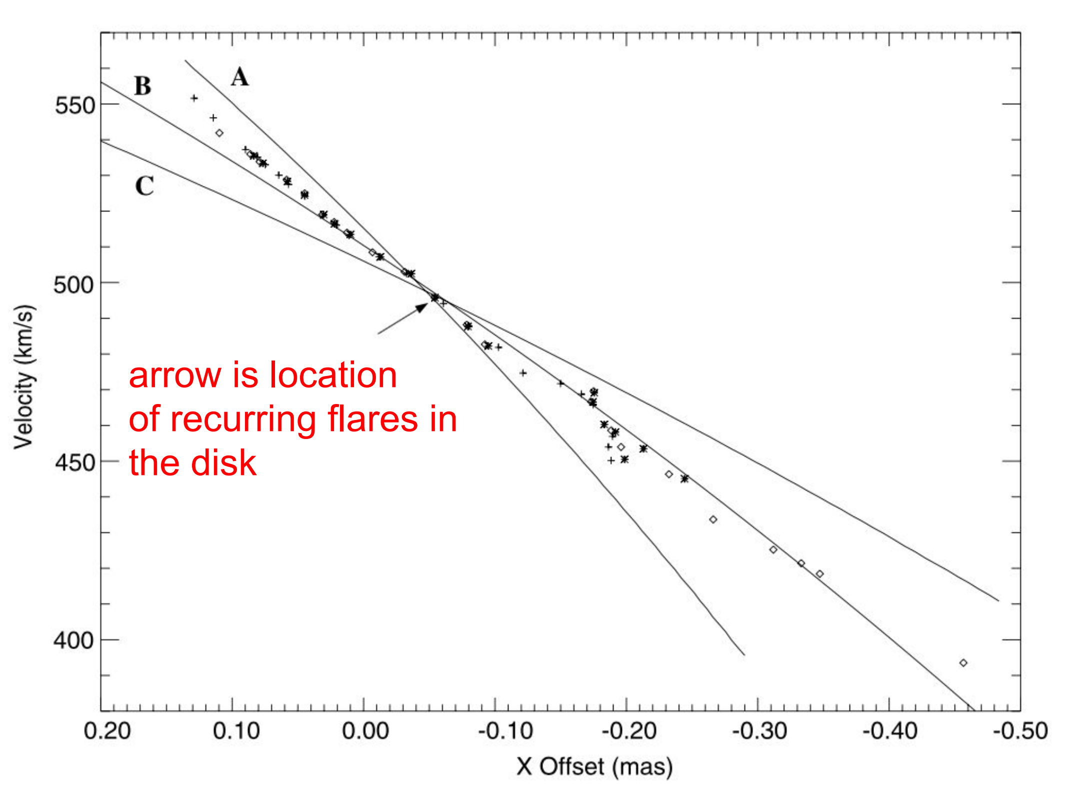
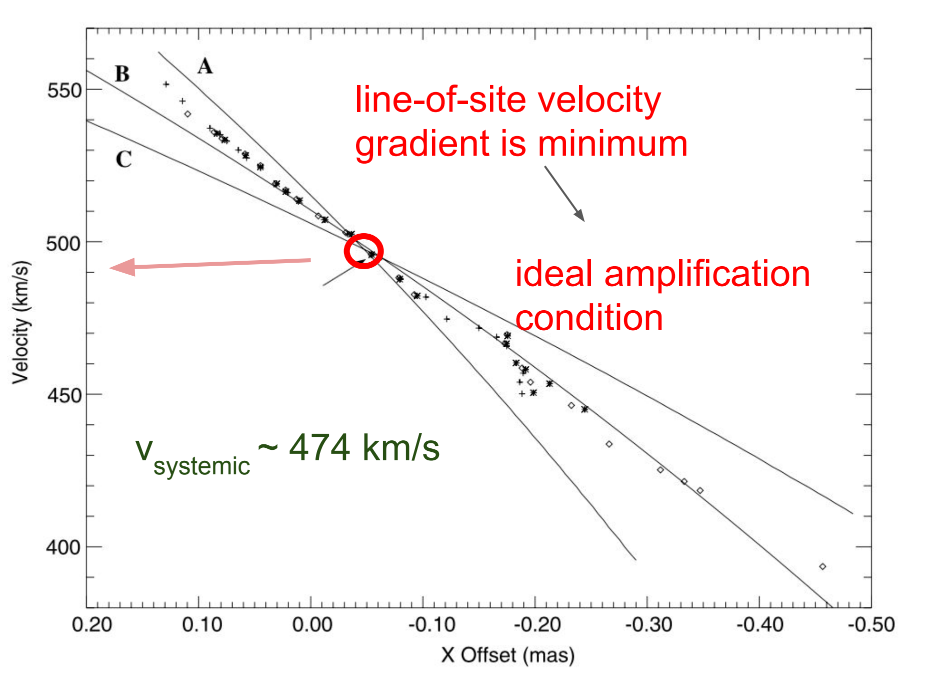
