Extragalactic Maser Surveys

Detect and locate tiny regions with exceptional activity across the Universe

Great impact also on other fields of research

1. Massive Star Formation (SF)
2. Active Galactic Nuclei (AGN)

Extragalactic Maser Surveys

Where were we in Jan./Feb.2012
(IAU Symp. 287, Stellenbosch)?



Wikipedia

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State of the Art in 2012

OH megamasers (Baan/Darling)

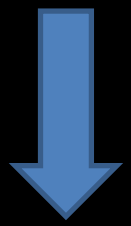
H_2CO (Baan and collaborators)

State of the Art in 2012

22 GHz H_2O:

1. H_2O in 50 FR I galaxies, $z < 0.15$ (Henkel+98)
2. H_2O in 273 Type 2 QSOs, $z < 0.83$ (Bennert+09)
3. H_2O in 79 radio galaxies, mostly FR II galaxies, $z < 0.17$ (GBT)
4. H_2O in some gravitationally lensed QSOs, $z = 2.3\text{-}2.9$ (McKean+11)
5. H_2O in 17 Type 1 QSOs, $z < 0.06$ (König+12)
6. H_2O maser disks in NGC 4258 and UGC 3789 (Braatz,Greenhill, Herrnstein, Moran, Reid)

State of the Art in 2012



2017

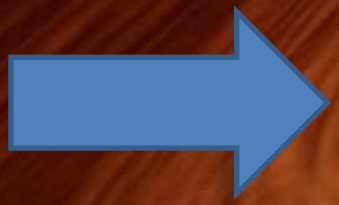
Incomplete

Bias

Doubling

Extragalactic Maser Surveys

Progress with the MCP
(Megamaser Cosmology Project)



Keplerian H_2O maser disks
Goals: Morphology of accretion disks, H_0, dark energy…

Wikipedia

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Progress with the MCP

I Reid et al. 2009 – UGC 3798

II Braatz et al. 2010 – UGC 3789

Greene et al. 2010 – M_{BH} versus M_{bulge}

III Kuo et al. 2011 – M_{BH} determinations

Progress with the MCP

I	Reid et al. 2009	–	UGC 3789
II	Braatz et al. 2010	–	UGC 3789
	Greene et al. 2010	–	M_{BH} versus M_{bulge}
III	Kuo et al. 2011	–	M_{BH} determinations
	Greene et al. 2013	–	galactic structure
IV	Reid et al. 2013	–	UGC 3789
V	Kuo et al. 2013	–	NGC 6264
VI	Kuo et al. 2015	–	NGC 6323
VII	Pesce et al. 2015	–	Maser disk physics, magnet. field limits
VIII	Gao et al. 2016	–	NGC 5765b
	Läsker et al. 2016	–	M_{BH} versus M_{bulge} and M_*, morphology
	Greene et al. 2016	–	M_{BH} versus other parameters
IX	Gao et al. 2017	–	VLBI maps of five, M_{BH} in three galaxies
	Kamali et al. 2017	–	Radio continuum
	Pjanka et al. 2017	–	galactic structure

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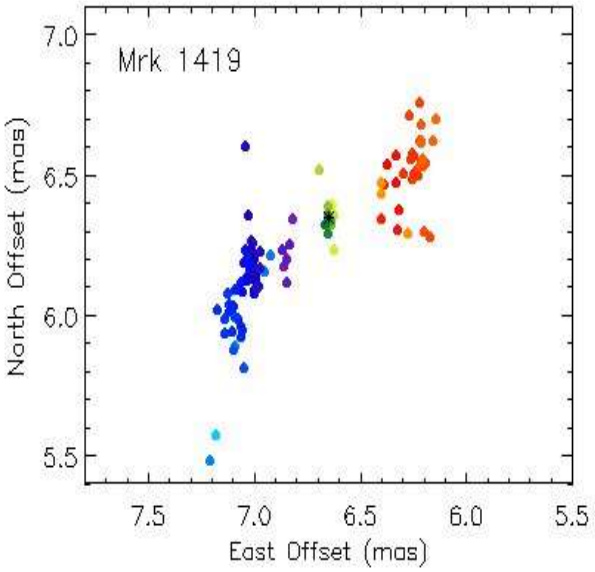
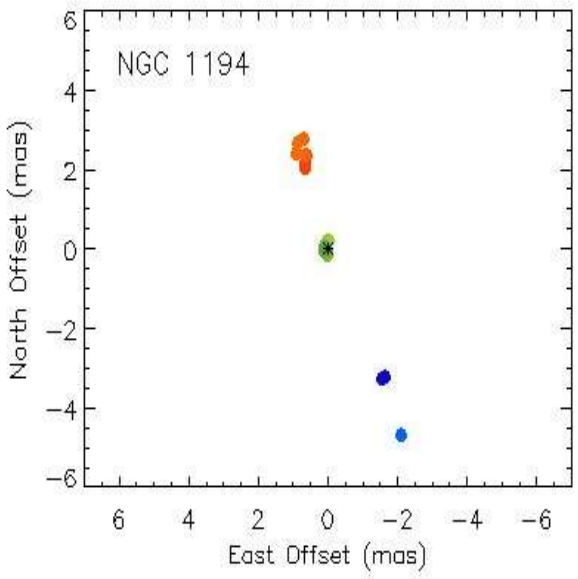
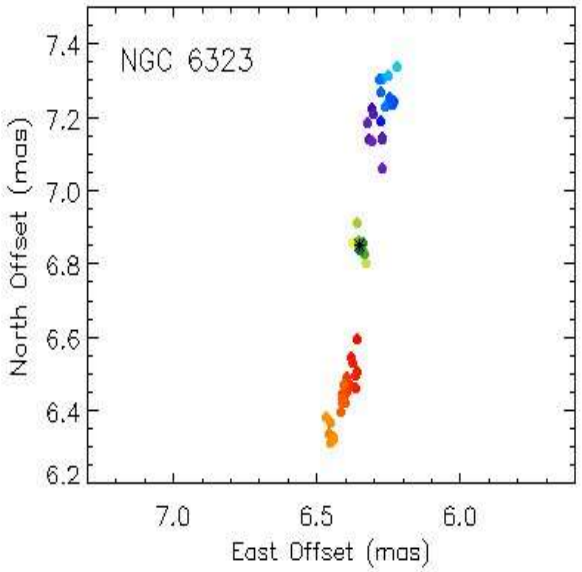
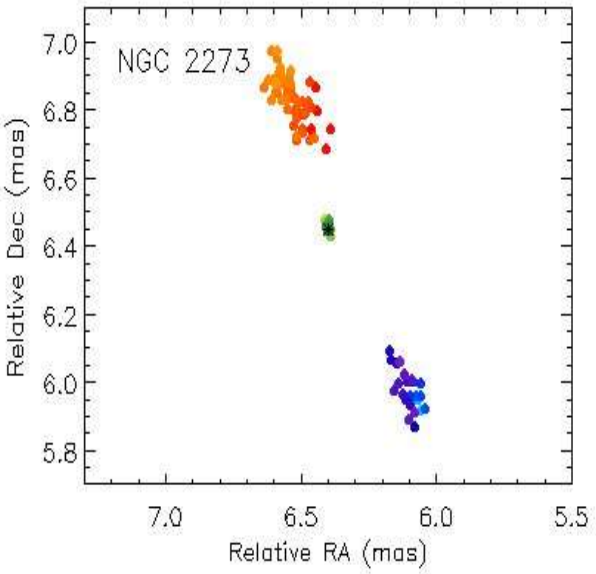
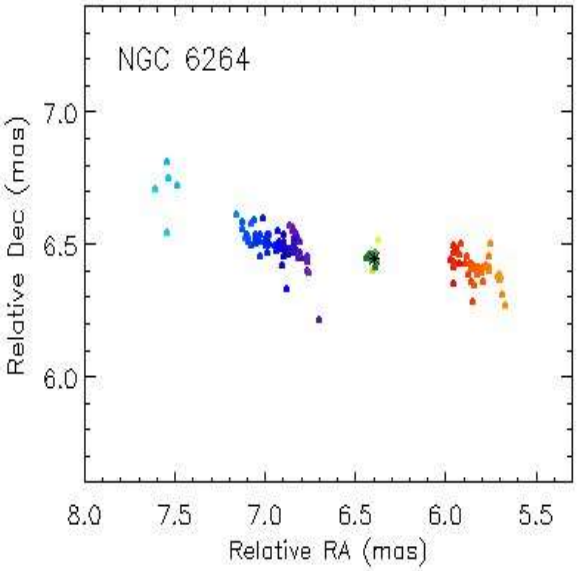
Progress with the MCP

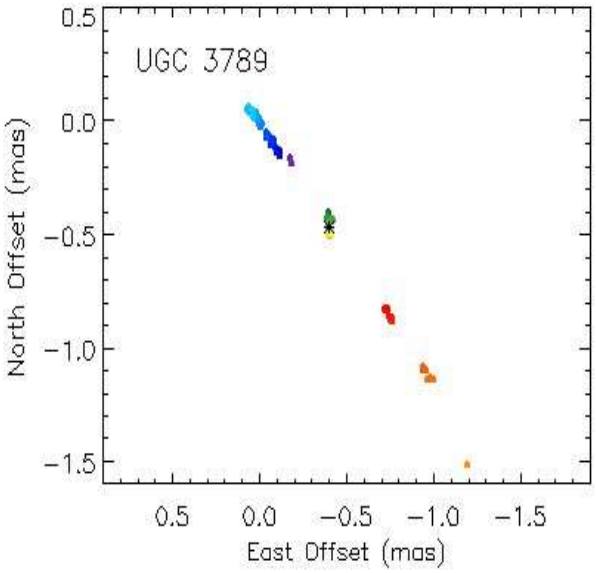




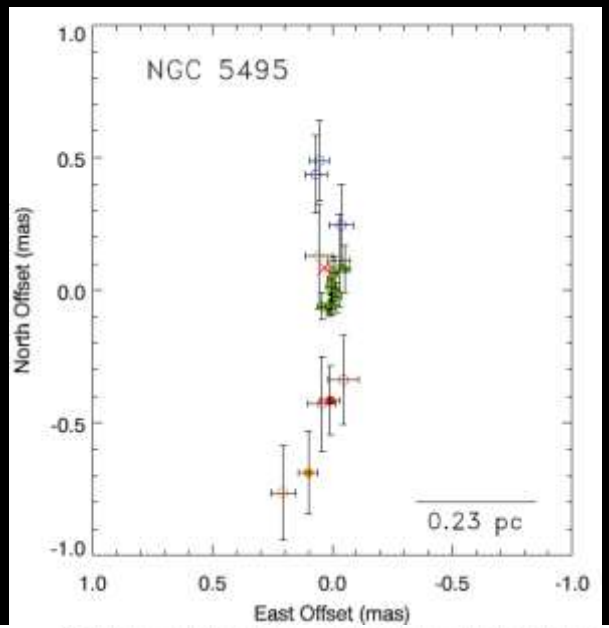


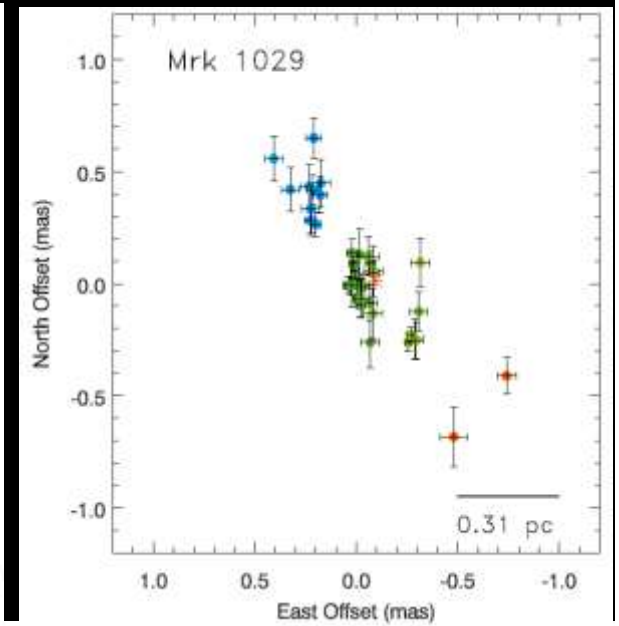


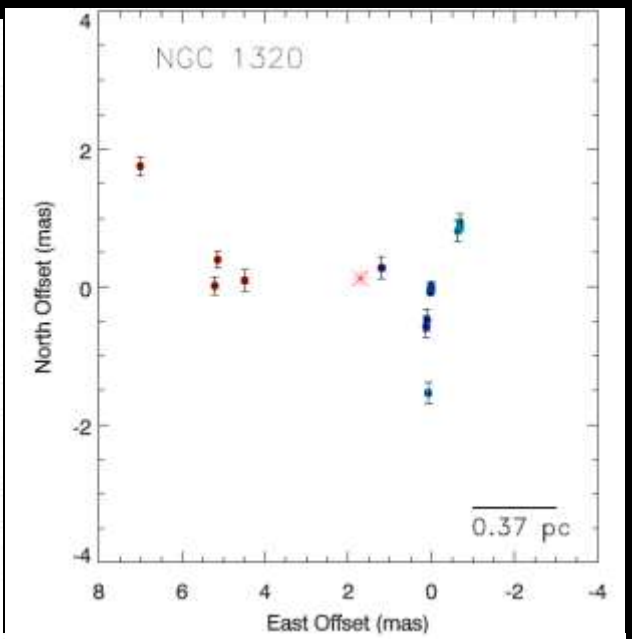


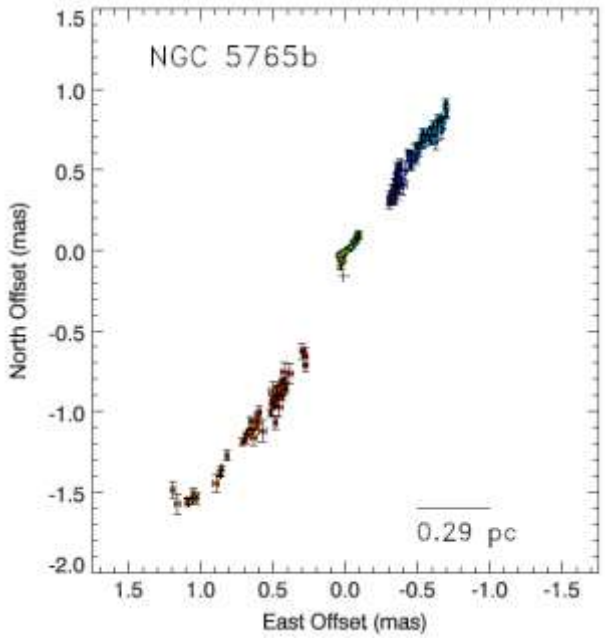


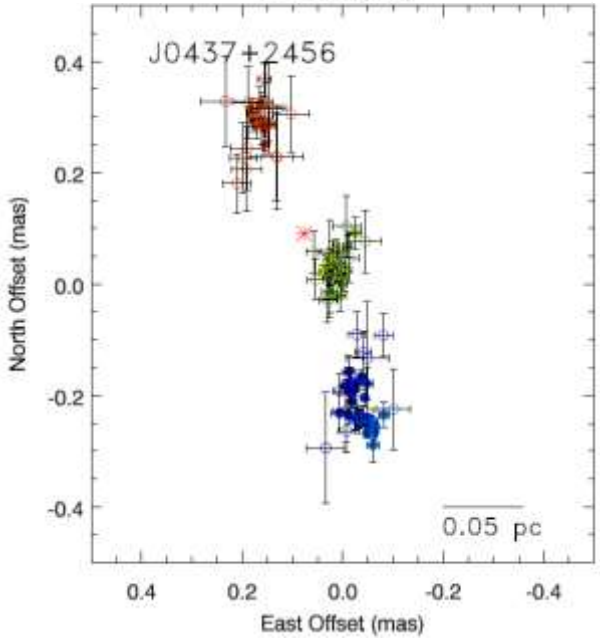
Progress with the MCP

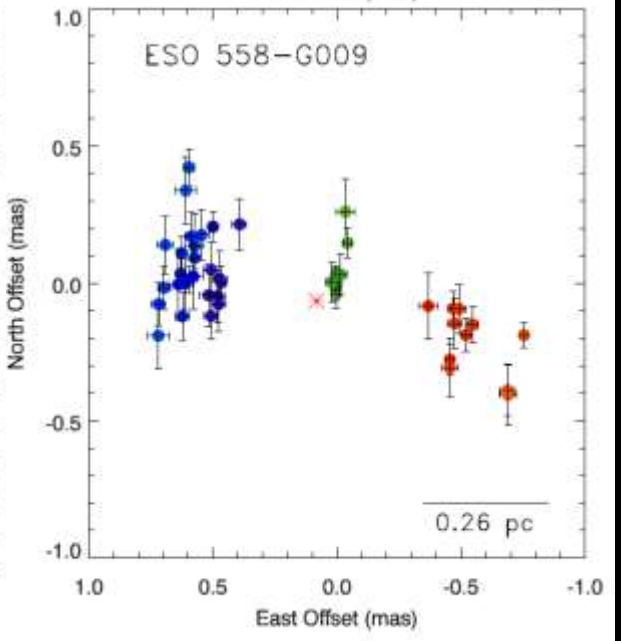












Extragalactic Maser Surveys



"Unsuccessfull" H_2O Maser Surveys

Wikipedia

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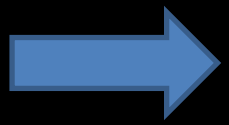
Search for Megamasers with Large AGN-Gravitational Sphere

Problem: How to calibrate dynamically determined nuclear masses?

Solution: Find an H_2O disk megamaser in a galaxy, where the sphere of influence of the nuclear source can be resolved also optically (> 0.”06).



Van den Bosch et al. 2016

Search for Megamasers with Large AGN-Gravitational Sphere

Targets: 87 mostly elliptical galaxies with large velocity dispersions, ~250 km/s, and small distances <130 Mpc.

Result: No new detection

So far: Only NGC 4258, where dynamical M_{BH} values diverge to lower and higher values (e.g., Siopis+09, Drehmer+15)

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Search for Megamasers with Large AGN-Gravitational Sphere

It seems that H_2O megamaser disks do not exist in AGN with masses of order $10^8 M_{\odot}$.

Similar result also obtained with FRI radio galaxies years ago.

H_2O Megamasers in NL-Sy1s

Properties: Low mass AGN w.r.t. bulge mass, but luminosities similar to those of broad line BL-Sy1s. Vigorously accreting AGN?

→ Hagiwara et al. 2013

Result: No detection down to ~5 $L_\odot$ (line width?)
26 galaxies (Nobeyama)

Apparently, disk megamasers cover a rather narrow range of nuclear physical properties.

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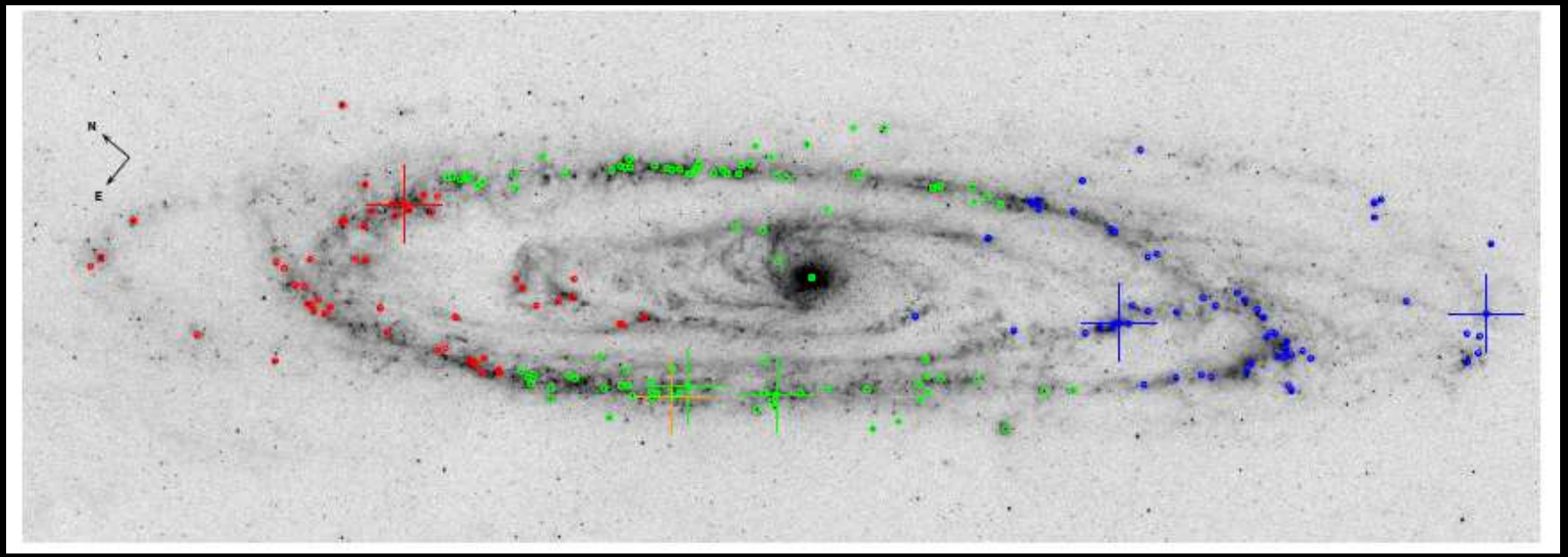
Search for H_2O Masers in Andromeda (M 31)

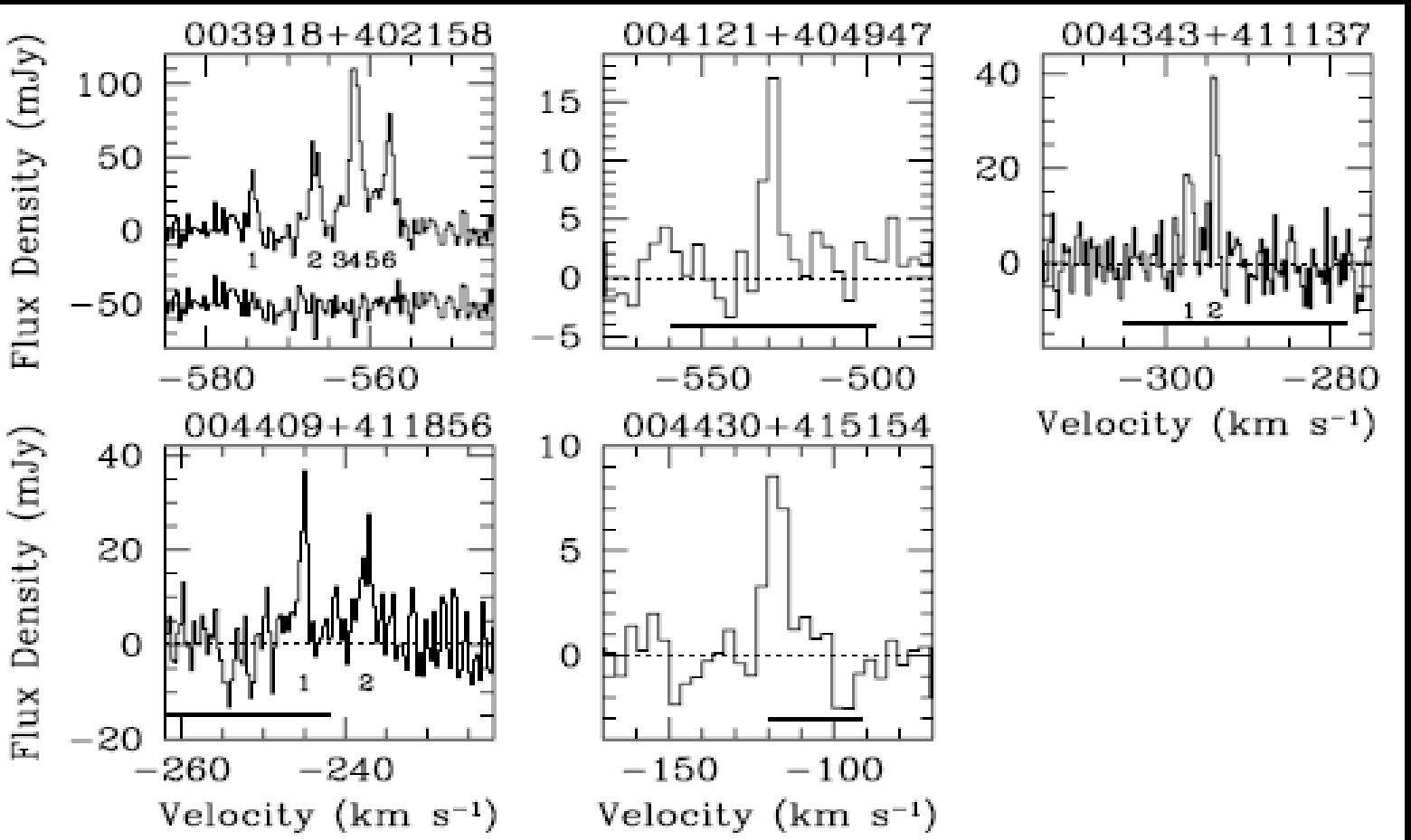
Darling et al. (2011): 5 masers in M 31



Cagliari 2017

Search for H_2O Masers in Andromeda (M 31)

Darling et al. (2011): 5 masers in M 31



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Search for H_2O Masers in Andromeda (M 31)

Darling et al. (2011): 5 masers in M 31

Fundamental for the dynamics of the Local Group:
3-D velocity vector through proper motion measurements.

Maser luminosities: $L = (0.3 - 1.9) \times 10^{-3}\ L_{\odot}$

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Search for H_2O Masers in Andromeda (M 31)

Darling et al. (2011): 5 masers in M 31

Darling et al. (2016): No more masers.

506 sources with 24 μm emission (bulk of the stronger SF regions).

rms: 3 mJy, ΔV = 3 km/s.

Consistent with Galactic extrapolations

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Extragalactic Maser Surveys

Successful H_2O Megamaser Surveys



Wikipedia

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Successful Megamaser Surveys

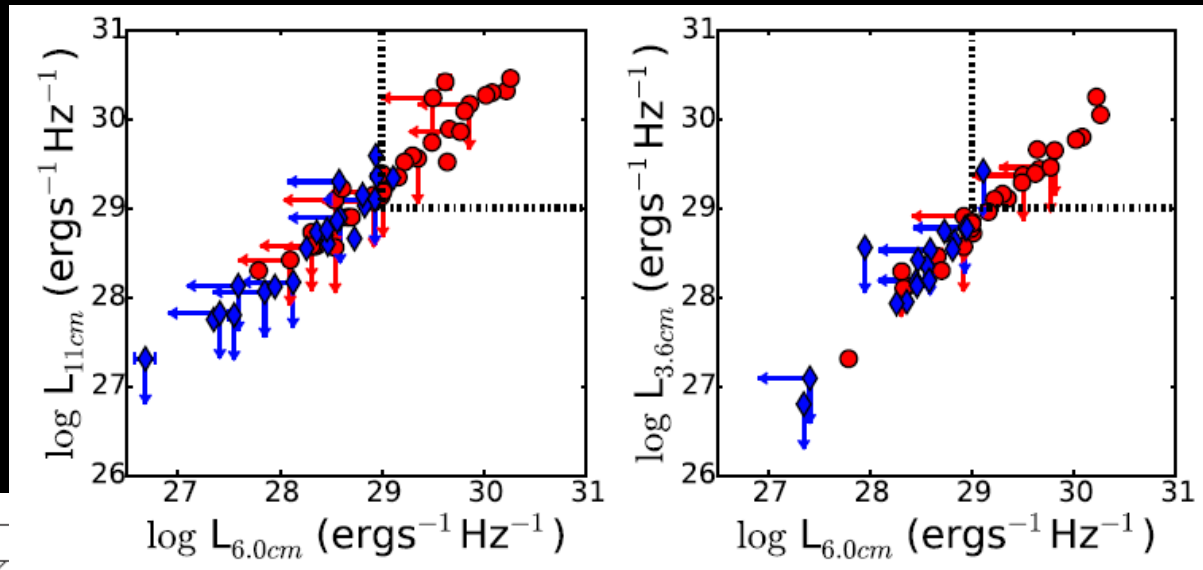
Seyfert 2s with high radio luminosity

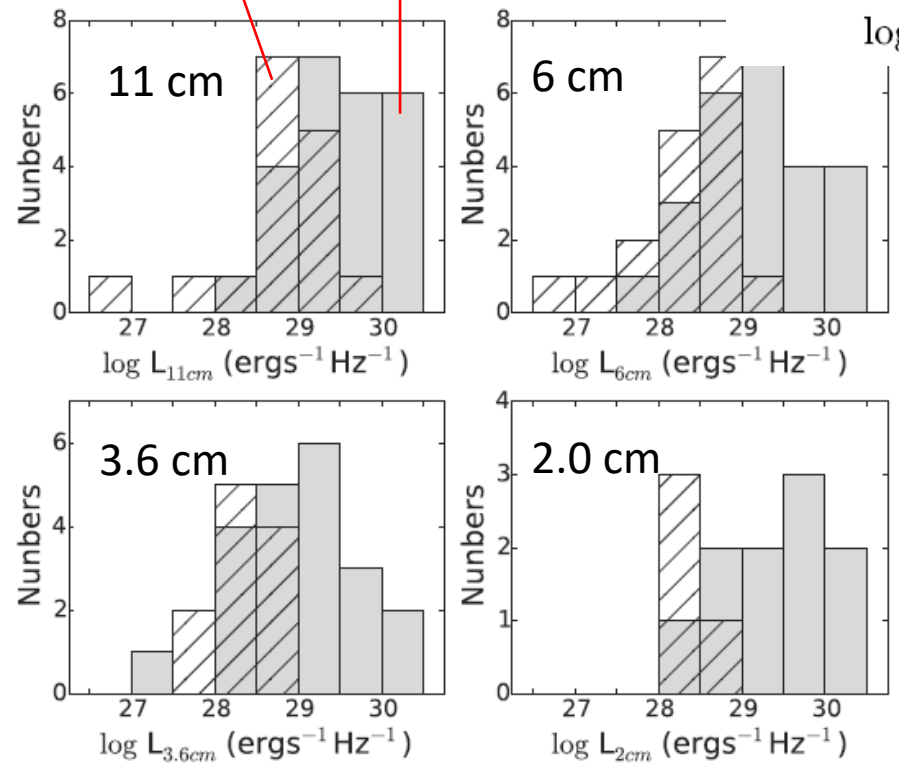
Zhang et al. 2012, A&A 538, A152
Zhang et al. 2017, ApJ 836, L20
Liu et al. 2017, MNRAS 466, 1608

Successful Megamaser Surveys

Non-maser Sy2s

Maser Sy2s





Detections: Red

Non-Detections: Blue

Liu et al. 2017

(Sy2 galaxies)

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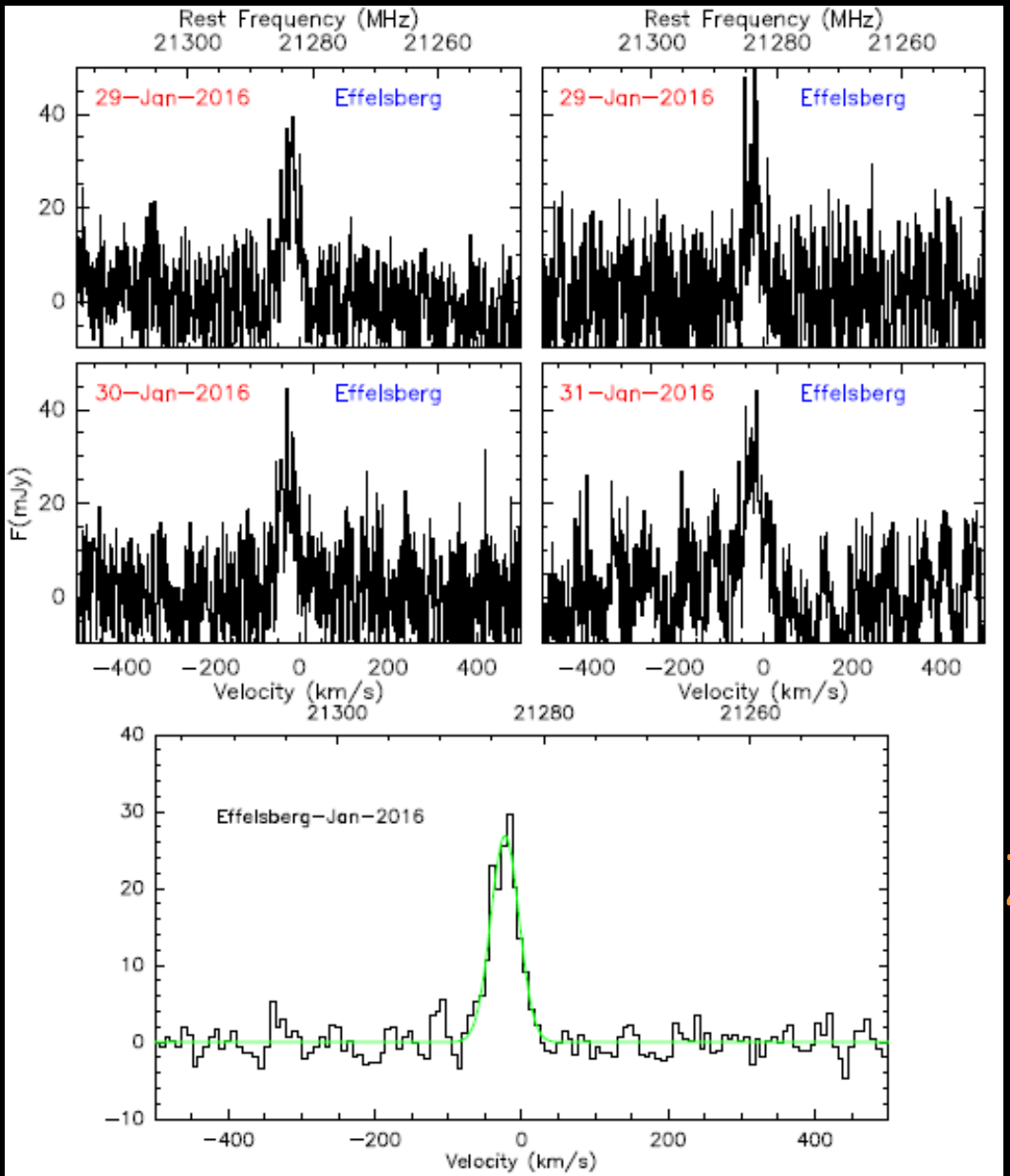
Successful Megamaser Surveys



Zhang et al. 2017
(Sy2 galaxies
1-2 out of 18) Cagliari 2017

Successful Megamaser Surveys

X-ray and IR properties combined:

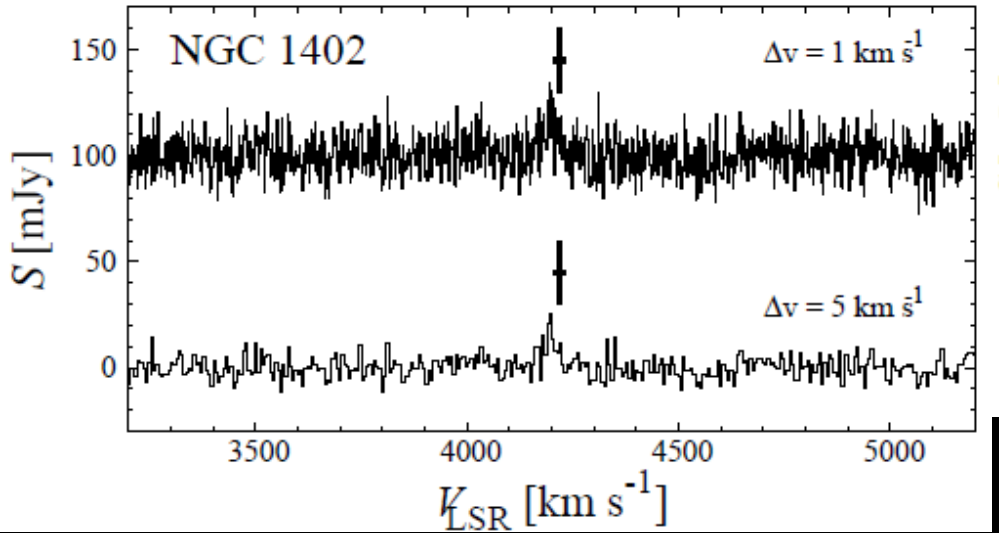
a) Absorbed 2 keV continuum

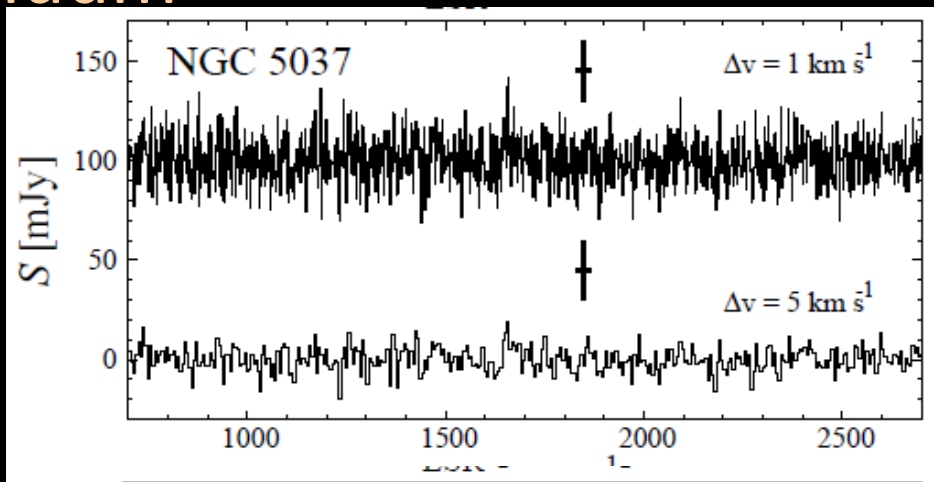
b) Strong 6.4 keV line

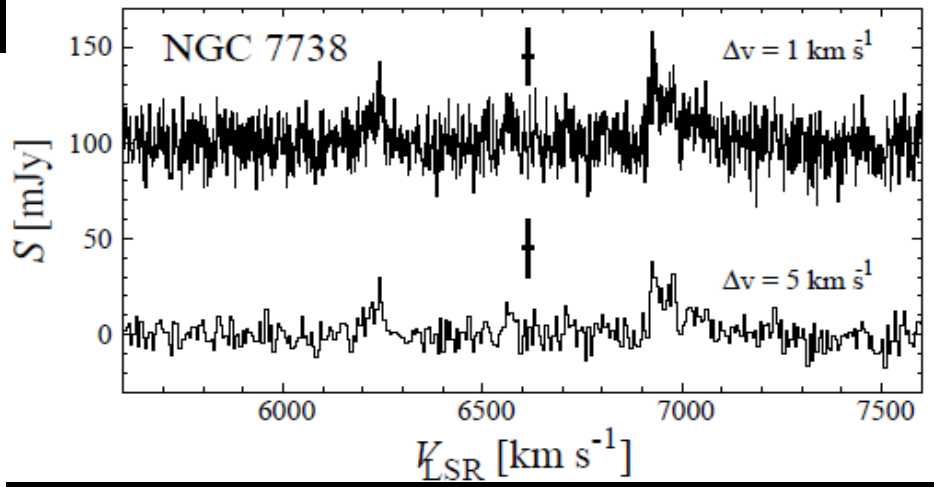
c) IR emission

Yamauchi et al. 2017

(3 out of 10)







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Successful Megamaser Surveys

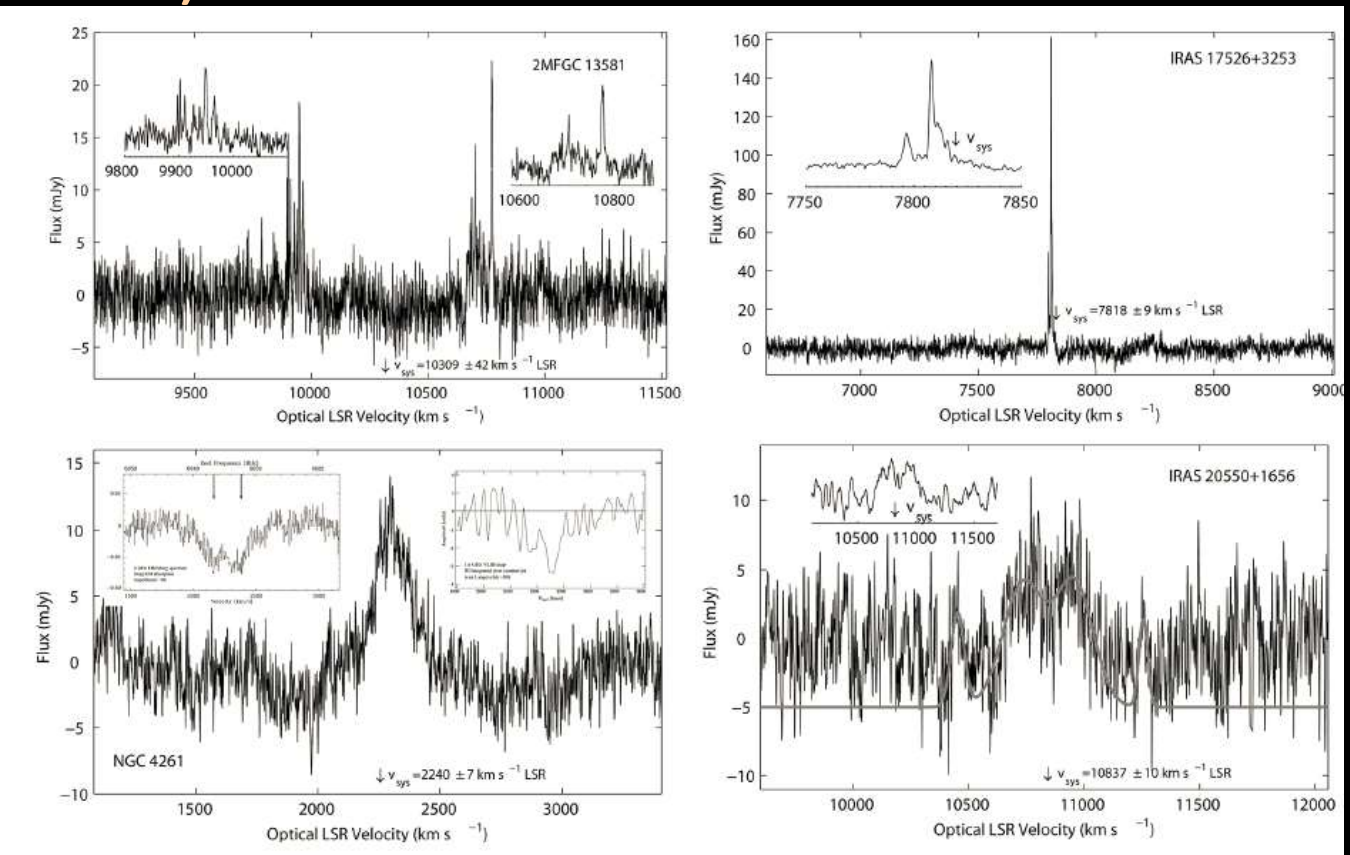
Sy2 galaxies

a) High L_X

b) High N(H)

c) A few OH Absorbers

Wagner 2013
(4 out of 37)



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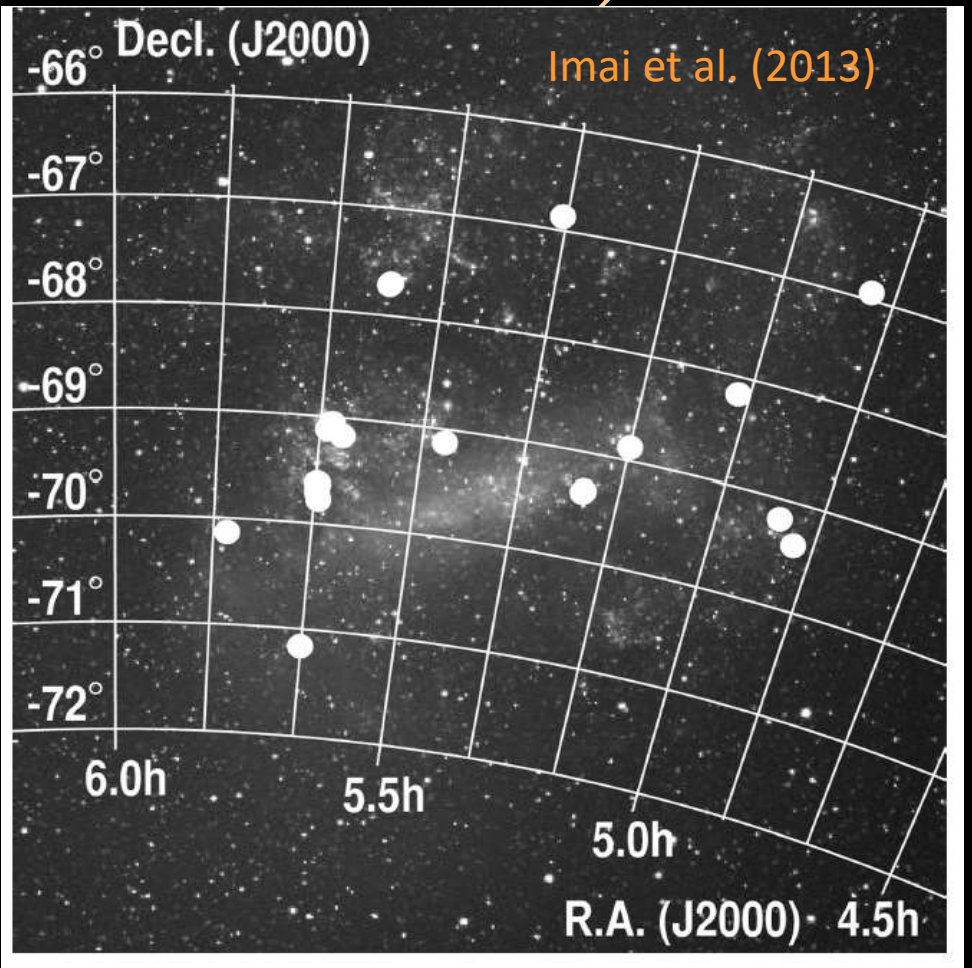
Successful Megamaser Surveys

LMC: ~ 25 H_2O masers in 14 star froming regions
3 H_2O masers in late type stars



Imai et al. (2013)

Imai et al. 2013 – ATCA
Breen et al. 2013 – ATCA/Tidb.
Johanson et al. 2014 – ATCA

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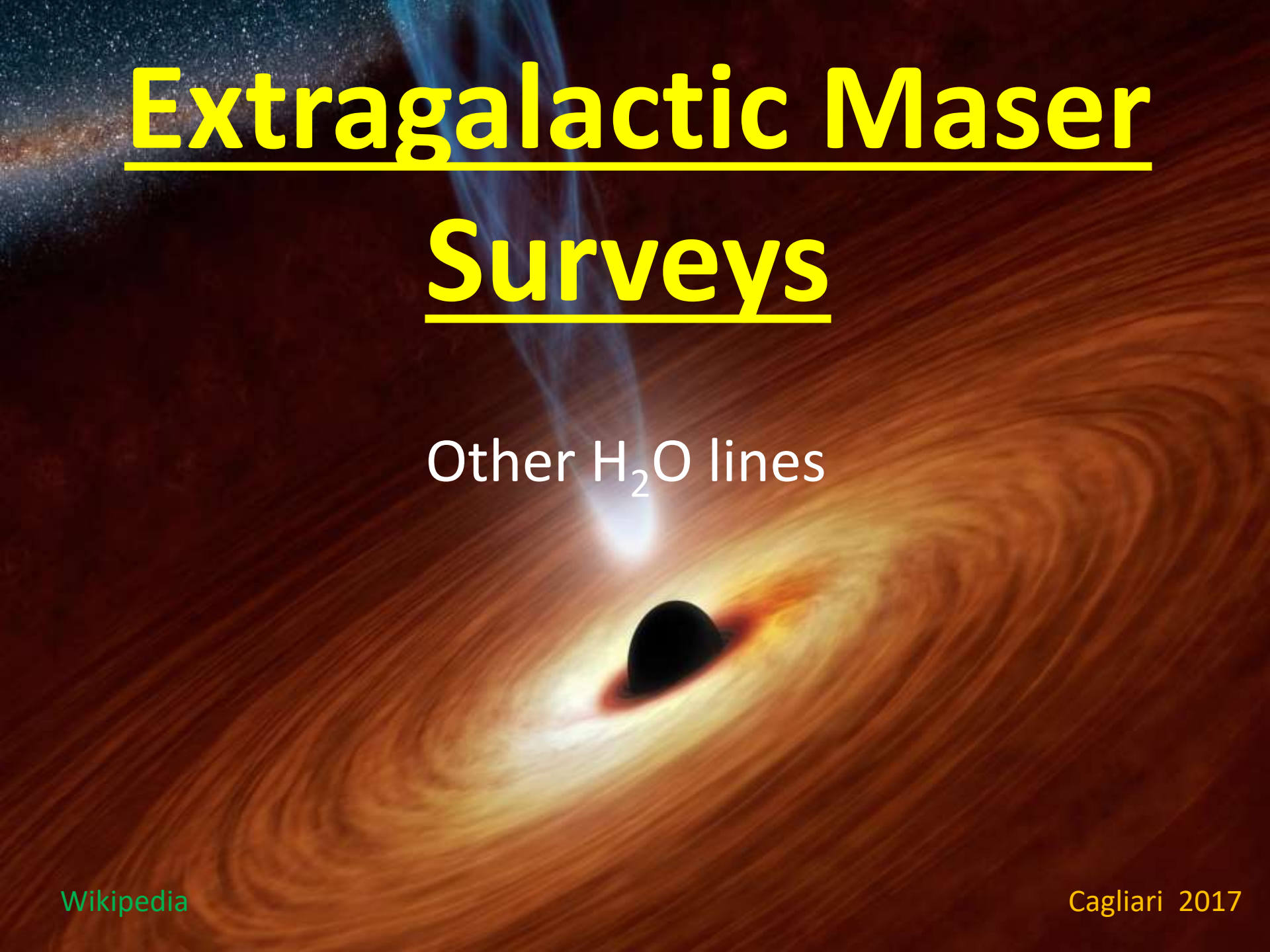
Extragalactic Maser Surveys

Other H_2O lines



Wikipedia

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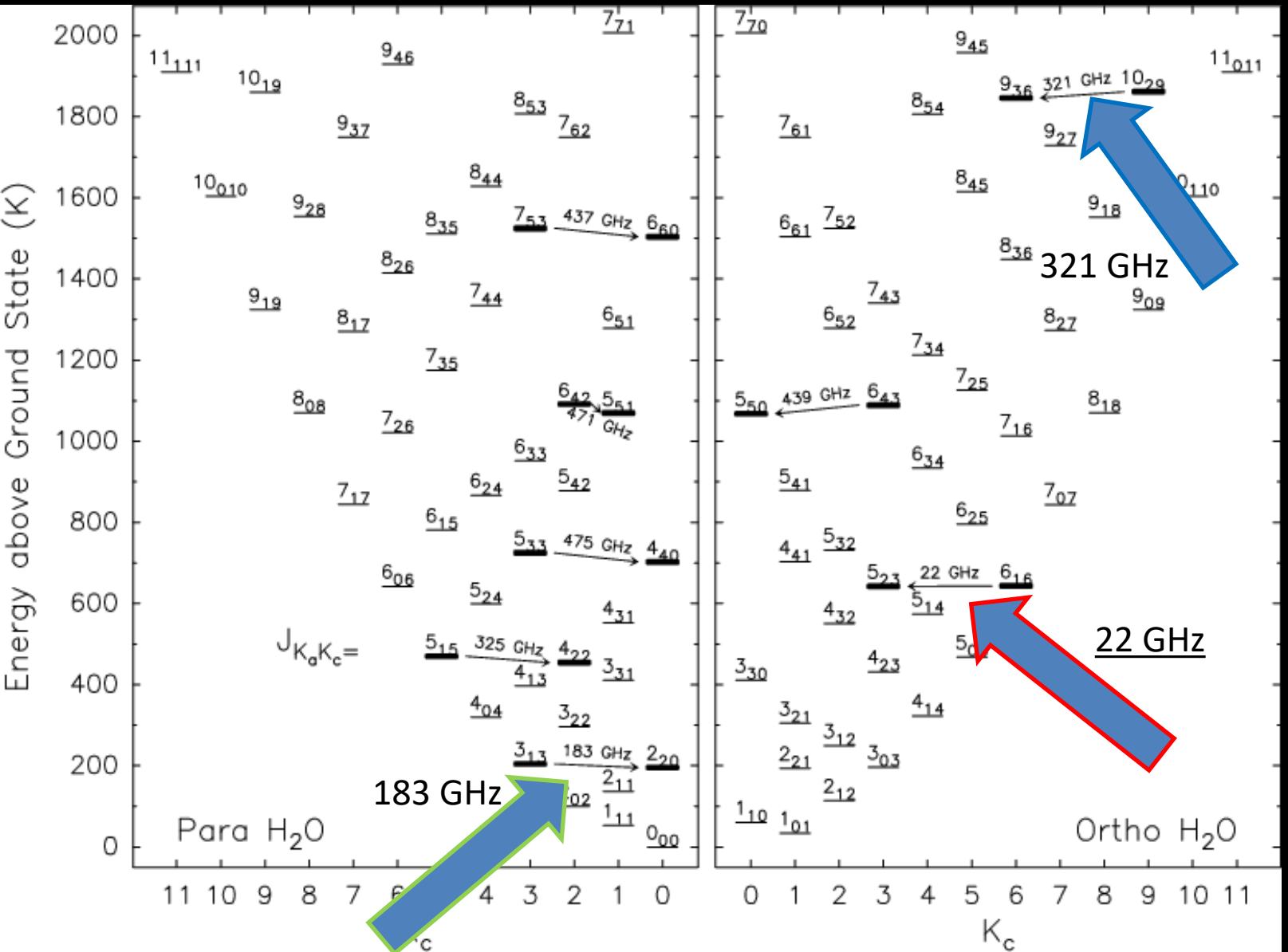
Other H_2O lines

Humphreys et al. 2005:	NGC 3079,	183 (+439?) GHz
Cernicharo et al. 2006:	Arp 220	183 GHz

Other H_2O lines



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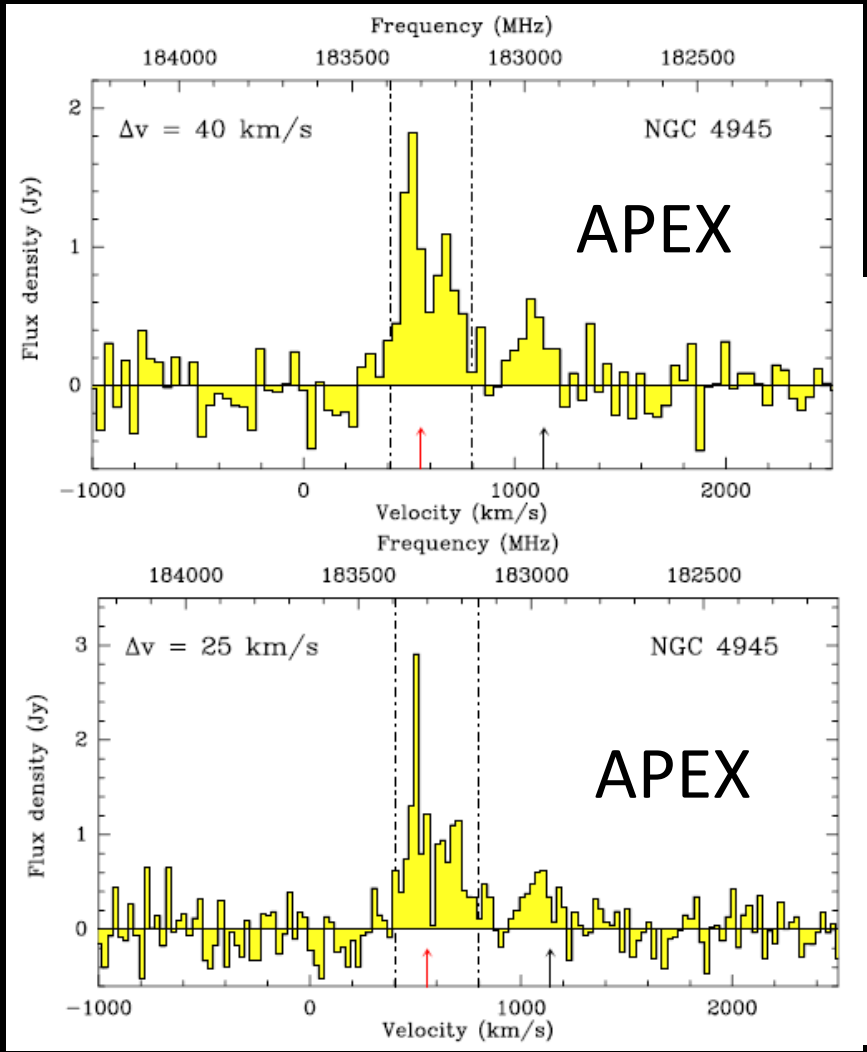
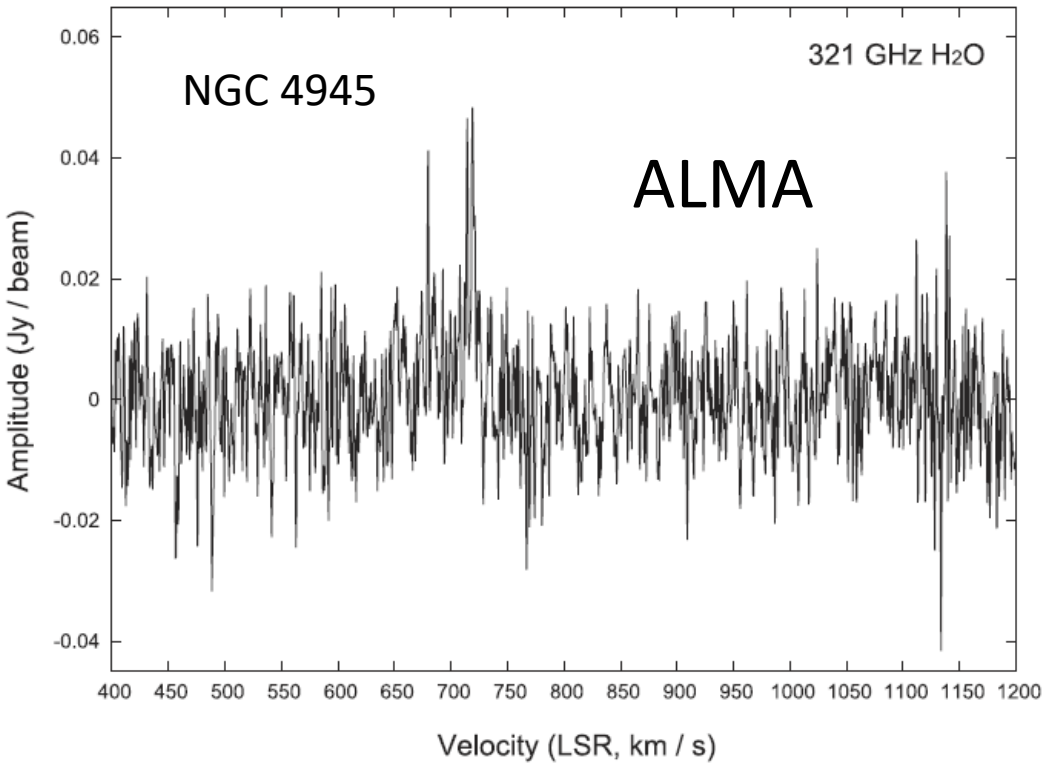
Other H_2O lines

Humphreys et al. (2016)



NGC4945

Hagiwara et al. (2016)



NGC 4945

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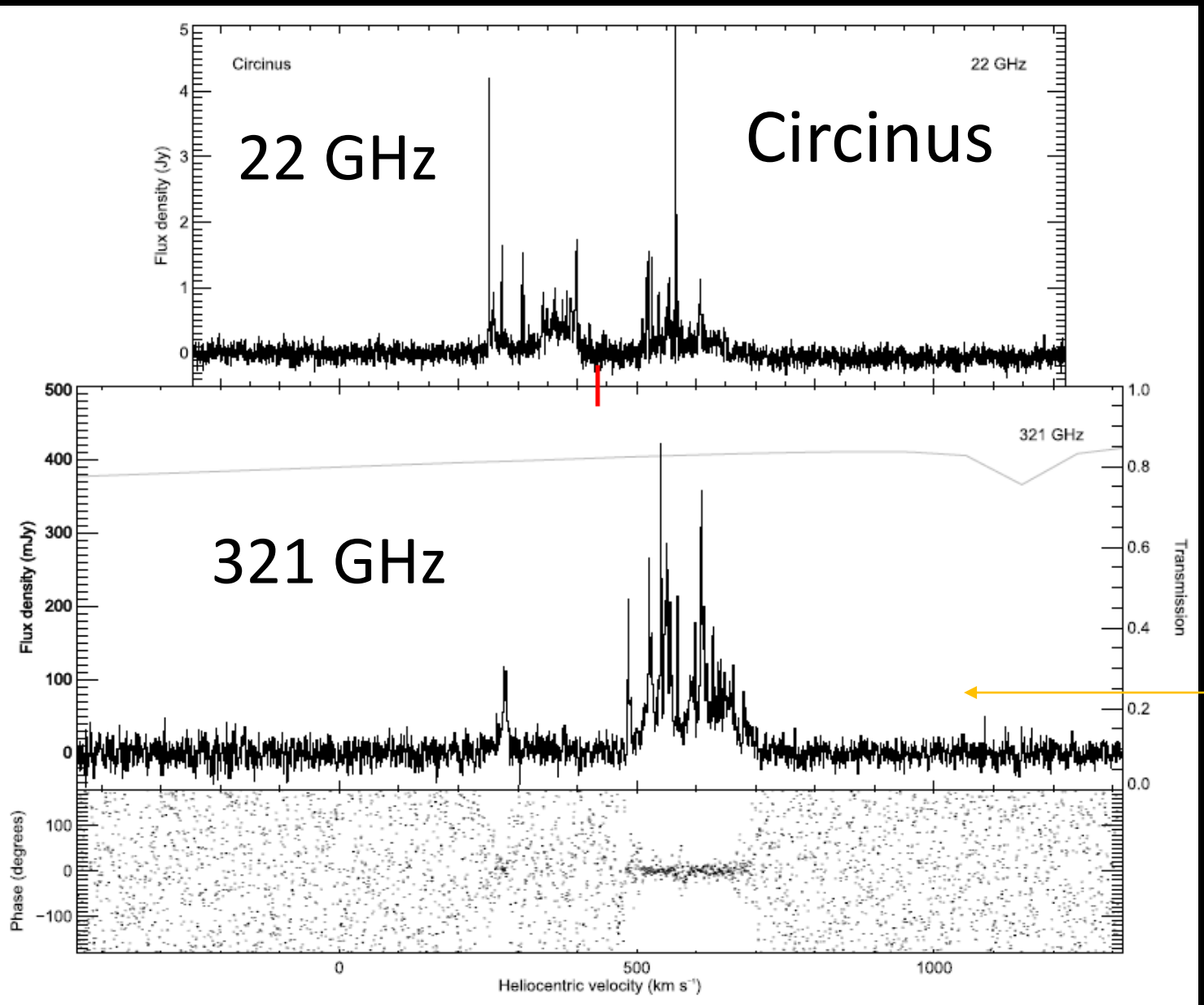
Other H_2O lines



Pesce et al. (2016)

ALMA data

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Other H_2O lines

Humphreys et al. 2005:	NGC 3079,	183 (+439?) GHz
Cernicharo et al. 2006:	Arp 220	183 GHz
Hagiwara et al. 2015:	Circinus	321 GHz
Galametz et al. 2016:	Arp 220	183 GHz
Hagiwara et al. 2016:	NGC 4945	321 GHz
Humphreys et al. 2016:	NGC 4945	183 GHz
Pesce et al. 2016:	Circinus	321 GHz
	NGC 4945	321 GHz

Missing: Really high resolution images
321 GHz emission from inside
the 22 GHz megamaser disks???

