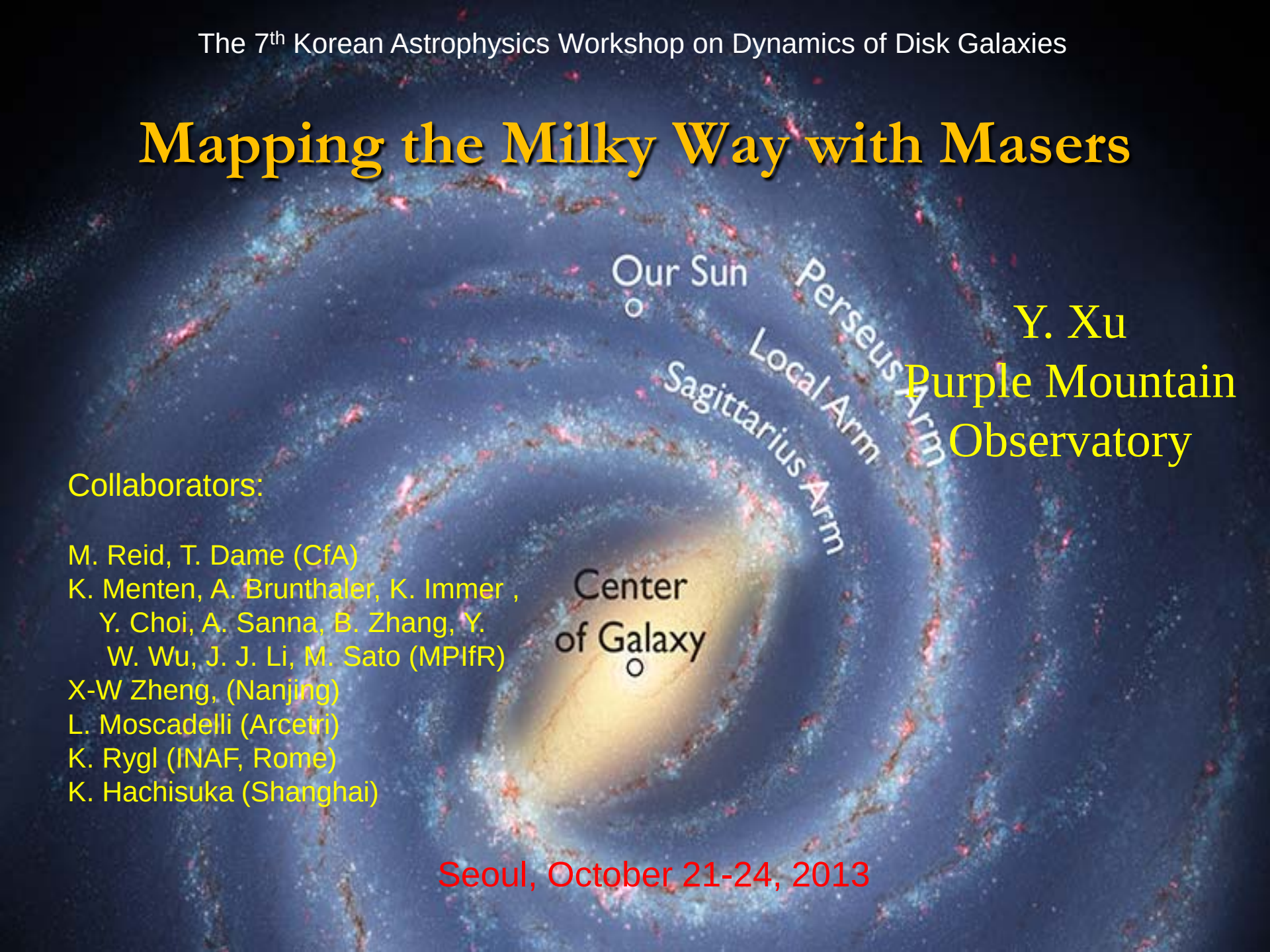
The 7th Korean Astrophysics Workshop on Dynamics of Disk Galaxies

Mapping the Milky Way with Masers



Y. Xu
Purple Mountain
Observatory

Collaborators:

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K. Hachisuka (Shanghai)

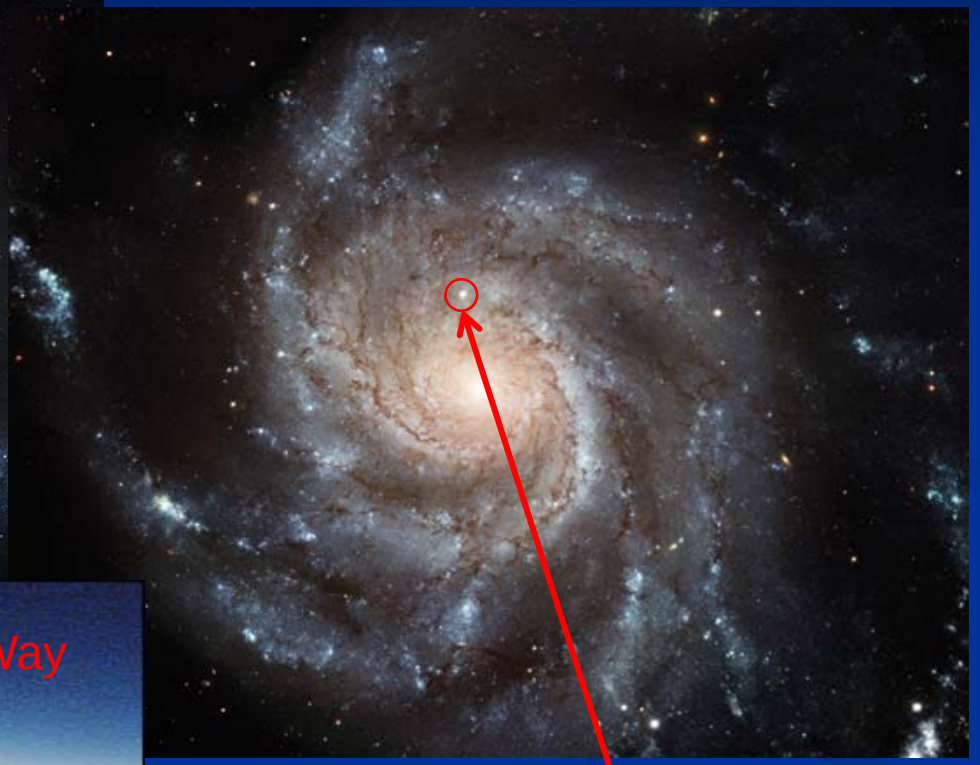
Seoul, October 21-24, 2013

Outline

- Puzzle about the spiral structure of the Milky Way
- Results of VLBI observations
- Future aspect and Conclusions

What does the Milky Way look like?

