The Structure and Dynamics of the Milky Way: Results from the BeSSeL Survey

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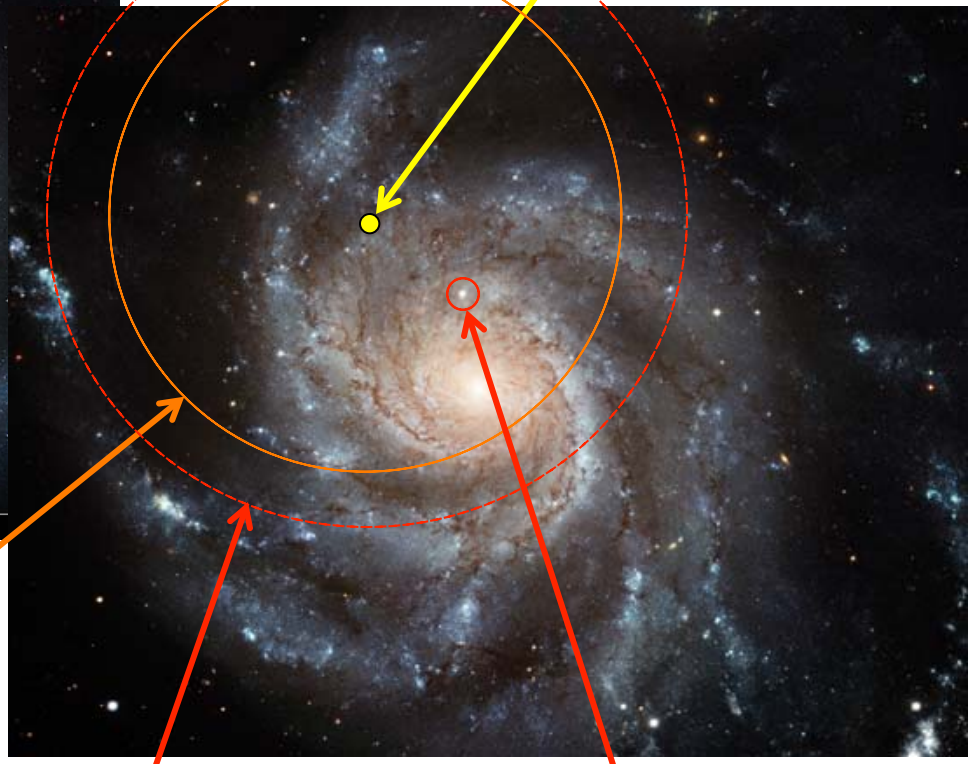
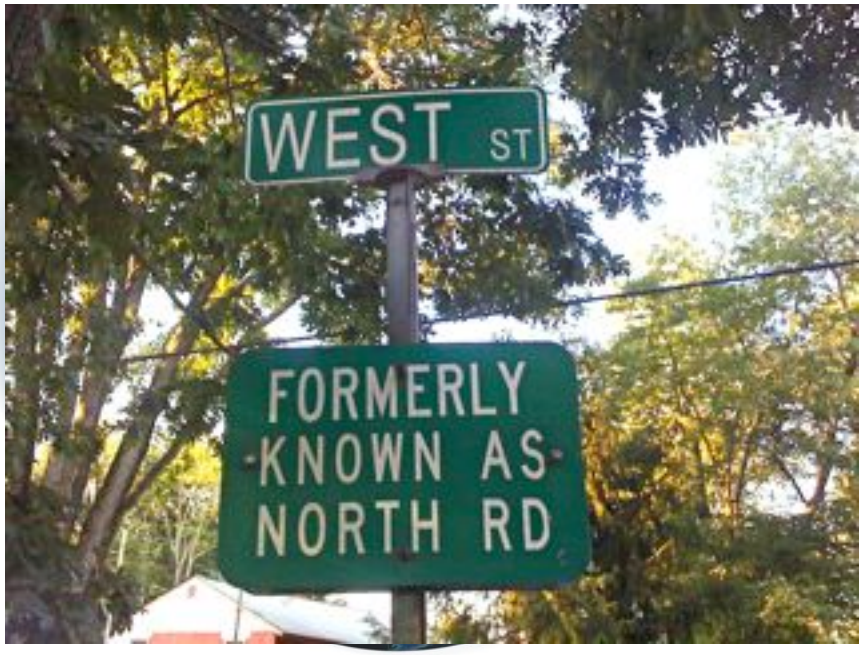
What does the Milky Way look like?



Gaia range (± 10 to 20 μas); but cannot see through dust in Galactic plane

VLBI range (± 5 to 20 μas): can "see" through plane to massive star forming regions that trace spiral structure

Very Long Baseline Interferometry: VLBA, VERA & EVN



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

Fringe spacing (eg, VLBA):

$\theta_f \sim \lambda/D$ ~ 1 cm / 8000 km = 250 μas

Centroid Precision:

0.5 θ_f / SNR ~ 10 μas

Systematics:

path length errors ~ 2 cm (~2 λ)

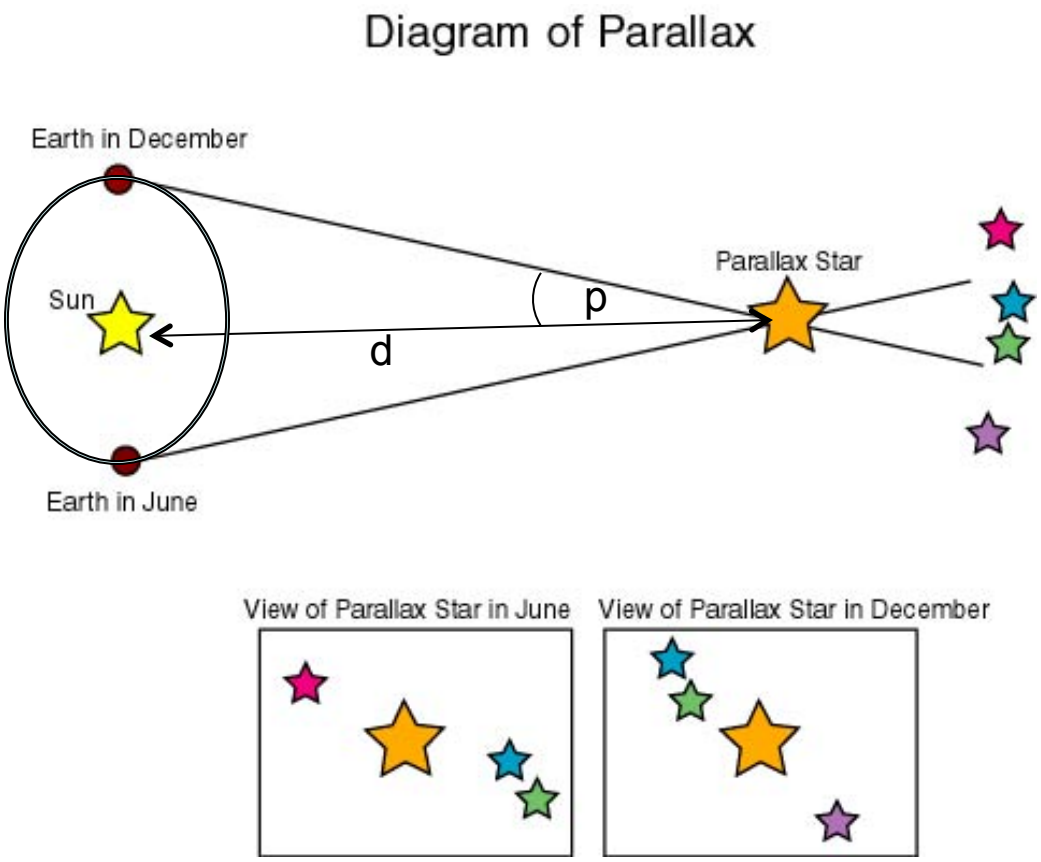
shift position by ~ $2\theta_f$ ~ 500 μas

Relative positions (to QSOs):

$\Delta\Theta$ ~ 1 deg (0.02 rad)

cancel systematics: $\Delta\Theta * 2\theta_f$ ~ 10 μas

Trigonometric (Annual) Parallax



$d = 1\ AU / p$

Nearest stars:

d = 1 parsec (pc)

