

Masers and the structure of the Milky Way



Andreas Brunthaler for the BeSSeL Team



Structure of the Milky Way

Structure of the Milky Way still under debate!

- Spiral arms: Number, Positions?
- Rotation speed of LSR: $\Theta_0 = 170 - 270 \text{ km/s}$
- Distance Sun Sgr A*: R₀ ~ 8.4 kpc (± 5%)
- IAU recommended values:

 Θ_{o} = 220 km/s R_o= 8.5 kpc





Galactic Plane Surveys





Structure of the Milky Way

Going to the third dimension!









Going to the third dimension!

- Current Milky Way surveys are only 2d (*I*,*b*) (sometimes v_{ISR}).
- Accurate distances needed to go to 3d.
- Kinematic distances highly unreliable.



Structure of the Milky Way





Going to the third dimension!

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Trigonometric parallaxes are "gold standard"

- Gaia parallaxes not yet accurate enough
- Gaia will be limited in the dusty spiral arms
- Radio observations not affected by dust => VLBI astrometry



VLBI Parallaxes: Example





Rygl et al. (2012)

Image: van Langevelde





- **B**ar and **S**piral **S**tructure Legacy survey, a VLBA Key Science project
- ~ 5000 hours over 5 years
- ~ 250 masers
- BeSSeL will yield accurate distances to most HMSFR, locate the spiral arms and the bar, measure R₀ and Θ₀ to ~1%, and measure the rotation curve.



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• Also first projects in southern hemisphere (Australian LBA, with S. Ellingsen)

