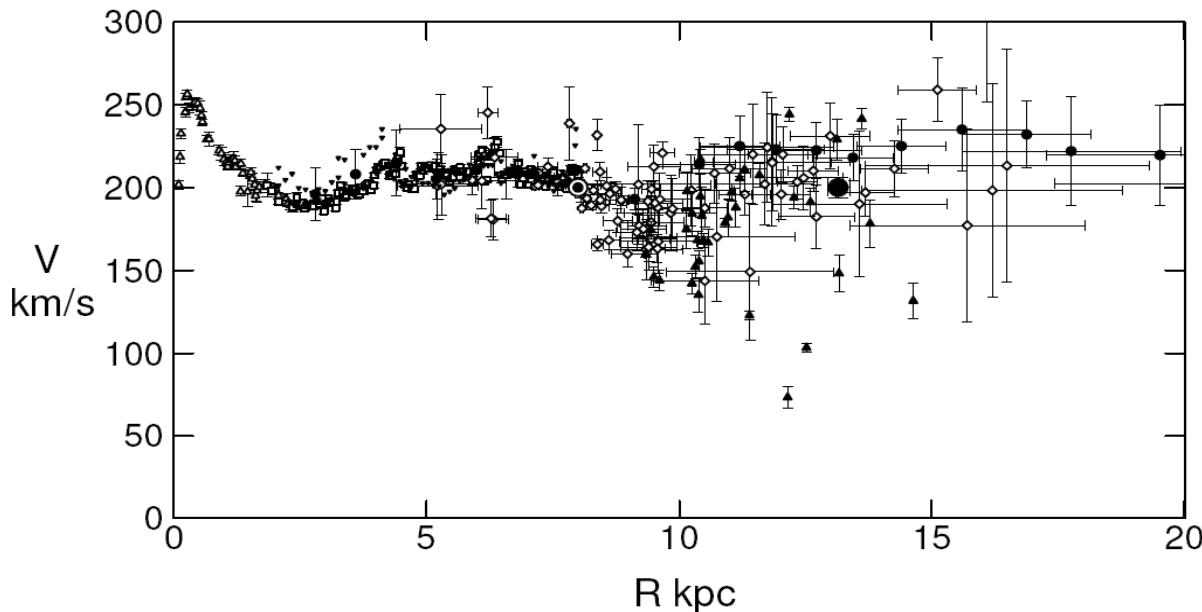


# **SISTEMAS ESTELARES**

**Material didáctico para las clases de  
“Rotación Galáctica”**

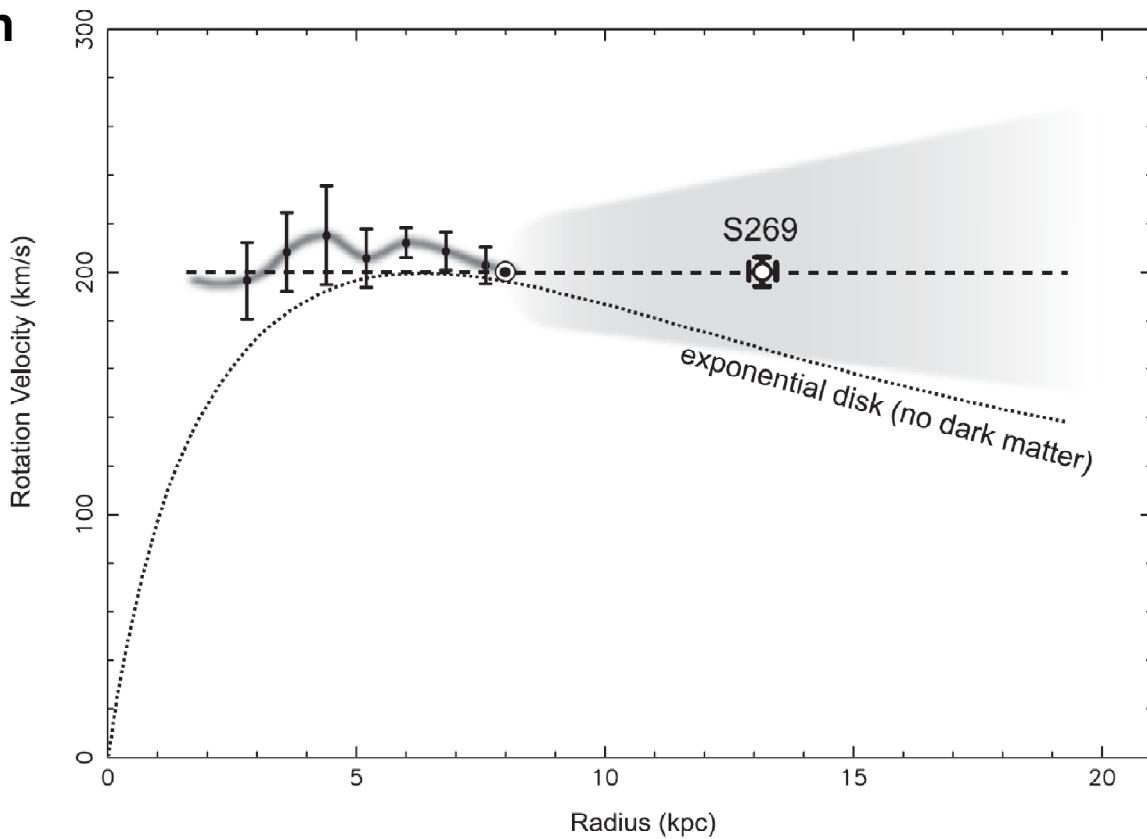
**Clases teóricas dictadas por:  
Dra. Lilia P. Bassino**

