Structure and Kinematics of the Milky Way:



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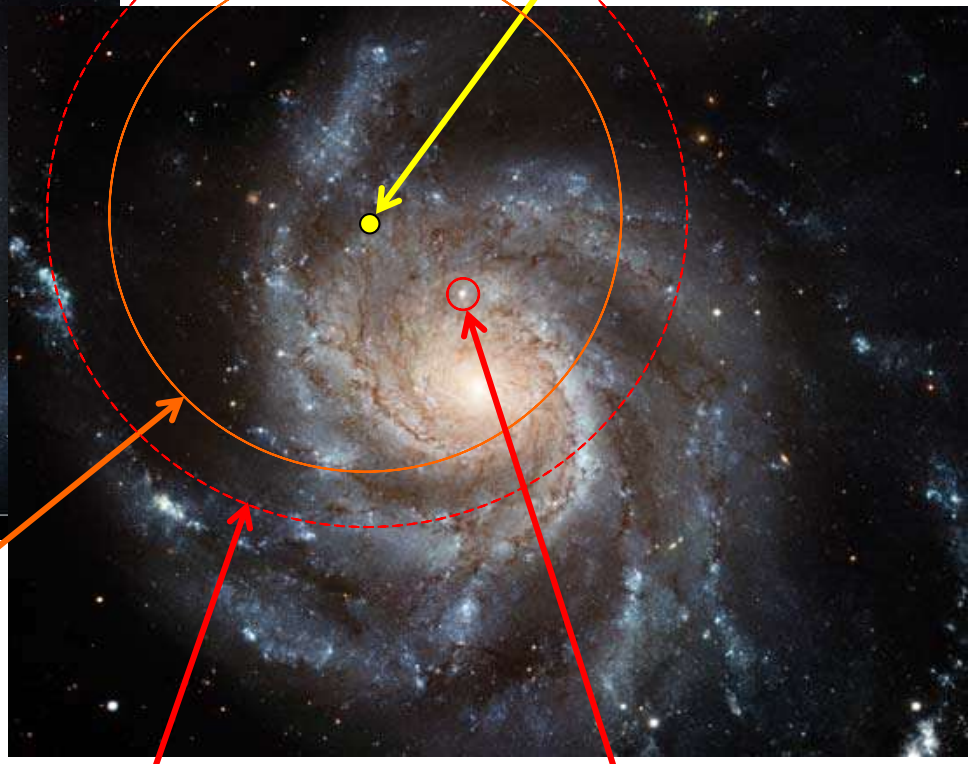
What does the Milky Way look like?

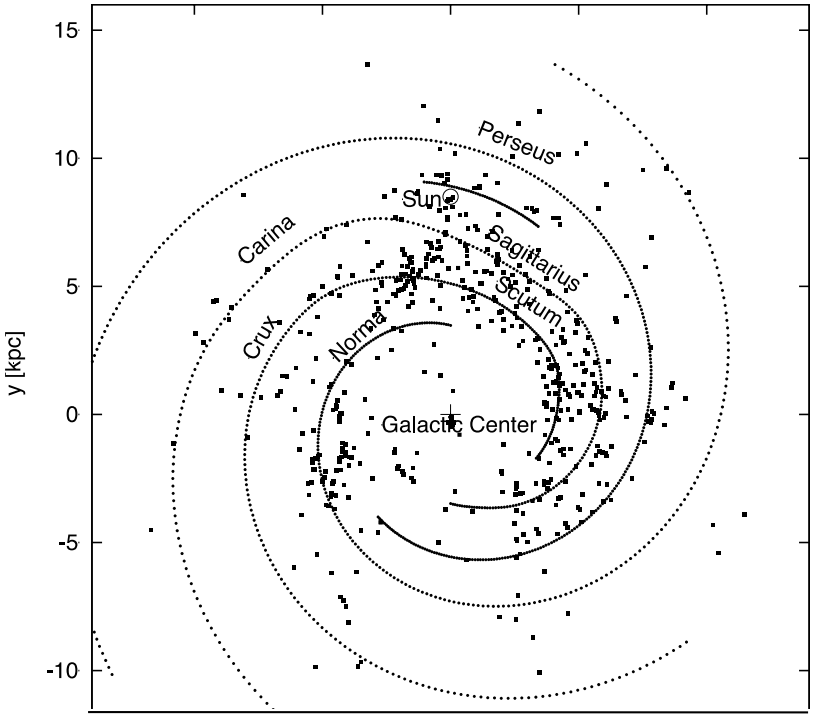




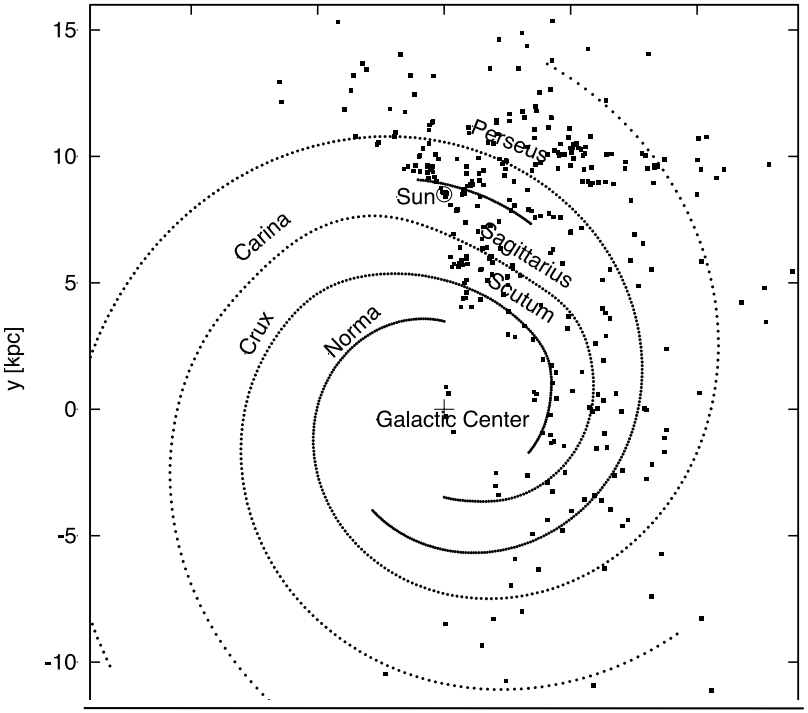
Gaia range (± 10 to 20 μas); but cannot see through dust in Galactic plane

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

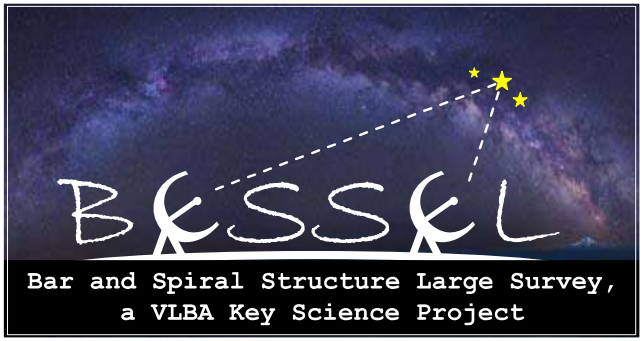
Mapping the Milky Way



6.7/12.2 GHz CH_3OH masers



22 GHz H_2O masers



VLBA Key Science Project: 3500 hours over 5 years

100 masers published;
80 more recently completed;
20 distant sources in progress

The BeSSeL Survey Team

M. Reid, T. Dame (USA)

K. Menten, A. Brunthaler, A. Sanna, (Germany)

X-W Zheng, Y. Xu, B. Hu, J. Li, B. Zhang, Y. Wu (China)

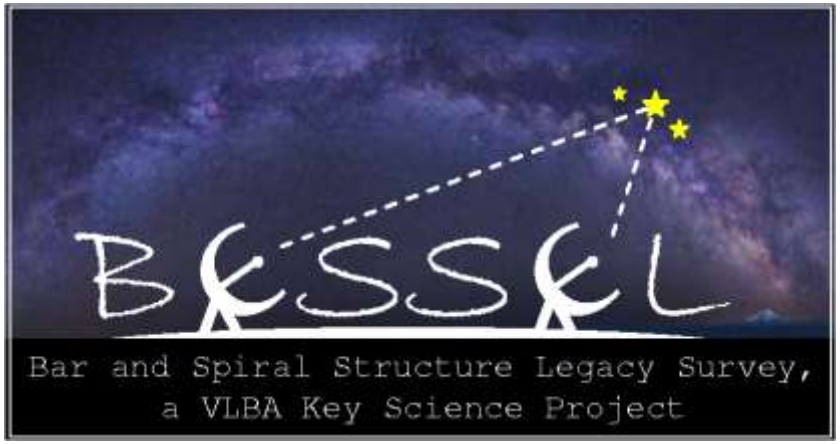
L. Moscadelli (Italy)

A. Bartkiewicz (Poland)

K. Rygl , H. van Langevelde, L. Nunez, K. Immer (Netherlands)

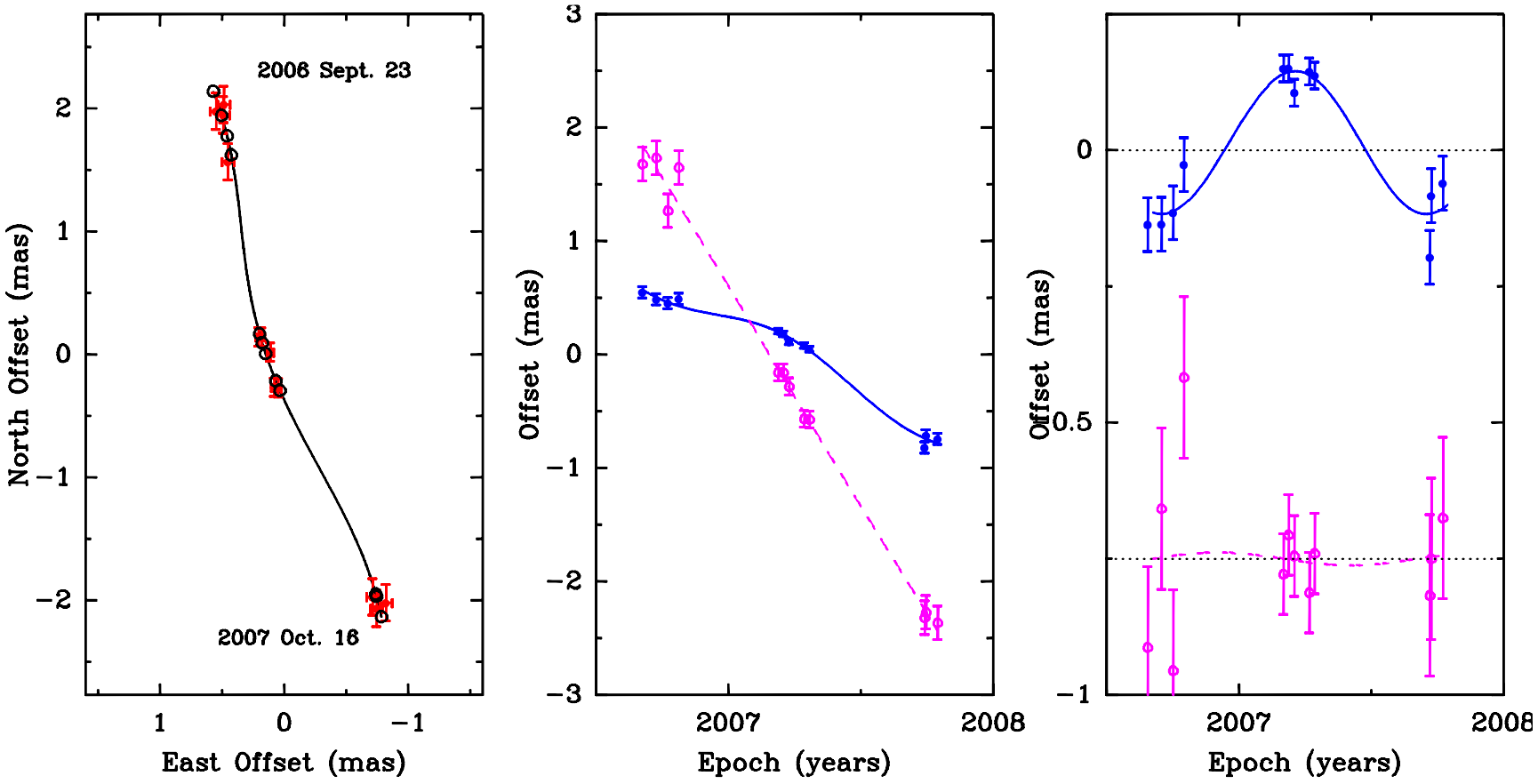
Y. Choi (Korea)

L. Hyland, S. Ellingsen (Tasmania)



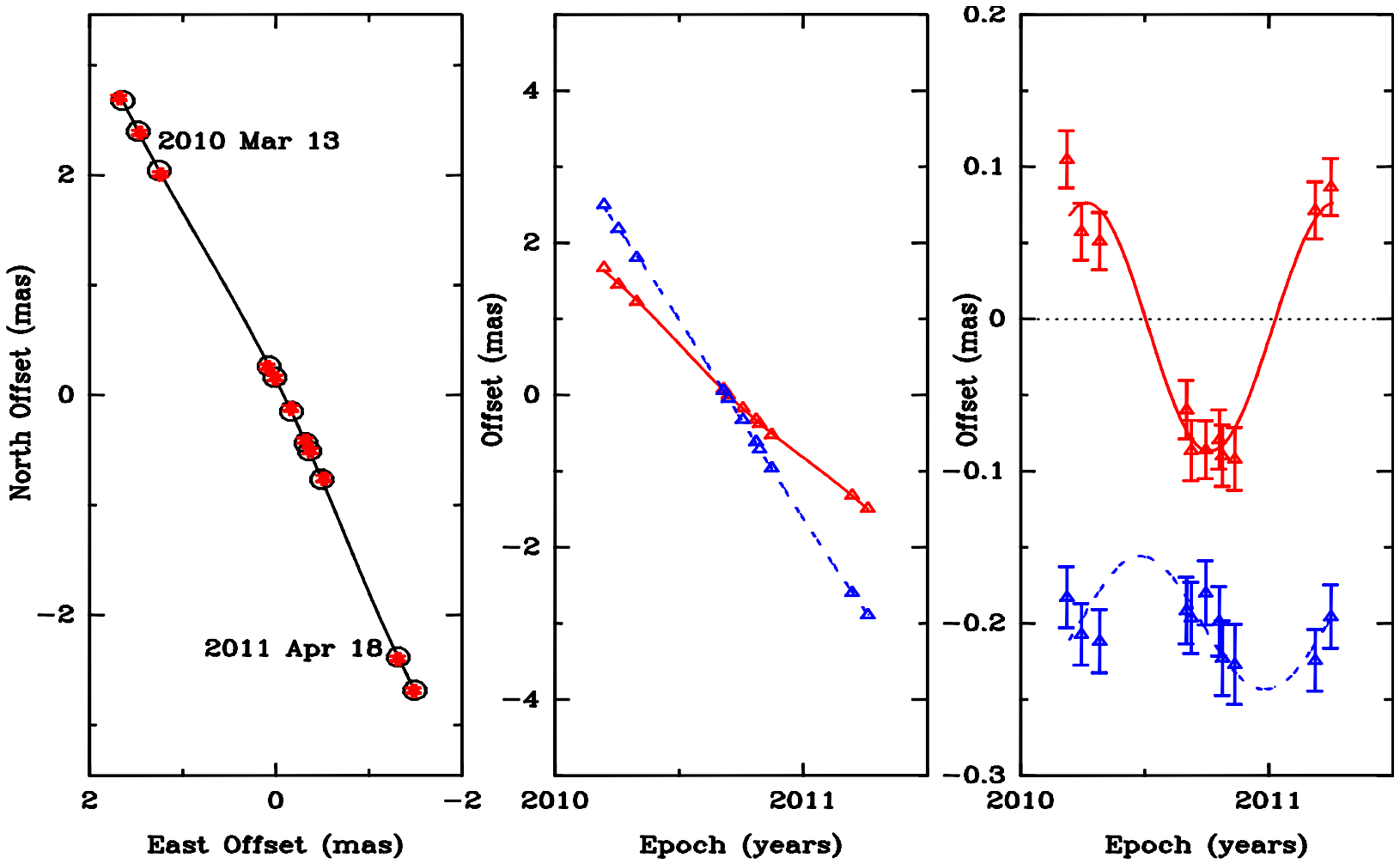
Parallax for Sgr B2 H_2O masers

p = 129 ± 12 μas (D=7.8 ± 0.8 kpc)



