Chapter 1
Cosmic Distance Scale and the Hubble Constant

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Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Megamaser Cosmology Project II : The prospects for measuring a 1% H_0 and distances to high-z galaxies

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Abstract. H_2O megamaser emission from sub-parsec circumnuclear disks at the center of active galaxies allows a single-step, direct distance measurements to galaxies in the Hubble flow without any external calibration. Based on accurate distance determinations of six maser galaxies within 150 Mpc, the Megamaser Cosmology Project (MCP) team recently obtained $H_0 = 73.9 \pm 3.0$ km/s/Mpc ($\sim$4% accuracy), independent of distance ladders and the cosmic microwave background. To further applying the megamaser technique to attain a 1% H_0 measurement, detecting more high-quality disk maser systems is crucial. In this conference proceeding, we update the status of the MCP and discuss strategies of detecting additional high-quality disk maser galaxies within z $\sim$ 0.1. In addition, we show the prospects of reaching a 1% H_0 measurement with the supreme sensitivity of the ngVLA. Finally, we demonstrate that applying the maser technique to distance measurements of high-z galaxies with future submm VLBI systems is promising and this will allow for investigation of the new tension between the ΛCDM model and the high-z Hubble diagram.

Keywords. H_2O maser, megamaser, cosmology, quasar

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1. Introduction

Astrophysical water masers are natural microwave amplifiers by stimulated emission of radiation. Observations in the past three decades have shown that maser emissions from the $6_{16} - 5_{23}$ transition of ortho-H_2O at 22.23508 GHz are abundant in star-forming regions and in the nuclear regions of some galaxies hosting active galactic nuclei (AGNs). When detected at galaxy centers, the 22 GHz H_2O masers are typically millions of times more luminous than those associated with typical star-forming regions in the Milky Way galaxy. They are therefore termed "megamasers."

H_2O megamasers provide a direct determination of the Hubble Constant, H_0, independent of standard candles (Reid et al. 2013), and enable precise measurements of supermassive black hole (BH) masses, M_{BH} (Gao et al. 2017), via sub-milliarcsecond

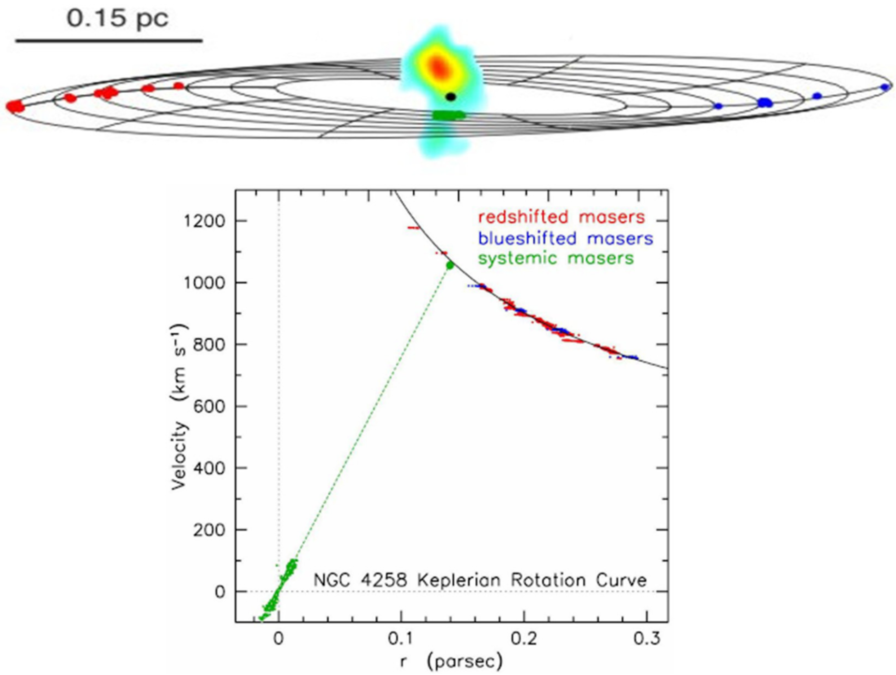

Figure 1. The distribution and Keplerian rotation curve (Argon et al. 2007) of the 22 GHz H_2O masers in NGC 4258.

