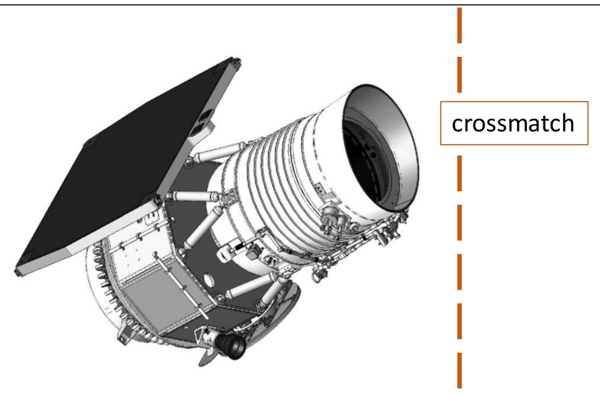
A WISE Look at Variability of Maser Galaxies

Erika Cherpes, Dr. Anca Constantin
Department of Physics & Astronomy, James Madison University

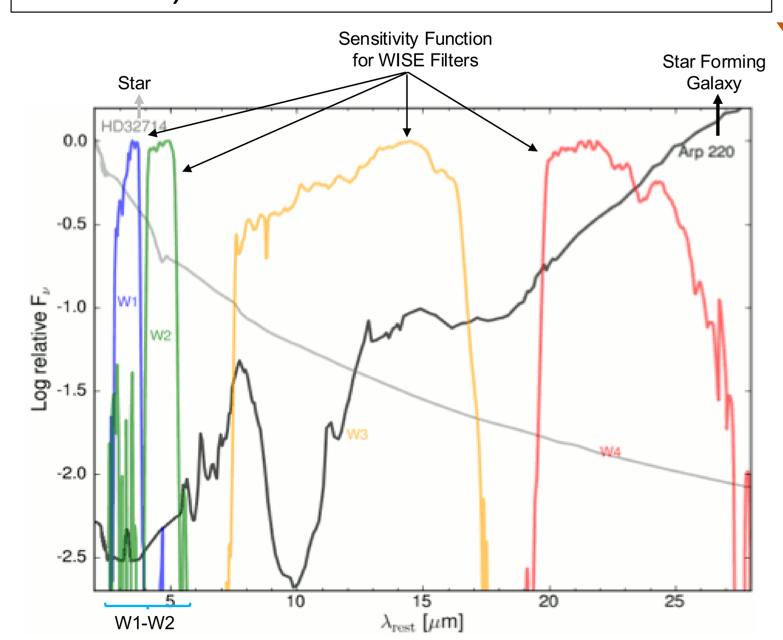
Abstract: Current cosmological models for the fate of the universe and its geometry lack constraints that can be found with observations of powerful laser-like microwave emission (maser) from galaxy centers. These so called megamasers are however very rare, with detections in only about 3% of all surveyed galaxies. We explore here ways of efficiently detecting megamasers via a possible connection between this type of emission and accreting matter on supermassive black holes at galaxy centers, known as Active Galactic Nuclei (AGNs). An important feature of AGNs is light variability, which can now be exploited with multi-epoch observations in mid-infrared from the Wide-field Infrared Survey Explorer (WISE). We present here results from our calculations and parameterization of the Structure Function for galaxies with and without maser emission, as a tool to identify and compare the most prominent variability features, and therefore AGN emission, associated with maser activity.

The Megamaser Cosmology Project provides the largest catalog of galaxies surveyed for maser emission in 22 GHz.



The Wide-field Infrared Survey Explorer (WISE) surveyed the night sky for multiple years in four bands: W1 (3.4 μm), W2 (4.6 μm, W3 (12 μm), W4 (22 μm) (Wright et al. 2010). Our study primarily uses the W1 and W2 bands.

