Water Megamasers in Galaxies

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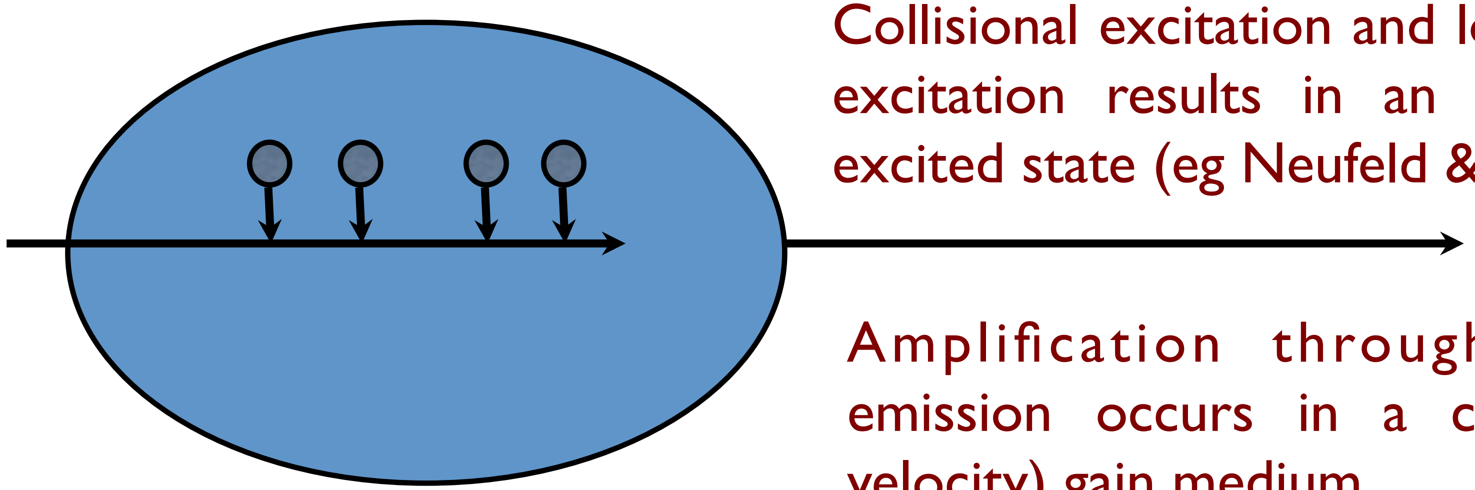
Water in the Universe : from Clouds to Oceans

Water masers emission at 22 GHz

Maser emission ($6_{12} - 5_{23}$) from water is seen at 22.2 GHz (rest frame)



Collisional excitation and low radiative de-excitation results in an over populated excited state (eg Neufeld & Melnick 1991)

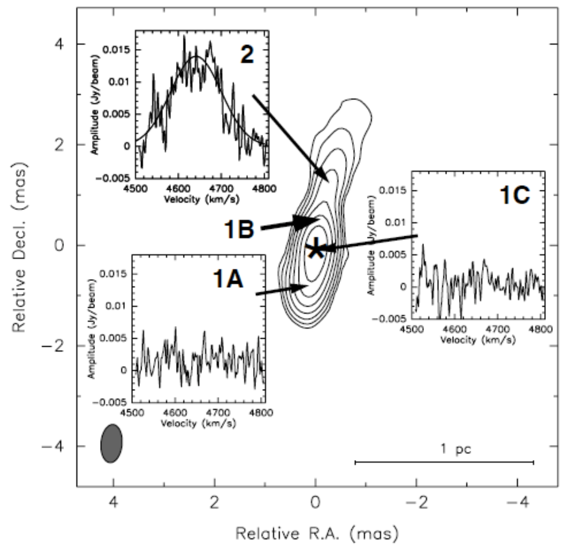
Amplification through stimulated emission occurs in a coherent (freq/velocity) gain medium.

Radiation has a very high surface brightness and is beamed to the observer.

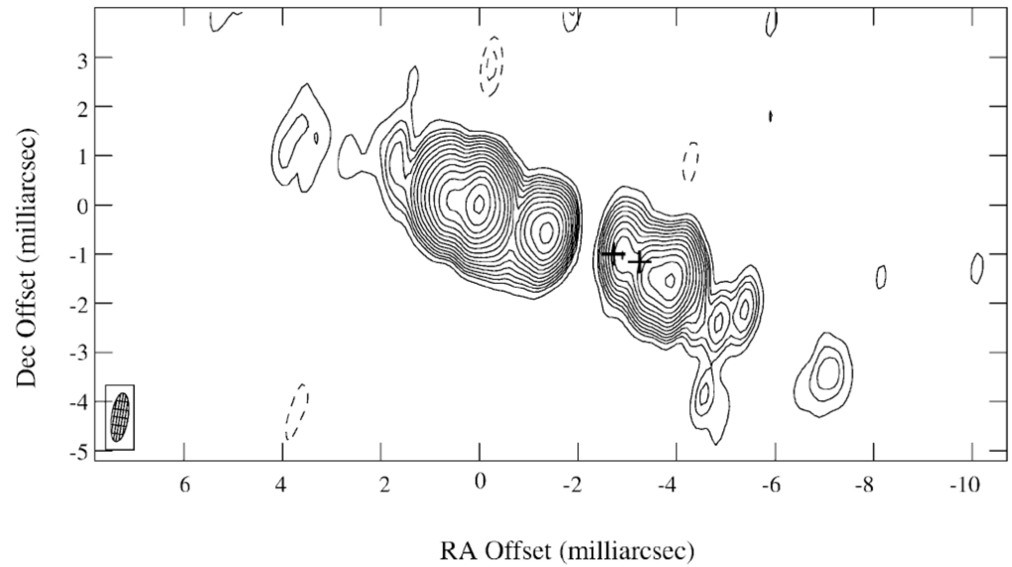
Found in regions of dense gas (10^8 - 10^{10} cm^{-3}) => most luminous (> 10 $L_\odot$) are found very close to the super-massive black hole of an AGN.

Probing AGN – jet masers

MRK348 (Peck et al. 2003)



NGC 1052 (Claussen et al. 1998)

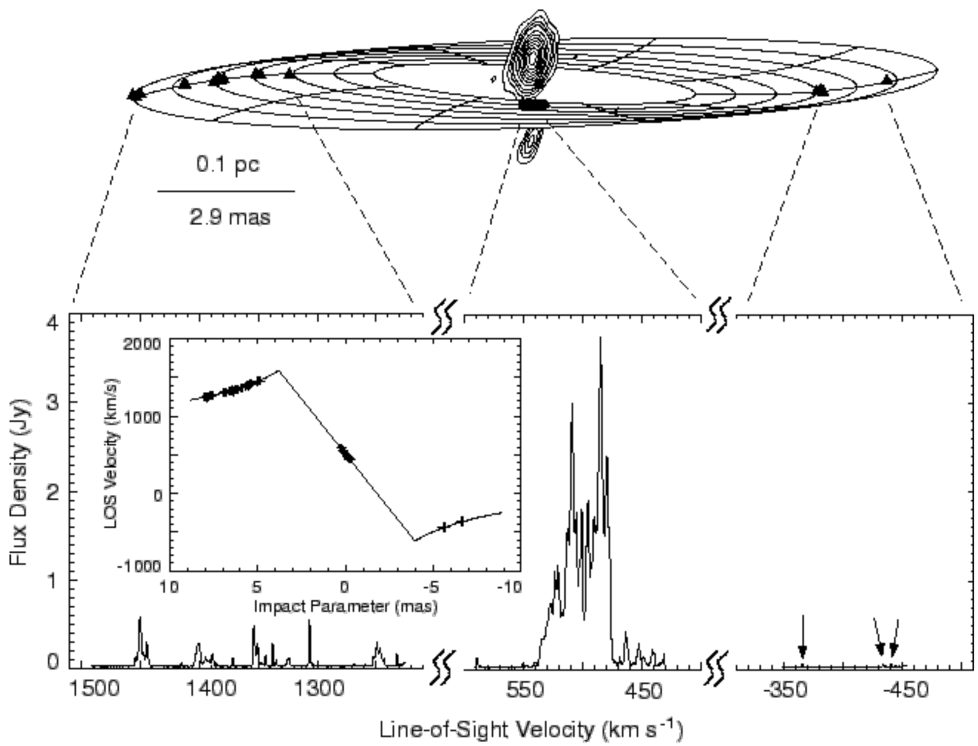


Broad line (<100 km s^{-1}) emission in the radio jet out to 30 pc from the core.

Due to interaction of the jet with a molecular cloud.

Used to study e.g. shock speeds (~ 300 kms^{-1}) and jet densities (100 cm^{-3}) for MRK 348.

Probing AGN – disk masers



Blueshifted, redshifted and systemic components.

Tend to have narrow emission lines (<1--3 km s^{-1}) and variable !

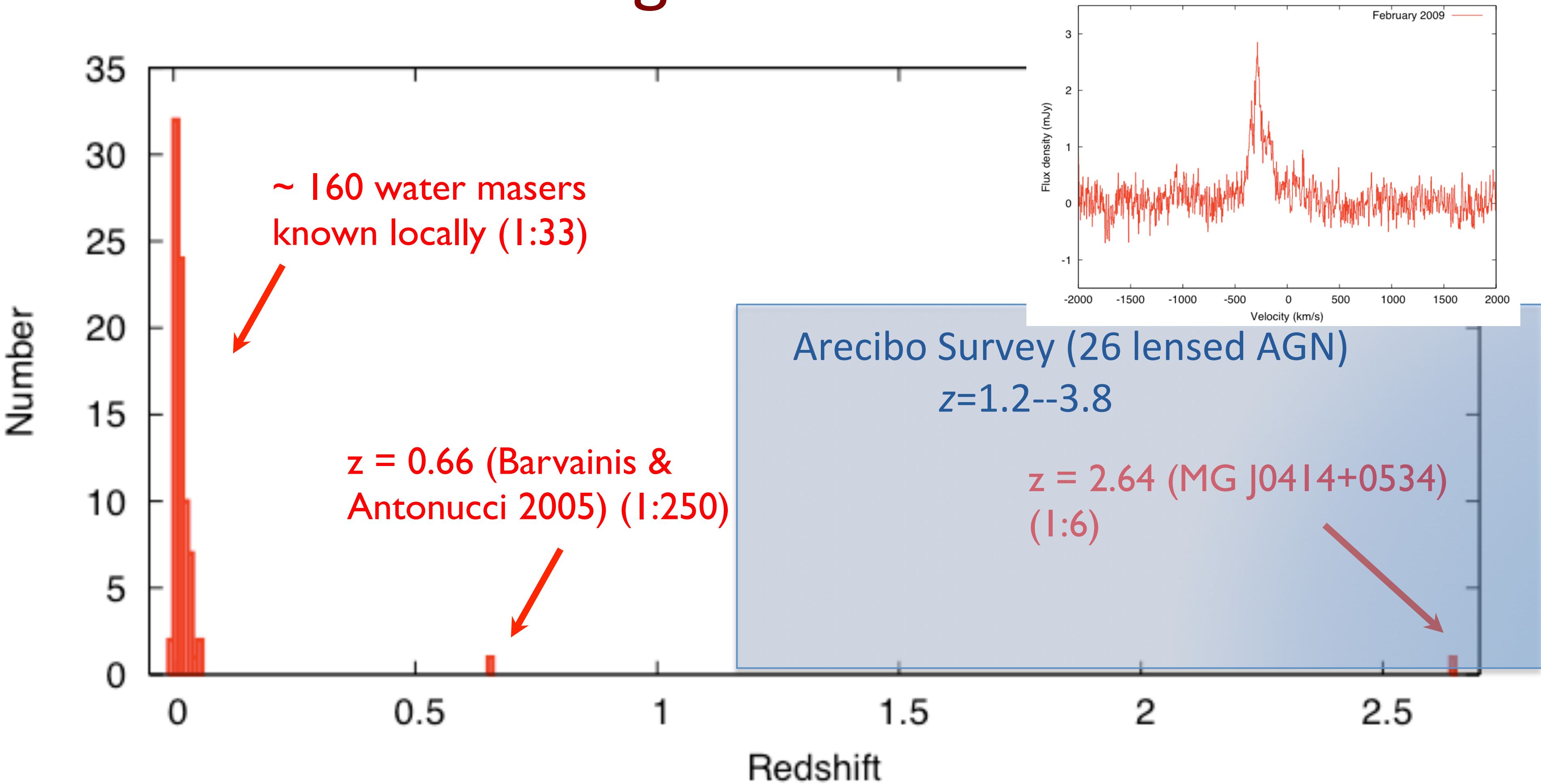
Estimate Black hole mass

NGC 4258 M_{BH} = 3 x 10^7 M_{solar} (Miyoshi et al. 1995)