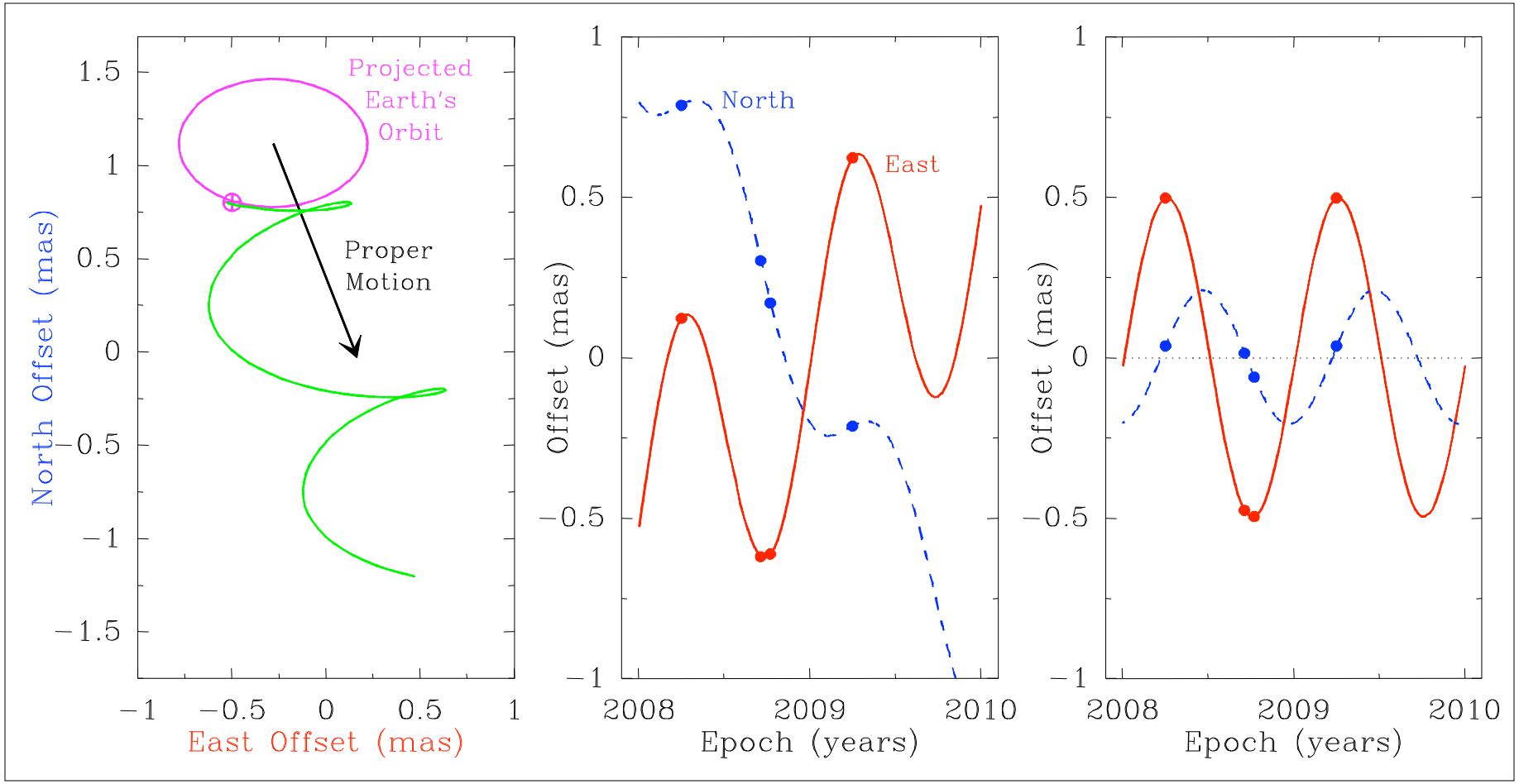
p = 1 arcsec

Center of Milky Way:

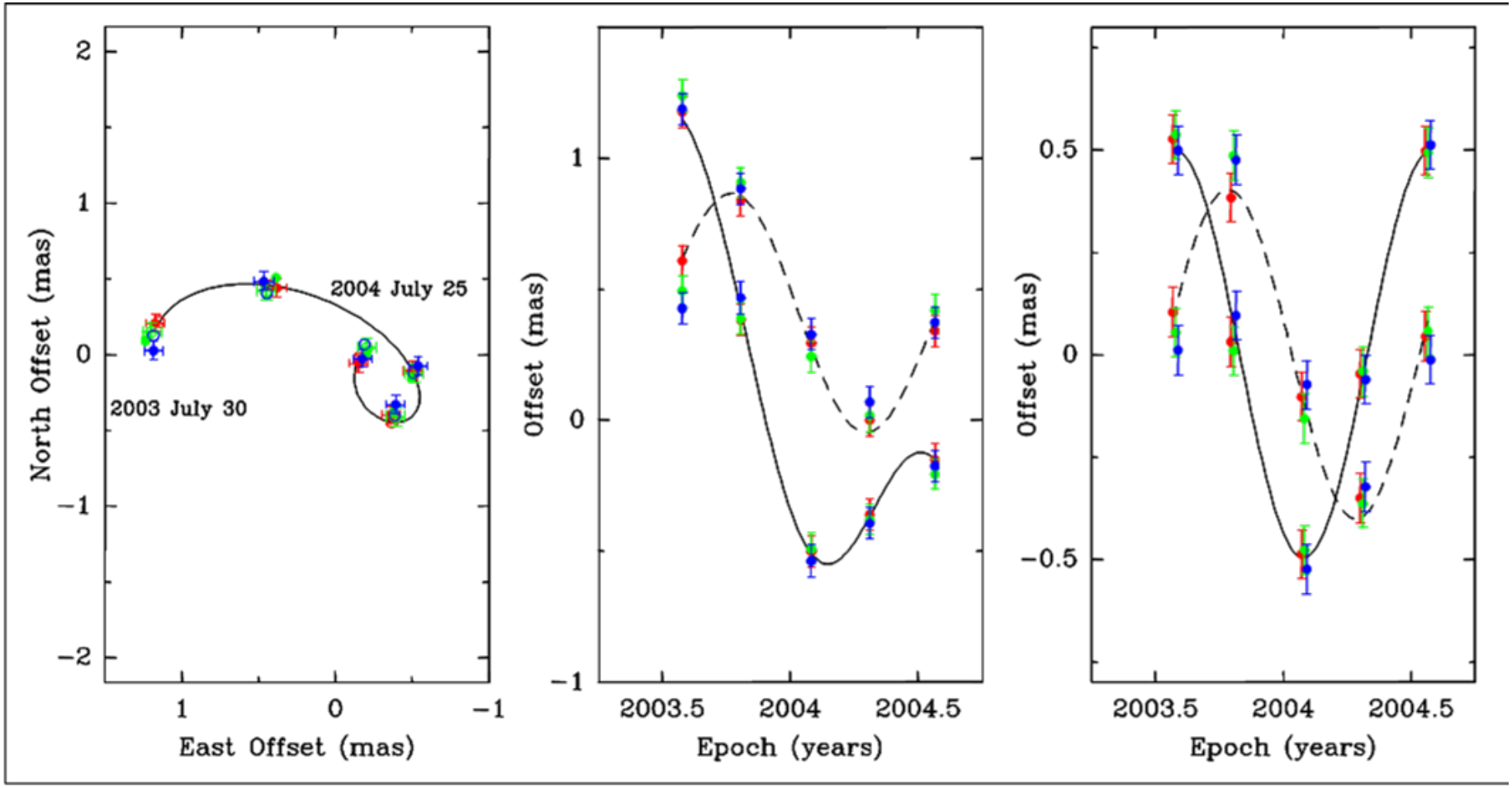
d = 10 kpc

p = 0.1 milli-arcsec

Parallax Signatures



W3OH parallax: methanol (CH_3OH) masers

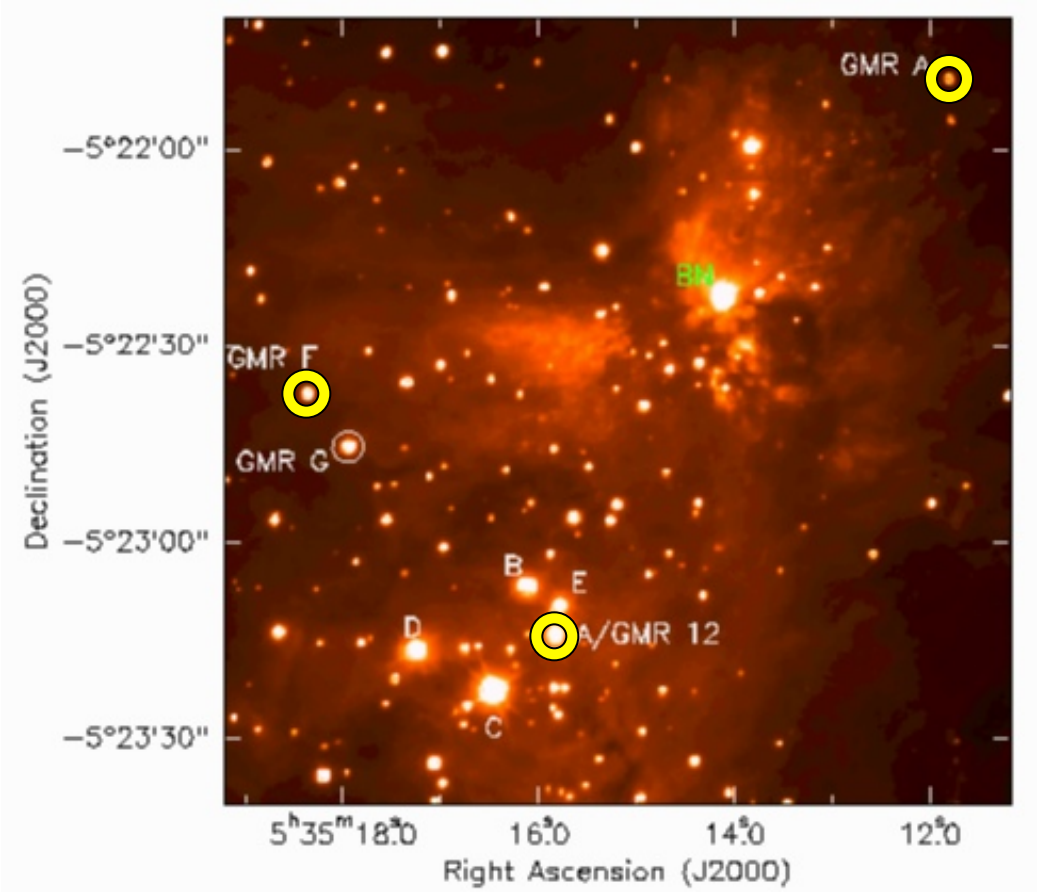


Xu, Reid, Zheng & Menten (2006)