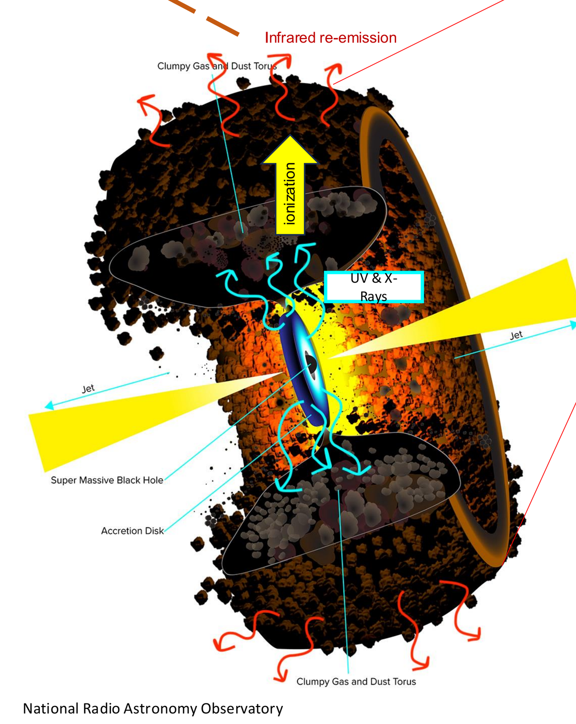
Why Mid IR? - infrared emission is less sensitive to obscuration -- revealing optically elusive AGN (e.g., Padovani et al. 2017).



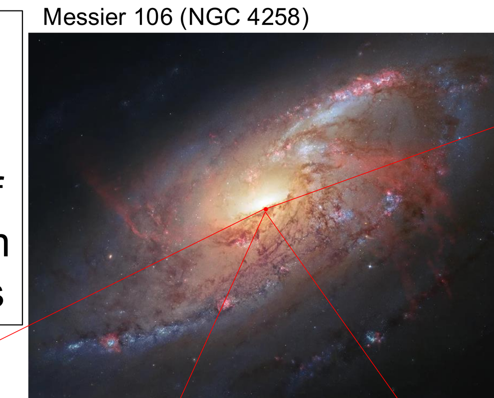
$$\mathrm{W1}[3.4\mu\mathrm{m}] - \mathrm{W2}[4.6\mu\mathrm{m}] = -2.5\log_{10}\frac{\mathrm{flux}(3.4\mu\mathrm{m})}{\mathrm{flux}(4.6\mu\mathrm{m})}$$

Redder (W1 - W2 ≥ 0.5) = AGN behavior

Model of AGN – Powerful emission from accreting matter on supermassive black holes; note the origin of reprocessed IR radiation from the circumnuclear dusty torus