Max-Planck-Institut für Radioastronomie

The BeSSeL Survey

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		l [deg]	b [deg]	Parallax [mas]	μ_α cos (δ) [mas/yr]	μ_δ [mas/yr]	v_LSR [km/s]	Frequency [GHz]	Telescope	Refer	ence					
Ser B	2M	 [deg]	b [deg]	Parallax [mas]	μ_α cos (δ) [mas/yr]	μ_δ [mas/yr]	v_LSR [km/s]	Frequency [GHz]	Telescope	Refer	ence)5 154	RR			
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Sgr B Sgr B	2M 2N 20120	 [deg] 0.67 0.68	b [deg] -0.04 -0.03	Parallax [mas] 0.130±0.012 0.128±0.015 0.194±0.023	μ_α cos (δ) [mas/yr] -1.23±0.04 -0.32±0.05 -0 58±0.05	μ_δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27	v_LSR [km/s] 61.0±5.0 64.0±5.0	Frequency [GHz] 22.2 22.2 12.2	Telescope VLBA VLBA VIBA	2009A	ence (pj70 (pj70)5.154)5.154	8R 8R			
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Sgr B Sgr B G009 G010 G010	2M 12N 9.62+00.19 9.47+00.02 9.62-00.38	I [deg] 0.67 0.68 9.62 10.47 10.62	b [deg] -0.04 -0.03 0.20 0.02 -0.38	Parallax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.117±0.008 0.202±0.019	μ_α cos (δ) [mas/yr] -1.23±0.04 -0.32±0.05 -0.58±0.05 -3.86±0.02 -0.37±0.08	μ_δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.06	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7	Frequency [GHz] 22.2 22.2 12.2 22.2 22.2 22.2 22.2 22.	Telescope VLBA VLBA VLBA VLBA VLBA	2009A 2009A 2009A 2009A 2014A 2014A	ence (p)70 (p)70 (p)70 (p)70 (p)78	05.1544 05.1544 06464 81108 81108	8R 8R IS IS			
Sgr B Sgr B G009 G010 G010 G011	22M 12N 9.62+00.19 9.47+00.02 9.62-00.38 1.49-01.48	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49	b [deg] -0.04 -0.03 0.20 0.02 -0.38 -1.48	Parallax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.117±0.008 0.202±0.019 0.800±0.033	μ_α cos (δ) [mas/yr] -1.23±0.04 -0.32±0.05 -0.58±0.05 -3.86±0.02 -0.37±0.08 1.42±0.52	μ_δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.06 -0.60±0.05	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0	Frequency [GHz]22.222.222.222.222.222.222.222.222.222.2	Telescope VLBA VLBA VLBA VLBA VLBA VLBA	Refer 2009A 2004A 2014A 2014A	ence (pj70 (pj70 (pj78 (pj78 (pj78 (kA5	05.154 05.154 06464 81108 81108	8R 8R 8S 85 7W			
Sgr B Sgr B G009 G010 G010 G011 G012	22M 12N 0.62+00.19 0.47+00.02 0.62-00.38 1.49-01.48 2.02-00.03	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03	b [deg] -0.04 -0.03 0.20 0.02 -0.38 -1.48 -0.03	Parallax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.117±0.008 0.202±0.019 0.800±0.033 0.106±0.008	μ_α cos (δ) [mas/yr] -1.23±0.04 -0.32±0.05 -0.58±0.05 -3.86±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02	μ_δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.65 -7.76±0.27	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4	Frequency [GHz] 22.2 22.2 12.2 22.2 22.2 12.2 12.2 12.	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA	2009A 2009A 2009A 2014A 2014A 2014A 2014A 2014A	ence (p]70 (p]70 (p]70 (p]78 (p]78 (sA5 (p]78	05.154 05.154 06.464 81108 81108 666A1 81108	8R 8R IS IS 7W			
Sgr B Sgr B G009 G010 G010 G011 G012 G012	22M 12N 0.62+00.19 0.62+00.38 0.62-00.38 0.49-01.48 0.02-00.03 2.68-0.18	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03	Parallax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.117±0.008 0.202±0.019 0.800±0.033 0.106±0.008 0.416±0.028	&mur_α cos (δ) [mas/yr] -1.2340.04 -0.32±0.05 -0.38±0.05 -3.86±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02 -1.00±0.30	μ_δ [mas/yr] -3.840.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.06 -0.60±0.65 -7.76±0.27 -2.85±0.29	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0	Frequency (GHz)22.222.222.222.222.222.212.222.222.2	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA	Refer 2009A 2009A 2009A 2009A 2014A 2014A 2014A 2014A 2014A 2014A 2014A 2014A	ence (p]70 (p]70 (p]70 (p]78 (p]78 (&A5 (&A5 (&A5)	05.154 05.154 06.464 81108 81108 666A1 81108	8R 8R 8S 55 57W 55 17I			
