Maser observations with VLBI

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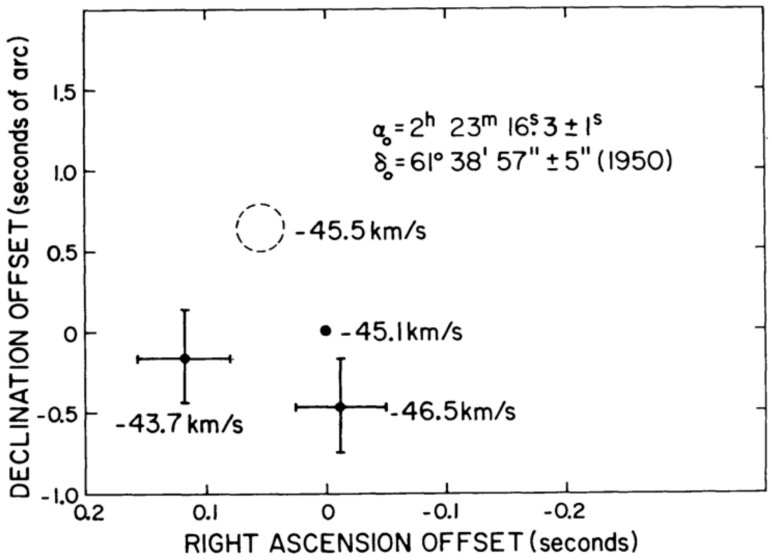
Outline

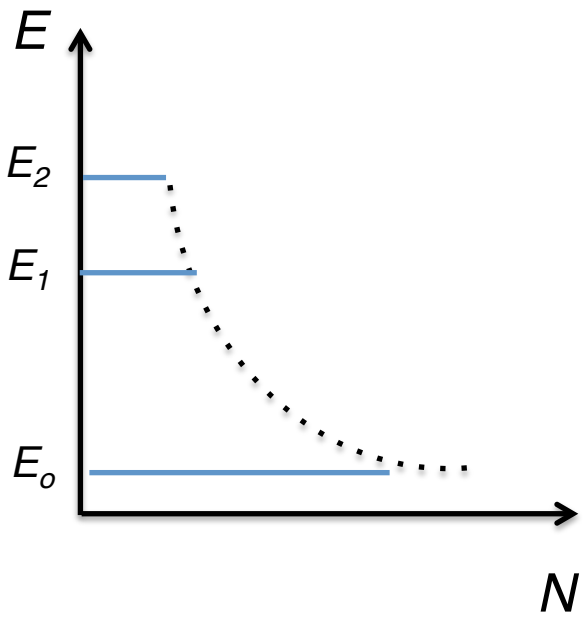
- The connection maser-VLBI
- The maser as a probe
  - Environment/kinematics in star forming regions, evolved stars
  - Magnetic fields
- The maser as a distance tool
  - Within the Galaxy
  - Extragalactic megamasers

The VLBI & maser connection

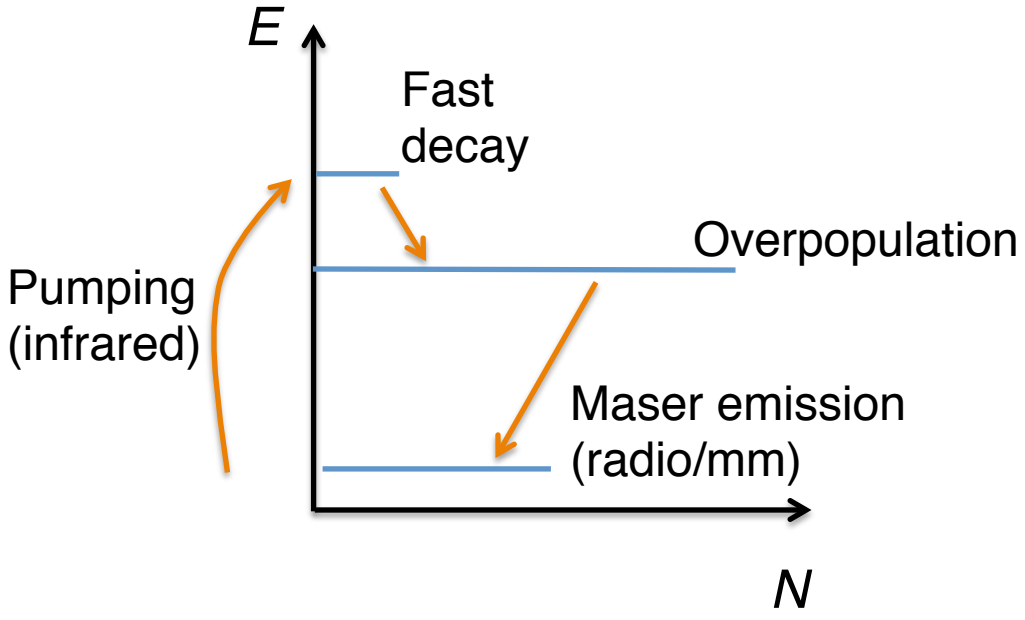


- Moran, Rogers et al. (1967), Davies et al. (1967), Rogers et al. (1966): Resolving 1665 MHz OH features in W3(OH)
- VLBI and masers have been connected for 50+ years!

Equilibrium versus maser populations



$$\frac{N_u}{N_l} = \frac{g_u}{g_l} e^{-(\frac{h\nu}{kT})}$$



Pumping by infrared radiation or collisions

What VLBI can provide

$$T_B = 0.32 \left(\frac{S}{[mJy/bm]} \right) \left(\frac{B_{max}}{[km]} \right)^2 \; K$$

Due to brightness temperature limit, suitable to observe:

- Synchrotron emission
- Thermal absorption against non-thermal continuum
- Maser emission

Masers are **bright** and **compact** and VLBI provides the spatial resolution and imaging capabilities.

