Mid-Infrared Variability of Galaxies Surveyed for Water Megamaser Emission

Emily McPike, Dr. Anca Constantin
Department of Physics & Astronomy, James Madison University

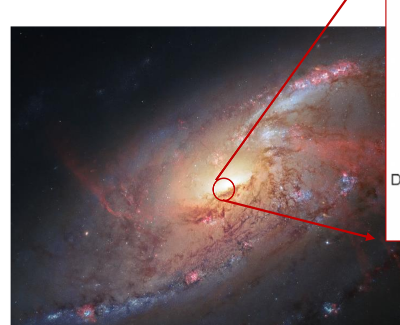
Abstract

Cosmic masers are natural microwave amplifiers by stimulated emission of radiation. Microwave amplification by stimulated emission of radiation, or maser, is the microwave analog of a laser and is found within star formation regions and, keenly, within nuclear regions of galaxies that host accreting supermassive black holes, otherwise known as AGN. When very luminous (10^6 times more luminous than similar emission detected in our own galaxy, hence, megamaser) and in a disk-like configuration, they prove immensely valuable as they can (1) uniquely probe the inner works of active galactic nuclei (AGNs; i.e., SMBHs actively accreting matter onto them) and provide accurate SMBH mass measurements, and (2) provide a crucial constraint to the value of the Hubble constant in the local universe via direct geometric angular distance measurements. Unfortunately, water megamaser disks prove exceedingly rare, with a detection rate of far less than 1% to date (among a similarly low detection rate of ~3% for any type of central water maser emission). In this study, we search for clues leading us to additional host galaxy candidates. There is tentative evidence for a connection between the maser pumping mechanism and the accretion of matter onto SMBHs in AGN systems. Because the UV and optical emission from the matter accreting onto the SMBH goes on to be absorbed by surrounding toroidal dust and re-emitted in the mid-infrared, flux variations present in the accretion disk give rise to variability in the mid-infrared. Herein, we investigate the degree to which AGN activity, as probed by mid-infrared variability, correlates with water maser emission. Mid-infrared observations offer the advantage of being less sensitive to cosmic obscuration, revealing AGN signatures that are missed in other wavelengths. We work here with the Megamaser Cosmology Project (MCP), which offers the most up-to-date list of galaxies surveyed for water maser emission, as well as ~10 years of multi-epoch mid-infrared data from Wide-field Infrared Survey Explorer (WISE) and present a comparative analysis of variability in galaxies with and without maser emission in their centers.

Active Galactic Nuclei & Mid-IR

Active Galactic Nucleus (AGN) = Supermassive black hole (SMBH) actively accreting matter onto it.

- IR is useful in AGN identification as UV and optical emission from the accretion disk is absorbed by surrounding dust and re-emitted in mid-IR.



Composite of infrared and optical light of NGC 4258 (Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), and R. Gendler (for the Hubble Heritage Team))

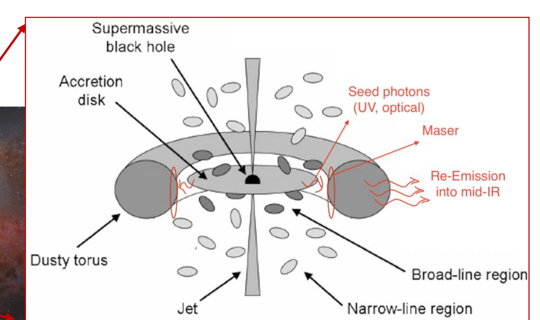
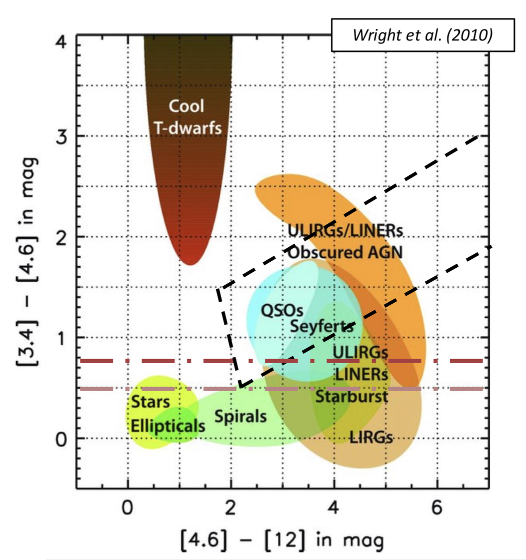


Diagram of an AGN (individual components not to scale; model from Zackrisson, E. 2005). UV and optical photons from the accretion disk are re-emitted into mid-IR by dusty torus.

