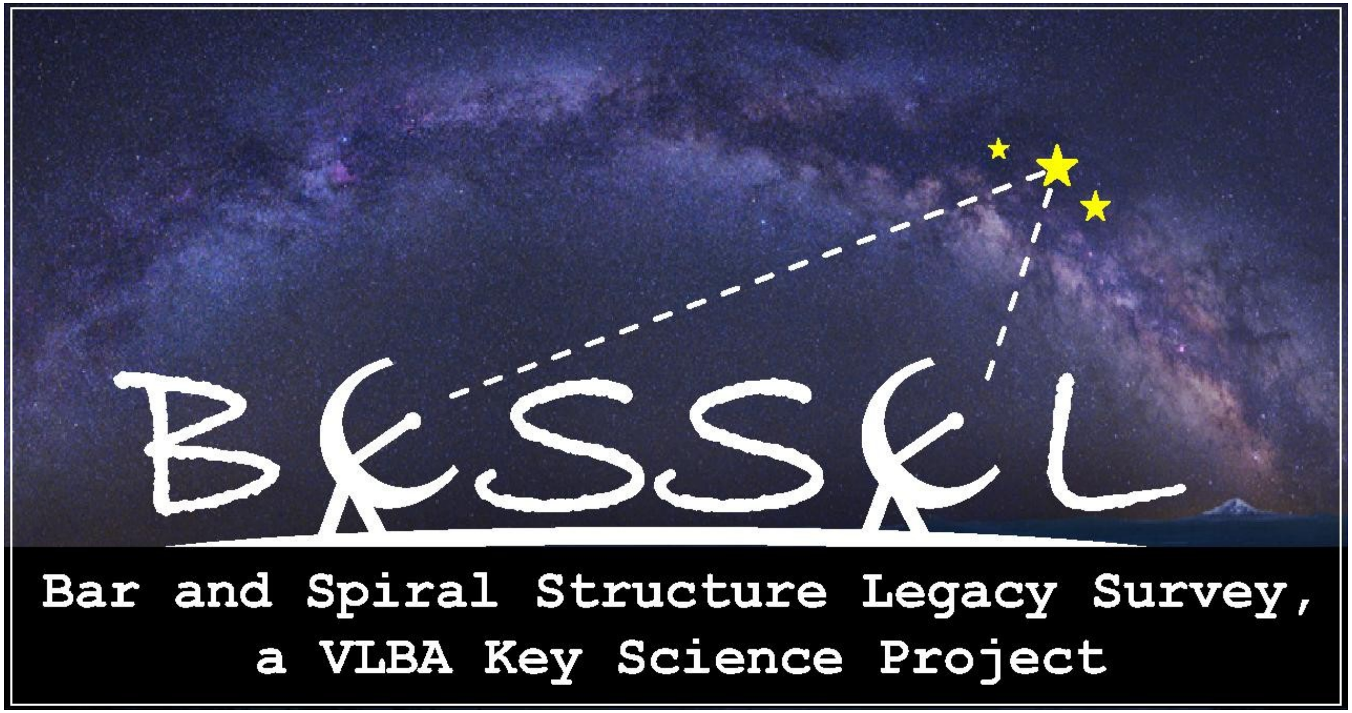


Masers and the structure of the Milky Way

Max-Planck-Institut
für
Radioastronomie

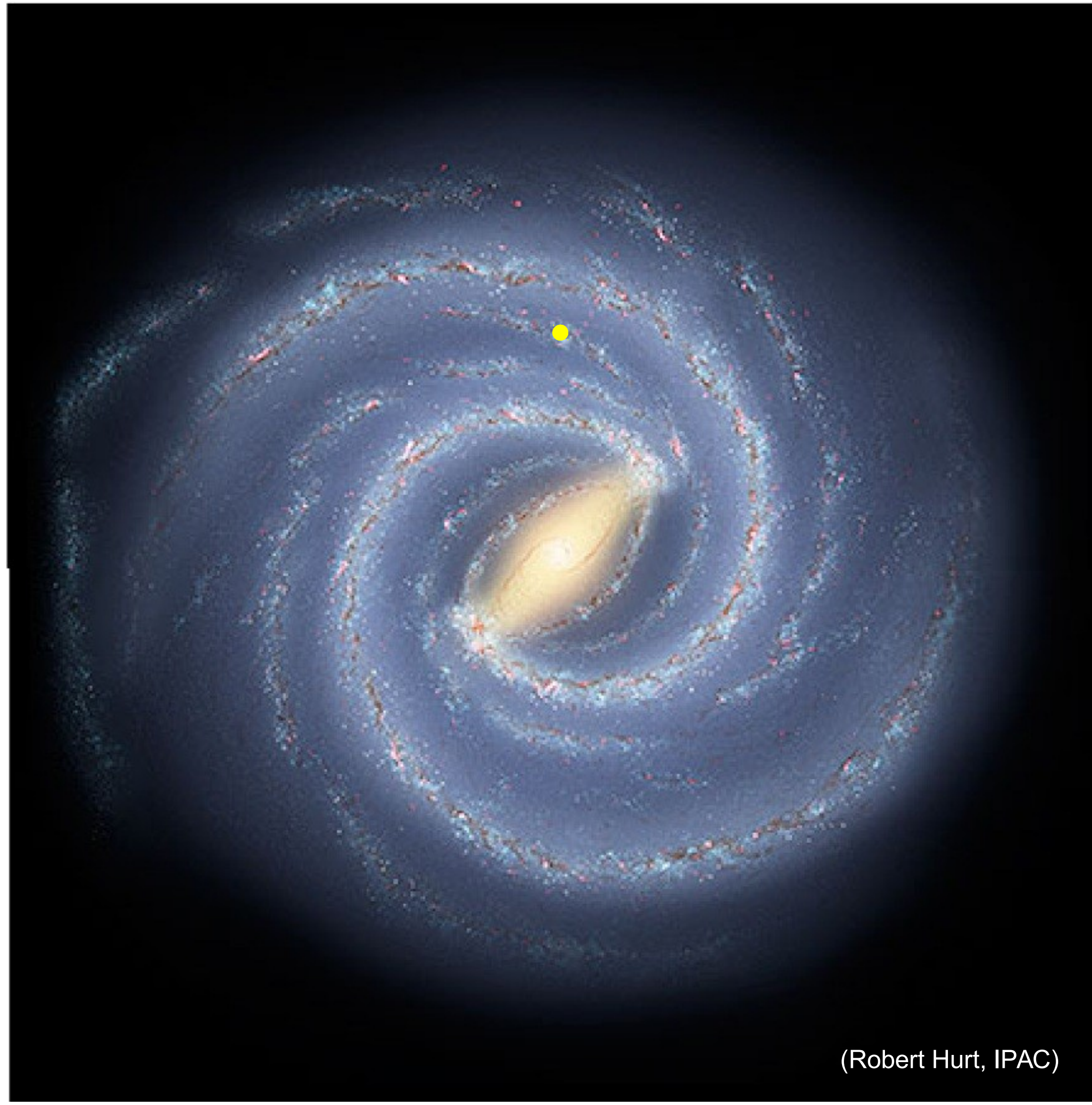
Andreas Brunthaler
for the BeSSeL Team

Structure of the Milky Way

Structure of the Milky Way still under debate!

