Mid-Infrared Variability of Galaxies Surveyed for Water Megamaser Emissions

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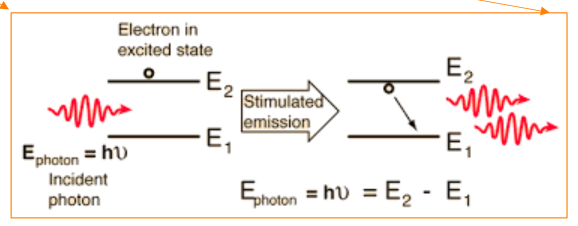
Abstract

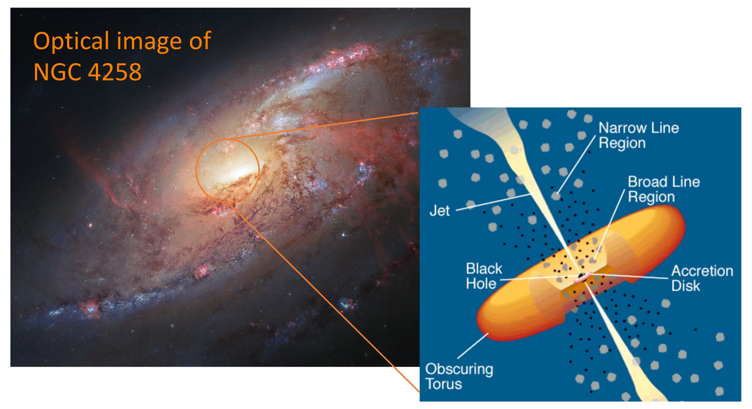
Astrophysical masers occur by the stimulated emission of molecules in interstellar objects. When detected in galactic centers, they prove crucial to our understanding of how the universe formed and continues to evolve. Water masers found in the centers of disk-like galaxies are a unique tool for probing the properties of supermassive black holes and providing direct distance measurements to extragalactic astrophysical sources. Unfortunately, luminous water masers are extremely rare, inciting the push to find more. Considering this, it is crucial to further our understanding of which galaxies this variety of maser emission can occur in and investigate the conditions in the centers of these host galaxies. Currently, there is tentative evidence that suggests a connection between the maser pumping mechanism with the accretion of matter onto supermassive black holes in galactic centers, the region known as the active galactic nucleus (AGN). Herein, we investigate the degree to which AGN activity, as probed by mid-infrared variability, correlates with maser emission and its properties in galactic centers. Employing the mid-infrared and its properties offers the advantage of being less sensitive to cosmic obscuration, therefore revealing AGN signatures that are missed in other wavelengths. We work here with the Megamaser Cosmology Project (MCP), which offers an up-to-date list of galaxies that have been surveyed for water maser emission, as well as multi-epoch mid-infrared data from Wide-field Infrared Survey Explorer (WISE), and present comprehensive comparative analysis of variability in maser host galaxies as and non-hosts. These results constrain the possibility that AGN activity may provide the necessary seed radiation for central maser emission in galaxies and offer new opportunities to guide future surveys.

Holy Grail of Astronomy

M.A.S.E.R. : Microwave **A**mplification by **S**timulated **E**mission of **R**adiation

Megamasers = cosmic masers **10^6** times more luminous than typical galactic masers



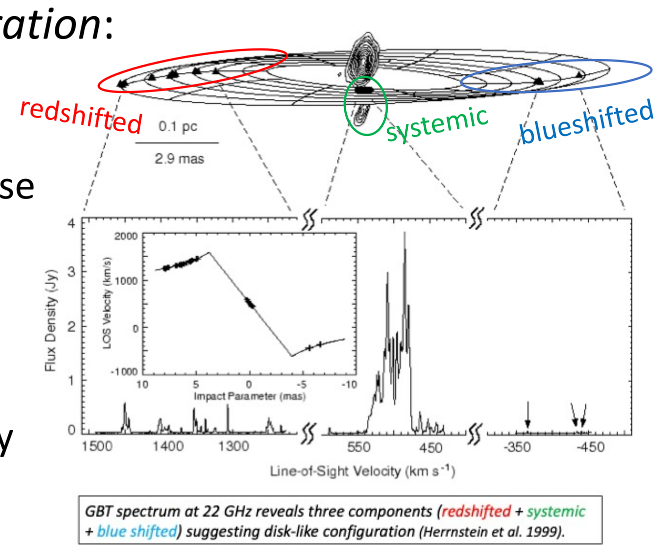


Megamasers in *galactic centers*:

I. Produced in shocks made by jets and winds
II. Produced in accretion disk of active galactic nucleus (AGN)

Megamasers found in *disk-like configuration*:

I. Measure direct distances
   > Constrains H_0 (Hubble) constant (rate at which universe is expanding)
   > More accurate than indirect distance measurements (standard candles)
   > Better understand dark energy
II. Measure masses of SMBH

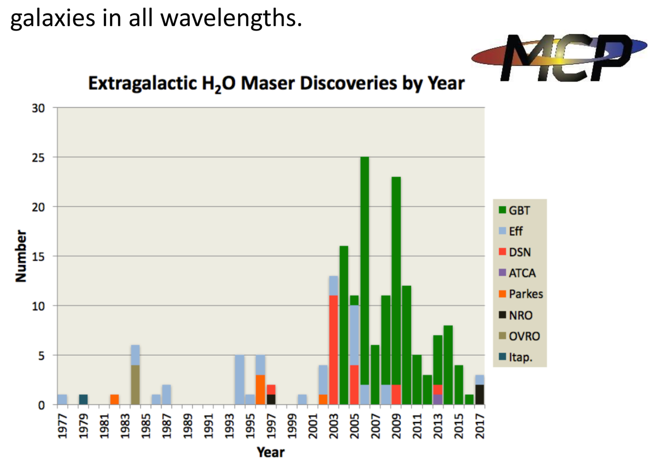


GBT spectrum at 22 GHz reveals three components (redshifted + systemic + blue shifted) suggesting disk-like configuration (Herrnstein et al. 1999).

Detection of Masers

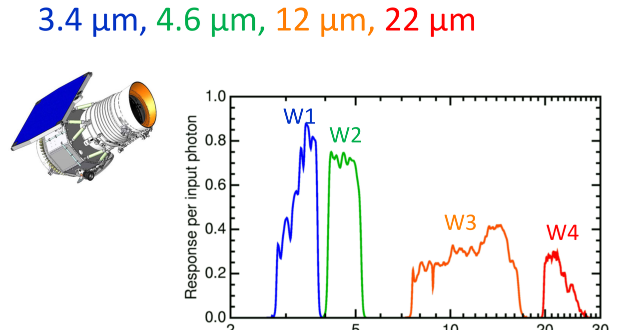
Megamaser Cosmology Project

- Largest catalog of galaxies surveyed for H2O maser emission in 22 GHz (>6000 galaxies; Braatz et al. 2018)
- ~3% of all surveyed galaxies host maser emission
- ~80% of maser galaxies show megamaser luminosities
- ~20% of megamaser host galaxies emission are found in a disk-like configuration
- Need better selection of potential maser disk candidates, which in turn needs a better understanding of how the masing activity relates to the properties of their host galaxies in all wavelengths.



Wide-field Infrared Survey Explorer (WISE) Telescope

- A mid-infrared survey of the entire sky with bands centered at wavelengths of: 3.4 µm, 4.6 µm, 12 µm, 22 µm



Wright et al. (2010)