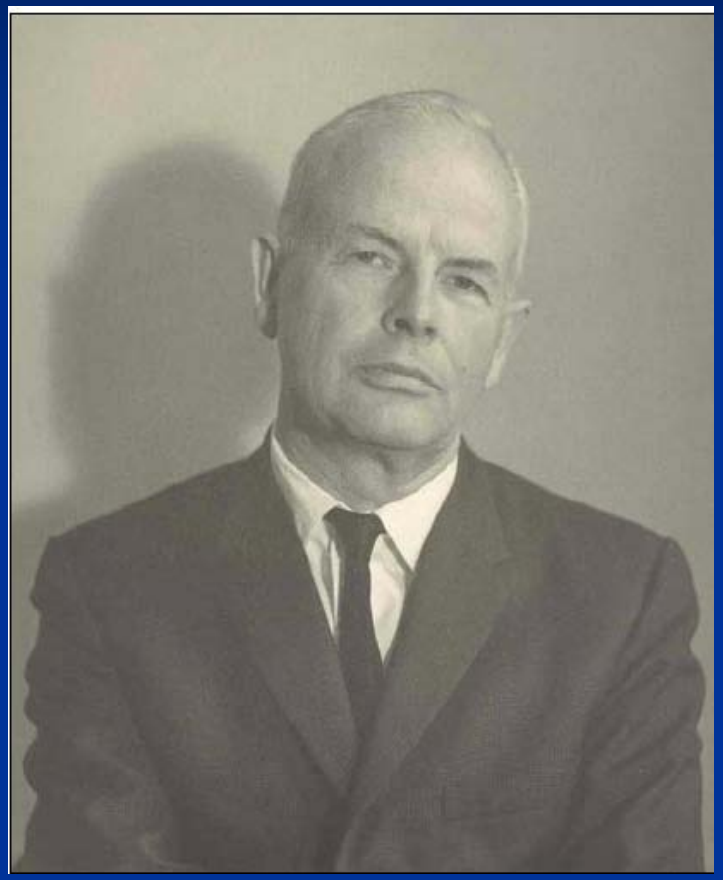
Seen face-on

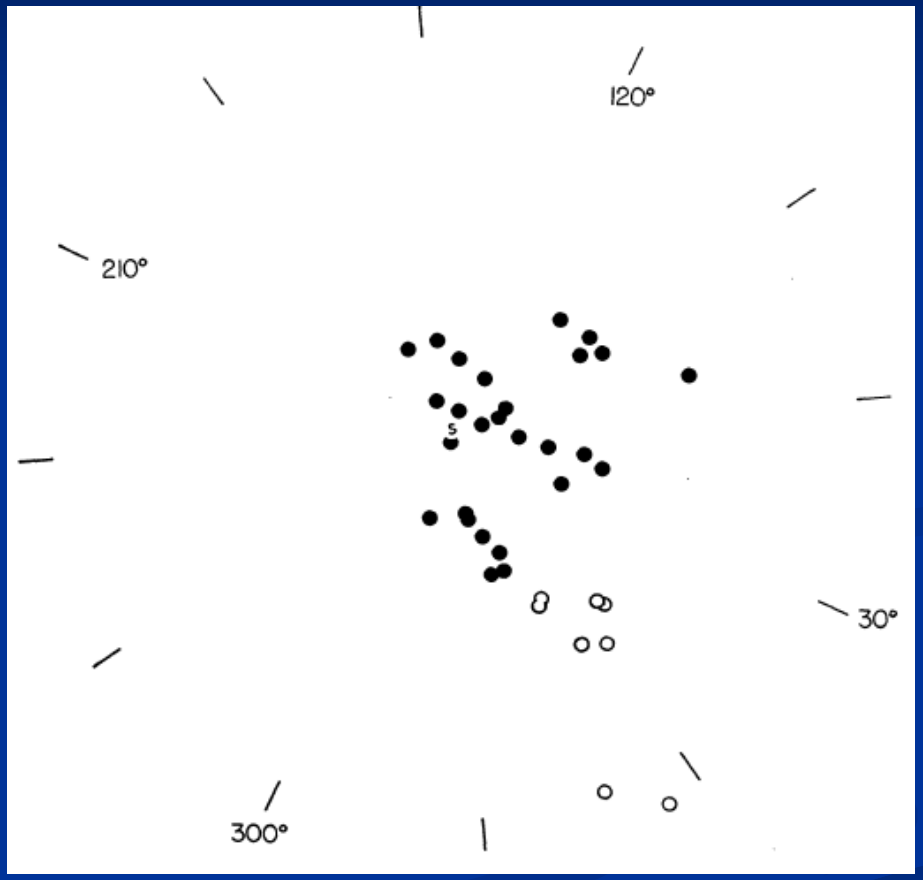


Star forming regions

Inside the Milky Way, edge-on,

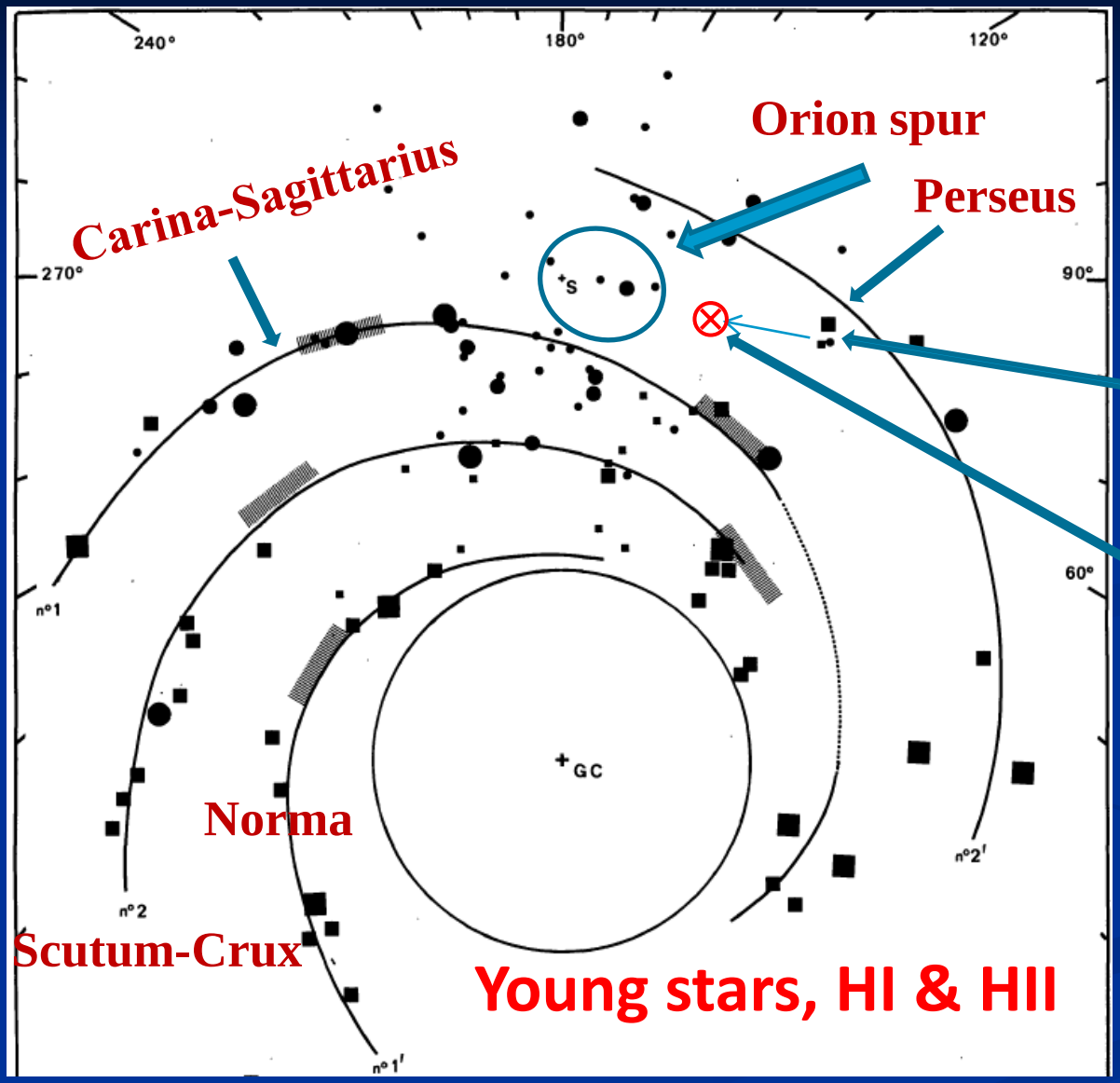
The First Evidence for Spiral Structure of MW