With VLBI accurate geometrical distances can be found (e.g. Herrnstein et al. 1999)

NGC 4258 distance = 7.2 ± 0.3 Mpc

Can be traced to high redshifts…

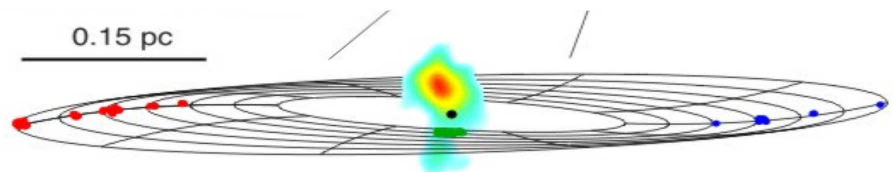


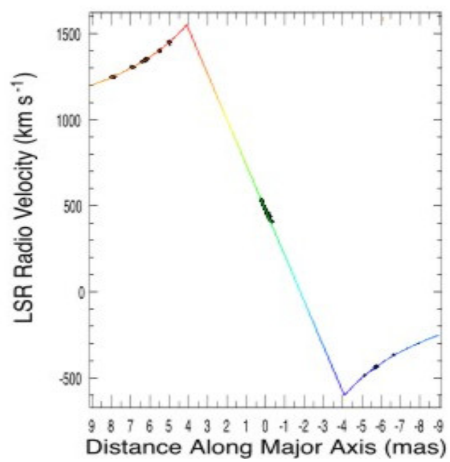
MG J0414+0534 is the most distant water megamaser water ever detected

(lensing decreases the integration time needed by ~1150; 1.8 years with Effelsberg)

Distances : NGC 4258 example

D = 7.2 ± 0.5 Mpc





$D = r/\Delta\theta$

$a = V_r^2/r$

$D = V_r^2/a\Delta\theta$

- Measure the linear size of the disk via an analysis of disk kinematics from single-dish monitoring (acceleration) and VLBI mapping (rotation curve)
- Compare the angular size of the disk to the linear size to obtain a distance

The angular offset y of the systemic masers from the black hole in the vertical direction, one can obtain the inclination i of the orbit for systemic masers
$i = \cos^{-1} (y / \Delta\theta)$

So one can obtain three parameters for the distance measurement from VLBI observation.

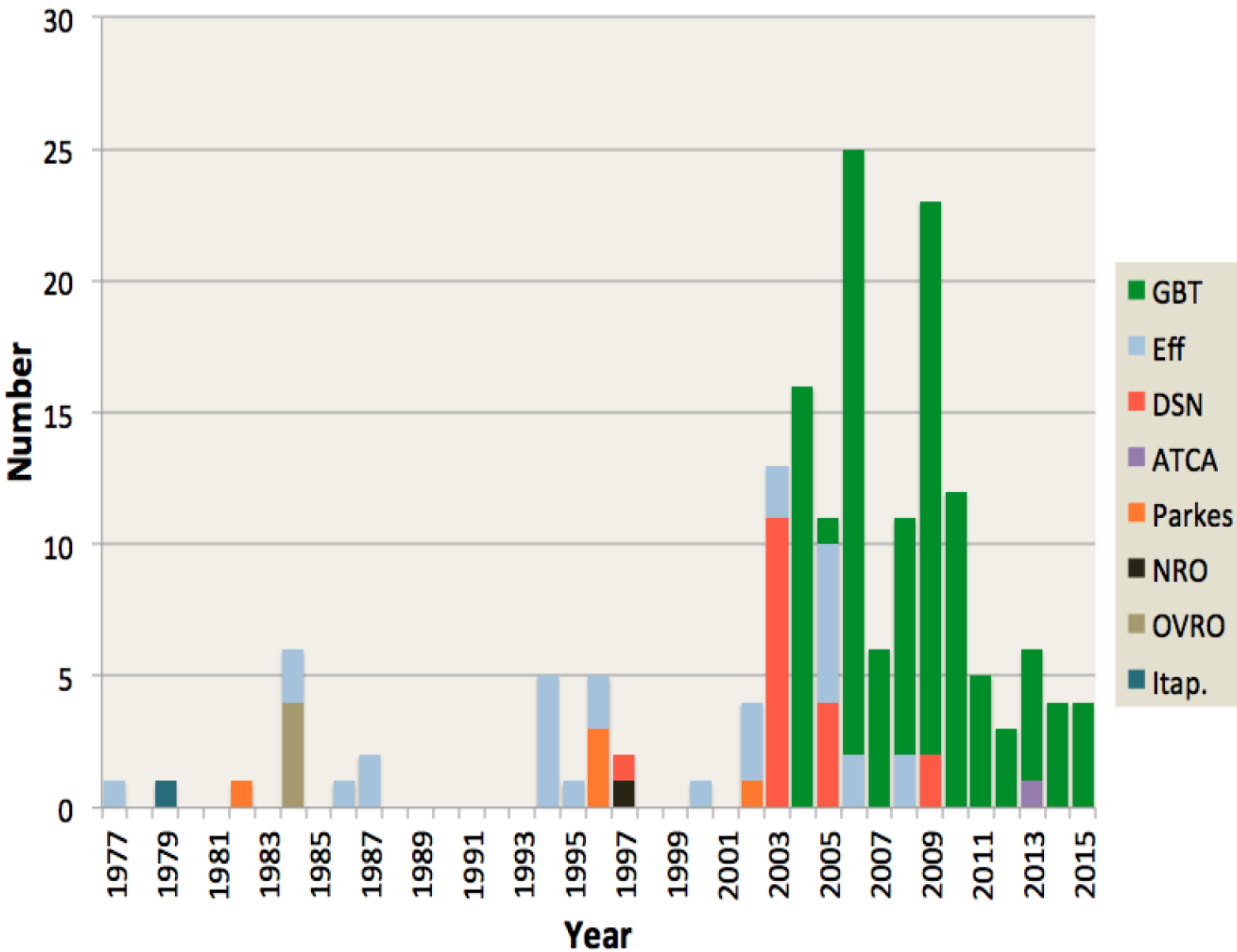
The remaining parameter, a, has to be measured from multi-epoch monitoring of maser spectra

The Megamasers Cosmology Project

- Measure H0 using *geometric* distances
- Constrain models of cosmology and Dark Energy
- Measure "gold standard" M_{BH} in external galaxies M-BH scaling relations, galaxy evolution
- Measure the geometry of the accretion disk and gas on sub-pc scales in AGNs

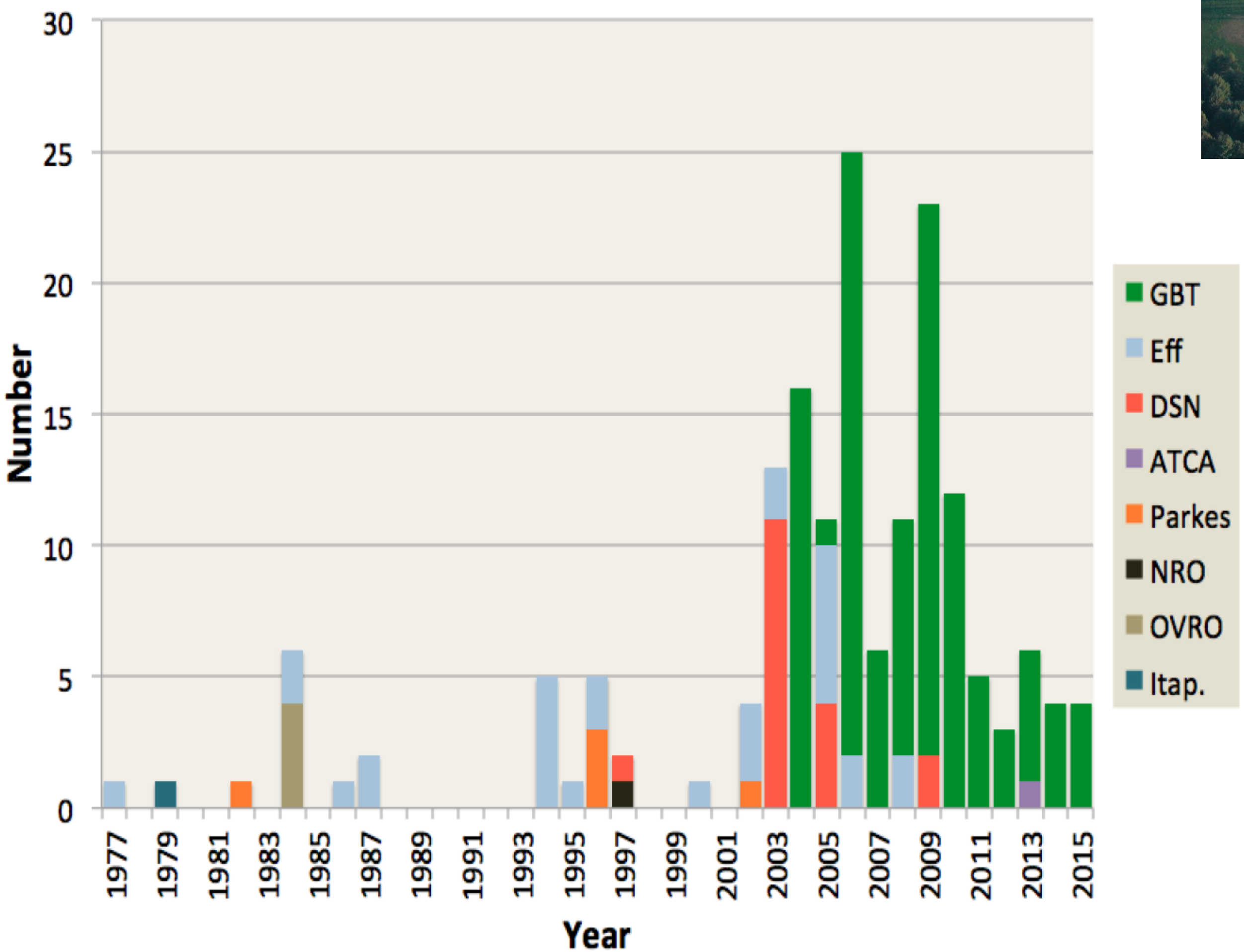
1. Survey with the GBT to identify maser disk galaxies
2. Image the sub-pc disks with the High Sensitivity Array (VLBA+GBT+EB+VLA)
3. Measure accelerations in the disk with GBT monitoring
4. Model the maser disk dynamics and determine distance to the host galaxy