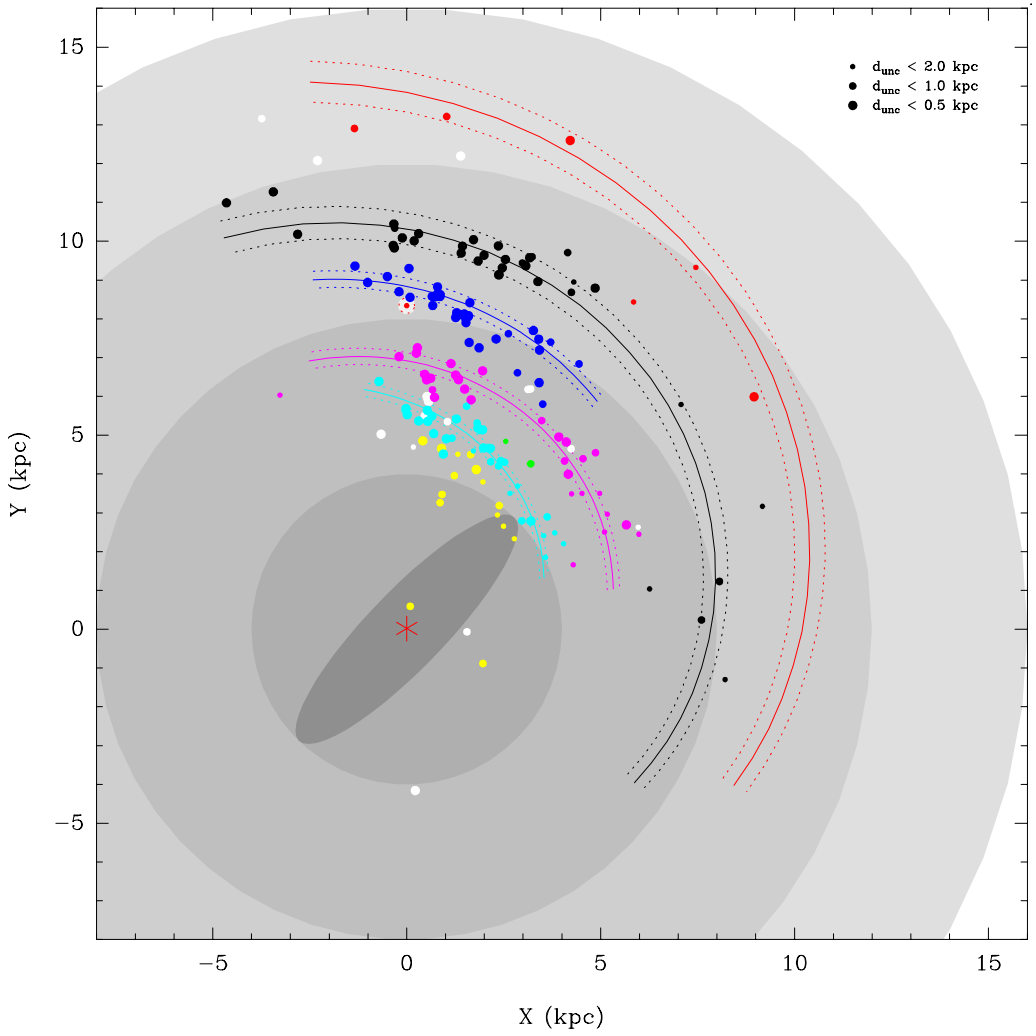
Parallax for W 49N H_2O masers

p = 90 ± 7 μas (D=11.1 ± 0.9 kpc)

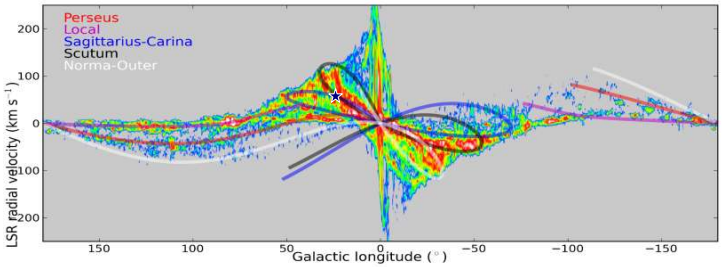


Zhang+ 2013

Mapping Spiral Structure

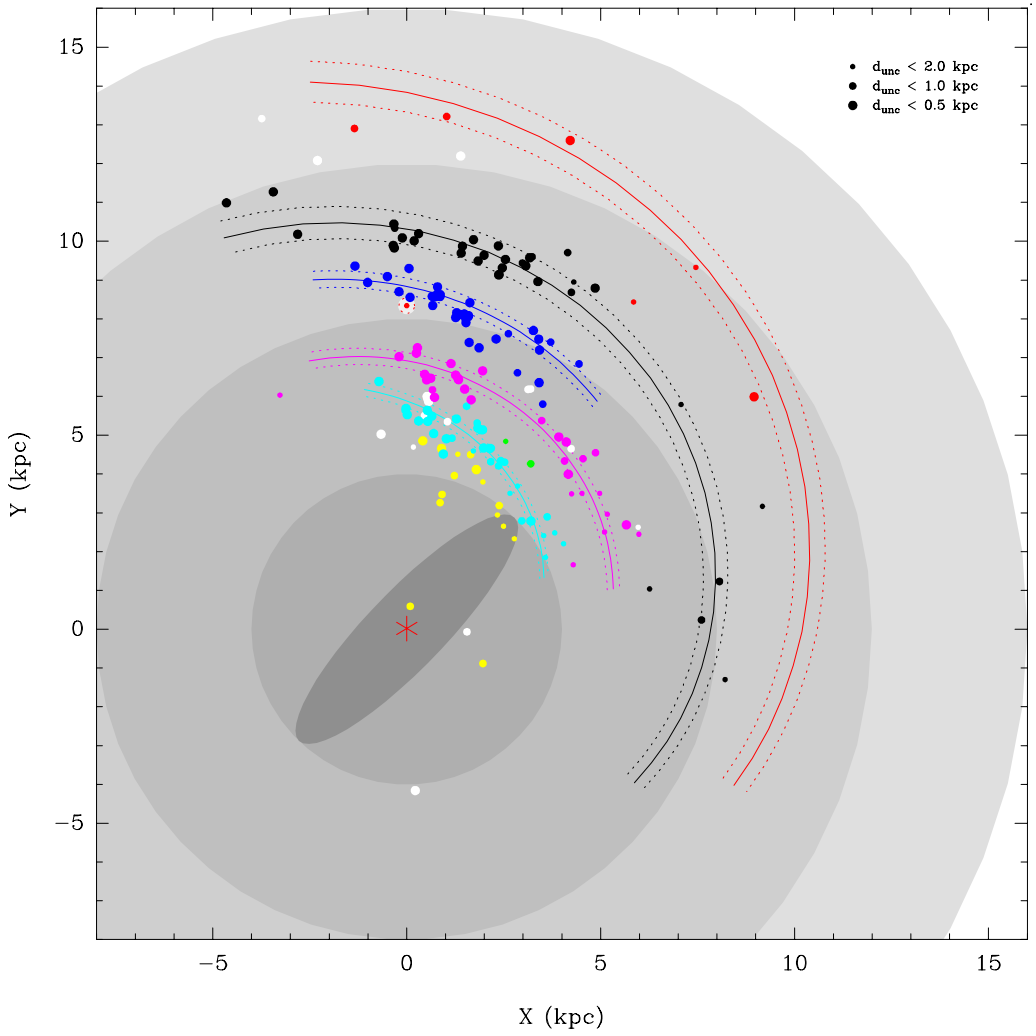


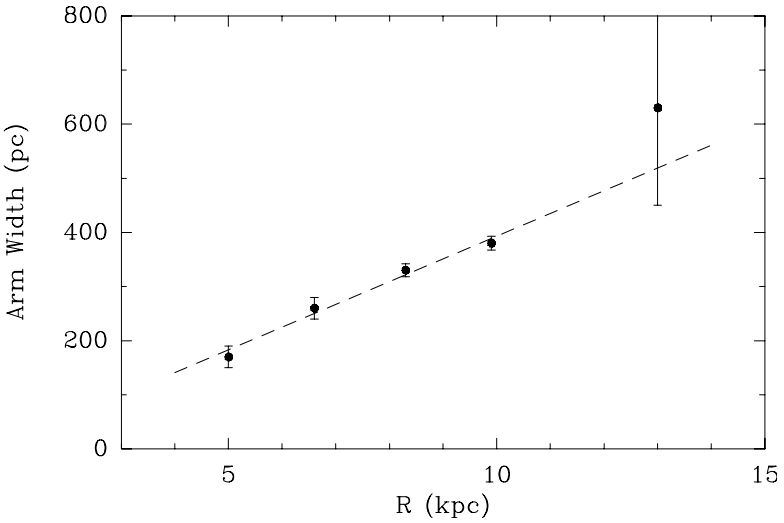
- Parallaxes: ~170 parallaxes for massive young stars
- Arms assigned by CO l-v plot



- Tracing most spiral arms, eg…
  - Outer arm traced
  - Perseus arm “gap”
  - Local arm significant
- Inner, bar-region is complicated

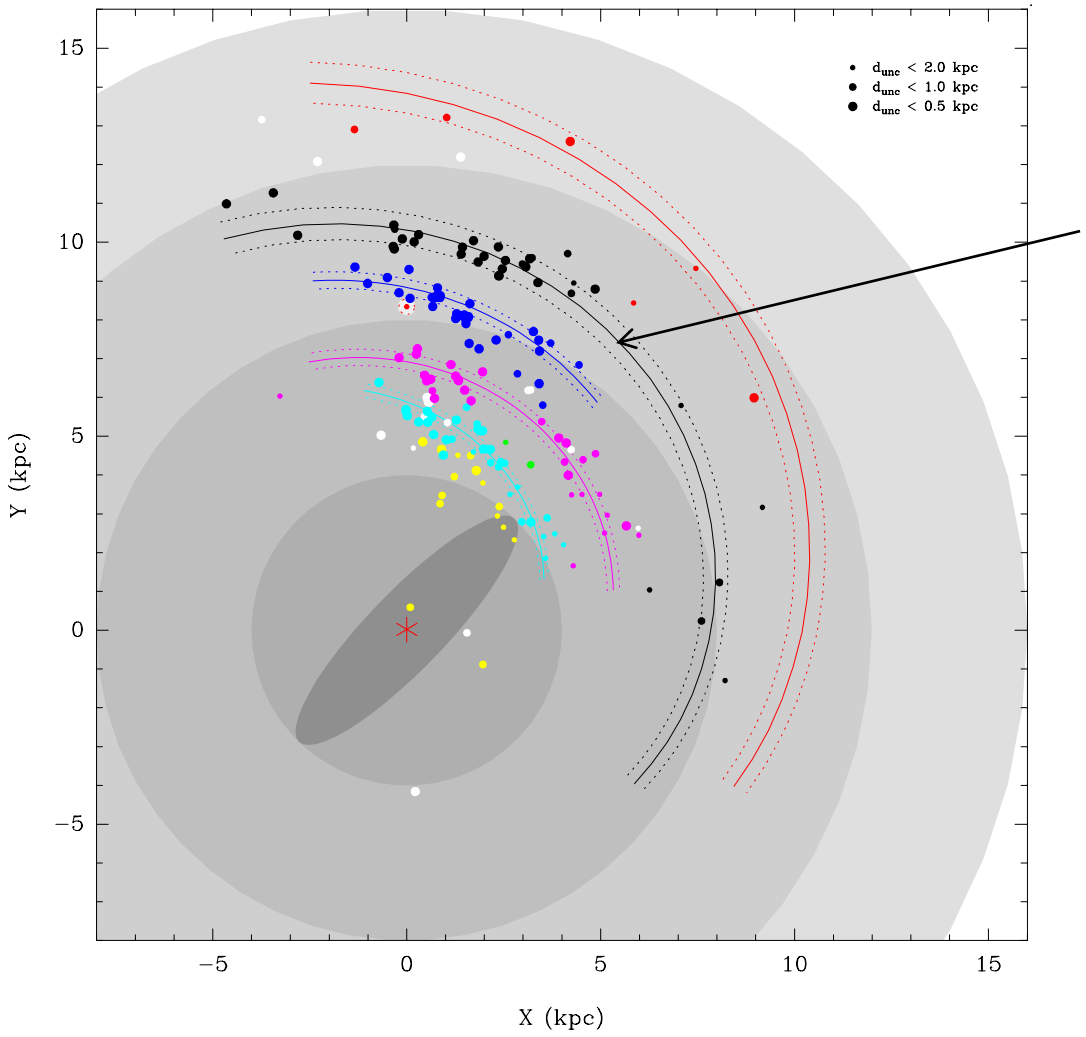
Structure of Spiral Arms





Lynds (1970, IAUS 38): For M101 like galaxies… “It appears that there is a general increase in thickness of the primary dust lane as it winds its way out from the nucleus.”

Better Distance Estimates



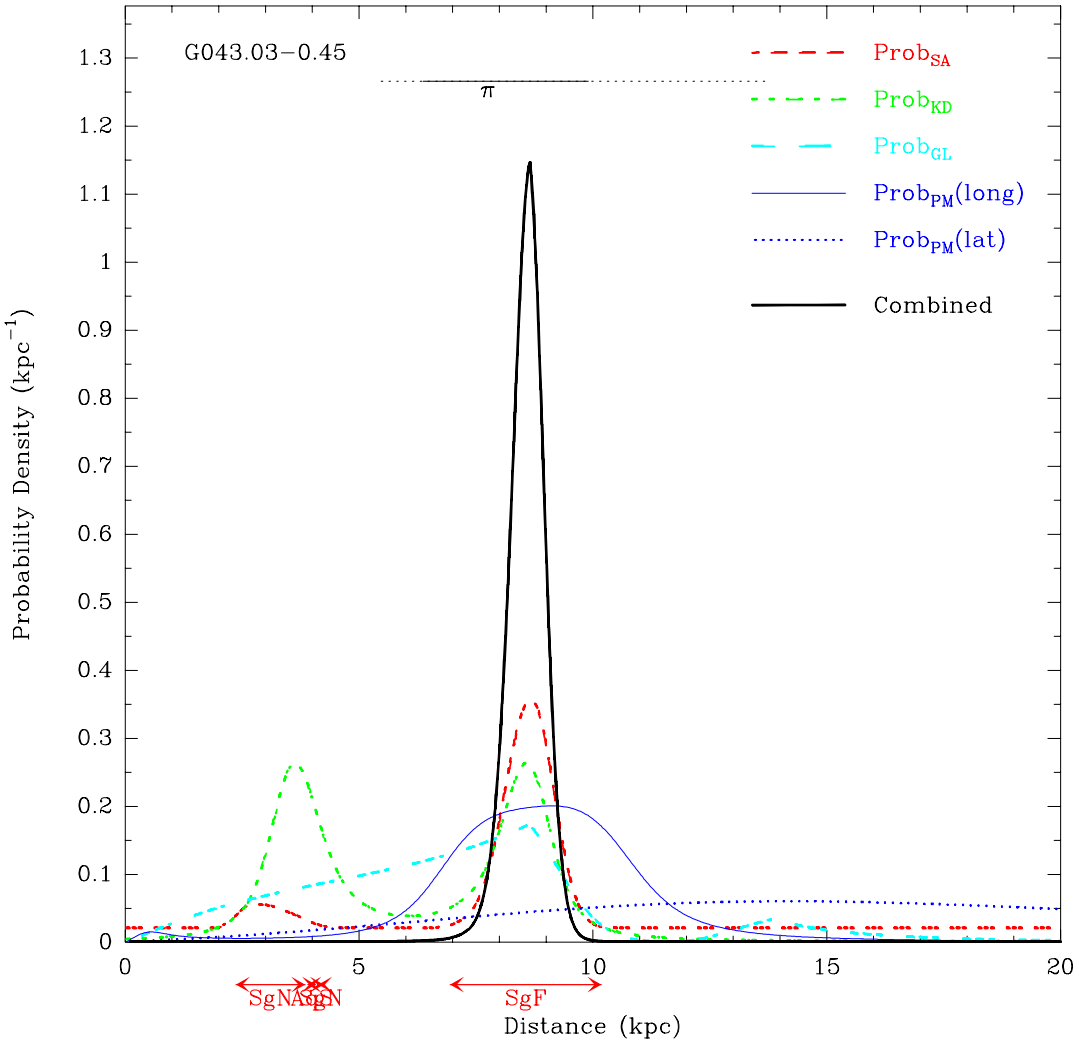
Along any arm, we know (l, b, V_{LSR}), & distance

If we can match catalog source (l, b, V_{LSR}) to a spiral arm…can often get distance