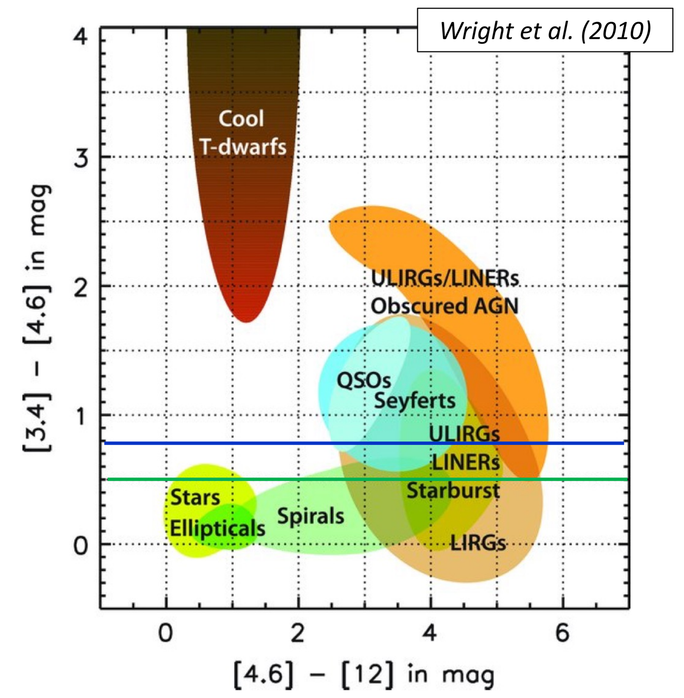
	All masers	Megamasers	Disks	Control
MCP Survey	180	116	34	6353
MCP-WISE Crossmatch	174	114	34	4095

AGN Selection

Conventional selection of possible maser candidate galaxies have been based on optical selection, which exhausted the SDSS data. Because of this, we are in need of improved selection techniques using mid-infrared light from WISE, which is a helpful tool for uncovering obscured AGN. This WISE color-color diagrams show select proposed WISE AGN selection techniques:

I. W1 - W2 > 0.8 (blue)
II. W1 - W2 > 0.5 (green)

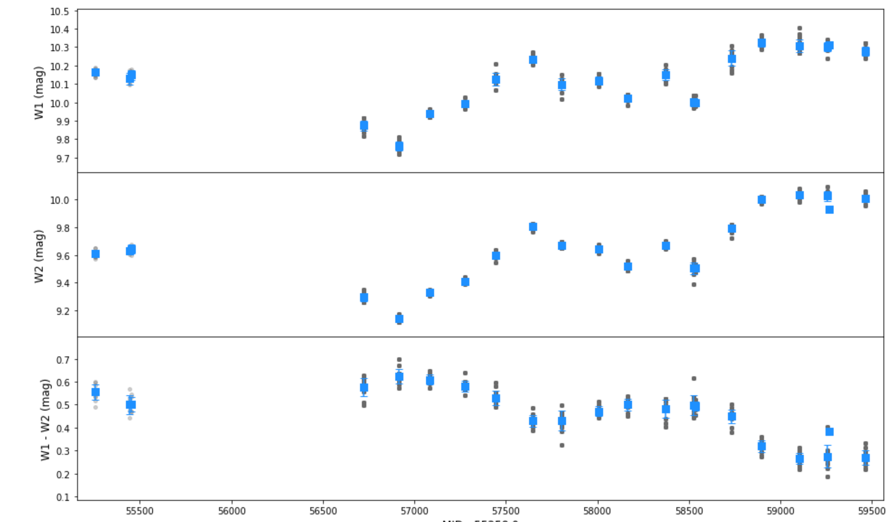
These color cuts improve maser detection rates at the cost of missing a substantially high percent of disk systems.



Data Processing

In order to accurately measure variability:

- We removed duplicate galaxies (single galaxies surveyed for emission multiple times) by keeping the MCP-WISE match closest to the coordinates provided by the MCP.
- We identify the WISE detection counterparts of all the MCP, via 6" search radii for matches in the IPAC/IRSA Extragalactic database, and retained only WISE detections with signal-to-noise ratio ≥ 3.
- For the best MCP-WISE matches, we then employ the WISE Multi-Epoch catalog to search and identify multiple observations over time scales of hours to years, and crossmatch the result to NeoWISE, taking into account 7-8 additional years of observations.
- We rejected points outside 3σ, where we employ the unbiased variance estimator in our calculation of standard deviation in order to reduce bias due to our small sample size



Light curve of maser host galaxy CGCG468-002

Measuring Variability

Variability : total power output of galaxy centers, with timescales of hours to years

I. e.g. Ulrich et al. 1997, Kozlowski et al. 2016
II. Can be associated with instabilities in the accretion disk or surface temperature fluctuations.
III. Variability selection can reveal accreting SMBHs as power sources (e.g., Trump et al. 2015).