Progress with maser surveys



- Discovery of the first Extragalactic H_2O in M33 (Churchwell et al. 1977)
- Discovery of masers in NGC 4258 and NGC 1068 (Claussen & Lo 1984)
- Survey finds NGC 3079 (Henkel+ 1984)
- Large surveys identify masers with type 2 AGN (Braatz+1993)
- NGC 4258 fully mapped (1995)
- Discovery of maser at z=0.66 (Barvainis & Antonucci 2005)
- Discovery of maser at z=2.64 (VI+ 2008)
- MCP makes first maser-based measurement of H_0 and maps multiple maser disks (2009+)

Progress with maser surveys



162 galaxies detected out of > 3000 observed

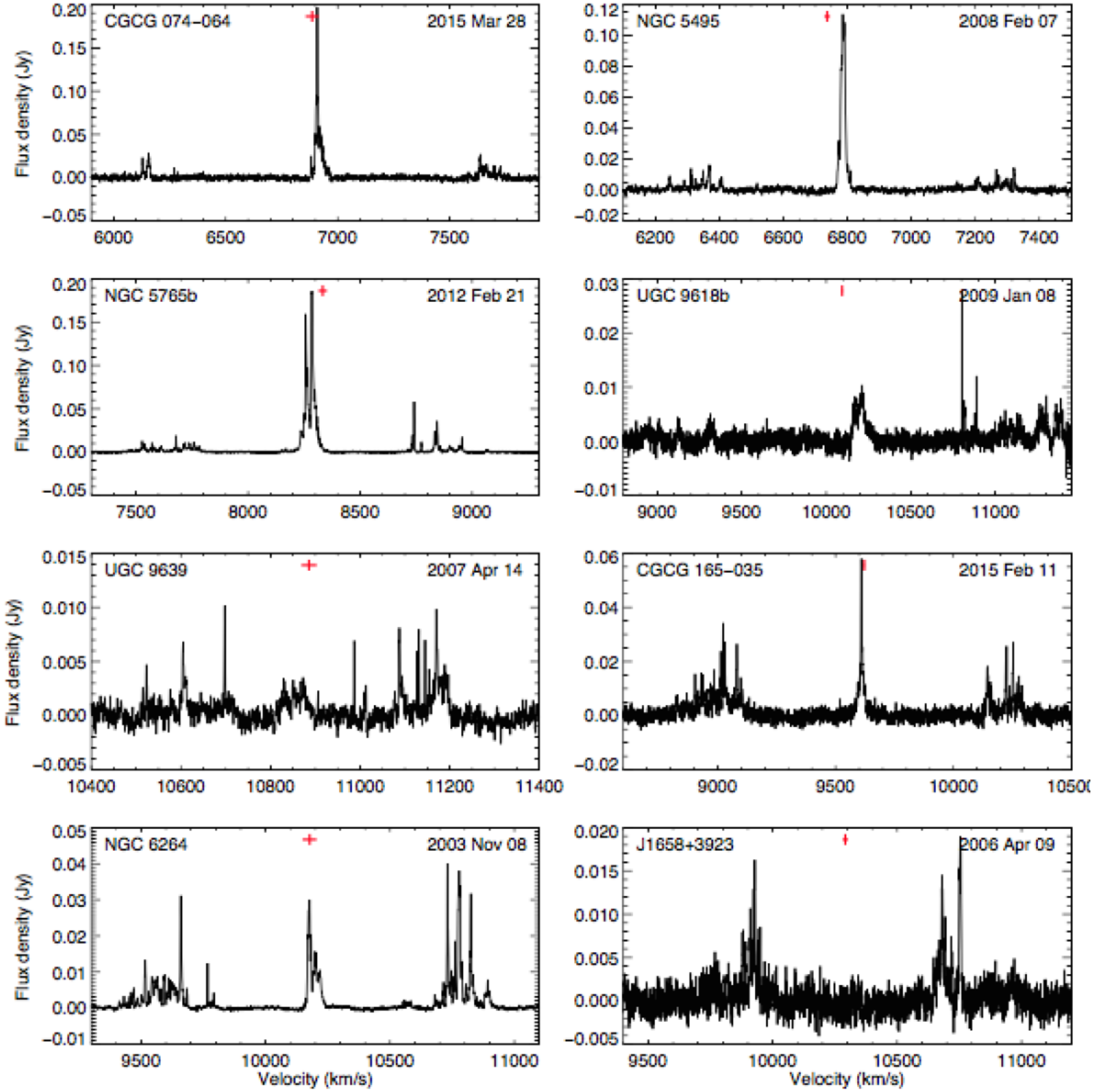
~ 140 are in AGNs

~ 37 have evidence of being in a disk and are suitable for MBH measurement