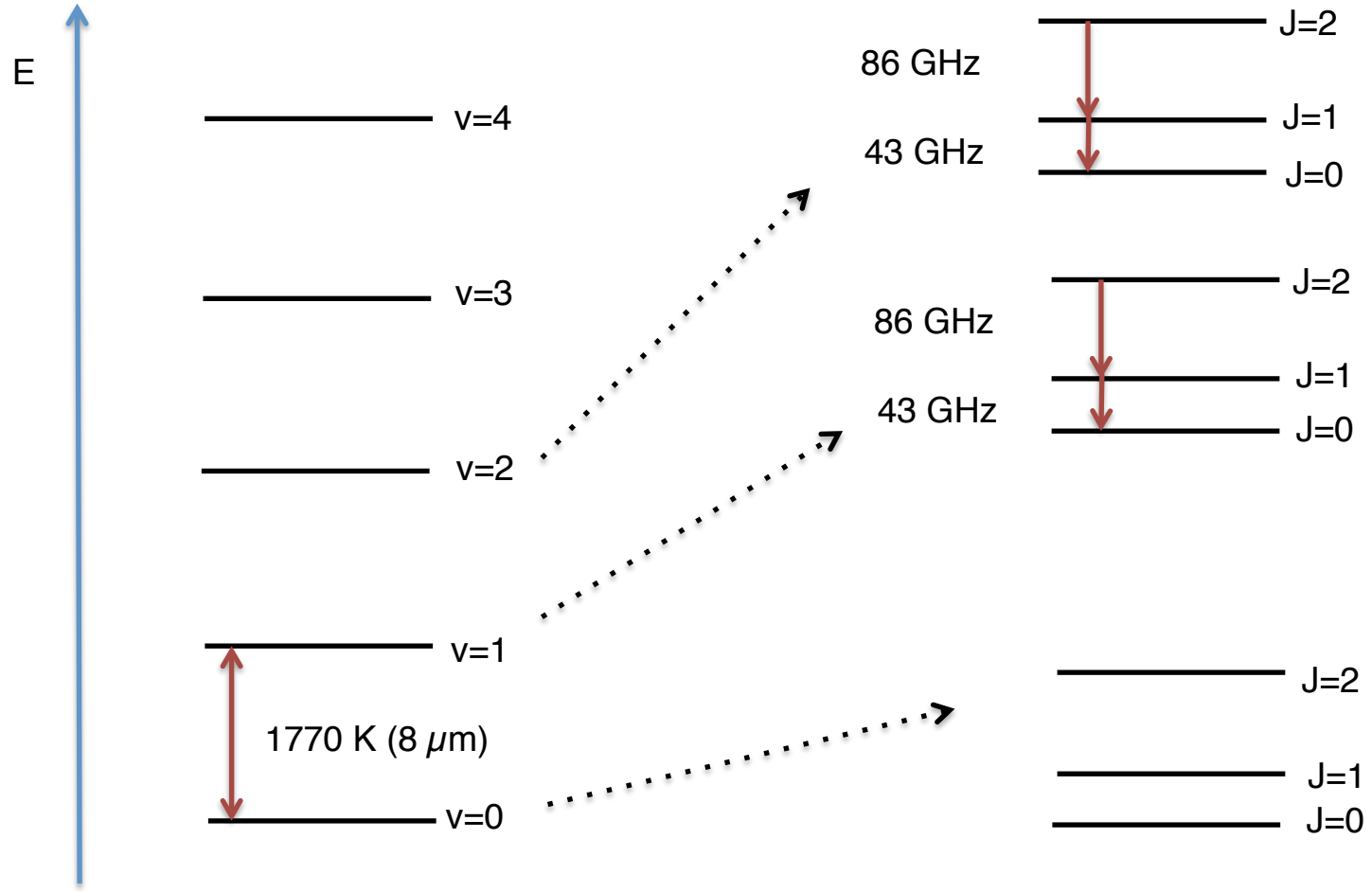
Maser VLBI observations provides morphology, line-of-sight velocities, kinematics, magnetic field measurements (Zeeman splitting), etc.

Observed maser molecules

Masers are observed in star forming regions evolved stars, supernova remnants, and in other galaxies including jets and circumnuclear AGN disks.

Enviroment	Molecule	Probing
Starforming regions	OH, CH_3OH, H_2O, SiO	Structure (disks, outflow)
		Astrometry, parallaxes
Evolved stars	SiO, H_2O	O-rich inner/outer shell
	OH	O-rich caps, distance estimate
	HCN	Carbon rich envelopes
Extragalactic	H_2O	Distances
	OH, CH_3OH	Structure

