Boosting Water Maser Studies in AGN with the SKA

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Extragalactic water maser sources are unique tools to derive fundamental physical quantities of the host galaxies. In nearby and distant active galactic nuclei (AGN), water masers are used to determine the geometry of accretion disks around supermassive black holes, precise black hole masses, and standard-candles-independent distances to the host galaxy. In addition, they allow detailed studies of the interaction between nuclear jets/outflows and the interstellar medium, providing clues on AGN feedback mechanisms. So far, however, extragalactic maser searches have yielded detection rates of few percent, and only relatively few maser sources have been found, mostly in the nearby Universe. Because of its unprecedented sensitivity, the SKA will allow to significantly increase the number of known water maser sources especially in the more distant Universe. This will lead to the chance of performing statistically-relevant studies of the maser phenomenon (and its occurrence), derive extragalactic maser luminosity functions and, ultimately, to perform the aforementioned studies for larger samples and up to cosmological distances. In this Chapter, we will provide a quantitative analysis of the expected number of new extragalactic water maser sources already at the reach of the SKA-Mid telescope (in AA4 configuration) through targeted and blinds surveys. In addition, we will discuss the main requirements for the upcoming SKA design, in terms of baselines and frequency coverage, that may maximize the exploitation of such wealth of new targets, allowing a true step forward in AGN-related maser science.

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1 Introduction

A fundamental element of the Unified Model of AGN is the dusty toroidal structure, known as the "torus" (e.g., Antonucci 1993; Urry and Padovani 1995), that surrounds the super massive black holes (SMBH). Such a structure is thought to block the direct emission from the accretion disk, scattering and reemitting it in the infrared (IR). In the last 10-15 years, IR and X-ray studies of AGN provided significant information of the obscuring material in the proximity of SMBH. As a consequence, the paradigmatic homogeneous dusty torus, seen as an isolated component, has been replaced by a discrete, "clumpy" structure, physically and dynamically connected with the host galaxy through gas inflows/outflows (e.g., Ramos Almeida and Ricci 2017). However, despite the great advances done, so far, the accurate geometry and dynamical origin of the absorbing material have not yet been fully understood. In addition, further importance for a better knowledge of the AGN phenomenon is represented by the yet debated accretion/ejection mechanisms taking place in the nuclear regions of radio-loud and, even more, radio-quiet AGN. The aforementioned studies are, however, made complicated by the very small linear dimensions and by the fact that the internal regions are often obscured at optical and UV wavelengths. IR, X-rays , and radio observations can, nevertheless, access such obscured regions.

In this Chapter, we will focus on the contribution of the 22-GHz water maser radio spectral lines in AGN to a better understanding of the aforementioned issues[1], and the chances offered by the use of SKA-Mid in its AA4 configuration to significantly increase the number of known sources up to cosmological distances. The range in frequencies covered by the 5a and 5b bands are suitable to detect the 22-GHz water maser line in galaxies with redshift, z, between 0.45 and 3.8. However, the possibility to extend the actual project design to higher frequency is also discussed, together with a remark on the importance of the availability of (very) long baselines for detailed follow-ups of individual sources.

Indeed, the radio emission from luminous H_2O masers, the so-called "megamasers" constitutes the only way to directly map the molecular gas at pc/sub-pc distance from SMBHs (for additional details on masers in AGN, please see the reviews by, e.g., Lo (2005), Henkel et al. (2005), Tarchi (2012), Pesce et al. (2018).

Some maser sources, labeled as "disk-masers", are associated with nuclear accretion disks or sometimes with the innermost boundary of a dusty torus in the region of the interaction with the outflows (e.g., Bannikova et al. 2023). Very Long baseline Interferometry (VLBI) and single-dish monitoring studies of these masers can be used to determine the geometry of accretion disks and to estimate the enclosed dynamical masses and provide a calibration of the cosmic distance scale (Miyoshi et al. 1995; Herrnstein et al. 1997; Kuo et al. 2011; Gao et al. 2017). H_2O masers currently provide the most precise method to determine black hole masses in external galaxies, especially in the case of type 2 AGN, where other methods, such as those based on optical broad lines emission, cannot be used. Measuring black hole masses in AGN, allows one to estimate Eddington luminosities and accretion efficiencies. In addition, these studies are extremely relevant

[1]A description of the potential of the SKA-Mid telescope for studies of stellar and interstellar masers in nearby galaxies is addressed in Rygl et al. (2026), this volume

to probe the low mass regime of the $M_{BH} - \sigma^*$ relation, so far, almost uniquely derived for elliptical galaxies with larger BH masses (e.g., Greene et al. 2010).

