VLBI Observations of H_2O Megamasers

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Primary Goals of H_2O Megamaser Studies

1. Measure H_0 using *geometric* distances to galaxies directly in the Hubble flow

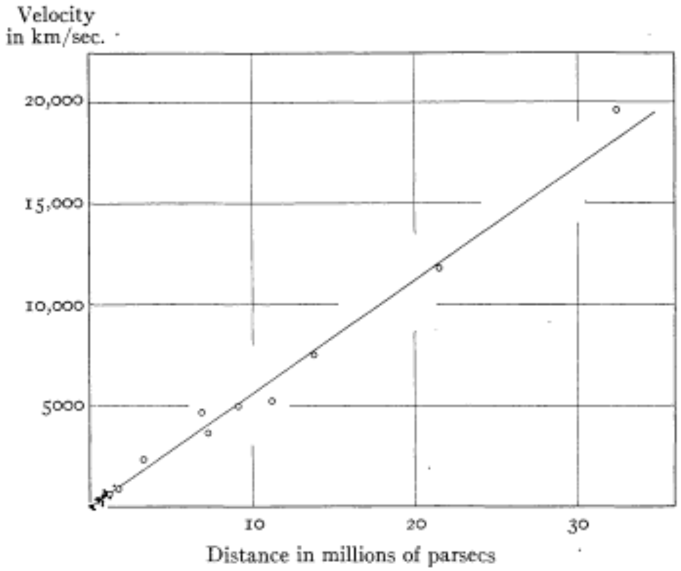
2. Measure "gold standard" masses of SMBH

3. Determine the geometry and physical conditions of AGN accretion disks on sub-pc scales

4. Measure SMBH peculiar motions

Three Observations that Shaped Our Understanding of the Universe

1. The Universe is expanding
   (Hubble and Humason, 1931)



Hubble's Law: $v = H_0 \times D$

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THE VELOCITY-DISTANCE RELATION AMONG EXTRA-GALACTIC NEBULAE[1]

By EDWIN HUBBLE and MILTON L. HUMASON

ABSTRACT

Methods of determining distances of extra-galactic nebulae are discussed, and the mean absolute magnitude is revised on the basis of (1) Shapley's revision of the zero-point of the period-luminosity curve for Cepheids, and (2) more extensive observations of stars involved in nebulae. The revised value is M (vis) $= -14.9$.

The mean color-index of the nearer extra-galactic nebulae appears to be of the order of $+1.1$ mag., hence $M(\mathrm{pg}) = -13.8$. A color-excess is suggested which is independent of distance but shows some relation to galactic latitude.

The velocity-distance relation is re-examined with the aid of 40 new velocities, 26 of which refer to nebulae in 8 clusters or groups. Distances of the clusters, ranging out to about 32 million parsecs, have been derived from the most frequent apparent magnitudes. The velocity displacements reduce the apparent magnitudes by amounts which become appreciable for the more distant clusters.

The new data extend out to about eighteen times the distance available in the first formulation of the velocity-distance relation, but the form of the relation remains unchanged except for the revision of the unit of distance. The relation is

$$\text{Vel.} = \frac{\text{Dist. (parsecs)}}{1790},$$

and the uncertainty is estimated to be of the order of 10 per cent.

$$v = H_0 D$$

$H_0 = 560$ km s^{-1} Mpc^{-1} $\pm$ 10%

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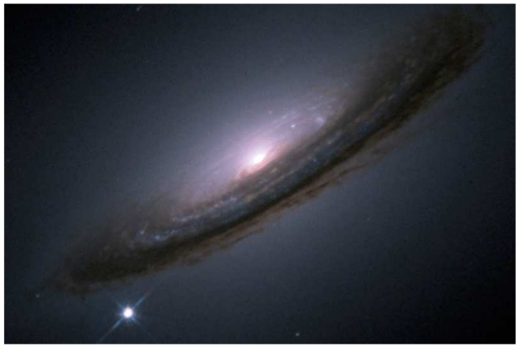
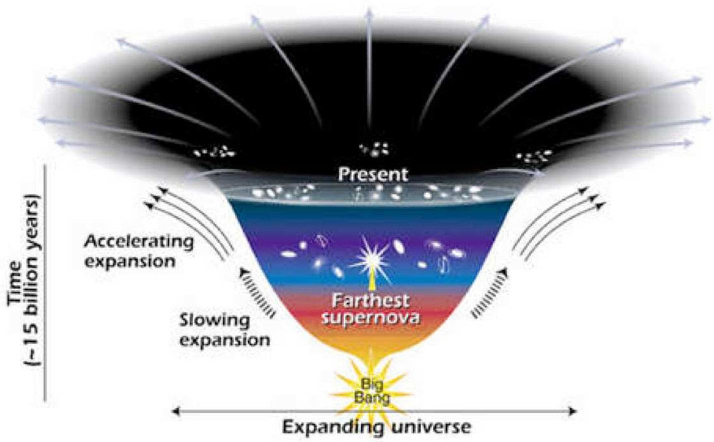
2. The expansion is accelerating
   (Riess et al. 1998; Perlmutter et al. 1999)





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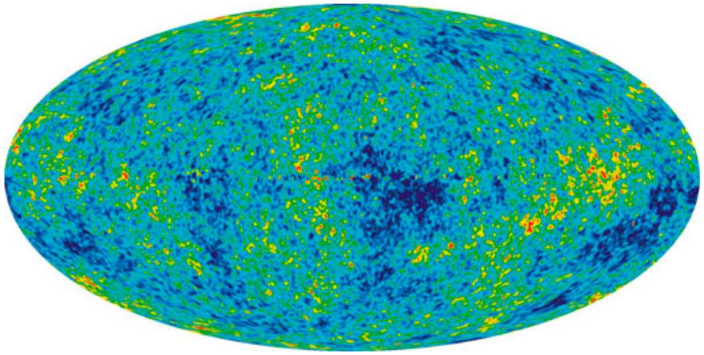
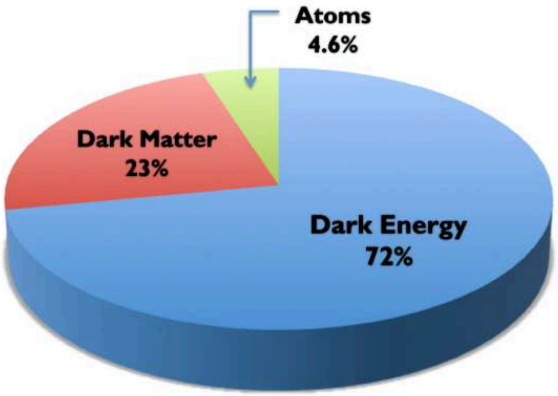
Three Observations that Shaped Our Understanding of the Universe

1. The Universe is expanding
   (Hubble and Humason, 1931)

2. The expansion is accelerating
   (Riess et al. 1998; Perlmutter et al. 1999)

3. Most of the Universe is made of Dark Matter and Dark Energy
   (e.g. WMAP, Planck)





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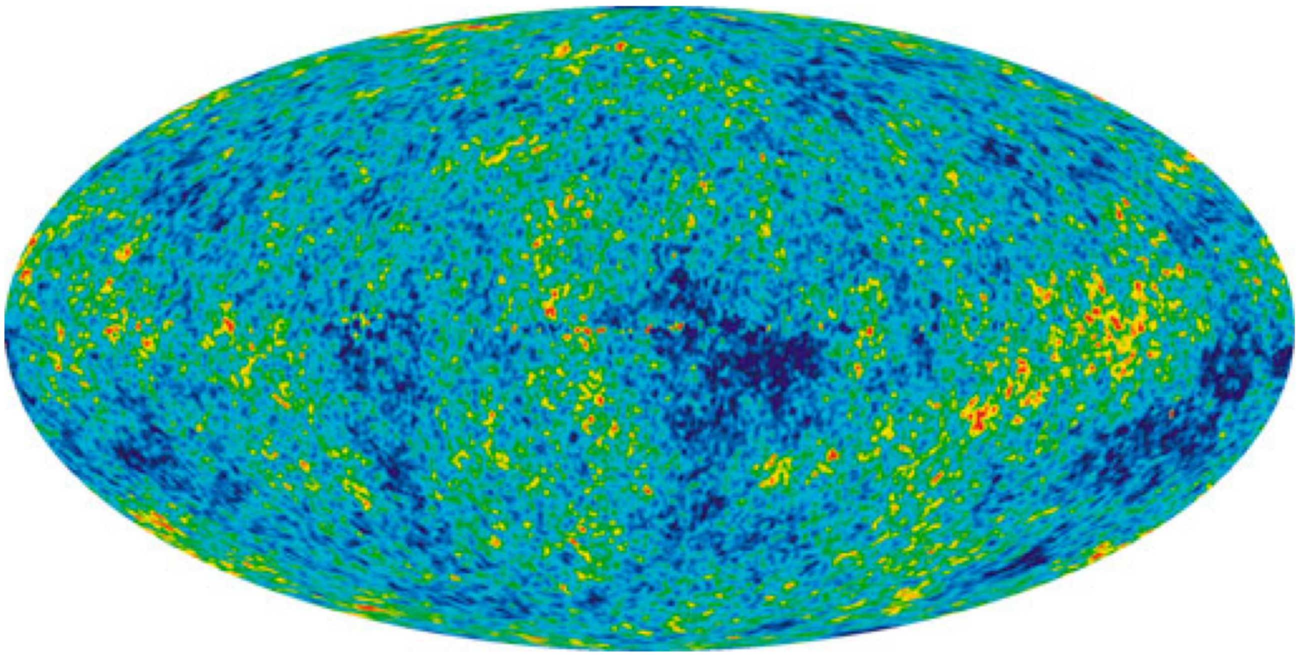
WMAP and Planck Map the CMB

In standard cosmology with a cosmological constant in a geometrically flat universe, Planck *predicts* H_0 = 67.27 +/- 0.60 km s^{-1} Mpc^{-1} (Planck 2018)