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Extragalactic Maser Surveys

Radioastron



Wikipedia

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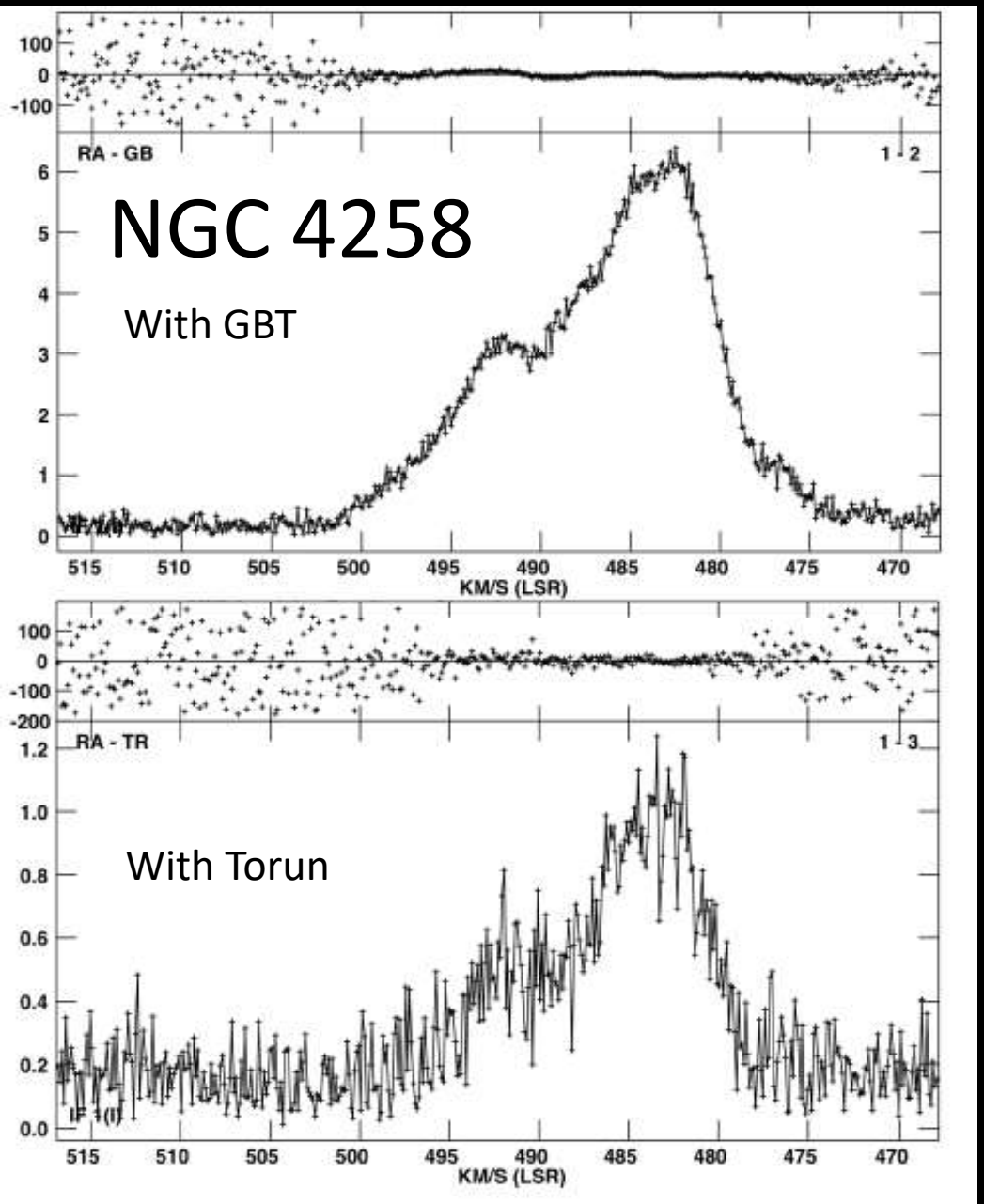
Radioastron



Kardashev & Kovalev 2015

Amplitude: arbitrary
Phase slope removed

See A. Sobolev,
and W. Baan

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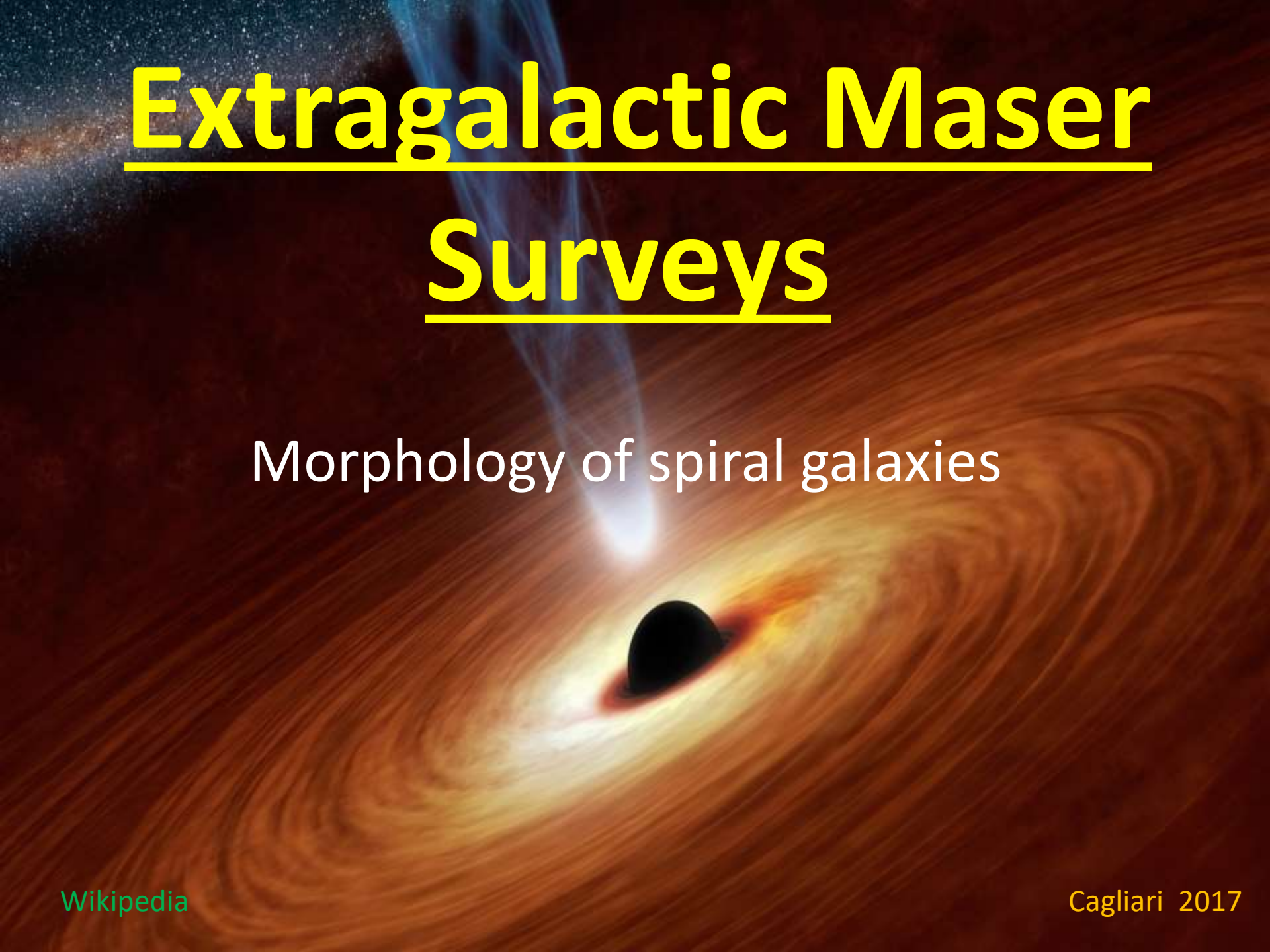
Morphology of spiral galaxies



Wikipedia

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Morphology of Spiral Galaxies

Is there a correlation in position angle (PA) and inclination (i) between largest and smallest scales in spirals?

None according to

Ulvestad & Wilson	**1984**
Nagar & Wilson	**1999**
Kinney et al.	**2000**
Gallimore et al.	**2006**

What happens at intermediate scales?

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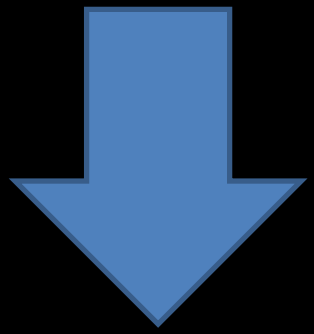
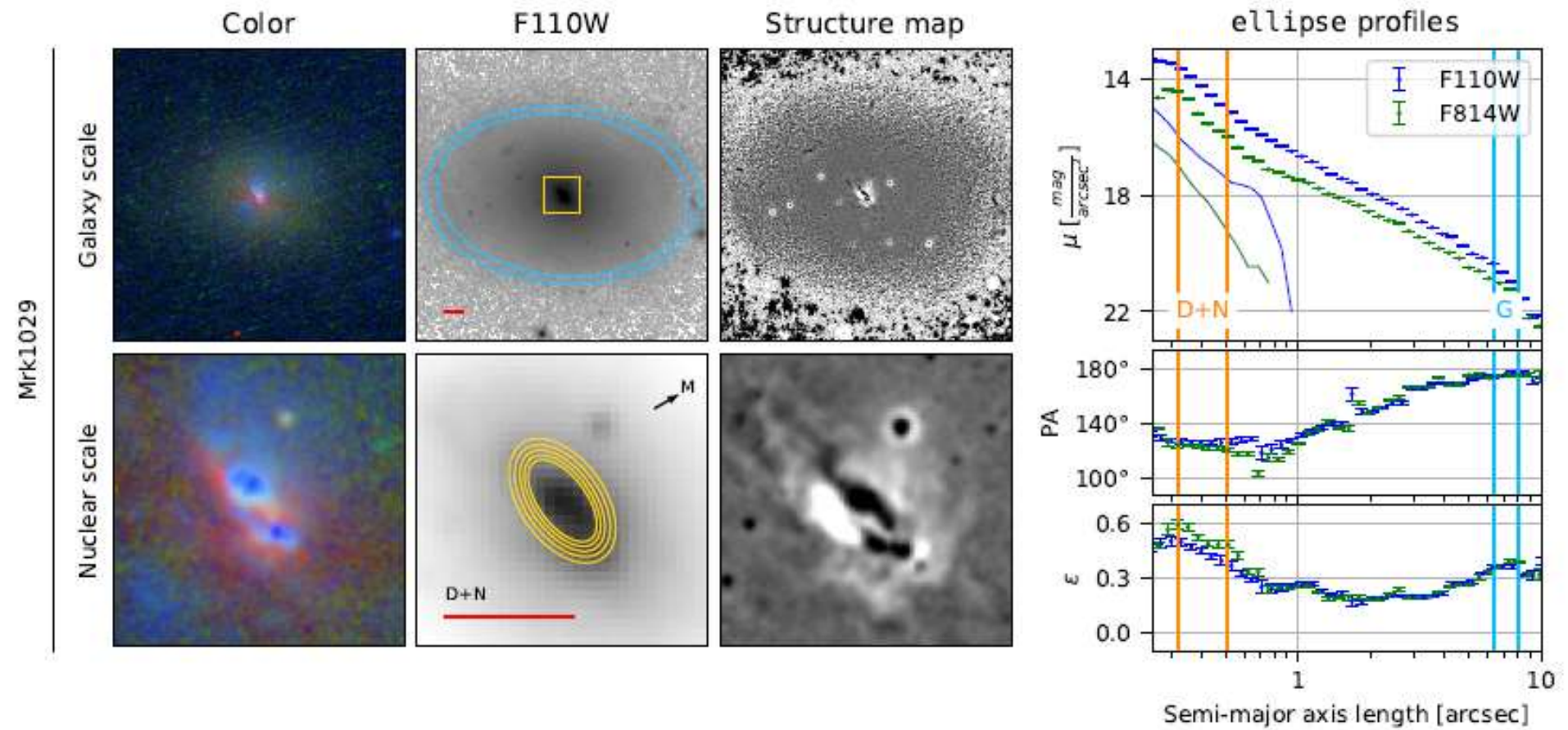
Morphology of Spiral Galaxies

Measure corresponding optical parameters



Hubble Space Telescope
Megamaser disk galaxies

Greene et al. 2013, ApJ 771, 121
Läsker et al. 2016, ApJ 825, 3
Pjanka et al. 2017, ApJ 844, 165



Blue: F335W
Green: F438W
Red: F814W

Size of lower image

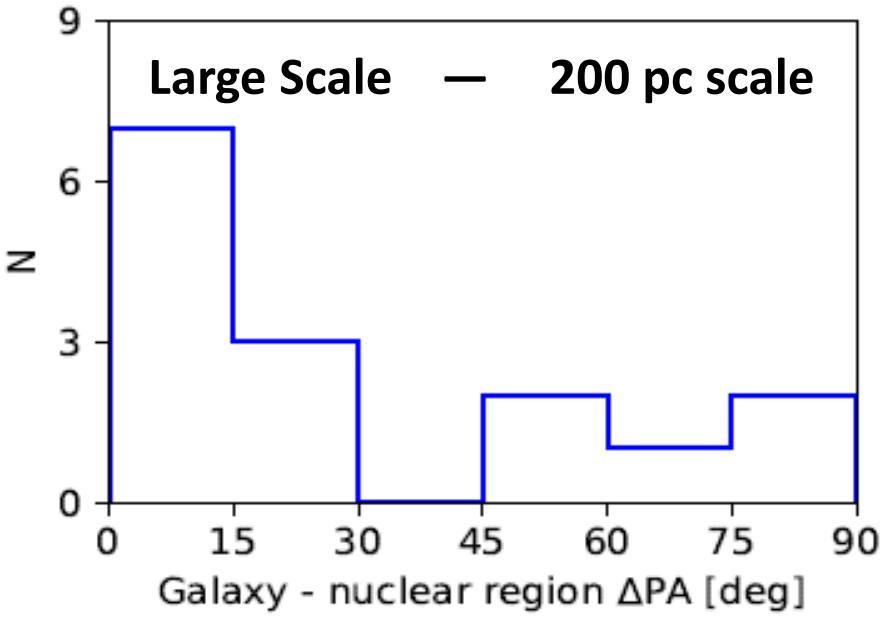
M: Orientation of maser disk

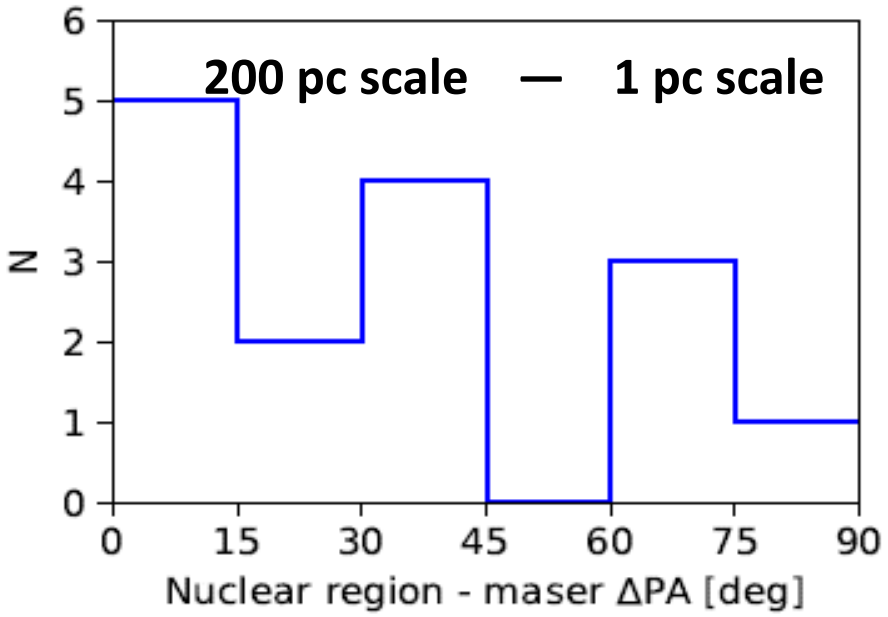
Red bar: 1 kpc

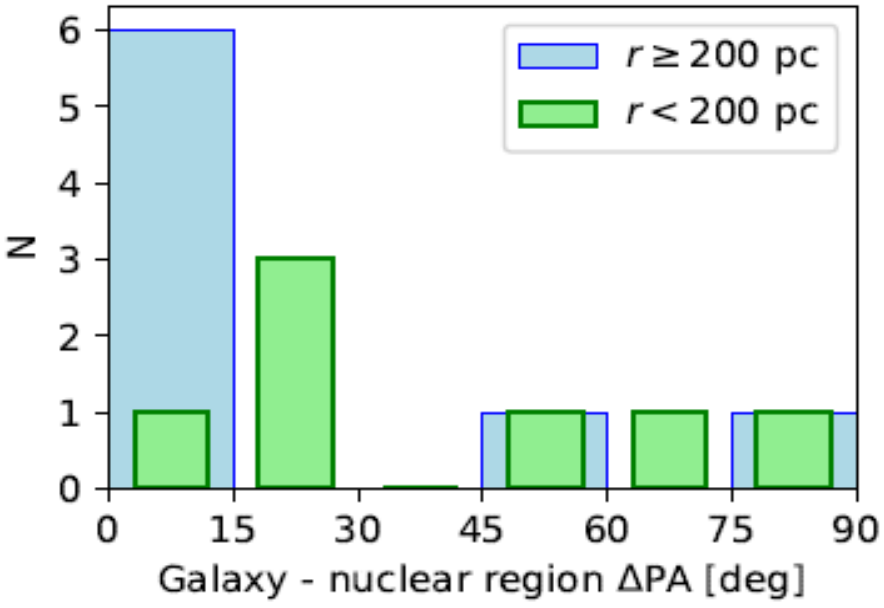
For small scale features like dust lanes

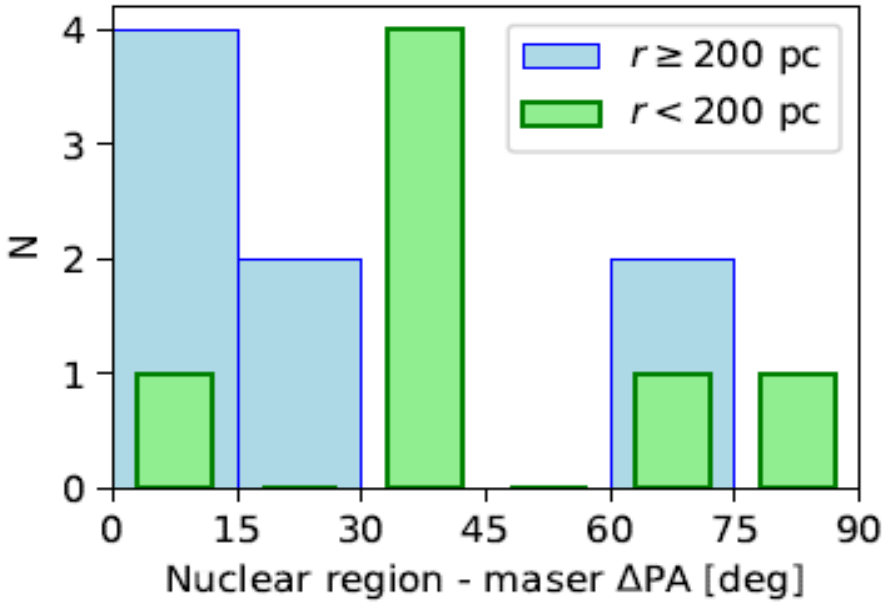
Blue and orange vertical lines limit ranges of ellipse major axes to extract galaxy orientation as a whole.

Kinematically cold and flattened disks,
100 - 500 pc sized









"Nuclear region" from HST data, r ≈ 200 pc

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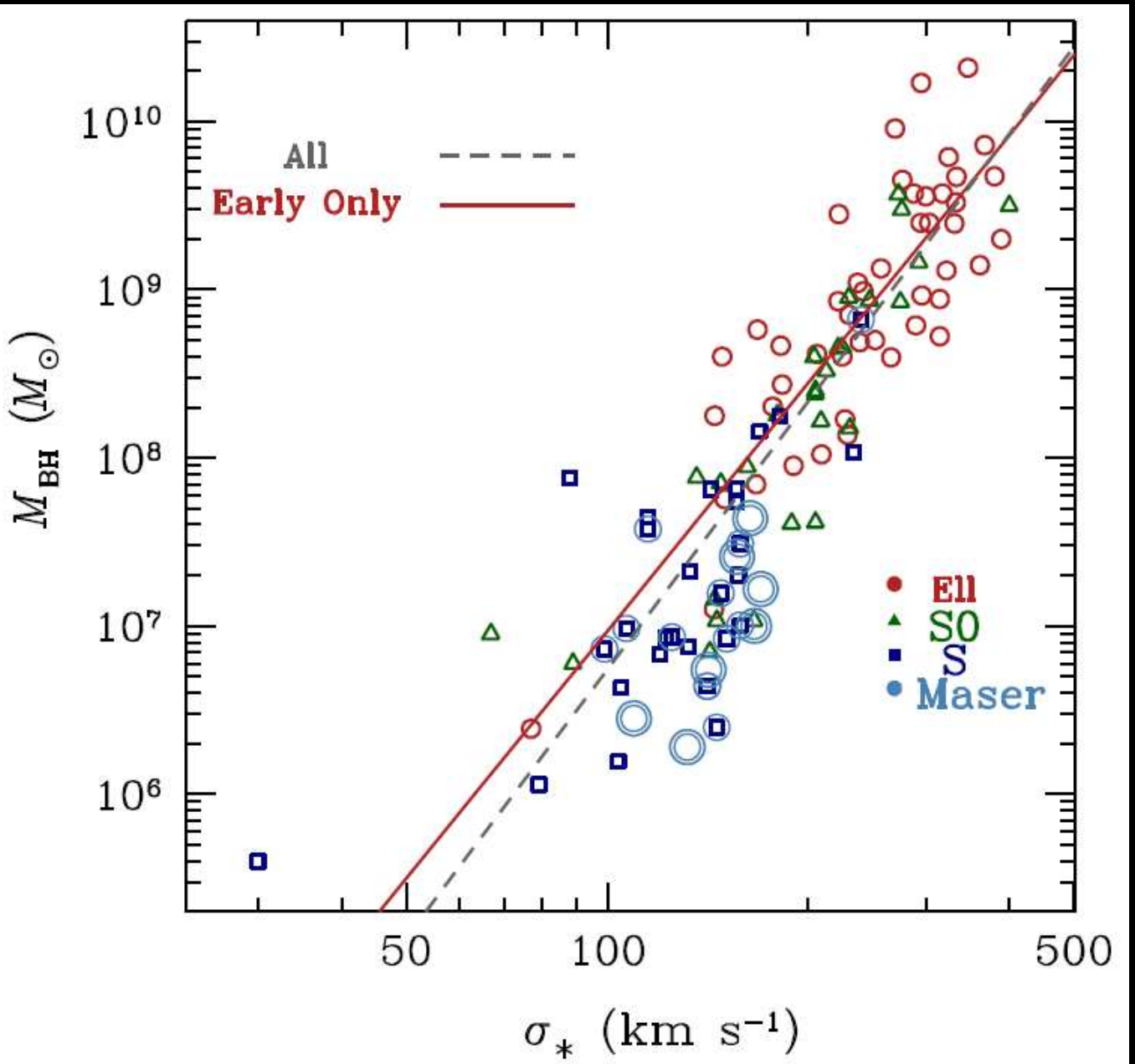
Morphology of Spiral Galaxies



Disk maser galaxies: low M_{BH}

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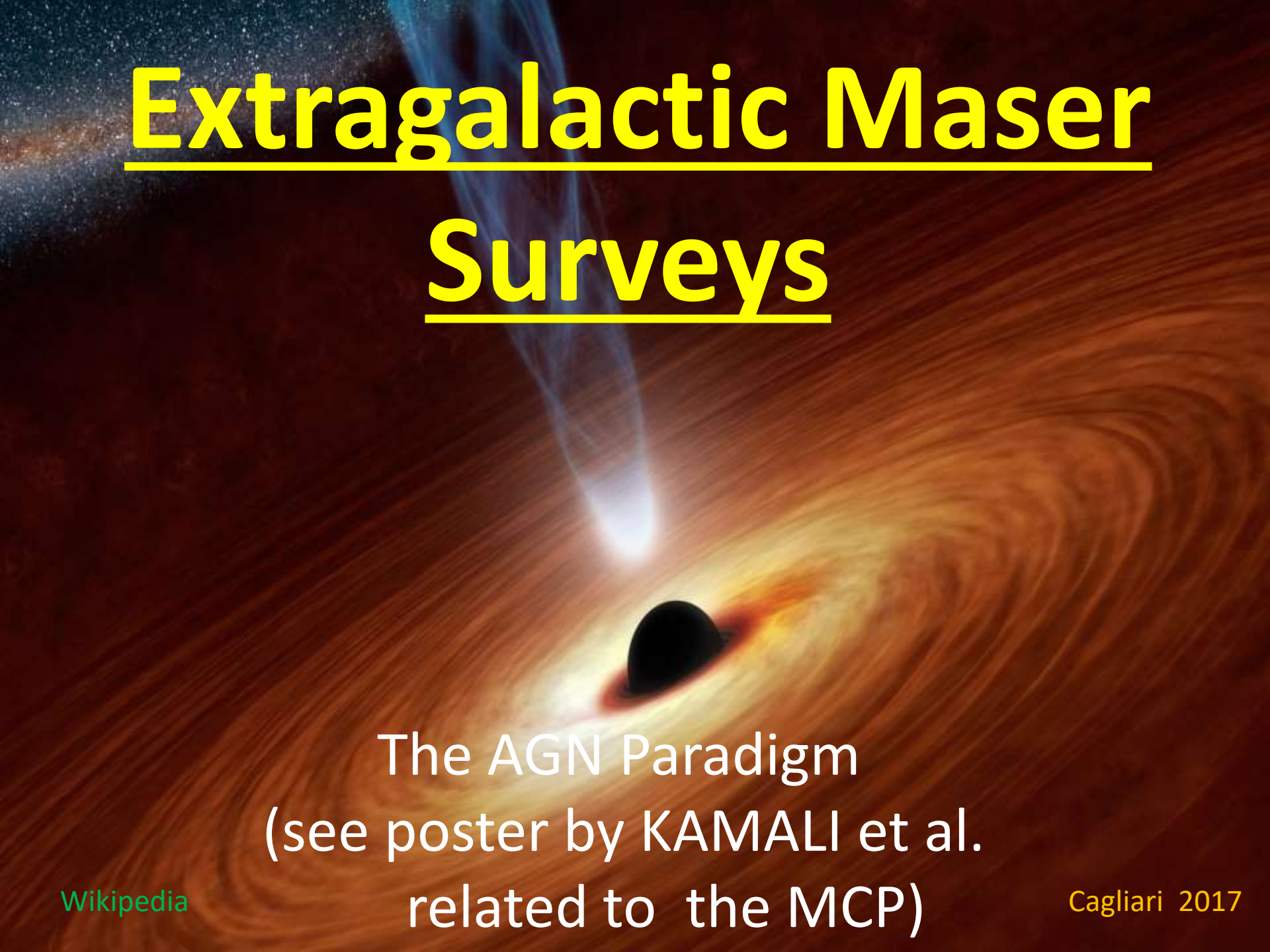

The AGN Paradigm
(see poster by KAMALI et al.
related to the MCP)

Wikipedia

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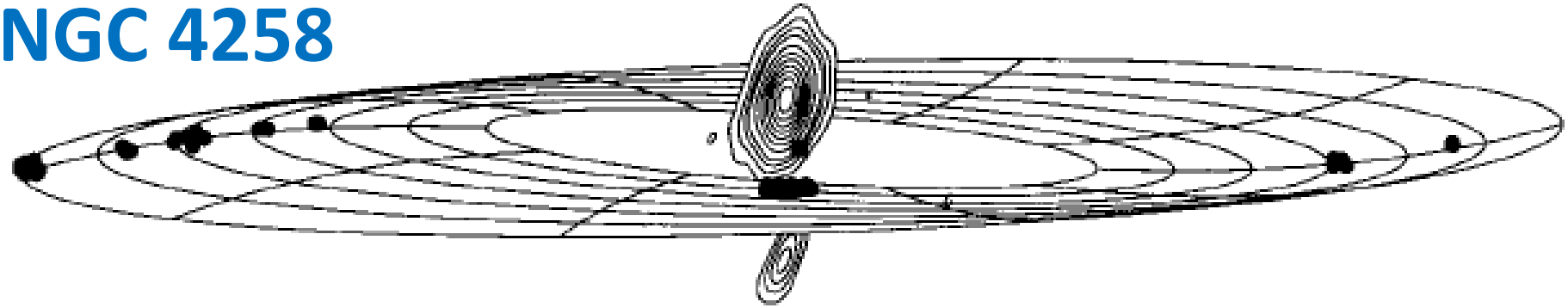
The AGN Paradigm

1) Supermassive Black Hole (SMBH)
2) Accretion Disk
3) Jet orthogonal to the disk plane

NGC 4258



Herrnstein et al. (1998)

The AGN Paradigm

1) Supermassive Black Hole (SMBH)
2) Accretion Disk
3) Jet orthogonal to the disk plane

Radio continuum data of H_2O disk-masers:

a) High resolution
b) Little extinction
c) Known geometry (edge-on-disk)
d) M_{BH} known

The AGN Paradigm

1) Supermassive Black Hole (SMBH)
2) Accretion Disk
3) Jet orthogonal to the disk plane

Questions to be tackled:

a) Are jets two sided?
b) Follow individual blobs? Bending jets?
c) Emission from inside the maser disk?
d) Correlations with M_{BH} and size of disk ?
e) Correlations with [OIII]?

The AGN Paradigm

Galaxy	R.A.	Dec. J2000	Bandpass calibrator	Amplitude and phase calibrator	R.A. J2000	δR.A. (arcsec)	Dec. J2000	δDec. (arcsec)
ESO558-G009	07:04:21.02	–21:35:19.2	3C147	J0731-2341	07:04:21.01	0.06	-21:35:19.03	0.05
IC 0485/ UGC 4156	08:00:19.77	+26:42:05.2	3C147	J0748+2400	...	...	...	...
IC 2560	10:16:18.72	–33:33:49.7	3C286	J1018-3144	10:16:18.71	0.16	-33:33:49.60	0.16
J0126-0417	01:26:01.66	–04:17:56.2	3C48	J0115-0127	01:26:01.64	0.04	-04:17:56.23	0.04
J0350-0127	03:50:00.35	–01:27:57.7	3C147	J0339-0146	03:50:00.35	0.15	-01:27:57.40	0.15
J0437+2456	04:37:03.69	+24:56:06.9	3C147	J0426+2327	...	...	...	...
J0437+6637	04:37:08.26	+66:37:42.3	3C147	J0449+6332	04:37:08.28	0.12	+66:37:42.10	0.12
J0836+3327	08:36:22.80	+33:27:38.7	3C286	J0827+3525	...	...	...	...
J1658+3923	16:58:15.50	+39:23:29.3	3C48	J1653+3945	16:58:15.54	0.22	+39:23:29.27	0.20
Mrk 0001/NGC 0449	01:16:07.25	+33:05:22.4	3C48	J0112+3208	01:16:07.20	0.02	+33:05:21.75	0.02
Mrk 0078	07:42:41.73	+65:10:37.5	3C286	J0805+6144	07:42:41.73	0.03	+65:10:37.39	0.03
Mrk 1029	02:17:03.57	+05:17:31.4	3C48	J0224+0659	02:17:03.57	0.18	+05:17:31.15	0.18
Mrk 1210/Phoenix	08:04:05.86	+05:06:49.8	3C147	J0811+0146	08:04:05.86	0.03	+05:06:49.83	0.03
Mrk 1419/NGC 2960	09:40:36.38	+03:34:37.2	3C147	J0948+0022	09:40:36.38	0.14	+03:34:37.36	0.13
NGC 0591/Mrk 1157	01:33:31.27	+35:40:05.7	3C48	J0148+3854	01:33:31.23	0.10	+35:40:05.79	0.11
NGC 1194	03:03:49.11	–01:06:13.5	3C48	J0312+0133	03:03:49.11	0.03	-01:06:13.48	0.03
NGC 2273	06:50:08.66	+60:50:44.9	3C147	J0650+6001	06:50:08.69	0.28	+60:50:45.10	0.27
NGC 2979	09:43:08.65	–10:22:59.7	3C286	J0943-0819	09:43:08.64	0.04	-10:23:00.02	0.04
NGC 3393	10:48:23.46	–25:09:43.4	3C286	J1037-2934	10:48:23.46	0.03	-25:09:43.44	0.03
NGC 4388	12:25:46.75	+12:39:43.5	3C286	J1218+1105	12:25:46.78	0.02	+12:39:43.77	0.02
NGC 5495	14:12:23.35	–27:06:28.9	3C286	J1409-2657	14:12:23.35	0.05	-27:06:29.14	0.06
NGC 5728	14:42:23.90	–17:15:11.1	3C286	J1439-1659	14:42:23.89	1.00	-17:15:10.76	1.00
UGC 3193	04:52:52.58	+03:03:25.9	3C147	J0503+0203	04:52:52.56	0.11	+03:03:25.52	0.29
UGC 3789	07:19:30.92	+59:21:18.4	3C147	J0728+5701	07:19:30.95	0.08	+59:21:18.37	0.08

Source list

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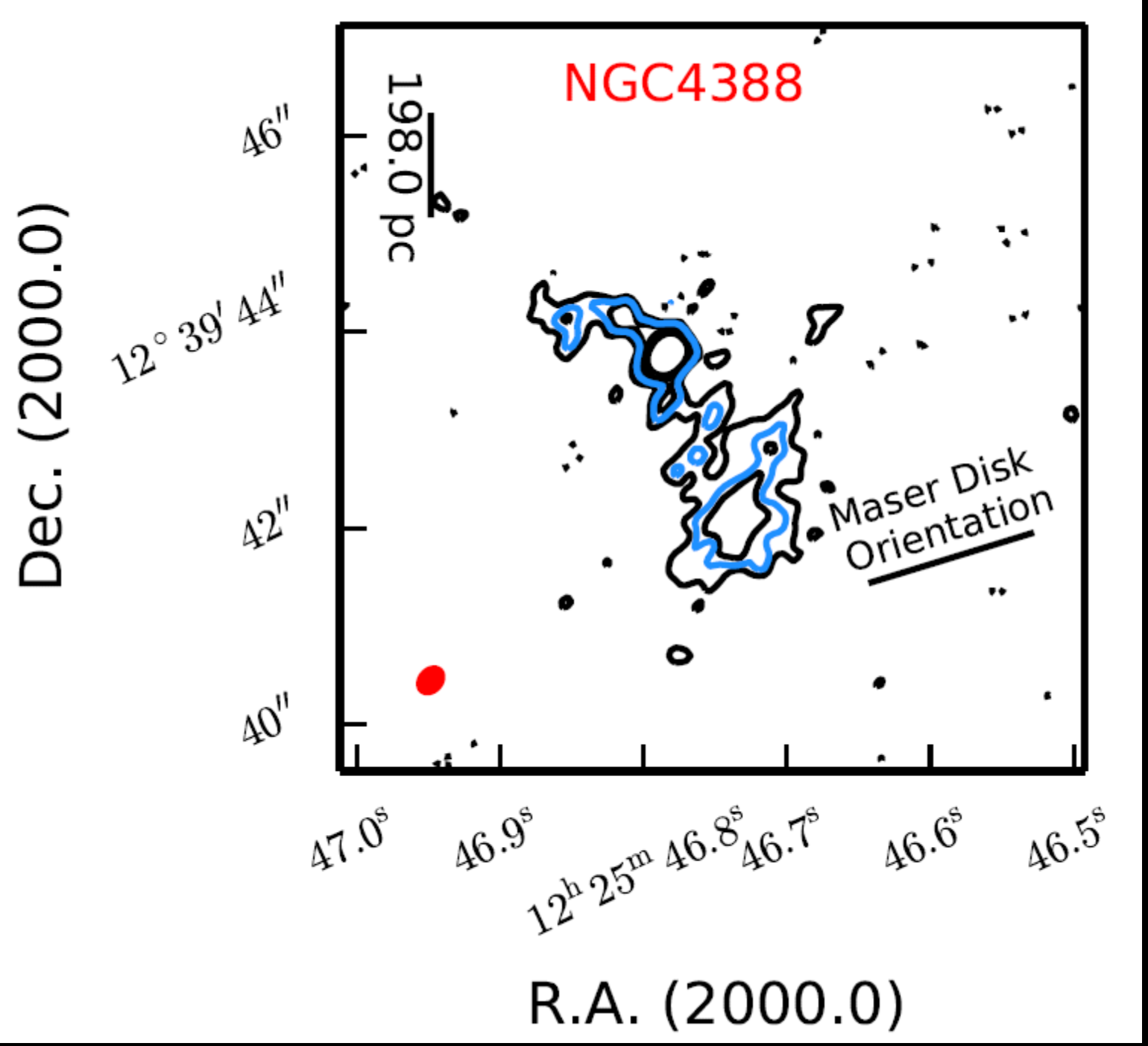

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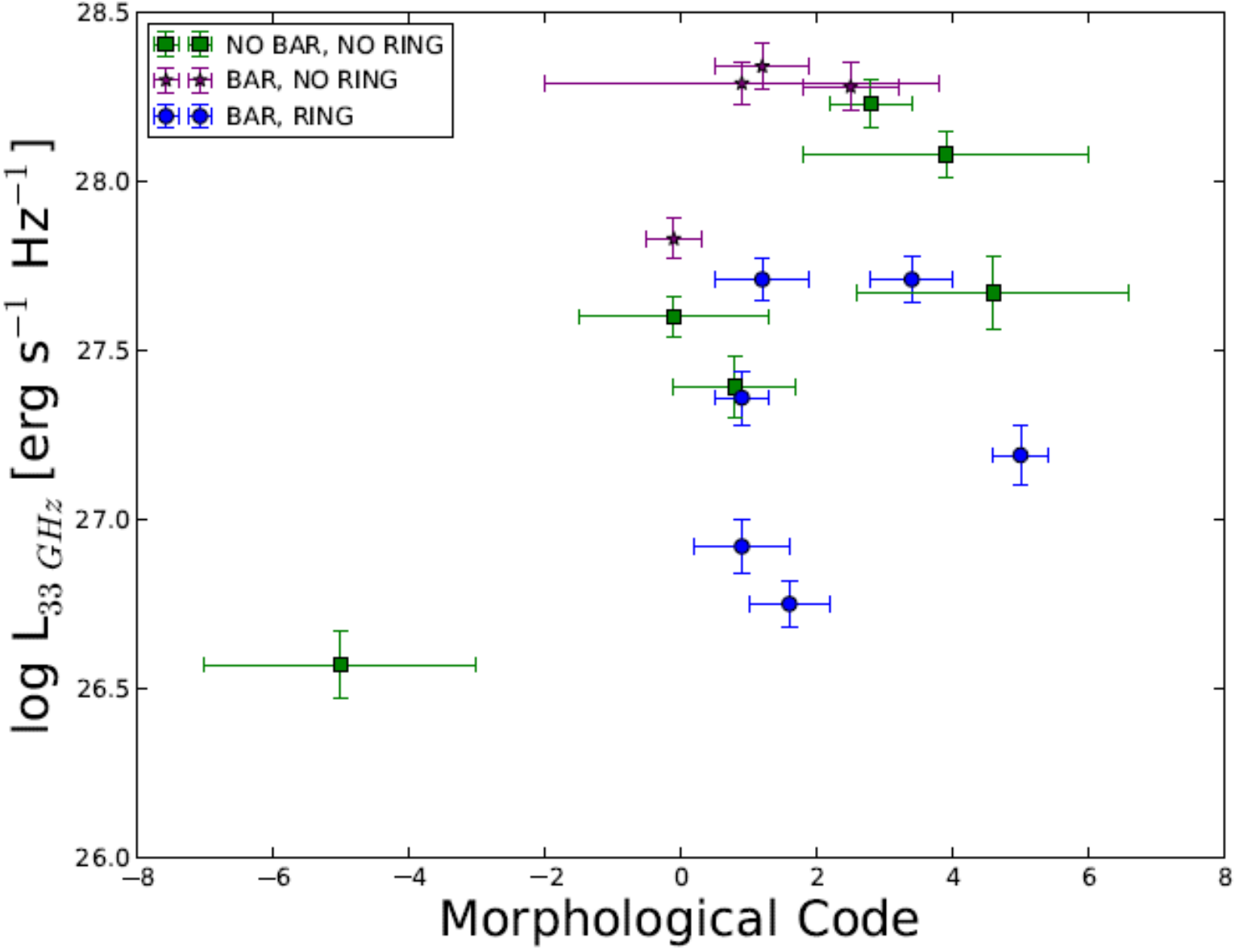
Morphology of Spiral Galaxies



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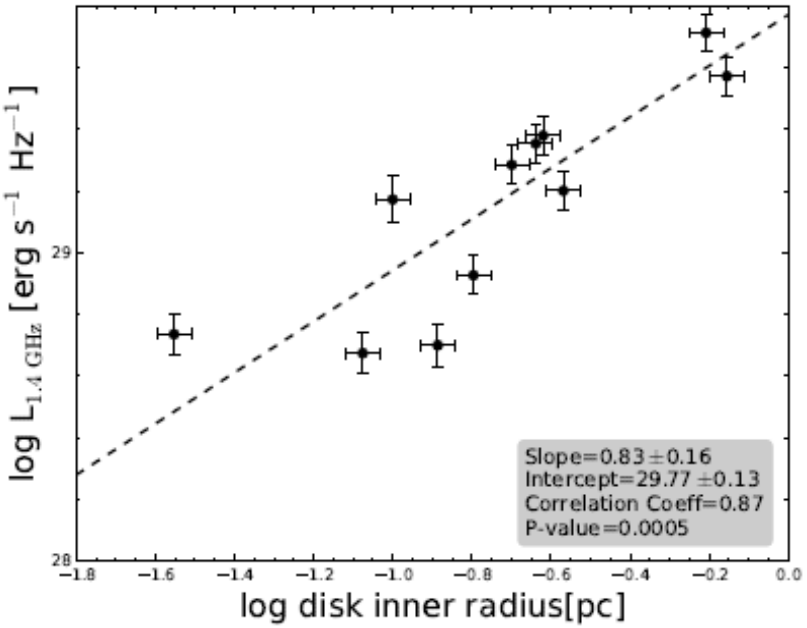
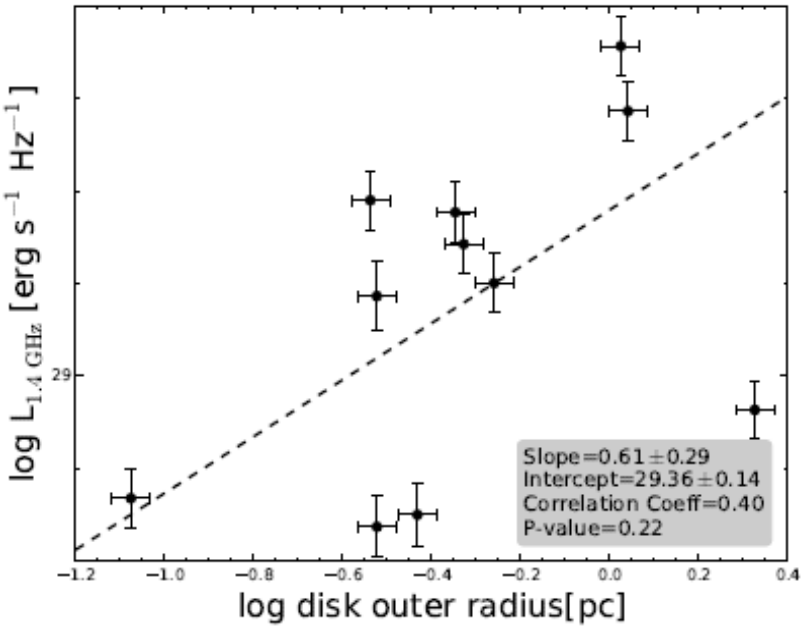
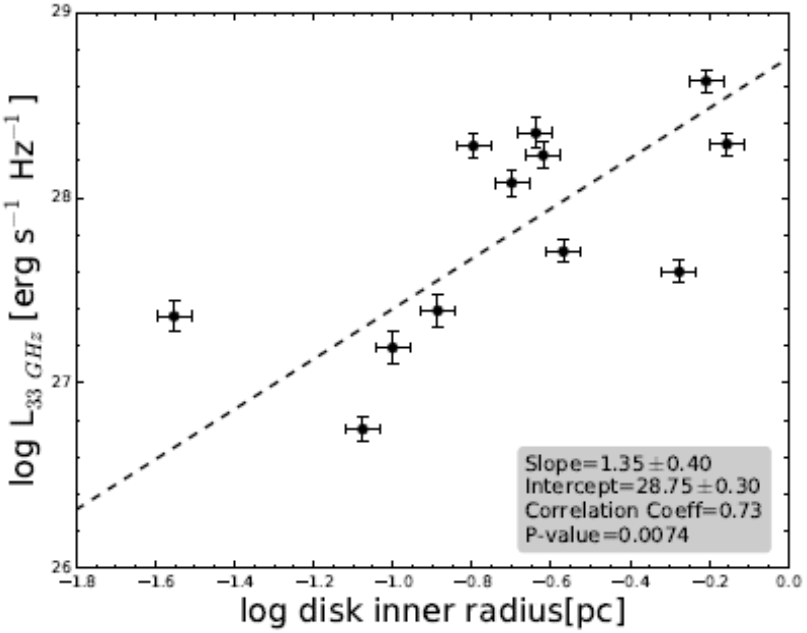
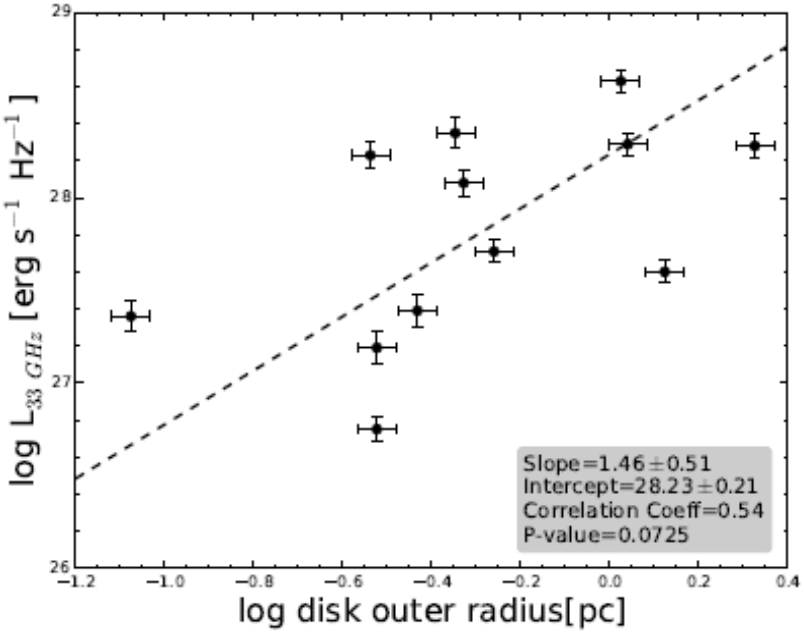


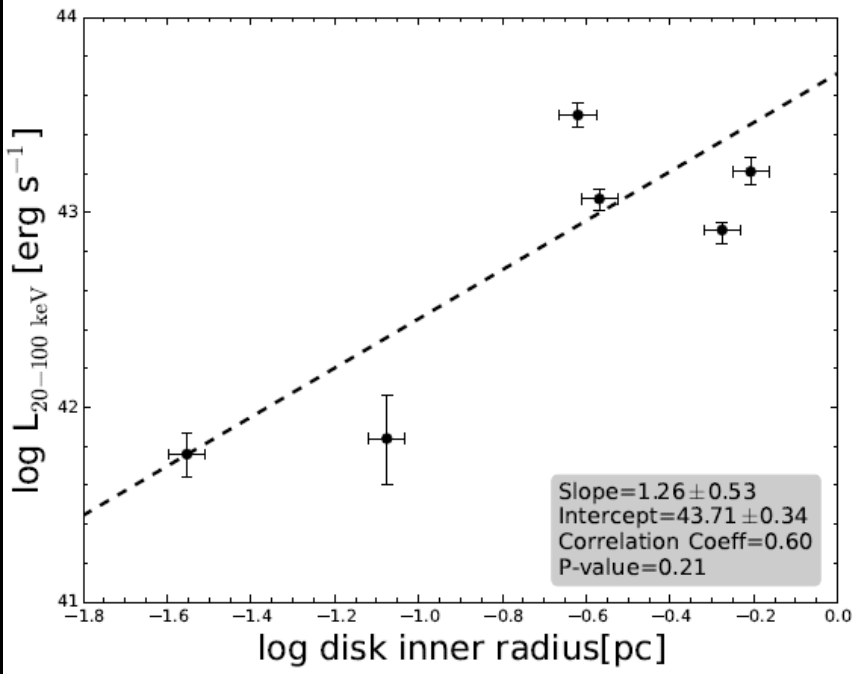
(a) 1.4 GHz continuum luminosity (NVSS) versus maser disk inner radius.



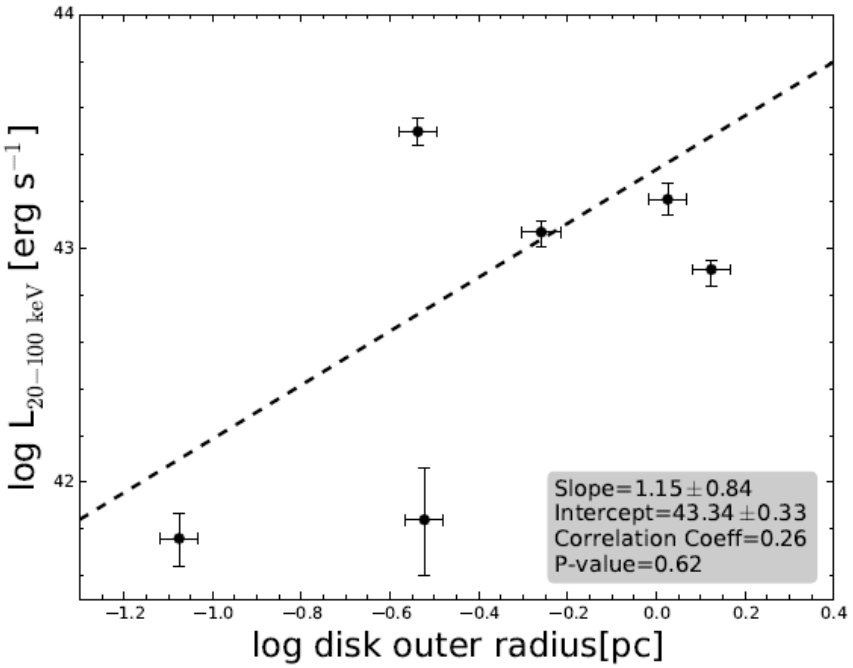
(b) 1.4 GHz continuum luminosity (NVSS) versus maser disk outer radius.







(g) Hard X-ray luminosity versus maser disk inner radius.



(h) Hard X-ray luminosity versus maser disk outer radius.

Hard X-ray luminosities versus maser disk radii

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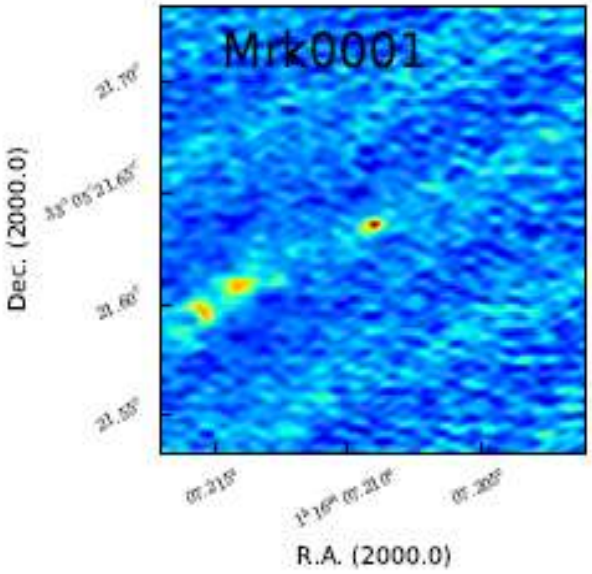
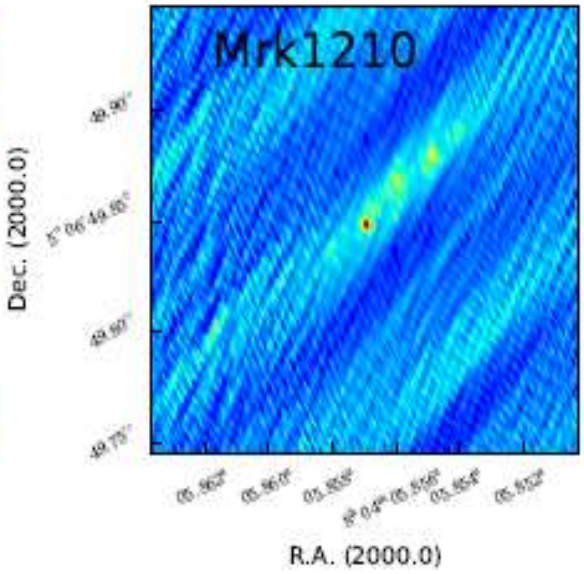
The AGN Paradigm

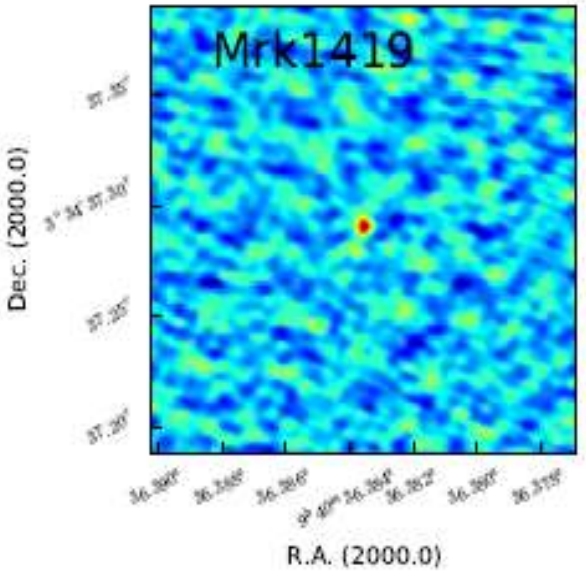
1) Supermassive Black Hole (SMBH)
2) Accretion Disk
3) Jet orthogonal to the disk plane

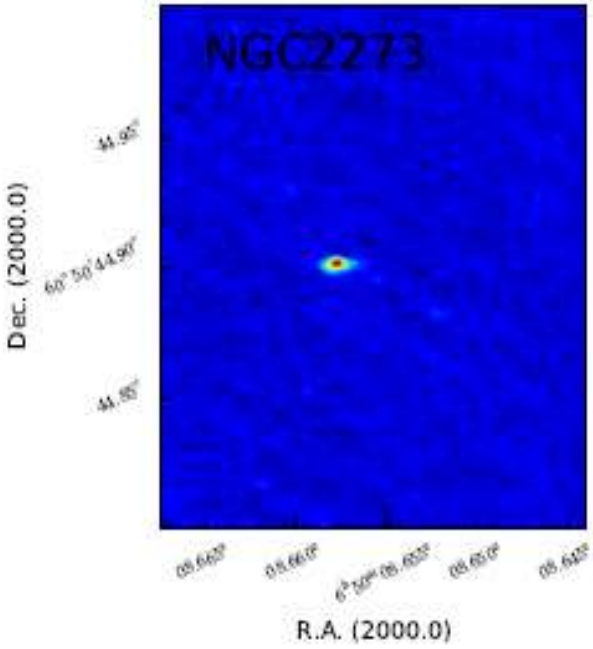
Second step:

VLBA 5 GHz continuum of
21 disk maser galaxies

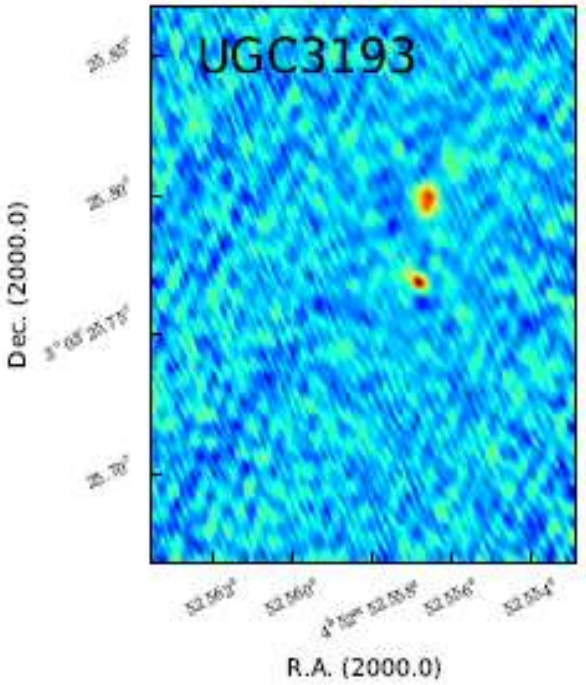






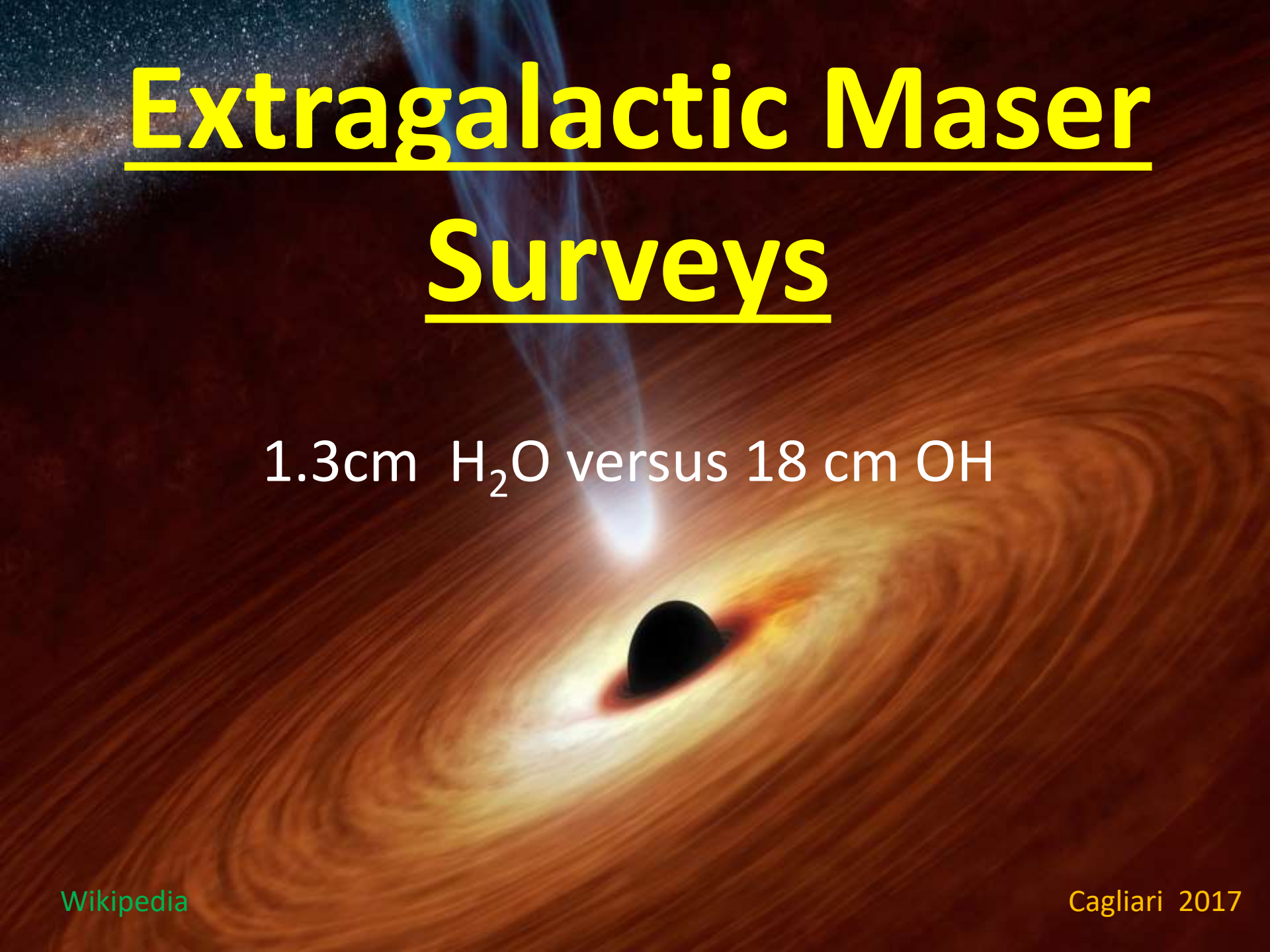


See poster by Kamali et al.



Extragalactic Maser Surveys

1.3cm H_2O versus 18 cm OH



Wikipedia

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1.3 cm H_2O versus 18 cm OH

How are they related to each other?



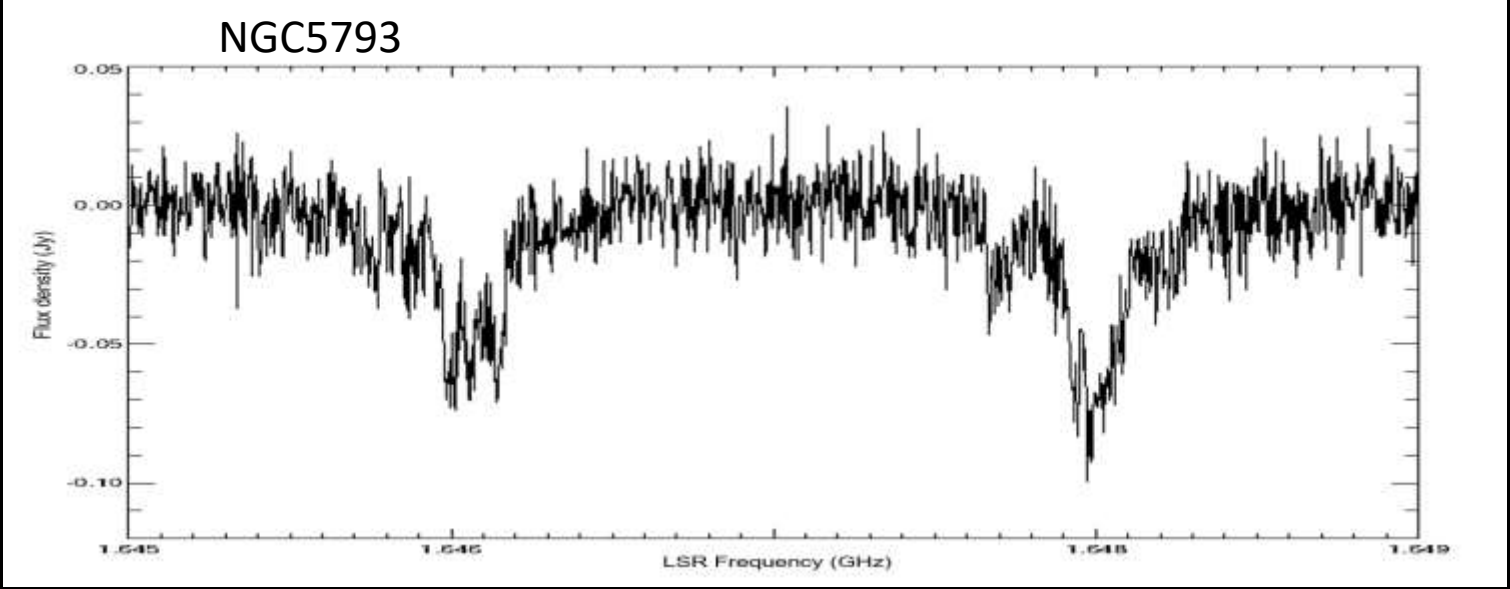
Search for galaxies which host both H_2O and OH masers

Poster by Ladu & Tarchi et al.
See also Wagner 2013

1.3 cm H_2O versus 18 cm OH

How are they related to each other?

