Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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A Holistic Search for Megamaser Disks and their Role in Feeding Supermassive Black Holes

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Abstract. If water megamaser disk activity is intimately related to the circumnuclear activity from accreting supermassive black holes, a thorough understanding of the co-evolution of galaxies with their central black holes should consider the degree to which the maser production correlates with traits of their host galaxies. This contribution presents an investigation of multiwavelength nuclear and host properties of galaxies with and without water megamasers, that reveals a rather narrow multi-dimensional parameter space associated with the megamaser emission. This "goldilocks" region embodies the availability of gas, the degree of dusty obscuration and reprocessing of the central emission, the black hole mass, and the accretion rate, suggesting that the disk megamaser emission in particular is linked to a short-lived phase in the intermediate-mass galaxy evolution, providing new tools for both 1) further constraining the growth process of the incumbent AGN and its host galaxy, and 2) significantly boosting the maser disk detection by efficiently confining the 22 GHz survey parameters.

Keywords. masers, galaxies: active

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1. The Hunt for Water Megamasers: the current state of affairs

Current discovery surveys for water megamasers ($L_{\mathrm{H_2O}} \geq 10L_{\mathrm{sun}}$) do not appear to improve the success rate; searches remain rather blind and expensive. Of more than 6000 galaxies surveyed for 22 GHz emission in their centers, only 180 (or $\lesssim 3\%$) of them have been found to host water maser emission; among these, only $\sim$30% show megamaser emission in a disk-like configuration†. An efficient scrutiny for new such systems requires a good understanding of the special physical characteristics that nurture them in galaxy centers which, to date, remains ambiguous. While there is some evidence that megamasers may be associated with the molecular disk or torus that surrounds and (partially) obscures an actively accreting massive black hole harbored by a galactic nucleus (AGN), the true connection between megamasers and AGN activity, or other

† i.e., based on continuously updated results of all 22 GHz surveys of galaxies, via the Megamaser Cosmology Project, or MCP; http://wiki.gb.nrao.edu/bin/view/Main/MegamaserCosmologyProject

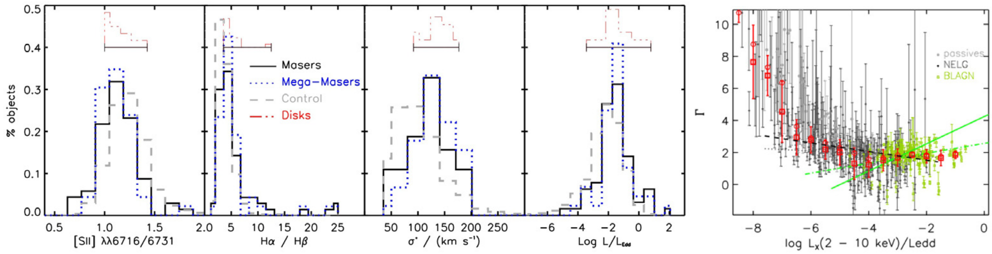

Figure 1. *Left:* Distributions of [S II]$\lambda\lambda$6716/6731 line flux ratios (as proxy for gas densities), Balmer Decrements H_α/H_β, stellar velocity dispersions σ^*, and Eddington ratios ($L/L_{\rm Edd}$) for masers (black), megamasers (dotted blue), disks (dot-dashed red), and non-masers (as control sample; gray dashed). *Right:* Inflection in the $\Gamma - L_X/L_{\rm Edd}$ relation at $L/L_{\rm Edd} \sim 1\%$ illustrated with a sample of $\sim$600 nearby galaxy nuclei from the Chandra Source Catalog with SDSS spectra (Constantin et al. 2023, in prep)

nuclear galactic properties, is still an open question. AGN identification is truly a multi-scale, multi-component, multi-wavelength challenge as for most of the active galaxies, a mix of emission processes (including star-forming regions, shocks, turbulence, etc.), nuclear obscuration, as well as host galaxy starlight, obfuscate their true classification. Searching for maser disks will therefore need to match in sophistication.

2. A "goldilocks" region of nuclear and host galaxy traits for maser disks

Kuo et al. (2018, 2020) have identified some special characteristics that nurture the maser emission in galaxy centers: the megamaser (disk maser) detection rate gets boosted abruptly from $\lesssim$3%($\lesssim$2%) to $\sim$12%($\sim$5%) for a certain wedge in the $w_1 - w_4$ mid-IR (*WISE*) colors and 12 μm AGN luminosities $L^{AGN}_{12\mu m} > 10^{42}$ erg s^{-1}, and to 15%(7%) and 20%(9%) if one select galaxies with $N_{\rm H} \geq 10^{23}$ cm^{-2} and $N_{\rm H} \geq 10^{24}$ cm^{-2}, respectively. These results identify efficient ways of targeting galaxies with megamaser disk emission and strengthen evidence that megamasers are associated with the molecular disk or torus that surrounds and (at least partially) obscures the central AGN. Nevertheless, the completeness rates remain compromised, as a fraction of maser disks would remain undiscovered under such selection criteria.

Interestingly, when adding optical properties (e.g., Constantin 2012), the maser disk galaxies associate with a narrow range of properties, including: the density of gas ($n_e \sim$ 100's cm^{-3}, as measured by the [S II]$\lambda\lambda$6716/6731 line flux ratios), the presence and geometric distribution of obscuration (e.g., Balmer Decrements H_α/H_β), the accretion rate (Eddington ratios; $L/L_{\rm Edd} \sim 10^{-2}$), and the black hole mass ($M_{\rm BH} \sim 10^7 M_{\rm sun}$, via stellar velocity dispersions σ^*), which also corresponds to the location of an inflection point in the X-ray spectral index Γ vs. $L/L_{\rm Edd}$ trend (Figure 1); this inflection is present for a wide range of galactic properties including the AGN fraction, the BH and host mass, the optical spectral classification, presence or absence of the broad line region, and even the host morphology.

These findings suggest that the disk megamaser emission in particular is linked to a short-lived phase in the intermediate-mass galaxy evolution, characterized by an apparent transition in both the availability of the intrinsic absorption (being blown away for higher accretion rates) and the accretion rate of the central engine (from inefficient, or ADAF to the standard quasar-like, Shakura-Sunyaev mode); the inflection location at $L/L_{\rm Edd} \sim 10^{-2}$ seems to also be where the "changing-look" AGN fluctuate from type 1 to type 1.8(2?) Seyferts, and sharp transitions in the column densities N_H have been detected (e.g., Noda & Done 2018; Ricci & Trakhtenbrot 2022). The accretion mode change might

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thus influence the maser production, also linked with the (just right!) amount of obscuring material.

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