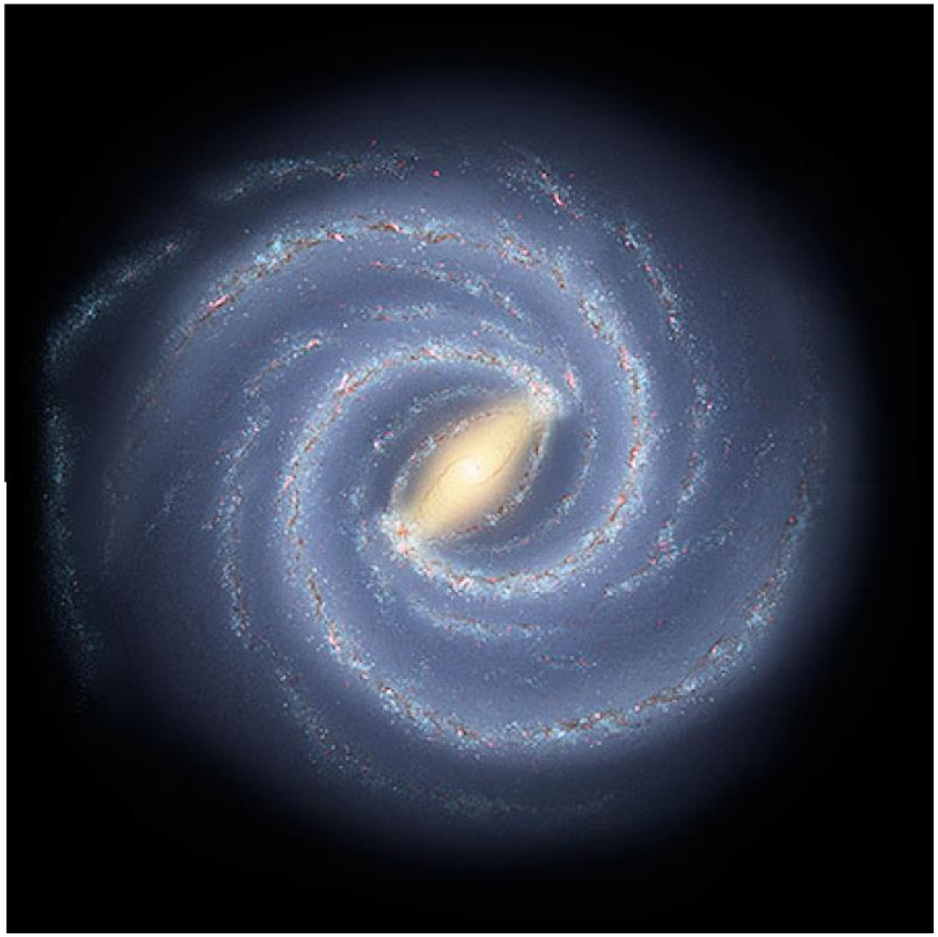
Structure and dynamics of the Milky Way



Max-Planck-Institut
für
Radioastronomie

Andreas Brunthaler

Outline

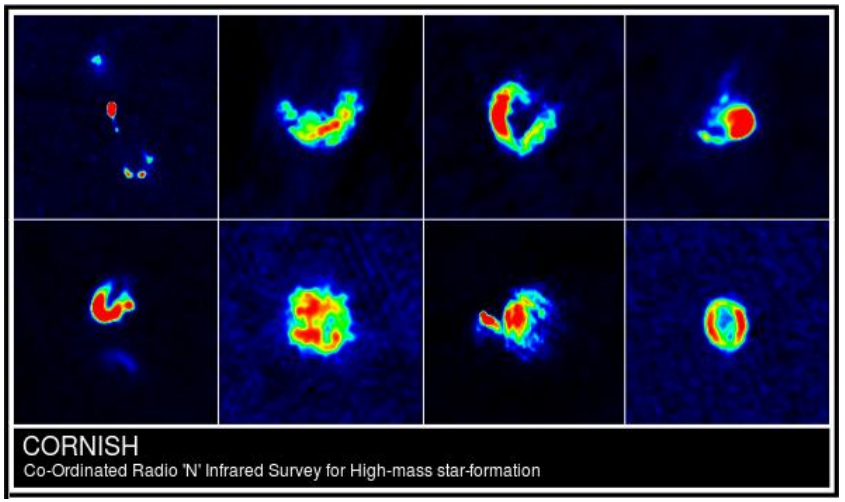
- Radio continuum and line surveys
- Astrometry of star forming regions

Galactic plane surveys

Current Radio Galactic Plane surveys:

- *Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation:* **CORNISH**

  - C-band (old) VLA B-configuration (1.5” res.)
  - 10° < l < 65 °; |b| < 1°
  - 200 – 400 µJy sensitivity
  - 50 MHz bandwidth



- Methanol Multi beam survey: **MMB**

  - blind methanol maser survey with Parkes
  - -180° < l < 60°; |b| < 2°
  - ~170 mJy sensitivity
  - 0.11 km/s velocity resolution
  - also excited OH (6035 MHz)

A VLA Galactic plane survey

The **Jansky Very Large Array** (VLA)

- much more powerful than old VLA
- Complete frequency coverage 1 – 50 GHz !
- Much higher bandwidth: 1, 2, or 8 GHz instead of 50 MHz
- New correlator: Up to 64 spectral lines simultaneously !
- New and more sensitive receivers !

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GLOSTAR

- **A VLA Galactic plane survey**

- 2° x 1° fields

- in D-configuration and B-configuration

- ~ 750 pointings, 2 scans of ~ 11 seconds => 5 hours total time per conf.

- 2 GHz continuum (4.2-5.2 GHz & 5.9-6.9 GHz) => 40 µJy sensitivity

- 6.7 GHz methanol maser (0.18 km/s; 370 km/s) => 20 mJy sensitivity
- 4.8 GHz H_2CO absorption (0.25 km/s; 260 km/s) => 20 mJy sensitivity
- 7 RRLs (3-4 km/s; ~400 km/s) => 5 mJy sensitivity

- ~2.8 TB correlated data

K.M. Menten, A. Brunthaler, F. Wyrowski, C. Carrasco-Gonzales, T. Csengeri, J. Urquhart, B. Winkel (MPIfR); M.J. Reid, (CfA); J. Ott, M. Claussen (NRAO); J. Pandian (Hawaii); P. Hofner (NMT); H. Beuther (MPA); B. Cotton (NRAO)