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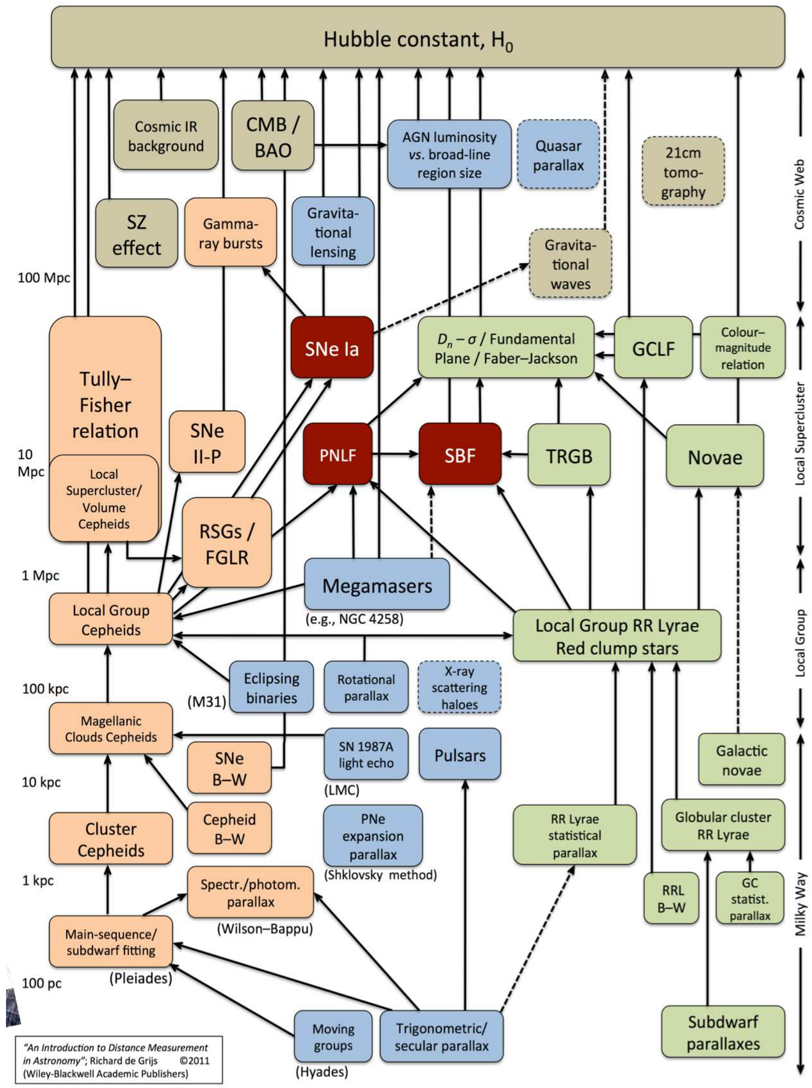
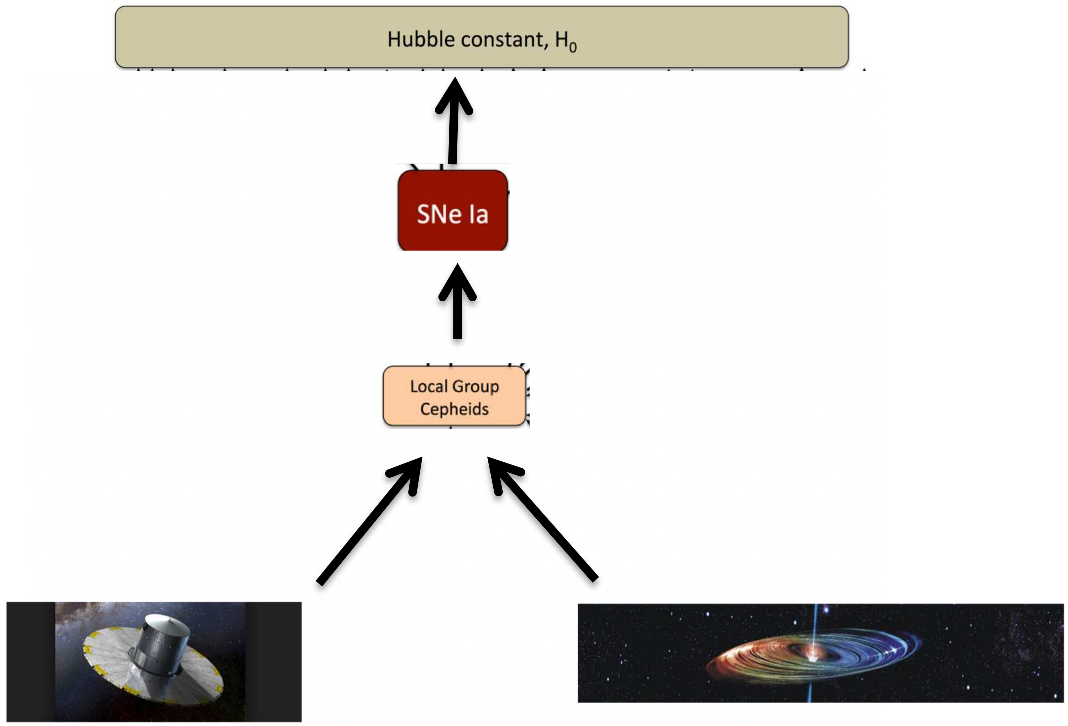
The Distance Ladder is Complex!



Courtesy Richard de Grijs

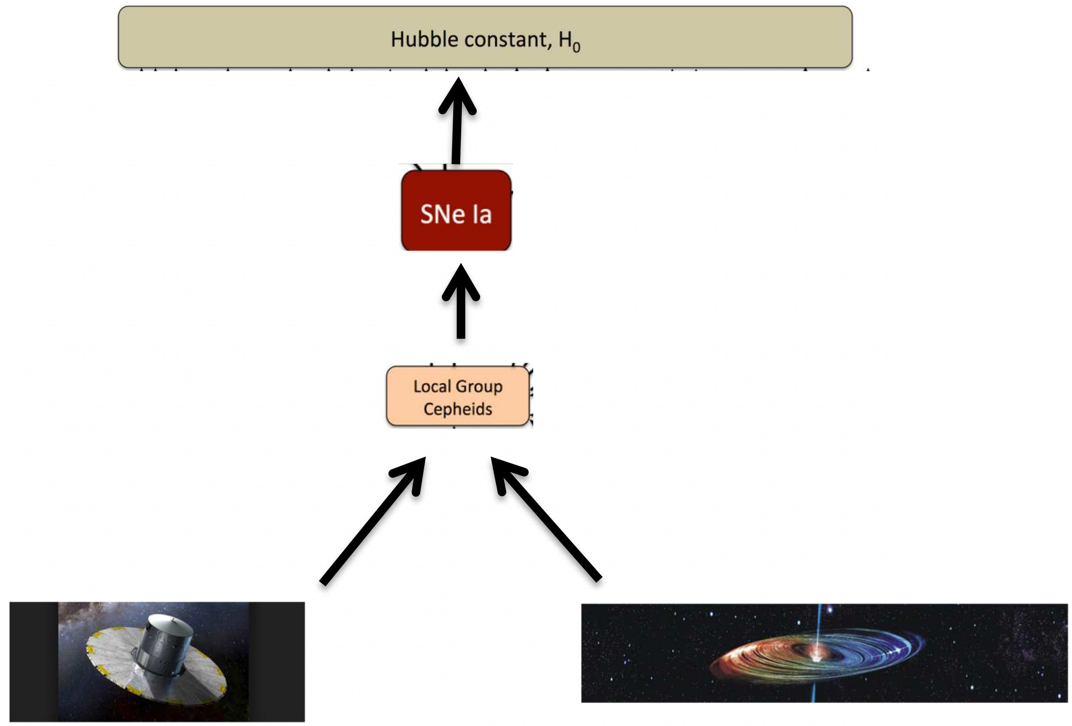
A Simpler Ladder is Better



Galactic parallaxes

NGC 4258 maser

A Simpler Ladder is Better



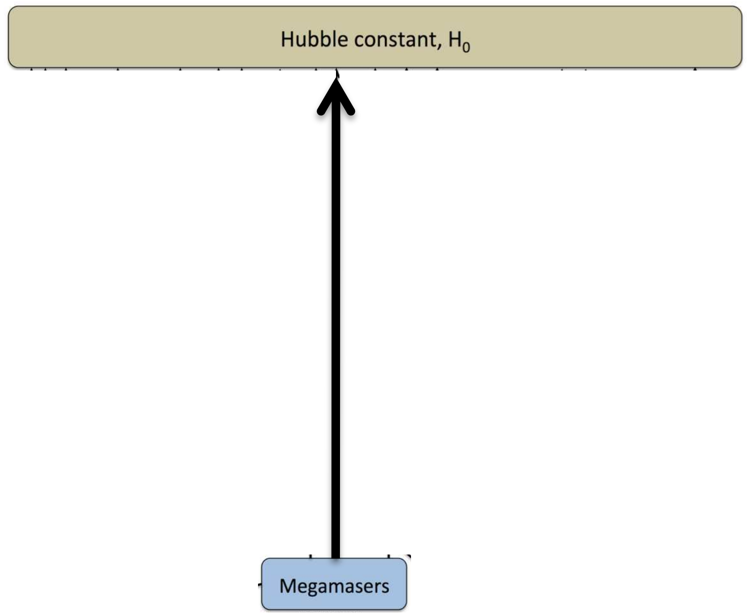
Galactic parallaxes

NGC 4258 maser

H_0 = 73.52 +/- 1.62 km s^{-1} Mpc^{-1}

(Riess et al. 2018)

But the Megamaser Method is One Step

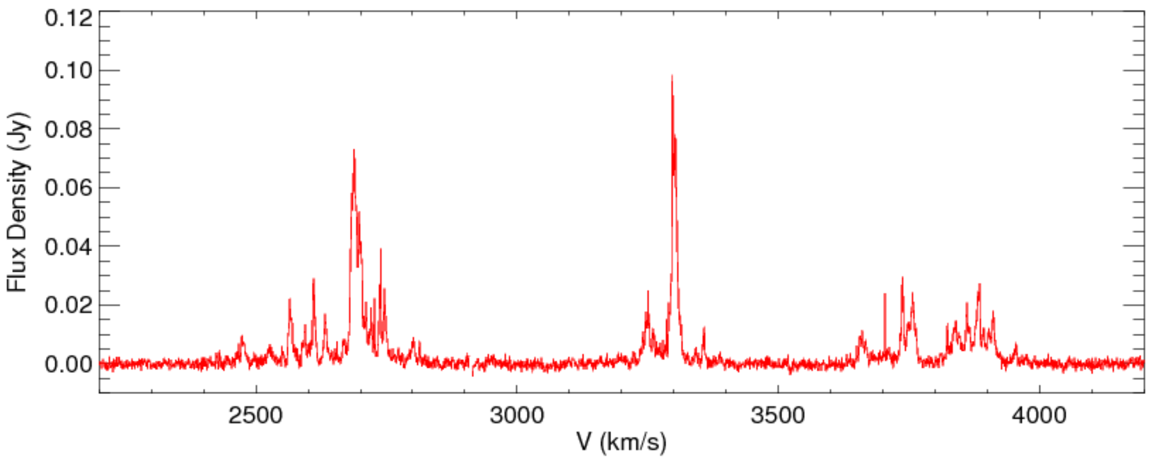


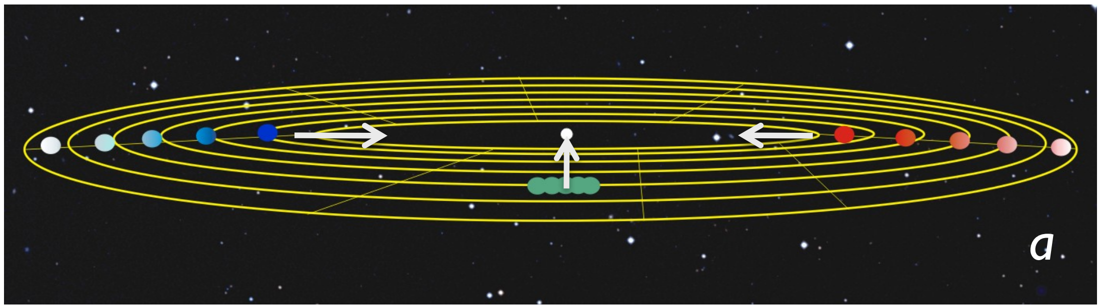
A Conceptual View of a Disk Megamaser

$$D = \frac{r}{\vartheta}$$

$$a = \frac{V_r^2}{r}$$

$$D = \frac{V_r^2}{a\vartheta}$$





Direct Geometric Measurement of H_0 with Megamasers

The Megamaser Cosmology Project has the goal of determining H_0 by measuring *geometric distances* to galaxies in the Hubble flow.

1. Survey with the GBT to identify maser disk galaxies
2. Image the sub-pc disks with the High Sensitivity Array (VLBA+GBT+EB+VLA)
3. Measure accelerations in the disk with GBT monitoring
4. Model the maser disk dynamics and determine distance to the host galaxy

