The Megamaser Cosmology Project

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Primary Goals of Megamaser Studies

1. Measure H_0 using *geometric* distances
   - Constrain models of cosmology and Dark Energy, spatial curvature, and neutrino physics

2. Measure "gold standard" M_{BH} in external galaxies
   - M_{BH} scaling relations, galaxy evolution

3. Measure the geometry and physical conditions of the accretion disk and gas on sub-pc scales in AGNs







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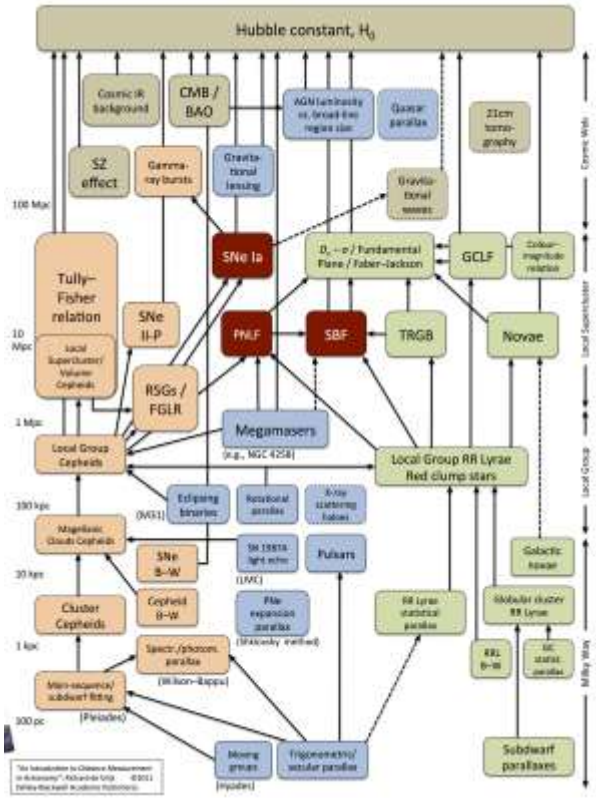
A Prediction and Measurements of H_0



In the base ΛCDM cosmology, Planck *predicts:*

- H_0 = 67.8 +/- 0.9 km s^{-1} Mpc^{-1} (Ade et al. 2015)

Measurements based on standard candles:

- H_0 = 73.24 +/- 1.74 km s^{-1} Mpc^{-1} (Riess et al. 2016)
- H_0 = 74.3 +/- 2.6 km s^{-1} Mpc^{-1} (Freedman et al. 2012)

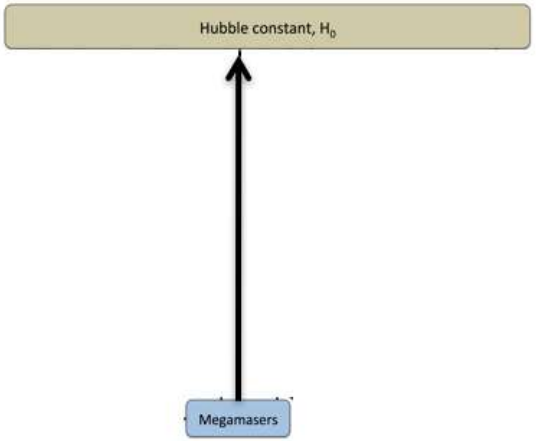
From Gravitational lensing:

- H_0 = 71.9 +2.4/-3.0 km s^{-1} Mpc^{-1} (Bonvin et al. 2017)

From BAO + SN Ia:

- H_0 = 67.3 +/- 1.0 km s^{-1} Mpc^{-1} (Alam et al. 2017)

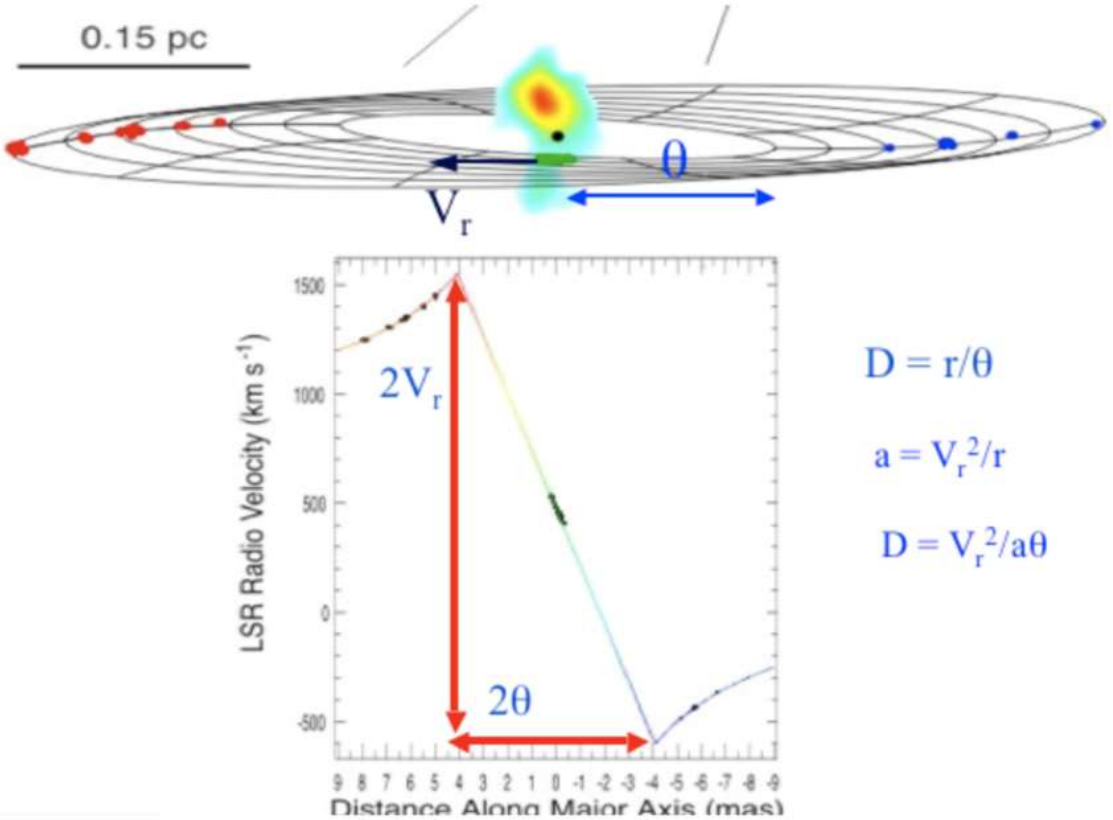
Astrophysical Measurements of H_0



Megamasers:

- Geometric measurement
- H_0 in a single step
- Measurement in a "sweet spot" range of distances where the measurement is not strongly model-dependent