Bayesian approach, including other (eg, kinematic) distance information

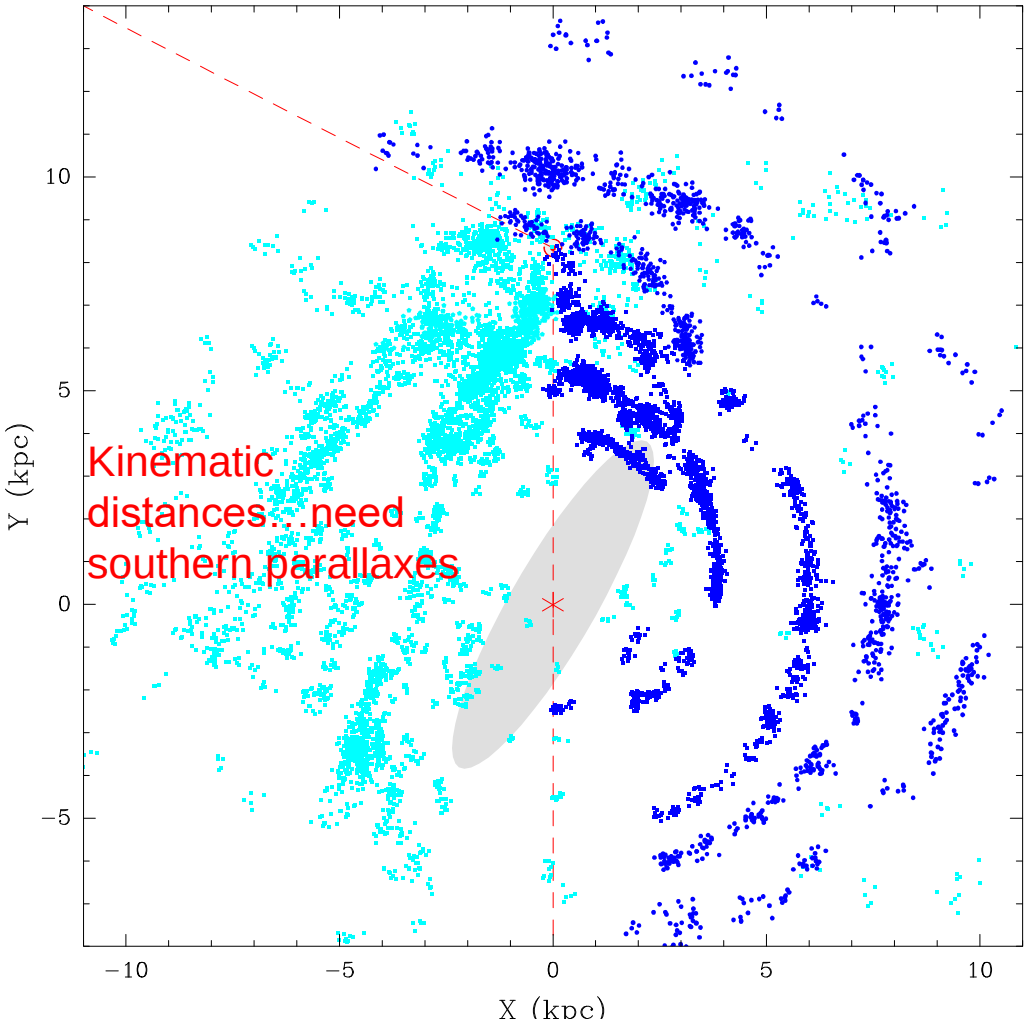
Reid et al (2016)

Bayesian Distance Estimation



- Prob(d) = $P_{SA}(d)$ x $P_{PAR}(d)$ x $P_{KD}(d)$ x $P_{LAT}(d)$
- P(SA) breaks D_k ambiguity

Visualization of Milky Way



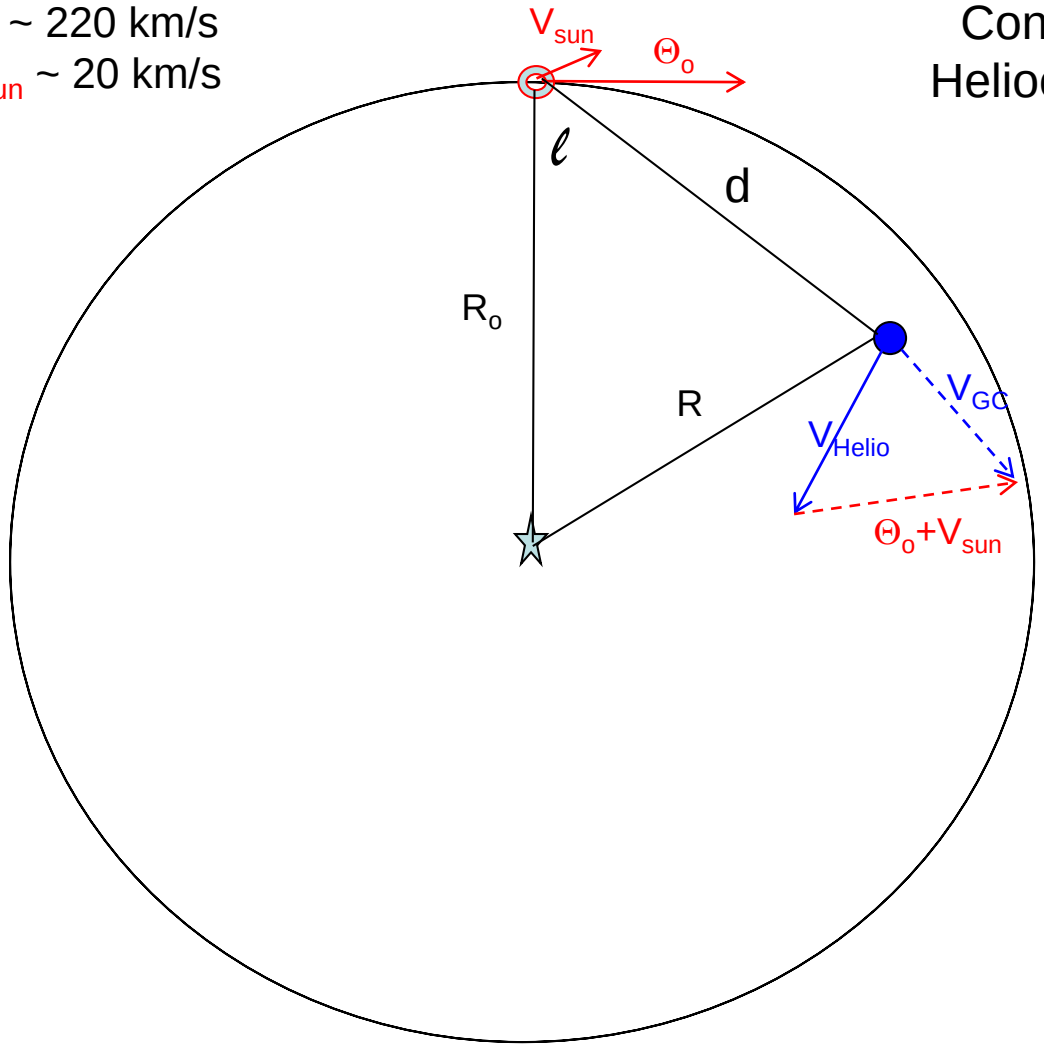
Input Catalogs:

- Red MSX sources (Urquhart+2014)
- GBT HII regions (Anderson+2012)
- Water masers (Valdettaro+2001)
- Methanol masers (Pestalozzi+2005)

“Sprinkled” 5 dots per source to simulate other HMSFRs in same GMC

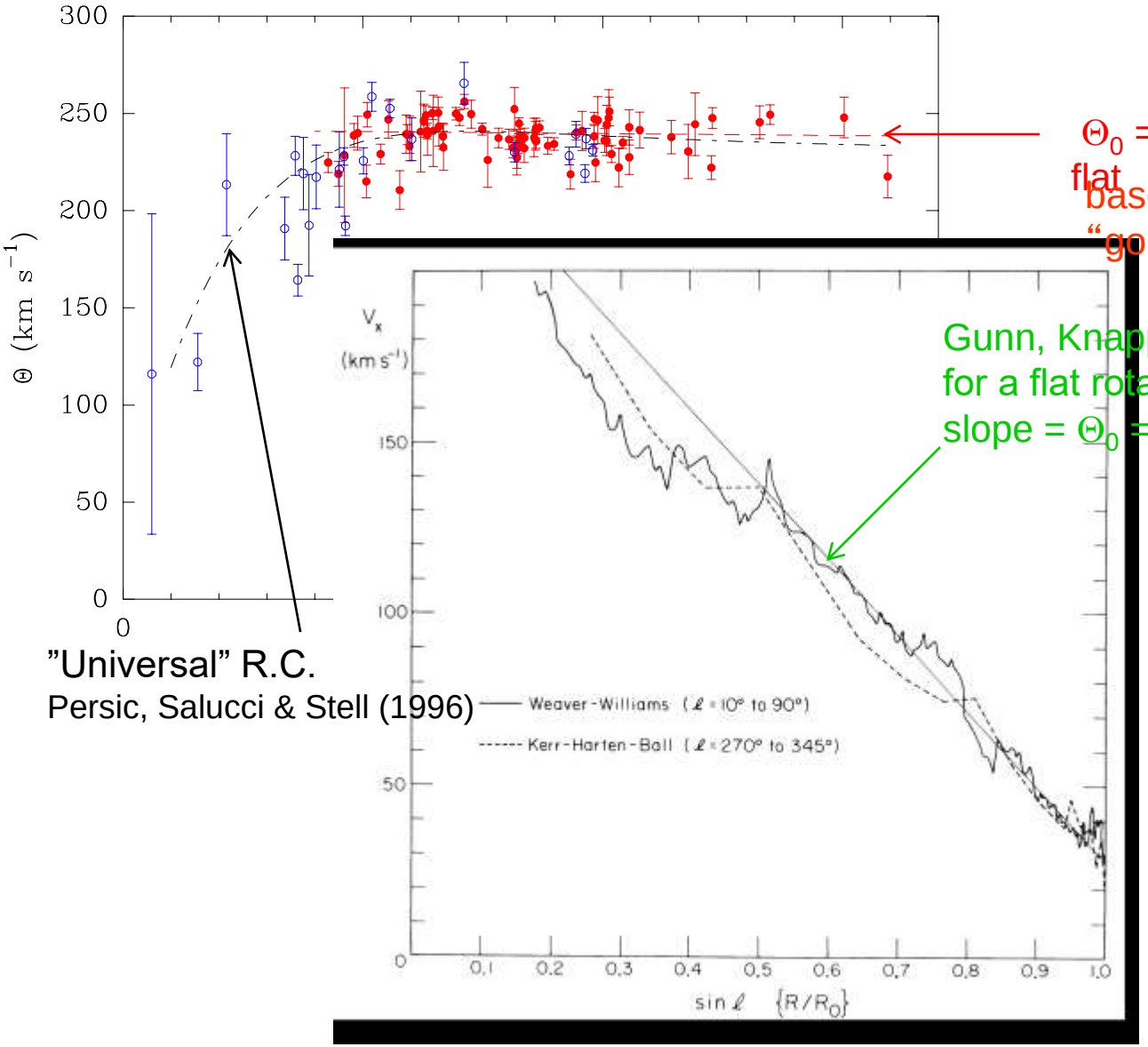
Galactic Dynamics

Θ_o ~ 220 km/s
V_{sun} ~ 20 km/s



Convert observations from Heliocentric to Galactocentric coordinates

The Milky Way's Rotation Curve

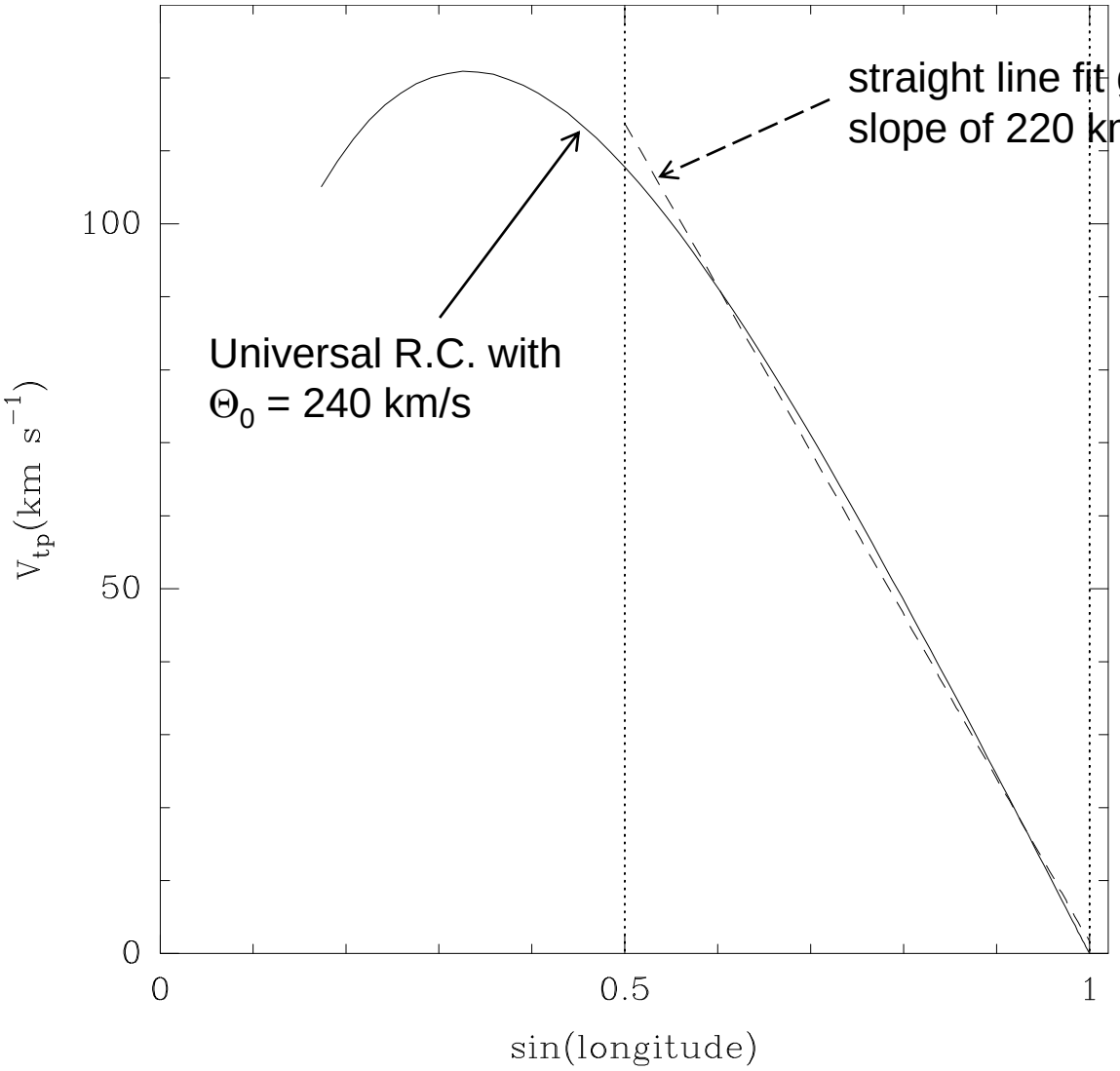


Θ_0 = ~240 km/s and nearly flat

based on 3-D motions and "gold standard" distances

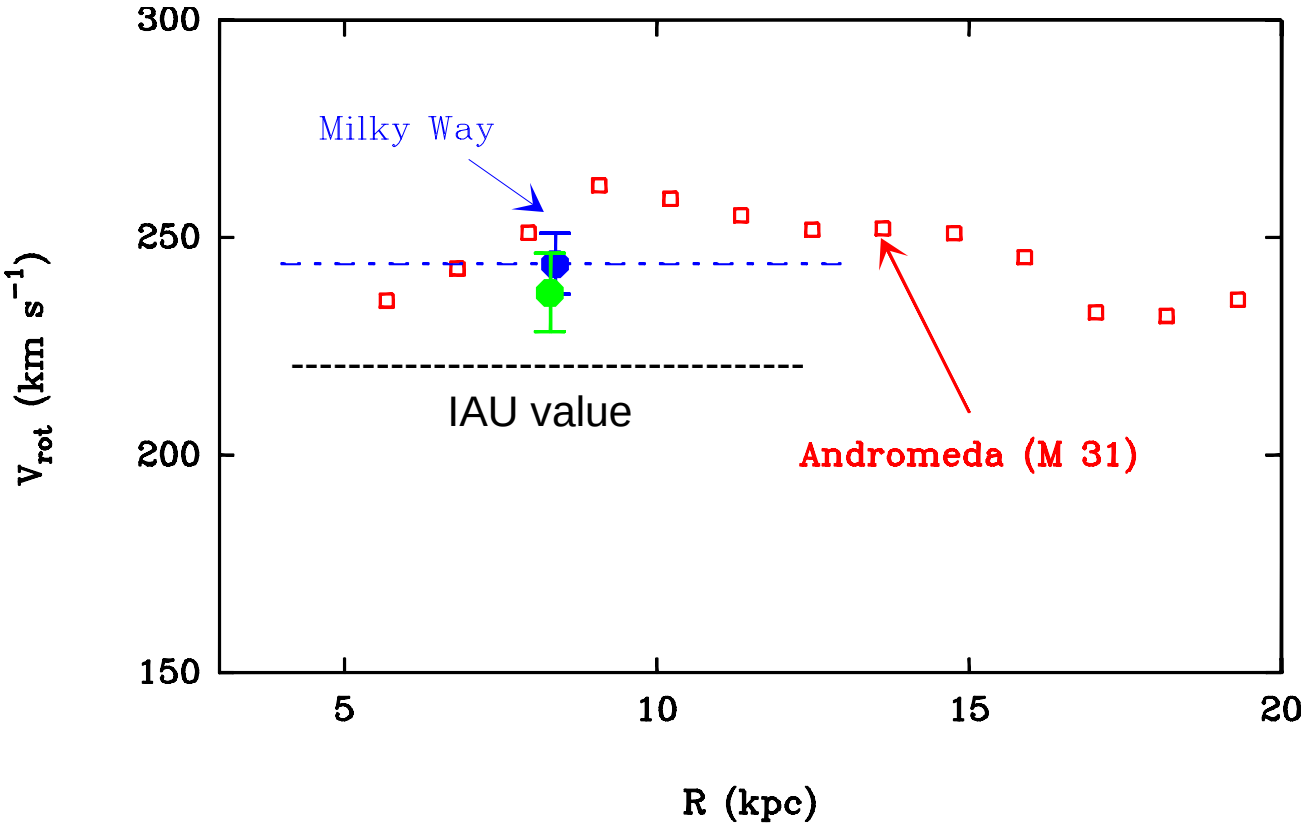
Gunn, Knapp & Tremaine (1979)
for a flat rotation curve…
slope = Θ_0 = 220 km/s

