Max-Planck-Institut
für
Radioastronomie

eVLBI spectral line applications

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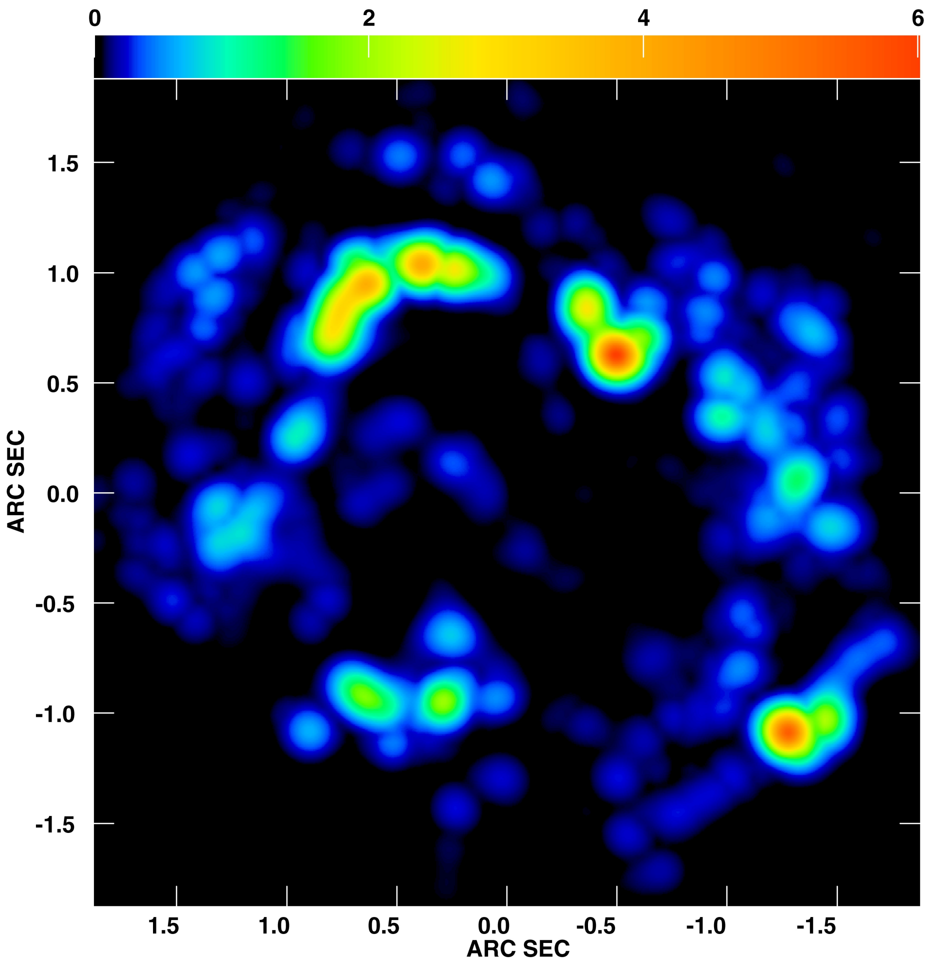
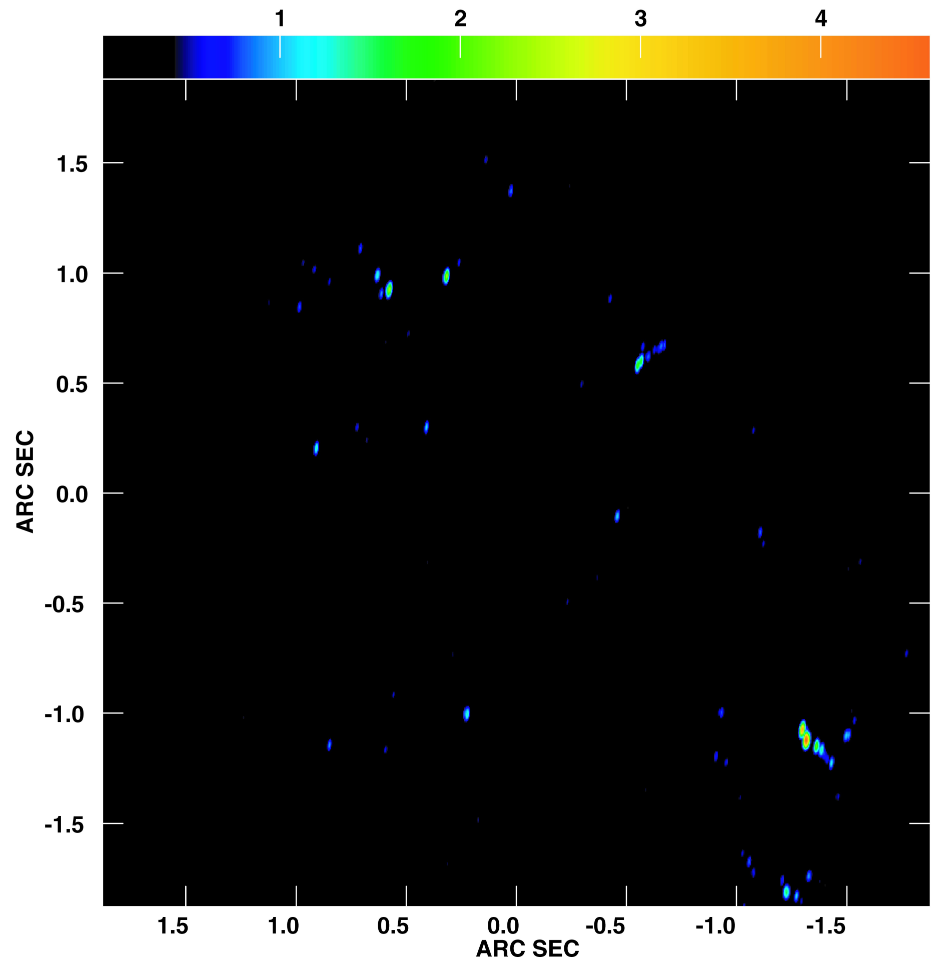
Science demo

- first e-VLBI science experiment: 22 September 2004
- OH maser emision in supergiant IRC+10420



MERLIN



eVLBI

What is eVLBI?

Theory	Practice
rapid results	**Yes!** (except TECOR files)
highly reliable	**Yes!**
highly flexible	**Not yet!**
	- only one session per month
	- only one frequency per session
	- limited telescopes
	- no dynamic scheduling
	- limited to one correlator pass

Maser Surveys

- > 500 6.7 GHz methanol masers known (Pestalozzi et al. 2005
- many more with Parkes methanol multi-beam survey

- only small fraction have accurate (interferometer) positions

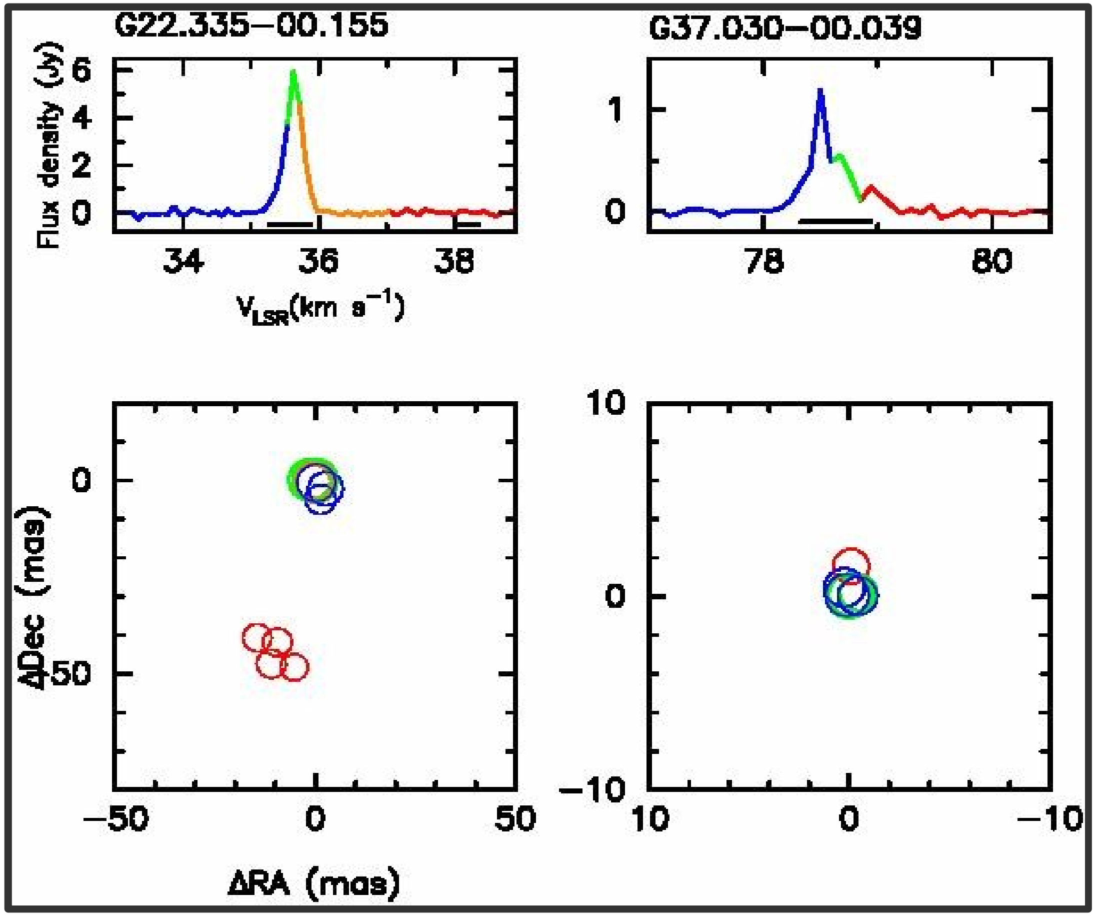
  - difficult to cross correlate with other surveys

- even smaller fraction have been imaged with VLBI

Maser Surveys

- Bartkiewicz et al. (2009) imaged 31 methanol masers with the EVN
- a large variety of morphologies

- 3 (9.5%) masers: *simple*



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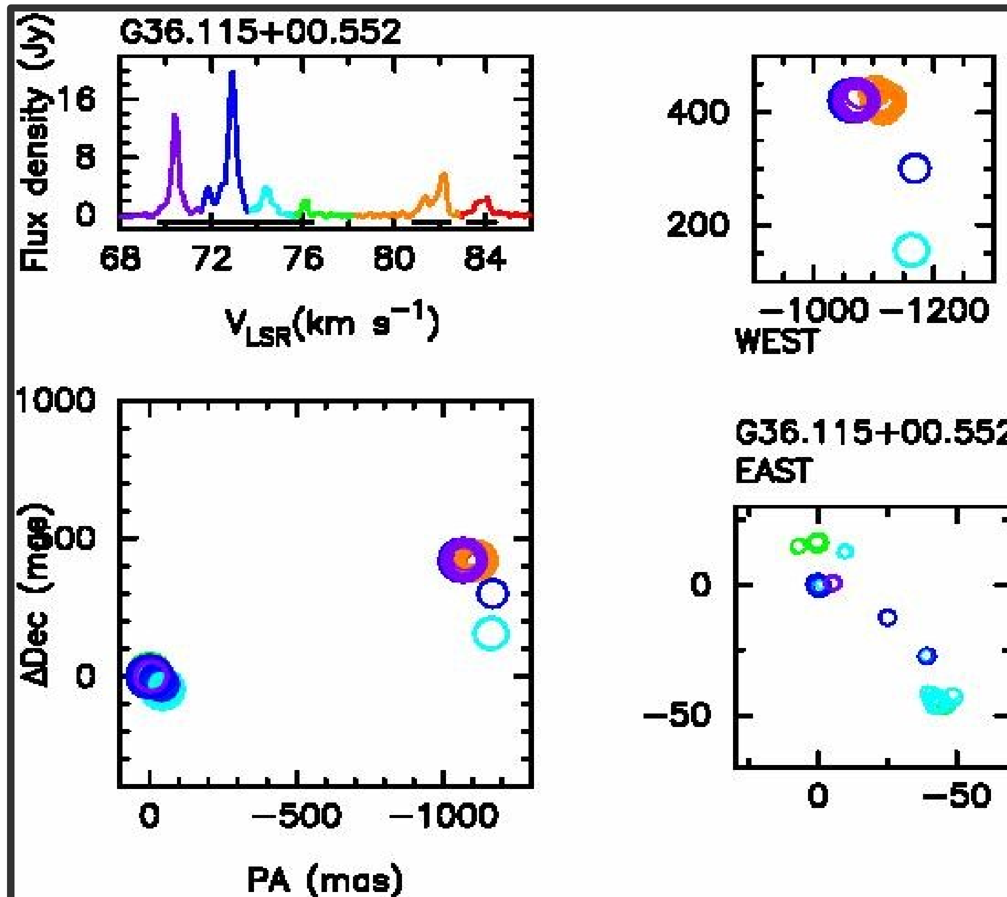