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Sgr B Sgr B G009 G010 G010 G012 G012 G012 G012 G012 G012	2M .62+00.19 0.47+00.02 0.62-00.38 1.49-01.48 2.02-00.03 1.68-0.18 2.81-0.19 2.81-0.19 2.88+0.48 2.89+00.49	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68 12.81 12.81 12.88 12.89	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03 -0.18 -0.19 -0.19 0.48 0.49	Parailax (mas) 0.130:0.012 0.128:0.015 0.194:0.023 0.117:0.008 0.202:0.019 0.800:0.033 0.106:0.008 0.416:0.028 0.343:0.037 0.340:0.036 0.4428:0.022	μ_α cos (δ) (ms/yr] -1.23±0.04 -0.32±0.05 -0.58±0.05 -3.86±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02 -1.00±0.30 -0.60±0.11 -0.24±0.17 0.1±0.13 0.1±0.03	μ δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.05 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0 36.0±4.0 32.0±4.0 32.0±4.0	Frequency (GHz)22.222.222.222.212.222.212.223242425262728292020202021222223242425262728292920 <tr< td=""><td>Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA</br></td><td>2009A 2009A 2009A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A</td><td>ence pj70 pj70 pj78 &A5 k&A5 k&A5 &A5 k&A5</td><td>05.154 05.154 06.464 81108 81108 666A1 81108 53A.1 53A.1 53A.1 53A.1 53A.1</td><td>8R 8R 8S 7W 5S 17I 17I 17I 17I</td><td></td><td></td><td></td></tr<>	Telescope VLBA VLBA 	2009A 2009A 2009A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A	ence pj70 pj70 pj78 &A5 k&A5 k&A5 &A5 k&A5	05.154 05.154 06.464 81108 81108 666A1 81108 53A.1 53A.1 53A.1 53A.1 53A.1	8R 8R 8S 7W 5S 17I 17I 17I 17I			
Sgr B Sgr B G009 G010 G011 G012 G012 G012 G012 G012 G012	22M .62+00.19 .62-00.28 .62-00.38 .49-01.48 .02-00.03 .68-0.18 .81-0.19 .81+0.19 .88+0.48 .89+00.49 .90-0.26	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68 12.81 12.81 12.81 12.88 12.89 12.90	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03 -0.18 -0.19 -0.19 0.48 0.49 -0.26	Parailax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.17±0.008 0.202±0.019 0.406±0.028 0.416±0.028 0.343±0.037 0.343±0.037 0.343±0.037	μ_α cos (δ) [mas/yt] -1.23c0.04 -0.32±0.05 -0.58±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02 -0.0020.11 -0.60±0.11 -0.24±0.17 0.15±0.03 -0.36±0.03	μ & delta; [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.05 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 1.0±3.0 109.8±2.4 56.0±4.0 36.0±4.0 32.0±4.0 31.0±7.0 36.0±4.0	Frequency (GHz) [GHz] 22.2 	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA	2009A 2009A 2009A 2014A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A	ence xpJ70 xpJ70 xpJ70 xpJ78 &A5 &A5 &A5 &A5 &A5 &A5 &A5 &A5 &A5 &A5	05.154 06.464 31.108 0664.1 31.108 0664.1 31.108 0534.1 0534.1 0534.1 0534.1	8R 8R 8S 55 7W 85 171 171 171 171 171			