Search for galaxies which host both H_2O and OH masers



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Extragalactic Maser Surveys

Other Masers



Wikipedia

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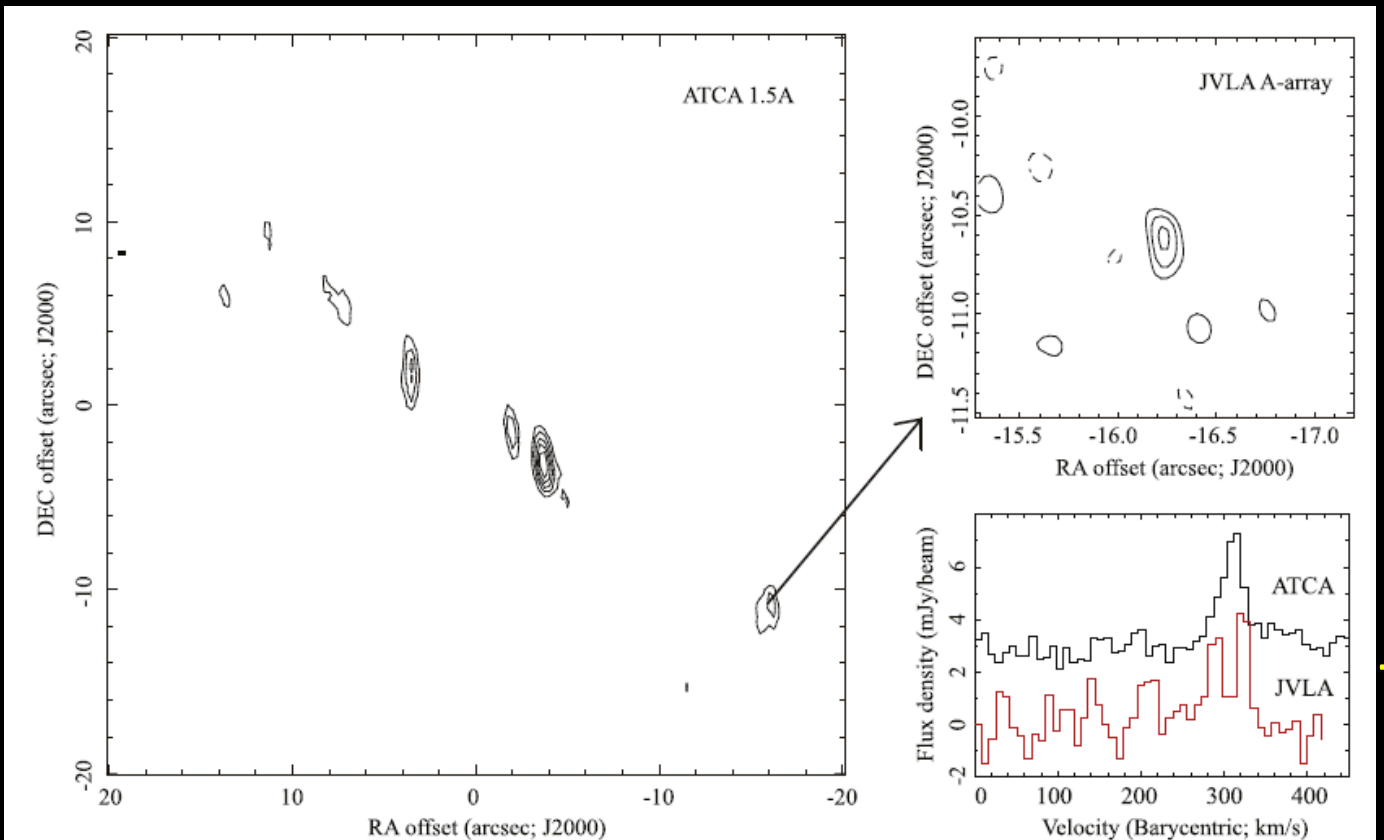
Other Masers

J. Wang et al. (2014): SiO J=2-1/CH_3OH 5(-1) – 4(0)
NGC1068
?

Ellingsen et al. (2017): HC_3N J = 4-3, NGC 253 ?



Statistically marginal, but …

$T_{mb} \geq$ 2500 K

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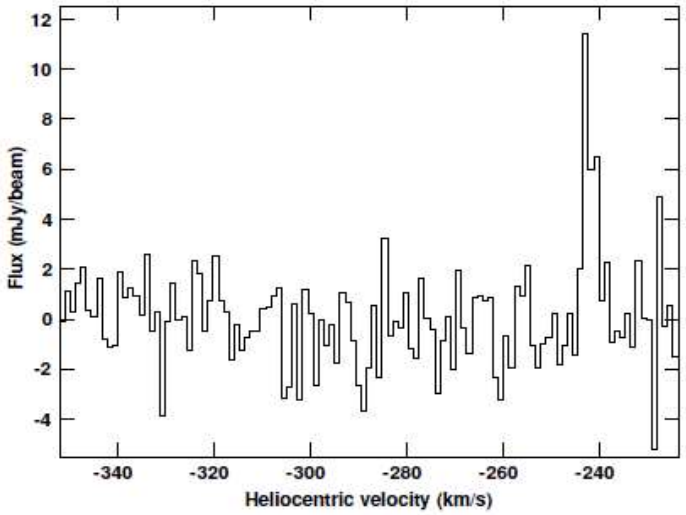
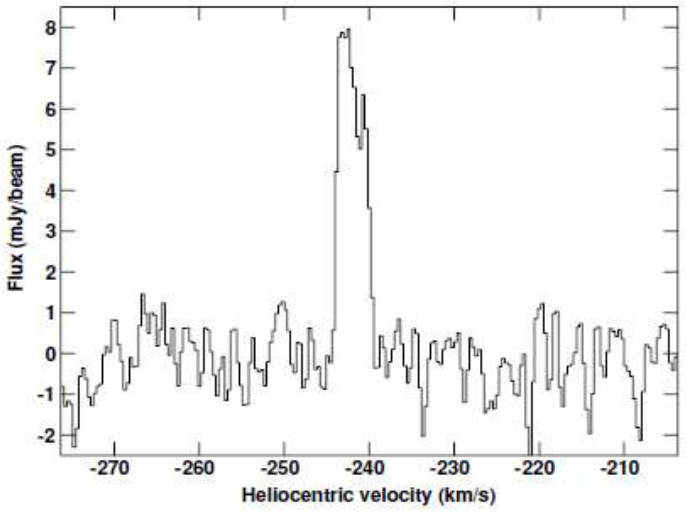
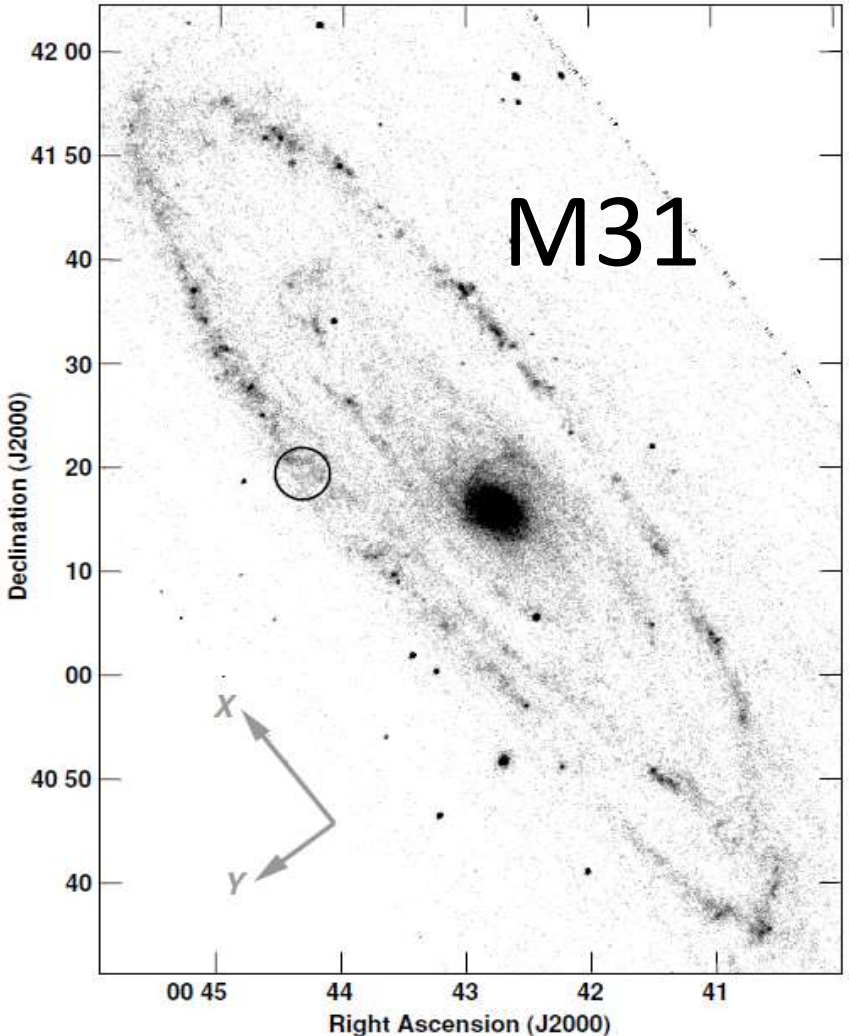
Other Masers

Sjouwerman et al. (2010): CH_3OH 6.7 GHz







No Class II Super-Masers

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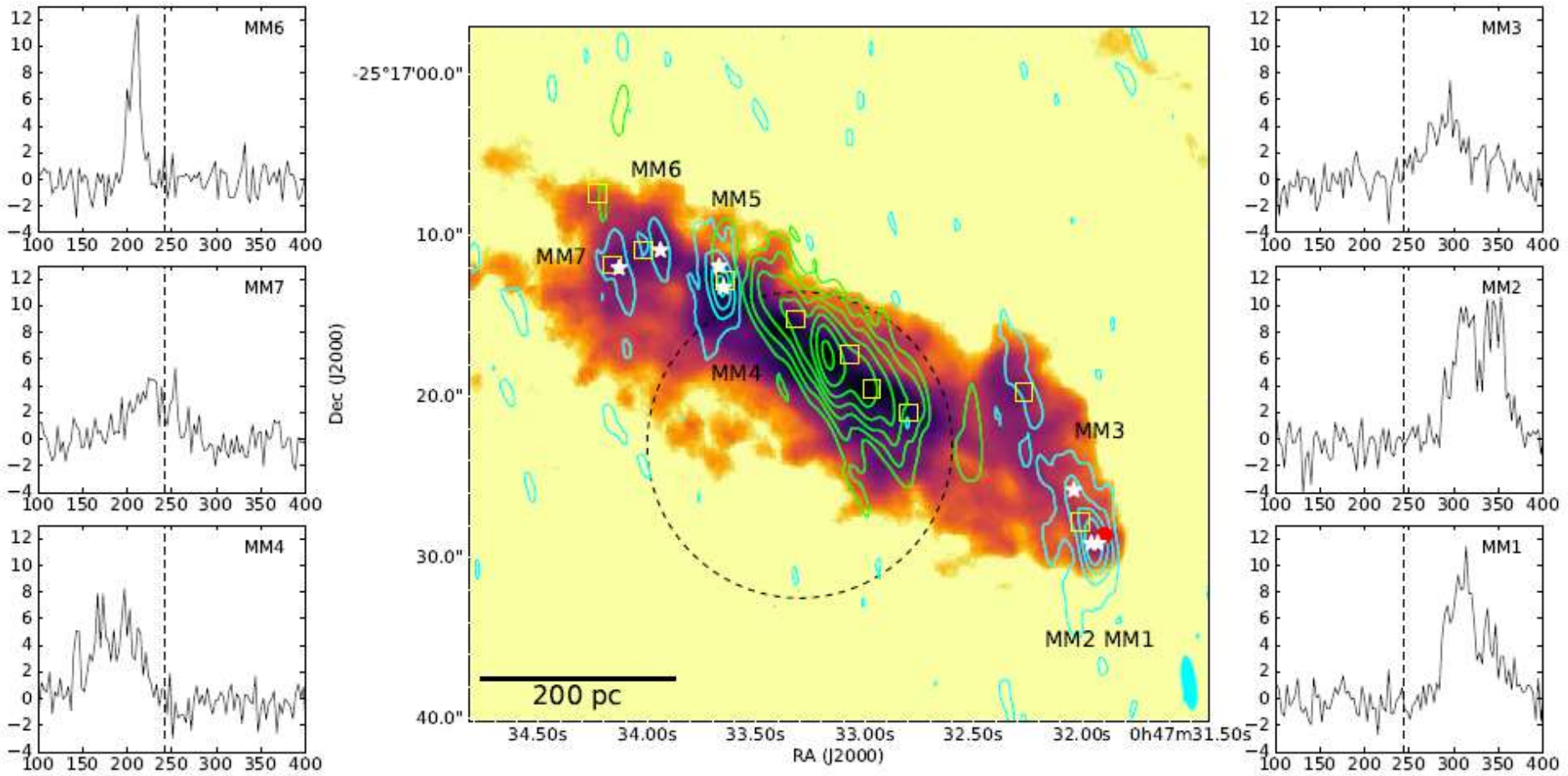
Other Masers

Ellingsen/Chen: CH_3OH 36 + 44 GHz, CLASS I

Ellingsen et al. (2014) : 36 GHz, NGC 253 ?
Chen et al. (2015) : 36 GHz, Arp220 ?
Chen et al. (2016) : 36 GHz, 16 galaxies ?
Ellingsen et al. (2017) : 44 GHz, NGC 253
McCarthy et al. (2017): 36 GHz, NGC 4945

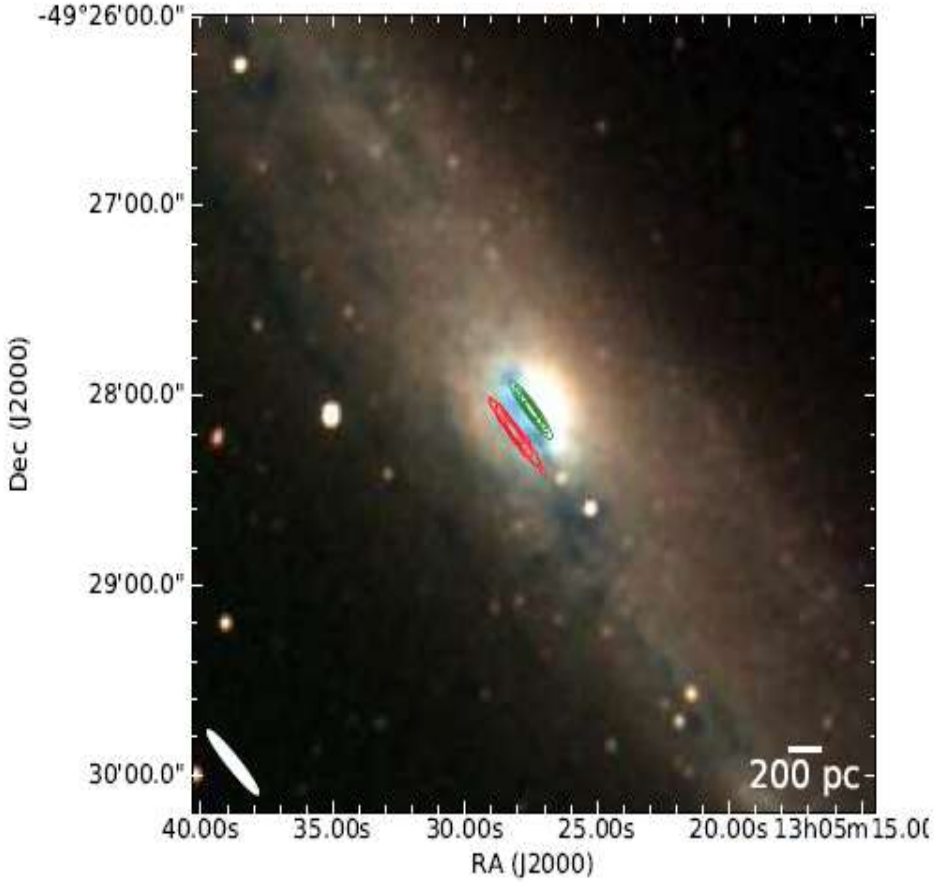
Other Masers

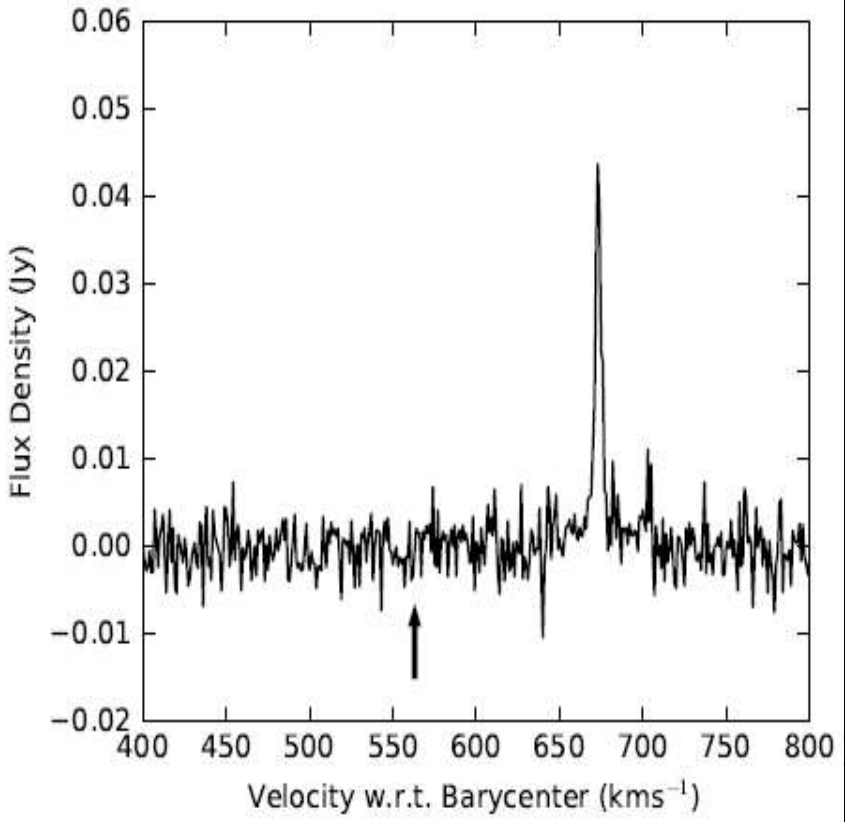


Ellingsen et al. 2017

Cagliari 2017

Other Masers





McCarthy et al. 2017

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Other Masers

Ellingsen/Chen: CH_3OH 36 + 44 GHz, CLASS I

Ellingsen et al. (2014) :	36 GHz, NGC 253	?
Chen et al. (2015) :	36 GHz, Arp220	?
Chen et al. (2016) :	36 GHz, 16 galaxies	?
Ellingsen et al. (2017) :	36+44 GHz, NGC 253	!!!
McCarthy et al. (2017):	36 GHz, NGC 4945	!!!

Class I CH_3OH supermasers must exist!

Other Masers

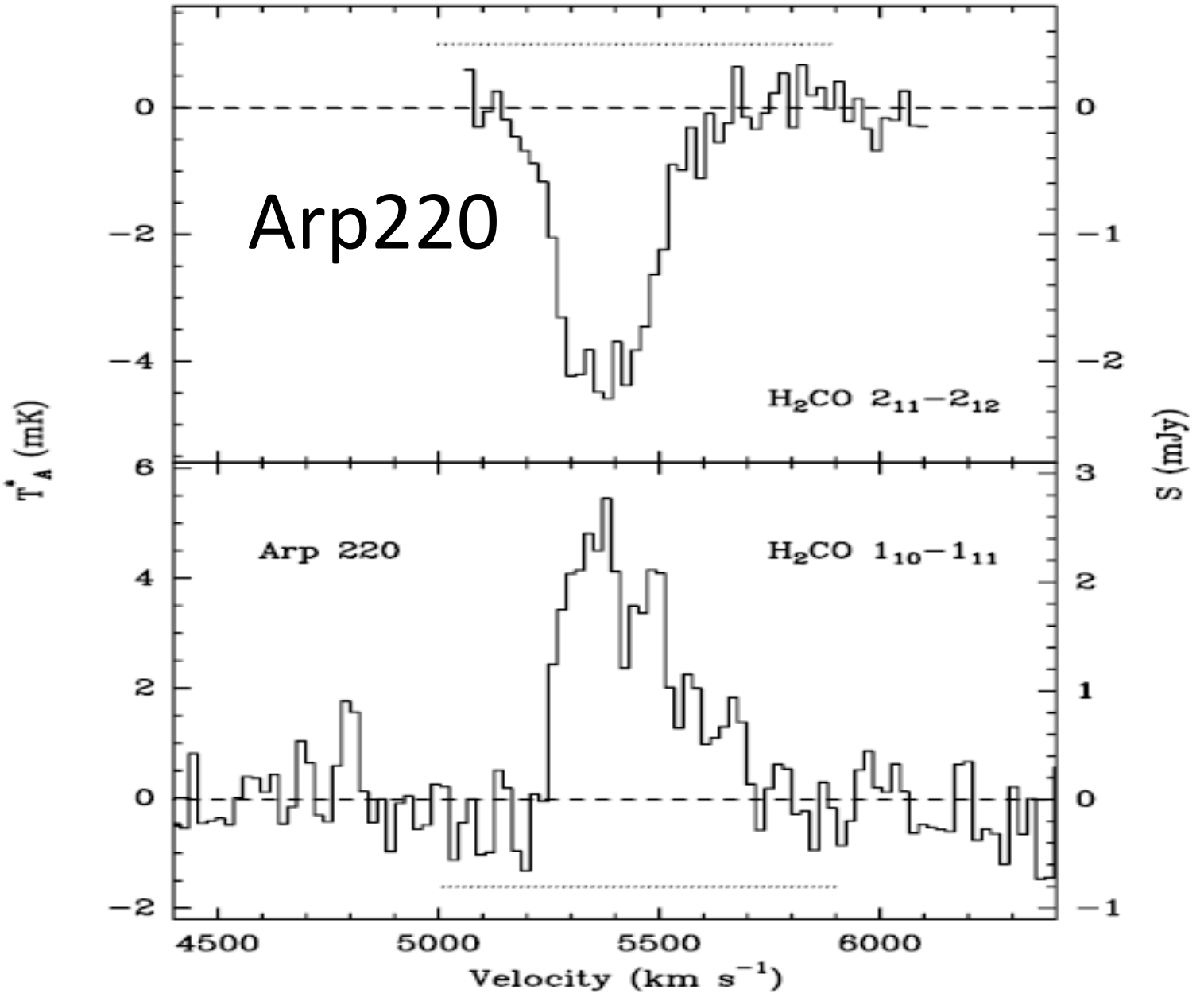
Mangum et al. (2013):

Extragalactic 2 and 6 cm H_2CO survey (GBT)

in 56 sources. Both lines detected in 13.

Assumed: Quasi-thermal emission.

Other Masers



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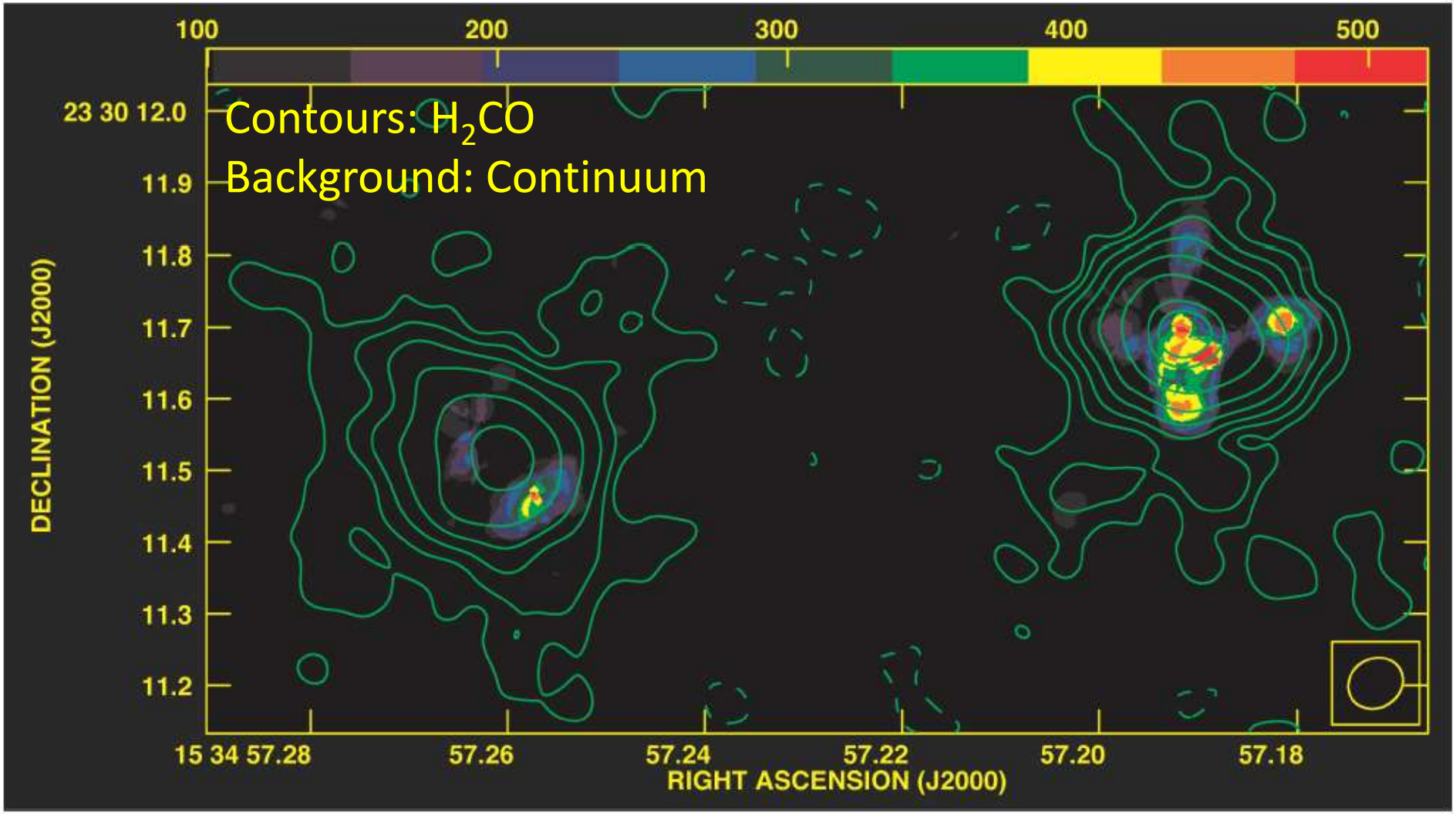
Other Masers

Mangum et al. (2013):

Extragalactic 2 and 6 cm H_2CO survey (GBT)
in 56 sources. Both lines detected in 13.
Assumed: Quasi-thermal emission.

Baan et al. (2017): H_2CO 6 cm in
IC 860, IRAS 15107+0724, Arp220
MERLIN

Other Masers



Baan et al. (2017)

Cagliari 2017

Other Masers

Mangum et al. (2013):

Extragalactic 2 and 6 cm H_2CO survey (GBT) in 56 sources. Both lines detected in 13.

Assumed: Quasi-thermal emission.

Baan et al. (2017): H_2CO 6 cm in IC 860, IRAS 15107+0724, Arp220

MERLIN



Maser emission with about 10^4 K (lower limit)

Other masers: 18 cm OH

MeerKAT ? ASKAP ? Apertif ? Deep GMRT field ? FAST ?

MeerKAT:

MALS = MeerKAT Absorption Line Survey
(HI and OH – with OH also providing clues for changes of fundamental physical constants)
Gupta, Srianand et al.

LADUMA = Looking at the Distant Universe with the MeerKAT Array
(ultradeep survey of HI in the early Universe)
Blyth, Holwerda, Baker et al.


THANK YOU
THANK YOU
THANK YOU
THANK YOU
Wikipedia
Cagliari 2017

SUMMARY

1. H_2O Megamaser Disks (MCP)
2. H_2O disks with large BH sphere of influence
3. Morphology of Spiral Galaxies
4. The AGN Paradigm
5. Recent H2O Surveys
6. OH versus H2O Megamasers
7. OH Megamasers
8. H2O + HC3N Masers in Nearby Galaxies
9. CH3OH supermasers (only Class I ?)

Morphology of Spiral Galaxies

Decomposition

1. Nuclear disks
2. Bars
3. Rings
4. Spiral arms
5. Envelopes

F336W, F435W, F814W, F110W, F160W - F110W starlight, F814W –W110W dust

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MeerKAT/ASKAP

MeerKAT
64 13.5 m antennas
48 within the 1 km core
8 km longest distance

ASKAP
48 12m antennas
36 independent beams, each ~1 deg across
6 km longest baseline, use of PAFs

Apertif
Use of PAFs, WSRT with highly increase FOV

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NL-Sy1s

AGN masses:

Woo et al. 2015: $1 - 15 \times 10^6 M_\odot$

Orientation of the masing disk, galaxy and nuclear region for each of the galaxies.

	Object	D_A	Maser			Galaxy			Nuclear region				
		[Mpc]	i	PA	ref.	e	i	PA	Class	r [pc]	e	i	PA
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
This work	ESO558−G009	109	90	350	G16p†	0.97	104	277[d]	Ch+N	210	0.87	61	99
	J0437+2456	70	90	115	G16p†	0.82	125	126[d]	Bu+N	120	0.77	51	131
	Mrk1029	117	90	300	G16p†	0.77	130	176[d]	D+N	220	0.83	57	126
	Mrk1210	58	101	333	Z17p	0.33	19	36[r]	D/R+Stw	170	0.45	26	119
	NGC5495	93	90	270	G16p†	0.63	141	119, 299	D/R+Sgd	170	0.49	29	57
	NGC5728	41	90	329	K17p†	0.91	114	302[r]	R+Stw	460	0.36	21	121
	NGC5765b	126	95	237	G16	0.67	42	337[r]	R+Stw	450	0.45	27	67
	UGC3193	60	90	60	W17p†	0.95	72	80[d]	D?+N	220	0.90	65	79
	UGC6093	147	94	70	Z17p	0.47	152	0[r]	Bu?+N	150	0.26	15	92
Greene et al. (2013)	IC2560	44	90	44	Y12	0.88	62	133[r]	D+Stw	100	0.74	48	136
	NGC1194	52	85	67	K11	0.84	57	50[r]	Ch+N	120	0.63	39	68
	NGC2273	26	84	63	K11	0.68	43	176[r]	R+Stw	150	0.86	59	131
	NGC2960	71	89	139	K11	0.64	140	314[r]	D+N	260	0.83	56	139
	NGC3393	55	90	56	K08†	0.72	46	252[r]	R+Sgd	270	0.68	43	58
	NGC4388	19	90	17	K11†	0.98	78	0	D+N	100	1.00	89	345
	NGC6264	134	90	185	K11	0.79	52	290[d]	Ch+N	290	0.68	43	123
	NGC6323	103	89	280	K11	0.94	70	85[r]	Bu?+N	200	0.62	38	95
	UGC3789	45	89	311	K11	0.87	120	243[r]	D+Sgd	100	0.62	39	88

1. From Largest to Smallest Scales

Structure maps:

As a second method to characterize nuclear morphology, we use structure maps to remove large-scale smooth galaxy components and highlight the small-scale features (such as dust lanes). The concept of structure maps was introduced by Pogge & Martini (2002). The technique is designed to remove low-frequency (smooth) features of the map, and highlight high-frequency features around the scale of the PSF. The method is closely related to Richardson-Lucy deconvolution (Richardson 1972; Lucy 1974). It is also similar in spirit to unsharp masking, but with structure maps the convolution is done with the PSF itself rather than a boxcar.

1. From Largest to Smallest Scales

Structure maps:

$$S = \left[\frac{I}{I \otimes P} \right] \otimes P^T, \qquad (1)$$

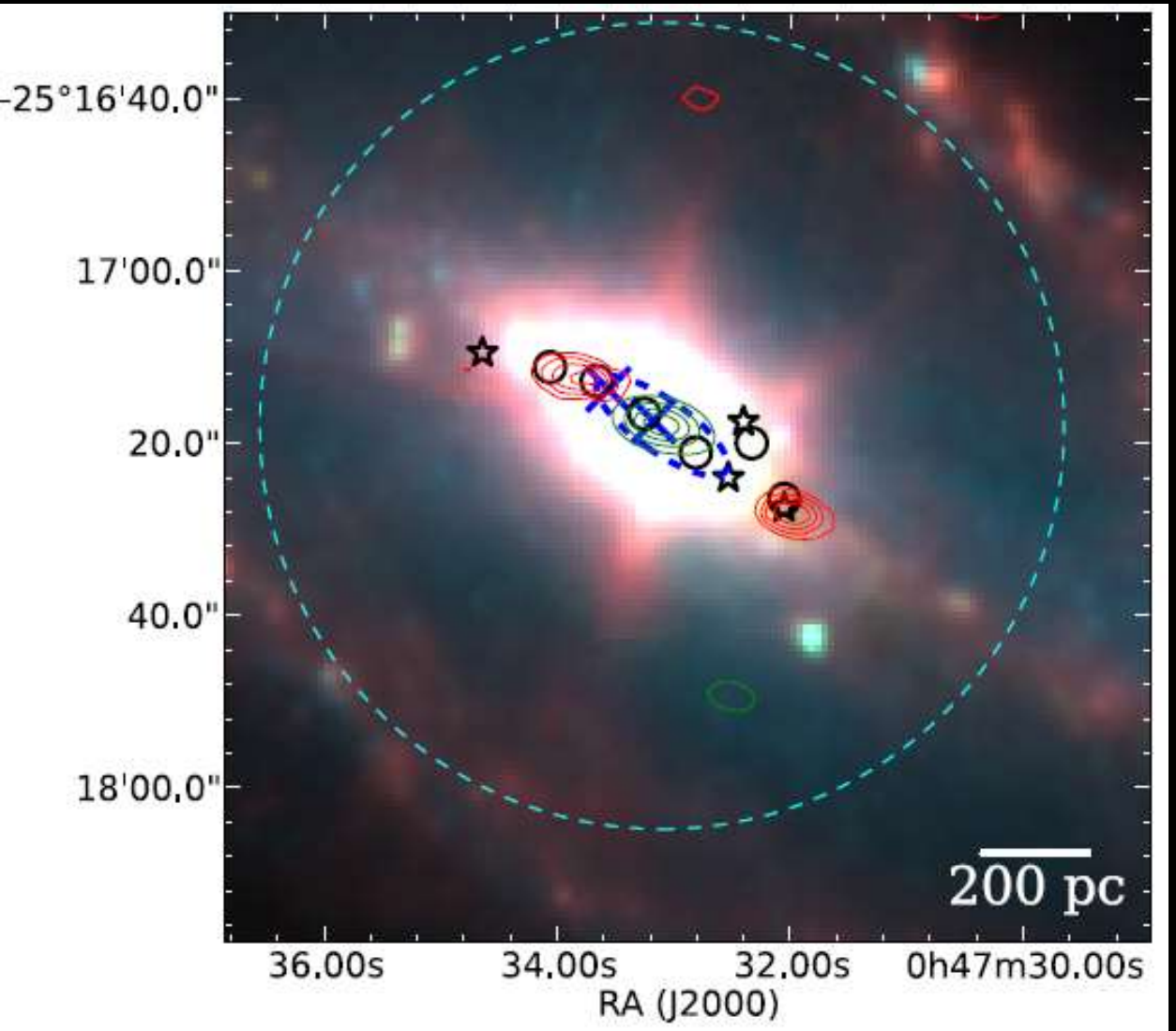
where S is the structure image pixel matrix, I is the original image, P is the point-spread function (PSF), P^T is the transposed PSF and $\otimes$ denotes convolution. Structure maps emphasize high frequency features that are nearly unresolved in the original image.

Questions

1. What changes the orientation in spirals?
2. Radius where the orientation of the accretion disk is reached?
3. Is the σ_* - M_{BH} correlation really breaking down in Milky Way sized spirals?
4. Is there a bias between megamaser and dynamical BH-masses?
5. Search for a source allowing for a comparison between maser and dynamical BH-mass.
6. Systematic VLBA+MERLIN measurements of disk-maser galaxies: results?

Other Masers

Ellingsen/Chen: CH_3OH 36 + 44 GHz, CLASS I



NGC 253

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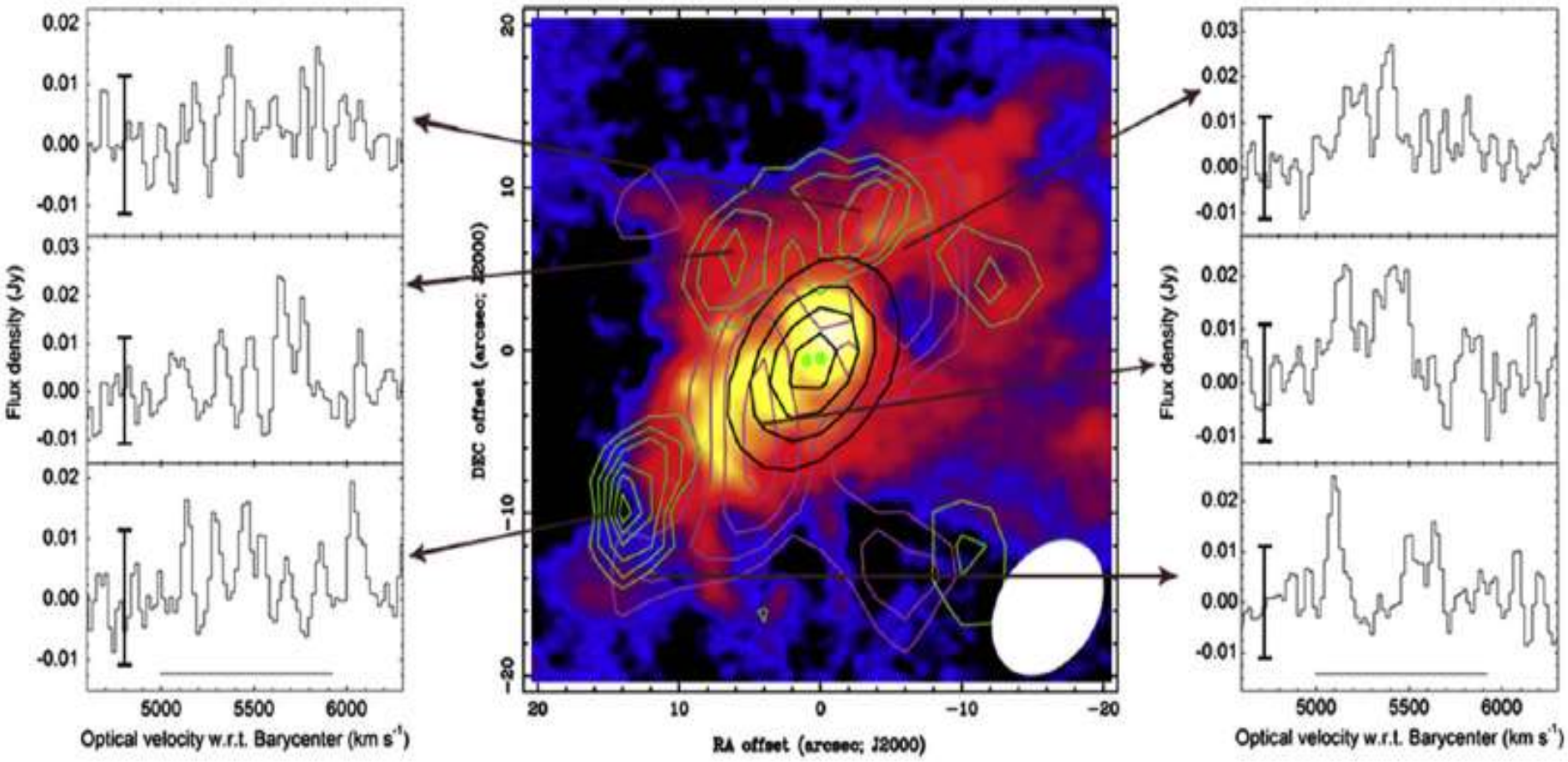
Other Masers



Chen et al. 2015

Center: Background Hα + [NII]
Black contours: 36 GHz continuum
Magenta contours: 36 GHz Methanol

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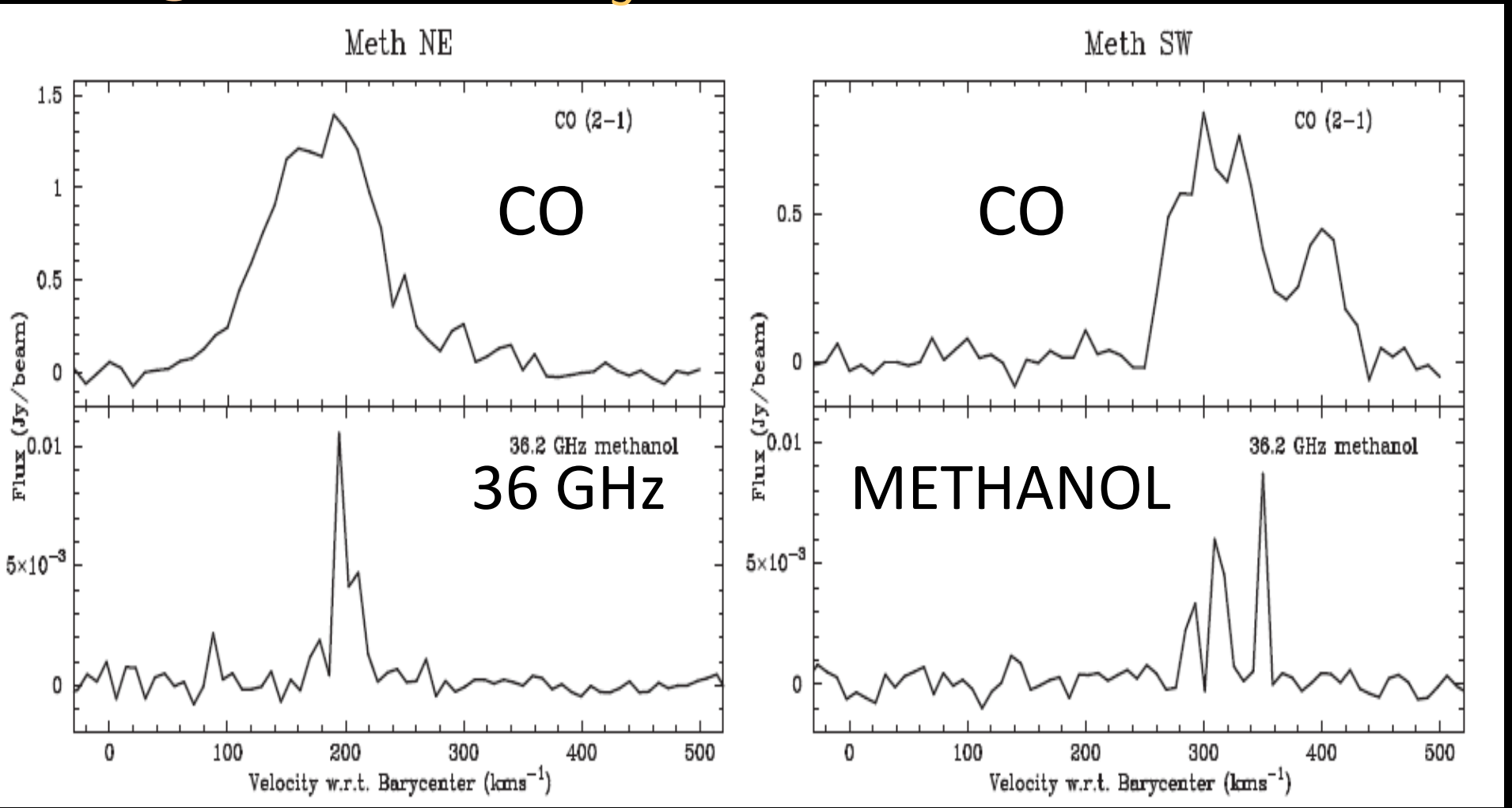
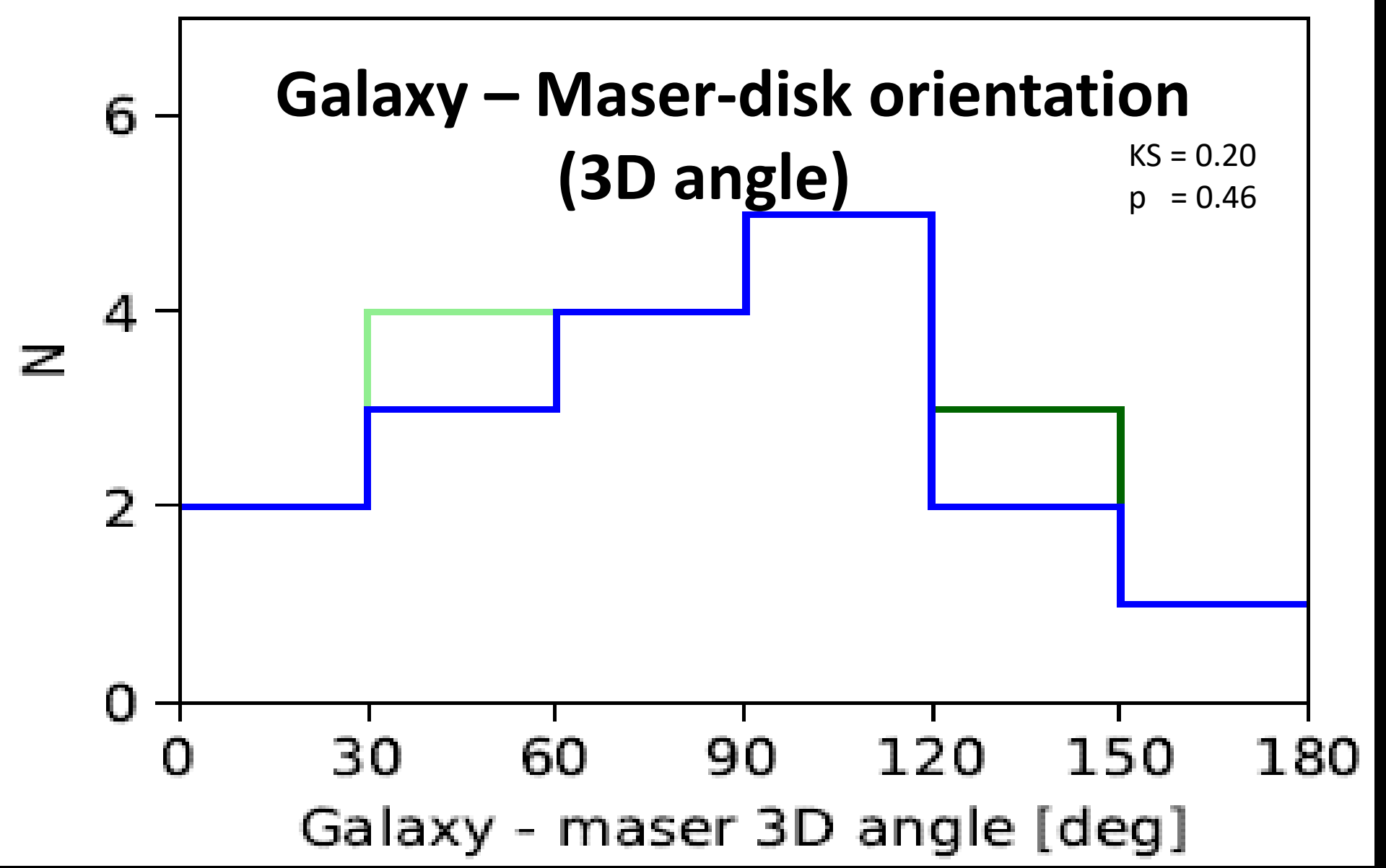
Other Masers

Ellingsen/Chen: CH_3OH 36 + 44 GHz, CLASS I





Green: Addition of the two possible angles for NGC 5495.

Random distribution

Cagliari 2017

3. The AGN Paradigm

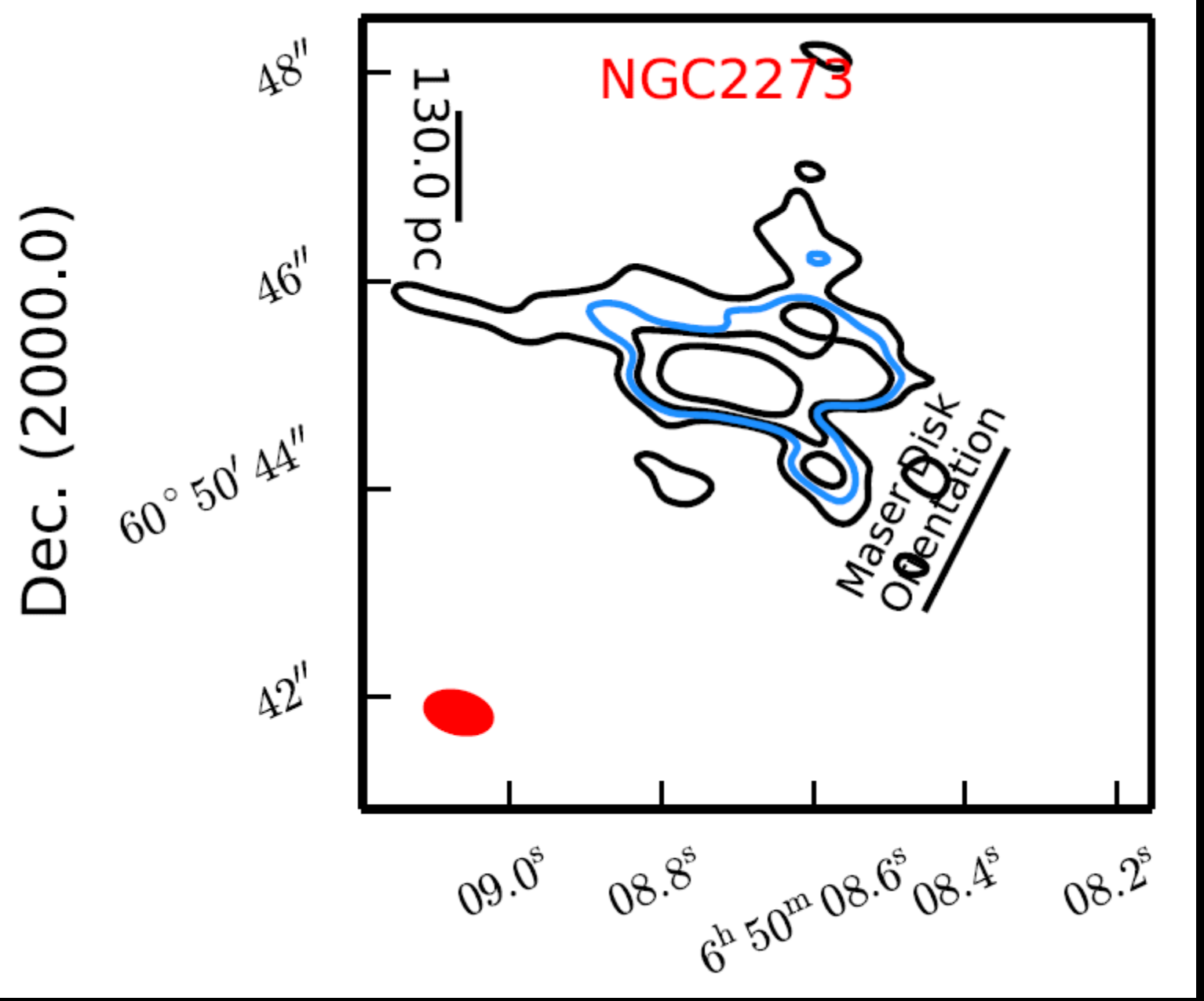
1) Supermassive Black Hole (SMBH)
2) Accretion Disk
3) Jet orthogonal to the disk plane

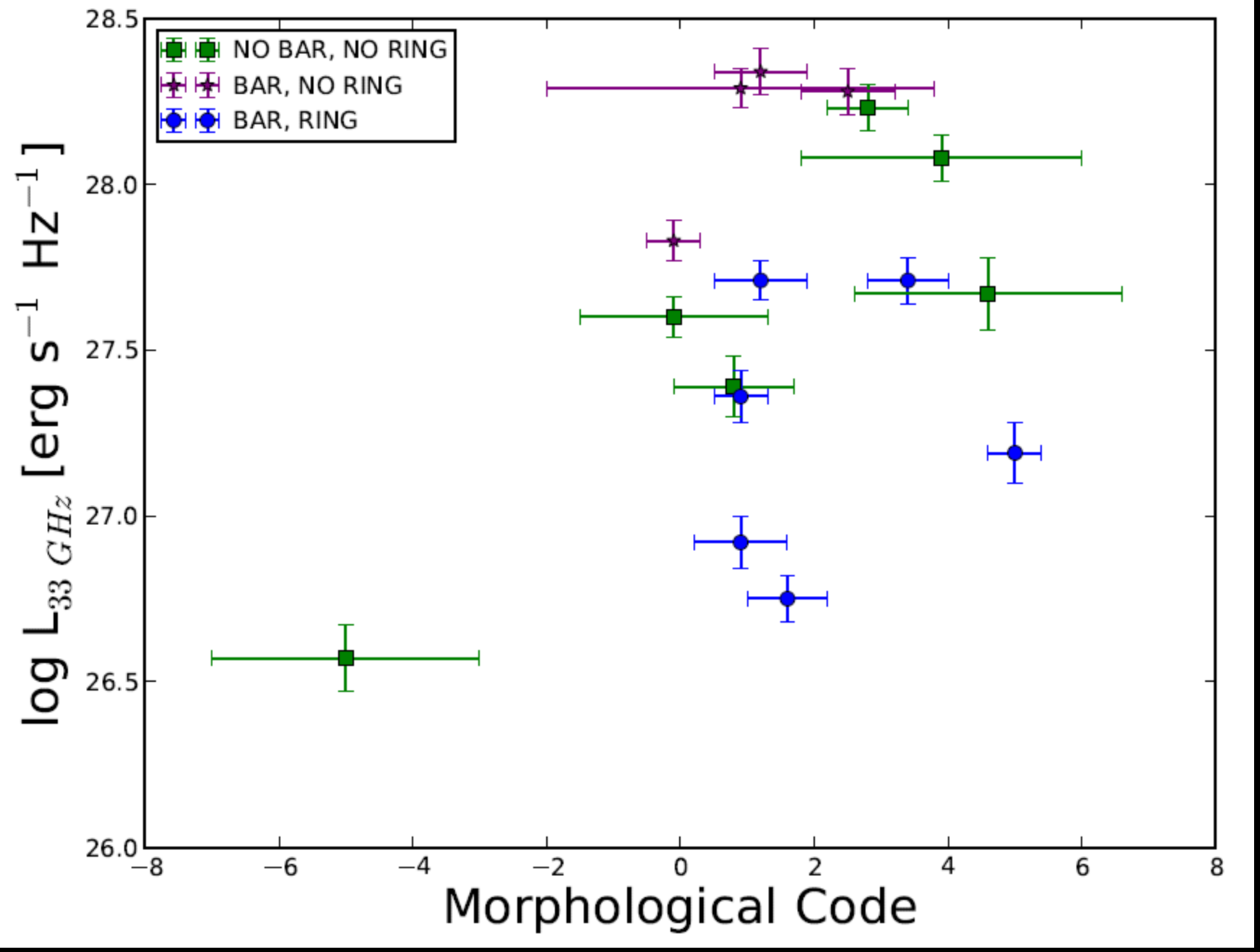
Kamali et al. 2017, arXiv:1706.02699:
VLA 33±4 GHz continuum of
24 disk maser galaxies

0.2” – 0.5” resolution ≡ 100 pc

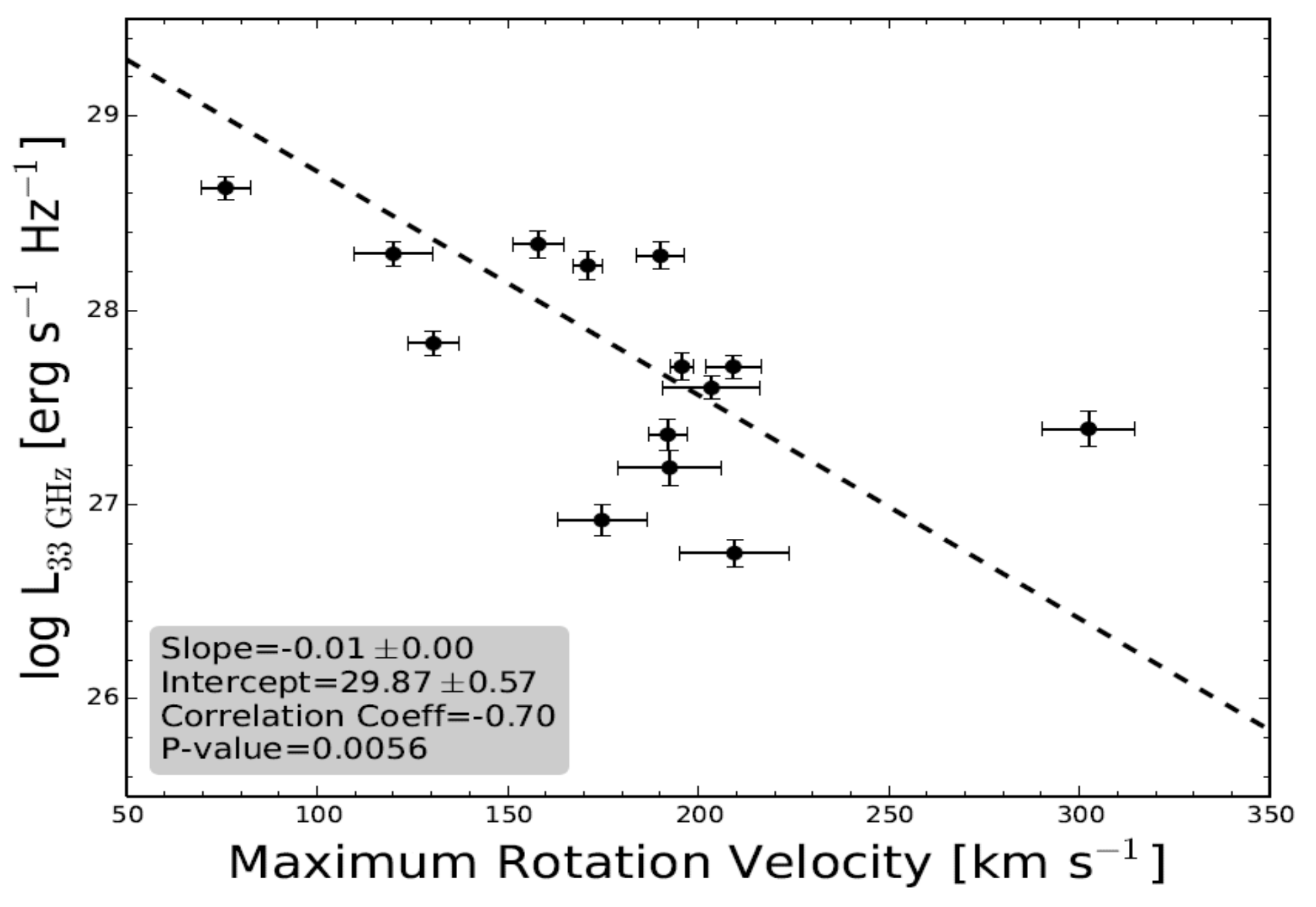
3. The AGN Paradigm

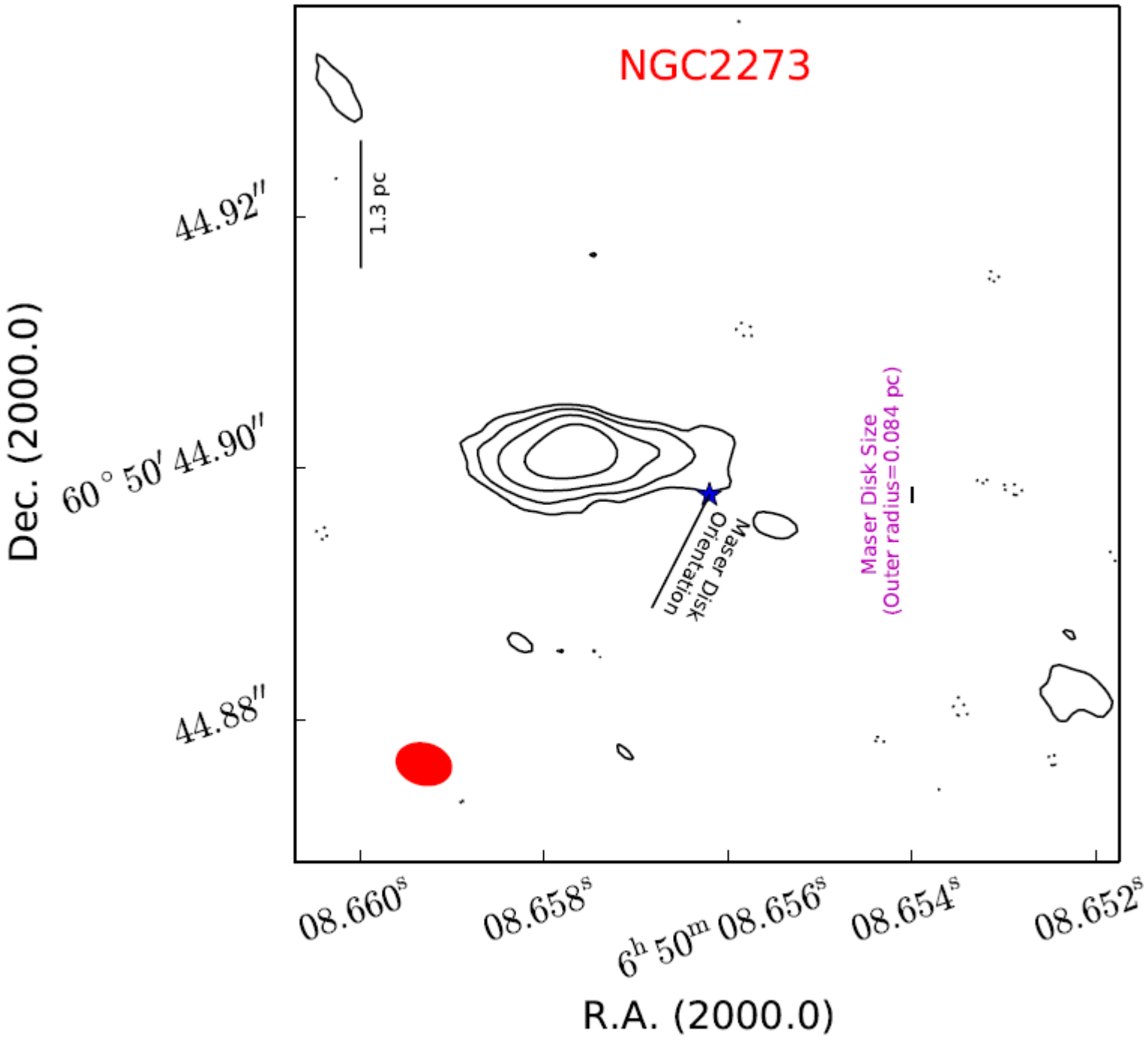
Best detected sources with orientation of the maser disk known:


NGC2273
130.0 pc
Maser Disk
Orientation
Dec. (2000.0)
48″
46″
60° 50′ 44″
42″
09.0s
08.8s
6h 50m 08.6s
08.4s
08.2s