Morgan et al. 1952, 1953

The "Standard" Model

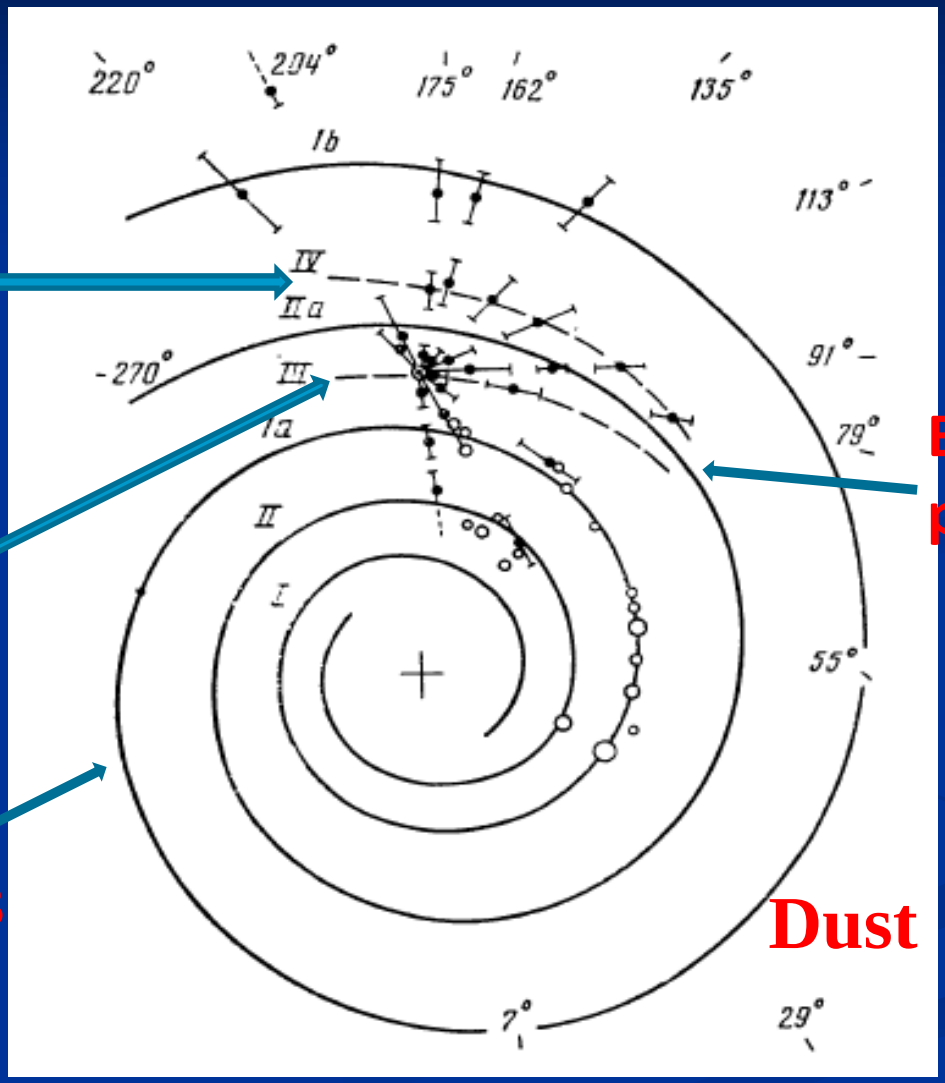


G75.8+0.4
~ 5.7 kpc
Perseus

3.2 kpc
Local

Geogelin & Georgelin 1976

Double-arm structure
----Sagittarius & Perseus/Local Arm



Perseus

Local

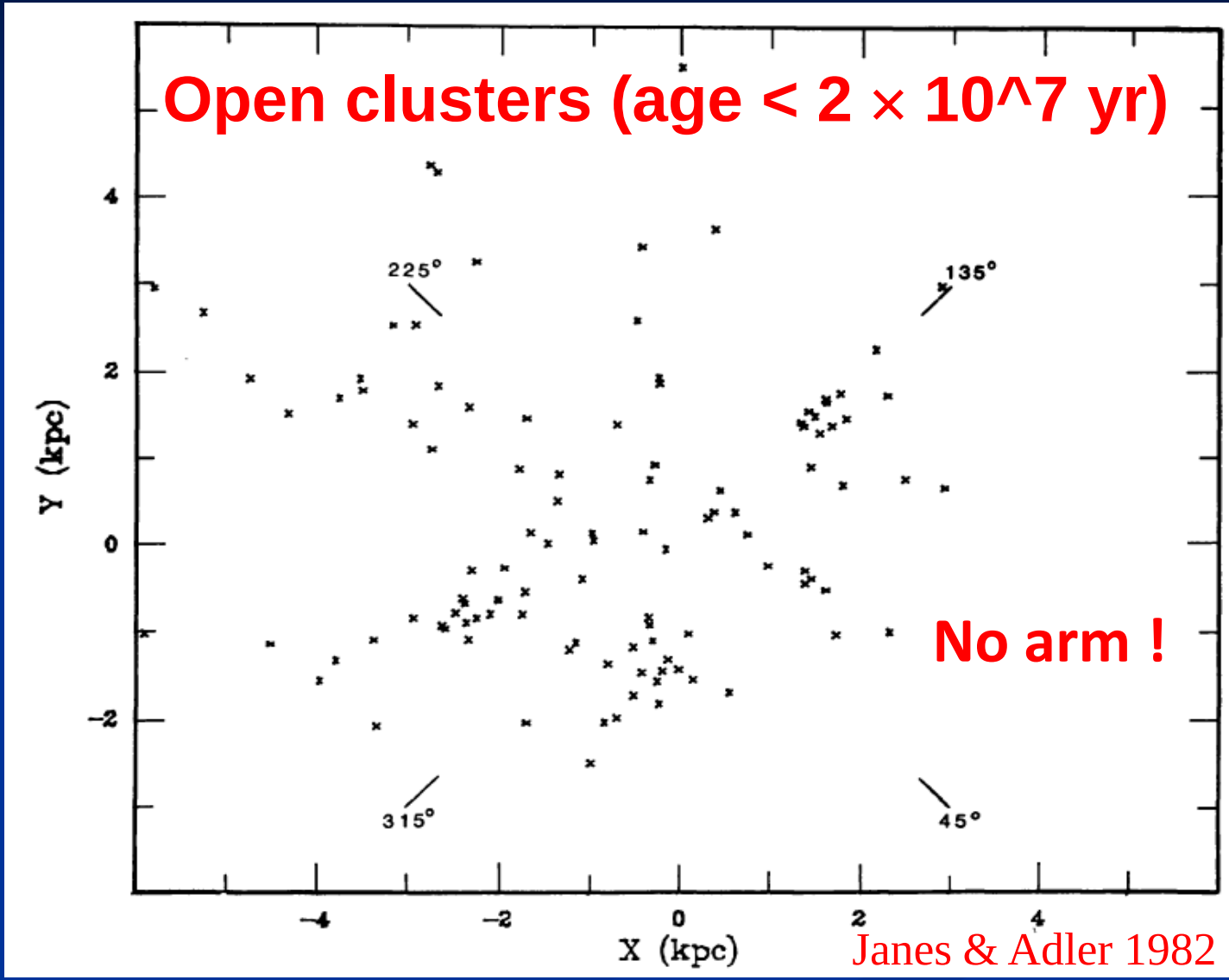
Sagittarius

Bifurcation point ~ 60°

Dust

Urasin 1987

No Arm !

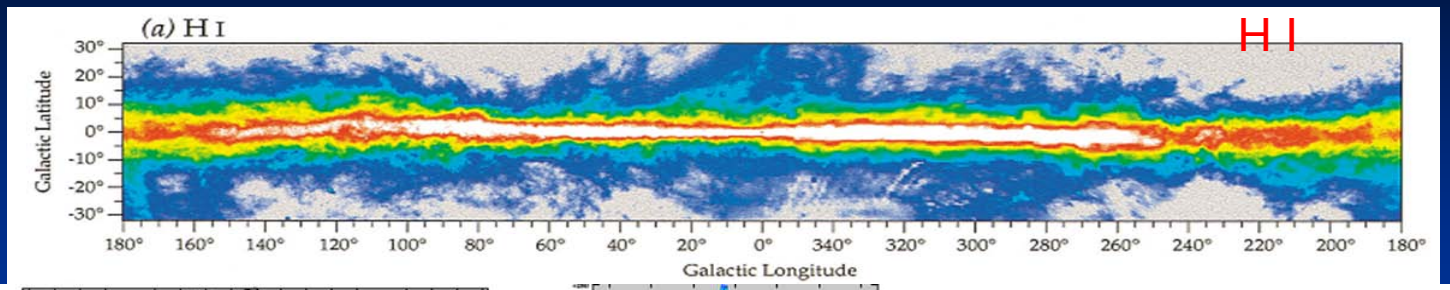

Open clusters (age < 2 × 10^7 yr)
225°
135°
315°
45°
No arm !
Y (kpc)
X (kpc)
4
2
0
−2
−4
−2
0
2
4
Janes & Adler 1982

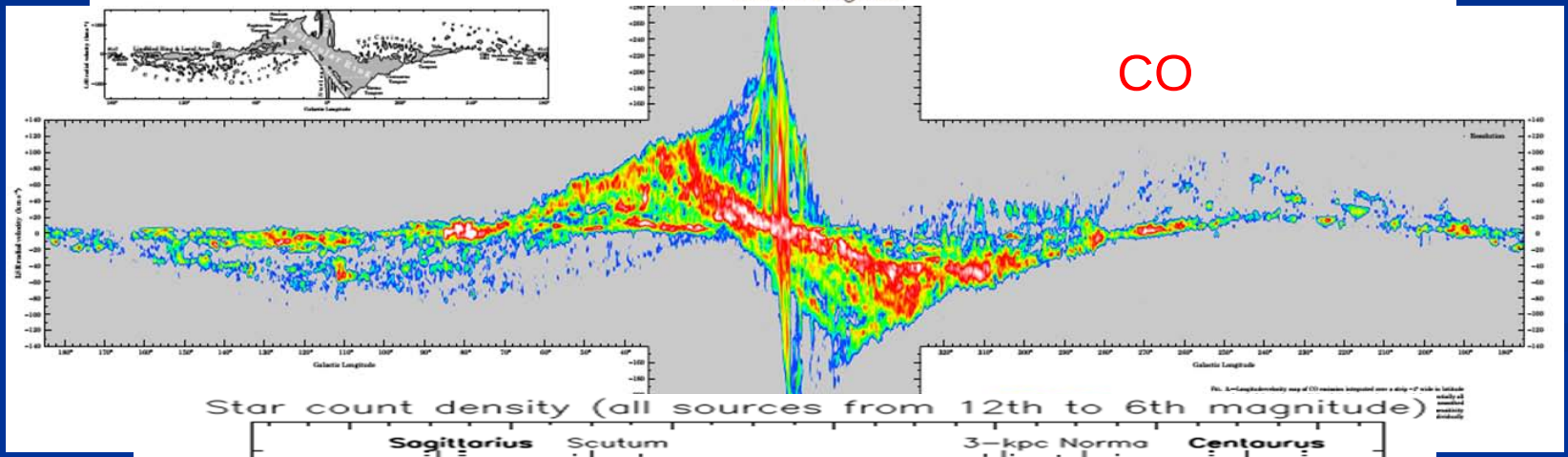
Puzzle for spiral structure

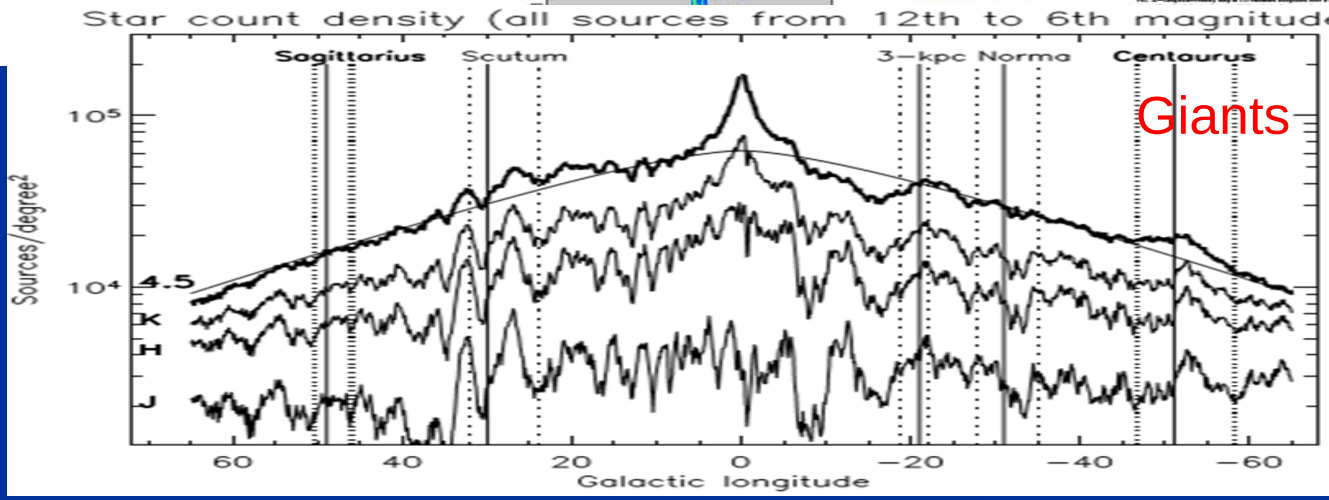
- Number of arms --- 2 3 4 5 ?
- Type of MW --- SBb or SBc ?
- Position, length and angle of the bar ?
- Parameters of MW ?
- Rotation curve?