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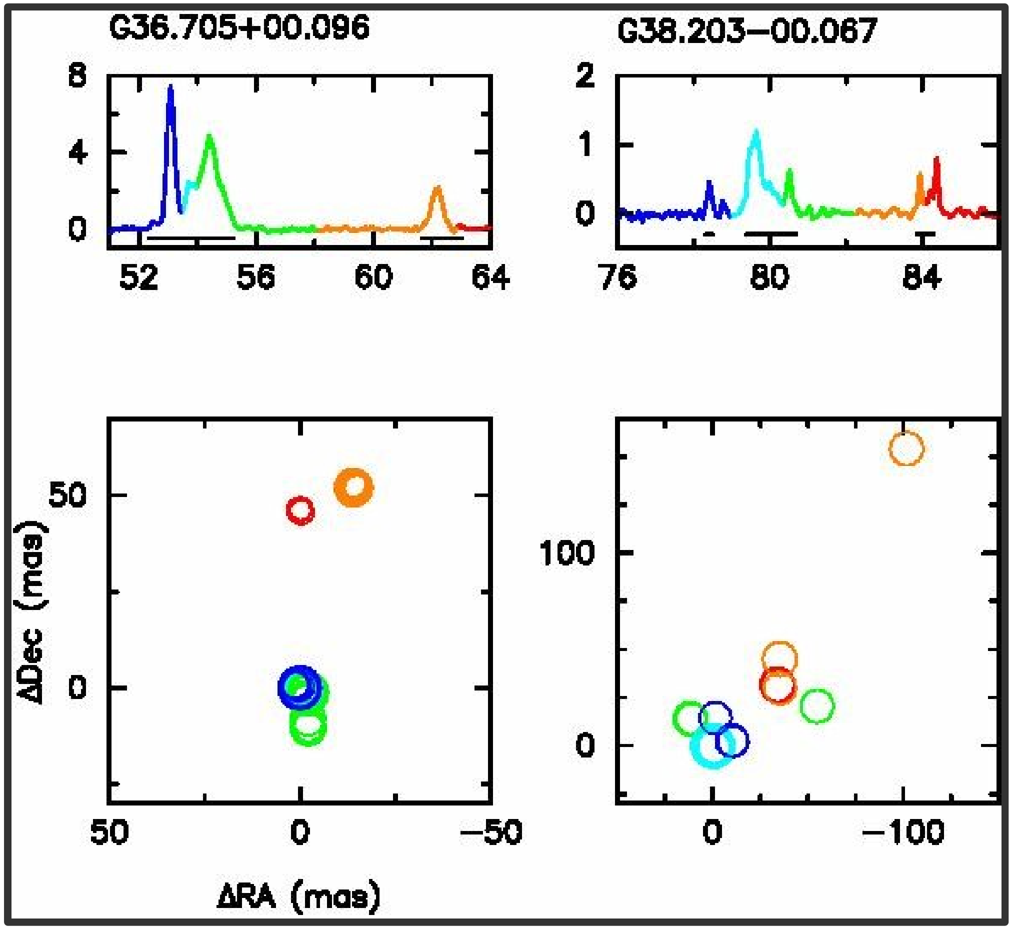

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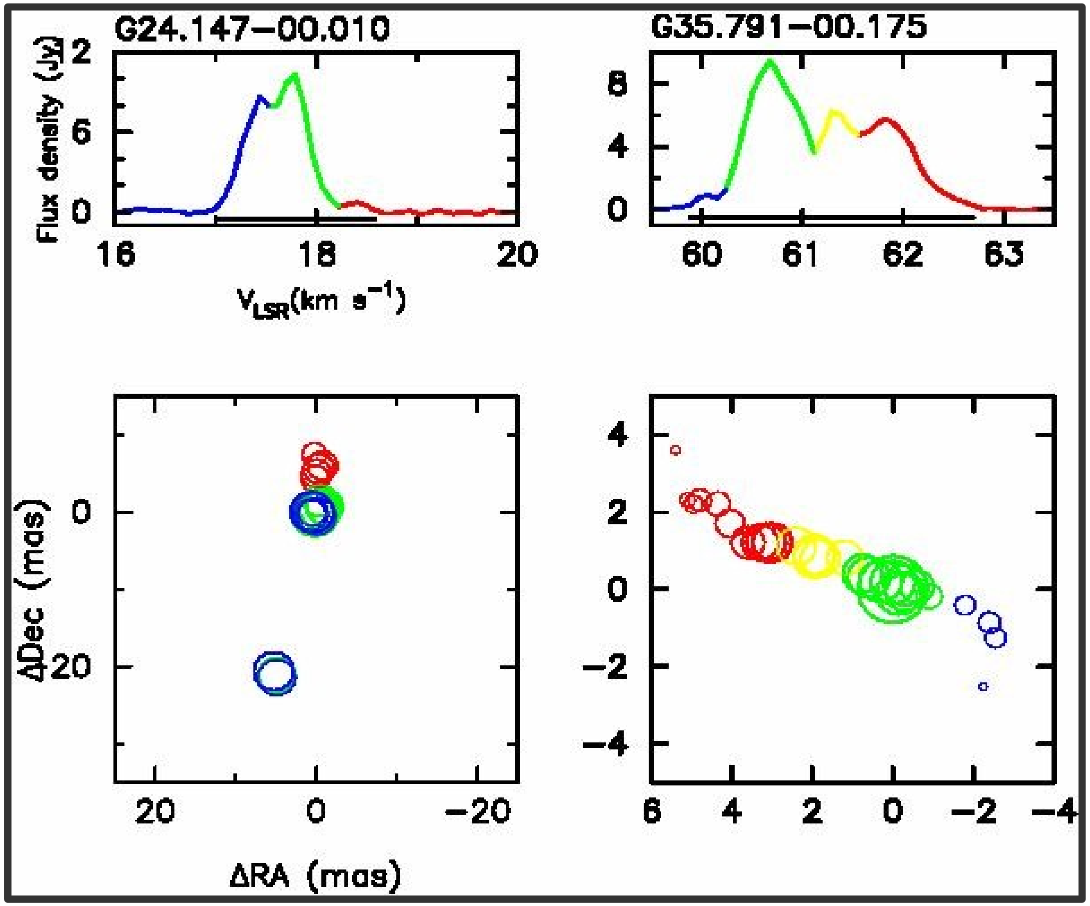
- 3 (9.5%) masers: *linear*



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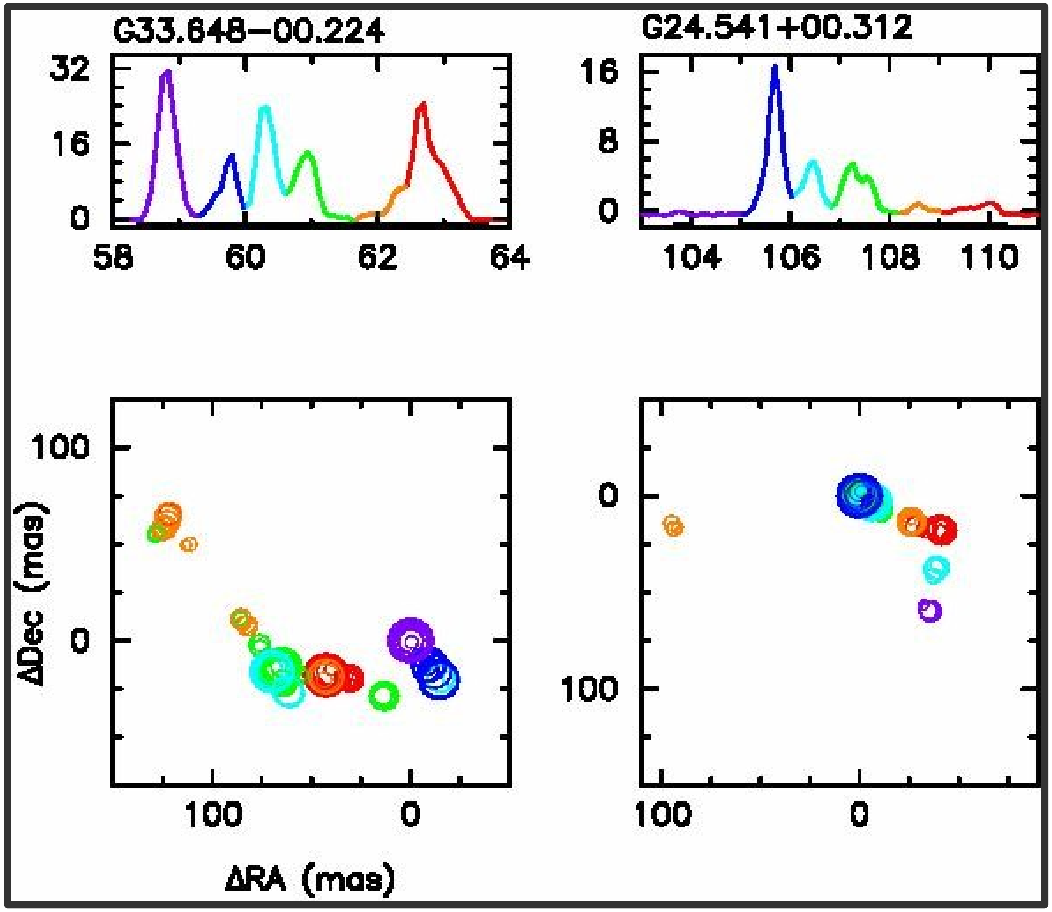
- 3 (9.5%) masers: *arc-like*



