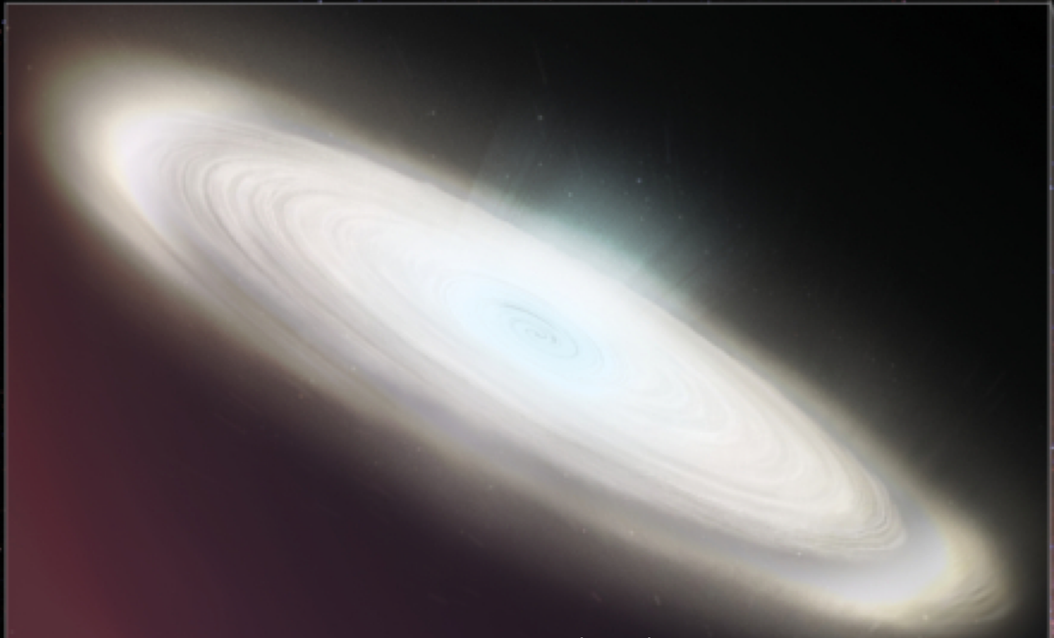
Image credit: Sophia Dagnello, NRAO/AUI/NSF

A geometric measurement of H_0 by the Megamaser Cosmology Project

Dom Pesce

__In collaboration with__: Jim Braatz (PI), Mark Reid, Jim Condon, Feng Gao, Christian Henkel, Violette Impellizzeri, Cheng-Yu Kuo, Anca Constantin, Jenny Greene, Lei Hao, Adam Riess, Dan Scolnic, Fred Lo

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CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

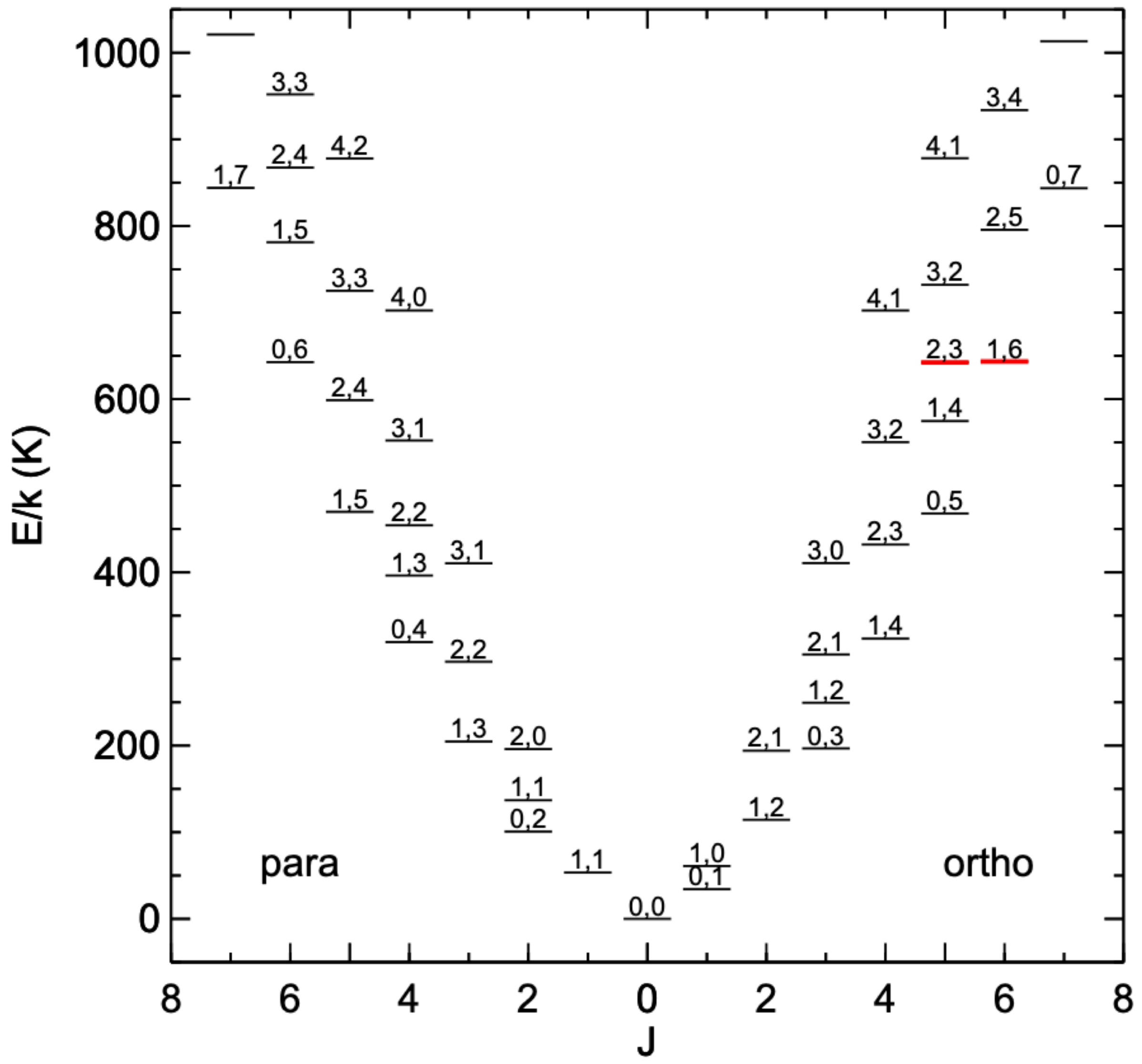
AGN accretion disk megamasers

The warm ($T \approx 1000$ K), dense ($n \approx 10^9$ cm^{-3}) molecular gas in AGN accretion disks on ~pc scales contains water

One rotational transition of the water molecule, with a rest frequency of ~22 GHz, can sustain maser emission under these physical conditions

The name “megamaser” comes from their large luminosities:

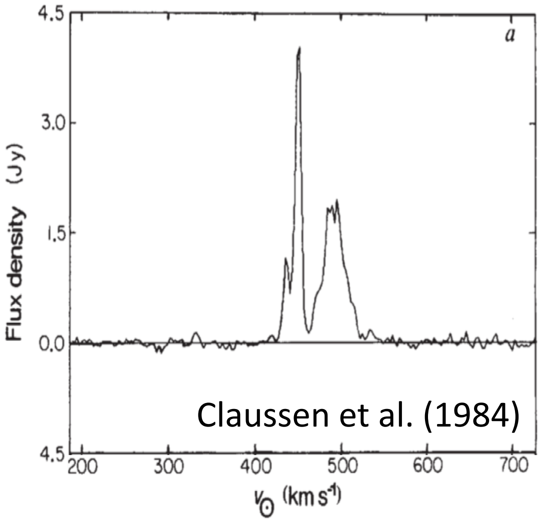
- Galactic masers $L \lesssim 10^{-4}\ L_\odot$
- Megamasers $L \gtrsim 10^{2}\ L_\odot$



NGC 4258 – the original megamaser galaxy

The galaxy NGC 4258 hosts the first discovered disk megamaser system

First observed by Claussen et al. (1984)