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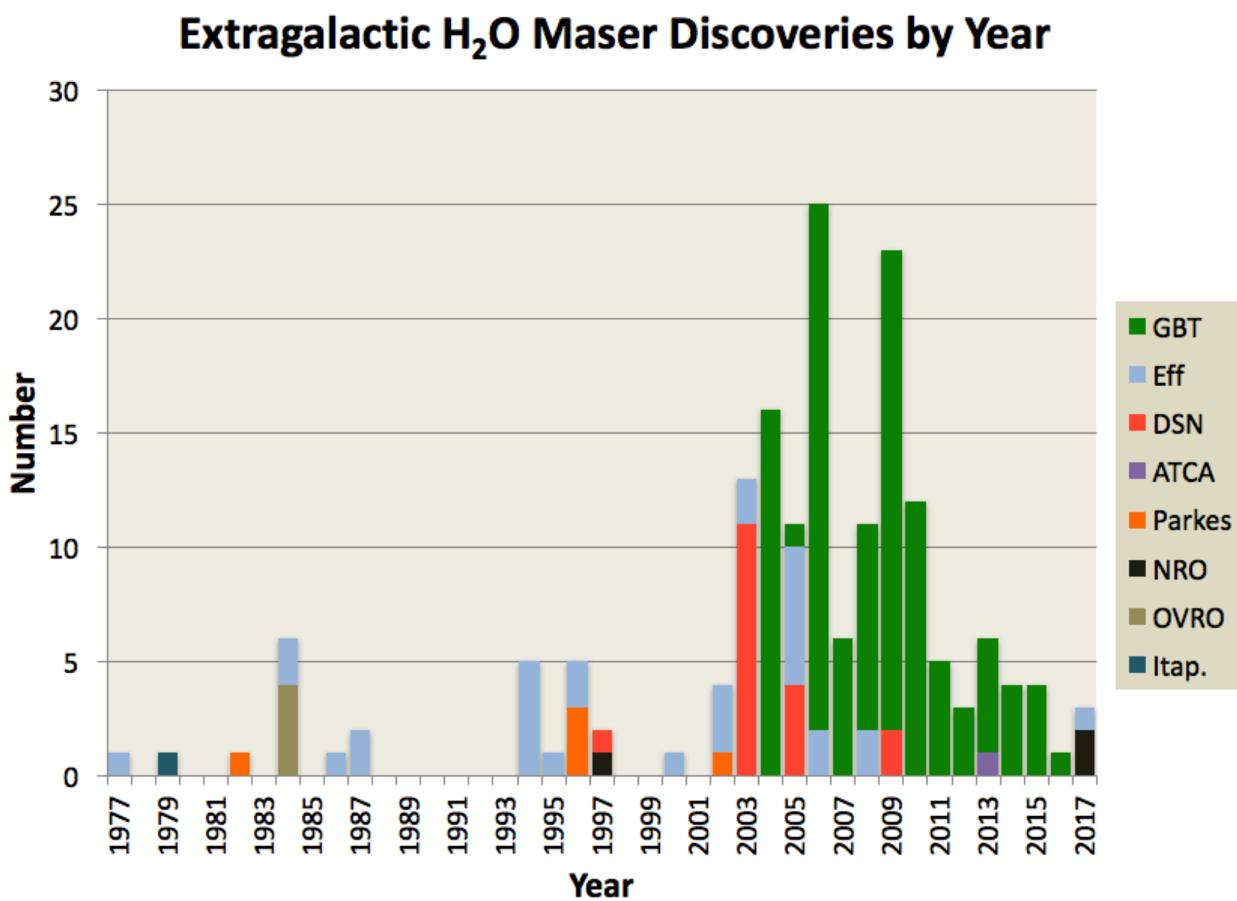
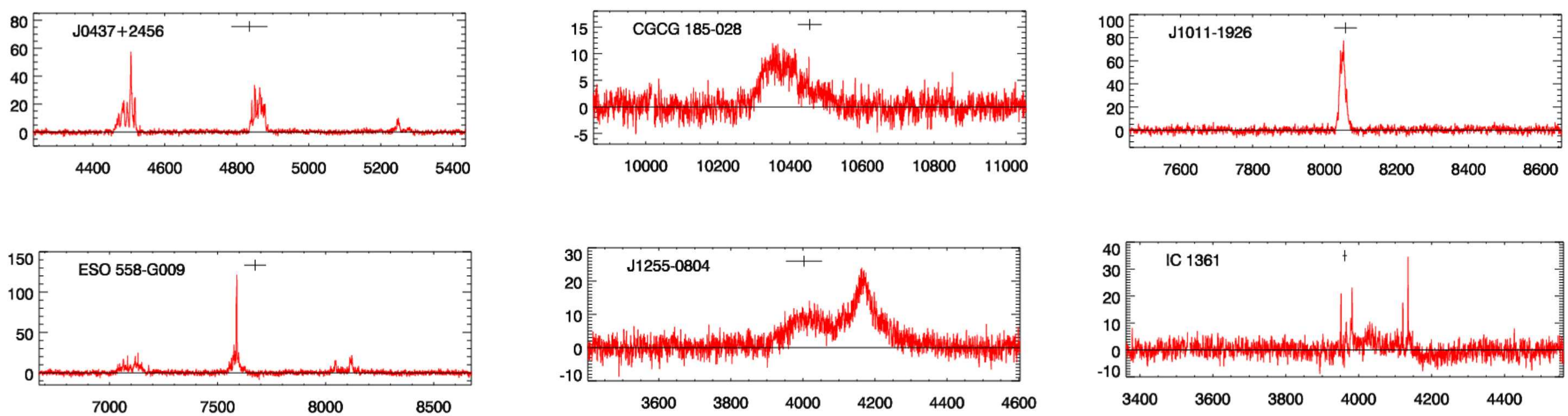
Progress with Megamaser Surveys



- 180 galaxies detected out of > 3000 observed
- 37 show spectra indicative of a disk and are suitable for M_{BH} measurement
- 10 suitable for distance measurement
- Primary sample for MCP surveys: Type 2 AGNs at $z < 0.05$

Spectral Classification of AGN Megamasers

Currently ~160 known 22 GHz Megamasers in AGN



Clean Disk

~ 30%

Broad-profile (jet?)

~ 3%

Others/Unknown

~ 67%

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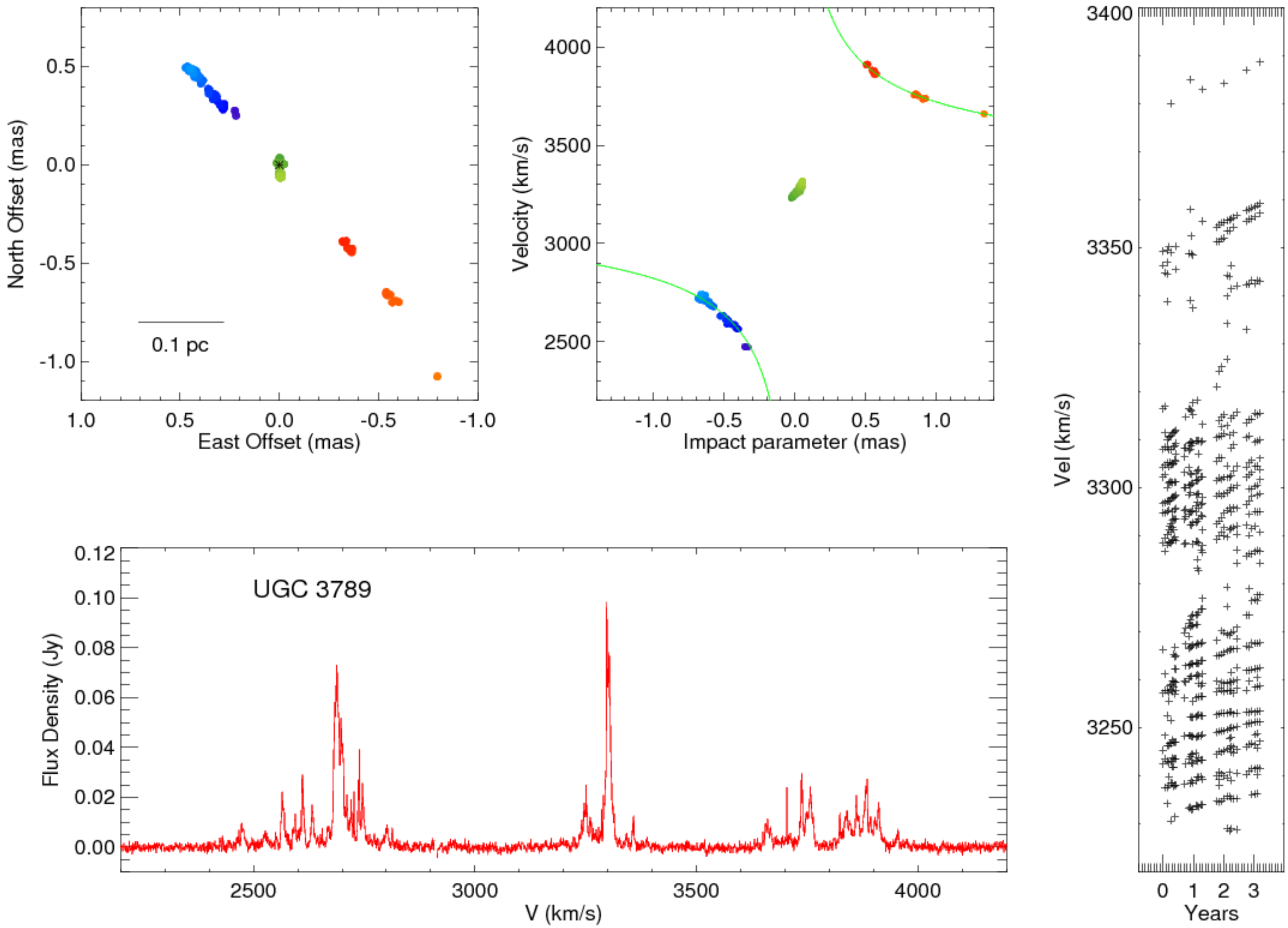
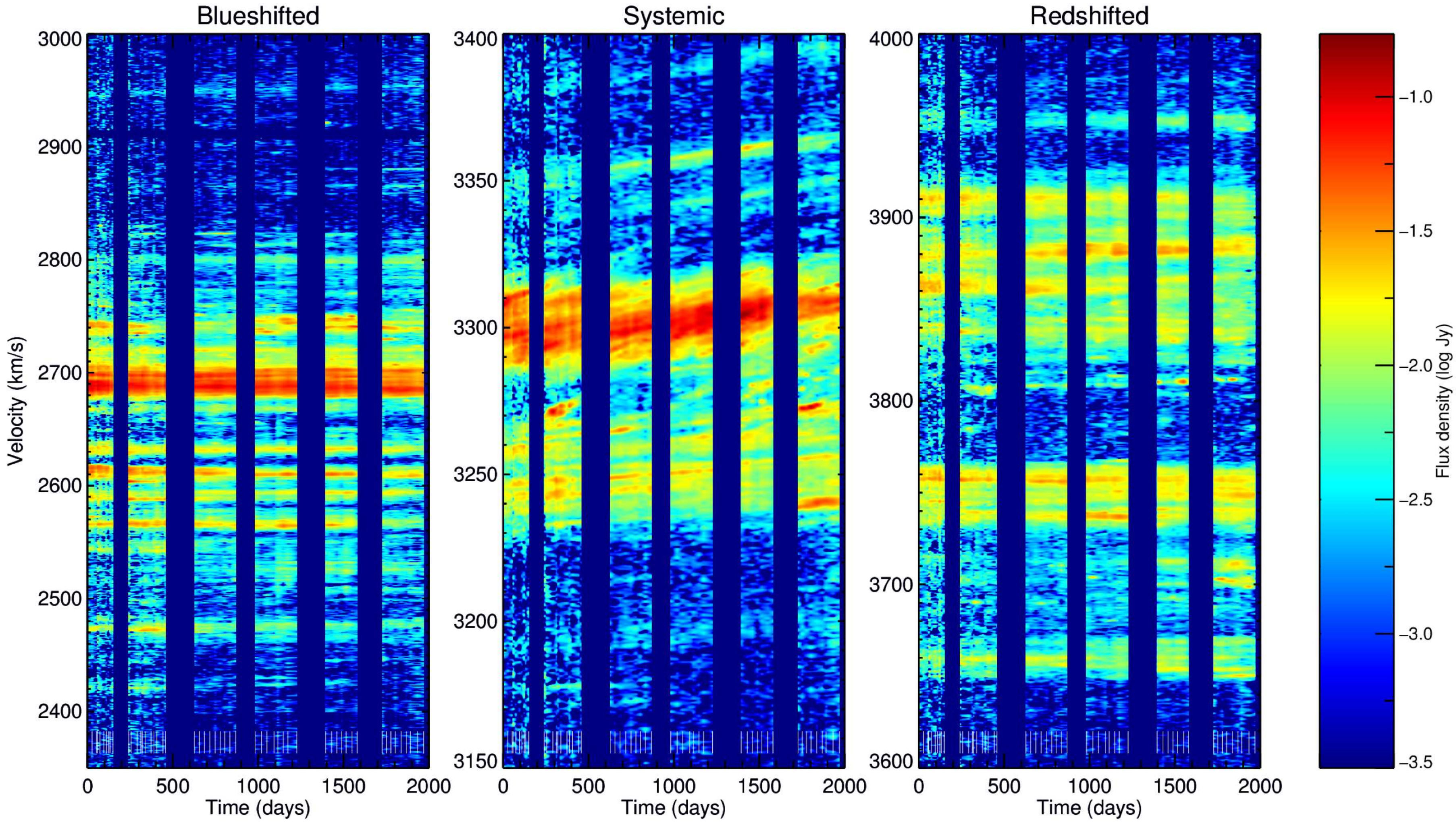
UGC 3789