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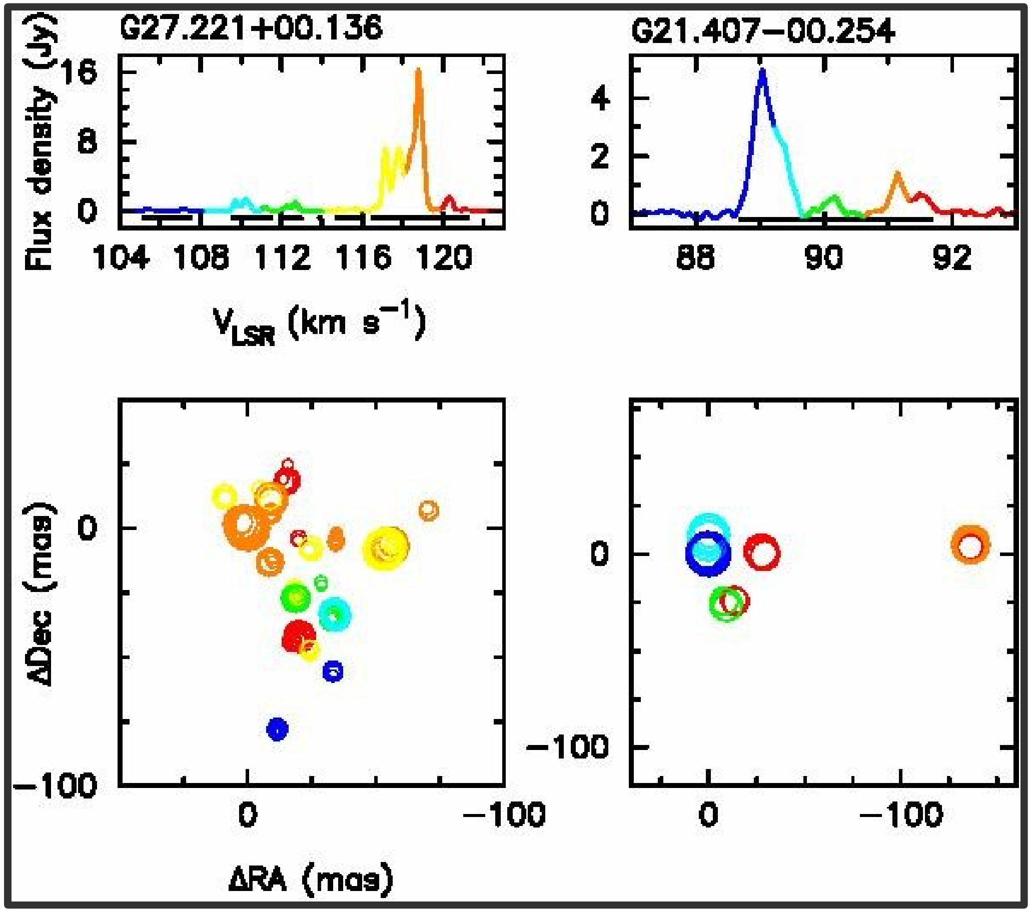
- **7 (23%) masers: *complex***



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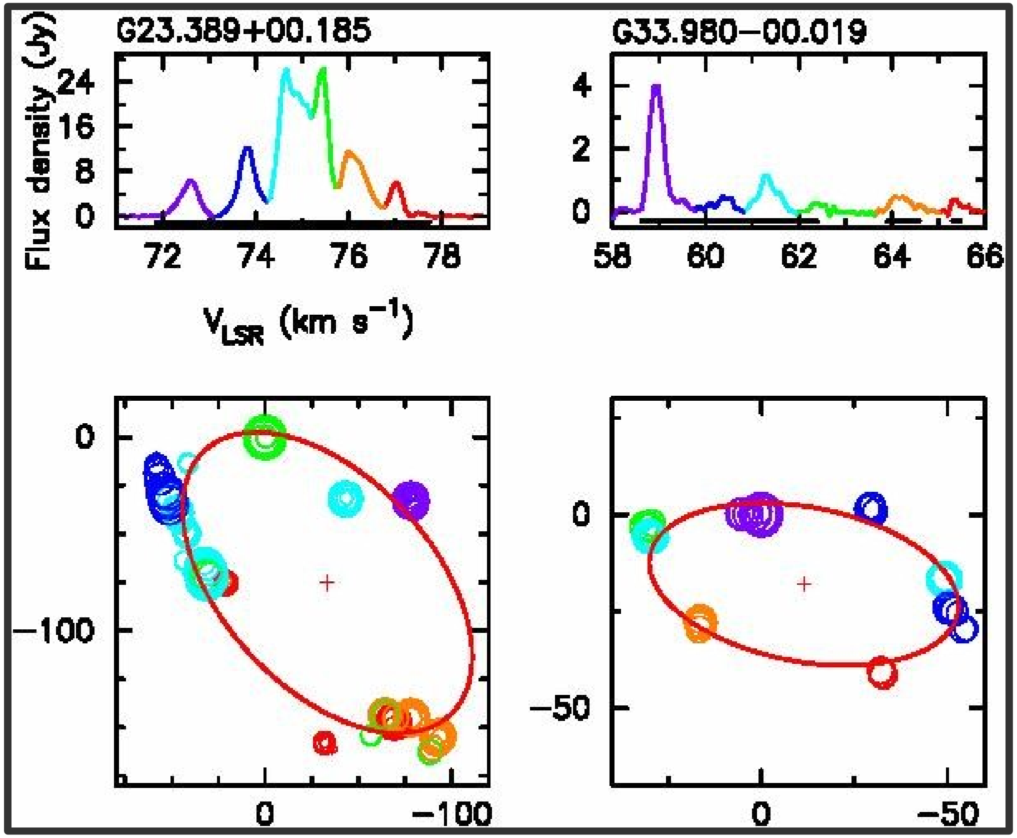
- 7 (23%) masers: *complex*

- 12 (39%) masers: *elliptical*



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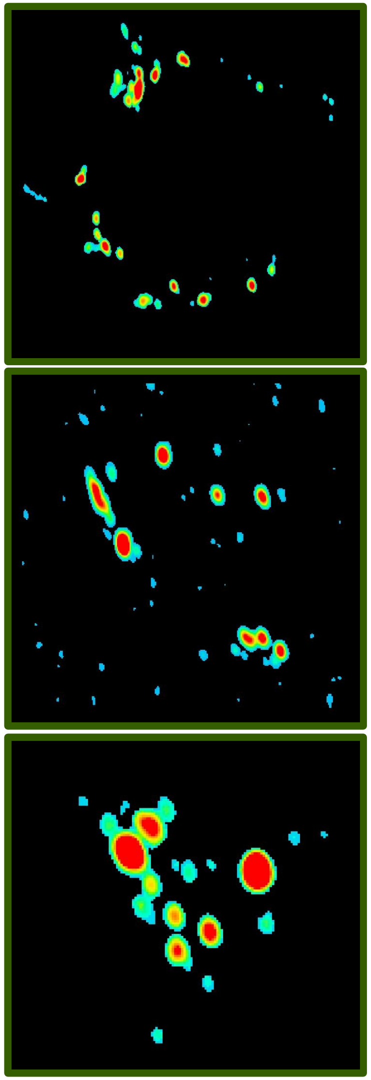


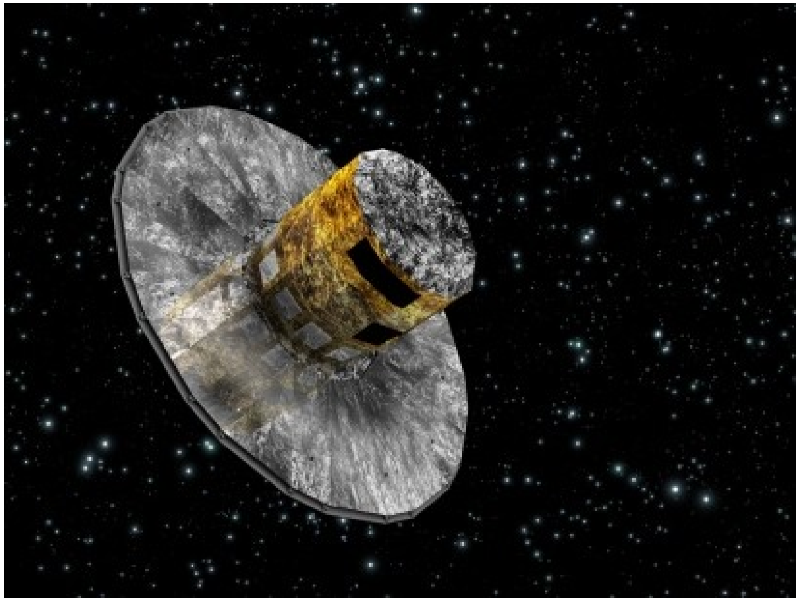
- a large variety of morphologies
- only the tip of the iceberg
- similar for OH and water masers
- VLBI maps of most masers could be done in a reasonable time
- stronger masers need only small dishes
- can be used for follow up parallax measurements

Maser Surveys

Requirements:

• resolution (baselines)	medium (more distant sources are scatter broadened) OK!
• continuum sensitivity (data rates)	low (no very accurate astrometry needed) OK!
• line sensitivity	medium to high OK!
• correlator constraints	1 IF with high spectral resolution OK!
• scheduling constraints	none for OH and methanol, OK! dynamic scheduling for water No!

Trigonometric Parallax



- ESA Cornerstone Mission: GAIA
- Launch: Dez, 2011, Mission ends: 2020
- 10^9 stars with up to ~20 μas
- **But:** large parts of Milky Way obscured by dust (optical)