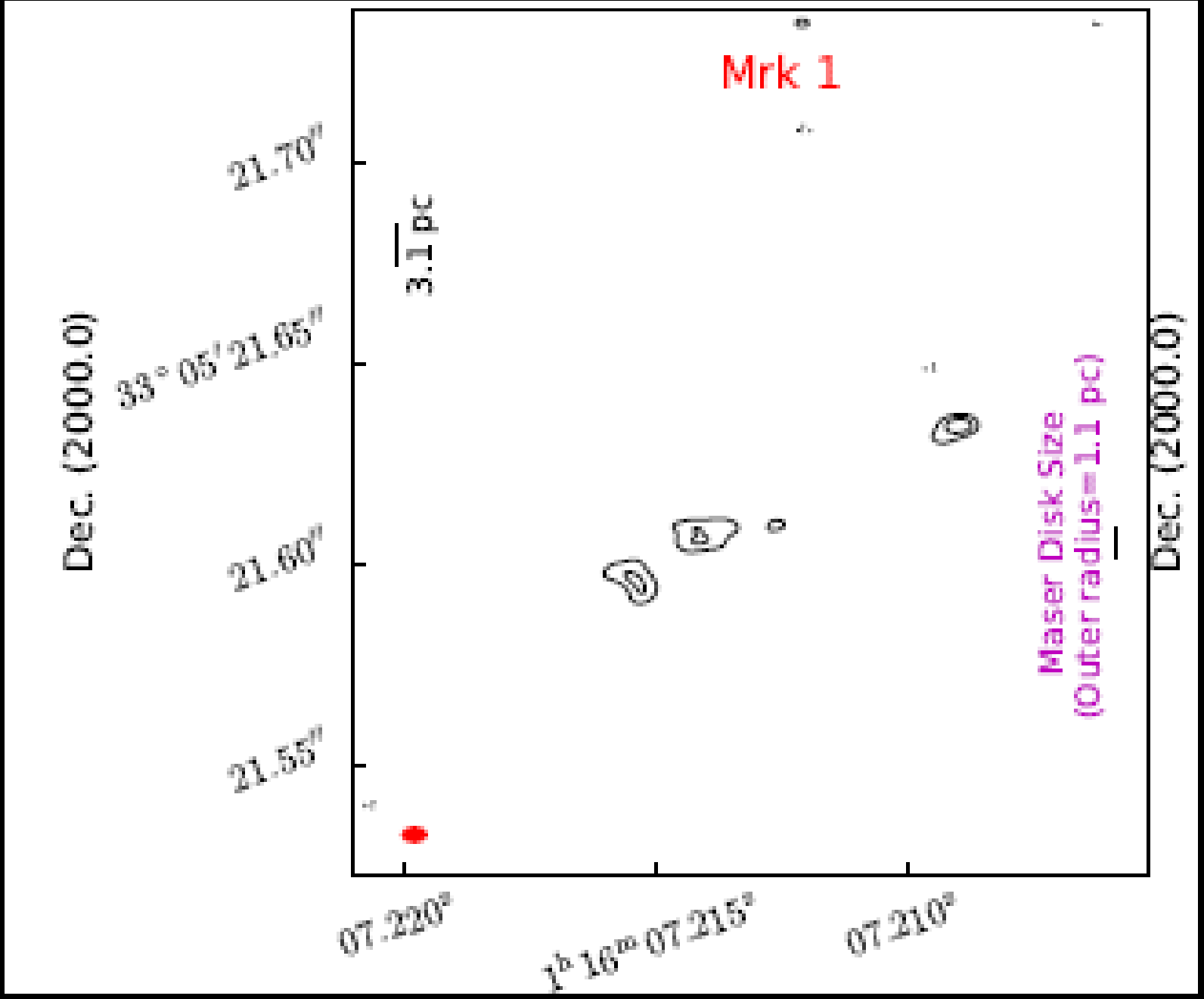


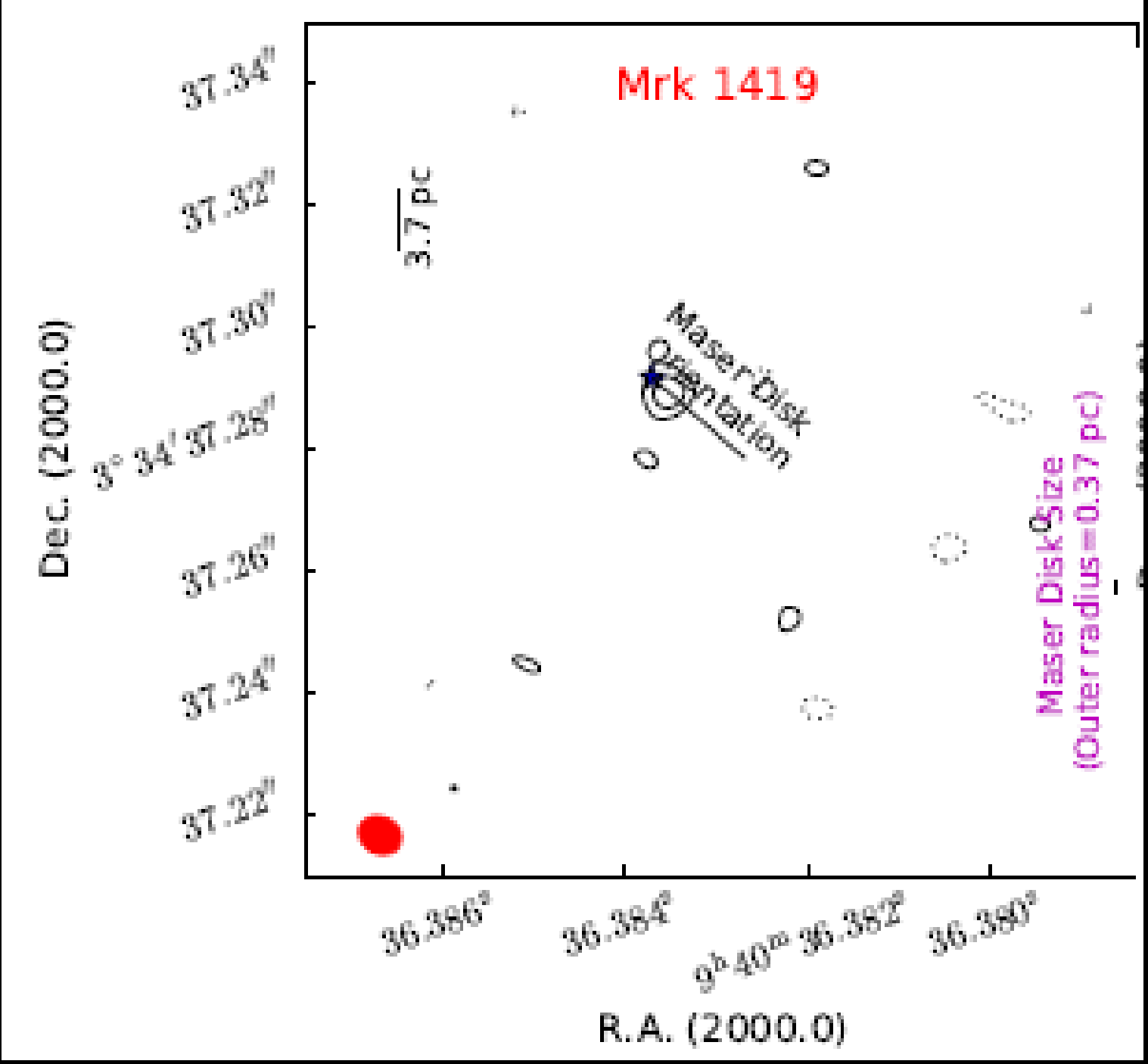
Bar = Ring: Lower continuum luminosity? Cagliari 2017


log $L_{33\ \mathrm{GHz}}$ [erg s^{-1} Hz^{-1}]
29
28
27
26
50
100
150
200
250
300
350
Maximum Rotation Velocity [km s^{-1}]
Slope=-0.01 ±0.00
Intercept=29.87 ±0.57
Correlation Coeff=-0.70
P-value=0.0056

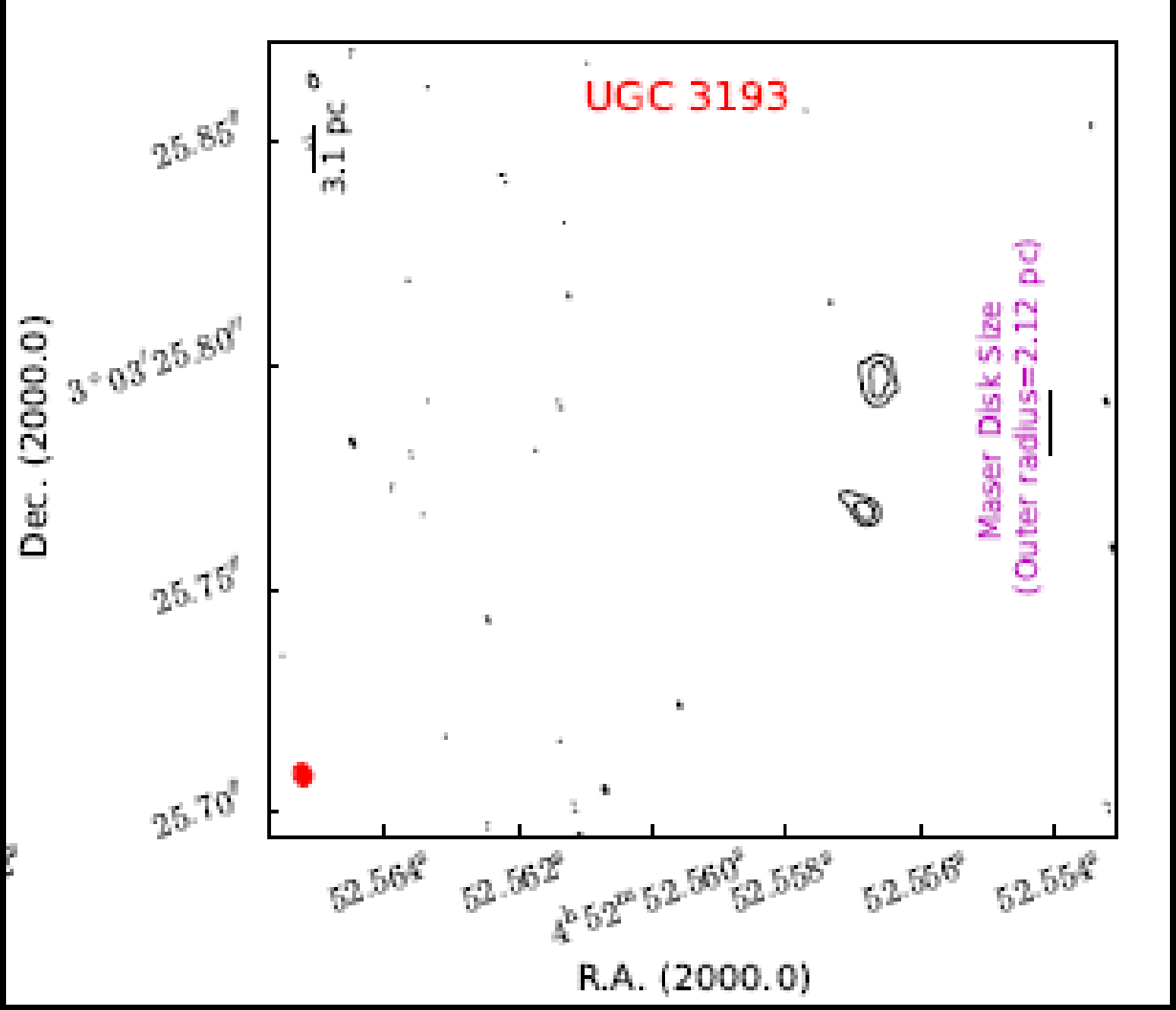


Cagliari 2017


Mrk 1
3.1 pc
Maser Disk Size
(Outer radius=1.1 pc)
Dec. (2000.0)
21.70"
33° 05' 21.65"
21.60"
21.55"
07.220"
1h 16m 07.215s
07.210"

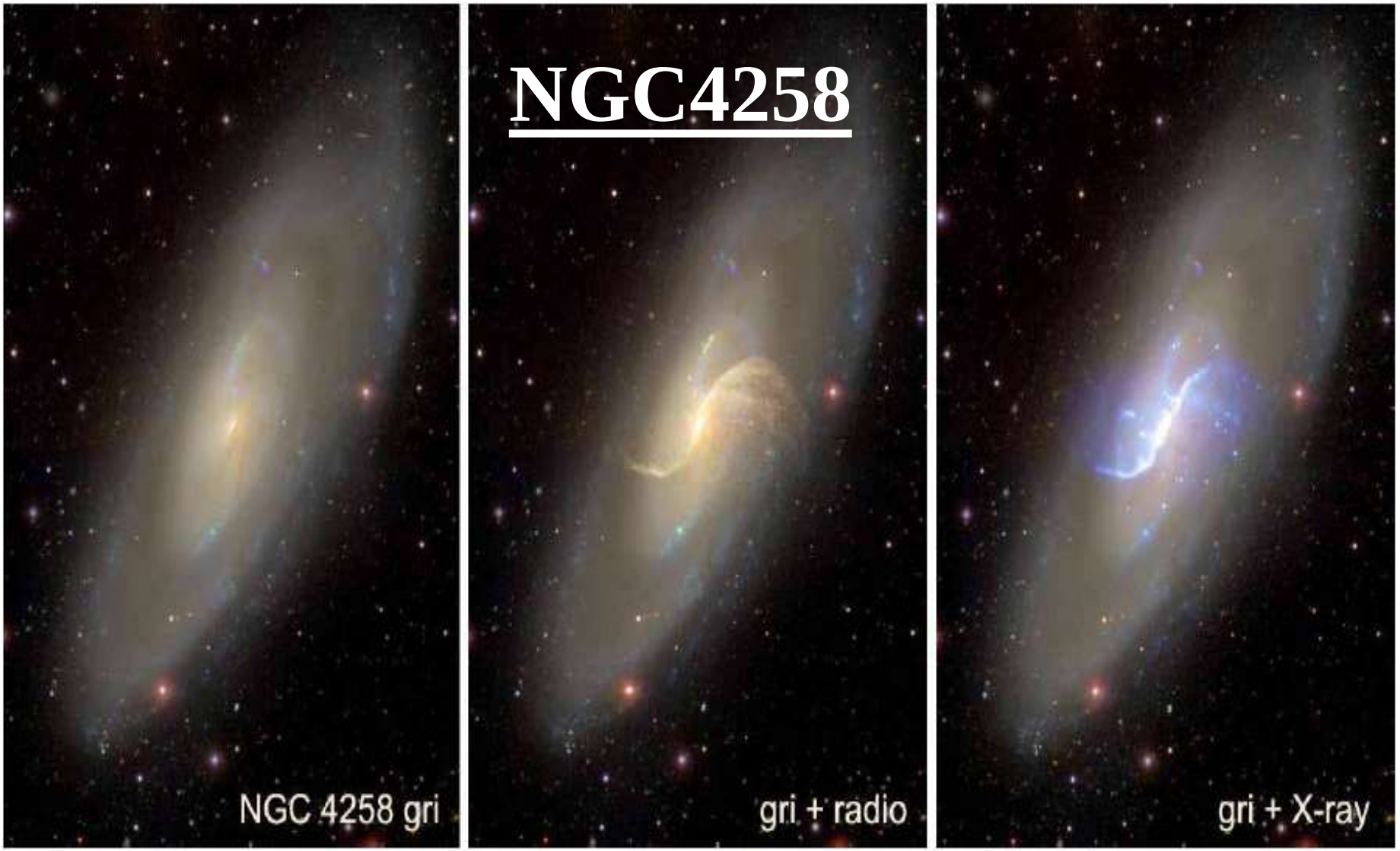


Cagliari 2017



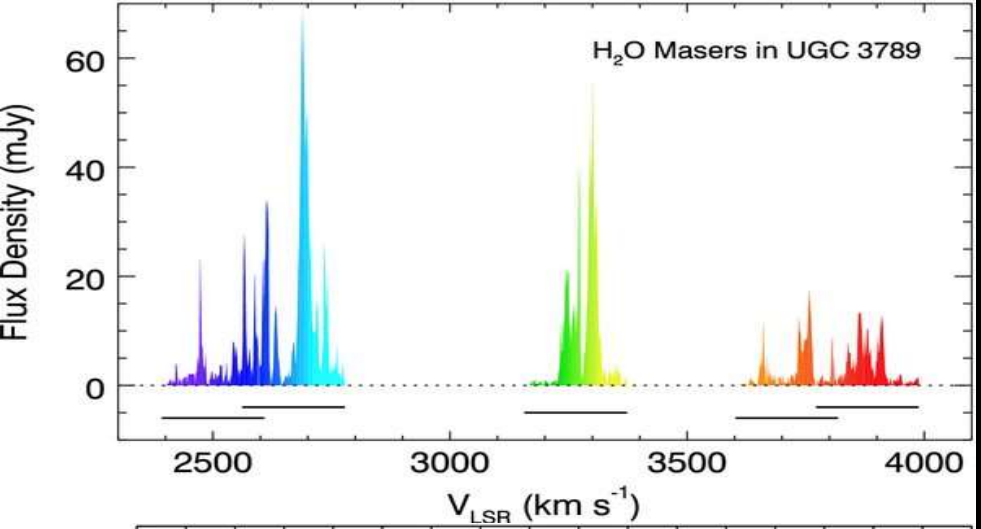
Cagliari 2017

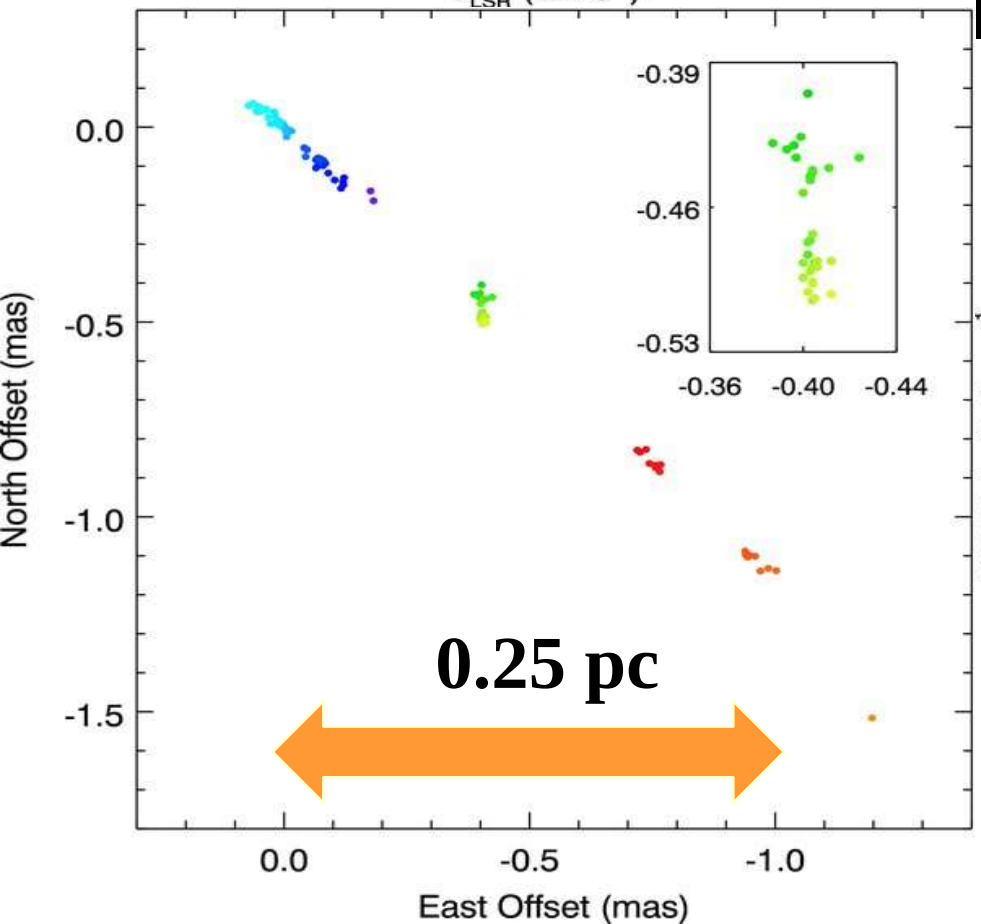
1. From Largest to Smallest Scales

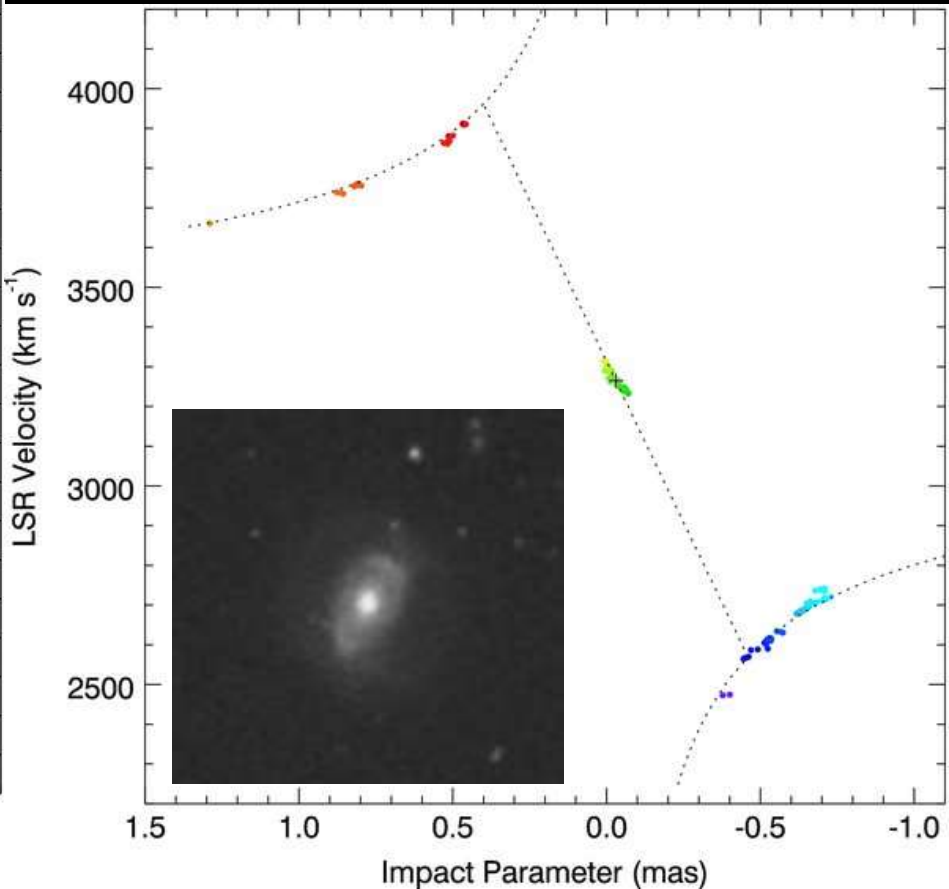


UGC3789

Reid et al. 2009,
ApJ 695, 287







Measure corresponding optical parameters, i.e. σ_* in this case



Dupont 2.5 m B&C Spectrograph
Apache 3.5 m Dual Imaging Spect.
SDSS 2.5 m Bulge/disk decomposition

2. Black Hole Masses

Megamaser derived M_{BH}: 10^{6-8} $M_{\odot}$

M_*, ρ_*, σ_*: smaller range
Best fit with σ_*

At fixed σ_*, maser M_{BH} offset by -0.6±0.1 dex
relative to early-type galaxies
and apparently also to spirals
with non-maser dynamical M_{BH}

Bias in dynamical or
in maser M_{BH} sample???

Urumqi 2017

Bars: Region of constant PA,
e decreasing inwards
rapid e and PA changes at outer edge

Spirals: Smoothly rotating PA

Disks: Constant PA, significant e > 0

Rings: Like disks, but discontinuity in PA at edges
bumps in surface brightness profiles

Bulges: Complex, detailed 2D-modelling required

$i = 0^o$: Angular momentum vector points toward Earth

$PA = 30^o$: Angular momentum vector 30° east of North

Ambiguities: PA or PA + 180°

i or $180^o - i$

Discriminating between the 4 possibilities:

Assume spiral arms are trailing: i fixed

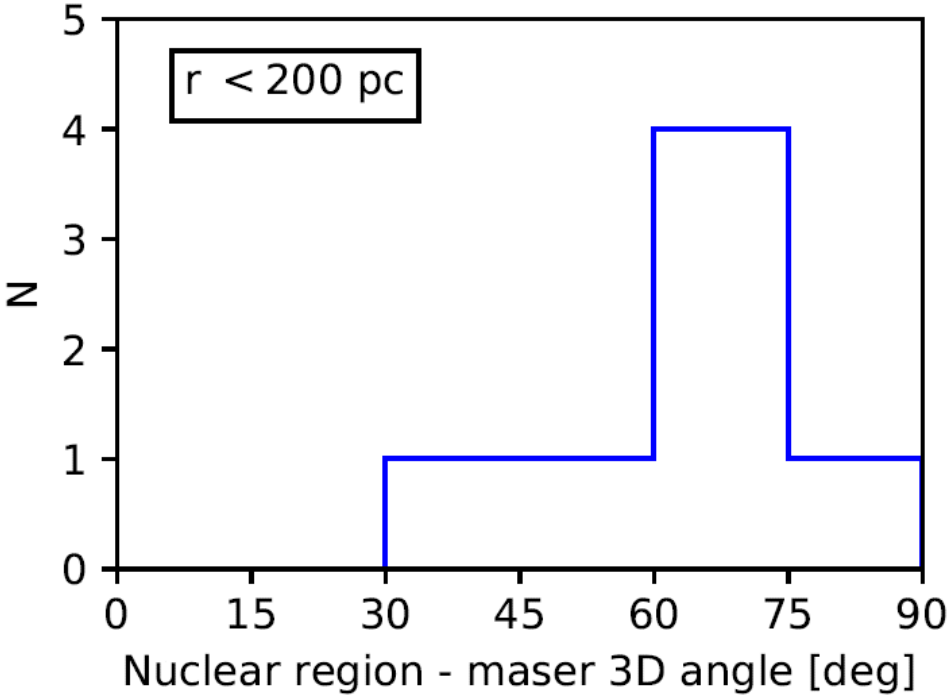
Rotation curve: PA fixed

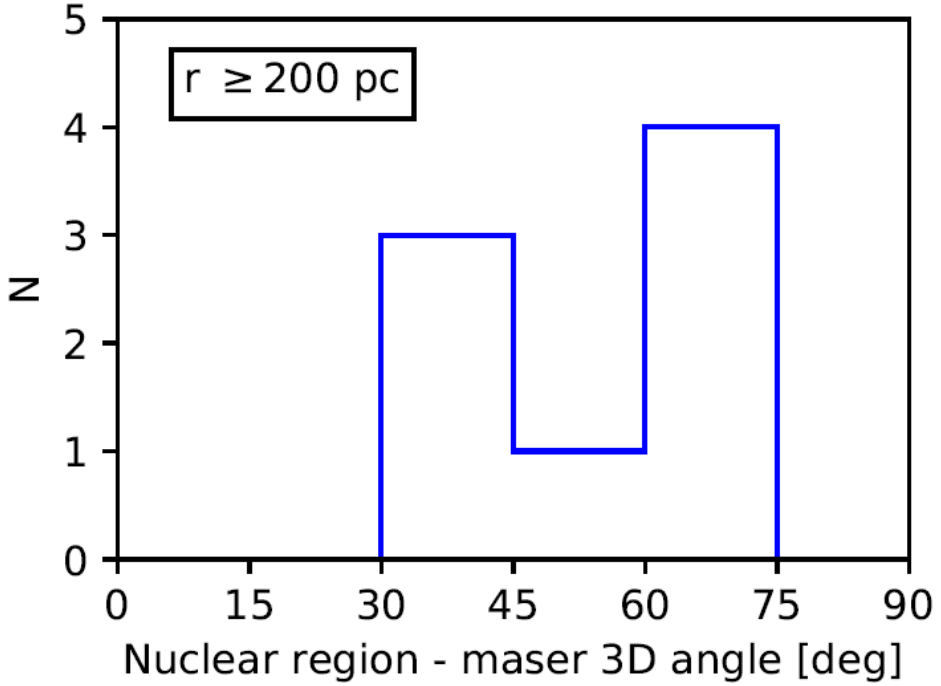
Otherwise dust lanes to decide between fore- and background.

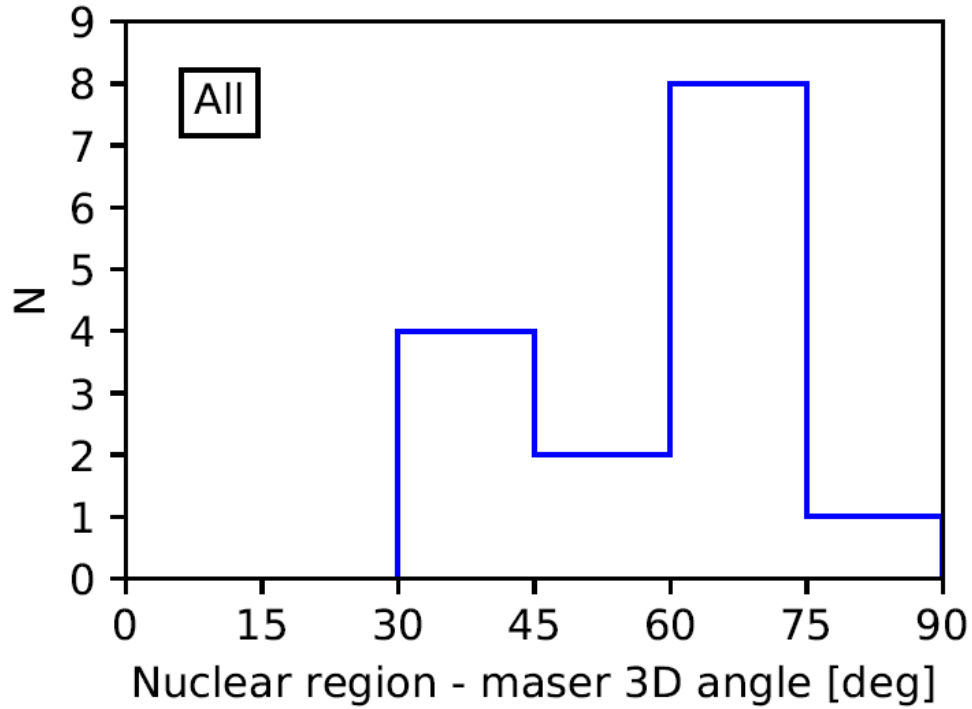
Urumqi 2017

Results of the KS tests
for nuclear regions larger than 0.5 arcsec.

Species		Angle	Limit	N	KS-stat	p-value
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Gal	Nuc	ΔPA	30°	10	0.30	0.27
Gal	Nuc	ΔPA	90°	10	0.42	0.04
Gal	Nuc(S)	ΔPA	30°	5	0.50	0.11
Gal	Nuc(S)	ΔPA	90°	5	0.32	0.59
Gal	Nuc(L)	ΔPA	30°	5	0.43	0.23
Gal	Nuc(L)	ΔPA	90°	5	0.64	0.02
Nuc	Mas	ΔPA	90°	10	0.42	0.04
Nuc(S)	Mas	ΔPA	90°	5	0.32	0.59
Nuc(L)	Mas	ΔPA	90°	5	0.69	0.01
Nuc	Mas	3D	90°	10	0.31	0.24
Nuc(S)	Mas	3D	90°	5	0.32	0.61
Nuc(L)	Mas	3D	90°	5	0.31	0.64
Gal*	Mas	ΔPA	90°	10	0.30	0.27
Gal*	Mas	3D	180°	10	0.30	0.26







3D angles between angular momentum axes:

nuclear HST region – maser disk.

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Reines & Volonteri 2015

262 local broad-line AGN galaxies
79 galaxies with dynamical BH masses

SDSS spectroscopy
Seyfert-like narrow-line ratios and broad Hα
Standard virial techniques

Conclusion

M_{BH} (H_2O) = 10^6 – 10^8 $M_\odot$

Stellar mass, bulge mass, central velocity dispersion, circular velocity lie within a smaller range.

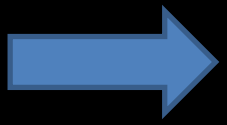
No galaxy property correlates tightly with M_{BH} in Milky Way sized galaxies.

Urumqi 2016

Conclusion

M_{BH} (H_2O) = 10^6 – 10^8 $M_\odot$

Stellar mass, bulge mass, central velocity dispersion, circular velocity lie within a smaller range.



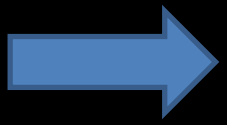
Best correlation with stellar velocity dispersion, but at fixed σ_*, the megamaser masses are lower by 0.6±0.1 dex relative to early type galaxies.

Urumqi 2016

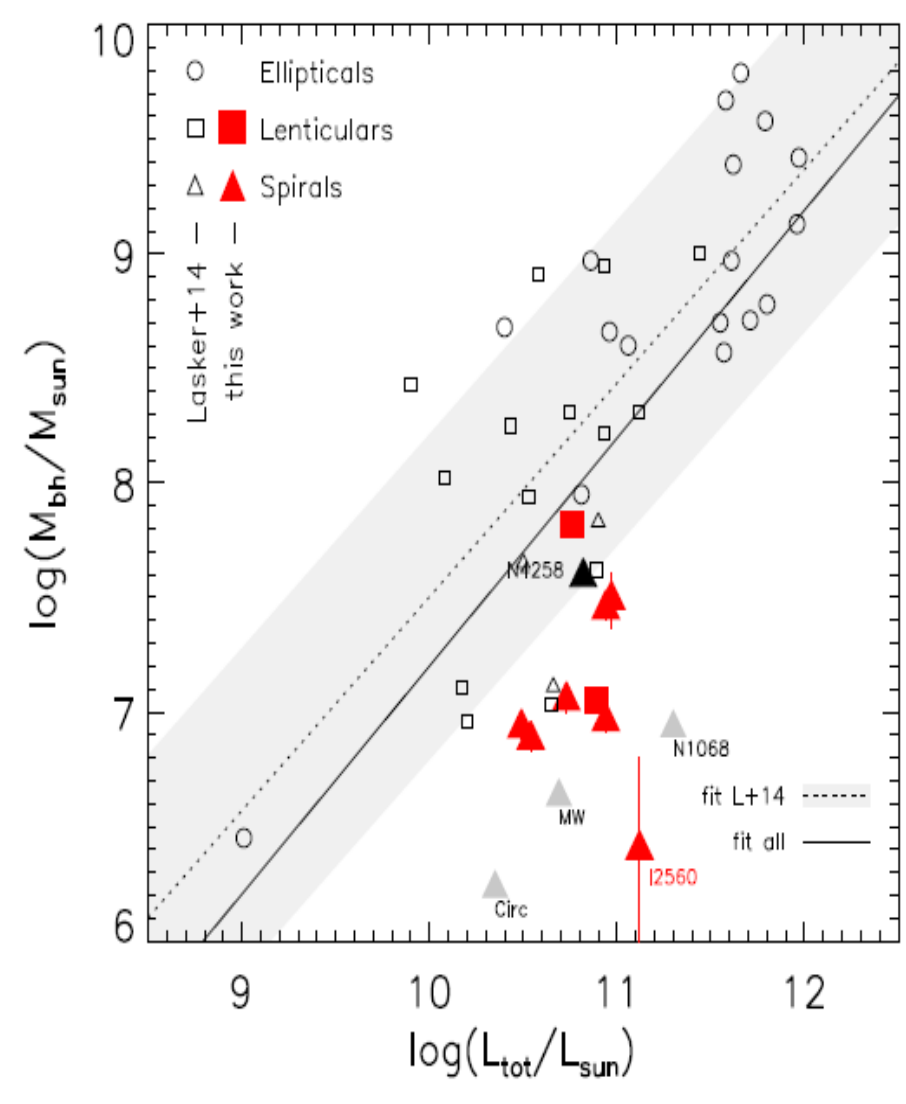
Conclusion

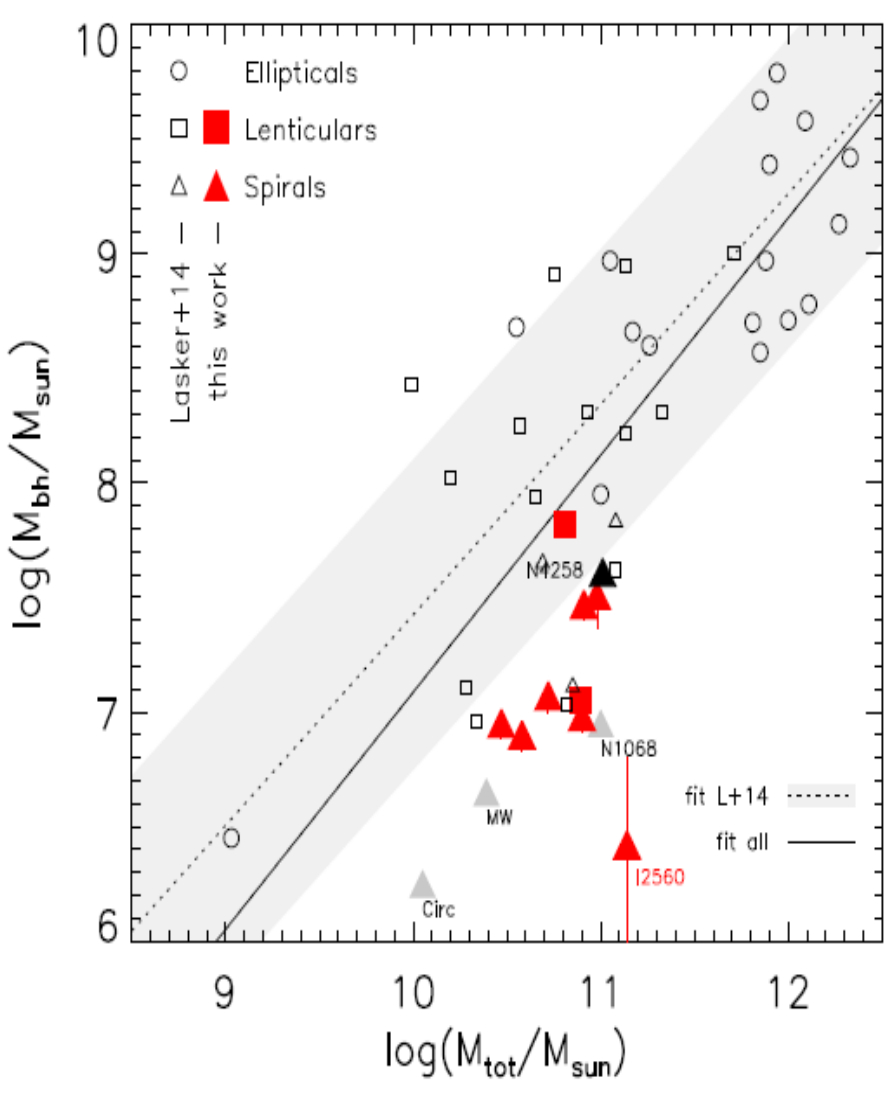
M_{BH} (H_2O) = 10^6 – 10^8 $M_\odot$

Stellar mass, bulge mass, central velocity dispersion, circular velocity lie within a smaller range.



Either the non-maser dynamical data miss the low-mass end of the BH distribution (unresolved spheres of Influence) or the maser disks provide a bias.

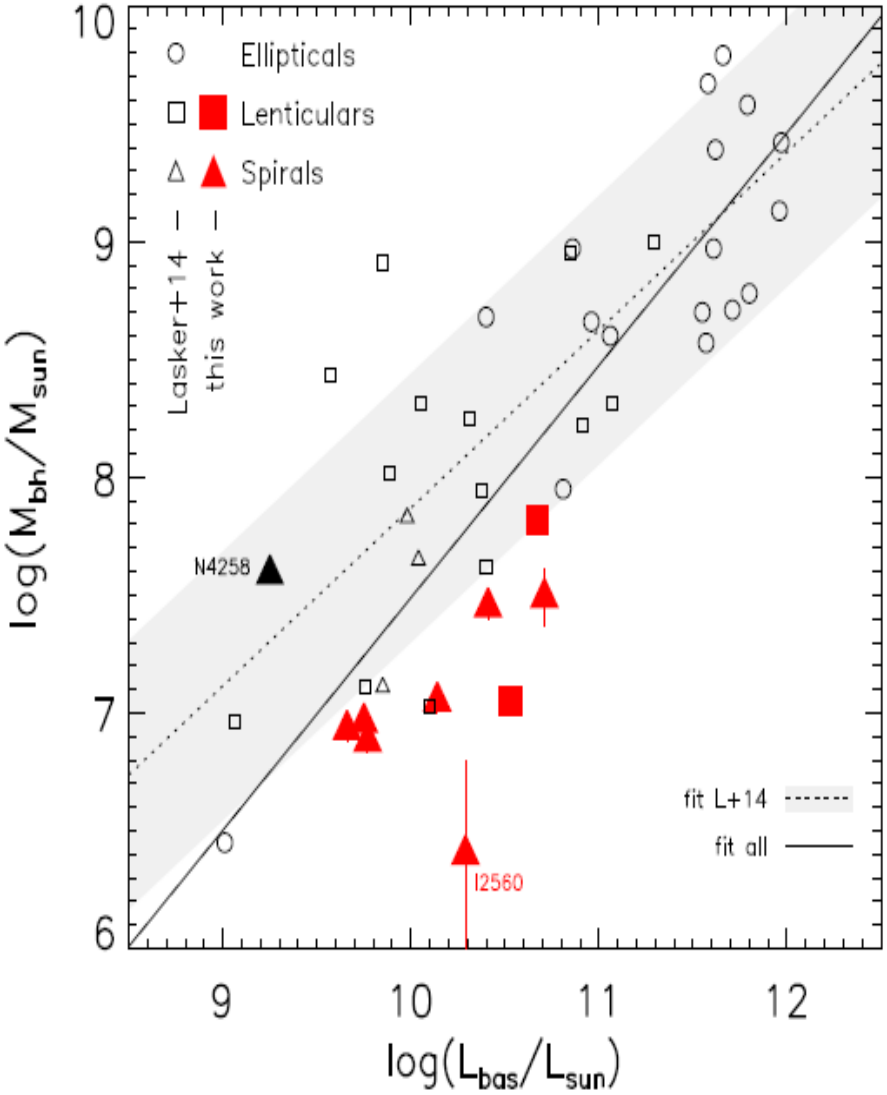


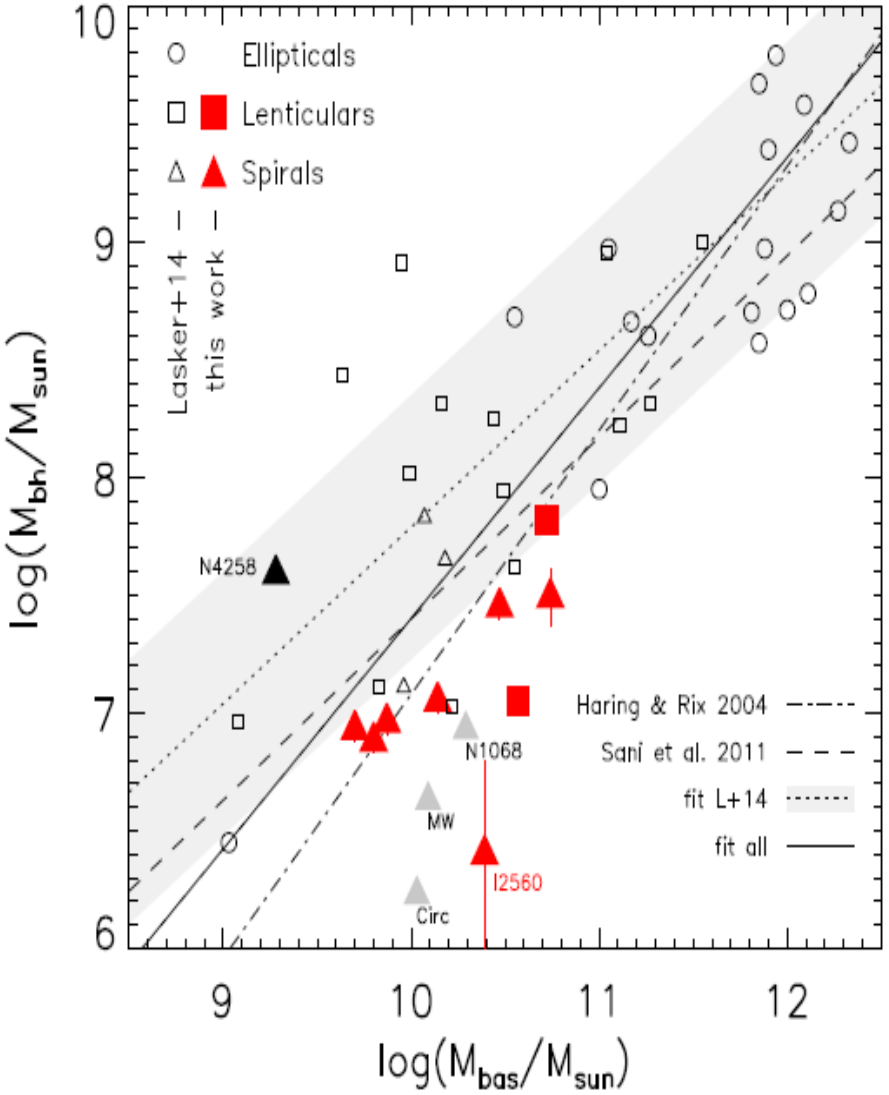


M_{BH} versus total L and M

Laesker et al. 2015

Urumqi 2016

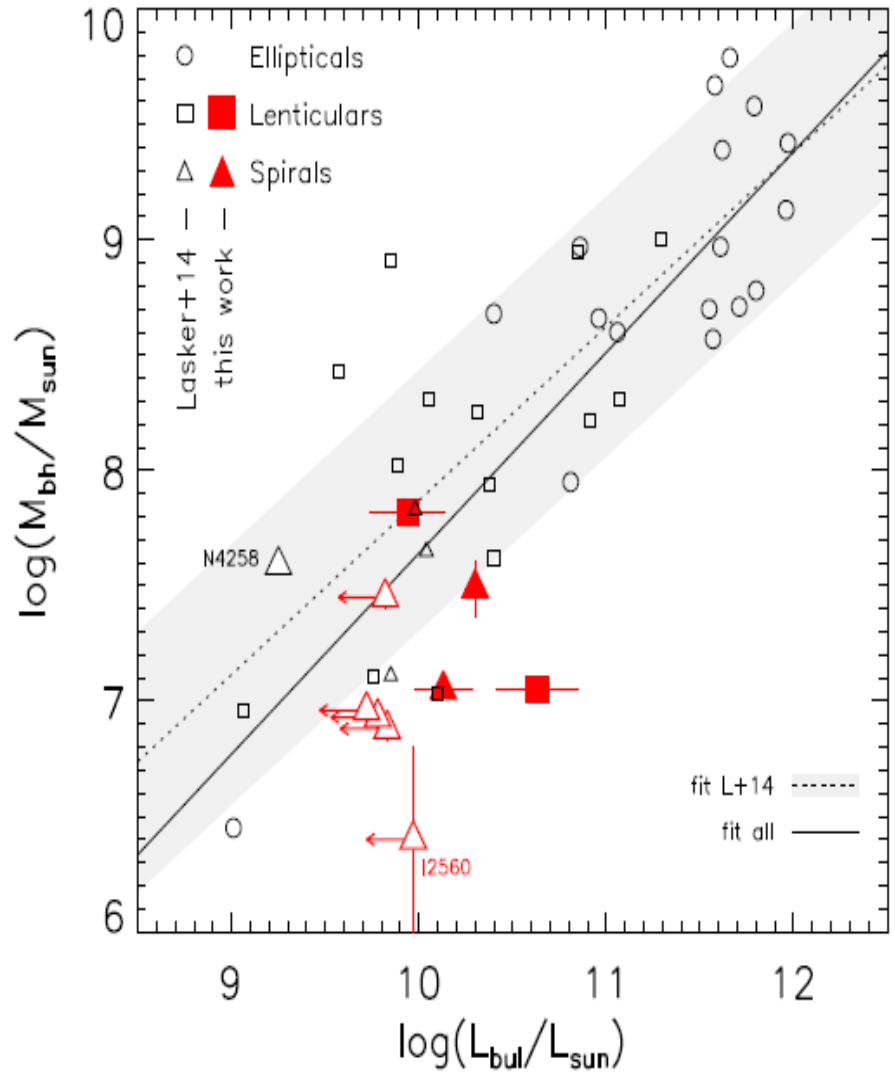


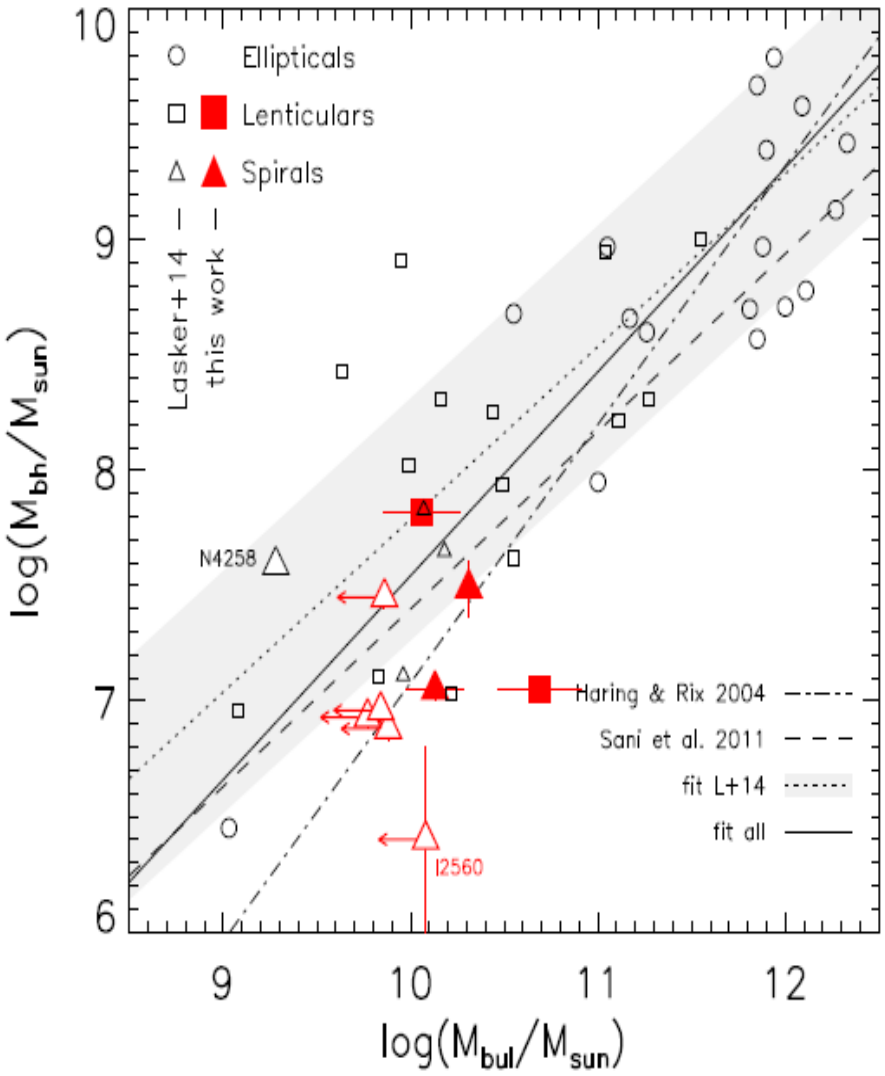


Bulge + disk + point source decompositon

Laesker et al. 2015

Urumqi 2016

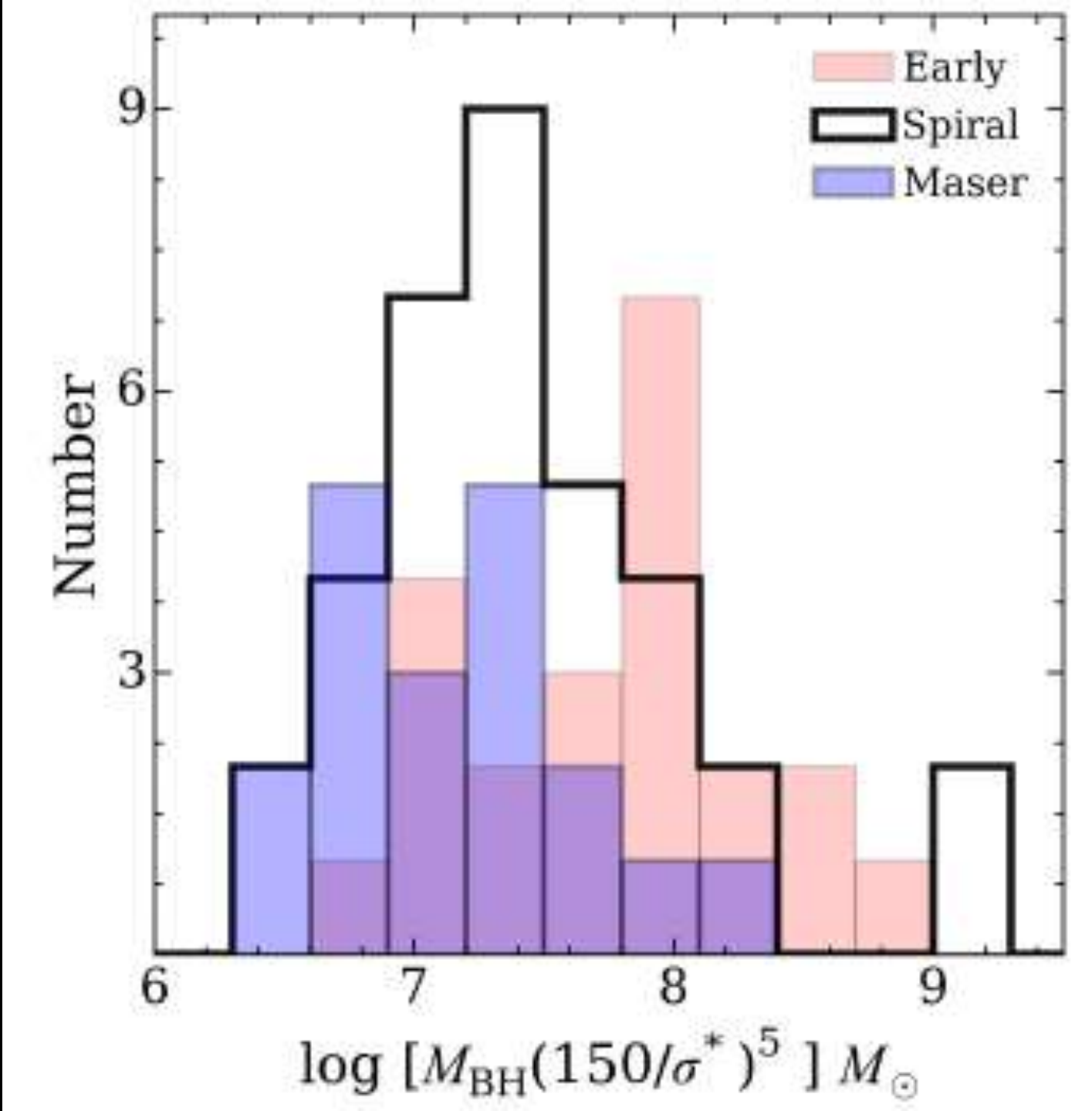




Classical bulges (if not detected, open symbols)

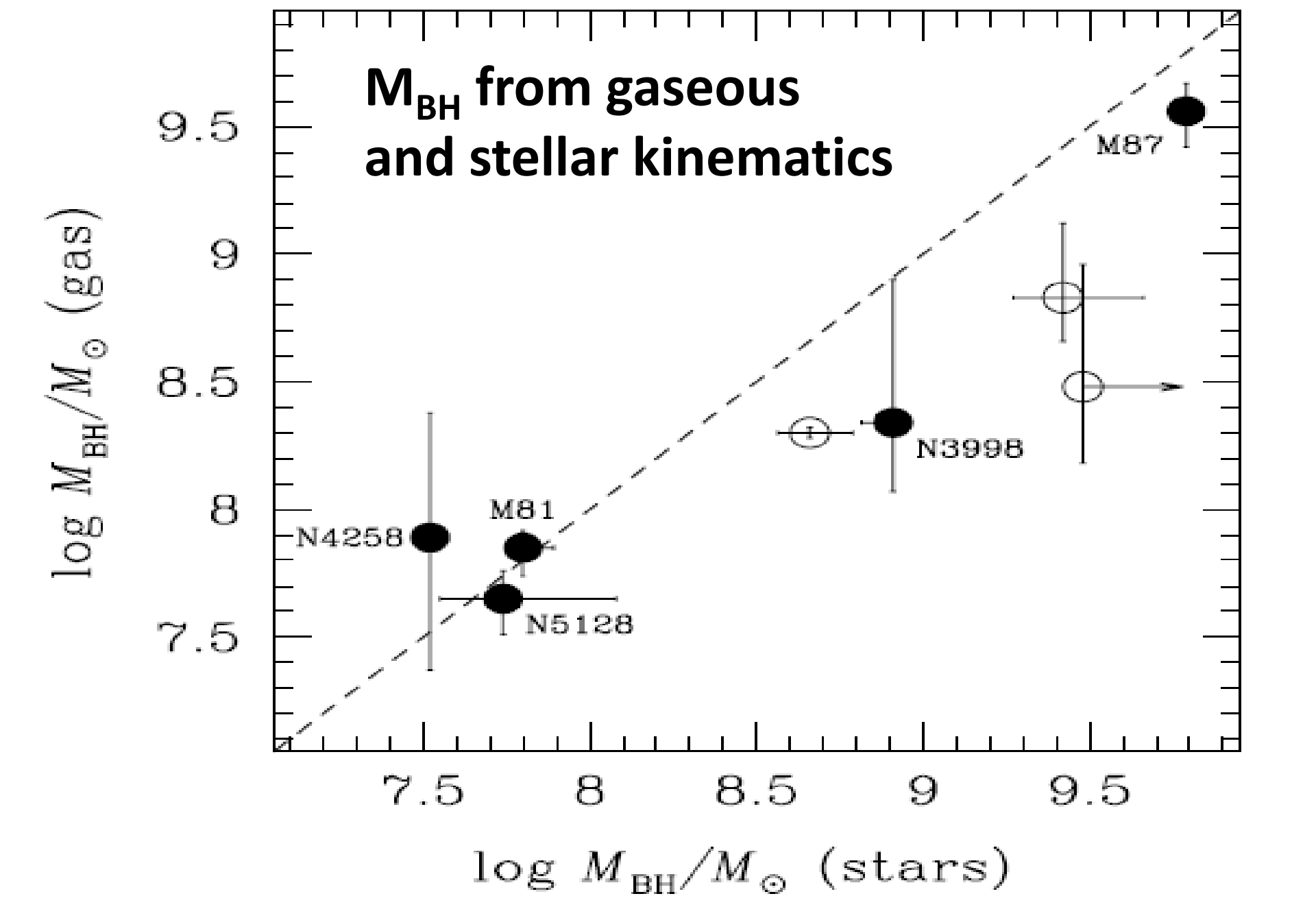
Laesker et al. 2015

Urumqi 2016



Greene et al. 2016

Urumqi 2016



Kormendy & Ho 2013

Urumqi 2016

Background

One galaxy is not sufficient – what about other nearby sources?

Highest attainable resolution!

Sphere of gravitational influence:

$$R_G = 0.22\ (M_{BH}/10^8 M_\odot) \times (200 \mathrm{kms}^{-1}/\sigma_*)^2 \times (10\mathrm{Mpc}/D)\ \ \mathrm{arcsec}$$

Background

Determination of nuclear mass by:

1) **Nuclear stellar velocity dispersion**

Background

Determination of nuclear mass by:

1) **Nuclear stellar velocity dispersion**
2) **Nuclear velocity dispersion of the gas**
   (best: Hα, Hβ, Mg II, (C IV))

Background

Determination of nuclear mass by:

1) **Nuclear stellar velocity dispersion**
2) **Nuclear velocity dispersion of the gas**
   (best: Hα, Hβ, Mg II, (C IV))

M_{BH} to be compared, e.g., with

1) **Bulge mass**
2) **Galaxy mass**
3) **Large scale rotation velocity**

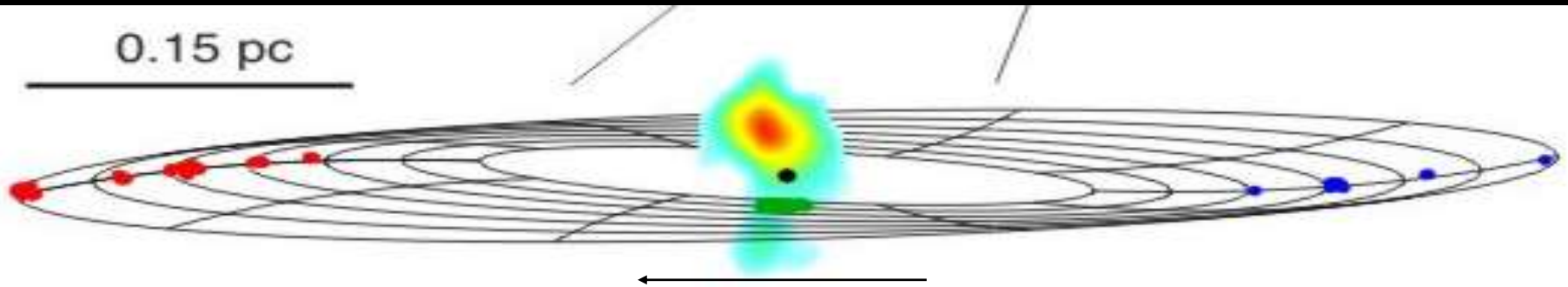
Background

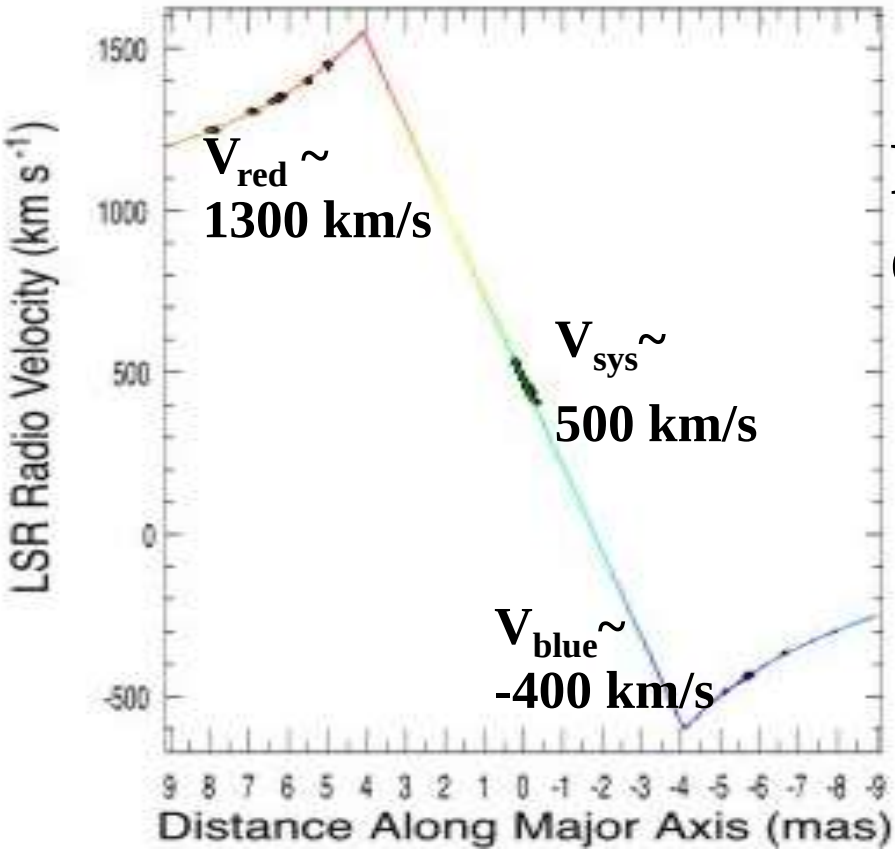
Determination of nuclear mass by:

1) **Nuclear stellar velocity dispersion**
2) **Nuclear velocity dispersion of the gas (best: Hα, Hβ, Mg II, (C IV))**

Brightness profiles provide per se no evidence in favor or against the presence of a nuclear monster.