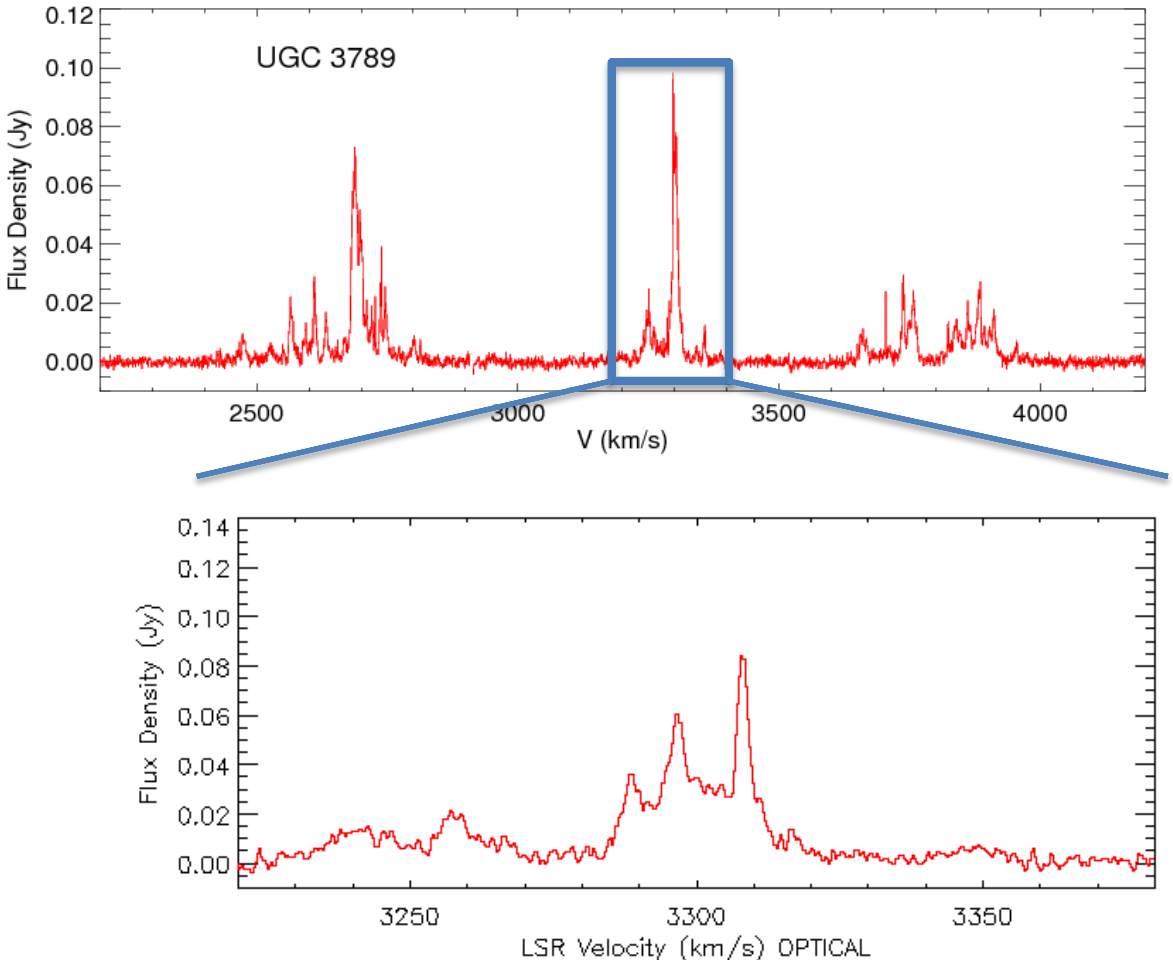

0.5
0.0
-0.5
-1.0
North Offset (mas)
0.1 pc
1.0
0.5
0.0
-0.5
-1.0
East Offset (mas)
4000
3500
3000
2500
Velocity (km/s)
-1.0
-0.5
0.0
0.5
1.0
Impact parameter (mas)
3400
3350
3300
3250
Vel (km/s)
0
1
2
3
Years
UGC 3789
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Flux Density (Jy)
2500
3000
3500
4000
V (km/s)

UGC 3789 dynamic spectra



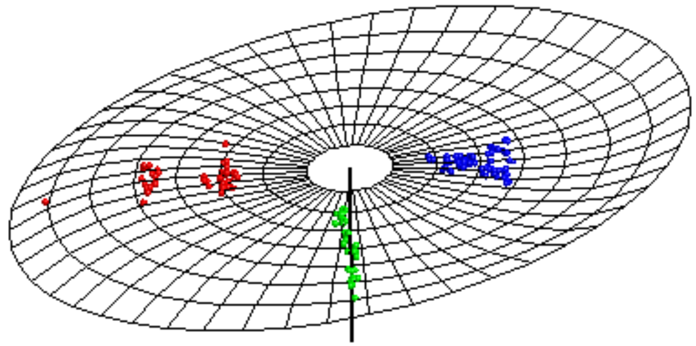
Pesce et al. 2015

UGC 3789: Systemic Features

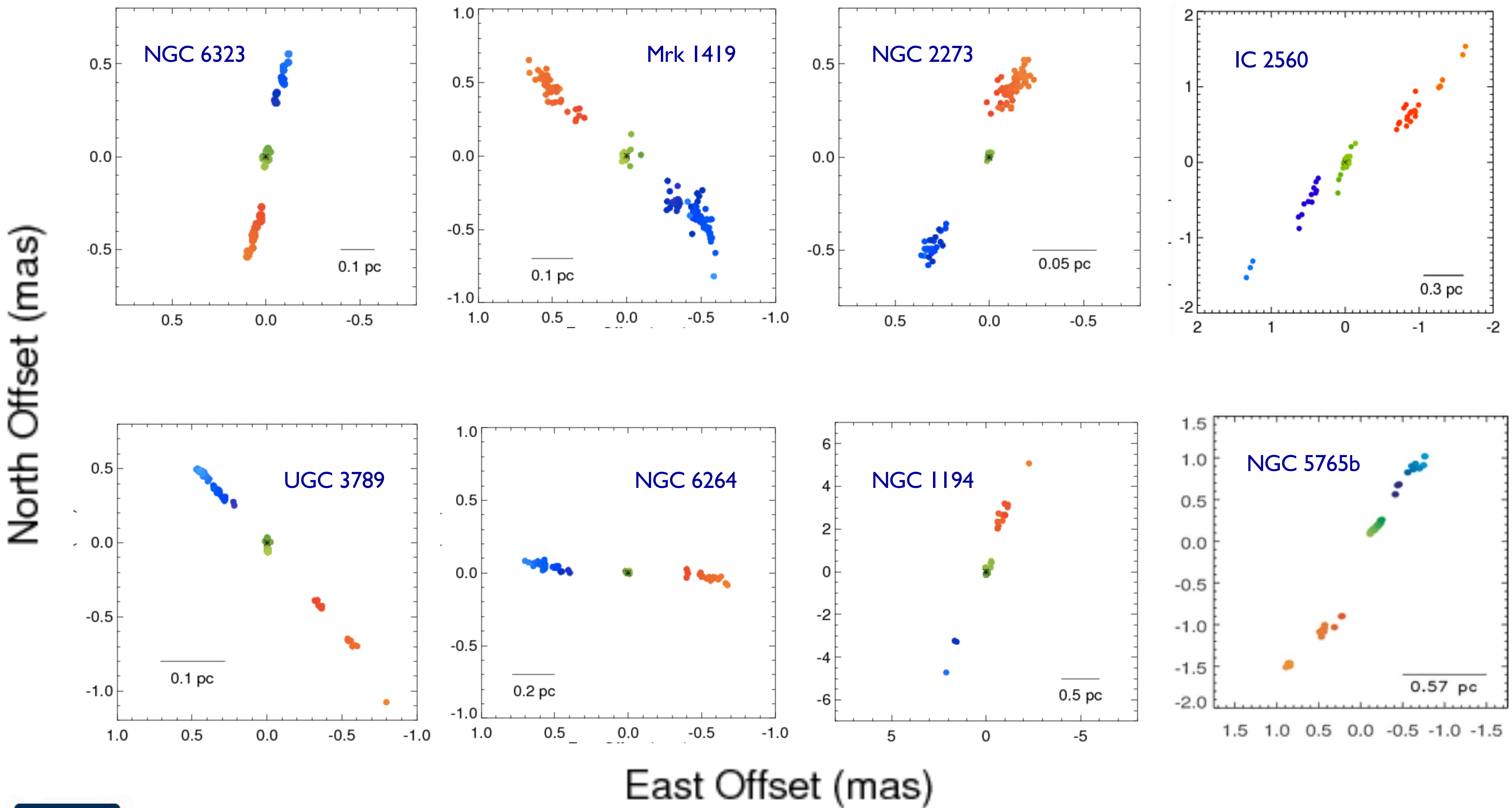


MCMC Estimation of the H_0 PDF

- Fit a warped disk model, marginalize over global parameters incliuding v_{sys}, M_{BH}, dynamical center, and warp
- Inputs: (x, y, v_{LOS}, a_{LOS}) for each maser spot
- Provide V_{pec} and fit H_0 directly
- For UGC 3789:
  - D = 49.6 $\pm$ 5.1 Mpc
  - H_0 = 76 $\pm$ 8 (Reid et al. 2013; Braatz et al. 2018)



H_2O Megamaser Disks



H_0 from Direct Geometric Distances to Megamasers

$H_0 = 69.9 \pm 3.8$ km s^{-1} Mpc^{-1} (5%)

UGC 3789	49.6 ± 5.1 Mpc	$H_0 = 76 \pm 8$	(Reid et al. 2013) updated
NGC 6264	137 ± 19 Mpc	$H_0 = 68 \pm 9$	(Kuo et al. 2013)
NGC 6323	107 ± 42 Mpc	$H_0 = 73 \pm 26$	(Kuo et al. 2015)
NGC 5765b	126 ± 11 Mpc	$H_0 = 66 \pm 6$	(Gao et al. 2016)
CGCG 074-064	94 ± 13 Mpc	$H_0 = 73 \pm 10$	(Pesce et al. 2018) prelim

With final analysis of four additional maser disk galaxies, we expect to improve the measurement to ~ 4% within a year

The Challenge of Imaging Distant Disks

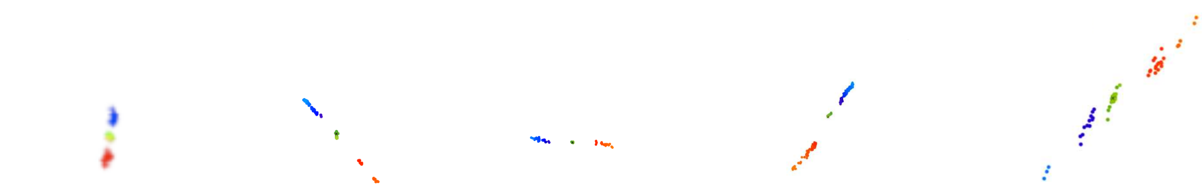
NGC 4258 (D = 7.5 Mpc)

Beam ≈ 0.3 mas x 1 mas

$\Delta\theta = 0.5*\theta_{beam}/(S/N)$

The Challenge of Imaging Distant Disks

NGC 4258 (D = 7.5 Mpc)



NGC 6323 | UGC 3789 | NGC 6264 | NGC 5765b | IC 2560

Beam ≈ 0.3 mas x 1 mas

$\Delta\theta = 0.5*\theta_{beam}/(S/N)$

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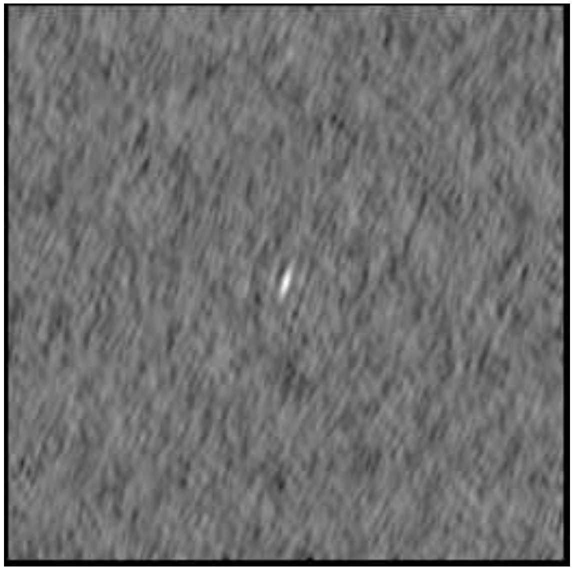
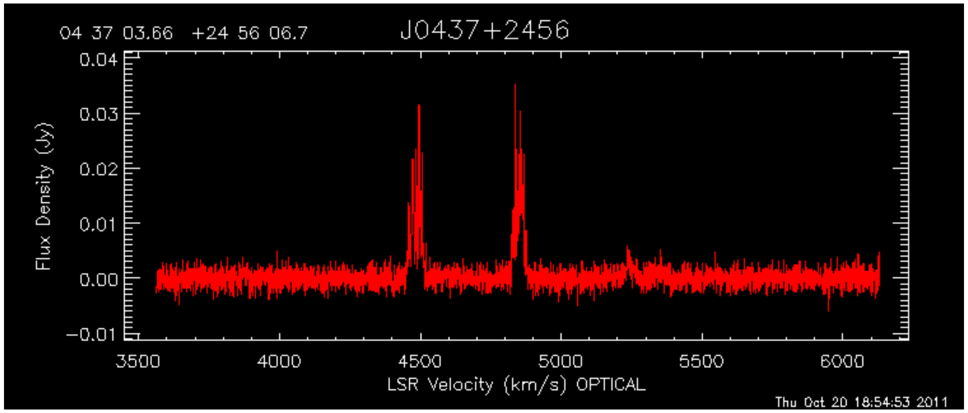
Measuring M_{BH} is Relatively Easy!