NGC 4258: The Maser Disk Archetype



$D = r/\theta$

$a = V_r^2/r$

$D = V_r^2/a\theta$

Measuring H_0 with the MCP

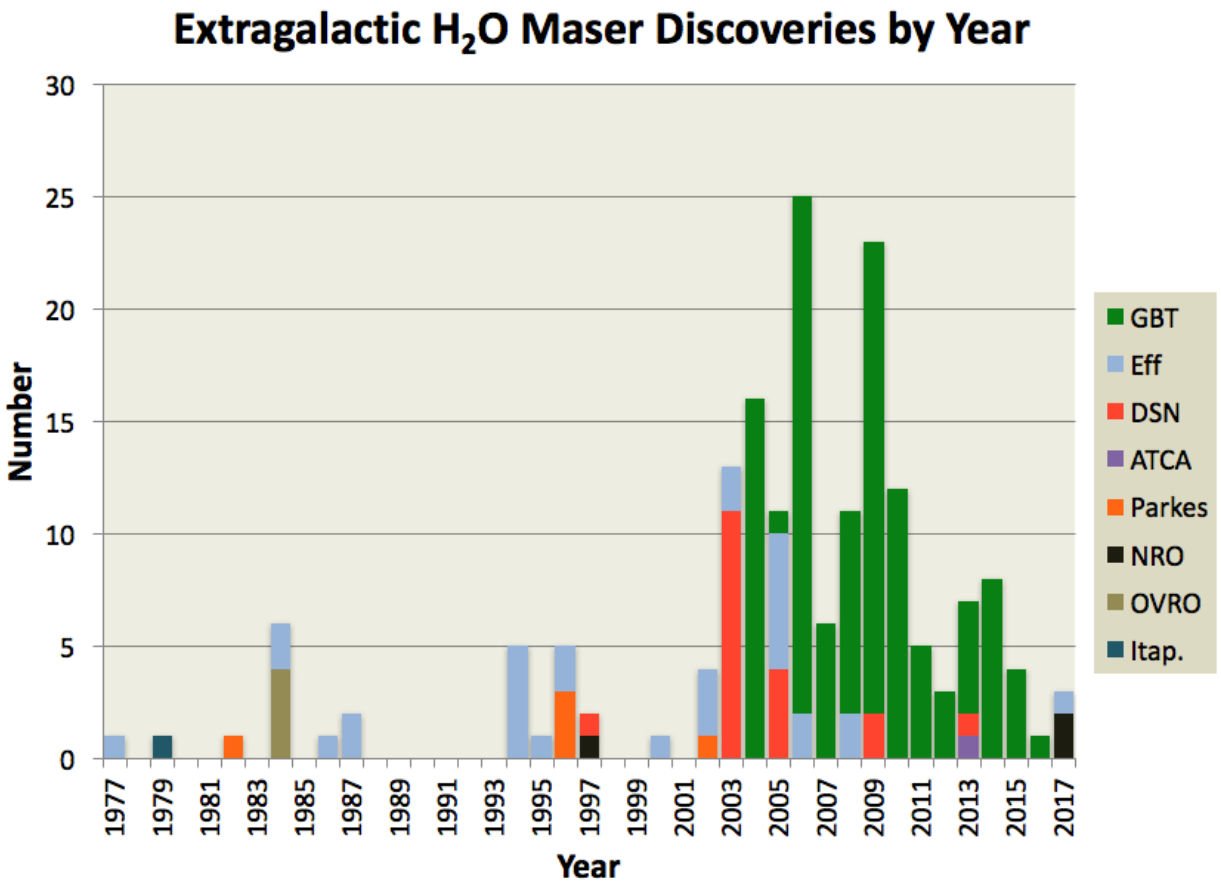
The MCP is a multi-year NRAO "Key Project" with the goal of determining H_0 precisely by measuring *geometric distances* to galaxies in the Hubble flow.