- Radio waves not obscured by dust
- VLBI can reach accuracies of 10 μas

Observing strategy important

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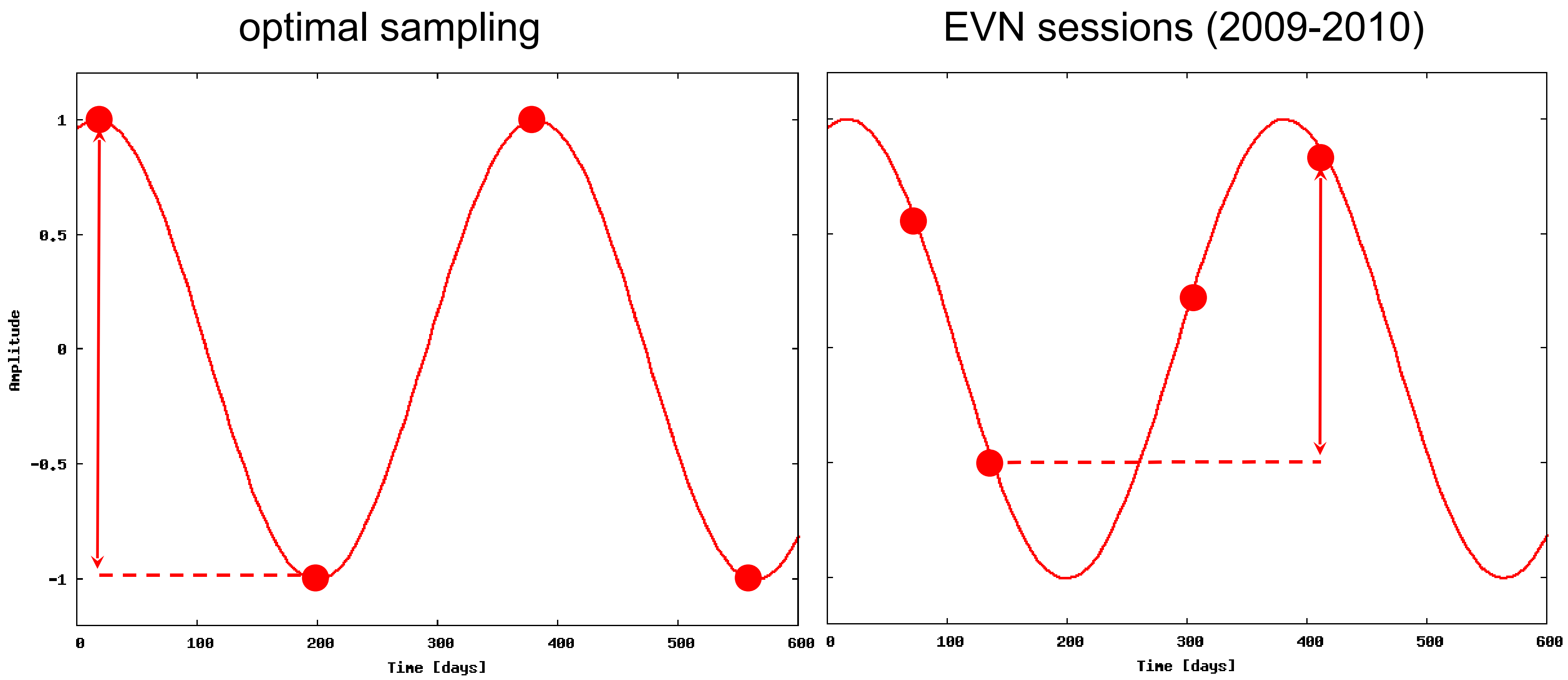
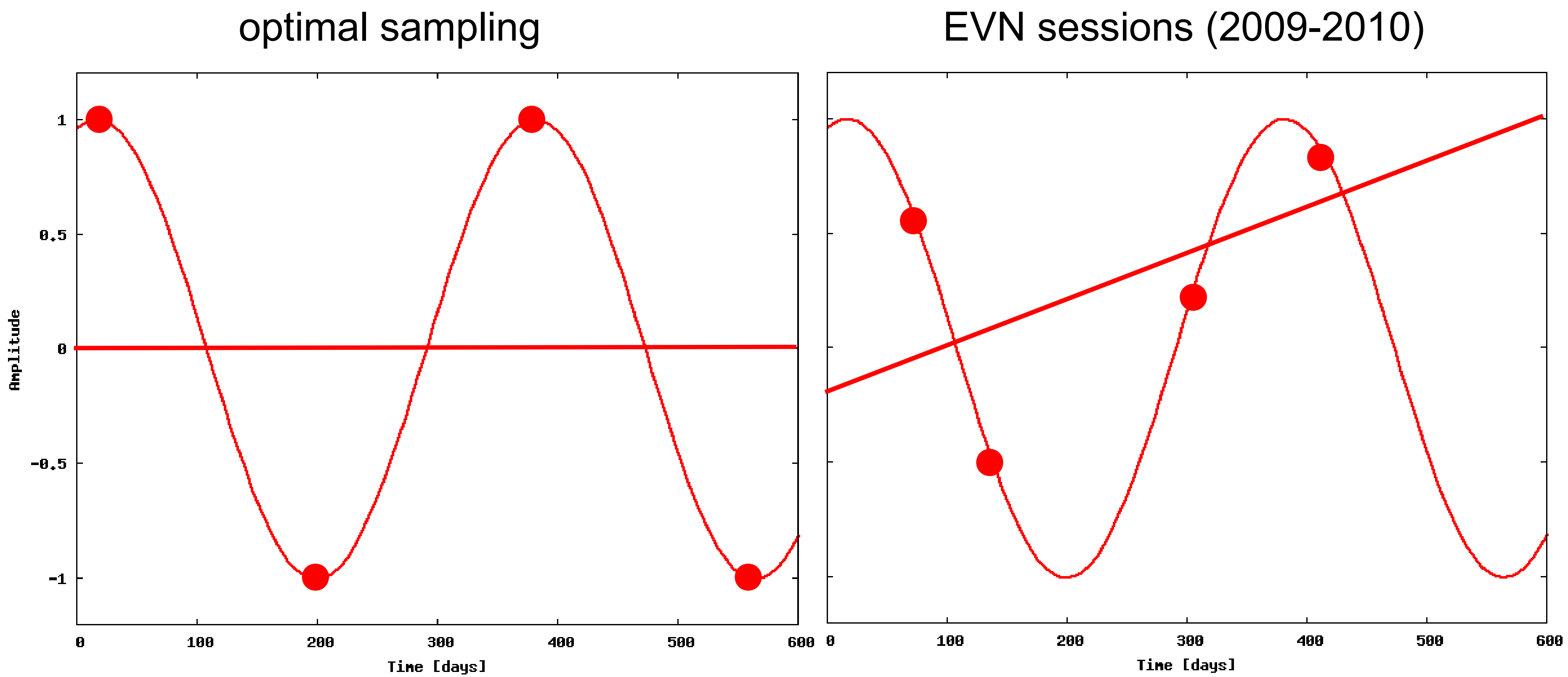


- less accurate (even if accuracy of individual measurements is identical)

Observing strategy important



- less accurate (even if accuracy of individual measurements is identical)
- correlation between parallax and proper motion

Observing strategy important

- optimal sampling important

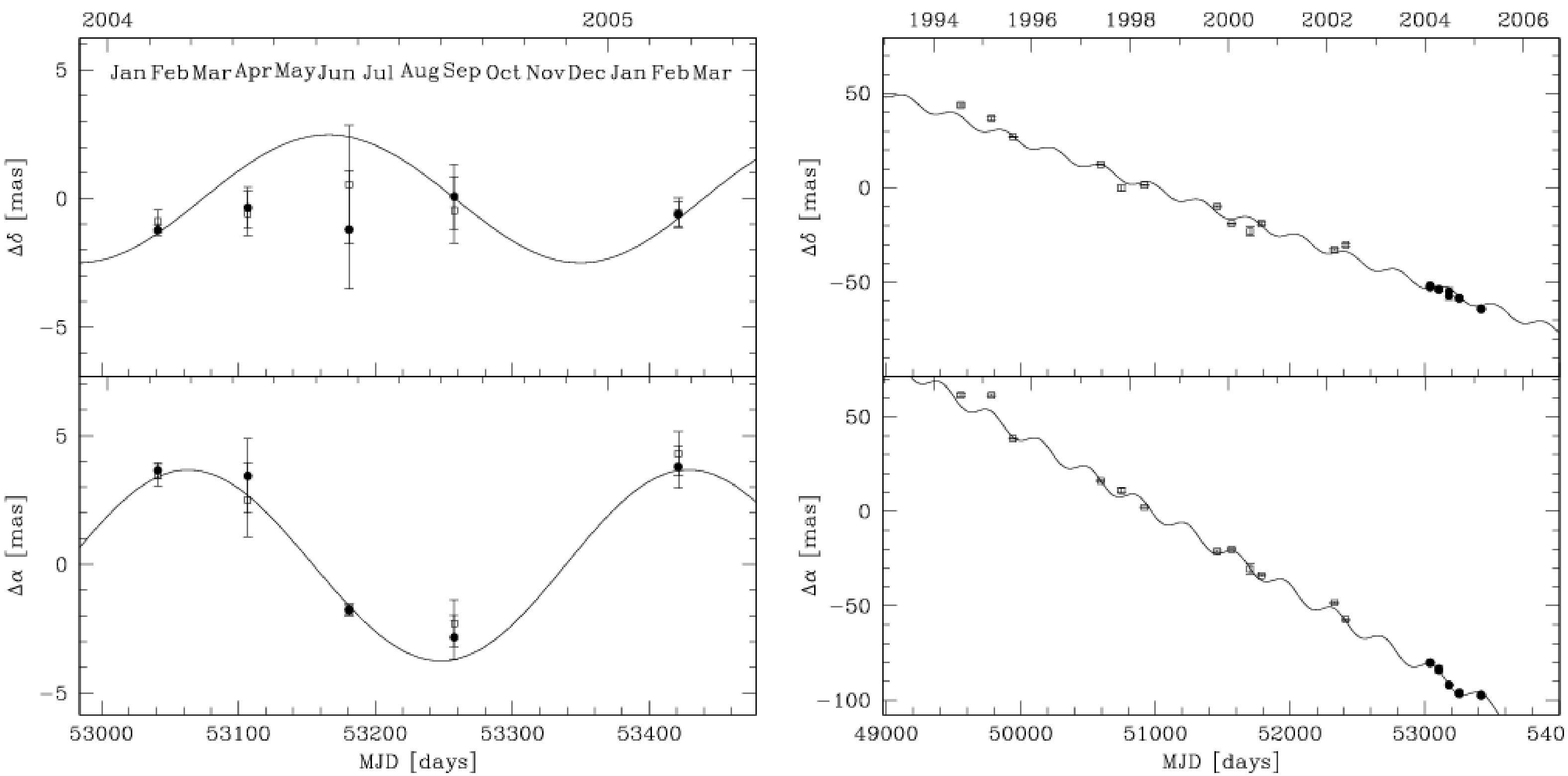
- several nearby calibrators
  - astrometric errors scale with angular separation
  - closer calibrators are usually weaker **(high sensitivity needed)**
  - calibrators can show ‚motions' of ~ 1 mas/yr at lower frequencies
  - in-beam calibrators optimal

- tropospheric calibration reasonably well with GPS or *geodetic blocks*

- ionosphere more problematic (for low frequencies)
  - increasing solar activity

OH Maser Astrometry

- Distances to OH maser AGB stars
- calibrate P-L relation for Mira stars



U Her: $\pi = 3.76 \pm 0.27$ mas

(Vlemmings & van Langevelde 2007)

OH Maser Astrometry

- Distances to OH maser AGB stars
- calibrate P-L relation for Mira stars

- ionosphere a big problem => need calibrators as close as possible
- in-beam calibrators optimal => large FoV, high sensitivity
  - small dishes, high data rates

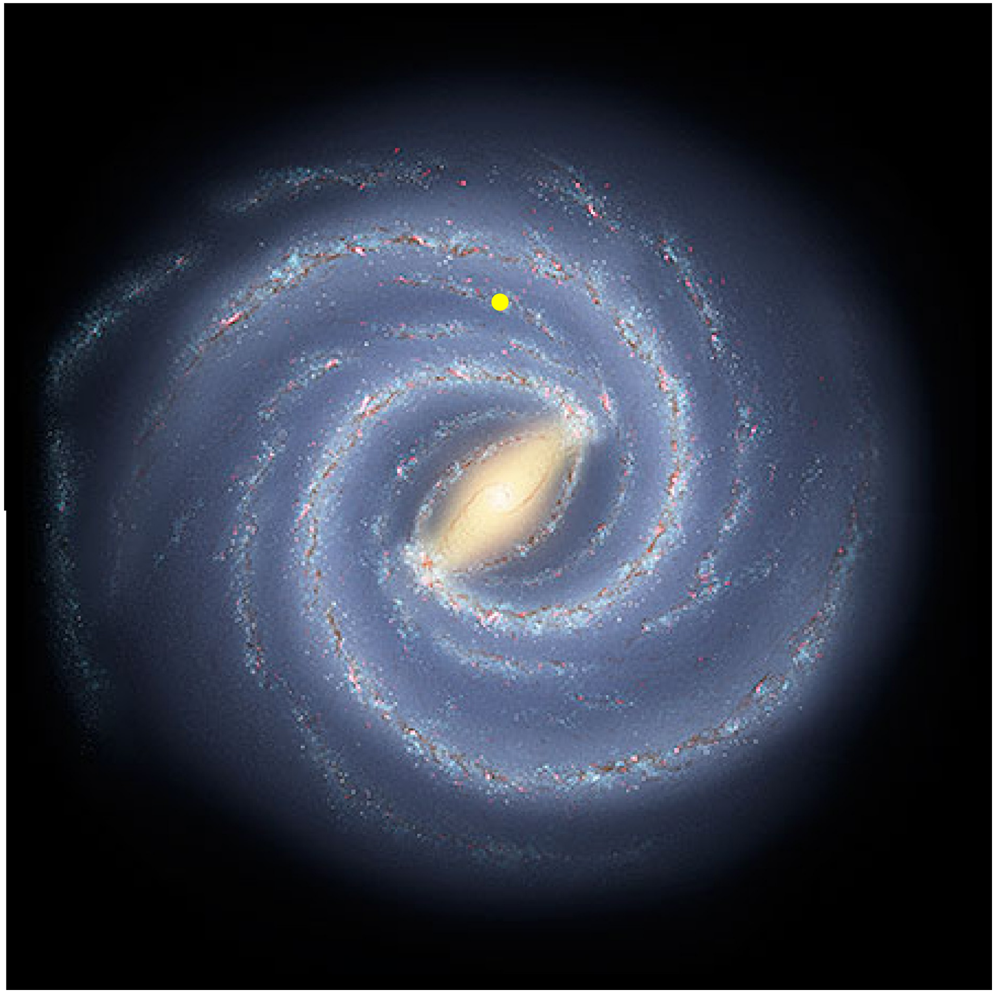
- interstellar scattering => some masers are resolved on longer baselines
- link between eEVN and eMERLIN

Structure of the Milky Way

Structure of the Milky Way still under debate!