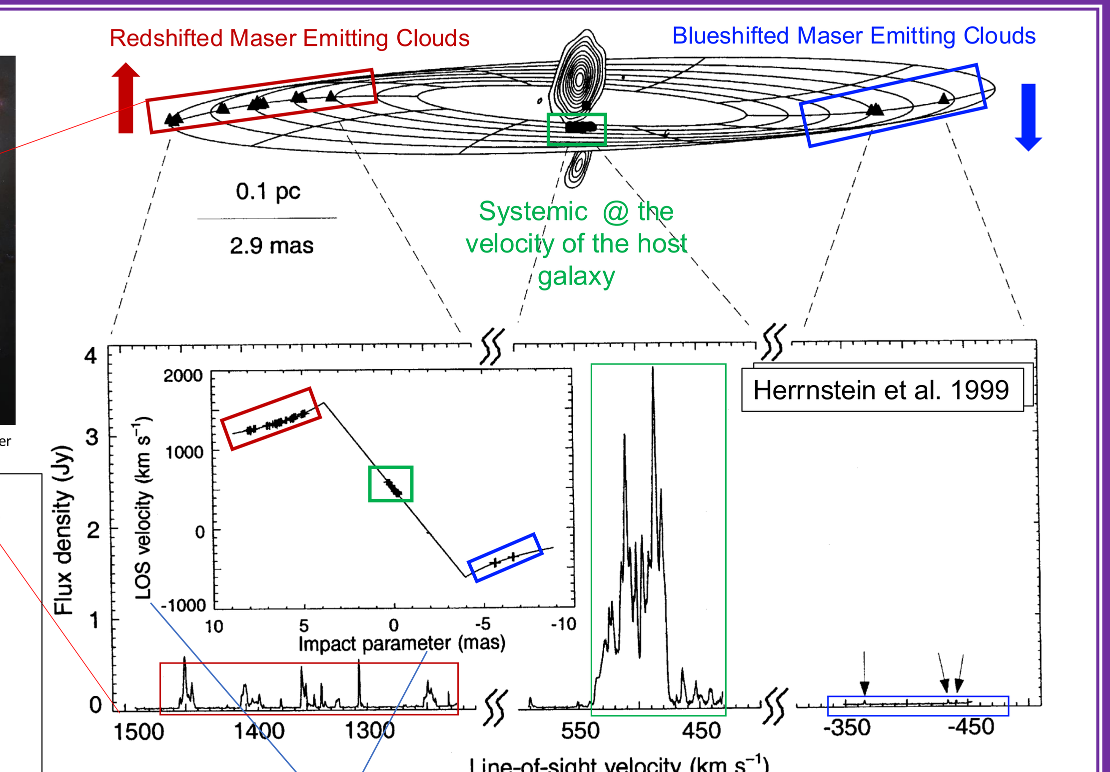
Messier 106 (NGC 4258)



NASA, ESA, the Hubble Heritage Team (STScI/AURA) and R. Gendler (for the Hubble Heritage Team); Acknowledgment: J. GaBany

How We Use Disk Masers

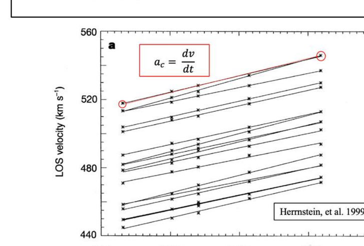
- Direct, not luminosity dependent, geometric distances to galaxies => Constraints on the Hubble constant H_0
- The most accurate masses of supermassive black holes



Get velocity (v) and angular radius (θ) from Keplerian rotation curve

$$v = \sqrt{\frac{GM}{r}} \quad M_{BH} = \frac{rv^2}{G}$$

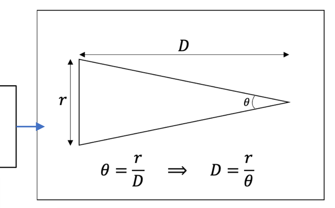
From rotational velocity, solve for black hole mass



Velocity over time gives centripetal acceleration (a_c)

$$a_c = \frac{v^2}{r} \Rightarrow r = \frac{v^2}{a_c}$$

Solve for linear radius (r)



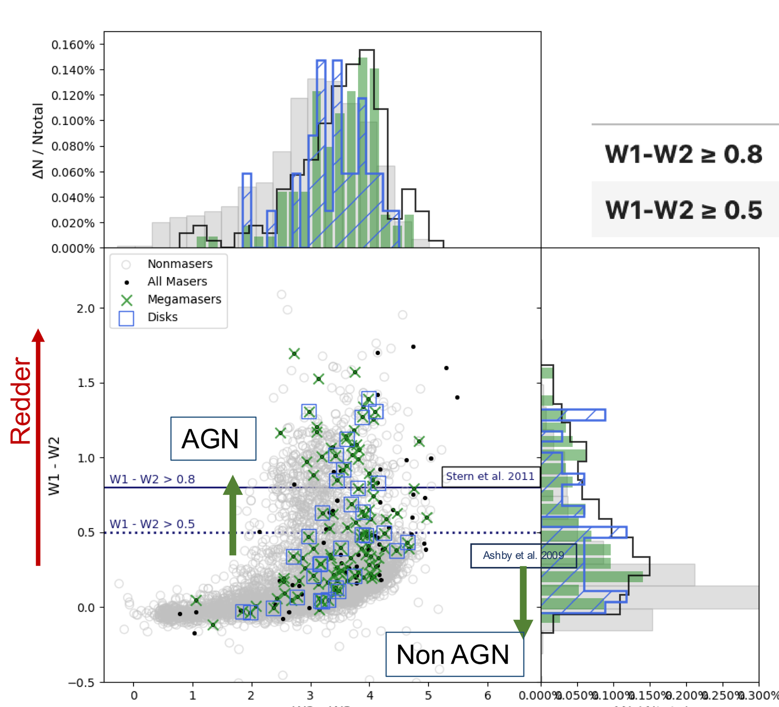
$$\theta = \frac{r}{D} \Rightarrow D = \frac{r}{\theta}$$