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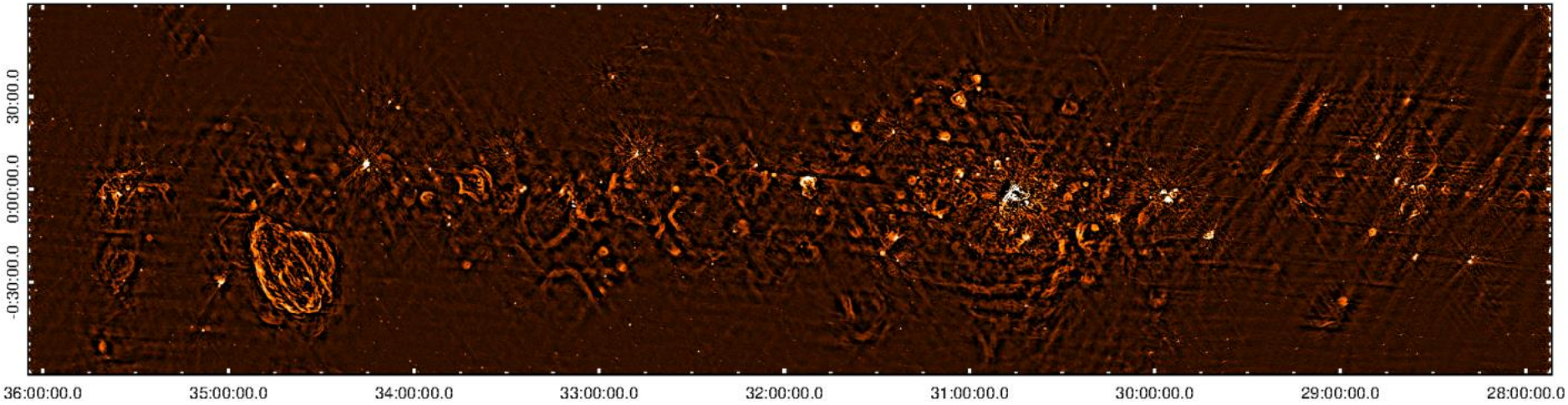
A VLA Galactic plane survey

- **First part of Survey: 28° < l < 36°; |b| < 1°**:

  - D-configuration data



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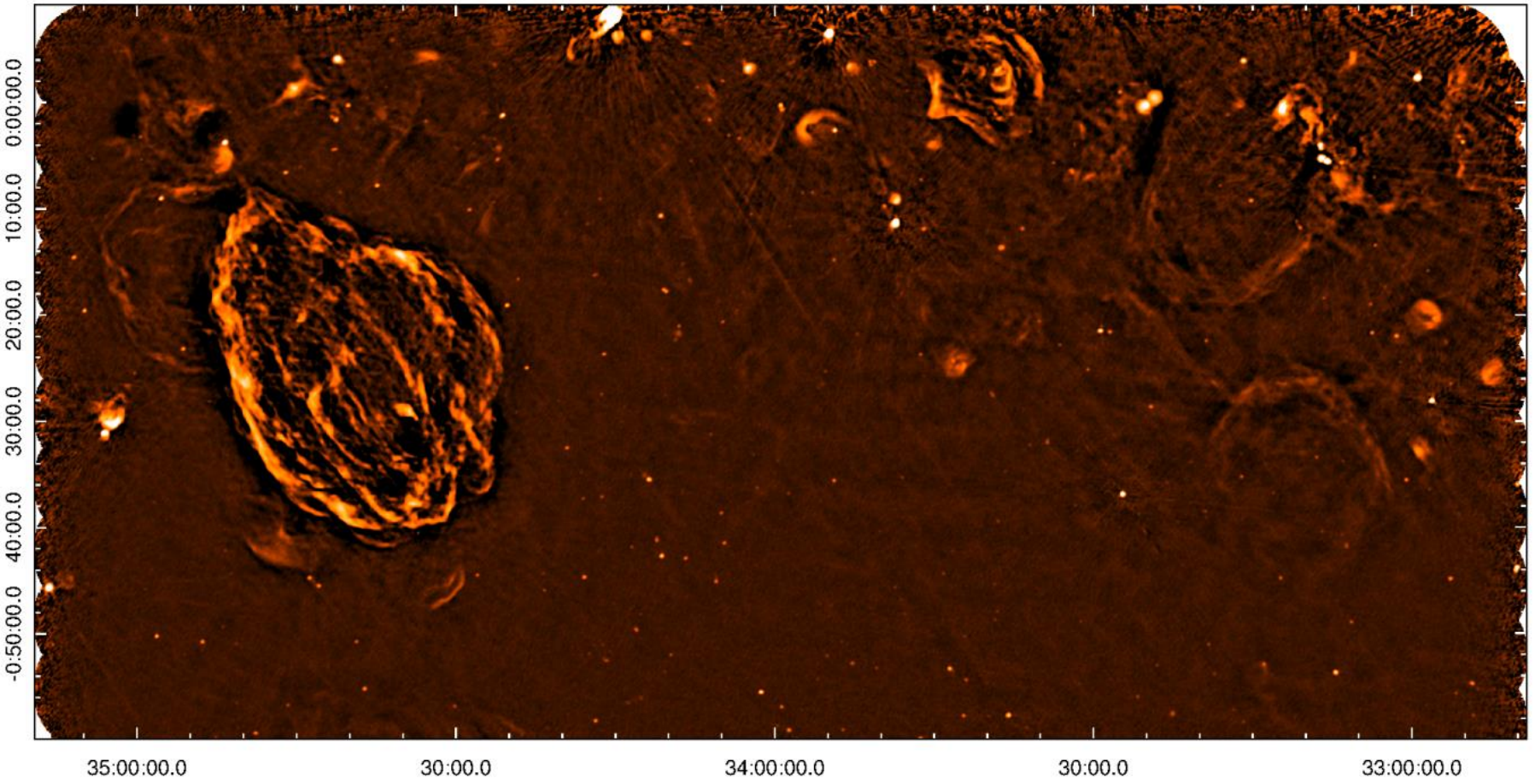