- WISE AGN mid-IR selection techniques based on distinctly red AGN color:
  - W1-W2 ≥ 0.8 **(dark red)** (Stern et al. 2012)
  - W1-W2 ≥ 0.5 **(brown)** – more relaxed AGN criterion (Stern et al. 2012)
  - Mateos et al. (2012) **(dashed black)** – least contamination
- This project investigates mid-infrared AGN selection criterion to determine the maser detection rates as a function of mid-IR properties.

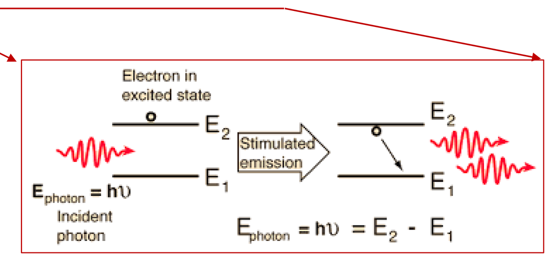


Color-color diagram displaying highlighted regions expected to harbor a higher number of active galaxies

Masers & Supermassive Black Holes

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

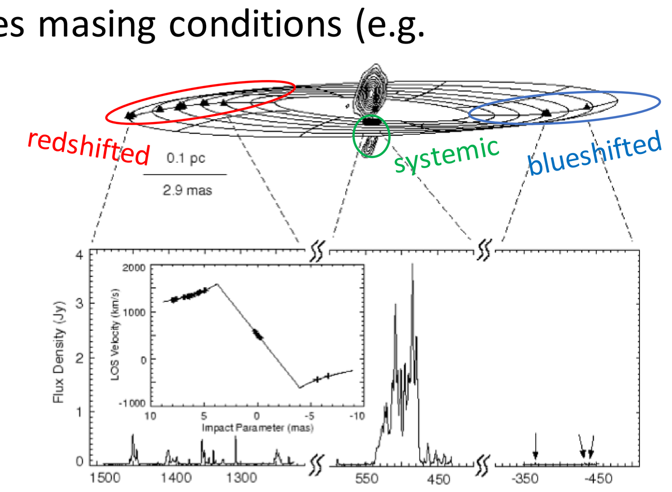


Megamasers in *galactic centers*:

- Produced in shocks made by jets and winds
- **Produced in association with the accretion disk**
  - Accretion disk supplies seed photons for maser emission
  - Dust in inner edge of torus provides masing conditions (e.g. temperature, number density)

Megamasers found in *disk-like configuration*:

- 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
- Measure masses of SMBHs via simple (but not easy!) Keplerian fits (inset)

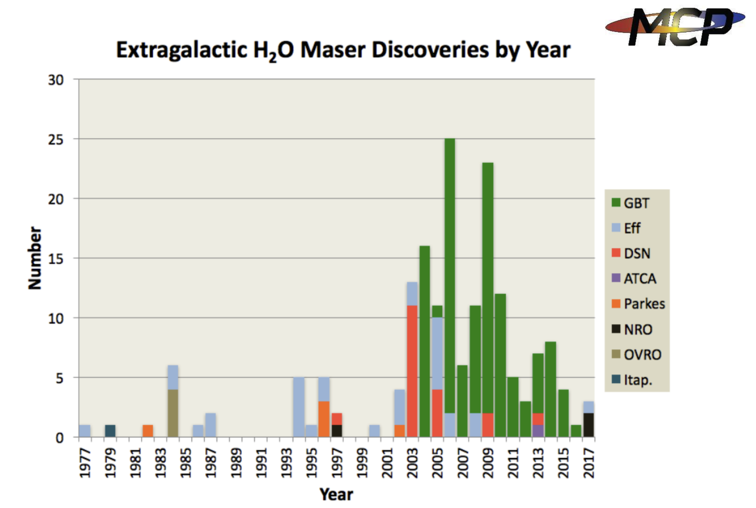


Best-fitted warped disk model superposed on actual maser positions as measured by the VLBA for NGC 4258. Filled square marks disk's center. Filled triangles show the positions of the high-velocity masers. The inset shows the relationship between systemic maser impact parameter and LOS velocity (inset) demonstrates that the disk is very thin and that these masers are confined to a narrow annulus in the disk (Herrstein et al. 1999).