imaging of H_2O maser emission from disk maser systems, such as NGC 4258 (see Figure 1; Herrnstein et al. 1999; Argon et al. 2007). In such a system, the masing gas resides in a subparsec-scale thin disk viewed almost edge-on and following near Keplerian rotation. These disk properties support M_{BH} measurements to percent-level accuracy (Kormendy & Ho 2013), and the disk maser geometrical and kinematic information can be modeled to provide a standard ruler for measuring an accurate angular-diameter distance to a galaxy well into the Hubble flow (Kuo et al. 2013) without relying on distance ladders and the cosmic microwave background (CMB).

2. The Hubble Tension Problem

From distance measurements of six maser galaxies within 150 Mpc, the Megamaser Cosmology Project (Reid et al. 2009; Braatz et al. 2010) team obtained $H_0 = 73.9 \pm 3.0$ km s^{-1} Mpc^{-1} (Pesce et al. 2020), well consistent with the majority of direct, *late universe* measurements of Hubble constant, including the H_0 obtained from Type 1a supernovae ($H_0 = 74.03 \pm 1.42$ km s^{-1} Mpc^{-1}; Riess et al. 2019) and strong gravitational lensing systems ($H_0 = 73.3 \pm 1.8$ km s^{-1} Mpc^{-1}; Wong et al. 2020), but is in tension with indirect, *early universe* H_0 predictions based on CMB data assuming a flat ΛCDM universe (e.g. $\mathrm{H}_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}; Planck Collaboration 2020). The discrepancy between the early- and late-universe determinations of H_0 is known as the "*Hubble tension problem*", which suggests new physics beyond the standard ΛCDM model (Adballa et al. 2022).

To resolve the Hubble tension, *numerous* models (i.e. >30) have been proposed to modify or replace the ΛCDM model, such as dynamical dark energy, early dark energy, phantom crossing, and modified theory of gravity (see a thorough review in Di Valentino et al. 2021). Many of these models have been shown to resolve the Hubble

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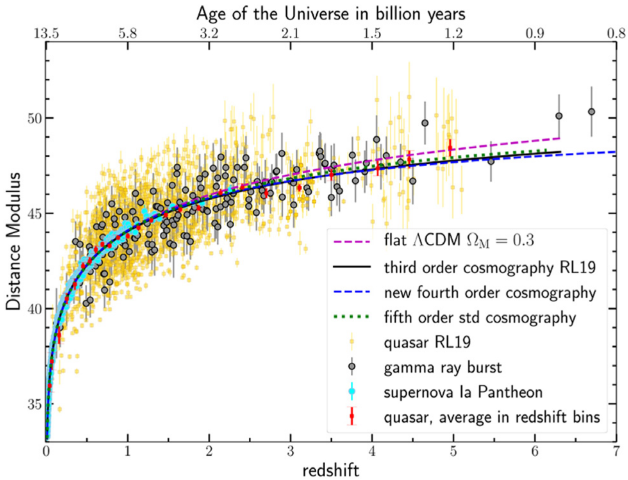

Figure 2. Hubble diagram showing a distance modulus, μ, normalized to that expected for a ΛCDM universe. The yellow dots indicate distance measurements using the quasar technique (Lusso et al. 2019).

tension if one only uses CMB data for modeling. However, when Baryon Acoustic Oscillation (BAO) data is included in the analysis, tension is restored for some models (e.g. Yang et al. 2021), making these models less favorable. This suggests that more cosmological datasets from various different probes are needed to break degeneracies between models (King et al. 2014) and to identify the best solutions that could resolve the Hubble tension.

3. The Need for New High-z Distance Indicator

In recent years, accurate measurements of distances to high-z galaxies have been proposed as an important probe that could break degeneracies between cosmological models. To demonstrate an example, King et al. (2014) show that the differences between distance moduli predicted from the standard ΛCDM and various models of dynamical dark energy are large enough to be distinguishable only at z $\gtrsim$ 1, which is probed only by a small fraction of Type Ia supernovae. One needs new distance indicators beyond z$\sim$1 to differentiate between the dynamical dark energy and ΛCDM models.