Reason: large uncertainty on distances

Large-scale structures







Large distance uncertainty

- Difficulties in determining an accurate rotation curve
- Non-Circular Rotation
- Kinematic Distance Ambiguity

  G9.62+0.20:

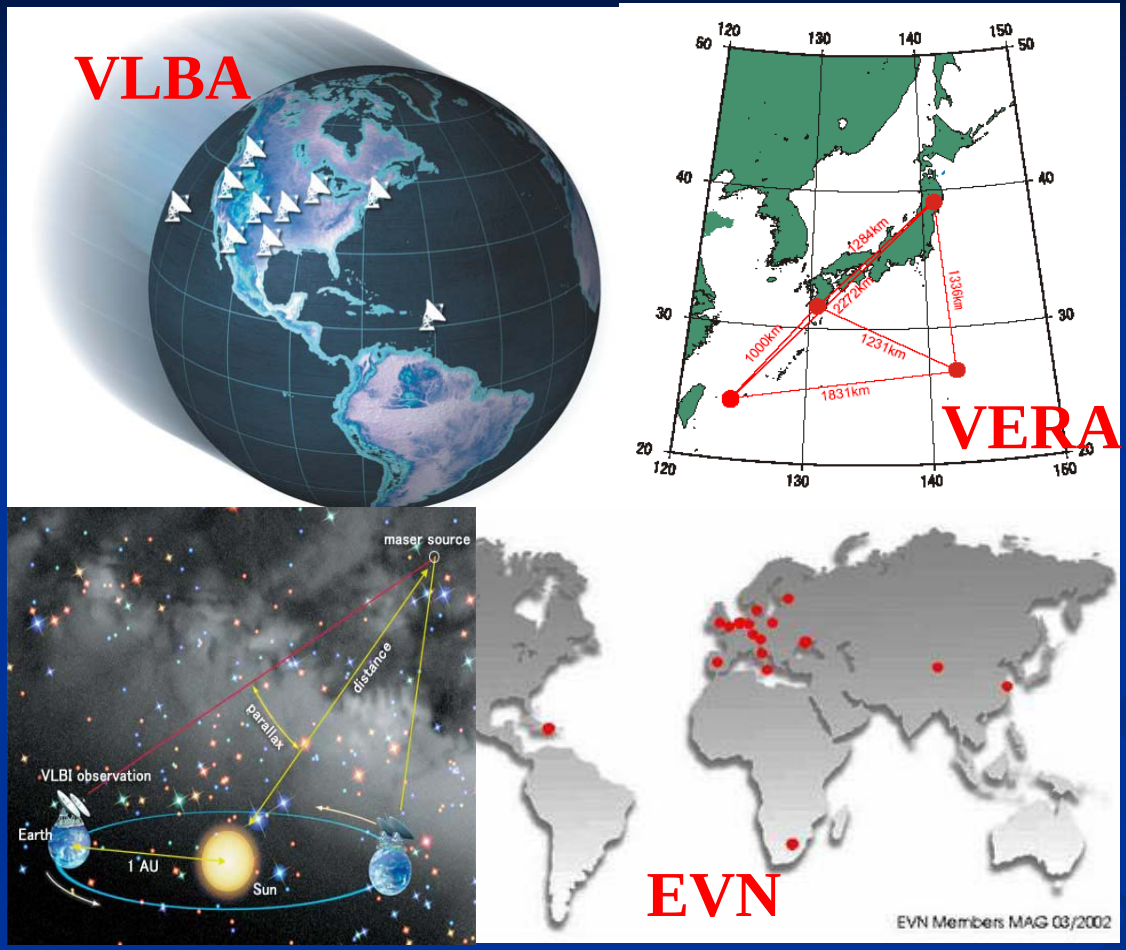
far kinematic dist.	15 kpc
near	0.5 kpc
Parallax Distance	5.7 kpc

- Kinematically anomalous

  W3OH:

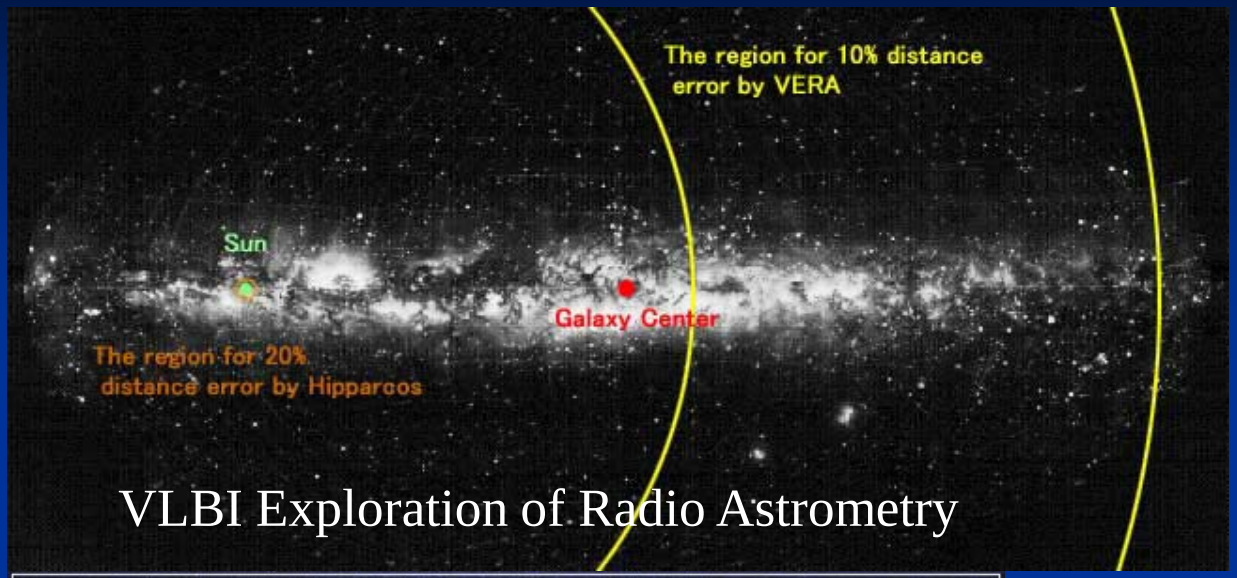
Kinematic Distance	~ 4.3 kpc
Parallax Distance	~ 2.0 kpc

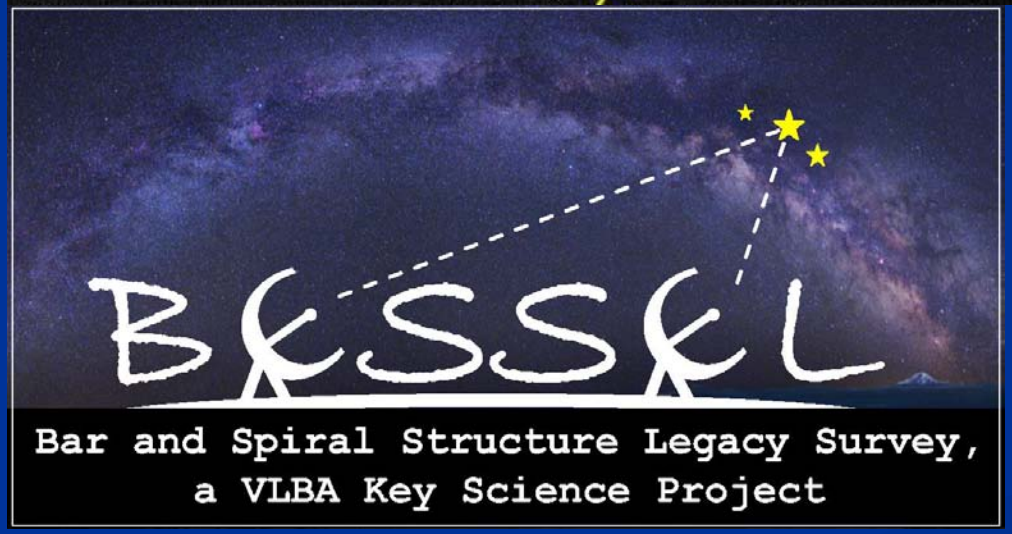
Very Long Baseline Interferometry



- Radio waves "see" through galaxy
- Can "synthesize" telescope the size of the Earth