The Milky Way's Rotation Curve



Reid & Dame (2016)

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)



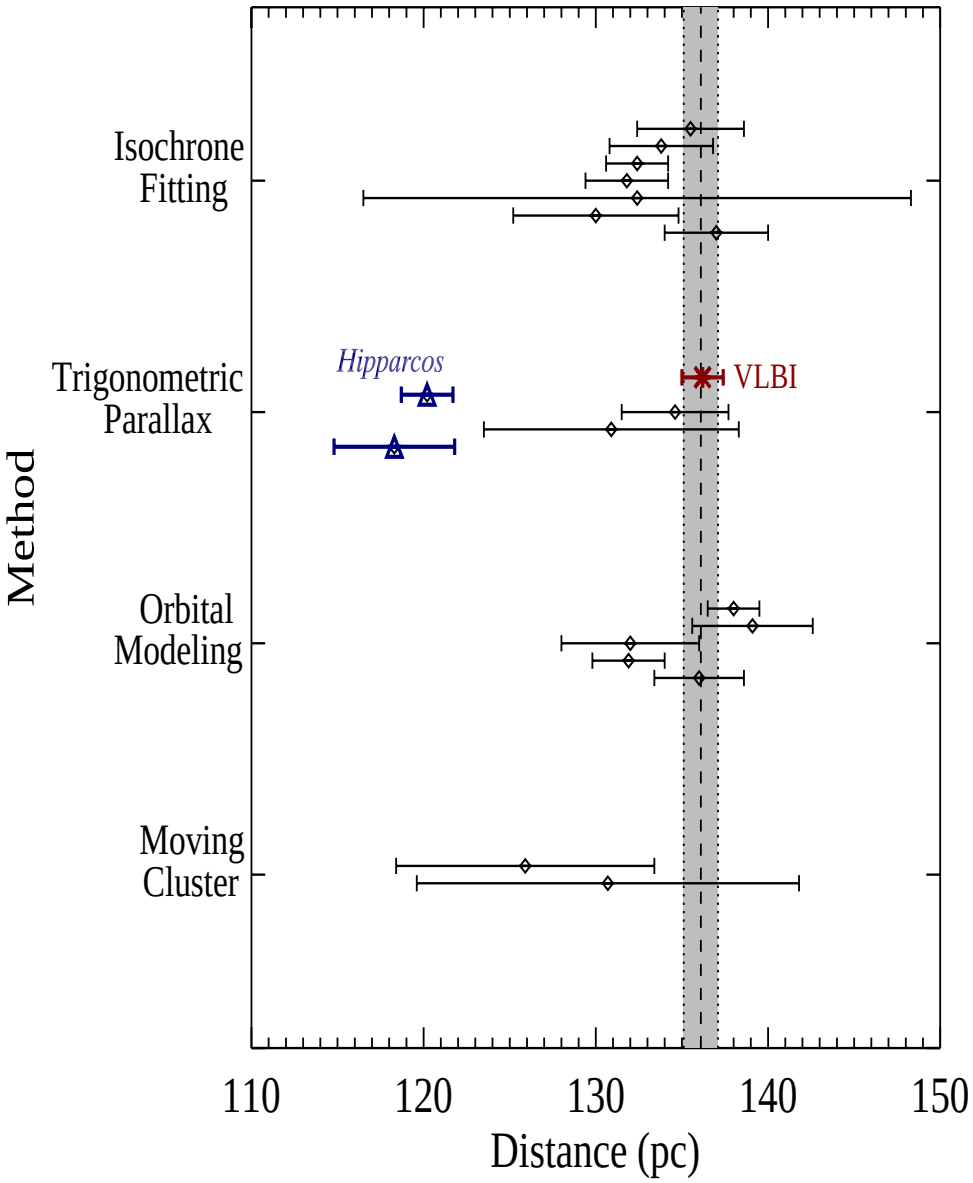
Photograph: Robert Gendler

Milky Way

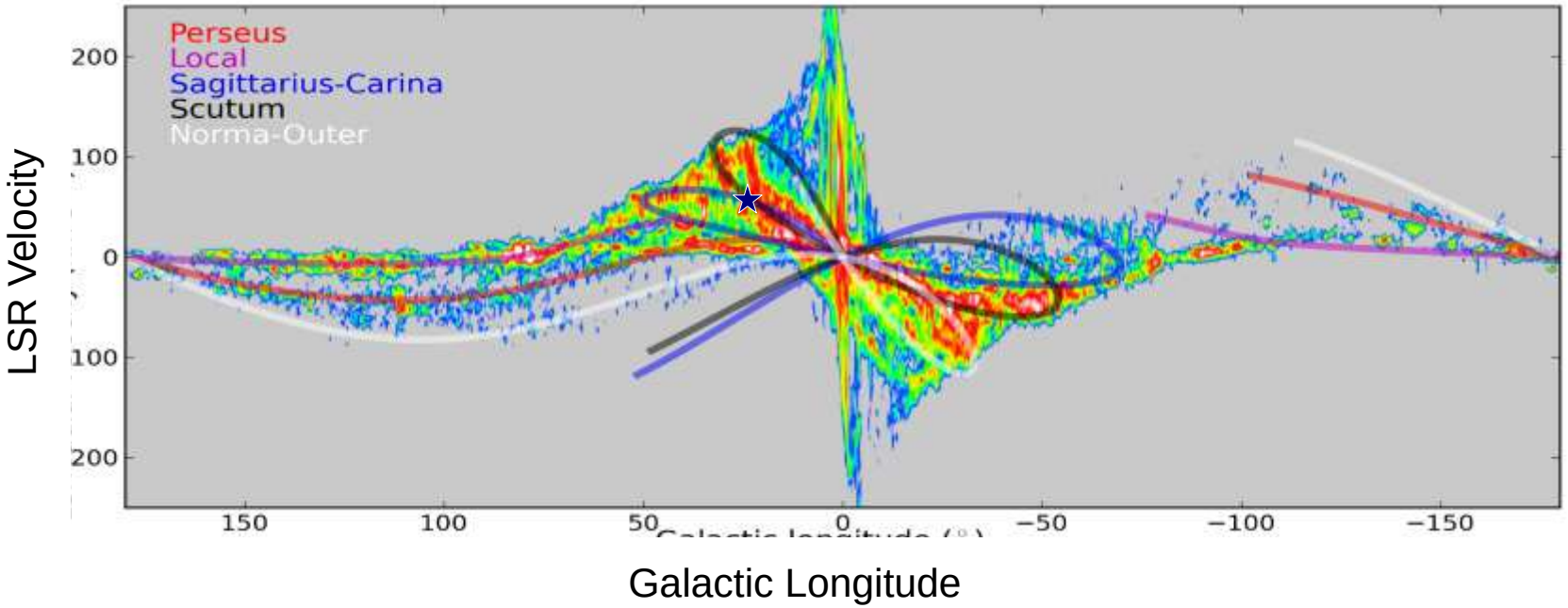


Artist conception: Robert Hurt (NASA:SSC)

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

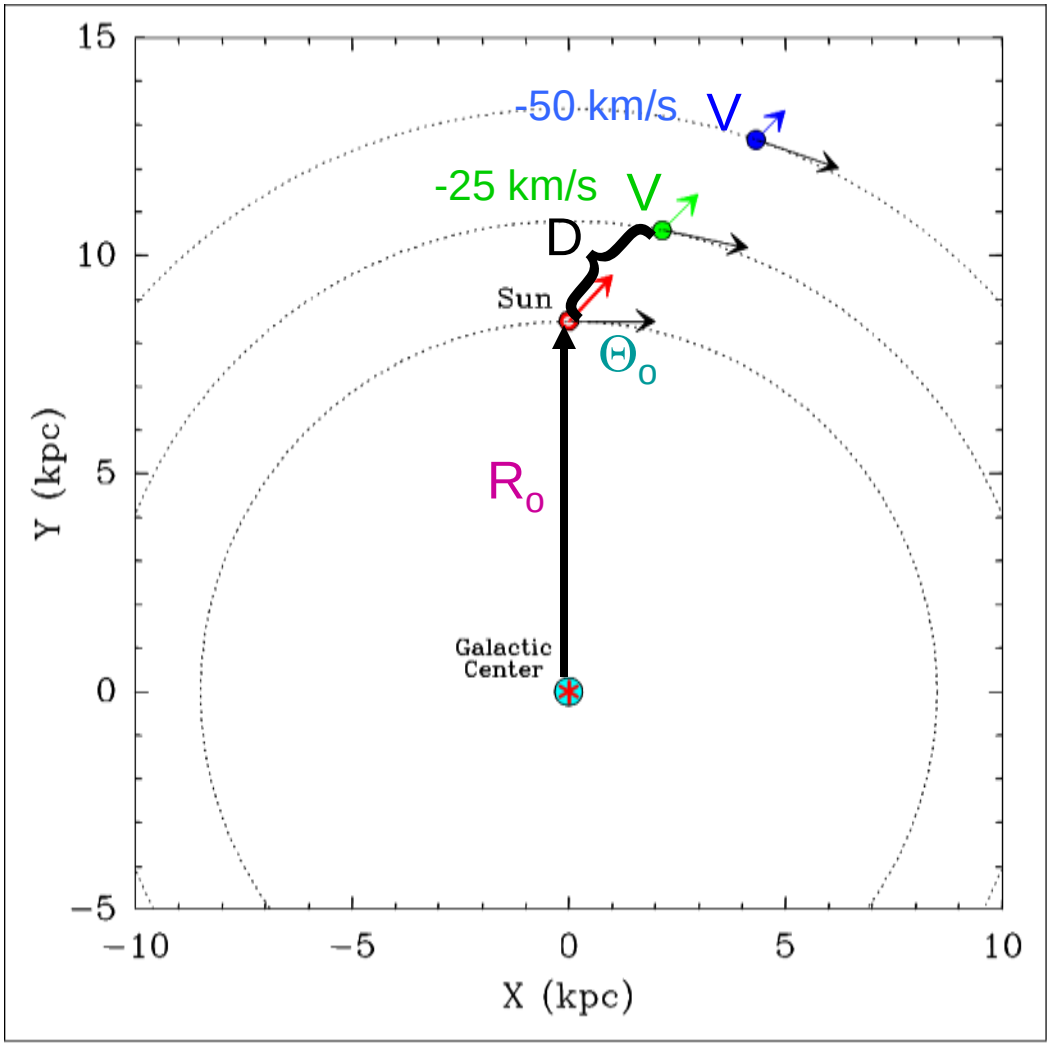

Isochrone Fitting
Trigonometric Parallax
Orbital Modeling
Moving Cluster
Method
Hipparcos
VLBI
110
120
130
140
150
Distance (pc)

Spiral Structure ?



CO emission: Dame, Hartmann & Thaddeus 2001

Kinematic Distances



Doppler shift:

$V_{Dop} = V - V_{sun}$

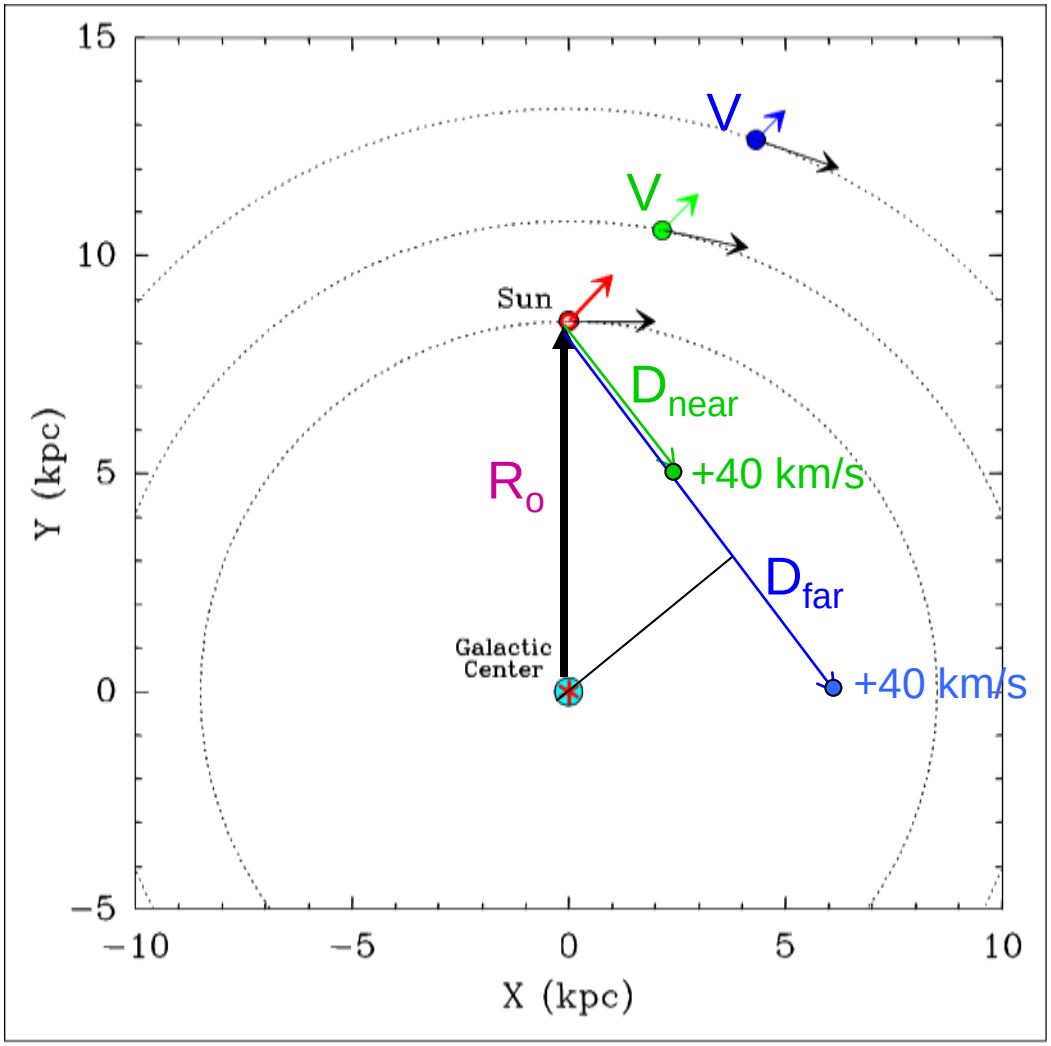
Model (Gal. Rotation):