$\Pi = 0.512 \pm 0.010$ mas

D = 1.95 ± 0.04 kpc

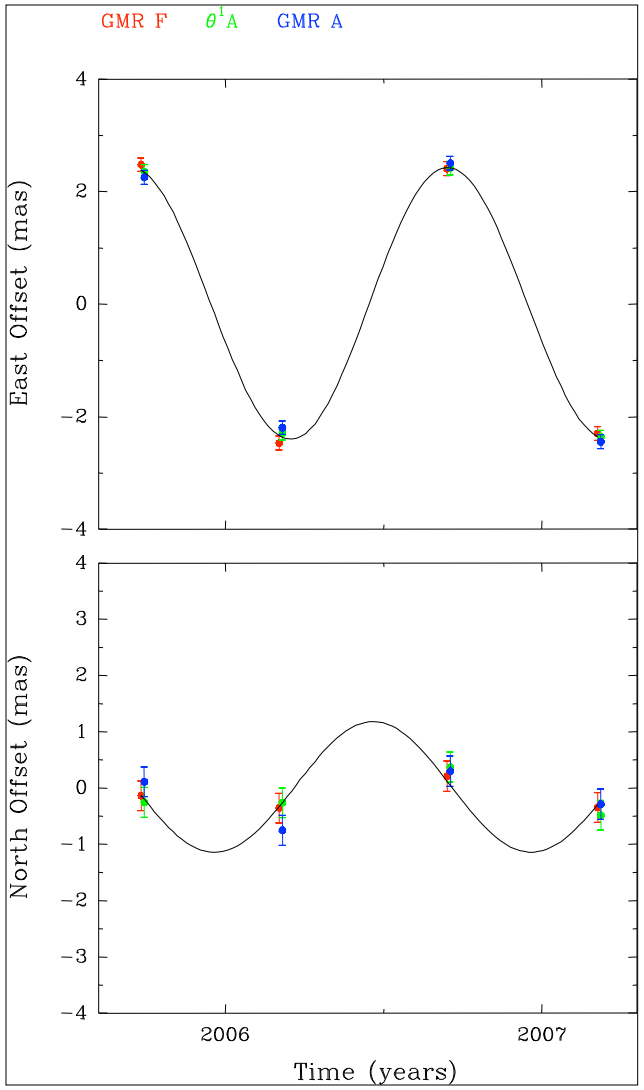
Orion Nebular Cluster Parallax



VLBA: $\Pi = 2.42 \pm 0.04$ mas

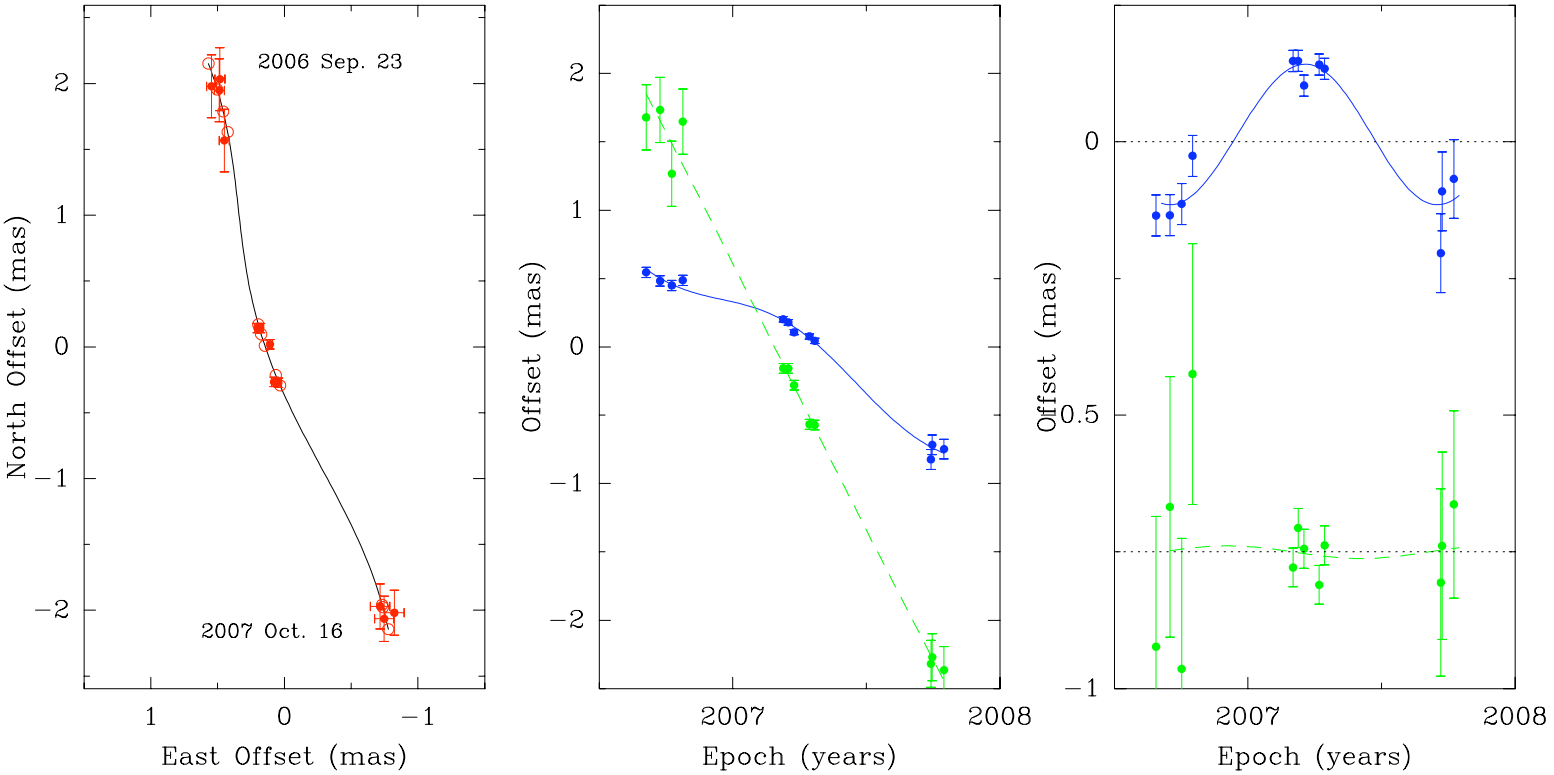
$D = 414 \pm 7$ pc

VERA: $D = 419 \pm 6$ pc



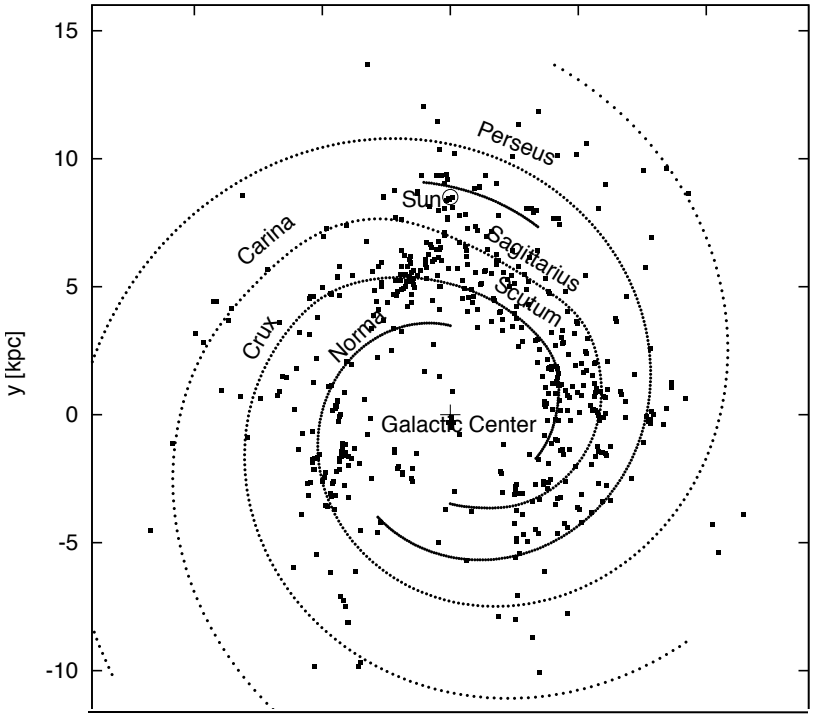
Menten, Reid, Forbrich & Brunthaler (2007)