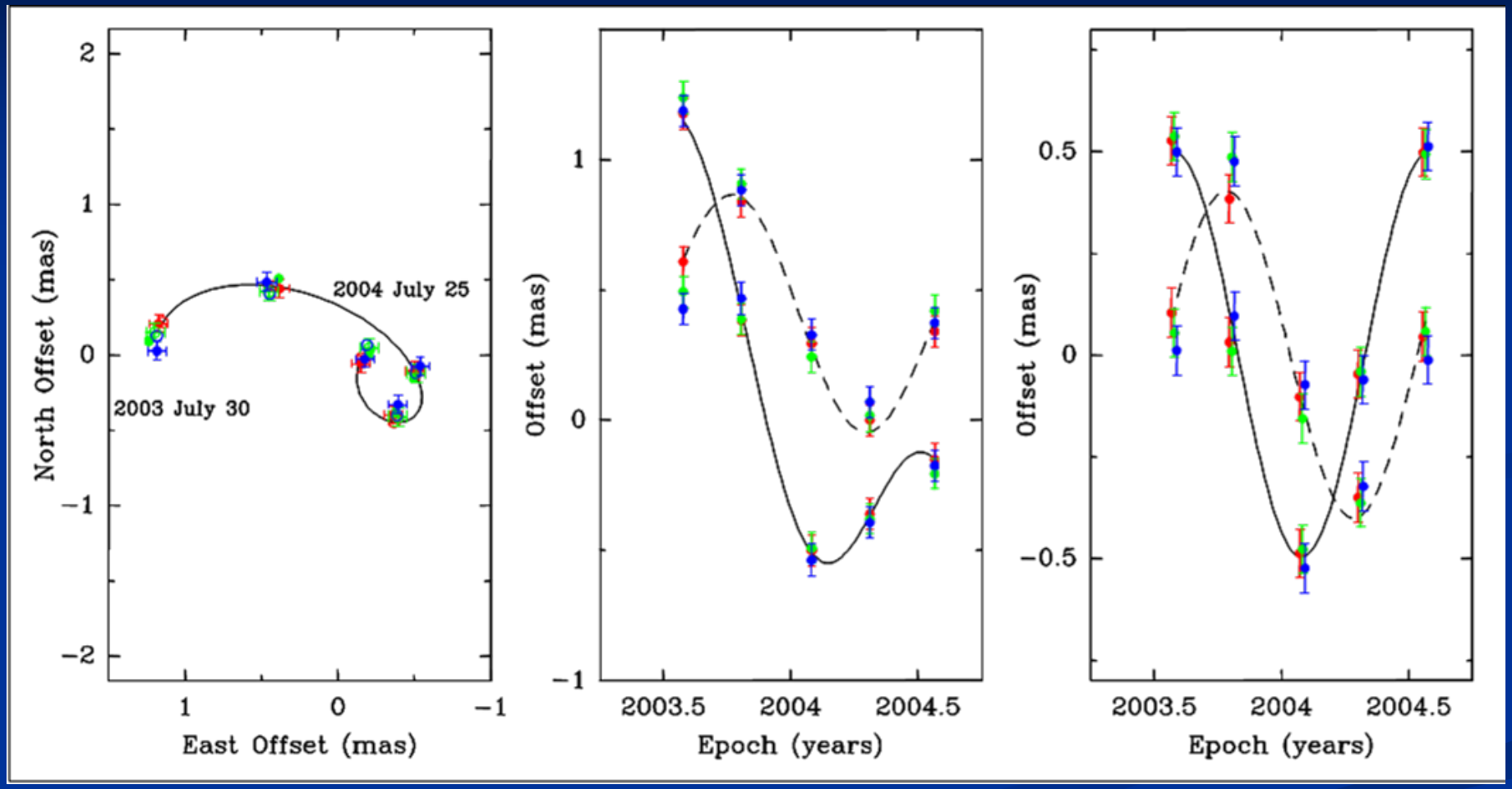
The BeSSeL Survey & VERA





- ~ 1000 masers
- 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.

Parallax results: W3OH (Masers)



Xu, Reid, Zheng & Menten (2006)

$\Pi = 0.512 \pm 0.010$ mas

D = 1.95 $\pm$ 0.04 kpc

2.0%

Orion Nebula (Masers & Radio Stars)

Literature: 350 – 500 pc

(usually 480 ± 80 pc by Genzel et al. 1981)

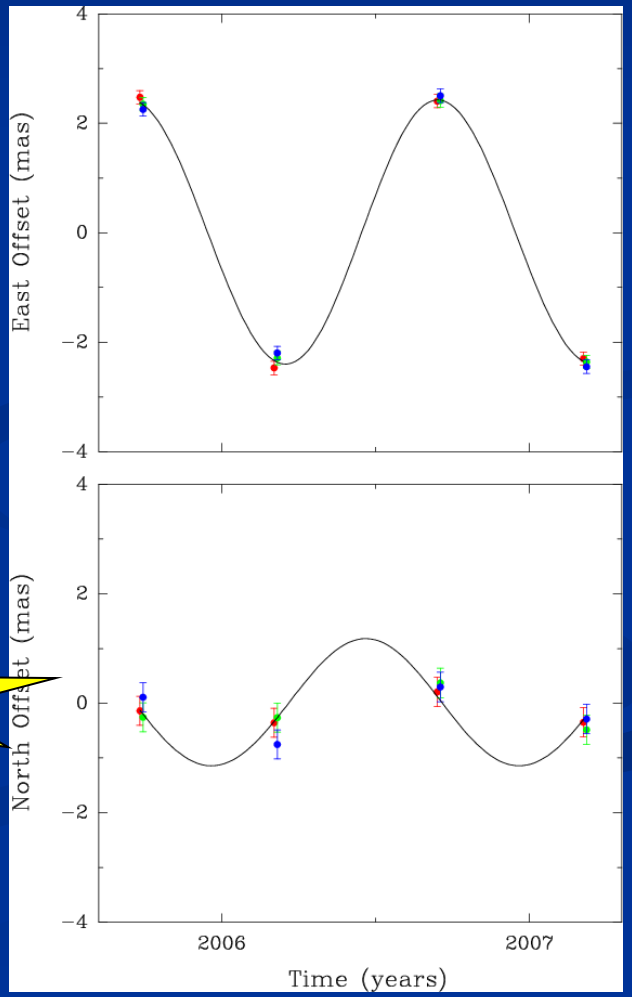
D = 389 ± 21 pc (Sandstrom et al. 2007)

D = 437 ± 19 pc (Hirota et al. 2007)

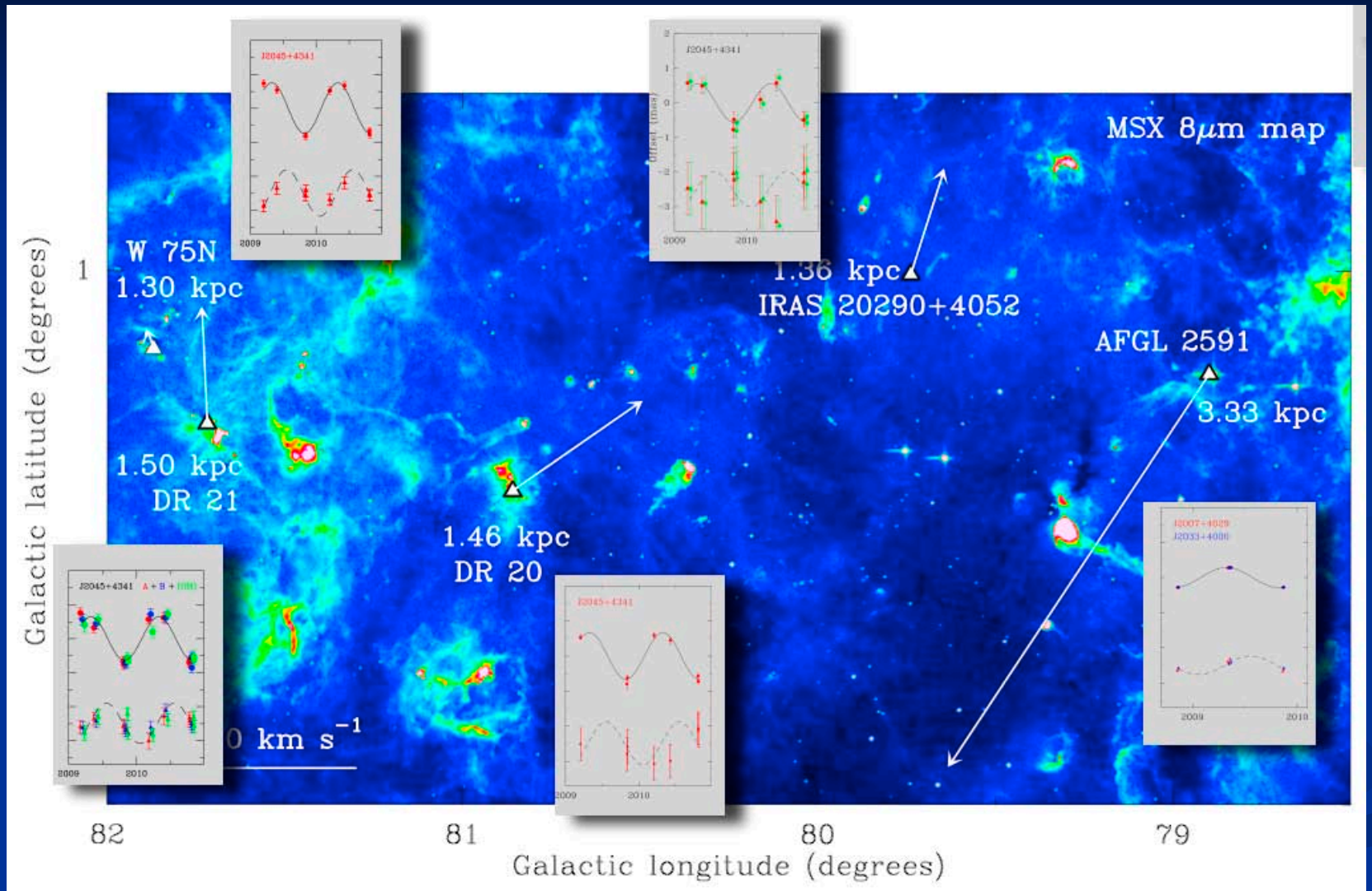
D = 414 ± 7 pc (Menten et al. 2007)