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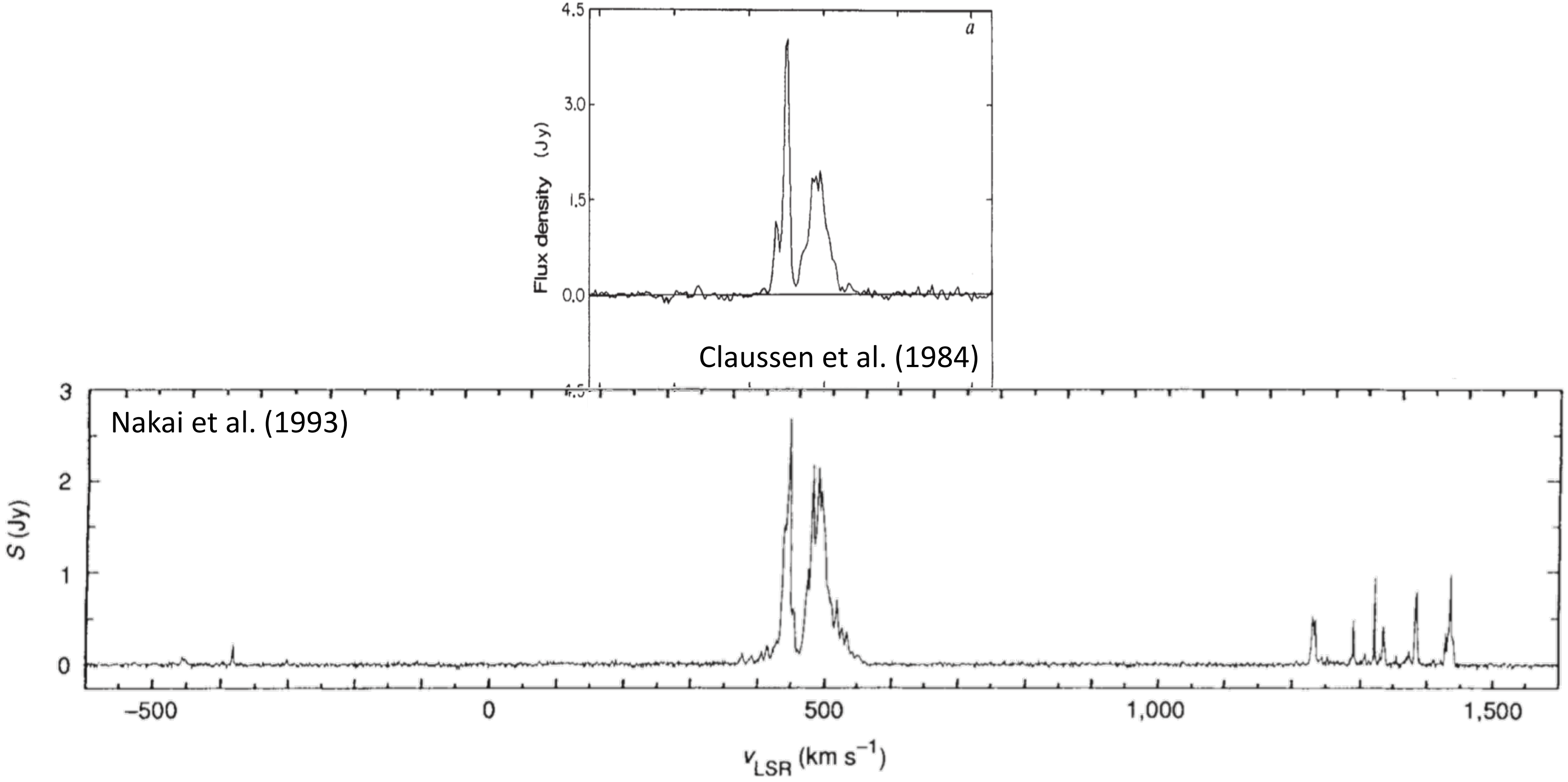

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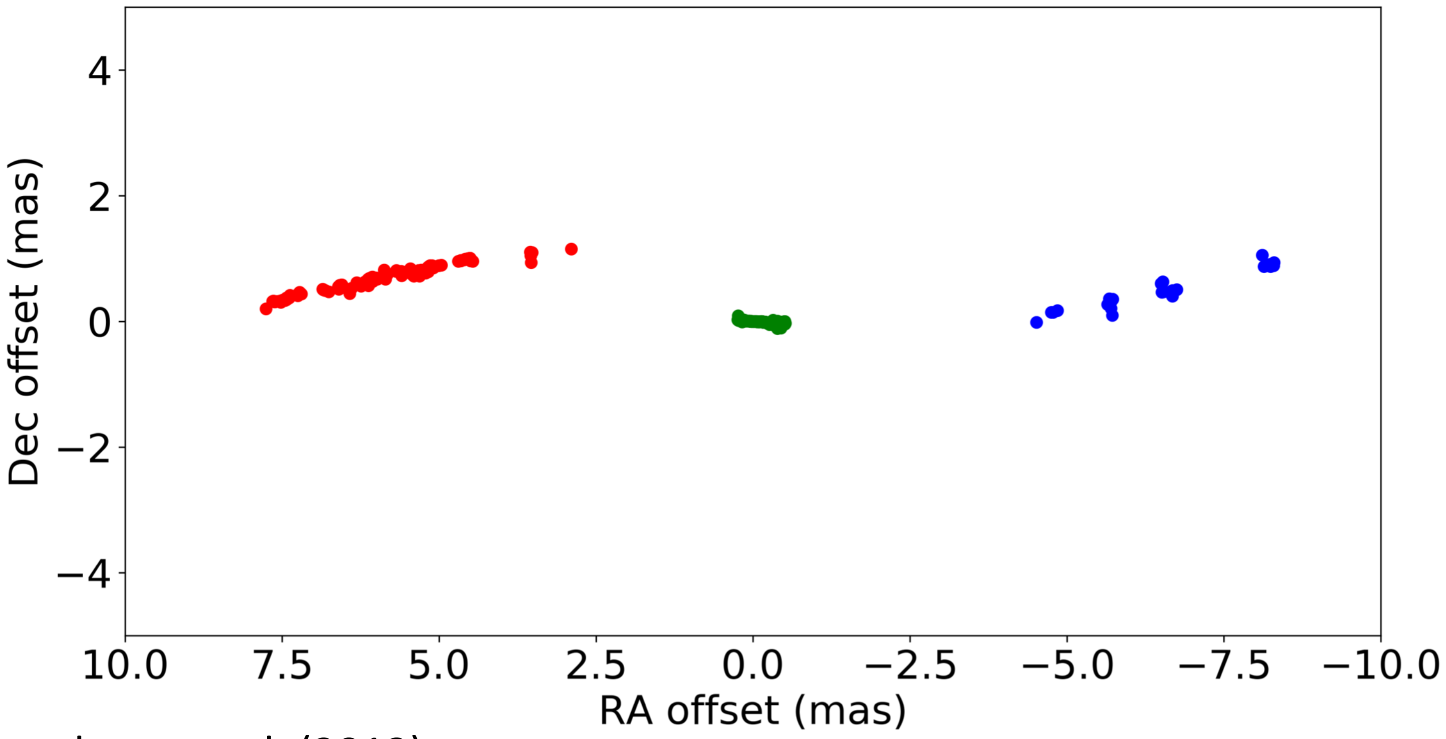

Humphreys et al. (2013)