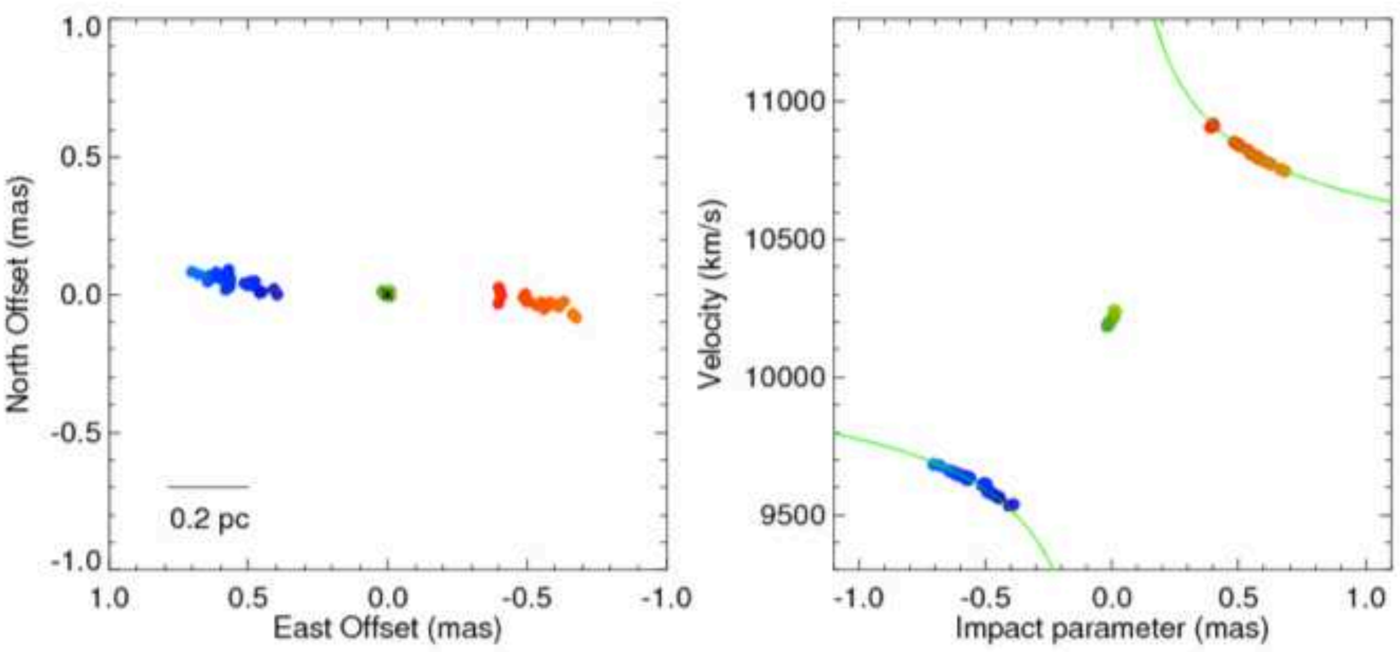


R = 0.07 pc
V = 343 km s^{-1}

M_{BH} = 1.9 x 10^6 M_{sun}



Measuring BH masses



- $\rho(R) \sim (0.1 - 60) \times 10^{10}\ M_{sun}/pc^3 \gg \rho(\text{stars + dark halo})$
- high density rules out compact cluster of stars or star remnants, based on stability time scale < 1 Gyr

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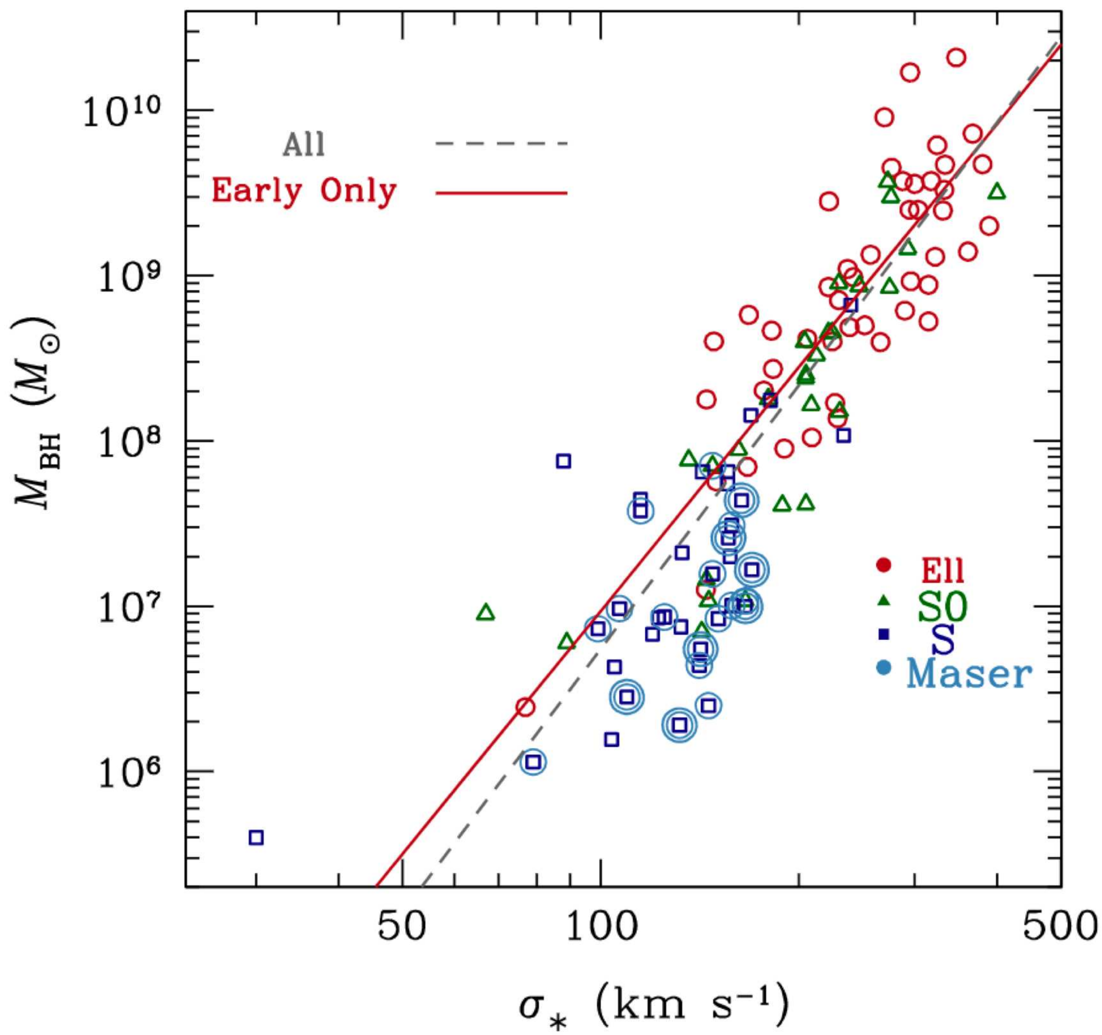
SMBH measurements: Galaxy scaling relations

Maser disk galaxies do not match the M-sigma correlation determined by massive ellipticals, nor low-mass spirals

Greene et al. 2016



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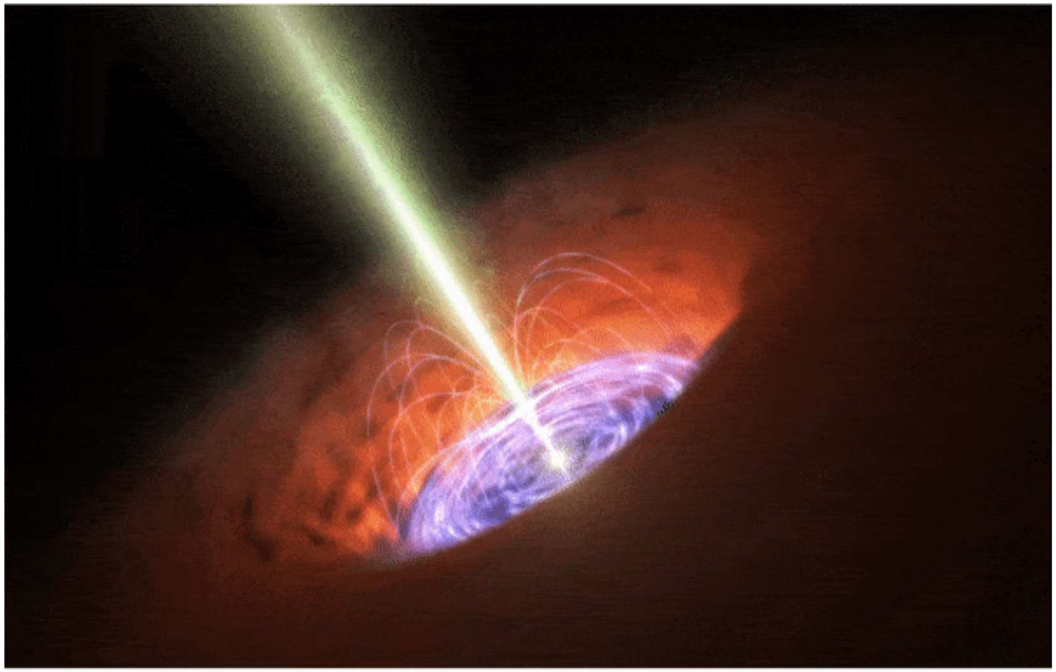
How is the thin maser disk related to the optically and geometrically thick obscuring region in AGN nuclei?