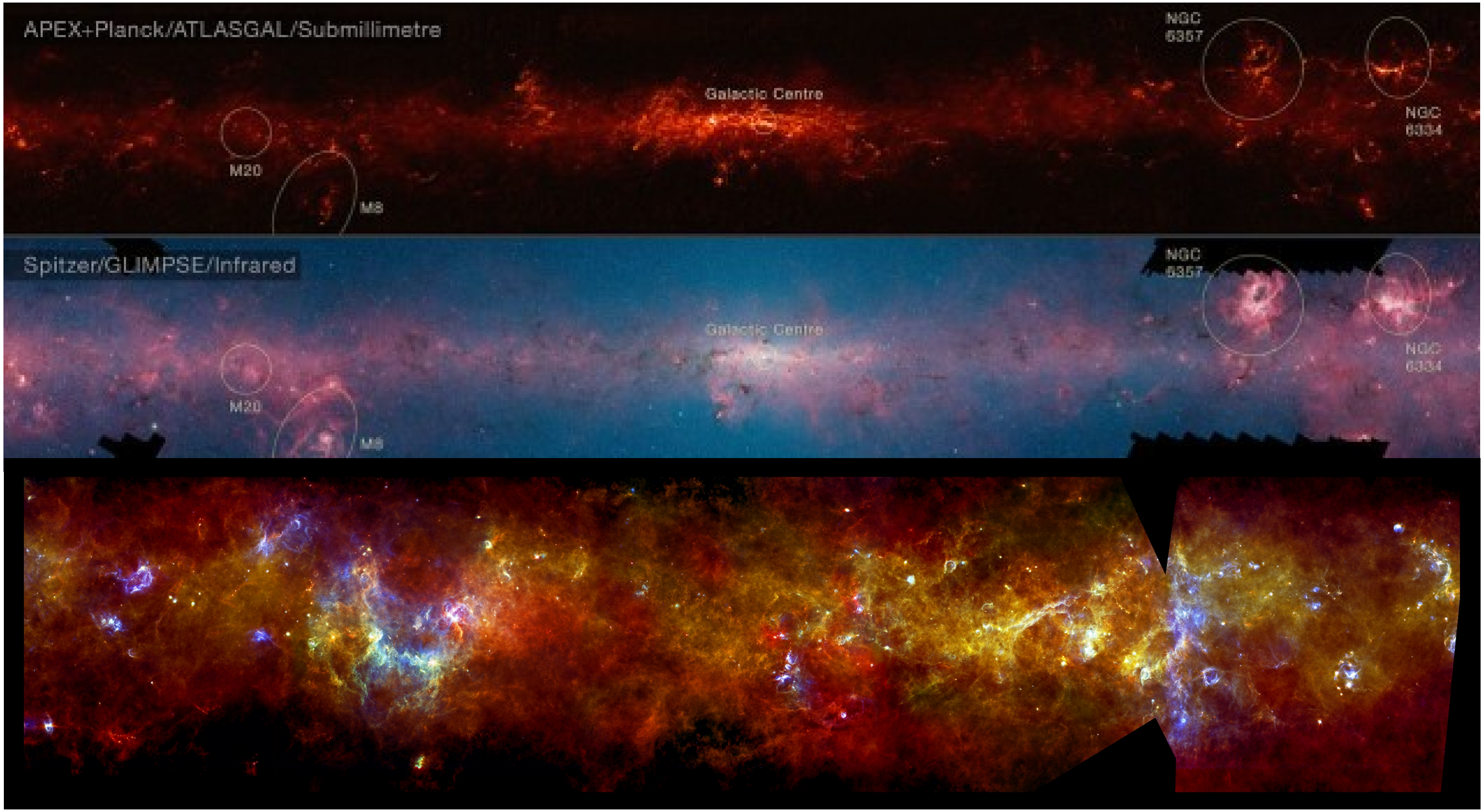
- Spiral arms:
  Number, Positions?
- Rotation speed of LSR:
  Θ_0 = 170 – 270 km/s
- Distance Sun – Sgr A*:
  R_0 ~ 8.4 kpc (± 5%)
- IAU recommended values:

Θ_o= 220 km/s R_o= 8.5 kpc



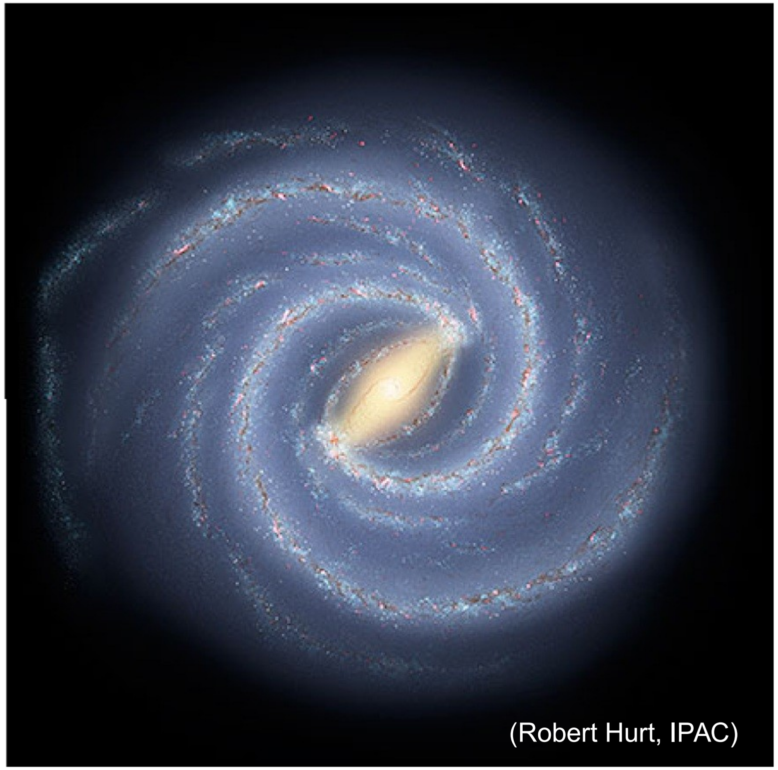
(Robert Hurt, IPAC)

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 (*l*,*b*) (sometimes v_{LSR}).
- Accurate distances needed to go to 3d.
- Kinematic distances highly unreliable.

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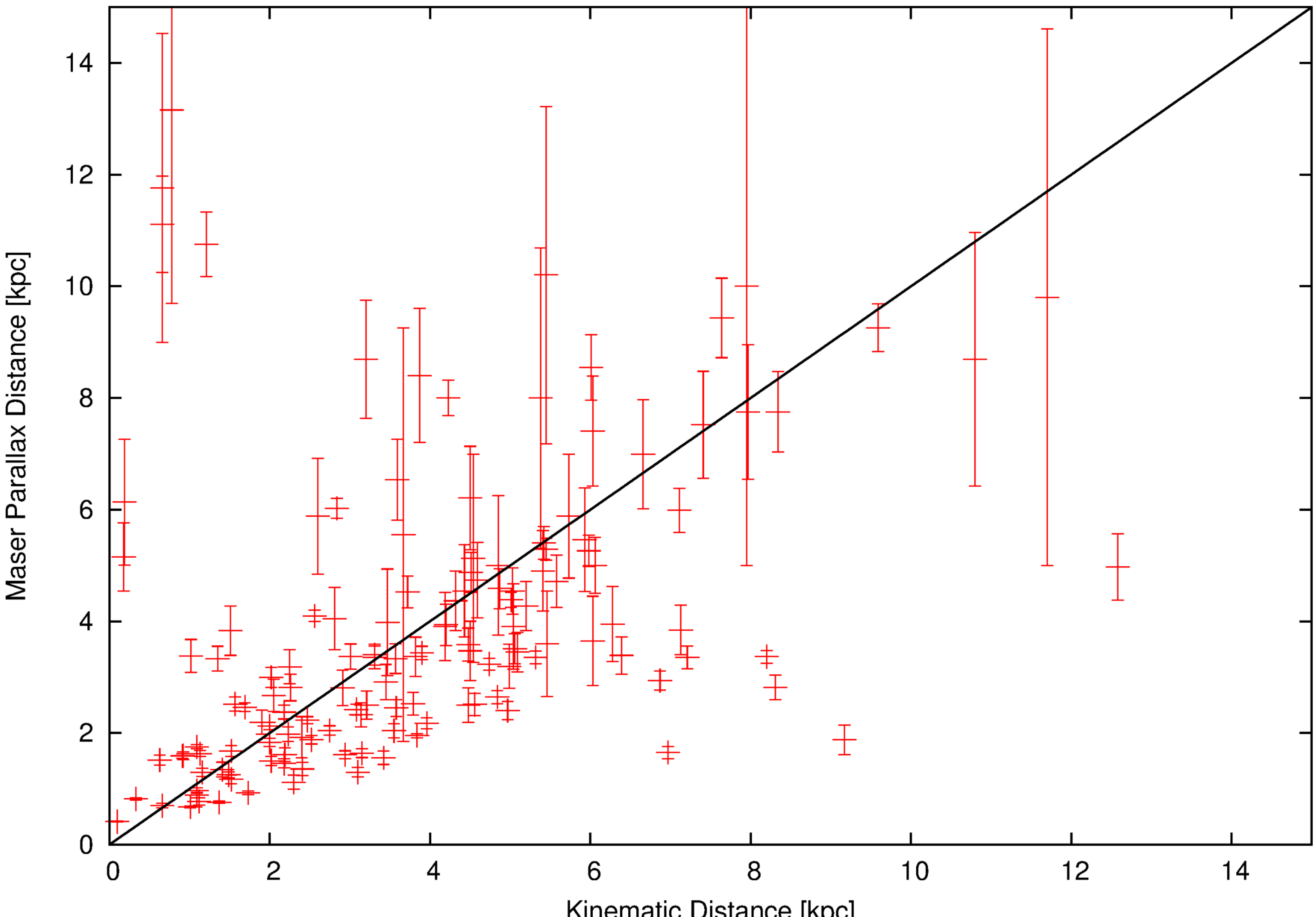
Structure of the Milky Way



Going to the third dimension!