Water maser emission can also be associated with radio jets, produced by either the interaction between the radio jet and an encroaching molecular cloud or by the amplification of the radio continuum from the jet from excited water molecules in a foreground cloud. Detailed studies of these masers allow us to pinpoint regions of strong interaction of the jets with the interstellar medium of the host galaxy (e.g., Castangia et al. 2019) and derive relevant physical quantities of the jet material, like its velocity and density (e.g., Peck et al. 2003).

A third class of AGN-associated water masers is named "outflow-masers". They trace the velocity and geometry of nuclear winds at ≤ 1 pc from the nucleus, as in the case of Circinus (Greenhill et al. 2003) and NGC 3079 (Kondratko et al. 2005), offering a promising means to probe the structure and motion of the clouds in the toroidal obscuring region predicted by clumpy torus models (e.g., Nenkova et al. 2008), and to help studies of AGN tori in general.

Each megamaser source is therefore a goldmine of information on the (sub)-parsec-scale environment around AGN, making the discovery of new sources and their interferometric follow-ups crucial for their study. So far, however, among the ≥ 6000 galaxy nuclei surveyed for 22-GHz water maser emission, only 180 sources are detected, with $\sim 30\%$ of them possibly originating in disc (Kuo et al. 2020), and the vast majority being hosted in radio-quiet AGN, mainly Seyfert 2s and LINERs, in the local Universe ($z < 0.05$). Indeed, the combination of the high sensitivity required in surveys and the large number of objects to be searched for maser emission has played a role against a more conspicuous number of detections. The NRAO Key Science Megamaser Cosmology Project (MCP; Reid et al. 2009), for example, observed about 3000 obscured AGN (Seyfert 2), mainly selected from large optical surveys, such as SDSS, 6dF and 2MRS, detecting water maser emission in only 3% of the targets (Braatz et al. 2018). Higher detection rates have been obtained by selecting galaxies on the basis of their IR and X-ray properties. In particular, a sample of galaxies with IRAS point source flux density >50 Jy, yielded a maser detection rate of 23% (Henkel et al. 2005; Surcis et al. 2009). More recently, Panessa et al. (2020) obtained a detection rate of ~20% in a complete sample of AGN selected in the 20–40 keV energy range. Through a combination of mid-IR (*IRAS*) and X-ray (*XMM-Newton*) data, instead, Severgnini et al. (2012) selected a well defined sample of 36 heavily absorbed AGN ($N_{\rm H} \geq 10^{23}$ cm^{-2}) that have been searched for 22 GHz water maser emission. The maser detection rate of this sample is a remarkable 50%, one of the highest ever obtained in extragalactic maser searches (Castangia et al. 2019). No water maser source has been reported, so far, at redshifts larger than 0.1, with the exception of two cases, the type 2 QSO J0804+3607 (at z=0.66; Barvainis and Antonucci 2005) and the grativationally-lensed type 1 quasar J0414+0534 (at z=2.64, Impellizzeri et al. 2008) .

2 Water masers at cosmological redshifts with the SKA-Mid in AA4 Configuration

The discovery of a water maser in the gravitational lens MG J0414+0534 at z=2.64 (Impellizzeri et al. (2008)), opened the door for the study of H_2O masers at high redshifts. Indeed, using the magnification provided by the foreground gravitational lens to increase the observed flux density and the angular extent of any water maser in the background, it is in principle possible to map parsec-scale accretion disks in distant AGN, also with current instrumentation. Furthermore, this discovery suggests that the space density of luminous water masers was larger at high redshift than in the local Universe (Impellizzeri et al. 2008).