TORUS 2018: The Many Faces of AGN obscuration

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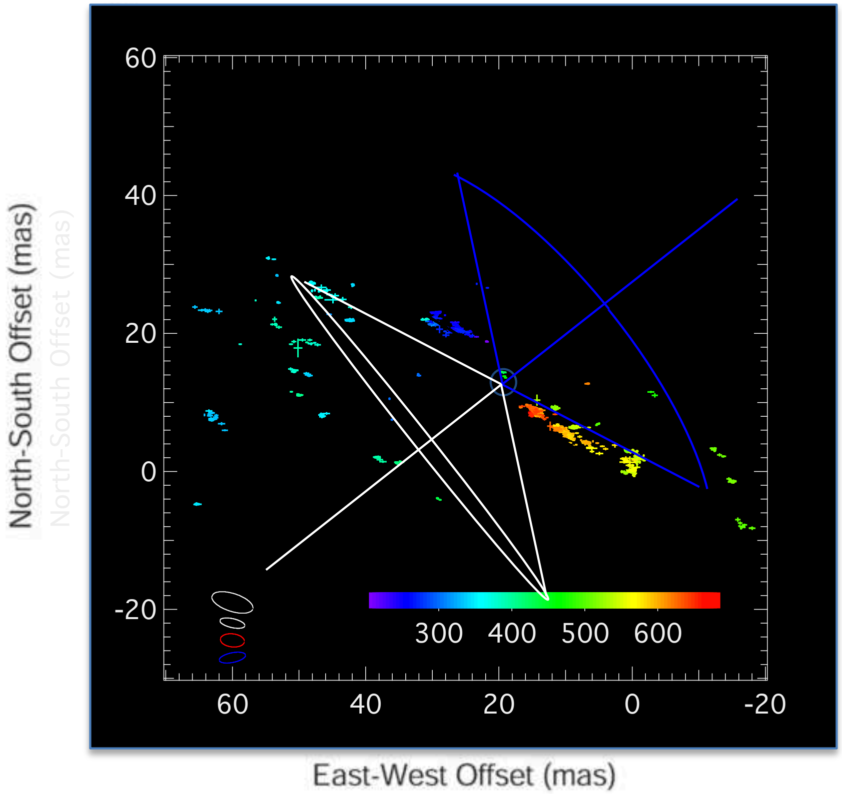
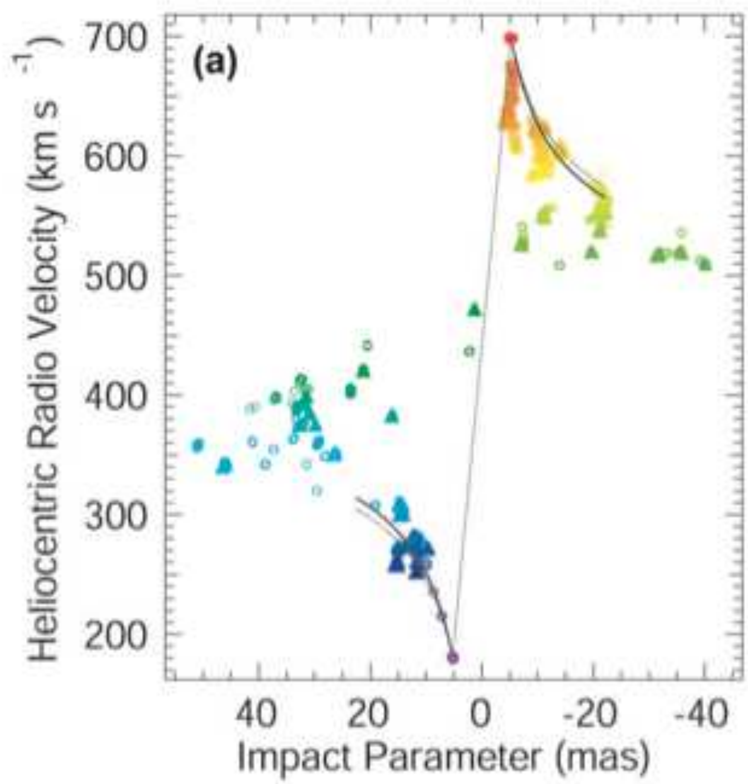
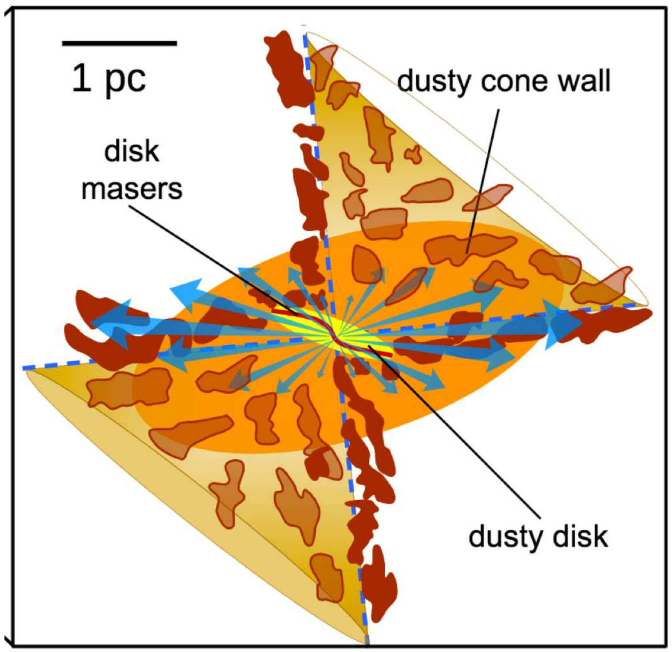
The Water Megamaser in Circinus



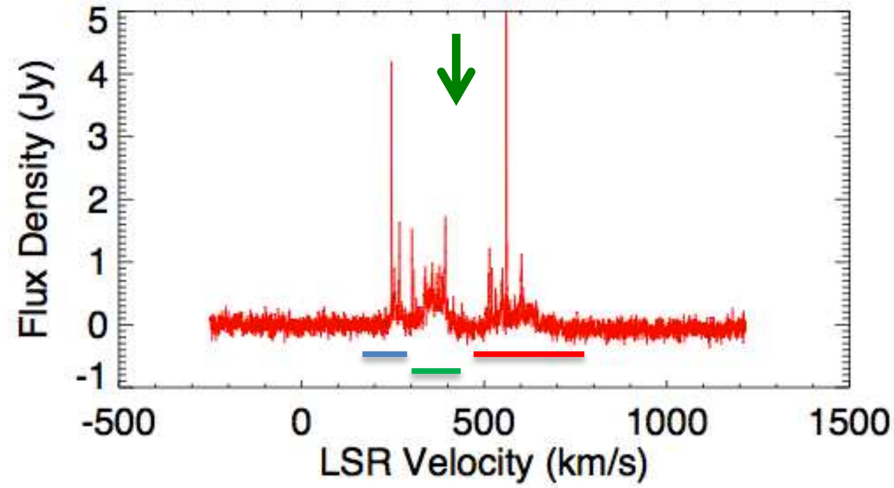


- VLBI imaging shows a disk+outflow (Greenhill et al. 2003)
- Enclosed mass = 1.7 x 10^6 M_{sun}
- Disk diameter ~ 1 pc