- Current Milky Way surveys are only 2d (*l*,*b*) (sometimes v_{LSR})
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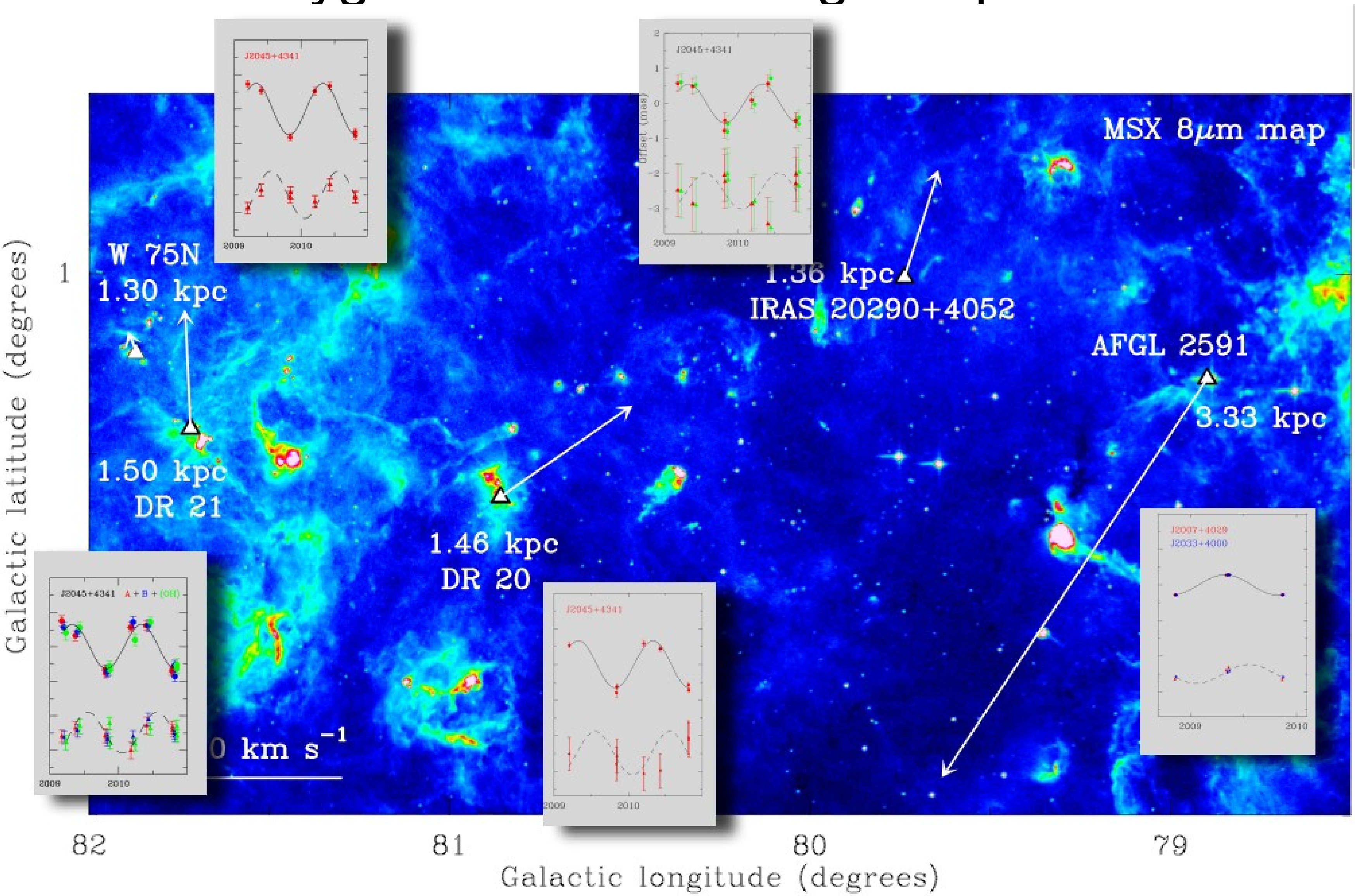
- Kinematic distances highly unreliable.

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

Cygnus X Star forming complex



Rygl et al. (2012)

Image: van Langevelde

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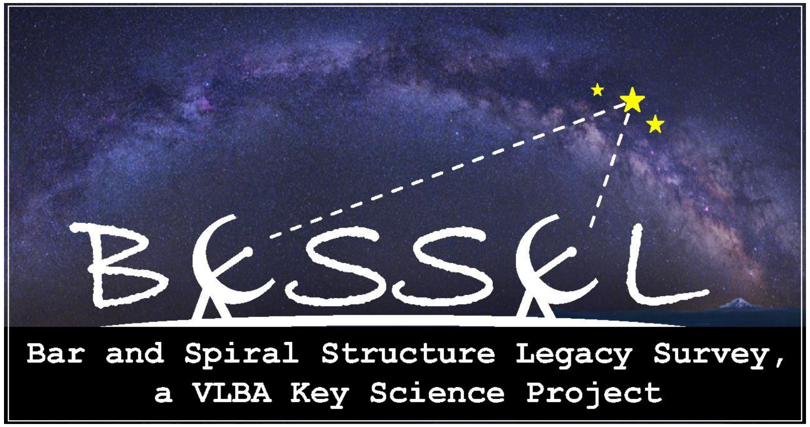
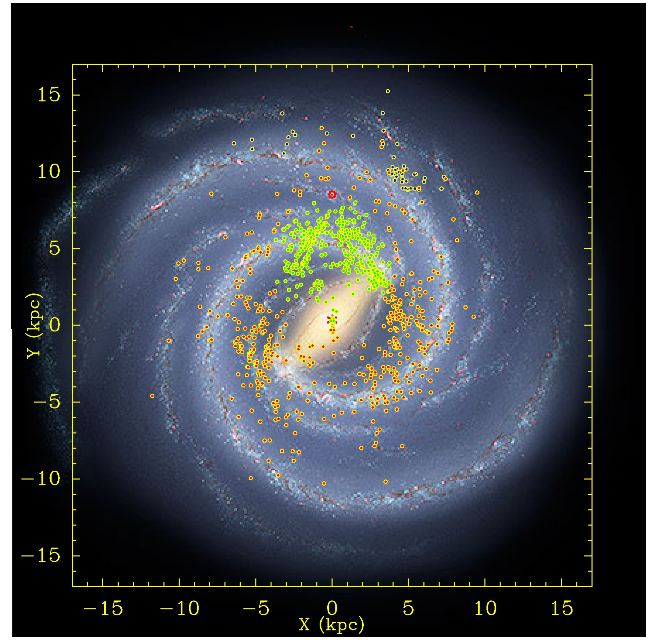
The BeSSeL Survey