Following the detection of the maser in the gravitational lens MG J0414+0534 at z=2.64 (Impellizzeri et al. 2008), McKean et al. (2011) (hereafter M11) performed a search for water maser emission in a small sample of (five) dusty, gravitationally lensed quasars and star-forming galaxies at redshifts between 2.3 and 2.9. Despite no new confident detection (above the 3σ level) was found, this study allowed to update the water maser luminosity function (LF) derived by Henkel et al. (2005) and Bennert et al. (2009) at high redshift. In particular, M11 demonstrates that there must be some evolution in the LF at moderate redshifts, thus motivating high-sensitivity blind surveys for the water maser transition at high z. Some results from the *Herschel* space observatory also suggest that high-z ultra-luminous infrared galaxies tend to be very strong emitters in water vapor (Omont et al. 2013), reinforcing the motivation to search for H_2O masers at cosmological distances. Applying the reasoning of M11, with all the reported assumptions and caveats, by parametrizing the evolution of the LF with redshift, i.e. $(1 + z)^m$, with the parameter m equal to 0, 4 or 8, to account for a no, moderate, and strong evolution, respectively, we can predict the number of water maser galaxies found in pointed and/or blind surveys for a certain survey detection limit. Indeed, with the advent of the next generation of radio telescopes, such as the SKA and the ngVLA, it will become straightforward to perform either blind surveys of large areas in the sky and/or deep targeted surveys of large samples of selected galaxies up to cosmological redshifts.

Targeted searches: In this framework, the SKA-Mid will be able to obtain significant results by performing targeted searches for water maser lines of extremely large samples of galaxies. The same spectral-line sensitivity of a 100-m class single-dish (i.e., the antennas that are typically involved in water maser searches) will be reached by SKA-Mid in a factor 10 less time, thus allowing to search (with comparable sensitivity) much larger samples and/or providing detections of a still significant number of maser sources also at larger distances ($z > 0.5$). These latter sources will likely be detected among the brighter members of the megamaser class (a 30-minutes observation would detect a 250 solar luminosity source at redshift of 0.5). Moreover, any such detection will yield the potential to detect and explore the maser phenomenon, and the AGN activity at which it is associated, in classes of galaxies where, so far, no maser have been found (e.g., radio loud objects, typically located at larger distances). Deeper targeted survey will then allow to push further the detection limit also to cosmological redshifts. Indeed, using 10-h long measurements, will potentially yield detections of maser sources with 1000 solar luminosities out to redshift 2.

Blind searches: as shown by M11, when approaching cosmological distances $z \geq 1$, blind surveys of water maser sources with SKA-Mid will also become valuable, particularly if, as expected, an evolution of the water maser LF is present. Under this latter assumption, as shown in Fig. 1[2], also blind searches with the SKA-Mid array would yield, at $z \geq 0.45$ (the lowest redshift observable in the 22-GHz maser line at the frequency of 15.4 GHz) , a number of new maser detections between

[2]The plot was produced by adapting the computational steps reported by Darling and Giovanelli (2002) for OH megamasers (their Eq. 18) for the water maser case.

$\sim$ 170 and 14000, for a LF evolution exponent of 4 and 8, respectively, when areas of the order of a square degree (about 65 pointings, considering the field of view of the array at 10 GHz) are searched for. This can be attained with a sensitivity (3σ)[3] of $\sim$ 0.06 mJy for a 10-km/s channel (reachable in about 10 hours on-source per pointing, and hence, a total of $\sim$ 1000 hours for each of the three configurations necessary to cover the 5a and 5b bands). This is surely feasible thanks to the enhanced sensitivity and the large field of view of the SKA array, and together with the large instantaneous bandwidths (3.9 and 2$\times$ 2.5 GHz for band 5a and 5b, respectively) available, that allow to cover at once relevant redshift ranges with suitable spectral resolution. At relatively low redshifts, blind surveys are less effective than targeted ones. However, they become increasingly relevant if and when large portions of the sky are surveyed with sufficient sensitivity. Since this may imply to invest a considerable amount of observing time, a good degree of commensality and complementarity with other projects would be ideal. In Fig. 2, we show a plot with the number of masers as a function of redshift ($z \geq 0.45$) for a quarter-sky search, with a total integration time of $\sim$ 1000 hours for each configuration (with integration time and 3-σ sensitivity, per pointing, of 5 sec and 6 mJy/chan, respectively). Assuming an evolution of the LF with redshift (see above), in the aforementioned survey, at redshift between 0.45 and 1.2, we would expect to detect between $\sim$ 80 and 800 new maser sources, for a LF evolution exponent of 4 and 8, respectively.