Calculate geometric distance

Megamaser disks allow direct calculations of cosmic distances (and thus quantify the universe's fate) and of masses of supermassive black holes.
➔ *We need to understand how maser emission is connected with other galactic properties, in particular, the AGN activity:*

- Mid-IR observations provide information behind the veil of dust.
- Mid-IR data available for wide sky surveys (WISE)!
- Multi-epoch mid-IR observations available from wide-sky surveys (WISE)!
- We calculate, quantify, and compare variability (i.e., AGN activity) in mid-IR, for maser and non-maser galaxies

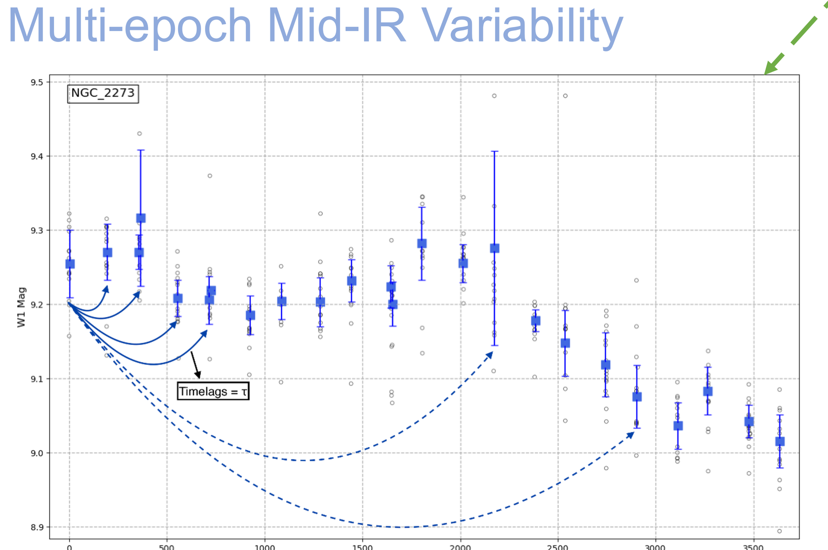
Mid-IR Color-Color Diagram Allows for AGN Identification



	All Masers	Megamasers	Disk Masers
W1-W2 ≥ 0.8	26%	29%	26%
W1-W2 ≥ 0.5	43 %	44 %	38 %

- Maser classification does not show a strong correlation with mid-IR AGN behavior defined by red W1-W2 ≥ 0.5 colors.
- Is mid-IR variability more successful?

Multi-epoch Mid-IR Variability



Example of light-curve revealing how flux in W1 bandpass changes across periods of time, reflecting variability for NGC 2273. Arrows illustrate how time lags for SF are defined. Note, the blue squares show W1 flux in 10 day bins.