Data Selection

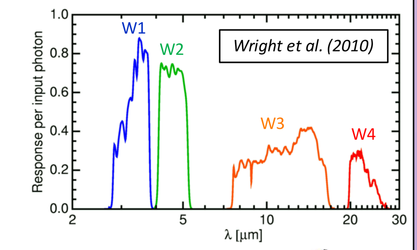
Megamaser Cosmology Project (MCP)

- Largest catalog of galaxies surveyed for H2O maser emission in 22 GHz (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.



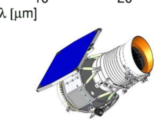
Wide-field Infrared Survey Explorer (WISE) Telescope

- A mid-infrared survey of the entire sky with bands centered at wavelengths of:
  - 3.4 µm (W1), 4.6 µm (W2), 12 µm (W3), 22 µm (W4)



WISE-MCP Crossmatching

- Crossmatched MCP catalog with AllWISE observations to within 6" for completeness, and retained only WISE detections with SNR ≥ 5
- Removed galaxies surveyed multiple times with name-based queries in Python, retaining closest match to mid-IR WISE match.

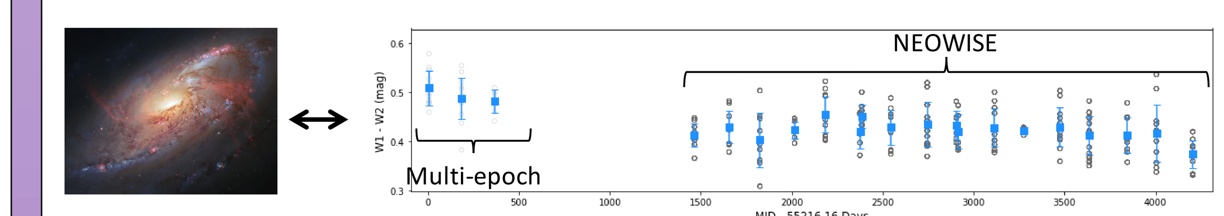


AllWISE Multi-Epoch (3 years) + NeoWISE (~7-8 years)

- Crossmatched AllWISE counterparts coordinates to within 3" of AllWISE Multiepoch Photometry (AllWISE MEP) Table and the NEOWISE-R Single Exposure (L1b) Source Table data, leaving us with **~7-10 years of mid-IR observations**

MCP-WISE Crossmatching

	Masers	Megamasers	Disks	Nonmasers
MCP	180	116	34	4003
MCP-WISE	170	114	34	4003



W1-W2 color galaxy NGC 4258 changing over ~10 years, mean magnitudes for 10-day epochs detailed as blue boxes.

Quantifying Mid-Infrared Variability

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

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

Variability in the mid-IR can reveal a selection of galaxies can reveal changes towards redder (higher) W1-W2 colors, i.e., moving them to AGN color-color selections in the WISE color-color diagrams (e.g., Stern et al. 2012, Mateos et al. 2012).

- Mid-IR variability allows for new identification of AGN activity where other wavelength selection can miss them.
- 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 alone.

Quantifying Variability:

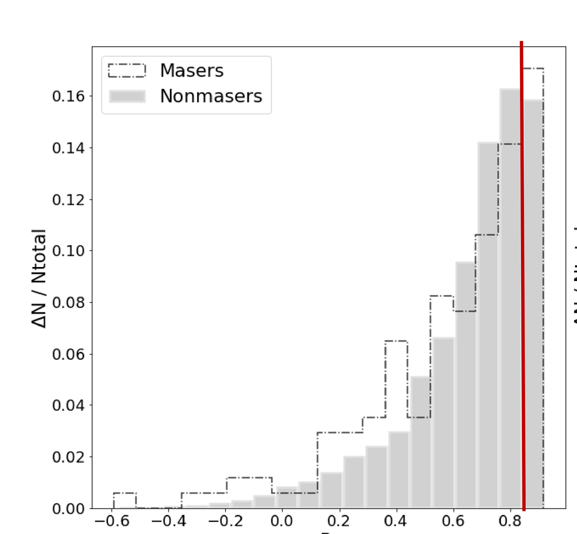
- To look at how this light changed over time, we have built Python code to bin individual observations into 10-day epochs, removing any observations that fell outside 3σ from the median before calculating the mean magnitude for each epoch. With these summary statistics, we found the distribution of Pearson correlation coefficients *r* between W1 and W2 for each galaxy. Following the methodology presented in Secrest & Satyapal (2020), we chose *Pearson's r* to minimize false positives and produce a sample of candidate variables:

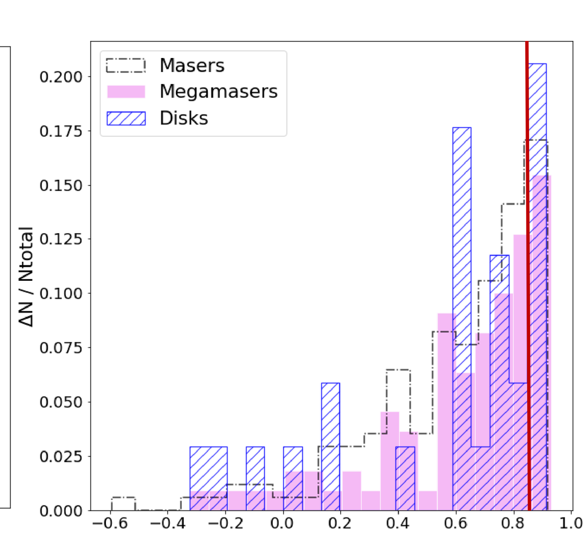
$$r = \frac{C_{m_1,m_2}}{\sigma_{m_1}\sigma_{m_2}}$$

$$C_{m1,m2} = \frac{1}{N-1}\sum_{i}^{N}(m_{1,i} - \langle m_1\rangle) \times (m_{2,i} - \langle m_2\rangle)$$

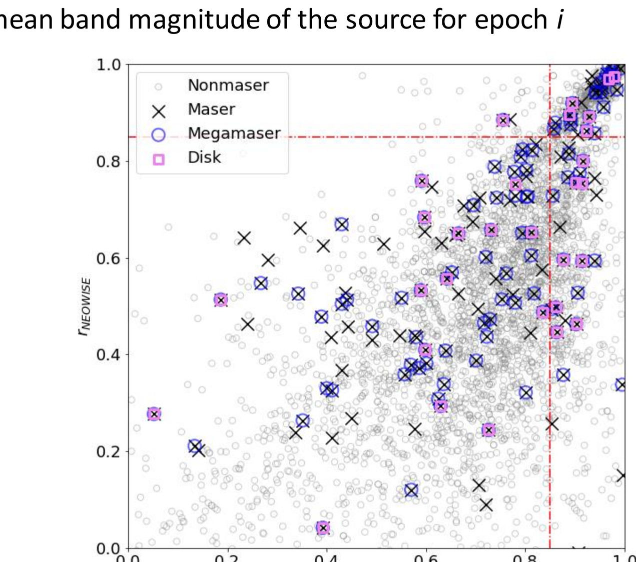
$$\sigma_m^2 = \frac{1}{N-1}\sum_{i}^{N}(m_i - \langle m\rangle)^2$$

- *r* = Pearson's correlation coefficient
- *C* = measure of covariance
  - Covariance = how two variables vary together
  - Here, a measure of covariance between W1 and W2
- σ_1 , σ_2 = variability amplitudes
- m_i = band magnitude of the source during for epoch *i*
- $\langle m_i\rangle$ = mean band magnitude of the source for epoch *i*