$V_{mod}(R_o, \Theta_o, l, D)$

Adjust D to match

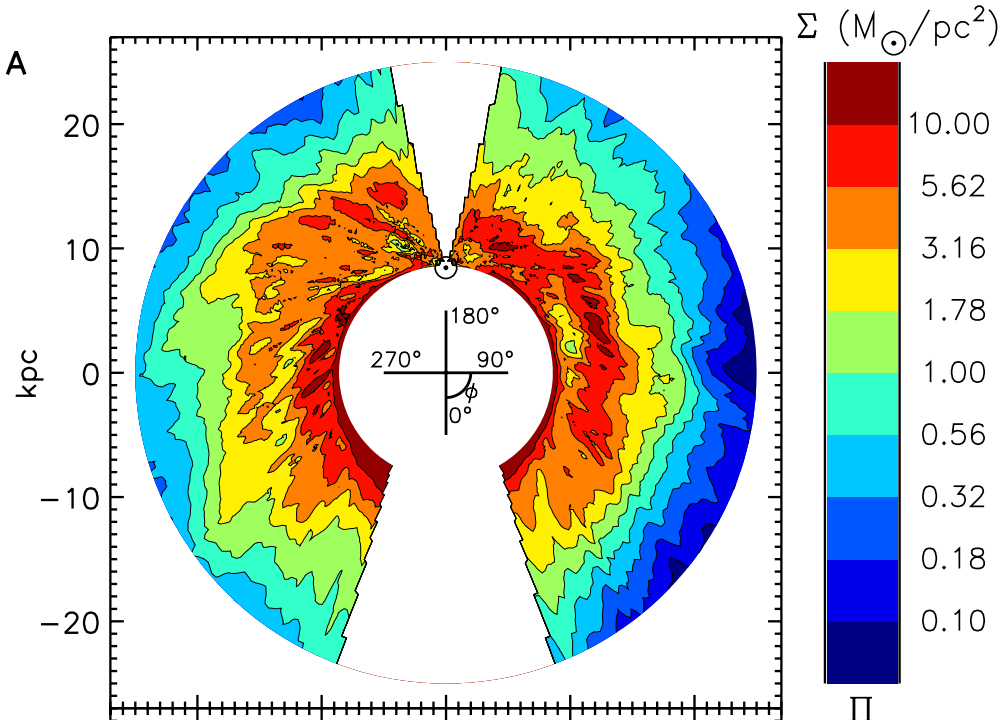
V_{mod} to V_{Dop}

Kinematic Distances



Inside “Solar Circle”
D is double valued

H I Mapping of the Milky Way

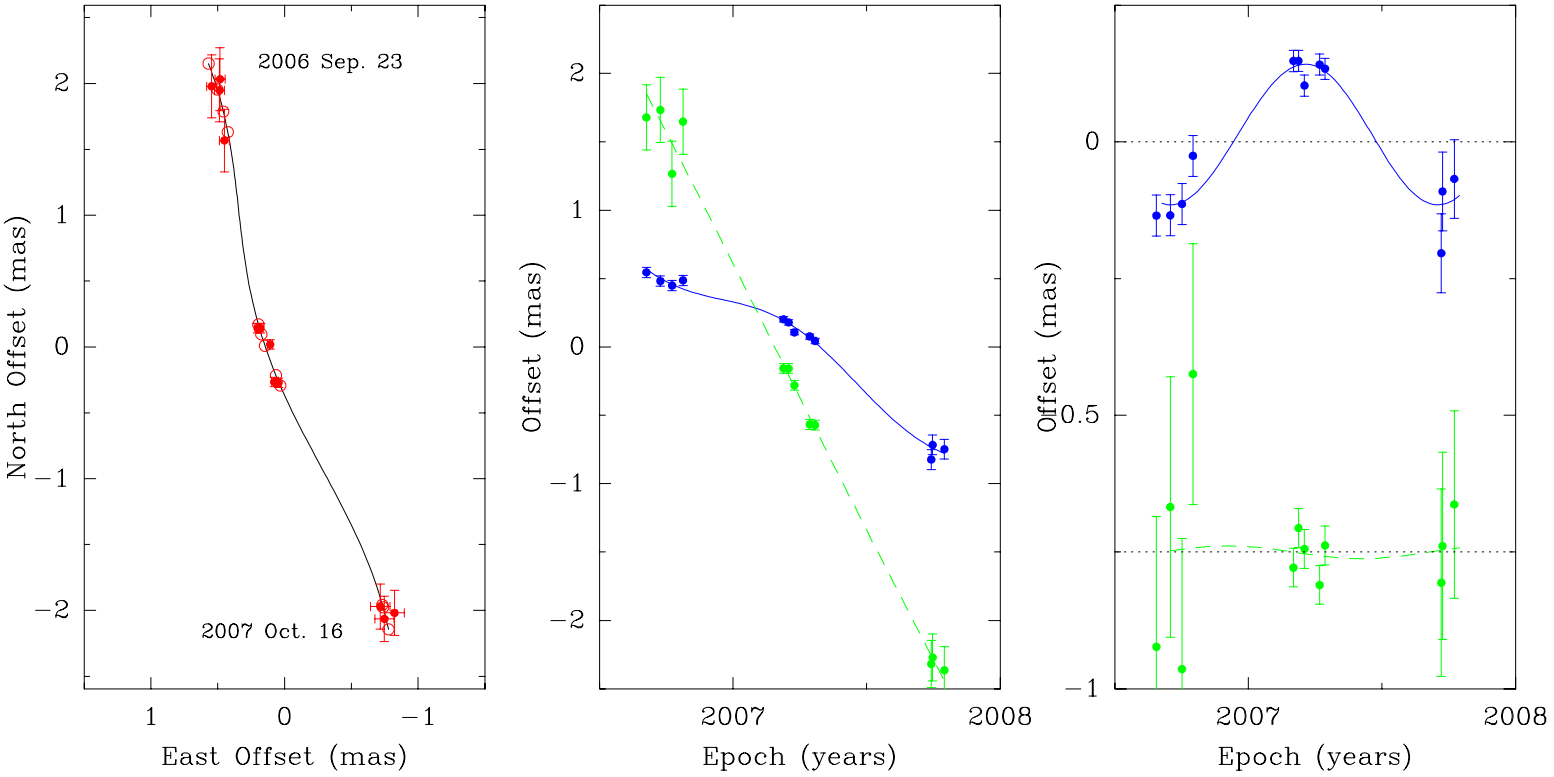


Levine, Blitz & Heiles 2006

Kinematic distance issues:

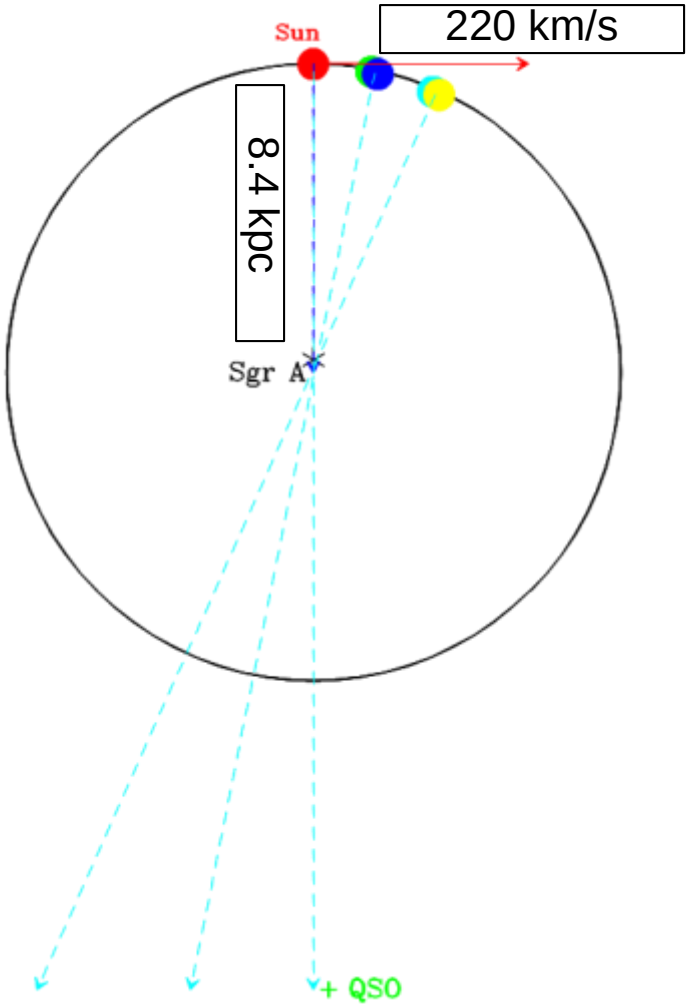
1. Bi-valued inside Solar Circle
2. Inaccurate toward GC and anticenter
3. Assume circular rotation
4. Assume R_0, Θ_0 values
5. Assume Solar Motion values

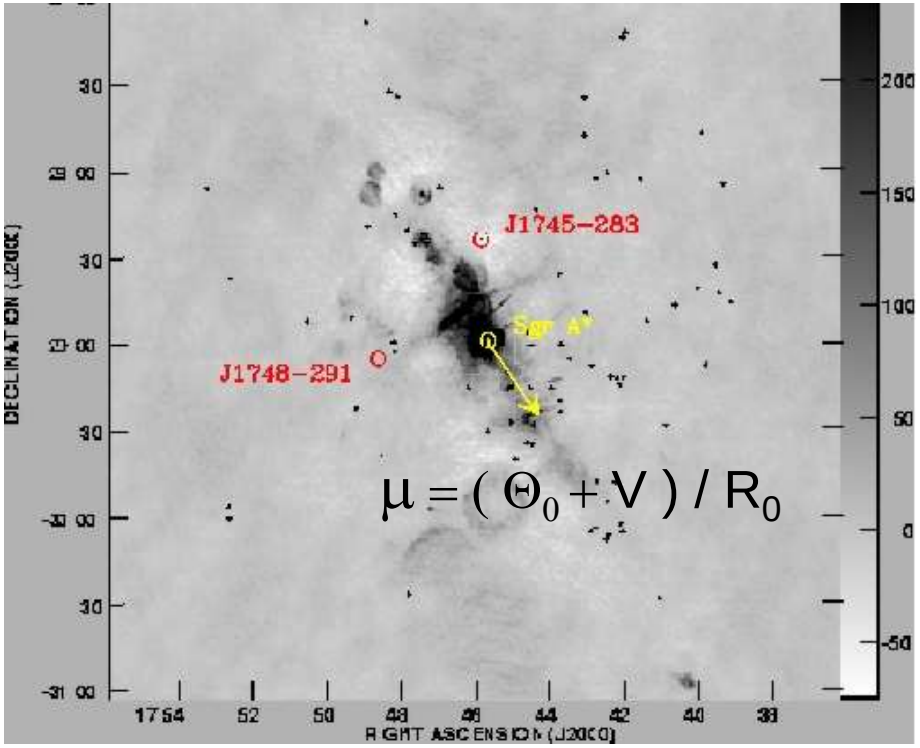
Parallax for Sgr B2(Middle) H_2O masers



p = 129 ± 12 μas (D=7.8 ± 0.8 kpc)

Sgr A*'s Proper Motion





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)

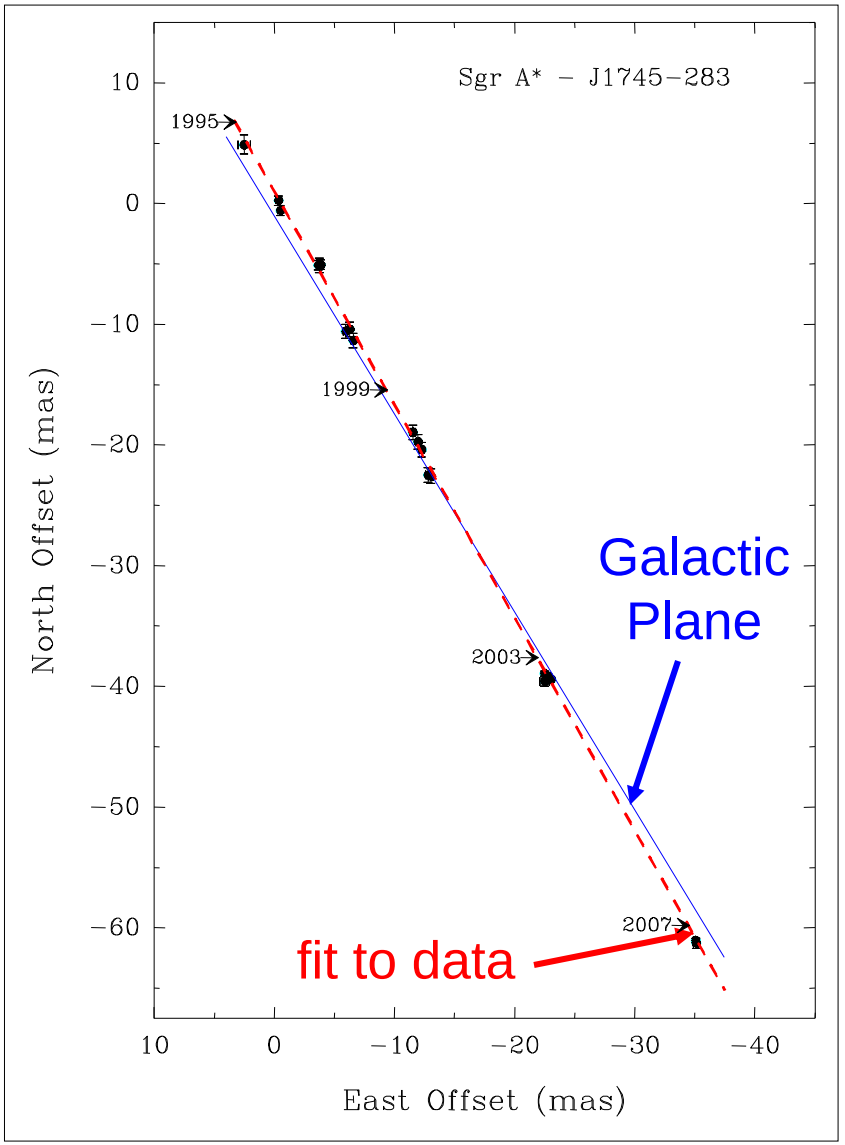
- Perpendicular to Gal. Plane:

  –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

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

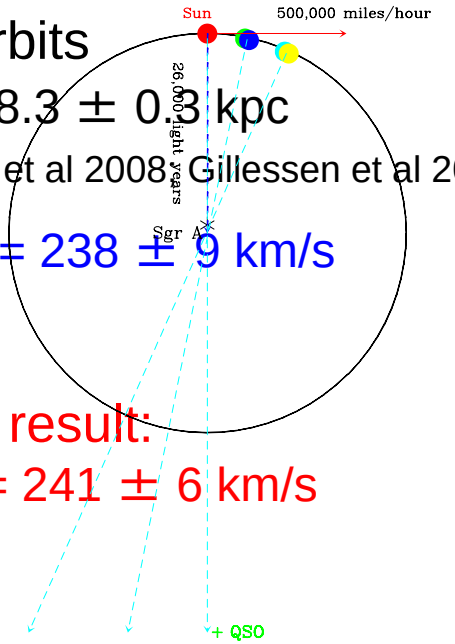
  (Reid & Brunthaler 2004)

IR stellar orbits

$R_0 = 8.3 \pm 0.3$ kpc

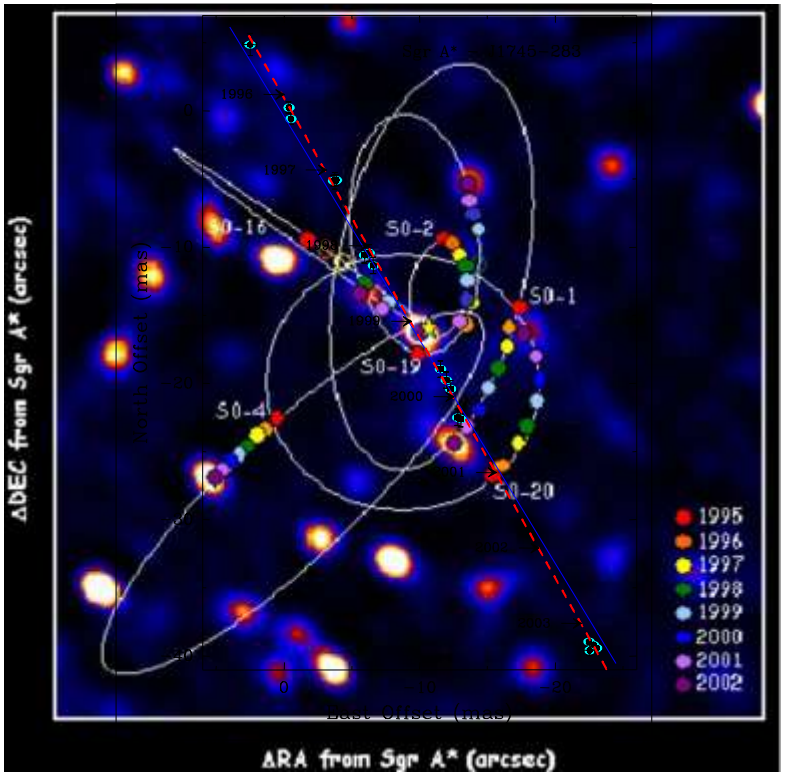
(Ghez et al 2008; Gillessen et al 2009)

