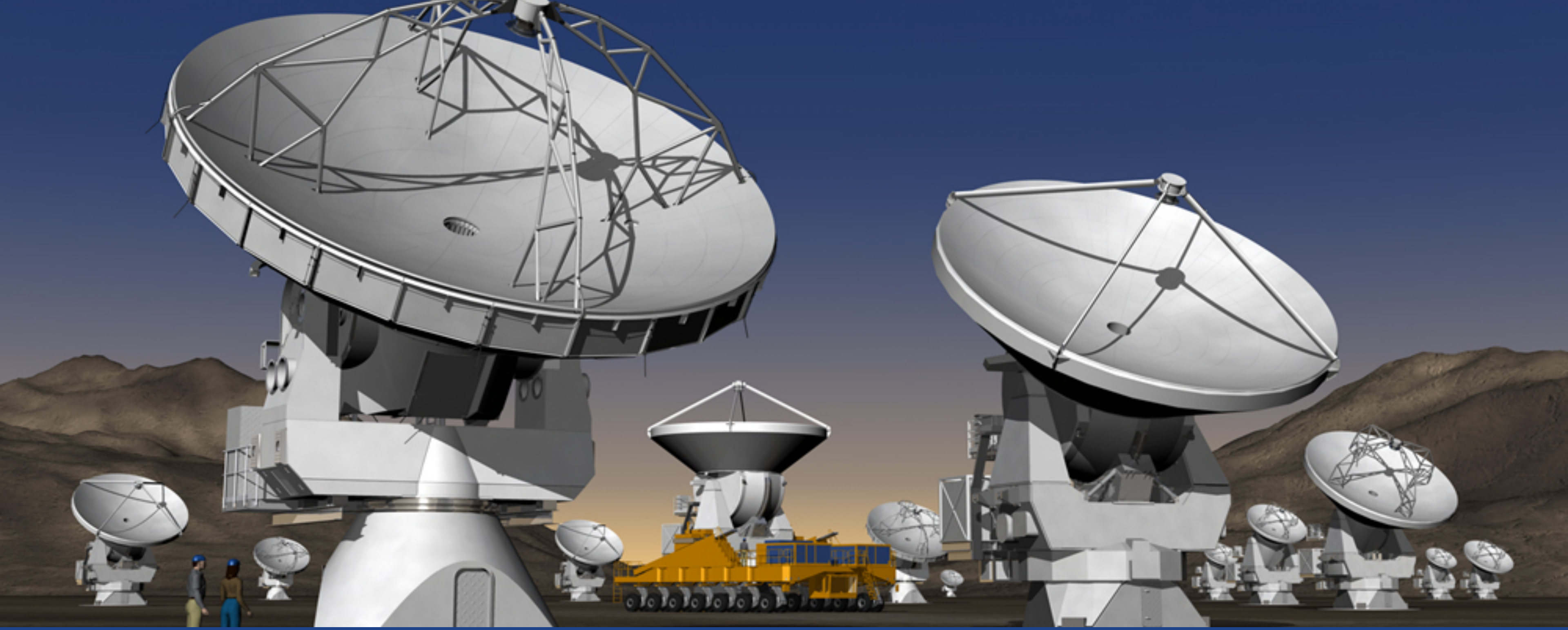

Extragalactic Masers with ALMA and mmVLBI

Liz Humphreys

European ALMA Regional Centre (ESO)

EUROPEAN ARC
ALMA Regional Centre

Mm VLBI Network

- 3mm to 0.85mm (100 to 345 GHz)
- 11 μas at 345 GHz (Krichbaum 2008)

Table 1: Properties of Radio Telescopes suitable for VLBI at $\nu = 230\,\mathrm{GHz}$ and above

Station	Location	Country	Altitude [m]	D [m]	Surface [μm]	Eff.	SEFD[1] [Jy]	H-maser
PdB-1	Plateau de Bure	France	2550	15	55	0.45	5182	yes
PdB	Plateau de Bure	France	2550	6x15	55	0.45	864	yes
PV	Pico Veleta	Spain	2900	30	67	0.39	1485	yes
APEX	Chajnantor	Chile	5100	12	18	0.58	6295	no
HHT	Mt. Graham	AZ, USA	3100	10	15	0.59	8979	yes
KP	Kitt Peak	AZ, USA	2000	12	75	0.35	10322	no
JCMT	Mauna Kea	HI, USA	4100	15	25	0.57	4141	yes[c]
CSO	Mauna Kea	HI, USA	4100	10	25	0.57	8618	yes[c]
SMA	Mauna Kea	HI, USA	4100	8x6	12	0.59	3093	yes
Hawai-6	Mauna Kea	HI, USA	4100	[a]	25	0.57	1696	yes[c]
CARMA-1	Cedar Flat	CA, USA	2200	10.4	60	0.43	11373	yes
CARMA	Cedar Flat	CA, USA	2200	[b]	60	0.43	1142	yes
LMT	Sierra Negra	Mexico	4600	50	70	0.38	556	no
ALMA-1	Chajnantor	Chile	5000	12	25	0.57	6469	no
ALMA	Chajnantor	Chile	5000	50x12	25	0.57	129	no

Extragalactic Maser (cm) Environments

- **Active Galactic Nuclei**
  - disk and/or jet origin
  - AGN physics, galaxy evolution
  - Maser cosmology, independent H_0
- **Starbursts**
- **Galactic Analog Star-forming Regions**
  - Water masers in e.g. Antennae (Brogan et al. 2010)
  - Submm hydrogen maser (? M82; Seaquist et al. 1996)
  - Methanol – variation in fundamental constants
- **AGB Stars & Red Supergiants**
  - SiO, H_2O OH masers in the LMC (van Loon et al.)
  - 2 O-rich AGB-stars associated with dwarf-galaxy tidal tails (Deguchi et al. 2007)
  - Effect of metallicity on stellar evolution

Extragalactic Maser (cm) Environments

- **Active Galactic Nuclei**
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- **Galactic Analog Star-forming Regions – Goddi talk**
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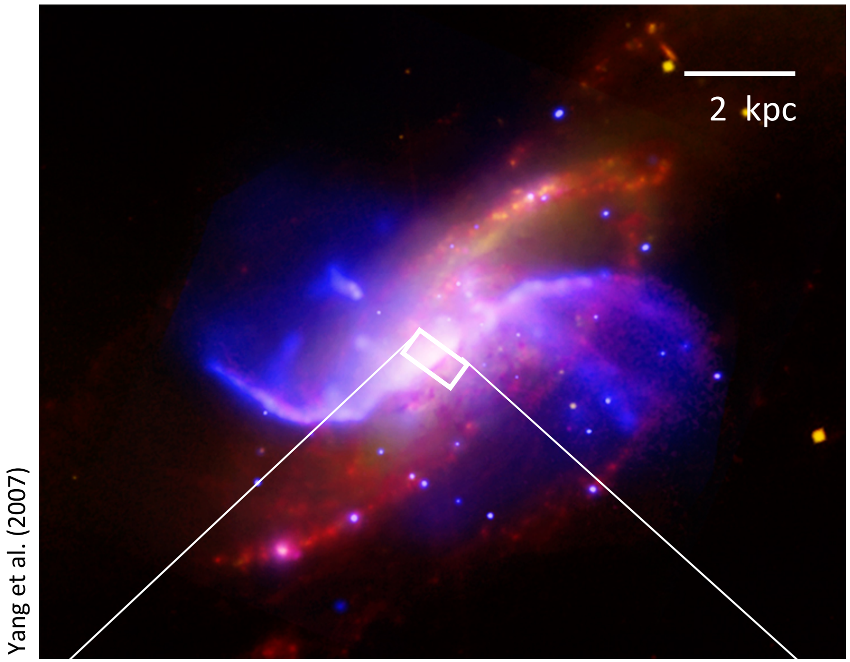
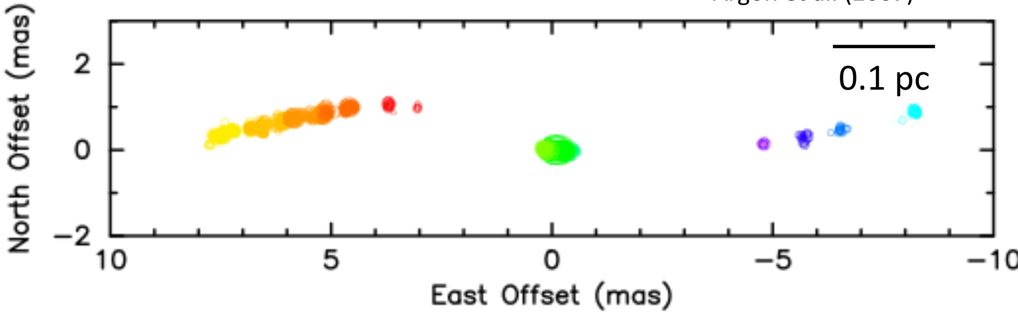
  - Effect of metallicity on stellar evolution

Active Galaxies and Nuclear H_2O Masers

NGC 4258

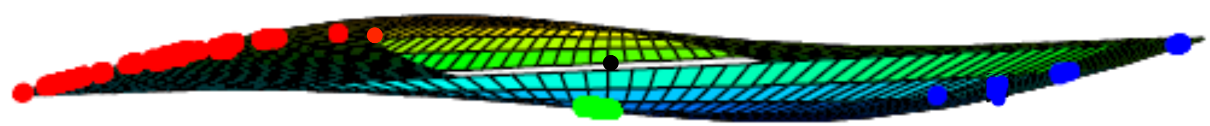


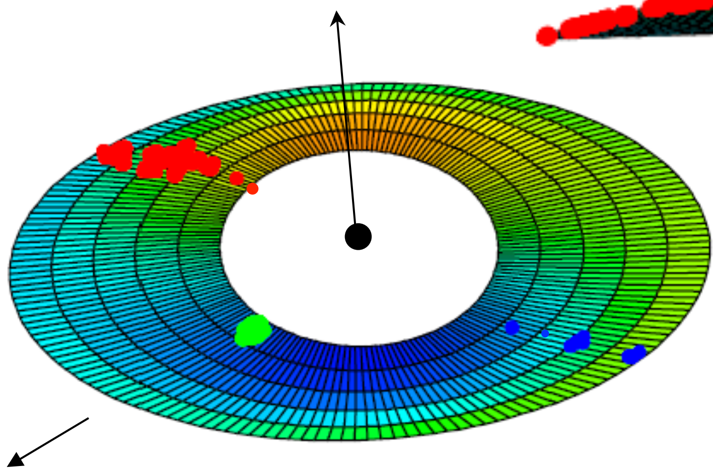
Argon et al. (2007)

