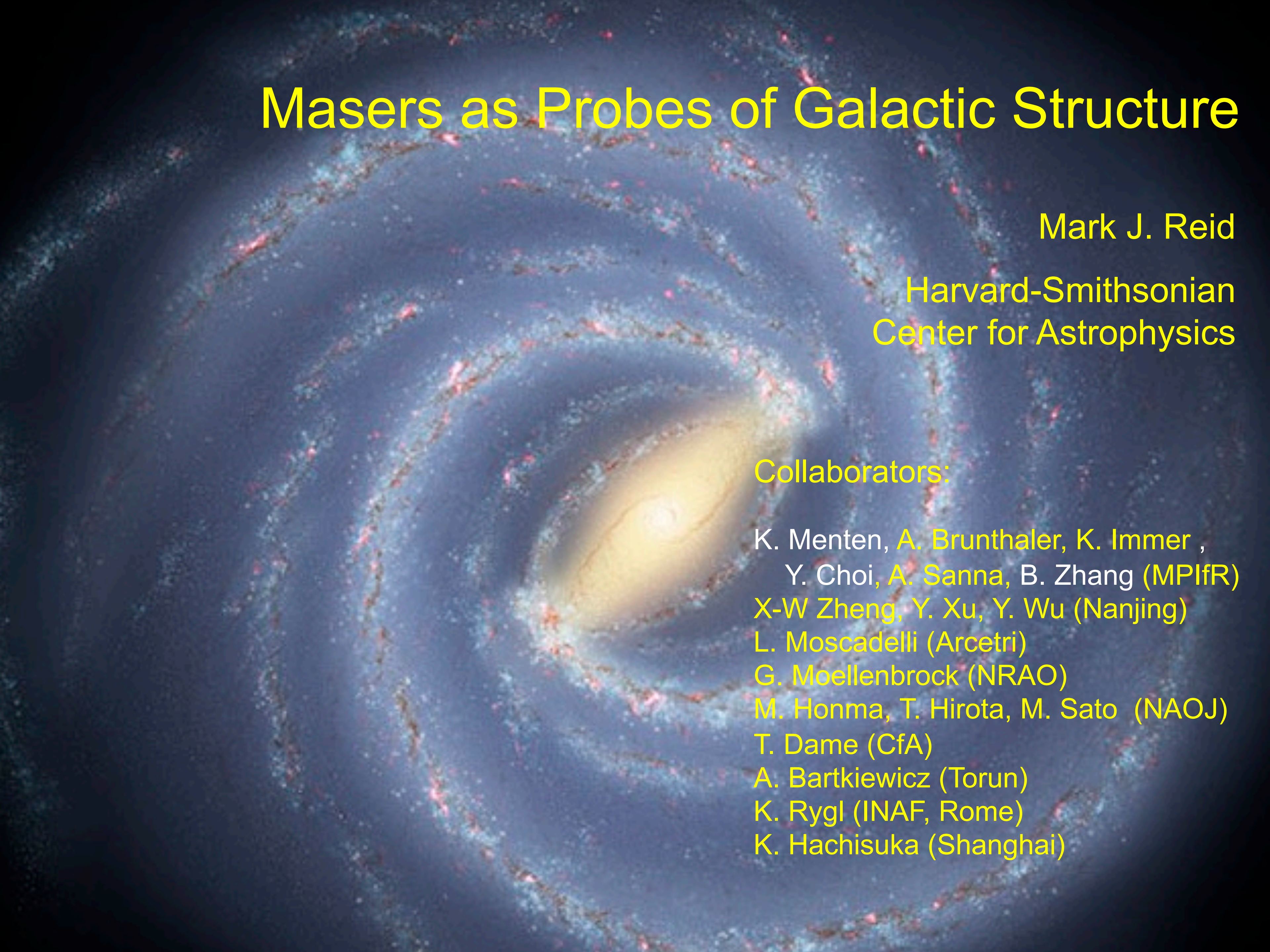

Masers as Probes of Galactic Structure

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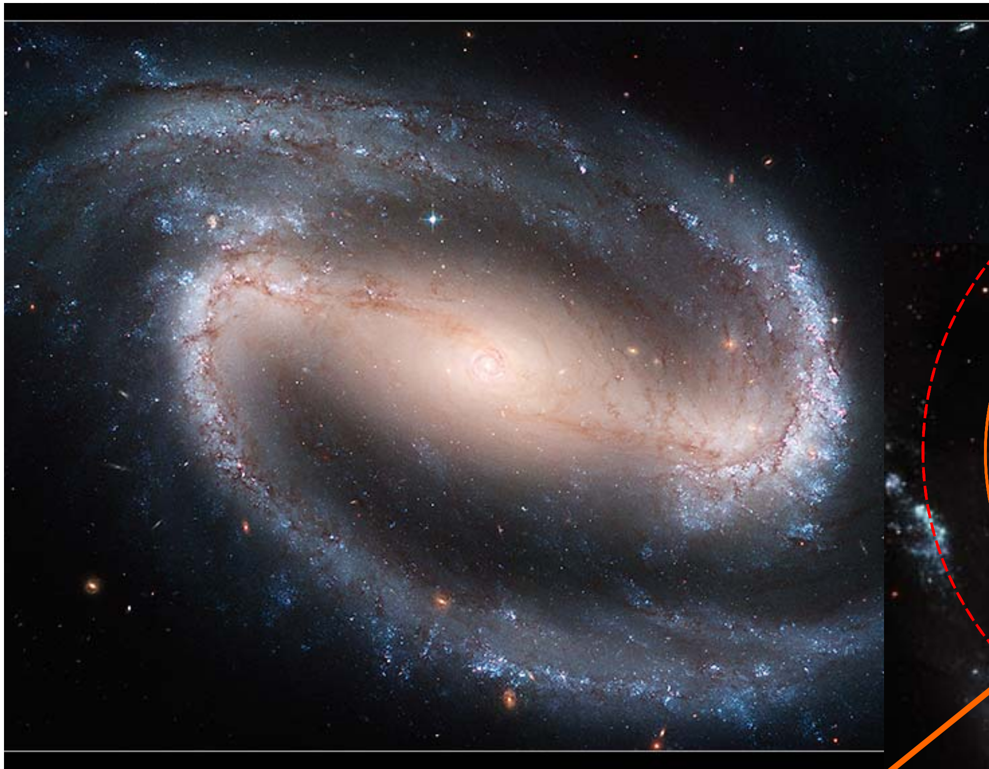
What does the Milky Way look like?



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):

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

Centroid Precision:

0.5 θ_f / SNR ~ 10 μas

Systematics:

path length errors ~ 2 cm (~2 λ)

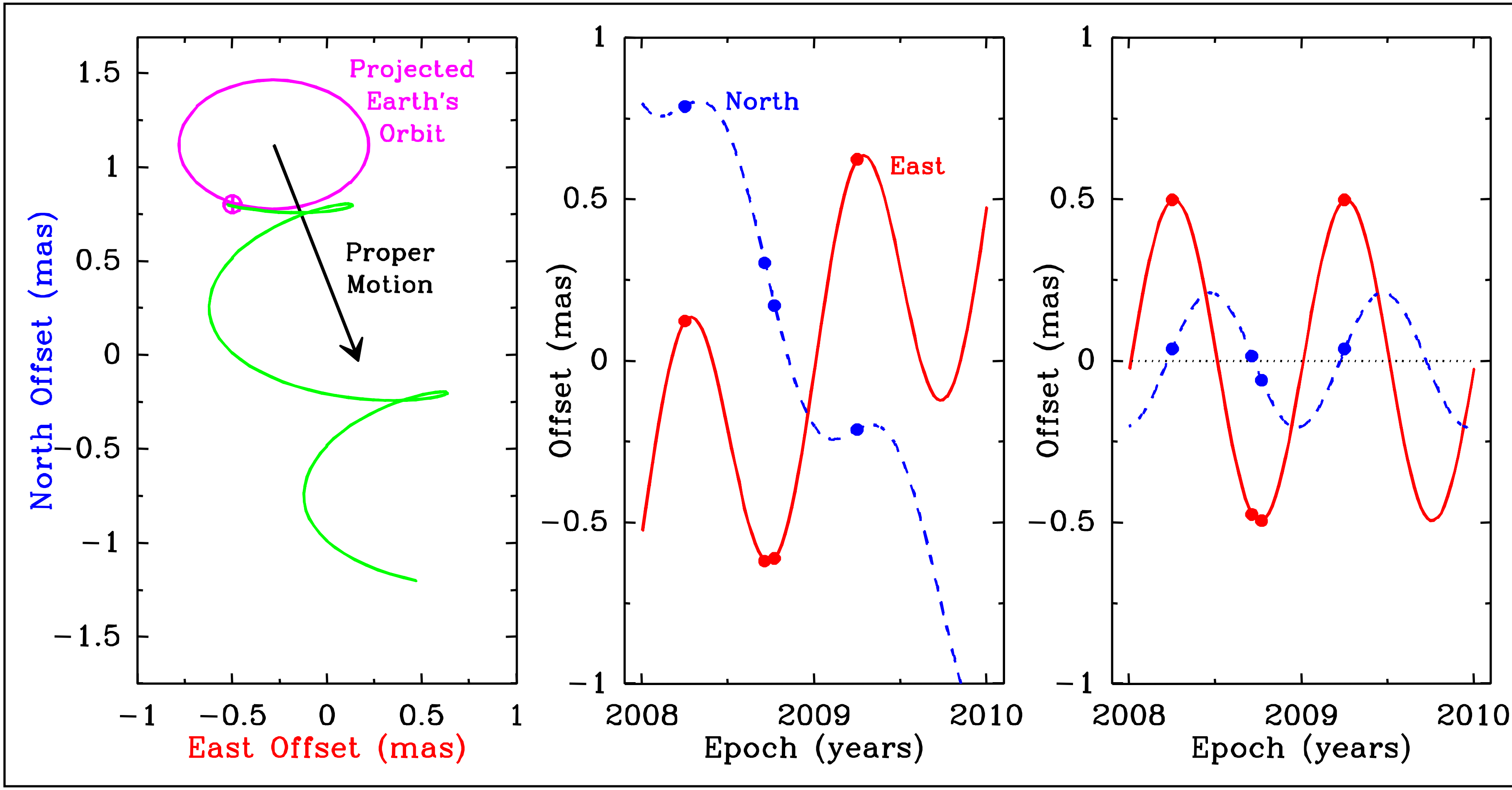
shift position by ~ $2\theta_f$ ~ 500 μas