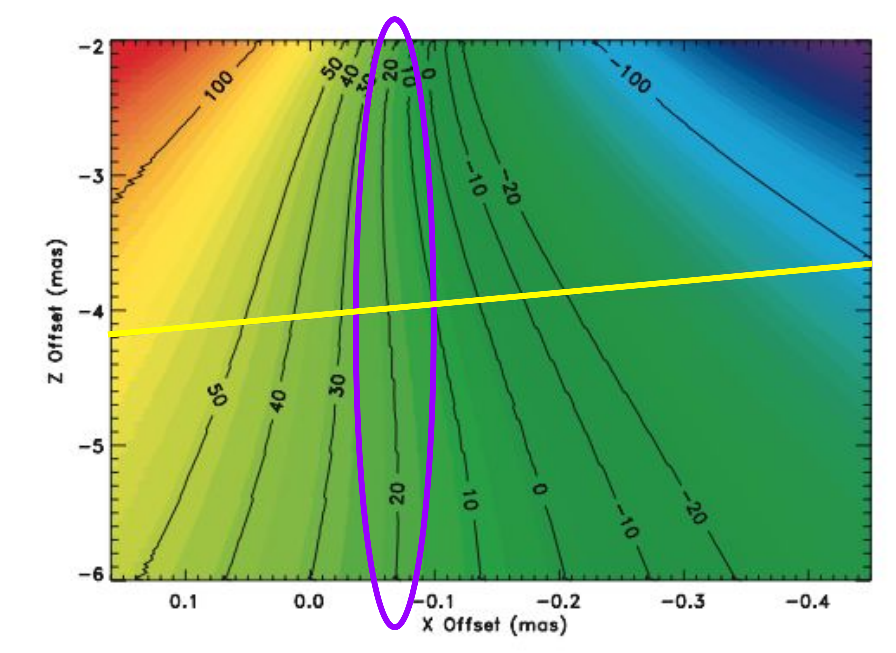