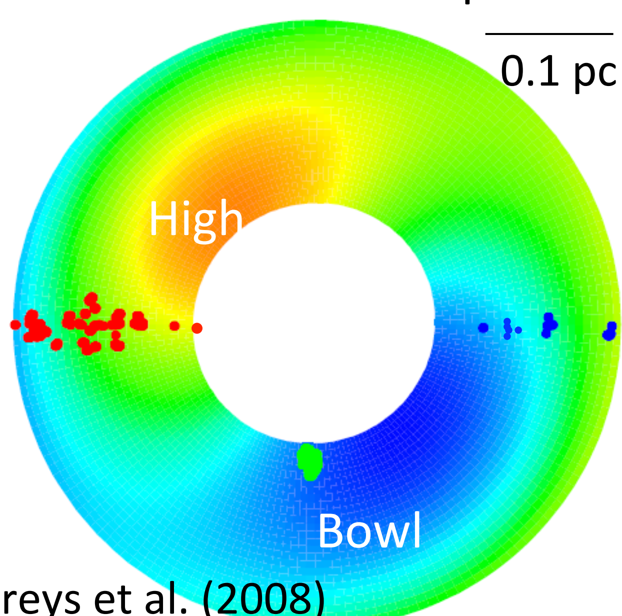


- 22 GHz water masers in AGN central engines
  - **Nuclear disks (r<1 pc)**
  - **Jet/ISM interactions (r<10 pc)**
- >100 water maser galaxies now detected via the *Water Maser Cosmology Project*
  - **Hubble Flow, D=50 - 200 Mpc**
  - **Gravitationally-lensed maser from MG J0414+0534 z=2.64 (Impellizzeri et al. 2009)**
- Only current way to map the structure of AGN nuclear disks
  - **distances, warping, AGN unified model, dynamical masses, spiral structure**

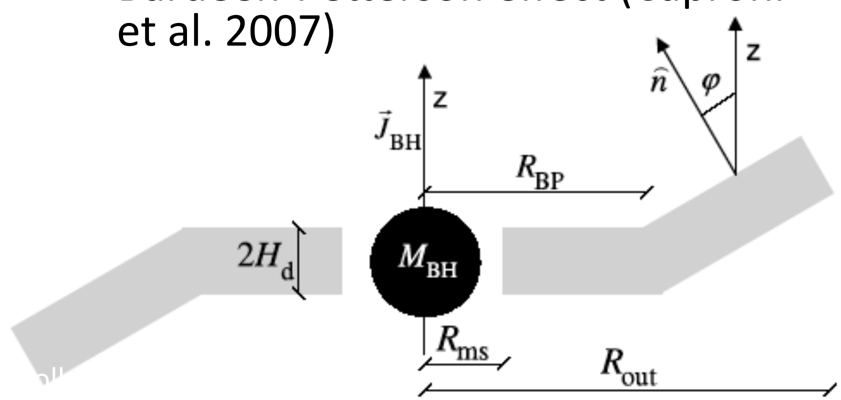
Disk Modelling







- Inclination & warp (flattening of high velocity rotation curve): 8° across reds. At 7.4 mas, edge-on.
- Position angle warp (declinations): 9° across reds
- Disk obscures central region – no need for torus? - and black hole mass 38 million $M_\odot$
- Systemic masers originate from bowl in front side of side, depth 0.04 pc (also Herrnstein et al.)
- Warp parameters suggest origin from Bardeen-Petterson effect (Caproni et al. 2007)



Humphreys et al. (2008)

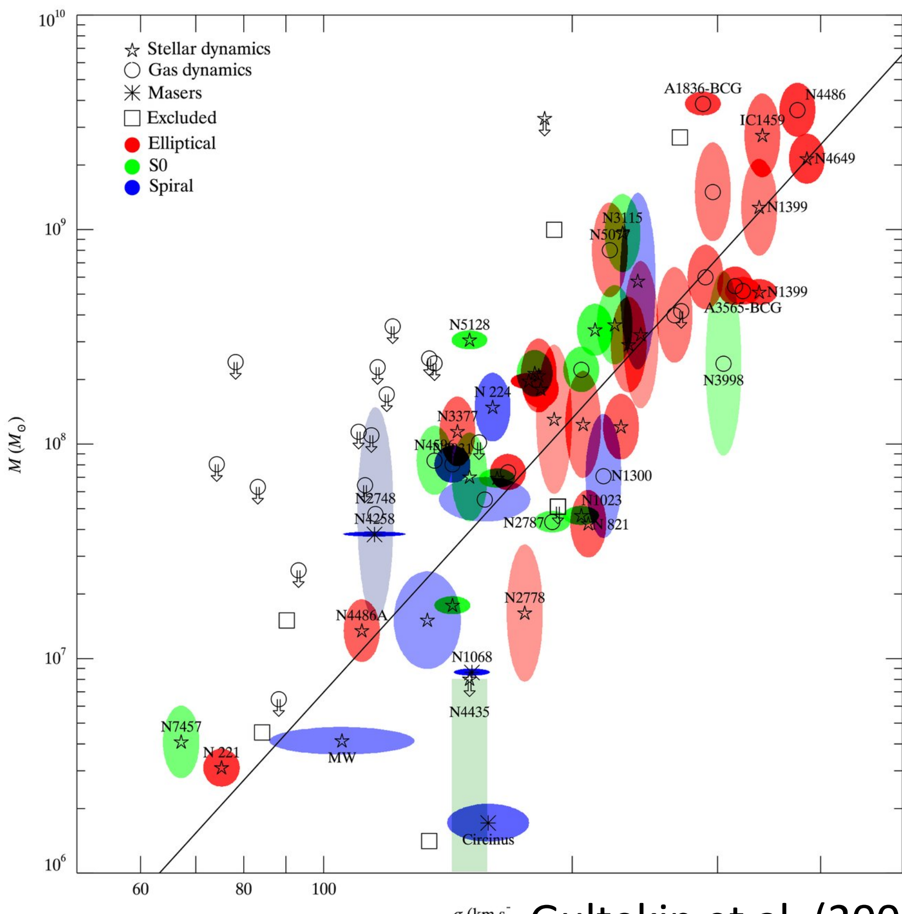
Characterization of AGN accretion disks & supermassive black hole systems

NGC 4258: warped, thin (H/R ~0.0015), evidence of spiral structure

Black hole mass: 38 million $M_{\odot}$

Geometric Distance: < 3 % (Humphreys et al., in prep)

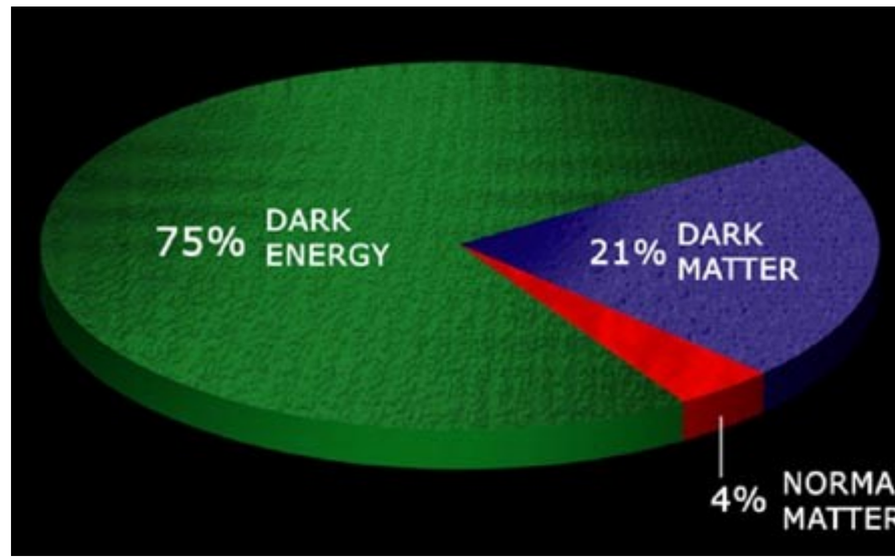
High-Accuracy Black Hole Masses



Gultekin et al. (2009)