The Water Megamaser in Circinus

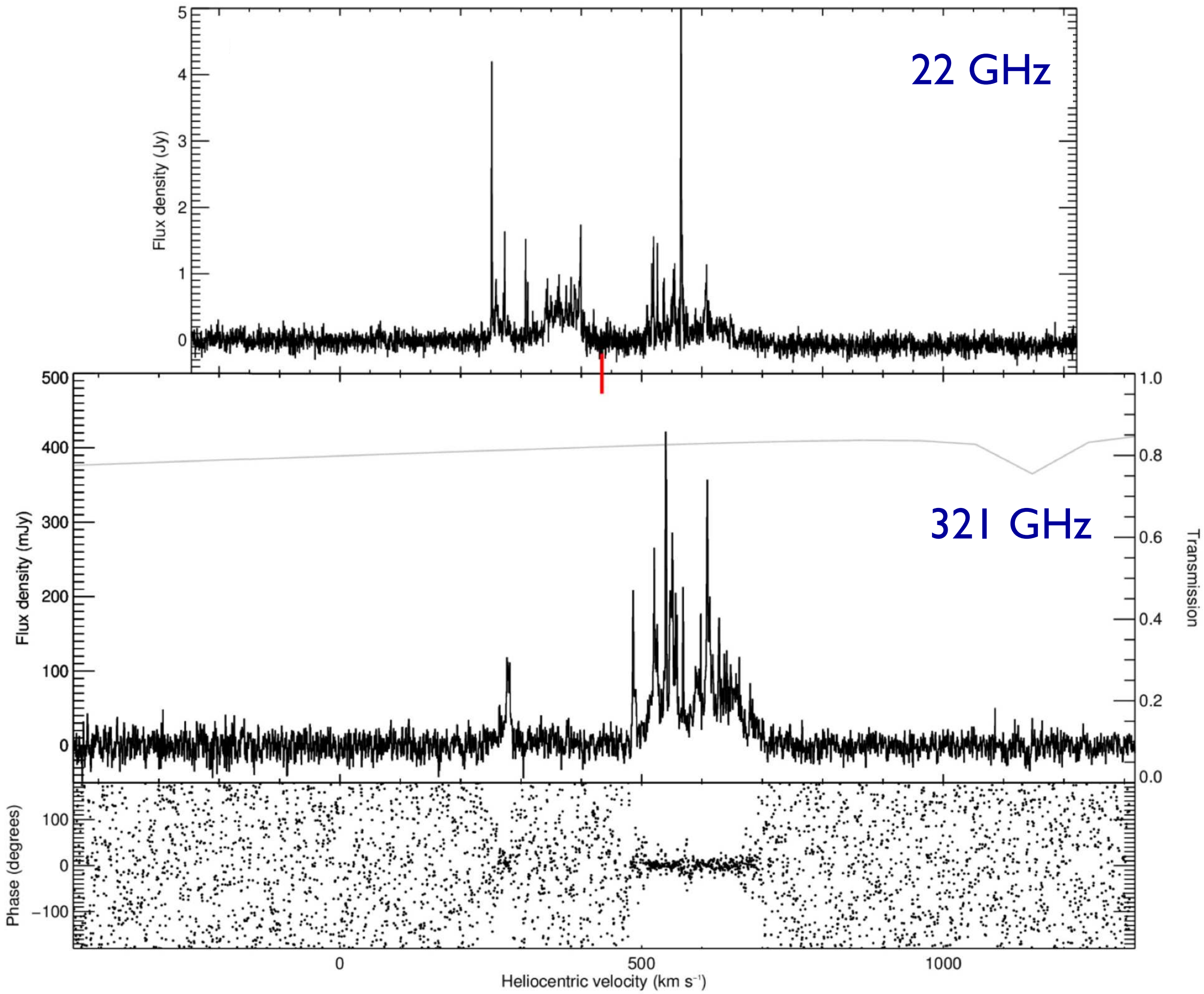


Stalevski et al. 2017



The megamaser system contains both a warped disk and an outflow component

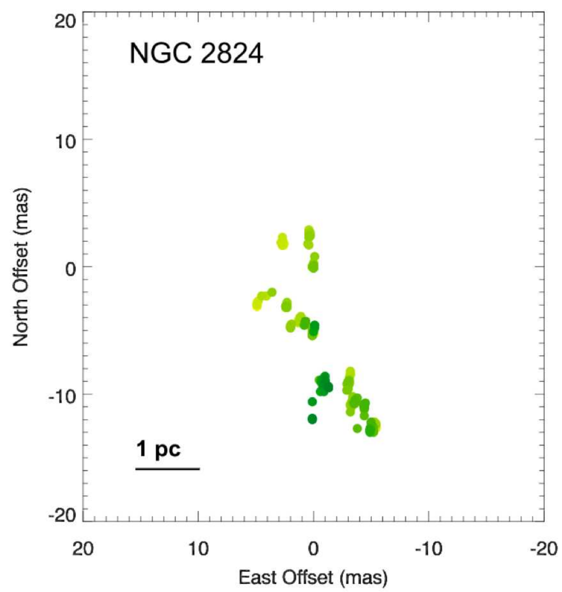
Submm megamasers in Circinus

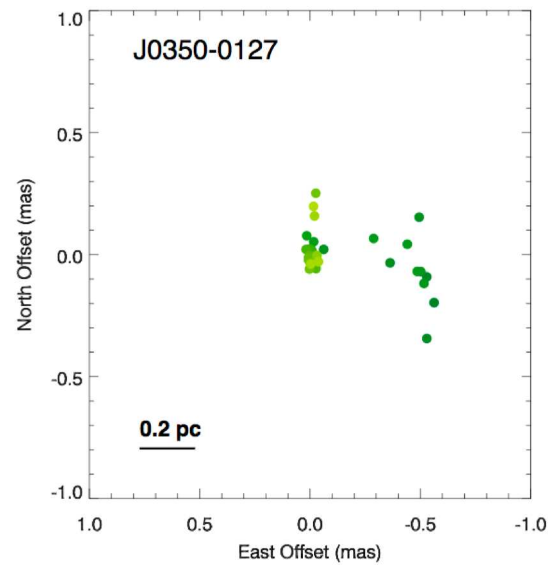


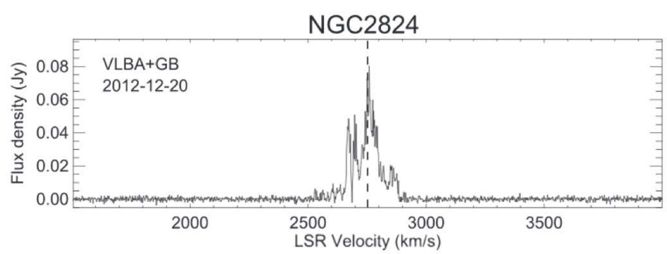
Hagiwara et al. 2013; Pesce et al. 2016

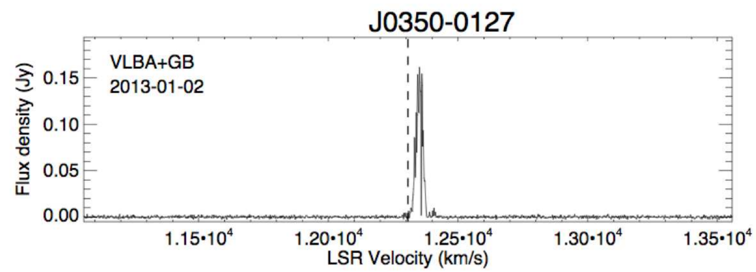
VLBI maps of non-disk systems

Zhao et al. 2018









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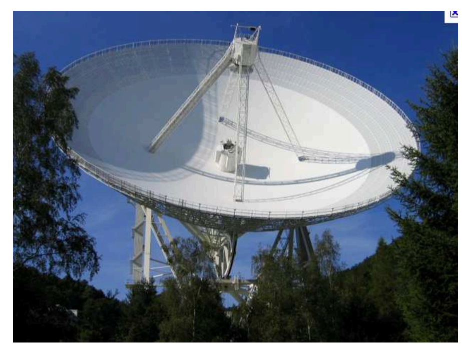
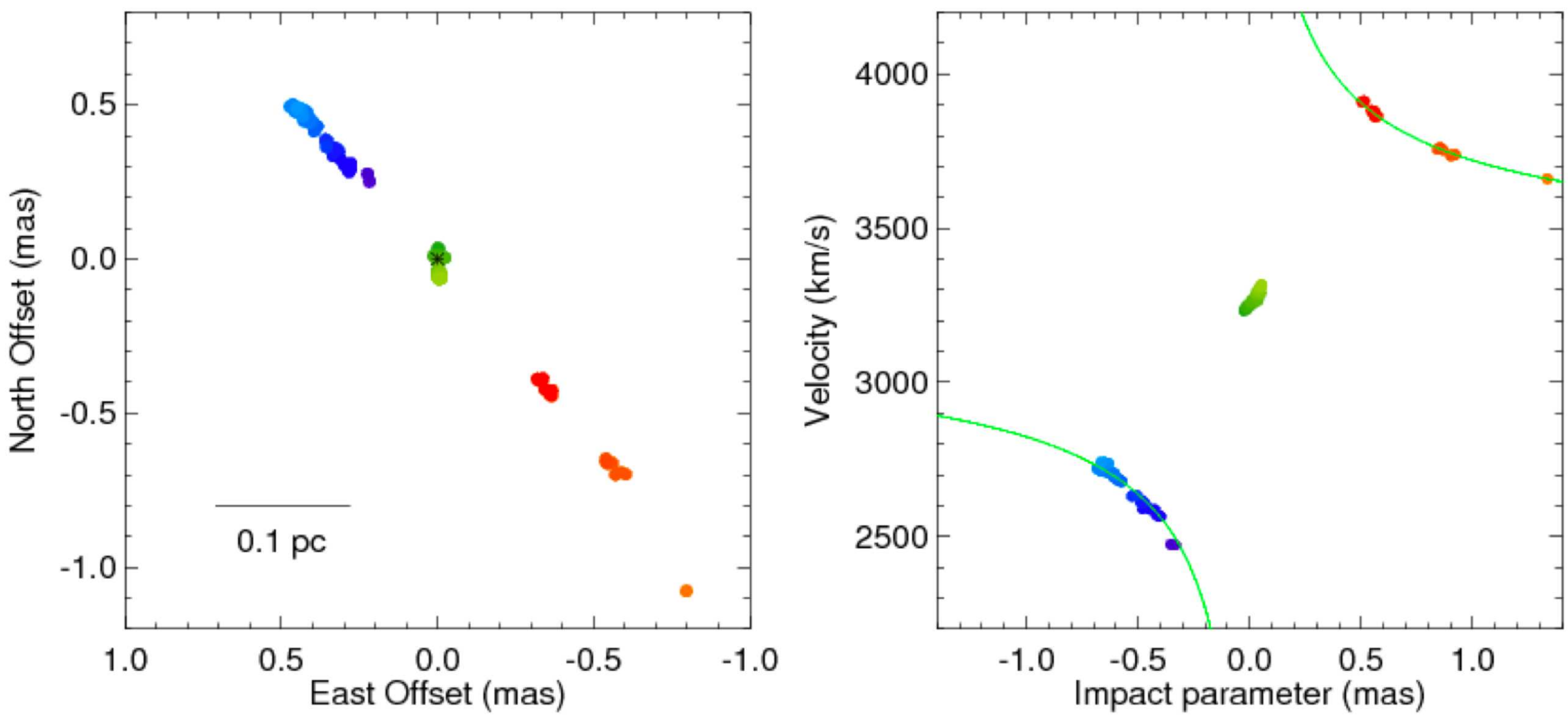


Megamasers provide precise recession velocities of the SMBH



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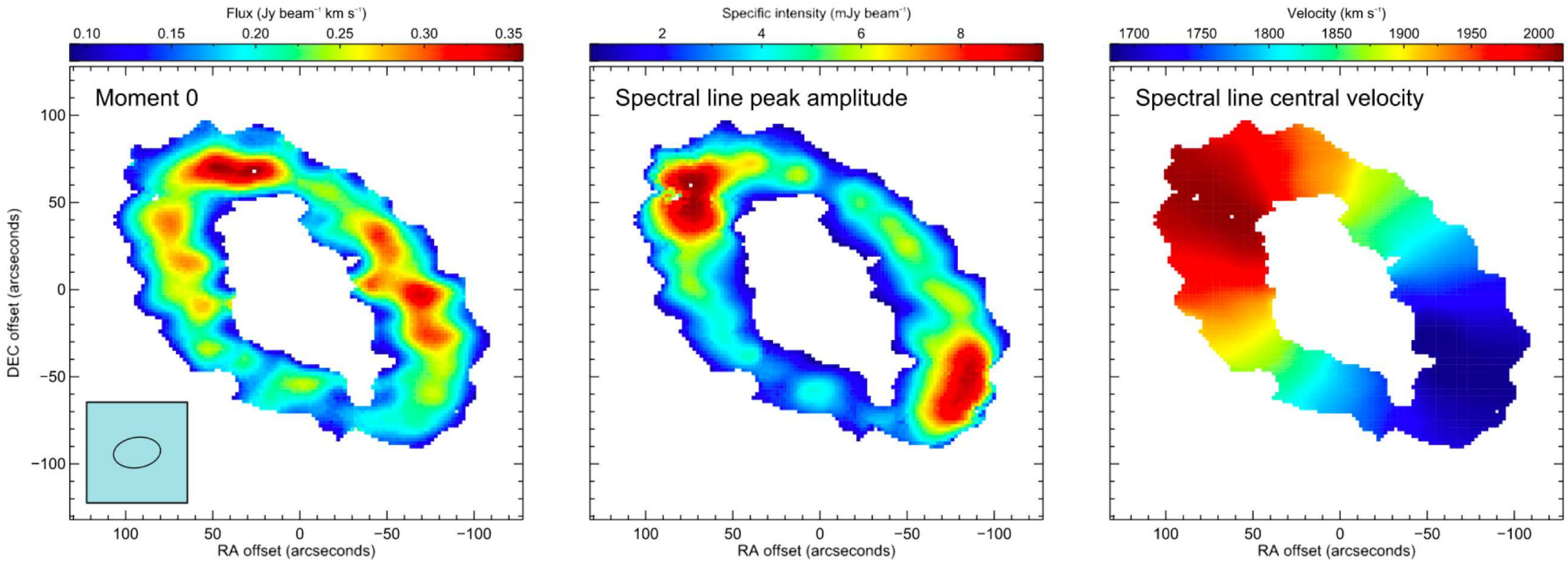
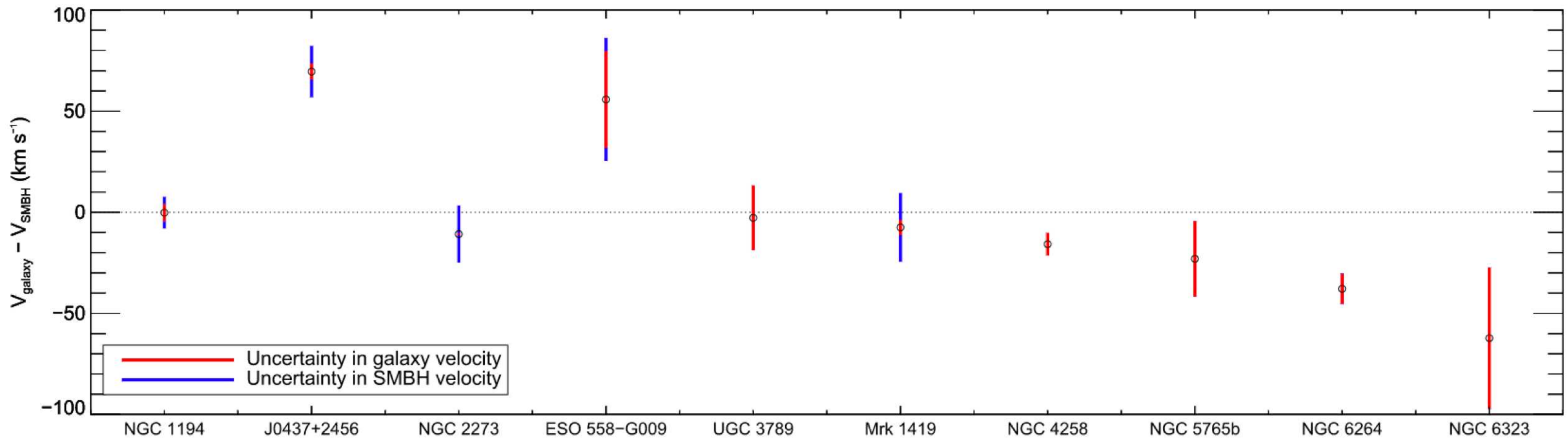
VLA HI Maps to determine Galaxy Recession Velocity

NGC 2273



Pesce et al. 2018

Detecting Kinematically Offset SMBH



Maser systems determine ~ 1 km/s LOS velocities for SMBH. Compare to host galaxy velocities to detect peculiar motion. (Pesce et al. 2018)