To reach the high-z universe, Lusso et al. (2019) use luminous quasars as new standard candles for measuring galaxy distances up to z$\sim$5 based on the quasar X-ray/ultraviolet luminosity correlation. Their work shows that the best fit to the high-z Hubble diagram indicates a $\sim$4σ deviation from the ΛCDM prediction (see Figure 2), suggesting a tension with the standard model at high redshifts. However, recent studies argue that the quasar luminosity correlation is redshift-dependent, and the $\sim$4σ deviation seen in Lusso et al. (2019) could be a result of redshift evolution of quasar properties (e.g. Li et al. 2022). To avoid the impact of galaxy evolution on distance measurements, we need an alternative tool such as the H_2O maser technique, which is based on well-known gas dynamics and does not suffer from the redshift-dependent effects. When applied to high-z galaxies, this technique is promising to provide substantially more accurate distance measurements than the quasar method. In addition, it will enable direct, dynamical measurements of BH masses at z $\gtrsim$ 1 for the first time, enhancing studies of the black hole/host-galaxy coevolution (Kormendy & Ho 2013) in the early universe.

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4. The Importance of Improving the Hubble Constant Measurements

While resolving the Hubble tension may require new cosmological probes of the high-z universe, continuing to improve the accuracy of the Hubble constant is equally important. The long-term goal of the observational cosmology community is to attain a 1% H_0 measurement with agreement across multiple, independent observational approaches, including the H_2O megamaser technique. Having an H_0 with such an accuracy would be essential to check whether the current discrepancy in different H_0 measurements could partly or entirely result from unrecognized systematic uncertainties in underlying observations. In addition, it can provide the theoretical community a more precise determination of the difference between H_0 obtained from direct and indirect methods, giving a tighter constraints on various models of cosmology. It is likely that future joint analysis of cosmological datasets that include a 1% H_0 and accurate distances to high-z galaxies could substantially deepen our understanding of the Hubble tension problem.

5. The 2nd Phase of the Megamaser Cosmology Project : MCPII

To fully harness the potential of using the H_2O megamaser technique for studying cosmology, we attempt to apply the maser technique to both low-z and high-z galaxies in the next stage of the Megamaser Cosmology Project (MCPII). In the "low-z MCPII" project, we continue to use the H_2O megamaser technique to measure accurate distances to additional maser galaxies at low redshifts (i.e. z $\lesssim$ 0.1) to achieve a $\sim$1% H_0. For the "high-z MCPII", we aim to apply the H_2O megamaser technique to high-z galaxies and use their maser-based distances as a new cosmological probe to identify the origin of the Hubble tension. The details of the two aspects of the MCPII are described as follows:

5.1. *Accurate H_0 measurements with the ngVLA at Low Redshifts*

From the latest H_0 determination from (Pesce et al. 2020), the current accuracy of H_0 achieved with the H_2O maser technique is $\sim$4%. To improve the accuracy from $\sim$4% to $\sim$1%, we need accurate distances (i.e. accuracy $\sim$ 7%) to additional 50 maser galaxies (Braatz et al. 2019). Before making new distance measurements for additional galaxies, it is essential to first looking for new, high-quality disk maser galaxies within z $\sim$ 0.1 with improved survey strategy. The number of disk maser systems that have been found by previous single-dish H_2O maser surveys is $\gtrsim$30, insufficient for a 1% H_0 measurement. To find out additional >20 new disk megamasers, a blind survey on all Seyfert 2 galaxies and Liners as done in the MCP is no longer practical because the detection rate of disk megamasers is found to be only $\sim$1% based on this survey strategy. To improve the detection rate of disk maser systems, Kuo et al. (2020) found that it is easiest to find disk masers if a survey targets *Compton-thick* (CT) AGNs (i.e. column density of X-ray obscuring medium $N_{\rm H} \gtrsim 10^{24}$ cm^{-2}). As shown in Figure 4, the detection rate of disk masers reach $\sim$20% if an AGN has $N_{\rm H} \geq 10^{24}$ cm^{-2}. In contrast, the disk maser detection rate drops rapidly when $N_{\rm H} < 10^{24}$ cm^{-2}. This suggests that targeting Compton-thick AGNs can boost the disk maser detection rate by a factor of $\sim$20, allowing one to identify the required number of disk megamasers by surveying a much smaller sample of galaxies.

