GBT Surveys for 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

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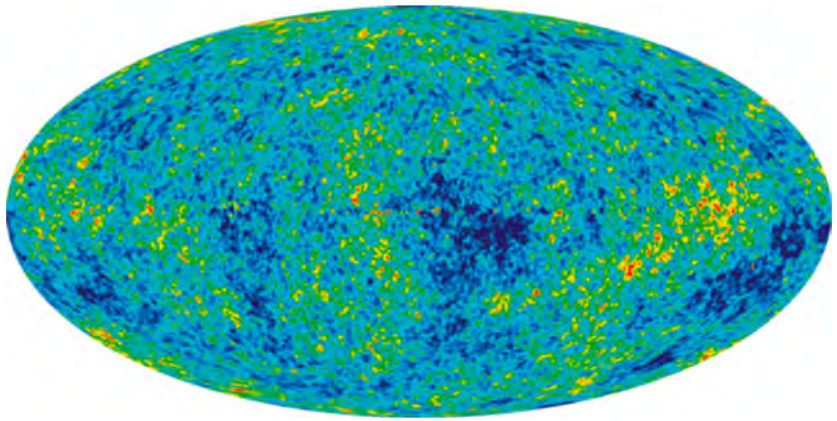
Tension in Measurements of H_0



Planck Prediction:

H_0 = 67.8 +/- 0.9 km s^{-1} Mpc^{-1} (Ade et al. 2016)

Measurements using standard candles:

H_0 = 73.5 +/- 1.6 km s^{-1} Mpc^{-1} (Riess et al. 2018)

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

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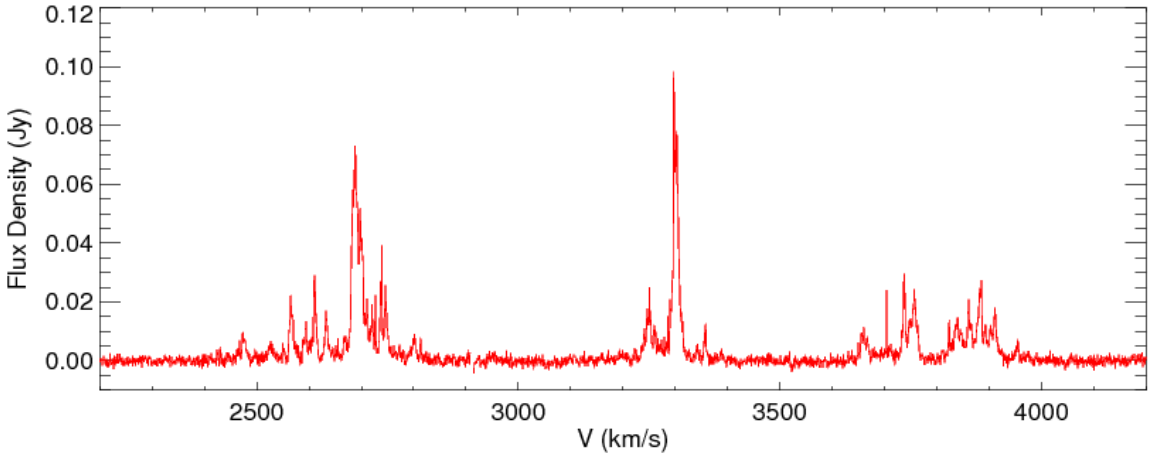
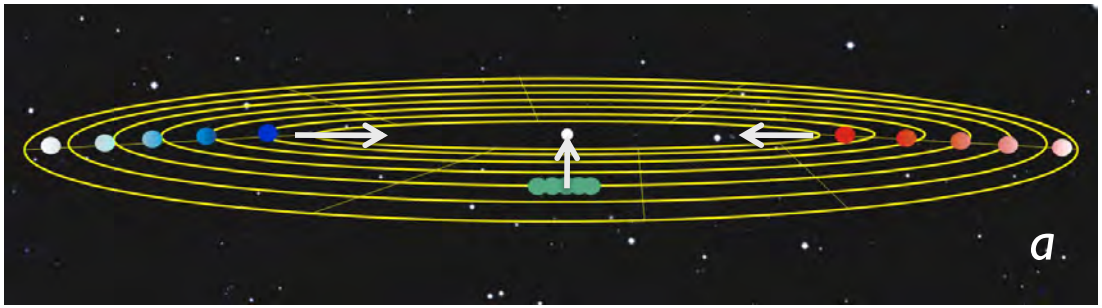
A Conceptual View of a Disk Megamaser

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

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

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





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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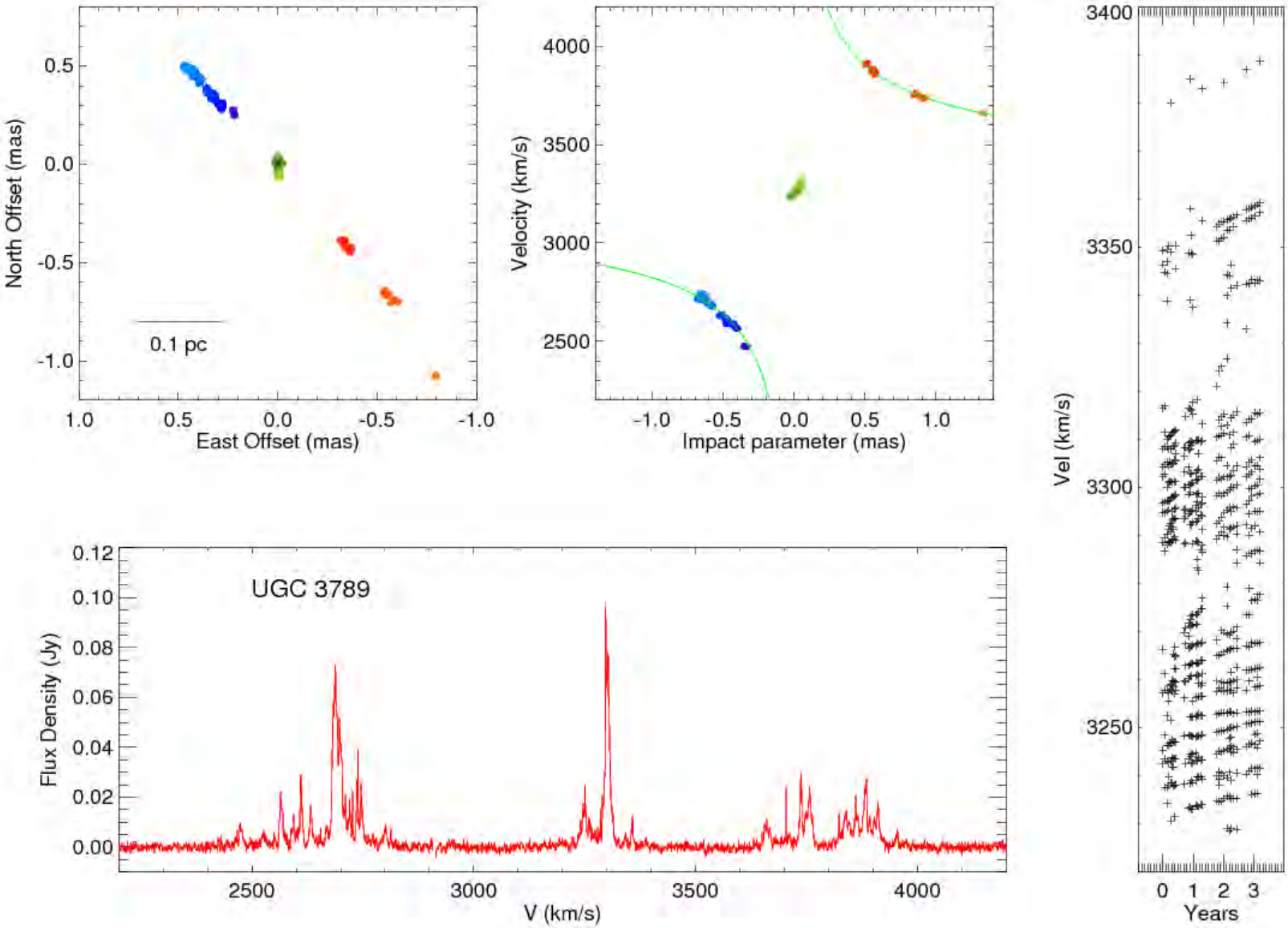
UGC 3789


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)