Geometric Distances of a Number of Sources →

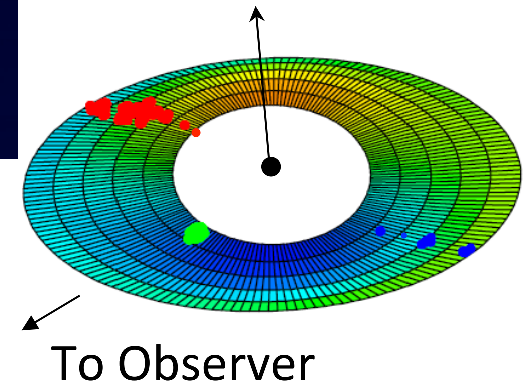
High-Accuracy Hubble constant



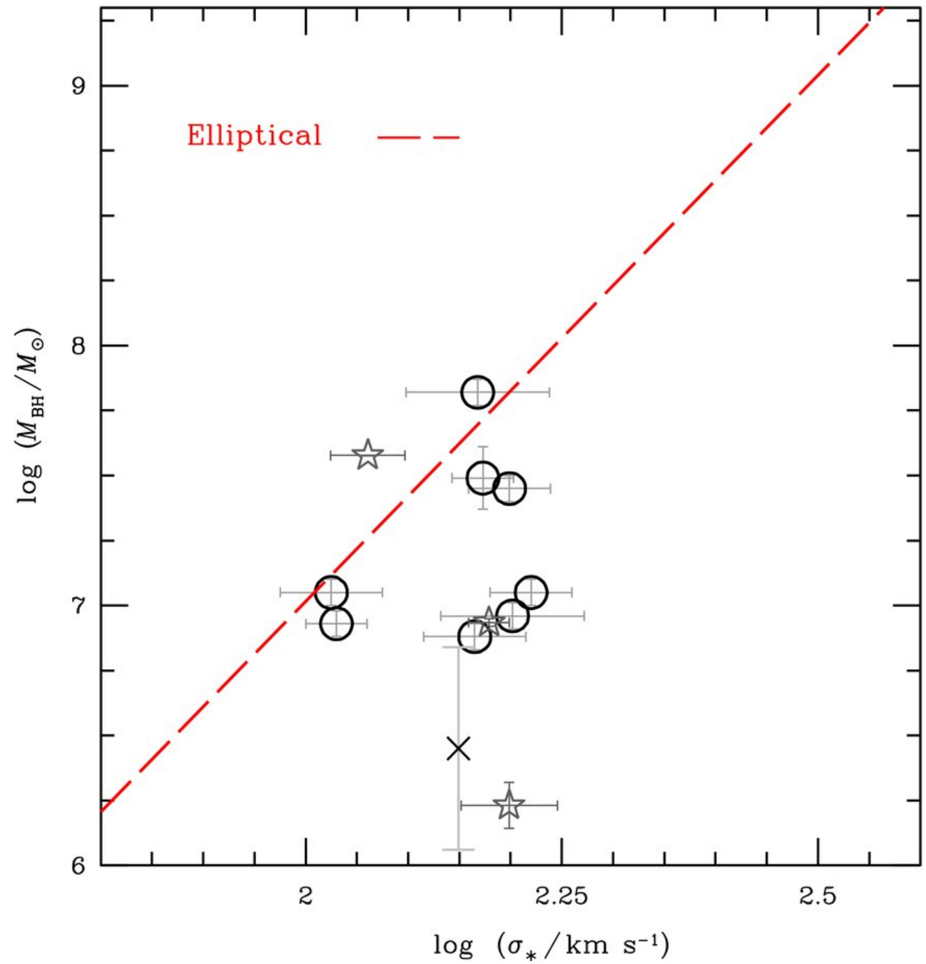
Water Maser Cosmology Project

Braatz, Impellizzeri, Reid, Lo, Henkel, et al.

Outstanding Issues at 22 GHz



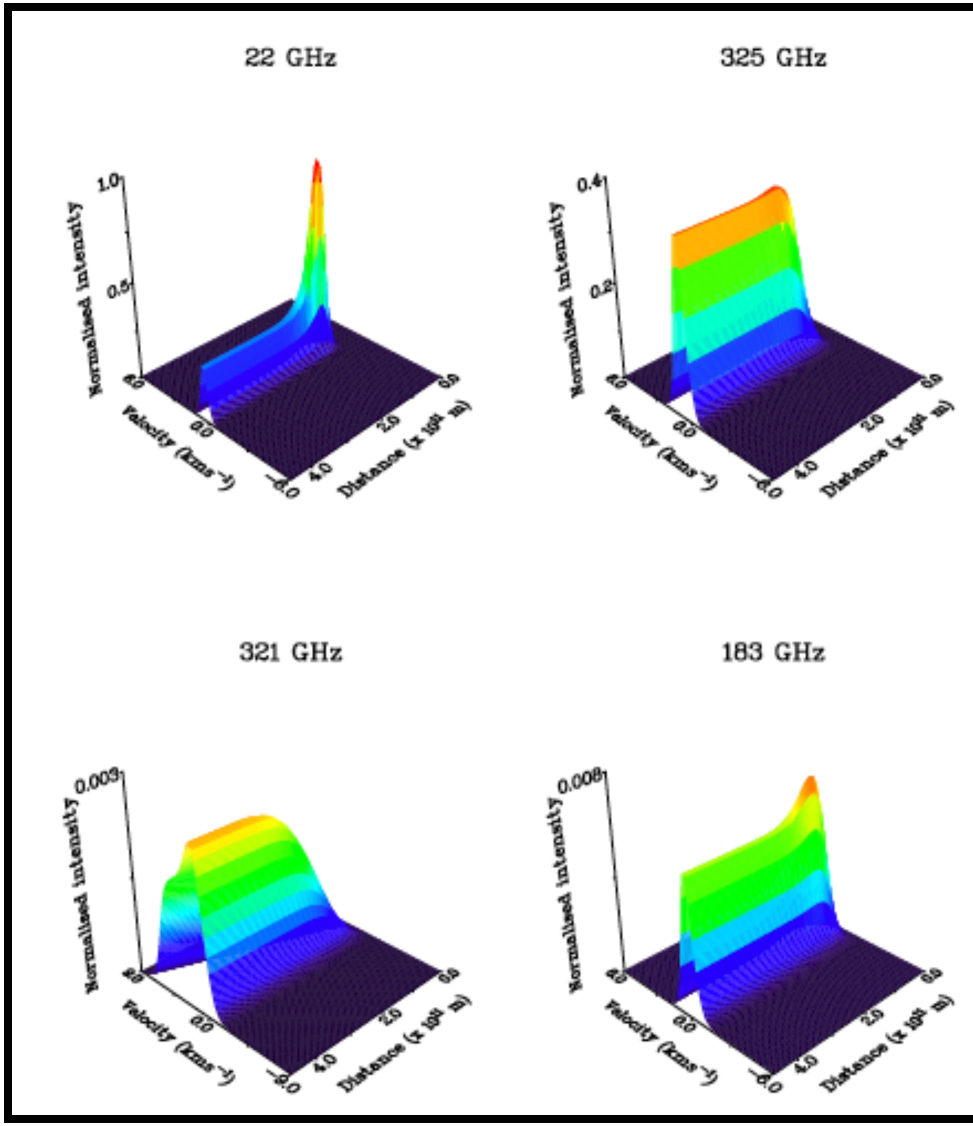
- M – σ diagram poorly sampled by masers
  - **Need larger range of mass**
- AGN disks poorly sampled by masers
  - **Never detect emission from back of disks**
- Determination of H_0 relies on imaging
  - **Need stronger masers to probe further out**



Greene et al. 2010; Kuo et al. 2011

Why the Search for Mm/Submm Masers?

- Probe same regions of AGN as 22 GHz masers:
  - **constrain radiative transfer models**
  - **Map out density and T in AGN central engines**
- Probe different regions:
  - **trace out conditions and dynamics of uncharted portions of AGN (closer to black hole?)**
  - **Improve geometric models**
  - **test AGN unified model**
- Search for “supermasers”:
  - **probe more distance sources**
- Search for masers from “back” of disks:
  - **improve geometric disk models**
- Better angular resolution
  - **Higher accuracy H_0**
- Probe different SMBH mass range?
  - **Constrain the $M - \sigma$ diagram**

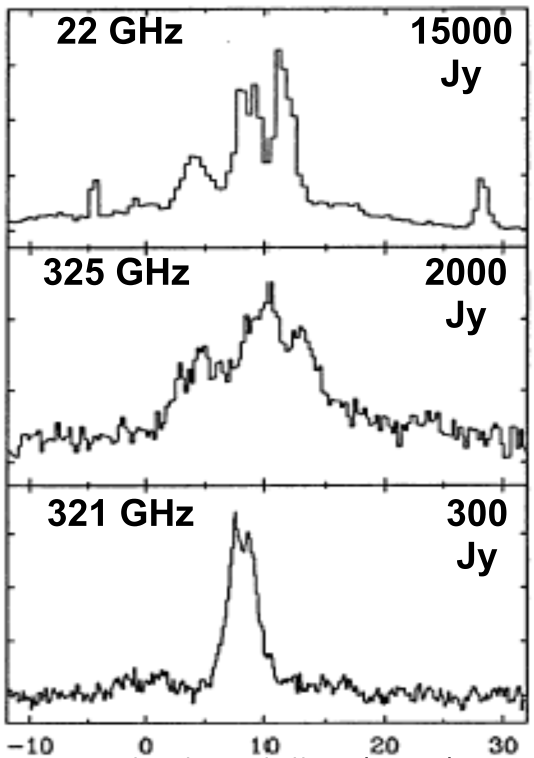


Humphreys et al. (2001)