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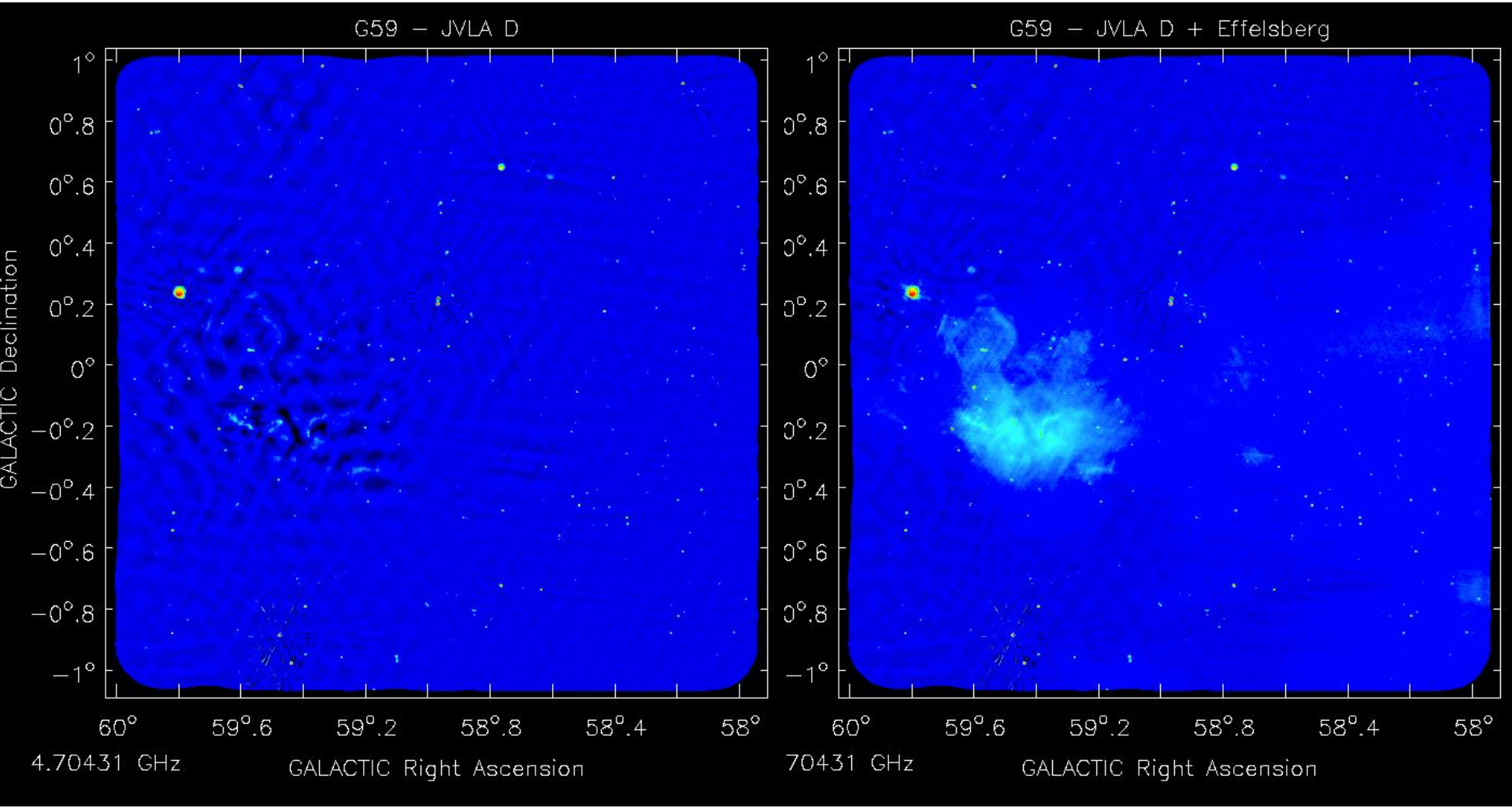
A VLA Galactic plane survey

- **Effelsberg single dish data for short spacings**:

- 2° x 2° field, centered on G59.0+0.0 (HERSCHEL science demonstation field)



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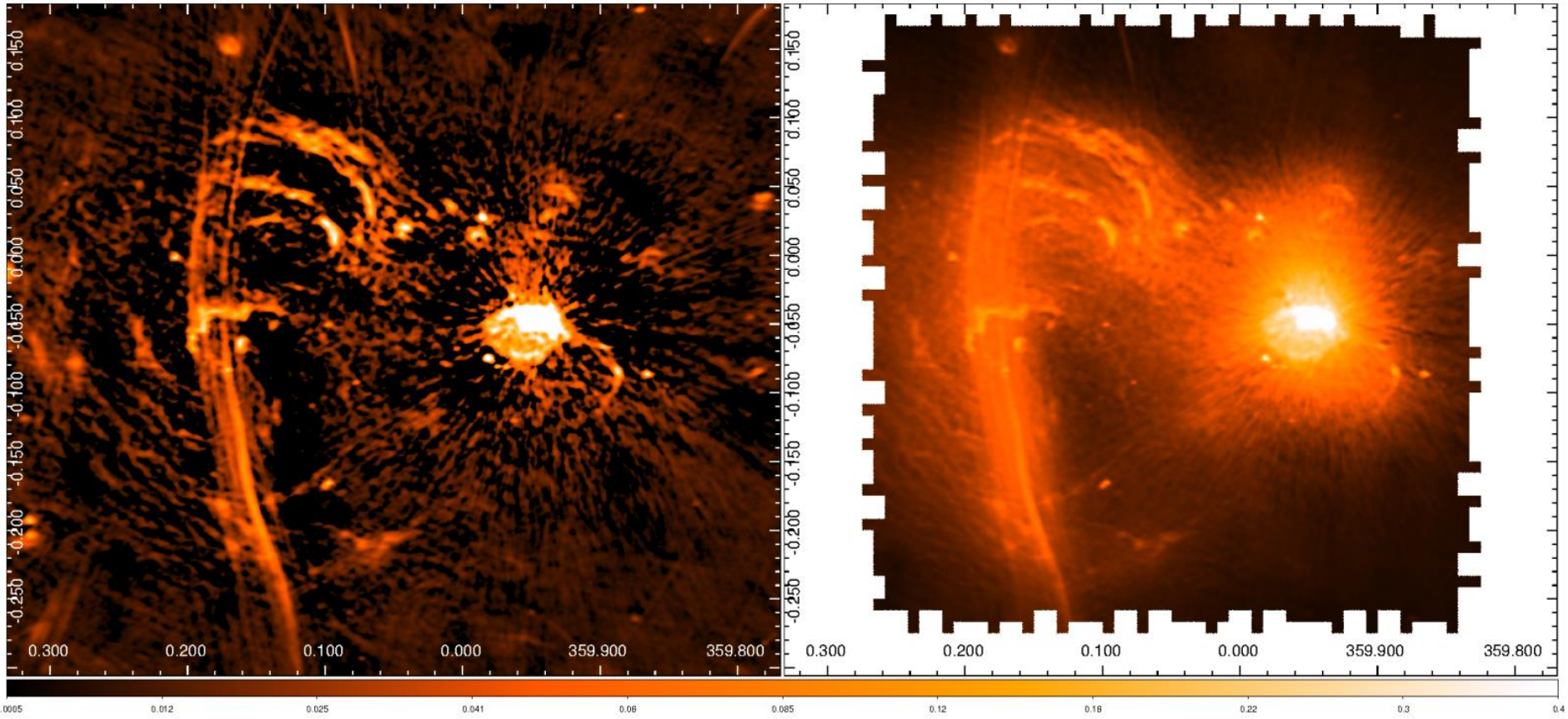
A VLA Galactic plane survey

- **Effelsberg single dish data for short spacings**:

  - Galactic Center region



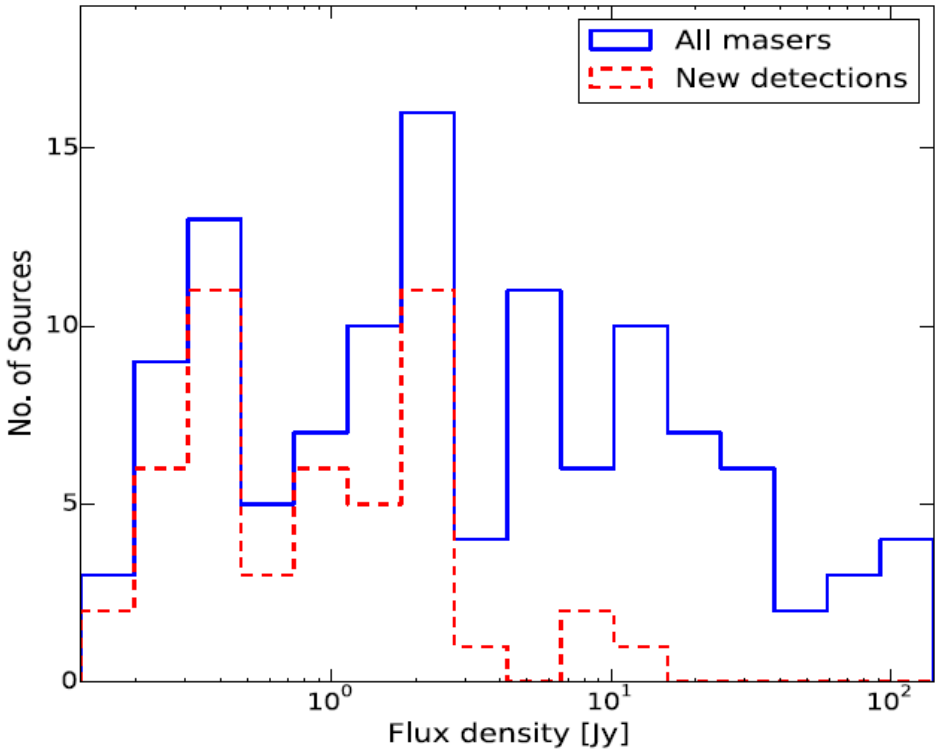
A VLA Galactic plane survey

- **6.7 GHz methanol masers:**

- so far 116 detections (48 new) in first part of Survey: 28° < l < 36°; |b| < 1°:

- MMB finds 72 sources in comparable region (324° < l < 332°)

- luminosity function not consistent with single power law



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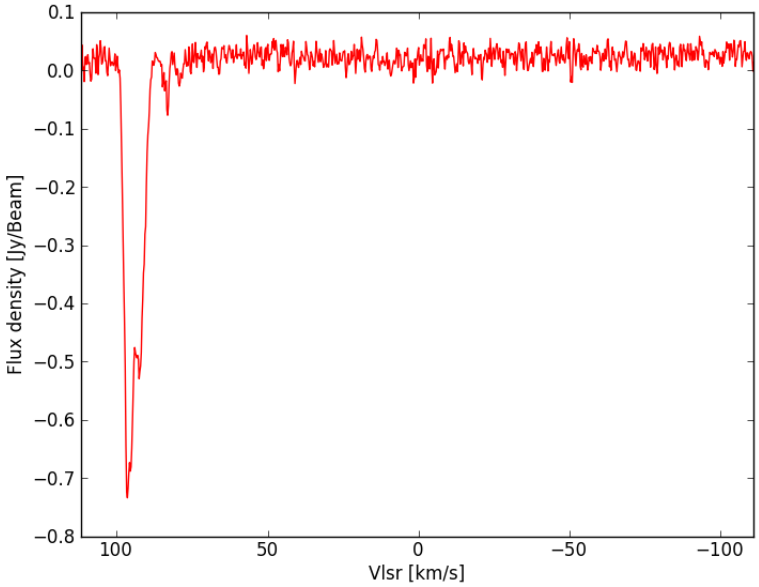
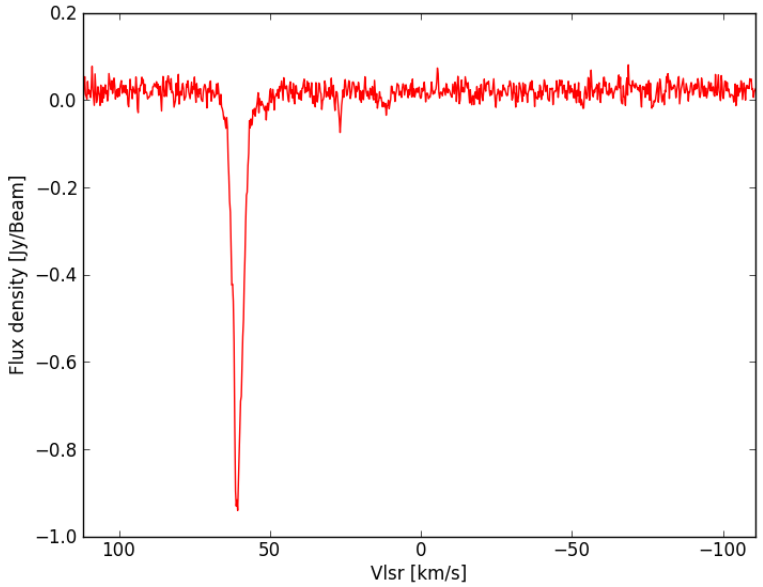
A VLA Galactic plane survey

- **First part of Survey: 28° < l < 36°; |b| < 1°**:

- D-configuration data: 4.8 GHz H_2CO absorption

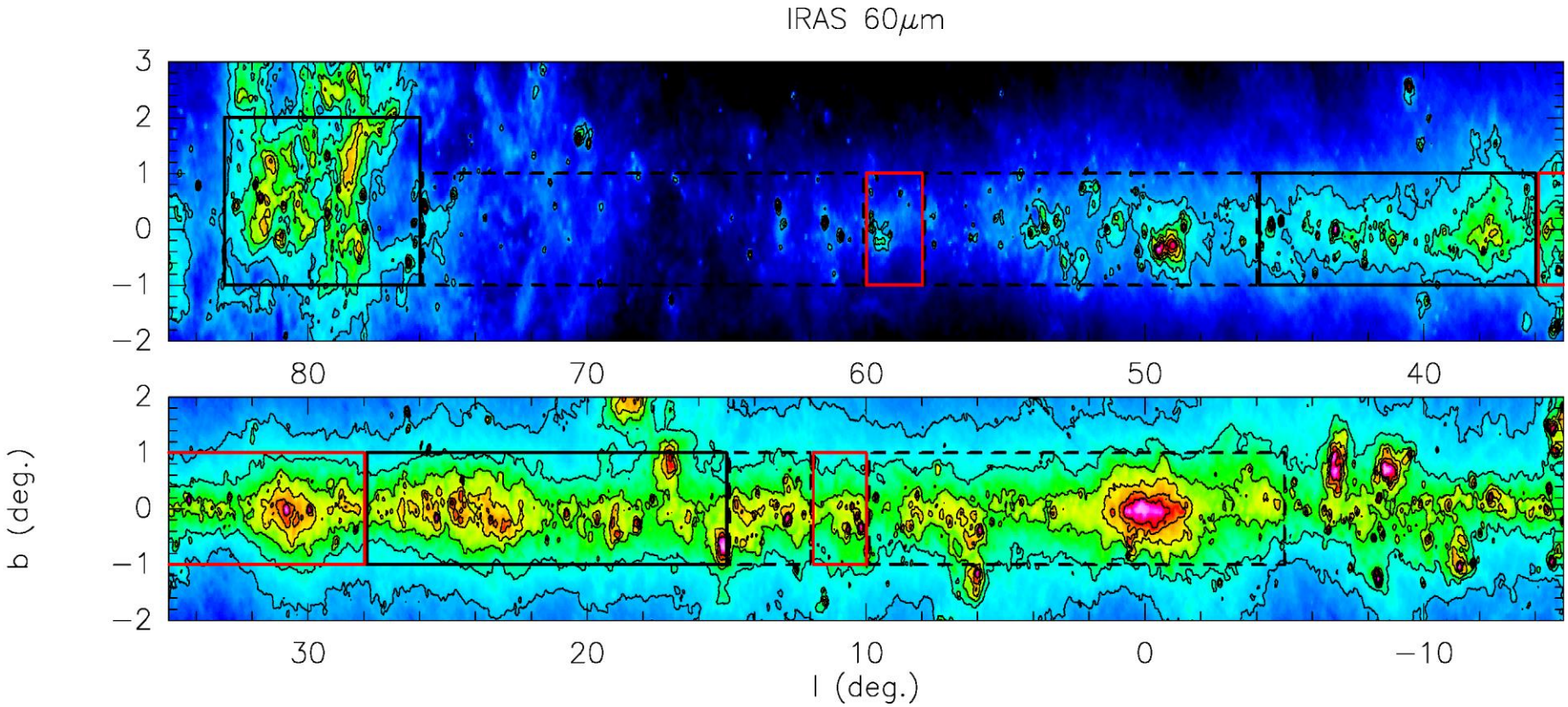
  16 detections





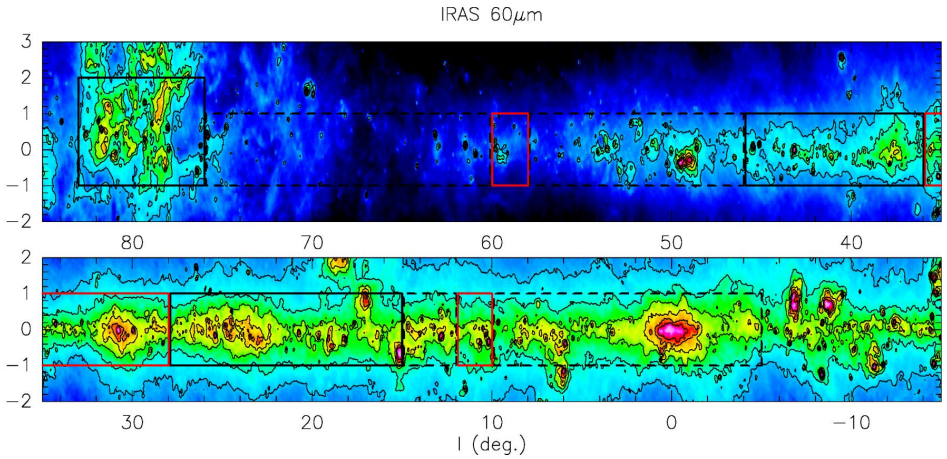
A VLA Galactic plane survey

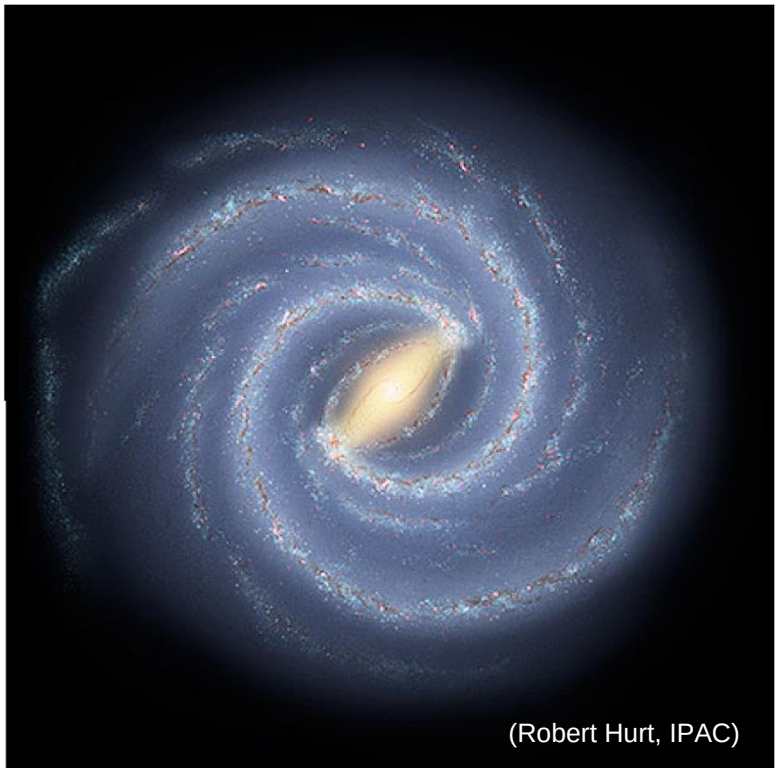
- Full survey on “Global view of star formation” (GLOSTAR) underway now:



Structure of the Milky Way

Going to the third dimension!





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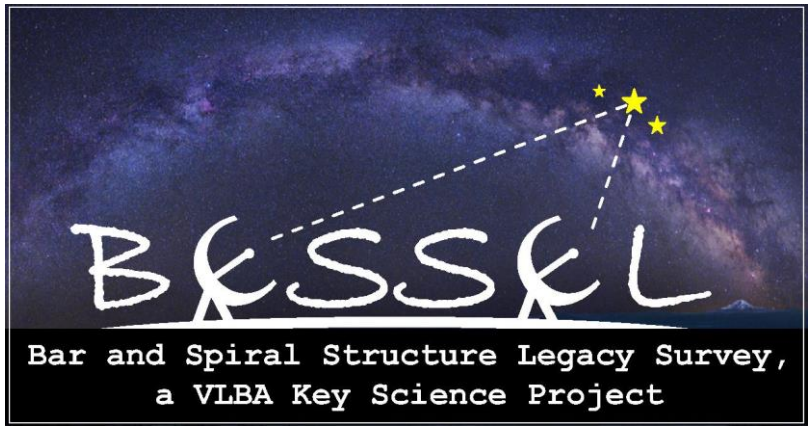
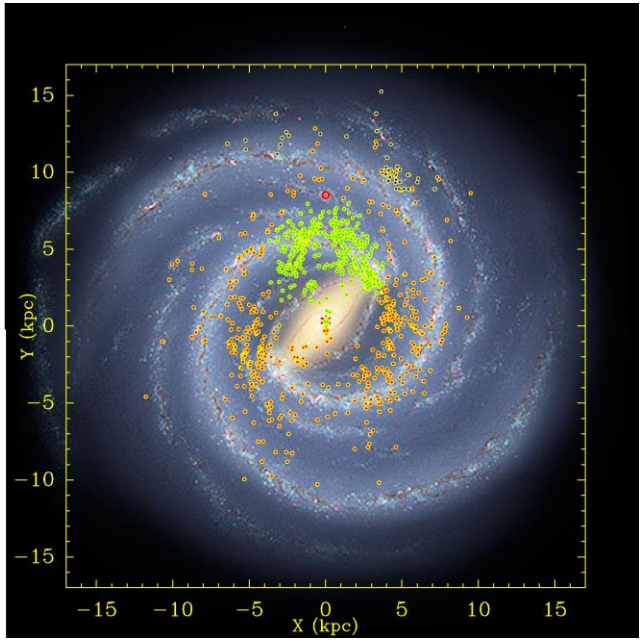
The BeSSeL Survey