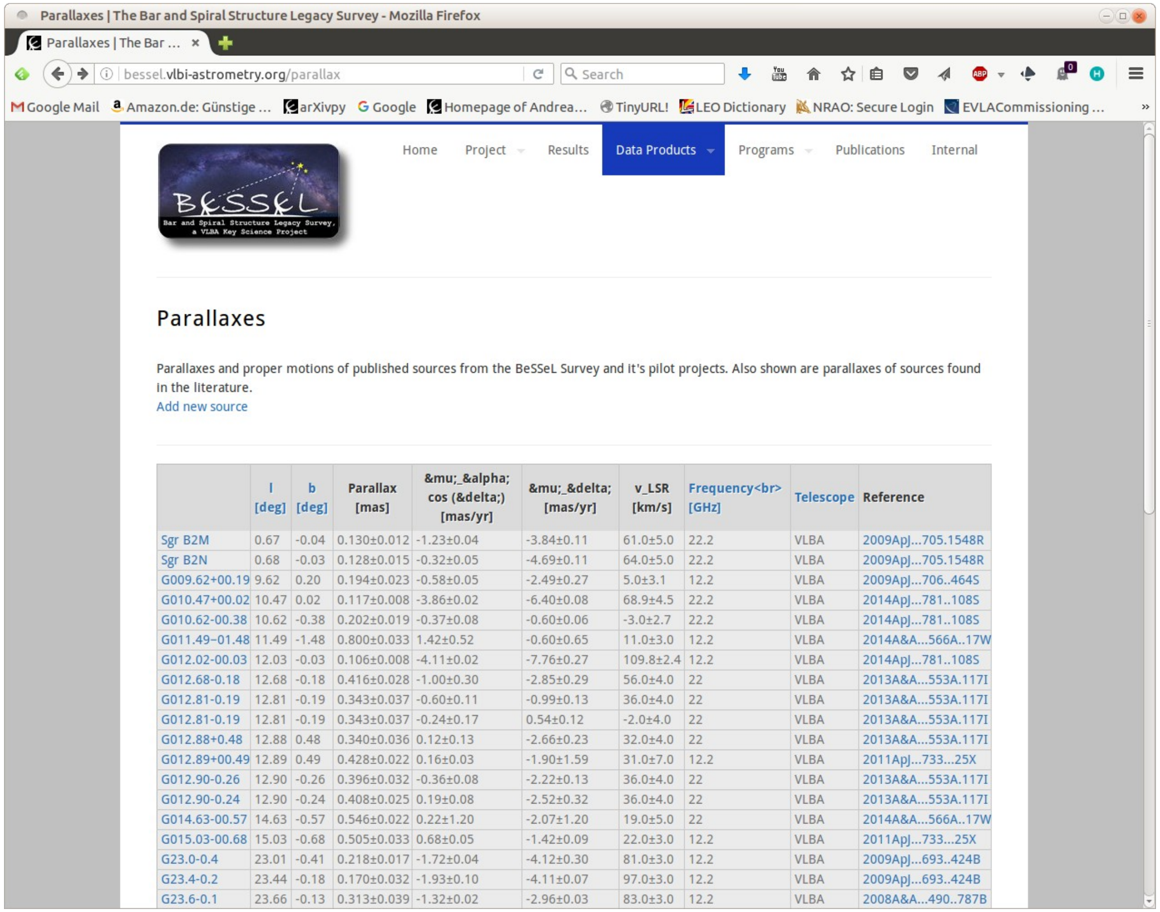


- **B**ar and **S**piral **S**tructure **L**egacy survey, a VLBA Key Science project
- ~ 5000 hours over 5 years
- ~ 250 masers
- BeSSeL will yield accurate distances to most HMSFR, locate the spiral arms and the bar, measure R_0 and Θ_0 to ~1%, and measure the rotation curve.

M.J. Reid, T. Dame (CfA); K.M. Menten, A. Brunthaler, Y.K. Choi, M. Sato, B. Zhang, A. Sanna, Yuanwei Wu, Hu Bo, Jing Jing Li (MPIfR); . K. Rygl (INAF-IAPS); Y. Xu, X.W. Zheng (Nanjing); L. Moscadelli (Arcetri); G. Moellenbrock (NRAO) Bartkiewicz (Torun)); K. Hachisuka (Shanghai); H. van Langevelde (JIVE)

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

The BeSSeL Survey



Parallaxes

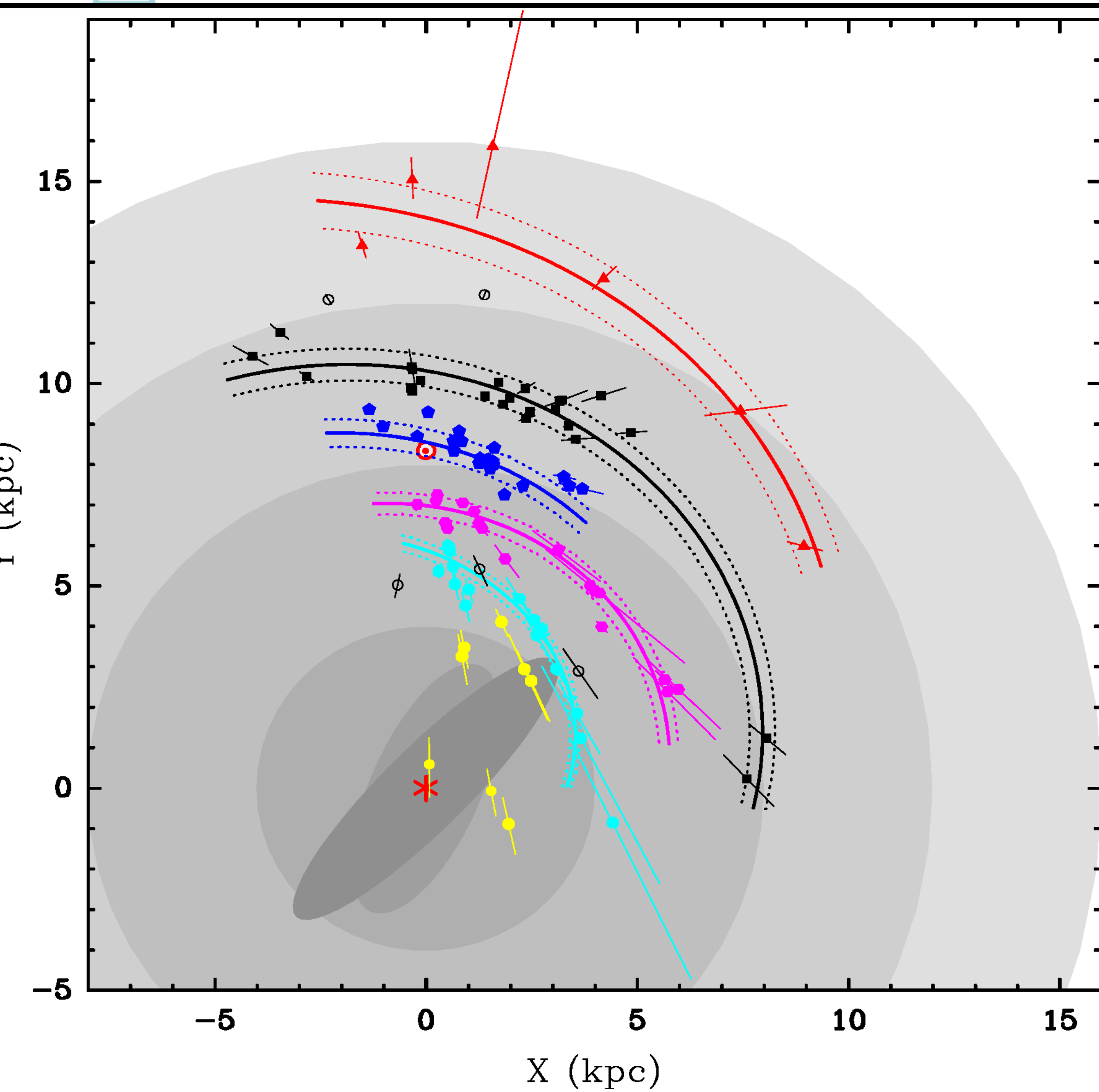
Parallaxes and proper motions of published sources from the BeSSeL Survey and it's pilot projects. Also shown are parallaxes of sources found in the literature.

Add new source

	l [deg]	b [deg]	Parallax [mas]	μ_α cos (δ) [mas/yr]	μ_δ [mas/yr]	v_LSR [km/s]	Frequency [GHz]	Telescope	Reference
Sgr B2M	0.67	-0.04	0.130±0.012	-1.23±0.04	-3.84±0.11	61.0±5.0	22.2	VLBA	2009ApJ...705.1548R
Sgr B2N	0.68	-0.03	0.128±0.015	-0.32±0.05	-4.69±0.11	64.0±5.0	22.2	VLBA	2009ApJ...705.1548R
G009.62+00.19	9.62	0.20	0.194±0.023	-0.58±0.05	-2.49±0.27	5.0±3.1	12.2	VLBA	2009ApJ...706..464S
G010.47+00.02	10.47	0.02	0.117±0.008	-3.86±0.02	-6.40±0.08	68.9±4.5	22.2	VLBA	2014ApJ...781..108S
G010.62-00.38	10.62	-0.38	0.202±0.019	-0.37±0.08	-0.60±0.06	-3.0±2.7	22.2	VLBA	2014ApJ...781..108S
G011.49−01.48	11.49	-1.48	0.800±0.033	1.42±0.52	-0.60±0.65	11.0±3.0	12.2	VLBA	2014A&A...566A..17W
G012.02-00.03	12.03	-0.03	0.106±0.008	-4.11±0.02	-7.76±0.27	109.8±2.4	12.2	VLBA	2014ApJ...781..108S
G012.68-0.18	12.68	-0.18	0.416±0.028	-1.00±0.30	-2.85±0.29	56.0±4.0	22	VLBA	2013A&A...553A.117I
G012.81-0.19	12.81	-0.19	0.343±0.037	-0.60±0.11	-0.99±0.13	36.0±4.0	22	VLBA	2013A&A...553A.117I
G012.81-0.19	12.81	-0.19	0.343±0.037	-0.24±0.17	0.54±0.12	-2.0±4.0	22	VLBA	2013A&A...553A.117I
G012.88+0.48	12.88	0.48	0.340±0.036	0.12±0.13	-2.66±0.23	32.0±4.0	22	VLBA	2013A&A...553A.117I
G012.89+00.49	12.89	0.49	0.428±0.022	0.16±0.03	-1.90±1.59	31.0±7.0	12.2	VLBA	2011ApJ...733...25X
G012.90-0.26	12.90	-0.26	0.396±0.032	-0.36±0.08	-2.22±0.13	36.0±4.0	22	VLBA	2013A&A...553A.117I
G012.90-0.24	12.90	-0.24	0.408±0.025	0.19±0.08	-2.52±0.32	36.0±4.0	22	VLBA	2013A&A...553A.117I
G014.63-00.57	14.63	-0.57	0.546±0.022	0.22±1.20	-2.07±1.20	19.0±5.0	22	VLBA	2014A&A...566A..17W
G015.03-00.68	15.03	-0.68	0.505±0.033	0.68±0.05	-1.42±0.09	22.0±3.0	12.2	VLBA	2011ApJ...733...25X
G23.0-0.4	23.01	-0.41	0.218±0.017	-1.72±0.04	-4.12±0.30	81.0±3.0	12.2	VLBA	2009ApJ...693..424B
G23.4-0.2	23.44	-0.18	0.170±0.032	-1.93±0.10	-4.11±0.07	97.0±3.0	12.2	VLBA	2009ApJ...693..424B
G23.6-0.1	23.66	-0.13	0.313±0.039	-1.32±0.02	-2.96±0.03	83.0±3.0	12.2	VLBA	2008A&A...490..787B