Relative positions (to QSOs):

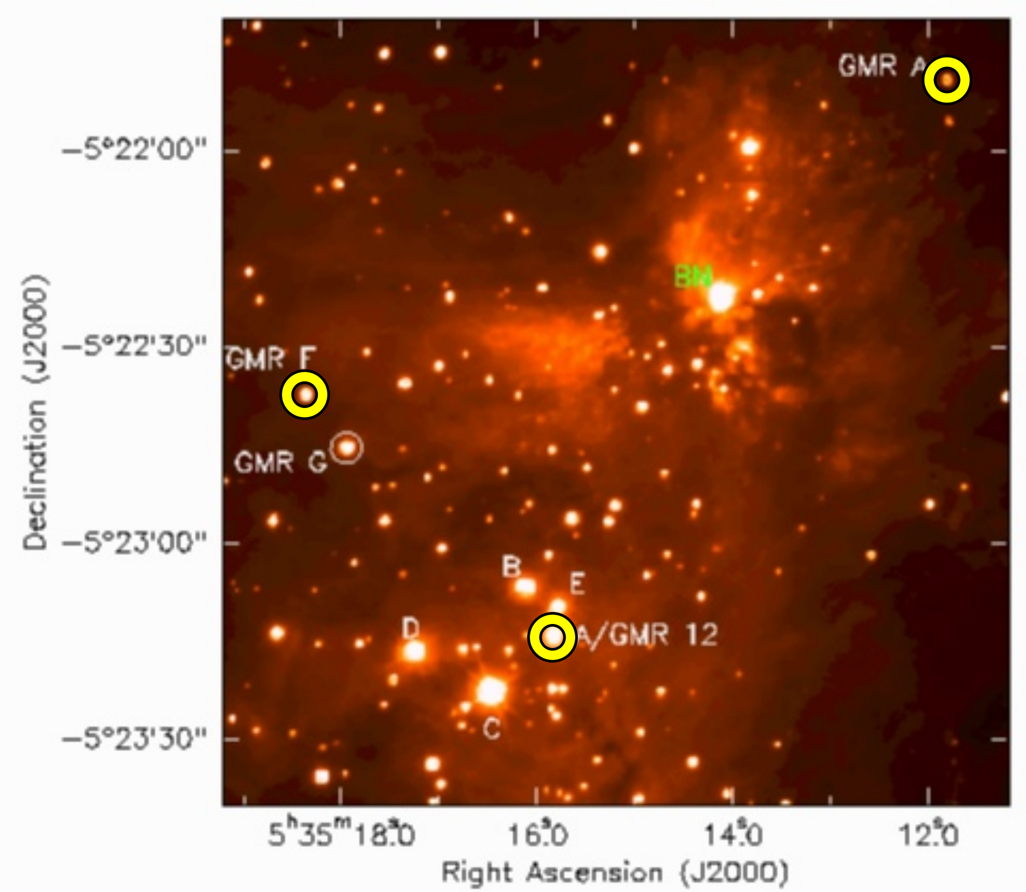
$\Delta\Theta$ ~ 1 deg (0.02 rad)

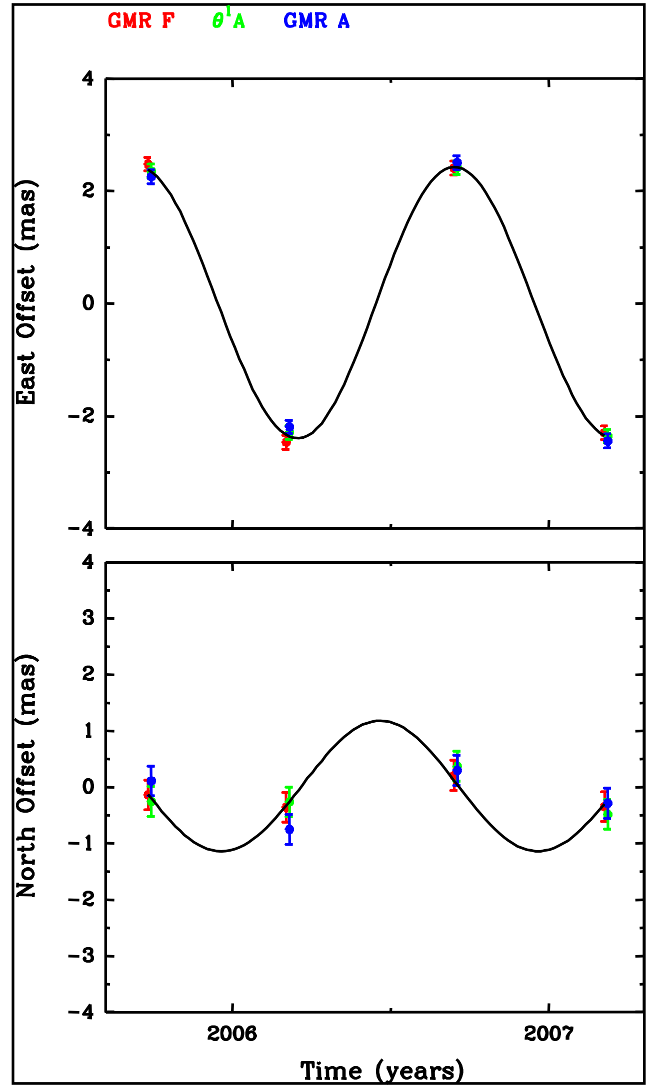
cancel systematics: $\Delta\Theta * 2\theta_f$ ~ 10 μas

Parallax Signatures



Orion Nebular Cluster Parallax





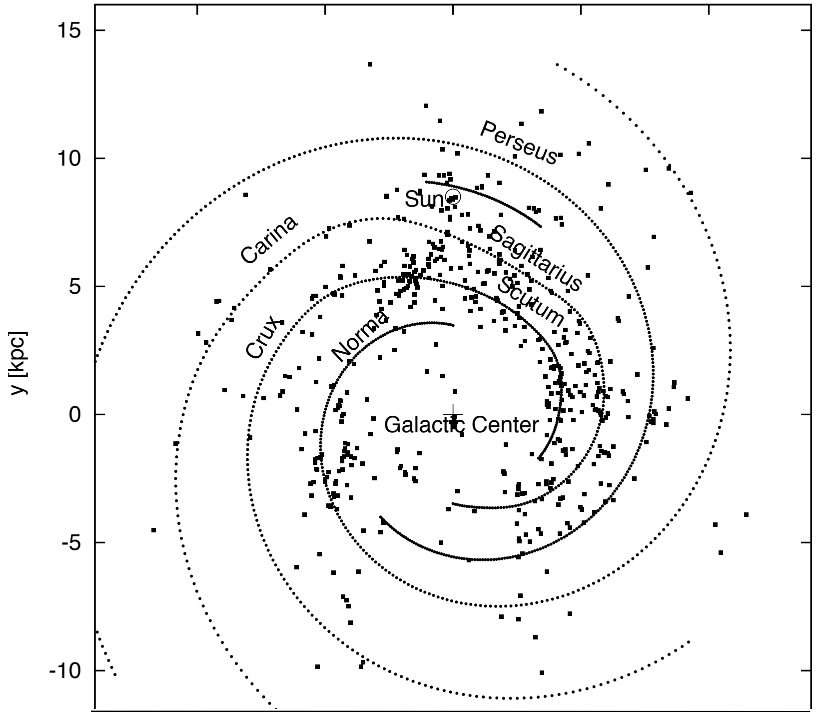
VLBA: $\Pi = 2.42 \pm 0.04$ mas

$D = 414 \pm 7$ pc

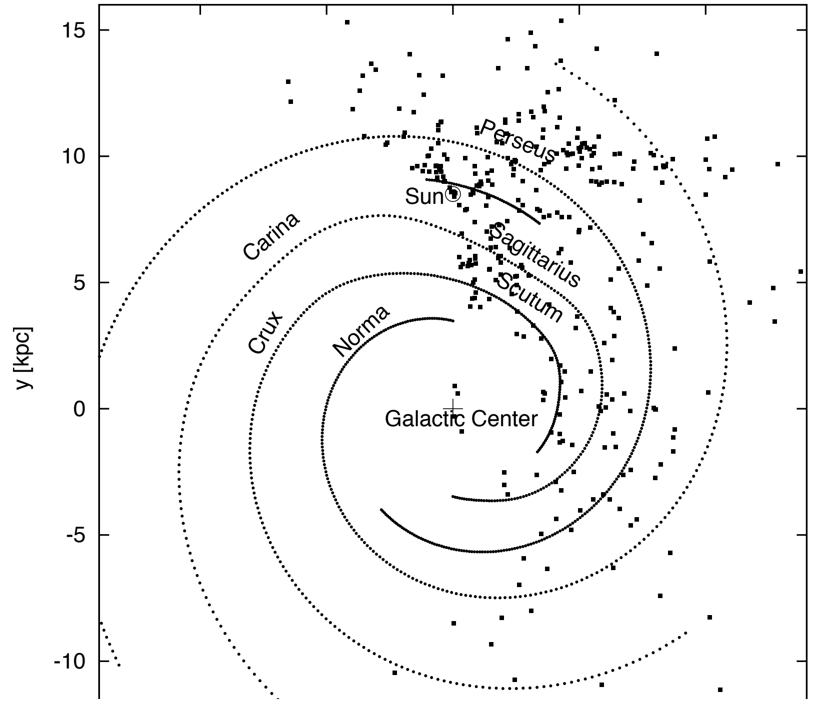
VERA: $D = 419 \pm 6$ pc

Menten, Reid, Forbrich & Brunthaler (2007)