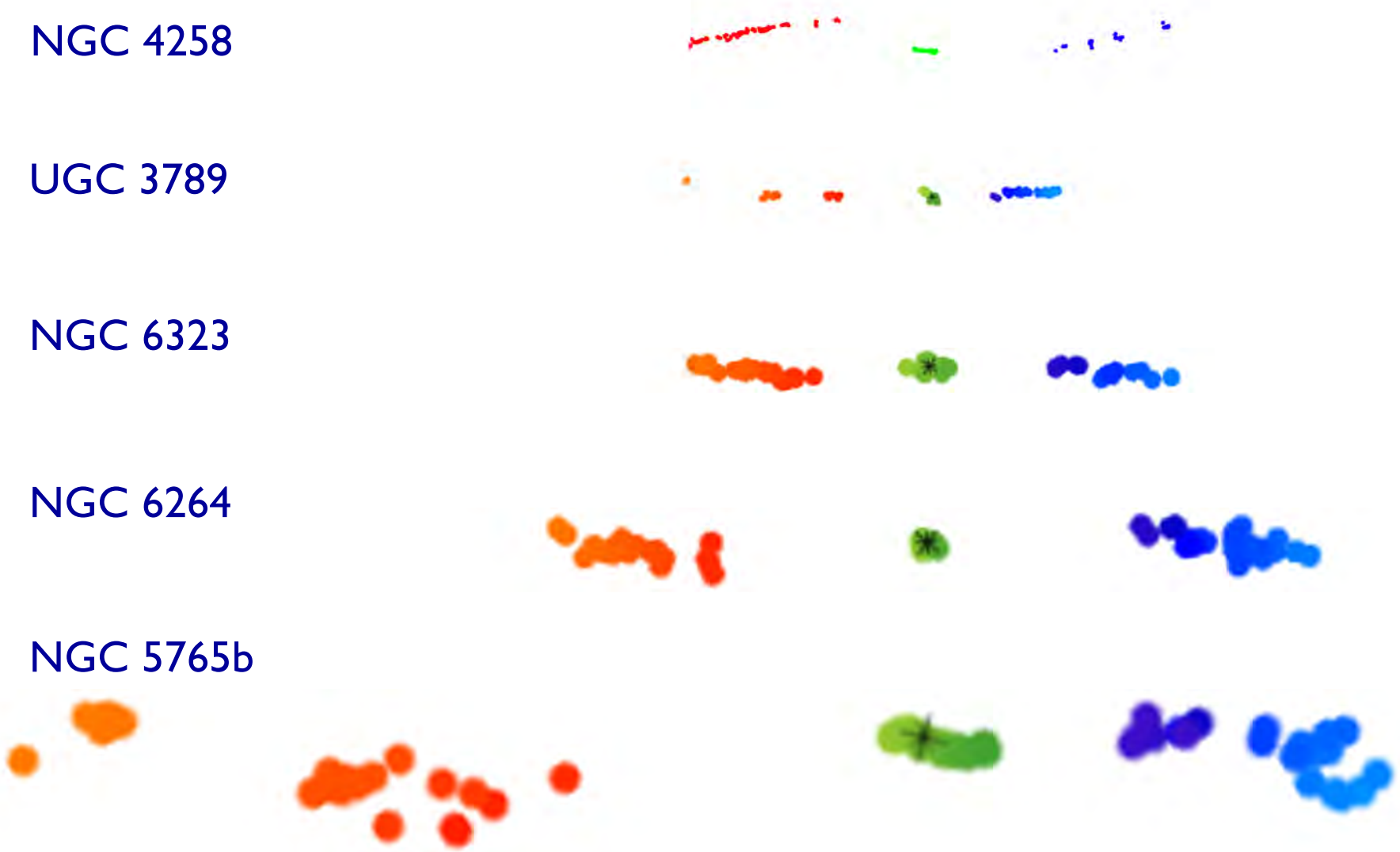
NGC 4258

UGC 3789

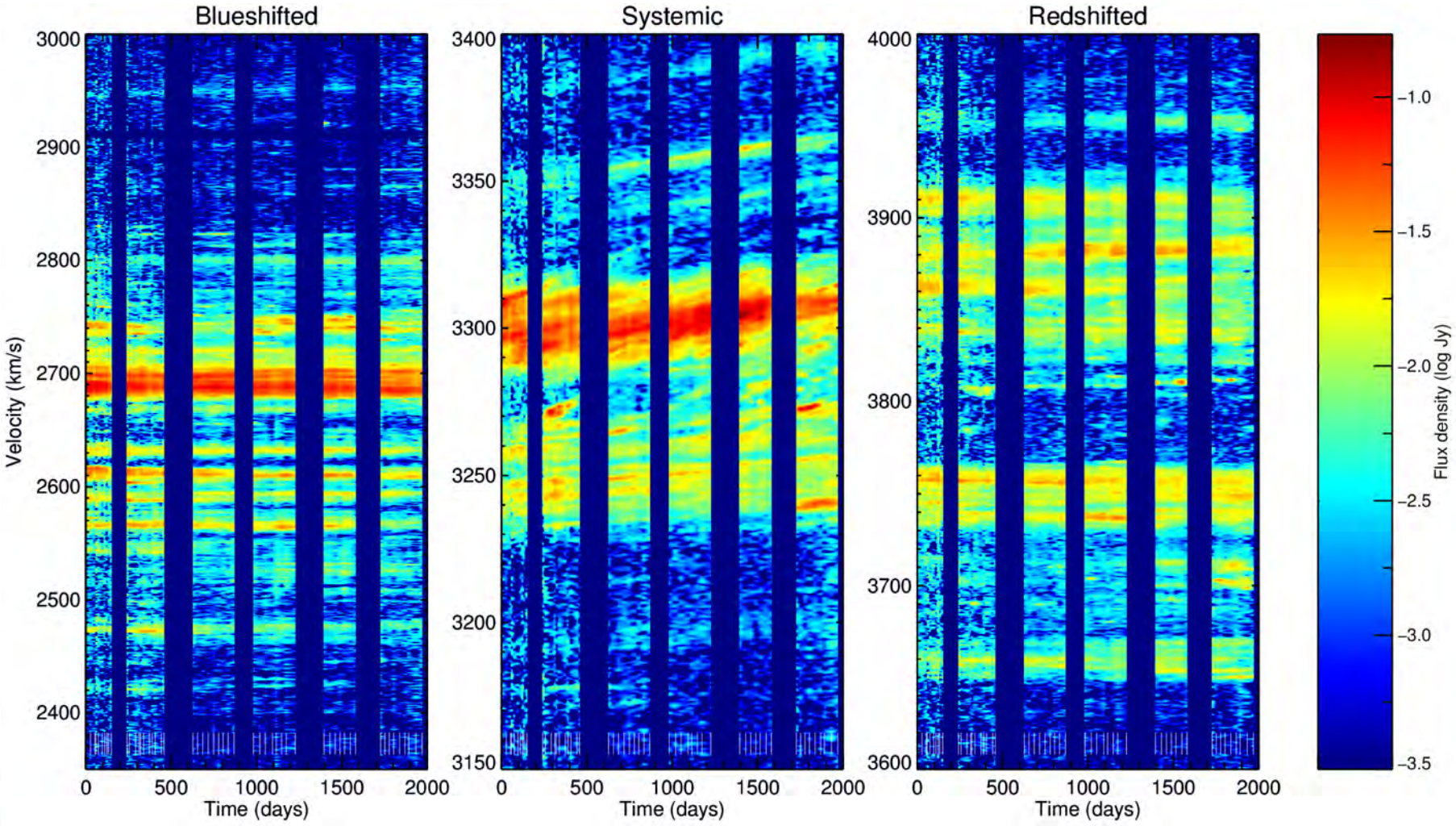
NGC 6323

NGC 6264

NGC 5765b

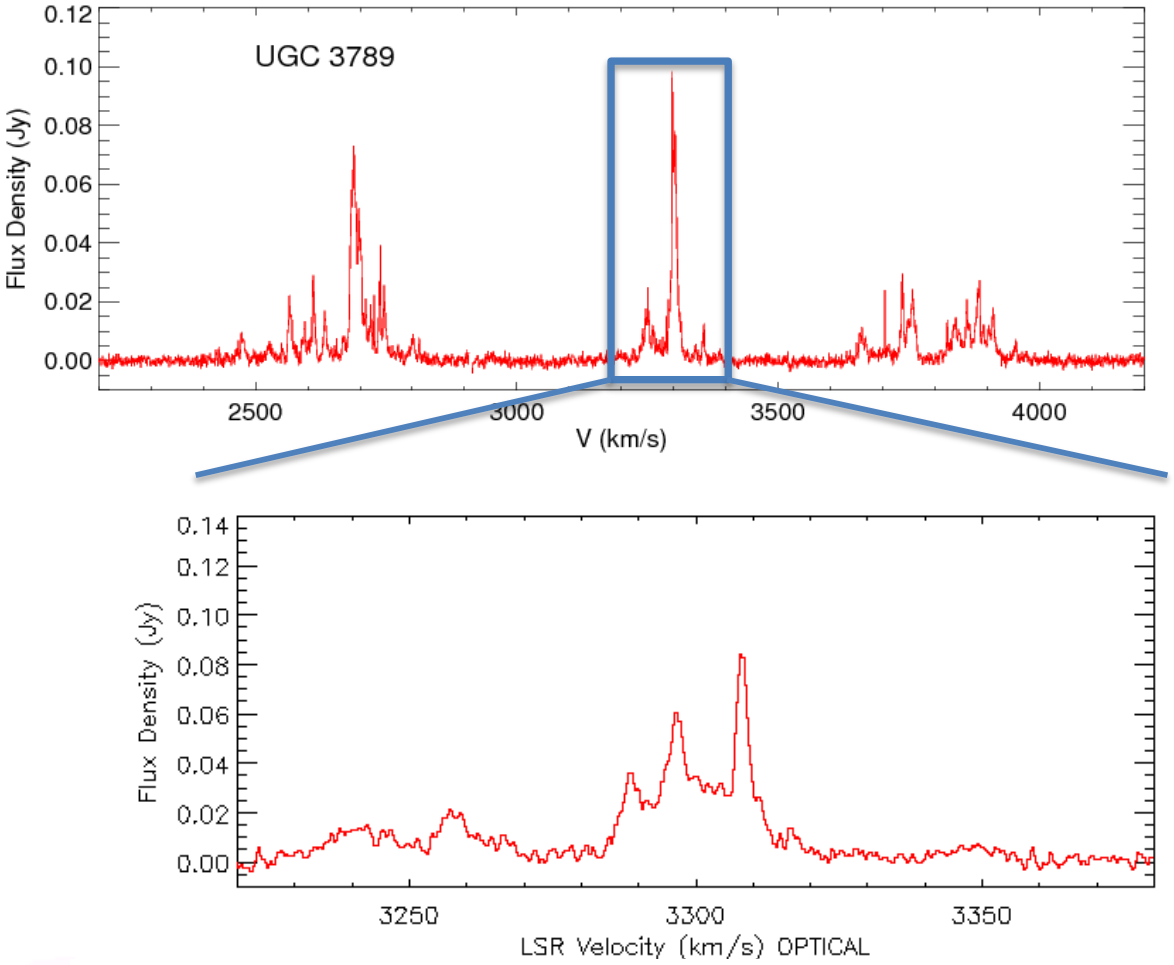


UGC 3789 dynamic spectra



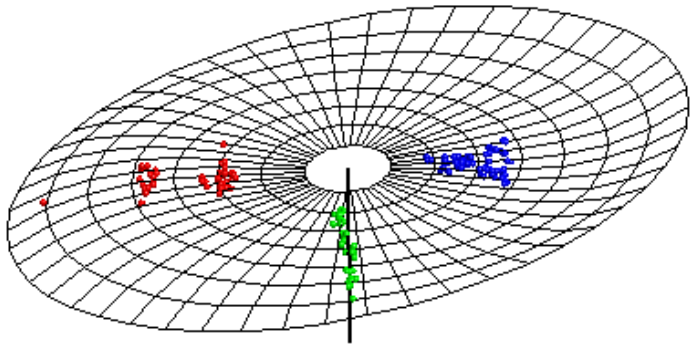
Pesce et al. 2015

UGC 3789: Systemic Features



Bayesian Estimation of the H_0 PDF

- We fit a warped disk model with a MCMC approach, and use the Metropolis-Hastings algorithm to choose successive trial parameters
- Measured: (x, y, v_{LOS}, a_{LOS}) for each maser spot
- Fit ϑ_r and ϕ for each maser spot
- Fit v_{sys} and marginalize over global parameters for M_{BH}, dynamical center, and warp
- Provide V_{pec} and fit H_0 directly



Alternative Modeling and MC Sampling