Sgr B Sgr B G009 G010 G011 G012 G012 G012 G012 G012 G012	22M (2N) (62+00.19) (62+00.38) (49-01.48) (20-00.38) (58-0.18) (58-0.18) (58-0.18) (58-0.19) (58+0.48) (59-0.26) (59-0.26) (59-0.26)	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68 12.81 12.81 12.81 12.88 12.89 12.90	b [deg] -0.04 -0.03 0.20 -0.38 -0.38 -0.38 -0.18 -0.19 0.48 0.49 0.49 0.49 -0.26 -0.24	Parallax [mas] 0.130±0.012 0.128±0.015 0.128±0.015 0.104±0.023 0.202±0.019 0.800±0.033 0.416±0.028 0.343±0.037 0.343±0.037 0.343±0.032 0.346±0.022 0.396±0.032 0.396±0.032	&mur, α cos (δ) [mas/yr] 1.23±0.04 -0.32±0.05 -0.58±0.05 -0.37±0.08 1.42±0.52 -4.11±0.02 -1.00±0.30 -0.60±0.11 -0.24±0.17 0.12±0.13 0.15±0.03 -0.35±0.08 0.19±0.08	μ δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.65 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13 -2.52±0.32	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 668.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0 36.0±4.0 36.0±4.0 31.0±7.0 36.0±4.0	Frequency [GH2] 22.2 22.2 22.2 22.2 22.2 12.2 22.2 22	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA	Refer 2009A 2009A 2009A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A	ence xpj70 xpj70 xpj78 x845 x84	05.1544 05.1544 06464 81108 81108 853A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1	88R 88R 15 15 15 171 171 171 171 171 171 171			
Sgr B Sgr B G009 G010 G010 G012 G012 G012 G012 G012 G012	12M 12N 1.62+00.19 1.62+00.20 1.62-00.03 1.68-0.18 1.81-0.19 1.88+0.48 1.89+00.49 1.99-0.26 1.99-0.24 1.93-0.27	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68 12.88 12.89 12.89 12.90 12.40	b [deg] -0.04 -0.03 0.20 -0.38 -0.44 -0.38 -0.48 -0.19 -0.19 -0.41 -0.19 -0.42 -0.24 -0.24 -0.25	Parailax (mas) 0.130±0.012 0.128±0.015 0.194±0.023 0.117±0.008 0.202±0.019 0.800±0.033 0.166±0.008 0.416±0.028 0.343±0.037 0.3440±0.036 0.443±0.037 0.340±0.036 0.428±0.022 0.340±0.036 0.428±0.022 0.408±0.025	&mur, α cos (δ) [mas/yr] -1.2340.04 -0.3240.05 -0.5840.05 -3.86±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02 -1.00±0.30 -0.60±0.11 -0.24±0.13 0.12±0.13 0.12±0.08 0.19±0.08 0.22±1.20	μ.δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.65 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13 -2.52±0.32 -2.07±1.20	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 09.8±2.4 56.0±4.0 36.0±4.0 31.0±7.0 36.0±4.0 31.0±7.0 36.0±4.0	Frequency (GH2)22.222.222.222.222.222.222.222	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA	Refer 2009A 2009A 2009A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A 2013A 2013A 2013A 2013A	ence pj70 pj70 pj72 pj72 pj78 &A5	05.1544 06464 81108 81108 853A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1	88R 88R 55 55 55 77W 55 171 171 171 171 171 171 77W			
Sgr B Sgr B G009 G010 G011 G012 G012 G012 G012 G012 G012	12M 12N 1.62+00.19 1.47+00.02 1.62-00.38 1.49-01.48 1.02-00.03 1.68+0.18 1.81+0.19 1.88+0.48 1.89+00.49 1.99+0.24 1.99+0.24 1.63+00.57 1	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.68 12.88 12.89 12.90 14.63 15.03	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03 -0.19 0.49 -0.24 -0.25 -0.57 -0.58	Parailax [mas] 0.130±0.012 0.128±0.015 0.194±0.023 0.107±0.008 0.2022.0.019 0.800±0.033 0.166±0.008 0.416±0.028 0.343±0.037 0.343±0.037 0.343±0.037 0.343±0.032 0.396±0.032 0.505±0.033	μ_α cos (δ) [mas/yt] -1.23±0.04 -0.32±0.05 -0.38±0.05 -3.86±0.02 -0.37±0.08 1.42±0.52 -4.11±0.02 -1.00±0.30 -0.60±0.11 -0.24±0.17 0.15±0.03 -0.36±0.08 0.19±0.08 0.24±1.20 0.68±0.05	μ δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.05 -7.76±0.27 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13 -2.52±0.32 -2.07±1.20 -1.42±0.09	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0 32.0±4.0 32.0±4.0 31.0±7.0 36.0±4.0 36.0±4.0 19.0±5.0 22.0±3.0	Frequency (GHz)22.222.212.222.212.212.22324252612.2	Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA	2009A 2009A 2009A 2014A 2014A 2014A 2014A 2013A 2013A 2013A 2013A 2013A 2013A 2013A	ence pj70 pj70 pj72 pj72 pj78 &A5 &A.	05.1544 06.464 31.108 31.108 366A.1 33.11 53A.1 53A.1 53A.1 53A.1 53A.1 53A.1 3325 53A.1 3325	88R 88R 55 55 55 7W 55 171 171 171 171 171 171 7W X			