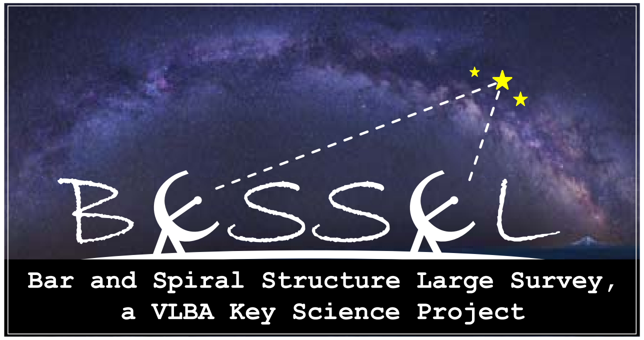
Mapping the Milky Way



6.7/12.2 GHz CH_3OH masers



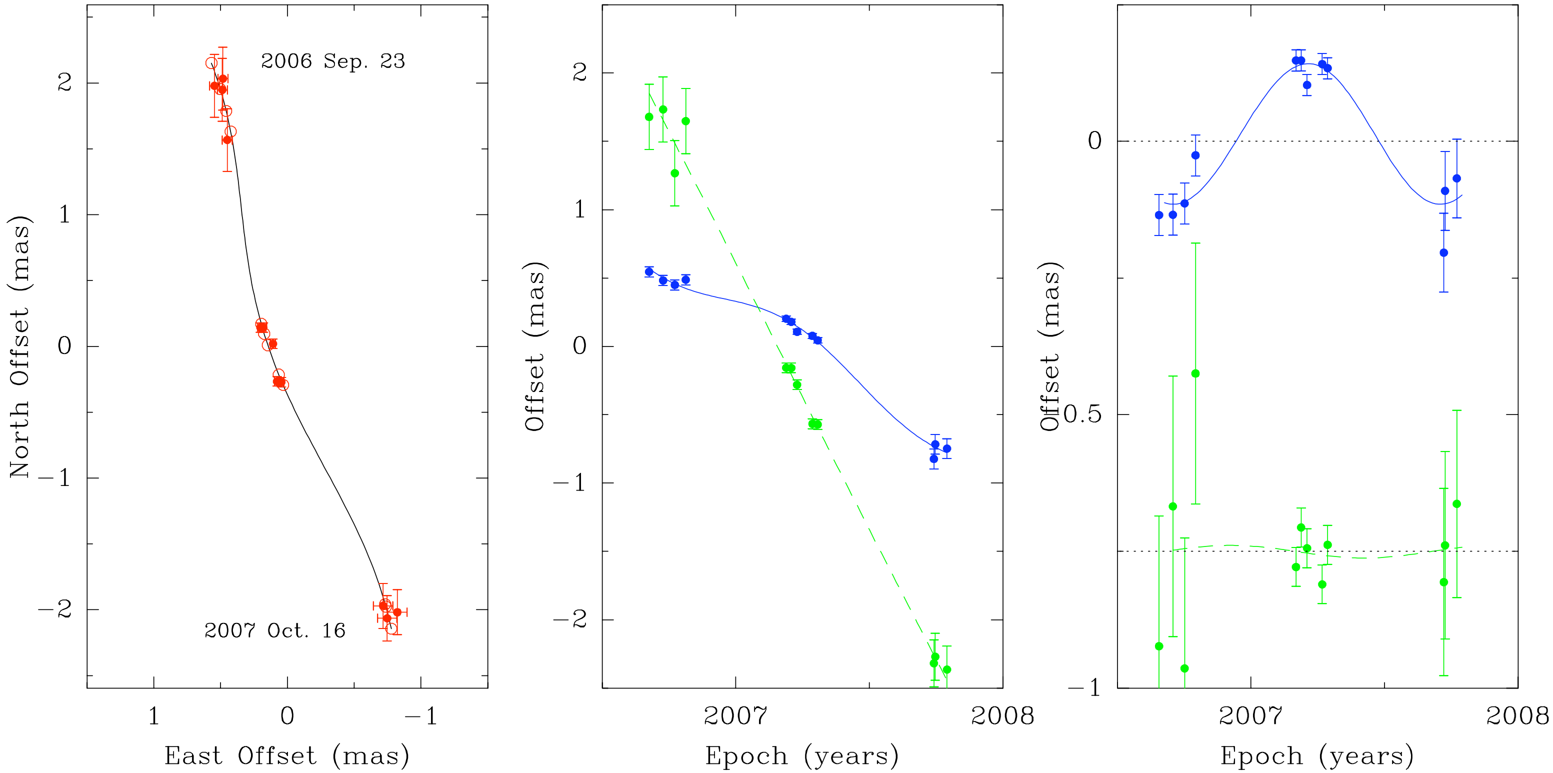
22 GHz H_2O masers



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

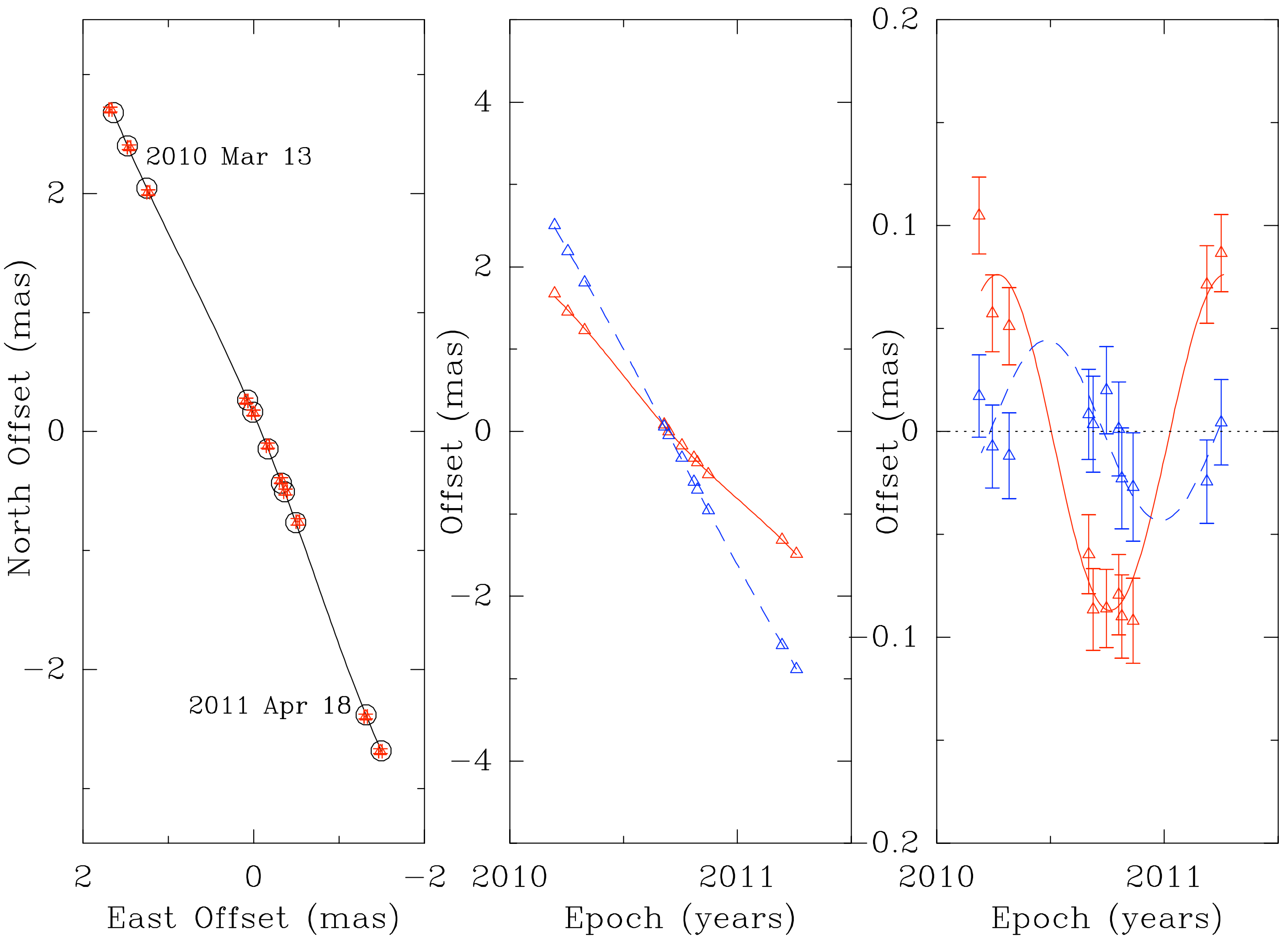
Observations for ~70 masers started 2010/2011 recently completed