In addition to searching for additional disk maser systems with new survey strategy, improving the sensitivity of current Very Long Baseline Interferometry (VLBI) facilities is also critical. Among the $\sim$30 disk megamasers that have been discovered, only $\sim$10 have sufficiently strong maser lines and the required spectral characteristics† for accurate

† An accurate distance measurement with the H_2O megamaser method requires detections of multiple blueshifted and redshifted maser features to accurately characterize the Keplerian rotation curve of a disk maser system. In addition, the systemic masers also need to be strong enough for precise acceleration measurements (e.g. Kuo et al. 2015).

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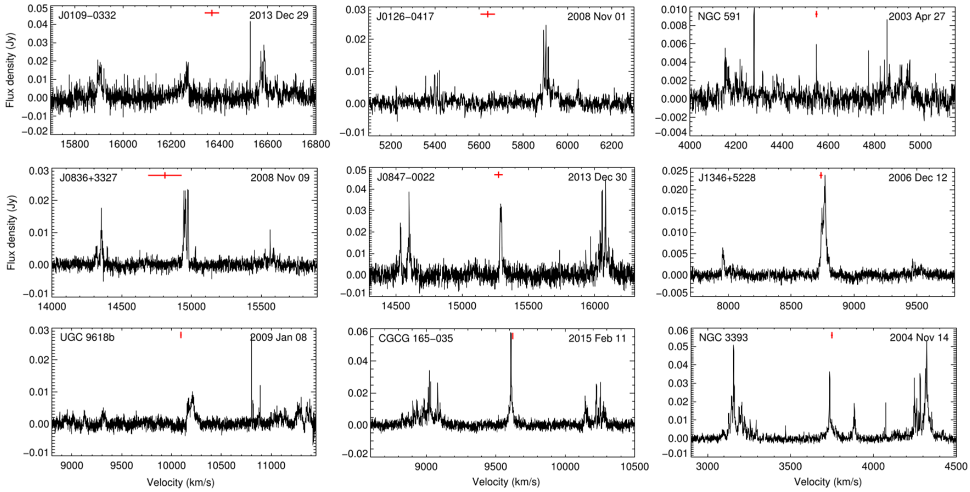

Figure 3. The 22 GHz H_2O maser spectra of nine disk maser systems discovered by the MCP (Pesce et al. 2015). These systems are a subset of the candidate disk megamasers in which the maser features are either too faint or the velocity ranges covered by the systemic masers are too narrow to allow for accurate distance measurements with the sensitivity of current VLBI facilities such as the High Sensitivity Array.

distance measurements. For the rest of ∼20 disk maser systems (see Figure 3; Pesce et al. 2015), the maser emissions are too faint to enable accurate distance measurements. To measure accurate distances to these maser galaxies, the sensitivity of current VLBI facilities needs to be improved significantly. This will be realized soon with the advent of the next-generation Very Large Array (ngVLA), which would bring about an order of magnitude improvement in sensitivity. The enhanced sensitivity of the ngVLA will not only allow for efficient detections of maser systems in a ∼30 times larger volume, it will also permit accurate distance measurements for the fainter disk maser systems, making a 1% H_0 determination possible with the maser technique in the future.

5.2. *Reaching the High-z Universe with Submillimeter H_2O Gigamaser Emissions*

Based on a relatively recent modeling of H_2O maser emissions (Gray et al. 2016), it has been shown that some of submillimeter H_2O maser lines can be significantly stronger than the well-known 22 GHz water maser, suggesting that submillimeter water masers may be a better tool to access the high-z universe than the 22 GHz maser given the availability of Atacama Large Millimeter/submillimeter Array (ALMA). Among the most luminous submillimeter water masers that could be present in the circumnuclear gas disks in high-z galaxies, the H_2O maser emissions $4_{14} - 3_{21}$ at 380.19736 GHz is one of the most promising lines that would allow for distance measurements of high-z galaxies. The 380 GHz transition corresponds to the back-bones levels, i.e. levels with the lowest energy for a given rotational quantum number (e.g. de Jong 1973). Members of the back-bone group are expected to display large line strengths resulting in large optical depths, slowing down radiative decay and thus carrying the bulk of the population. Based on modelling done by (Gray et al. 2016), the 380 GHz maser transition can be intrinsically brighter than the 22 GHz water maser line by a factor of $\gtrsim$10 under certain physical conditions, making high signal-to-noise detections of high-z maser emissions possible.