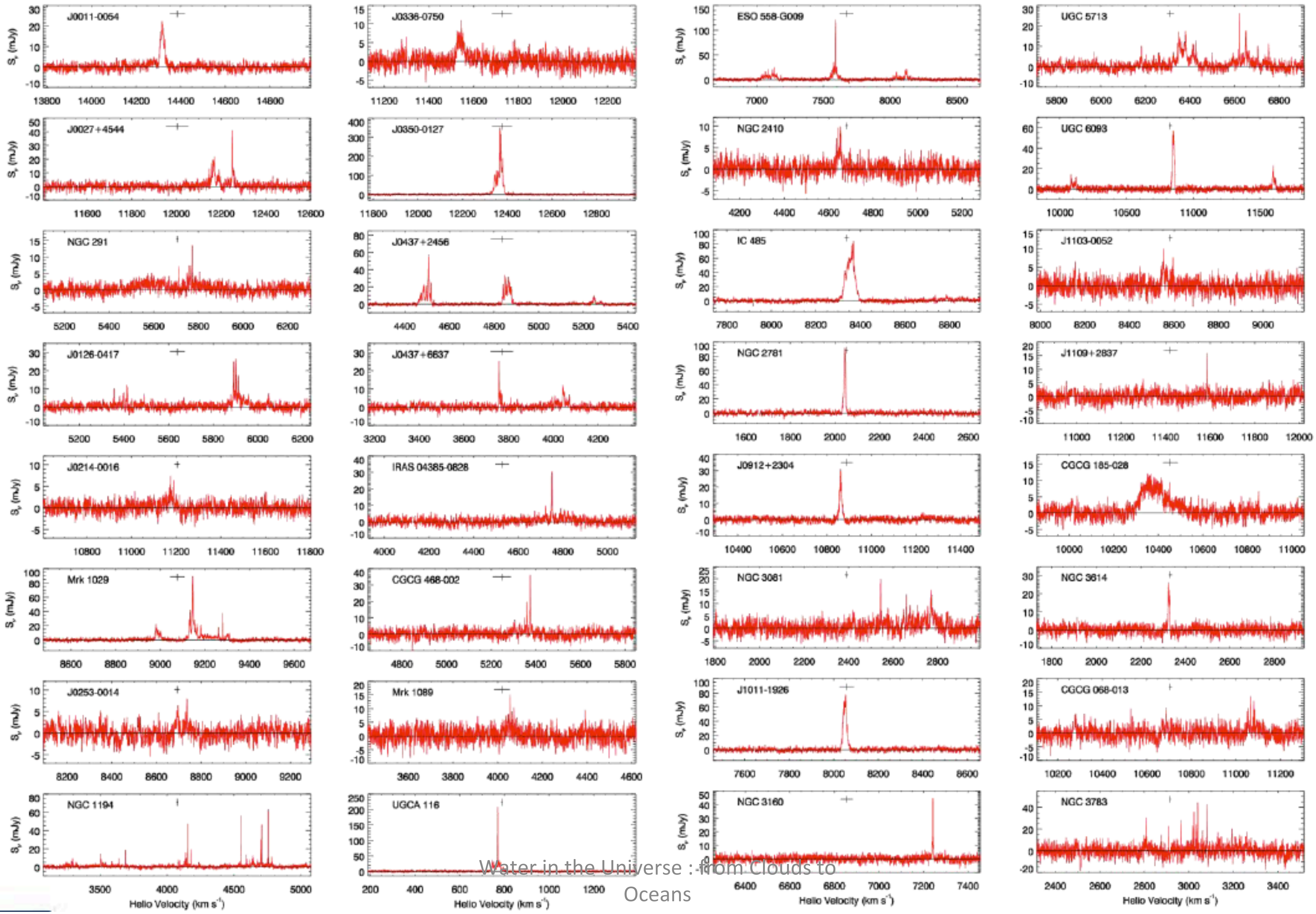
~ 10 suitable for distance measurement

Primary sample for surveys: Type 2 AGNs at $z < 0.05$

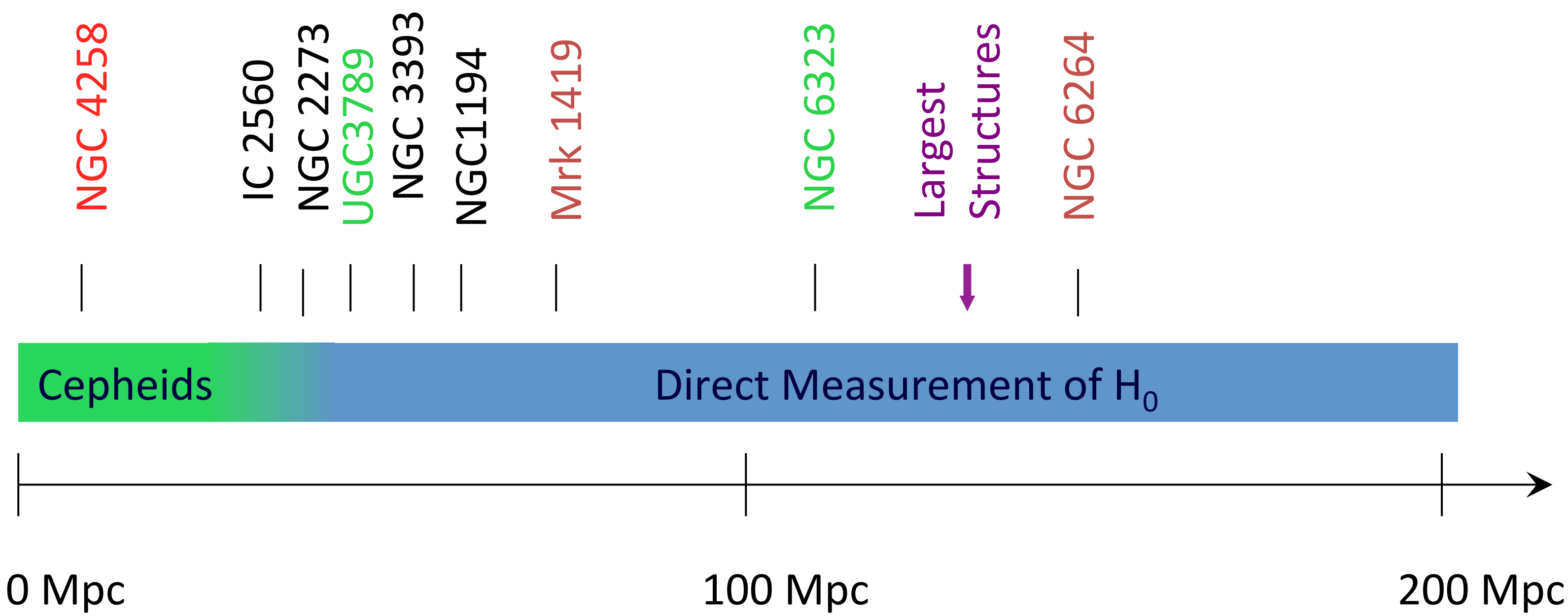
Recent GBT disk maser spectra



Single dish spectra

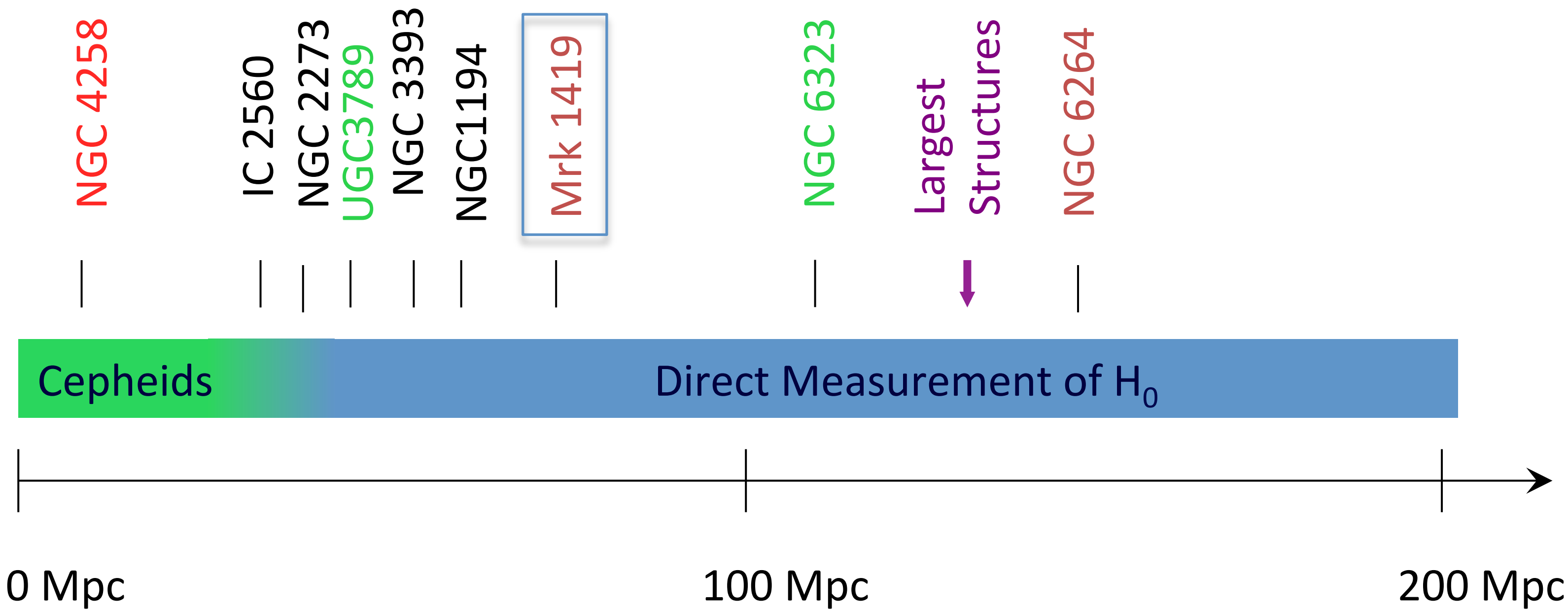


Extragalactic distance scale



- One method covers all scales out to the size of largest structures
- Maser distances can be used to calibrate other distance methods e.g. Cepheids, SN Ia, Tully-Fisher

Extragalactic distance scale



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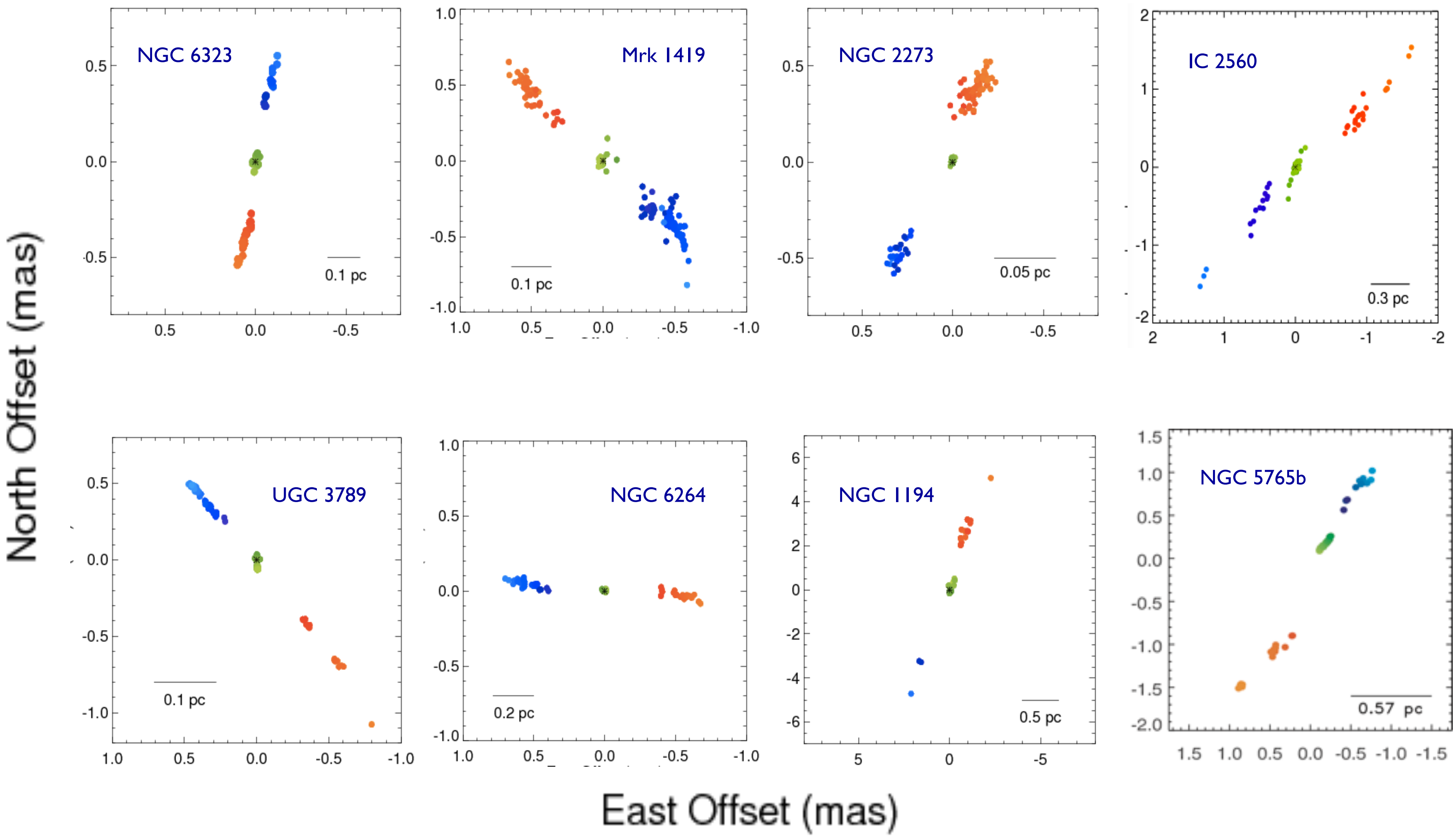
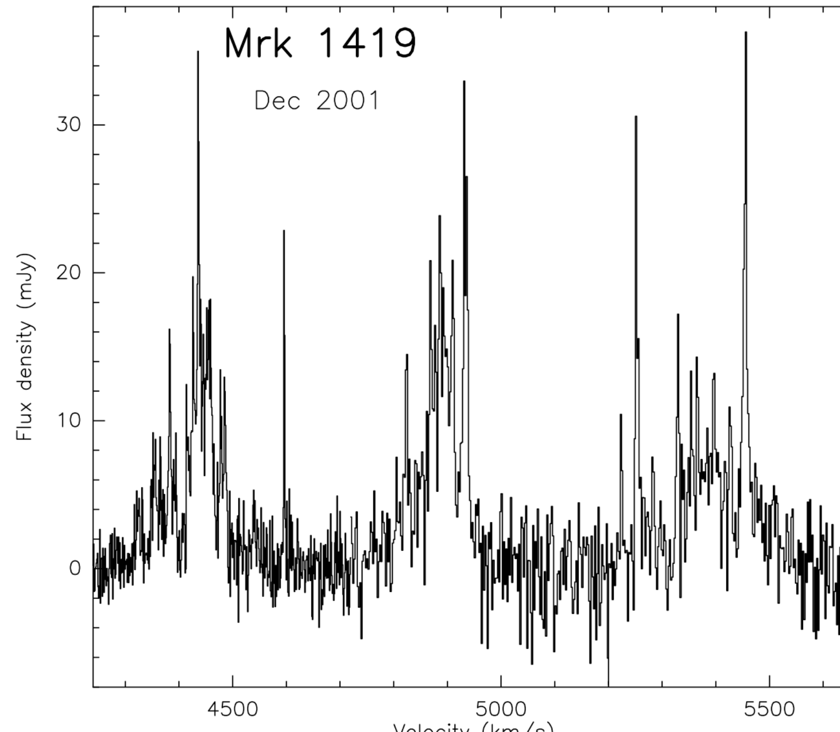
H_2O Megamaser Disks