D = 419 ± 6 pc (Kim et al. 2008)

1.7%



Cygnus X Star forming complex (Masers)

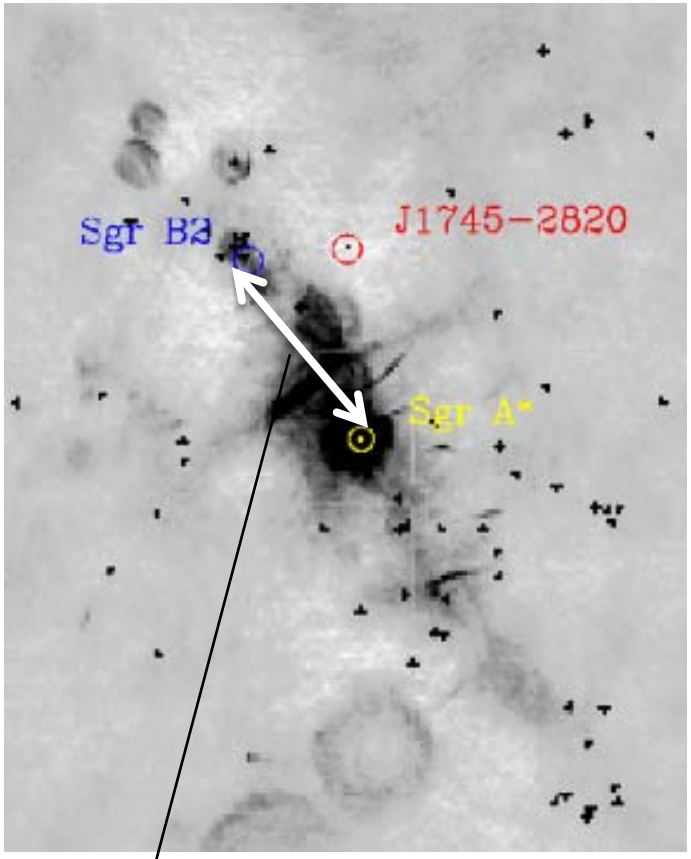


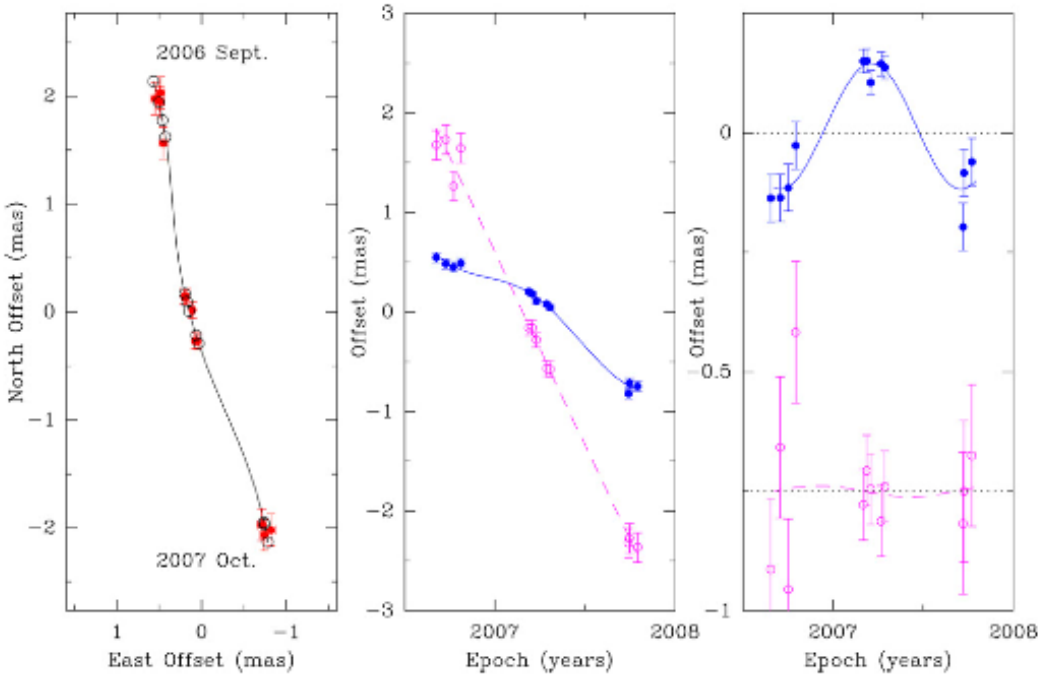
Rygl et al. (2012)

Image: van Langevelde

Galactic Center (H_2O masers)

Π = 129 ± 12 μas (D=7.8 ± 0.8 kpc)





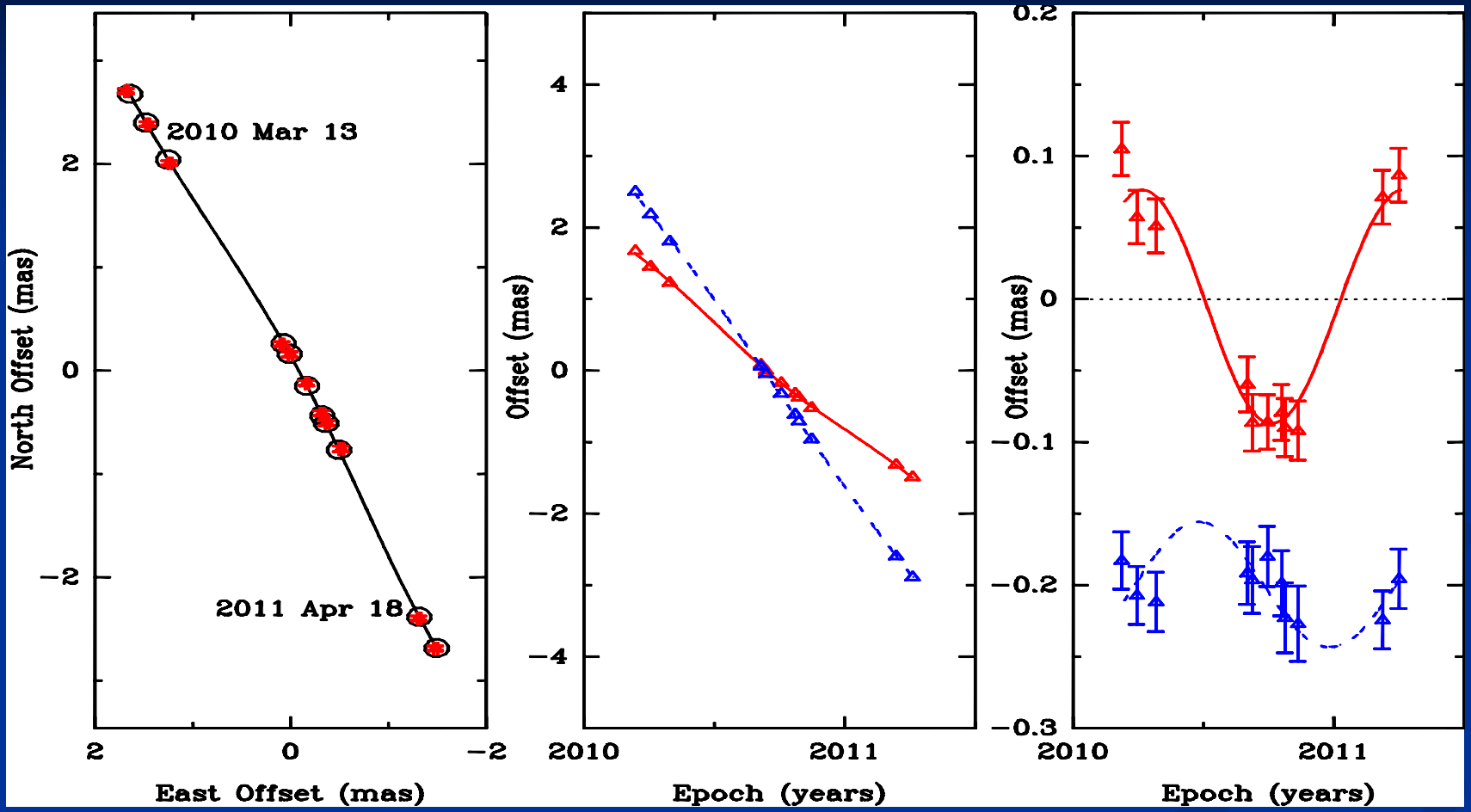
Sgr B2

0.13 kpc

$$R_0 = 7.9^{+0.8}_{-0.7}\ \text{kpc}$$

Reid et al. 2009

W 49N (H_2O masers)