To recapitulate: the use of the SKA-Mid telescope in the AA4 configuration will offer the unique chance to unveil hundreds to thousands of new water maser sources in a, so far, almost maser-undetected range of redshift (between 0.5 and 2), and, possibly, larger variety of objects. While the use of SKA-Mid in its AA* configuration will already show promising avenues for water maser surveys, it has to be pointed out that the almost factor of two loss in sensitivity w.r.t. the AA4 configuration, will turn into a corresponding significant decrease by half in efficiency for targeted searches, and of a factor two and six in the number of maser detections in a square degree or quarter-sky blind searches, respectively. Independently from which surveying strategy (targeted or blind) will be adopted, it is evident that the inclusion of the SKA-Mid array, particularly in its AA4 configuration, in the search for water masers will be a game changer by definition, since it will permit the detection of many more sources in a part of the sky – the southern one – so far, largely unexplored or observed with shallow sensitivity. Indeed, the radioastronomical facilities that have access to the sky with declination below -40 degrees (e.g., the Murriyang 64-m radio telescope and the Australia Telescope Compact Array) are presently not sensitive enough to perform searches for extragalactic water masers, as the one described above, in a reasonable amount of time. Noticeably, relevant complementary information on AGN detected in the 22-GHz water maser line can be derived from studies of water maser transitions at mm/sub-mm wavelengths recently made possible by the remarkable capabilities of ALMA and NOEMA (e.g., Tarchi et al. 2024, and references therein).

[3]The reported values are computed using the SKA-Mid sensitivity calculator, available at: 'https://sensitivity-calculator.skao.int/', for a compromise frequency of 10 GHz.

3 Technical requirements and possible enhancements beyond the design baseline

In the previous section, the capability for the SKA-Mid to detect new water maser sources has been quantitatively discussed. Indeed, a number of relevant details can be inferred from the spatially-unresolved spectra of the water maser emission alone. The spectral line profiles can in fact provide indications if the maser originates from an accretion disk, where three groups of narrow features centered at the systemic velocity of the host galaxy are observed, or in radio jets/outflows, where a single broad line displaced from the systemic velocity is often displayed (e.g., Tarchi 2012). However, in order to maximize the return of any new maser detection and, in particular, to determine precise black-hole mass and distance estimates of the host galaxies in disk masers, high spatial resolution imaging capabilities are required to map the distribution of the water maser spots. While the prototypical disk-maser case is that in NGC 4258 whose accretion disk has a subparsec scale size, more and more disk-maser sources have been and are under investigation, especially in the framework of the Megamaser Cosmology Project (see, e.g., Braatz et al. 2010). In some cases, disk sizes of the order of 1 pc have been also observed and, possibly, even larger accretion disks are expected in radiogalaxies were more massive black-holes are present (Tarchi et al. 2007). Hence, as shown in Fig. 3, a sensitive array with baselines of thousands of kms would open up the possibility to lead detailed studies of accretion disks and jets/outflows in AGN also in distant galaxies (up to $z \approx 1$ or more, if also space-VLBI baselines will become available in the future), for which mJy/sub-mJy sensitivities and sub-parsec/parsec linear resolutions are necessary. Therefore, a synergy between the SKA-Mid and the Global VLBI framework is then absolutely desirable. Clearly, in order to resolve a 1-pc structure at z=1, at 11 GHz (the frequency at which the water maser line is Doppler-shifted), baselines $>10^5$ km are required. Consequently, only maser sources (much) closer than z=1, masing structures with larger extent, or gravitationally-lensed maser galaxies (for such a case, see Impellizzeri et al. 2008 and Castangia et al. 2011), will provide substantial advantage in obtaining relevant information of the AGN components through follow-up interferometric studies with earth-based antennas only. For these studies, a network of radiotelescopes is then recommended that combines the SKA-Mid array (possibly used in phased mode) with a number of antennas (or other suitable arrays, e.g., the ATCA, KVN, or VERA) at relatively-large distances to provide the necessary baseline lengths (few thousands of km). Instead, as shown before, in the case of unlensed water masers at cosmological distances, only space VLBI (presently represented by RadioAstron) may grant the necessary resolution for detailed studies of the emission.