Despite the line strength of the 380 GHz maser could be significantly higher than that of the 22 GHz H_2O maser, its frequency falls into a deep absorption trough in the Earth's atmosphere. As a result, it can only be observed from space if the maser emission

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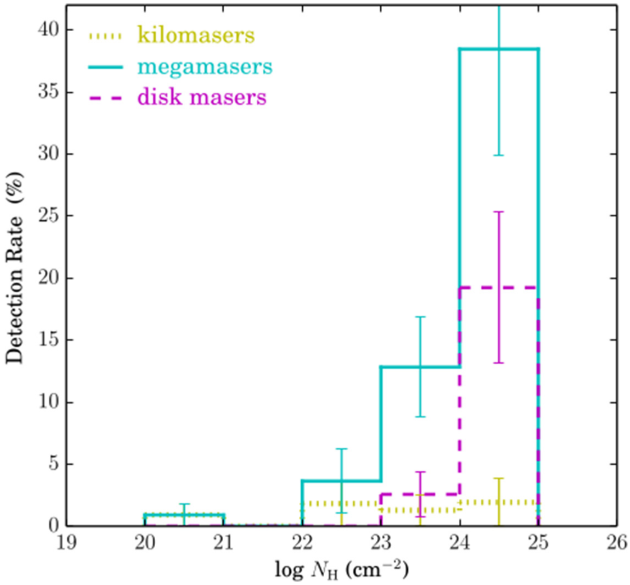

Figure 4. Detection rates of megamasers and disk masers as a function of column density N_H (Kuo et al. 2020).

is from a source in the local universe. However, since we are targeting high-z galaxies, the 380 GHz lines are redshifted to frequency bands that can be easily accessible for follow-up by existing VLBI facilities, which can provide extremely high resolution maser mapping (e.g. ~20−40 μas). Based on our recent model prediction of the angular sizes of H_2O maser disks at z > 1 (i.e. ~3.4 mas or ~30 pc in physical size; Kuo et al. in prep.), we infer that if $\gtrsim 5\sigma$ detections of the 380 GHz maser emissions can be achieved in future follow-up VLBI observations that include ALMA, the maser maps would have fractional uncertainties (i.e. maser position uncertainties $\lesssim$10 μas) nearly as small as those in the maser disk in NGC 4258 (Figure 1), making highly accurate distance and BH mass measurements feasible at high redshifts.

The 380 GHz H_2O maser line has been detected toward ~10 starburst galaxies and 1 type-1 quasar at z $\gtrsim$ 2 in recent ALMA cycles (Yang et al. in prep.), but robust detections of disk maser systems have not yet been made. To optimize the chance of detecting disk maser systems, it is beneficial to first target *Compton-thick* quasars at z ~ 2 (i.e. the peak of quasar space density) in future ALMA observations.

One expects higher maser detection rates in these systems because the fraction of nearly edge-on disk masers is known to be highest in CT AGNs (see Figure 4; Kuo et al. 2020). In addition, a recent modeling of the physical conditions in disk maser systems (Kuo et al. in prep.) suggests that the maser amplification path length $L_{\rm amp}$ for an edge-on maser disk is strongly correlated with BH mass. Given that the BH mass function of luminous quasars at z ~ 2 peaks at $M_{\rm BH} \sim (1-3)\times10^9 M_\odot$ (i.e. $\gtrsim$100 times more massive than BHs in local H_2O megamasers; see Figure 5; Vestergaard & Osmer 2009), this model predicts that $L_{\rm amp}$ for a quasar maser disk at z ~ 2 would be significantly greater than that for a low-z disk maser, leading to a boost in maser intensity by a factor of $\gtrsim$100 for saturated masers.