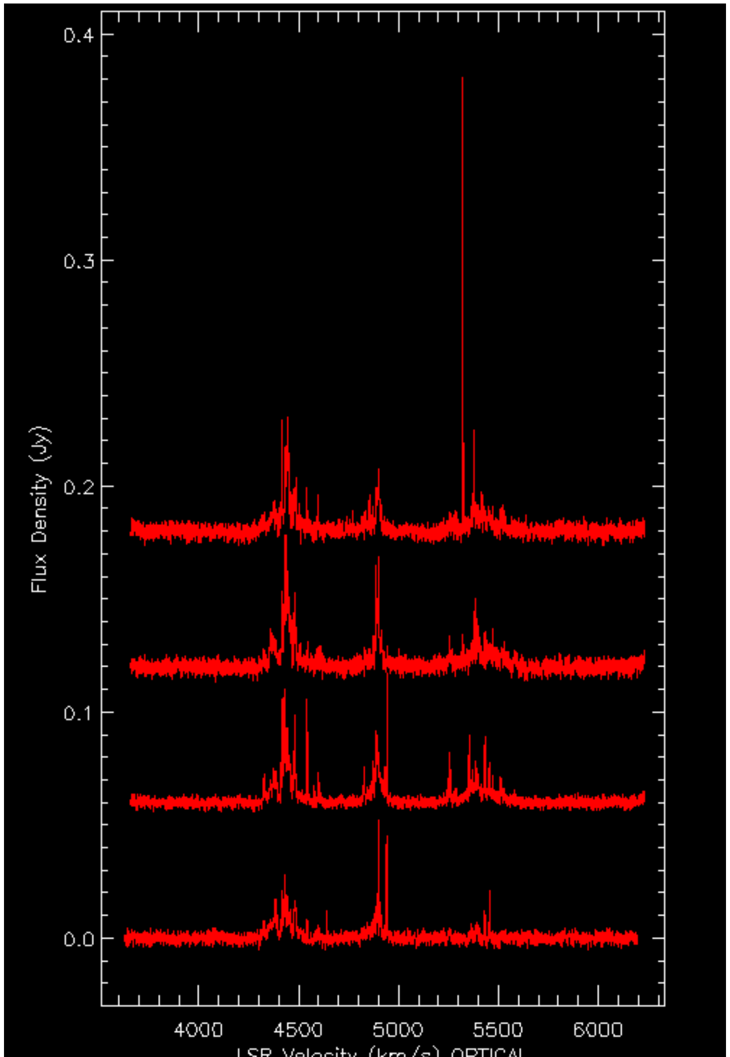
Mrk 1419

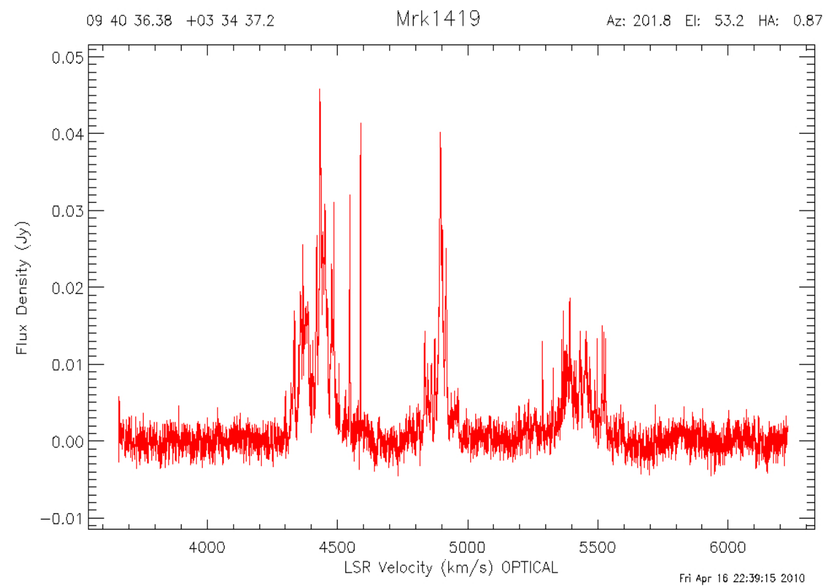
- Water maser discovered in 2002 with Effelsberg (Henkel+02)
- Sa galaxy w/ LINER nucleus, ~10 times farther than NGC 4258
- Vrot ~330-600 km s^{-1}
- R ~ 0.13 – 0.43 pc
- dV/dt ~ 2.8 ± 0.5 km s^{-1} yr^{-1}



Henkel et al. 2002

Mrk 1419



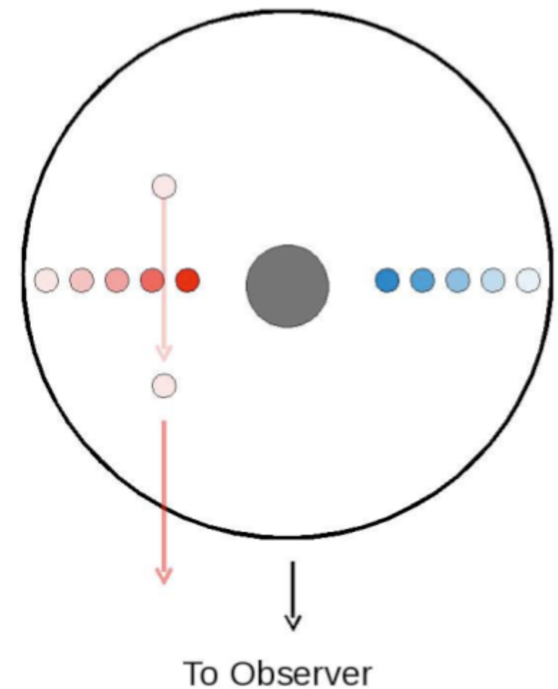


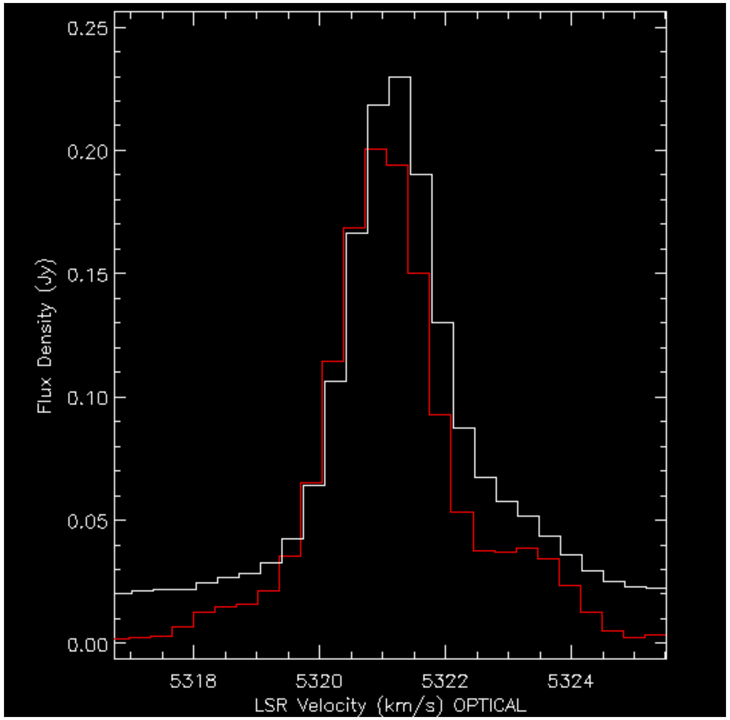
GBT single dish spectra

Blue-shifted masers strongest ~ 40 mJy

Flare in 2007 in red-shifted portion of the spectrum ~ 300 mJy.

Mrk 1419 flare

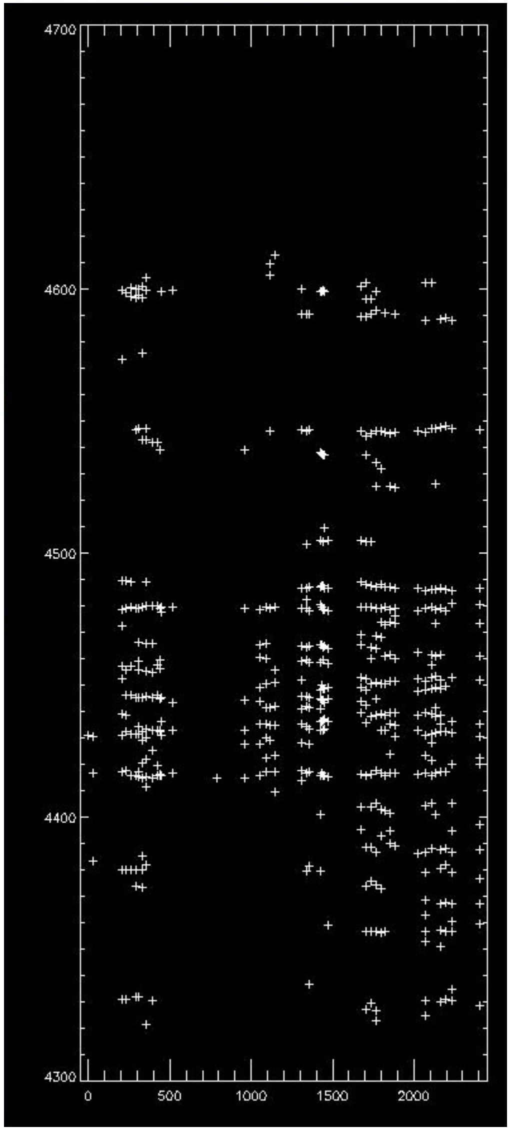




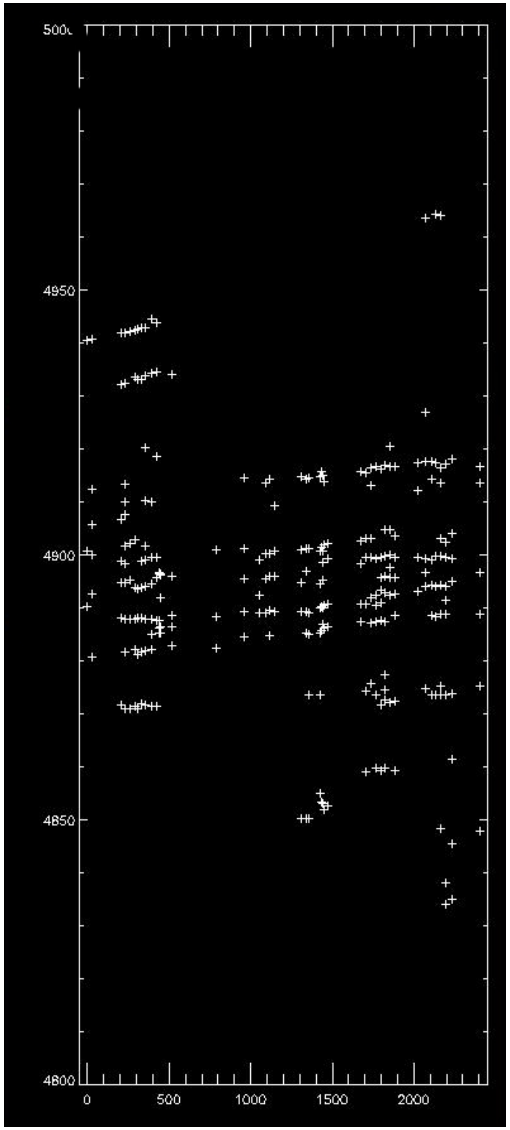
Flare lifetime ≈ 300 days
Cloud size ≈ 100 AU