Parallax for Sgr B2(Middle) H_2O masers

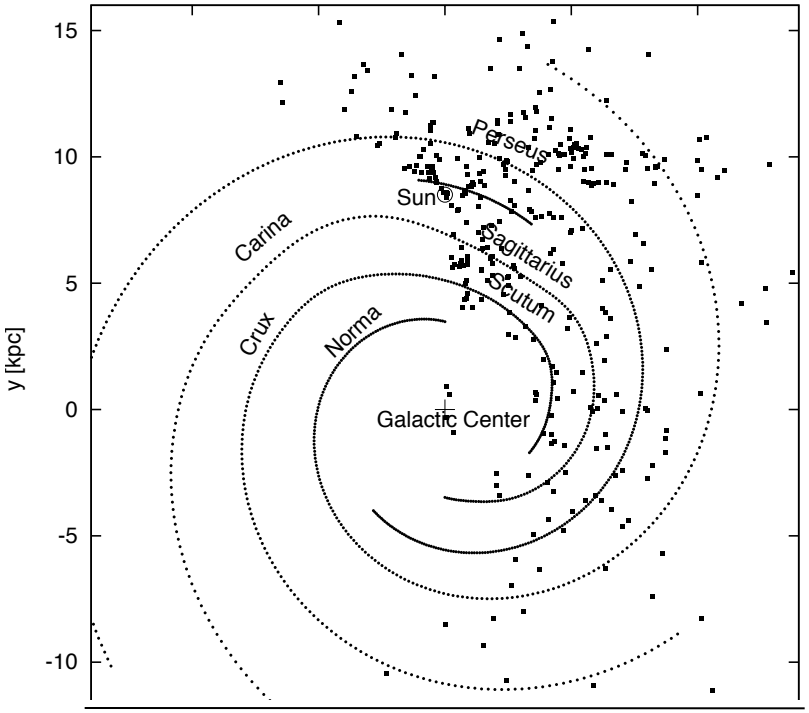


Π = 129 ± 12 μas (D=7.8 ± 0.8 kpc)

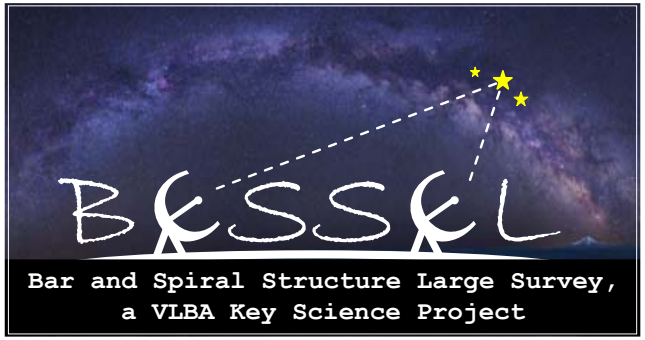
Mapping the Milky Way



6.7/12.2 GHz CH_3OH masers



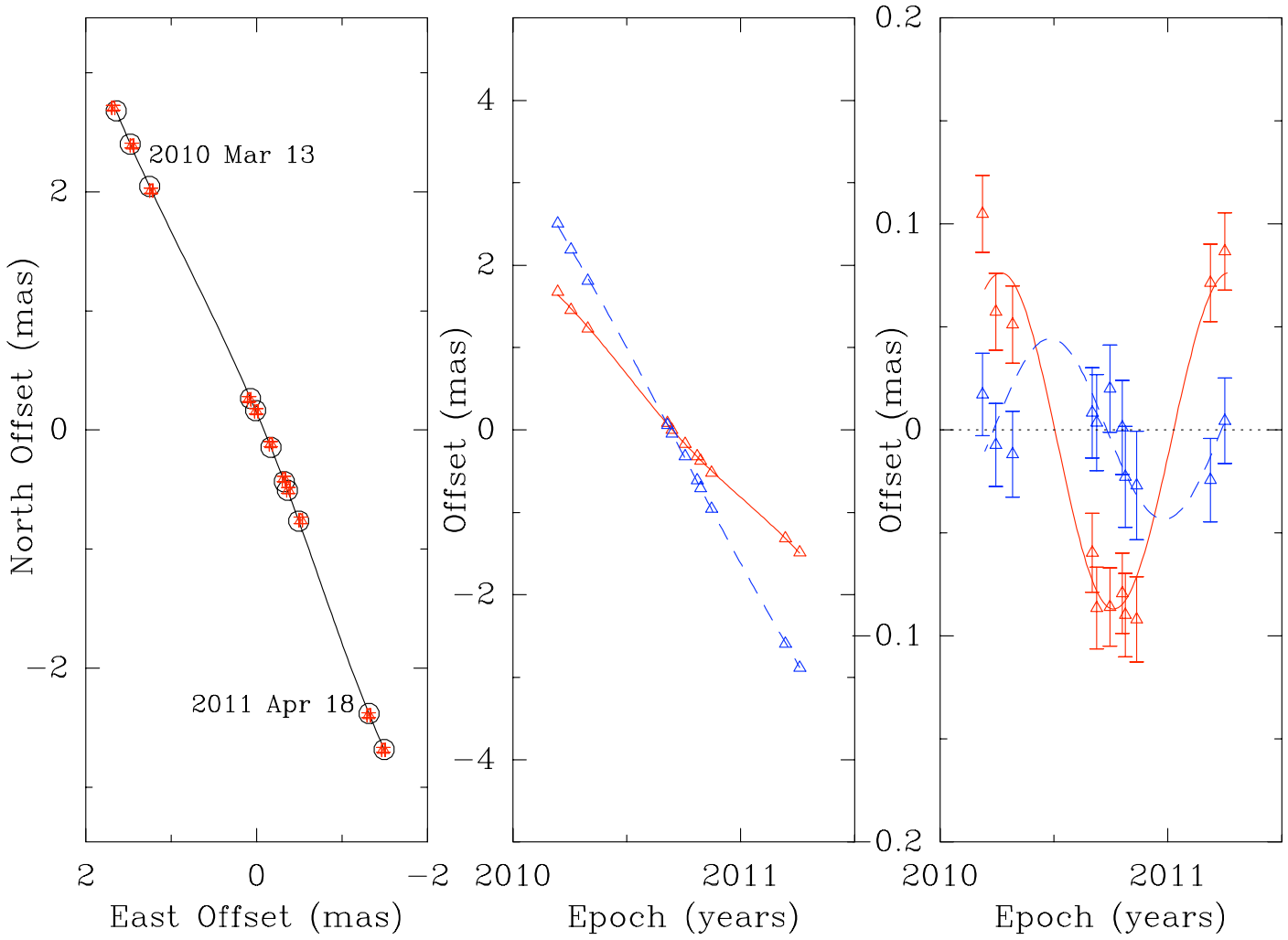
22 GHz H_2O masers



VLBA Key Science Project: 5000 hours over 5 years to measure hundreds of parallaxes/proper motions

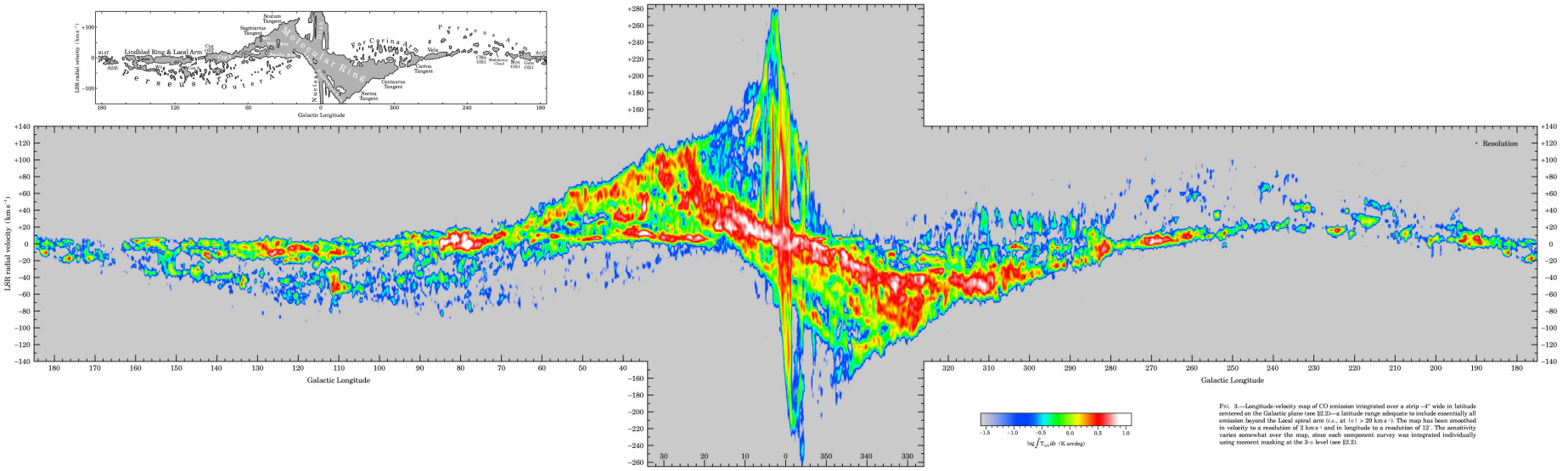
Observations for ~70 masers started 2010/2011 recently completed