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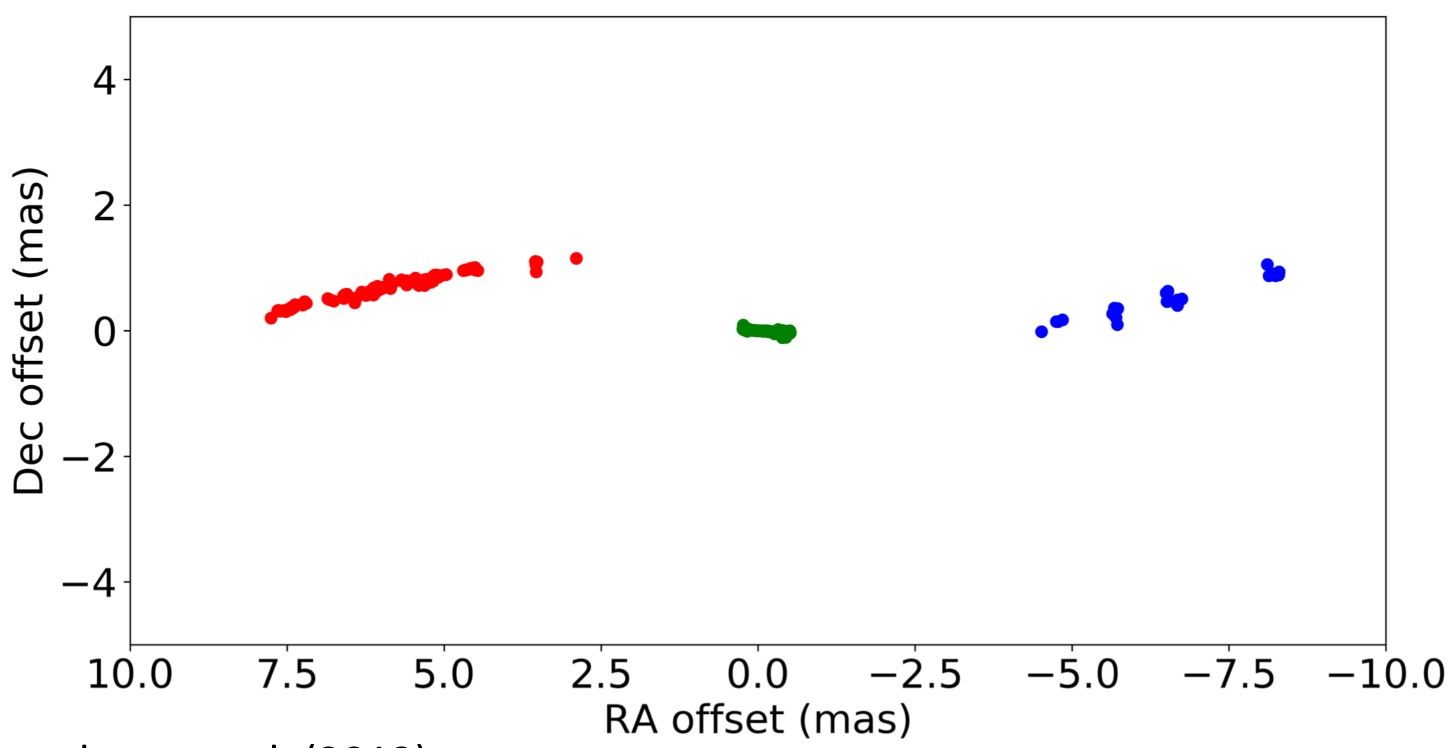

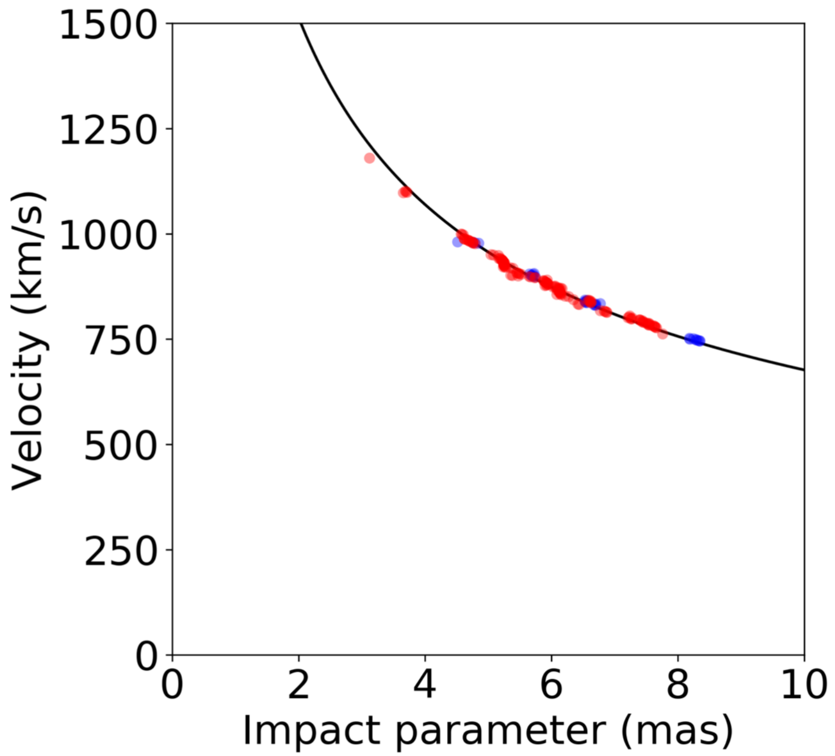

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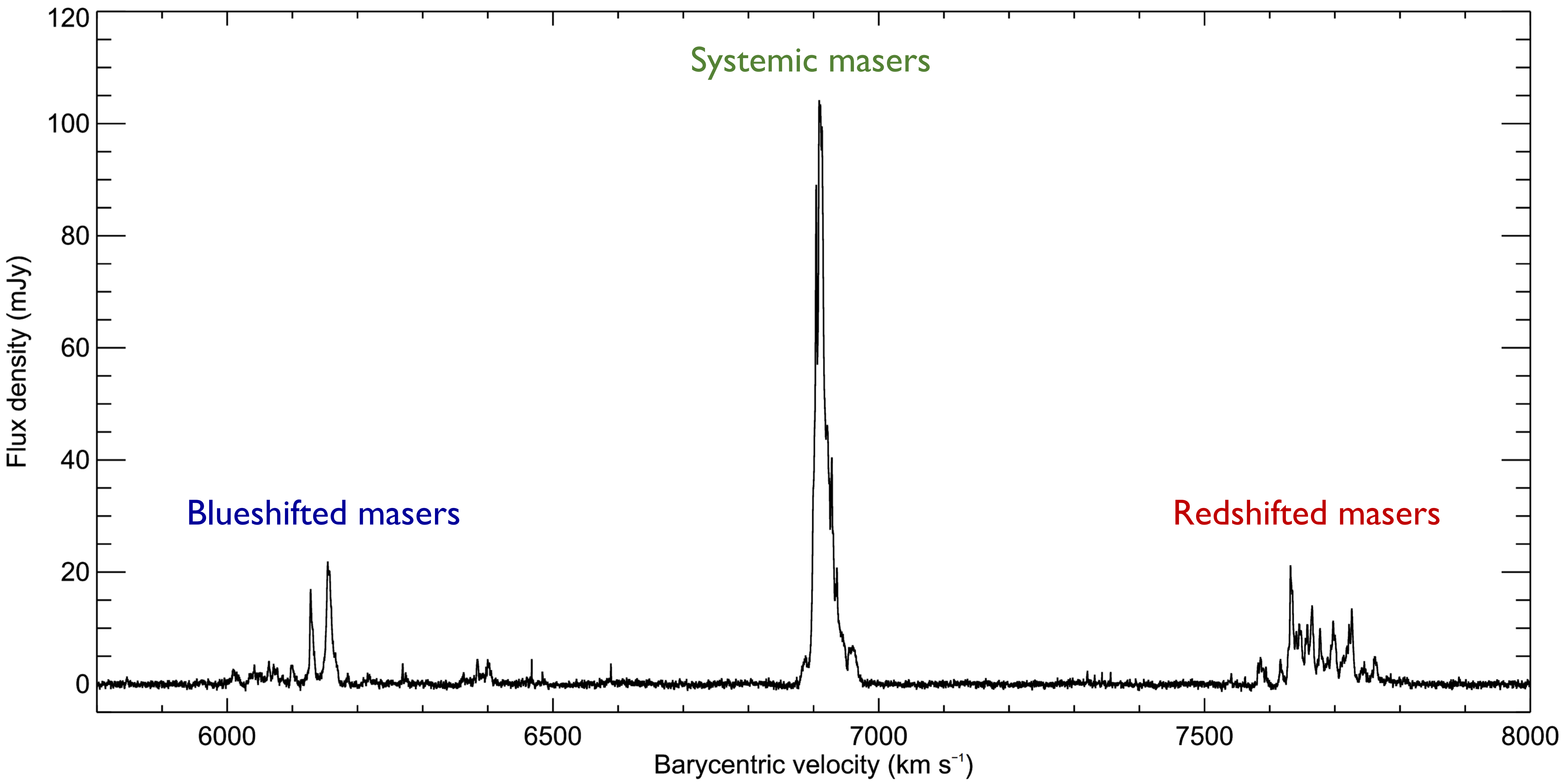
The interpretation is that the masers reside in an edge-on disk orbiting a central point mass