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

The BeSSeL Survey



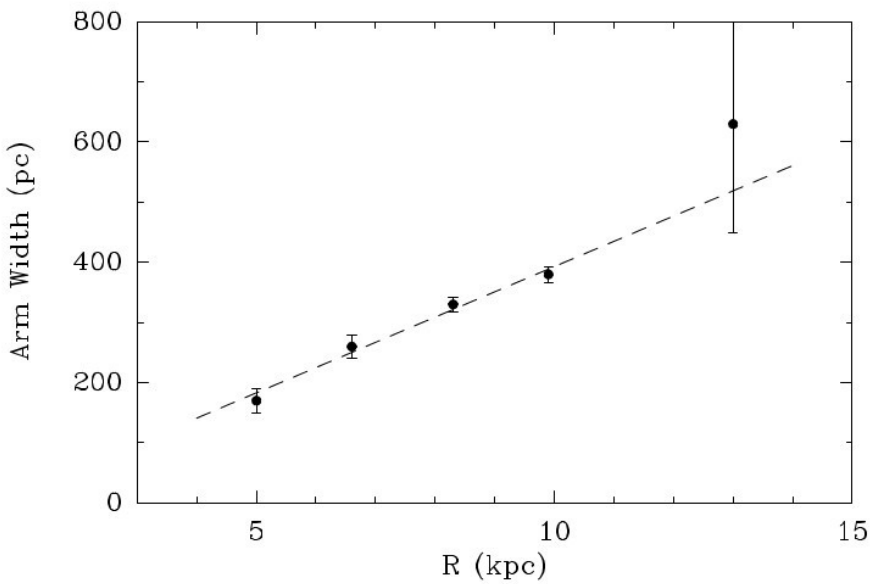
(Reid et al. 2014, ApJ 783, 130)

- Results of parallaxes from VLBA, EVN & VERA:
- ~100 sources with accuracies between 6 and 40 μas
- Arms assigned by CO l-v plot
- Tracing most spiral arms
- Inner, bar-region is complicated

The BeSSeL Survey

Spiral arm details:

Arm	N	β_{ref} (β Range) (deg)	R_{ref} (kpc)	Width (kpc)	ψ (deg)
Scutum	17	27.6 (+3 → 101)	5.0 ± 0.1	0.17 ± 0.02	19.8 ± 2.6
Sagittarius	18	25.6 (−2 → 68)	6.6 ± 0.1	0.26 ± 0.02	6.9 ± 1.6
Local	25	8.9 (−8 → 27)	8.4 ± 0.1	0.33 ± 0.01	12.8 ± 2.7
Perseus	24	14.2 (−21 → 88)	9.9 ± 0.1	0.38 ± 0.01	9.4 ± 1.4
Outer	6	18.6 (−6 → 56)	13.0 ± 0.3	0.63 ± 0.18	13.8 ± 3.3



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

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The BeSSeL Survey

Method / Rotation Curve used	R_0 (kpc)	Θ_0 (km/s)	$d\Theta/dR$ (km/s/kpc)	$\langle V_{src} \rangle$ (km/s)	$\langle U_{src} \rangle$ (km/s)	Θ_0/R_0 (km/s/kpc)

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Method / Rotation Curve used	R_0 (kpc)	Θ_0 (km/s)	$d\Theta/dR$ (km/s/kpc)	$\langle V_{src} \rangle$ (km/s)	$\langle U_{src} \rangle$ (km/s)	Θ_0/R_0 (km/s/kpc)
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)

"Outlier-tolerant" Bayesian fitting: $\text{Prob}(D_i|M,\sigma_i) \propto \left(1 - \exp(-R_i^2/2)\right) / R_i^2$ where $R_i = (D_i - M_i) / \sigma_i$

Θ_0 and R_0 now only weakly correlated.

$\Theta_0 + V_{sun} = 255$ km/s

$V_{sun} - \langle V_{src} \rangle = 18$ km/s

Notes:

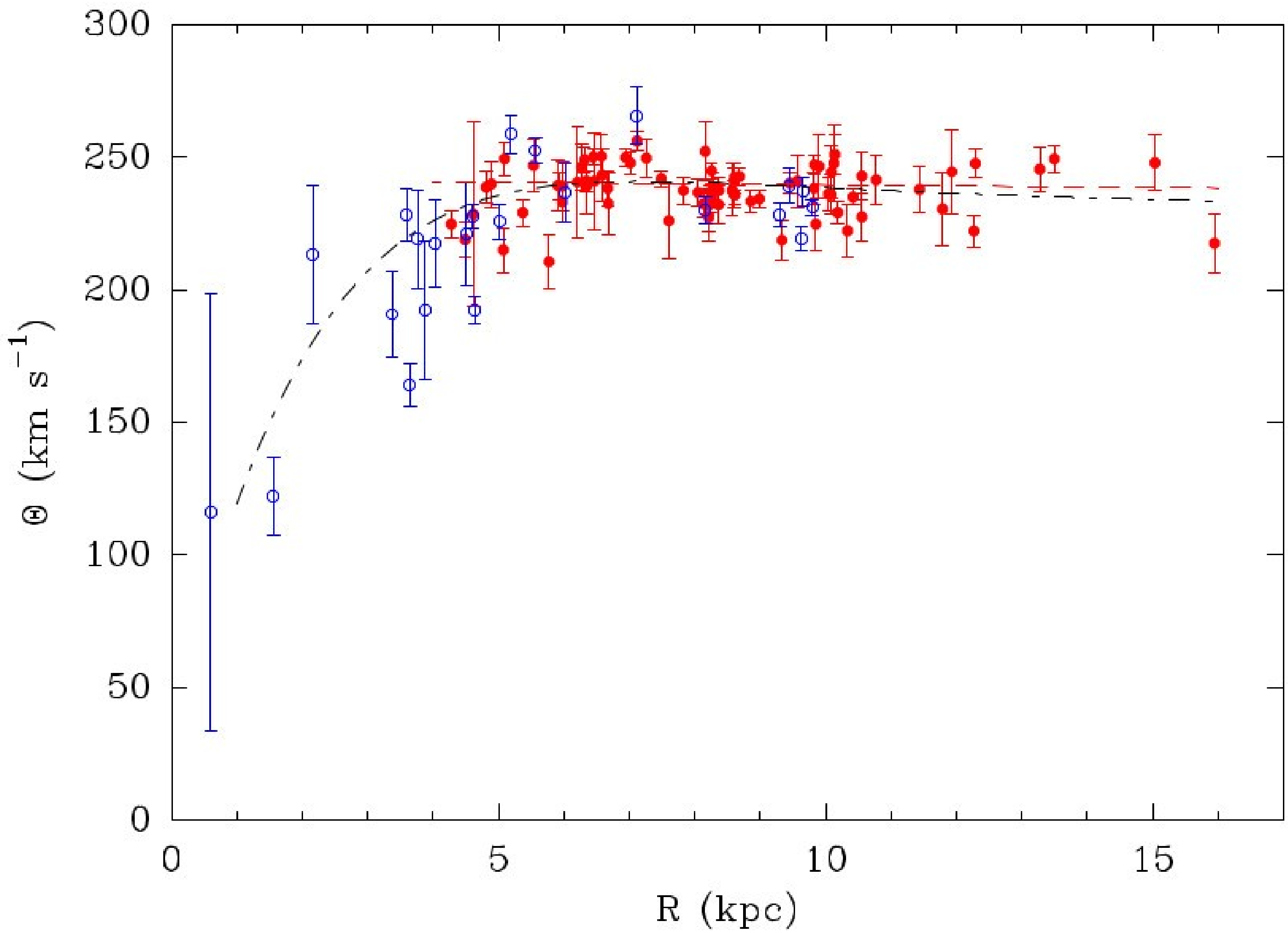
*Assuming new Solar Motion component: $V_{sun} = 12$ km/s (Schœnrich et al 2010)

$\langle V_{src} \rangle$ = average deviation from circular rotation of maser stars