D

M_{bh}

v_{sys}

x_0

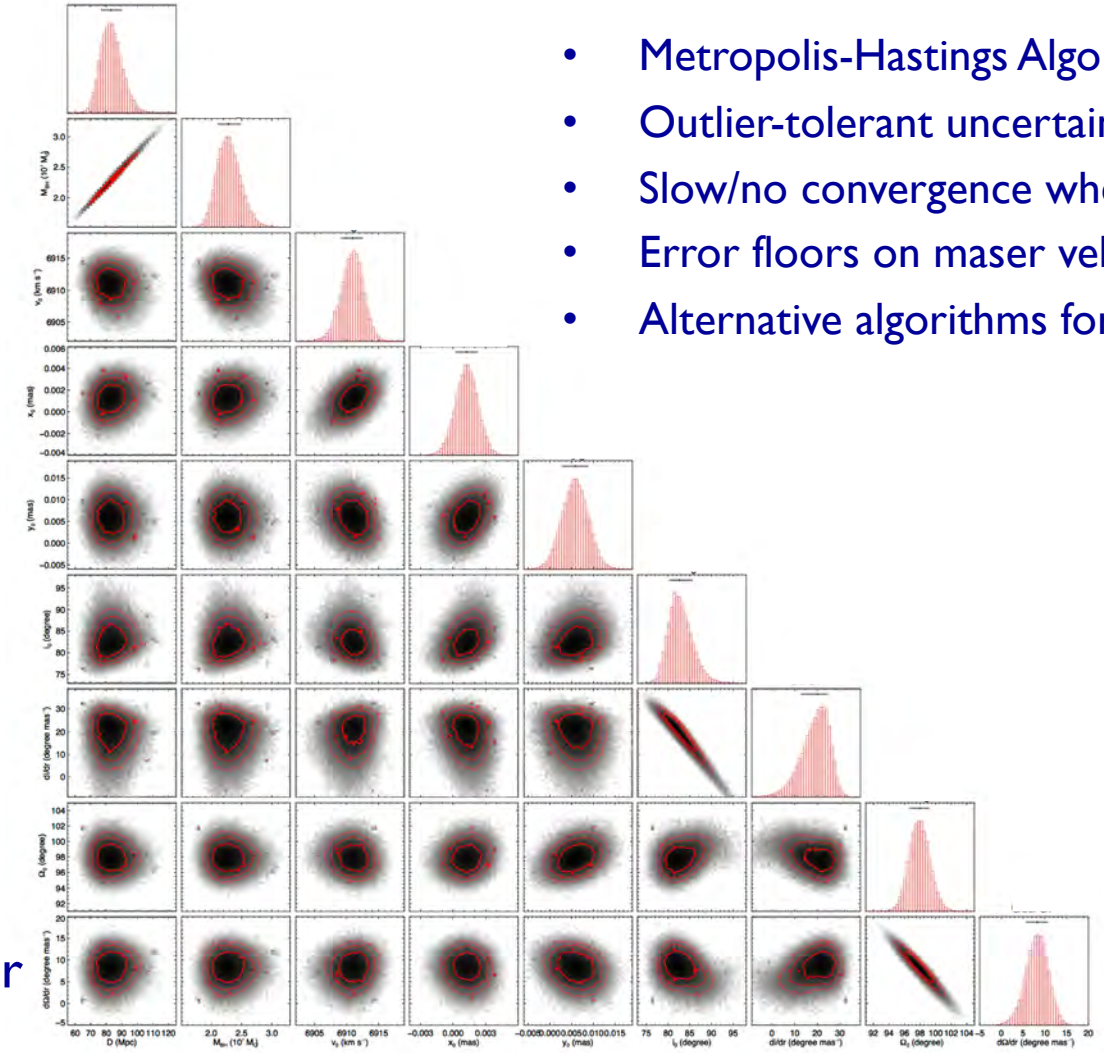
y_0

i_0

di/dr

Ω_0

$d\Omega/dr$



- Metropolis-Hastings Algorithm is our standard
- Outlier-tolerant uncertainties give conservative estimates
- Slow/no convergence when using Gaussian errors
- Error floors on maser velocities determined empirically
- Alternative algorithms for MC trials: emcee, Hamiltonian

D M_{bh} v_{sys} x_0 y_0 i_0 di/dr Ω_0 $d\Omega/dr$

H_0 from Direct Geometric Distances to Megamasers

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

UGC 3789	49.6 ± 5.1 Mpc	H_0 = 76 ± 8 (Reid et al. 2013) updated
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)
CGCG 074-064	94 ± 13 Mpc	H_0 = 73 ± 10 (Pesce et al. in prep) prelim