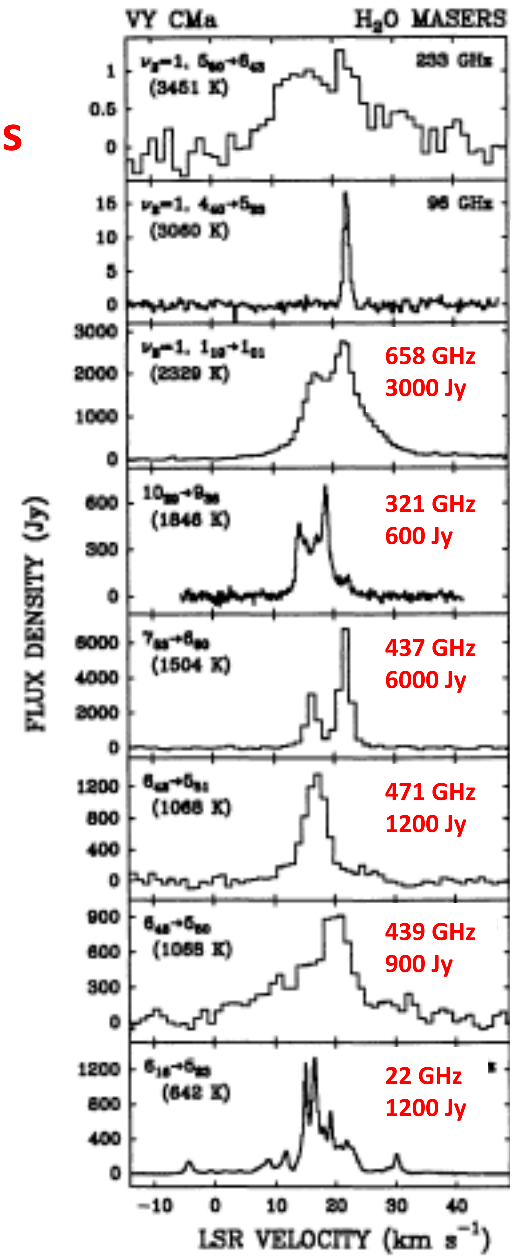
Observations: Galactic Sources

Many masers observed towards the same objects

H_2O : W49N

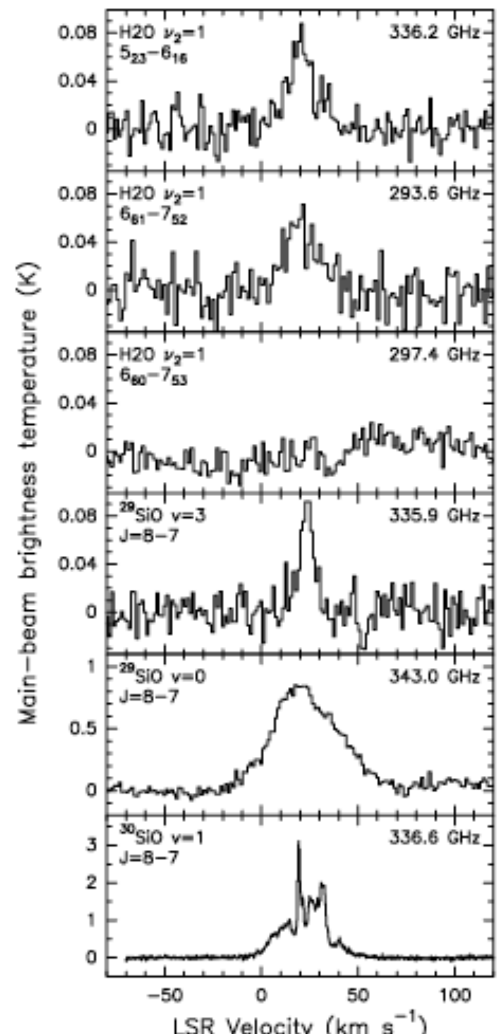


Menten, Melnick & Phillips (1990)



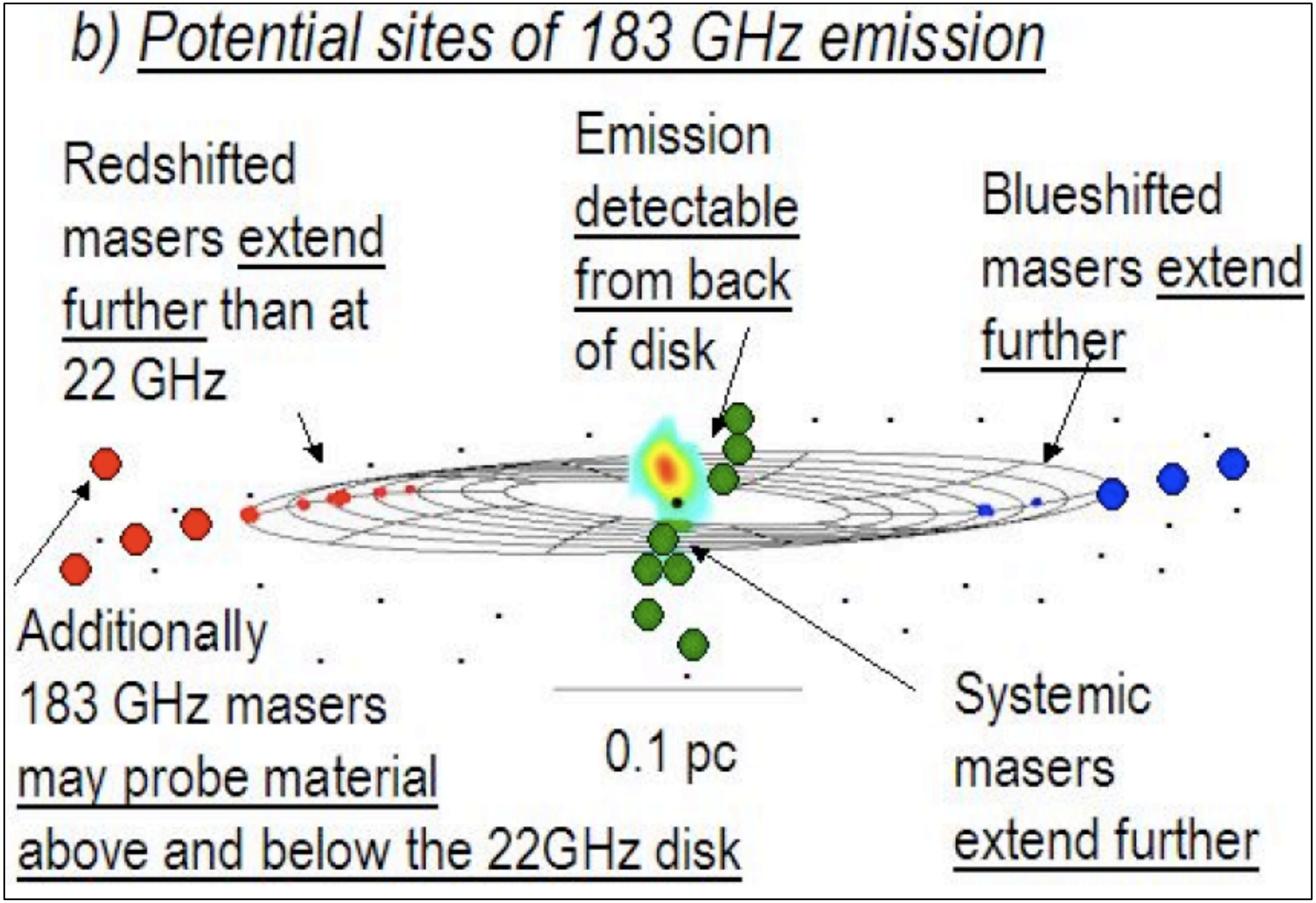
VY CMa

(Menten et al. 1996; 2006)



Mm/Submm Super Masers?

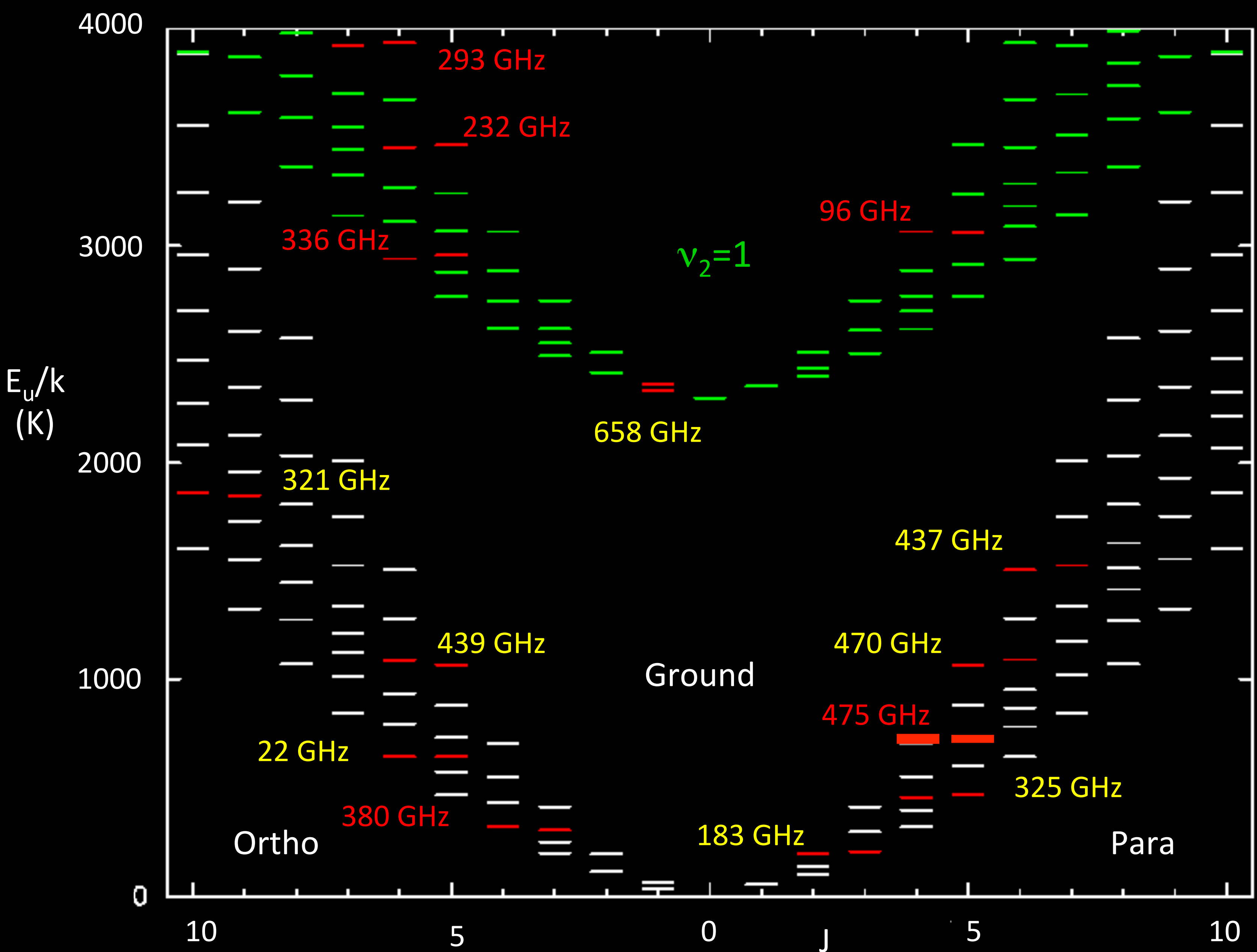
Plasma in the jet core/ionised layer above disk, optically thick at 22 GHz due to free-free opacity, obscures back of the disk. This is optically thin at mm/submm-λ, so supermasers can form.