Disk megamasers – basic model



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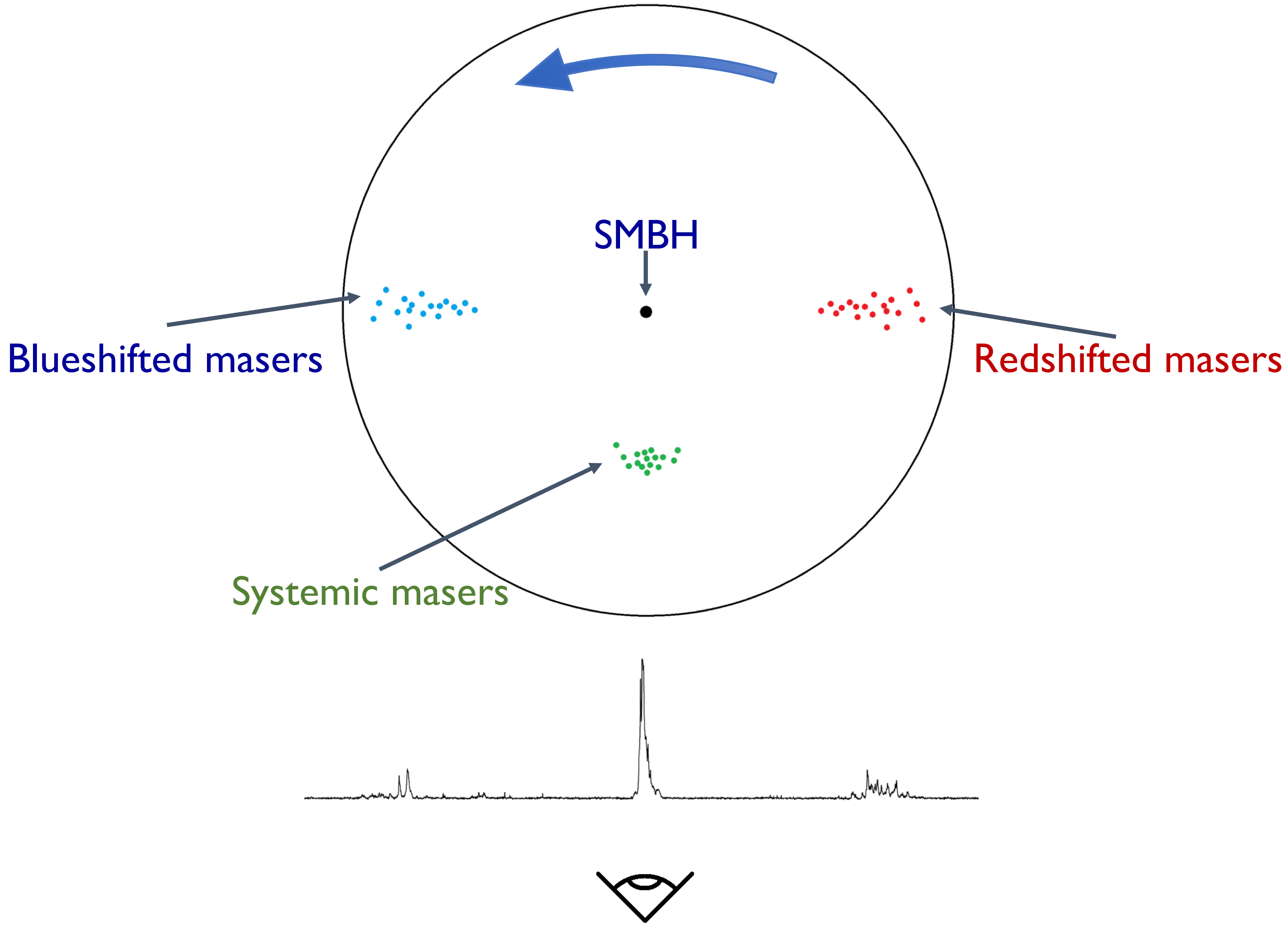
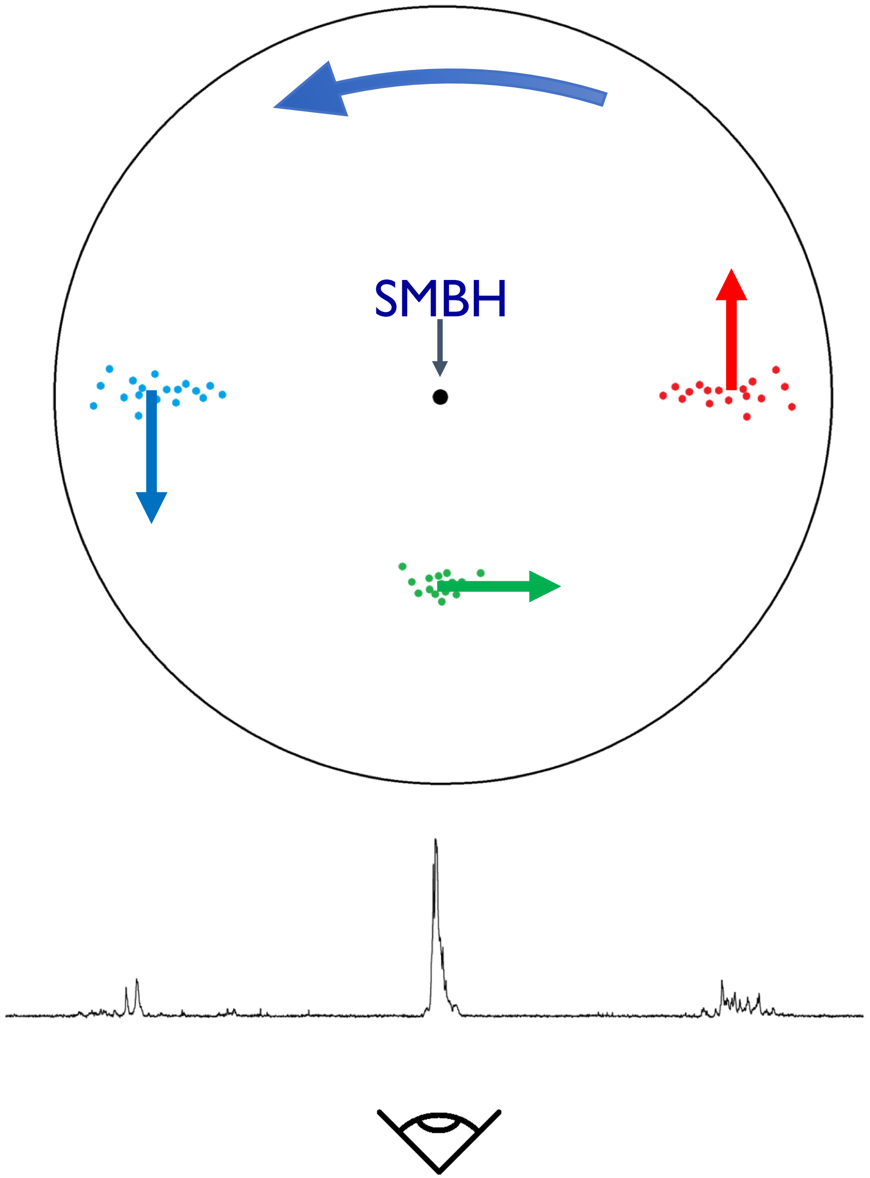