Question: what's causing the flare?

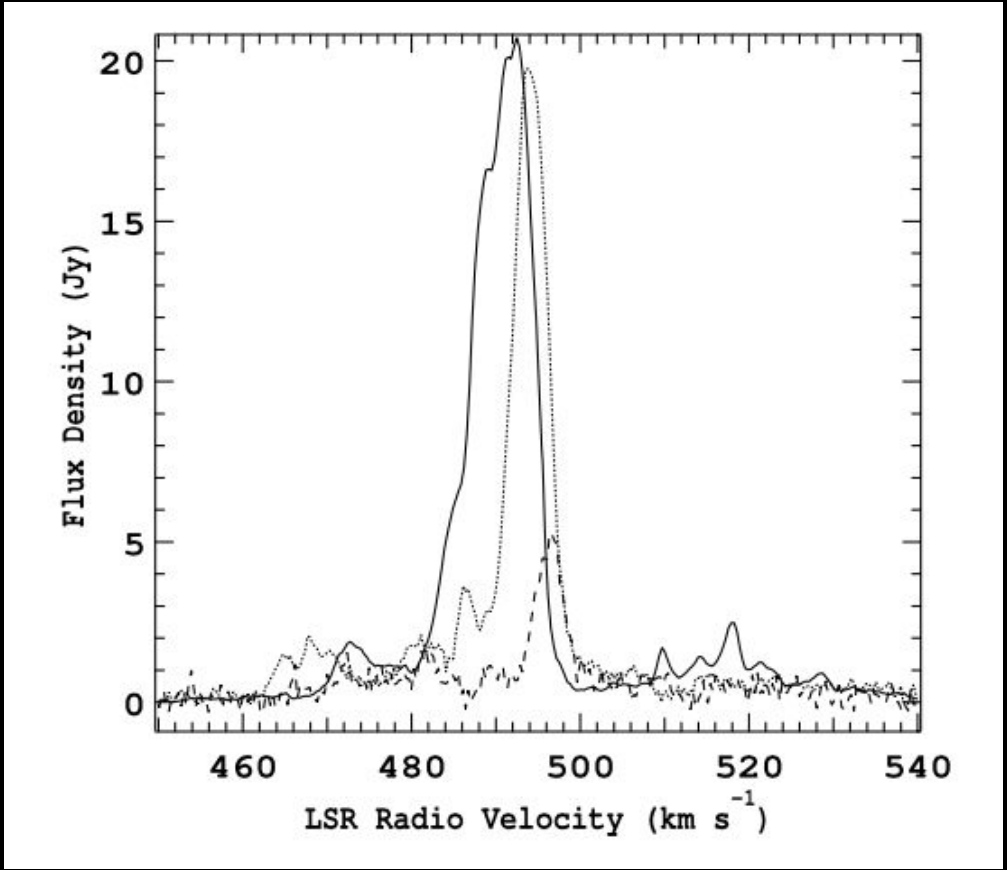


another way to see this:



most ideal masing conditions are 20 km/s red of the systemic velocity

Question: what's causing the flare?



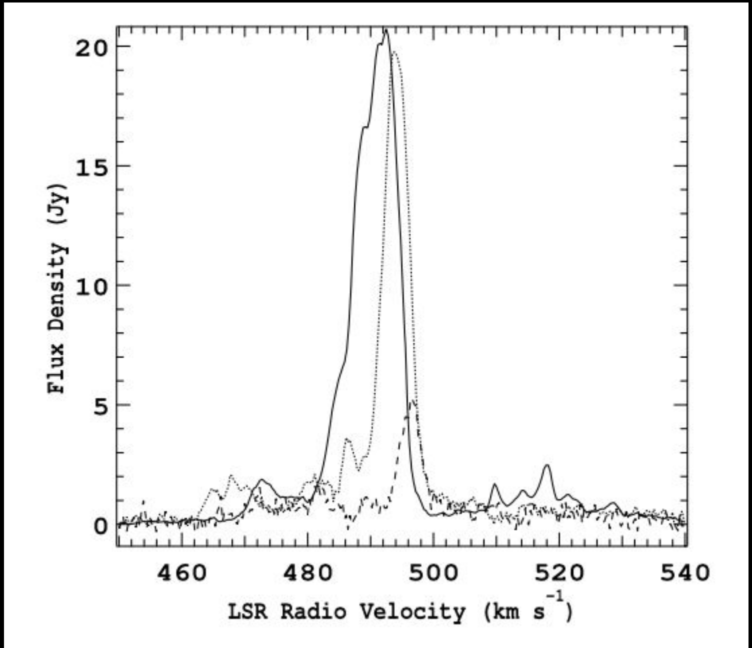
Solid: 1996 flare maximum (492.6 km/s)

Dotted: 1997 flare maximum (494.6)

Question: what's causing the flare?

spectra of the flares suggest the flares are a recurring event a particular location in the disk

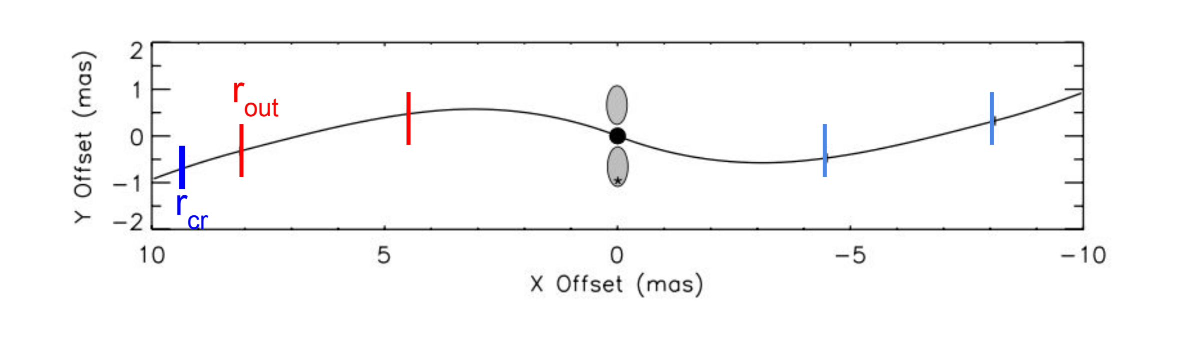
→ 20 km/s red of the systemic velocity!