$\langle U_{src} \rangle$ = average motion toward Galactic Center

$\Theta_0/R_0 = 28.8 \pm 0.2$ km/s/kpc from proper motion of Sgr A* (Reid & Bruntheler 2004)

The BeSSeL Survey



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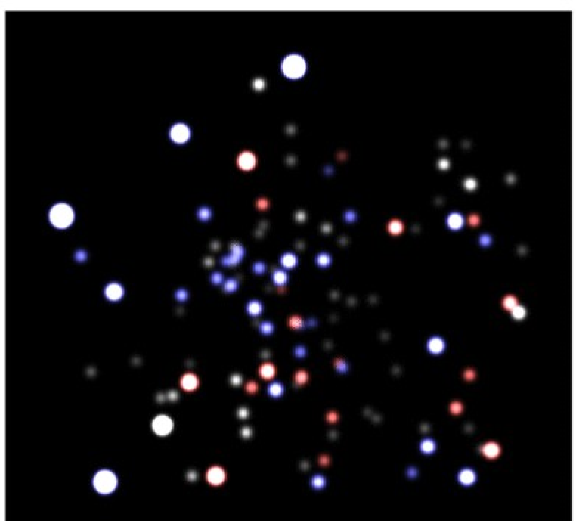
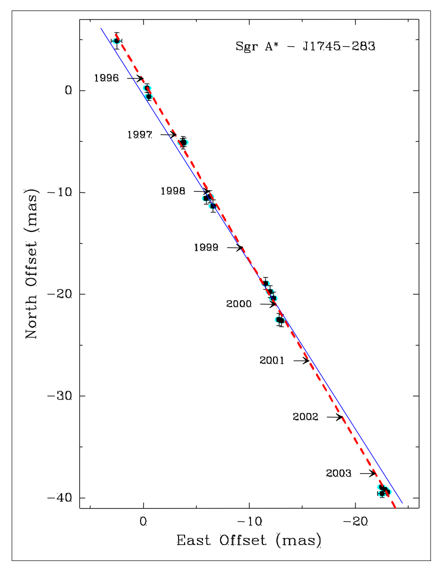
Galactic Rotation

- 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)


(Gillessen et al. 2009)



(Reid & Brunthaler 2004)

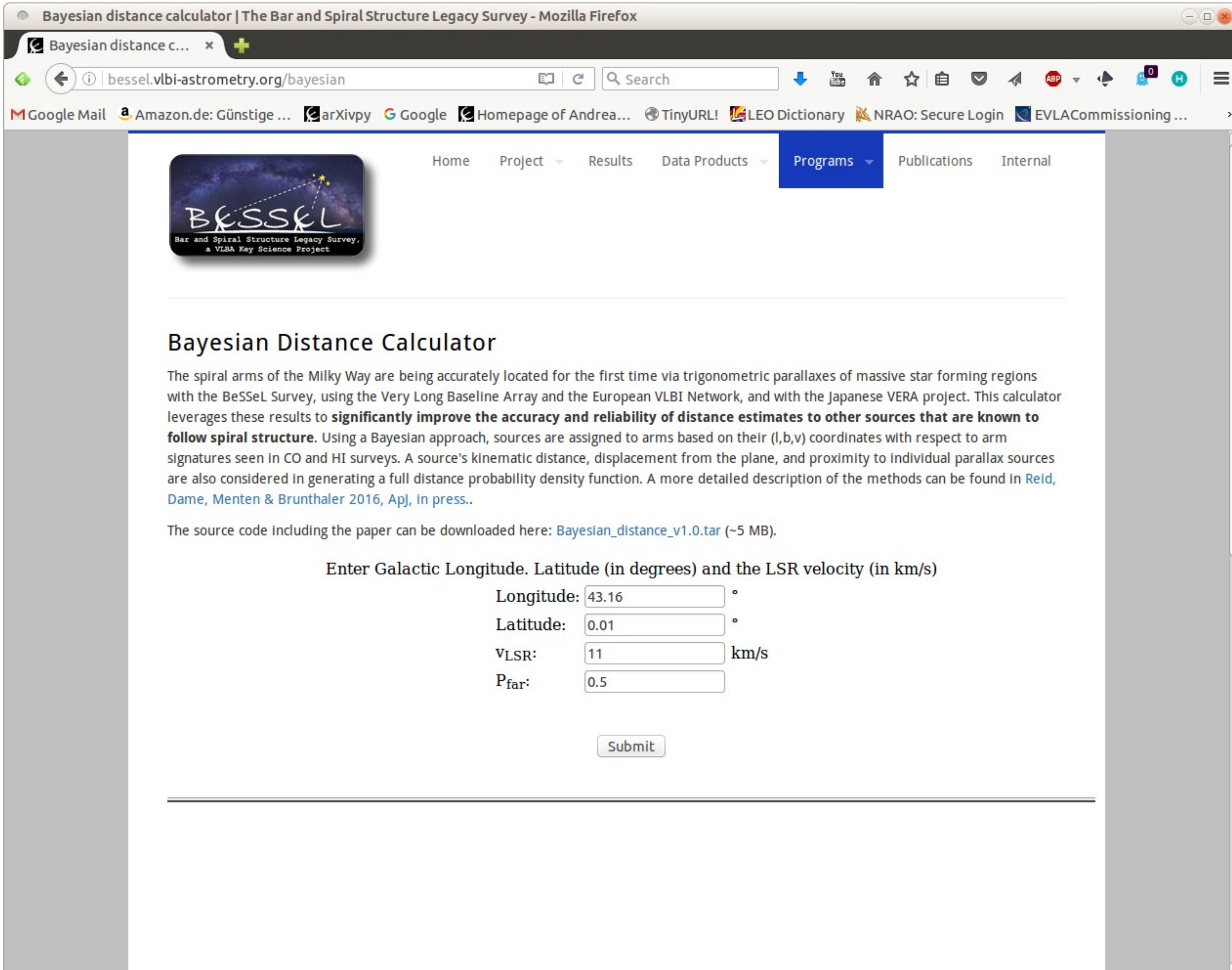
Bayesian Distance calculator

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

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

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

Bayesian Distance calculator



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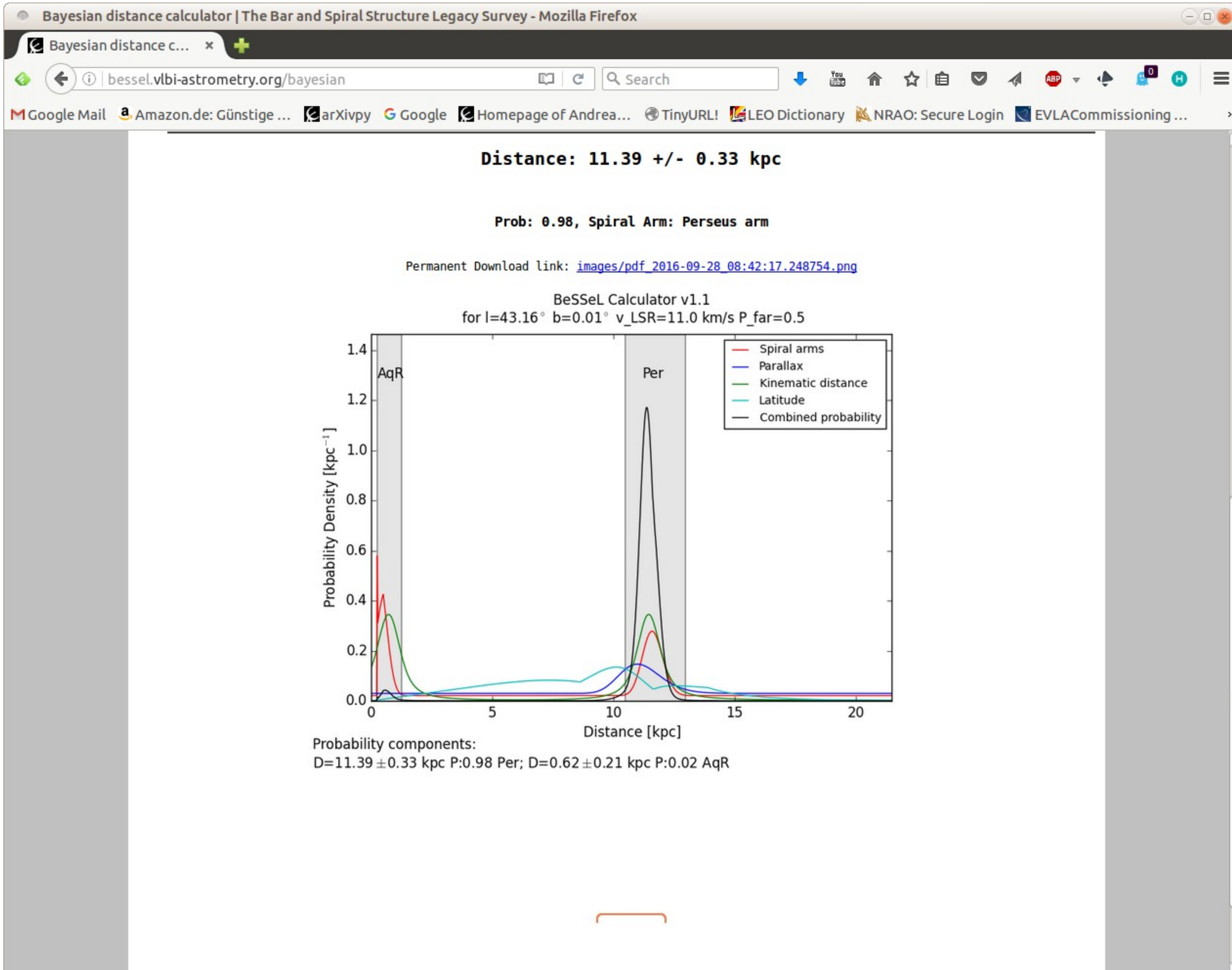