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

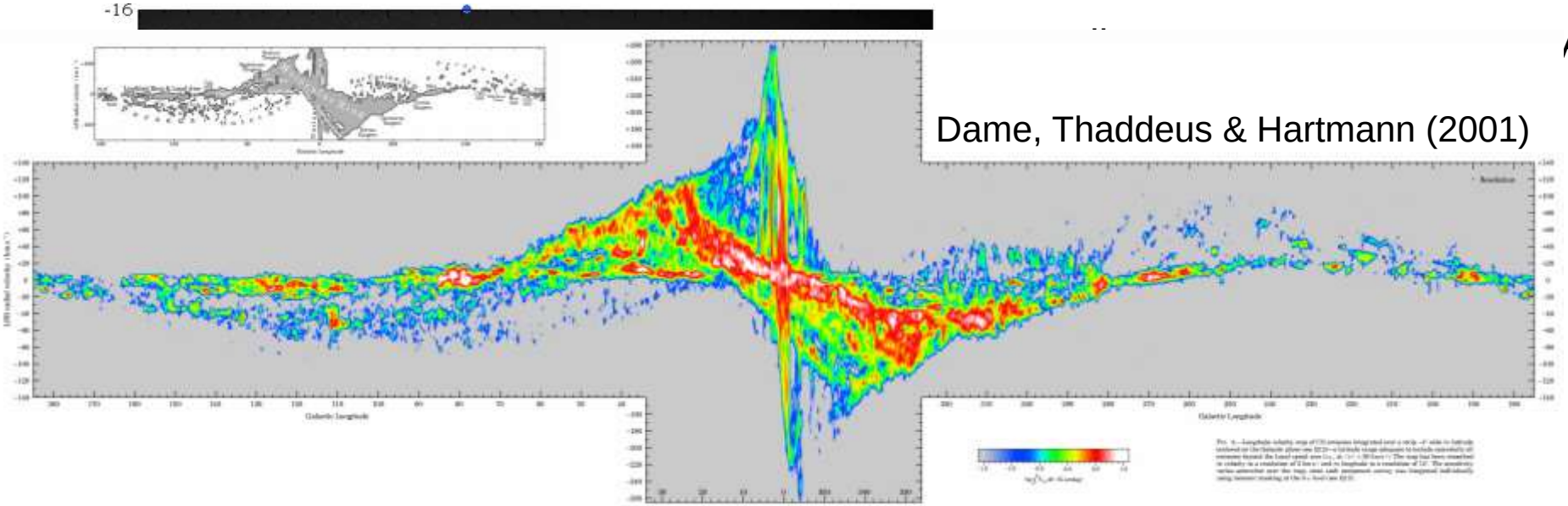


- Combined result:

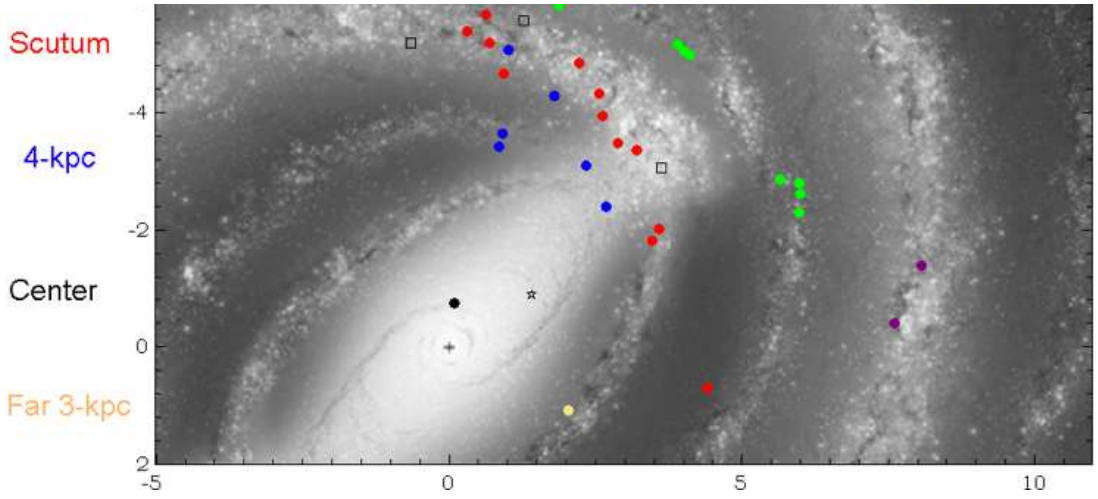
  $\Theta_0 = 241 \pm 6$ km/s



Mapping Spiral Structure



Dame, Thaddeus & Hartmann (2001)

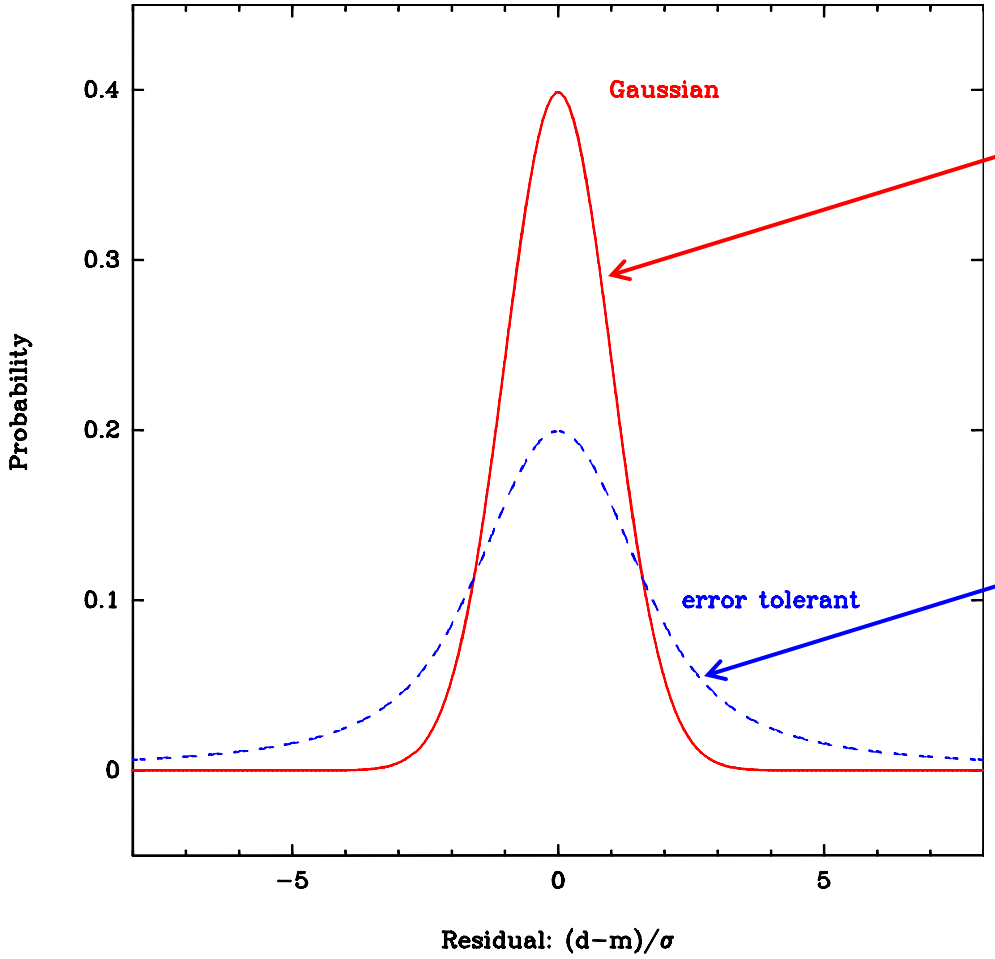


Local arm significant

- Inner, bar-region is complicated

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

“Outlier-tolerant” Bayesian fitting



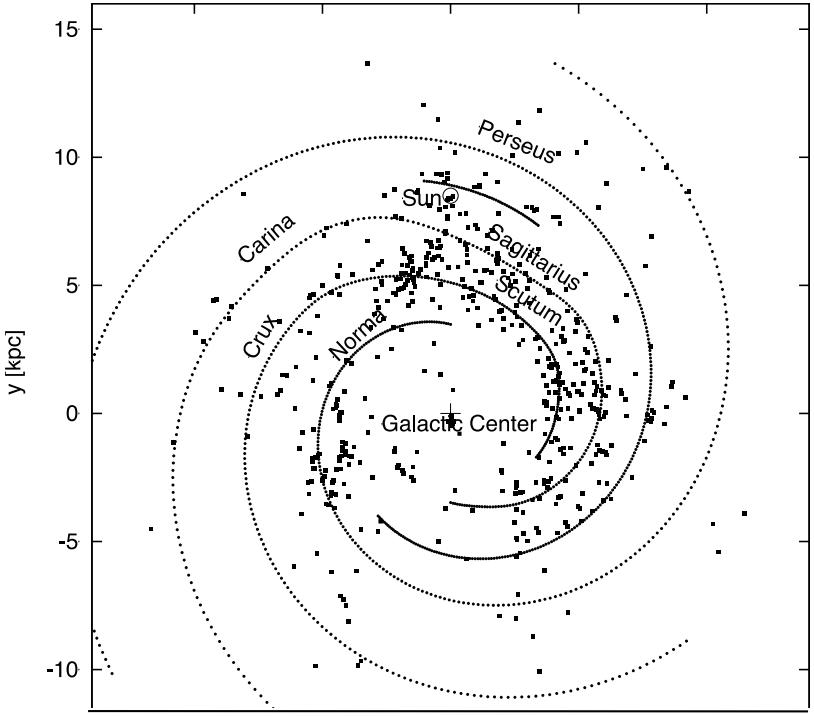
$Prob(D_i|M,\sigma_i) \propto \exp(-R_i^2/2)$

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

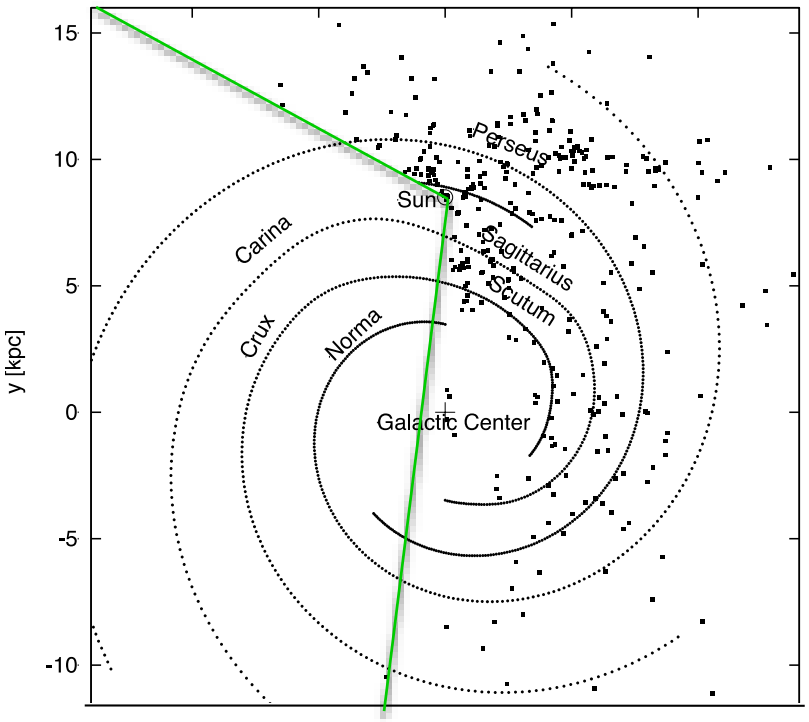
$Prob(D_i|M,\sigma_i) \propto (1 - \exp(-R_i^2/2)) / R_i^2$

Sivia “A Bayesian Tutorial”