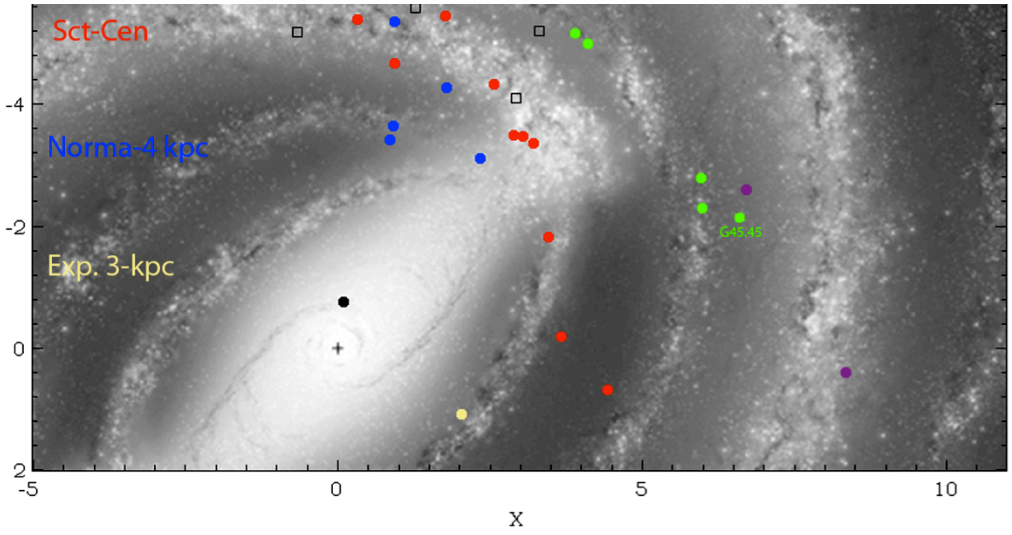
Parallax for W 49N H_2O masers



Π = 82 ± 6 μas (D=12.2 ± 0.9 kpc)

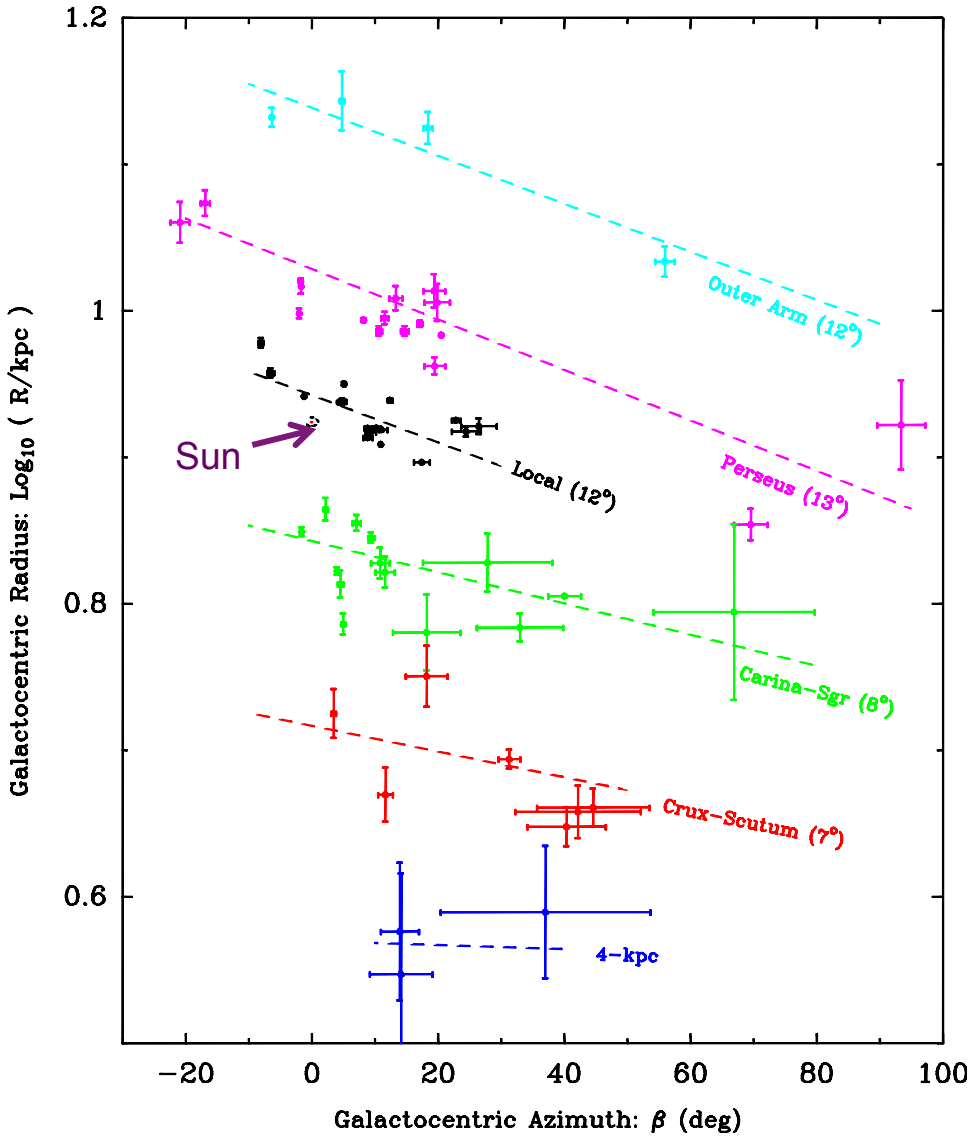
Mapping Spiral Structure





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

Spiral Arm Pitch Angles



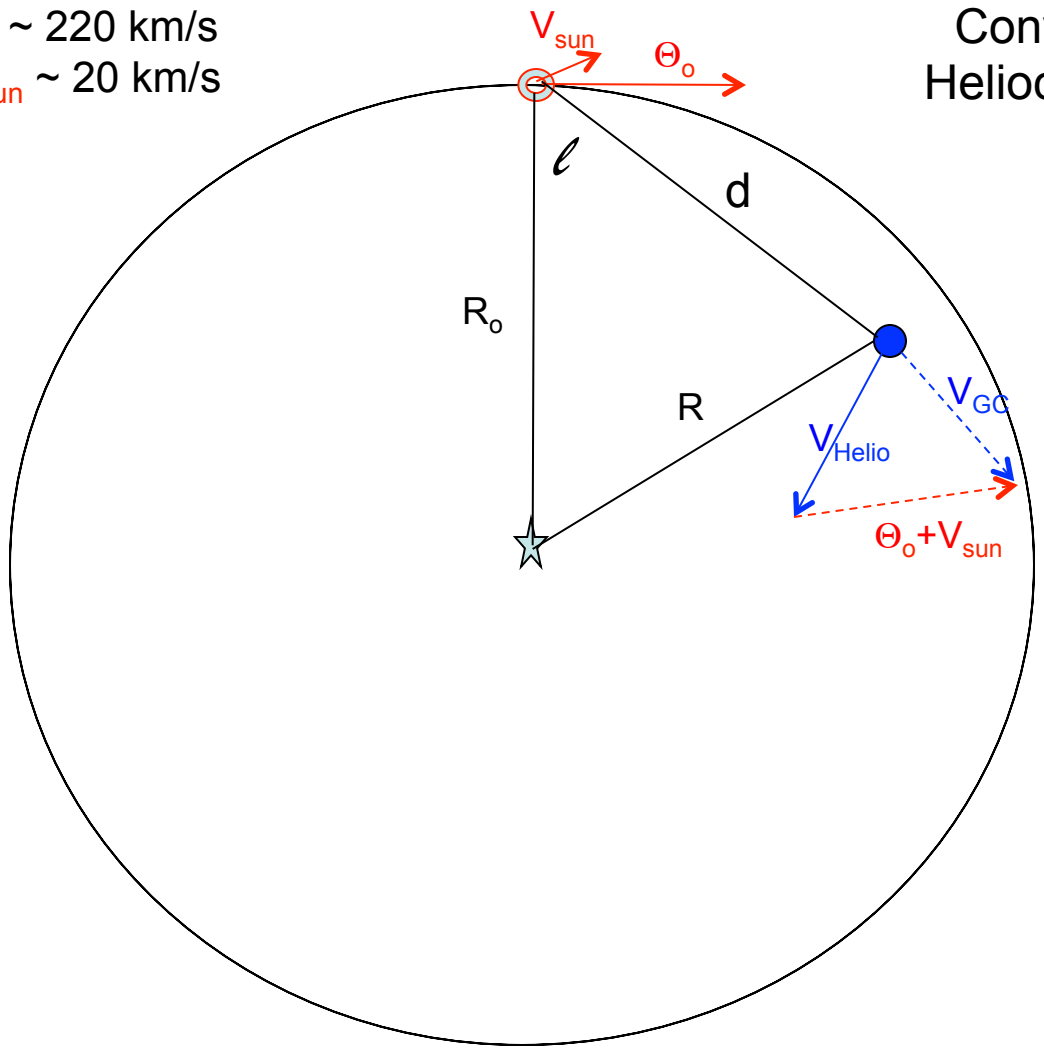
- For a log-periodic spiral:

$$\log(R / R_{ref}) = -(\beta - \beta_{ref}) \tan \psi$$

- Outer spiral arms: ~13˚ pitch angles
- Inner arms may have smaller pitch angels (need more observations)