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

Primary Goals of H_2O Megamaser Studies

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3. Determine the geometry and physical conditions of AGN accretion disks on sub-pc scales
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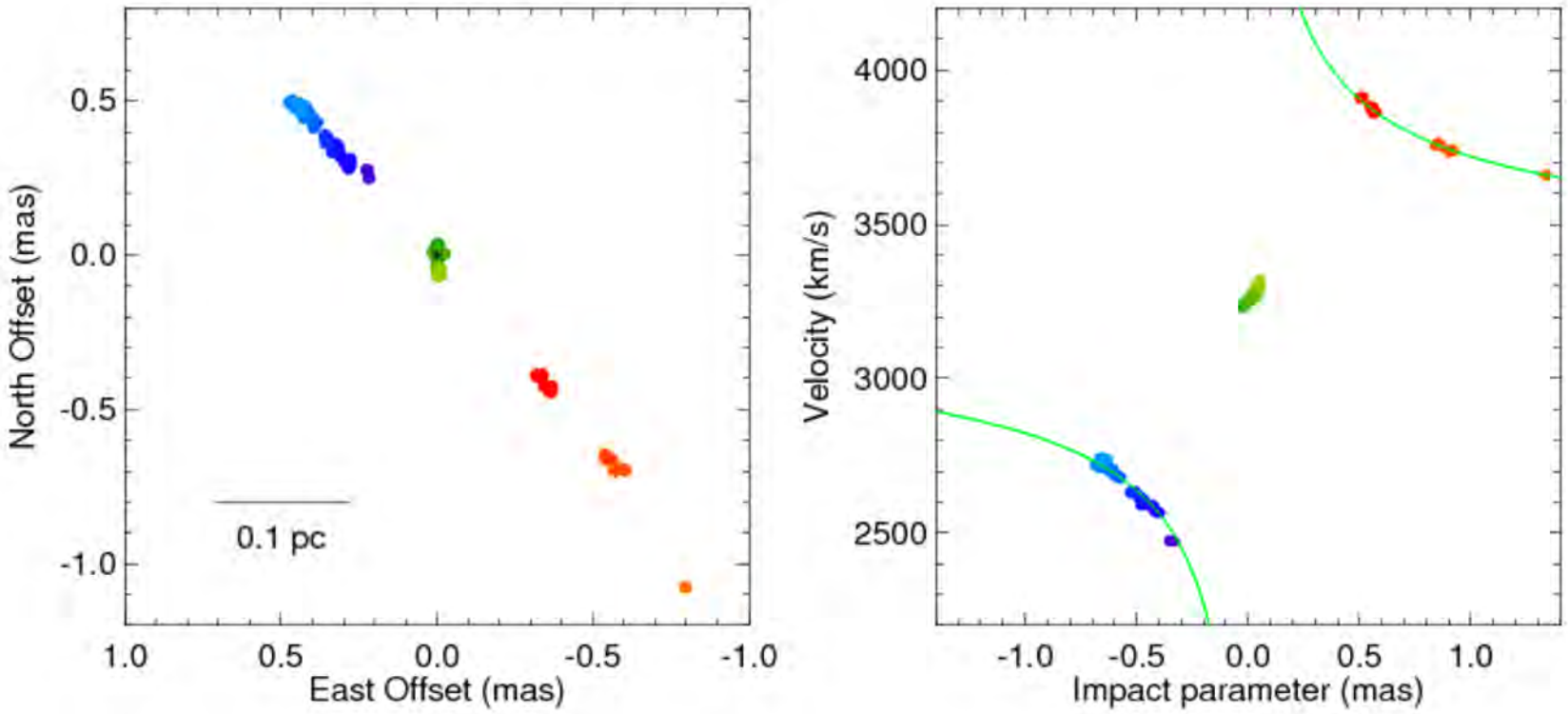
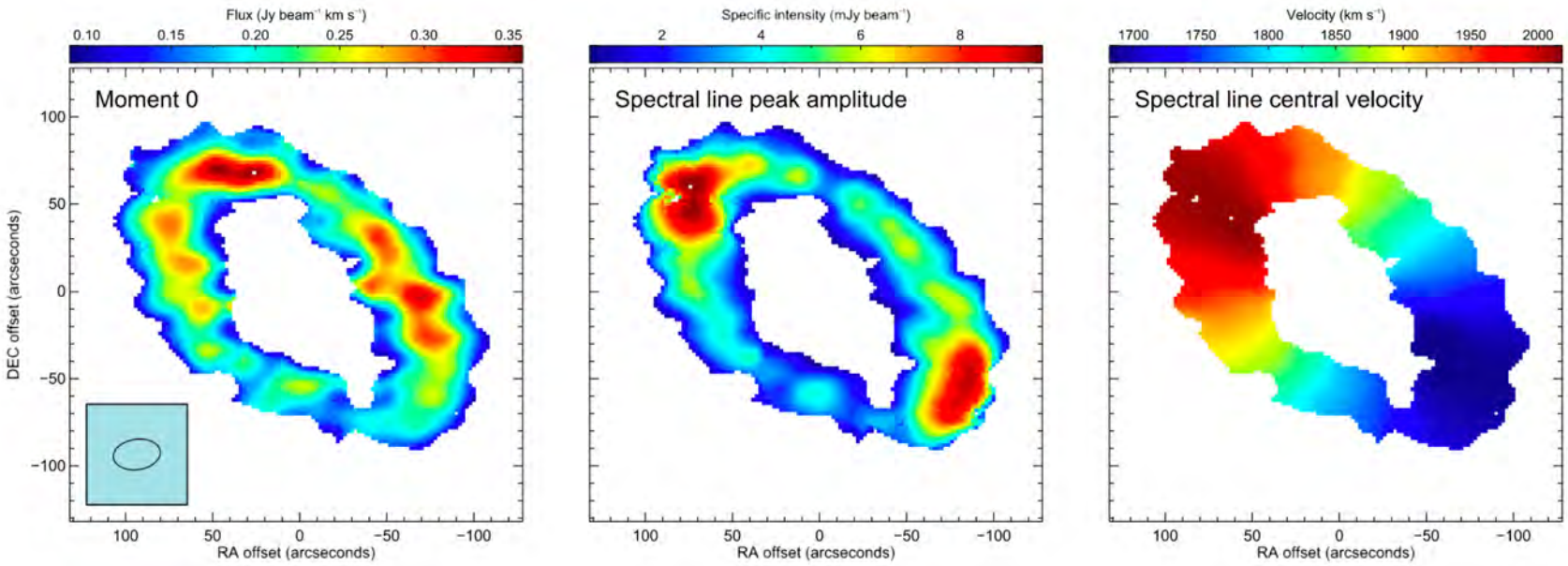
Megamasers provide precise recession velocities of the SMBH



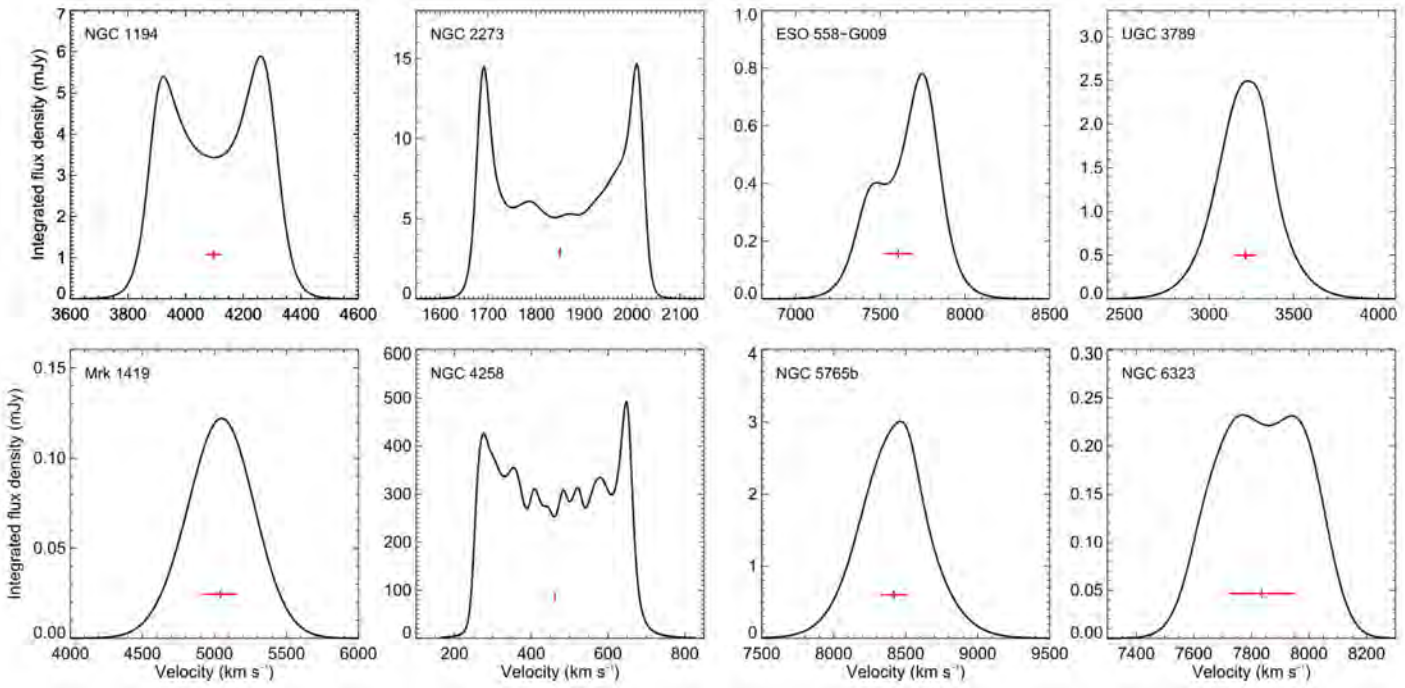
VLA HI Maps to determine Galaxy Recession Velocity