BeSSeL Survey Candidates

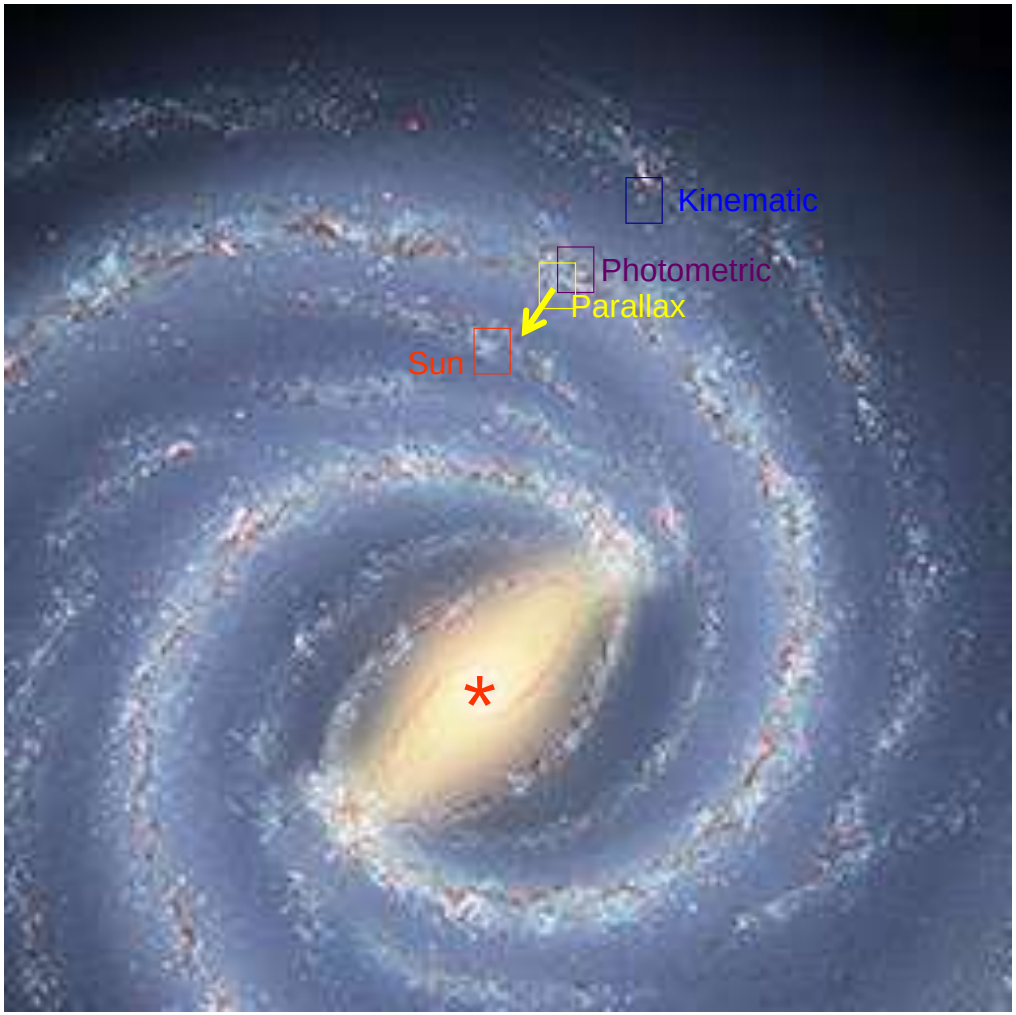


6.7 & 12.2 GHz CH_3OH masers



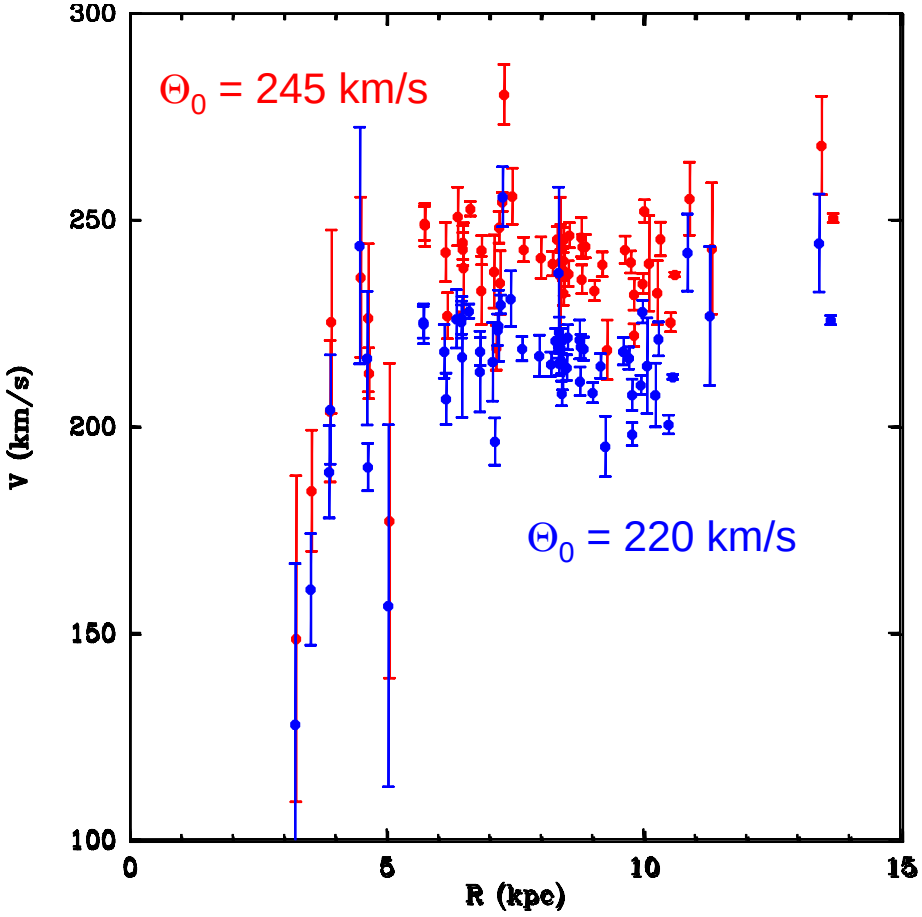
22 GHz H_2O masers

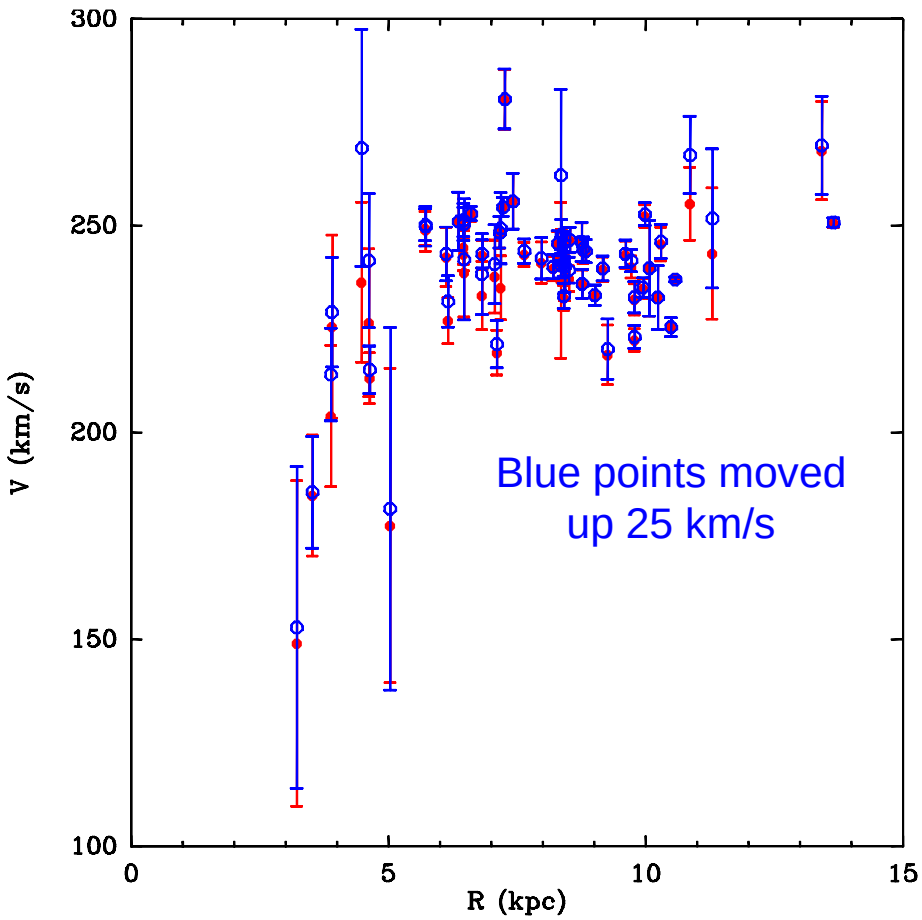
W3OH parallax



- $D_{photo} \sim D_{parallax}$
- D_k way off
- In Perseus Arm, not in Outer Arm
- Large peculiar V, explains bad D_k

The Milky Way's Rotation Curve





(Assuming V_{sun} = 12 km/s)

Probability Density Function for Distance

$$\mathrm{Prob}(d) \propto \mathrm{Prob}_{SA}(d) \times \mathrm{Prob}_{KD}(d) \times \mathrm{Prob}_{GL}(d) \times \mathrm{Prob}_{PS}(d)$$

$$\mathrm{Prob}_{SA}(d|l,b,v,I) = \sum_{j=1}^{J} \mathrm{Prob}(d|\mathrm{arm}_j,l,b,v,I) \times \mathrm{Prob}(\mathrm{arm}_j|l,b,v,I)$$

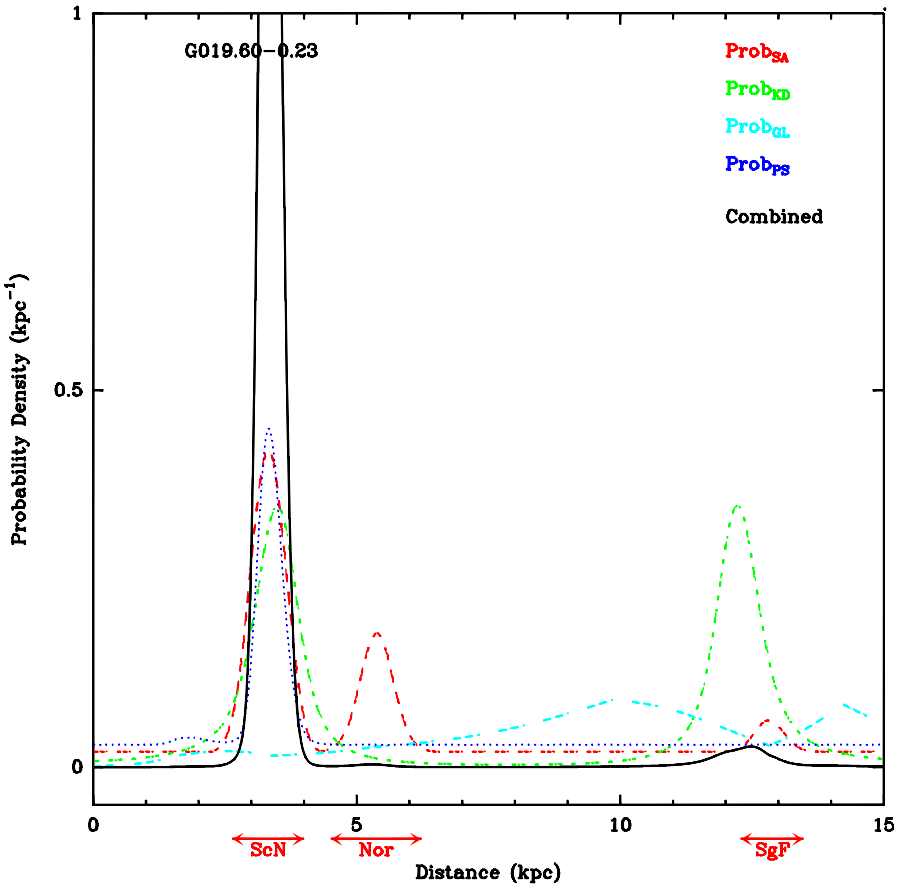
$$\frac{1}{\sigma_s} e^{-\Delta s^2/2\sigma_s^2} \quad \frac{1}{\sigma_z} e^{-\Delta z^2/2\sigma_z^2}$$

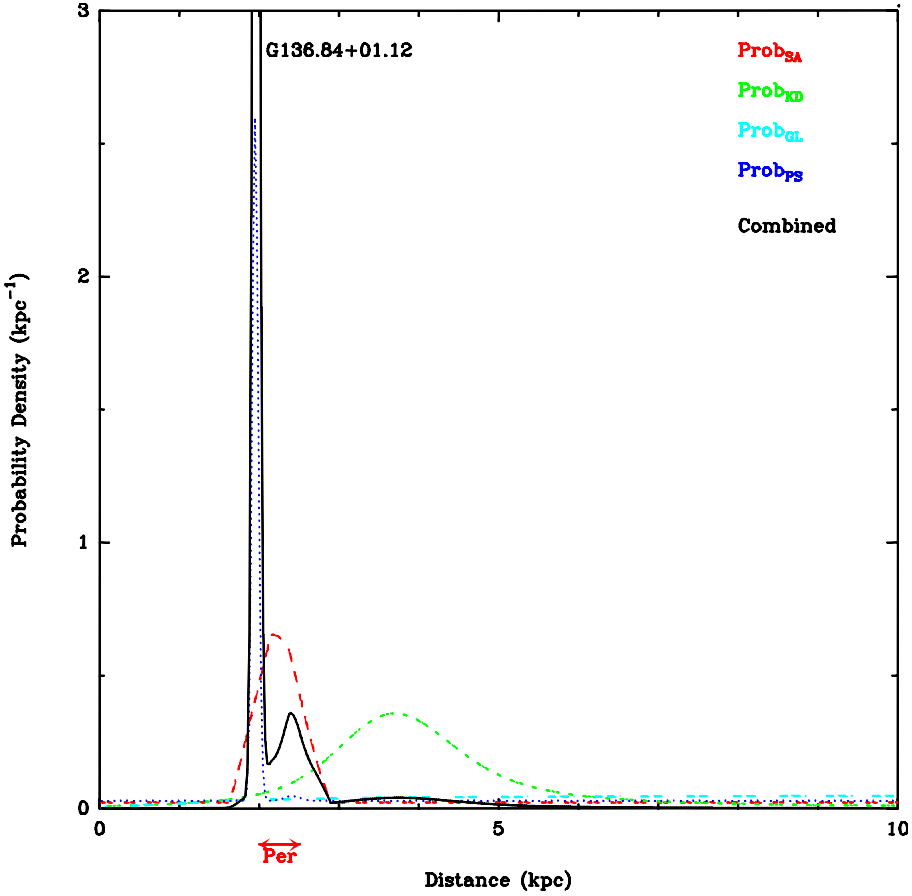
Arm “density” along ray from source

$$e^{-\Delta l_j^2/2\sigma_{l_j}^2} \quad e^{-\Delta b_j^2/2\sigma_{b_j}^2} \quad e^{-\Delta v_j^2/2\sigma_{v_j}^2}$$

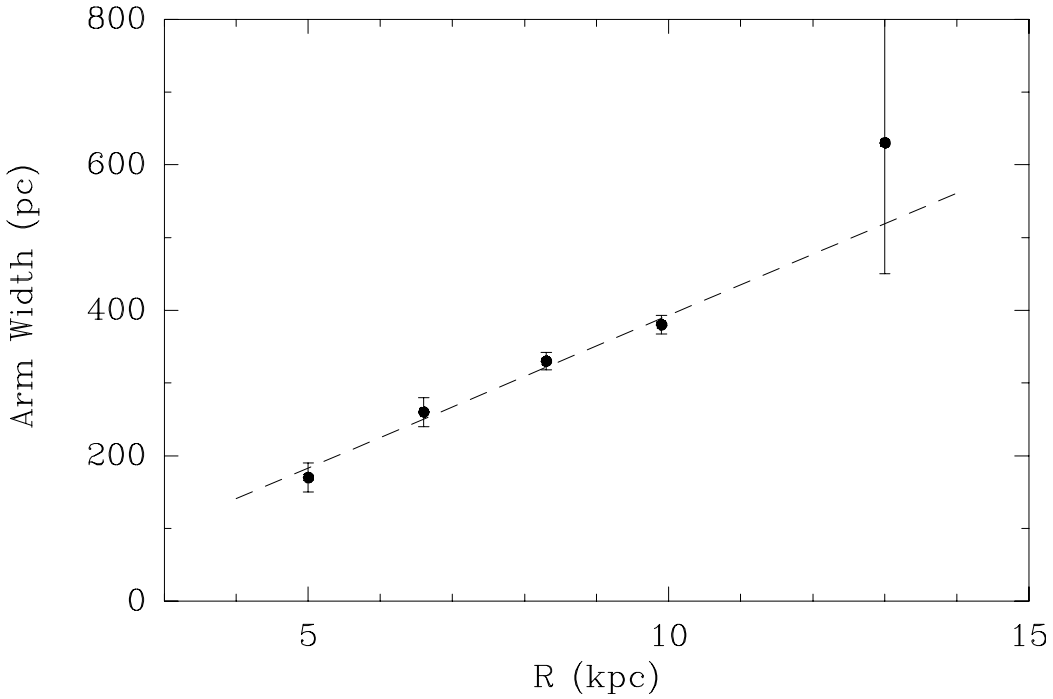
Source(l,b,V) – Arm(l,b,V)