Unified Rotation Curve of the Milky Way Galaxy



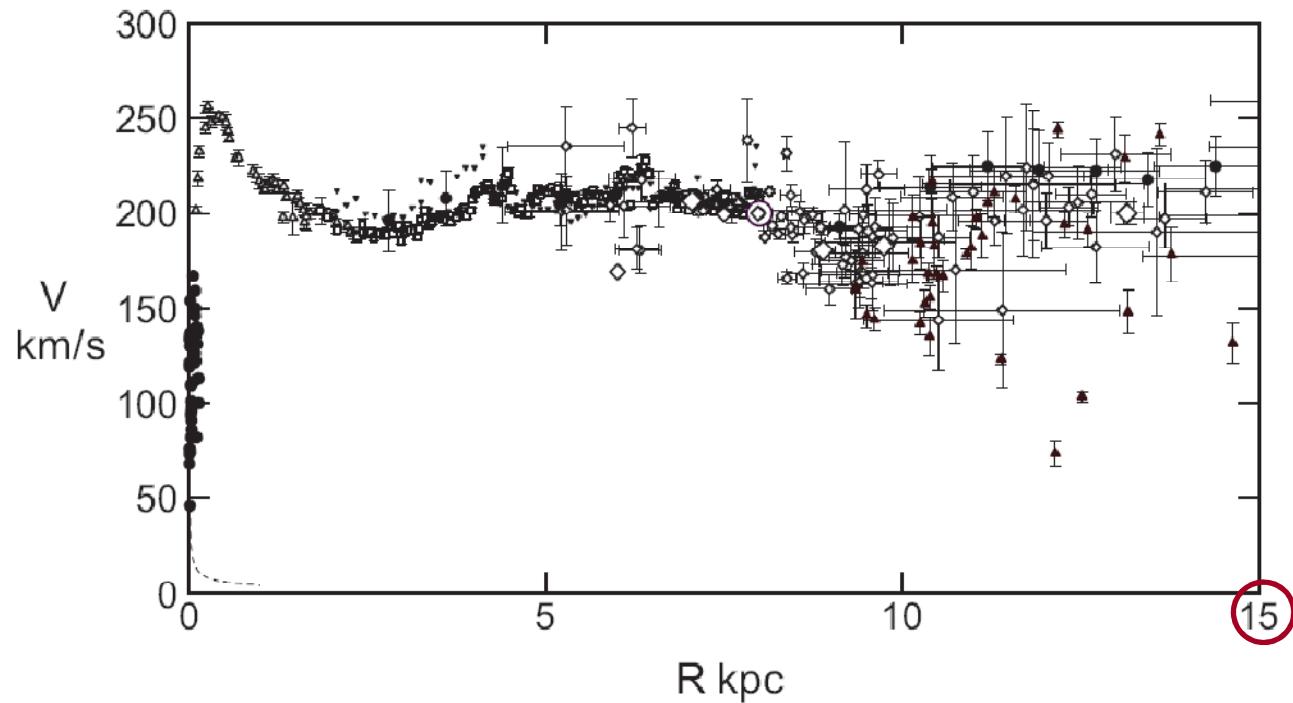
**Fig. 1.** Observed circular velocities representing the rotation curve of the Galaxy. Open triangles: HI tangent velocity method (Burton and Gordon 1978); Rectangles: CO tangent (Clemens 1989); Reverse triangles: HI tangent (Fich et al. 1989); Diamonds: CO and HII regions (Fich et al. 1989, Blitz et al. 1982); filled triangles: Demers and Battinelli (2007); Circles: HI thickness (Honma and Sofue 1997a,b); Big circle at 13.1 kpc: VERA-parallax, proper motion and velocity (Honma et al. 2007). All data have been converted to  $(R_0, V_0) = (8.0, 200.0 \text{ km s}^{-1})$ . The plotted data are in table 1.