Parallax for Sgr B2(Middle) H_2O masers



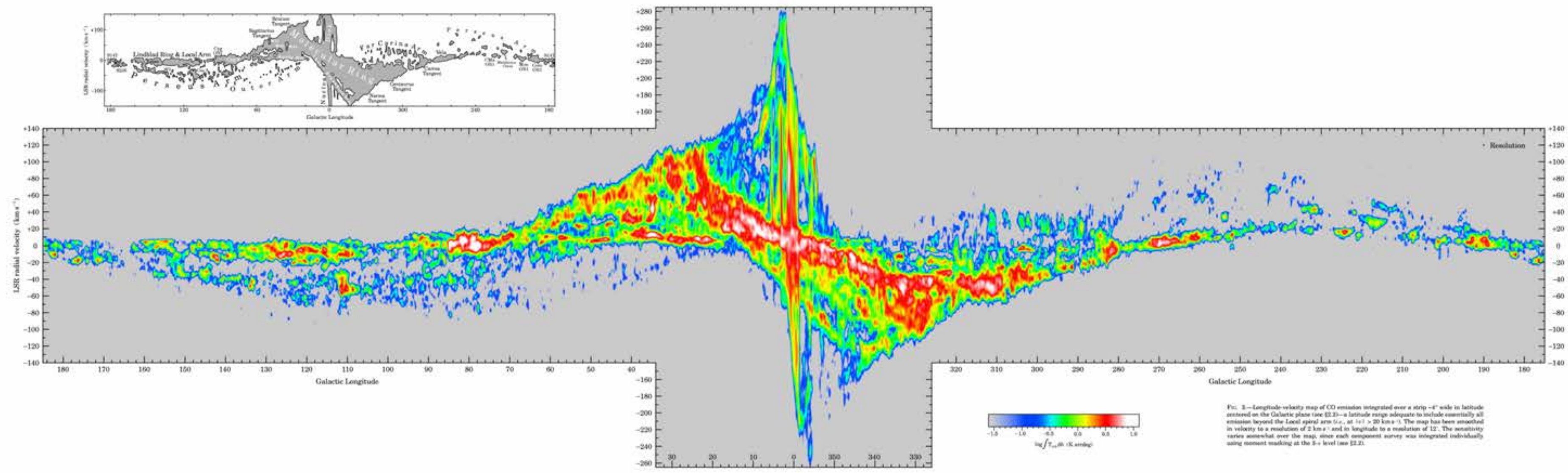
Π = 129 ± 12 μas (D=7.8 ± 0.8 kpc)

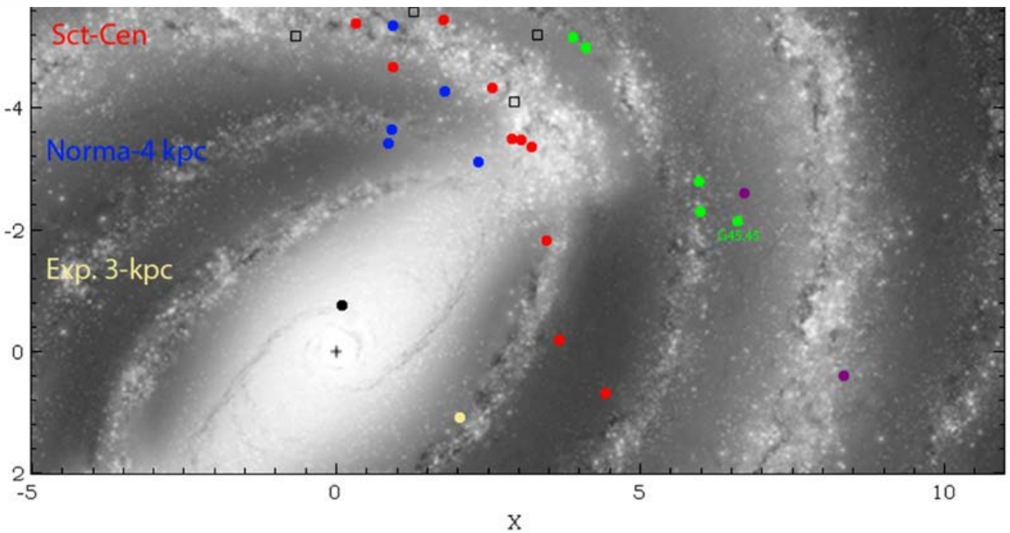
Parallax for W 49N H_2O masers



Π = 82 ± 6 μas (D=12.2 ± 0.9 kpc)

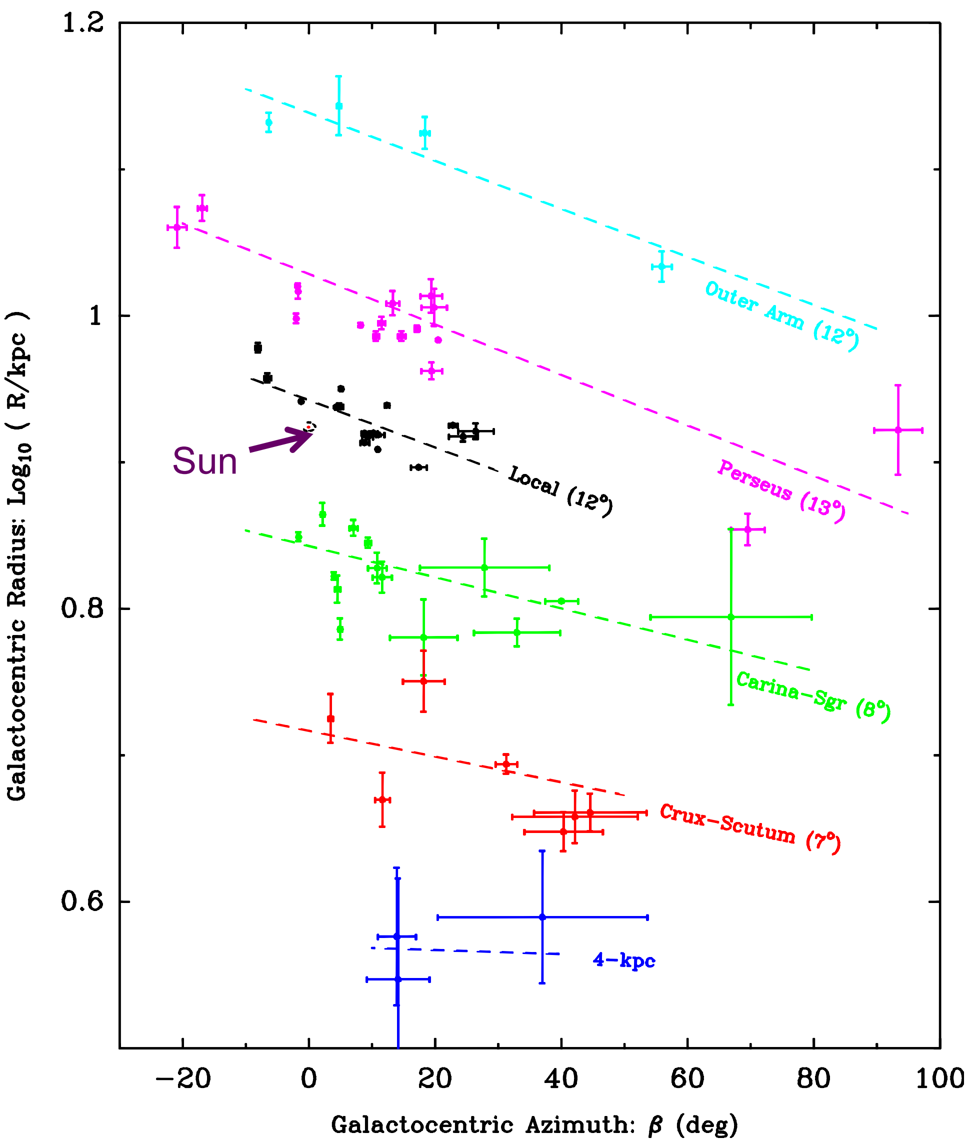
Mapping Spiral Structure





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

Spiral Arm Pitch Angles



- For a log-periodic spiral:

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

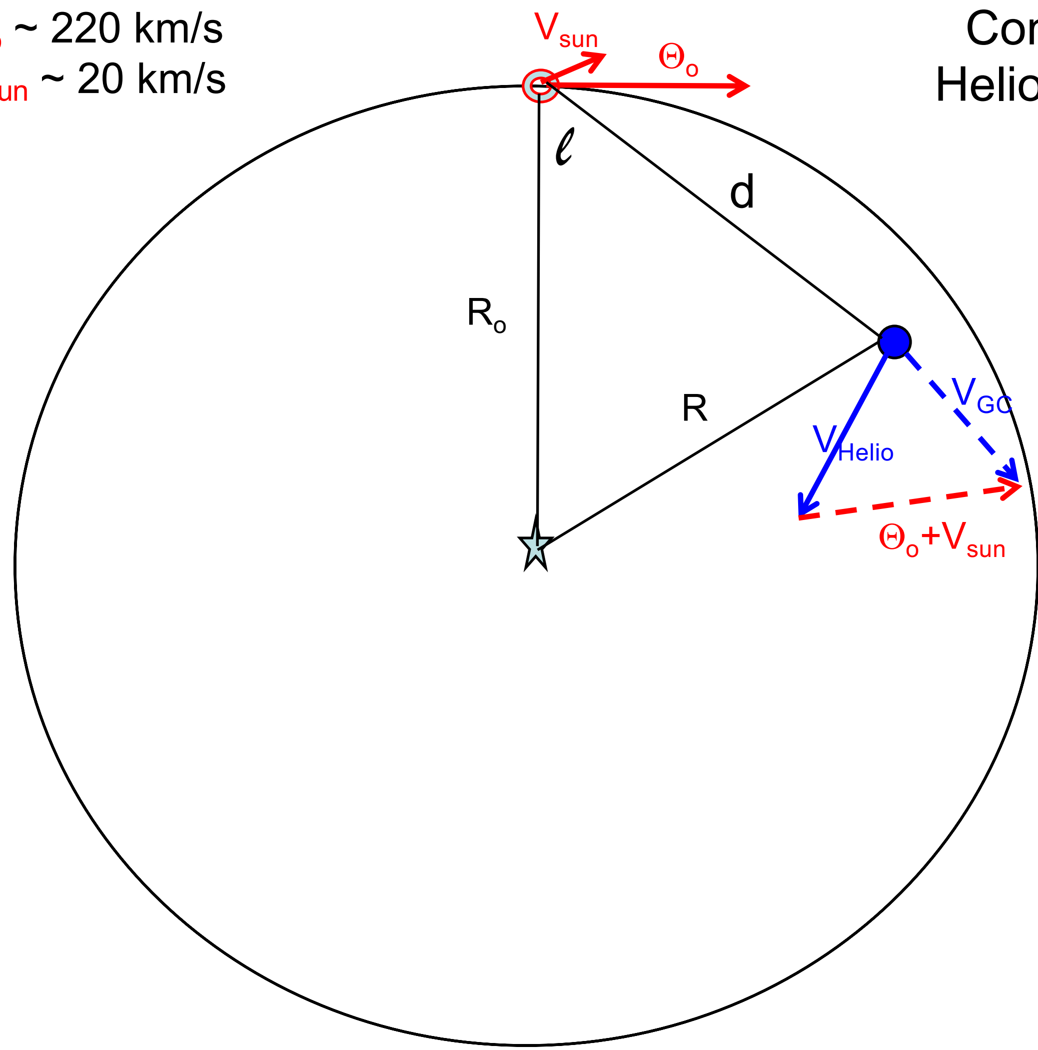
- Outer spiral arms: ~13˚ pitch angles

- Inner arms may have smaller pitch angels (need more observations)

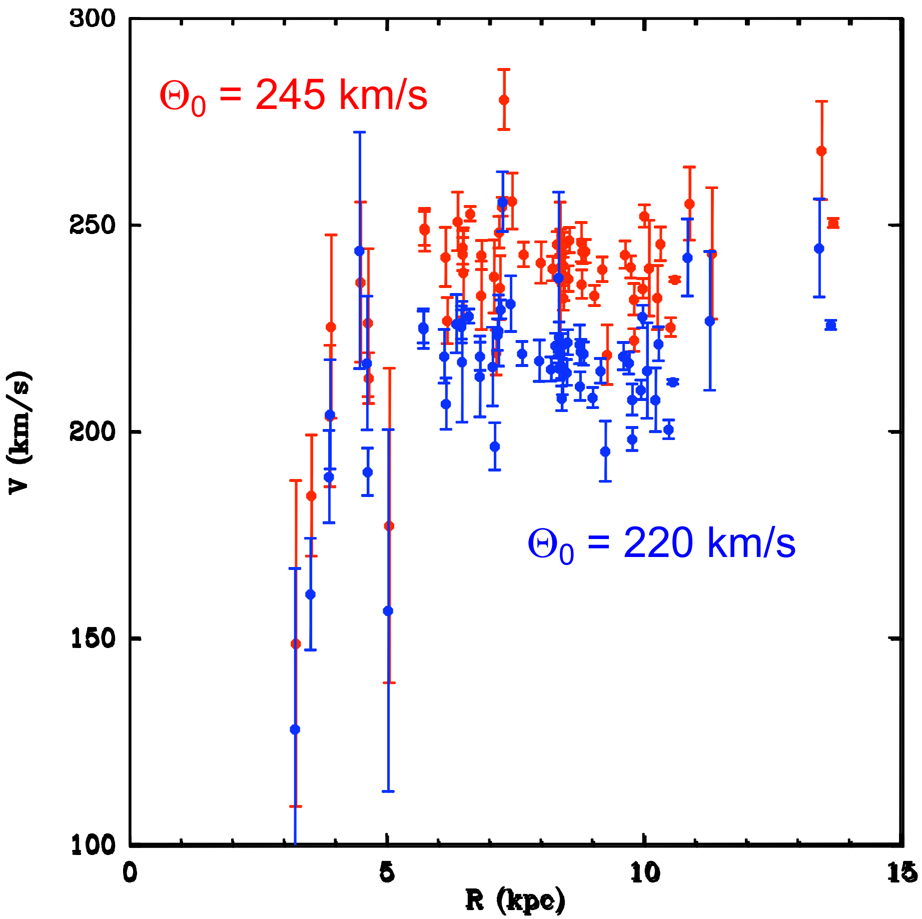
Galactic Dynamics

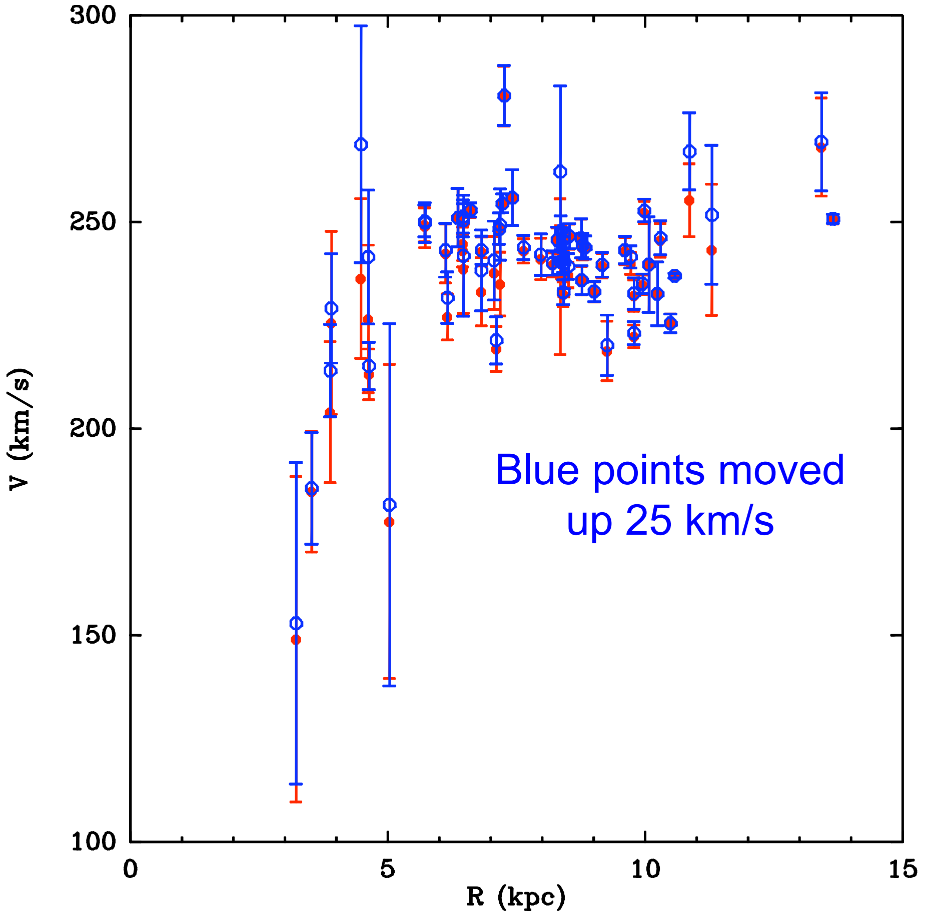
Θ_o ~ 220 km/s
V_{sun} ~ 20 km/s

Convert observations from Heliocentric to Galactocentric coordinates



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)