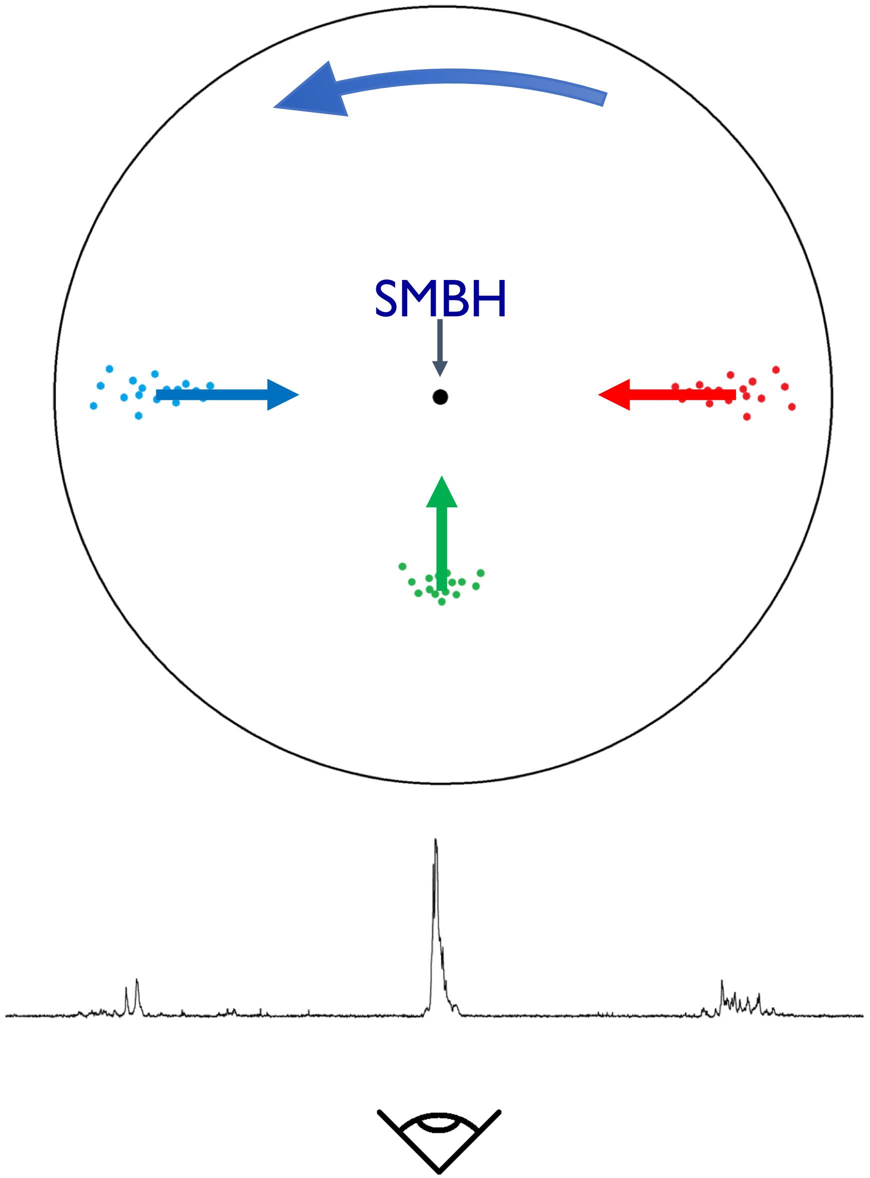
Disk megamasers – basic model

velocity vectors



Disk megamasers – basic model

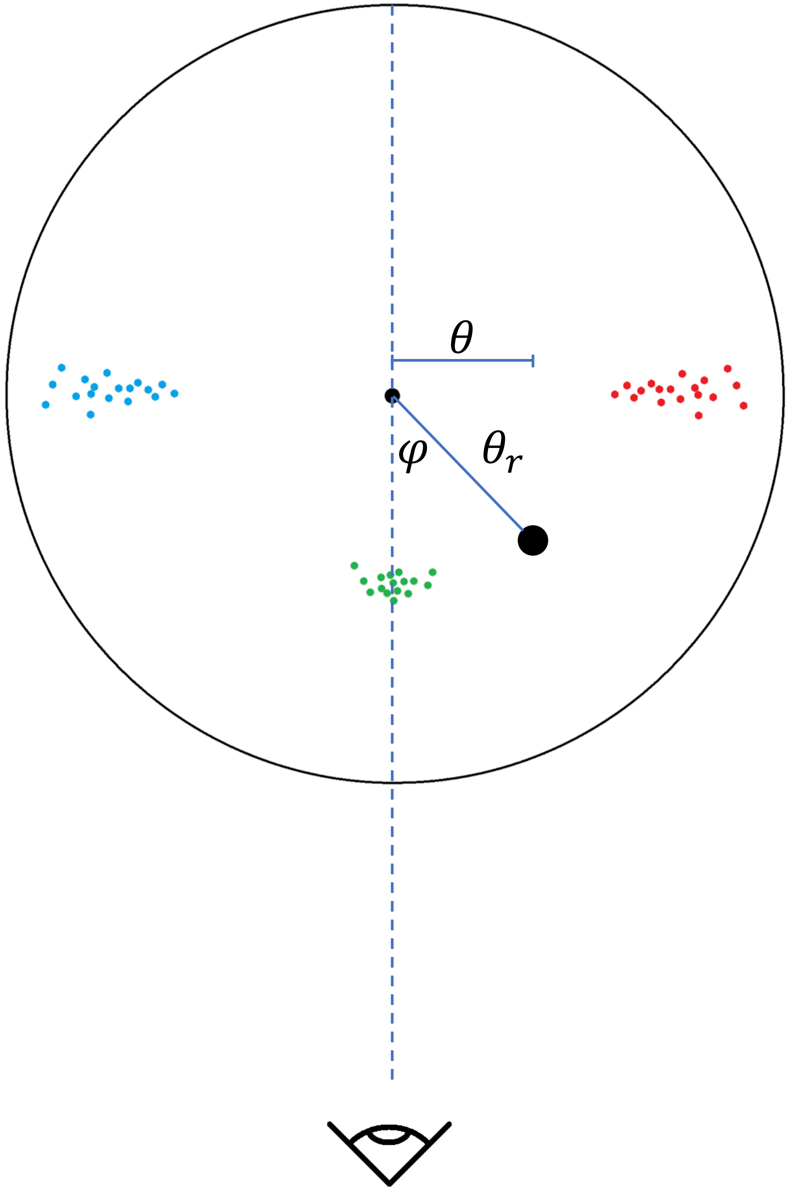
acceleration vectors



Disk megamasers – basic model

Consider a masing cloud on a circular orbit at (angular) radius θ_r around a central SMBH of mass M and situated at an azimuthal angle φ with respect to the line of sight

Observed (on-sky) position: $\theta = \theta_r \sin(\varphi)$



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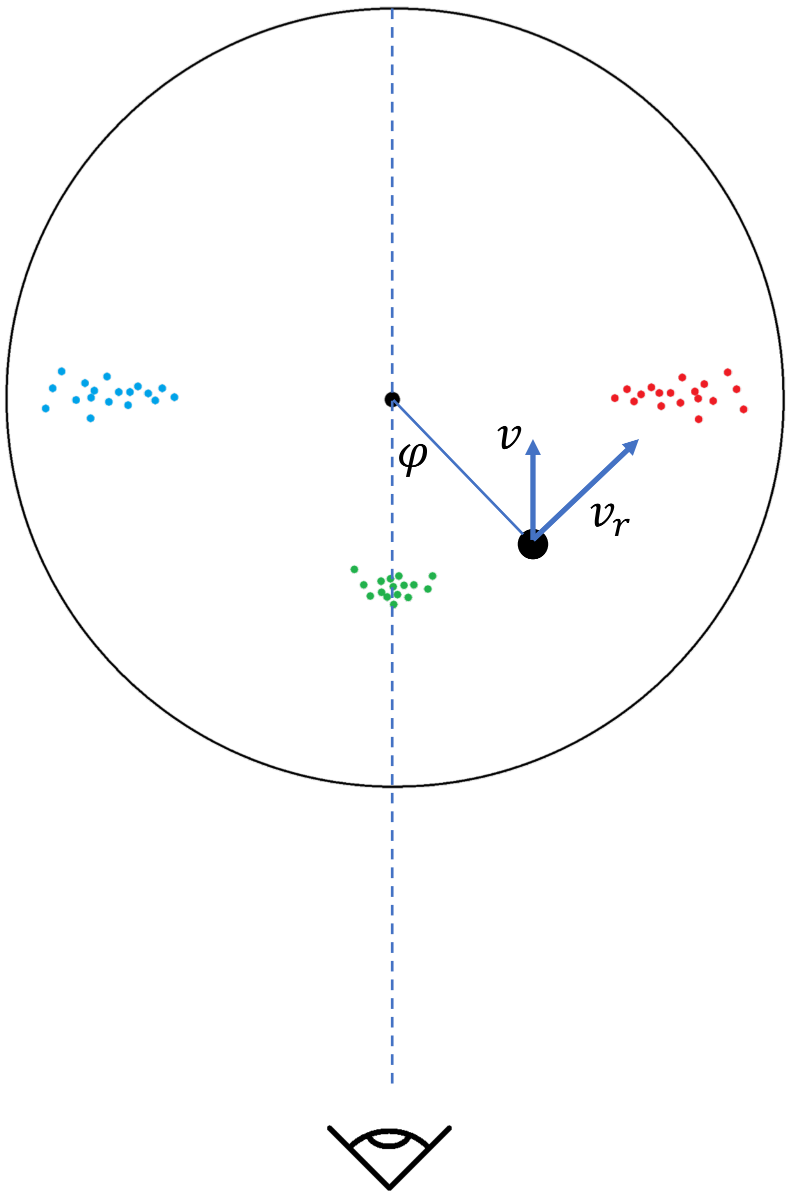
$$v_r = \sqrt{\frac{GM}{\theta_r D}}$$