Example Distance PDFs





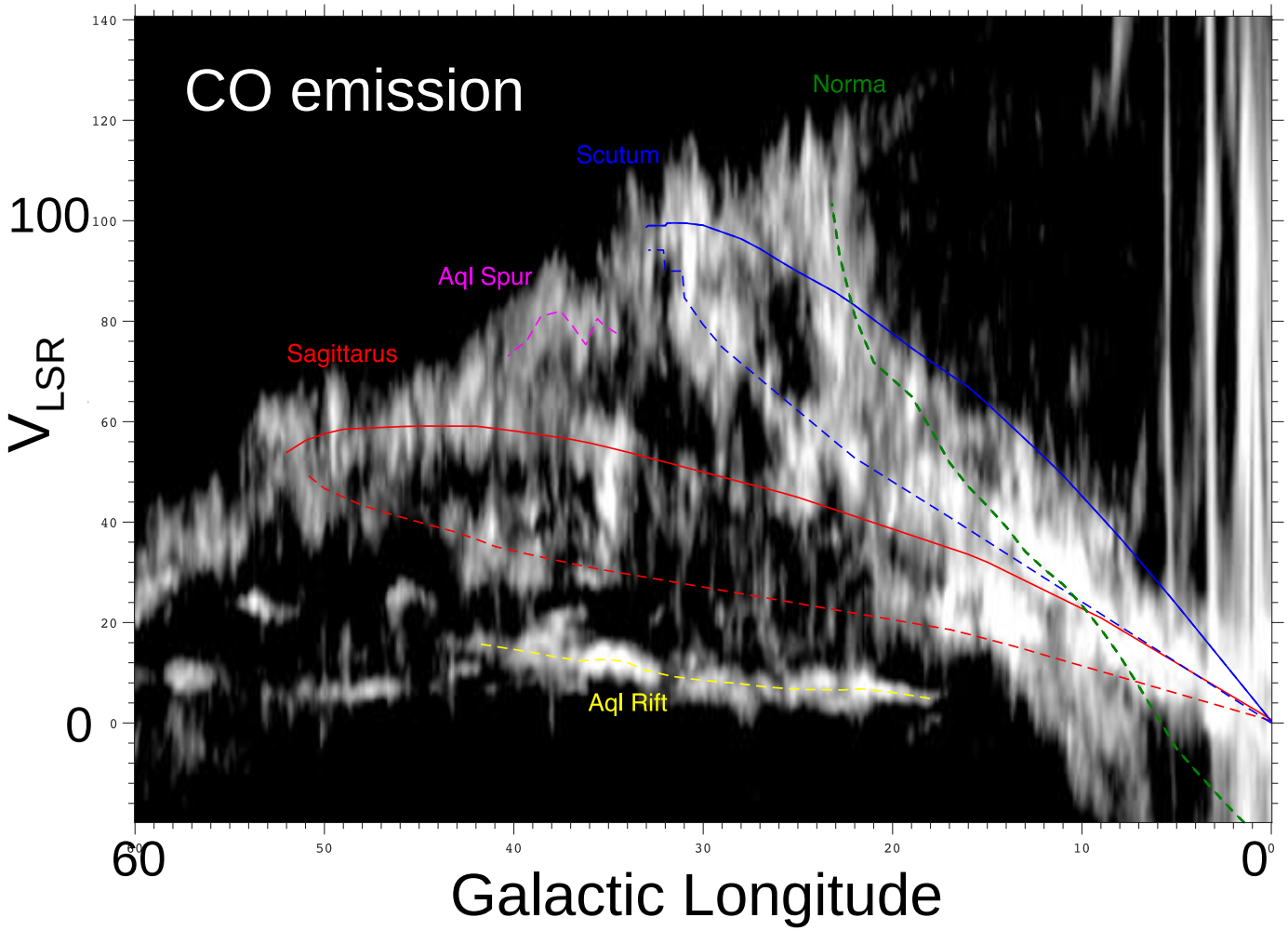
Spiral Arm Widths



Reid et al 2014

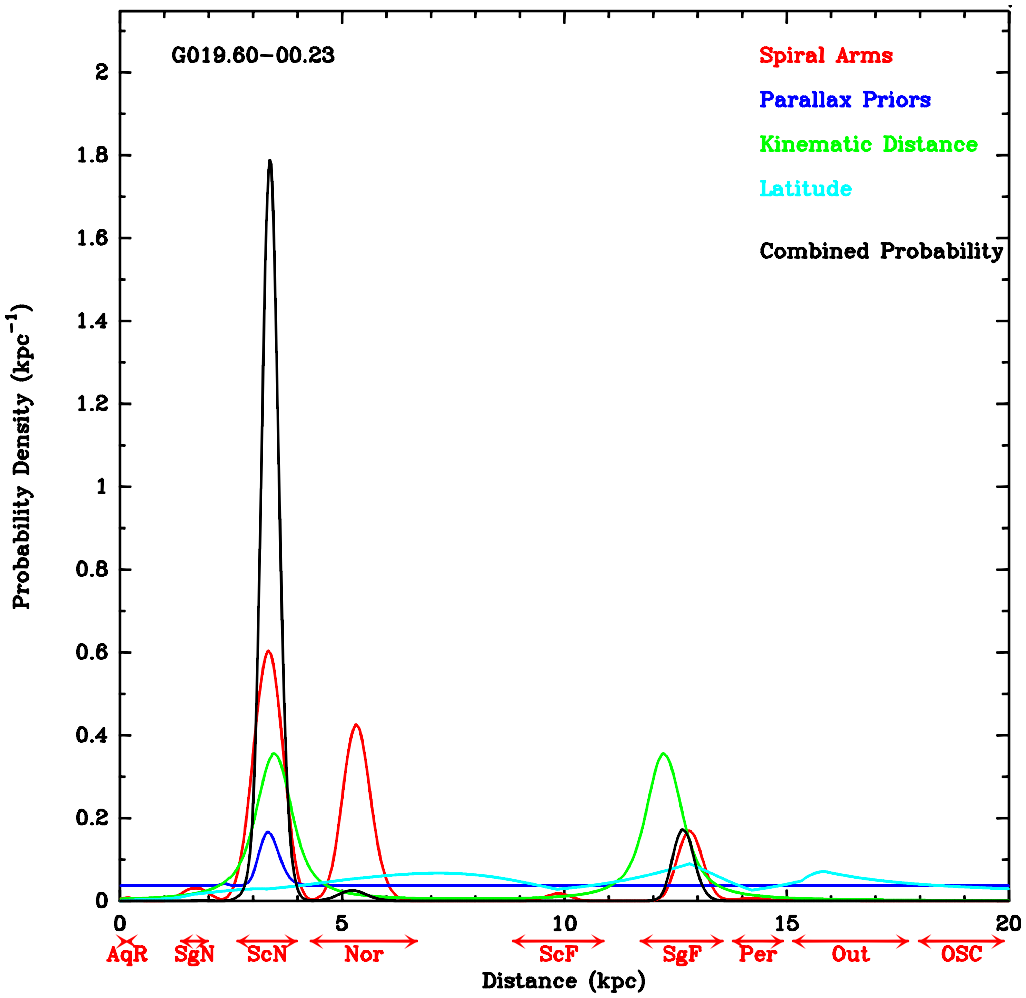
- Widths (scatter) of spiral arms increase with distance from Galactic Center
- Recently also measured in other galaxies (Honig & Reid 2015)
- Expected for “swing amplification”

“Spiral Arms” in (*l*,*V*) space



T. Dame, p.c.

Bayesian Distance Estimation



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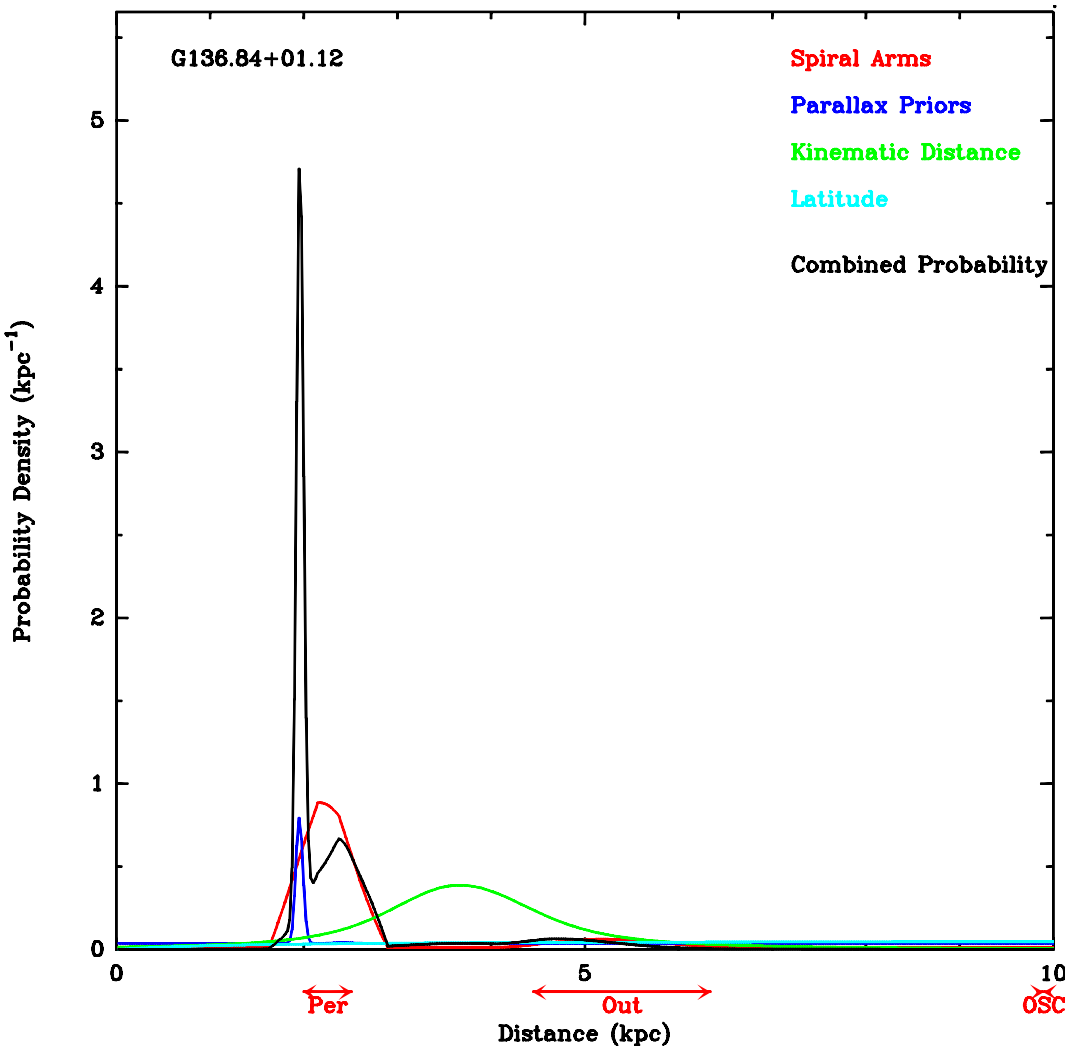
- P(SA) breaks D_k ambiguity

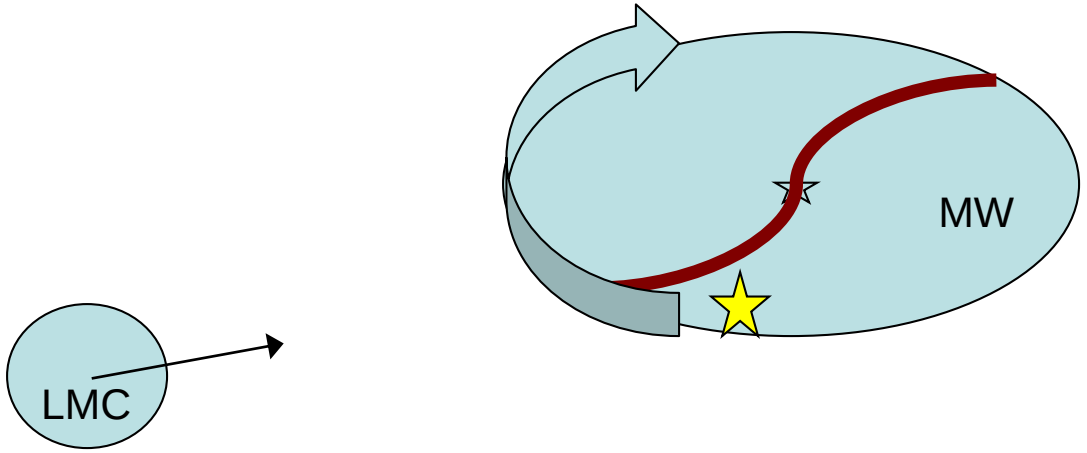
Bayesian Distance Estimation



- Prob(d) = $P_{SA}(d)$ x $P_{PAR}(d)$ x $P_{KD}(d)$ x $P_{LAT}(d)$
- Clear D_k anomaly

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)



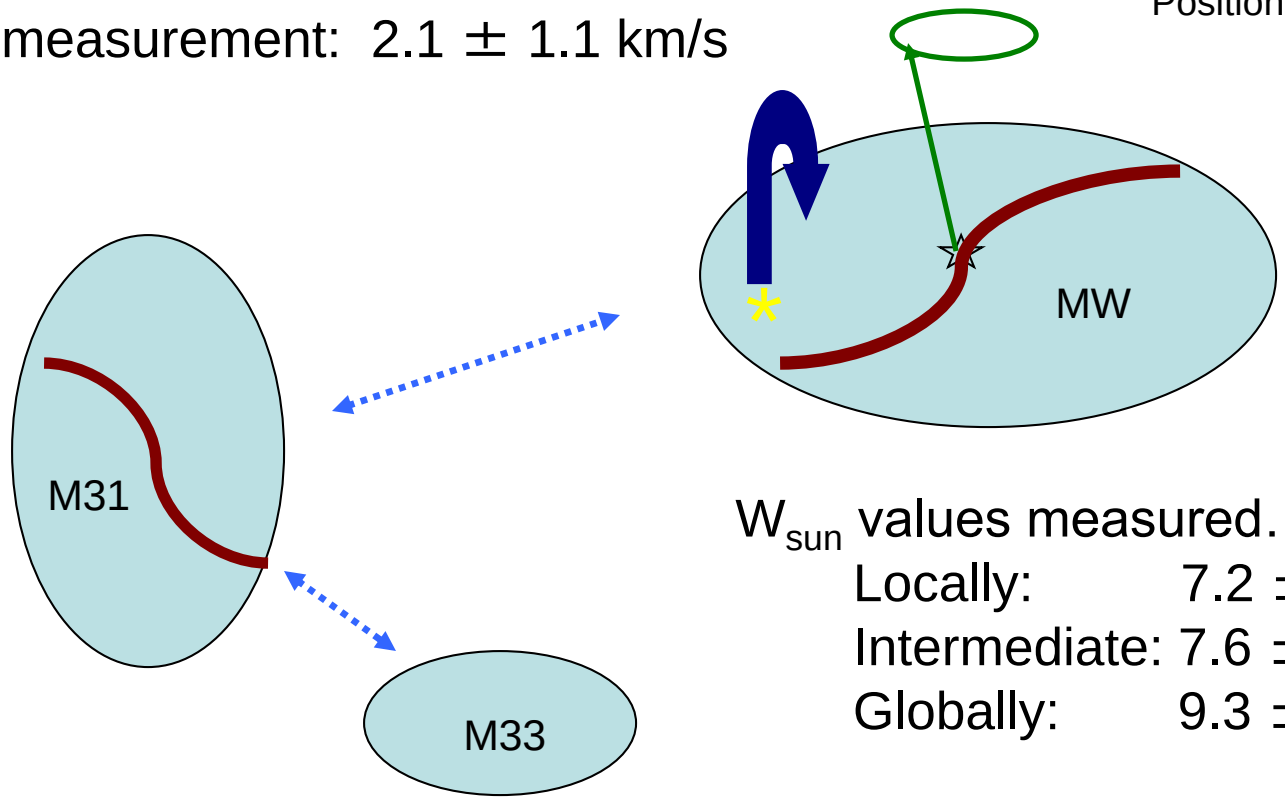
- Increases likelihood of an Andromeda-Milky Way collision

Milky Way Precession

- Local Group torques → spin axis precession
- Expected "tumbling" speed ~ $R_o H_o$ ~ 0.6 km/s
- Current measurement: 2.1 ± 1.1 km/s

QSO

Position reference



W_{sun} values measured…

Locally:	7.2 ± 0.5 km/s
Intermediate:	7.6 ± 0.5 km/s
Globally:	9.3 ± 1.0 km/s

Some Effects of Increasing Θ_0

- Reduces kinematic distances: D_k by 10%, hence…

  Molecular cloud sizes ($R \propto \varphi D$) by 10%

  Young star luminosities: $L \propto R^2$ by 20% (increasing YSO ages)

  Cloud masses (from density & size): $M \propto R^3$ 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 30%

- Increases likelihood that Magellanic Clouds bound to Milky Way

- 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 Hulse-Taylor 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±1.1) and Θ_0 (220±20) *c.*1993:
  dP/dt: (Observed – Gal. Acc) / GR-theory = 0.9994 ± 0.0023
- Using new values for R_0 (8.34±0.16) and Θ_0 (240±8):
  dP/dt: (Observed – Gal. Acc) / GR-theory = 0.9976 ± 0.0008
- Dominant source of error is now assumed pulsar distance (9.9 kpc)
  If GR correct, D_{pulsar} = 7.2 ± 0.5 kpc

Modeling the Milky Way

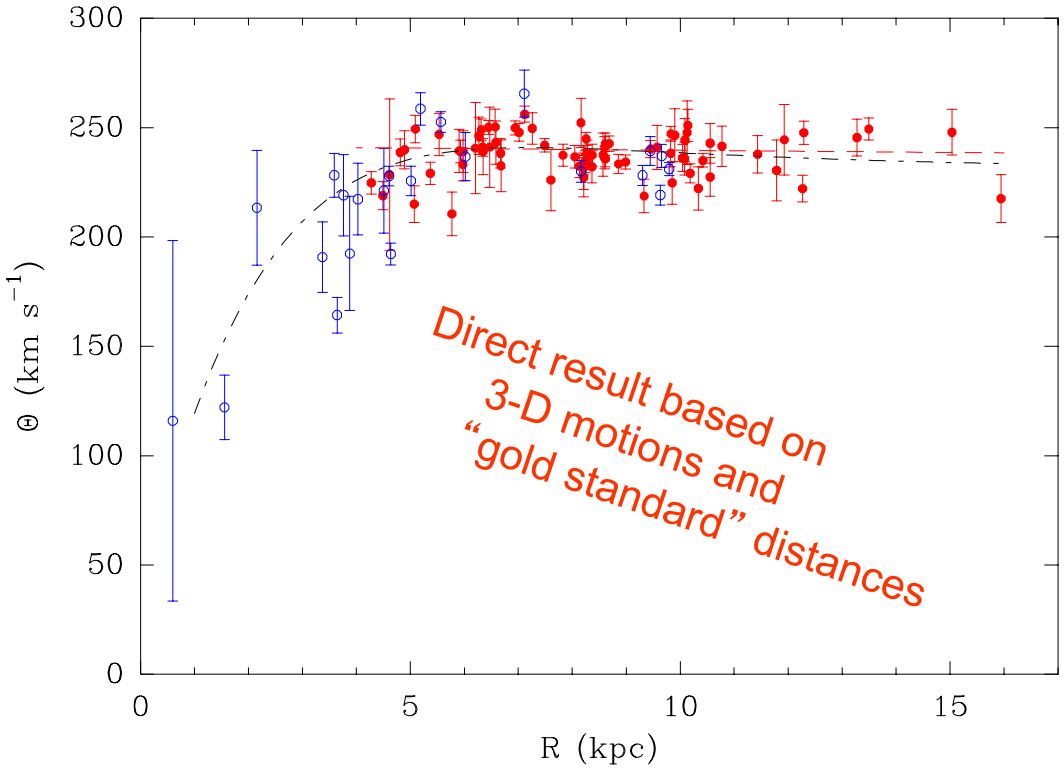
Priors	R_0 (kpc)	Θ_0 (km/s)	$(\Theta_0+V_{sun})/R_0$ (km/s/kpc)
V_{sun}=15±10; $\langle V_{src}\rangle$=–3±10	8.34 ± 0.16	240 ± 8	30.6 ± 0.4
V_{sun}=12± 2; $\langle V_{src}\rangle$ flat	8.33 ± 0.16	243 ± 6	30.6 ± 0.4
V_{sun} flat; $\langle V_{src}\rangle$=–3±5	8.30 ± 0.19	239 ± 8	30.6 ± 0.4
V_{sun} flat; $\langle V_{src}\rangle$ flat	8.29 ± 0.21	238 ±15	30.6 ± 0.4

Notes:

Solar Motion V_{sun} component: 5 km/s (Dehnen & Binney 1998)
12 km/s (Schœnrich, Binney & Dehnen 2010)
26 km/s (Bovy et al 2012)

$(\Theta_0+V_{sun})/R_0$ = 30.35 ± 0.05 km/s/kpc
directly from proper motion of Sgr A* (Reid & Brunthaler 2004, 2017)

The Milky Way's Rotation Curve



- For R_0 = 8.34 kpc, Θ_0 = 240 km/s
- 80 red points used for fitting
- 23 blue points not used
  (most near galactic bar)
- linear RC (dashed red line)
- "Universal" RC (dot-dash black line)
  Persic, Salucci & Stell (1996)