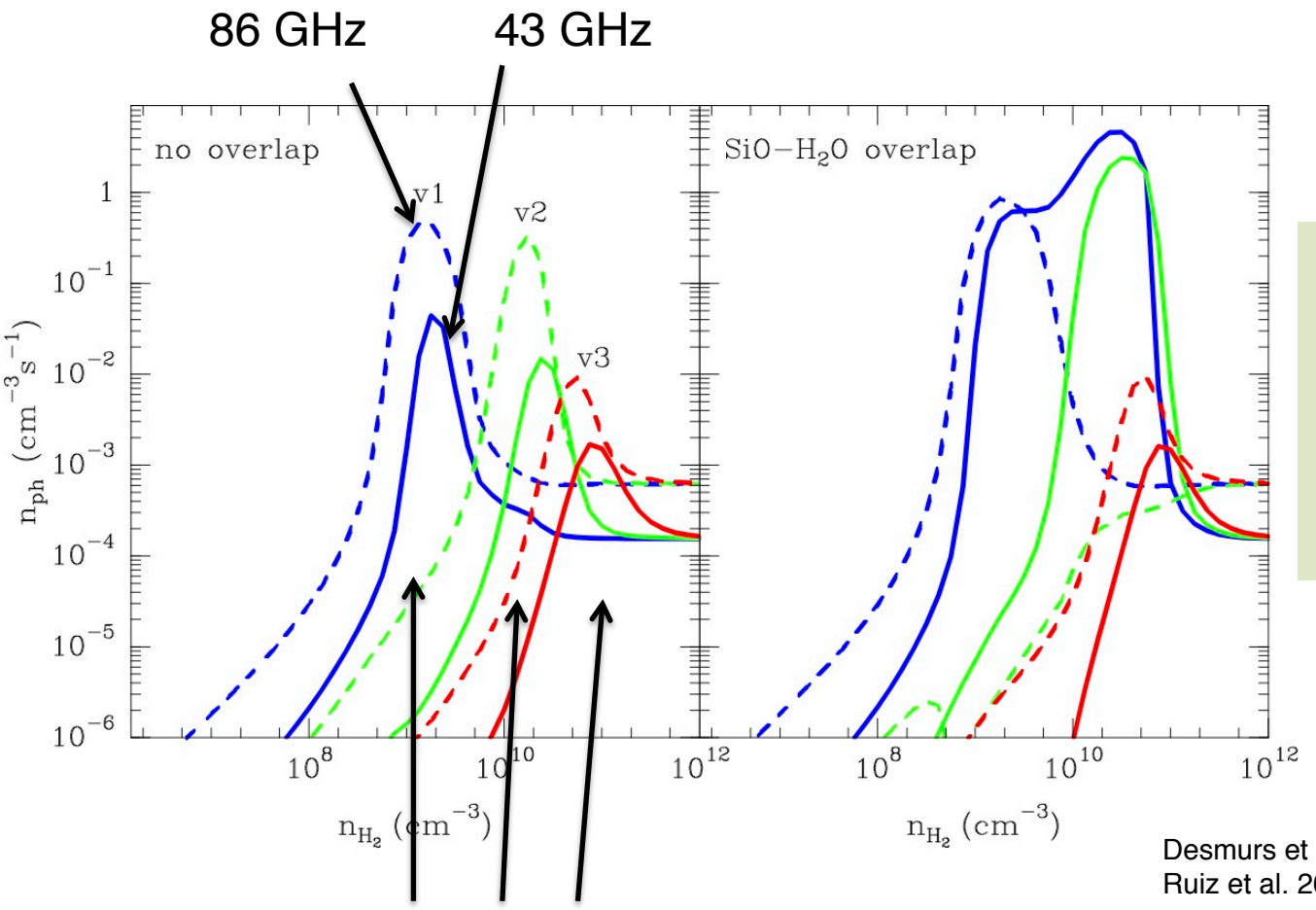
SiO energy levels



Transitions observable with VLBA

Courtesy P. Colomer

SiO pumping



VLBI observations provide the necessary spatial information

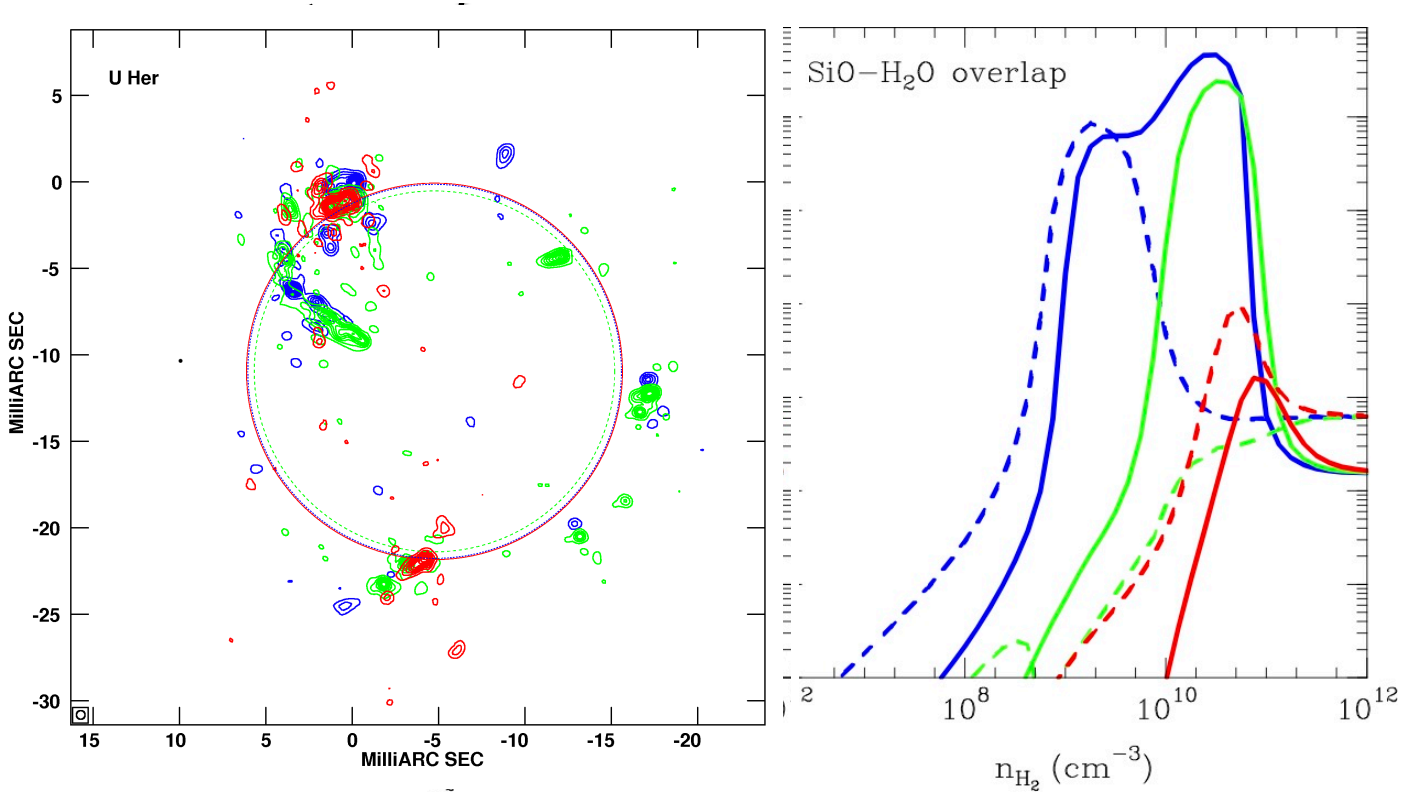
Desmurs et al. 2014, Soria-Ruiz et al. 2004.