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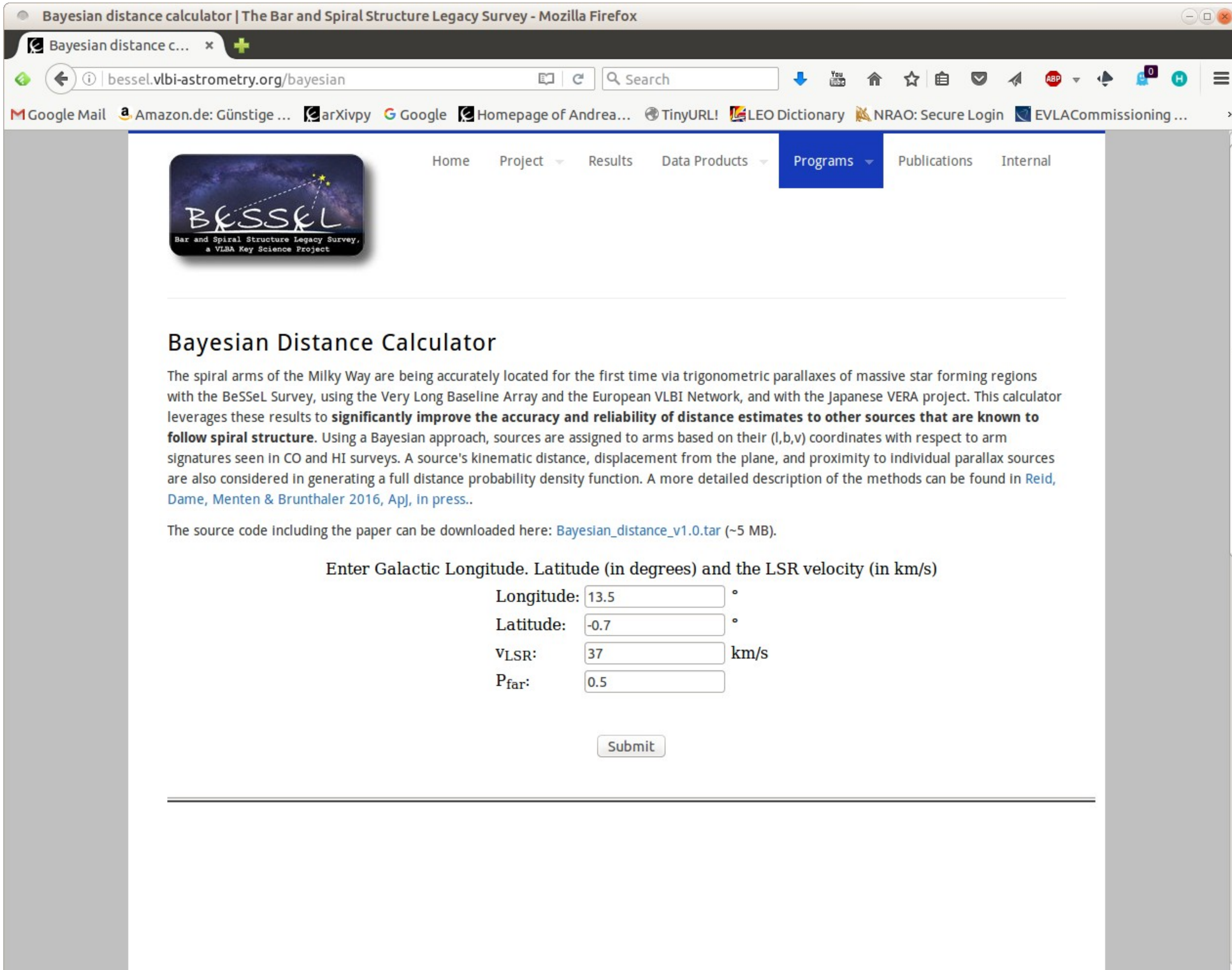

Bayesian distance calculator | The Bar and Spiral Structure Legacy Survey - Mozilla Firefox

bessel.vlbi-astrometry.org/bayesian

Home | Project | Results | Data Products | Programs | Publications | Internal

BeSSeL — Bar and Spiral Structure Legacy Survey, a VLBA Key Science Project

Bayesian Distance Calculator

The spiral arms of the Milky Way are being accurately located for the first time via trigonometric parallaxes of massive star forming regions with the BeSSeL Survey, using the Very Long Baseline Array and the European VLBI Network, and with the Japanese VERA project. This calculator leverages these results to **significantly improve the accuracy and reliability of distance estimates to other sources that are known to follow spiral structure**. Using a Bayesian approach, sources are assigned to arms based on their (l,b,v) coordinates with respect to arm signatures seen in CO and HI surveys. A source's kinematic distance, displacement from the plane, and proximity to individual parallax sources are also considered in generating a full distance probability density function. A more detailed description of the methods can be found in Reid, Dame, Menten & Brunthaler 2016, ApJ, in press..

The source code including the paper can be downloaded here: Bayesian_distance_v1.0.tar (~5 MB).

Enter Galactic Longitude. Latitude (in degrees) and the LSR velocity (in km/s)

Longitude:	13.5	°
Latitude:	-0.7	°
v_{LSR}:	37	km/s
P_{far}:	0.5	

Submit

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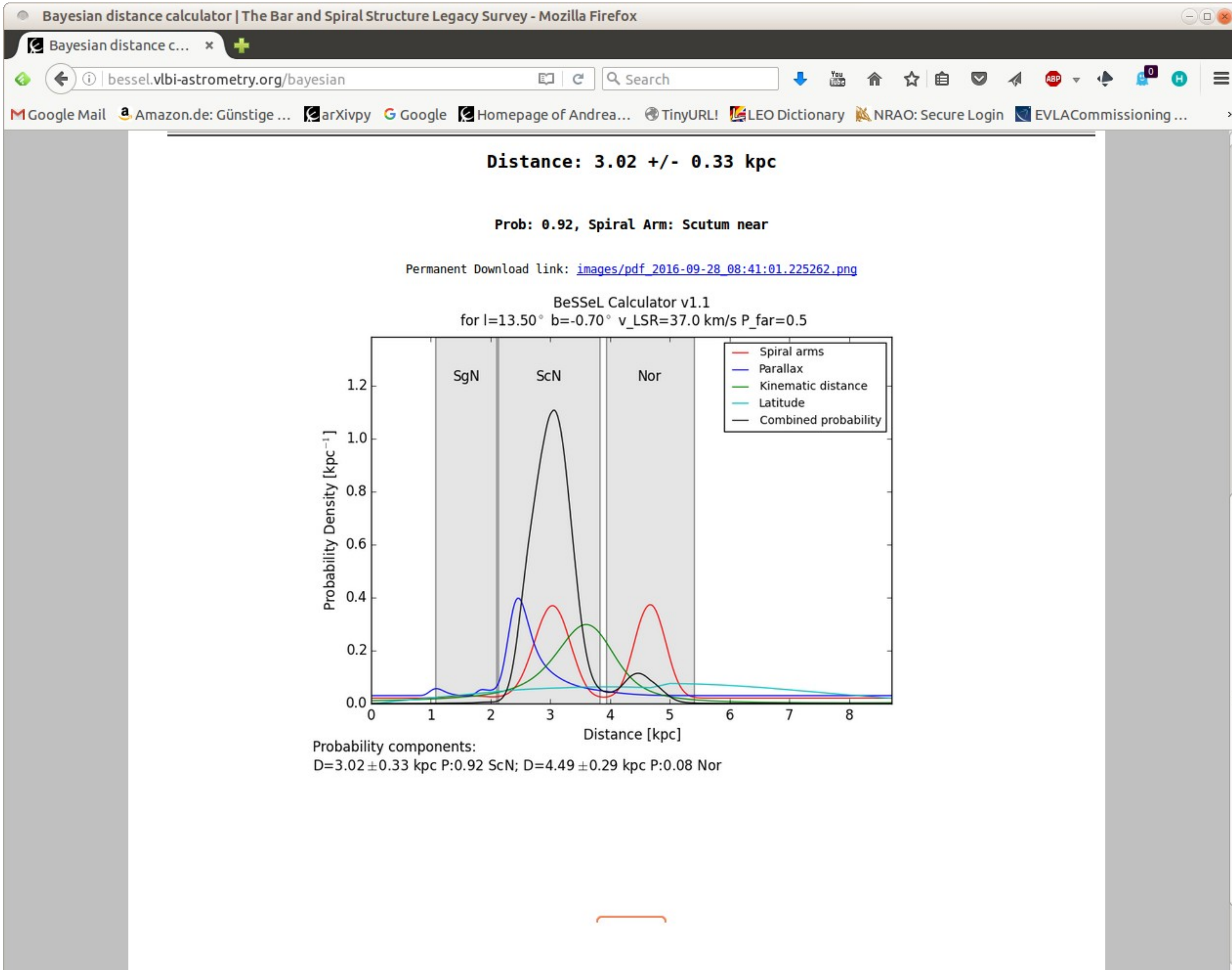
Bayesian Distance calculator