- Spiral arms: Number, Positions
- Rotation speed
  Θ_0 = 170 – 270 km/s
- Distance Sun – Sgr A*
  R_0 ~ 8.4 kpc
- IAU recommended values
  Θ_o = 220 km/s
  R_o = 8.5 kpc

Solution: Distances and proper motions on global scale



(R. Hurt, NASA)

Measuring the Milky Way

- Example: W3(OH) in Perseus spiral arm

Kinematic distance: ~ 4.3 kpc

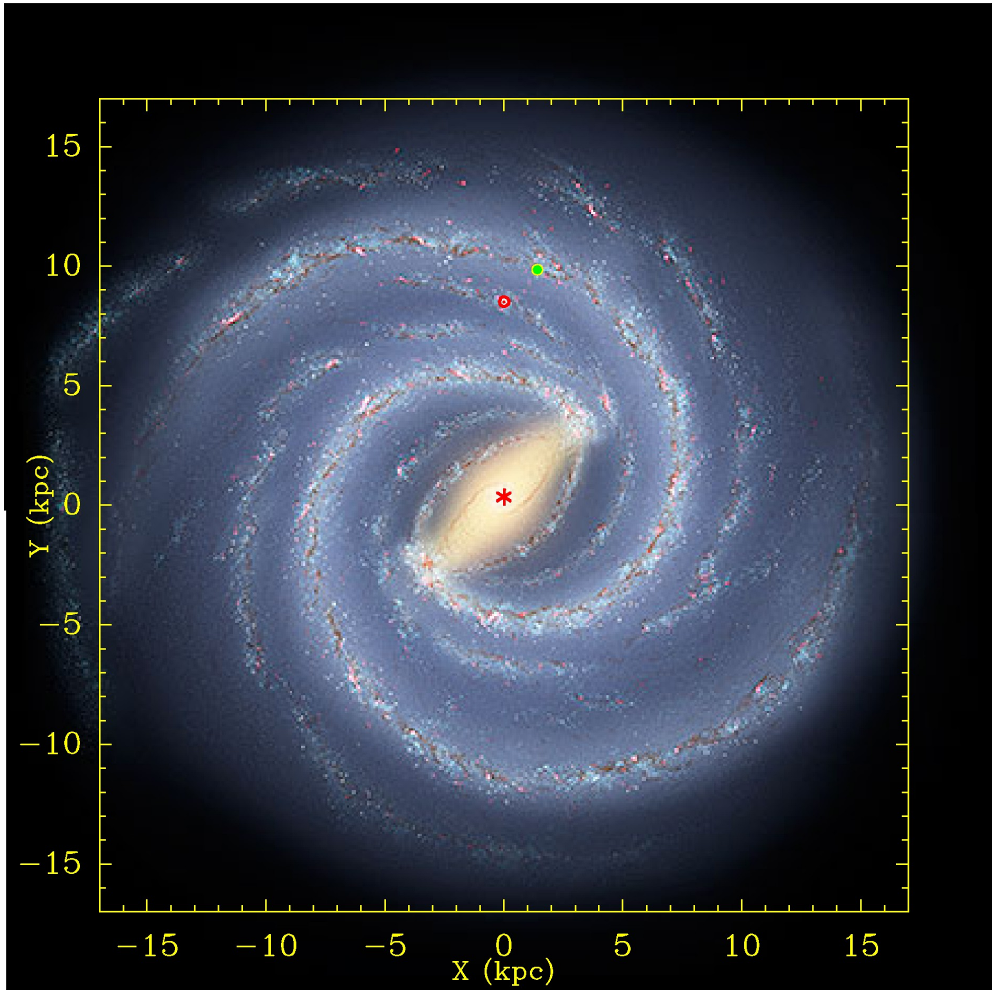
- H_2O (Hachisuka, Brunthaler et al. 2006):

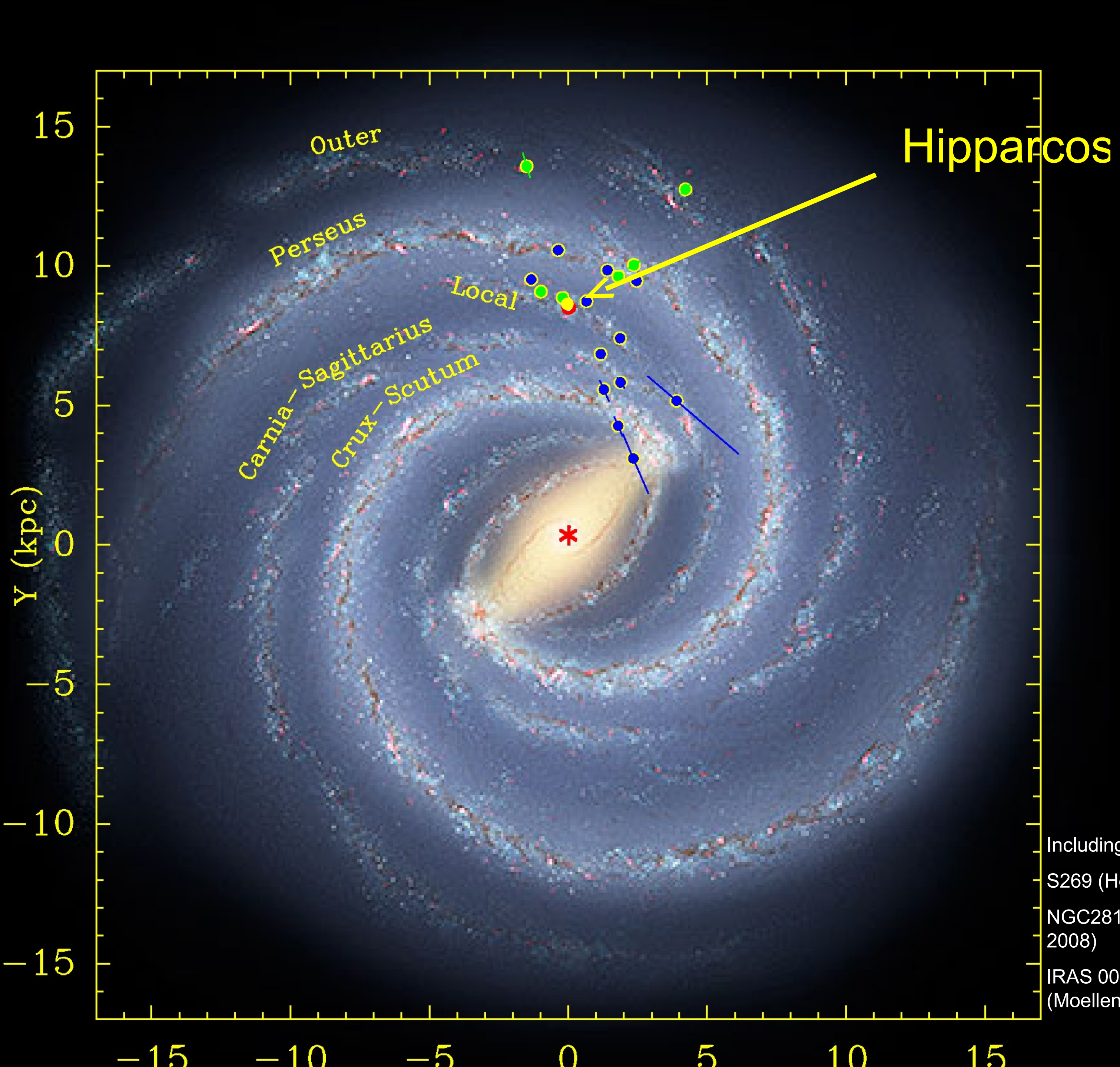
π = 489 ± 17 μas (3.5%)
D = 2.04 ± 0.07 kpc

- CH_3OH (Xu et al. 2006):

π = 512 ± 10 μas (1.9%)
D = 1.95 ± 0.04 kpc

- Motion of ~20 km/s relative to circular orbit





Including:

S269 (Honma et a. 2006)

NGC281 (Sato et al. 2008)

IRAS 00420 (Moellenbrock et al. 2009)

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Current Status:

Source	Distance [kpc]	U [km/s]	V [km/s]	W [km/s]	Reference
W3(OH)	1.95 ± 0.04 2.04 ± 0.07	17 ± 1	-14 ± 1	-0.8 ± 0.5	Xu et al. 2006 Hachisuka et al. 2006
Orion	0.414 ± 0.007	-8 ± 1	-11 ± 2	3 ± 2	Menten et al. 2007
G23.657-00.127	3.19 ± 0.4	42 ± 6	2 ± 3	4 ± 1	Bartkiewicz et al. 2008
VY CMa	1.14 ± 0.09	1 ± 3	-16 ± 2	-6 ± 2	Choi et al. 2008
S252	2.10 ± 0.027	-4 ± 3	-16 ± 1	-2 ± 1	Reid et al. 2009
G232.6+1.0	1.68 ± 0.1	-4 ± 3	-10 ± 3	0 ± 2	Reid et al. 2009
Cep A	0.70 ± 0.04	5 ± 3	-12 ± 3	-5 ± 2	Moscadelli et al. 2009
NGC7538	2.65 ± 0.12	25 ± 2	-30 ± 3	-10 ± 1	Moscadelli et al. 2009
G59.7+0.1	2.16 ± 0.1	7 ± 1	-10 ± 3	-4 ± 1	Xu et al. 2009
W51 IRS2	5.1 +2.9 -1.4	21 ± 15	-5 ± 10	-3 ± 5	Xu et al. 2009
G35.20-0.74	2.19 ± 0.22	0 ± 2	-13 ± 3	-8 ± 2	Zhang et al. 2009
G35.20-1.74	3.27 ± 0.5	1 ± 7	-16 ± 5	-9 ± 3	Zhang et al. 2009
G23.01-0.41	4.59 ± 0.35	37 ± 7	-29 ± 5	-1 ± 3	Brunthaler et al. 2009
G23.44-0.18	5.88 ± 1.4	22 ± 27	-26 ± 8	2 ± 3	Brunthaler et al. 2009
WB89-437	6.0 ± 0.2	23 ± 3	-4 ± 6	1 ± 1	Hachisuka et al. 2009
Sun	0	10.0 ± 0.4	5.2 ± 0.6	7.2 ± 0.4	Dehnen & Binney 1998

(almost) **All sources rotate slower than Milky Way!**

Systematic Motions

- (most) sources rotate slower than Milky Way, independent of rotation model
- (most) sources are closer (few – 50 %) than their kimenatic distance!
- Fitted different Galactic rotation models to 6d data