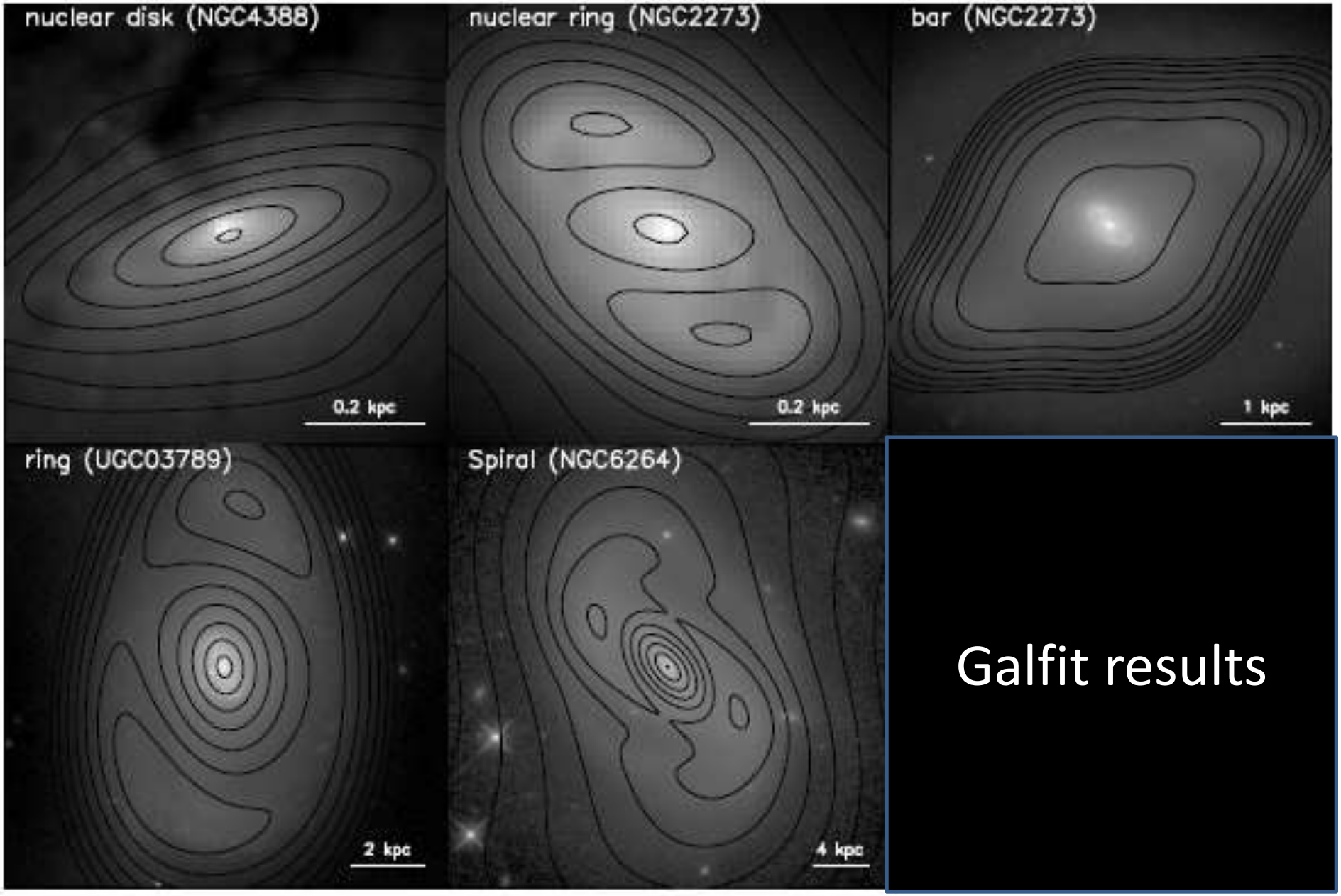
The prototypical H_2O disk-megamaser





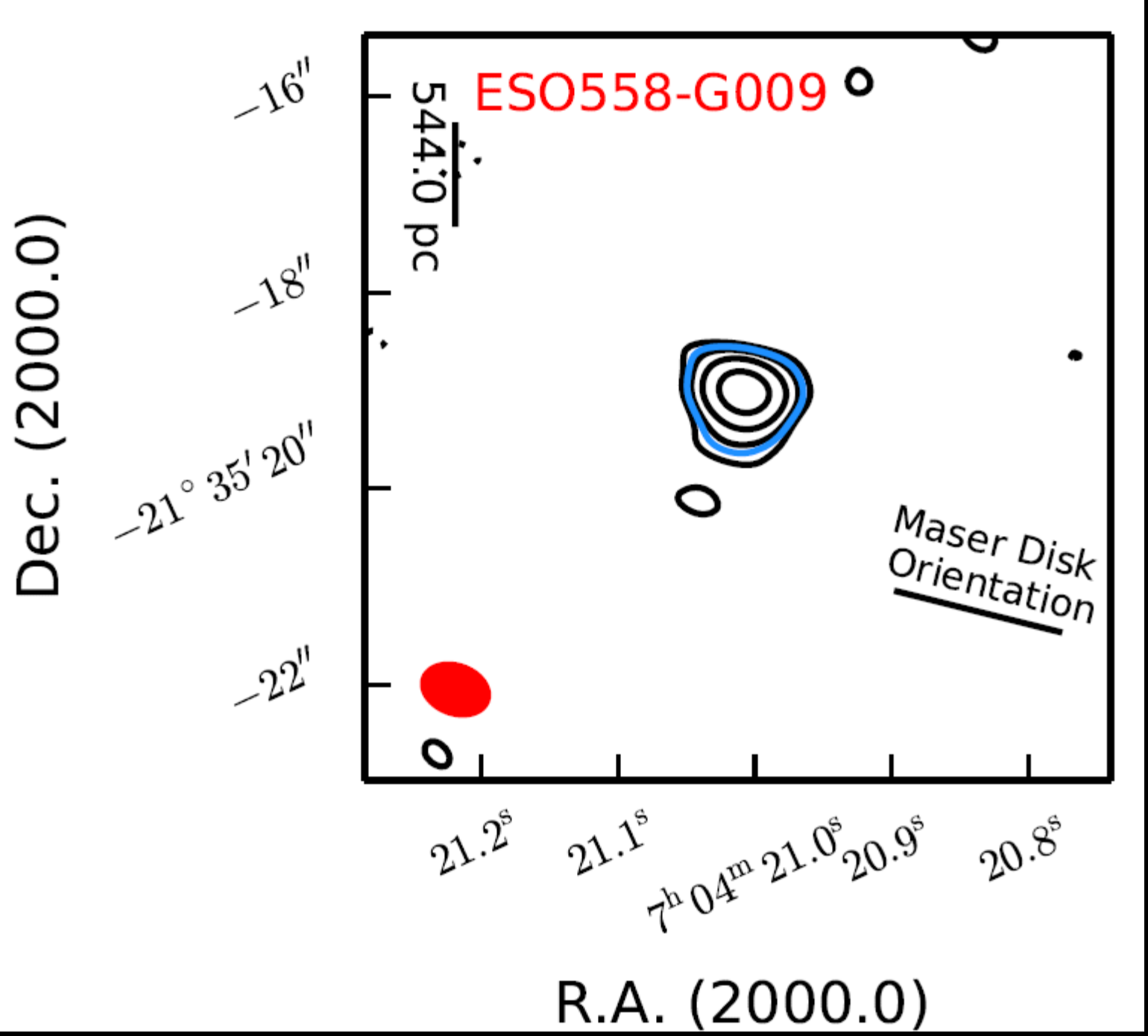
Position-velocity diagram

Urumqi 2017

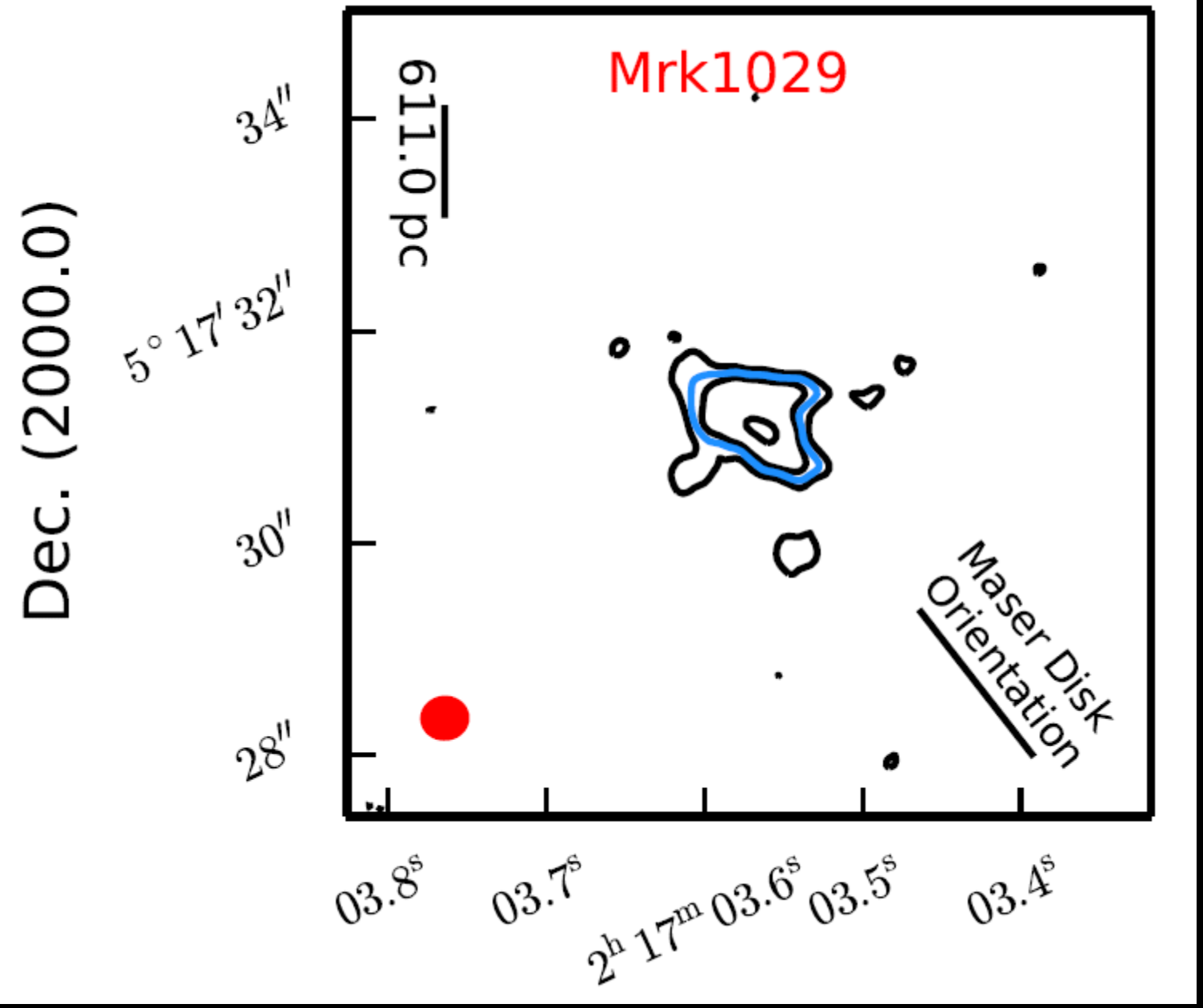


Läsker et al. 2016

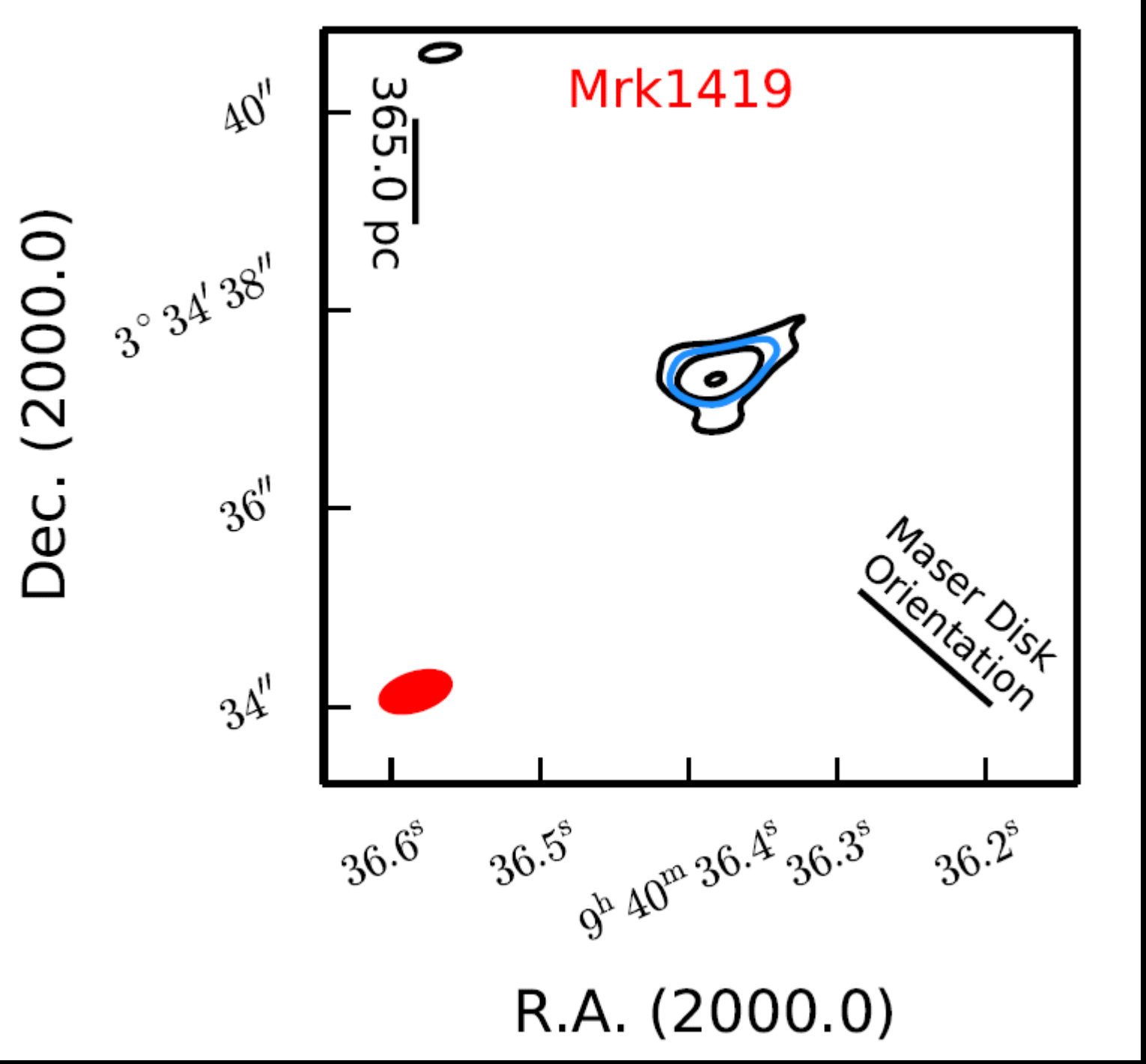
Urumqi 2017


ESO558-G009
544.0 pc
Maser Disk Orientation
−16″
−18″
−21° 35′ 20″
−22″
Dec. (2000.0)
21.2s
21.1s
7h 04m 21.0s
20.9s
20.8s
R.A. (2000.0)

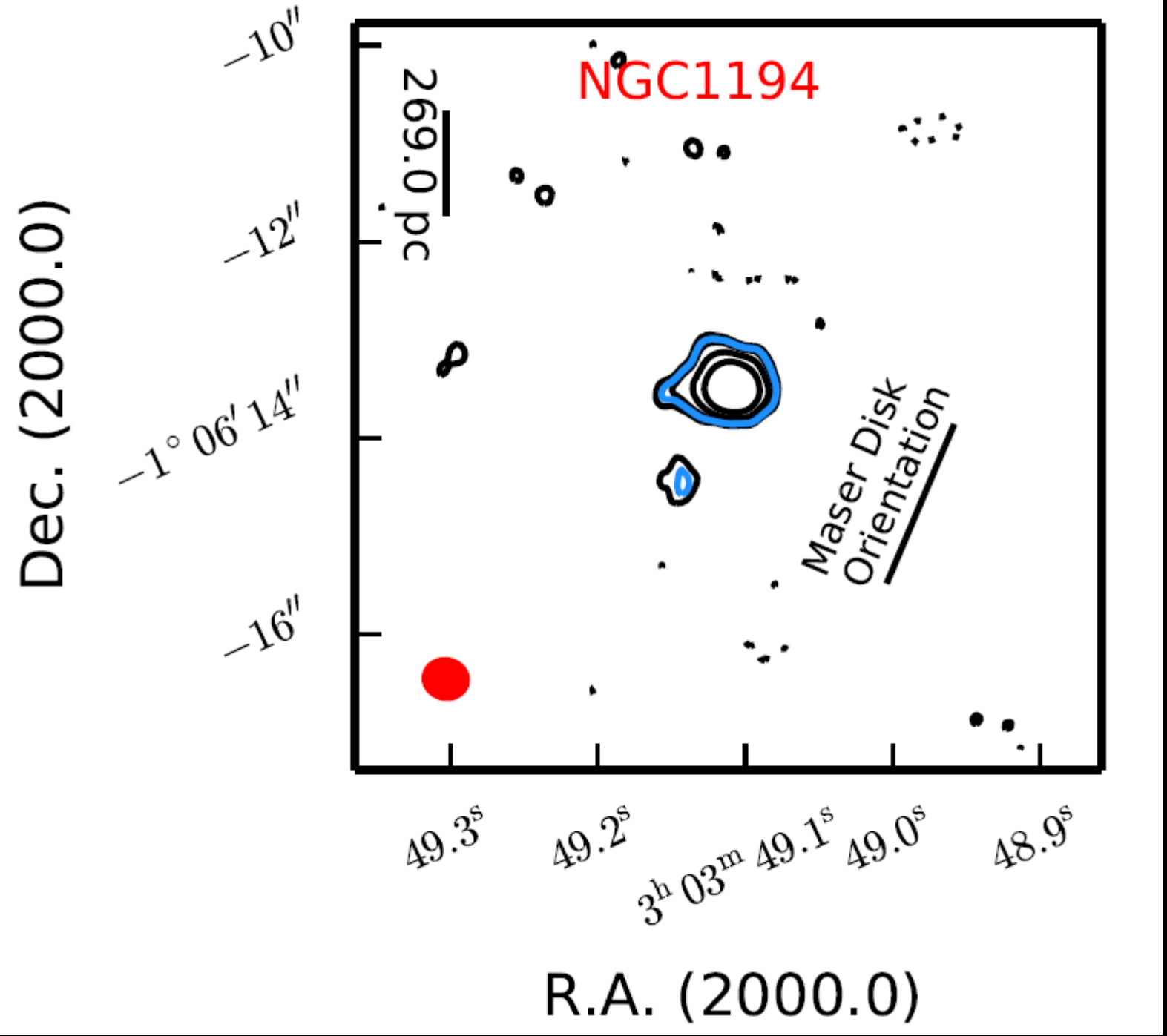
Urumqi 2017


Mrk1029
611.0 pc
Maser Disk
Orientation
Dec. (2000.0)
34″
5° 17′ 32″
30″
28″
03.8ˢ
03.7ˢ
2ʰ 17ᵐ 03.6ˢ
03.5ˢ
03.4ˢ

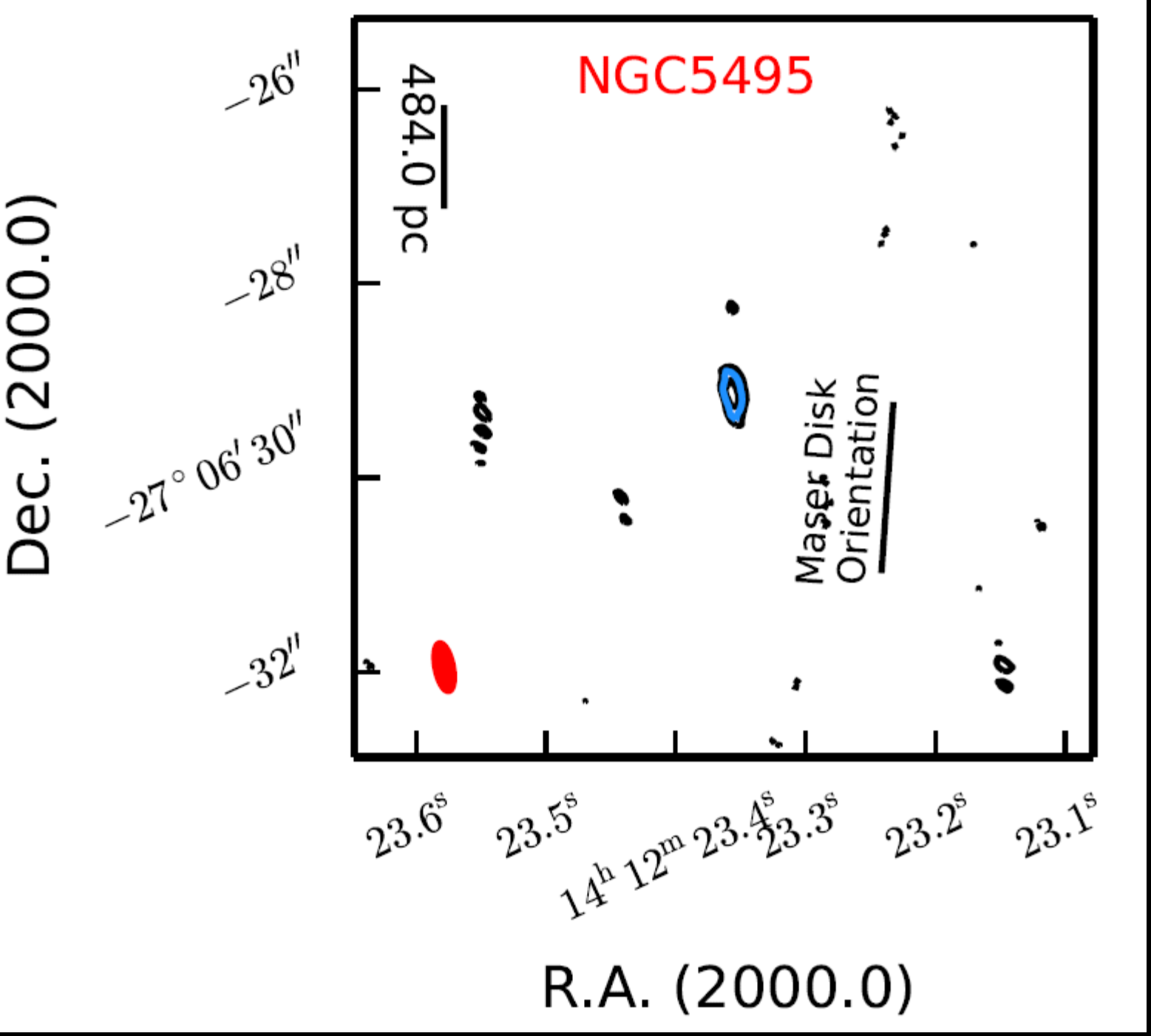
Urumqi 2017


Mrk1419
365.0 pc
Maser Disk Orientation
Dec. (2000.0)
R.A. (2000.0)
40″
36″
34″
3° 34′ 38″
36.6s
36.5s
9h 40m 36.4s
36.3s
36.2s

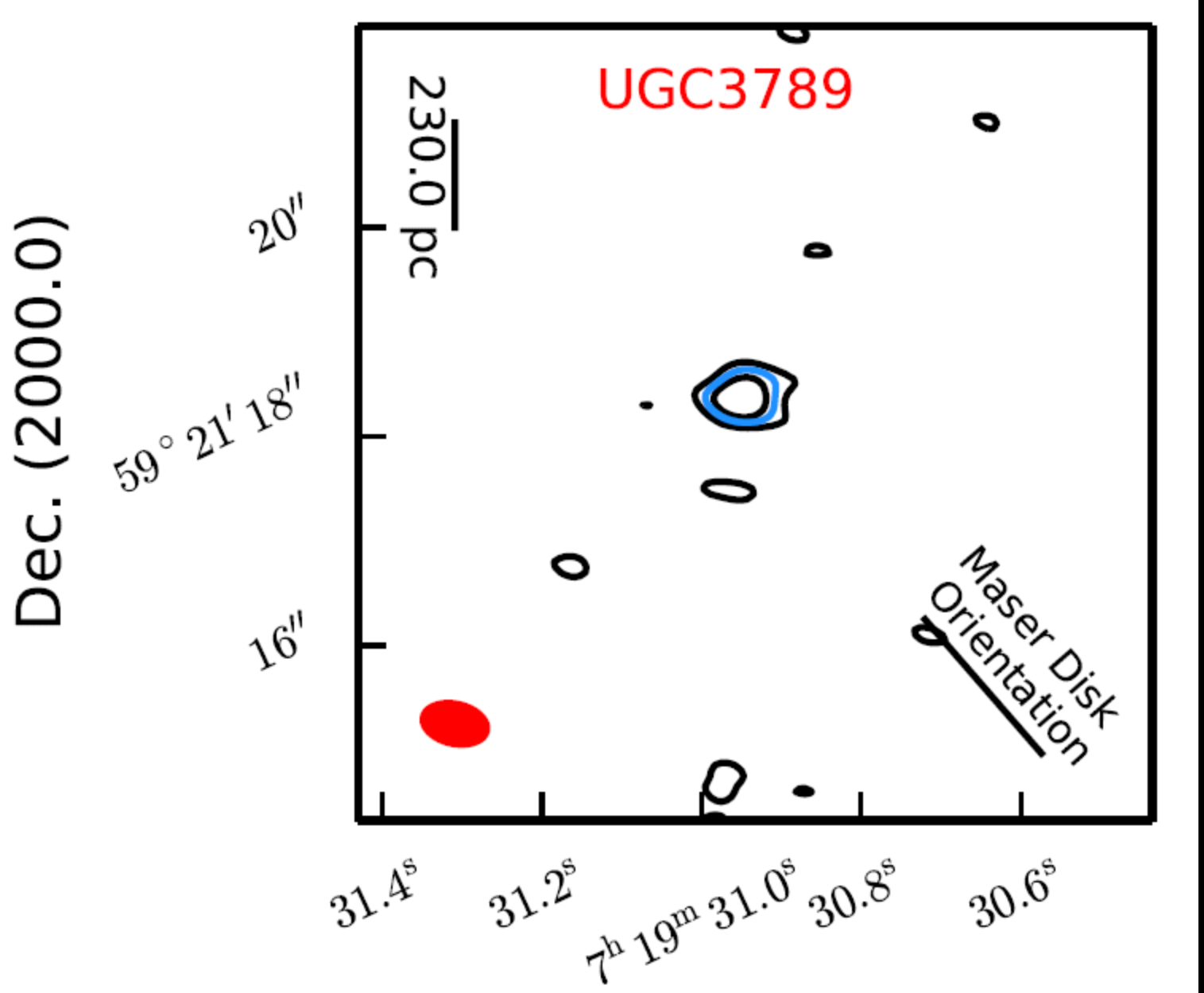
Urumqi 2017


NGC1194
269.0 pc
Maser Disk
Orientation
−10″
−12″
−1° 06′ 14″
−16″
Dec. (2000.0)
49.3s
49.2s
3h 03m 49.1s
49.0s
48.9s
R.A. (2000.0)

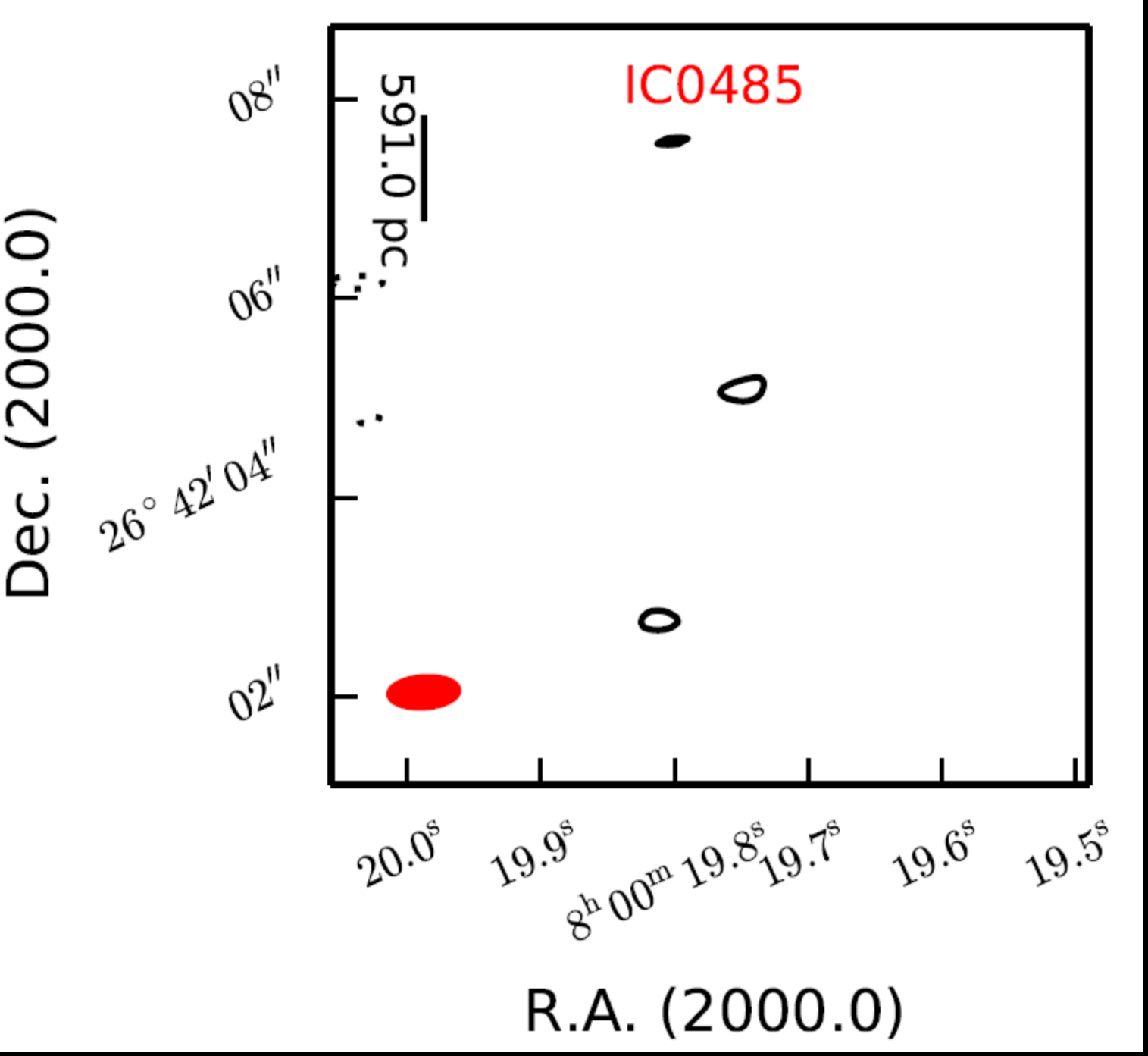
Urumqi 2017


NGC5495
484.0 pc
Maser Disk
Orientation
−26″
−28″
−27° 06′ 30″
−32″
Dec. (2000.0)
23.6s
23.5s
14h 12m 23.4s
23.3s
23.2s
23.1s
R.A. (2000.0)

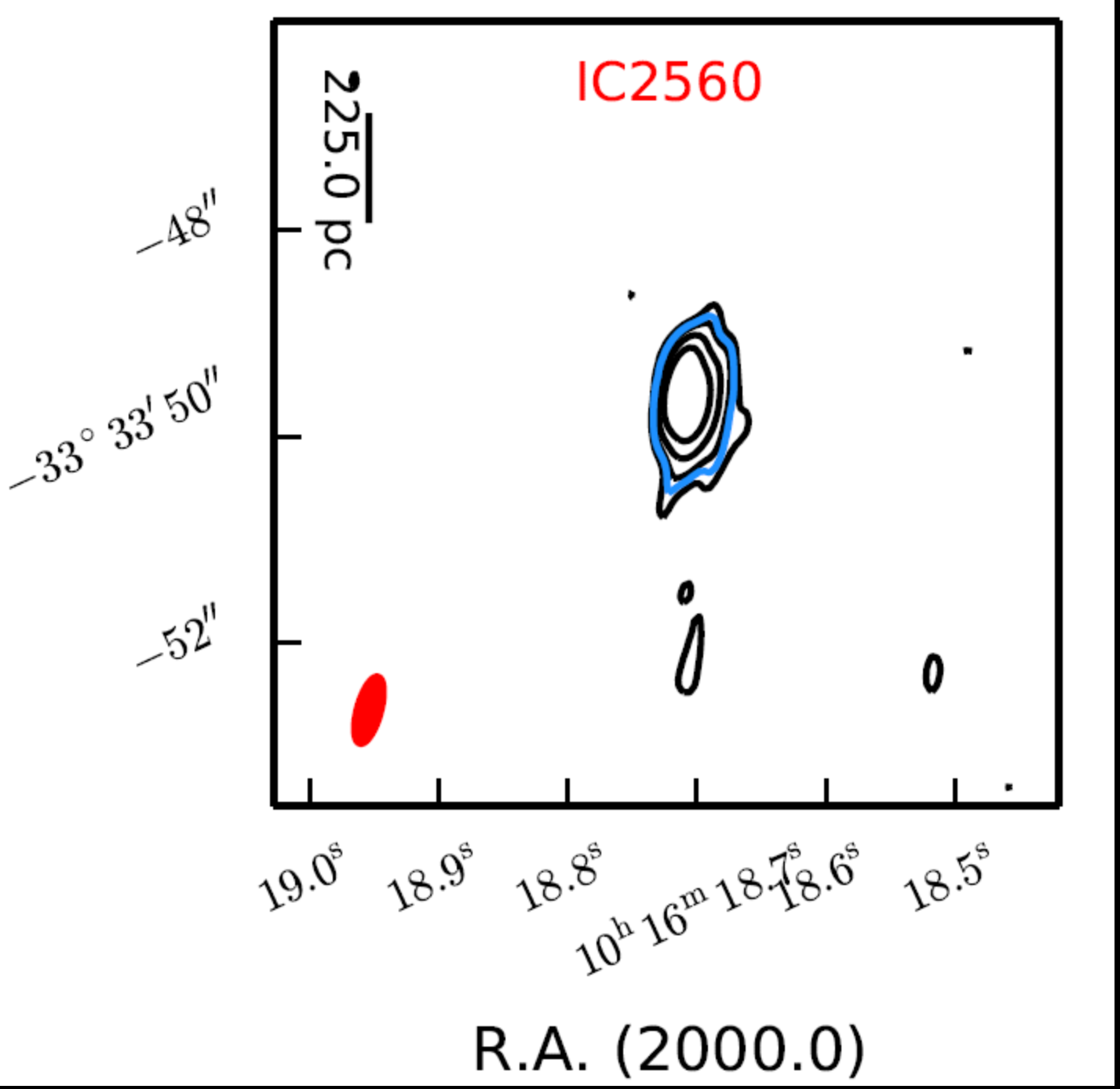
Urumqi 2017


UGC3789
230.0 pc
Maser Disk Orientation
Dec. (2000.0)
20″
59° 21′ 18″
16″
31.4s
31.2s
7h 19m 31.0s
30.8s
30.6s

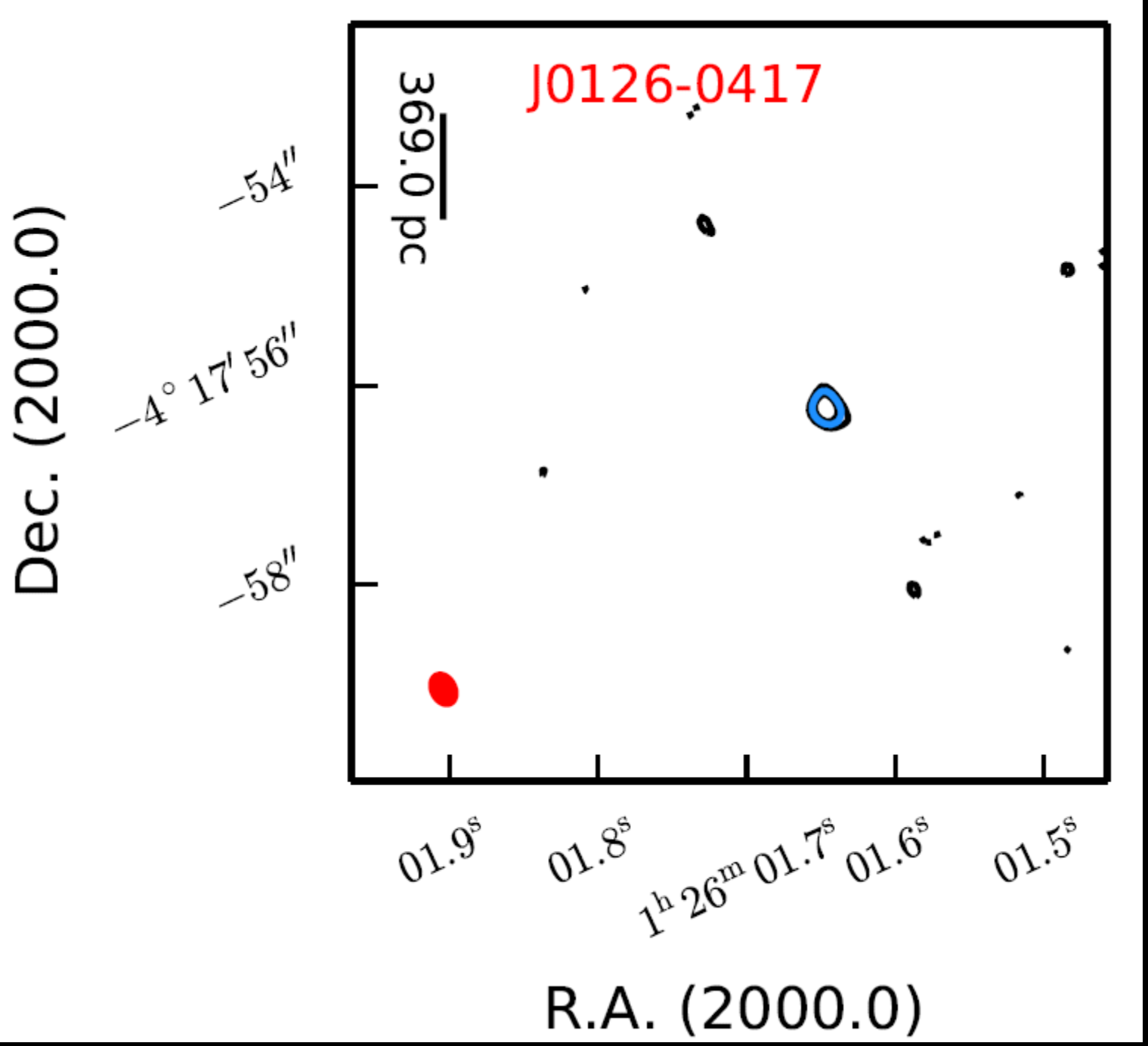
Urumqi 2017


IC0485
591.0 pc
08″
06″
02″
26° 42′ 04″
Dec. (2000.0)
20.0s
19.9s
8h 00m 19.8s
19.7s
19.6s
19.5s
R.A. (2000.0)

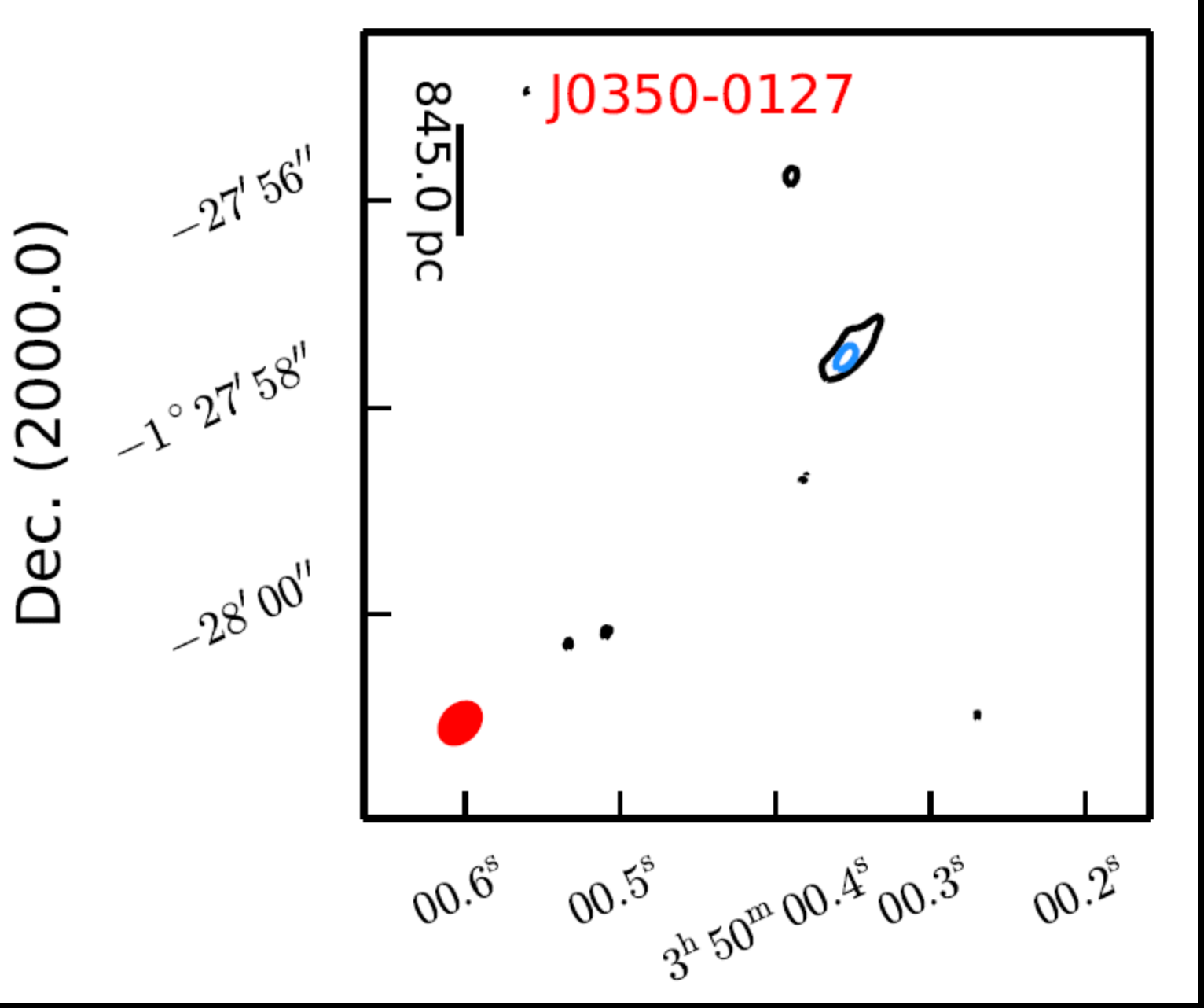
Urumqi 2017


IC2560
225.0 pc
−48″
−33° 33′ 50″
−52″
19.0s
18.9s
18.8s
10h 16m 18.7s
18.6s
18.5s
R.A. (2000.0)

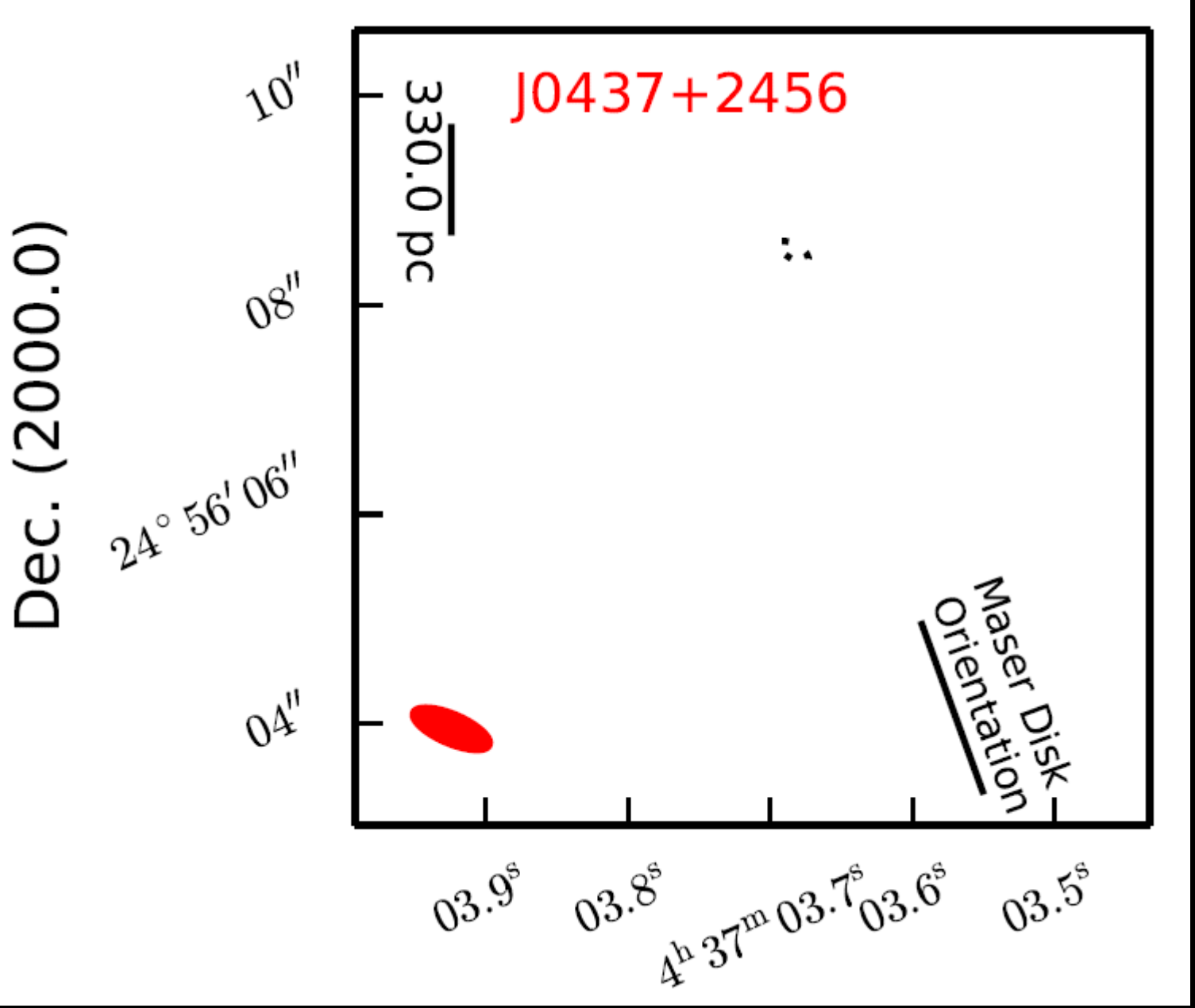
Urumqi 2017


J0126-0417
369.0 pc
−54″
−4° 17′ 56″
−58″
Dec. (2000.0)
01.9s
01.8s
1h 26m 01.7s
01.6s
01.5s
R.A. (2000.0)

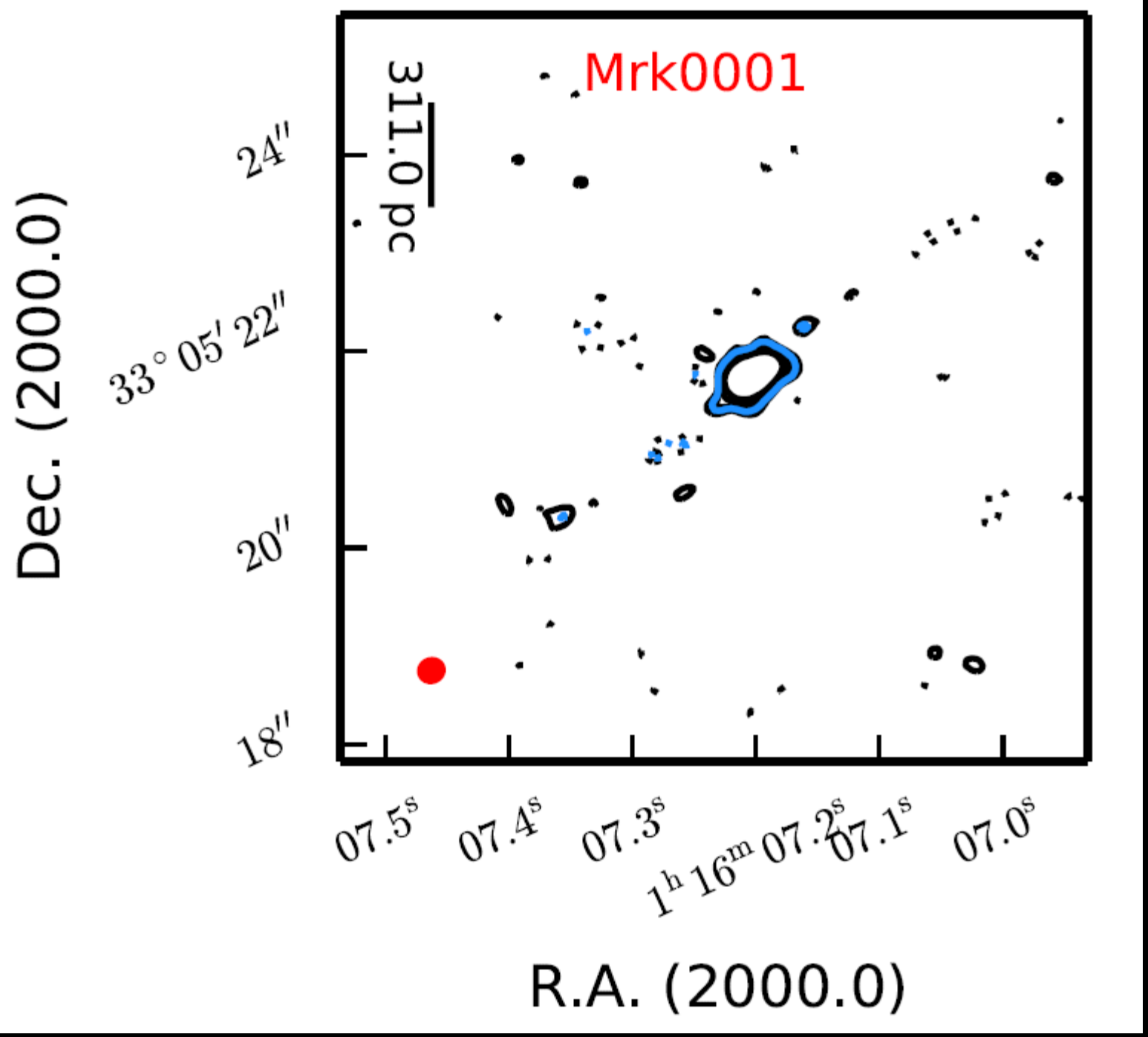
Urumqi 2017


J0350-0127
845.0 pc
Dec. (2000.0)
−27′ 56″
−1° 27′ 58″
−28′ 00″
00.6s
00.5s
3h 50m 00.4s
00.3s
00.2s

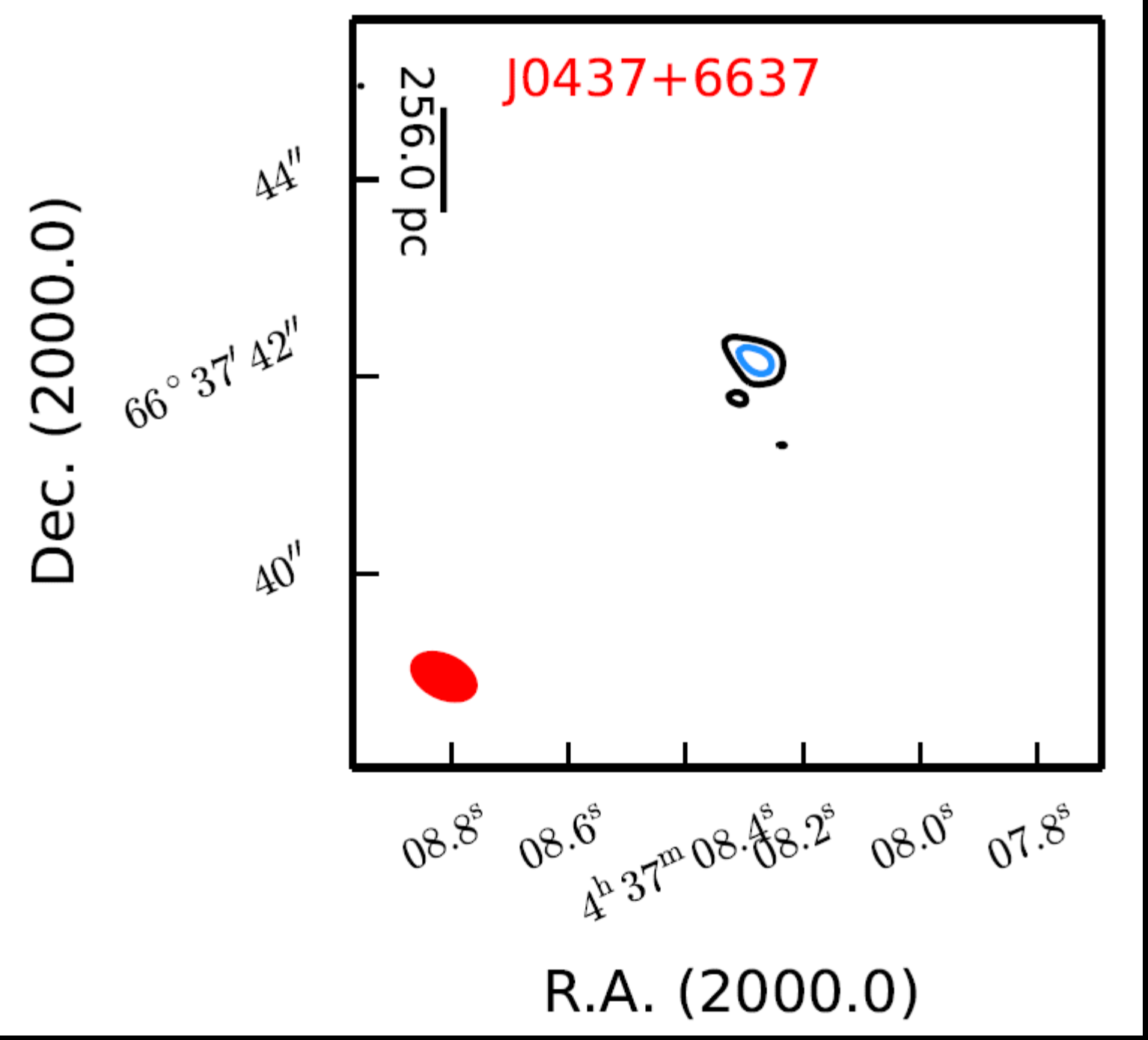
Urumqi 2017


J0437+2456
330.0 pc
Maser Disk
Orientation
Dec. (2000.0)
10″
08″
24° 56′ 06″
04″
03.9s
03.8s
4h 37m 03.7s
03.6s
03.5s

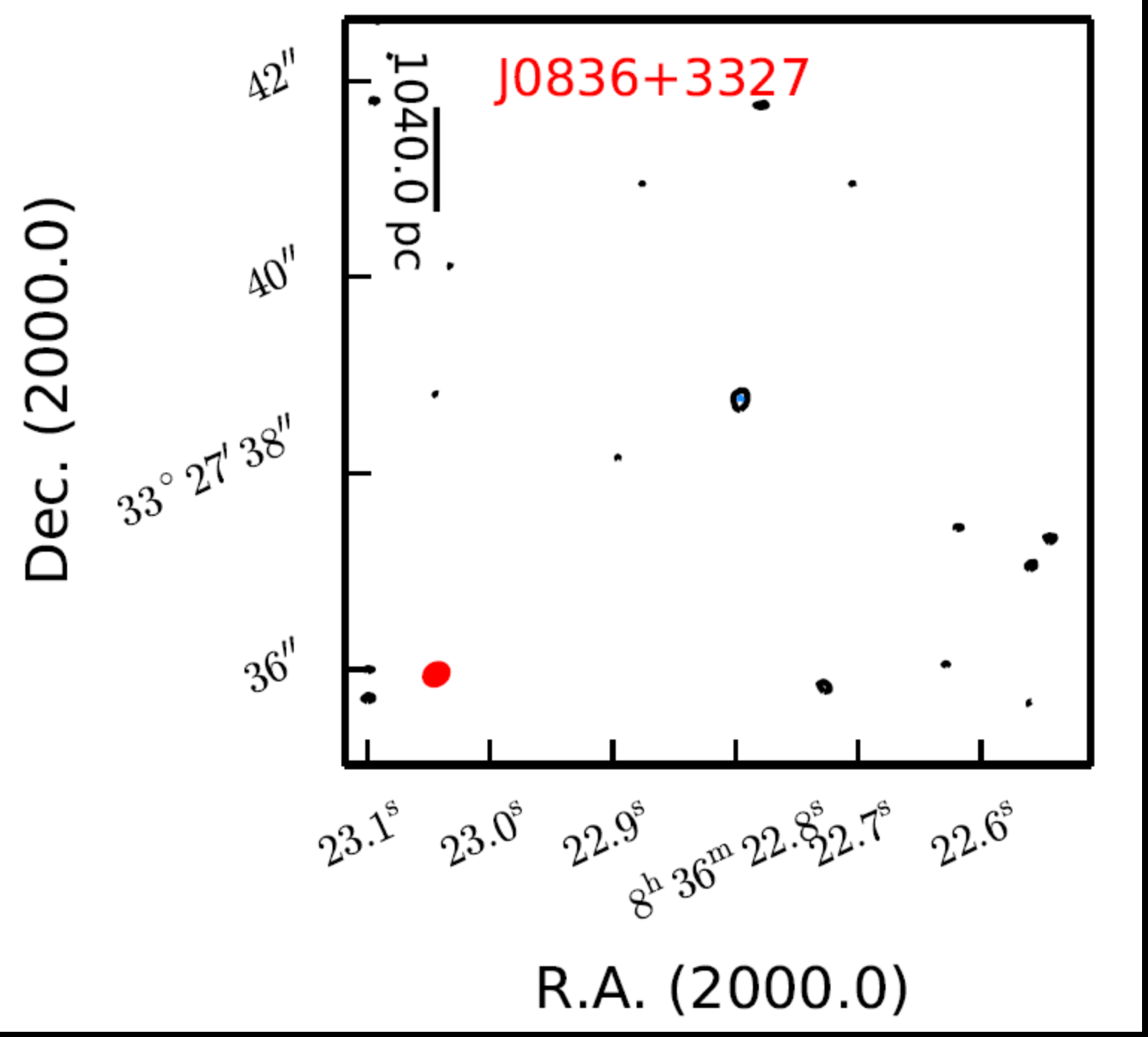
Urumqi 2017


Mrk0001
311.0 pc
24″
20″
18″
33° 05′ 22″
Dec. (2000.0)
07.5s
07.4s
07.3s
1h16m07.2s
07.1s
07.0s
R.A. (2000.0)

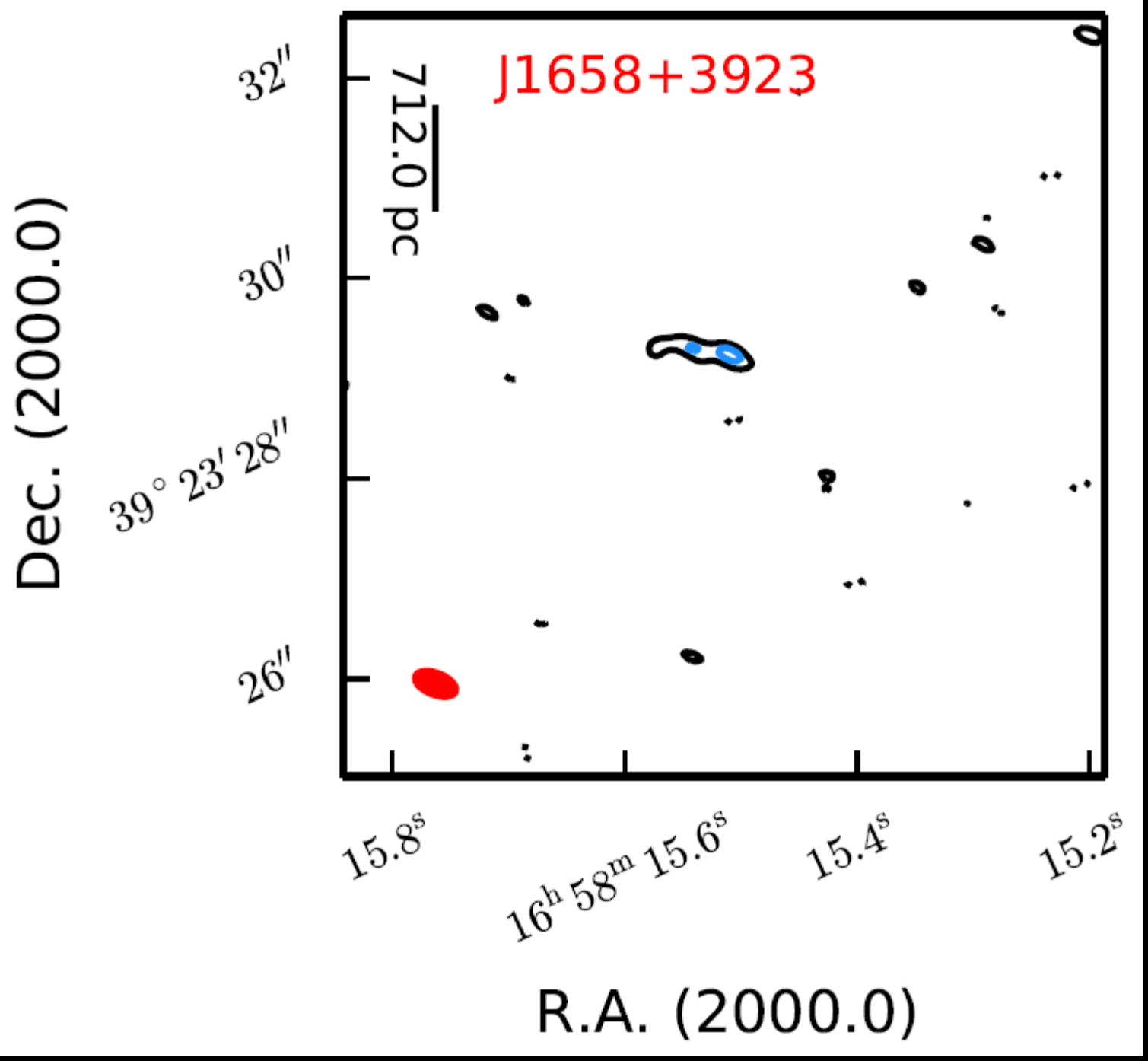
Urumqi 2017


J0437+6637
256.0 pc
44″
66° 37′ 42″
40″
Dec. (2000.0)
08.8s
08.6s
4h 37m 08.4s
08.2s
08.0s
07.8s
R.A. (2000.0)

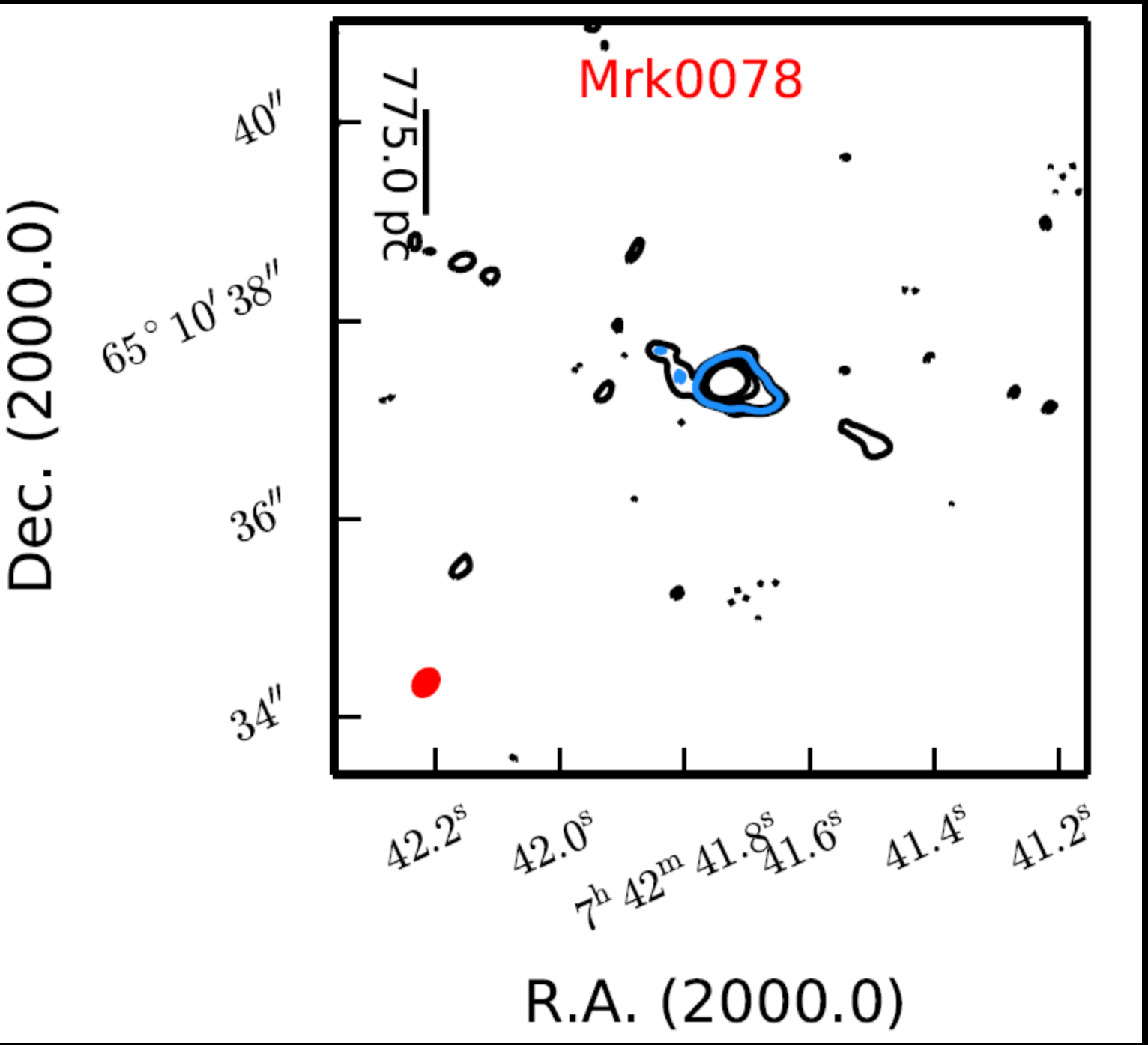
Urumqi 2017


J0836+3327
1040.0 pc
42″
40″
36″
33° 27′ 38″
Dec. (2000.0)
23.1s
23.0s
22.9s
8h 36m 22.8s
22.7s
22.6s
R.A. (2000.0)