Finally, since the 380 GHz maser transition could be intrinsically brighter than the 22 GHz water maser line by a factor of $\gtrsim$10 (Gray et al. 2016), the total maser luminosity of the 380 GHz line of a quasar maser disk at z ~ 2 is likely to be $\gtrsim$1000 times greater than that of a low-z 22 GHz water maser disk, making detections of high-z 380 GHz

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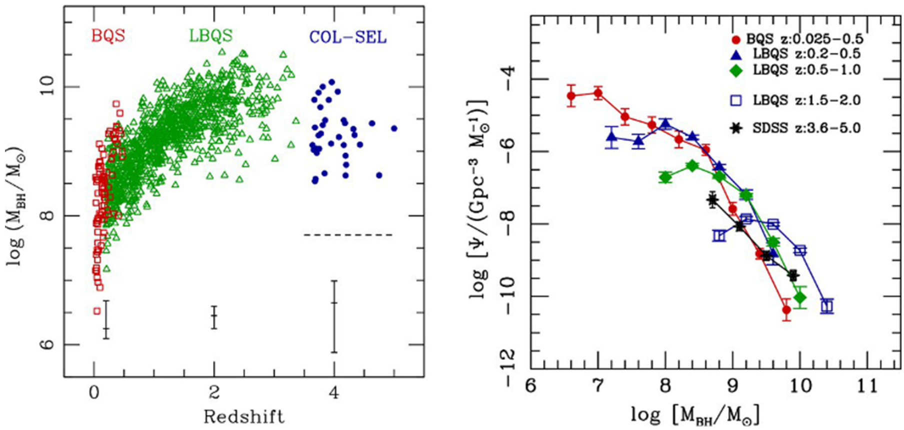

Figure 5. The BH masses distributions of luminous quasars obtained from Vestergaard & Kumar (2009). The left panel shows the BH mass as a function of redshift and the right panel shows the BH mass functions for various redshift bins. These figures show that at the redshift around z $\sim$ 2, the BH mass function peaks at $M_{BH} \sim 10^9\ M_\odot$.

maser emissions possible without gravitational lensing. We can thus call these high-z 380 GHz water maser systems "*Gigamasers*". Depending redshifts (i.e. $1.2 < z < 3.5$; set by the spectral coverage of ALMA bands 3 through 5), the peak flux densities of the 380 GHz maser emissions from CT quasars are expected to be $\sim$1.5$-$4 mJy, estimated based on the typical peak luminosity densities of the 22 GHz water maser lines L_ν in the low-z disk megamaser systems ($L_\nu \sim (2-4) \times 10^{29}$ erg/s/Hz; see Figure 6) plus the expectation that the 380 GHz maser emissions from high-z quasar maser disks could be $\gtrsim$1000 stronger than the local 22 GHz maser disks. Given the sensitivities of ALMA, the 380 GHz lines of high-z CT quasars can be detected within integration times of $\sim$1$-$5 hours.

In the past two decades, deep X-ray observations of high-z galaxies have led to detections of more than 100 CT quasars at $z > 1$ (e.g. Lanzuisi et al. 2009; Gilli et al. 2022). Table 1 shows some CT quasars discovered by (Brightman et al. 2014). If our modeling of disk maser systems is correct, it is promising that ALMA will detect H_2O gigamasers from the high redshift universe in the near future.

6. Conclusion

The studies of H_2O disk megamaser systems in the past two decades have demonstrated that the H_2O megamaser technique enables an accurate, robust determination of the Hubble constant and provide an important consistency check for H_0 values obtained across multiple, independent observational approaches. Comparisons of H_0 from different methods have clearly indicated a significant tension between direct measurements of H_0 and predictions based on the CMB assuming the ΛCDM model. To understand the origin of the Hubble tension problem, we have shown that achieving a 1% H_0 measurement is important. In addition, accurate distance measurements of high-z galaxies would be a new probe that could break degeneracies between models that could resolve the Hubble tension. For the purpose of improving the accuracy of H_0 and measuring precise distances to high-z galaxies, the H_2O megamaser technique will play an important role in the future. At low redshifts, the supreme sensitivity of the ngVLA will allow for efficient detections of disk megamaser systems within $z \lesssim 0.1$ and enable accurate distance measurements for $\gtrsim$50 galaxies, making a 1% Hubble constant measurement possible. For the high redshift universe, we predict that some of the submillimeter H_2O maser lines such as the 380 GHz

Table 1. Compton-thick Quasars in the Chandra Deep Field South and the COSMOS field.