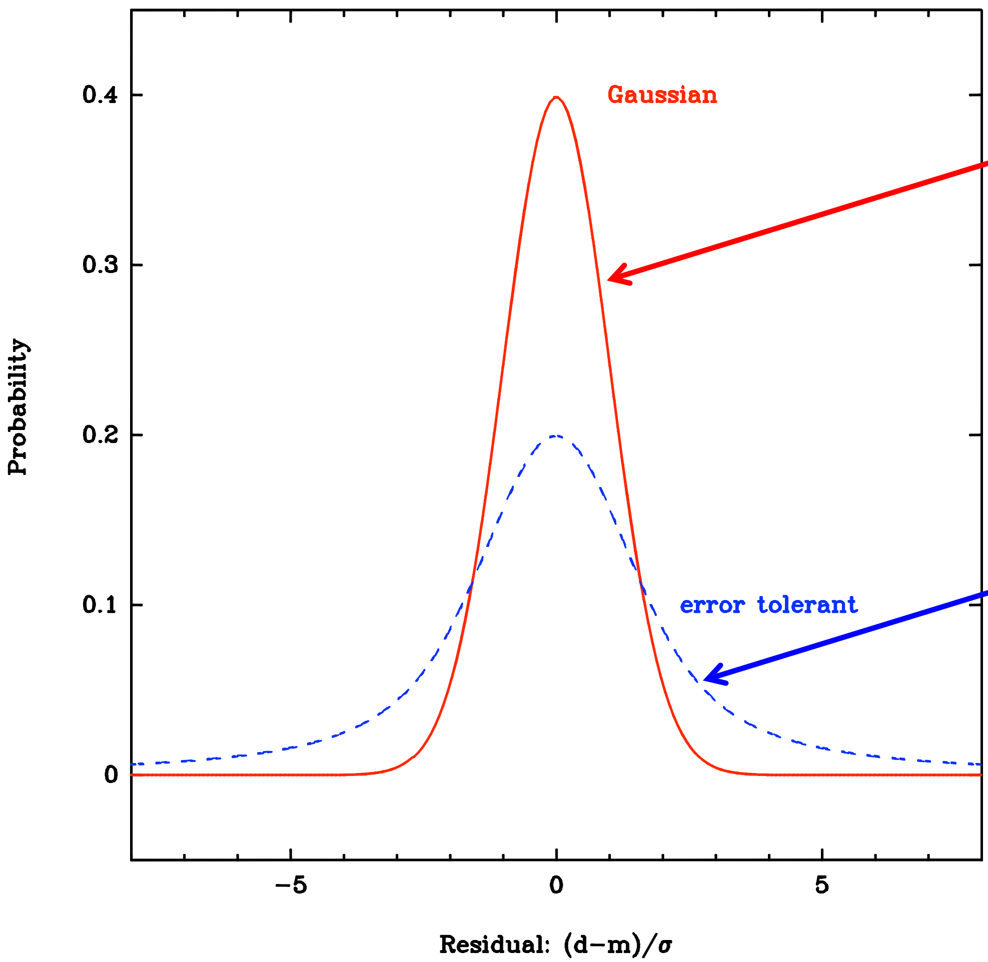
Model: Galaxy with axially symmetric rotation:

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:

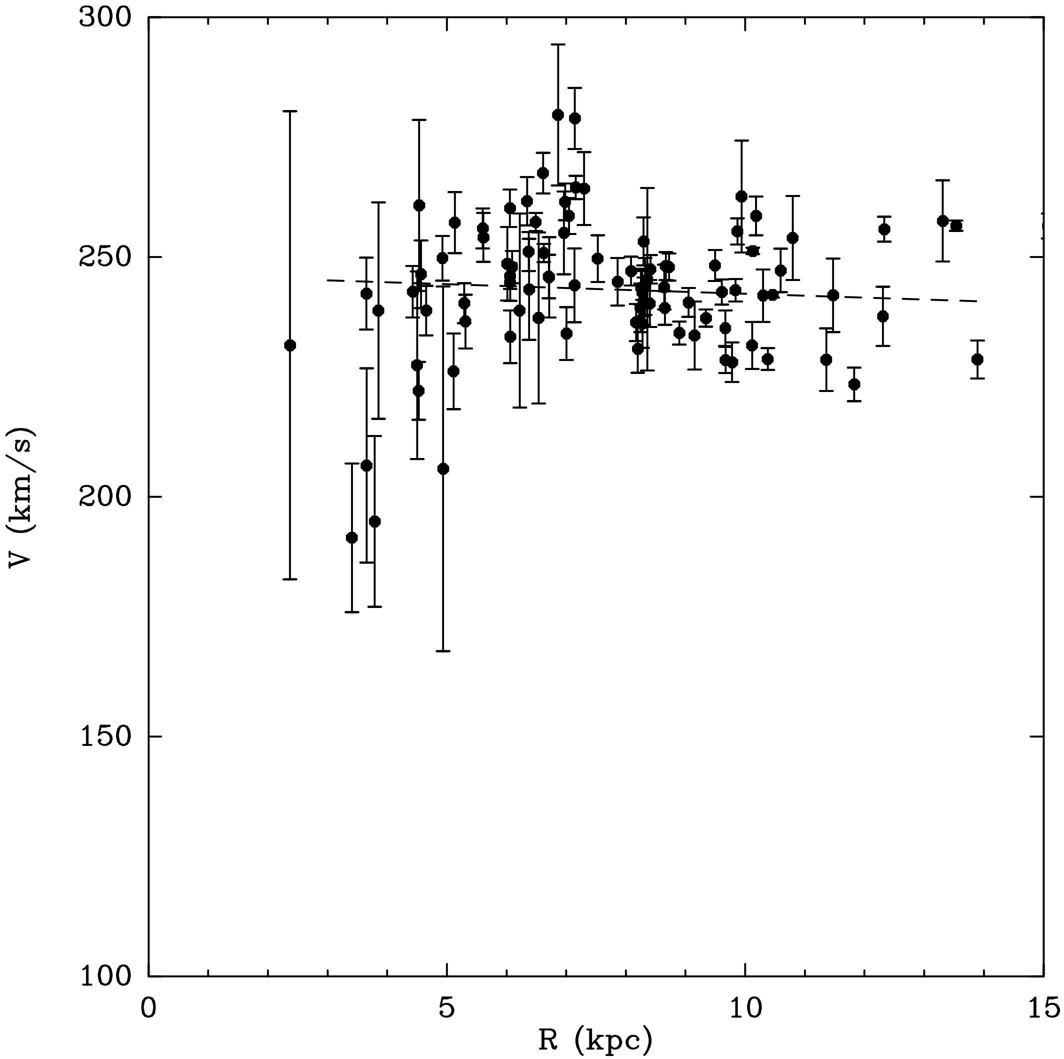
Assuming Solar Motion V-component = 12 km/s (Schœnrich et al 2010)

$\langle V_{src} \rangle$ = 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

Conclusions

- 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: $R_o \sim 8.38 \pm 0.18$ kpc; $\Theta_o \sim 243 \pm 7$ km/s/kpc

Conclusions

- VLBA, VERA & EVN parallaxes to massive young stars (via masers) 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 $\pm$ 0.18 kpc; Θ_o ~ 243 $\pm$ 7 km/s/kpc
  G.C. stellar orbits + Sgr A* p.m.: R_o ~ 8.2 $\pm$ 0.3 kpc; Θ_o ~ 236 $\pm$ 10 km/s/kpc

Is Θ_0 really >220km/s ?

- Parallax/Proper Motions of Star Forming Regions

  $R_0 = 8.4 \pm 0.2$ kpc & $\Theta_0 = 243 \pm 7$ km/s

  $\Theta_0 / R_0 = 29.0 \pm 0.9$ km/s/kpc

  (assuming Schoenrich, Binney & Dehnen 2010 Solar Motion)

- Sgr A*'s proper motion (caused by Sun's Galactic orbit)

  $\Theta_0 / R_0 = 28.62 \pm 0.15$ km/s/kpc

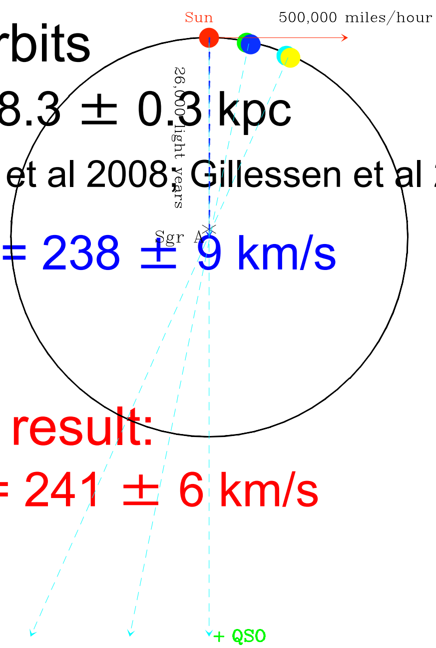
  (Reid & Brunthaler 2004)

IR stellar orbits

$R_0 = 8.3 \pm 0.3$ kpc

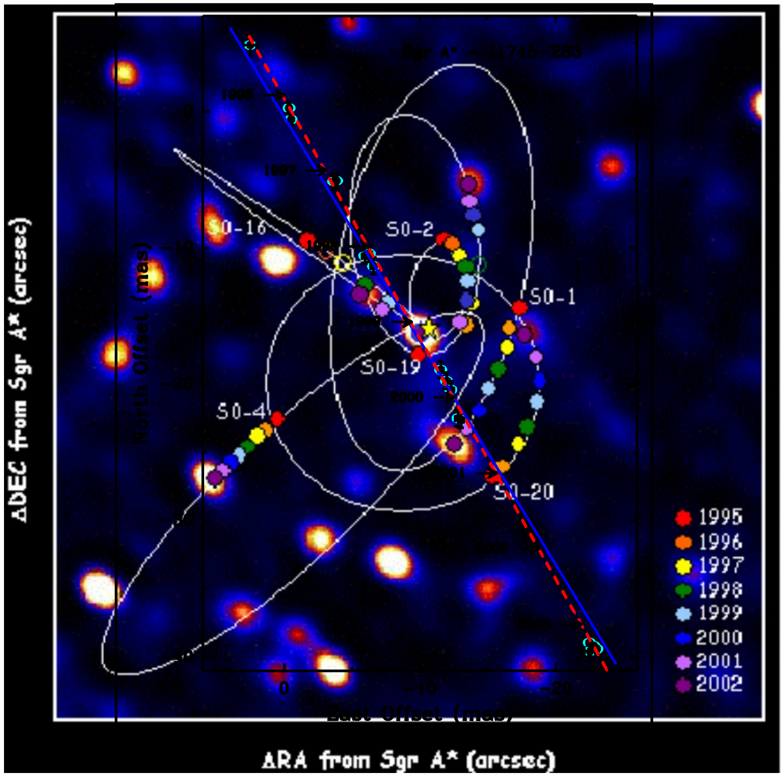
(Ghez et al 2008; Gillessen et al 2009)