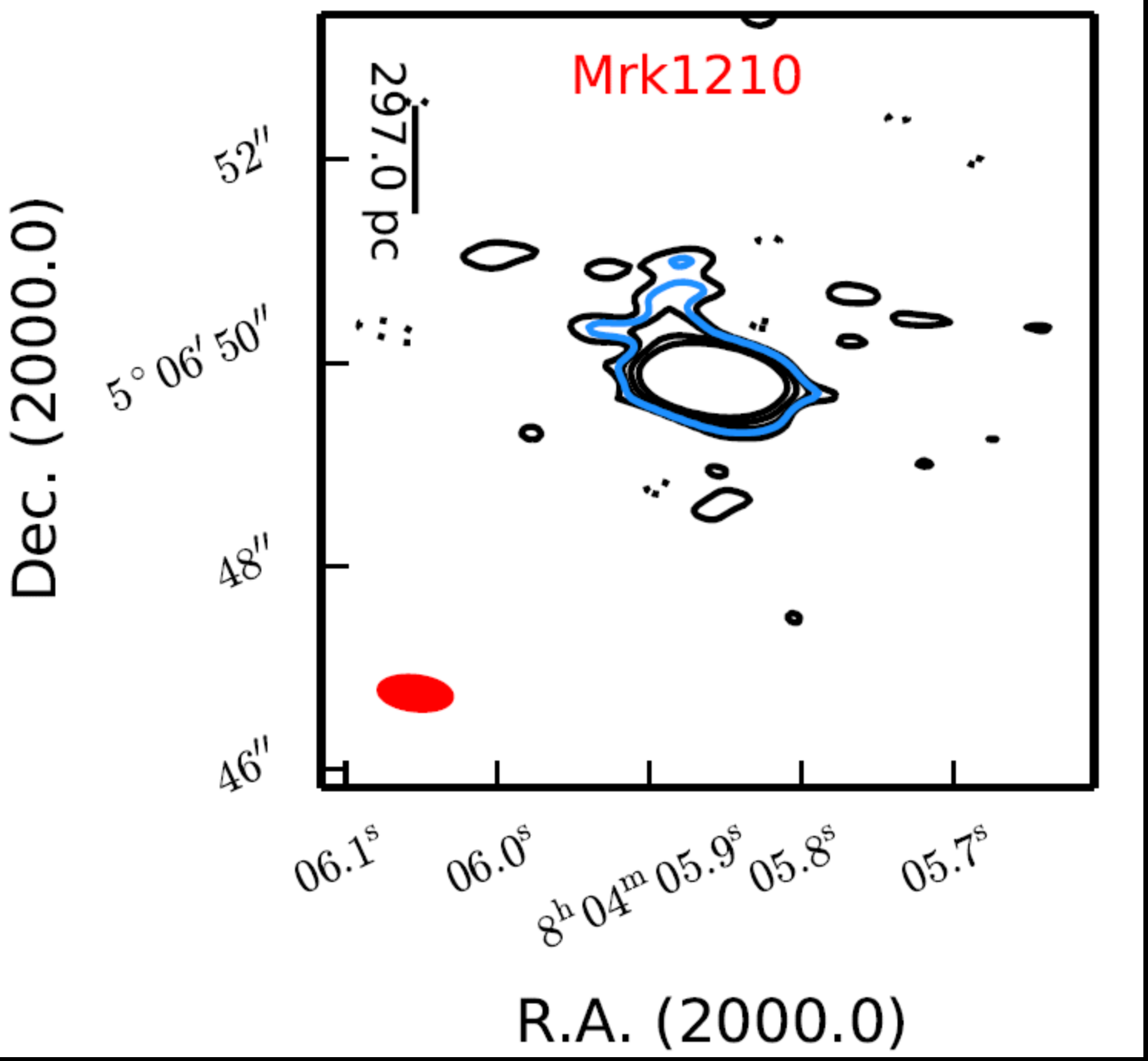
Urumqi 2017


J1658+3923
712.0 pc
32″
30″
39° 23′ 28″
26″
Dec. (2000.0)
15.8s
16h 58m 15.6s
15.4s
15.2s
R.A. (2000.0)

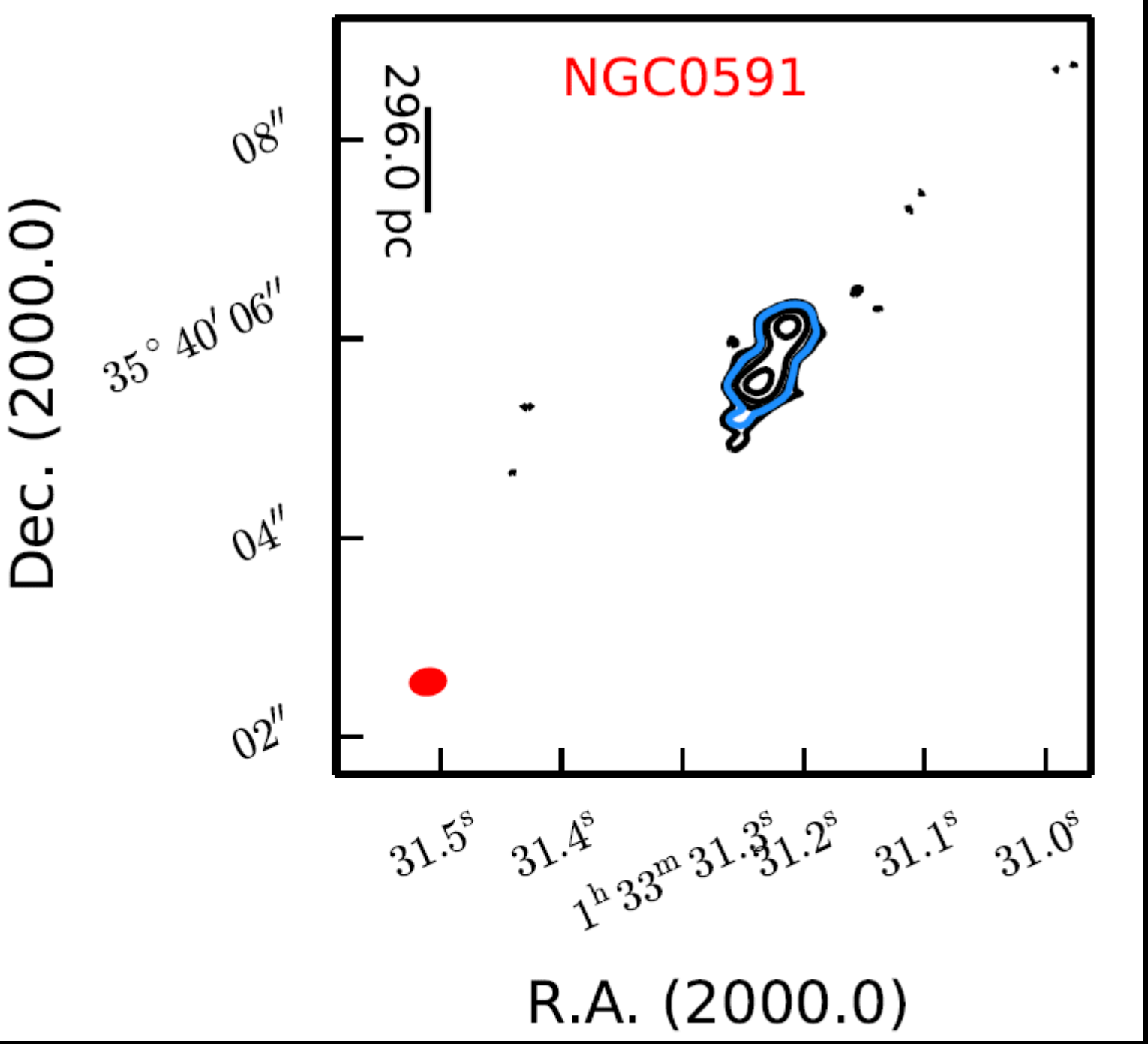
Urumqi 2017


Mrk0078
775.0 pc
40″
65° 10′ 38″
36″
34″
Dec. (2000.0)
42.2s
42.0s
7h 42m 41.8s
41.6s
41.4s
41.2s
R.A. (2000.0)

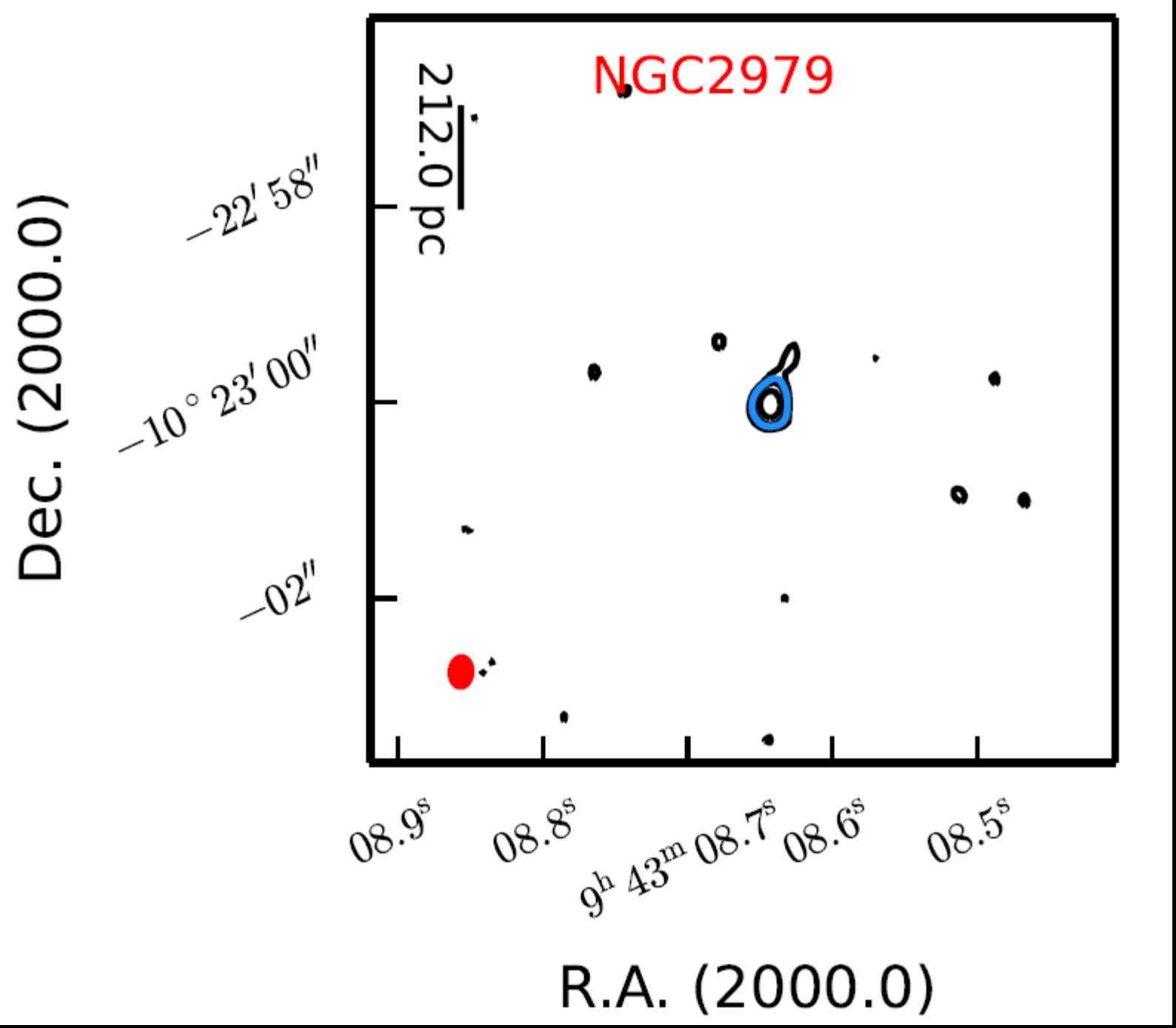
Urumqi 2017


Mrk1210
297.0 pc
52″
5° 06′ 50″
48″
46″
Dec. (2000.0)
06.1s
06.0s
8h 04m 05.9s
05.8s
05.7s
R.A. (2000.0)

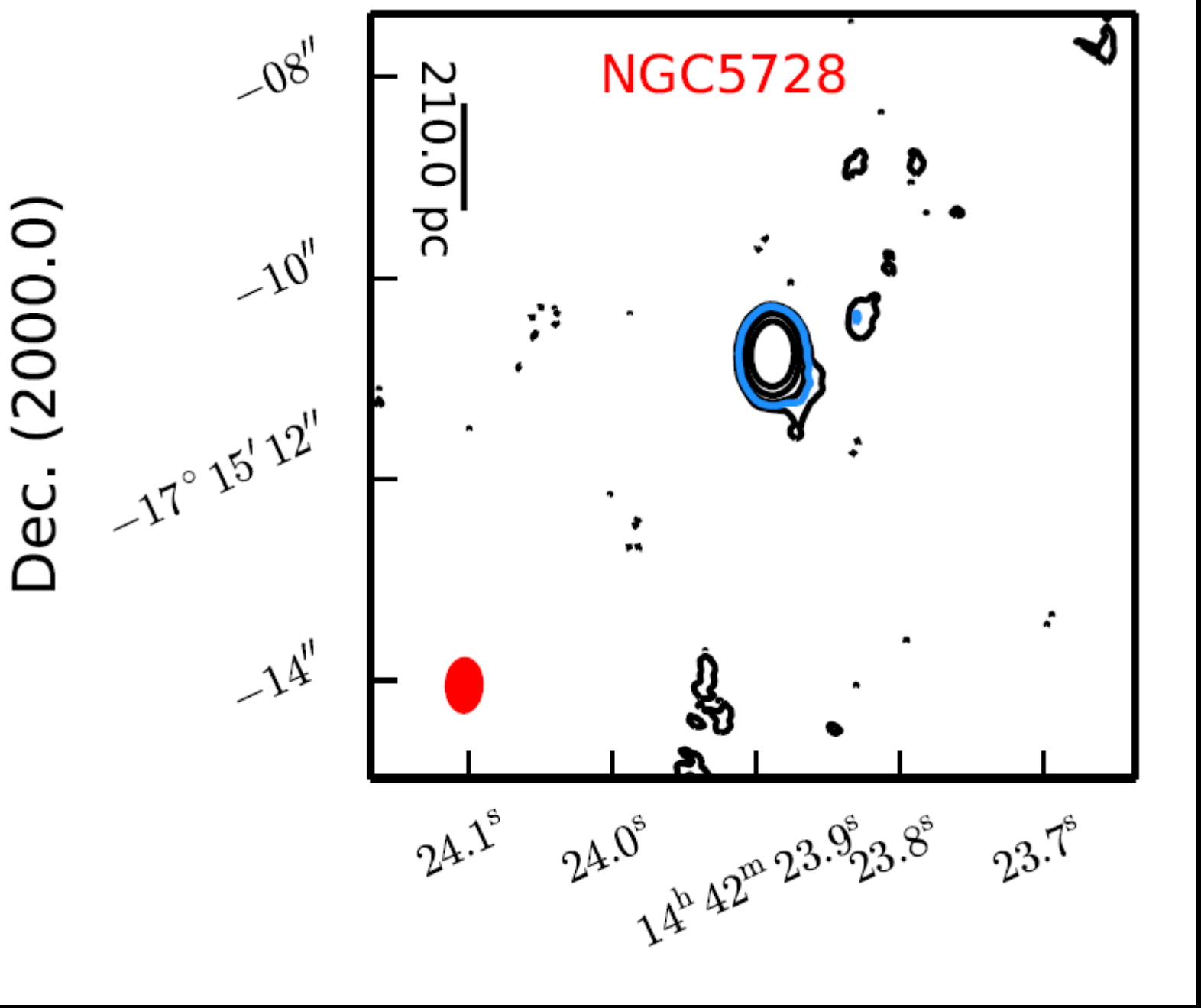
Urumqi 2017


NGC0591
296.0 pc
08″
35° 40′ 06″
04″
02″
Dec. (2000.0)
31.5s
31.4s
1h 33m 31.3s
31.2s
31.1s
31.0s
R.A. (2000.0)

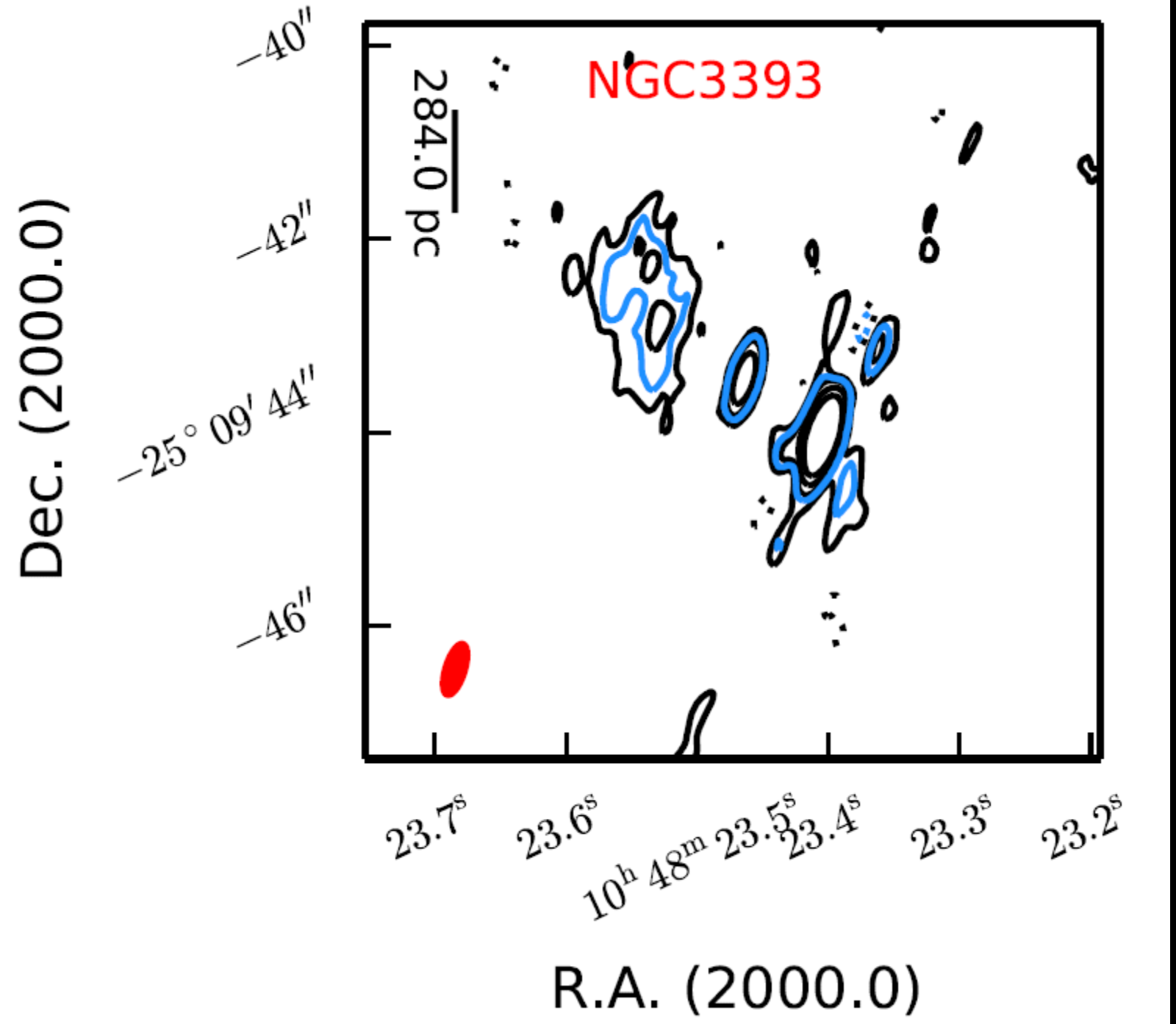
Urumqi 2017


NGC2979
212.0 pc
−22′ 58″
−10° 23′ 00″
−02″
Dec. (2000.0)
08.9s
08.8s
9h 43m 08.7s
08.6s
08.5s
R.A. (2000.0)

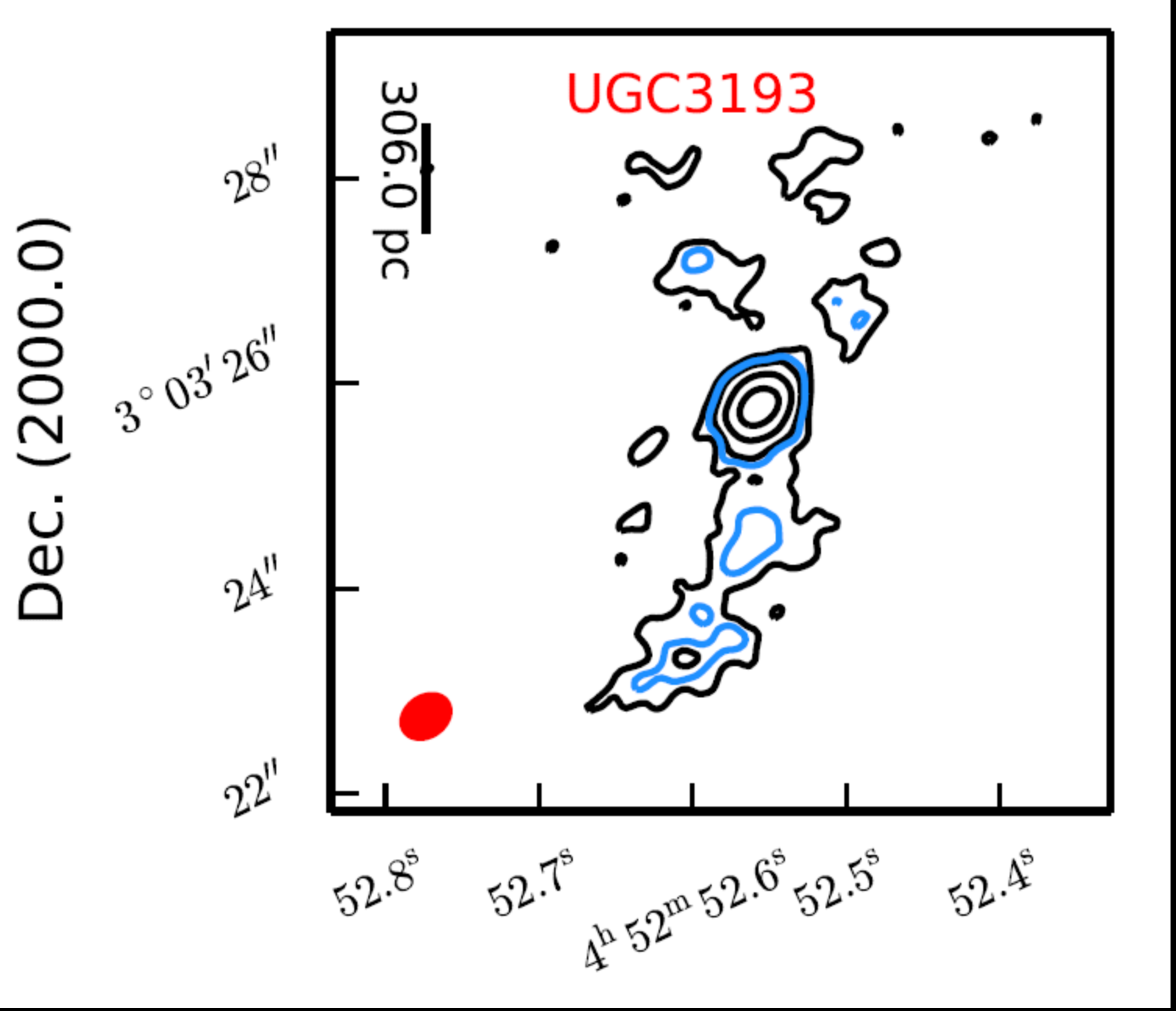
Urumqi 2017


NGC5728
10.0 pc
Dec. (2000.0)
−08″
−10″
−17° 15′ 12″
−14″
24.1s
24.0s
14h 42m 23.9s
23.8s
23.7s

Urumqi 2017


NGC3393
284.0 pc
−40″
−42″
−25° 09′ 44″
−46″
Dec. (2000.0)
23.7s
23.6s
10h 48m 23.5s
23.4s
23.3s
23.2s
R.A. (2000.0)

Urumqi 2017


UGC3193
306.0 pc
28″
3° 03′ 26″
24″
22″
Dec. (2000.0)
52.8s
52.7s
4h 52m 52.6s
52.5s
52.4s

Urumqi 2017

Urumqi 2017

Calibrate the non-maser M_{BH}

Search for disk H_2O megamasers
a) sufficiently nearby and
b) with high enough M_{BH}
to reach a sphere of influence with large enough angular scale.

No new such maser found

Van den Bosch et al. 2016

Urumqi 2016

Calibrate the non-maser M_{BH}

Search for disk H_2O megamasers
a) sufficiently nearby and
b) with high enough M_{BH}
to reach a sphere of influence with large enough angular scale.

Only one such source so far: NGC4258.

Van den Bosch et al. 2016

Calibrate the non-maser M_{BH}

Search for disk H_2O megamasers
a) sufficiently nearby and
b) with high enough M_{BH}
to reach a sphere of influence with large enough angular scale.

Only one such source so far: NGC4258.
HST spectroscopy: M_{BH} 15% too small (Siopis et al. 2009)

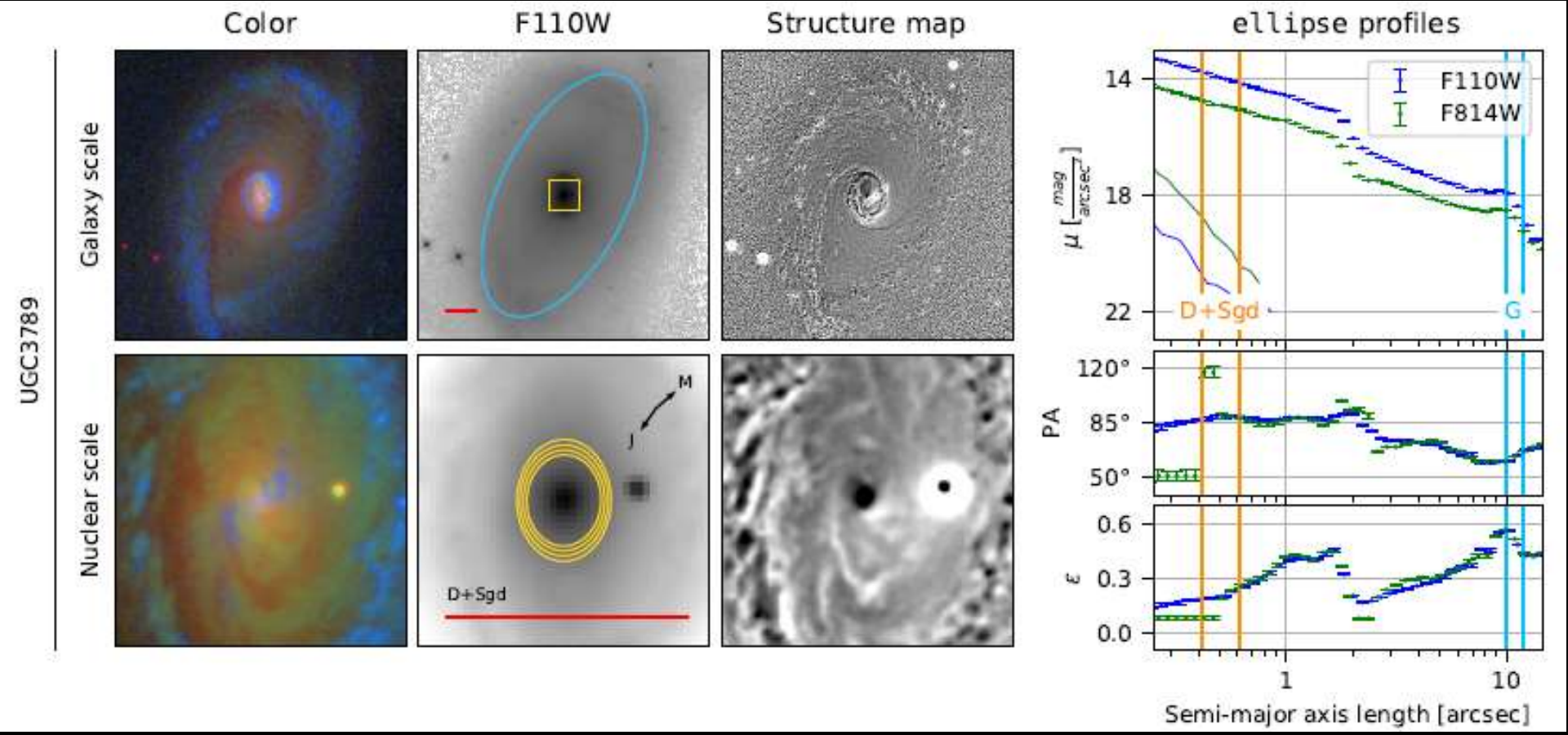
Van den Bosch et al. 2016

Calibrate the non-maser M_{BH}

Search for disk H_2O megamasers
a) sufficiently nearby and
b) with high enough M_{BH}
to reach a sphere of influence with large enough angular scale.

Only one such source so far: NGC4258.
Adaptive optics: M_{BH} 25% too large (Drehmer et al. 2015)

Van den Bosch et al. 2016



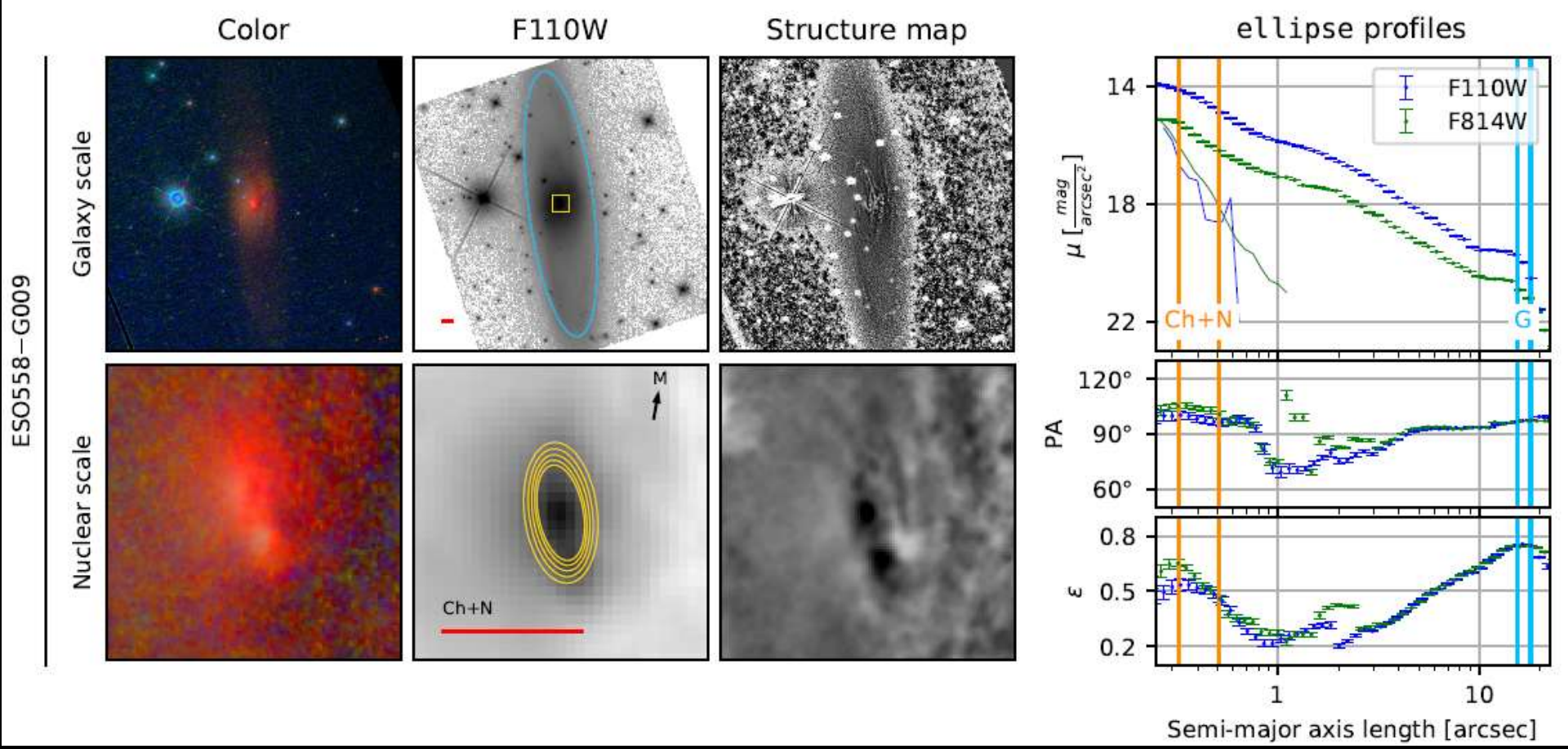
Blue: F335W
Green: F438W
Red: F814W

Size of lower image
M: Orientation of maser disk
Red bar: 1 kpc

For small scale features like dust lanes

Blue and orange vertical lines limit ranges of ellipse major axes to extract galaxy orientation as a whole

Urumqi 2017



Blue: F335W
Green: F438W
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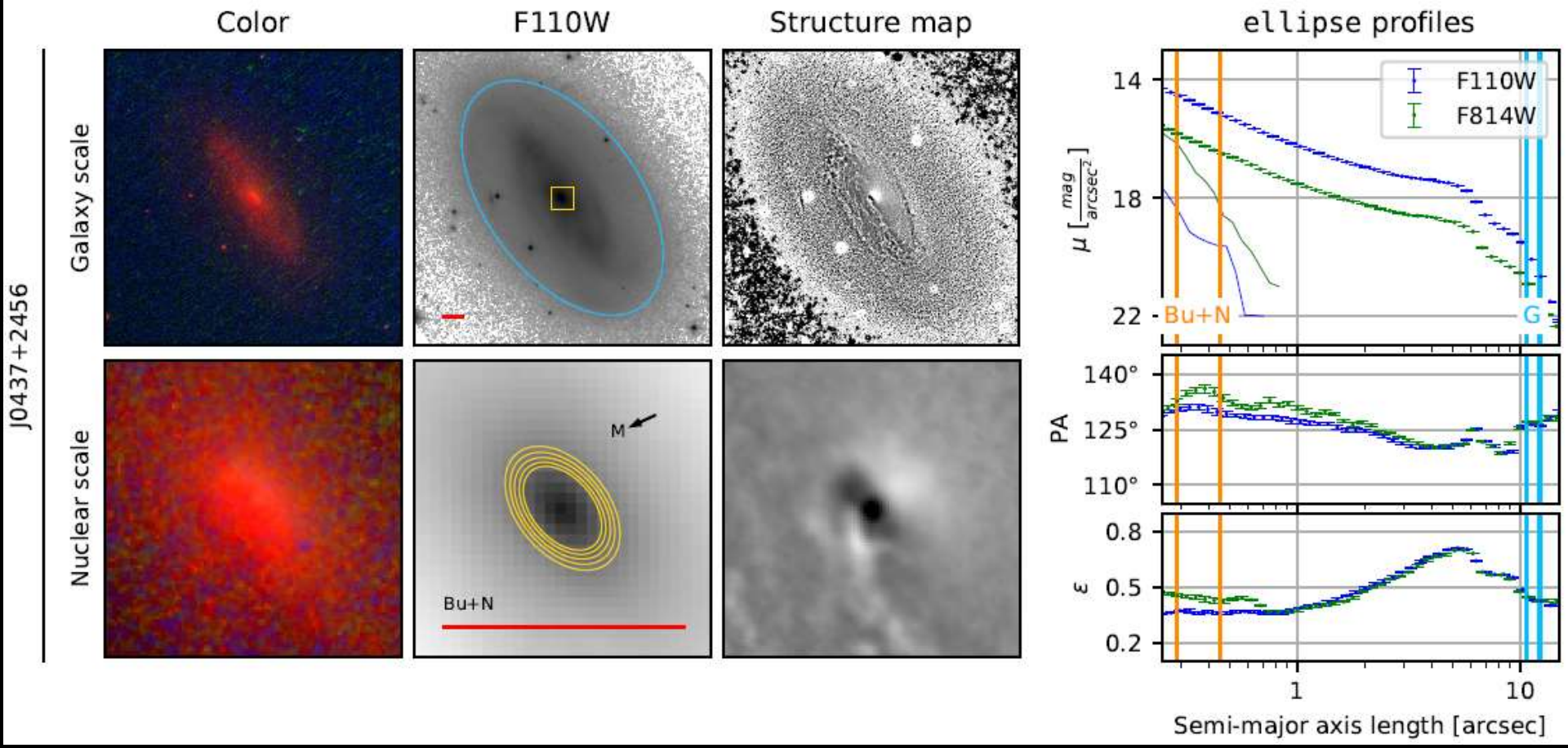
Urumqi 2017



Blue: F335W
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Size of lower image
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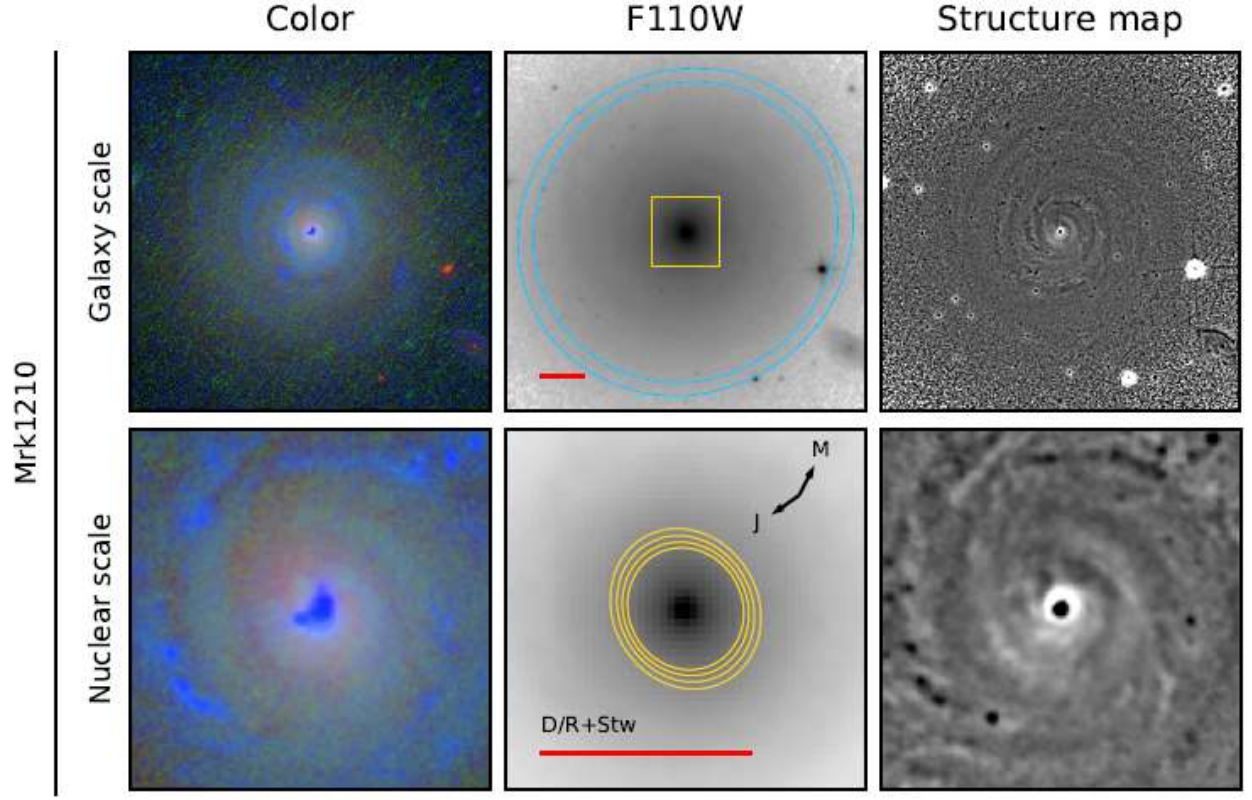
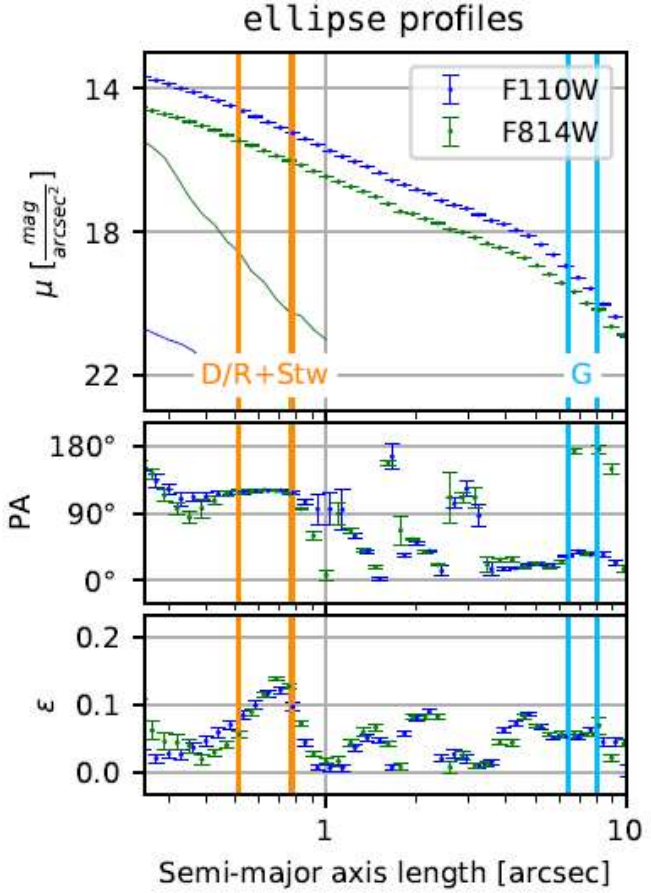
Urumqi 2017





Blue: F335W
Green: F438W
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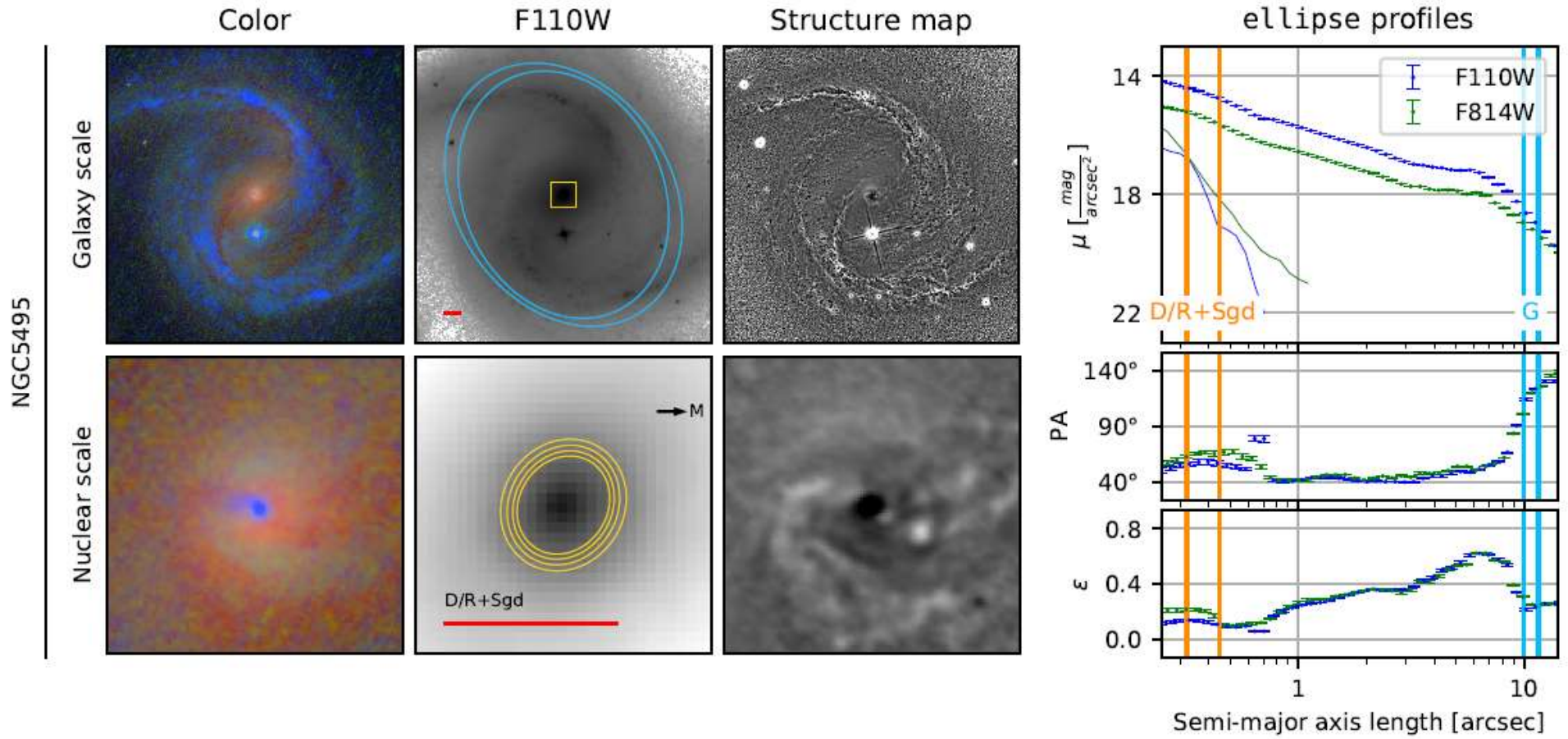
Urumqi 2017



Blue: F335W
Green: F438W
Red: F814W

Size of lower image
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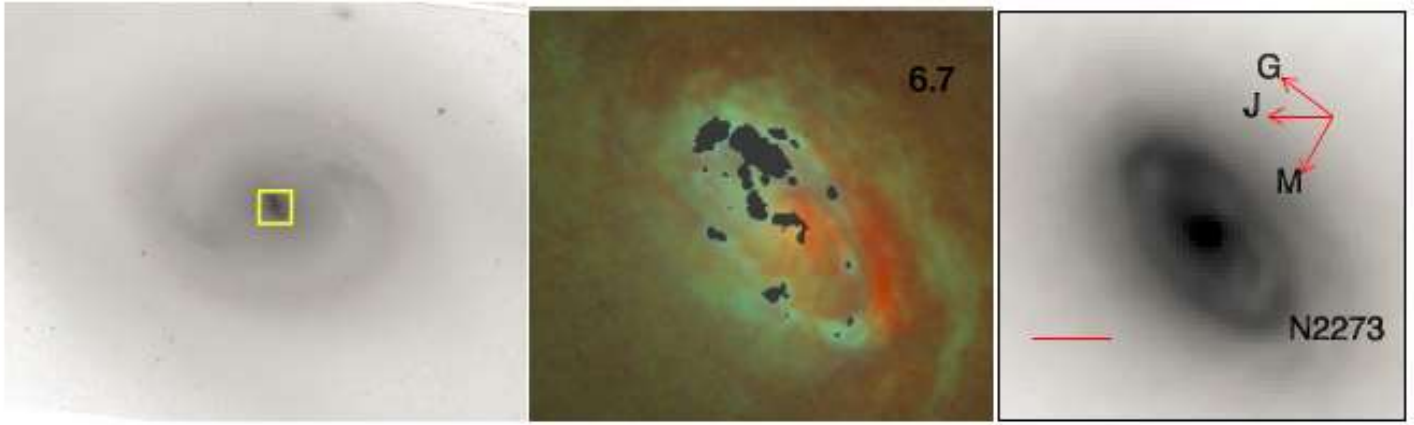
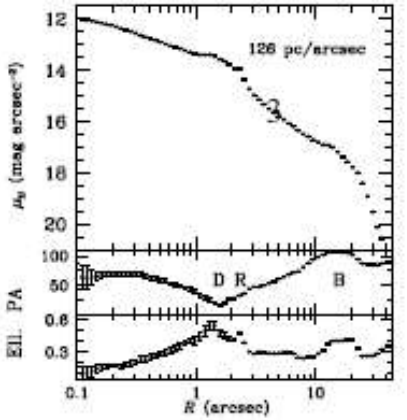
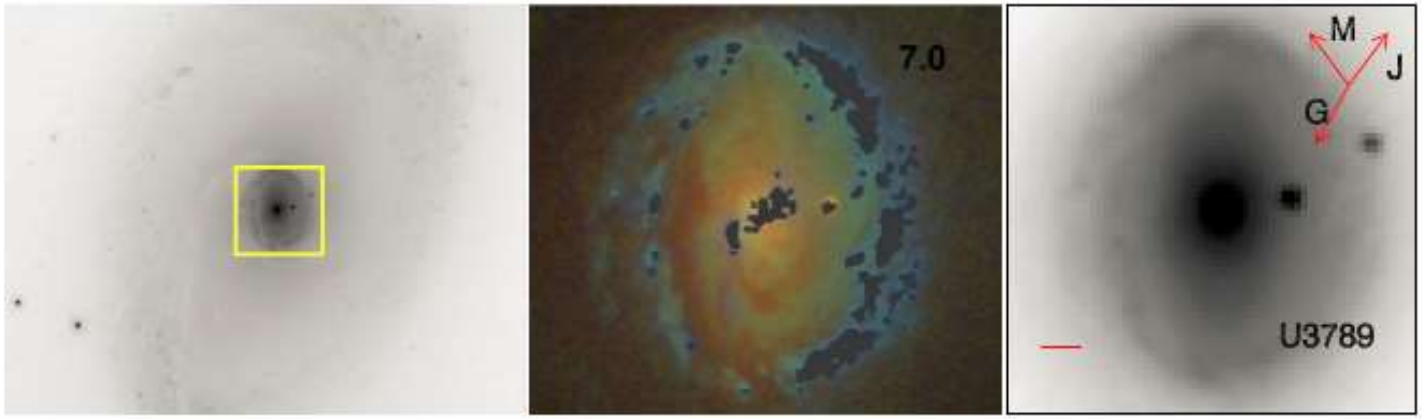
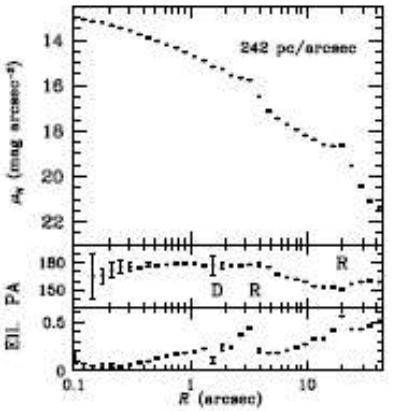
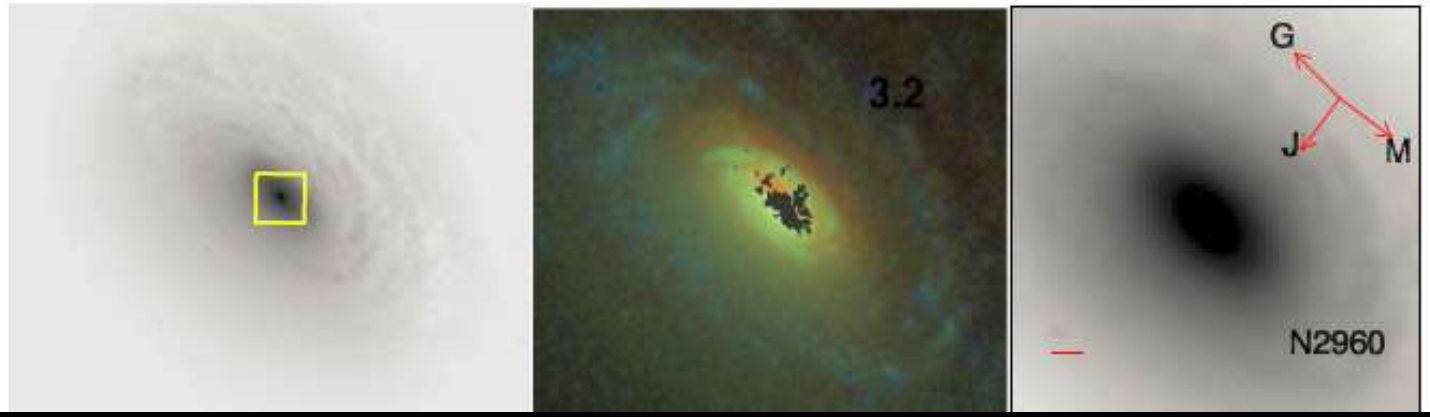
Urumqi 2017

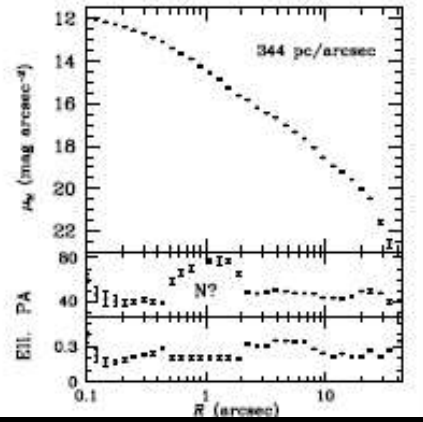




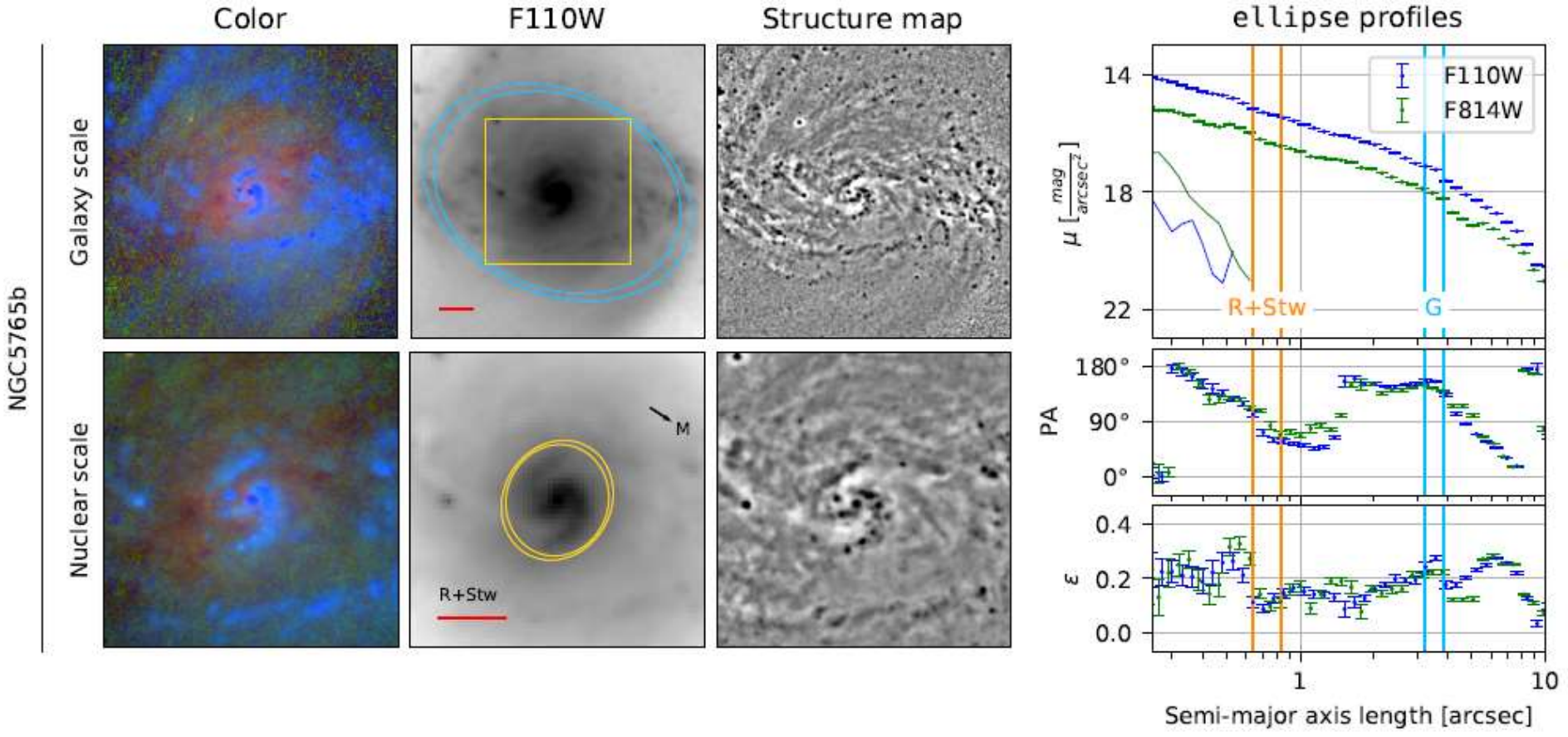








0.8µm **0.3/0.4/0.8 µm** **1.6 µm**



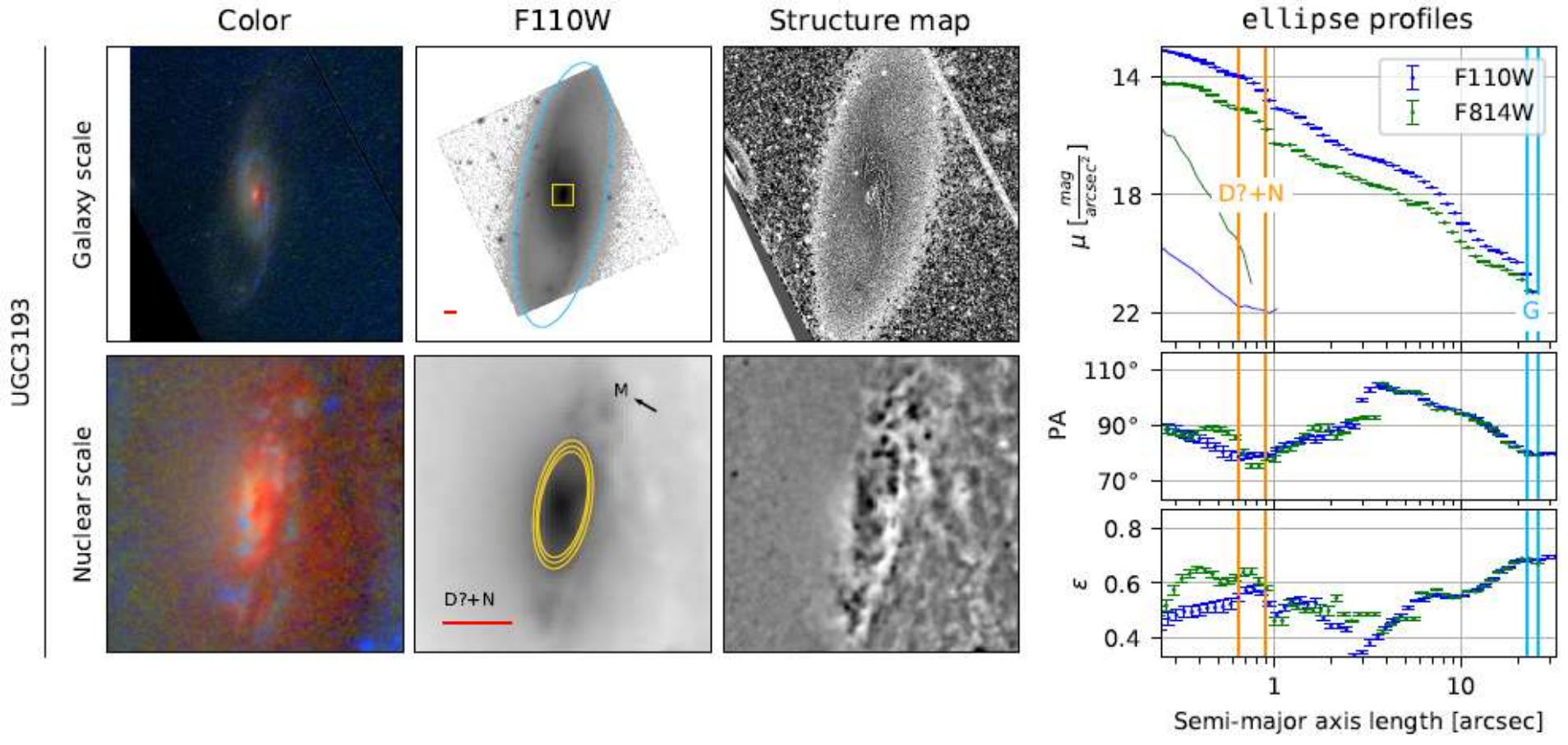
Blue: F335W
Green: F438W
Red: F814W

Size of lower image
M: Orientation of maser disk
Red bar: 1 kpc

For small scale features like dust lanes

Blue and orange vertical lines limit ranges of ellipse major axes to extract galaxy orientation as a whole

Urumqi 2017



Blue: F335W
Green: F438W
Red: F814W

Size of lower image
M: Orientation of maser disk
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For small scale features like dust lanes

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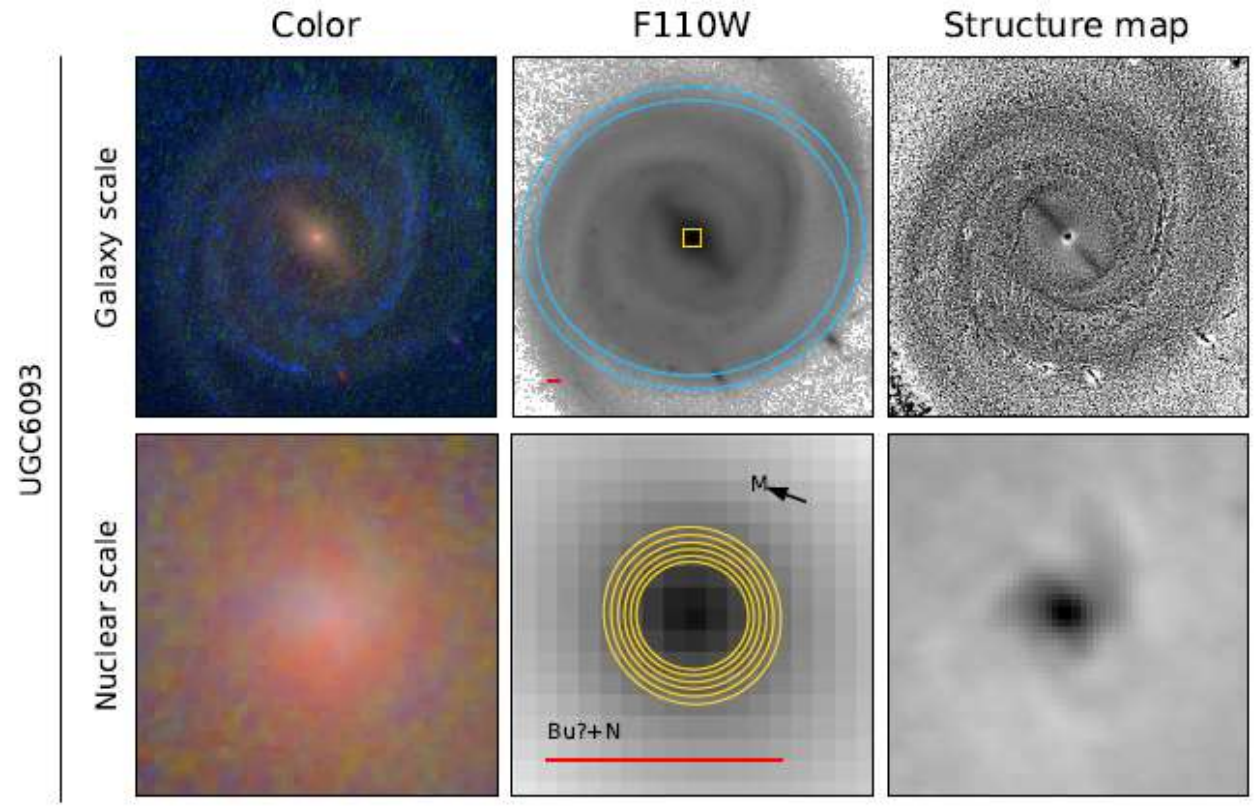
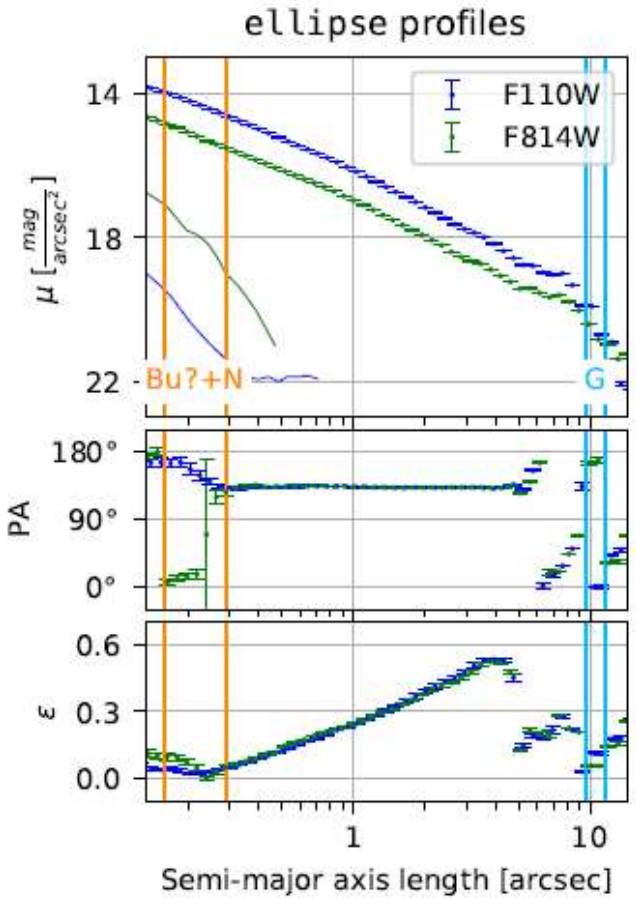
Urumqi 2017