Positional differences expected for v=1,2 and 3

SiO masers in AGB stars: density

Desmurs et al. 2014

v=1
v=2
v=3



Model where a water line overlaps in the pumping gives better agreement due to little positional difference and relative line strengths.

Challenges: Alignment

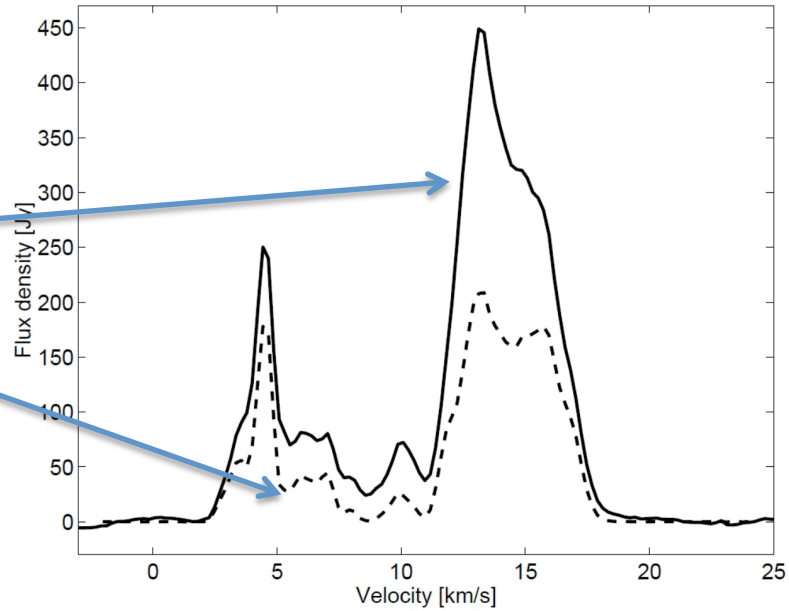
Relative alignment between transitions as well as to the position of central star/object needed:

1. Absolute astrometry using phase referencing to calibrators
2. Matching velocity centroids of a feature to a specific position
3. Transfer phase from one frequency/maser to another

Need: More calibrators, translating into better sensitivity (larger bandwidth, larger collecting area).