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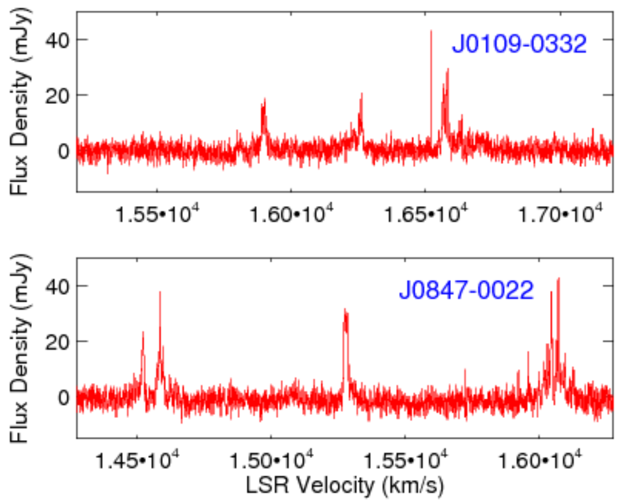
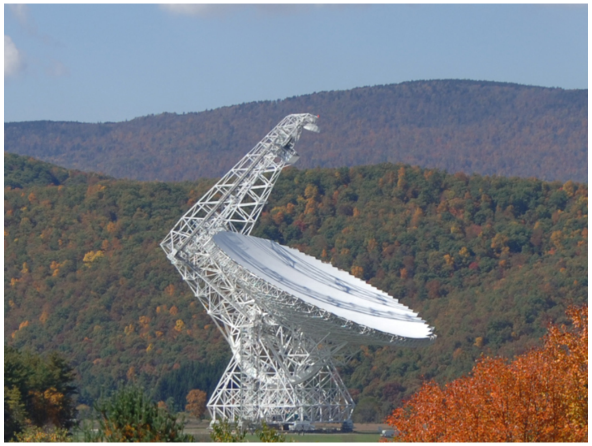
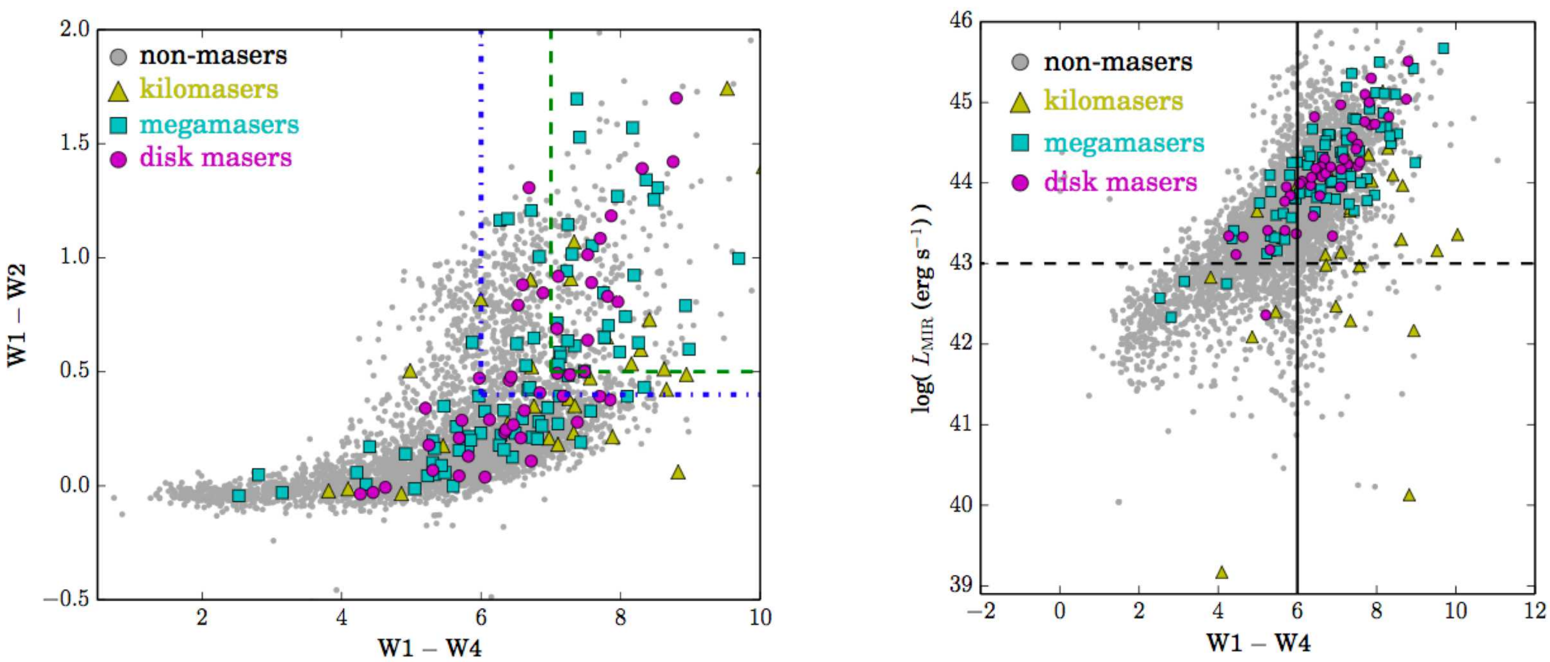
Future Megamaser Surveys

- Candidate lists are mainly AGNs
- MCP has focused on narrow-line AGN identified through optical emission lines
- Other large surveys have focused on ULIRGs, early types, disturbed, and Sy 1
- Significant efforts are being made to improve maser detection efficiency





Improving the Measurement of H_0 with Megamasers: Brute Force Continuation of the MCP



Incorporation of IR colors and luminosities for survey candidate galaxies can improve maser detection rate for disk masers. (Kuo et al. 2018)

A Few Technical Points

- For single dish observations we "nod" 2 beams of the 7-beam KFPA
- On GBT, we use 10 minutes on-source per galaxy for the survey, longer integrations to characterize the spectrum fully
- 22.235 GHz line at z < 0.05 so ν_{sky} ~ 21.0 - 22.2 GHz
- All-sky coverage of potential targets and eady observing mode make maser surveys a good filler program
- Scheduling and weather are critical for K-band …

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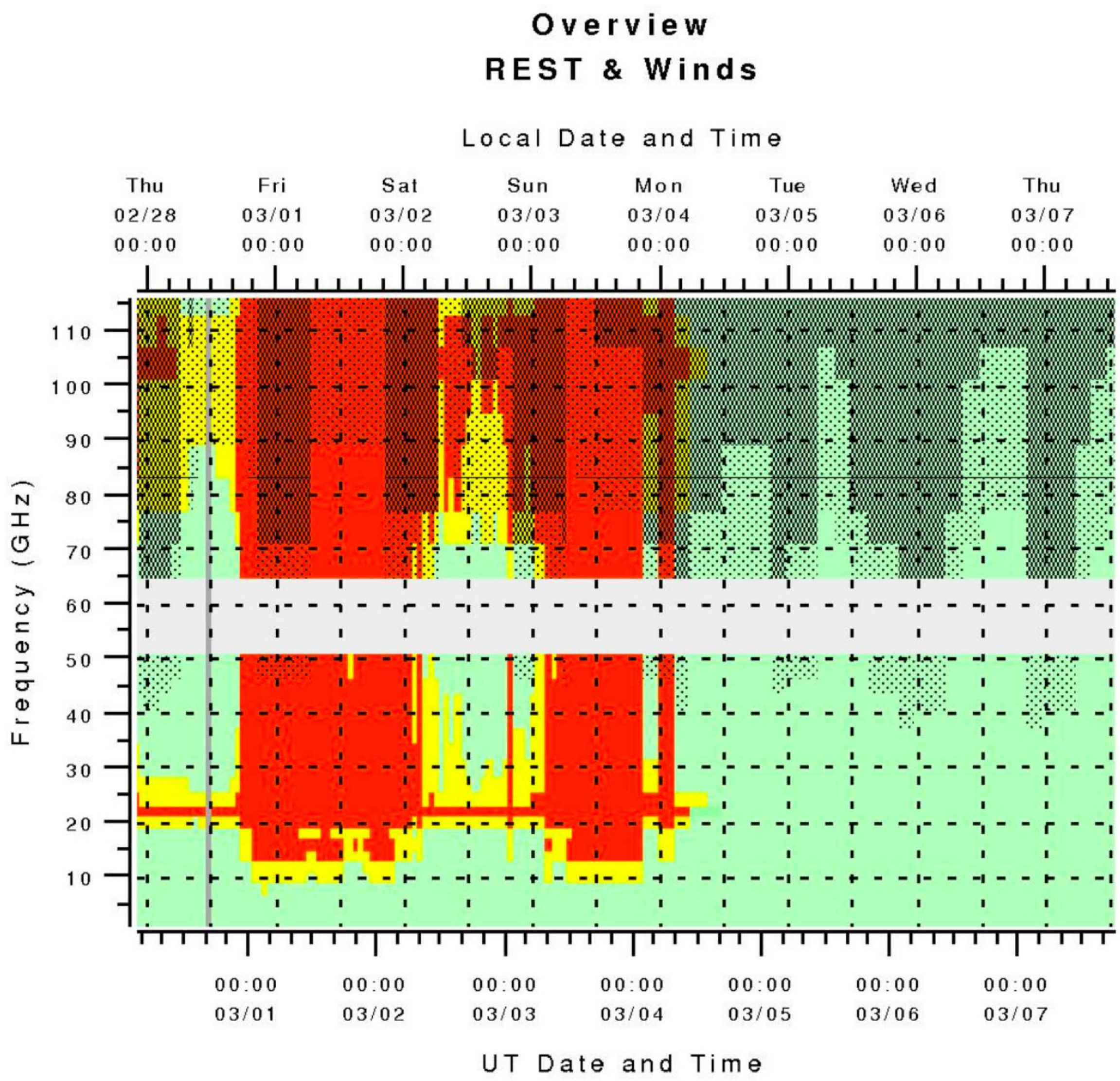
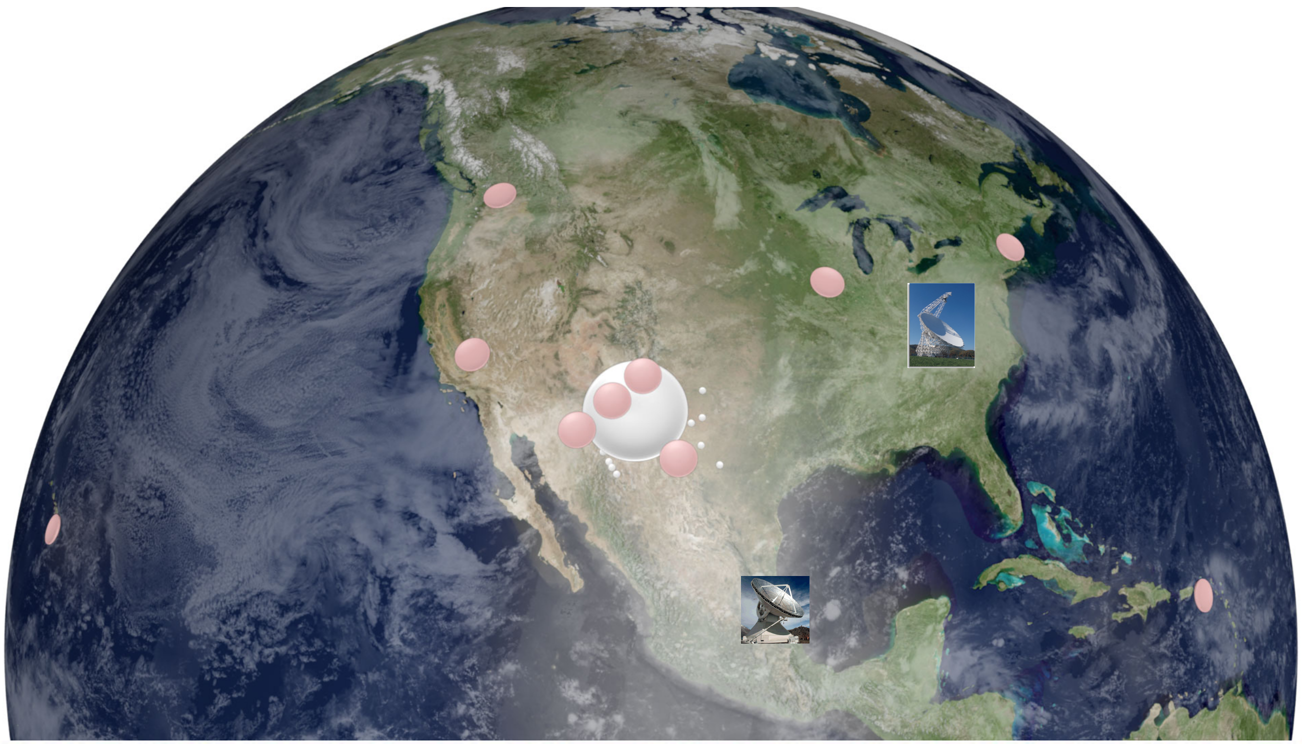
K-band Weather sensitivity



The Future of H_0 with Megamasers: the ngVLA

- 216 x 18m dishes with compact core and outrigger long baselines
- Order of magnitude sensitivity improvement
- Immediate gains by remeasuring known maser disks
- ~1% H_0 could be achieved, e.g., with ~50 distances of ~7% each



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Summary

- Sensitive VLBI of megamaser disks enables significant contributions to cosmology, SMBHs, galactic evolution, and AGN physics.
- $H_0 = 69.9 \pm 3.8$ km s^{-1} Mpc^{-1}(5%). Analysis of additional galaxies will improve the measurement to ~4%.
- One more VLBI antenna can make a big difference.
  - LMT for N-S baselines
  - A southern antenna with long baselines to existing Australian antennas
- A sensitive single-dish telescope could contribute to surveys and monitoring, especially in the south.
- ngVLA will enable geometric, percent-level measurement of H_0 .

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The End