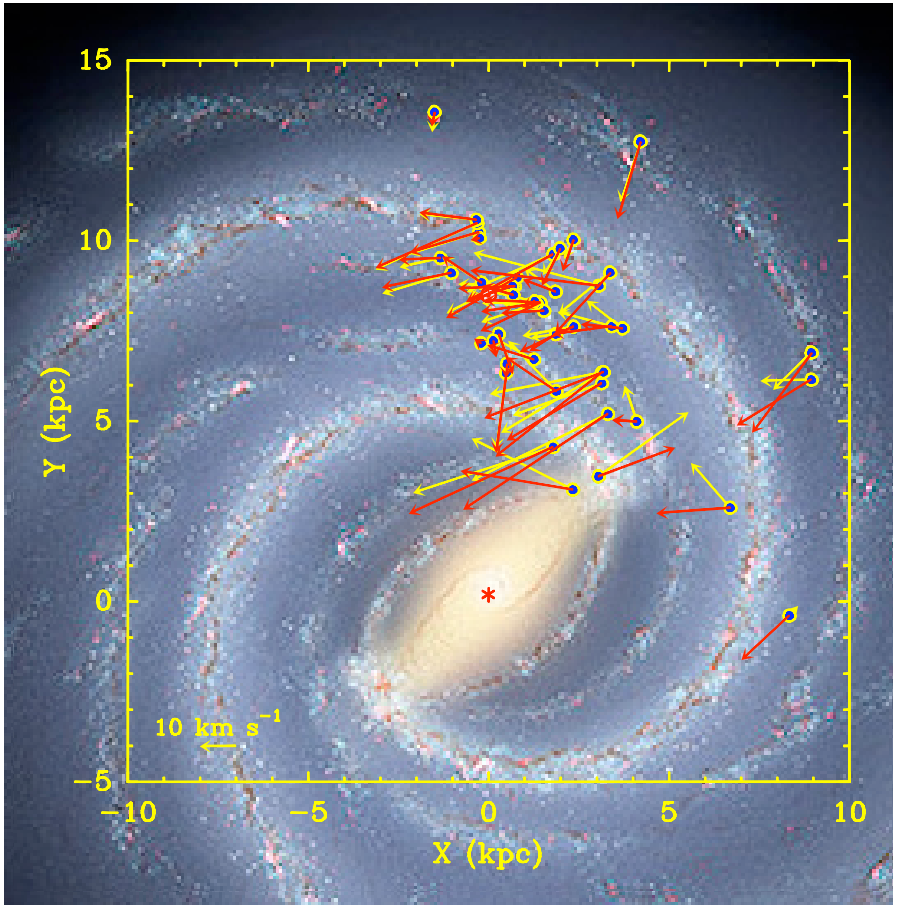
Galactic Dynamics

Θ_o ~ 220 km/s
V_{sun} ~ 20 km/s



Convert observations from Heliocentric to Galactocentric coordinates

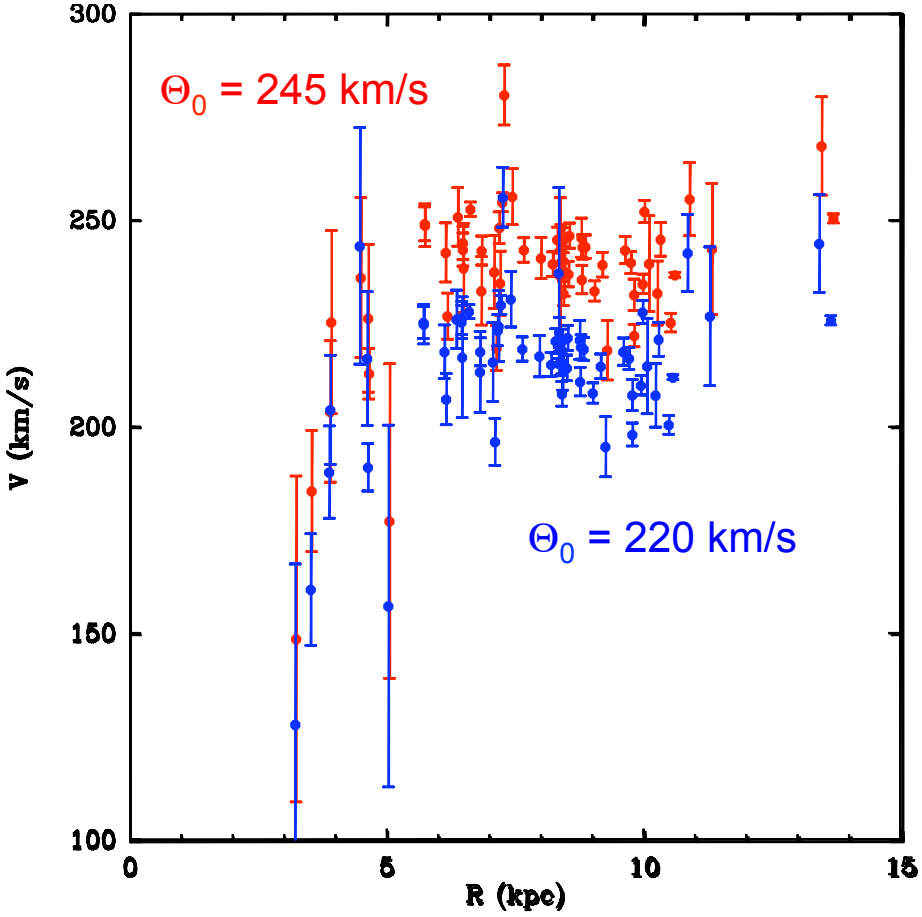
Counter-Rotation of Star Forming Regions

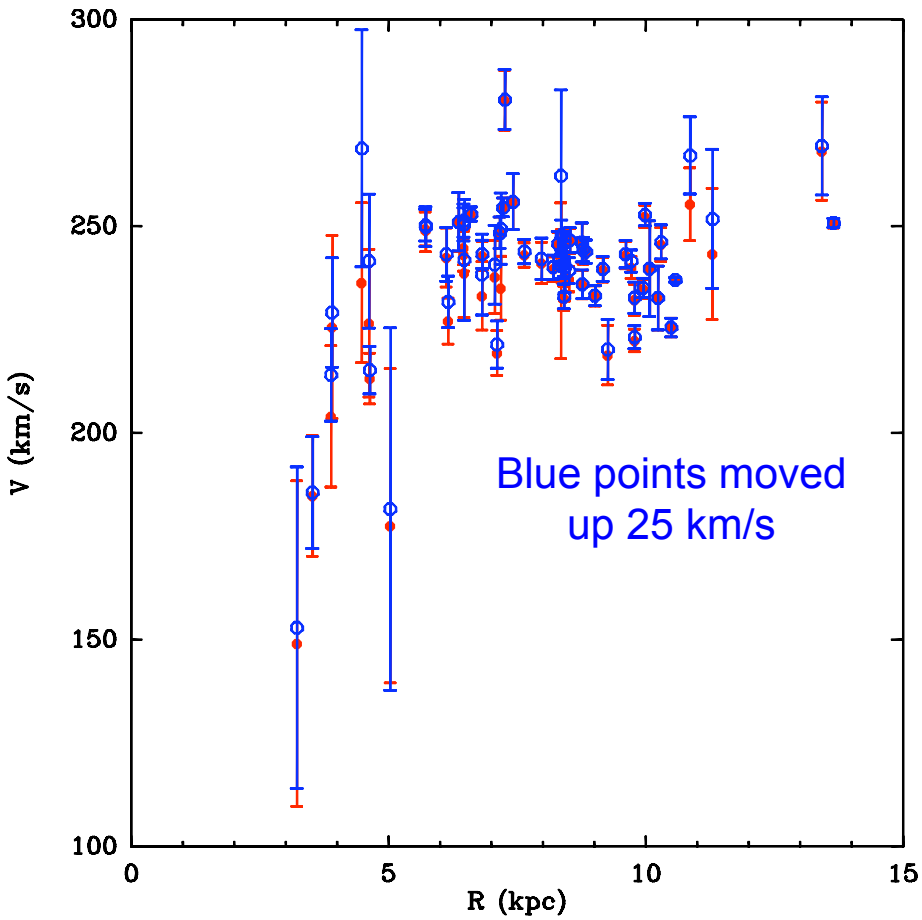


Compute Galacto-centric V
Transform to frame rotating at
Θ_o = 245 km/s (yellow)
See peculiar (non-circular) motions
…clear counter-rotation

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

The Milky Way's Rotation Curve





Modeling Parallax & Proper Motion Data

Data: have complete 3-D position and velocity information for each source:

Independent variables: $\alpha,\ \delta$

Data to fit: $\pi,\ \mu_\alpha,\ \mu_\delta,\ V$

Data uncertainties include:

measurement errors

source "noise" of 7 km/s per component (Virial motions in MSFR)

Model: Galaxy with axially symmetric rotation:

R_0 Distance of Sun from G. C.