- **B**ar and **S**piral **S**tructure **L**egacy survey, a VLBA Key Science project
- ~ 5000 hours over 5 years
- ~ 400 more 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)

VLBI Parallaxes: Example

Example: Orion Nebula

Literature: 350 – 500 pc
(usually 480 ± 80 pc by Genzel et al. 1981)

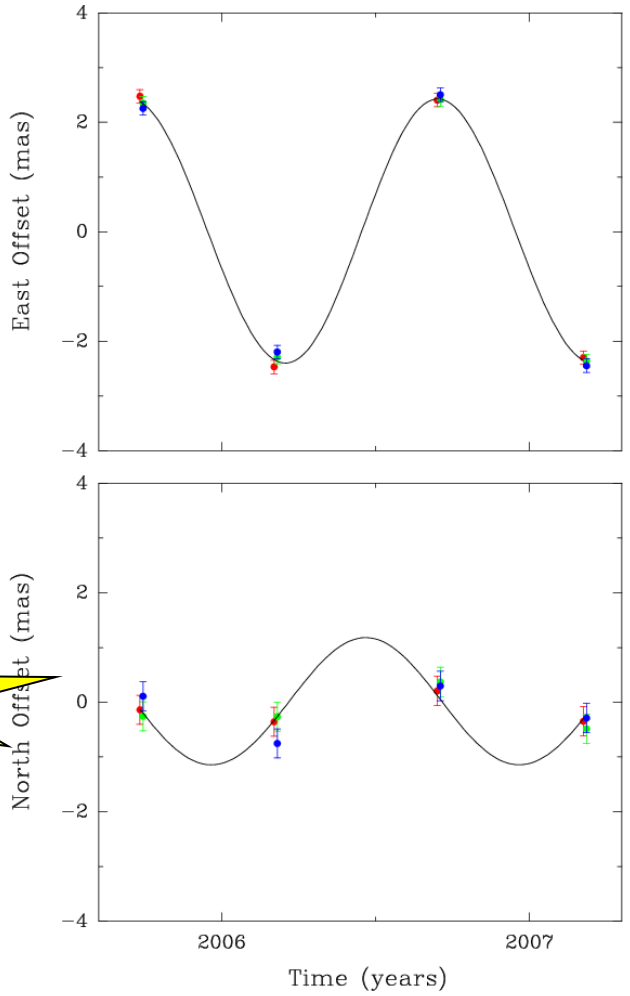
D = 389 ± 21 pc (Sandstrom et al. 2007)

D = 437 ± 19 pc (Hirota et al. 2007)

D = 414 ± 7 pc (Menten et al. 2007)

D = 419 ± 6 pc (Kim et al. 2008)

1.7%



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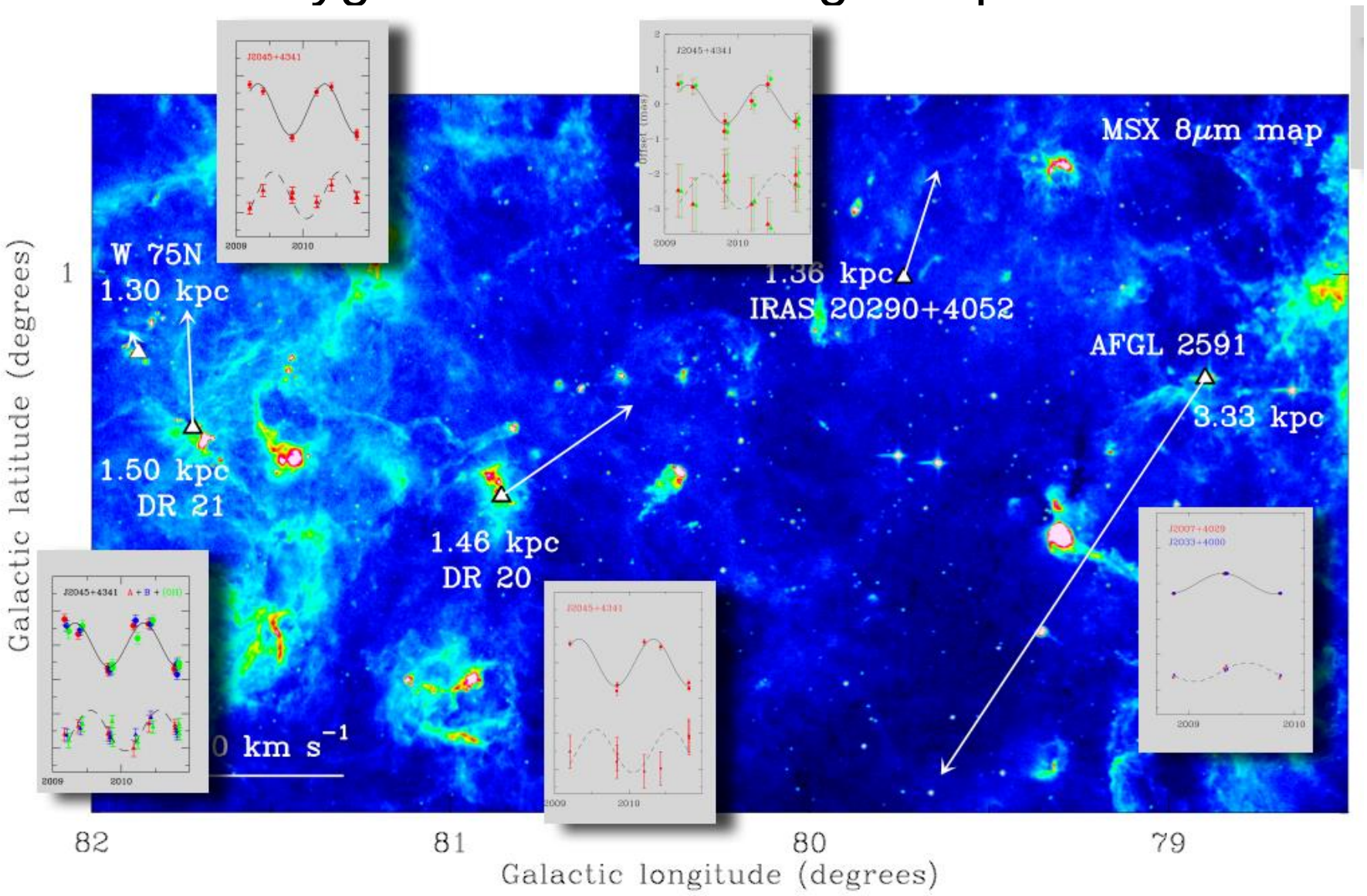
VLBI Parallaxes: Example

Cygnus X Star forming complex



Rygl et al. (2012)