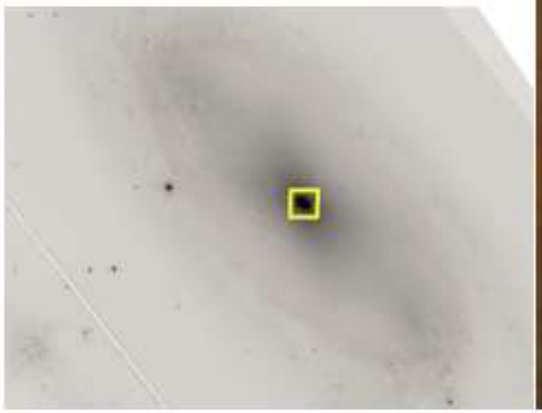
Blue: F335W
Green: F438W
Red: F814W

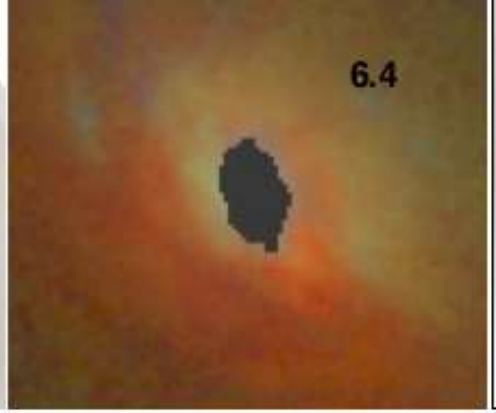
Size of lower image
M: Orientation of maser disk
Red bar: 1 kpc

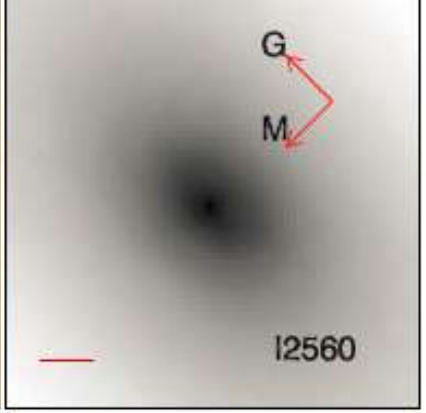
For small scale features like dust lanes

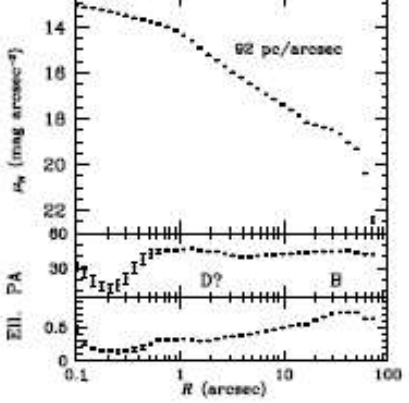
Blue and orange vertical lines limit ranges of ellipse major axes to extract galaxy orientation as a whole

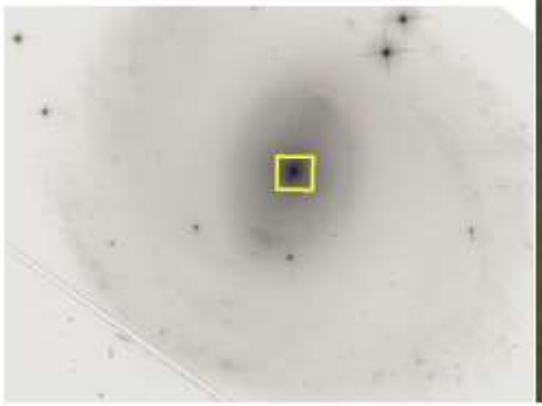
Urumqi 2017

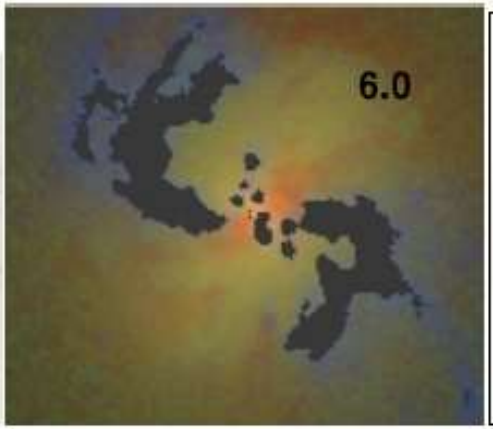


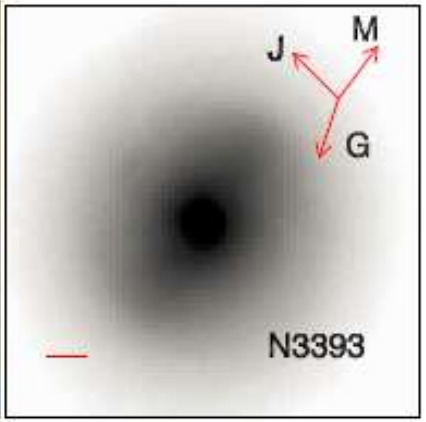

6.4

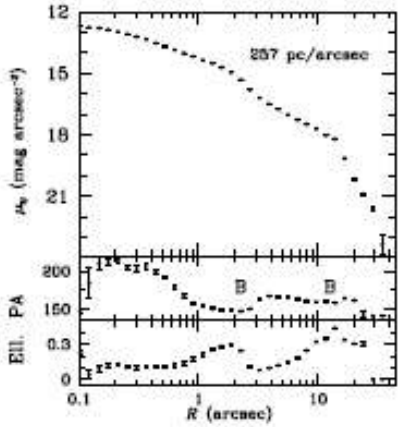

G
M
I2560

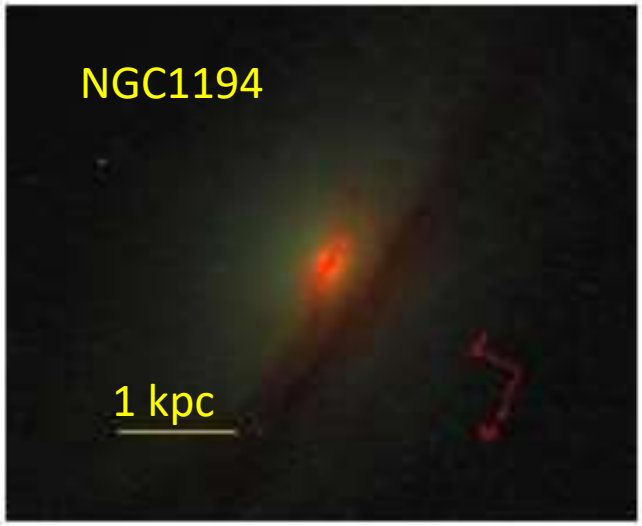

92 pc/arcsec
D?
B
R (arcsec)

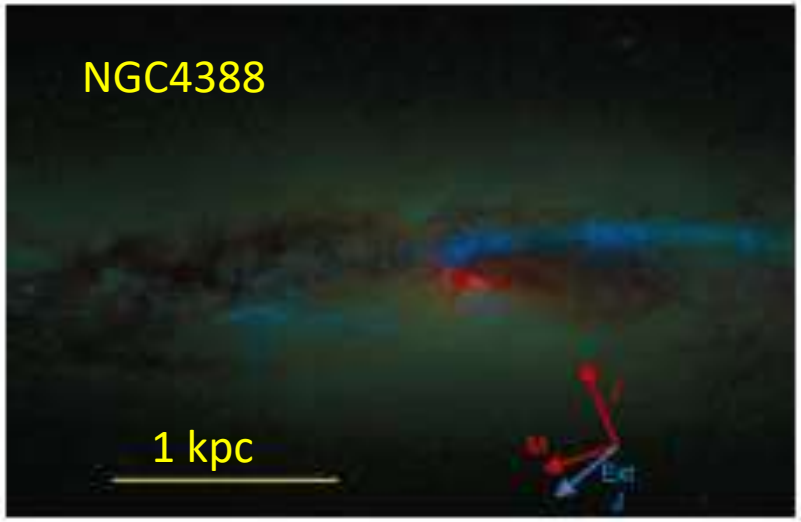



6.0

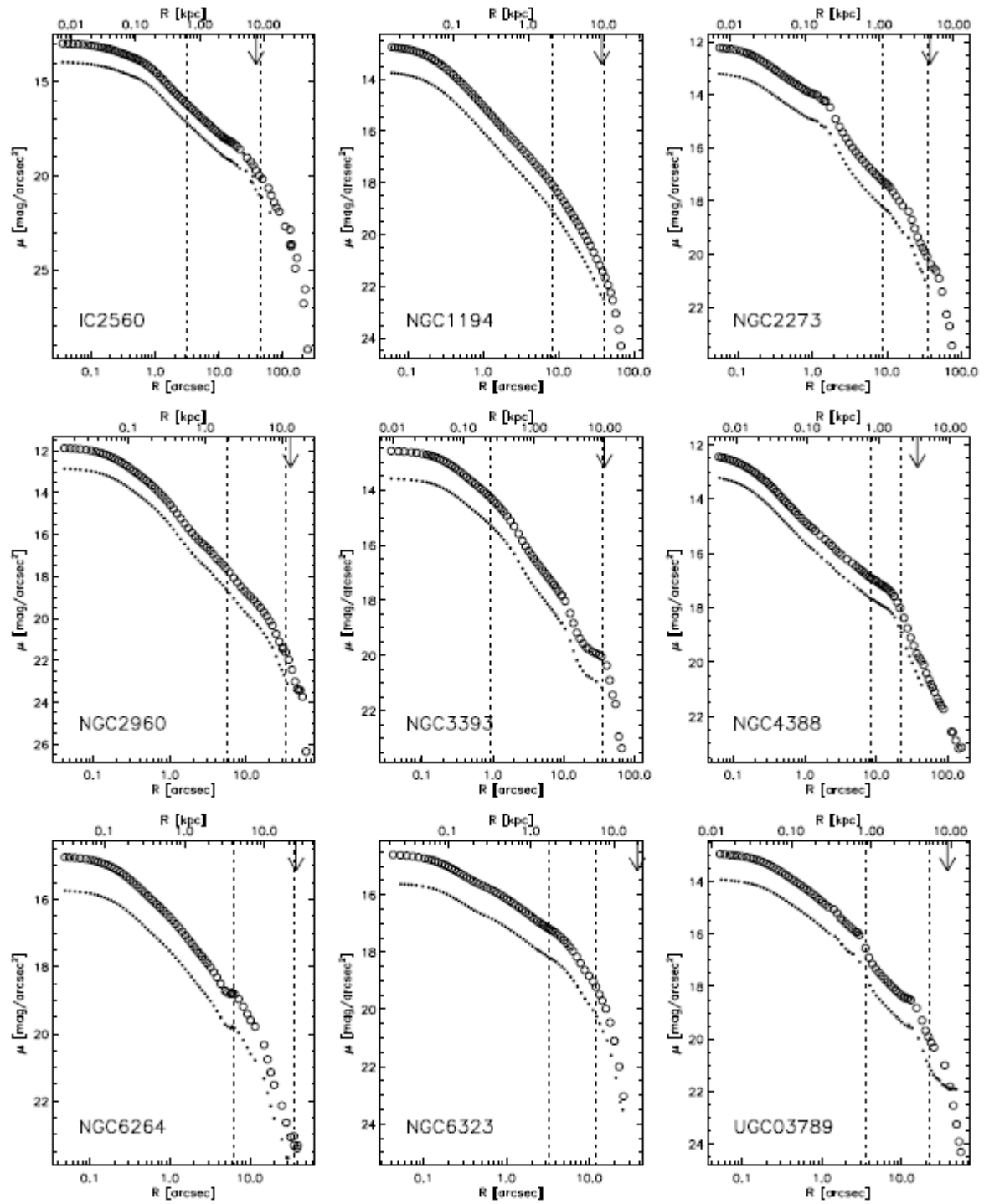

J
M
G
N3393


257 pc/arcsec
B
B
R (arcsec)


NGC1194
1 kpc


NGC4388
1 kpc

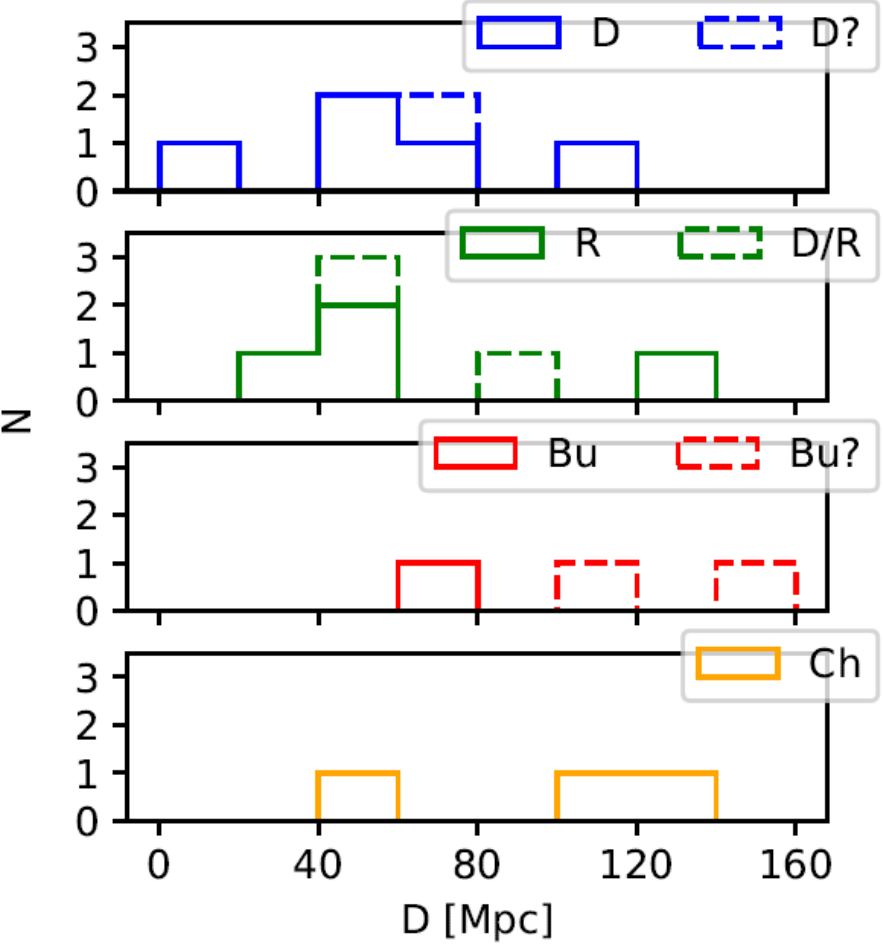
Urumqi 2016

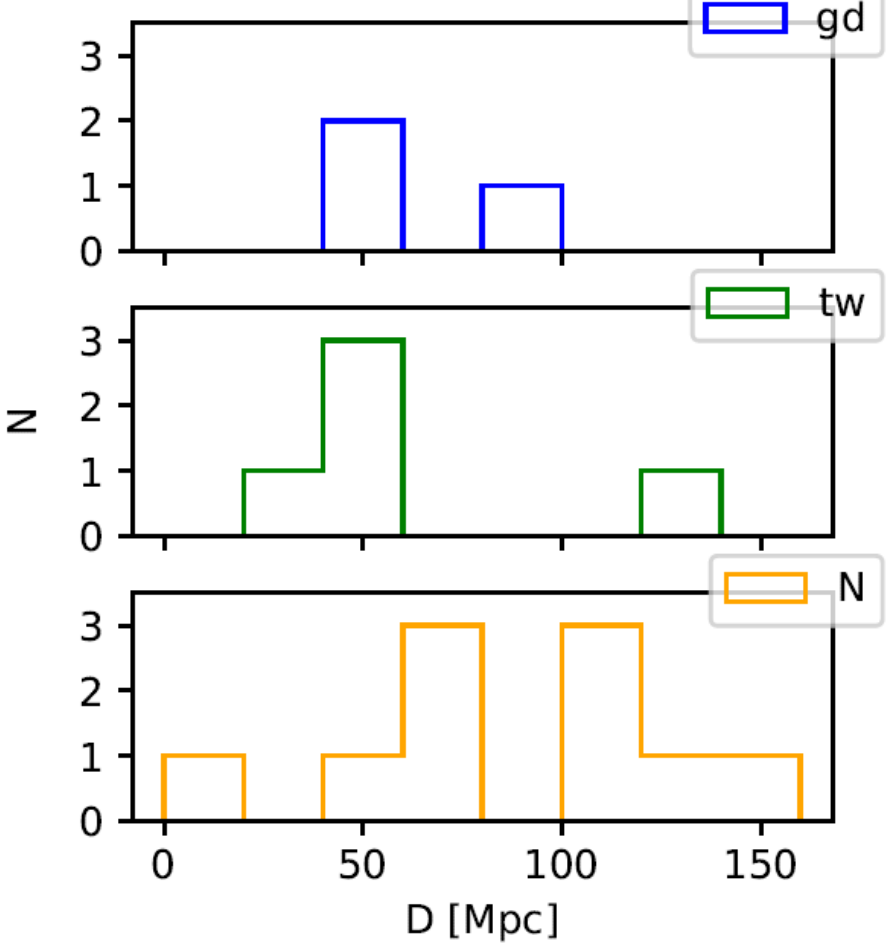


More HST observations (wide field and HST data combined, but offset by half a magnitude).

Laesker et al. 2015

Urumqi 2016





D = Disk

R = Ring

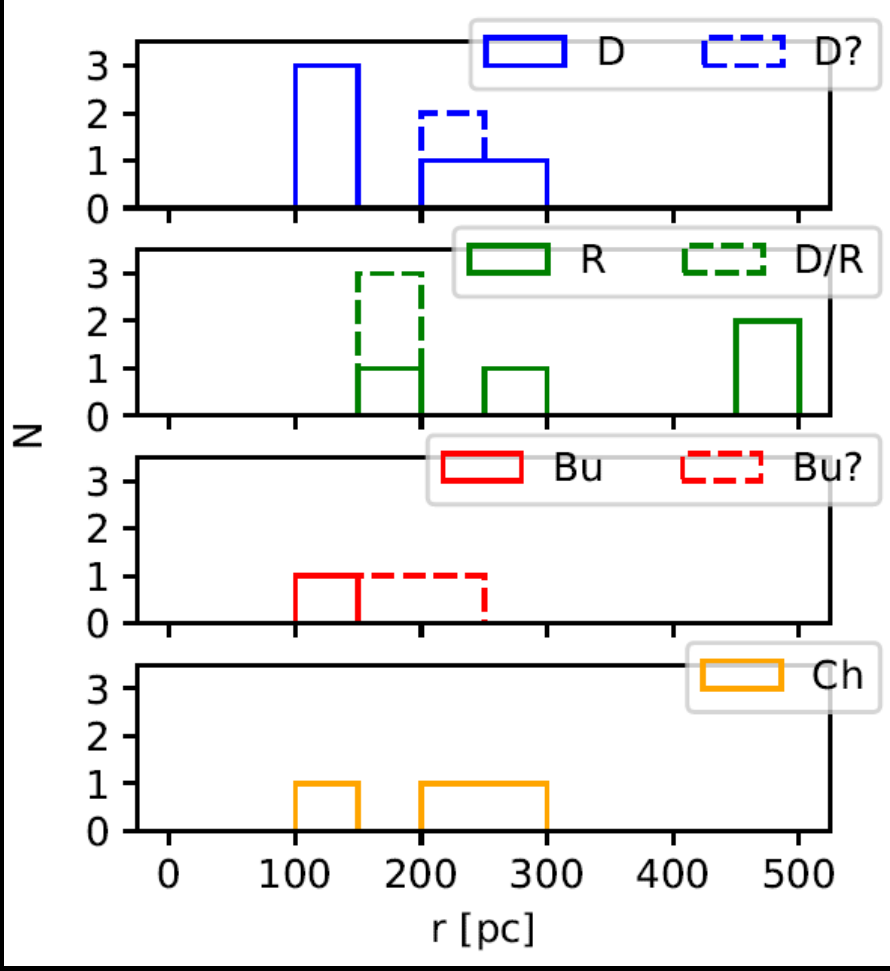
Bu = Bulge

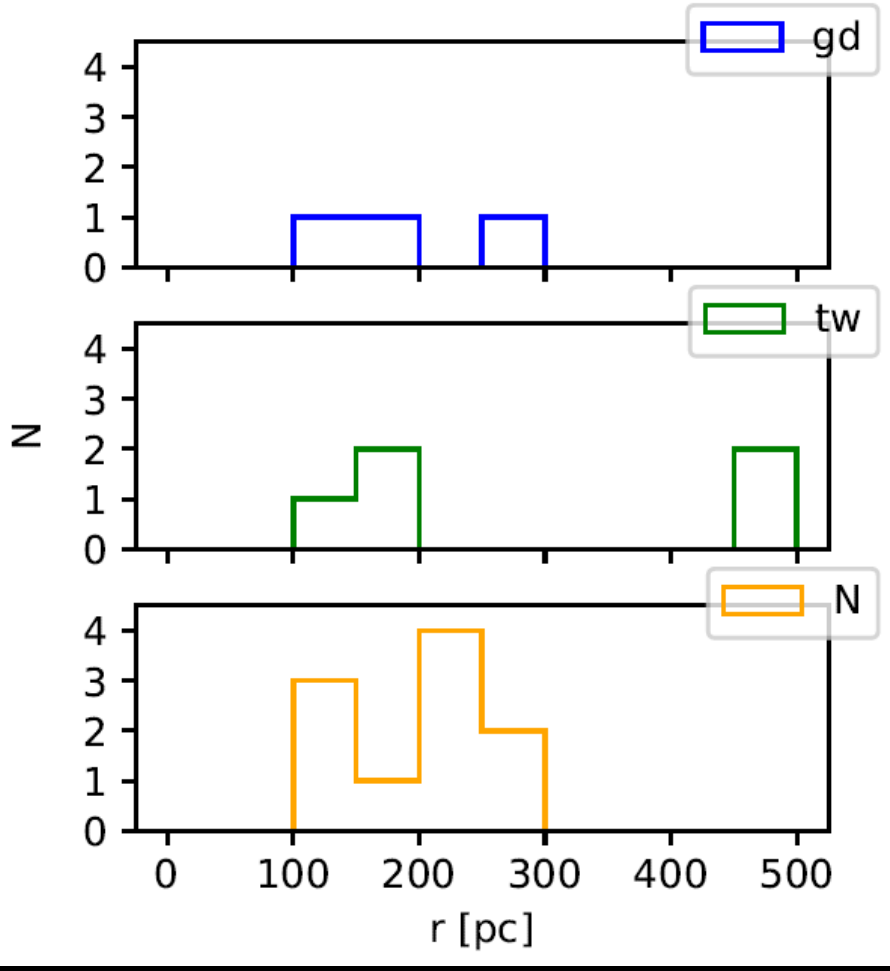
Ch = Chaotic

gd = Grand Design nuclear spiral

Tw = tighlty wound nuclear spiral

Urumqi 2017





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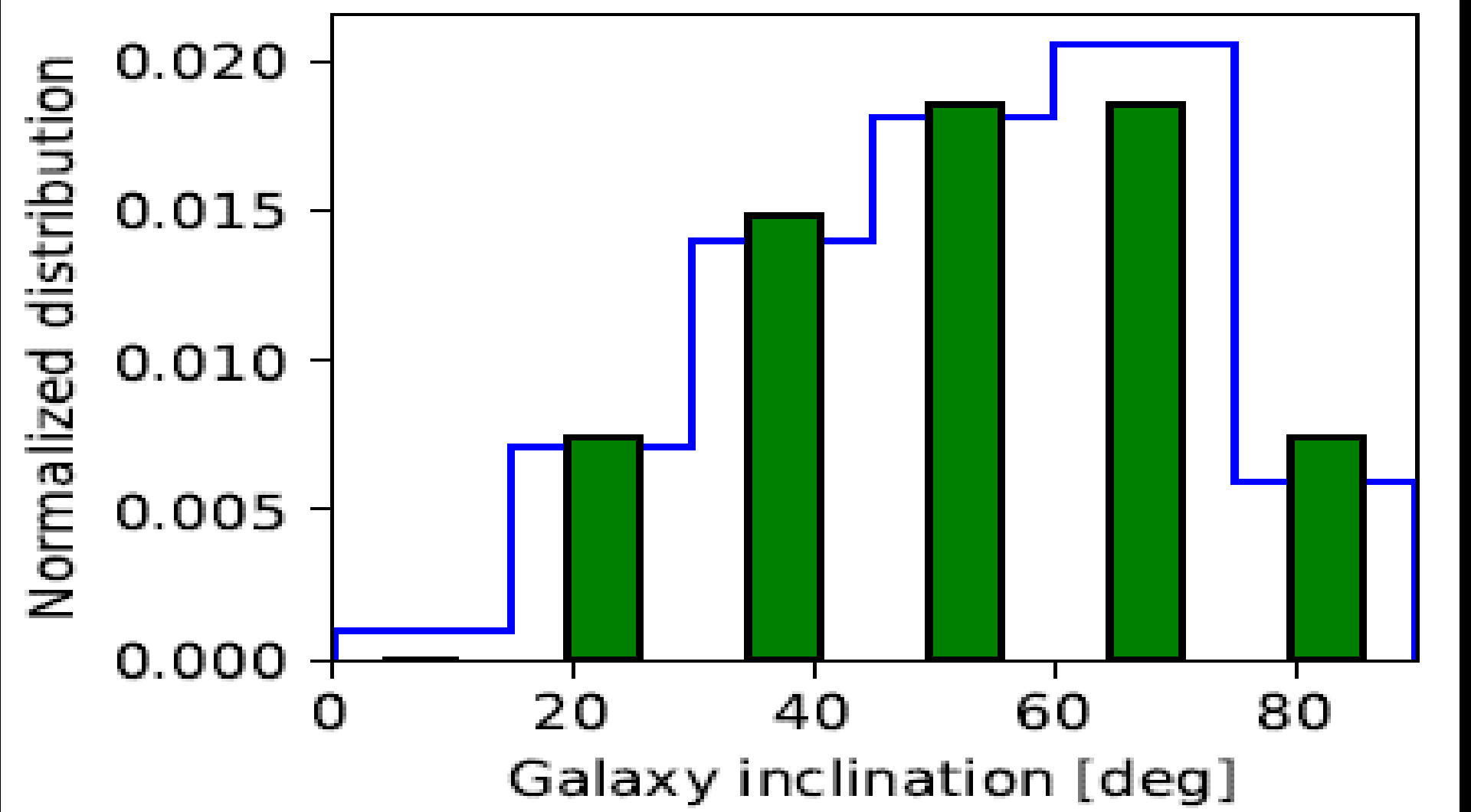
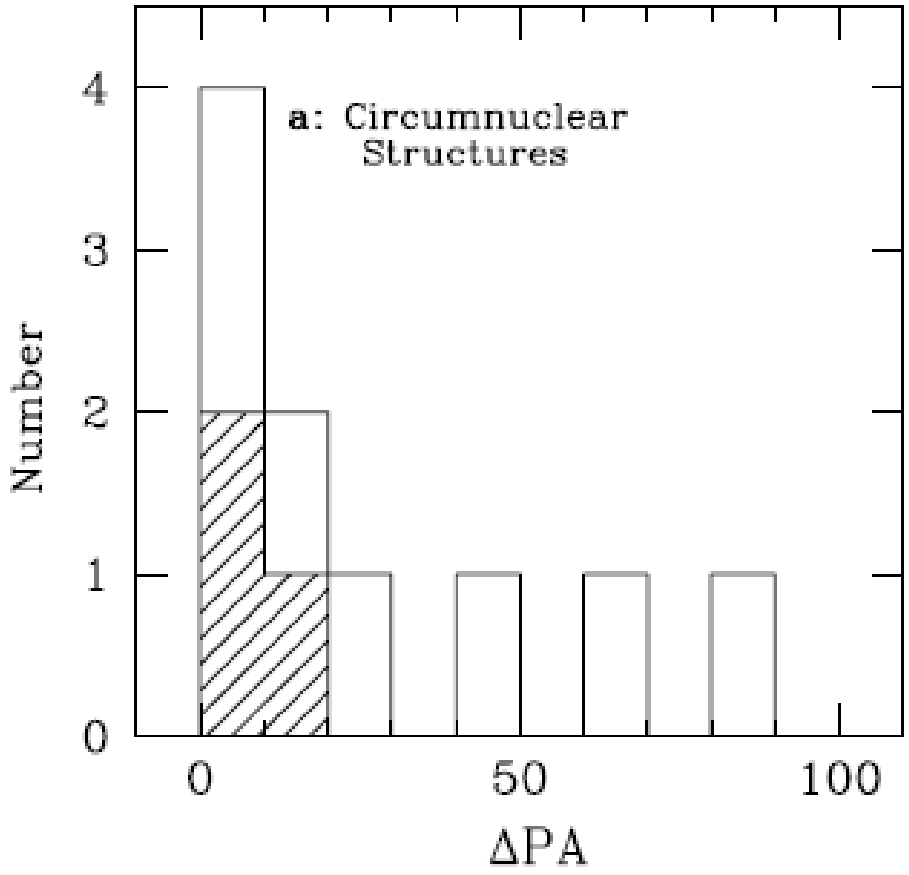
Urumqi 2017

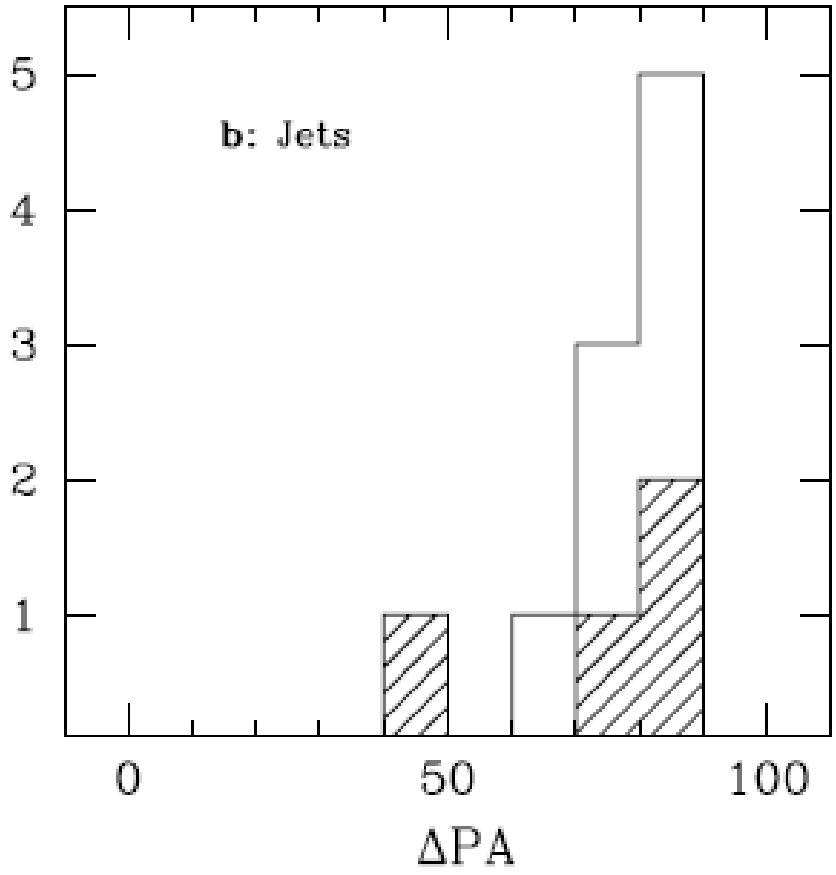


Galaxy inclinations of 788 disk galaxies (SDSS DR4 – Nair & Abraham 2010): blue

Galaxy inclinations of megamaser galaxies (green)

Urumqi 2017

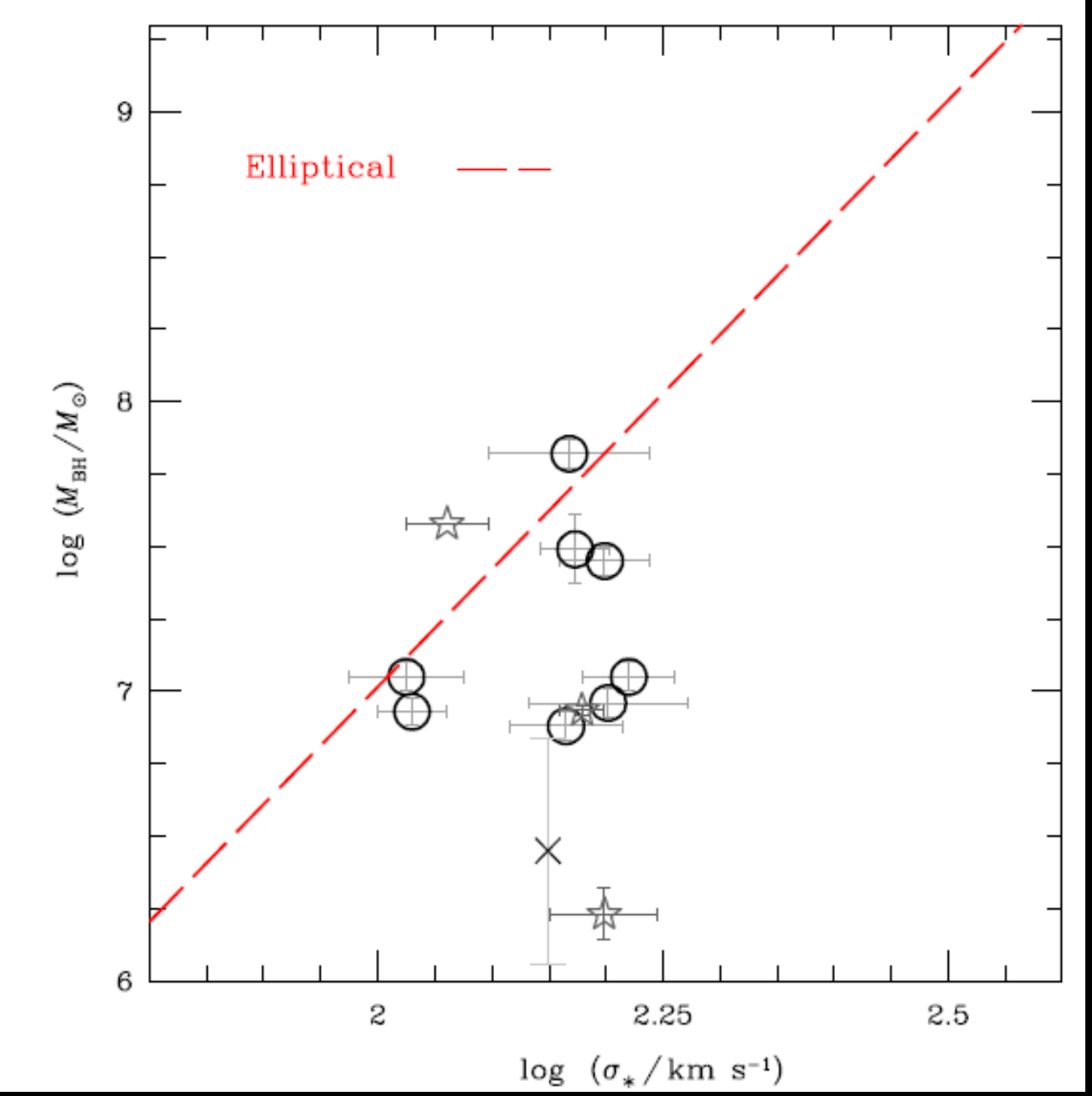




a) Little correlation between <~500 pc structures and maser disks. Dashed: CO inclination taken from the literature.

b) Correlation between maser disks and jets.

Urumqi 2016

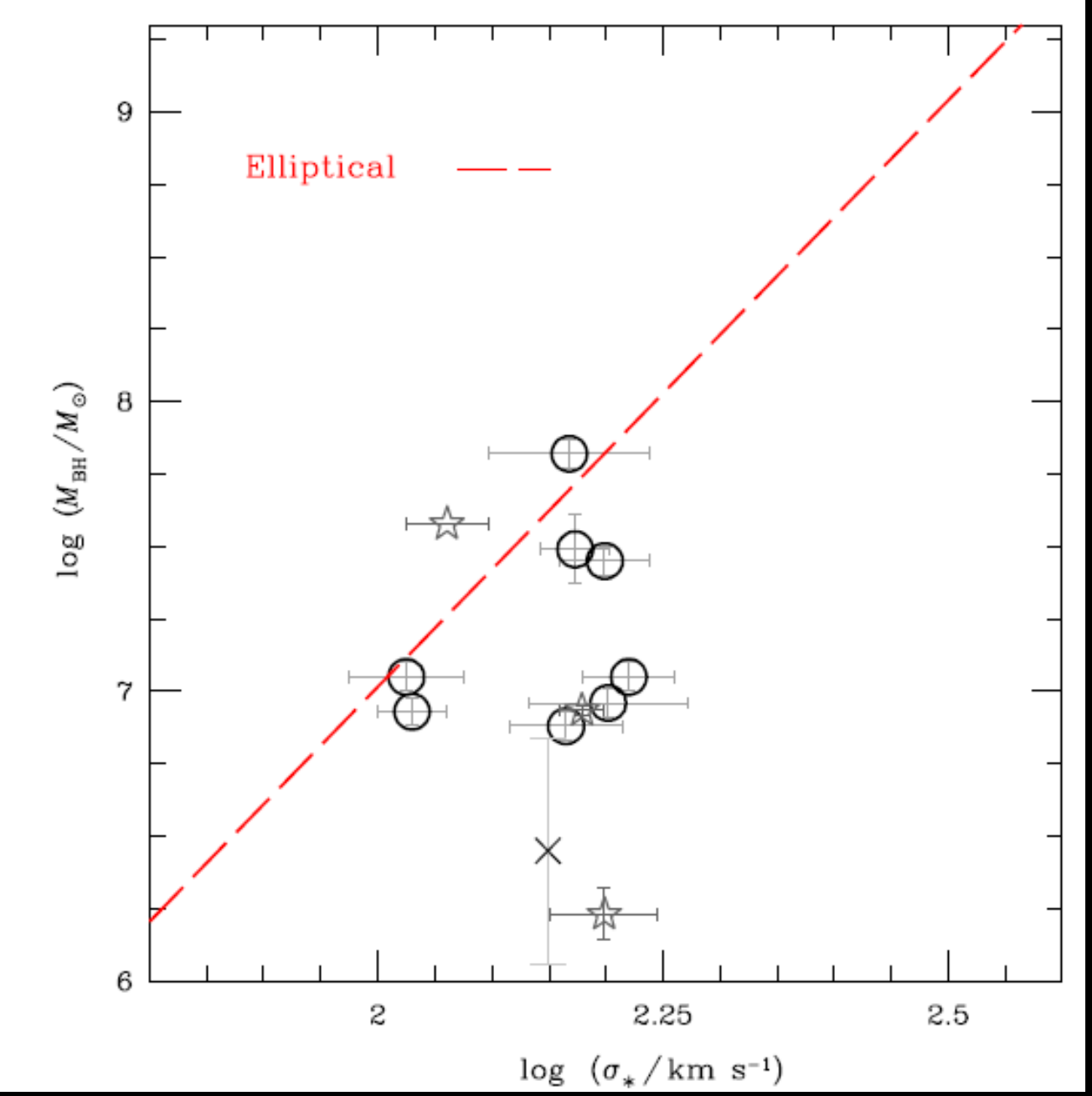


Megamaser galaxies show M_{BH}-masses, which are too small.

Why?

Greene et al. 2010

Urumqi 2016

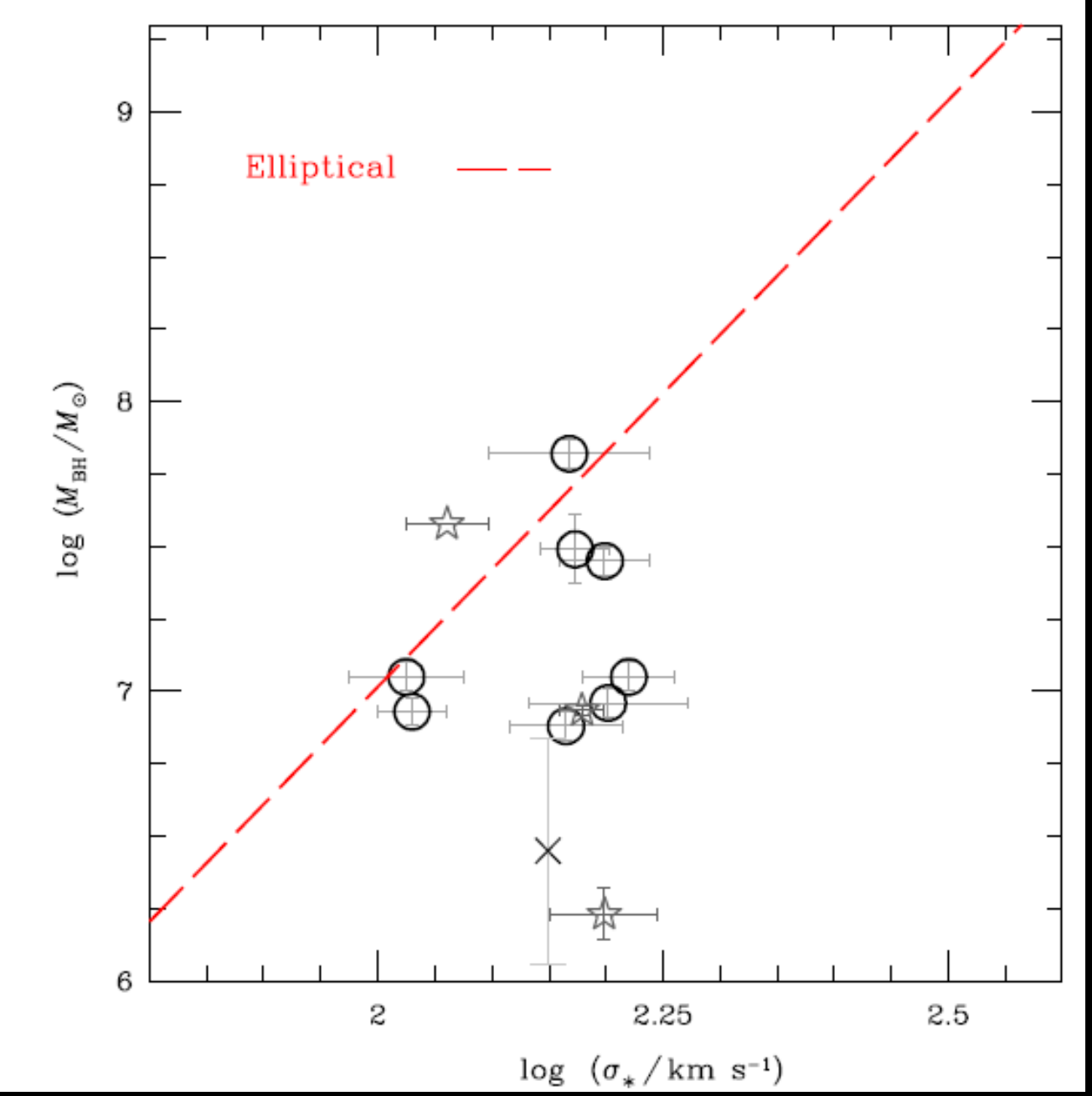


Megamaser galaxies show M_{BH}-masses, which are too small.

Scatter?

Greene et al. 2010

Urumqi 2016

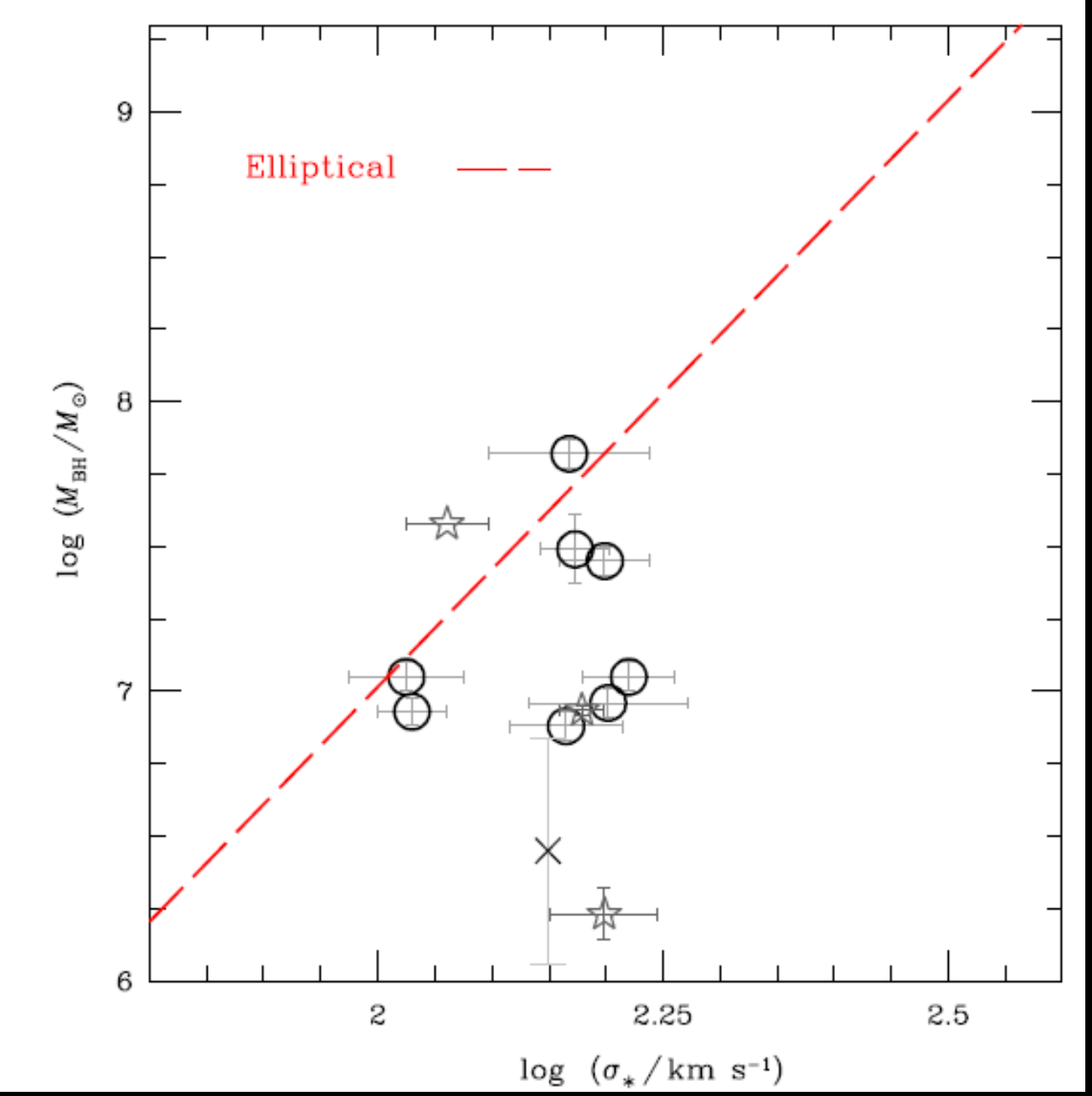


Megamaser galaxies show M_{BH}-masses, which are too small.

Astro-physics ?

Greene et al. 2010

Urumqi 2016

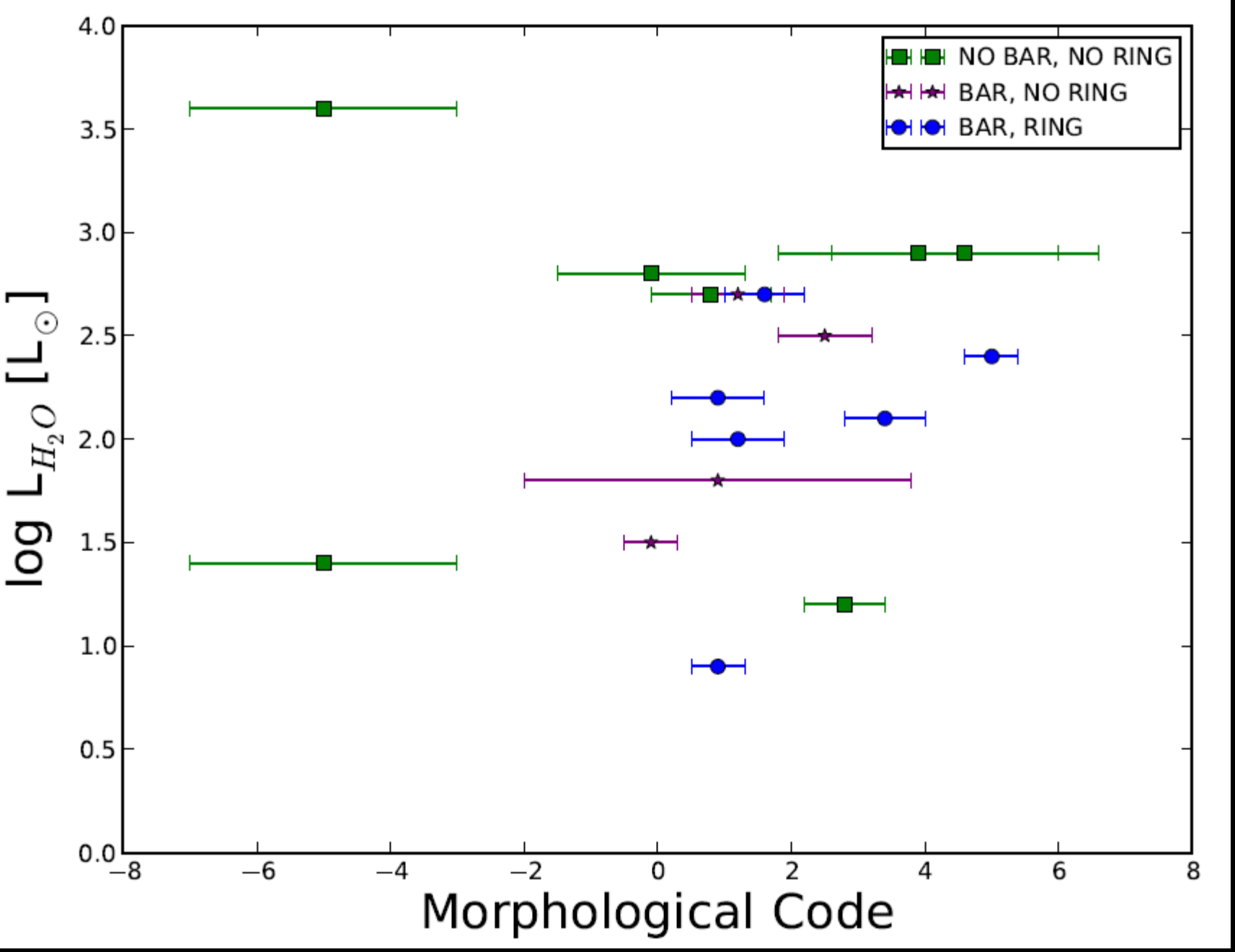


Megamaser galaxies show M_{BH}-masses, which are too small.

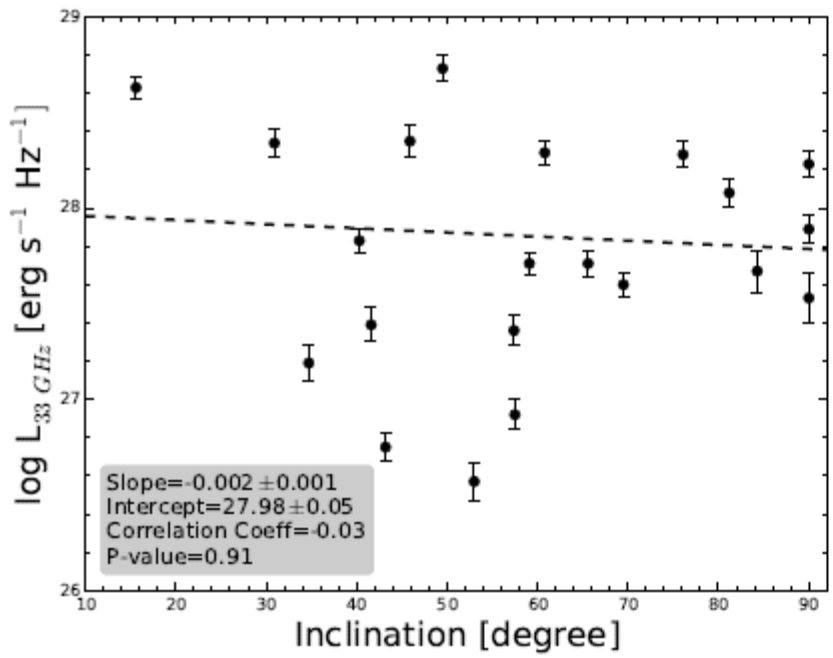
Low number ?

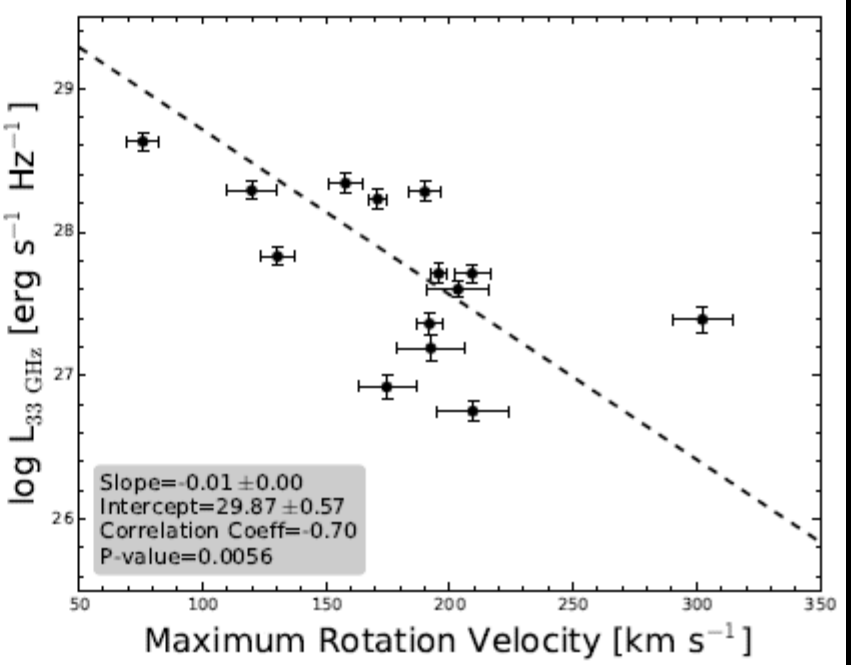
Greene et al. 2010

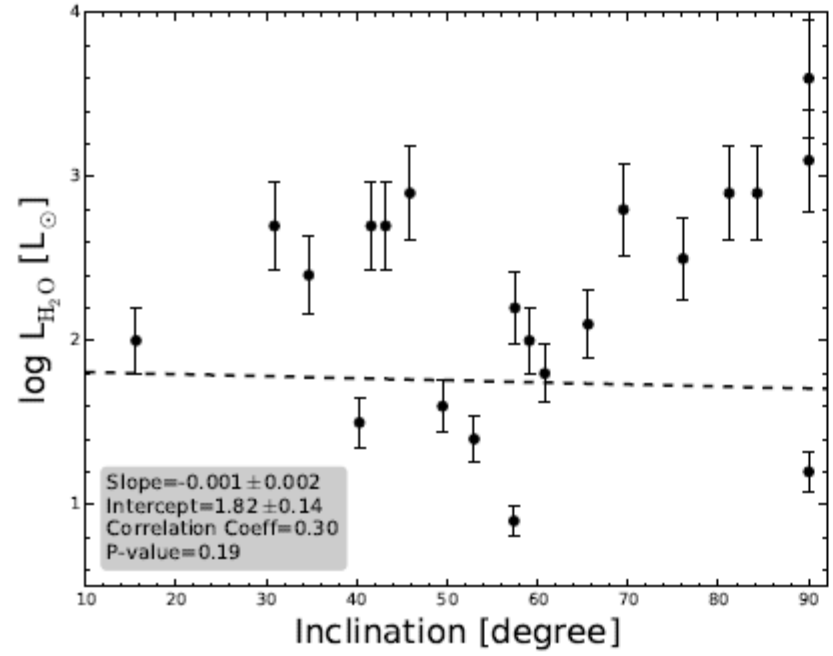
Urumqi 2016

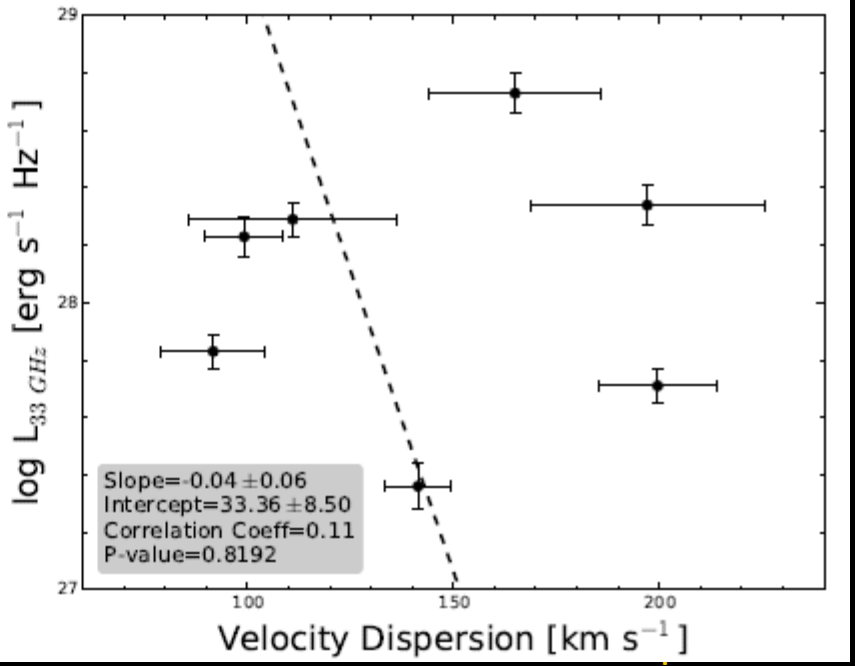

NO BAR, NO RING
BAR, NO RING
BAR, RING
log L_{H_2O} [$L_\odot$]
Morphological Code
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−8
−6
−4
−2
0
2
4
6
8

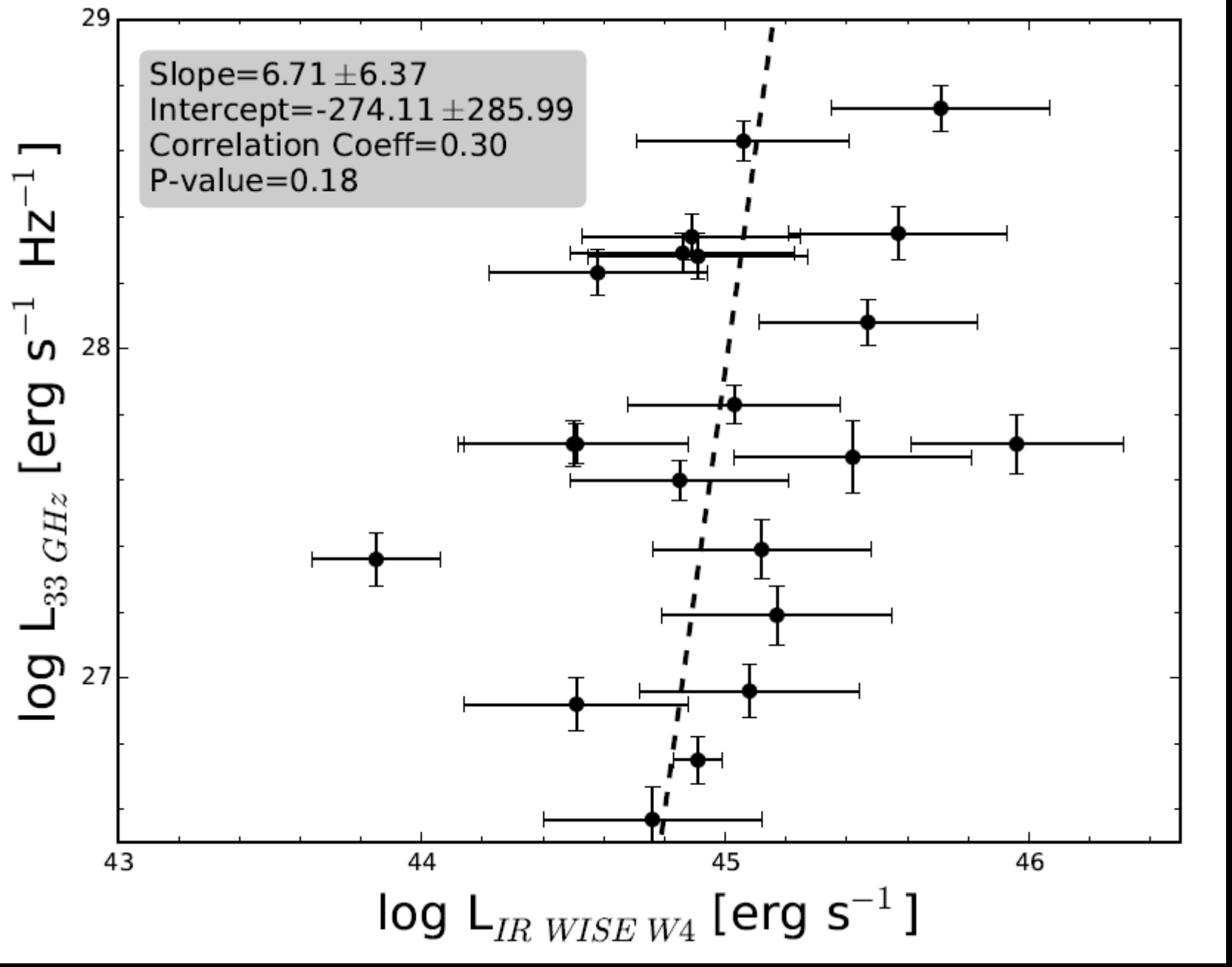
Urumqi 2017

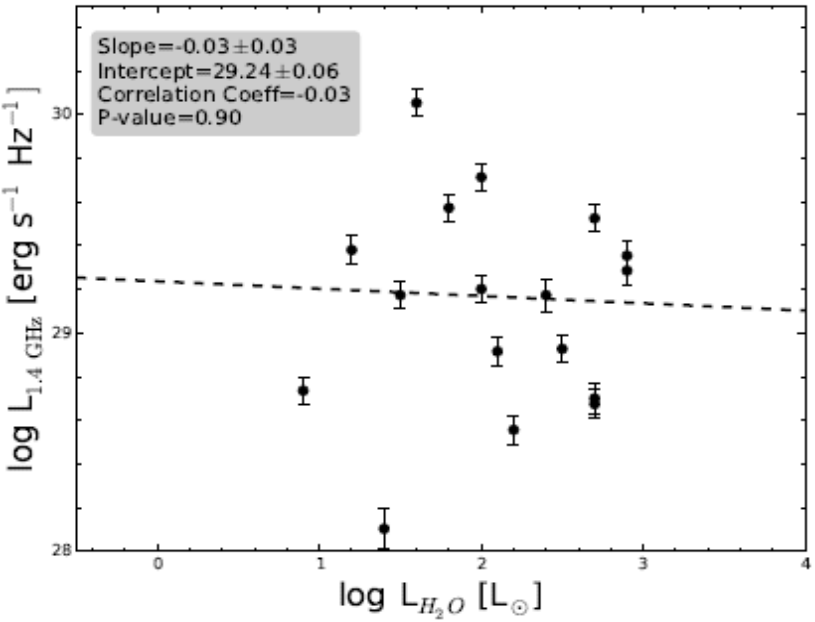

log $L_{33\ GHz}$ [erg s^{-1} Hz^{-1}]
Inclination [degree]
Slope=-0.002 ±0.001
Intercept=27.98 ±0.05
Correlation Coeff=-0.03
P-value=0.91


log $L_{33\ GHz}$ [erg s^{-1} Hz^{-1}]
Maximum Rotation Velocity [km s^{-1}]
Slope=-0.01 ±0.00
Intercept=29.87 ±0.57
Correlation Coeff=-0.70
P-value=0.0056

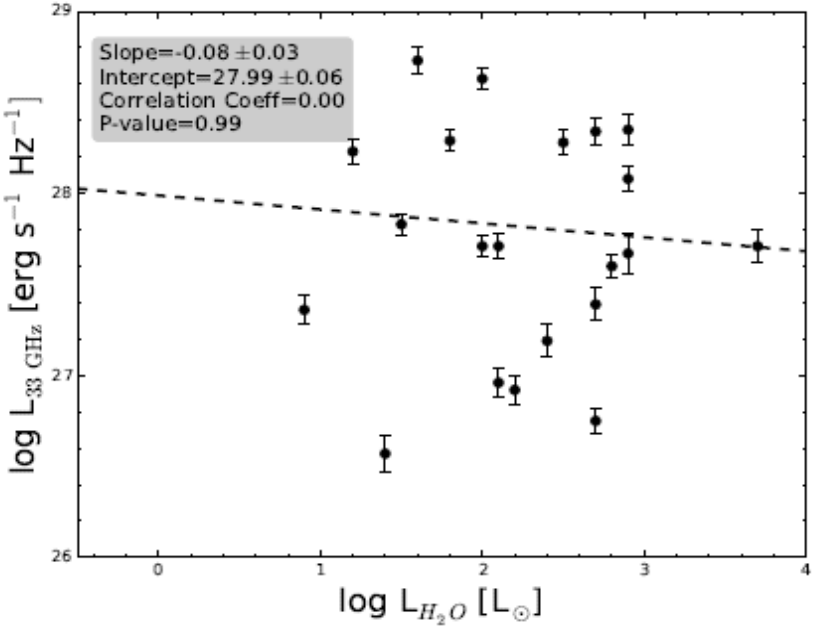

log L_{H_2O} [$L_\odot$]
Inclination [degree]
Slope=-0.001 ±0.002
Intercept=1.82 ±0.14
Correlation Coeff=0.30
P-value=0.19


log $L_{33\ GHz}$ [erg s^{-1} Hz^{-1}]
Velocity Dispersion [km s^{-1}]
Slope=-0.04 ±0.06
Intercept=33.36 ±8.50
Correlation Coeff=0.11
P-value=0.8192

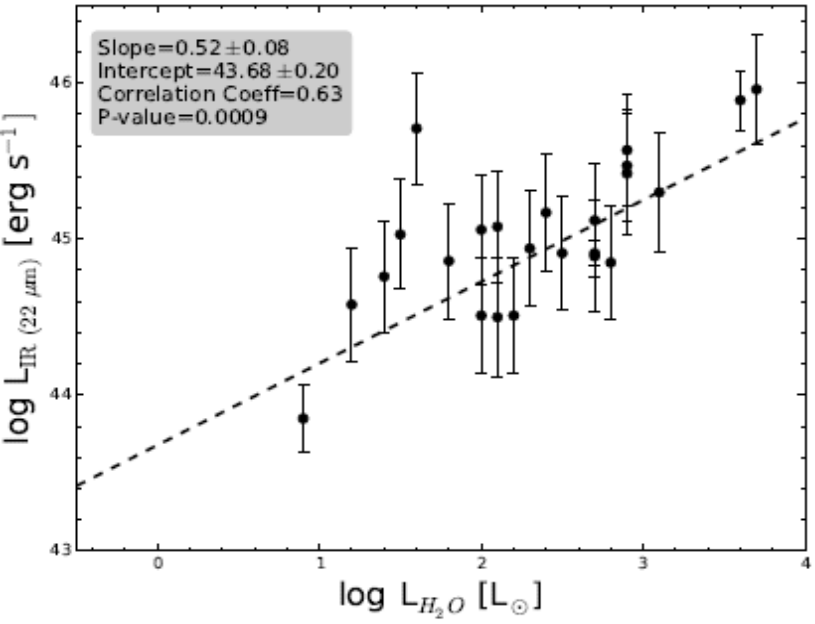

Slope=6.71 ±6.37
Intercept=-274.11 ±285.99
Correlation Coeff=0.30
P-value=0.18
log $L_{33\ GHz}$ [erg s^{-1} Hz^{-1}]
log $L_{IR\ WISE\ W4}$ [erg s^{-1}]
29
28
27
43
44
45
46



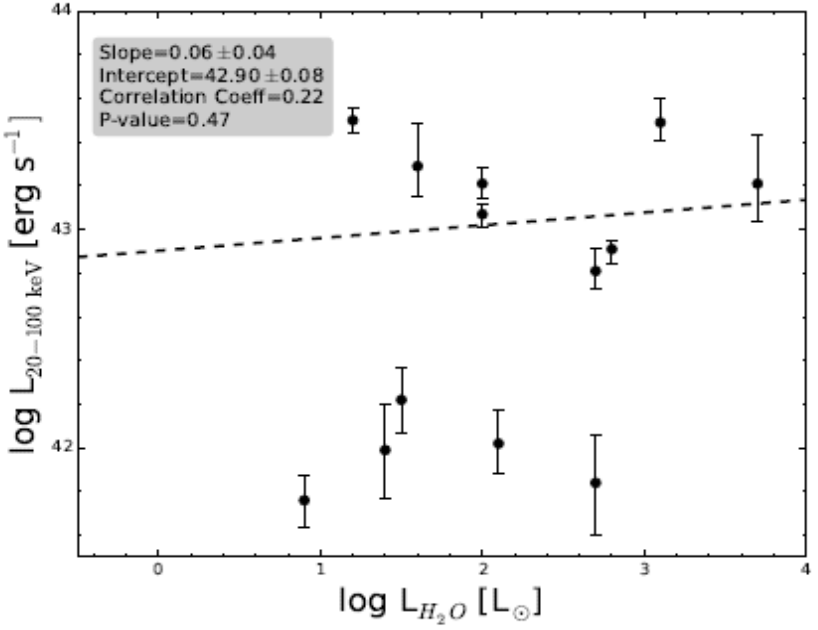
(a) 1.4 GHz continuum luminosity versus H_2O maser luminosity.