Furthermore, the highest frequency presently planned for SKA-Mid is 15.4 GHz, thus preventing the exploitation of its enhanced capabilities also for searches and detailed studies of 22-GHz water maser sources in nearby (z<0.45) targets. This "gap" will, however, be filled by taking profit of the future ngVLA project (at least for source declinations above −40 degrees) and/or by the possible extension of the SKA-mid observing frequency beyond band 5b. Overall, the joint effort of these instruments will allow us to significantly increase the number of nearby and distant water maser sources with the particularly appealing possibility, among others, to study, for the first time, these objects in radio loud galaxies, and to test the possible evolution of the maser LF with redshift.

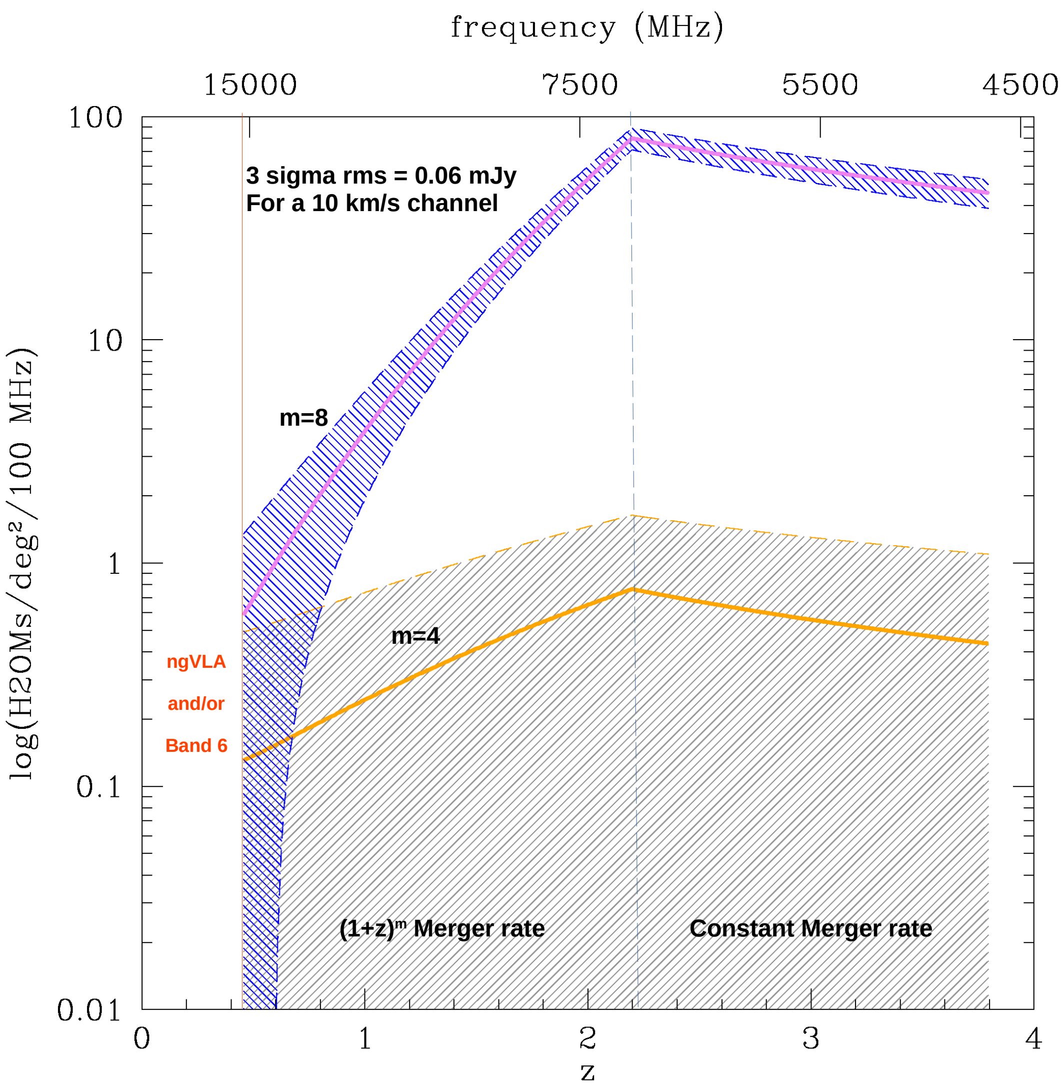

Figure 1: Sky density of detectable water masers with the SKA-Mid telescope (AA4) blind-searching a portion of sky of 1 square degree at a sensitivity of 0.06 mJy. Shaded areas indicate the 1σ confidence level. The evolution of the LF with redshift is parametrized as $(1+z)^m$, where m is 4 and 8 for moderate and very high evolution, respectively. The dashed line marks the redshift (z=2.2), after which there is assumed to be constant density evolution. The red solid line defines the actual lower limit in redshift ($z \sim 0.45$) for 22-GHz water maser studies possible with the SKA-Mid telescope due to the highest frequency threshold of band 5b (15.4 GHz).