Some H_2O Masers

Freq. (GHz)	Transition $J_{ka,kc}$ -> $J_{ka,kc}$	Vib. State	Ortho/ Para	E_u/k (K)	CSE	SFR	EXG	Primary Reference
22.235	6_{16}-5_{23}	G	O	644	Y	Y	Y	Cheung et al. (1969)
96.261	4_{40}-5_{33}	ν_2=1	P	3065	Y			Menten & Melnick (1989)
183.308	3_{13}-2_{20}	G	P	205	Y	Y	Y	Waters et al. (1980)
232.687	5_{50}-6_{43}	ν_2=1	O	3463	Y			Menten et al. (1989)
293.439	6_{61}-7_{52}	ν_2=1	O	3935	Y			Menten et al. (2006)
321.226	10_{29}-9_{36}	G	O	1862	Y	Y		Menten & Melnick (1991)
325.153	5_{15}-4_{22}	G	P	470	Y	Y		Menten & Melnick (1991)
336.228	5_{23}-6_{16}	ν_2=1	O	2956	Y			Feldman et al. (1992)
354.885	$17_{4\ 13}$-$16_{7\ 10}$	G	O	5782	Y			Feldman et al. (1992)
380.194	4_{14}-3_{21}	G	O	324		Y		Phillips et al. (1980)
437.347	7_{53}-6_{60}	G	P	1525	Y	Y		Melnick et al. (1993)
439.151	6_{43}-5_{50}	G	O	1089	Y	Y	T	Melnick et al. (1993)
470.889	6_{42}-5_{51}	G	P	1091	Y	Y		Melnick et al. (1993)
474.689	5_{33}-4_{40}	G	P	702	Y			Menten et al. (2008)
658.007	1_{10}-1_{01}	ν_2=1	O	2361	Y			Menten & Melnick (1989)

H_2O Energy Levels

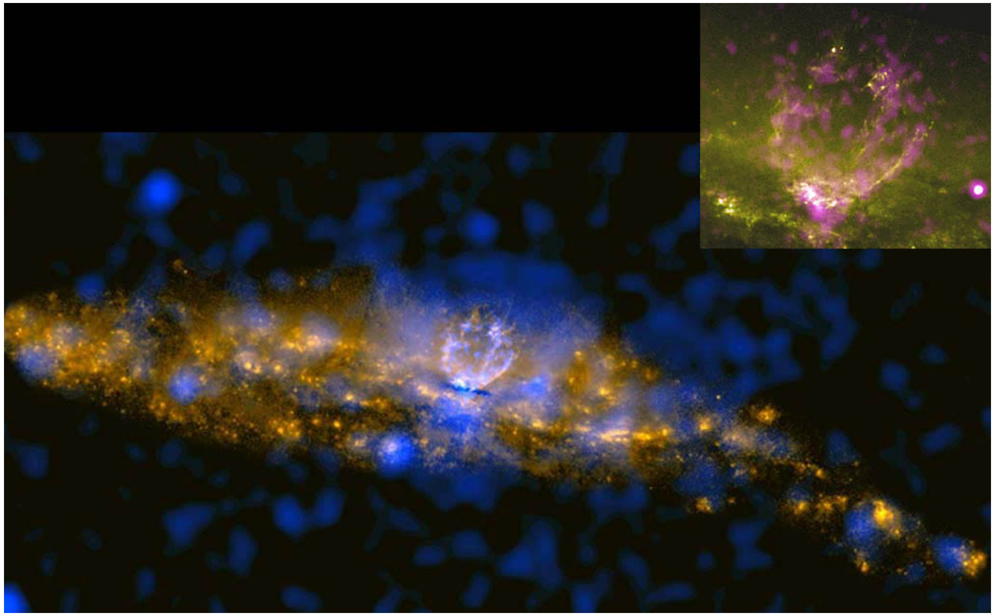


Data from Tennyson et al. (2001)

What we know so far

- 183 GHz emission - detected
  - **AGN NGC 3079 (Humphreys et al. 2005)**
  - **starburst galaxy Arp 220 (Cernicharo et al. 2006)**
  - **No evidence of supermaser, ratio ~20%**
- 439 GHz maser emission – tentative detection
  - **NGC 3079 (Humphreys et al. 2005)**
- ALMA Cycle 0: Search for Submillimeter H_2O Maser Towards Active Galactic Nuclei
  - **321 /325 GHz extragalactic maser search**
  - **Previous unsuccessful searches**

SMA Observations of NGC 3079



Cecil et al. 2001

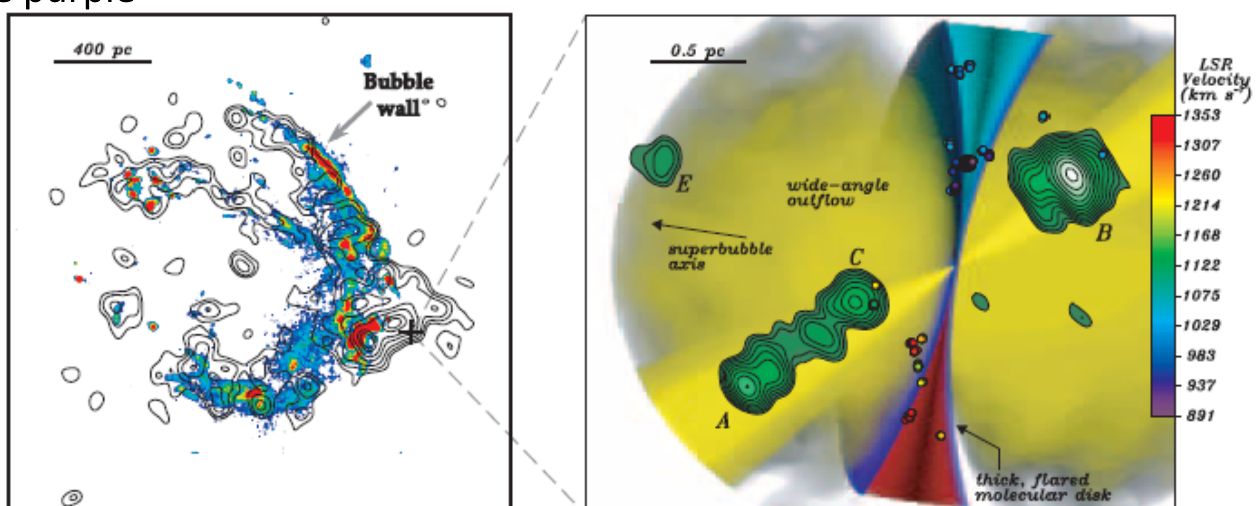
NGC 3079: blue shows X-rays (Chandra), gold is H-alpha+[N II] (HST). Insert: X-rays are purple

NGC 3079

NGC 3079 Seyfert 2/ LINER at 16 Mpc

Well-known host of 22 GHz H_2O maser emission (3 – 12 Jy)

22 GHz H_2O maser disk at apex of superbubble (Kondratko et al. 2005)



183 GHz Pumping Conditions

- Models indicate that the 183 GHz line is pumped at:
  - **High T, high n(H_2): T=400 – 1000 K, n(H2)=10^8-10^{10} cm^{-3}**
  - **Low T, low n(H_2): T= 200 K, n(H_2)=10^7 cm^{-3} (Yates et al. 1997), as low as 10^5 cm^{-3} (Cernicharo et al. 1999,2006)**

- Expect to find it in same regions as 22 GHz masers *and* out to lower densities and T

- 183 GHz emission less time-variable than the other well-studied H_2O masers

T=200 K (Yates et al. 1997)