Solid: 1996 Flare (492.6 km/s)
Dotted: 1997 Flare (494.6)

"flares arise as a result of a serendipitous alignment of and coherent self-amplification of masers along the bowl"

Question: what's the true accretion rate?



$$r_{\rm cr} = 0.04 L_{41}^{-0.426} (\dot{M}_{-5}/\alpha)^{0.809} \mu^{-0.383} M_8^{0.617} c_{s_7}^{-1.19} \text{ pc},$$

Neufield+Maloney (1995):
r_{cr}: radius beyond which the disk is atomic (not molecular)

→

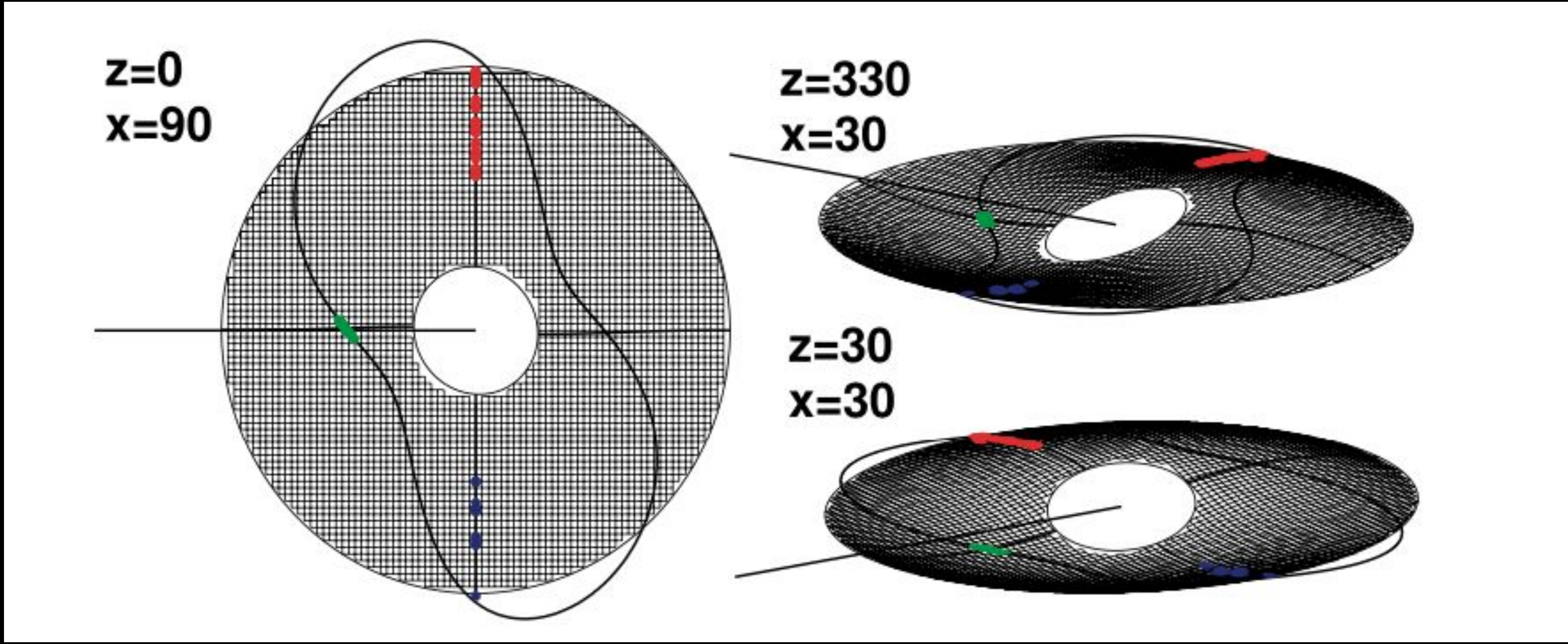
r_{out} = 8.1 mas
r_{cr} = 8.3 mas

$\sim 10^{-4}\,\alpha\, M_\odot\, yr^{-1}$

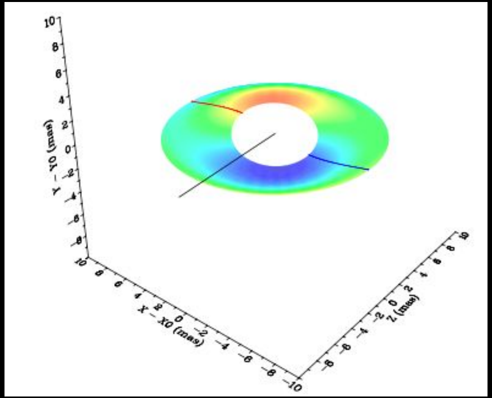
Note: α is related to kinematic viscosity (ν), local speed of sound in the disk (c_s) and the scale height (H) through:

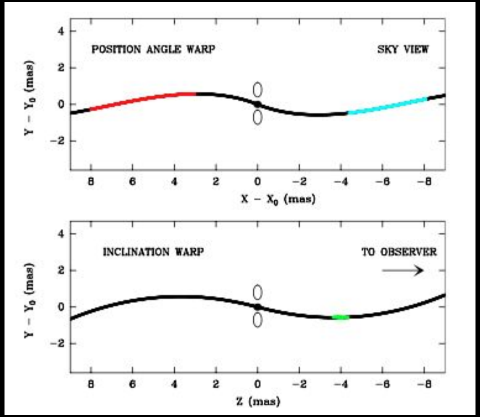
$\nu = \alpha c_s H$

A final picture



A final picture





Inclination warp →

Non-Keplerian rotation

Narrow declination of systemic masers bc of bowl geometry

Recurring flare 20 km/s red of systemic velocity

Accretion Rate

The Current Standing (Humphreys+2013)

TOWARD A NEW GEOMETRIC DISTANCE TO THE ACTIVE GALAXY NGC 4258. III. FINAL RESULTS AND THE HUBBLE CONSTANT

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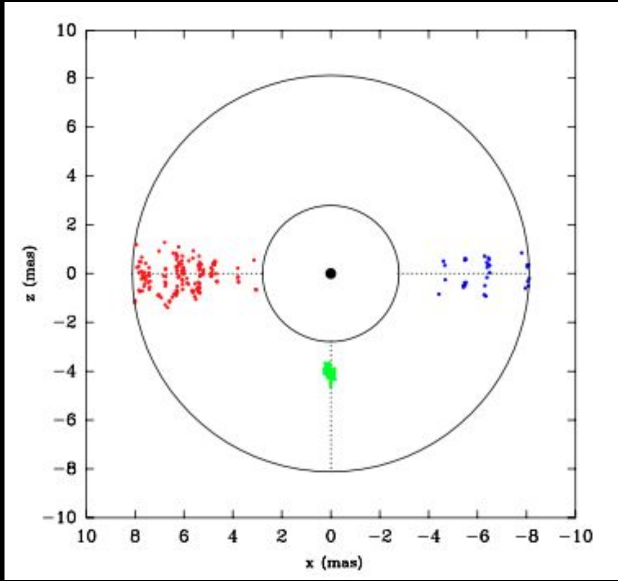
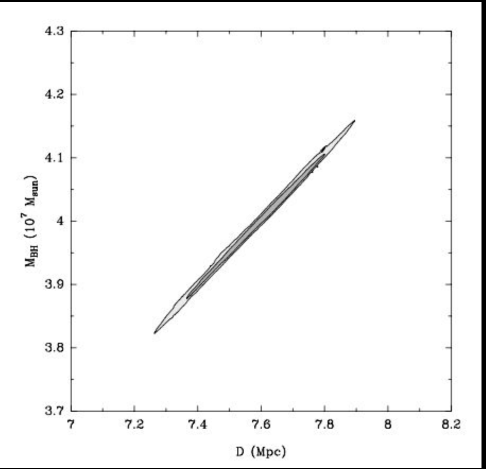
Table 3
The Distance Base Model

Parameter	Value[a]
Distance, D (Mpc)	7.60 ± 0.17
Black hole mass, M_{bh} ($\times 10^7\ M_\odot$)	4.00 ± 0.09
Galaxy systemic velocity, v_{sys} (km s^{-1})	474.25 ± 0.49
Dynamical center x-position, X_0[b] (mas)	-0.204 ± 0.005
Dynamical center y-position, Y_0[b] (mas)	0.560 ± 0.006
Inclination, i_0 (deg)	71.74 ± 0.48
Inclination warp, di/dr (deg mas^{-1})	2.49 ± 0.11
Position angle, Ω_0 (deg)	65.46 ± 0.98
Position angle warp, $d\Omega/dr$ (deg mas^{-1})	5.23 ± 0.30
Position angle warp, $d^2\Omega/2dr^2$ (deg mas^{-2})	-0.24 ± 0.02
Eccentricity, e	0.006 ± 0.001
Periapsis angle, ω_0 (deg)	293.5 ± 64.4
Periapsis angle warp, $d\omega/dr$ (deg mas^{-1})	59.5 ± 10.2



- 10 year monitoring program
- Kinematic and dynamic information
- Additional of differential precession into model

D = 7.60 +/- 0.17 +/- 0.15 Mpc
H_0 = 72.0 +/- 3.0 km s^{-1} Mpc^{-1}



Thanks!
Any questions?