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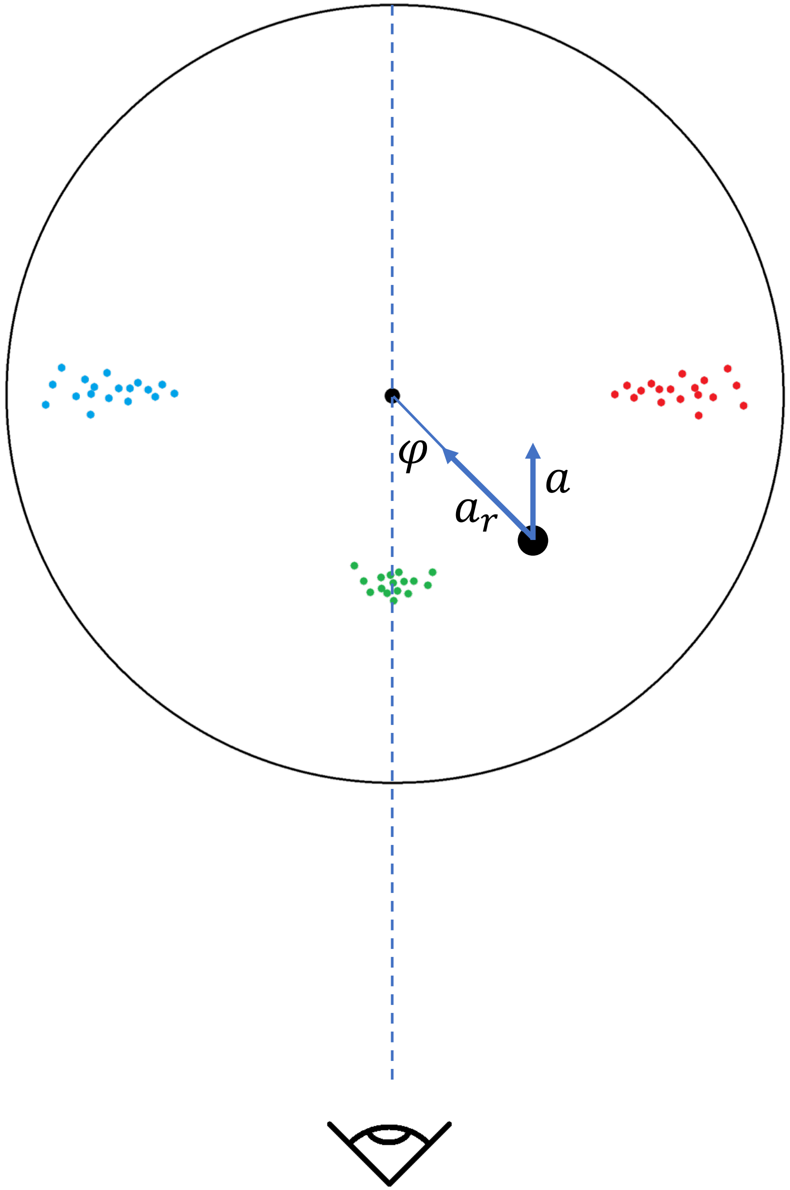
$$a_r = \frac{v_r^2}{\theta_r D} = \frac{GM}{\theta_r^2 D^2}$$



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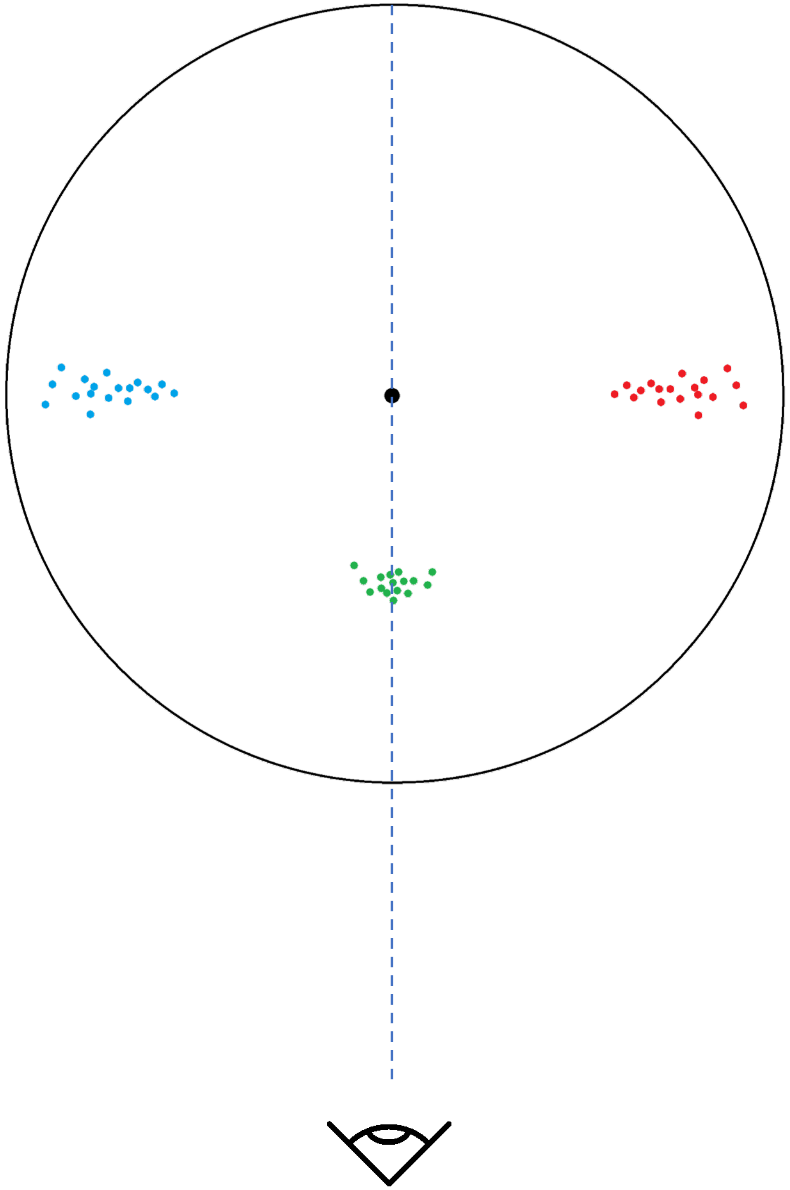
○ = measured ○ = fit

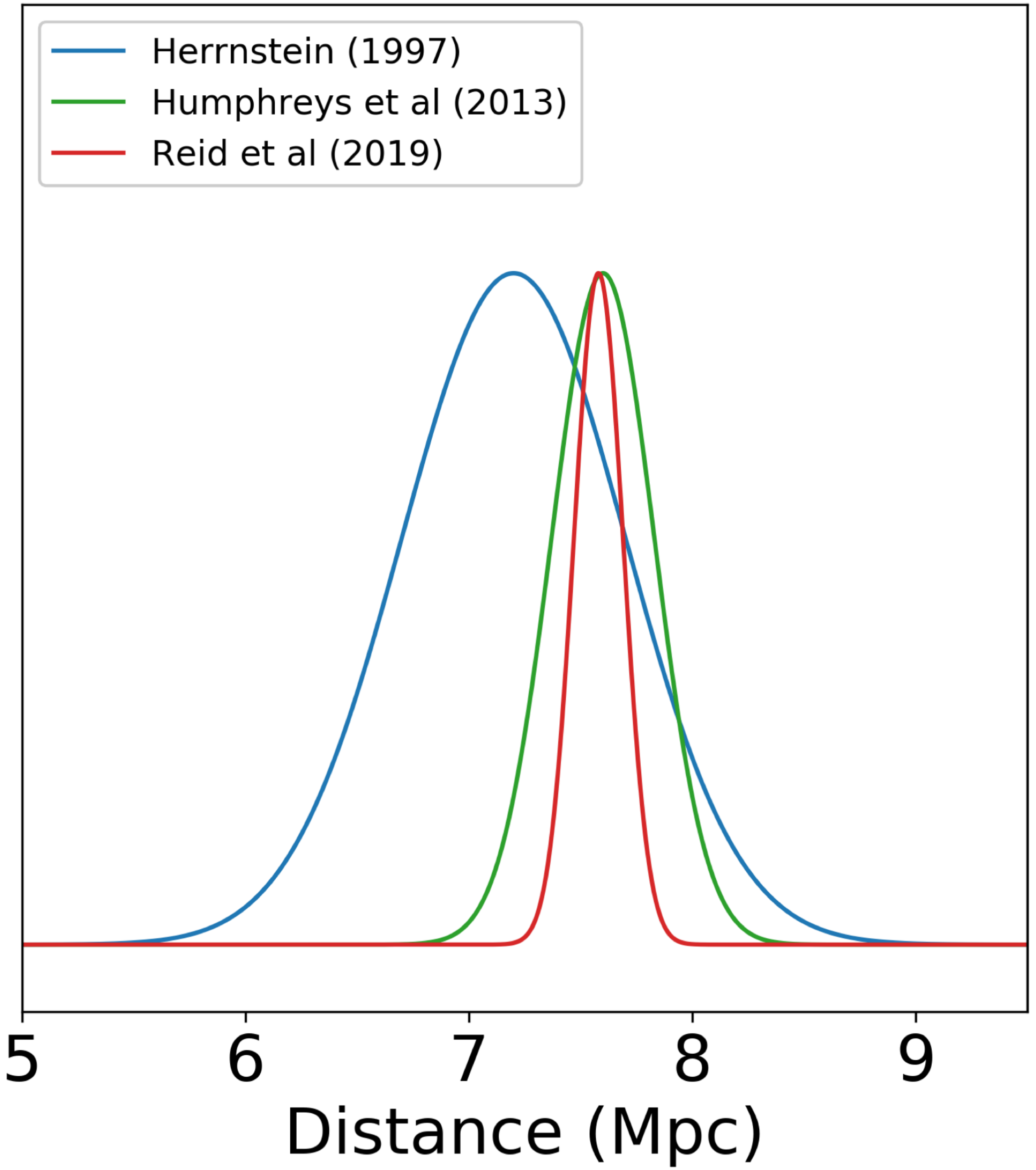


Recent modeling improvements

In practice, we include several additional parameters (besides just the mass and distance) during modeling to account for, e.g., velocity/position centroids, warping of the disk, and non-circular orbits