Sgr B Sgr B G000 G010 G011 G012 G012 G012 G012 G012	12M 12N 1.62+00.19 1.47+00.02 1.62-00.38 1.68-01.88 1.81-0.19 1.81-0.19 1.81-0.19 1.88+0.48 1.89+00.49 1.90-0.26 1.90-0.24 1.63-00.57 1.03-00.68 0-0.4	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.81 12.88 12.89 12.90 14.63 15.03 23.01	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03 -0.19 -0.44 -0.19 -0.24 -0.24 -0.257 -0.578 -0.571	Parailax [mas] 0.130±0.012 0.128±0.015 0.128±0.015 0.194±0.023 0.202±0.019 0.406±0.028 0.416±0.028 0.343±0.037 0.343±0.037 0.343±0.037 0.343±0.032 0.428±0.022 0.505±0.023 0.505±0.033	μ_α cos (δ) [mas/yt] -1.23c0.04 -0.32e0.05 -0.58e0.02 -0.37e0.08 1.42e0.52 -4.11e0.02 -0.0620.11 -0.6020.11 -0.32e0.03 0.16±0.03 -0.36±0.08 0.19±0.08 0.22±1.20 0.68±0.05 -1.72E0.04	μ δ [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.06 -0.60±0.05 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13 -2.52±0.32 -2.07±1.20 -1.42±0.09 -4.12±0.30	V_LSR [km/s] 61.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0 36.0±4.0 31.0±7.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0 36.0±4.0	Frequency (GHz)22.222.212.222.212.212.222.212.212.223242526272829202020212222232425262728292920202020202122232425262728292920 <td>Telescope VLBA VLBA VLBA VLBA VLBA VLBA VLBA VLBA</br></td> <td>2009A 2009A 2009A 2014A 2014A 2013A 2013A 2013A 2013A 2013A 2013A 2013A 2014A 2014A 2014A 2014A 2014A 2014A 2014A</td> <td>ence pj70 pj72 pj78 &A5</td> <td>05.1544 06.464 31.108 31.108 366A.1 33.11 53A.1 33.25 53A.1 53A.1 33.25 33A.1 33.25 33.424</td> <td>88 88 85 55 55 77 171 171 171 171 171 171 171 1</td> <td></td> <td></td> <td></td>	Telescope VLBA VLBA 	2009A 2009A 2009A 2014A 2014A 2013A 2013A 2013A 2013A 2013A 2013A 2013A 2014A 2014A 2014A 2014A 2014A 2014A 2014A	ence pj70 pj72 pj78 &A5	05.1544 06.464 31.108 31.108 366A.1 33.11 53A.1 33.25 53A.1 53A.1 33.25 33A.1 33.25 33.424	88 88 85 55 55 77 171 171 171 171 171 171 171 1			
Sgr B Sgr B G009 G010 G011 G012 G012 G012 G012 G012 G012	12M 12N 0.62+00.19 0.62-00.38 1.49-01.48 1.02-00.03 1.68-018 1.81-0.19 1.88+0.48 1.89+00.49 1.90-0.24 1.90-0.24 1.90-0.25 1.90-0.24 1.03-00.68 0-0.4 1.02 1.0	I [deg] 0.67 0.68 9.62 10.47 10.62 11.49 12.03 12.81 12.81 12.89 12.90 14.63 15.03 23.01 23.44	b [deg] -0.04 -0.03 0.20 -0.38 -1.48 -0.03 -0.19 -0.19 -0.44 -0.26 -0.24 -0.58 -0.41 -0.41	Parallax [mas] 0.130±0.012 0.128±0.015 0.128±0.015 0.124±0.023 0.172±0.008 0.406±0.028 0.343±0.037 0.343±0.037 0.343±0.037 0.343±0.032 0.346±0.022 0.396±0.032 0.396±0.032 0.505±0.033 0.218±0.017	μ_α cos (δ) [mas/yt] -1.23c0.04 -0.3220.05 -0.58c0.02 -0.37c0.08 -1.42c0.52 -1.42c0.52 -1.42c0.52 -0.000.00 -0.000.01 -0.02c40.17 0.12c0.03 -0.36c0.03 -0.36c0.03 -0.36c0.03 -0.36c0.03 -0.36c0.04 -0.19c0.08 0.19c0.08 -1.72c0.04 -1.793c0.01	Strut; Schelta; [mas/yr] -3.84±0.11 -4.69±0.11 -2.49±0.27 -6.40±0.08 -0.60±0.65 -7.76±0.27 -2.85±0.29 -0.99±0.13 0.54±0.12 -2.66±0.23 -1.90±1.59 -2.22±0.13 -2.52±0.32 -2.52±0.32 -2.07±1.20 -1.42±0.09 -4.11±0.07	v_LSR [km/s] 61.0±5.0 64.0±5.0 5.0±3.1 68.9±4.5 -3.0±2.7 11.0±3.0 109.8±2.4 56.0±4.0 36.0±4.0 32.0±4.0 31.0±7.0 36.0±4.0 36.0±4.0 36.0±4.0 19.0±5.0 22.0±3.0 81.0±3.0	Frequency [GH2] 22.2 22.2 12.2 22.2 12.2 22.2 12.2 22 22 22 22 22 22 22 22 22 22 22 22	Telescope VLBA VLBA	2009A 2009A 2009A 2014A 2014A 2013A 2005A	ence xpj70 pj72 xpj78 &A5 &A.	05.154i 15.154i 16464 11108 11108 153A.1 153A.1 153A.1 153A.1 153A.1 153A.1 13325 153A.1 13325 133.424 133.424	88 88 85 55 57 77 77 55 1771 1771 1771 1			