Mrk 1419 accelerations

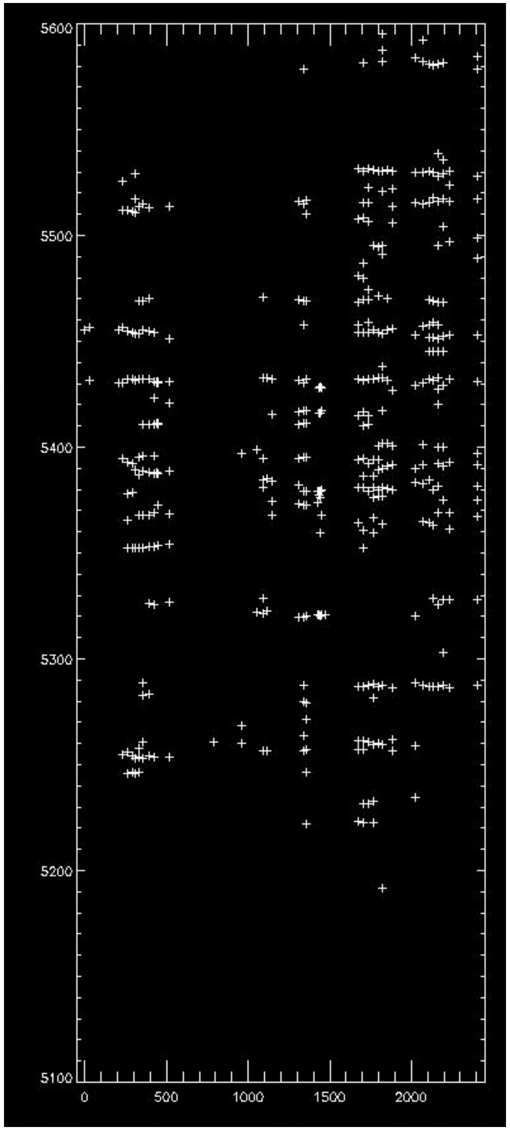
blueshift



Systemic masers

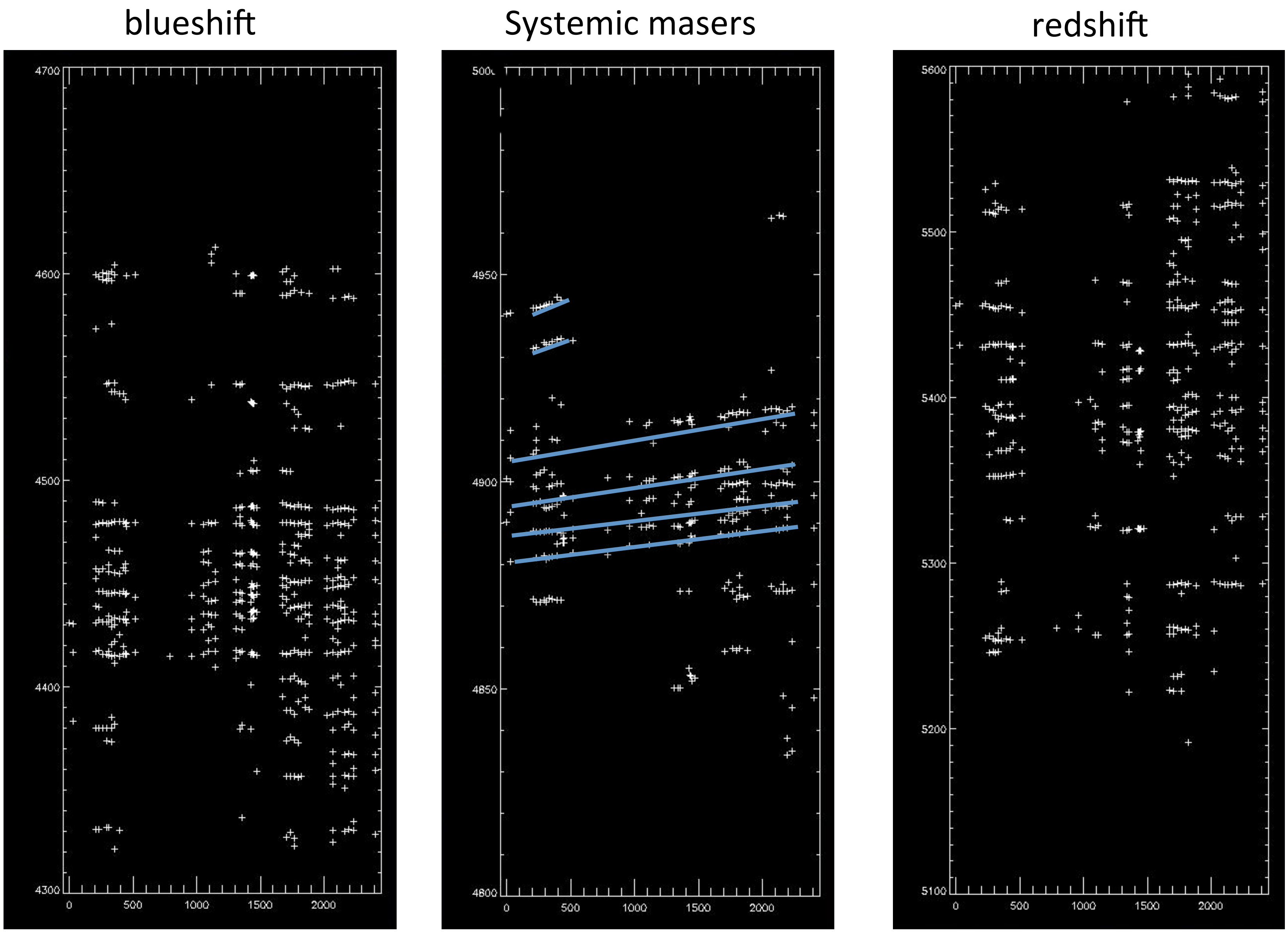


redshift

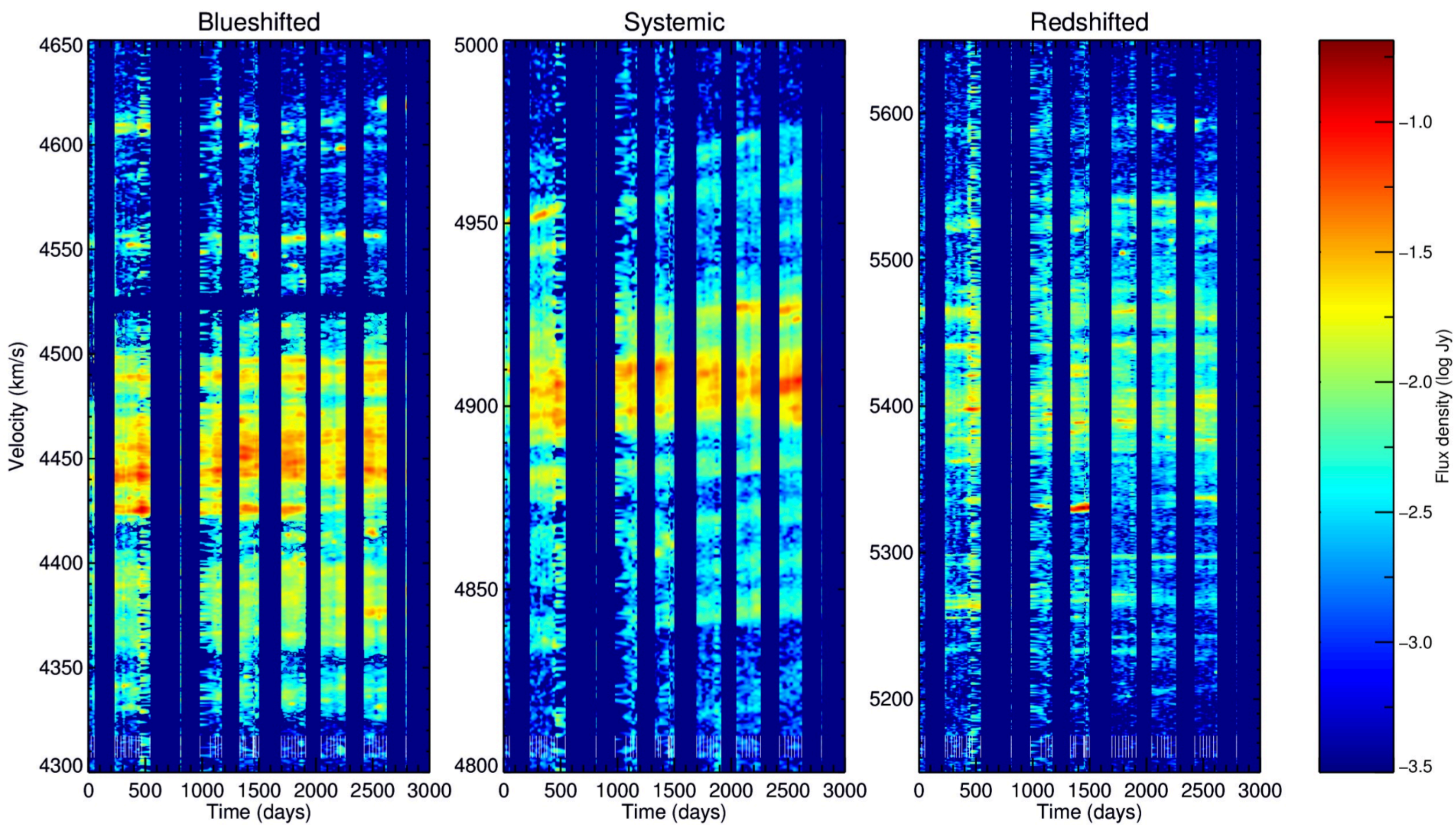


Mrk 1419 accelerations

a = (2.1 ± 0.2) km/s/yr

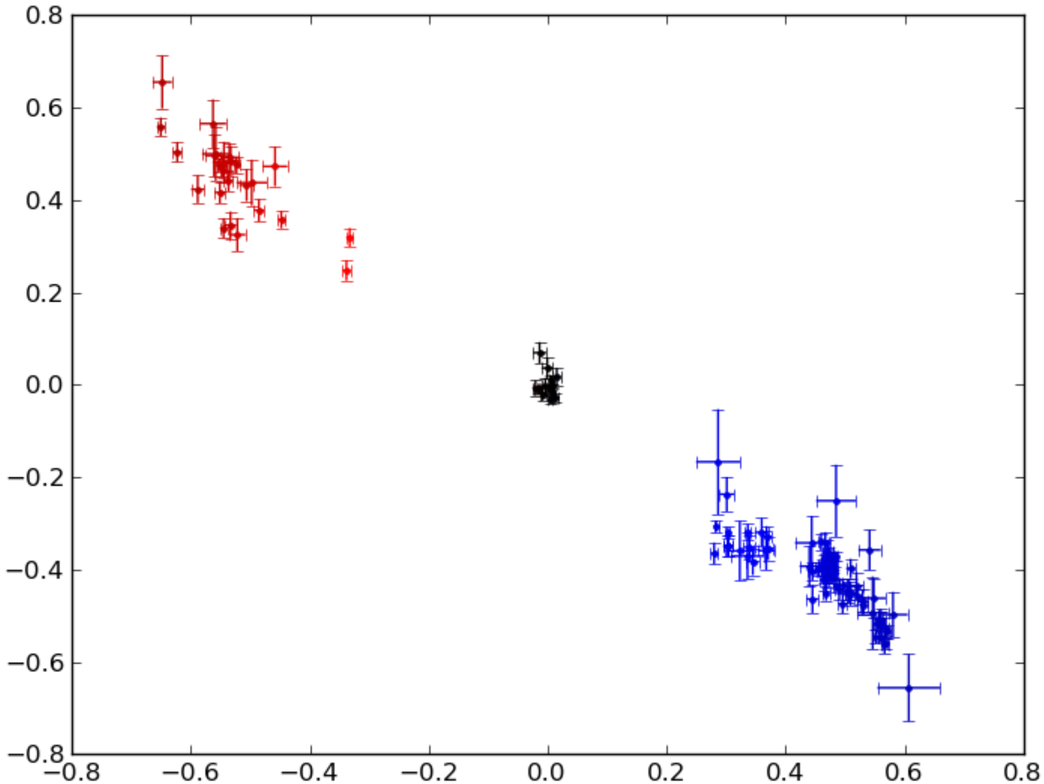


Mrk 1419 dynamic spectra



Pesce et al. 2015

Mrk 1419 VLBA observations



Six VLBI (VLBA+GBT+EFF) epochs, 12 h each

rms of each epoch ~0.8 mJy/beam

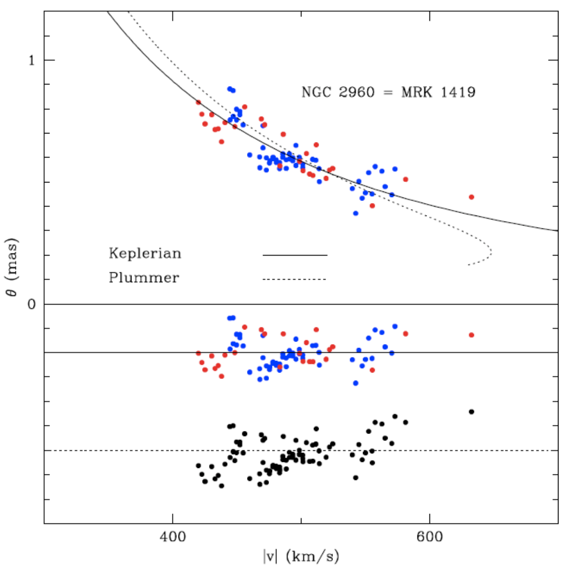
Two epochs also with (phased) VLA

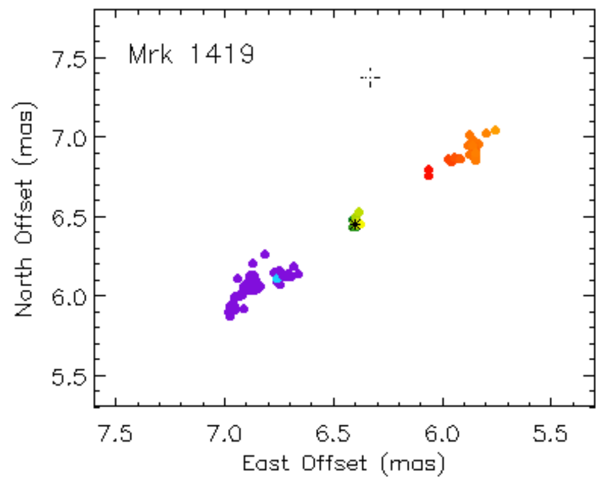
-Blue-shifted part of disk extremely warped
-Red-shifted part thick?