Θ_0 Rotation speed of Galaxy at R_0

$\partial\Theta/\partial R$ Derivative of Θ with R: $\Theta(R) \equiv \Theta_0 + \partial\Theta/\partial R\ (R - R_0)$

U_{sun} Solar motion toward G. C.

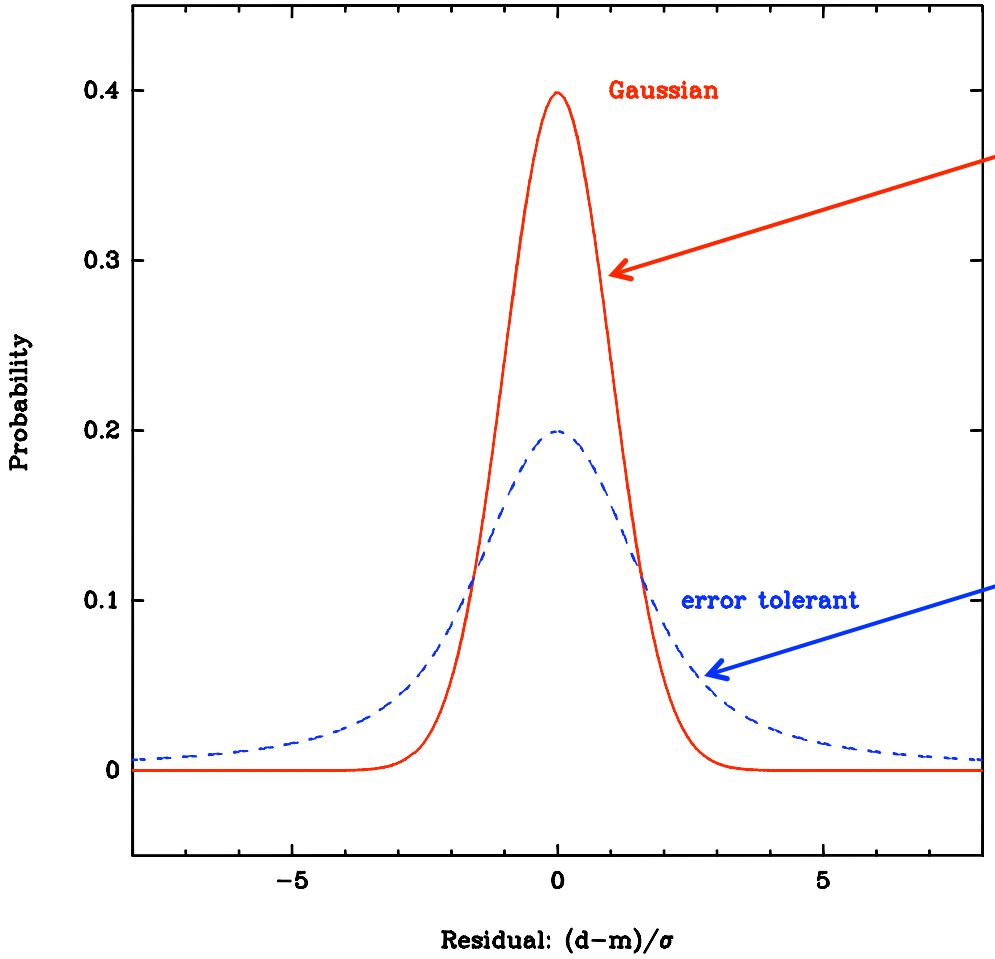
V_{sun} " " in direction of Galactic rotation

W_{sun} " " toward N. G. P.

$\langle U_{src} \rangle$ Average source peculiar motion toward G. C.

$\langle V_{src} \rangle$ " " " " in direction of Galactic rotation

“Outlier-tolerant” Bayesian fitting



$\text{Prob}(D_i|M,\sigma_i) \propto \exp(-R_i^2/2)$

$R_i = (D_i - M_i) / \sigma_i$

$\text{Prob}(D_i|M,\sigma_i) \propto (1 - \exp(-R_i^2/2)) / R_i^2$

Sivia “A Bayesian Tutorial”

Model Fitting Results for 93 Sources

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)
"Outlier-tolerant" Bayesian fitting						
Flat Rotation Curve	8.39 ± 0.18	245 ± 7	[0.0]	-8 ± 2	5 ± 3	(28.2)
Sloped " "	8.38 ± 0.18	243 ± 7	-0.4 ± 0.7	-8 ± 2	6 ± 2	(29.0)
Least-Squares fitting: removing 13 outliers (>3σ):						
Sloped " "	8.30 ± 0.09	244 ± 4	-0.3 ± 0.4	-8 ± 2	5 ± 2	(29.4)

Notes:

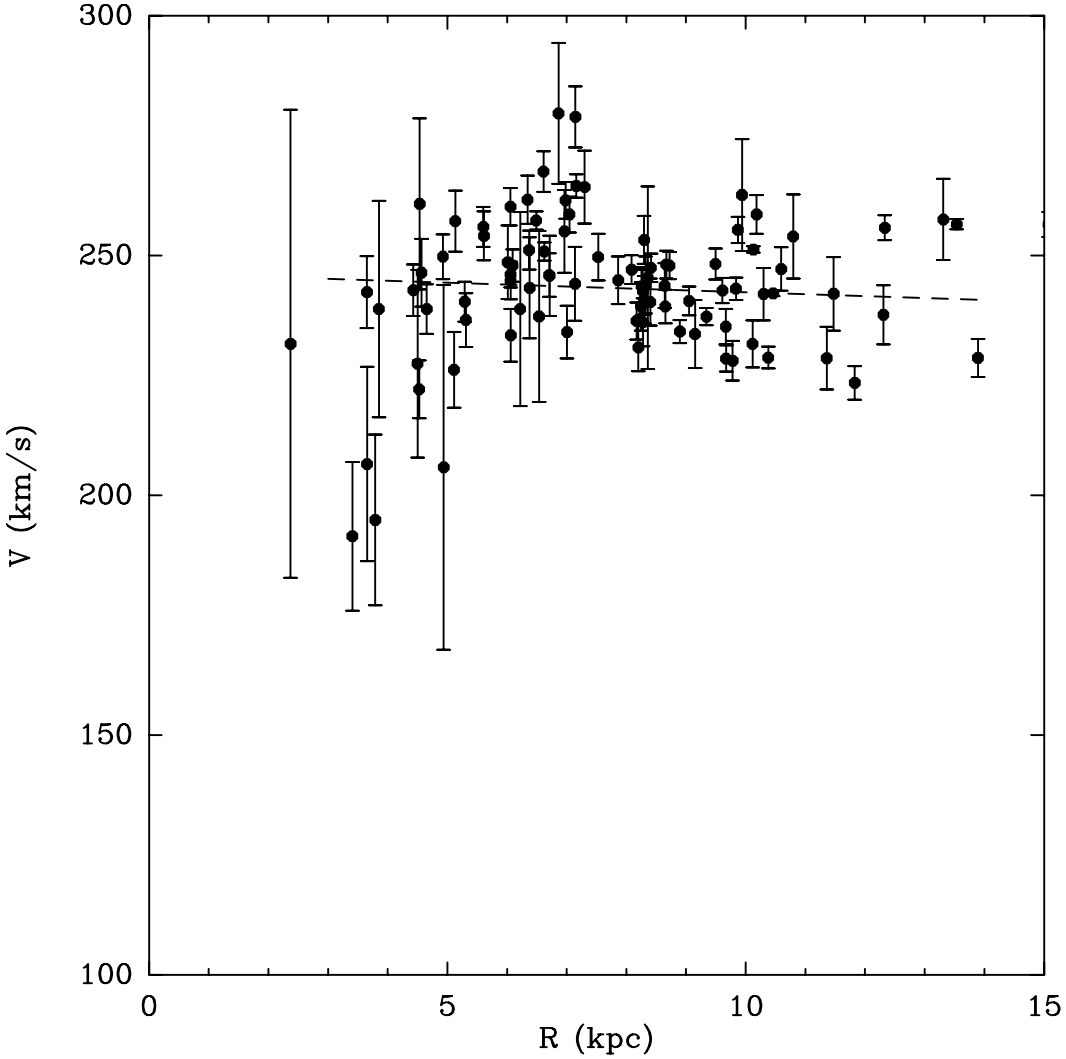
Assuming Solar Motion V-component = 12 km/s (Schœnrich et al 2010)

$\langle V_{src} \rangle$ = 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)

The Milky Way's Rotation Curve



- For R_0 = 8.4 kpc, Θ_0 = 243 km/s
- Assumes Schoenrich Solar Motion
- Corrected for maser counter-rotation

New and direct result based on
3-D motions
"gold standard" distances

Effects of Increasing Θ_0

- Reduces kinematic distances: D_k by 15%, hence…

  Molecular cloud sizes ($R \propto \varphi D$) by 15%

  Young star luminosities: $L \propto R^2$ by 30% (increasing YSO ages)