Challenges: Missing flux

Cross correlated flux < total

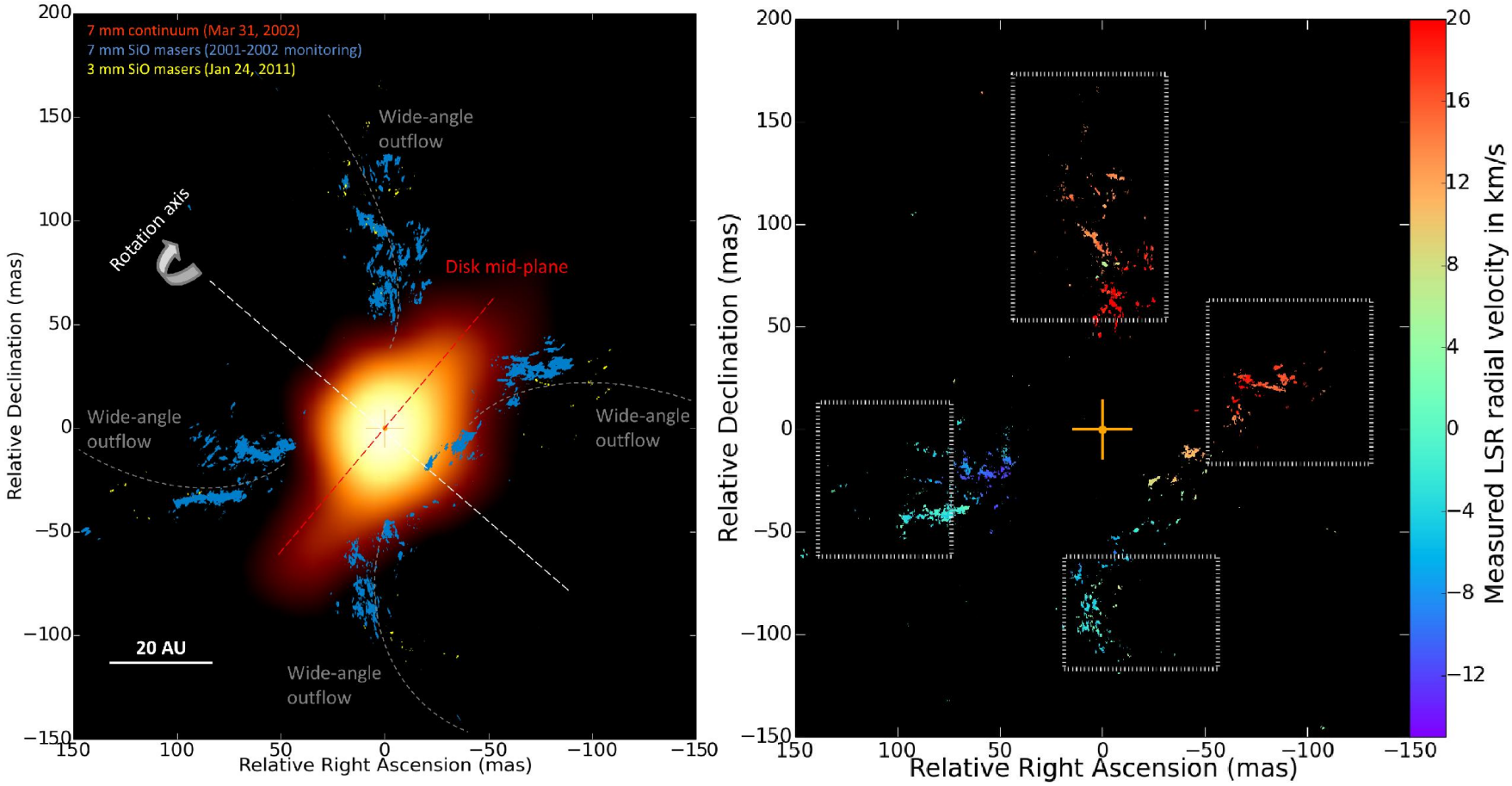


Yi et al. 2005

Extended maser emission?
A large set of weaker but compact features?
Could be the effect of a clumpy, inhomogeneous medium.

=> Need improved sensitivity to line features, and a large range of baseline lengths.

Star forming regions: Orion BN/KL



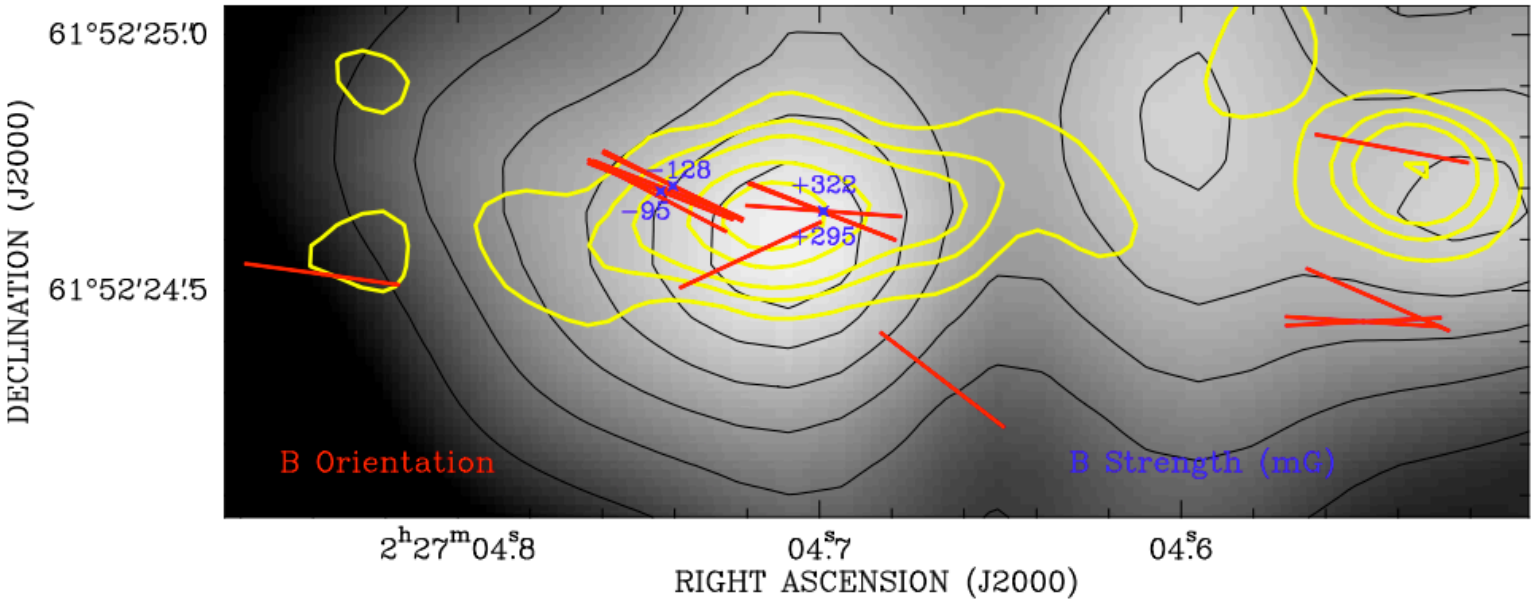
SiO close to the center of a young stellar object (YSO). VLBI may be the best way of getting details that close to the YSO base.