## Curva de rotación de la Vía Láctea



**Fig. 4.** Rotation curve of the Milky Way Galaxy obtained in previous studies together with our result for S269 using Galactic constants of  $R_0 = 8$  kpc and  $\Theta_0 = 200 \text{ km}^{-1}$ . The dashed line is the flat rotation curve with  $\Theta = 200 \text{ km}^{-1}$ ; the shadowed area shows the possible range of outer rotation curves considered in previous studies (Honma & Sofue 1997). Points at  $R \leq 8$  kpc are inner rotation curves determined from the tangential velocities of Galactic H $I$  gases (Honma & Sofue 1997), with a smoothed fit (thick curve). The dotted curve is the rotation curve for an exponential disk, corresponding to a constant mass-to-light ratio disk without dark matter. A discrepancy between the observed point for S269 and the exponential disk is evident, demonstrating the existence of a large amount of dark matter in the outer region of the Galaxy.

## Rotation Curve and Mass Distribution in the Galactic Center — From Black Hole to Entire Galaxy —

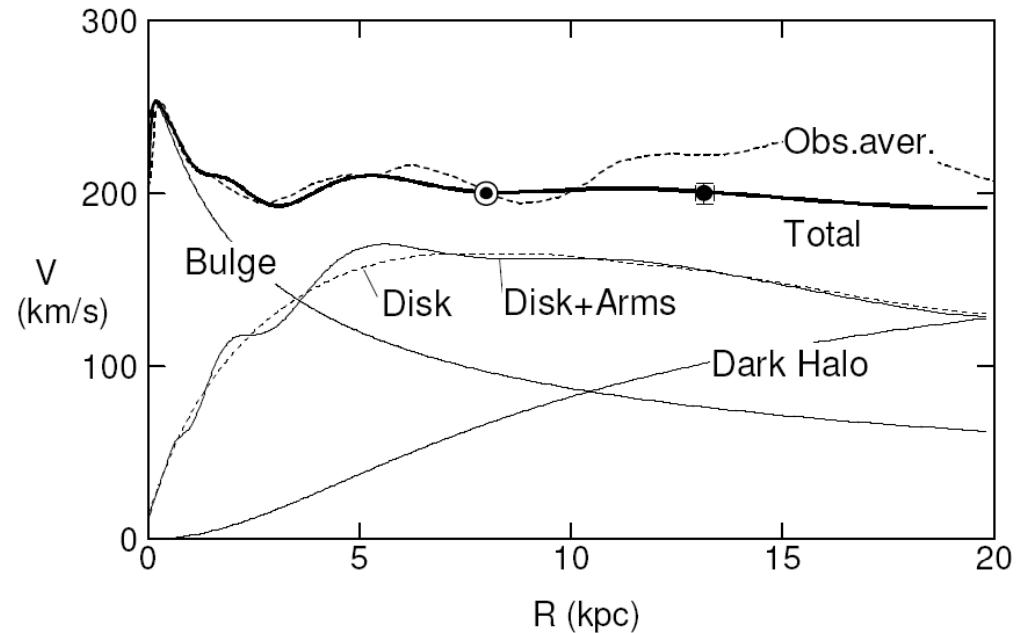


Sofue et al. (2013, PASJ 65, #18): agrega la zona central con el radiotelescopio de Nobeyama (45m), en CO y CS.