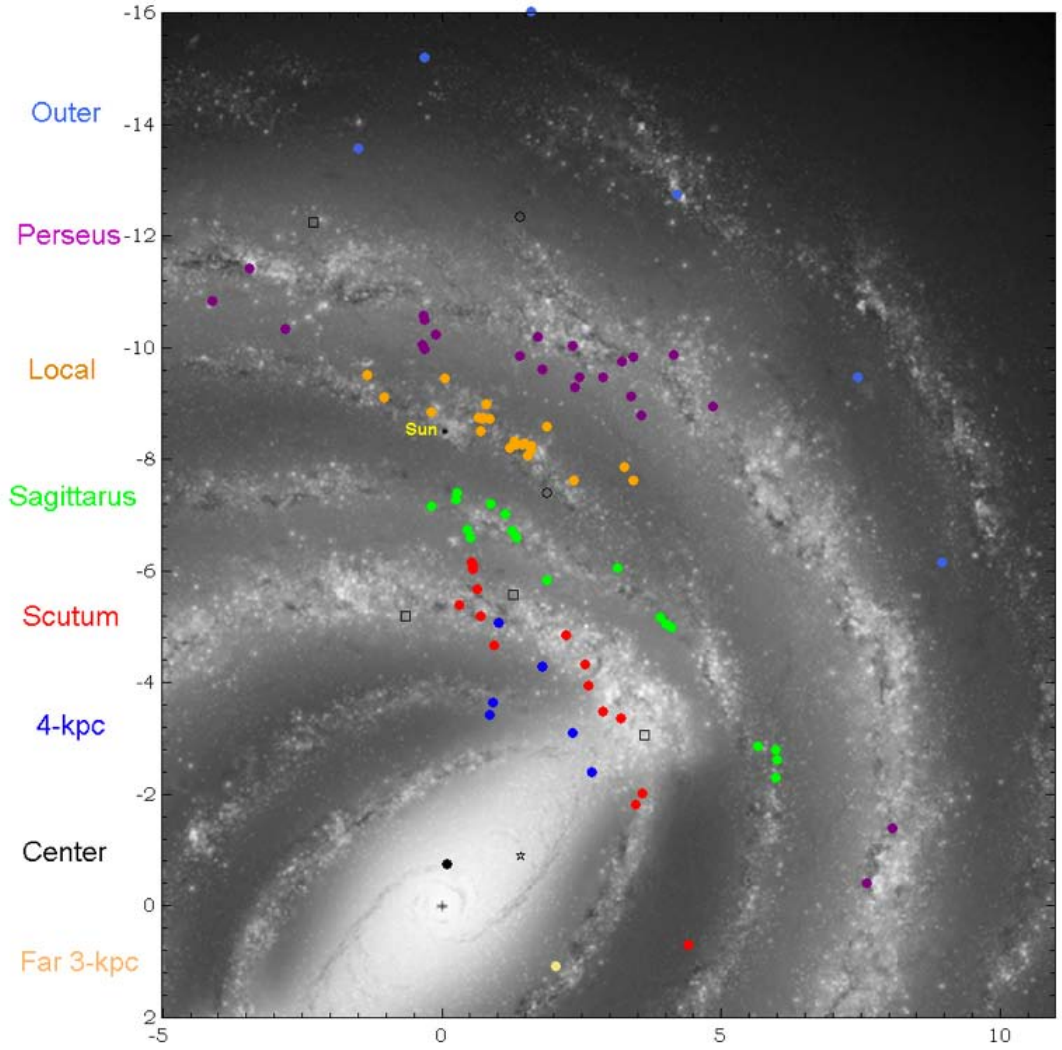


Π = 90 ± 6 μas (D=11.1 ± 0.8 kpc)

Smallest parallax !

Zhang et al. 2013

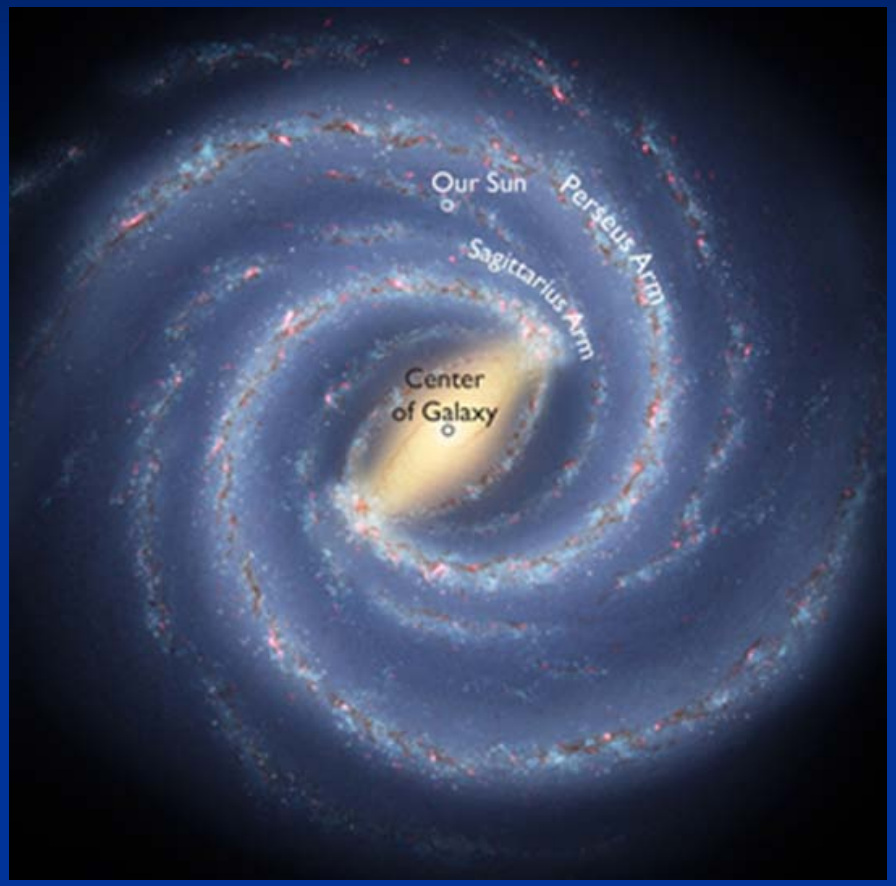
All parallax results



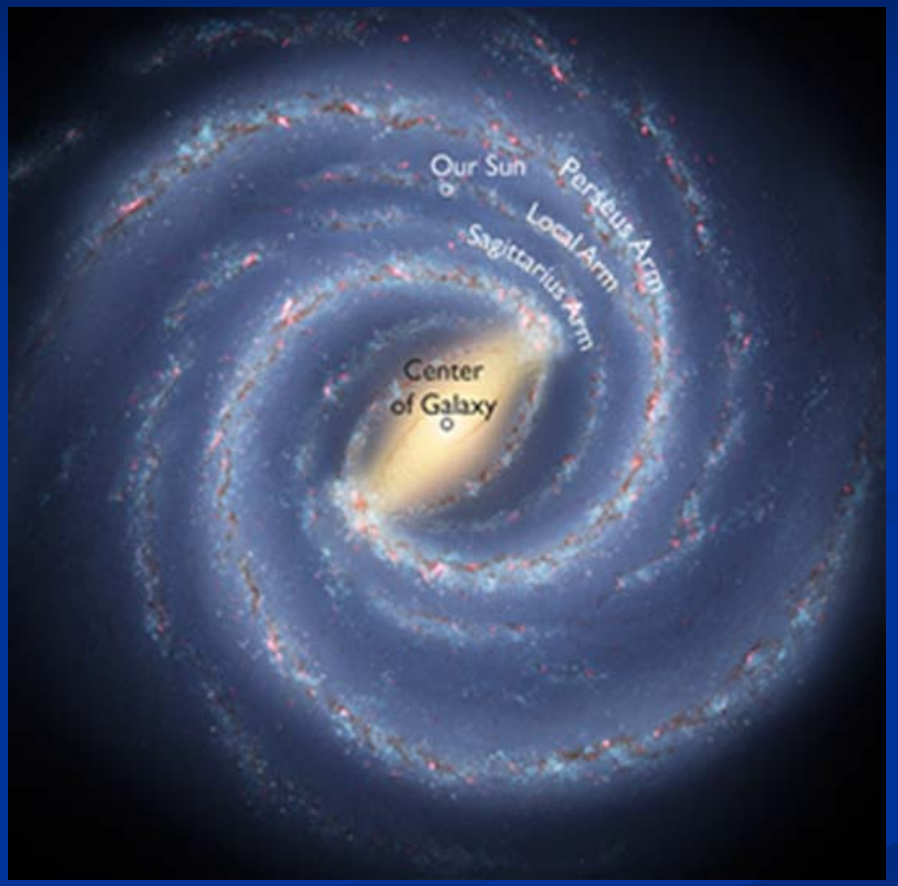
Background: artist conception by Robert Hurt (NASA: SSC)