Table 4. Least-squares Fitting Results

Fit	R_0 (kpc)	Θ_0 (km s^{-1})	$\frac{d\Theta}{dR}$ (km s^{-1} kpc^{-1})	$\overline{U_s}$ (km s^{-1})	$\overline{V_s}$ (km s^{-1})	$\overline{W_s}$ (km s^{-1})	χ^2	DF	Θ_0/R_0 (km s^{-1} kpc^{-1})
1	8.24±0.55	265±26	0.0	0.0	0.0	0.0	263.3	70	32.4±1.3
2	8.50±0.44	264±19	0.0	3.9±2.5	−15.9±2.1	3.1±2.5	111.5	67	31.1±1.1
3	8.40±0.36	254±16	0.0	2.3±2.1	−14.7±1.8	3.0±2.2	66.7	59	30.3±0.9
4	9.04±0.44	287±19	2.3±0.9	1.9±2.0	−15.5±1.7	3.0±2.1	59.0	58	31.1±0.9
5	8.73±0.37	272±15	Clemens-10	1.7±1.9	−12.2±1.7	3.1±1.9	52.9	59	31.0±0.8
6	7.88±0.30	230±12	Clemens-8.5	2.7±2.2	−12.4±1.9	3.1±2.3	71.2	59	29.6±1.0
7	8.79±0.33	275±13	Brand-Blitz	1.9±2.0	−18.9±1.8	3.0±2.1	59.0	59	31.0±0.9

– 17 –

Note. — Fits 1 & 2 used all 18 sources in Table 1 and have high χ^2 values, owing to two outliers: NGC 7538 and G 23.6−0.1. Fit 3 excludes the two outliers and provides our basic result, under the assumption of a flat rotation curve. Fits 4 – 7 explore the effects of non-flat rotation curves. "DF" is the degrees of freedom for the fit (i.e. number of data equations minus number of parameters). ($\overline{U_s}$,$\overline{V_s}$,$\overline{W_s}$) are average peculiar motions common to all sources (see Table 7 and Fig. 7), assuming the Hipparcos solar motion of Dehnen & Binney (1998) (see discussion in §3.1). All Θ_0/R_0 estimates were obtained by holding $R_0 = 8.50$ kpc and solving for Θ_0. "Clemens-10" and "Clemens-8.5" refer to the Clemens (1985) rotation curves for (R_0[kpc],Θ_0[km s^{-1}]) = (10,250) and

Galactic Rotation Model Fits

	Maser Parallaxes	IAU	Independent Measurements
R_0 [kpc]	8.4 ± 0.6	8.5	8.4 ± 0.4 (Ghez et al. 2008) 8.33 ± 0.35 (Gillessen et al. 2009)
Θ_0 [km/s]	254 ± 16	220	
Θ_0/R_0 [km/s/kpc]	30.3 ± 0.9	25.9	29.45 ± 0.15 (Reid & Brunthaler 2004)

Average peculiar motions:

$U_s = 2.3 \pm 2.1$ km/s, $V_s = -14.7 \pm 1.8$ km/s, $W_s = 3.0 \pm 2.2$ km/s

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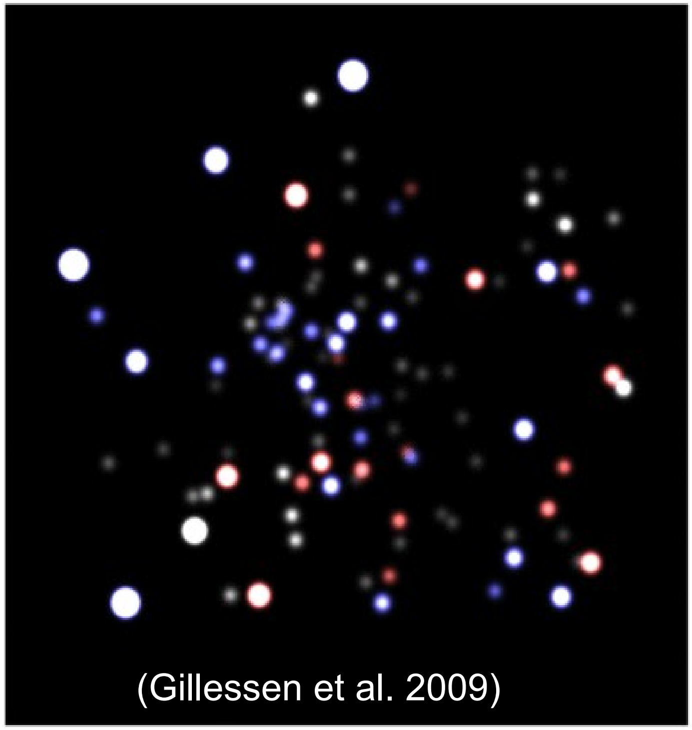
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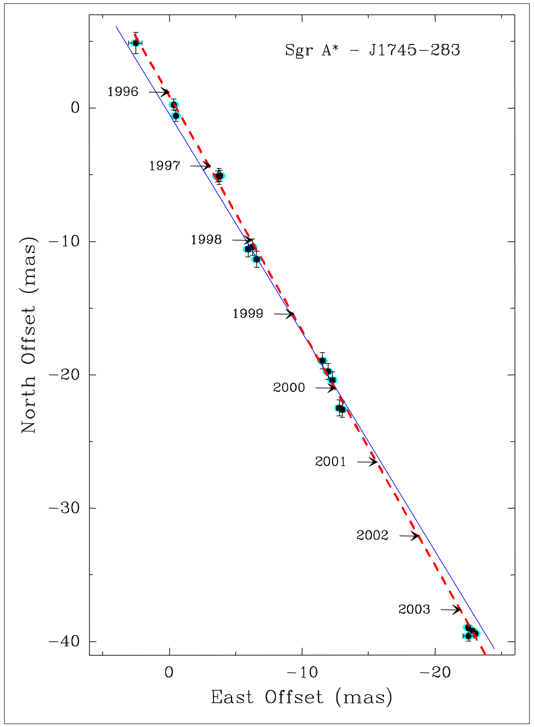

First EVN results

- Project to measure parallaxes of 6.7 Methanol masers with the EVN
- 5 epochs between June 2006 and March 2008
- 8 maser sources with 2 background quasars each in 24 hours
- ON1, L1287, L1206, NGC 281-W, Mon R2, S252, S255, S269
- only 25 min on each quasar and 75 min on each maser
- Telescopes: EF, TR, MC, NT, ON, WB(1), JB, CM, HH, EVLA(1)

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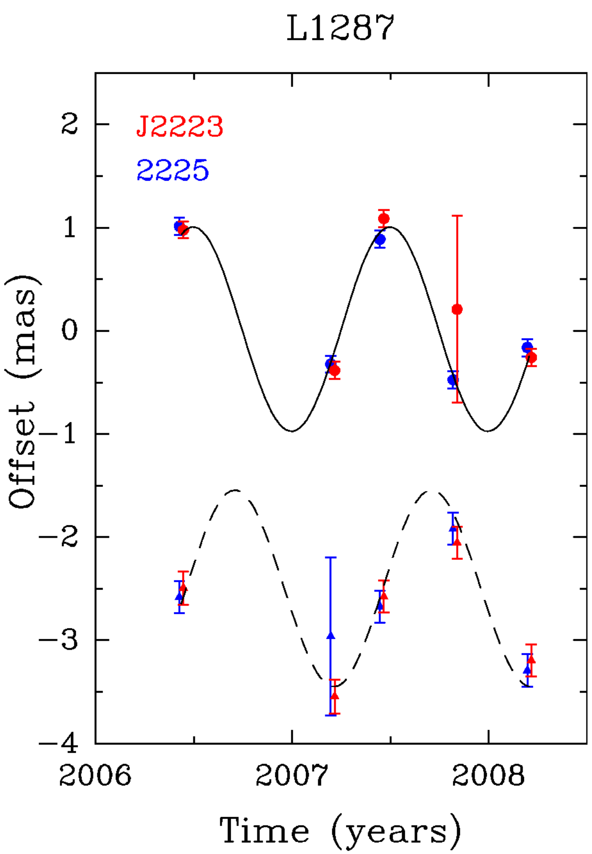
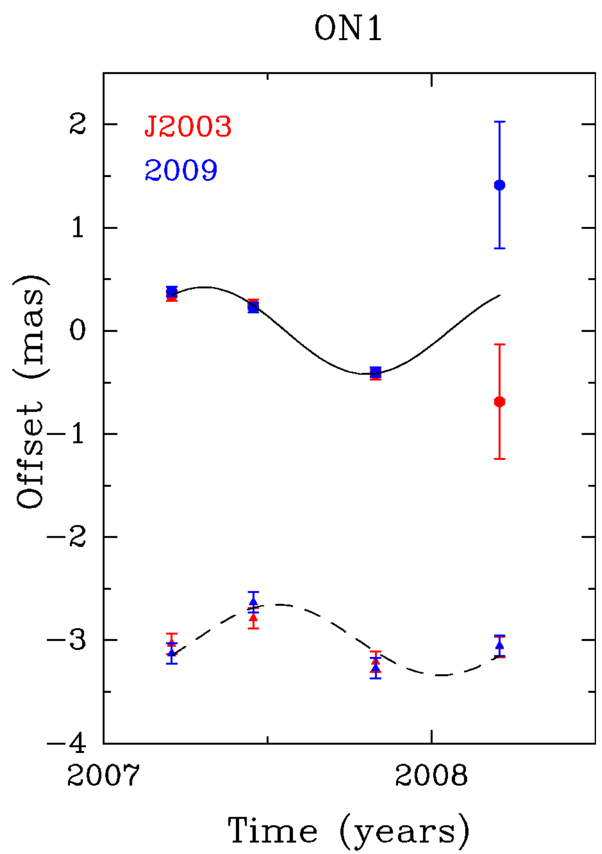
First EVN results