4 Acknowledgements

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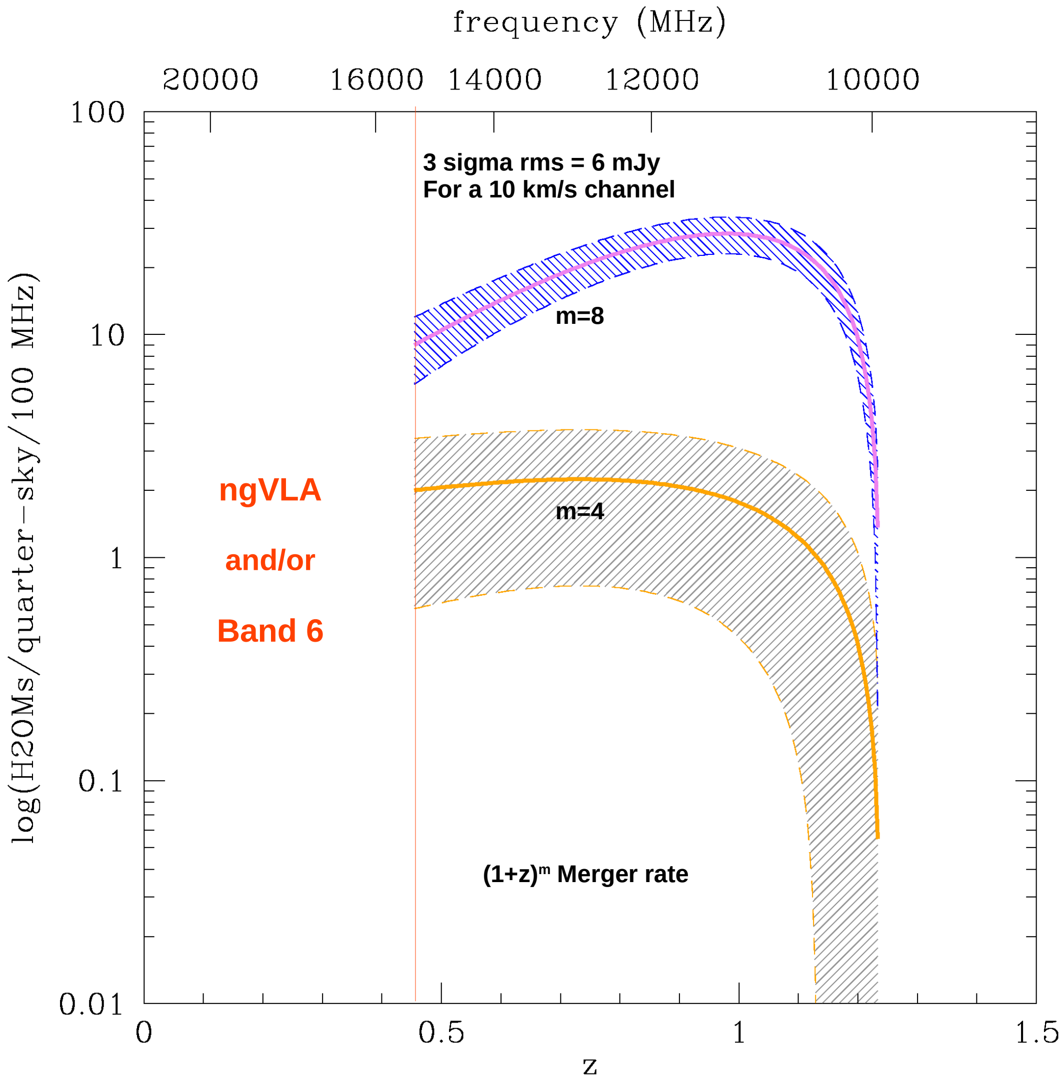

Figure 2: Sky density of detectable water masers with the SKA-Mid telescope (AA4) blind-searching a quarter-sky area at a sensitivity of 6 mJy. Shaded areas indicate the 1σ confidence level. The evolution of the LF with redshift is parametrized as $(1+z)^m$, where m is 4 and 8 for moderate and very high evolution, respectively. The red solid line defines the actual lower limit in redshift ($z \sim 0.45$) for 22-GHz water maser studies possible with the SKA-Mid telescope due to the highest frequency threshold of band 5b (15.4 GHz).