Issaoun et al. 2017

Protostellar jet: magnetic fields in W3(H_2O)

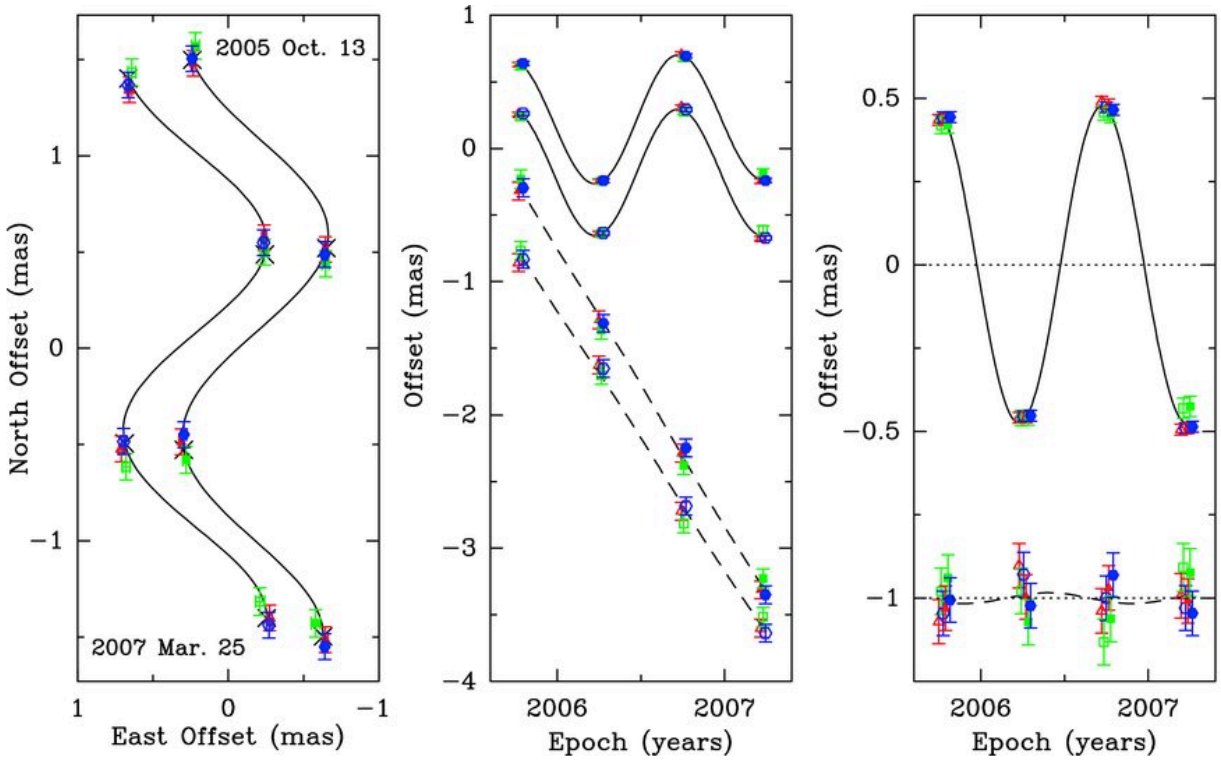
B-fields through polarization and Zeeman splitting of H_2O

- Outer B-field (~1000 AU) aligned with jet
- Inner magnetic field (~10-100AU) misaligned with motion, due to enhancement of perpendicular magnetic fields by the shocks which produce the masers.



Goddi et al. 2017

Maser parallaxes



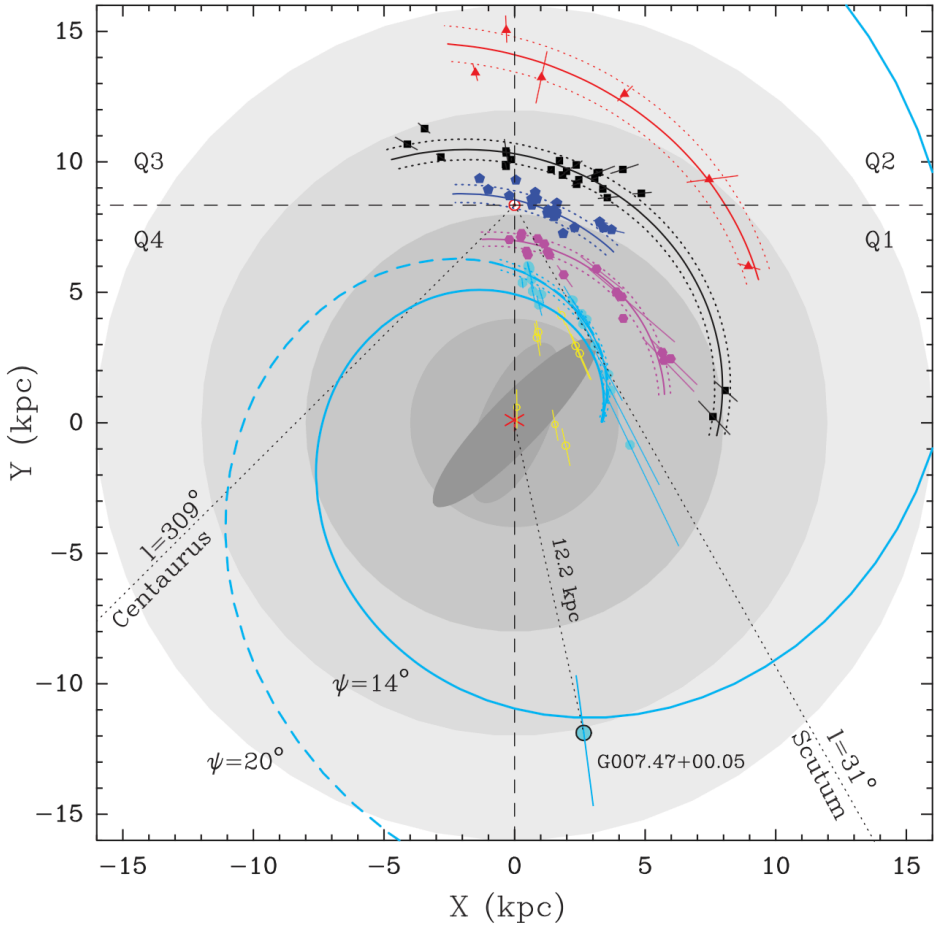
S 252 12 GHz CH_3OH maser parallax measurements with VLBA