VLA HI maps

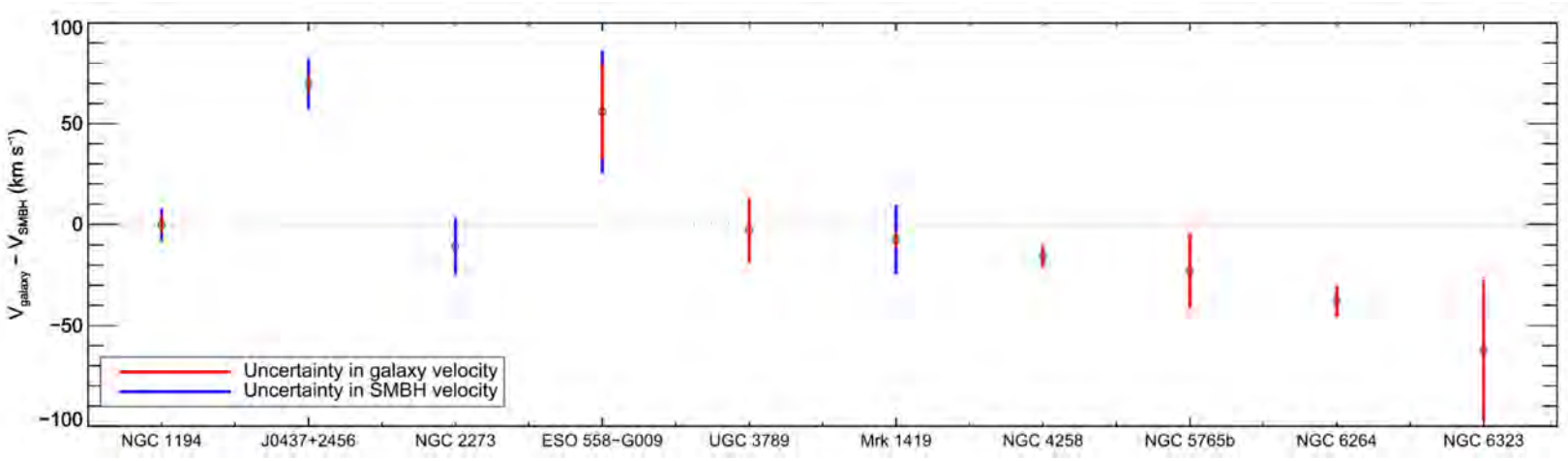
(Pesce et al. 2018)

VLA HI Maps to determine Galaxy Recession Velocity



Modeled Spectral Profiles from VLA HI maps. (Pesce et al. 2018)

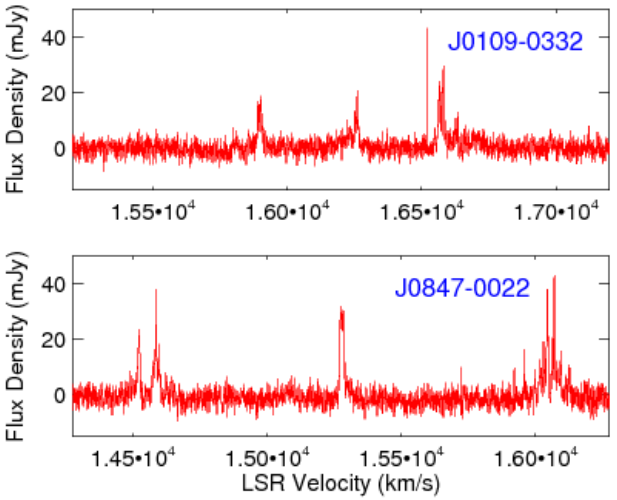
Detecting Kinematically Offset SMBH



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

GBT Megamaser Surveys

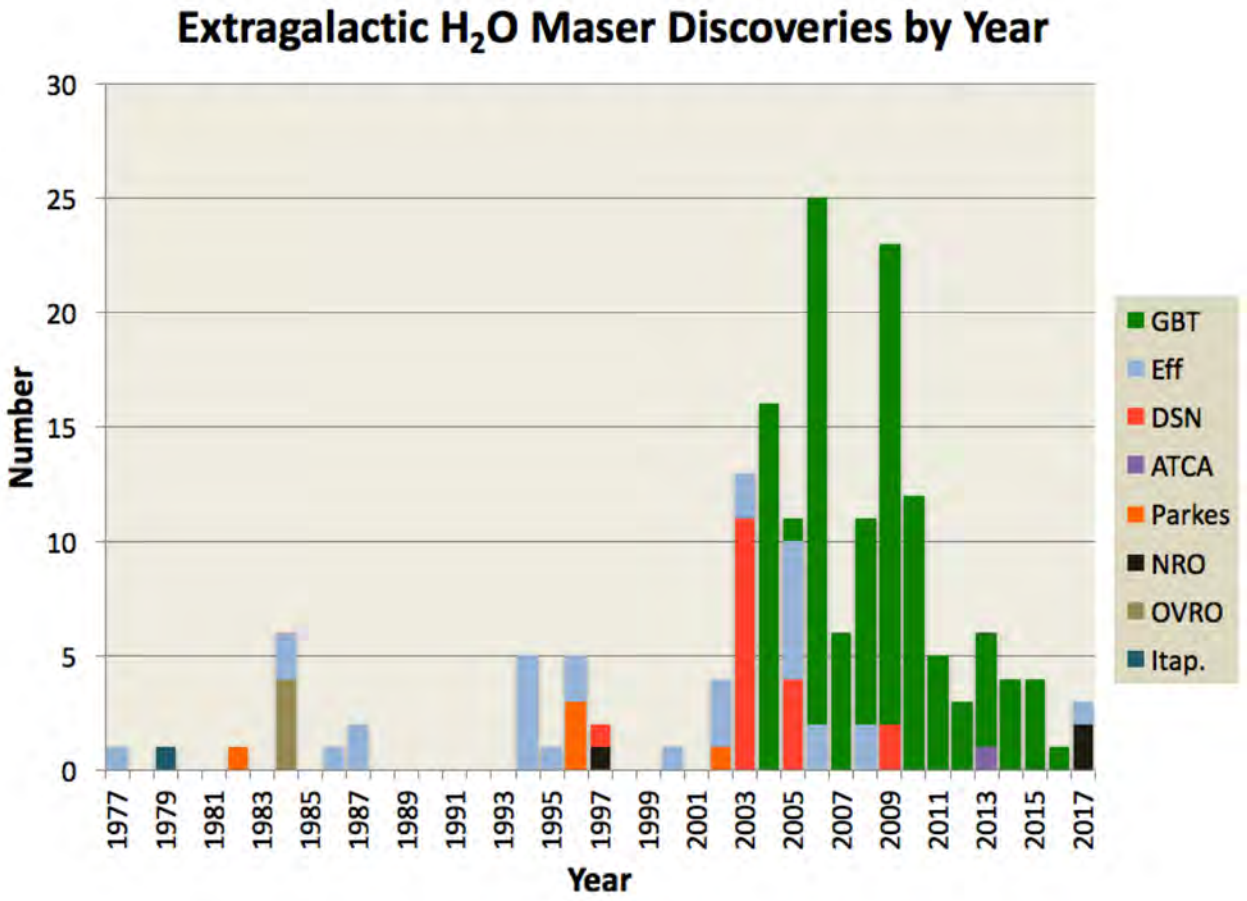
- Candidate lists are mainly AGNs
- MCP has focused on narrow-line AGN identified through optical emission lines
- Other large surveys have focused on ULIRGs, early types, disturbed, and Sy 1
- Direct calibration of Cepheid scale is possible with NGC 4258 but maser distances are unlikely calibrators for other standard candles