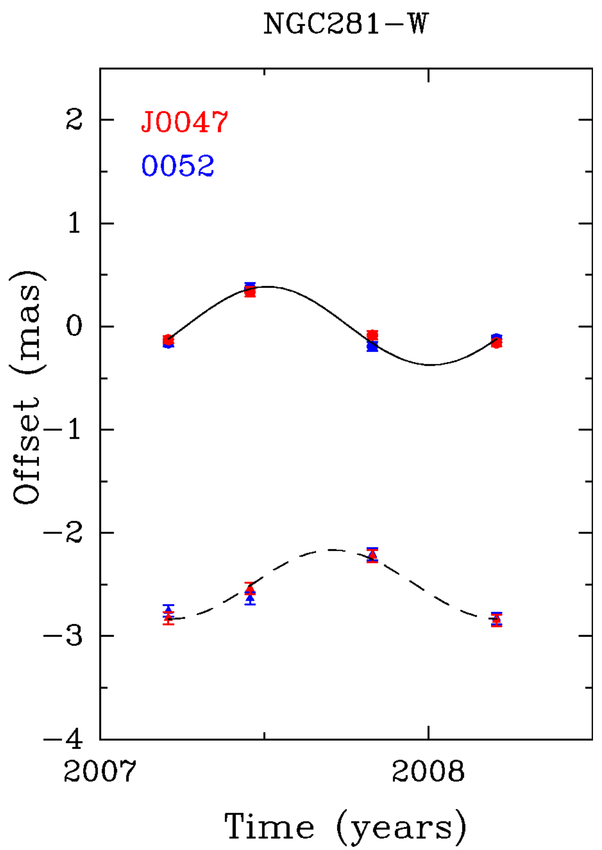
$\pi = 1076 \pm 39\ \mu as$



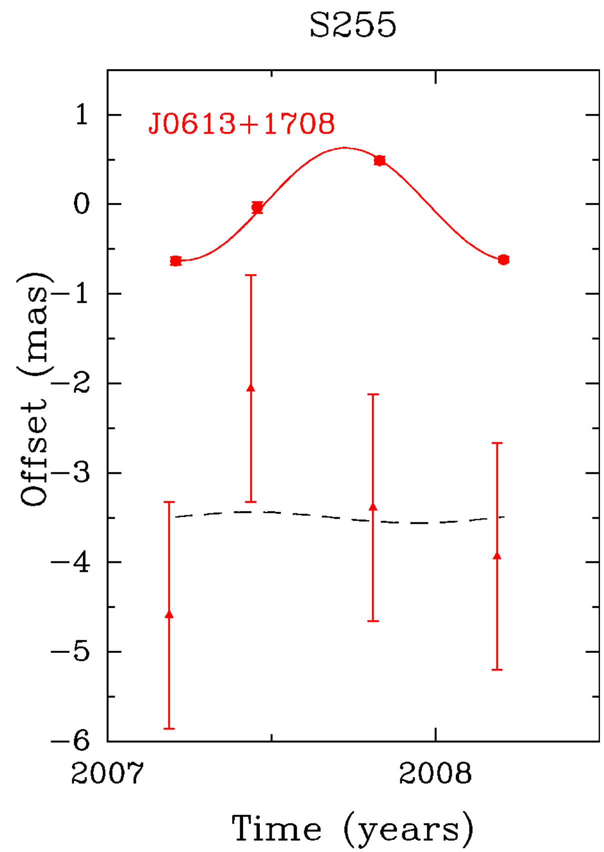
$\pi = 432 \pm 24\ \mu as$

- 4 sources with accuracies better than 40 μas

First EVN results



π = 421 ± 22 μas



π = 628 ± 38 μas

- 4 sources with accuracies better than 40 μas

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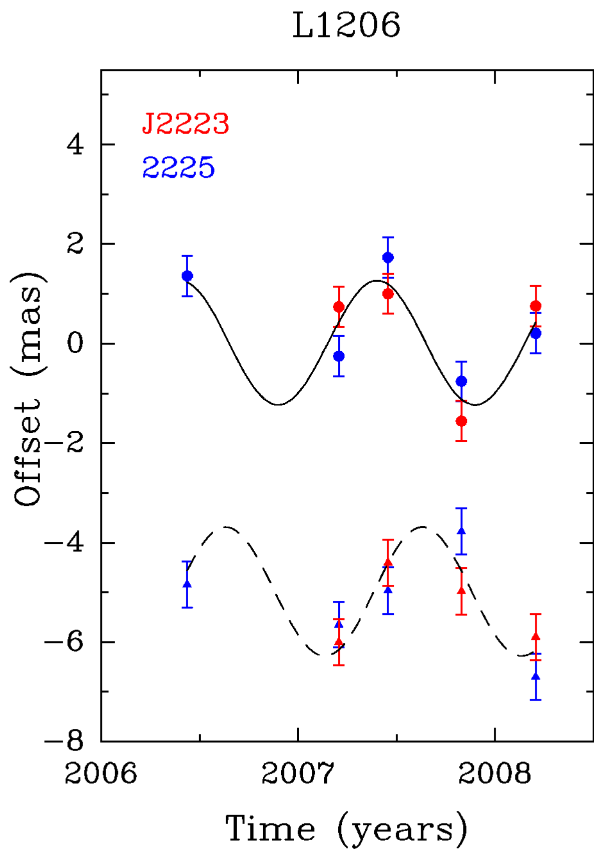

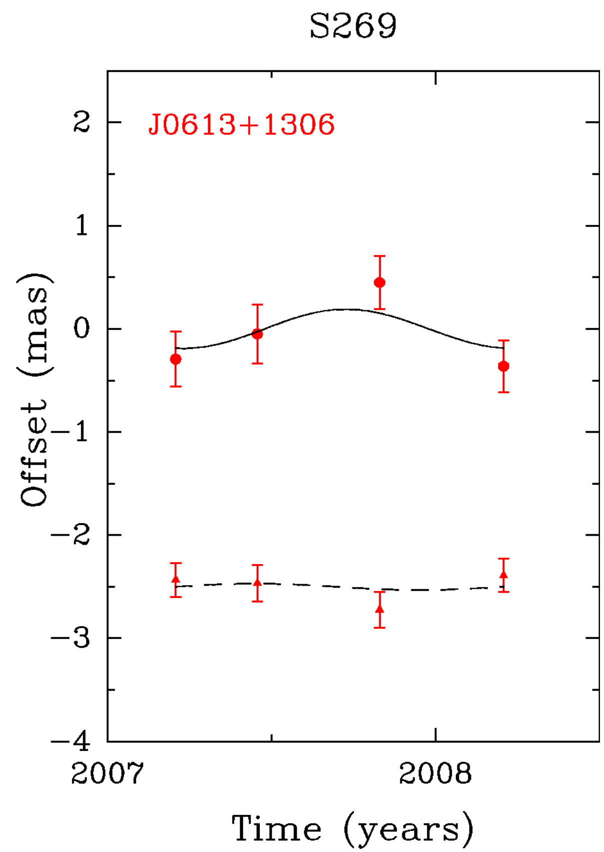

$\pi = 1343 \pm 153\ \mu as$

- 4 sources with accuracies better than 40 μas
- 1 source with accuracy of ~ 150 μas
- 3 sources with no good parallax

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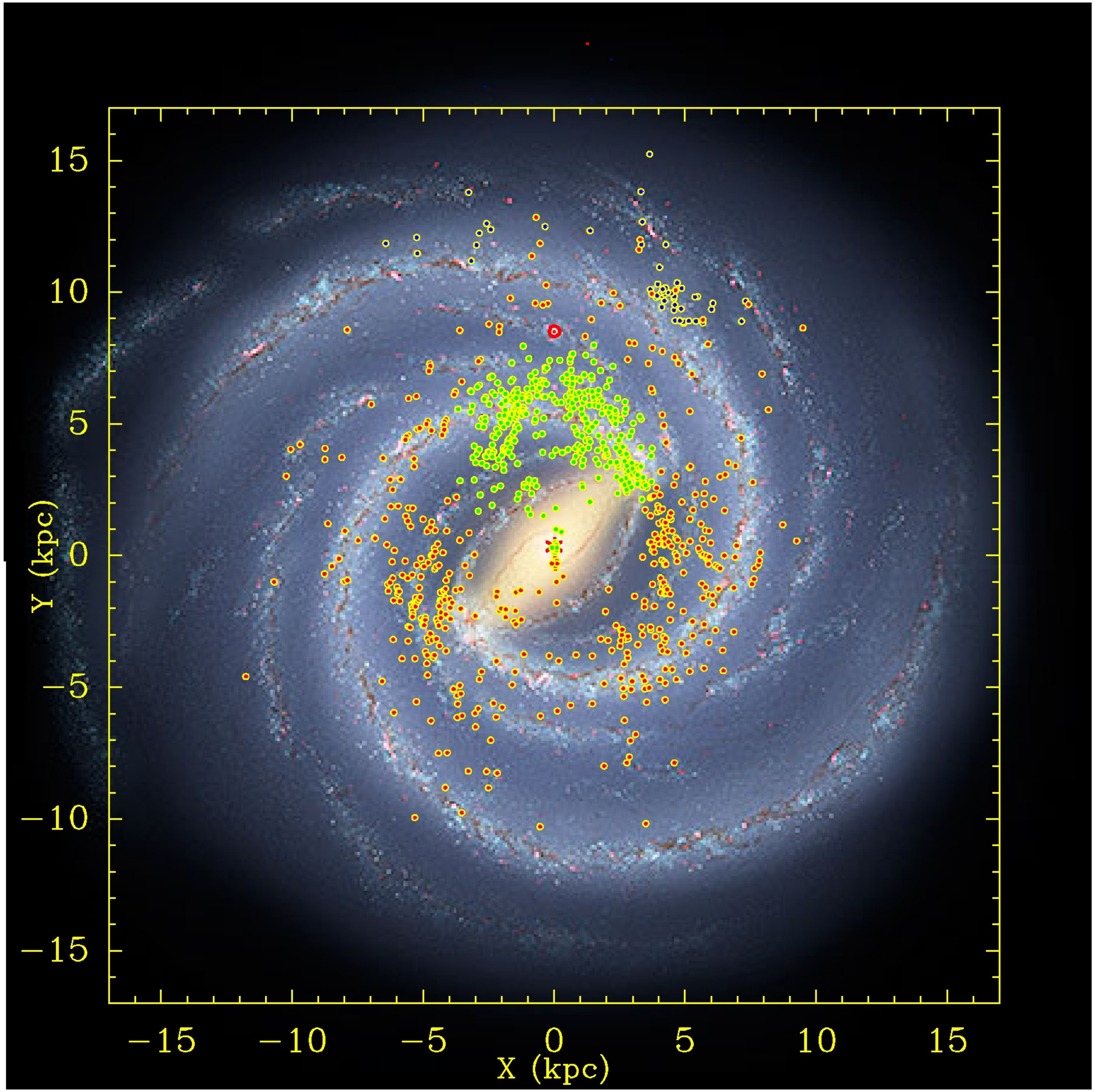
Much more is out there…



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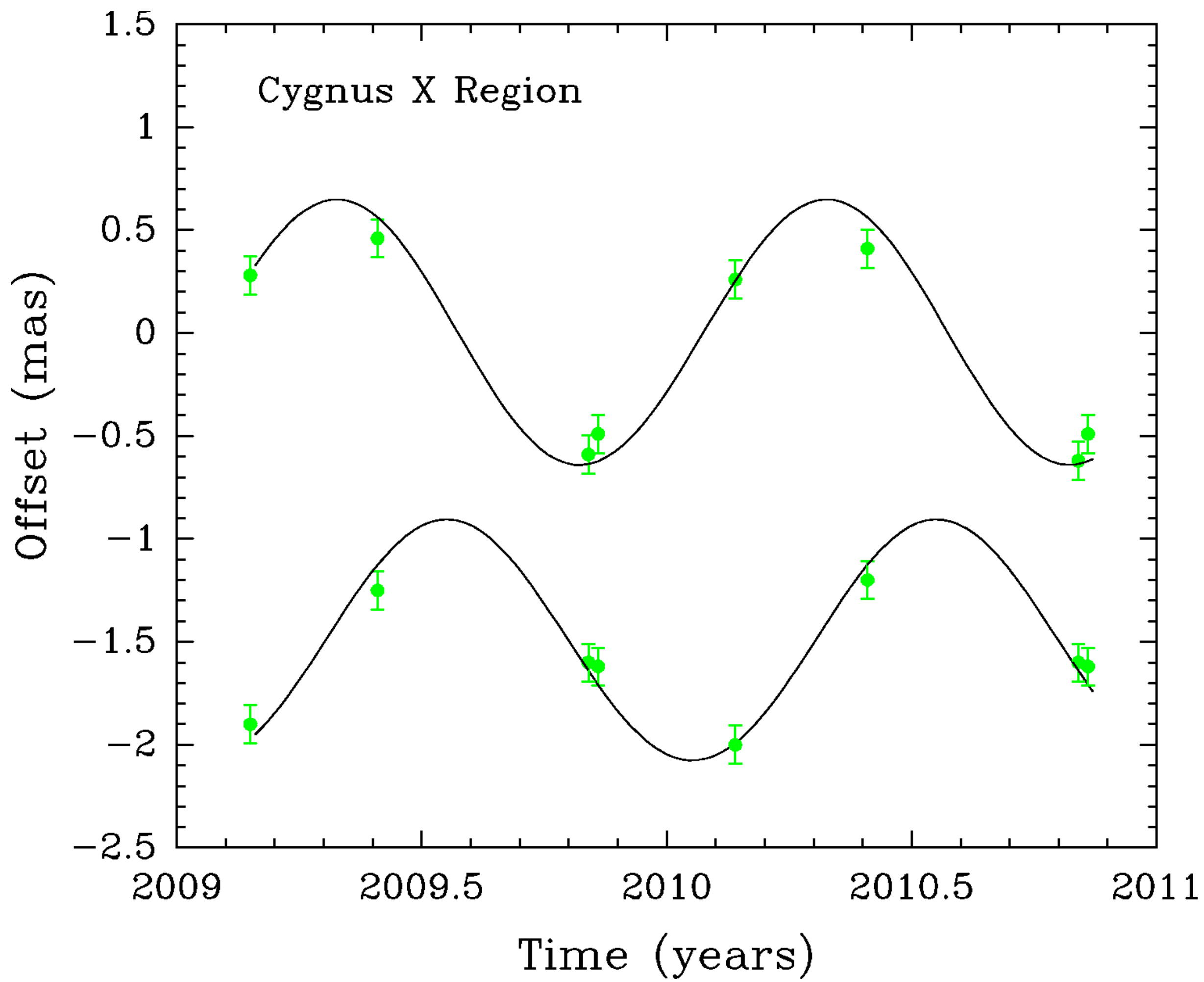
Much more is out there…