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

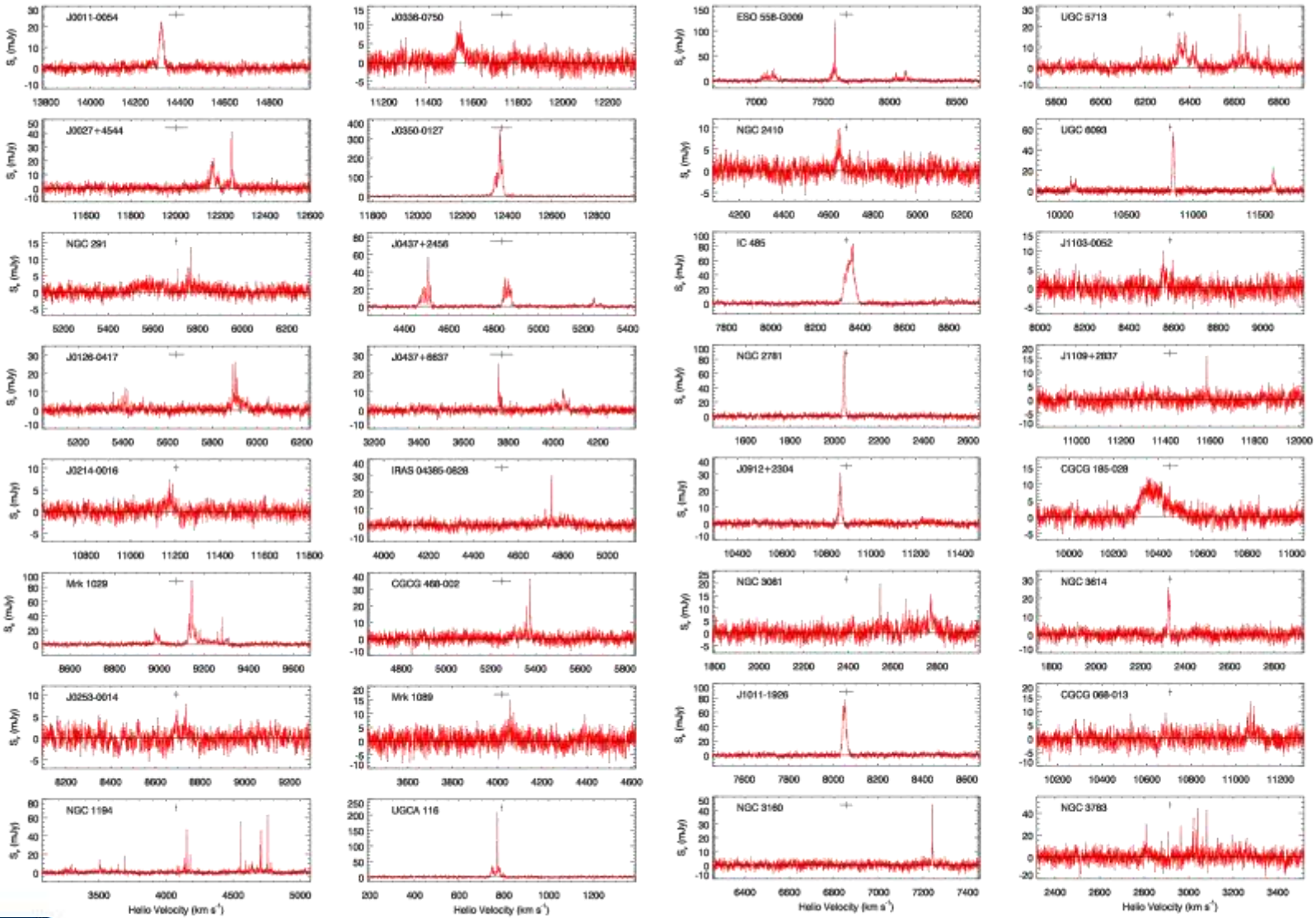


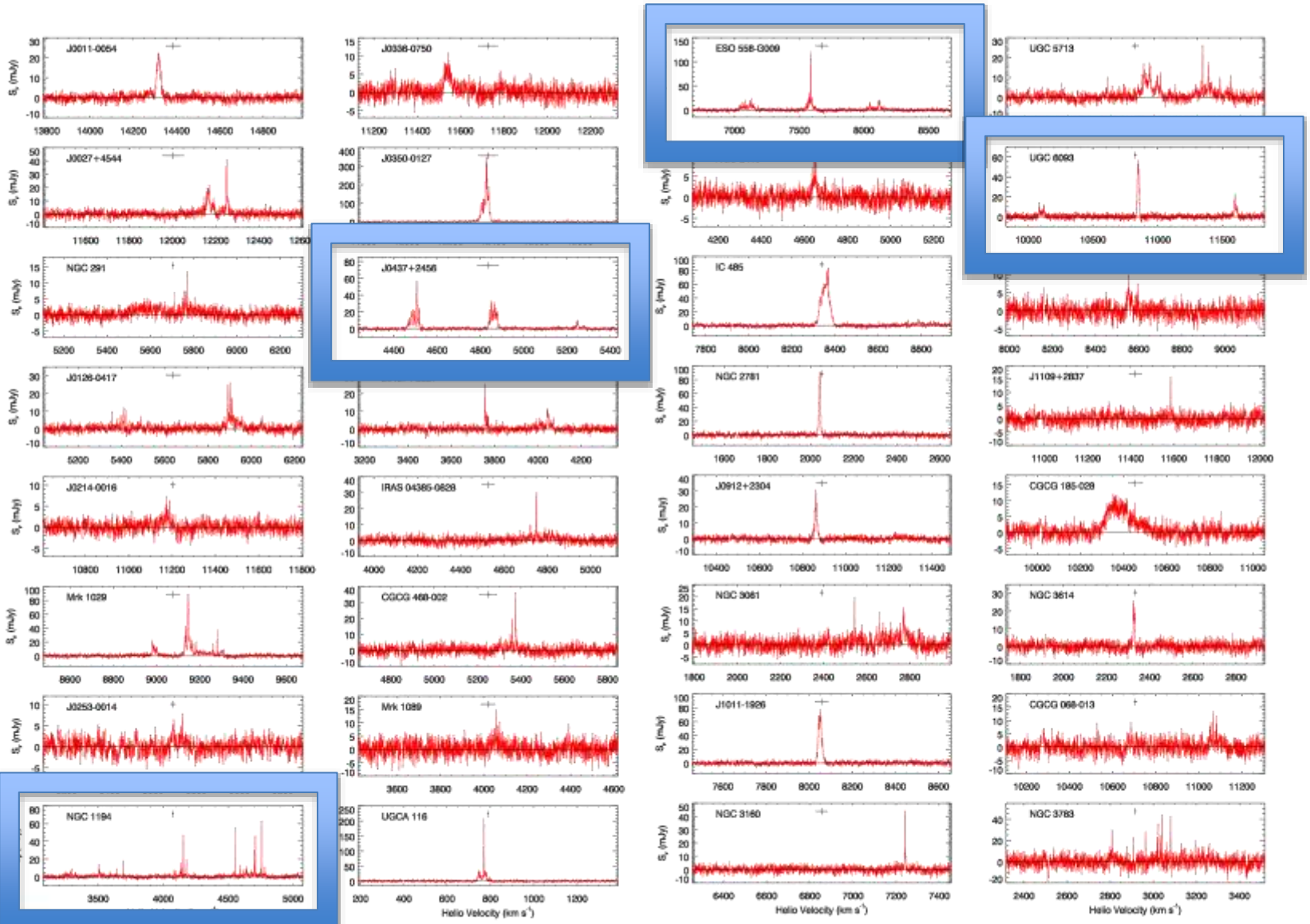
Progress with 22 GHz Megamaser Surveys



- 178 galaxies currently known as maser hosts
- MCP: 85/2800 = 3%
- ~ 37 are in disks and suitable for M_{BH} measurement
- 10 targeted for distance measurement
- Primary sample for MCP surveys: Type 2 AGNs at $z < 0.05$ from SDSS, 6dF, 2MRS

https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject


J0011-0054
J0336-0750
ESO 558-G009
UGC 5713
J0027+4544
J0350-0127
NGC 2410
UGC 6093
NGC 291
J0437+2456
IC 485
J1103-0052
J0126-0417
J0437+8637
NGC 2781
J1109+2837
J0214-0016
IRAS 04385-0828
J0912+2304
CGCG 185-029
Mrk 1029
CGCG 468-002
NGC 3061
NGC 3614
J0253-0014
Mrk 1089
J1011-1926
CGCG 068-013
NGC 1194
UGCA 116
NGC 3160
NGC 3783
S_v (mJy)
Helio Velocity (km s^-1)


J0011-0054
J0027+4544
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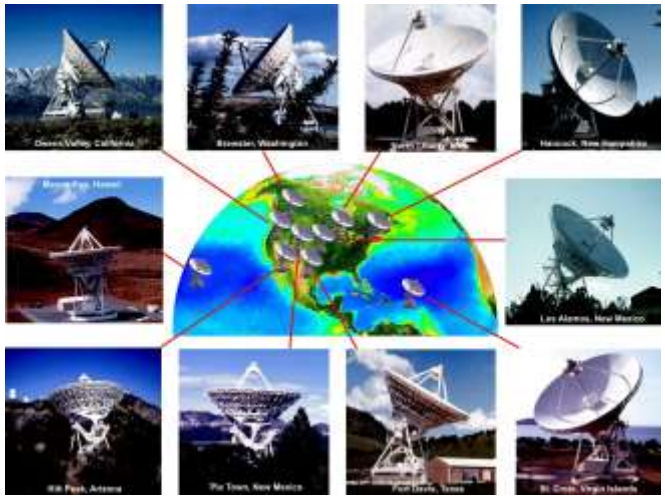
CGCG 098-013
NGC 3783
S$_\nu$ (mJy)
Helio Velocity (km s^{-1})

Ultra-high resolution mapping with the HSA:

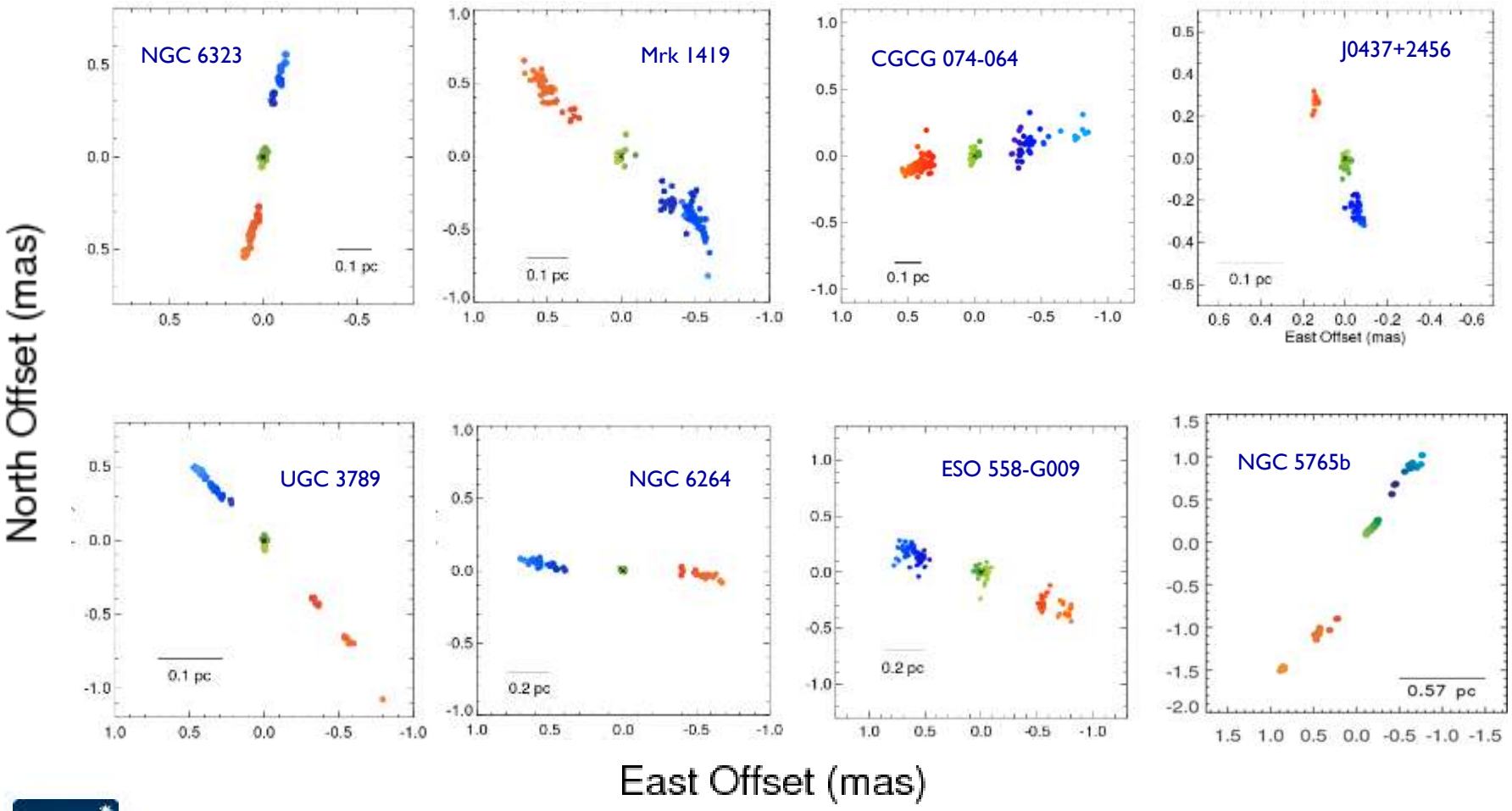






- For sensitivity, the MCP adds the GBT, EB, and phased VLA to the VLBA
- Adding sensitive dishes enables self-cal, greatly improving efficiency
- $\lambda/D \sim 0.33$ mas

H_2O Megamaser Disks



The Challenge of Imaging Distant Disks

NGC 4258
(D = 7.54 Mpc +/- 2.6%)