45m-Telescope with Spring mountains (Japan)

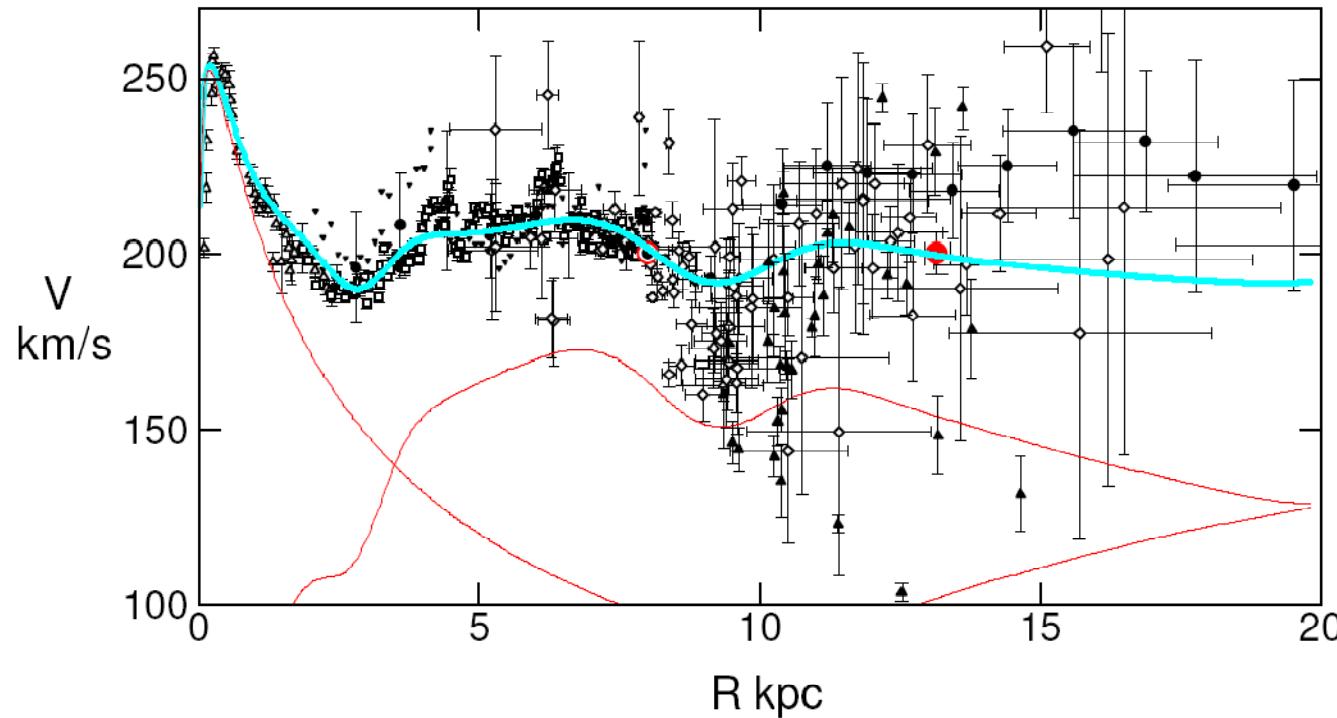
## Curva de rotación compuesta con bulbo, disco, brazos espirales y materia oscura



**Fig. 3.** Composite rotation curve including the bulge, disk, spiral arms, and dark halo. The big dot denotes the observed result from VERA (Honma et al. 2007). The pure disk component is also indicated by the thin dashed line. The thick dashed line indicates a simply averaged observed rotation curve taken from Sofue et al. (1999) where the outer curve is based only on the HI data of Honma and Sofue (1997a).