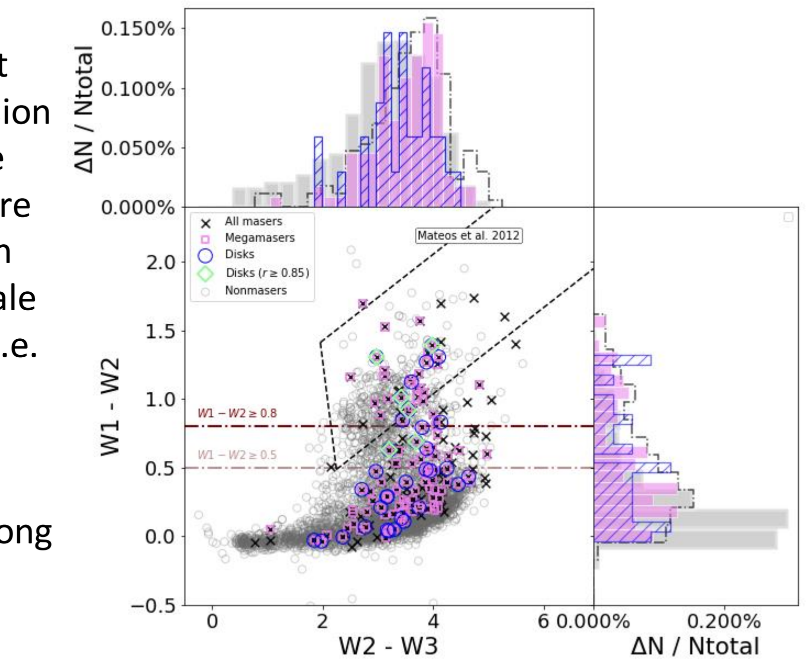
- We built and implemented this code to analyze WISE data. In quantifying variability this way, we have considered galaxies with $r \geq 0.85$ to be "variable" (highlighted by the vertical red line in the histograms displaying distributions of *r*).



- Further, to most conservatively measure variability, we compared calculations of *r* to *r* solely based off NEOWISE data and only use galaxies with both $r \geq 0.85$ (red line), shown highlighted in blue in the diagram.

Results: Mid-IR Variability & Maser Emission

- The WISE color-color diagram displays galaxies with and without circumnuclear water maser emission along various criteria for AGN-like behavior. Megamaser disks that are found in mid-IR variable (based on r ≥ 0.85) galaxies are shown as pale green circles, whose WISE color (i.e. W1 – W2 ≥ 0.5) indicates AGN activity.
- Megamaser disks in blue galaxies (W1 – W2 < 0.5) do not reveal strong signs for variability (r < 0.85)