Image: van Langevelde

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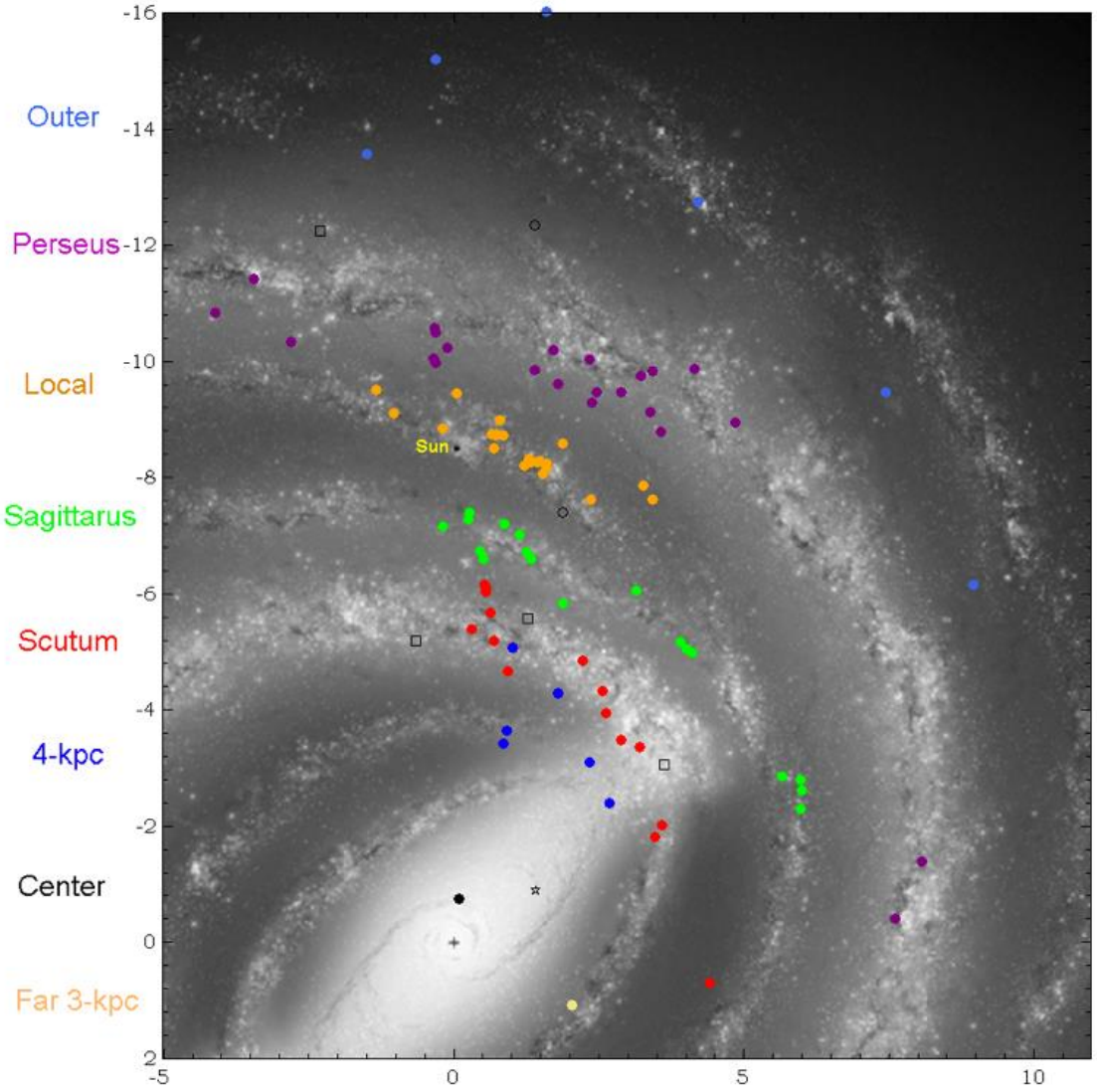
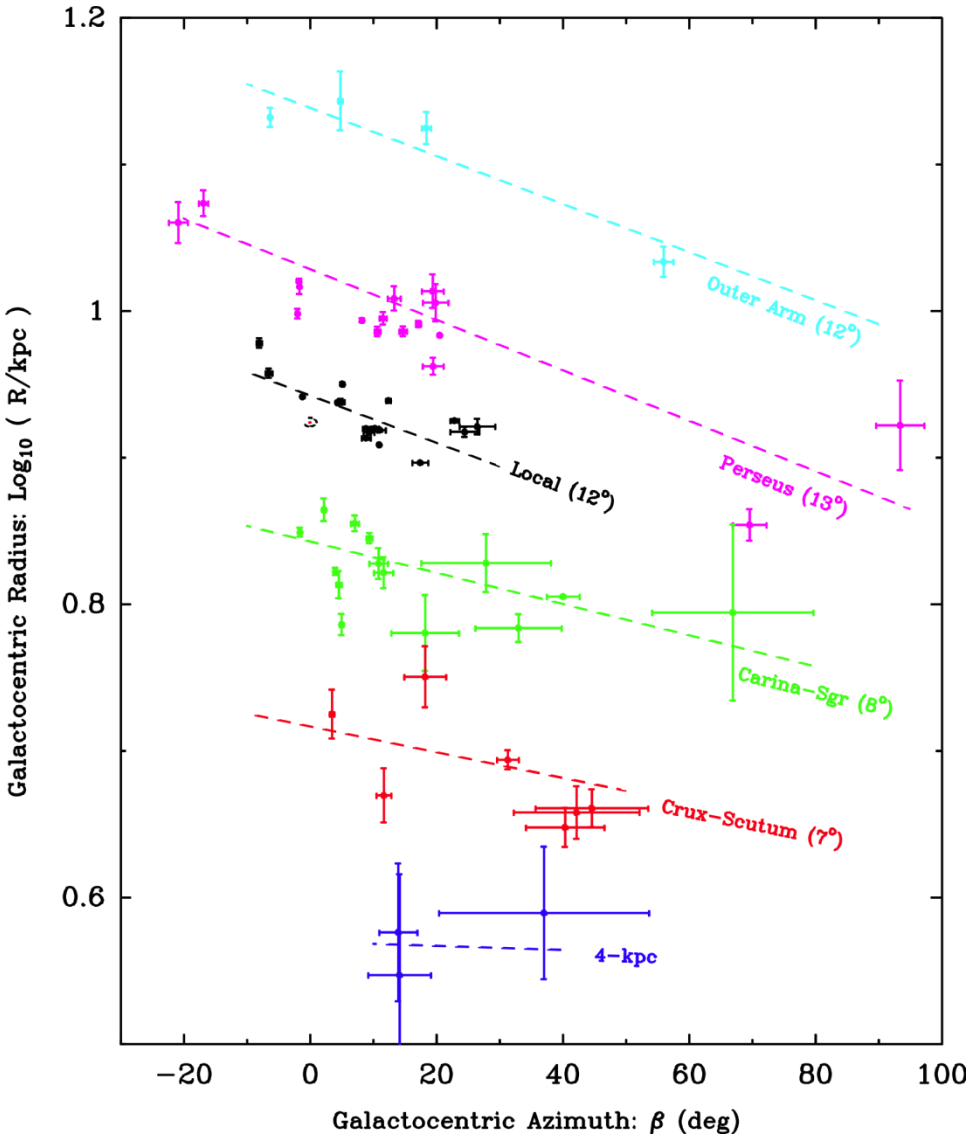
The BeSSeL Survey