- Preliminary results of parallaxes from VLBA, VERA & EVN:
- ~ 100 sources
- Tracing most spiral arms
- Inner, bar-region is complicated

The new result in the 222nd AAS meeting



Old: local spur

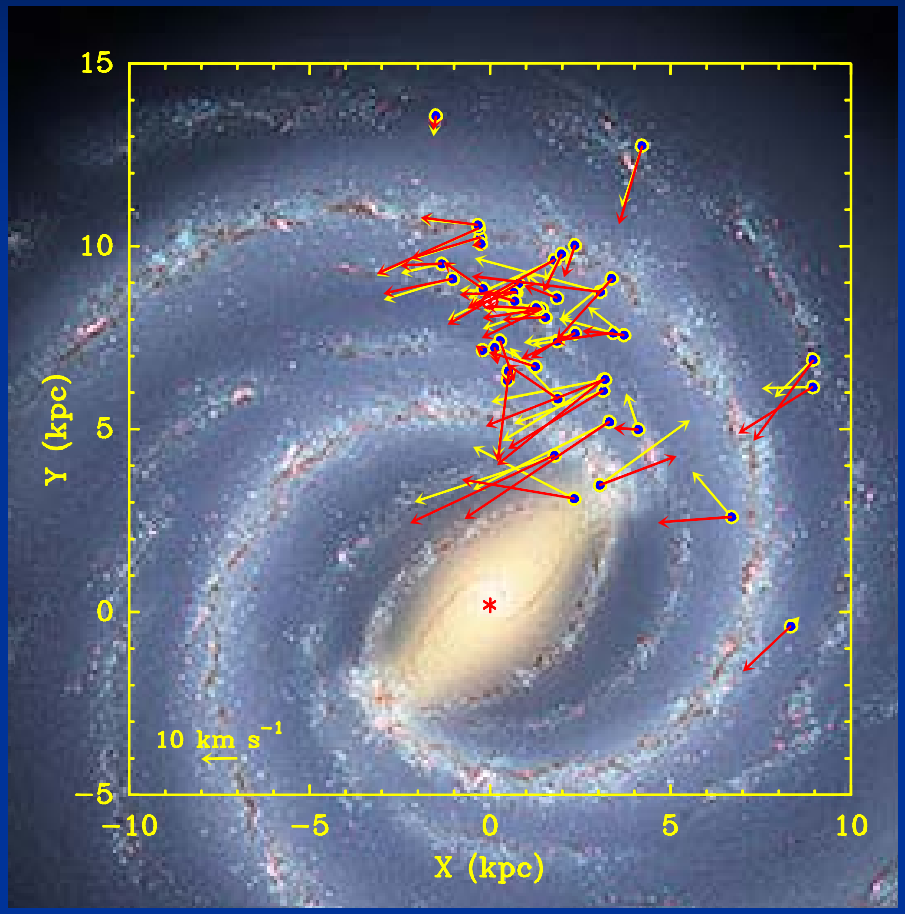


New: Local Arm (branch)

Xu et al. (2013)

Credit: Robert Hurt, IPAC; Bill Saxton, NRAO/IAUI/NSF

Counter-Rotation of Star Forming Regions



Compute Galacto-centric V:

Transform to frame rotating at
Θ_o = 245 km/s (**yellow**)
See peculiar (non-circular) motions
…clear counter-rotation

Transform to frame rotating at
Θ_o = 220 km/s (red)
Still counter-rotating

Change on Solar motion

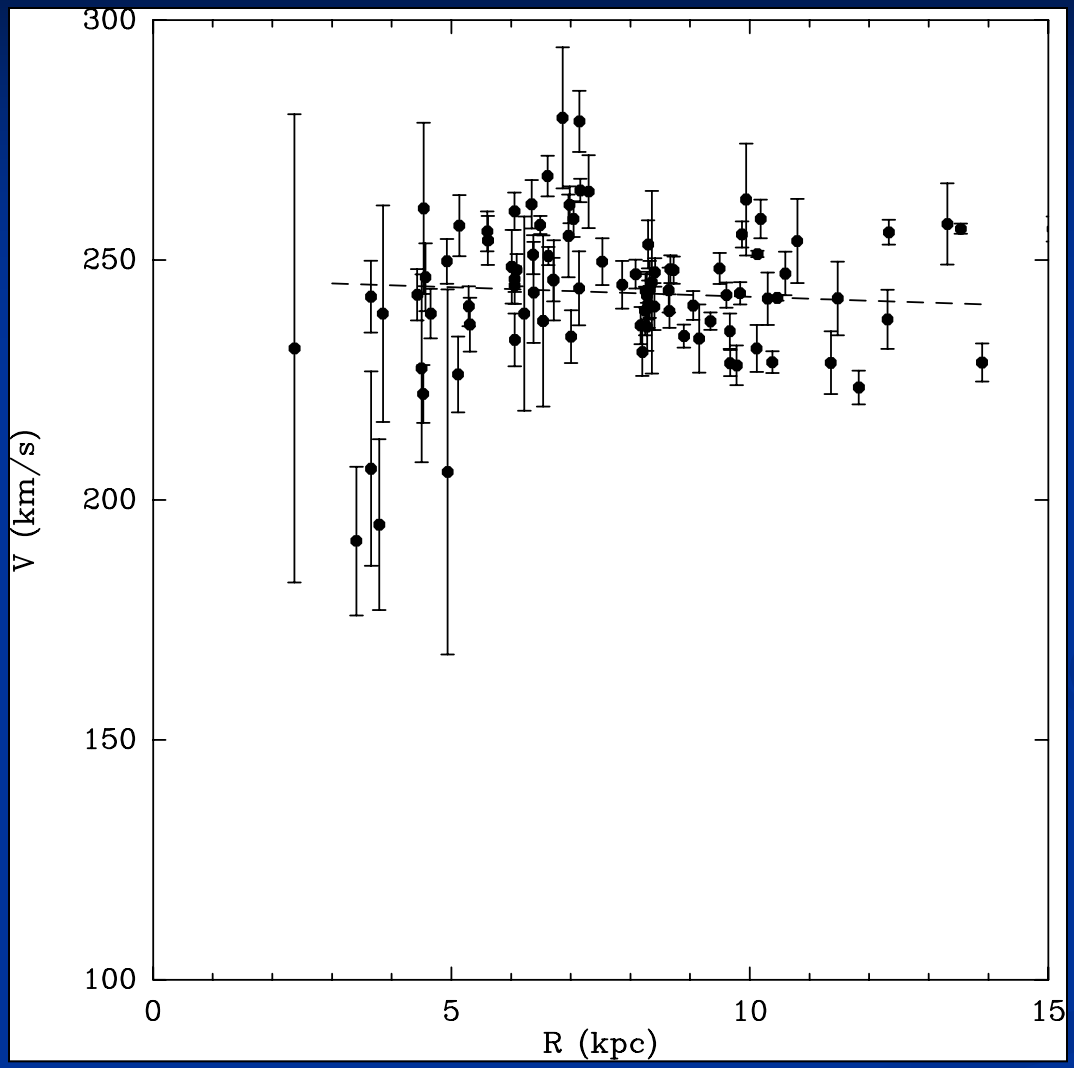
- Until 2009, the Dehnen & Binney (1998) HIPPARCOS Solar motion of

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

  was widely accepted.

- After part of parallax results published, HIPPARCOS revised: Schoenrich, Binney & Dehnen (2010)
  U_0 = 11.1 ± 2.0 k/ms,
  V_0 = 12.2 ± 2.1 km/s,
  W_0 = 7.2 ± 2.0 km/s

Milky Way's Rotation Curve



- Parallax data
- Schoenrich+2010 Solar Motion
- Corrected for maser counter-rotation
- Best fit: $R_0 = 8.35$ kpc, $\theta_0 = 248$ km/s

New and direct result based on 3-D motions "gold standard" distances, but close to the SUN.

Poor sensitivity & field of view

Sensitivity (VLBA):

Masers: coherence time (flux density threshold)

5 Jy for 22 GHz H_2O & 12.2 GHz CH_3OH ~300/3000

2 Jy for 6.7 GHz CH_3OH 400/2000

Most of sources available on our side of MW

Astrometric accuracy:

ionospheric & tropospheric effects

close calibrators (in-beam style)

Systematic errors scale with the separation between targets and calibrators:

W3OH: 0.5+/-0.010 mas (separation ~ 0.8°),

0.5+/-0.017 mas (separation ~ 1.5°)

Lack of stations in the southern sky

Future VLBI Astrometry ---- SKA

large field of view & sensitivity

- **Target sources**

  Masers: 1000 $\rightarrow$ 5000;

- **Calibrators**

  QSOs: $10^4 \rightarrow 10^6$

- **Accuracy**

  Several in-beam calibrators

  Systematic errors greatly reduced

  Parallaxes of ~ **1 μas**

Conclusions

- VLBA, VERA & EVN parallaxes to (massive) young stars (via masers) tracing spiral structure of Milky Way
- Star forming regions "counter-rotate" by ~8 km/s (for V_{sun}=12 km/s)
- Parallax/proper motions: R_o ~ 8.35 ± 0.2 kpc; Θ_o ~ 248 ± 8 km/s/kpc
- SKA will construct the accurate the spiral structure of the Milky Way finally