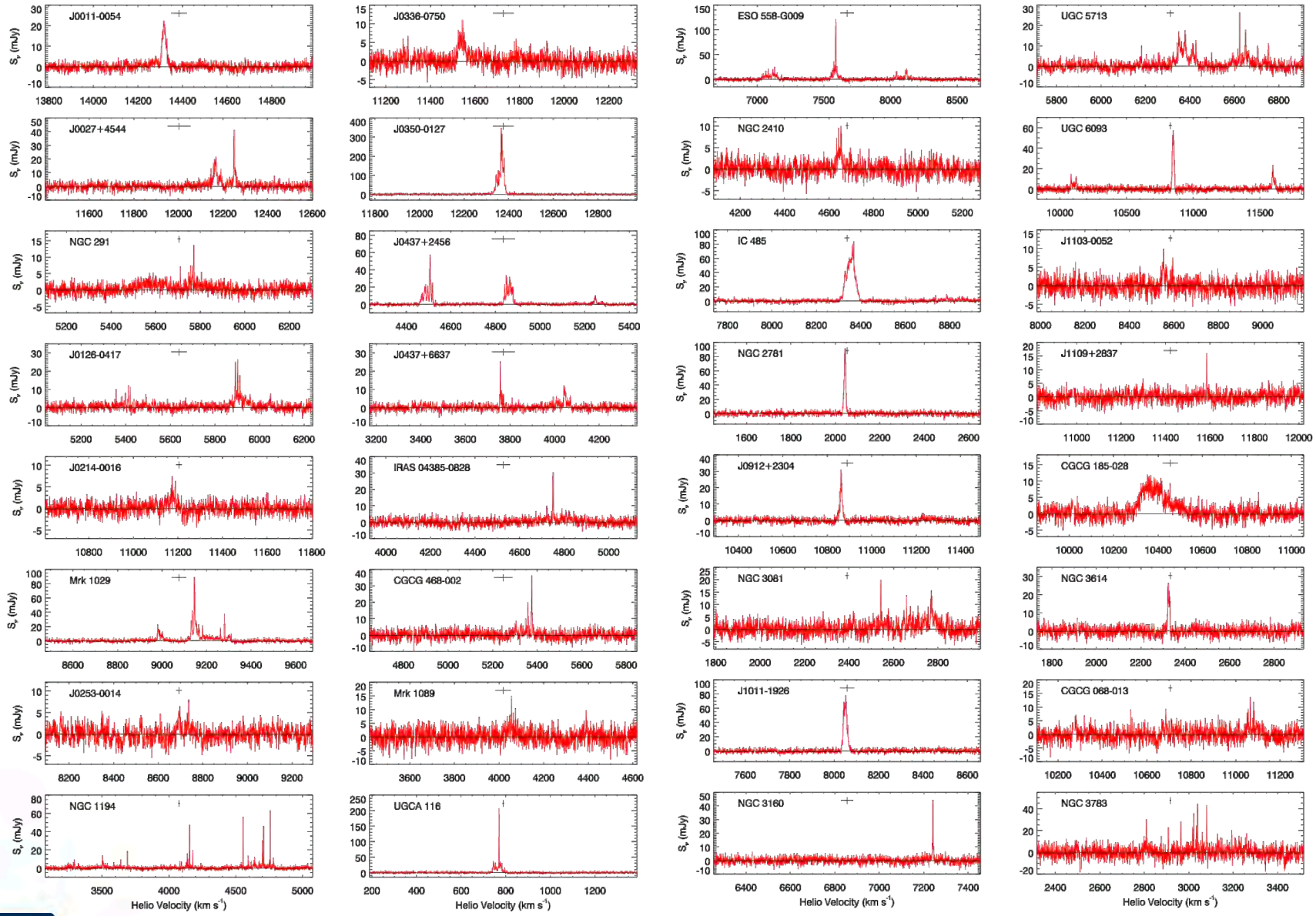
Some Technical Details

- We "nod" 2 beams of the 7-beam KFPA
- 10 minutes on-source per galaxy, longer integrations to characterize the spectrum fully
- 22.235 GHz line at z < 0.05 so ν_{sky} ~ 21.5 GHz
- All-sky coverage (should enable flexibility in scheduling, but it is not easy with the PST)
- Home-built pipeline in GBTIDL for uniform reduction; detections reduced with care by hand

Progress with Megamaser Surveys



- 180 galaxies detected out of > 4000 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 $z < 0.05$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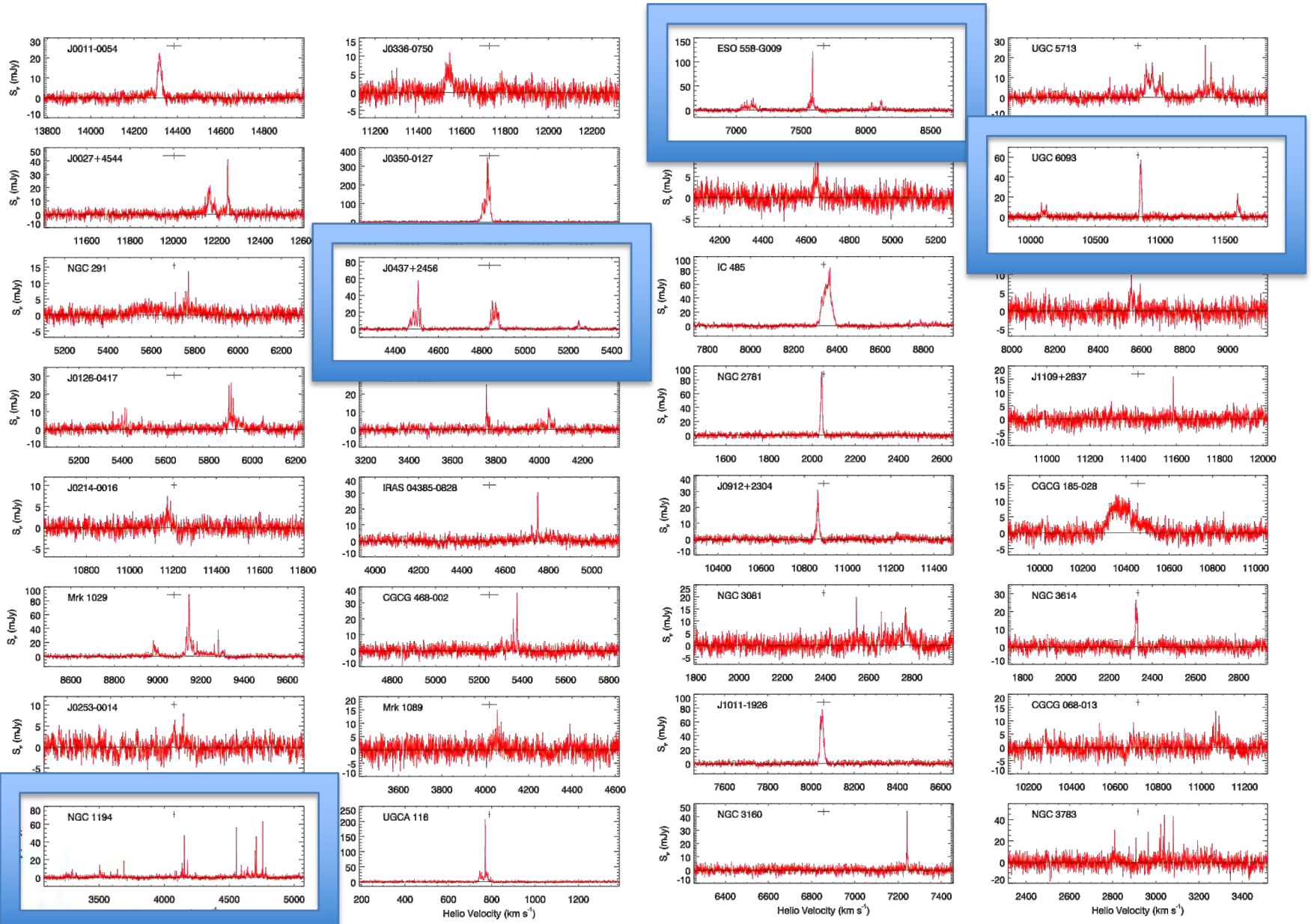
ESO 558-G009
UGC 5713
J0027+4544
J0350-0127
NGC 2410
UGC 6093
NGC 291
J0437+2456
IC 485
J1103-0052
J0126-0417
J0437+6637
NGC 2781
J1109+2837
J0214-0016
IRAS 04385-0828
J0912+2304
CGCG 185-028
Mrk 1029
CGCG 468-002
NGC 3081
NGC 3614
J0253-0014
Mrk 1089
J1011-1926
CGCG 068-013
NGC 1194
UGCA 116
NGC 3160
NGC 3783
S$_\nu$ (mJy)
Helio Velocity (km s^{-1})


J0011-0054
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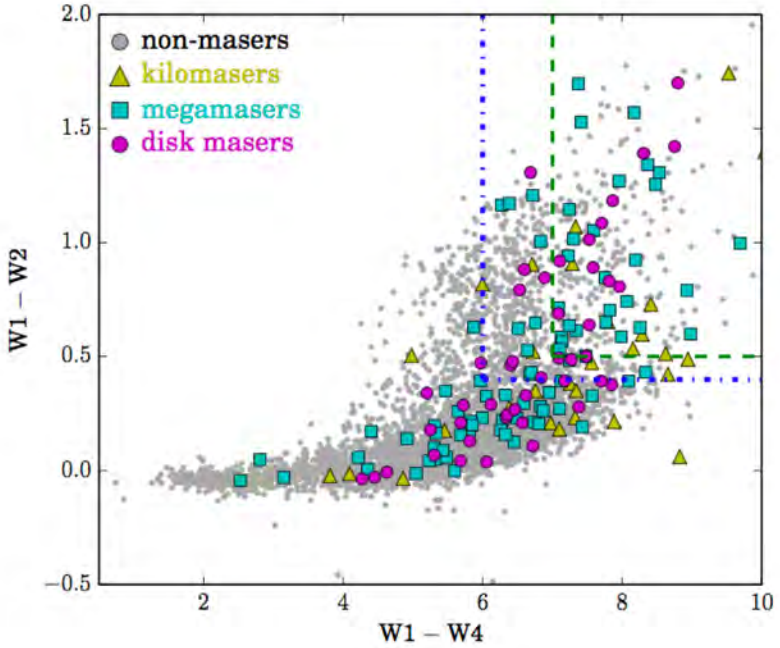
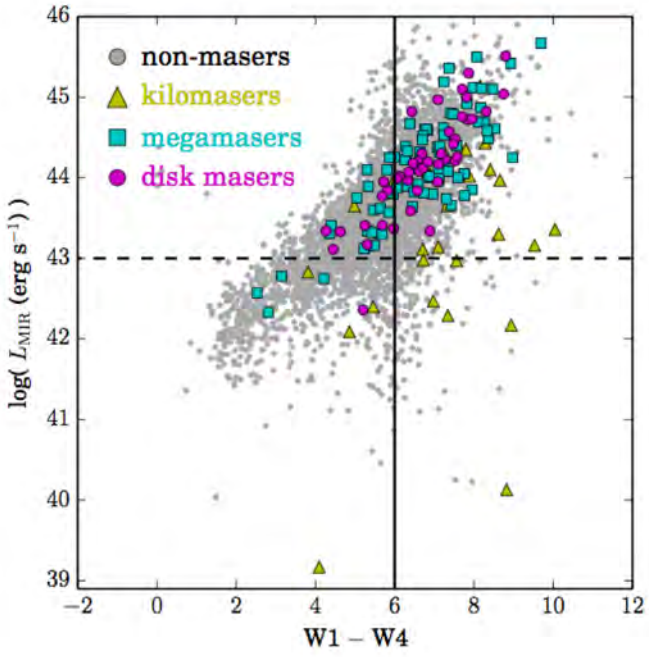
CGCG 068-013
NGC 1194
UGCA 116
NGC 3160
NGC 3783
S$_\nu$ (mJy)
Helio Velocity (km s^{-1})