Recent work incorporating systematic uncertainties into the modeling has improved the distance measurements

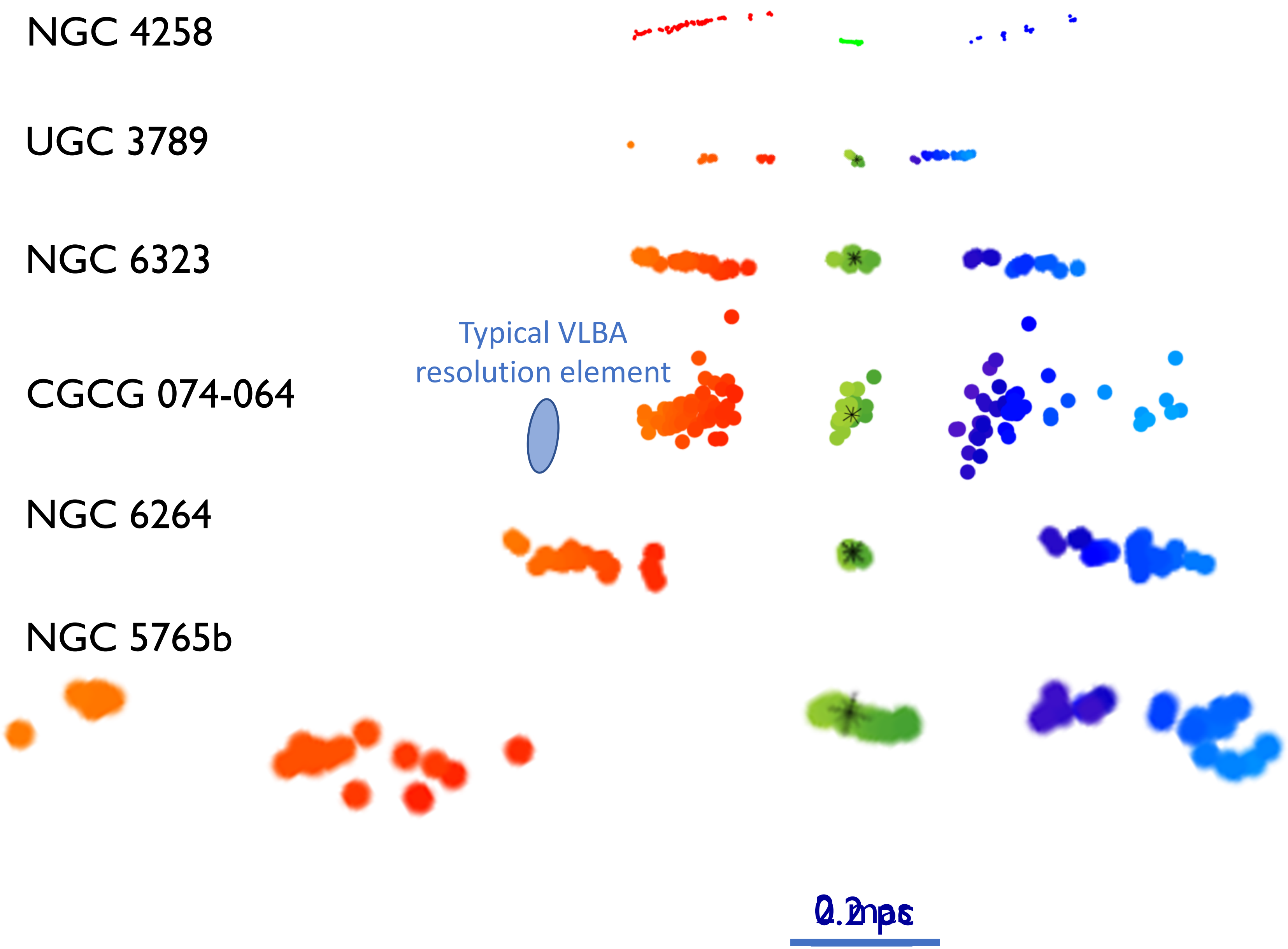
E.g., when applied to the megamaser system in NGC 4258, the updated modeling approach decreases the distance uncertainty by a factor of ~2



The Megamaser Cosmology Project

The Megamaser Cosmology Project (MCP) uses the megamaser technique to make one-step distance measurements to AGN residing in the Hubble flow

The Megamaser Cosmology Project



Maser galaxies in the Hubble flow have distance measurements that are individually much less precise than that of NGC 4258. So to obtain the best constraint on the Hubble constant, we need to combine measurements from multiple galaxies.

The Megamaser Cosmology Project

The Megamaser Cosmology Project (MCP) uses the megamaser technique to make one-step distance measurements to AGN residing in the Hubble flow

To date, the MCP has determined distances to 5 megamaser-hosting AGN:

- UGC 3789 (Reid et al. 2009, Braatz et al. 2010, Reid et al. 2013)
- NGC 6264 (Kuo et al. 2013)
- NGC 6323 (Kuo et al. 2015)
- NGC 5765b (Gao et al. 2016)
- CGCG 074-064 (Pesce et al. 2020a)

Because the megamaser technique also precisely determines the line-of-sight redshift of each galaxy, we can use the combined distance+redshift measurements to constrain H_0

MCP H_0 constraints

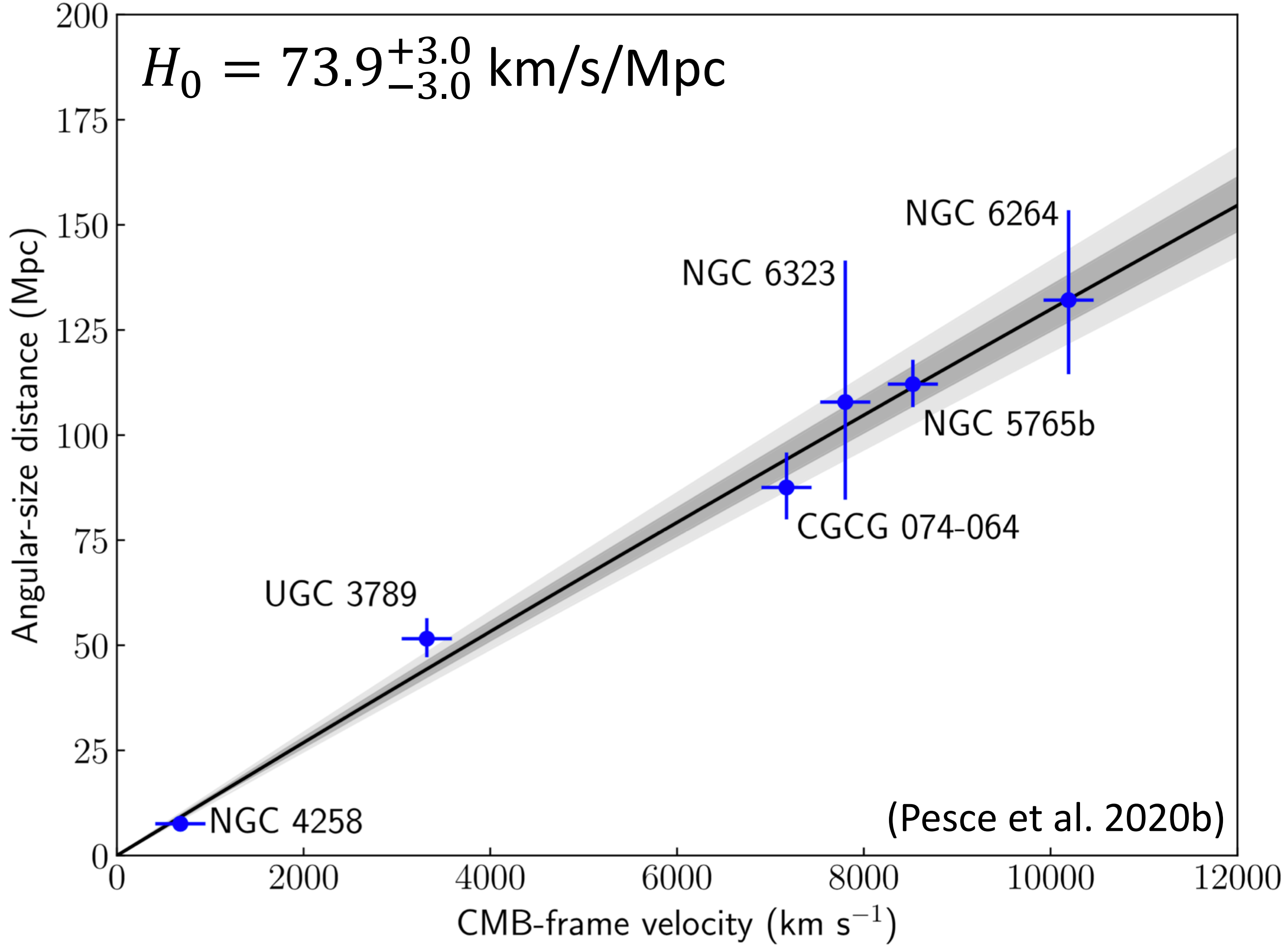
We have combined the 5 MCP targets with NGC 4258 to produce maser-only constraints on H_0