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

Background: artist conception by Robert Hurt (NASA: SSC)

The BeSSeL Survey



- Outer spiral arms: ~12˚ pitch angles
- Inner arms may have smaller pitch angels (need more observations)

The BeSSeL Survey

Note on Solar motion:

- Until 2009, the Dehnen & Binney 1998 HIPPARCOS Solar motion of

  U_0 =10.00 ± 0.36 km/s (radially inwards),
  V_0 = 5.25 ± 0.62 km/s (in the direction of Galactic rotation) and
  W_0 = 7.17 ± 0.38 km/s (vertically upwards)

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  U_0 = 11.1 ± 2.0 k/ms, V_0 = 12.2 ± 2.1 km/s, W_0 = 7.2 ± 2.0 km/s

- Bovy et al. 2012 claim even higher value of V_0 = 26 ± 3 km/s

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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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The BeSSeL Survey

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"Outlier-tolerant" Bayesian fitting: $\text{Prob}(D_i \mid M, \sigma_i) \propto (1 - \exp(-R_i^2/2)) / R_i^2$ where $R_i = (D_i - M_i)/\sigma_i$						
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	-7 ± 2	3 ± 2	(29.5)

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

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

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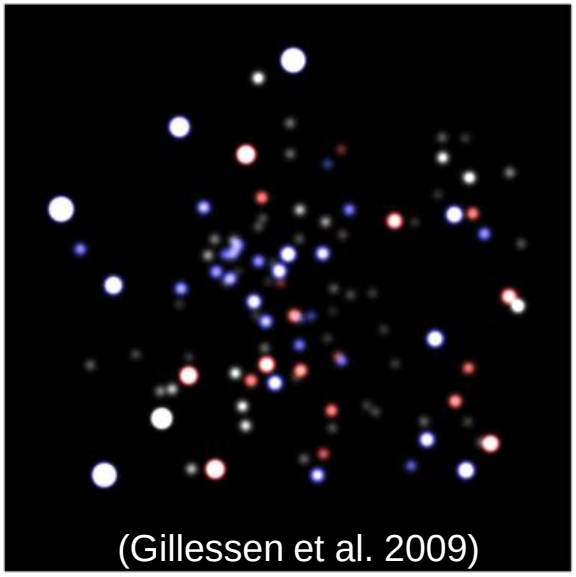
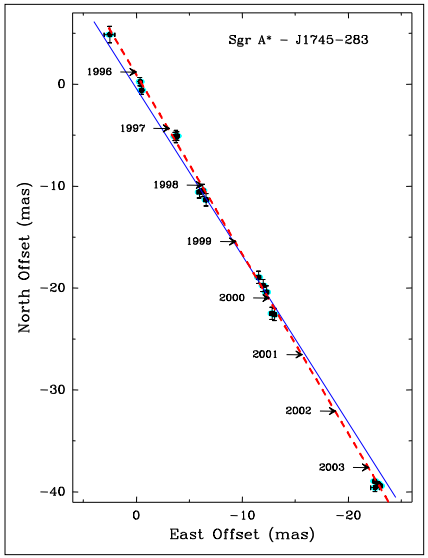
Independent Measurements

- Fitted different Galactic rotation models to 6d data
- Average motions: $U_s = 5 \pm 3$ km/s, $V_s = -8 \pm 2$ 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	28.7 (Reid & Brunthaler 2004)



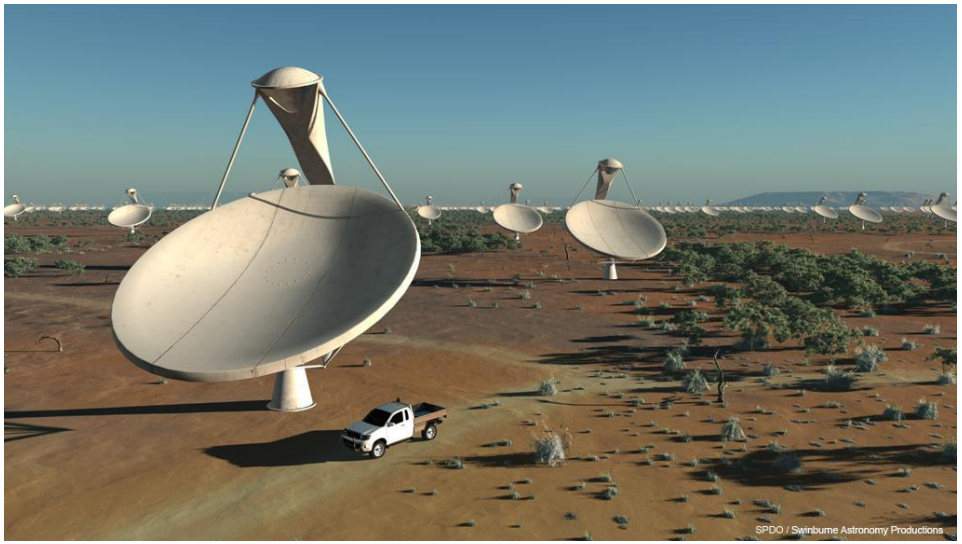
(Gillessen et al. 2009)



(Reid & Brunthaler 2004)

VLBI Astrometry in the Future

- VLBA (HSA) upgrade to 32 Gbps $\Rightarrow$ 8 $\times$ more sensitive than today
  - more target sources
  - more and closer calibrators
  - less systematic errors



- SKA: large field of view & sensitivity
  - several in-beam calibrators
  - systematic errors greatly reduced
  - astrometric accuracies of a few μas
  - parallaxes of ~ 1 μas

- SKA mid will cover the important 6.7 GHz methanol maser line
  - even a 5% trigonometric parallax to single maser in the LMC possible
  - and a rotational parallax

VLBI Astrometry in the Future

- VLBA (HSA) upgrade to 32 Gbps ⇒ [illegible] sensitive than today
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- SKA: l
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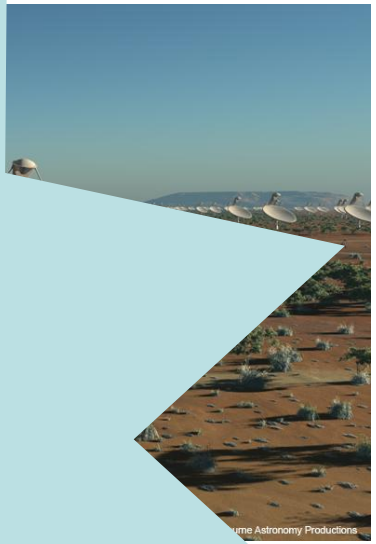
  - and a rotation



Long baselines of a few 1000 km essential!