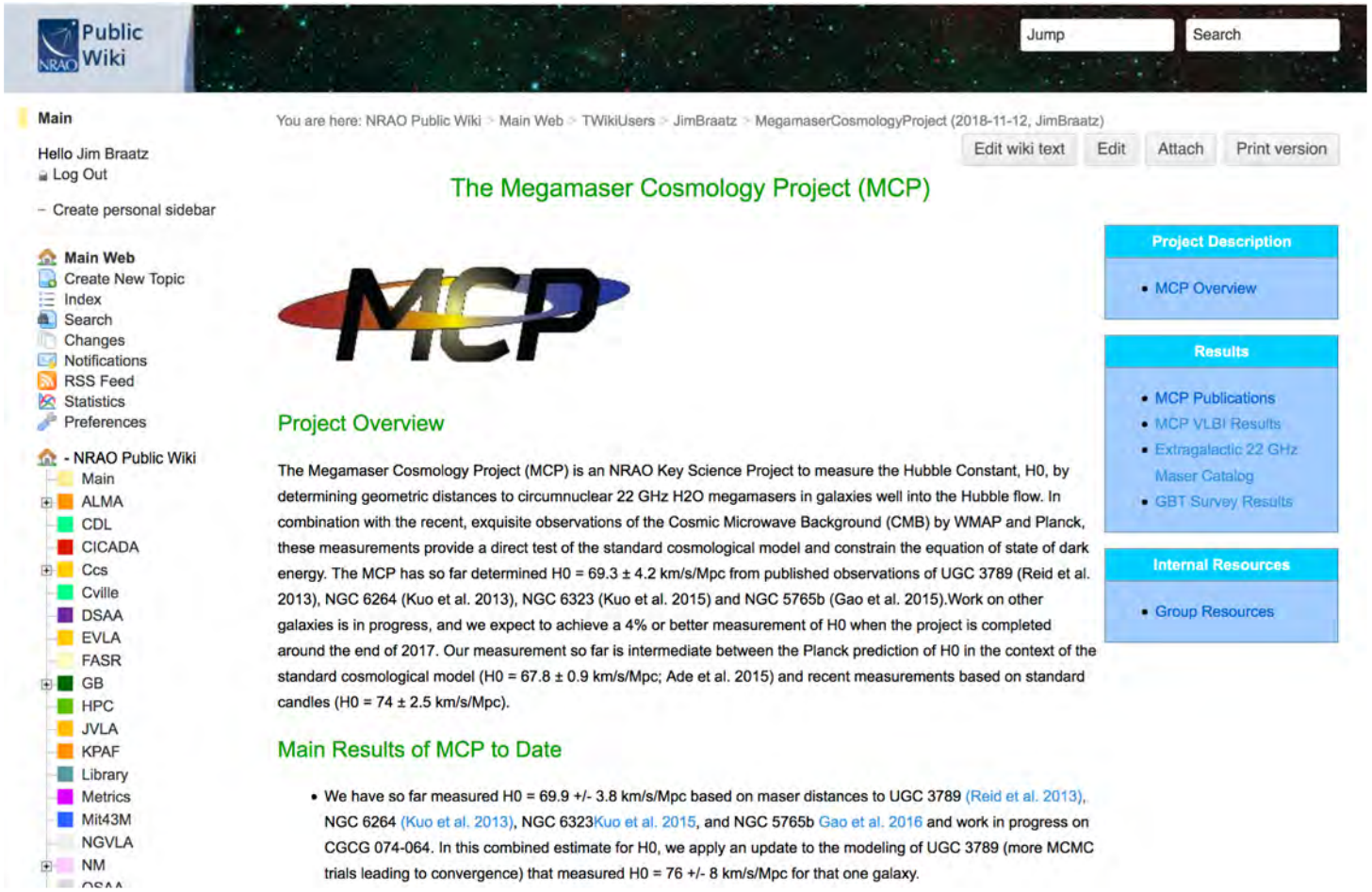
Improving the Measurement of H_0 with Megamasers: Brute Force Continuation of the MCP





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

Survey Organization



A catalog of GBT megamaser surveys is organized and maintained (by me) and hosted on MCP webpage

Survey Organization

A Catalog of Galaxies Detected in 22 GHz H2O Maser Emission

Jim Braatz (NRAO)

Updated November 10, 2018

Count	Source Name	RA (J2000)	Dec (J2000)	Vsys (km/s)	Lum	Class	Notes	Discovery Reference
1	NGC 23	00:09:53.6	+25:55:23	4565	180			Braatz08
2	NGC 17	00:11:06.5	-12:06:26	5931	<10			Greenhill09
3	J0011-0054	00:11:45.2	-00:54:31	14384	527			6A09
4	J0027+4544	00:27:25.3	45:44:27	12003	507			9C51/10C19
5	IC10	00:20:17.9	+59:18:31	-350	0.02	SF		Henkel86 (multiple positions)
6	M31	00:42:44	+41:16:09	-300		SF		Amiri & Darling 2016 (multiple positions)
7	NGC 235A	00:42:52.8	-23:32:28	6664	?			Kondratko03
8	NGC 253	00:47:33.1	-25:17:18	241	0.2	SF?		Ho87
9	Mrk 348	00:48:47.1	+31:57:25	4507	400	J		Falcke00
10	SMC	00:52:45	-72:49:43	158		SF		Breen+ 2013 (multiple positions)
11	NGC 291	00:53:29.9	-08:46:04	5705	74			6A09
12	ESO 013-G012	01:07:02.2	-80:18:28	5047	500			Greenhill02
13	J0109-0332	01:09:45.10	-03:32:32.8	16369				13A236
14	Mrk 1	01:16:07.2	+33:05:22	4780	50	D?		Braatz94
15	NGC 520	01:24:35.07	+03:47:32.7	2281	1	SF?		Castangia08
16	J0126-0417	01:26:01.66	-04:17:56.2	5639	112	D?		6dF
17	M33	01:33:16.5	+30:52:50	-180	0.3	SF		Churchwell77 (multiple positions)
18	NGC 591	01:33:31.2	+35:40:06	4547	25	D?		Braatz04

A catalog of all galaxies detected in the 22 GHz line is maintained on the MCP webpage

Survey Organization

You are here: NRAO Public Wiki > Main Web > TWikiUsers > JimBraatz > MegamaserCosmologyProject > PublicWaterMaserList (2018-11-12, JimBraatz)

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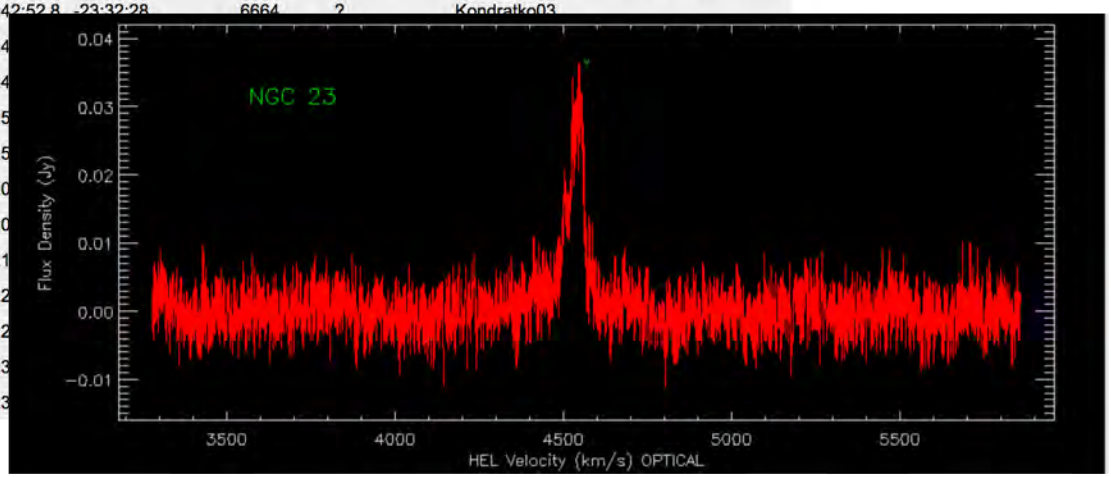
6	M31	00:42:44	+41:16:09	-300		SF		Amiri & Darling 2016 (multiple positions)
7	NGC 235A	00:42:52.8	-23:32:28	6664	2			Kondratko03
8	NGC 253	00:4						
9	Mrk 348	00:4						
10	SMC	00:5						
11	NGC 291	00:5						
12	ESO 013-G012	01:0						
13	J0109-0332	01:0						
14	Mrk 1	01:1						
15	NGC 520	01:2						
16	J0126-0417	01:2						
17	M33	01:3						
18	NGC 591	01:3						