Hence, $\Theta_0 = 238 \pm 9$ km/s

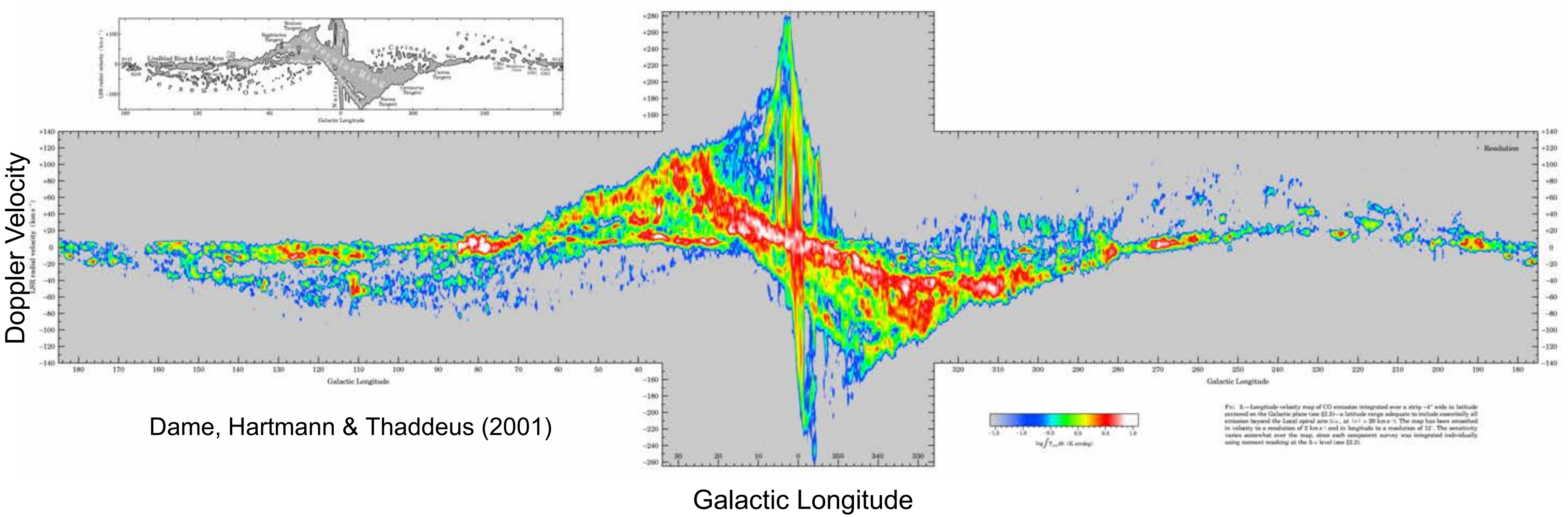


- Combined result:

  $\Theta_0 = 241 \pm 6$ km/s

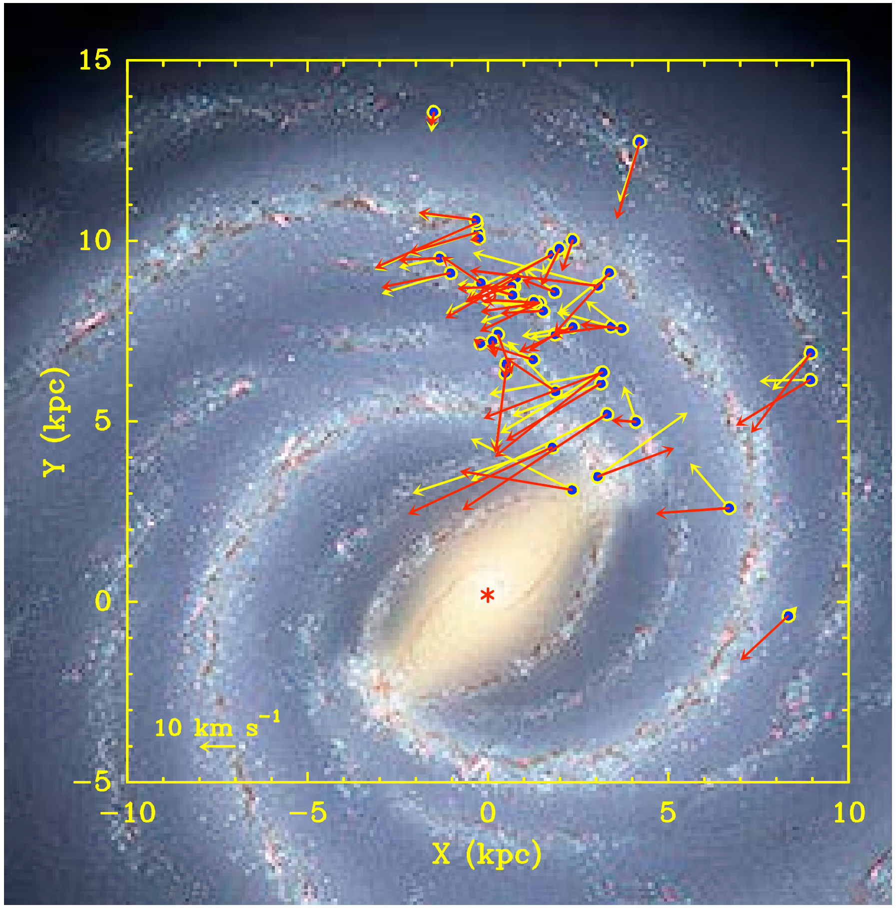


Carbon Monoxide (CO) Longitude-Velocity Plot



Dame, Hartmann & Thaddeus (2001)

Counter-Rotation of Star Forming Regions



Compute Galacto-centric V

Transform to frame rotating at

Θ_o = 250 km/s (yellow)

See peculiar (non-circular) motions

…clear counter-rotation

Transform to frame rotating at

Θ_o = 235 km/s (red)

Still counter-rotating

Sensitivity to Rotation Curve

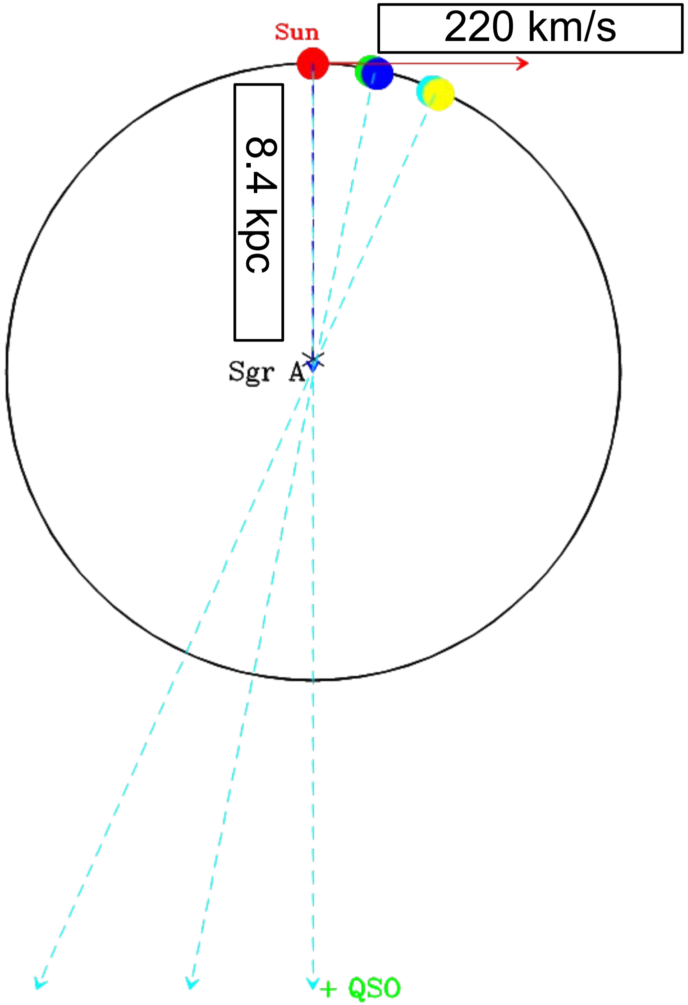
Method / Rotation Curve used	R_0 (kpc)	Θ_0 (km/s)	$d\Theta/dR$ (km/s/kpc)		C.R. (km/s)	G.C. (km/s)	Θ_0/R_0 (km/s/kpc)
"Error-tolerant" Bayesian fitting: $\text{Prob}(D_i\|M) \propto \left(1 - \exp(-R_i^2/2)\right) / R_i^2$ where $R_i = (D_i - M_i) / \sigma_i$							
Flat Rotation Curve	8.51 ± 0.25	244 ± 9	[0]		5 ± 2	5 ± 3	(28.6)
Sloped " "	8.53 ± 0.27	246 ± 9	1.1 ± 0.9		6 ± 2	5 ± 3	(28.9)
			R.C. params				
			a_1	a_2			
Brand-Blitz formulation	8.64 ± 0.28	250 ± 9	.06±.03	[0]	6 ± 2	5 ± 3	(29.0)
Polynomial formulation	8.77 ± 0.32	253 ±10	-1.0±1	-1.5±.5	5 ± 2	5 ± 3	(28.8)
"Universal" formulation	8.80 ± 0.30	250 ±11	1.1±.2	1.6±.7	5 ± 2	5 ± 3	(28.4)