Name	z	F_ν	band	$\log N_H$	$\log L_{bol}$	Field
GOODS-CDFS-MUSIC 07810	2.578	106.26	3	25.7	45.7	CDFS
VCDFS 69258	3.153	91.54	3	24.53	45.7	CDFS
[BMP 2010]2575	2.563	106.71	3	24.05	45.25	CDFS
ACS-GC 20094946	2.704	102.65	3	25.55	47.6	COSMOS
COSMOS2015 0663735	3.175	91.07	3	24.14	46.2	COSMOS
COSMOS2015 0441487	3.471	85.03	3	24.95	46.5	COSMOS
ACS-GC 90044755	2.026	125.63	4	24.12	45.7	CDFS
ACS-GC 90018695	1.374	160.42	4	26.0	45.7	CDFS
ACS-GC 20040645	1.796	135.98	4	24.05	46.2	COSMOS
NMBS C30828	1.692	141.63	4	24.8	46.2	COSMOS
ACS-GC 20125049	1.933	128.97	4	24.8	46.5	COSMOS
COSMOS2015 575250	1.407	157.95	4	24.1	45.4	COSMOS
ACS-GC 20088692	1.272	167.34	5	24.5	45.9	COSMOS
ACS-GC 20116538	1.265	167.86	5	24.6	46.4	COSMOS
COSMOS2015 797617	1.244	169.43	5	24.2	46.4	COSMOS

Note. CT quasars found by Brightman et al. (2014). Column (1): source name; Column (2): redshift; Column (3): observing frequency; Column (4): observing ALMA band; Column(5): absorption column density N_H (cm^{-2}); Column(6): the bolometric luminosity of the quasar estimated from absorption-corrected intrinsic X-ray luminosity.

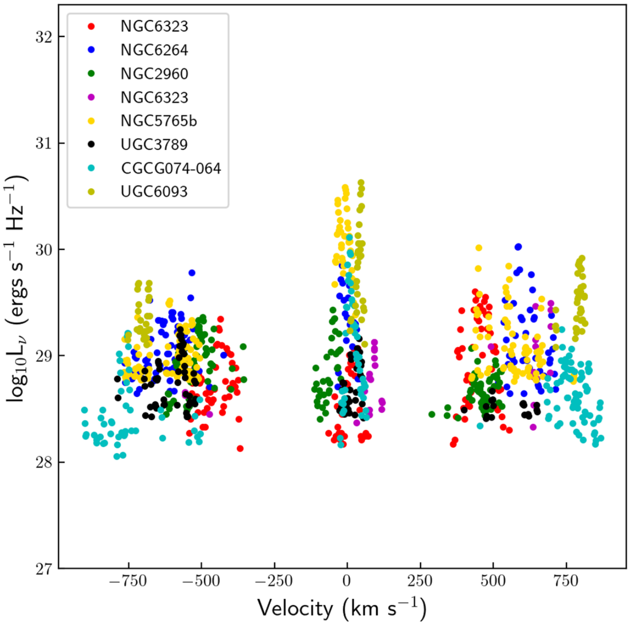

Figure 6. The luminosity densities L_ν of the 22 GHz H_2O maser emissions of eight edge-on disk maser systems discovered by the MCP (Kuo et al. in prep). The median luminosity densities of these systems, especially their redshifted and blueshifted maser components, are all around $L_\nu \sim 10^{29}$ erg s^{-1}Hz^{-1}, suggesting that edge-on maser disks behave like standard candles. This property enables predictions of the flux densities of maser emissions from edge-on H_2O maser disks at different redshifts.

maser transitions from highly obscured quasars could be $\gtrsim$1000 times more luminous that local 22 GHz disk megamasers. This makes the detections of these systems possible with ALMA without strong gravitational lensing. The follow-up VLBI observations of these water "gigamasers" are promising to give maser maps that are as accurate as the prototypical maser system NGC 4258, making precise distance measurements of high-z

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galaxies feasible. By combining the low-z and high-z distance measurements, the H_2O megamaser technique would provide a unique probe of the cosmic expansion history over a wide range of redshifts, permitting independent constraints on new models of cosmology.

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