  Cloud masses (from column density & size): $M \propto R^2$ by 30%

- Milky Way's dark matter halo mass:

  $M \propto (V_{max})^2 R_{Vir}$

  $V_{max} \propto \Theta_0$ & $R_{Vir} \propto \Theta_0$

  $M \propto \Theta_0^3$ or up by 50%

- Increasing Θ_0, increases expected dark matter annihilation signals

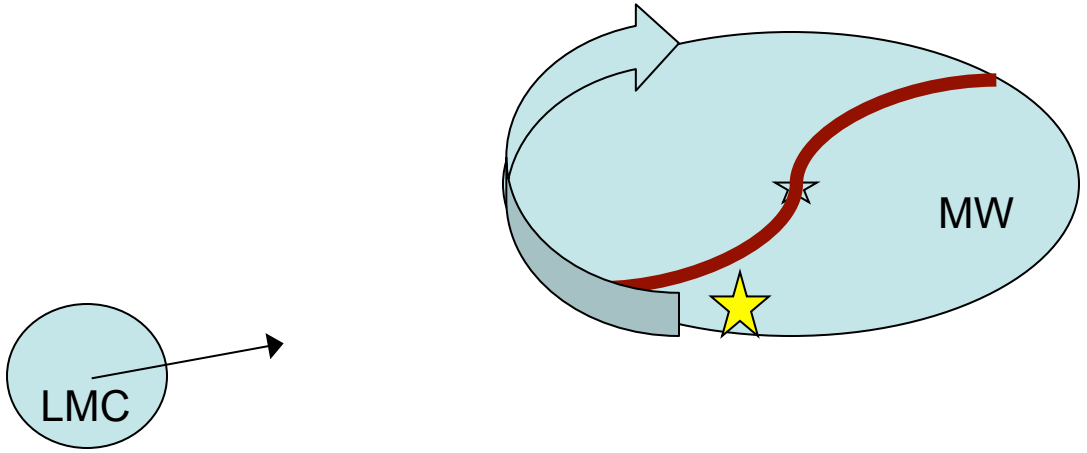
- Largest uncertainty for modeling Hulse-Taylor binary pulsar timing is accounting for Galactic accelerations: Θ_0^2 / R_0

Effects of Θ_0 on Binary Pulsar

- Gravitational Radiation Damping: decreases binary period (P_b)
- Need to account for Galactic accelerations: ~1% of observed dP/dt
- Using IAU values for R_0 (8.5±0.7) and Θ_0 (220±30):
  dP/dt: (Observed – Galactic) / GR-theory = 1.002 ± 0.003
- Using new values for R_0 (8.37±0.18) and Θ_0 (244±7):
  dP/dt: (Observed – Galactic) / GR-theory = 0.999 ± 0.002
- Dominant source of error is now distance (9.9±3.1 kpc)
  with ±8% distance measurement, get ±0.001 for GR test

More Effects of Increasing Θ_0

- 1) Increases mass and overall size of Galaxy
  2) Decreases velocity of LMC with respect to M.W.
  Both help bind LMC to M.W. (Shattow & Loeb 2009)

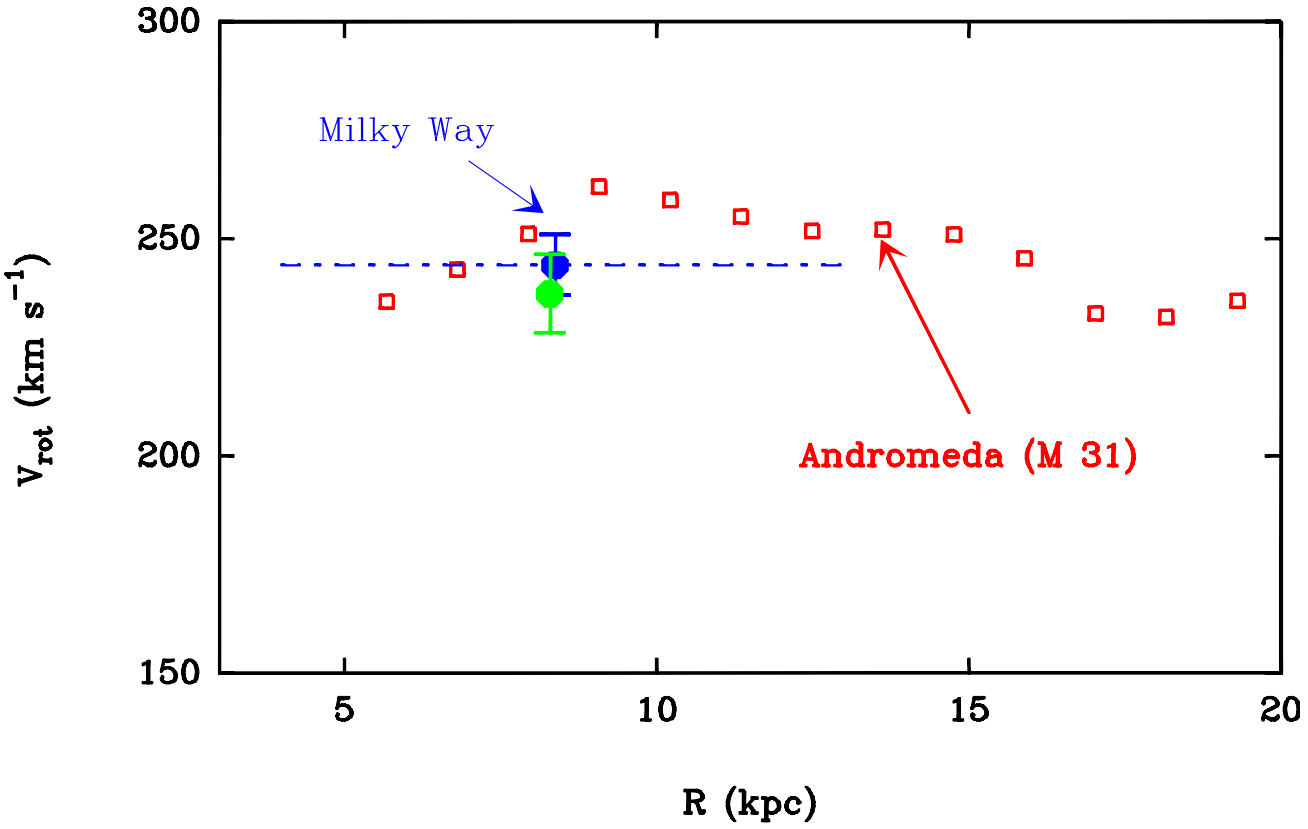


- Increases likelihood of an Andromeda-Milky Way collision

BeSSeL + VERA + EVN Results

- VLBA, VERA & EVN parallaxes tracing spiral structure of Milky Way
- Milky Way has 4 major gas arms (and minor ones near the bar)
- Outer arm spiral pitch angles ~13^{o}
- Star forming regions "counter-rotate" by ~8 km/s (for V_{sun}=12 km/s)
- Parallax/proper motions: R_o ~ 8.38 ± 0.18 kpc; Θ_o ~ 243 ± 7 km/s/kpc

Rotation Curves



Milky Way parallaxes/proper motions

Sgr A* proper motions & stellar orbit distance

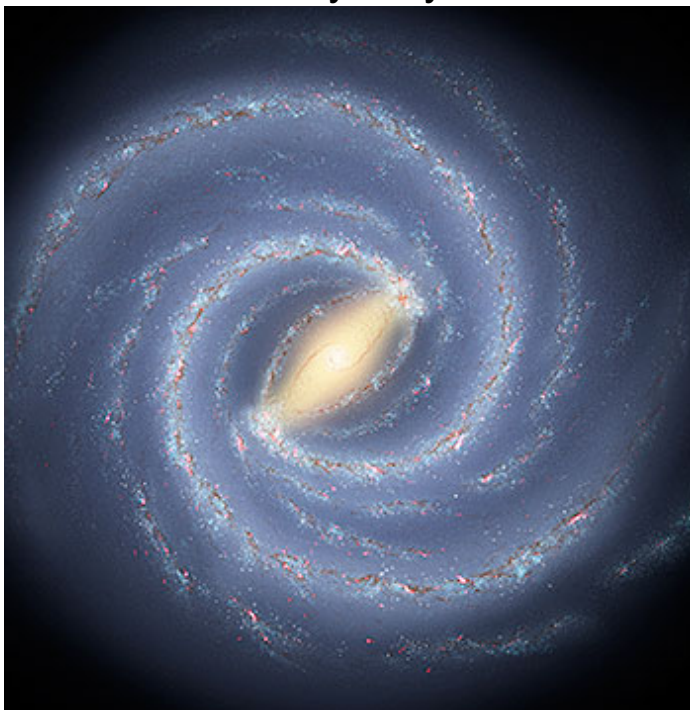
Andromeda H I emission: Carignan et al (2006)

Local Group Sisters

Andromeda (M31)

Photograph: Robert Gendler

Milky Way



Artist conception: Robert Hurt (NASA:SSC)

Milky Way no longer “little sister” of Andromeda…
more like “fraternal twins”


COMEDY CENTRAL