π = 0.476 +/- 0.006 mas

d = 2.10 +/- 0.026 kpc

Xu et al. 2007

BeSSeL survey: VLBA Legacy Program



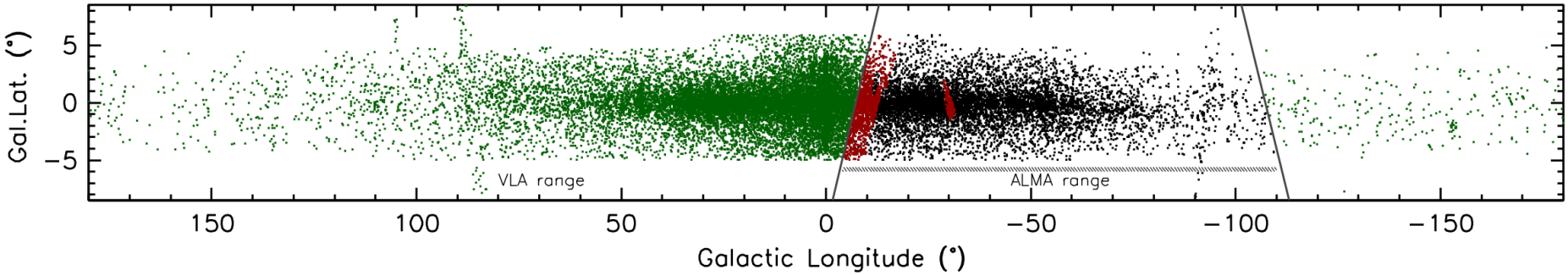
Reid et al. 2014; Sanna et al. 2017

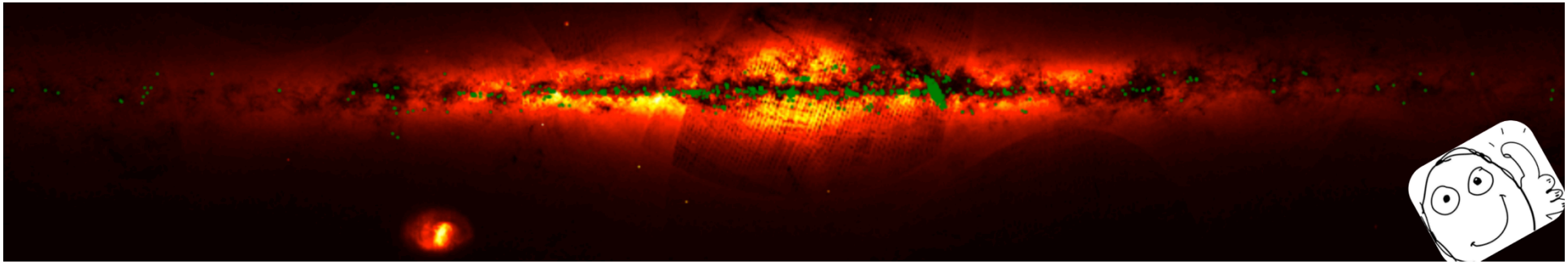
- 150+ parallaxes for massive stars using CH_3OH and H_2O using VLBA, EVN and VERA
- Trace the spiral arms well
  - find the inner/bar region to be complicated

BAaDE survey: VLA/ALMA + VLBA(?)

SiO maser survey of 30,000+ red giant stars along Galactic Plane

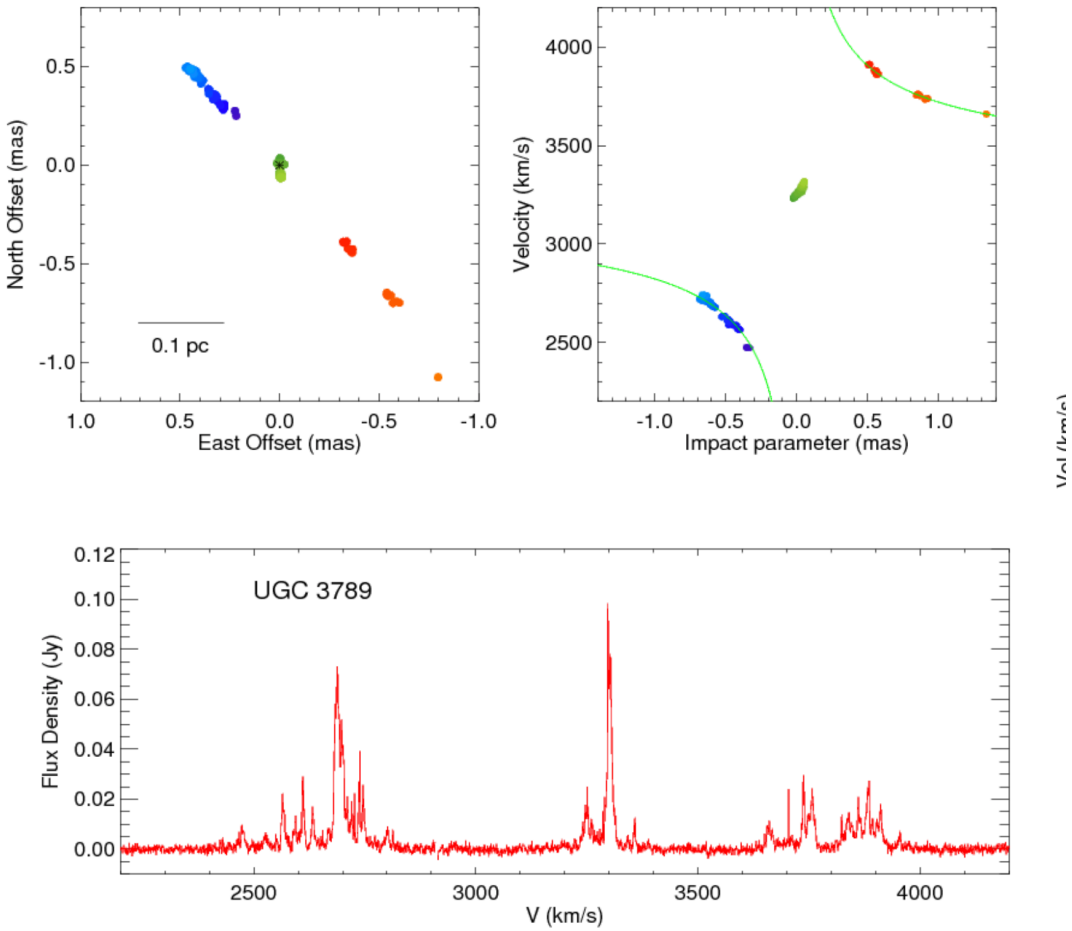
- Aim to test dynamical models of bulge and bar
- Later part of project goal is to derive parallax distances to a subset
  - Need 0.15mas resolution for a 10% distance accuracy
    => 4600 km at 86 GHz or 9200 km at 43 GHz