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Survey Organization

Index of /~jbraatz/AllH2O

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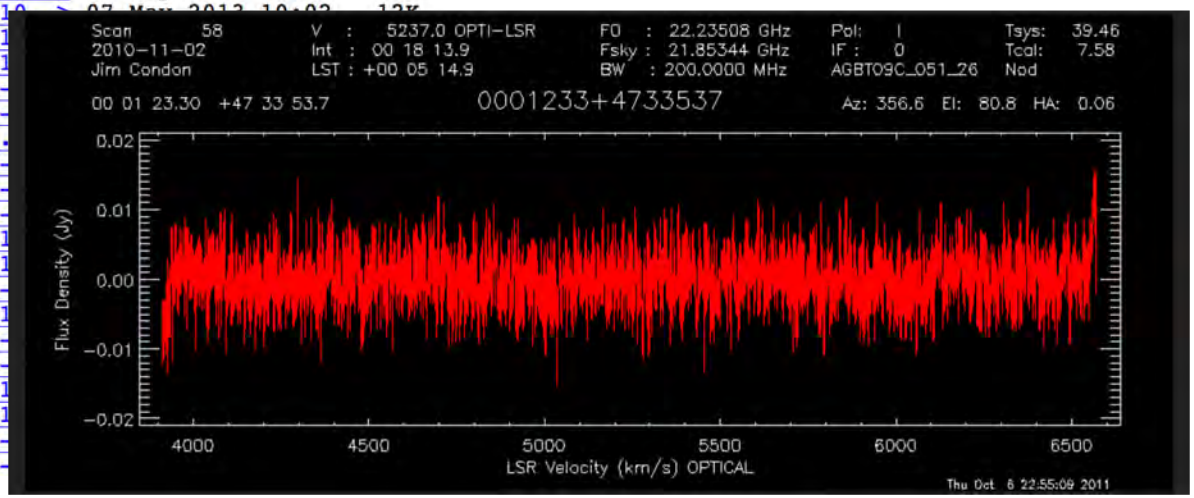

Pipeline-processed spectra of all GBT public data from extragalactic H2O observations is available from the MCP website

Survey Organization

Source	RA	Dec	Velo	Date-Obs	Tsys	Int	Rms1	Vlo1	Vhi1	Rms2	Vlo2	Vhi2
RXSJ00001+0523	00 00 11.78	+05 23 17.4	11992	2016-02-12	51.3	3	10.9	10631	13365			
KUG2358+330	00 00 58.10	+33 20 38.0	12921	2012-11-17	36.5	8	4.0	11461	14395			
0001233+4733537	00 01 23.30	+47 33 53.7	5237	2010-11-02	39.5	10	3.6	3848	6639	3.5	6358	9196
NGC-7805	00 01 26.76	+31 26 01.4	4850	2006-01-05	43.8	5	6.0	3464	6248	5.6	5968	8799
NGC-7806	00 01 30.06	+31 26 30.7	4768	2006-01-05	42.2	5	6.1	3383	6166	5.4	5885	8715
0001383+2329011	00 01 38.32	+23 29 01.1	4382	2010-12-24	38.9	10	3.8	3000	5776	4.1	5497	8319
0001419+2329452	00 01 41.90	+23 29 44.8	4393	2010-12-24	38.3	10	3.5	3011	5787	3.7	5508	8330
UGC12915	00 01 41.92	+23 29 45.3	4336	2005-02-02	27.1	28	1.5	3994	6788			
0001523+4020109	00 01 52.30	+40 20 10.7	13568	2010-11-13	36.9	10	3.1	12102	15048	3.1	14751	17747
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CGCG517-014	00 01 58.49	+36 38 57.1	9609	2012-11-17	38.8	10	3.8	8179	11051			
NGC7811	00 02 26.47	+03 21 06.8	7650	2013-12-24	41.9	9	4.4	6238	9074			
Mrk334	00 03 09.95	+21 57 37.9	6600	2003-04-27	28.1	36	1.8	5198	8014			
UM016	00 03 10.02	+04 44 56.2	17358	2005-09-28	45.6	44	2.0	16982	20021			
NGC7814	00 03 14.90	+16 08 44.1	1050	2010-04-11	34.9	10	3.1	-301	2414	3.2	2140	4900
UGC13	00 03 29.20	+27 21 05.9	7690	2010-04-11	31.9	10	2.9	6278	9115	2.6	8829	11713
NGC7808	00 03 32.10	-10 44 41.0	8787	2016-02-04	44.3	10	4.4	7454	10132			
MRK335	00 03 45.21	+20 12 10.4	7735	2009-01-22	38.6	10	3.6	6323	9160	3.5	8874	11759
NGC-7817	00 03 58.91	+20 45 08.3	2309	2005-12-14	42.4	5	5.4	946	3684	6.3	3408	6192
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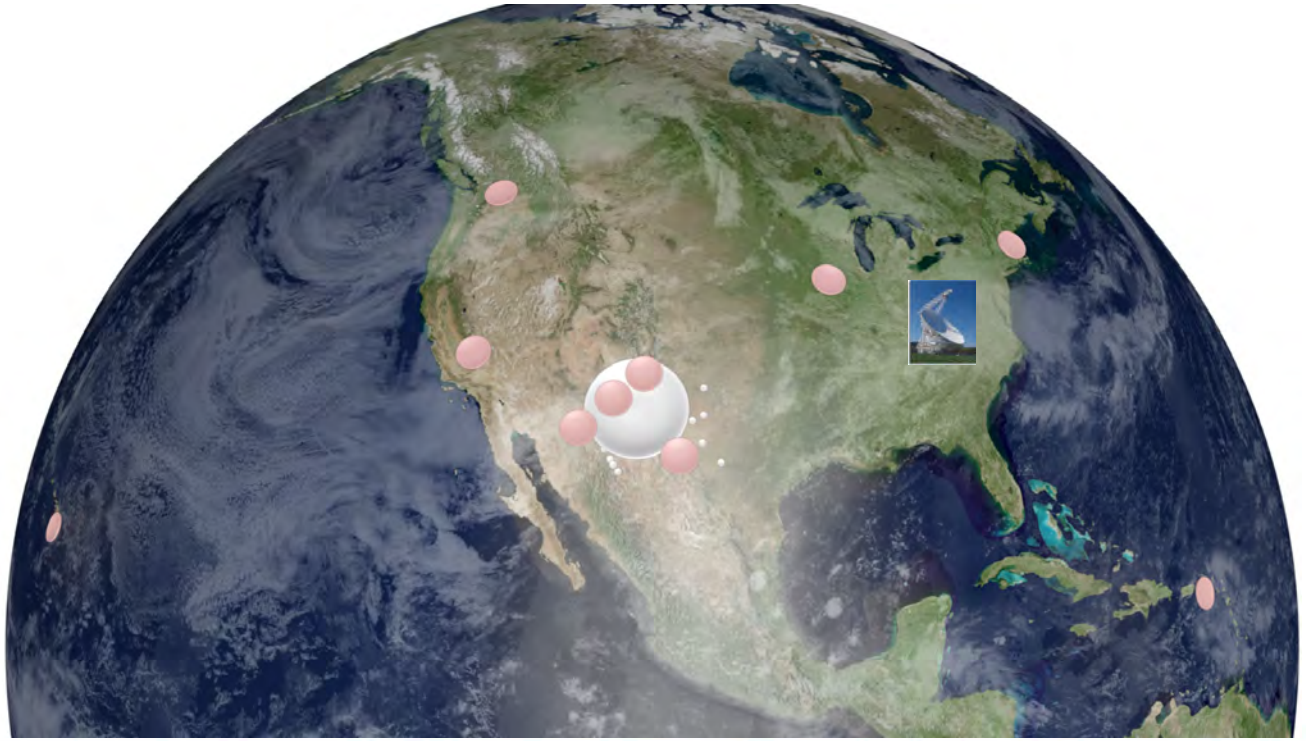
UGC46	00 06 21.70	+17 26 01.0	5506	2010-01-15	36.3	10	3.2	4114	6910	2.8	6629	9472
UGC00047	00 06 38.36	+17 17 03.2	873	2003-12-22	33.3	28	1.8	537	3268			
UGC00050	00 06 40.16	+26 09 16.1	7552	2005-02-01	26.8	24	1.6	7202	10056			
UGC52	00 06 49.48	+08 37 42.7	5257	2007-12-20	52.2	10	5.1	3867	6659	4.7	6378	9217
NGC-1	00 07 15.83	+27 42 29.1	4545	2005-12-14	41.1	5	5.9	3162	5941	6.7	5661	8486
2MASXJ00082041+	00 08 20.50	+40 37 57.0	13389	2013-05-03	69.4	10	7.7	11925	14867			
NGC-12	00 08 44.81	+04 36 44.9	3940	2005-10-02	60.6	5	8.3	3802	6592	9.1	1333	4078

An ascii catalog of all GBT observations of extragalactic H2O observations is maintained on the MCP website

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



Thoughts and Suggestions

- Linked VLBI time is essential to all of the scientific goals of surveys for megamaser disks
- Linked GBT or VLA time is essential for spectral line monitoring needed to measure galaxy distances
- Web hosting of observed galaxies by NRAO/GBO is effective. It is currently done as a service to the community.
- Megamaser surveys could serve as an effective filler/backup project for good weather conditions
- Availability of weather (wind/opacity) and ops logs as an attachment to the data would assist pipelines and identifying data reliability
- GBA/GBT will provide essential, sensitive long baselines in the ngVLA era

The End