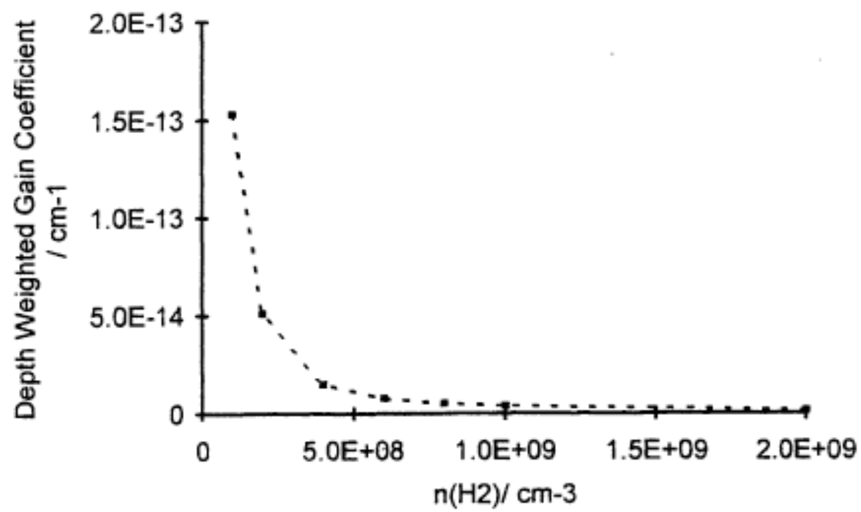
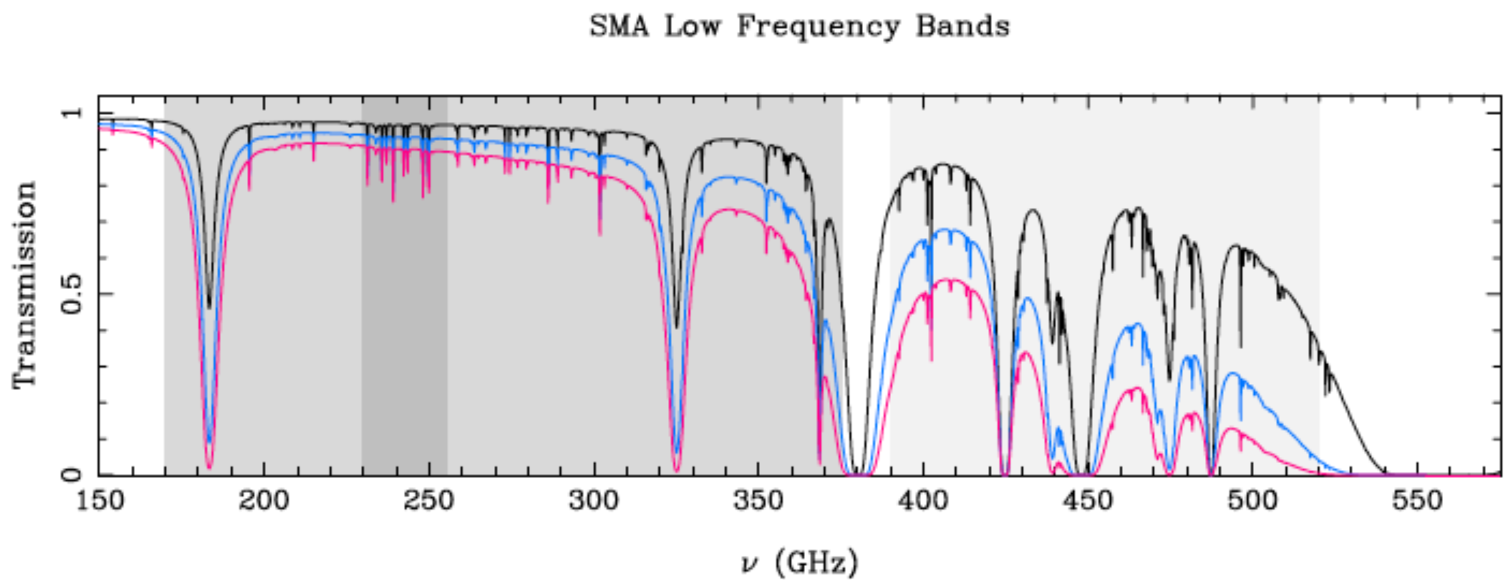


Figure 6. The variation of $\langle\gamma_{183}\rangle$ with molecular hydrogen number density $n(H_2)$ for $n(H_2O) = 10^4$ cm^{-3}, $T_d = 200$ and $T_d < 100$ K.

SMA Observations of NGC 3079

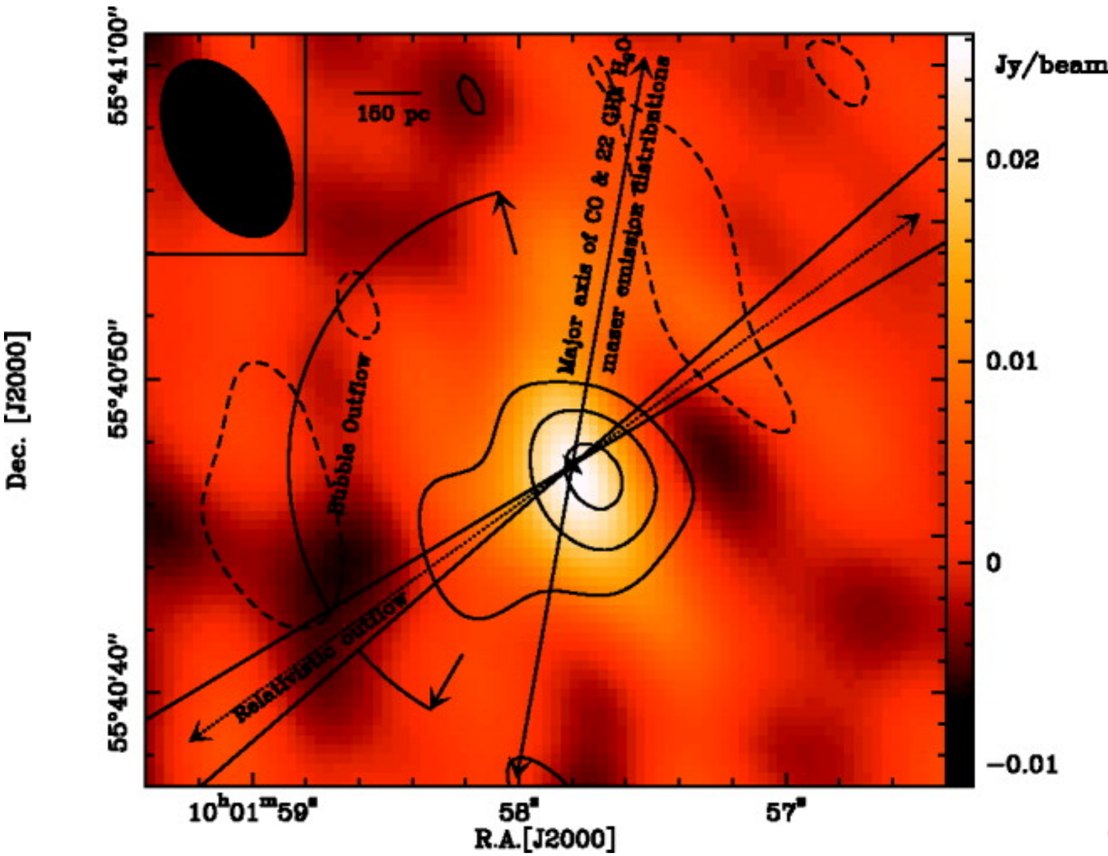


- 1 track at the SMA with six antennas
  - **compact configuration (projected baselines 8 – 72 m)**
  - **zenith opacity (225 GHz) 0.03 to 0.05 throughout**

- Redshift of the galaxy reduced line frequency by 0.7 GHz, lowering corresponding atmospheric opacity

- Amplitude calibration was performed as a function of frequency to reduce the effect of variation in terrestrial H_2O across the 2 GHz sideband

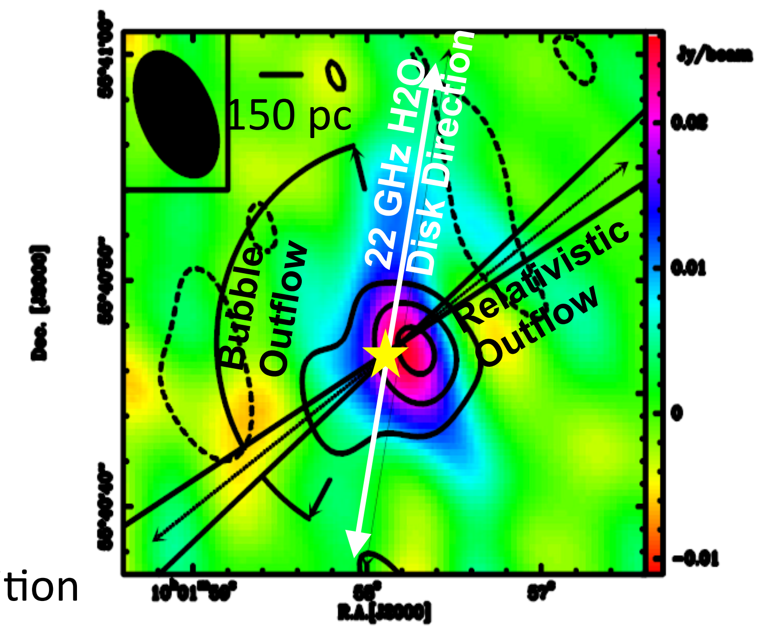
Results



Maser and dust Continuum

0.55 Jy, 7σ detection

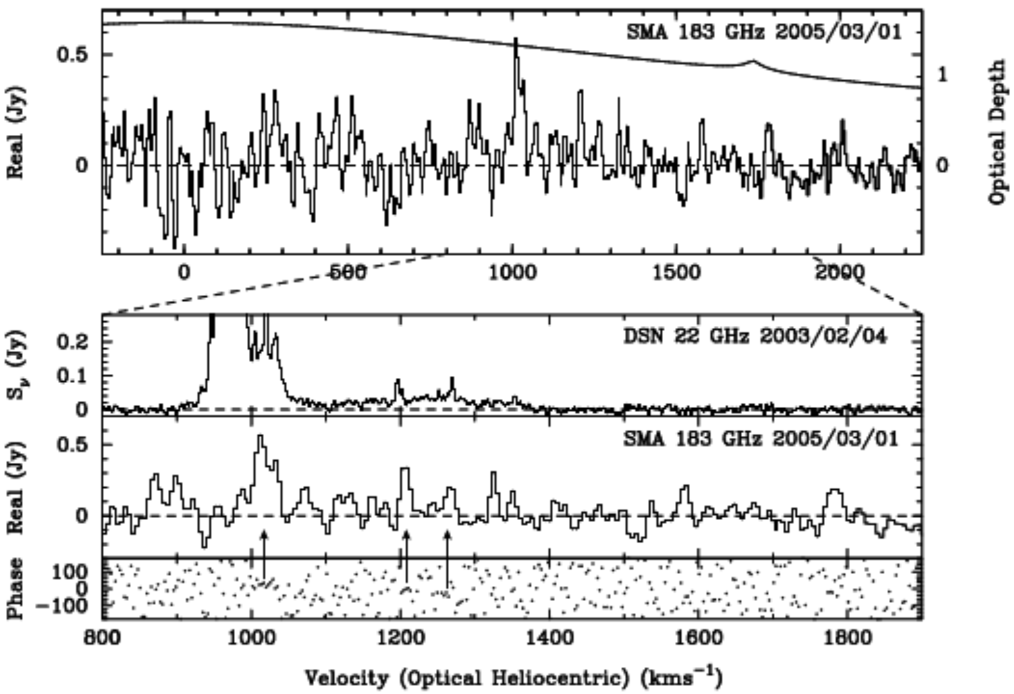
Humphreys, Greenhill, Reid, Beuther, Moran, Gurwell, Wilner, Kondratko (2005)