Sjouwerman et al. 2017, Pihlström et al in prep, Stroh et al. in prep, Quiroga-Nunez et al. 2017

H_2O Megamasers

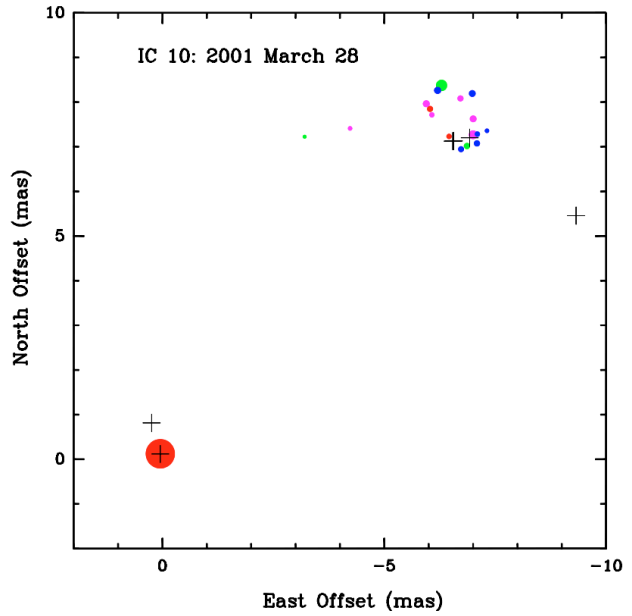


- Measuring SMBH masses
- Deriving geometric distances
- Determining H_0 : 69.3±4.2 km/s/Mpc

Reid et al. (2013), Kuo et all. (2013, 2015), Gao et al. (2015), etc.

Distances in the Local Group: IC10, M33

- H_2O masers in IC10 and M33, giving proper motions & space velocity relative to the MW
- Two groups of masers in M33 allowed for comparing their proper motion to that expected from the rotation curve, giving a 'rotational parallax'.
- Lower limit to M31 mass 7.5×10^{11} $M_\odot$



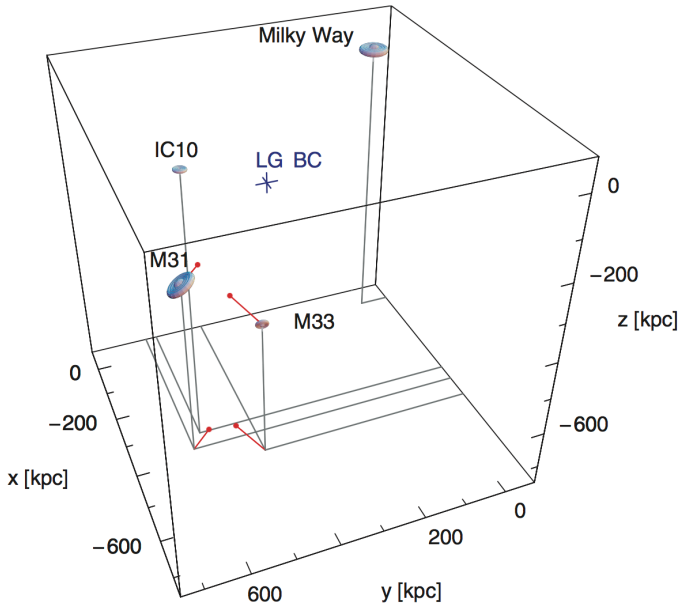
Brunthaler, Reid, Falcke, Henkel & Menten 2007, 2005

Distances in the Local Group: M31

M31?

- Radial component only
- Proper motion perhaps 15-50μas/yr
- No strong continuum sources, but a few masers
- Not yet detected at VLBI length baselines

More collecting area, larger set of baseline lengths desired.



Brunthaler et al. 2007, 2005

Summary remarks

Maser observations with VLBI continue to provide

- Details of physical conditions
- Kinematics
- Magnetic fields
- Parallaxes/distances

Desirable for continued progress include

- Higher sensitivity (line+continuum)
- Larger range of baseline lengths

Fits in with an ngVLA with the inclusion of current VLBA baselines lengths