- the latest maser disk modeling formalism has been applied to each galaxy

We jointly fit the 6 distance (D_i) and redshift (z_i) measurements to a simple cosmological model:

$$D_i = \frac{c}{H_0(1+z_i)} \int_0^{z_i} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}}$$

Assuming a 250 km/s peculiar velocity uncertainty for each galaxy, we determine H_0 = 73.9 ± 3.0 km/s/Mpc

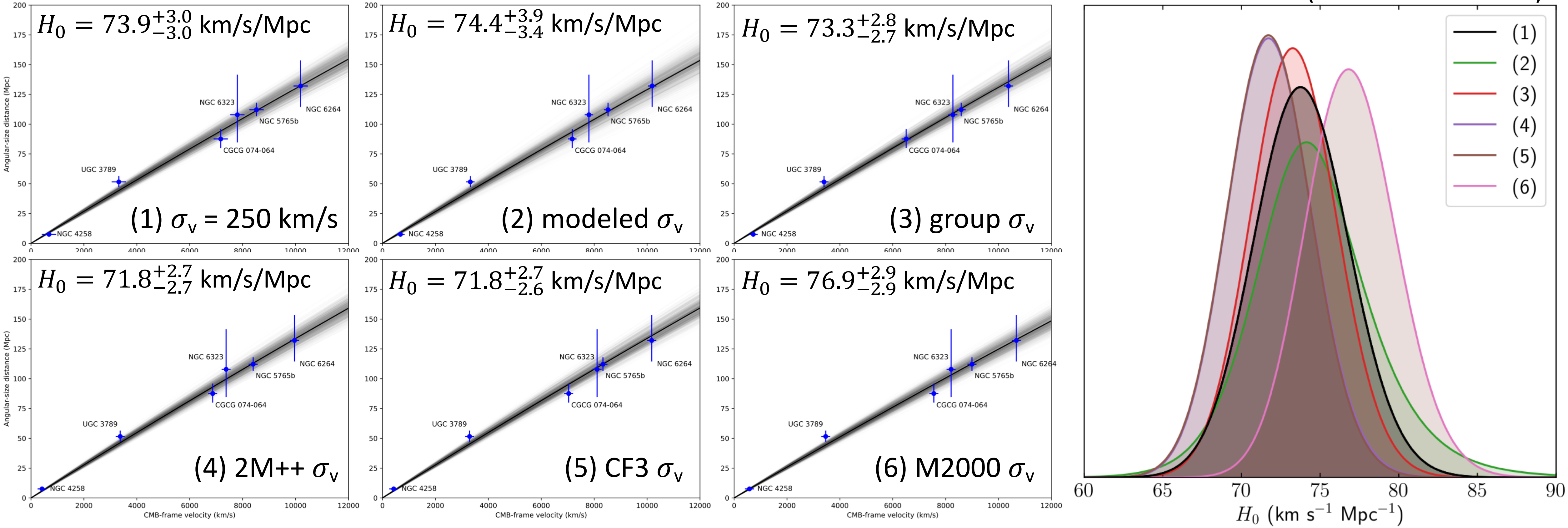


Sources of uncertainty in MCP H_0 constraints

Peculiar velocities

- Though the statistical uncertainty in each galaxy's redshift is tiny ($\lesssim$2 km/s), its systematic deviation from the Hubble flow is unknown
- <u>Mitigation</u>: explore a range of peculiar velocity prescriptions; incorporate peculiar velocities into the model as free parameters; increase sample size

(Pesce et al. 2020b)



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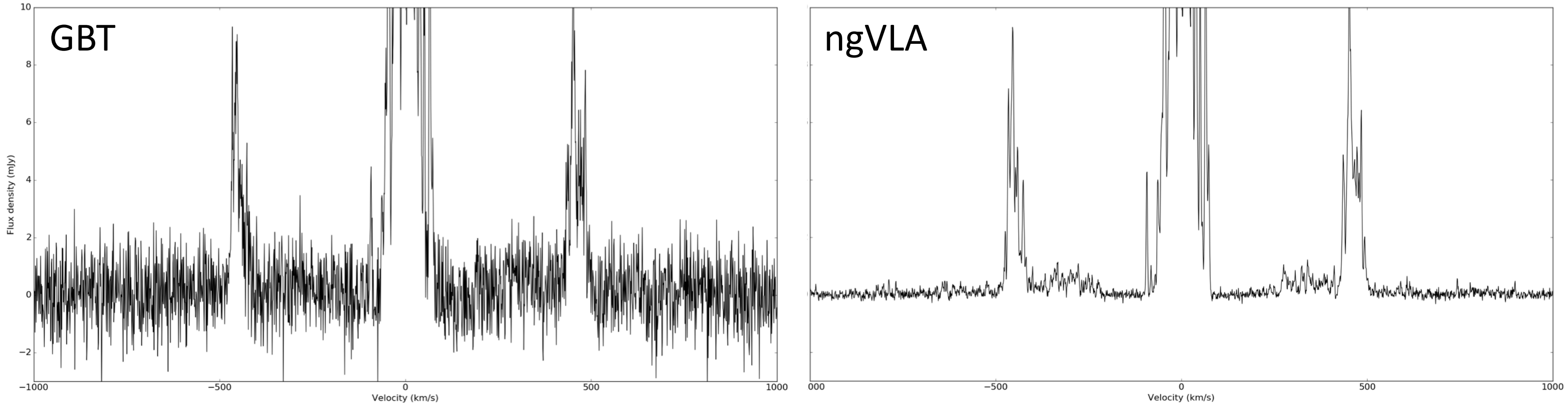
Quality of distance measurements

- Typical uncertainties in megamaser distances are ~10%, compared to $\lesssim 10^{-5}$ in redshift, and altogether they make up ~90% of the H_0 error budget
- Mitigation: next-generation facilities (e.g., ngVLA) operating at 22 GHz will provide ~an order of magnitude more sensitivity in both monitoring spectra and VLBI maps

synthetic 22 GHz maser spectra



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Small sample size

- Currently only 6 maser sources are being used to constrain H_0
- A comparable number (~4-6) have analyses ongoing
- Mitigation: leave-one-out jackknife tests; improved survey strategies are being developed (e.g., Kuo et al. 2020); next-generation facilities will see deeper and uncover fainter systems; (sub)mm water masers with ALMA (+ mm-VLBI) are being discovered and explored right now

Summary

H_2O megamasers residing in AGN accretion disks provide unique and valuable tools for measuring the distances to their host galaxies

The Megamaser Cosmology Project (MCP) had previously discovered and determined distances towards 5 megamaser-hosting AGN

We have improved the maser disk modeling and applied the new scheme uniformly to all MCP targets along with the megamaser system in NGC 4258

Using the distance and velocity measurements from the maser modeling, we have fit a simple cosmological model and constrained the Hubble constant to $H_0 = 73.9 \pm 3.0$ km/s/Mpc

- This constraint assumes a peculiar velocity uncertainty of 250 km/s associated with each galaxy
- Alternative peculiar velocity mitigation strategies have only modest ($<1\sigma$) impacts

Future MCP H_0 constraints will incorporate distance measurements from additional megamaser-hosting galaxies