Variability in the mid-infrared can reveal a selection of galaxies can reveal changes towards redder (higher) W1-W2 colors, i.e., moving them to AGN wedge of the WISE color-color diagrams (e.g., Stern et al. 2005).

I. Mid-Infrared variability selection allows for new identification of AGN activity where other wavelength selection can miss them.
II. Mid-Infrared variability studies have unique advantages: they are less sensitive to dust obscuration, which constitutes a large fraction of the nearby low-luminosity AGN population in general, and also believed to be strongly associated with the maser activity.

Therefore, we investigate changes in W1-W2 that would reveal AGN activity not detected by conventional methods

Quantifying Variability:

To measure variability, we estimate a covariance matrix using W1 and W2. For our study, we used the Pearson product-moment correlation coefficient R. The relationship between the correlation coefficient matrix, R, and the covariance matrix, C, is

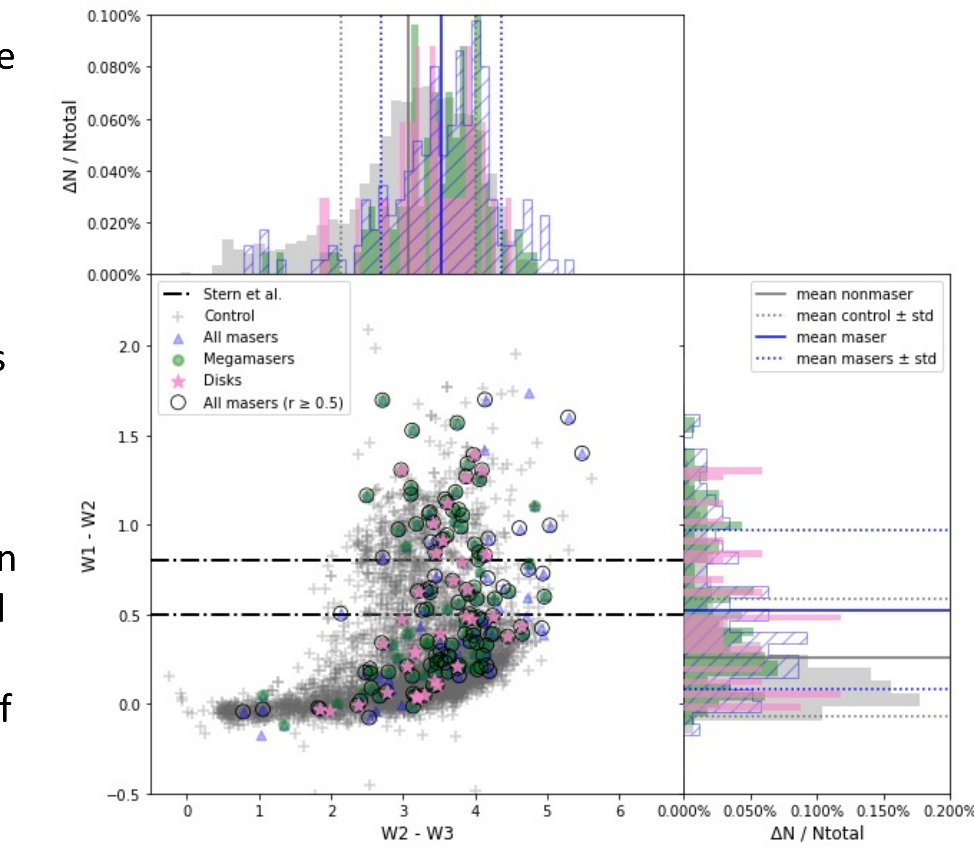
$$R_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$

where C is a measure of covariance. Covariance indicates the level to which two variables vary together. This produces the normalized correlation matrix. For our study, we take a value of R greater than 0.5 to be "variable".