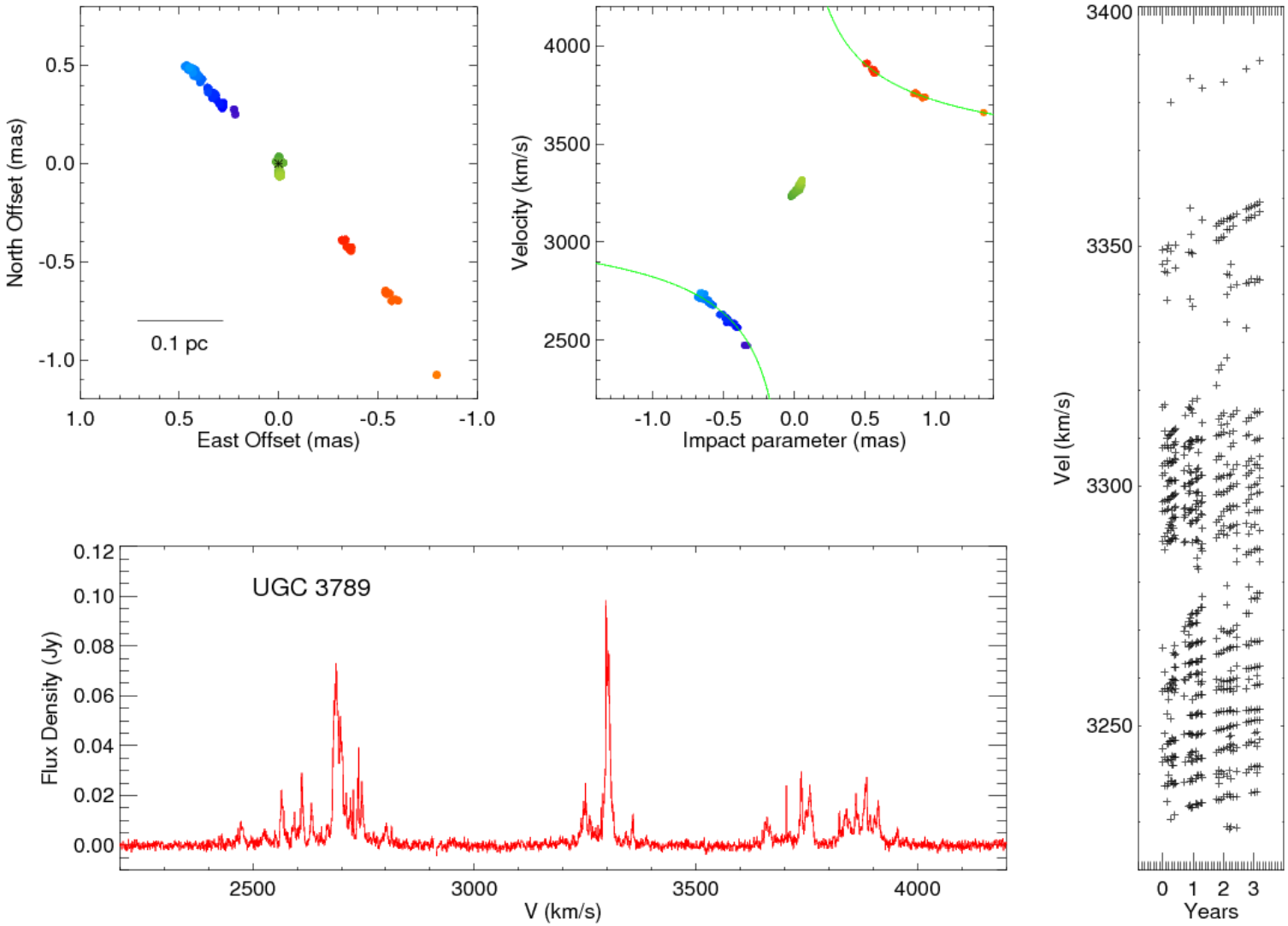
NGC 6323 UGC 3789 NGC 6264 NGC 5765b



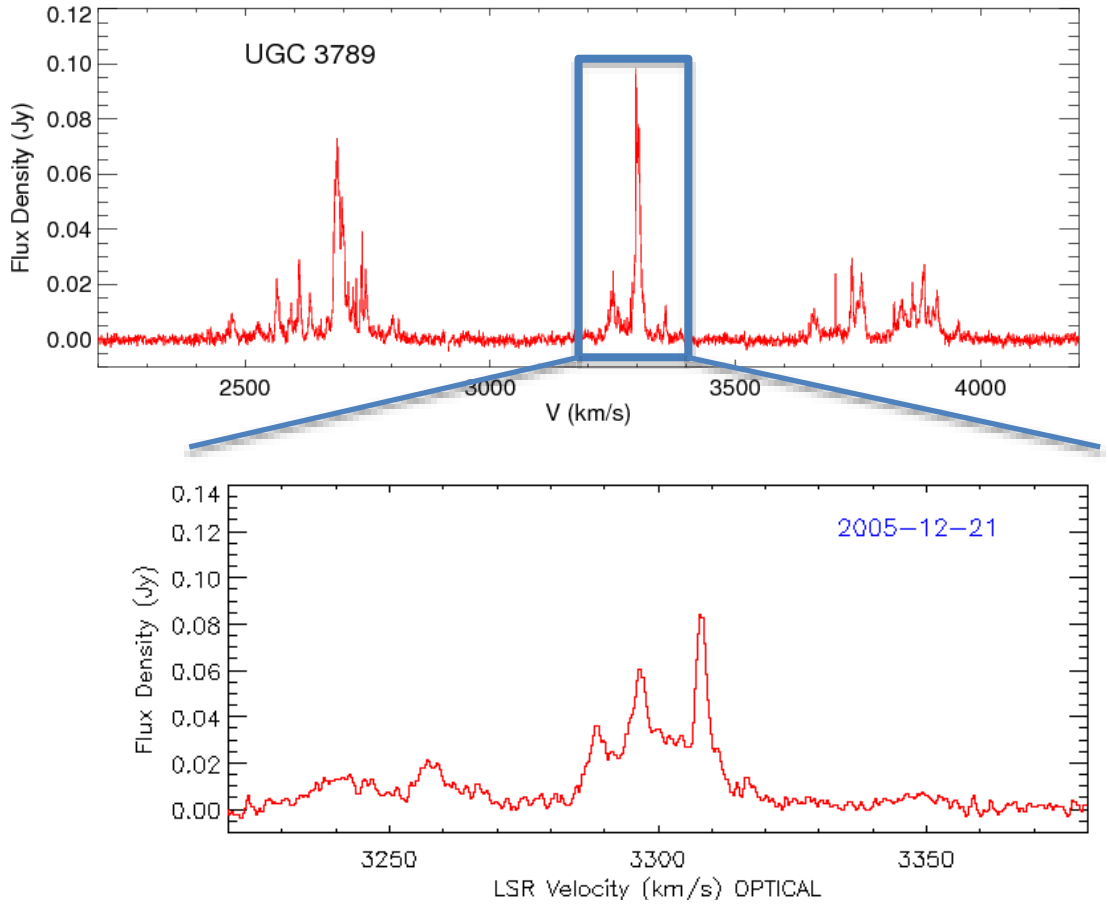
Beam ≈ 0.3 x 1.0 mas

$\Delta\theta$ = Beam/(S/N)

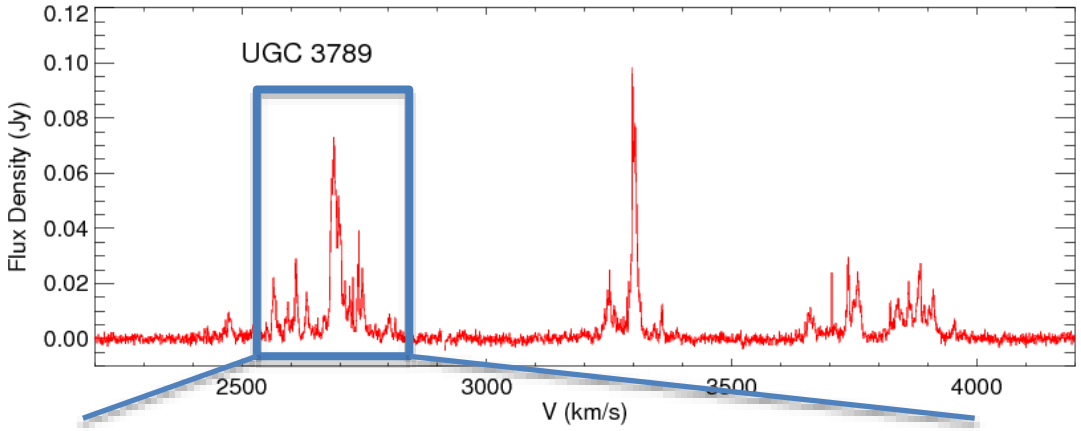
UGC 3789

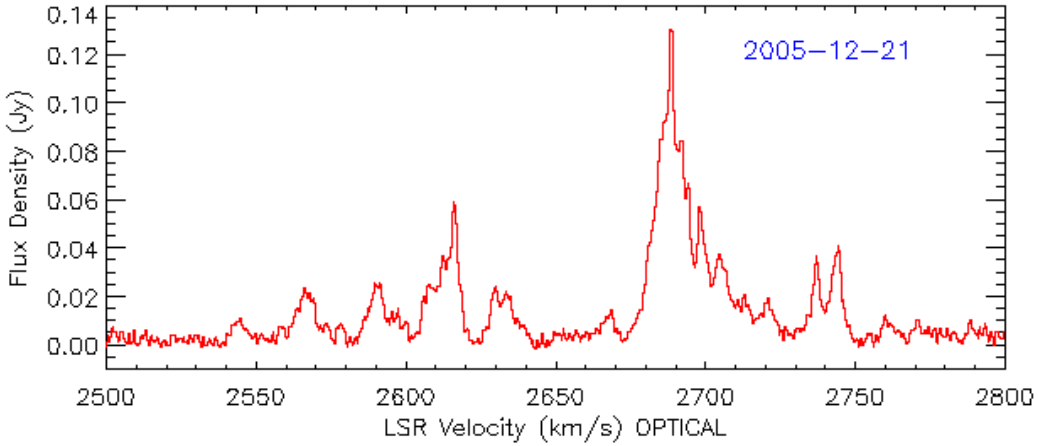

North Offset (mas)
East Offset (mas)
0.1 pc
Velocity (km/s)
Impact parameter (mas)
Vel (km/s)
Years
UGC 3789
Flux Density (Jy)
V (km/s)