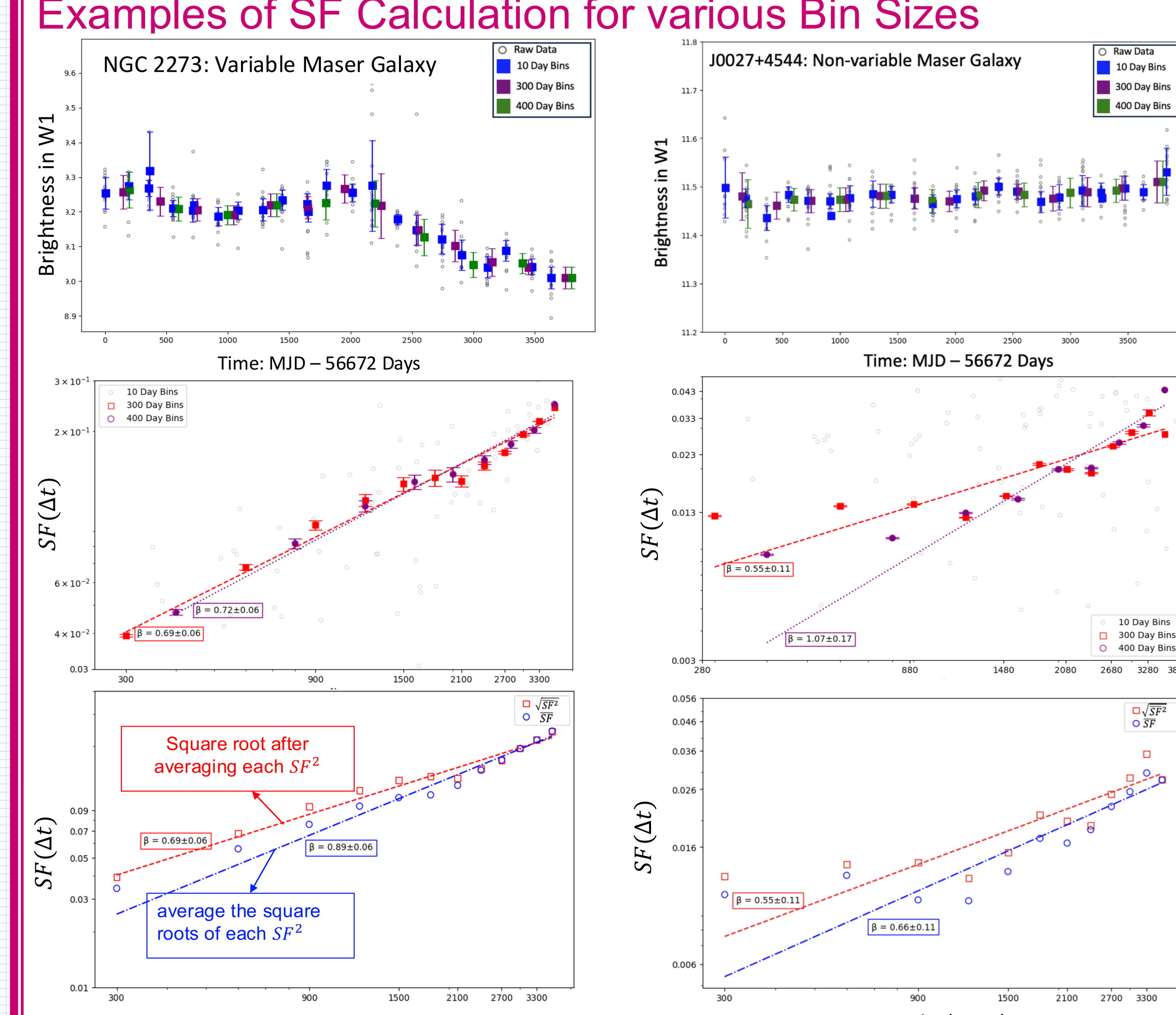
In order to quantify variability, we calculate the Structure Function (SF) which reveals average magnitude difference over a time lag (Son et al. 2023)

$$\mathrm{SF}^2(\Delta t) = \frac{1}{N_{\Delta t,\mathrm{pair}}}\sum_{i=1}^{N_{\Delta t,\mathrm{pair}}}(m(t) - m(t+\Delta t))^2$$