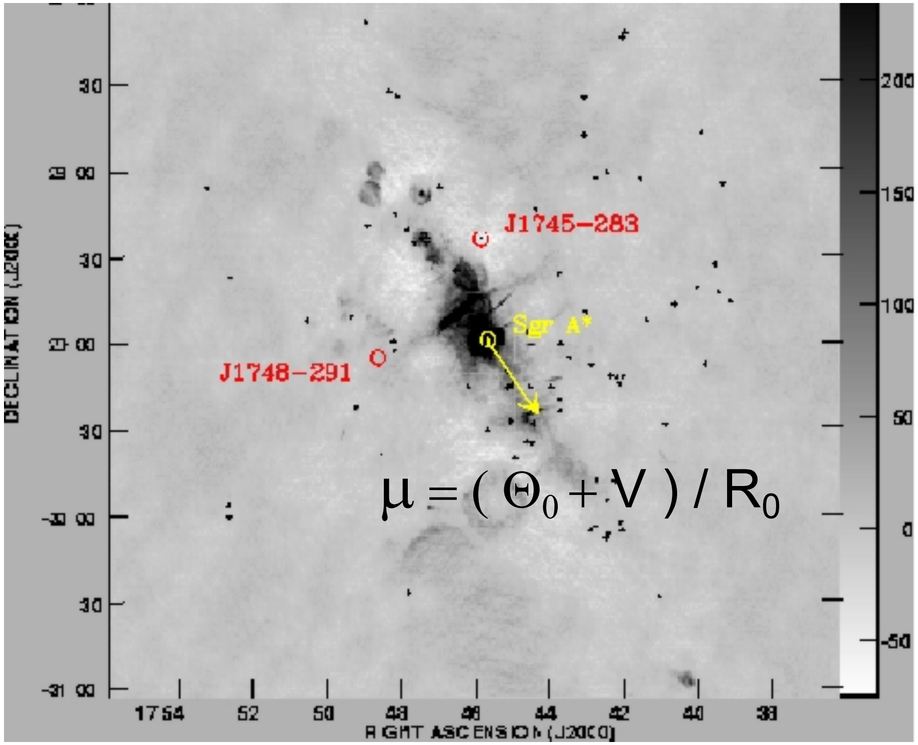
Brand-Blitz $\Theta = \Theta_0 \, \rho^{a1} + a_2$ where $\rho = R/R_0$

Polynomial $\Theta = \Theta_0 + a_1 (\rho - 1) + a_2 (\rho - 1)^2$

Universal $\Theta = f(\Theta_0, R_{opt} = a_1 R_0, L = a_2 L_*)$

Sgr A*' s Proper Motion





$$\mu = (\Theta_0 + V) / R_0$$

Proper Motion of Sgr A*

- Parallel to Galactic Plane:

  6.379 ± 0.026 mas/yr ➔

  Θ_o/R_o = 28.62 ± 0.15 km/s/kpc

  (after removing V=12 km/s)

  Remove Θ_o/R_o = 29.4 ± 0.9 km/s/kpc

  Sgr A*' s motion || to Gal. Plane

  –7.2 ± 8.5 km/s (R$_o$/8 kpc)

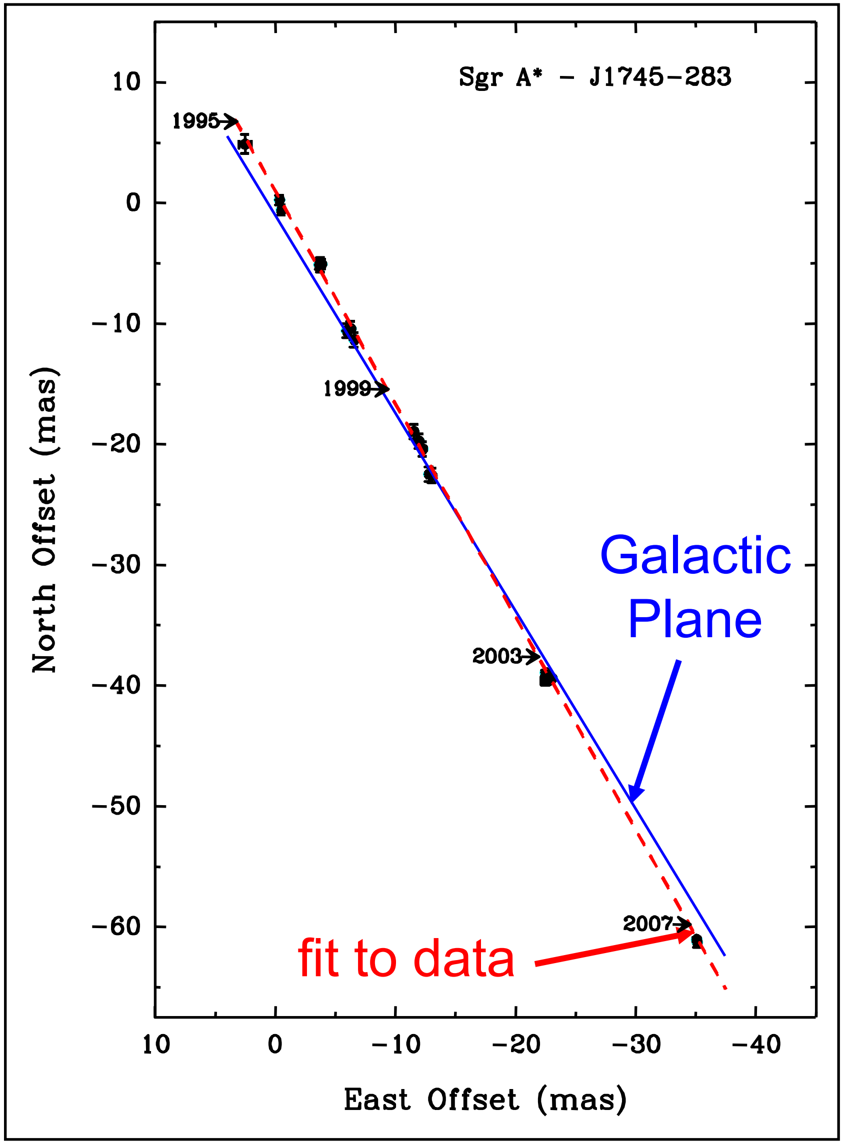
- Perpendicular to Gal. Plane:

  –7.6 ± 0.7 km/s

  Remove 7.2 km/s motion of Sun

  Sgr A*' s motion ⊥ to Gal. Plane

  –0.4 ± 0.9 km/s !



Reid & Brunthaler (2004) + new data

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:

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

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

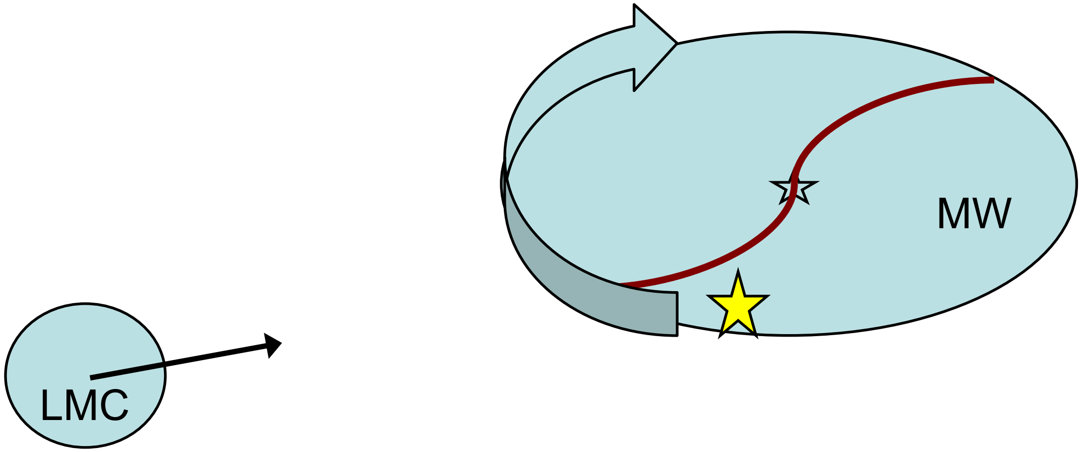
  $M \propto \Theta_0^3$ or up by 50%

- Increasing Θ_0, increases expected dark matter annihilation signals

- Largest uncertainty for modeling Hulse-Taylor binary pulsar timing is accounting for the acceleration of the Sun in its Galactic Orbit: Θ^2/R_0

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