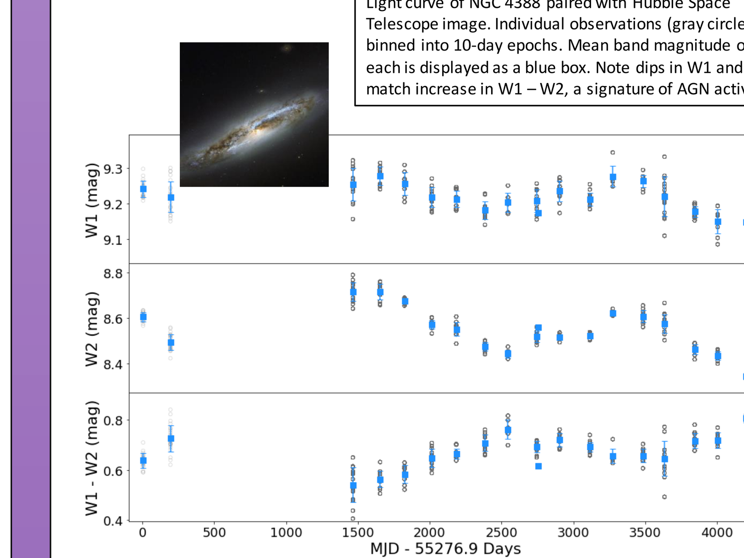


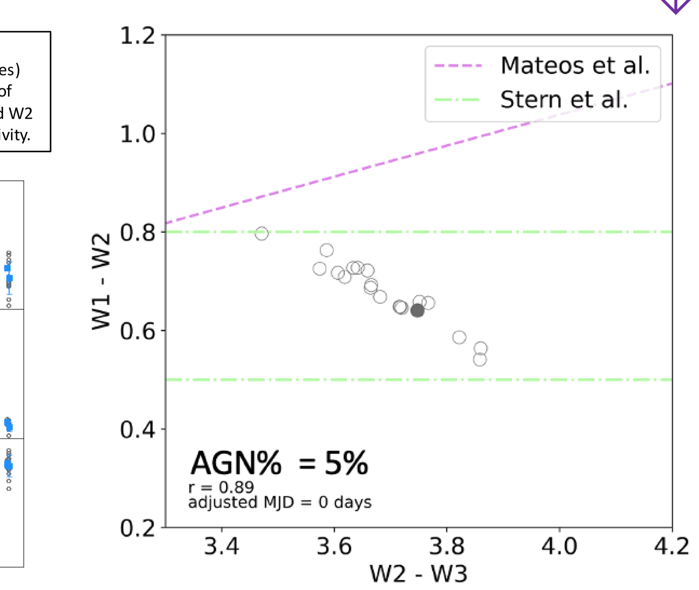
Galaxy Type	W1-W2 < 0.5 (%)	W1-W2 ≥ 0.8 (%)	$t_{AGN} \geq 10\%$ (%)
Masers	57 ± 7	26 ± 4	29 ± 5
Megamasers	56 ± 9	29 ± 6	31 ± 6
Disks	62 ± 17	26 ± 10	29 ± 11
Nonmasers	81 ± 2	10 ± 1	11 ± 1
Masers ($r \geq 0.85$)	36 ± 9	44 ± 10	47 ± 11
Mega ($r \geq 0.85$)	38 ± 11	50 ± 13	52 ± 14
Disks ($r \geq 0.85$)	50 ± 23	36 ± 19	36 ± 19
Non ($r \geq 0.85$)	61 ± 3	39 ± 2	23 ± 1
Masers ($r_{NEO}, r \geq 0.85$)	9 ± 5	70 ± 19	90 ± 23
Mega ($r_{NEO}, r \geq 0.85$)	12 ± 7	76 ± 23	88 ± 26
Disks ($r_{NEO}, r \geq 0.85$)	0	67 ± 43	100
Non ($r_{NEO}, r \geq 0.85$)	40 ± 3	32 ± 2	36 ± 2

With this, we find that:

- Masers are more likely to be variable in the mid-infrared than nonmasers
- Masers are more likely to be "redder" in W1 - W2 color (higher value of W1 - W2)
- Mid-IR variability reveals AGN-like behavior in masers
  - i.e. reddening pattern: we see brightening in both W1 and W2 that correspond to redder W1 – W2 colors *(see light curve below – dips in W1 and W2 match peaks in W1 – W2)*
- Single-epoch data not a good indicator of AGN status => multi-epoch mid-IR data paints a more accurate picture of AGN-maser disk connection
  - Some disk masers are in fact AGN even when classified as star-forming by most stringent mid-infrared color criterion

Light curve of NGC 4388 paired with Hubble Space Telescope image. Individual observations (gray circles) binned into 10-day epochs. Mean band magnitude of each is displayed as a blue box. Note dips in W1 and W2 match increase in W1 – W2, a signature of AGN activity.





Mean of NGC 4388 epochs detailed as gray circles. As time goes on, NGC 4388 *briefly* jumps into the criterion outlined in Stern et al. 2012, illustrating how single-epoch observations could miss a portion of active galaxies during certain periods. *Ask to see the gif!!*

Considering this:

- r ≥ 0.85 may be too conservative of a measure for variability.
- Mid-IR variability could be linked to other circumnuclear properties of these galaxies, to be explored further in future work.

References

Braatz, et al., 2018, https://safe.nrao.edu/wiki/bin/view/ Main/MegamaserCosmologyProject; **Herrnstein**, et al., 1999, A&A, 20, 165; **Kozłowski**, S., et al. 2016, ApJ, 817, 119; **Kuo, C.**, Constantin, A., et al., 2018, ApJ, 860, 169; **Secrest N.** & Satyapal S., 2020, ApJ, 900, 56, **Stern, D.**, et al., 2012, ApJ, 753, 30; **Trump** et al. 2015, ApJ, 811, 26; **Wright E.**, et al., 2010, AJ, 140, 1868; **Zackrisson**, E. Ph.D. thesis, 2005

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