UGC 3789: Systemic Features

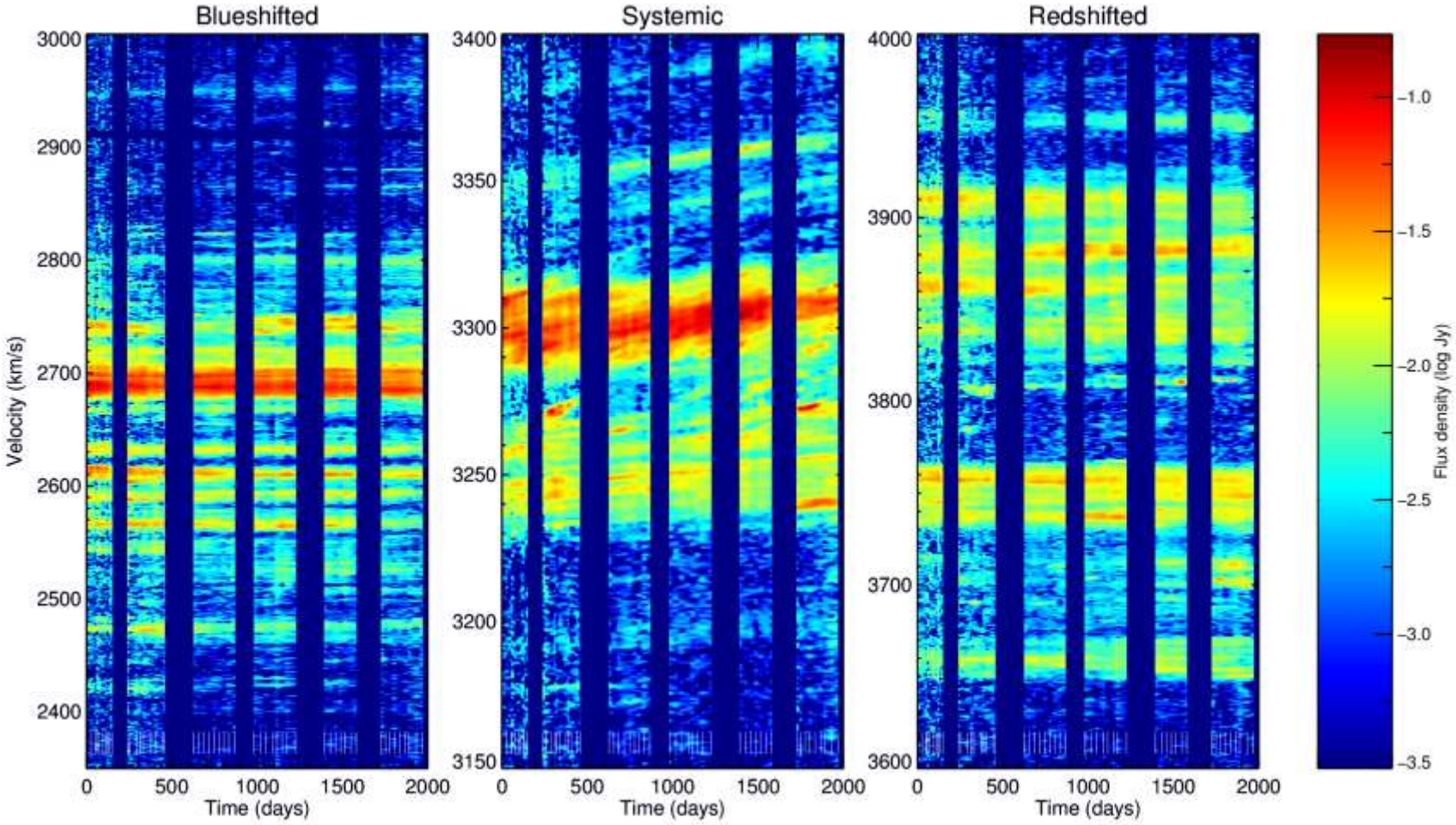


UGC 3789: Blue Features



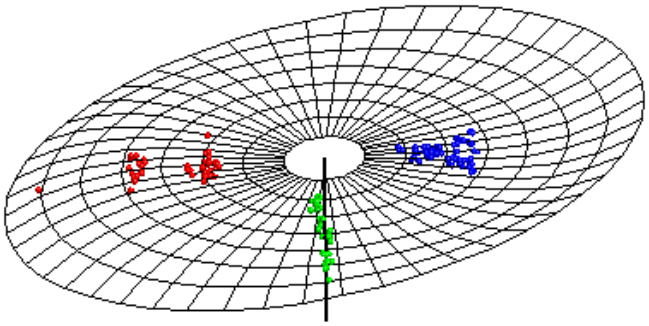


UGC 3789 dynamic spectra



Pesce et al. 2015

Bayesian Estimation of the H_0 PDF from Megamasers



- We use a custom MCMC code by Mark Reid
- Inputs: (x, y, v_{LOS}, a_{LOS}) for each maser spot
- Global parameters:
  - H_0 (or D, angular diameter distance)
  - M_{BH}
  - (x_0, y_0, V_0) of dynamical center
  - PA, inclination
  - Up to 4 parameters to describe the position angle & inclination warping
  - [eccentricity]

For UGC 3789: D = 45.6 ± 4.9 Mpc

H_0 = 76 ± 8 km s^{-1} Mpc^{-1}

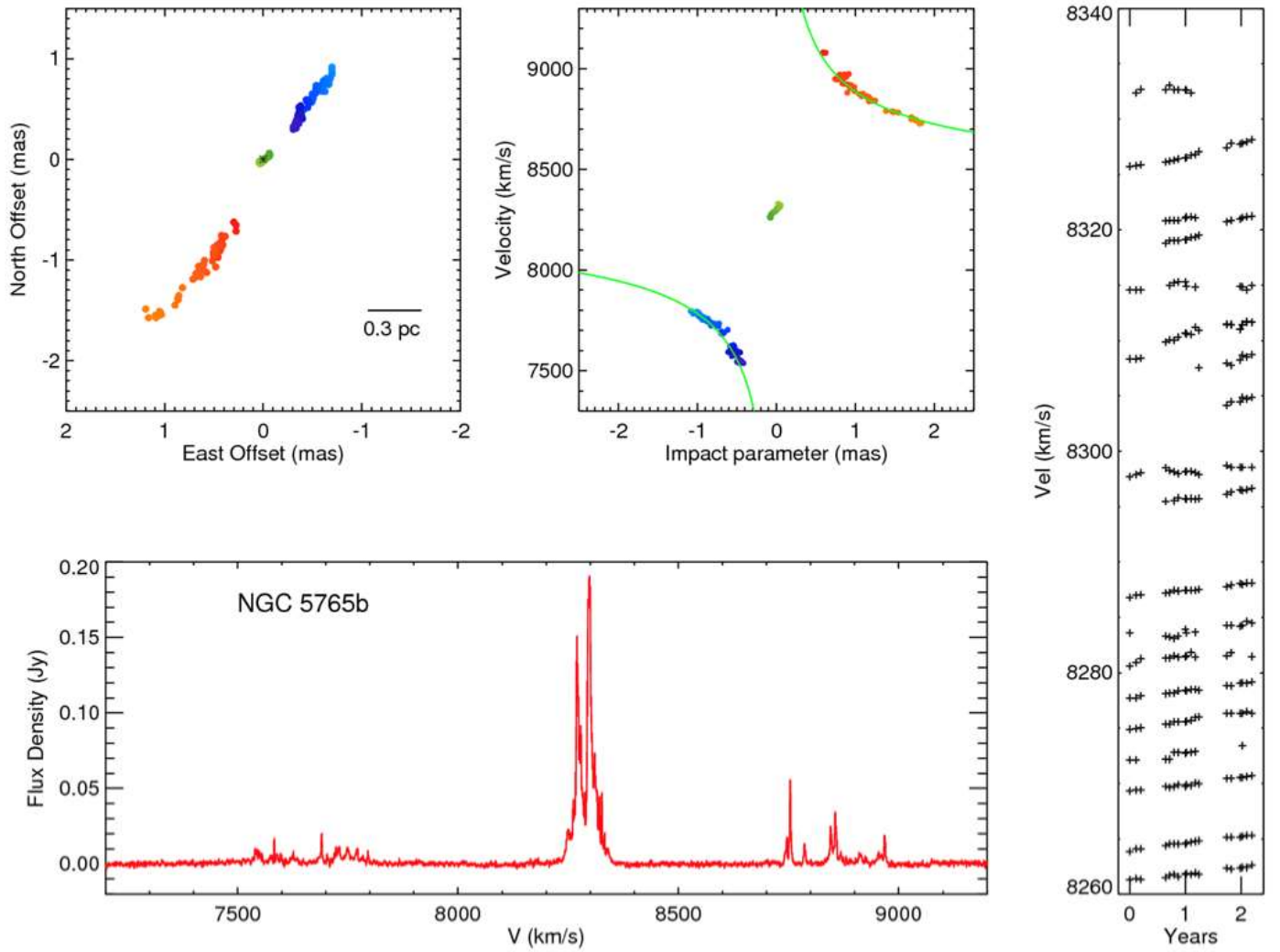
(updated from Reid et al. 2013)

Estimation of H_0 from Geometric Distances

$H_0 = 69.3 \pm 4.2$ km s^{-1} Mpc^{-1}

UGC 3789	45.0 ± 4.7 Mpc	H_0 = 76 ± 8	(updated from Reid et al. 2013)
NGC 6264	137 ± 19 Mpc	H_0 = 68 ± 9	(Kuo et al. 2013)
NGC 6323	107 ± 42 Mpc	H_0 = 73 ± 26	(Kuo et al. 2015)
NGC 5765b	126 ± 11 Mpc	H_0 = 66 ± 6	(Gao et al. 2016)