•

• 

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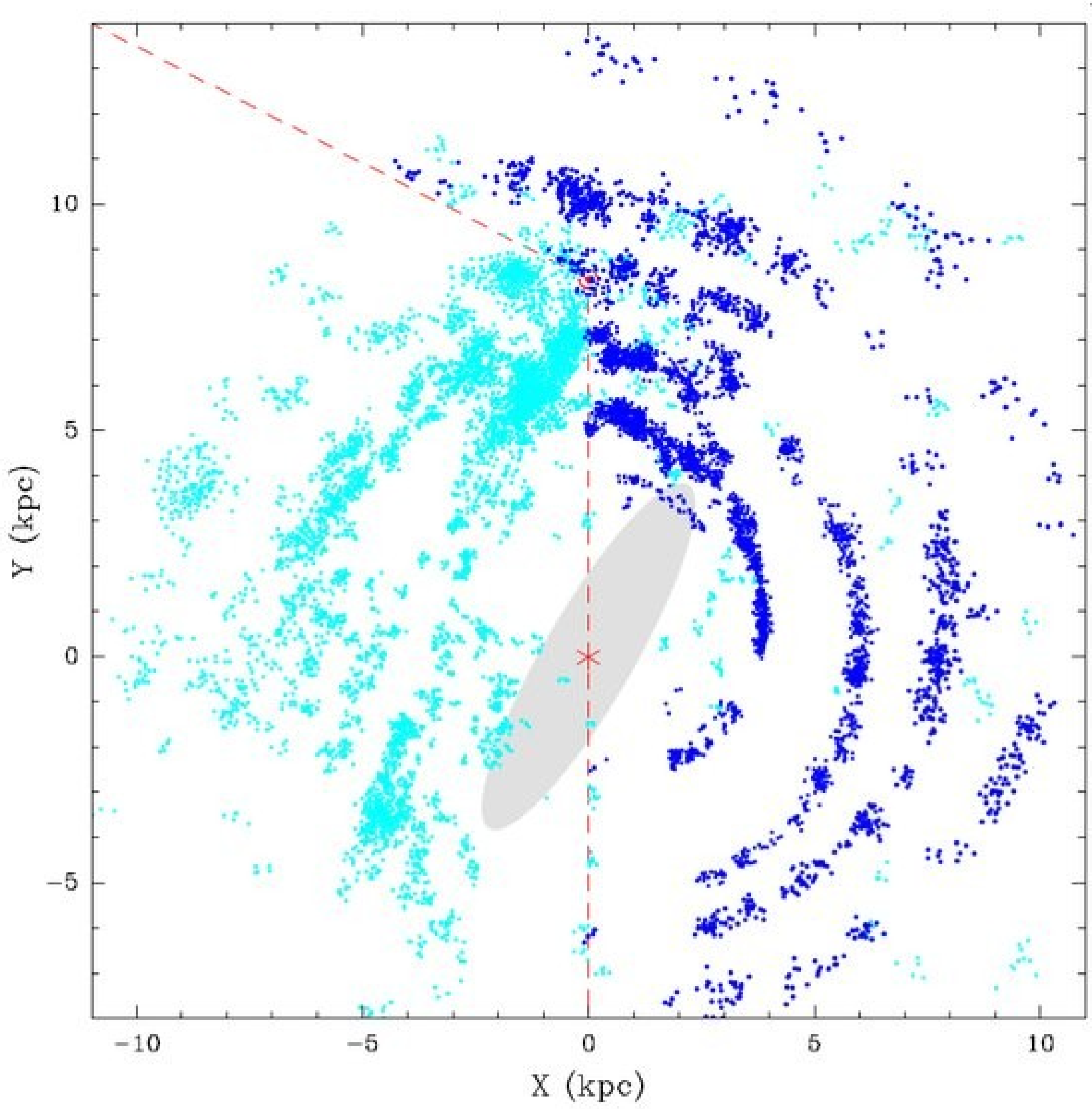
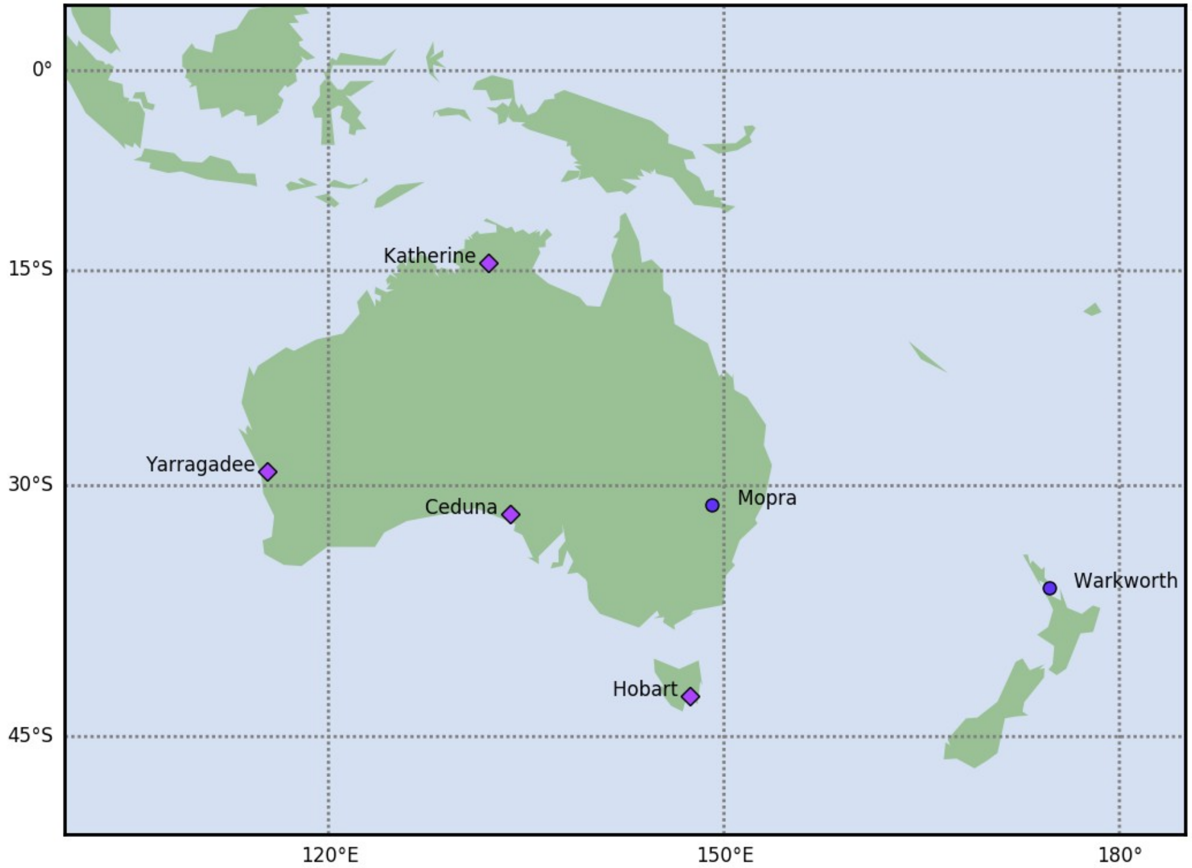
Bayesian Distance calculator



BeSSeL South



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

Future of VLBI Astrometry

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

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  e.g. *parallax gradients* caused by ionospheric wedges

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  - only small number of calibrator availabe
- SKA not designed for astrometric accuracy

  - limited baseline length

  - limited phase centers

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How to reach accuracies of better than 10 μas?

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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 µas => 5% @ 50 kpc)