★ 22 GHz Maser Peak Position

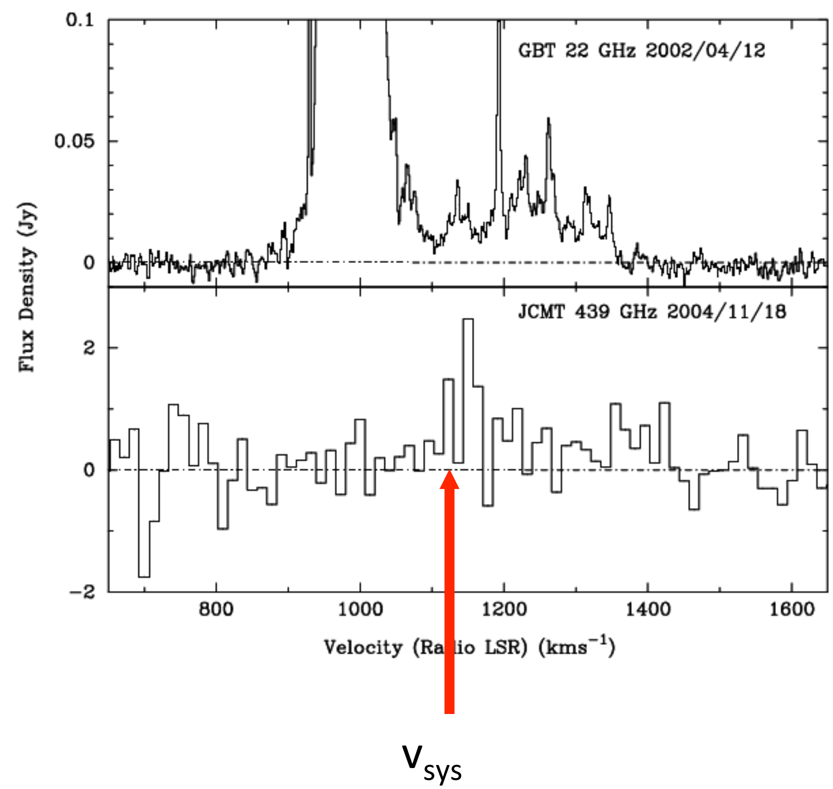
Spectra Associate Emission with AGN

183 GHz: SMA



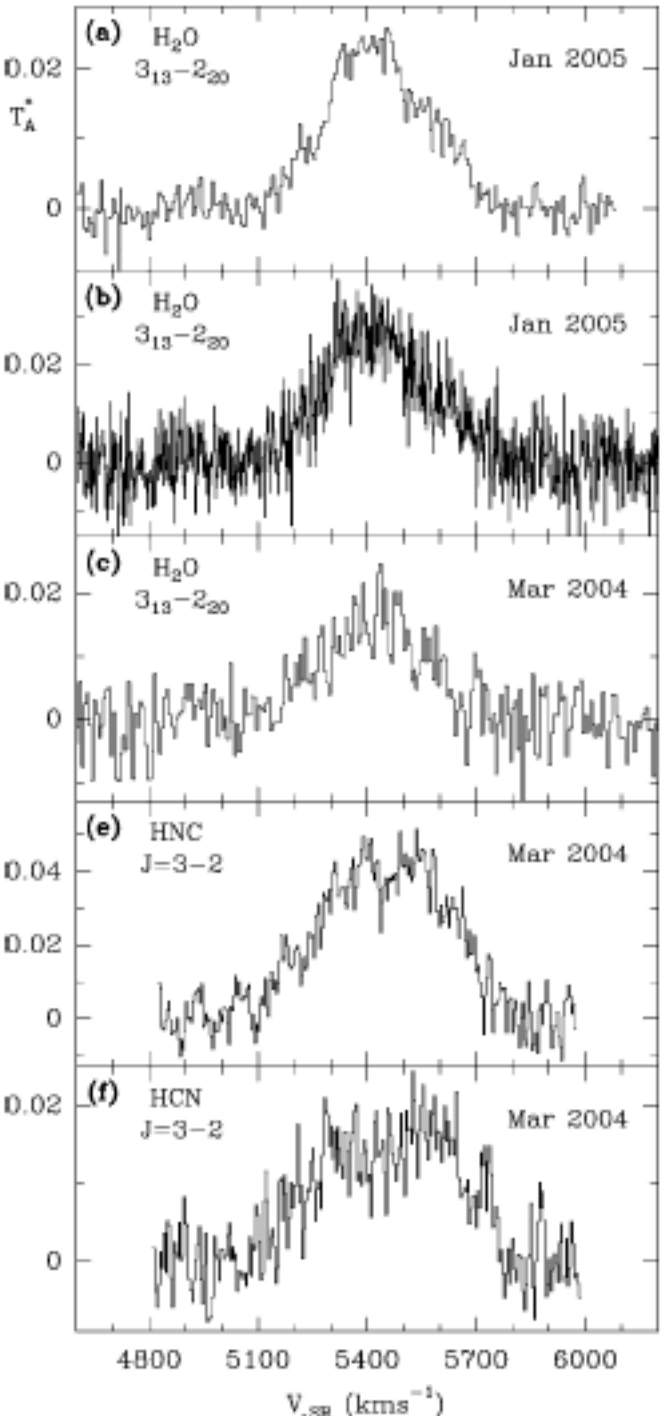
22 GHz and 183 GHz emission occur at overlapping velocities

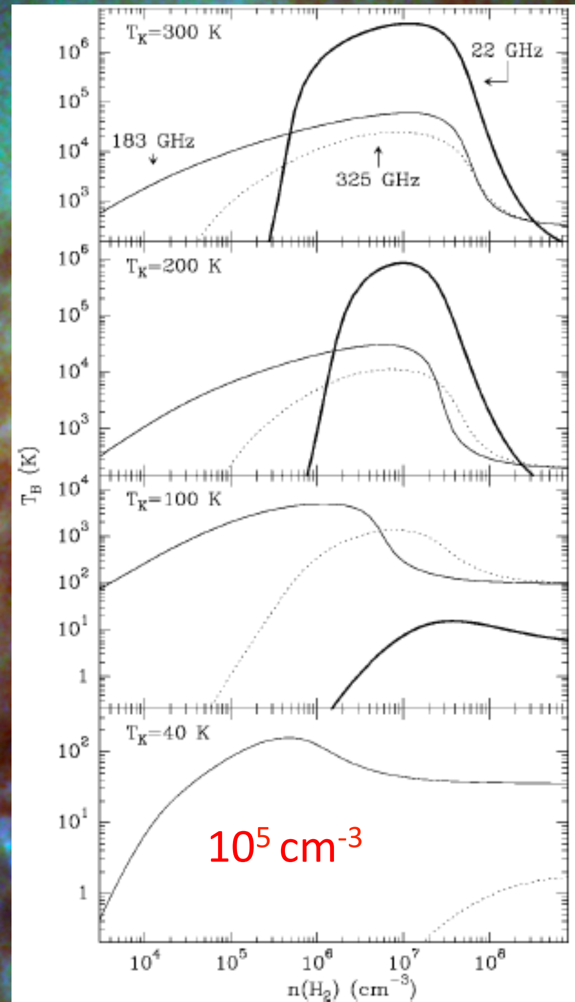
439 GHz: JCMT



mmVLBI and Starbursts: Arp 220 183 GHz

Cernicharo, Pardo & Weiss (2006)



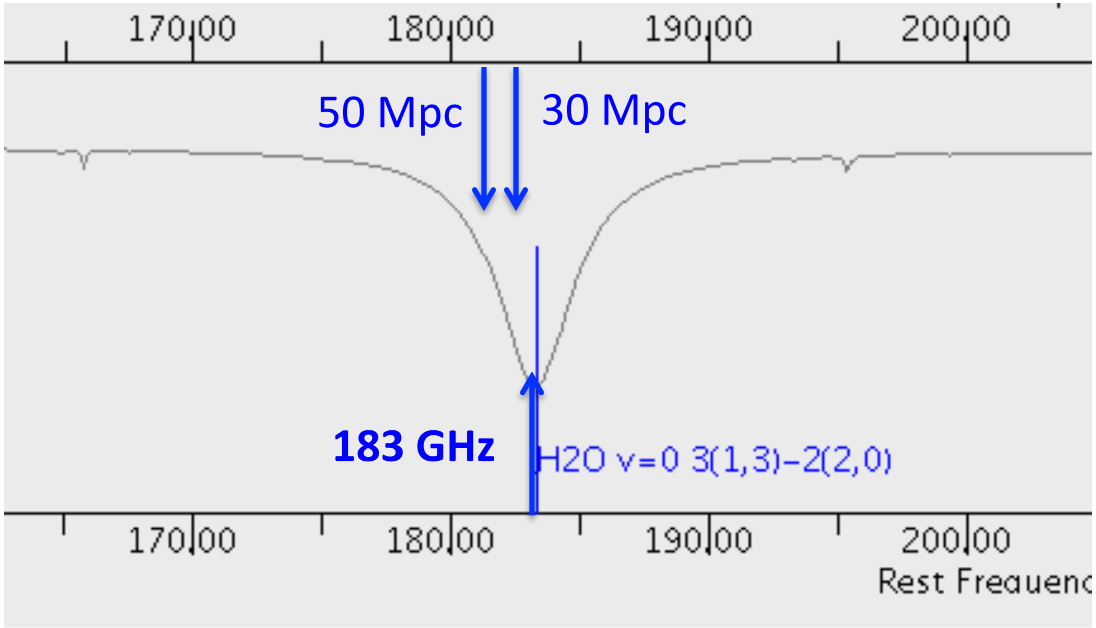


The detection of the $3_{1,3}$–$2_{2,0}$ line of H_2O with a luminosity of $\sim 2.5 \times 10^8$ K km s^{-1} pc^2 toward Arp 220 has been interpreted as being due to a starburst in the central kiloparsec or so, triggered by the merging nature of this object, with $\sim 10^6$ sources similar to the Galactic condensations Sgr B2(M) and Sgr B2(N). The luminosities of HCN and HNC in the $J = 1$–0 and $J = 3$–2 transitions further support this scenario.