NGC 5765b


North Offset (mas)
East Offset (mas)
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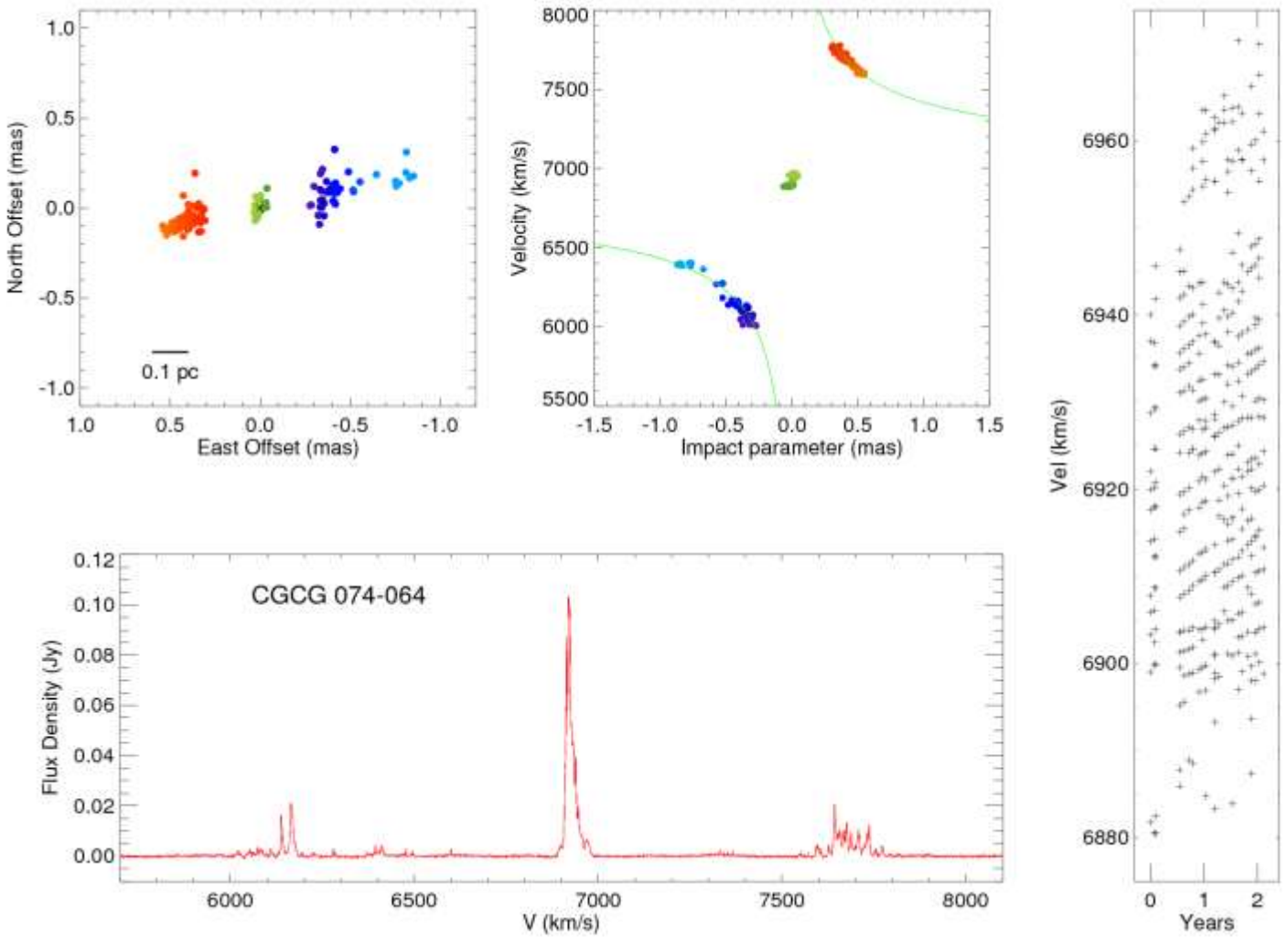
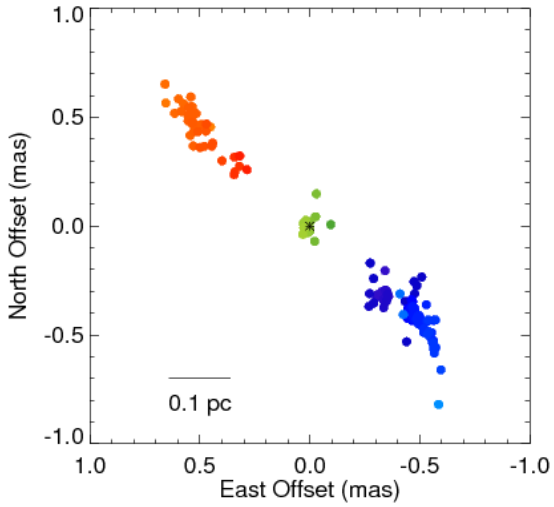
Velocity (km/s)
Impact parameter (mas)
Vel (km/s)
Years
NGC 5765b
Flux Density (Jy)
V (km/s)

CGCG 074-064


North Offset (mas)
East Offset (mas)
0.1 pc
Velocity (km/s)
Impact parameter (mas)
Vel (km/s)
Years
CGCG 074-064
Flux Density (Jy)
V (km/s)

Mrk 1419


North Offset (mas)
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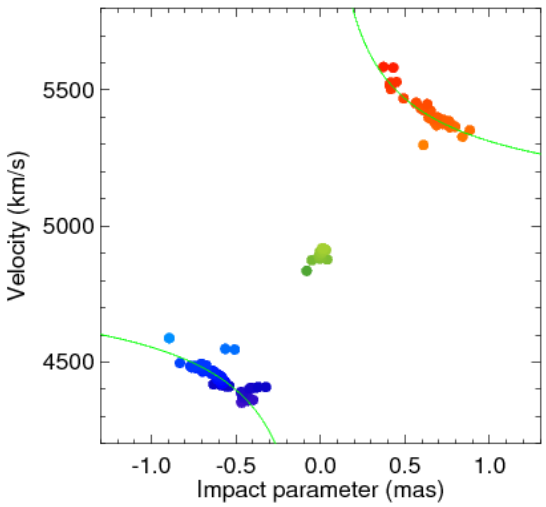
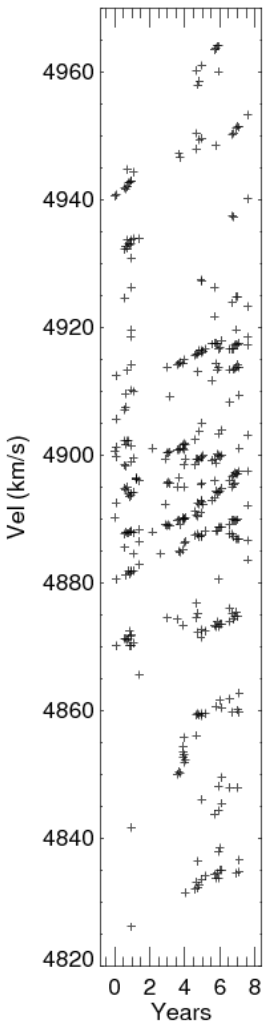
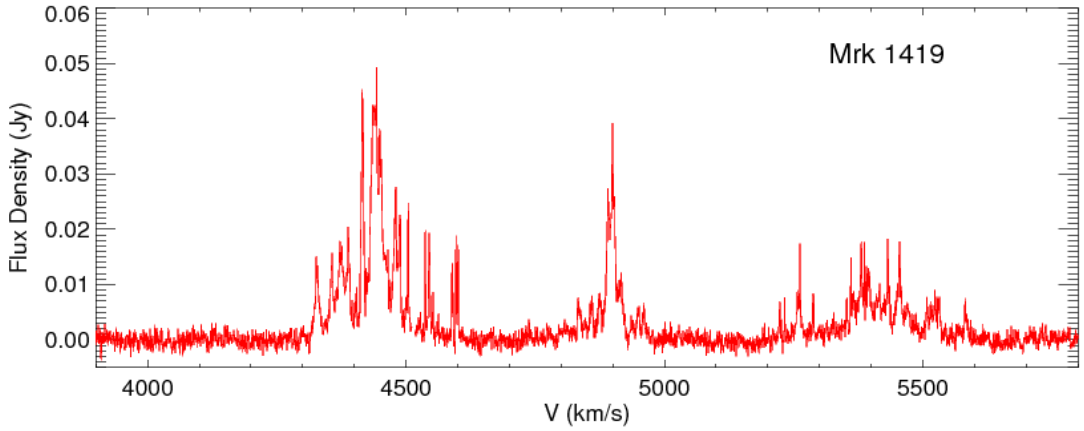