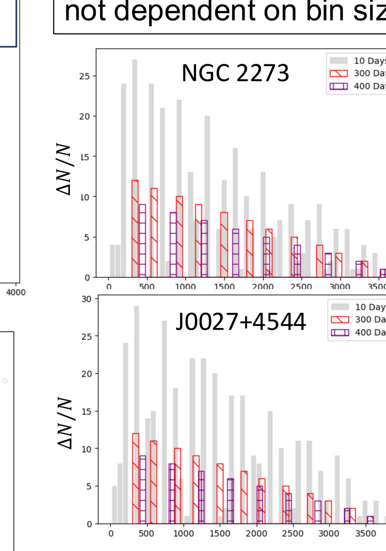
Son et al. 2023

- $m(t)$ and $m(t+\Delta t)$ are the observed magnitudes within the (i, j) time pair.
- $N_{\Delta t,pair}$ is the number of pairs associated with the time lag $t_j - t_i$

Examples of SF Calculation for various Bin Sizes



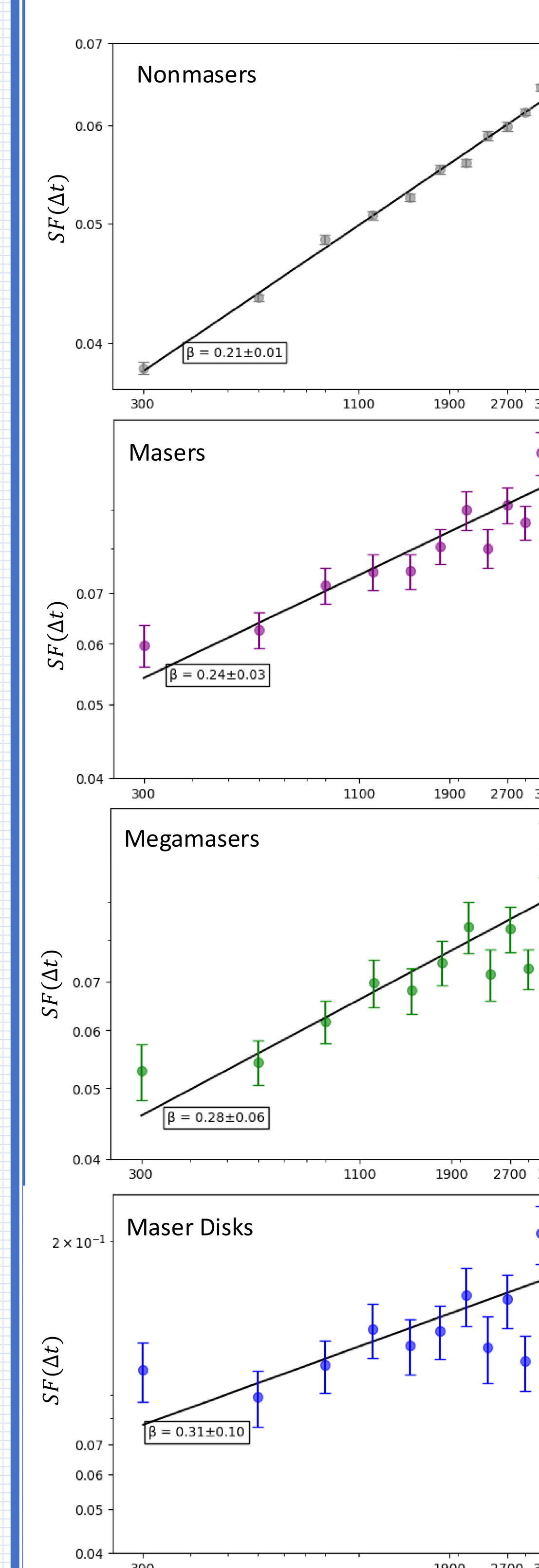
Time-lag distributions are not dependent on bin sizes