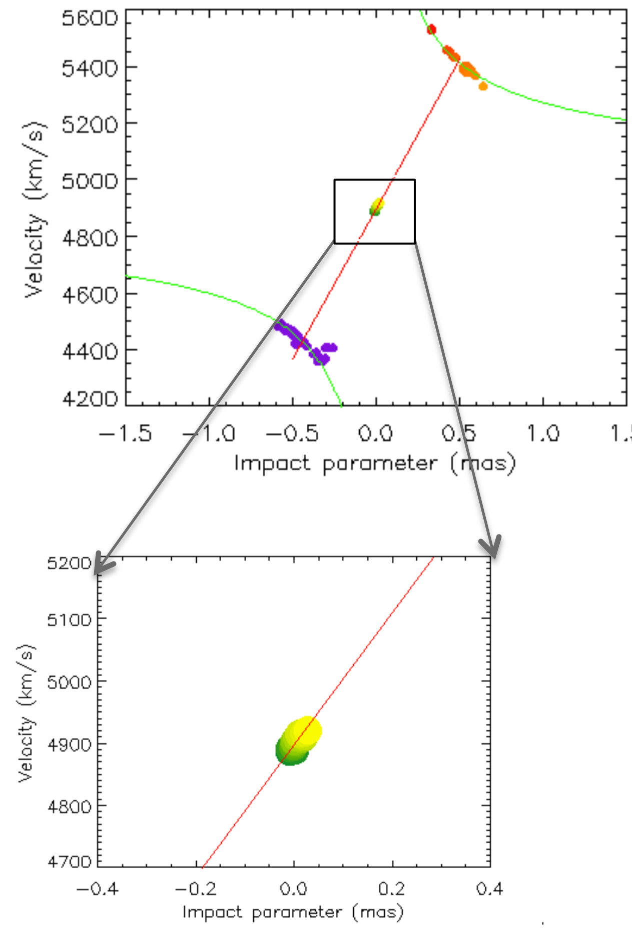
Distance to Mrk 1419 – method 1

Method 1 : plotting the data on a PV diagram

Distance 65 Mpc ± 17%
Vsys – 4935 km/s







But caveats:
Warped /thick disk? Torus?

$M_{BH} = 1.15 \times 10^{7}\ M_{aun}\ (D_A / 71\ \mathrm{Mpc})$

Distance to Mrk 1419 – method 2

Method 2 : Bayesian approach

Bayesian analysis allows one to use all prior information for the model parameters to constrain the fitting.

- We fit a model (15 global parameters) with a Markov chain Monte Carlo approach, and use the Metropolis-Hastings algorithm to choose successive trial parameters
- We model the disk with a warp (position angle and inclination angle) and can fit eccentric orbits.
- Inputs: (x, y, v, a) for each maser spot
- Provide V_{pec} and fit H0 directly
- Code developed by Mark Reid (CfA)

Rather than seeking a single (best) solution and formal uncertainties, the Bayesian approach can directly probe the probability distribution of parameters without the assumption that the uncertainties follow the Gaussian distribution

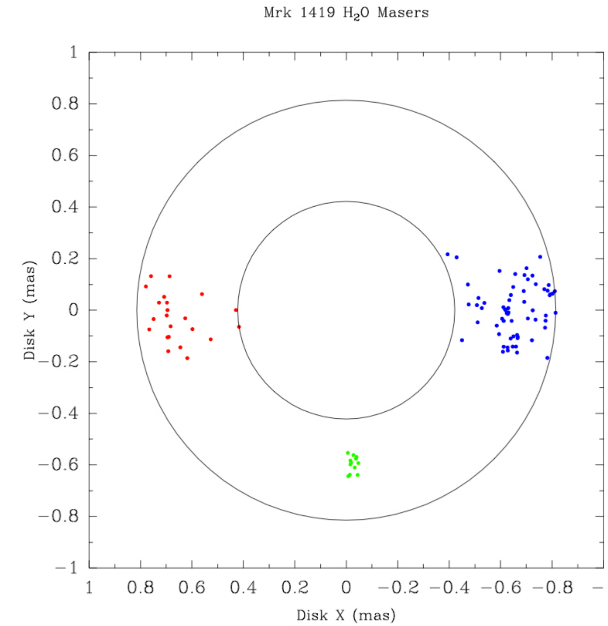
Distance to Mrk 1419 – method 2

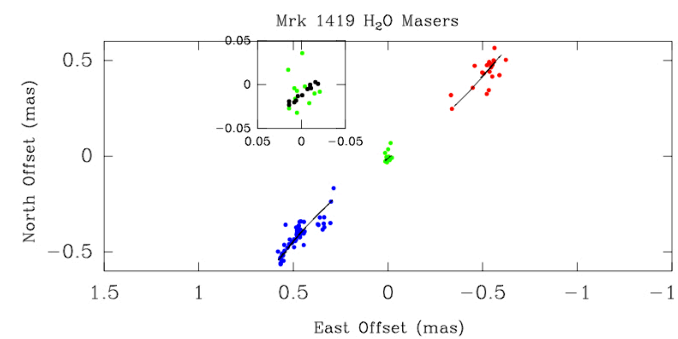
Method 2 : Bayesian approach

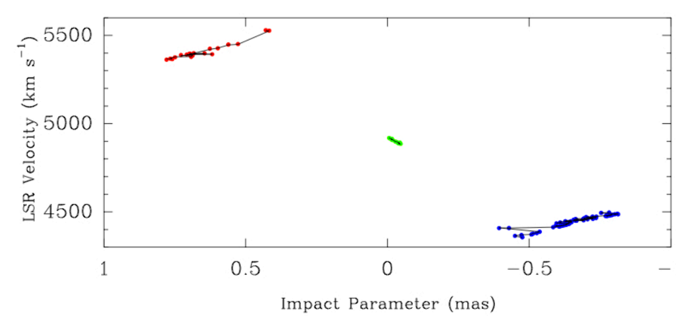
Vlsr = 4882 +/- 2 km/s , 91. inclination angle

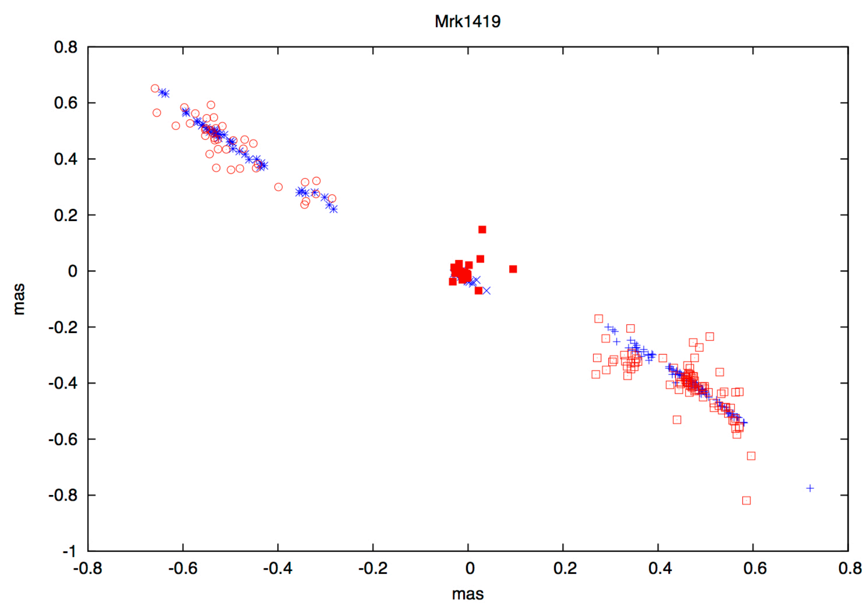
Dist = 72 +/- 14 Mpc

BH mass = 0.9 +/- 0.2 M_{solar}









Estimation of H_0 from Geometric Distances

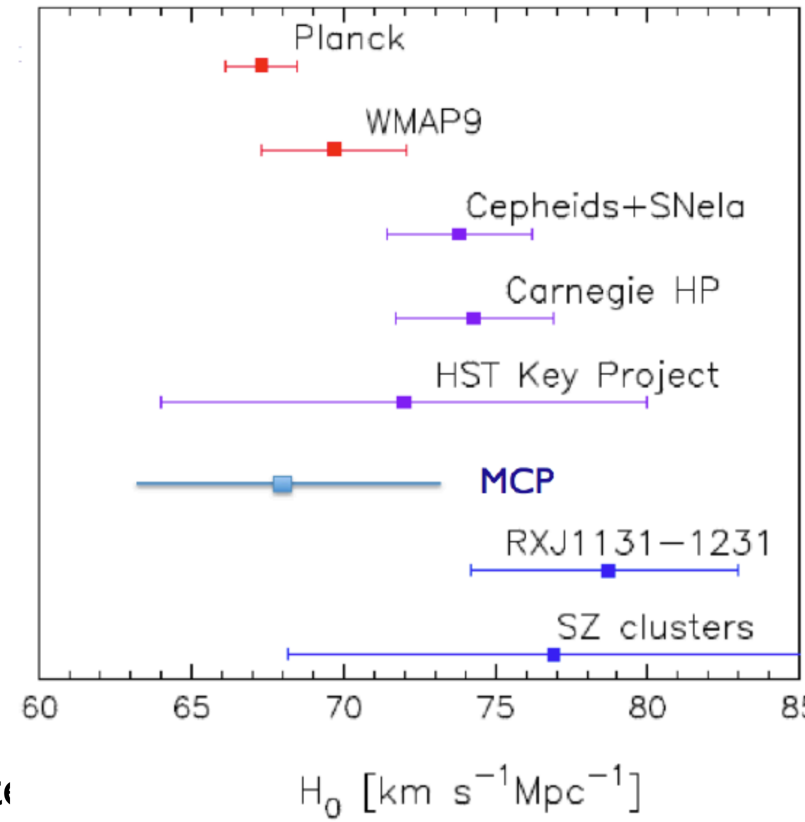
$H_0 = 67.6 \pm 4.0$ km s^{-1} Mpc^{-1} (6%)

- UGC3789 49.6±5.1Mpc H_0= 69±7 (Reid et al. 2013)
- NGC6264 137±19 Mpc H_0= 68±9 (Kuo et al. 2013)
- NGC6323 107±42 Mpc H_0= 73±26 (Kuo et al. 2015)
- NGC 5765b 126±11 Mpc H_0= 66±6 (Gao et al. 2016)
- Mrk 1419 H_0 = 69 ± 14 (Impellizzeri et al in prep)
- IC 2560 H_0 = 68 ± 12 (Wagner et al. in prep)

- Our measurement is in agreement with Planck prediction and supports the base Λ CDM cosmology
- Including new galaxies being studied, we expect to improve the measurement to < 4%.