Velocity (km/s)
Impact parameter (mas)


Vel (km/s)
Years


Mrk 1419
Flux Density (Jy)
V (km/s)

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CGCG 074-064

Mrk 1419

IC 2560

ESO 558-G009

J0437+2456

Estimation of H_0 from Geometric Distances

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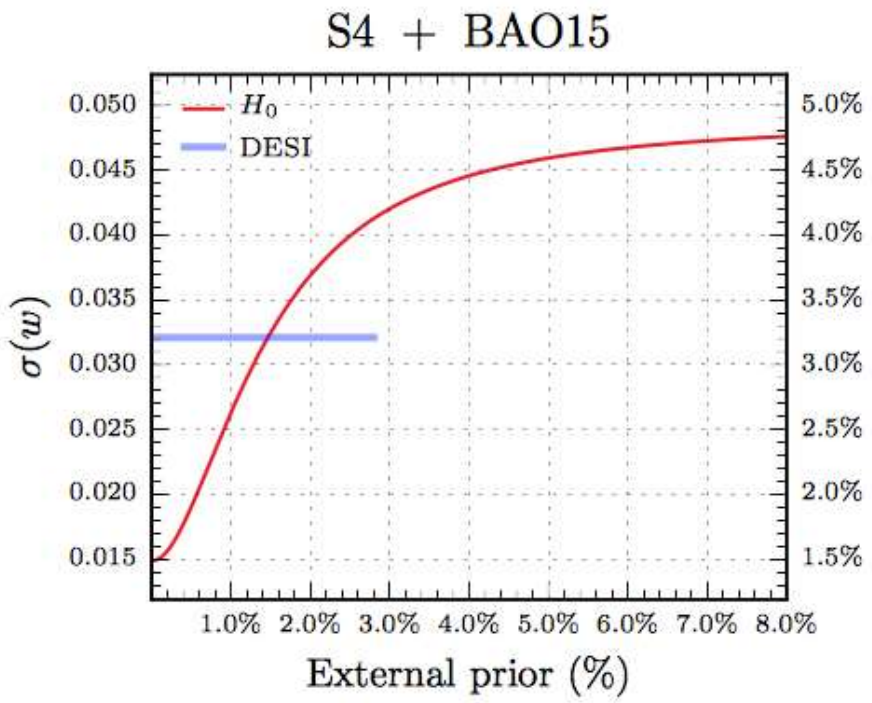
CGCG 074-064	(8%)
Mrk 1419	(25%)
IC 2560	(20%)
ESO 558-G009	(12% ?)
J0437+2456	(12% ?)

In the next year the MCP will finalize analysis and publish the 5 additional galaxies, and should achieve ~ 4% total uncertainty.

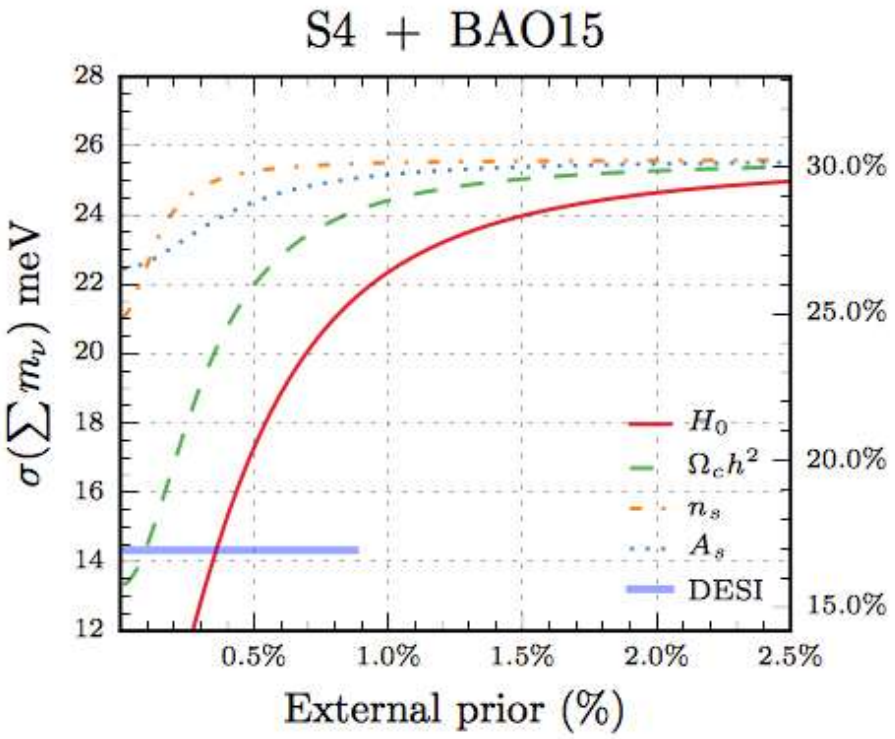
Motivation for even higher H_0 precision: CMB-S4



- CMB Stage-IV experiment will map polarization in CMB to nearly the cosmic variance limit available from the ground
- An external measurement of H_0 provides the best constraint on the DE Equation of State
- A 1% H_0 will reduce the uncertainty on *w* by a factor of 2

Manzotti, Dodelson & Park (2016)

Constraints on Neutrino Mass



- Oscillation experiments demonstrate $\Sigma m_\nu > 50$ meV
- Without priors, the CMB-S4 detection of Σm_ν may be significant at only ~2σ
- For a CMB-S4 experiment, a prior on H_0 at the ~percent level provides the best additional constraint on neutrino mass

Manzotti, Dodelson & Park (2016)

Toward a 1% H_0 with Megamasers



- MCP with GBT+VLA+EB+VLBA enables a ~4% H_0 measurement.
- Are new observations of known Megamasers "independent"?
- ngVLA: 10X the VLA collecting area and continental baselines
  - Need ~100 galaxies at ~10% each, to achieve 1% H_0.
- ngVLA would be enable larger number of measurements and would reach galaxies out to ~300 Mpc, reducing systematics

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Summary

- MCP measurement of H_0 is one-step, geometric measurement that provides a critical complement to measurements using standard candles.

- The MCP observing phase is complete. Now working on final data reduction and analysis. We have published 4 distances and expect to publish 5 more to complete the project.

- $H_0 = 69.3 \pm 4.2$ km s^{-1} Mpc^{-1}. We expect a ~ 4% measurement when analysis is complete within a year.