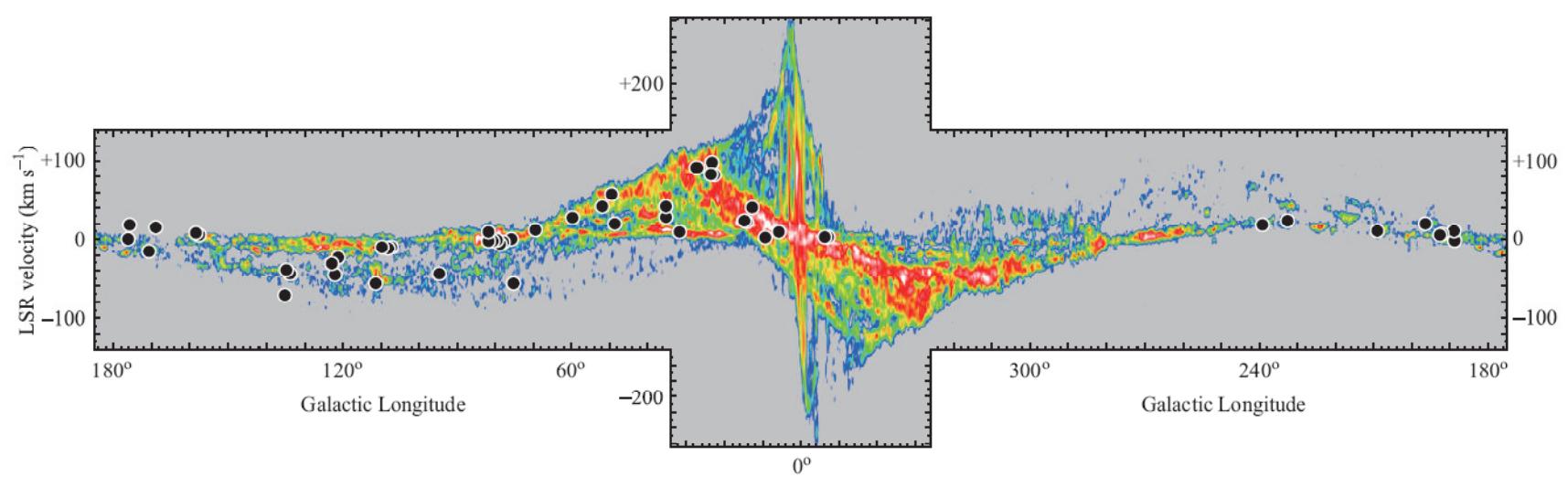
Sofue et al. 2009, PASJ 61, 227

## Fundamental Parameters of the Milky Way Galaxy Based on VLBI astrometry



**Fig. 5.** Model rotation curve compared with the observations. Thin lines represent the bulge, disk + rings, and dark halo components, and the thick line is the composite rotation curve. Data are the same as in figure 1.

# Fundamental Parameters of the Milky Way Galaxy Based on VLBI astrometry



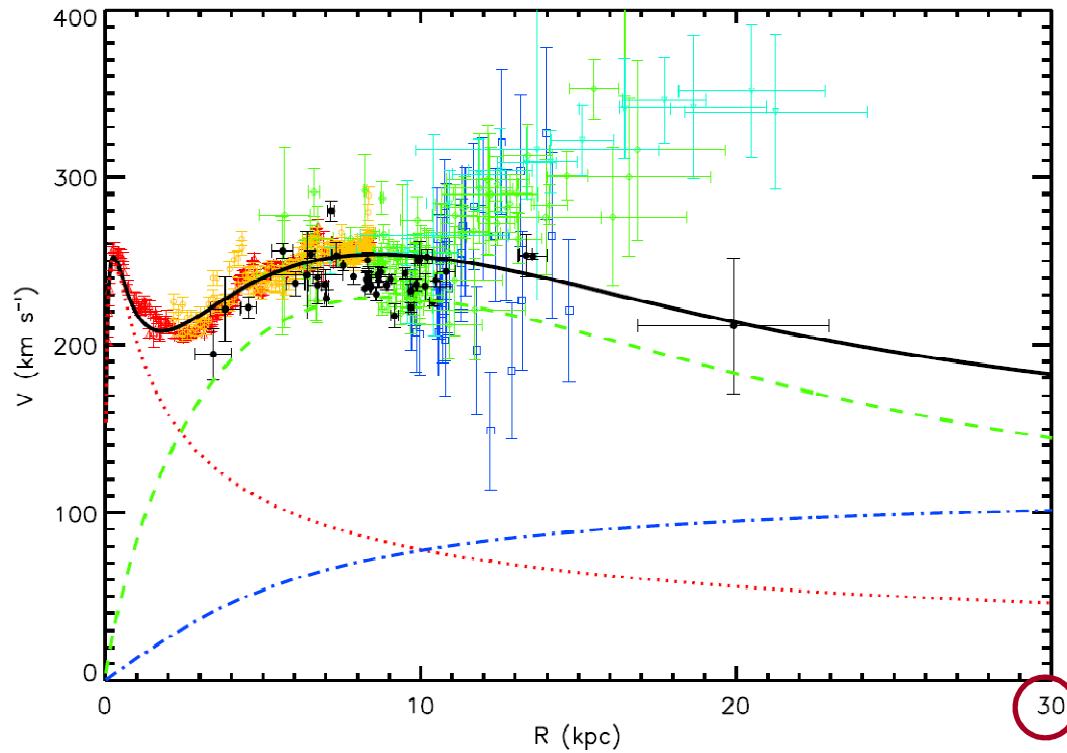
**Fig. 1.** Location of 52 maser sources for which accurate astrometric data are available (table 1), superposed on the longitude-velocity diagram of CO (Dame et al. 2001).