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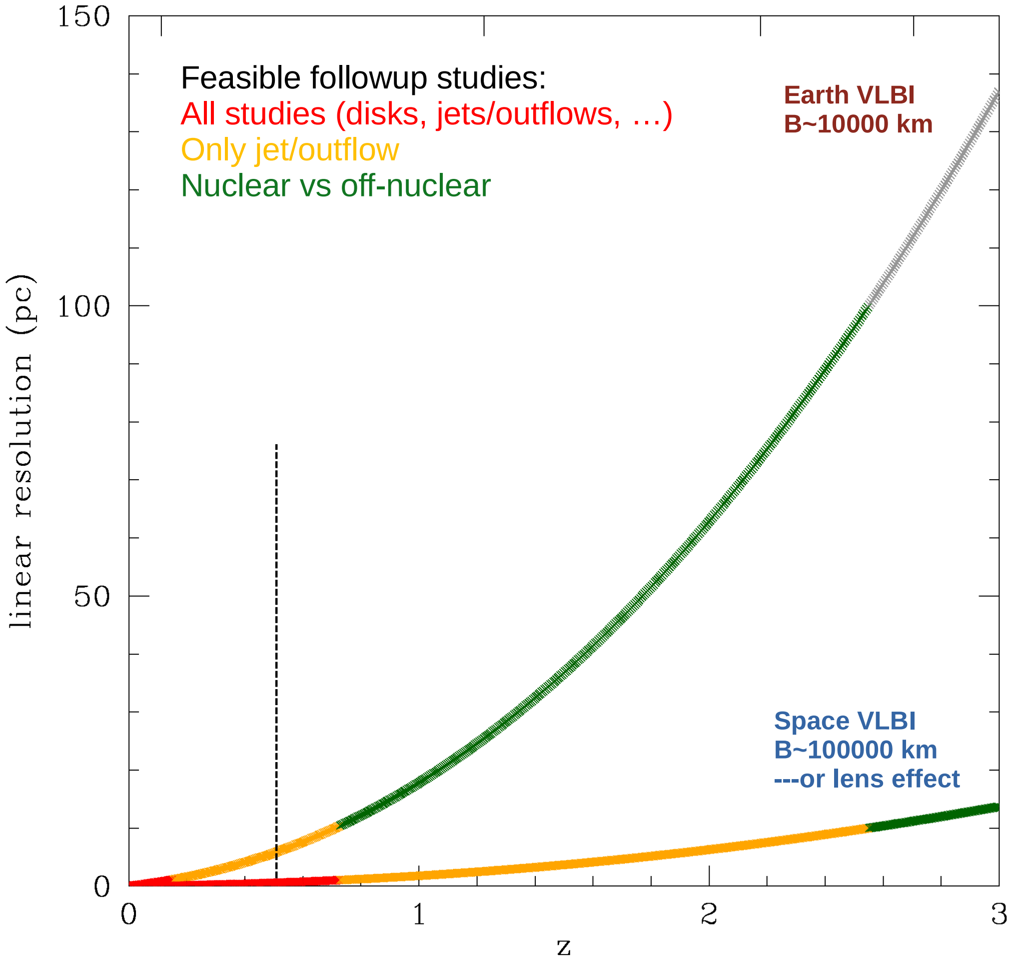

Figure 3: Linear resolution as a function of redshift z necessary to derive relevant information on the nuclear region of the host galaxies through water megamaser follow-up studies, for Earth-VLBI and Space-VLBI (or source lens-magnification) baselines, respectively. The color code is explained by the key appended in the top-left corner. The vertical black dashed-line marks the actual lower limit in redshift ($z \sim 0.45$) for 22-GHz water maser studies possible with the SKA-Mid telescope due to the highest frequency threshold of band 5b (15.4 GHz).

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