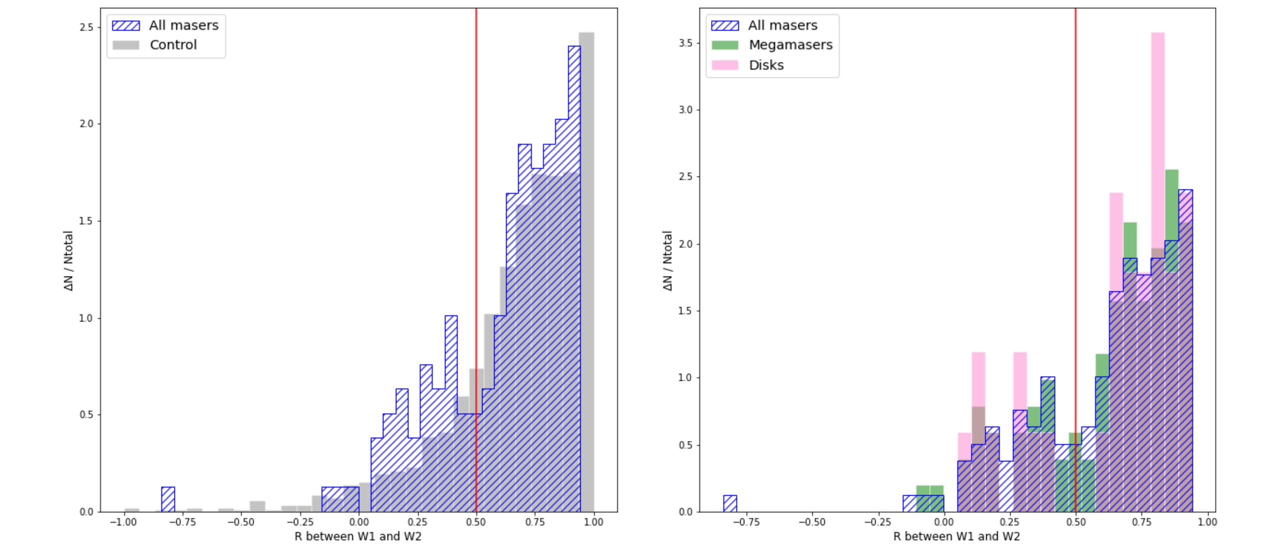
Results

Quantifying Variability:

- Here, we display the color-color diagram for our galaxy collection. With this, we investigate the detection rate of AGN-like systems with conventional color-cuts.
- Distribution of the differences between W1 and W2, as well as W2 and W3 outline the colors of these galaxies.



Distributions of R between W1 and W2:



	Fraction with W1 - W2 ≥ 0.5	Fraction with W1 - W2 ≥ 0.8
All masers	0.43 ± 0.139 (43%)	0.26 ± 0.166 (26%)
Megamasers	0.44 ± 0.170 (44%)	0.29 ± 0.198 (29%)
Disks	0.38 ± 0.326 (38%)	0.26 ± 0.375 (26%)
Control	0.18 ± 0.040 (18%)	0.10 ± 0.053 (10%)

R ≥ 0.5	Fraction with W1 - W2 ≥ 0.5	Fraction with W1 - W2 ≥ 0.8
All masers	0.50 ± 0.155 (50%)	0.32 ± 0.182 (32%)
Megamasers	0.49 ± 0.189 (49%)	0.34 ± 0.215 (34%)
Disks	0.46 ± 0.349 (46%)	0.35 ± 0.387 (35%)
Control	0.21 ± 0.042 (21%)	0.11 ± 0.055 (11%)

References

Braatz, J., et al., 2009, ApJ, 695, 287; **Braatz**, et al., 2018, https://safe.nrao.edu/wiki/bin/view/ Main/Megam aserCosmologyProject; **Herrnstein**, et al., 1999, A&A, 20, 165; **Kuo, C.**, Constantin, A., et al., 2018, ApJ, 860, 169; **Stern, D.**, et al., 2012, ApJ, 753, 30; **Trump** et al. 2015, ApJ, 811, 26; **Wright E.**, et al., 2010, AJ, 140, 1868; **Zierr, C.** & Biermann, P., 2018, A&A, 69, 1

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