- close to optimal sampling possible for some sources with current EVN sessions



Much more is out there…

- close to optimal sampling possible for some sources with current EVN sessions

- eVLBI is needed for most sources

- a large parallax survey has many different science products:

  - accurate distances to most high mass star forming regions in the Galaxy
  - 3d space motions of most high mass star forming regions
  - improved rotation model of the Milky Way: R_0 and Θ_0 to 1%
  - location and number of spiral arms
  - internal kinematics of most high mass star forming regions

- in particular the southern hemisphere is unexplored => eVLBI in Australia

eVLBI Astrometry

Requirements:

• resolution (baselines)	high (more distant sources are scatter broadened) **Not yet!**
• continuum sensitivity (data rates)	high (calibrators as close as possible) **OK!**
• line sensitivity	high **OK!**
• correlator constraints	1 IF with high spectral resolution all IFs with low resolution **No!**
• scheduling constraints	measuring the peak of the parallax **OK!** dynamic scheduling for water **No!**

Conclusions

Great spectral line science possible with eVLBI

- more telescopes needed
  - e.g. long baselines to Korea, China, and Japan
  - what about the gap in between?
  - also shorter baselines (for highly resolved sources): eEVN + eMERLIN?

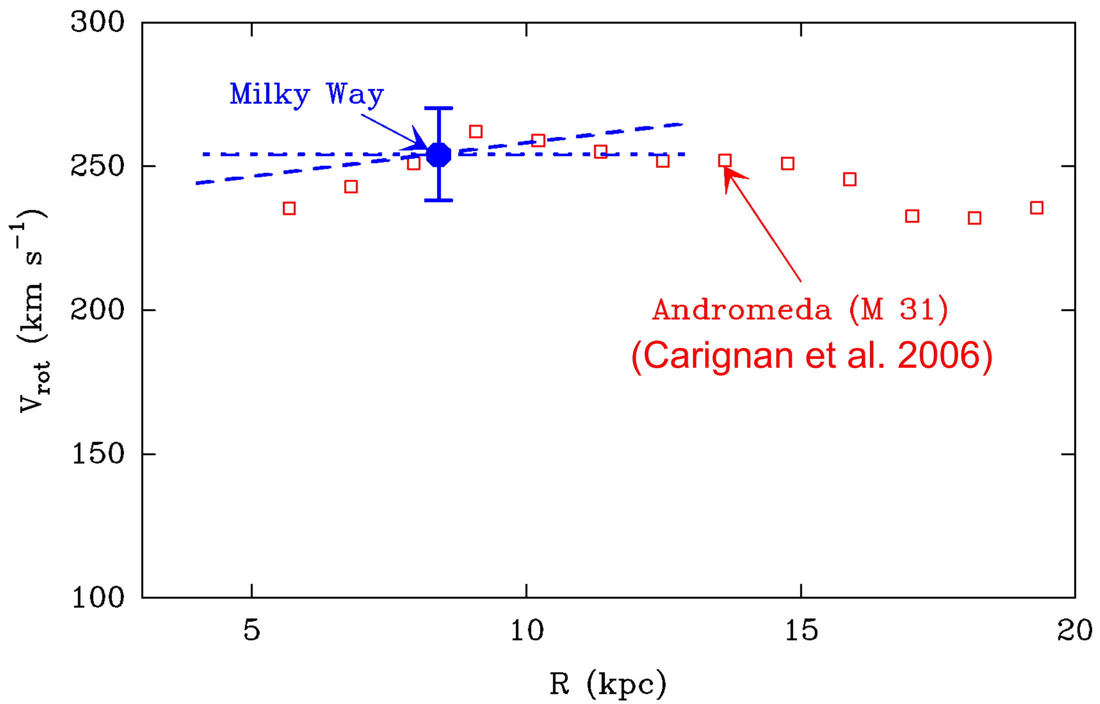
- high data rates needed (even for spectral lines)

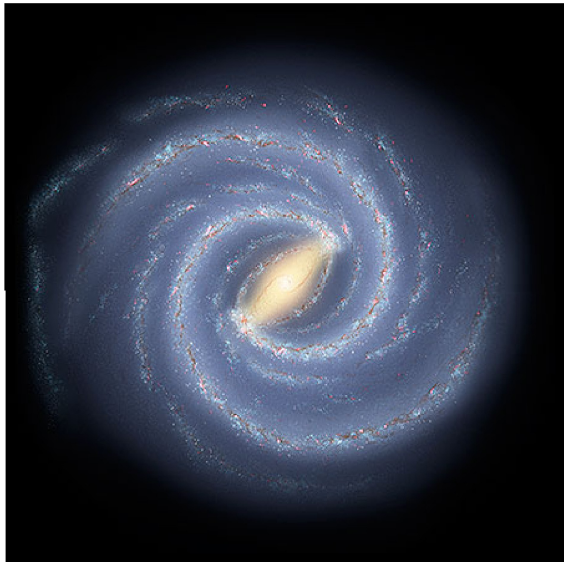
- new correlator needed
  - high spectral resolution and large bandwidth in one correlator pass

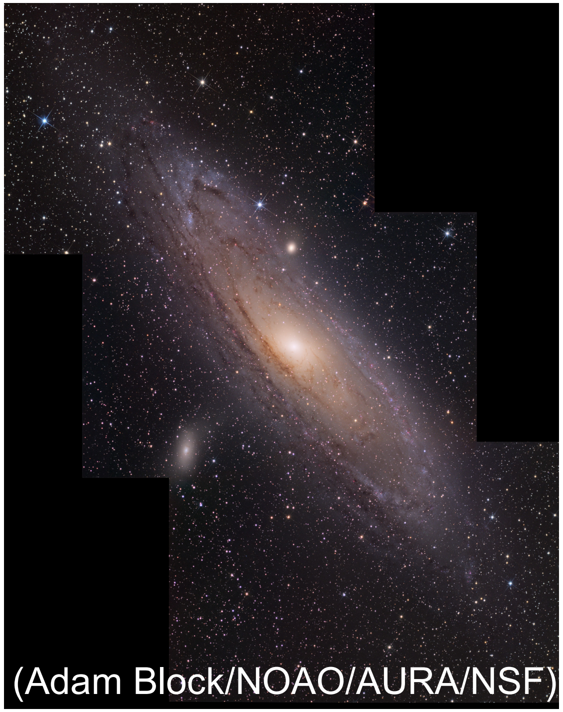
- more flexible scheduling
  - more time
  - more frequencies
  - dynamical scheduling

The Milky Way and Andromeda

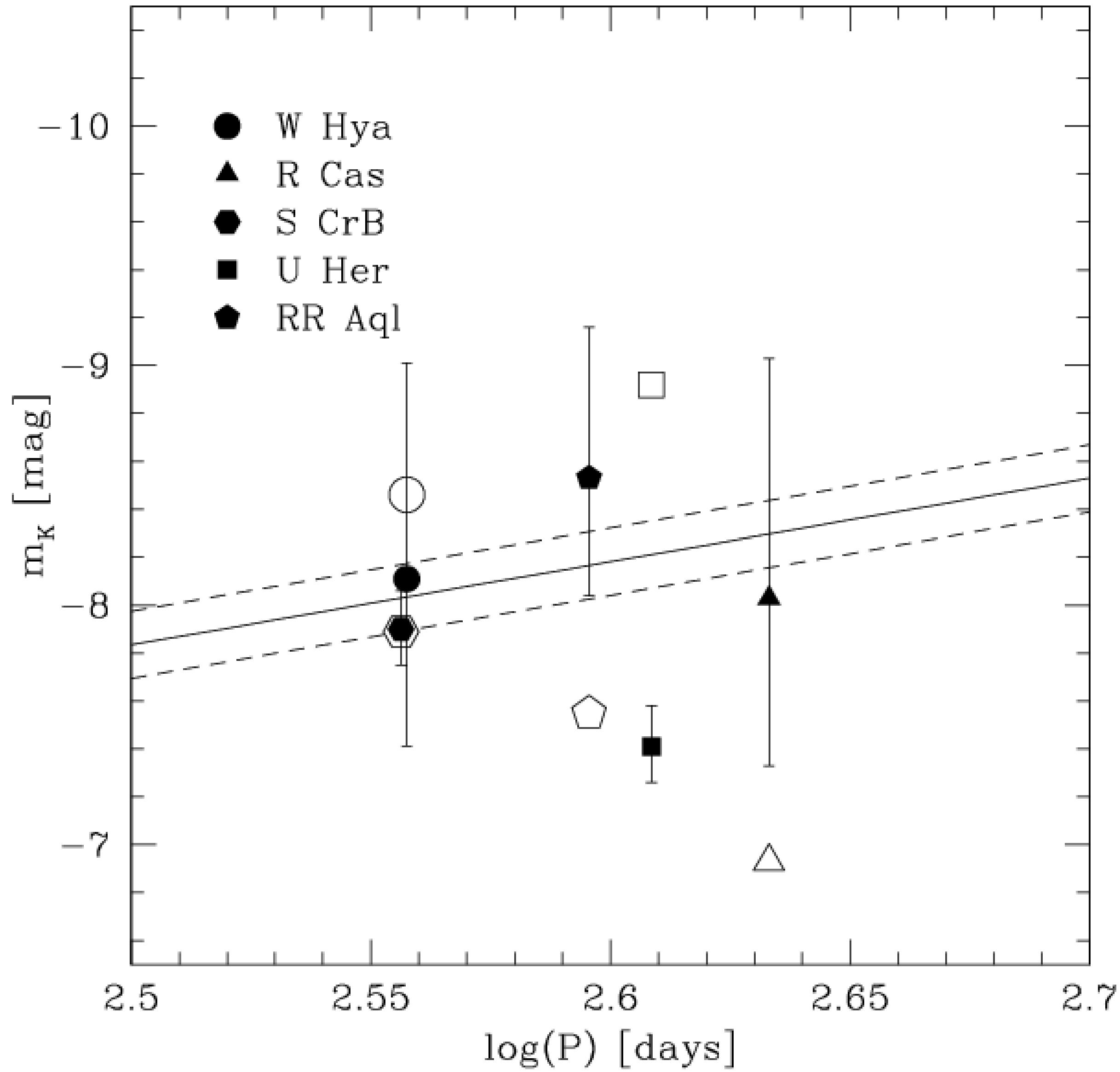
- Rotation curves of both Galaxies are now similar
- This implies very similar masses







OH Maser Astrometry



(Vlemmings & van Langevelde 2007)