Improving the MCP measurement of H_0

- Improving VLBI sensitivity
- Improving acceleration monitoring
- Measuring additional galaxies
- IC 2560
- NGC 1194
- NGC 2273
- ESO558-G009
- NGC 5765b
- J0437+2456



- Improving our acceleration measurement te
- Incorporating "blind analysis" methods • SKA:

Update to Fig. 16
Ade et al. 2013 (Planck paper XVI)

Black hole masses from megamasers

GALAXY	M_{BH} (M_{sun})
Mrk 1419	1.1×10^7
NGC 1194	6.6×10^7
NGC 2273	7.6×10^6
NGC 6264	2.5×10^7
NGC 6323	1.0×10^7
UGC 3789	1.1×10^7

$$M_{BH} = k^2 D/G$$

Previously Published BH masses

GALAXY	M_{BH} (M_{sun})
NGC 4258	3.8×10^7
NGC 1068	8.6×10^6
Circinus	1.7×10^6
NGC 3393	3.1×10^7
NGC 3079	2.0×10^6

BH masses from MCP

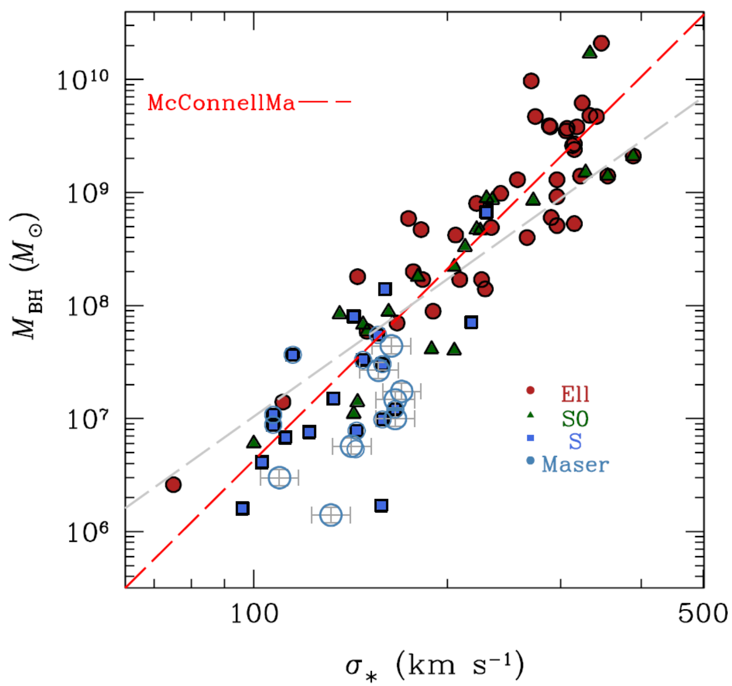
Galaxy	M_{BH} (M_{sun})
NGC 4388	1.5×10^7
NGC 5728	2.3×10^6
IC 2560	2.0×10^6
Mrk 1	in hand

Kuo et al. 2011

Galaxy	M_{BH} (M_{sun})
Mrk1210	1.3×10^7
J0437+2456	1.3×10^7
ESO 558	1.5×10^7

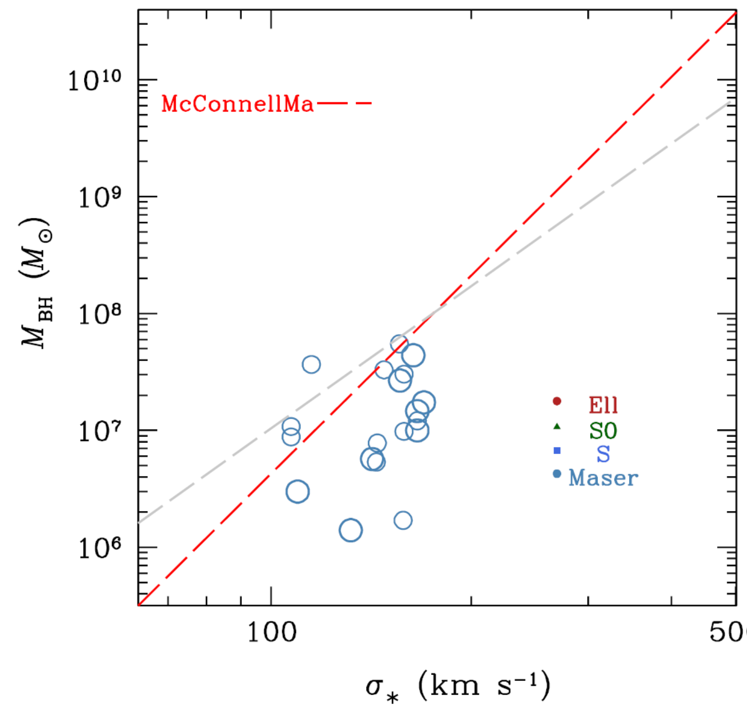
By measuring BH masses we can see how Galaxies evolve

M-σ Relation



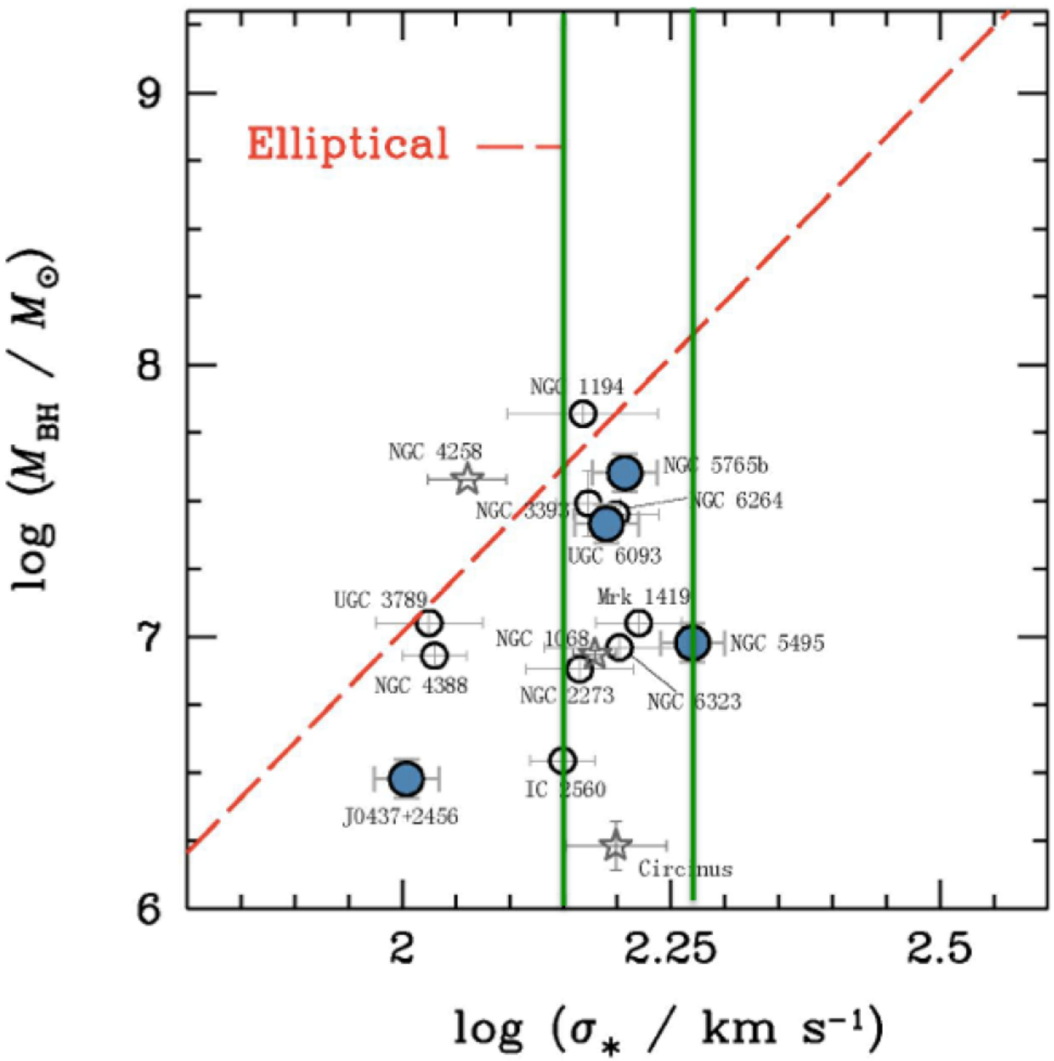
McConnell & Ma (2013)

M-σ Relation (Maser masses only)



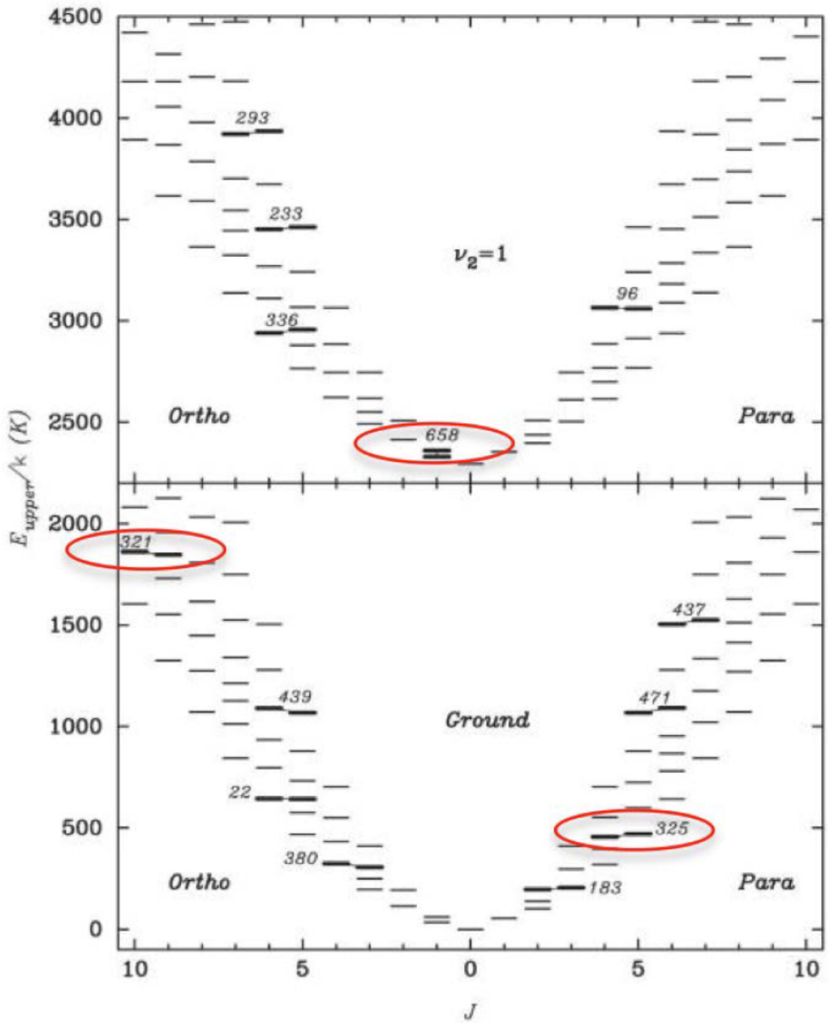
Updated from Greene et al. 2010

M-σ relation (megamasers black hole masses only)



Intrinsic scatter:
Within σ = 140 – 185 km/s
M_{BH}=(2–5)x10^6 M_{sun}
Galaxy types: S0 - Sc

Water megamasers in the ALMA era



H2O molecule has multiple masing transitions in the sub-mm

- We are beginning an exploratory program to look for sub-mm masers in disks with ALMA

Thank you for your attention