- Results of parallaxes from VLBA, EVN & VERA:
- ~100 sources with accuracies between 6 and 40 µas







Spiral arm details:

Arm	Ν	$\beta_{\text{ref}} (\beta \text{ Range})$ (deg)	R _{ref} (kpc)	Width (kpc)	ψ (deg)
Scutum	17	$27.6 \ (+3 \rightarrow 101)$	5.0 ± 0.1	0.17 ± 0.02	19.8 ± 2.6
Sagittarius	18	$25.6 (-2 \rightarrow 68)$	6.6 ± 0.1	0.26 ± 0.02	6.9 ± 1.6
Local	25	$8.9(-8\to27)$	8.4 ± 0.1	0.33 ± 0.01	12.8 ± 2.7
Perseus	24	$14.2 (-21 \rightarrow 88)$	9.9 ± 0.1	0.38 ± 0.01	9.4 ± 1.4
Outer	6	$18.6 (-6 \rightarrow 56)$	13.0 ± 0.3	0.63 ± 0.18	13.8 ± 3.3



- Pitch angles 7° 20°
- Arm width inceases with 42 pc/kpc



C						
<u>Method</u> /	R_{o}	Θ_0	dΘ/dR	<v<sub>src></v<sub>	<u<sub>src></u<sub>	Θ_0/R_0
Rotation Curve used	(kpc)	(km/s)	(km/s/kpc)	(km/s)	(km/s)	(km/s/kpc)



	<u><i>Method</i></u> / Rotation Curve used	R₀ (kpc)	Θ ₀ (km/s)	dΘ/dR (km/s/kpc)	<v<sub>src>) (km/s)</v<sub>	<u<sub>src> (km/s)</u<sub>	Θ₀/R₀ (km/s/kpc)
("Outlier-tolerant" Bayes	<u>ian fitting</u> : Pro	b(D _i M,σ _i) μ	ι (1 – exp(- R	R _i ² /2)) / R _i ²	where R	$r_i = (D_i - M_i) / \sigma_i$
	All source > 4 kpc	8.20 ± 0.20	248 ± 9	-0.5 ± 0.6	-10 ± 7	3 ± 2	(30.2)
	Removing 15 outliers*	8.34 ± 0.16	240 ± 8	-0.2 ± 0.4	-2 ± 7	3 ± 2	(28.8)
	Θ_{\circ} and R_{\circ} now only we	akly correlated	1.				
	$\Theta_0 + V_{sup} = 255$	km/s					
	$V_{sun} - \langle V_{src} \rangle = 18 k$	(m/s					
/	Notoo						

Notes:

*Assuming new Solar Motion component: V_{sun} = 12 km/s (Schœnrich et al 2010)

 $<V_{src}>$ = average deviation from circular rotation of maser stars

<U_{src}> = average motion toward Galactic Center

 Θ_0/R_0 = 28.8 ± 0.2 km/s/kpc from proper motion of Sgr A* (Reid & Brunthaler 2004)







- Fitted different Galactic rotation models to 6d data
- Average motions: $U_s = 3 \pm 2$ km/s, $V_s = -2 \pm 7$ km/s

	IAU	Maser data	Independent Measurements
R ₀ [kpc]	8.5	8.34 ± 0.16	8.4 ± 0.4 (Ghez et al. 2008) 8.33 ± 0.35 (Gillessen et al. 2009)
Θ_0 [km/s]	220	240 ± 8	239 ± 12
Θ_0/R_0 [km/s/kpc]	25.9	28.8	28.8 (Reid & Brunthaler 2004)