Two Methods of Averaging SF

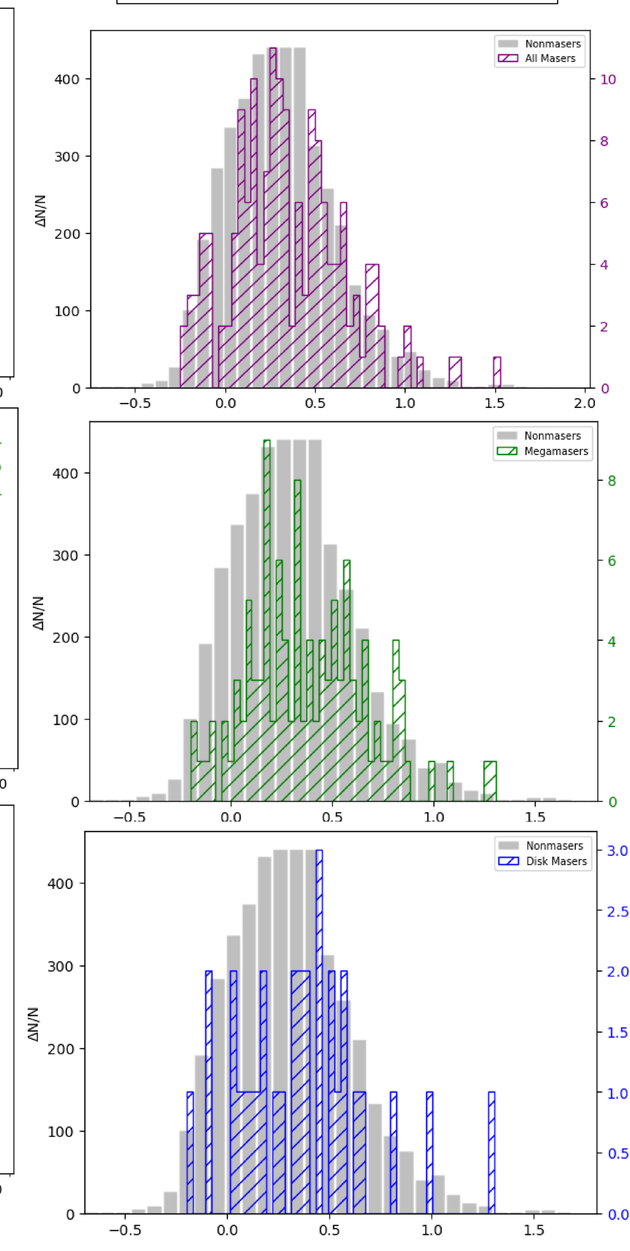
SF is underestimated for short time-lags when we average the square roots of each SF^2 (blue) vs. taking the square root after averaging together each SF^2 (red)

Results: Averages of $\sqrt{SF^2}$ for samples of maser and non-maser galaxies



Slope (β)	Averaged Slopes	Slope of Average SF
Masers	0.35±0.32	0.24±0.03
Megamasers	0.39±0.30	0.28±0.06
Maser Disks	0.36±0.32	0.31±0.10
Nonmasers	0.31±0.30	0.21±0.01

Averaged slopes for each SF (histograms) are larger than the slope of average SF (plots)



A more robust SF parametrization is needed to better quantify variability

Future Directions

- Include magnitude uncertainties in SF calculations
- Expand SF calculations to include W2 magnitude and W1-W2 color
- Experiment with broken power laws for fitting SF
- Explore calculations of SF in luminosity bins in an attempt to identify other possible parameters that influence the maser-variability connection

References: Herrnstein et al. 1999, Nature, 400, 539; **Kawaguchi** et al. 1998, ApJ, 504, 671; **Kozłowski** et al. 2016, ApJ, 826, 118; **Padovani** et al. 2017, A&A, 25, 2; **Simonetti** et al. 1985, ApJ, 296, 46; **Son** et al. 2023, ApJ, 958, 135; **Wright** et al. 2010, ApJ, 140, 1868