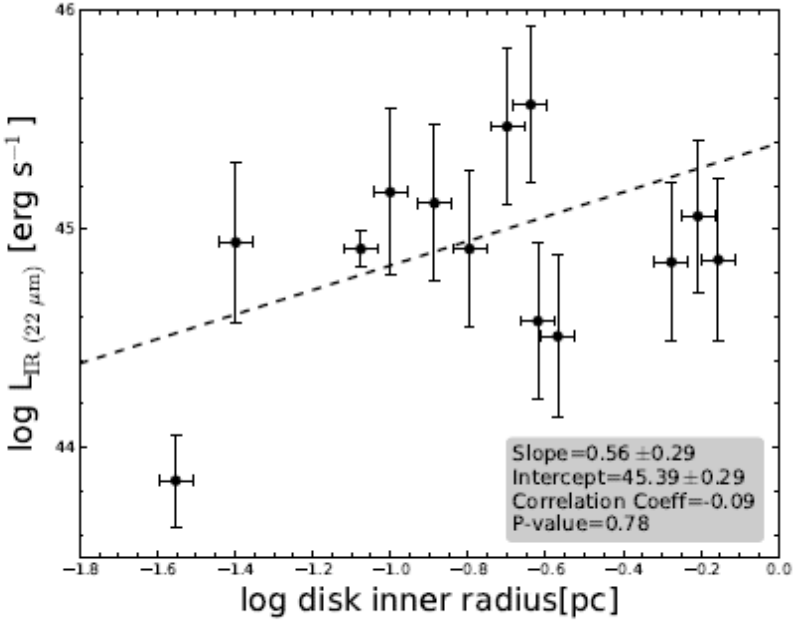
(b) 33 GHz continuum luminosity versus H_2O maser luminosity.



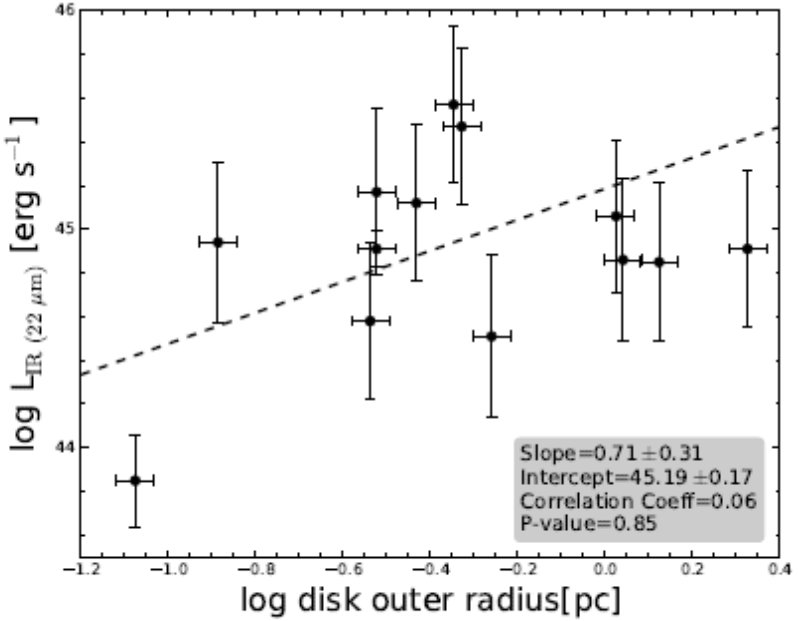
(c) IR luminosity versus H_2O maser luminosity.



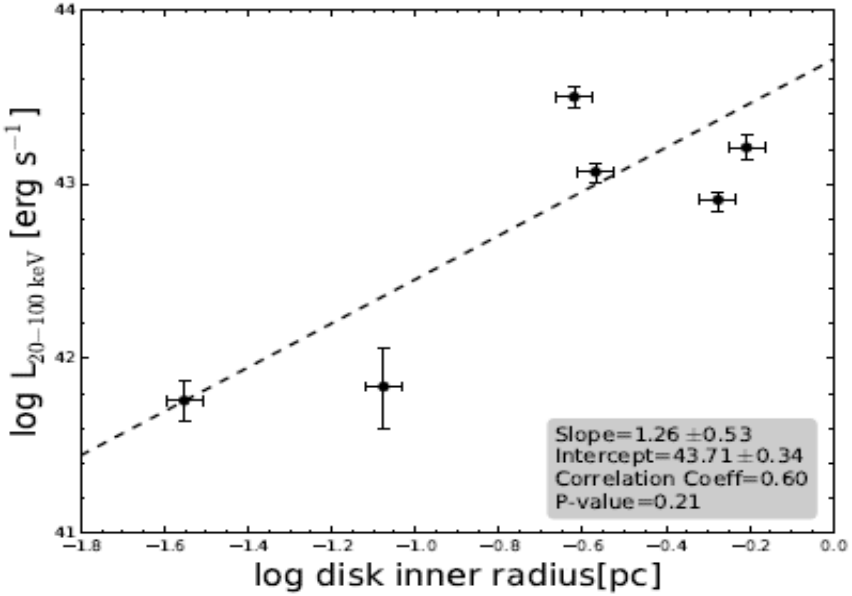
(d) Hard X-ray luminosity versus H_2O maser luminosity.



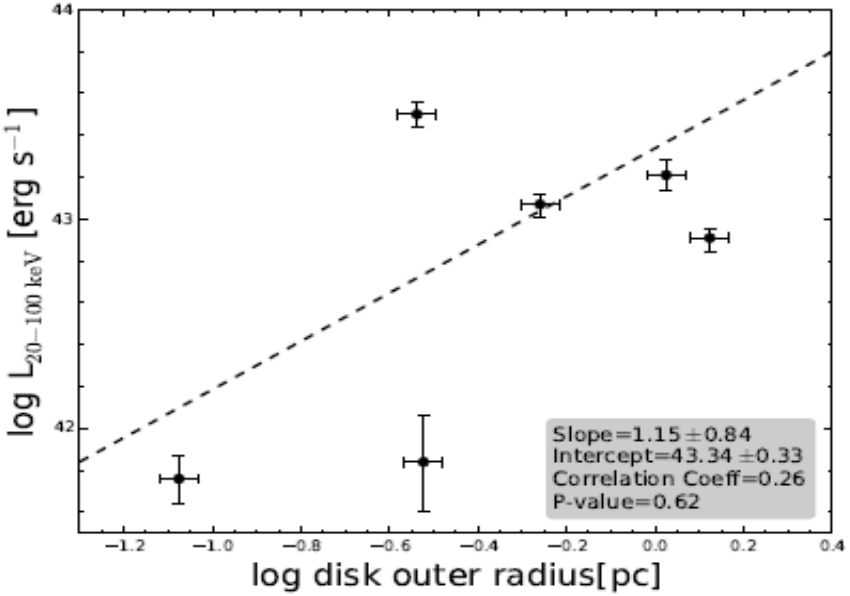
(e) IR luminosity (deduced from WISE 22 μm data) versus maser disk inner radius.



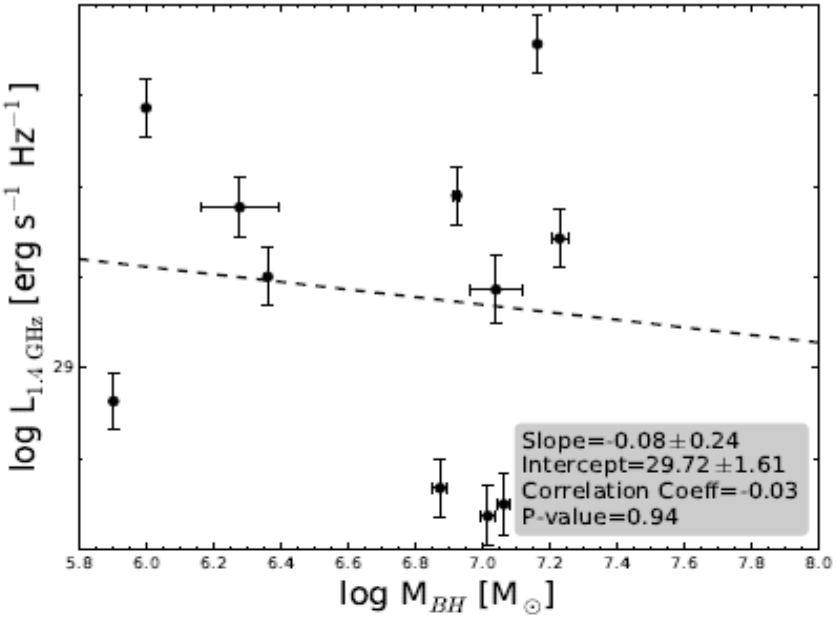
(f) IR luminosity (deduced from WISE 22 μm data) versus maser disk outer radius.



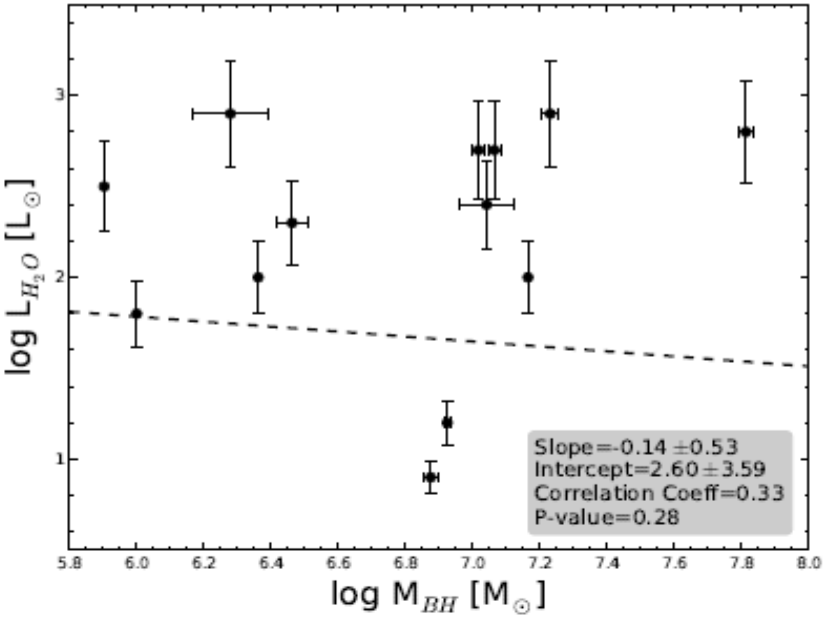
(g) Hard X-ray luminosity versus maser disk inner radius.



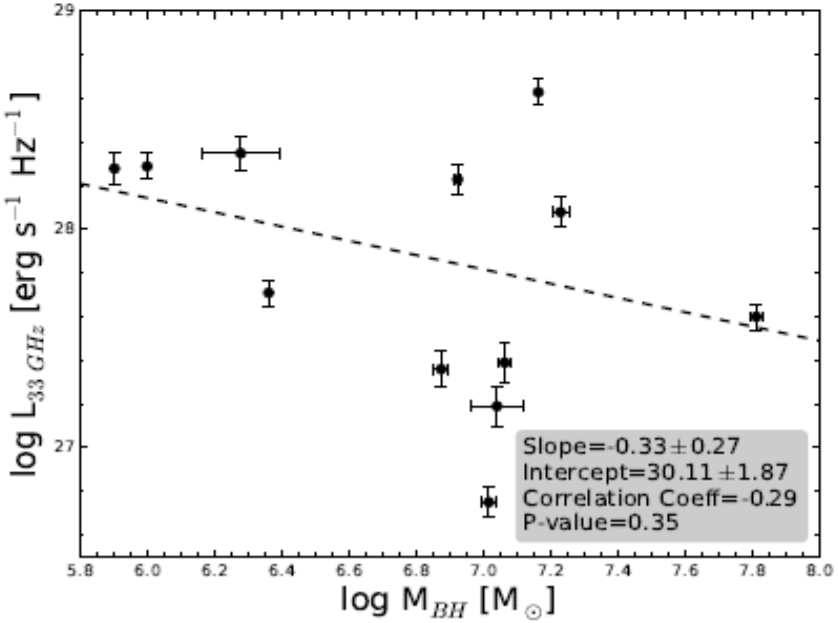
(h) Hard X-ray luminosity versus maser disk outer radius.



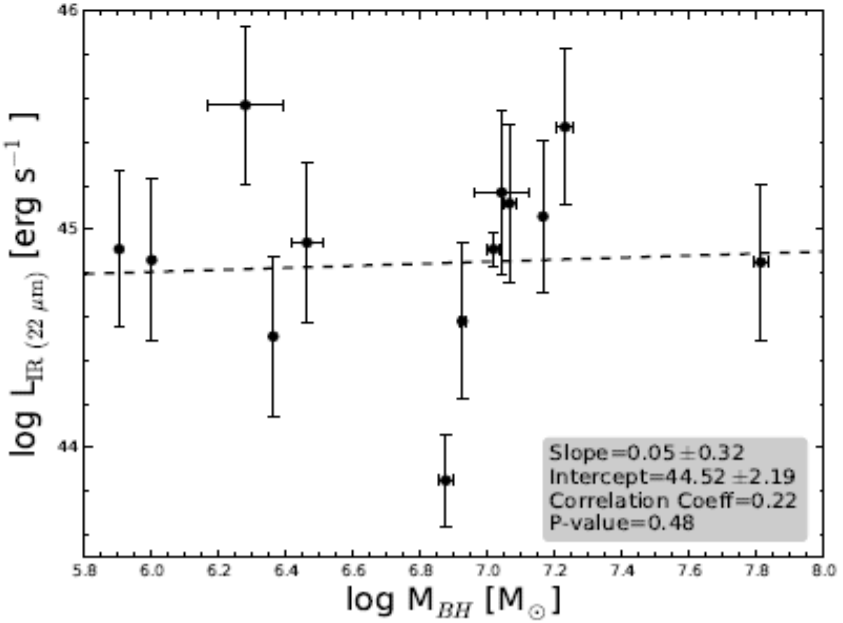
(a) 1.4 GHz luminosity versus black hole mass.



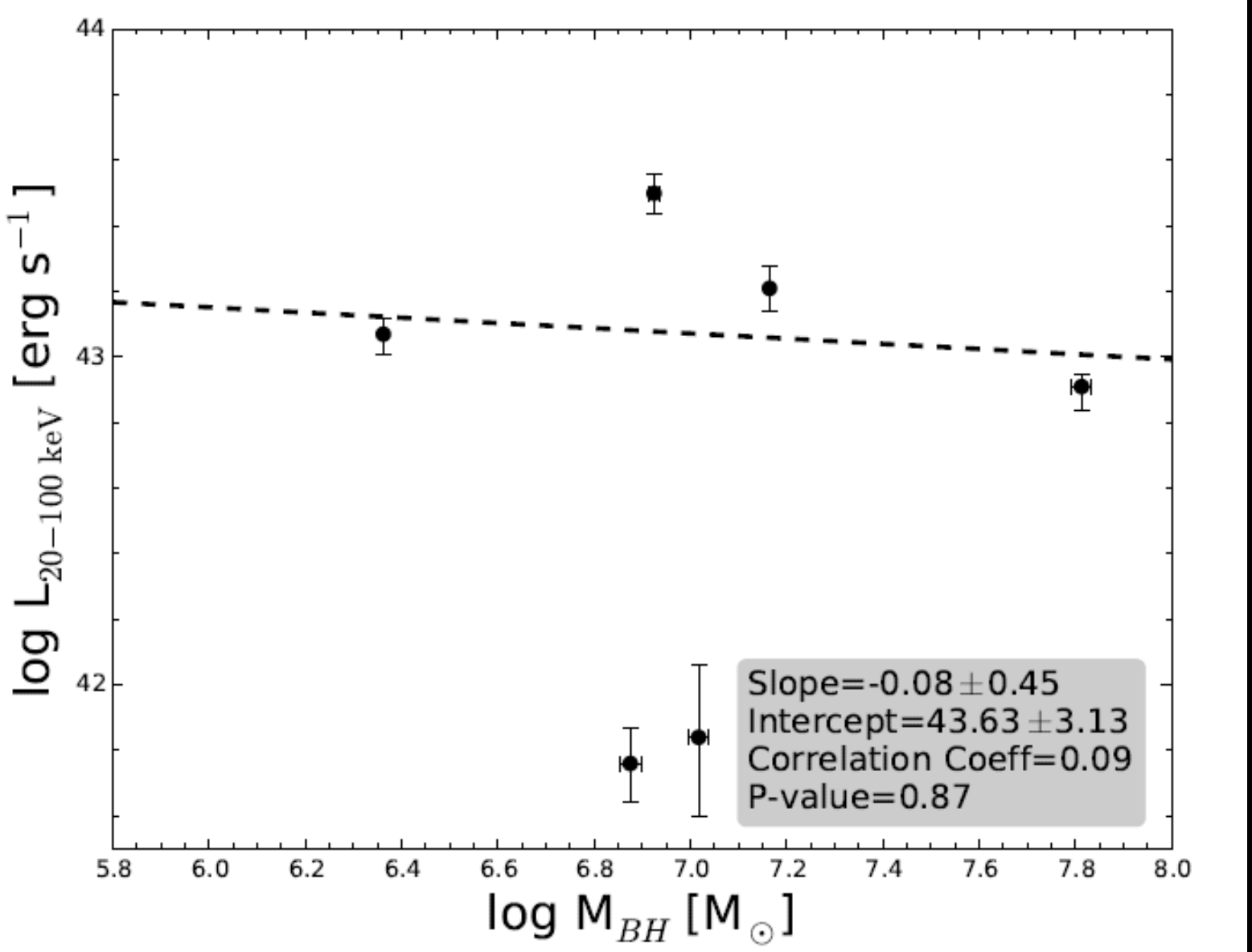
(b) H_2O-maser luminosity versus black hole mass.



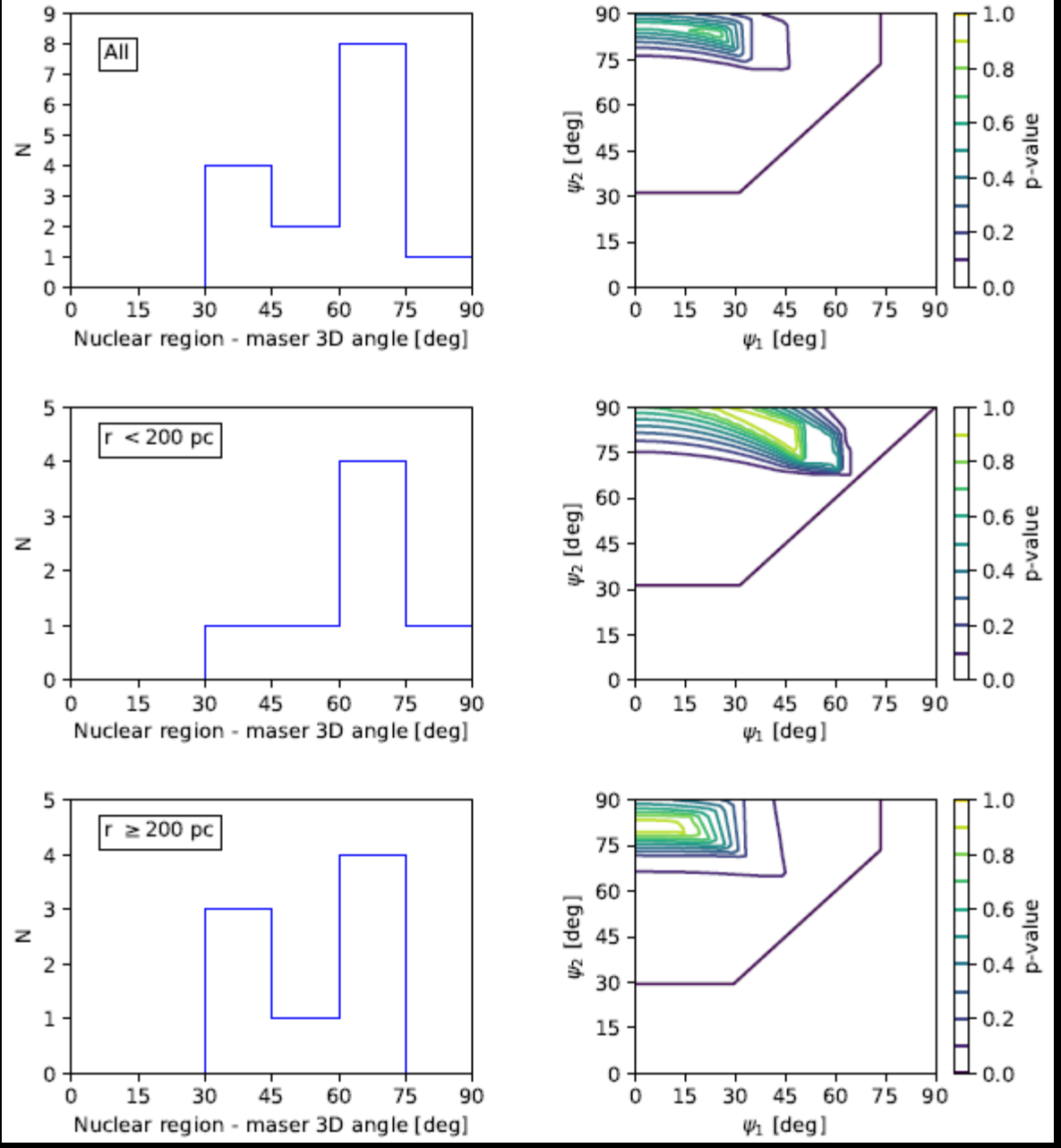
(c) 33 GHz continuum luminosity versus black hole mass.



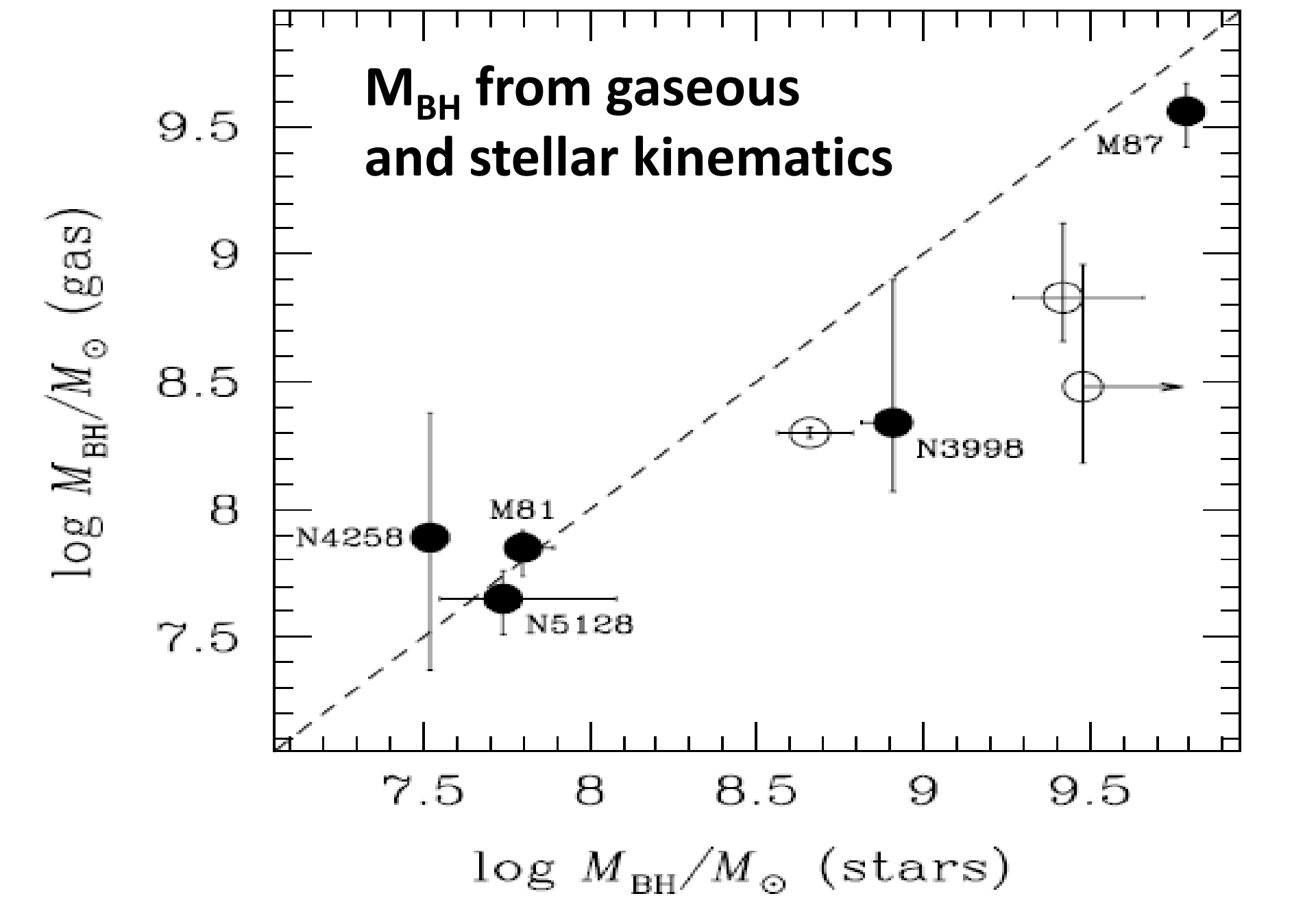
(d) IR luminosity (WISE 22 μm data) versus black hole mass.



(e) Hard X-ray luminosity versus black hole mass.


All
N
Nuclear region - maser 3D angle [deg]
r < 200 pc
N
Nuclear region - maser 3D angle [deg]
r ≥ 200 pc
N
Nuclear region - maser 3D angle [deg]
ψ2 [deg]
ψ1 [deg]
p-value
ψ2 [deg]
ψ1 [deg]
p-value
ψ2 [deg]
ψ1 [deg]
p-value

Urumqi 2017



Kormendy & Ho 2013

Urumqi 2016

Results

Potential reasons:

Results

Potential reasons:

1) **Unlike in high z interactions, there is less gas available near z = 0, yielding only insignificant fueling of the central monster.**

Results

Potential reasons:

1) Unlike in high z interactions, there is less gas available near z = 0, yielding only insignificant fueling of the central monster.
2) One of the progenitor BHs has not yet reached the center.

Results

Potential reasons:

1) Unlike in high z interactions, there is less gas available near z = 0, yielding only insignificant fueling of the central monster.
2) One of the progenitor BHs has not yet reached the center.
3) A mere statistical accident?

2 sources: H_2O megamasers – see below

Results

High z: Do nuclear engines grow faster than their parent galaxies?

Results

High z: Do nuclear engines grow faster than their parent galaxies?

Observational bias?

Results

High z: Do nuclear engines grow faster than their parent galaxies?

Observational bias?

Did the BH masses reach almost peak values early on due to gas-rich mergers while subsequent dry, minor mergers mainly increased the stellar mass by factors of 2–4 at z = 2 to 0?

Results

High z: Do nuclear engines grow faster than their parent galaxies?

Observational bias?

Submillimeter galaxies (SMGs) appear, however, to have underdeveloped nuclear engines. Apparently, gas-rich mergers reverse this in the end.

Virial theorem:

$$M_{core} = 1.12\ V_{rot}^2\ R\ D$$

(M in M . , V_{rot} in km/s, R in mas; D in Mpc).

VLBI maps provide V_{rot} as a function of R. With a Keplerian rotation curve:

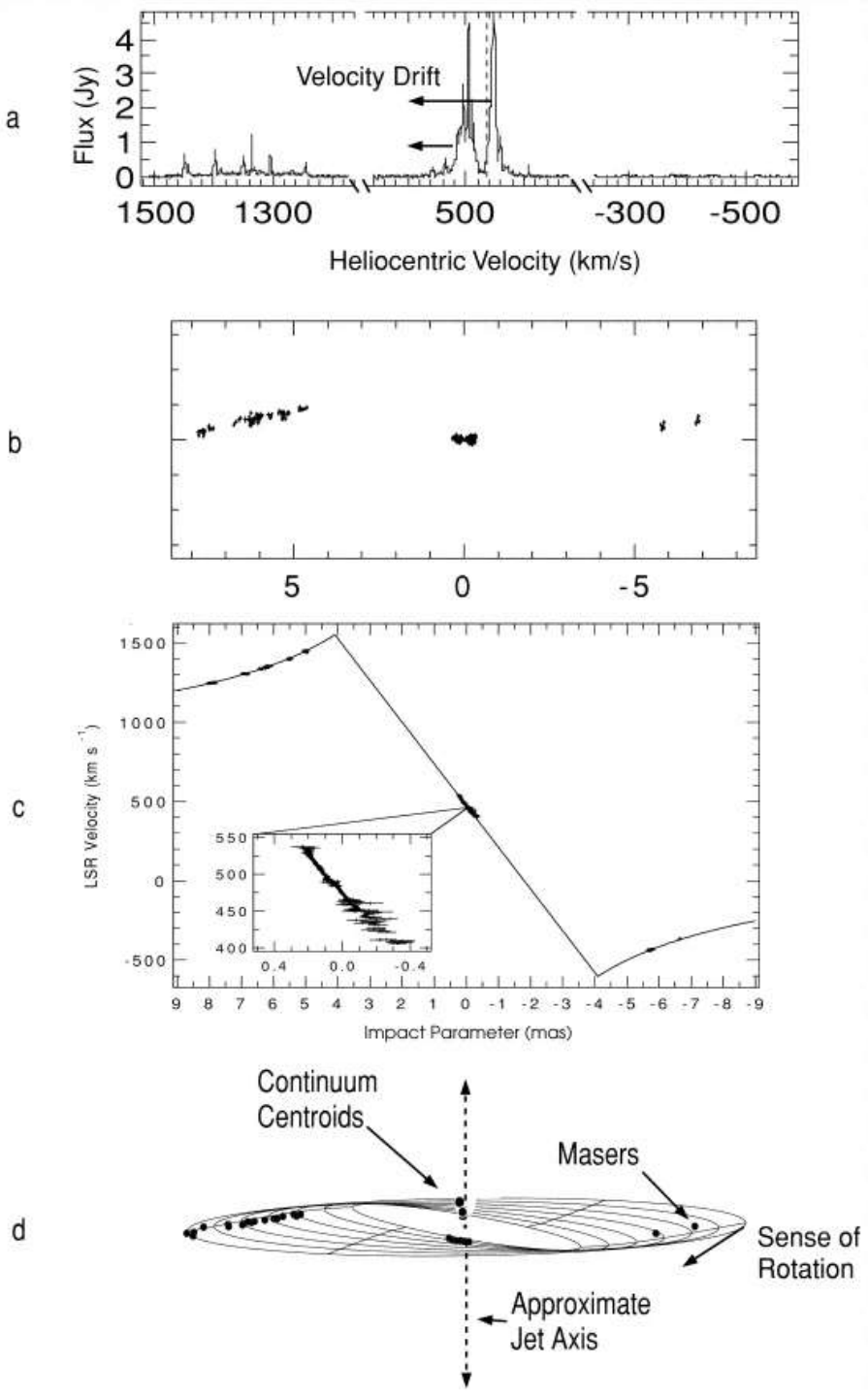
$$C_1 = V_{rot}\ \ R^{1/2}.`$$

From the E-W velocity gradient of the systemic features:

$$C_2 = V_{rot}\ \ R^{-1}.$$

$$C_1/C_2 = R^{3/2}$$

then gives the angular radius R_s of the systemic features as viewed from a direction in the plane of the disk, but perpendicular to the line of sight.



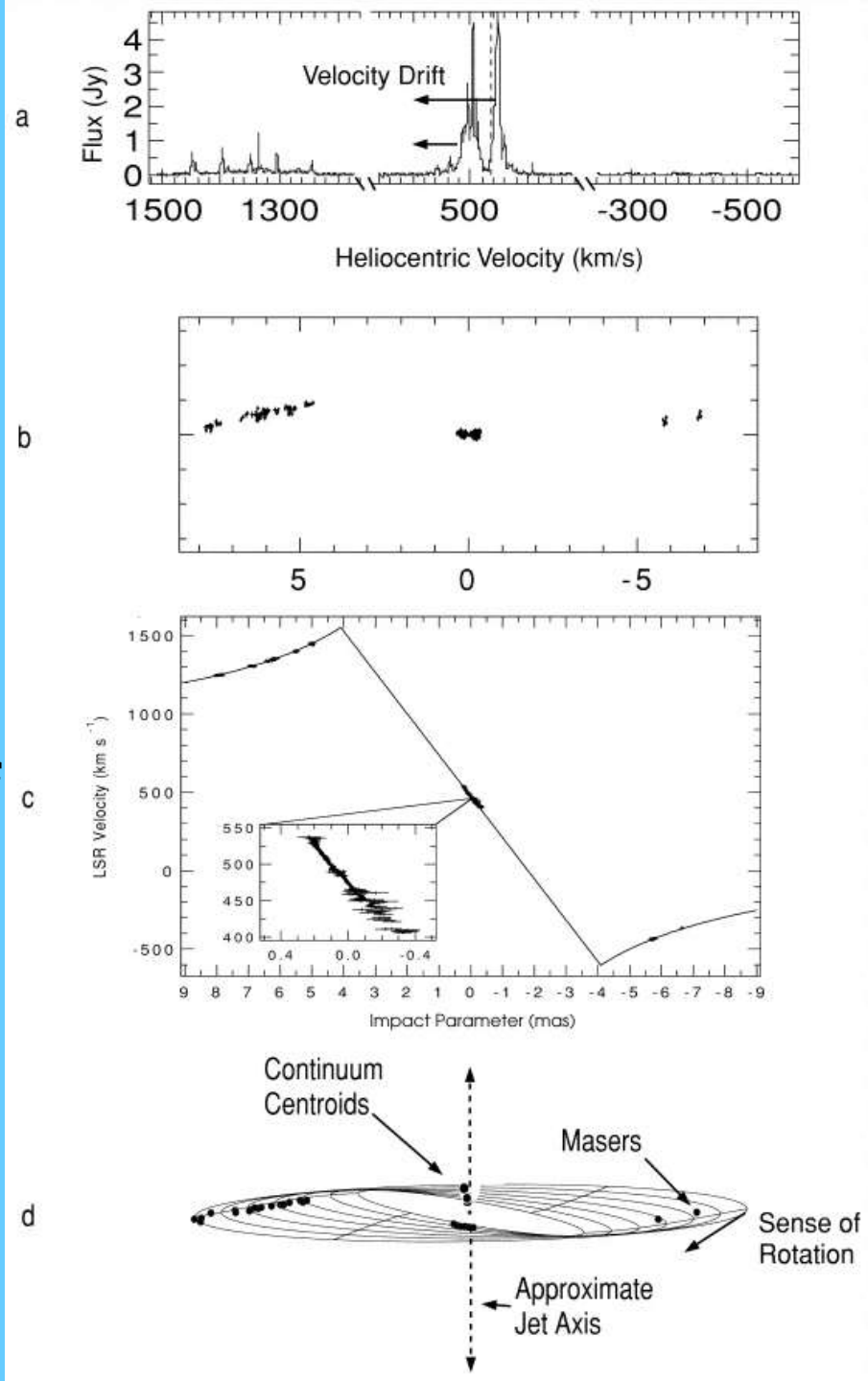
The distance, needed to estimate M_{core} is determined by measuring the centripetal acceleration

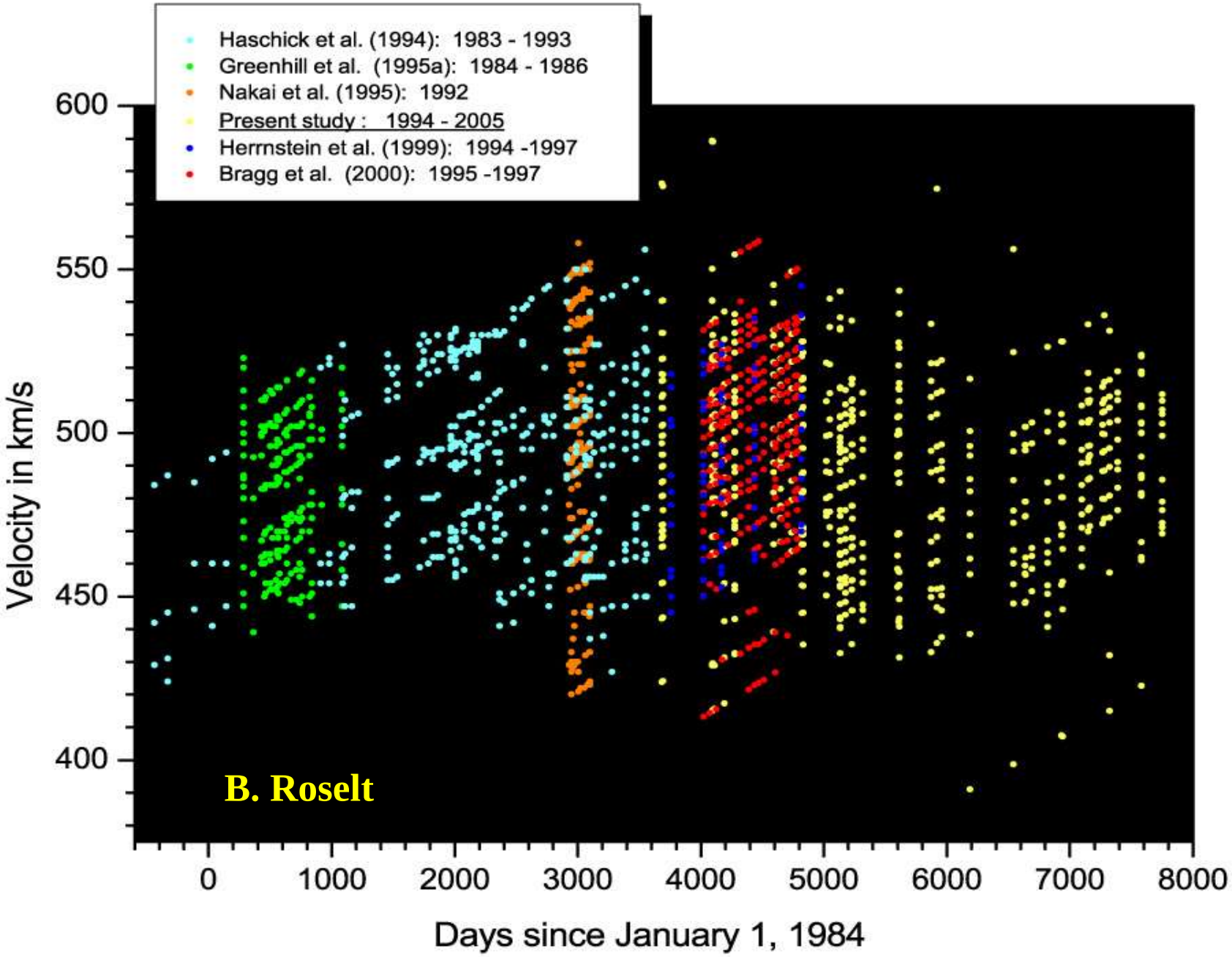
$$dV_s/dt = V_{rot}^2/r_s = 9.3 \pm 0.3 \text{ km/s/yr},$$

with r_s denoting the linear, not angular radius of the systemic features.

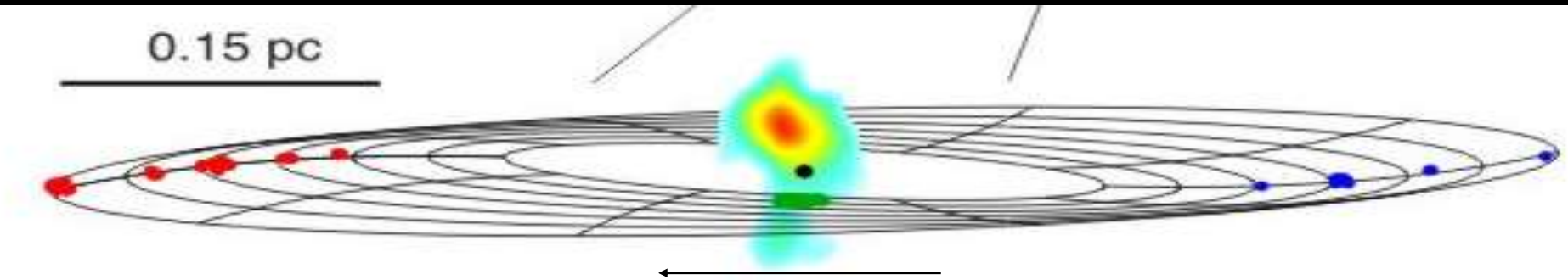
R_s and r_s directly provide a measure of D. Proper motions of the systemic maser spots, can be used to check the estimate.

With r_s, V_{rot} , and D the enclosed mass can also be determined.



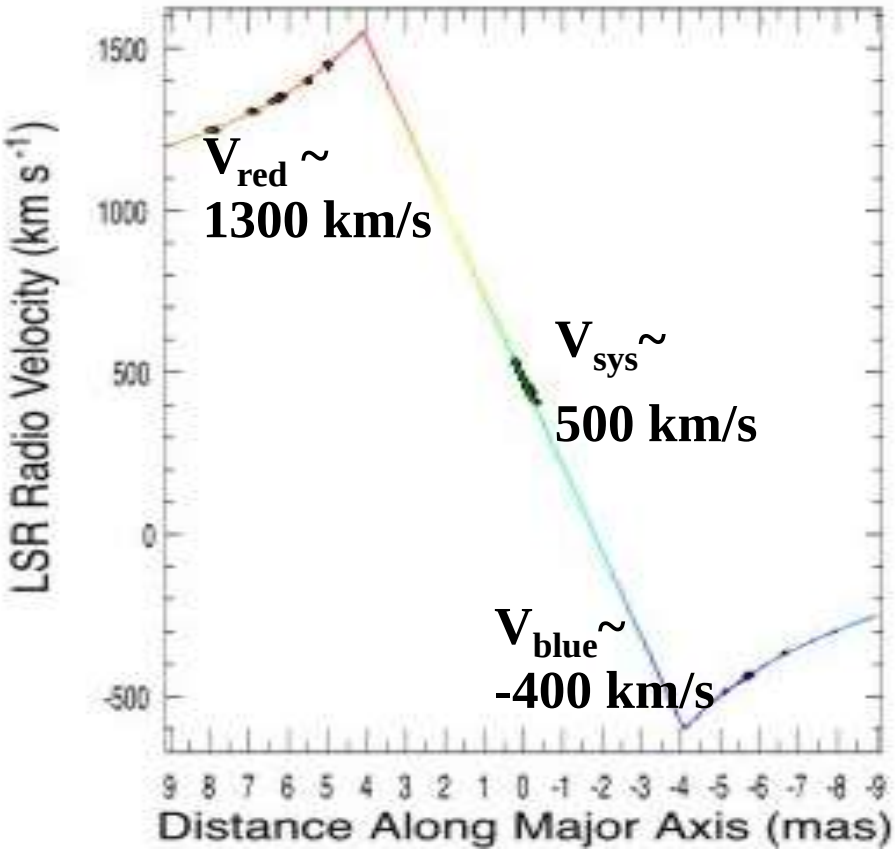

Haschick et al. (1994): 1983 - 1993
Greenhill et al. (1995a): 1984 - 1986
Nakai et al. (1995): 1992
Present study : 1994 - 2005
Herrnstein et al. (1999): 1994 -1997
Bragg et al. (2000): 1995 -1997
600
550
500
450
400
Velocity in km/s
0
1000
2000
3000
4000
5000
6000
7000
8000
Days since January 1, 1984
B. Roselt

Measuring Distances to H_2O Megamasers

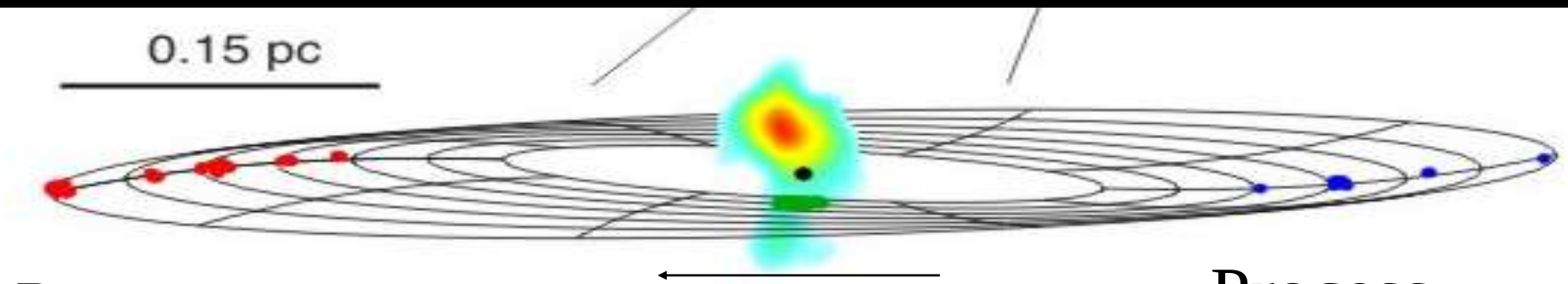


Process

1) Linear size from single-dish disk kinematics (acceleration + velocity spread) and VLBI mapping (rotation curve).

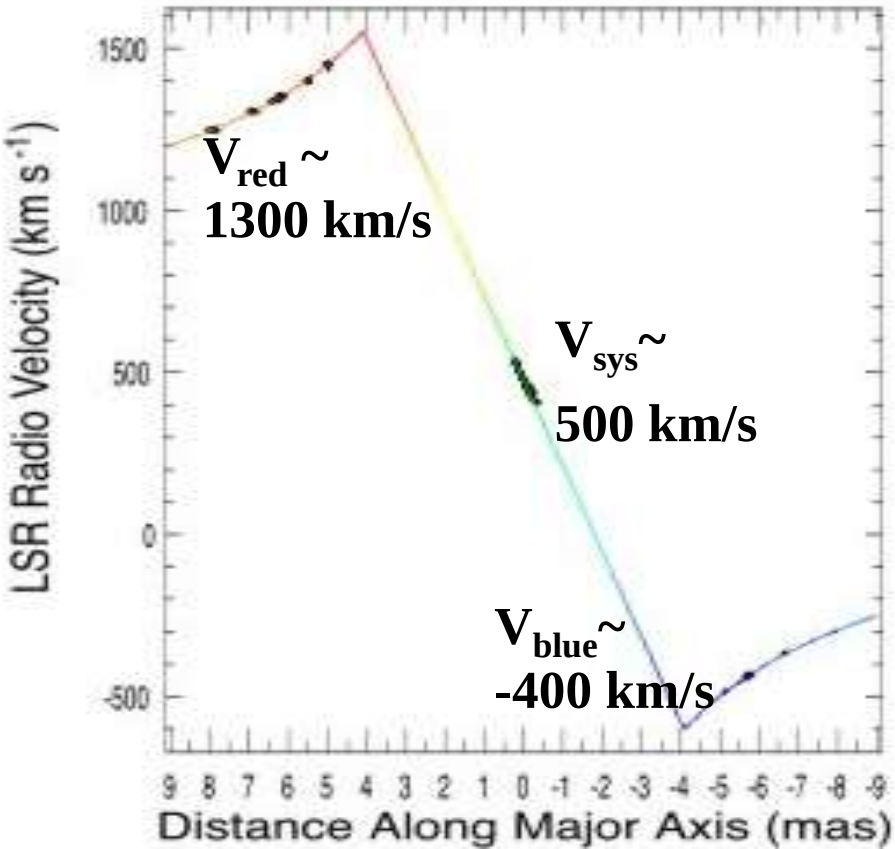


Measuring Distances to H_2O Megamasers



Process

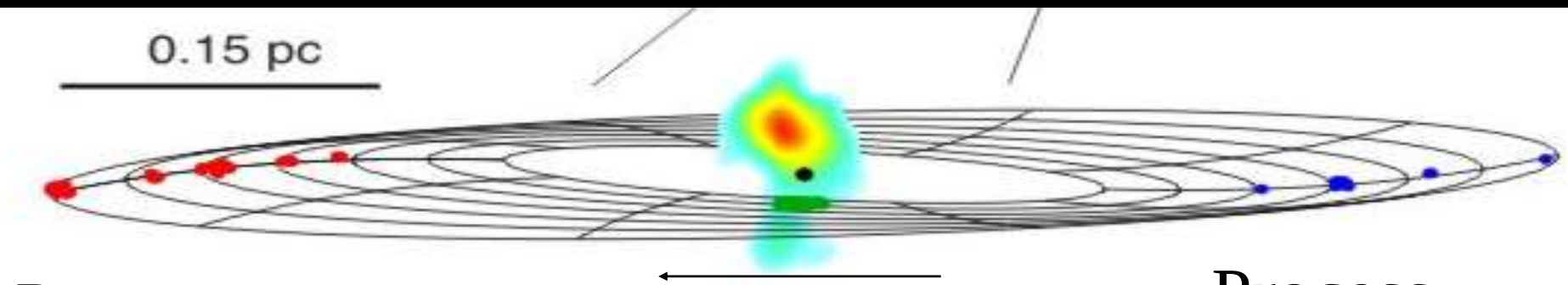
1) Linear size from single-dish disk kinematics (acceleration + velocity spread) and VLBI mapping (rotation curve).



Process

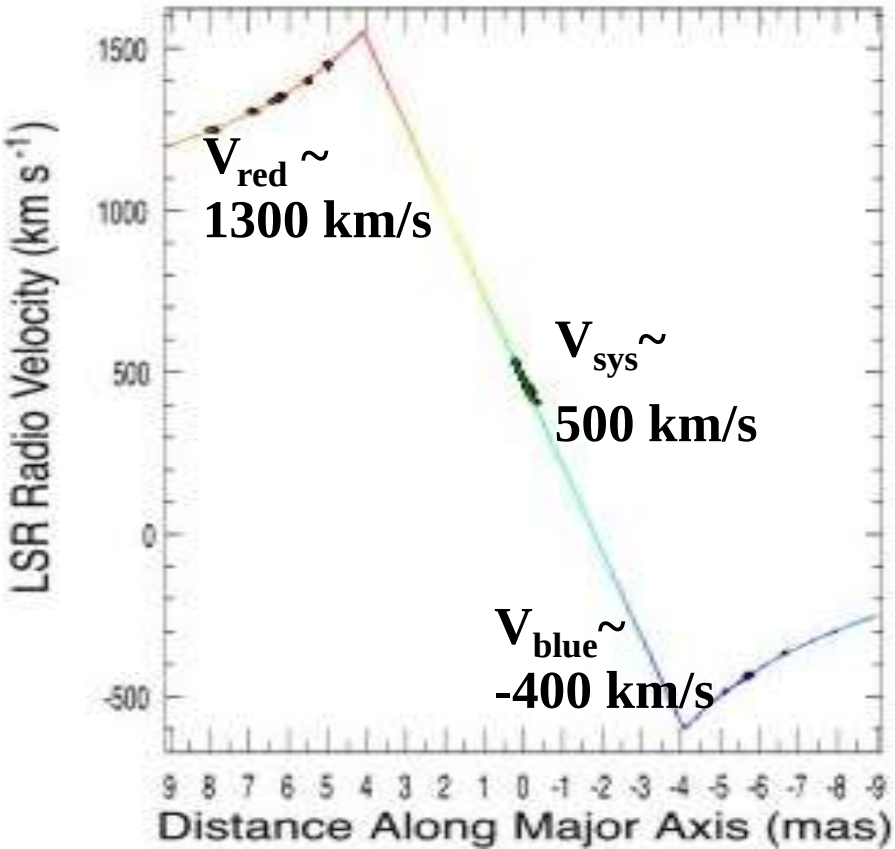
2) Compare angular size of disk with linear size and rotation velocity with proper motion

Measuring Distances to H_2O Megamasers



Process

1) Linear size from single-dish disk kinematics (acceleration) and VLBI mapping (rotation curve).



Process

2) Compare angular size of disk with linear size and/or rotation velocity with proper motion

Goal

10+ distances to determine H_0 with better than 3% uncertainty.

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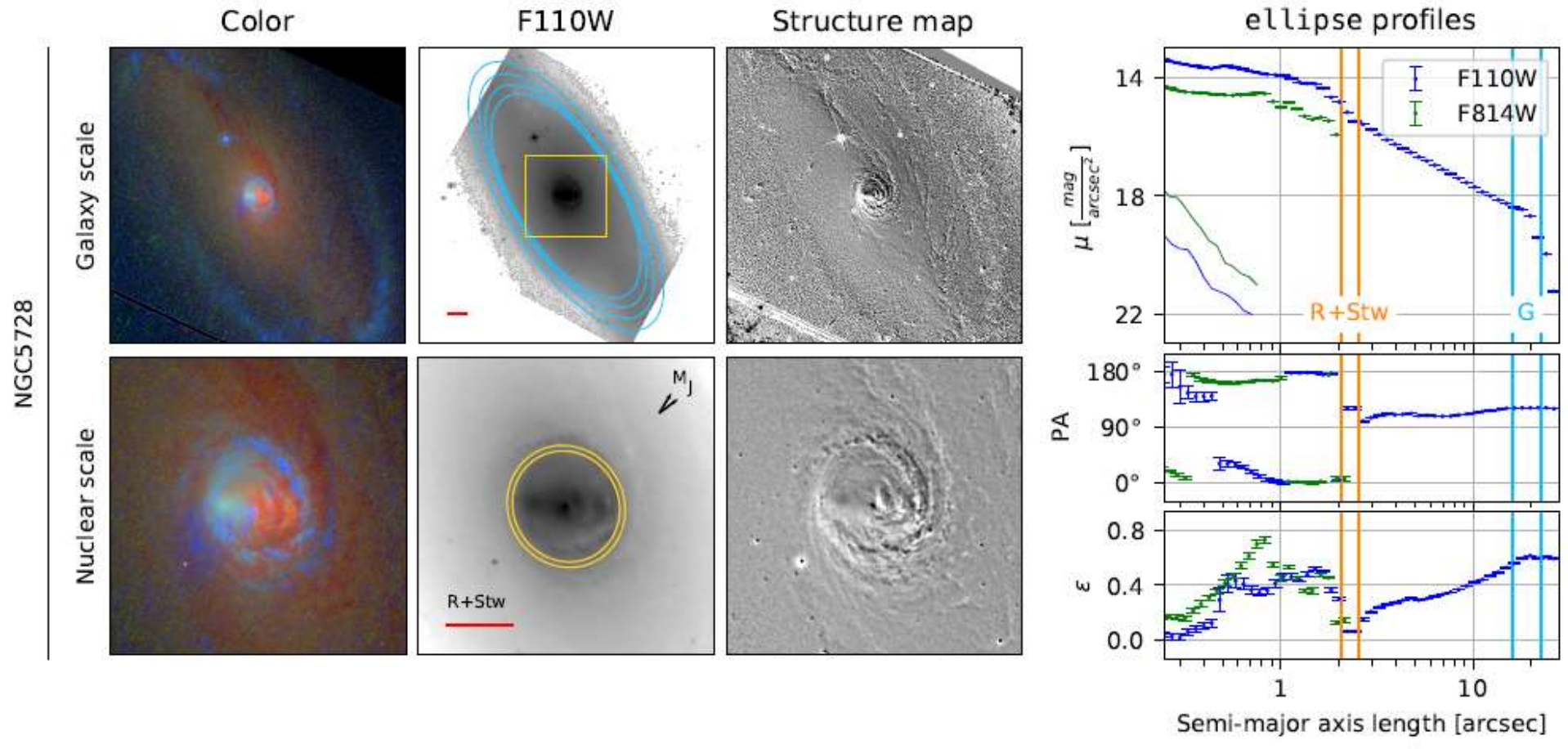

Blue: F335W
Green: F438W
Red: F814W

Size of lower image

M: Orientation of maser disk

Red bar: 1 kpc

For small scale features like dust lanes

Blue and orange vertical lines limit ranges of ellipse major axes to extract galaxy orientation as a whole

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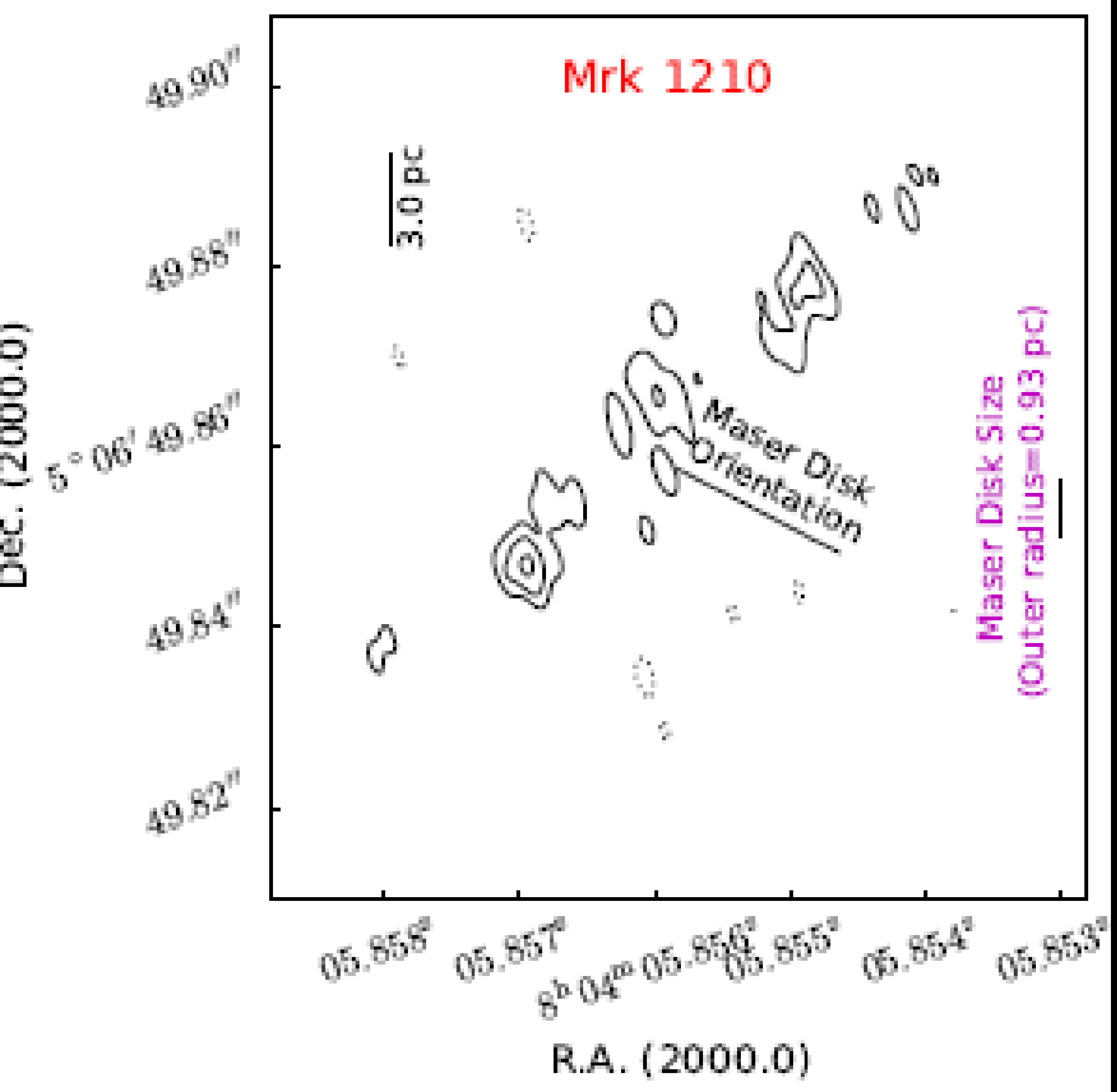
Mrk 1210
3.0 pc
Maser Disk Orientation
Maser Disk Size
(Outer radius=0.93 pc)
49.90"
49.88"
49.86"
49.84"
49.82"
5° 06'
Dec. (2000.0)
05.858s
05.857s
8h 04m 05.856s
05.855s
05.854s
05.853s
R.A. (2000.0)

Urumqi 2017

1. From Largest to Smallest Scales

a) Orientation of entire galaxy to the masing disk: random.

b) Nuclear regions likely increasingly mis-aligned from large scale disk as their scale decreases. Below 200 pc likely completely misaligned.

c) Orientation of 200 pc region to maser disk consistent with random.