(Reid & Brunthaler 2004)



Reid, Dame, Menten & Brunthaler (2016, ApJ)

• Use information about spiral arms, parallaxes, revised kinematic distance

http://bessel.vlbi-astrometry.org/bayesian



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	Bayesian D	istance C	Calculator								
	The spiral arms of th with the BeSSeL Surv leverages these resu follow spiral structu signatures seen in Cr are also considered Dame, Menten & Br	he Milky Way are vey, using the Vo ults to significar ure . Using a Bay O and HI survey in generating a f runthaler 2016, J	e being accurately located for ery Long Baseline Array and t ntly improve the accuracy a yesian approach, sources are a rs. A source's kinematic distan full distance probability densi ApJ, in press.	the first time via t the European VLBI nd reliability of d assigned to arms bac ce, displacement f ty function. A mor	rigonometric par Network, and wit istance estimate ased on their (l,b rom the plane, a e detailed descri	rallaxes of m th the Japane es to other v) coordinat nd proximity ption of the	assive star forn ese VERA projec sources that a es with respec v to individual j methods can b	ming regi ct. This ca r e know t to arm parallax s e found i	ons Ilculator n to ources n Reid,		
	The source code incl	luding the paper	can be downloaded here: Ba	yesian_distance_v1	.0.tar (~5 MB).						
		Enter Ga	alactic Longitude. Latit	ude (in degrees	and the LSI	R velocity	(in km/s)				
			Longitude	43.16	•	,					
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			P _{far} :	0.5							
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	Ine spiral arms of the Milky with the BeSSeL Survey, usin leverages these results to si follow spiral structure . Usi signatures seen in CO and H are also considered in gener Dame, Menten & Brunthale	way are being accurate ng the Very Long Baseli gnificantly improve to ng a Bayesian approach I surveys. A source's ki rating a full distance pro- r 2016, ApJ, in press.	ne Array and the Array and the Array and the accuracy and	ne first tin le Europea Id reliabili ssigned to e, displace y function.	ne via trigon in VLBI Netw ity of distan arms based ement from t . A more det	ometric part ork, and w ce estima on their (l, the plane, ailed descr	arailaxes o with the Jap otes to oth ,b,v) coordi and proxin ription of t	r massiv anese V er sour nates w nity to i he met	ve star for /ERA proje rces that a vith respect individual hods can b	ming re ct. This ire know t to arm parallax e found	gions calculate wn to sources l in Reid	or s l,		
	The source code including th	ne paper can be downlo	aded here: Bay	esian_dista	ance_v1.0.tai	(~5 MB).								
	Er	nter Galactic Long	itude. Latitu	de (in de	egrees) an	d the LS	SR veloci	ty (in	km/s)					
			Longitude:	13.5	5	•								
			Latitude:	-0.7		•								
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			P _{far} :	0.5										
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BeSSeL South



- Few sources done with LBA
- AuScope Geodetic Array plus Ceduna and Mopra (led by S. Ellingsen)
- Observations could start this year



 Tropospheric calibration (*geodetic blocks*) are being used for 15+ years at high frequencies (> 10 GHz) yielding accuracies of 10 µas



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 - MultiView (Rioja, Dodson et al. 2017)
 - "artifical quasars" (Reid, Brunthaler et al. 2017)
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 - only small number of calibrator availabe
- SKA not designed for astrometric accuracy
 - limited baseline length
 - limited phase centers





How to reach accuracies of better than 10 µas?

• Longer baselines: not feasible on Earth



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- Prime targets for PAF VLBI Astrometry:
 - Galactic 6.7 GHz Methanol Masers, OH masers, pulsars
 - nearby galaxy groups and Virgo Cluster (many target galaxies with AGN in and many more behind the cluster)
 - Direct parallax to Magellanic Clouds (1 μ as => 5% @ 50 kpc)