Site/redshift Considerations

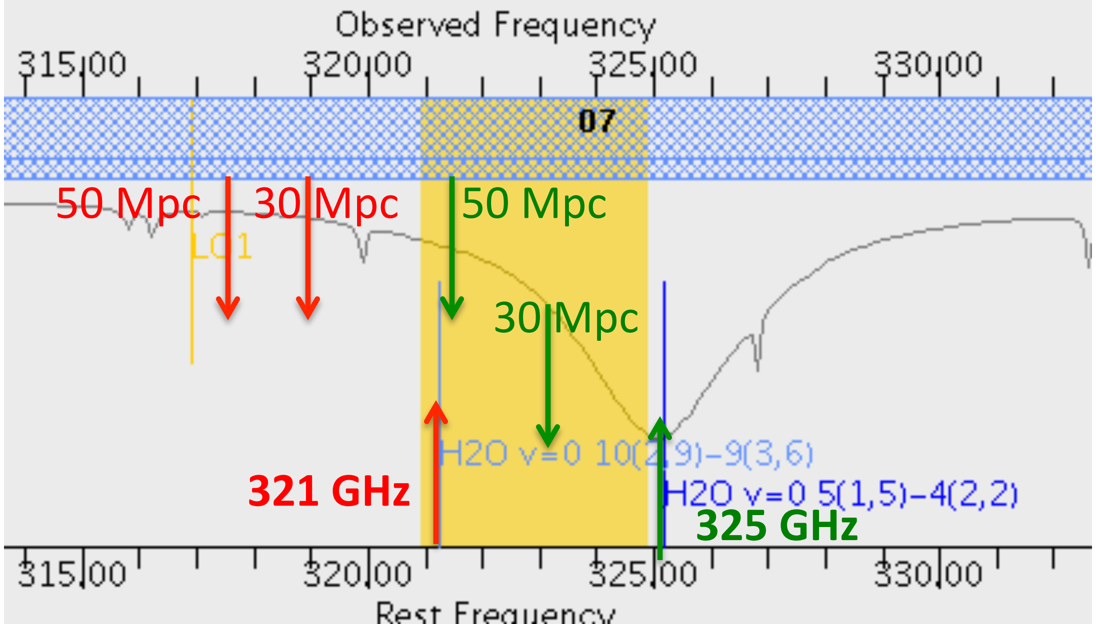
pwv = 0.5mm

183 GHz



321 GHz

325 GHz



Redshift out of the lines

Stronger masers
- gravitational lensing?

In terms of site:
- local: 321 GHz
- distant: 183, 325 GHz

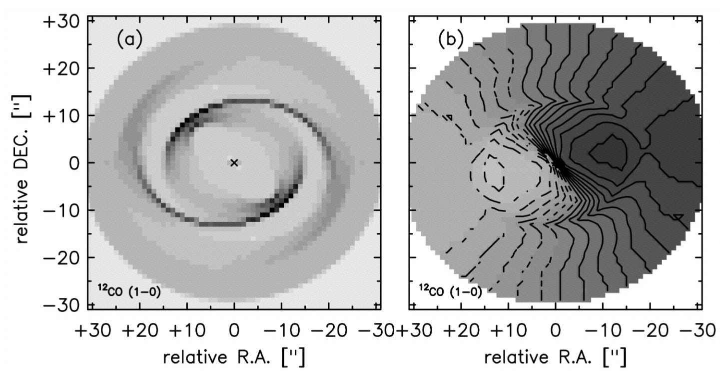
Prospects: Local AGN

Local AGN (< 30 Mpc)

- Water Maser Cosmology Project has ~30 sources, some of which accessible to the Southern sky
- Survey for 183 GHz emission:
  - NGC 3079 at 30 Mpc: 0.16 Jy
  - Taking 182.5 GHz, 0.5 kms^{-1} channels, a 5σ detection
    - **6 antennas: 10 hours per source on source in best weather octile (0.5 mm pwv), goes up to >60 hours for 0.9 mm pwv**
    - **50 antennas: 7 minutes (0.5 mm pwv), 40 minutes (0.9 mm)**
- Maximum angular resolution (B=14 km,λ=1.6mm): 24 mas
  - but can get position accuracy of beam/2*SNR, so could get ~2.5 mas spatial scale information i.e. < 0.4 pc at 30 Mpc

Science

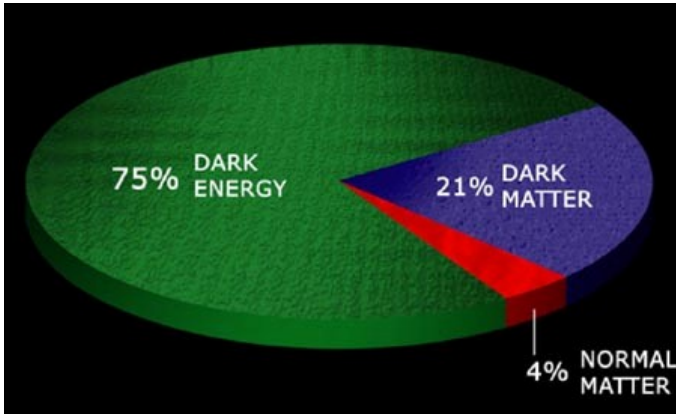
- AGN unified model – is there a puffed up torus? Disk-torus connection
- AGN accretion disk physics: warps, spiral structure, local distances, disk thickness, accretion mechanism

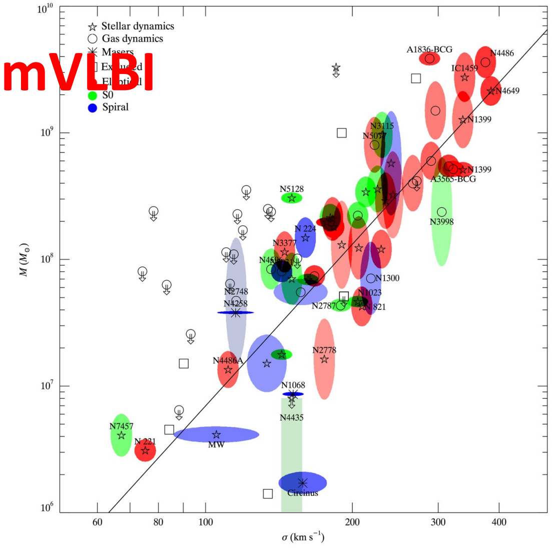


Schinnerer et al. 2001, NGC 1068, CO

Prospects: Maser Cosmology

- Band 5 will allow observation of the 183 GHz line out to z ~ 0.1 or v=30 000 kms^{-1}, D ~ 400 Mpc
- At **D=400 Mpc**, the NGC 3079 maser would be 0.8 mJy (0.5 kms^{-1}) (166.6 GHz)
  - **6 antennas: > 10 000 hrs (5σ)**
  - **50 antennas: ~130 hrs (5σ)**
- At **D=50 Mpc**, maser would be 56 mJy (181.2 GHz)
  - **6 antennas: 13 hrs (5σ), 184 hr (20σ)**
  - **50 antennas: 10 minutes (5σ), 2.3 hrs (20σ)**
- If resolution ~25 mas, SNR=20, can have 0.6 mas position accuracy. Rivals VLBA at 22 GHz….
- But, maser cosmology will require good imaging - **mmVLBI**





Summary: Extragalactic Masers

(sub-)mmVLBI & ALMA:

- **High spectral resolution**
- **High angular resolution**
- **High sensitivity**

- Local AGN < 30 pc
  - **Test unified model for AGN**
  - **AGN accretion physics**
  - **321 GHz maser may be best**
- Distant AGN > 50 Mpc
  - **Maser Cosmology, high accuracy Hubble constant, Dark energy….**
  - **183, 321 & 325 GHz masers**
  - **Gravitationally-lensed masers**
- ALMA pre-surveys: find out if we can populate the black hole mass range in the M-σ diagram

ALMA BAND (Freq Range GHz)		H_2O (GHz)	SIO & Isotop. (v=0 – 4) (GHz)	CH_3OH (GHz)	HCN (GHz)	H (GHz)	SiS (GHz)
1	31.3-45		~43	36,44			
2	69 - 90		~86	85			
3	84-116	96	~86	95,107,109	89	99	
4	125-169		~129	133,147,157			
5	163-211	183	~172		177	207,210	200
6	211-275	232	~215 ~258	217,229.8, 230	265	232,240, 256	254,272
7	275-373	321,325,354	~301 ~344		355	316,353, 367	
8	385-500	437,439, 471,475,488	~387 ~430,473				
9	602-720	658	more			662	
10	787-950	906	more		804,891	After Wootten (2007)	