We present analyses to determine the fundamental parameters of the Galaxy based on VLBI astrometry of 52 Galactic maser sources obtained with VERA, VLBA and EVN.

**Diagrama LV: Longitud - Velocidad** (Honma et al. 2012, PASJ 64, #136)

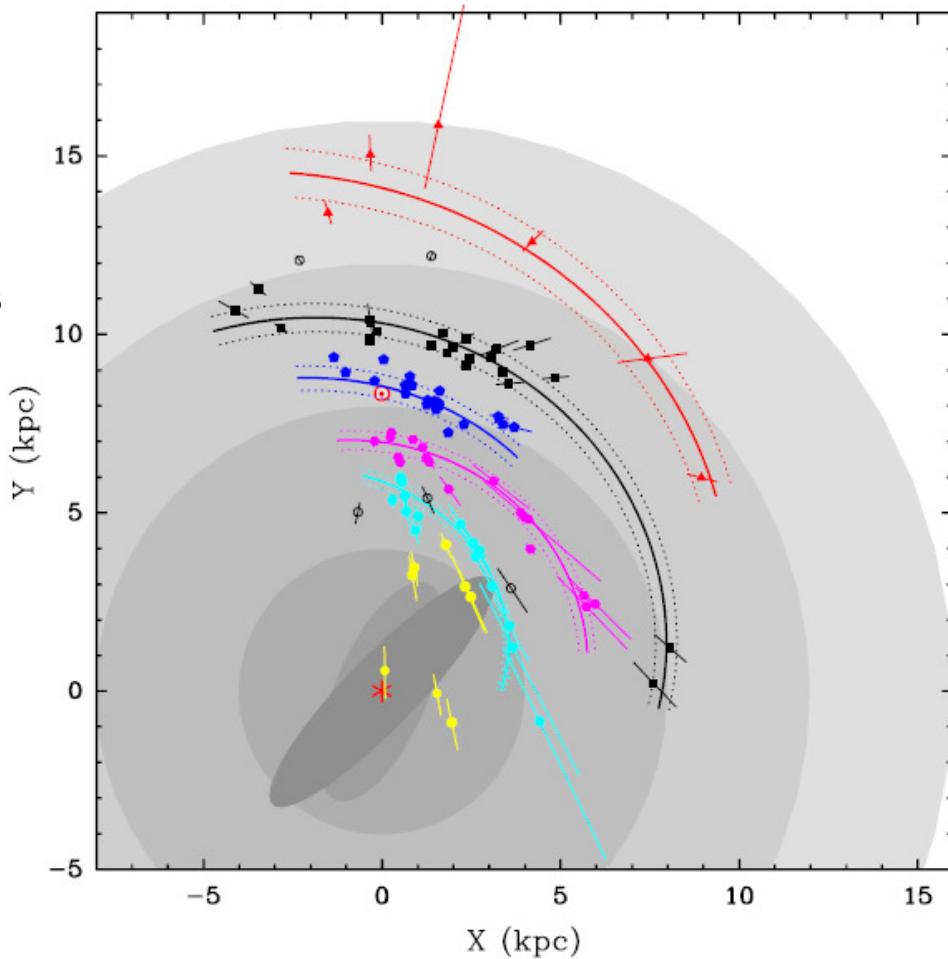
[ VLBA (Very Long Baseline Array), EVN (European VLBI Network) ]

# A Revised Rotation Curve of the Milky Way with Maser Astrometry



**Fig. 1** Recalculated rotation data of the Milky Way using the new Galactic constants  $(R_0, \Theta_0) = (8.4 \text{ kpc}, 254 \text{ km s}^{-1})$ , with the rotation curve corresponding to Fit #1 (thick solid line). The dotted, dashed and dash-dotted lines represent the bulge, disk and dark matter halo contributions respectively. Red triangles: HI- and CO-line tangent velocity method (Clemens 1985); yellow open circles: HI tangent velocity method (Fich et al. 1989); green diamonds: HII regions (Fich et al. 1989); blue squares: C stars (Demers & Battinelli 2007); cyan reverse triangles: HI-disk thickness method (Merrifield 1992; Honma & Sofue 1997); black filled circles: HMSFR data

Reid et al. (2014, ApJ 783, 130):  
 más de 100 paralajes trigonométricas  
 y movimientos propios de  
**masers asociados con HMSFRs**  
 (high-mass star-forming regions)



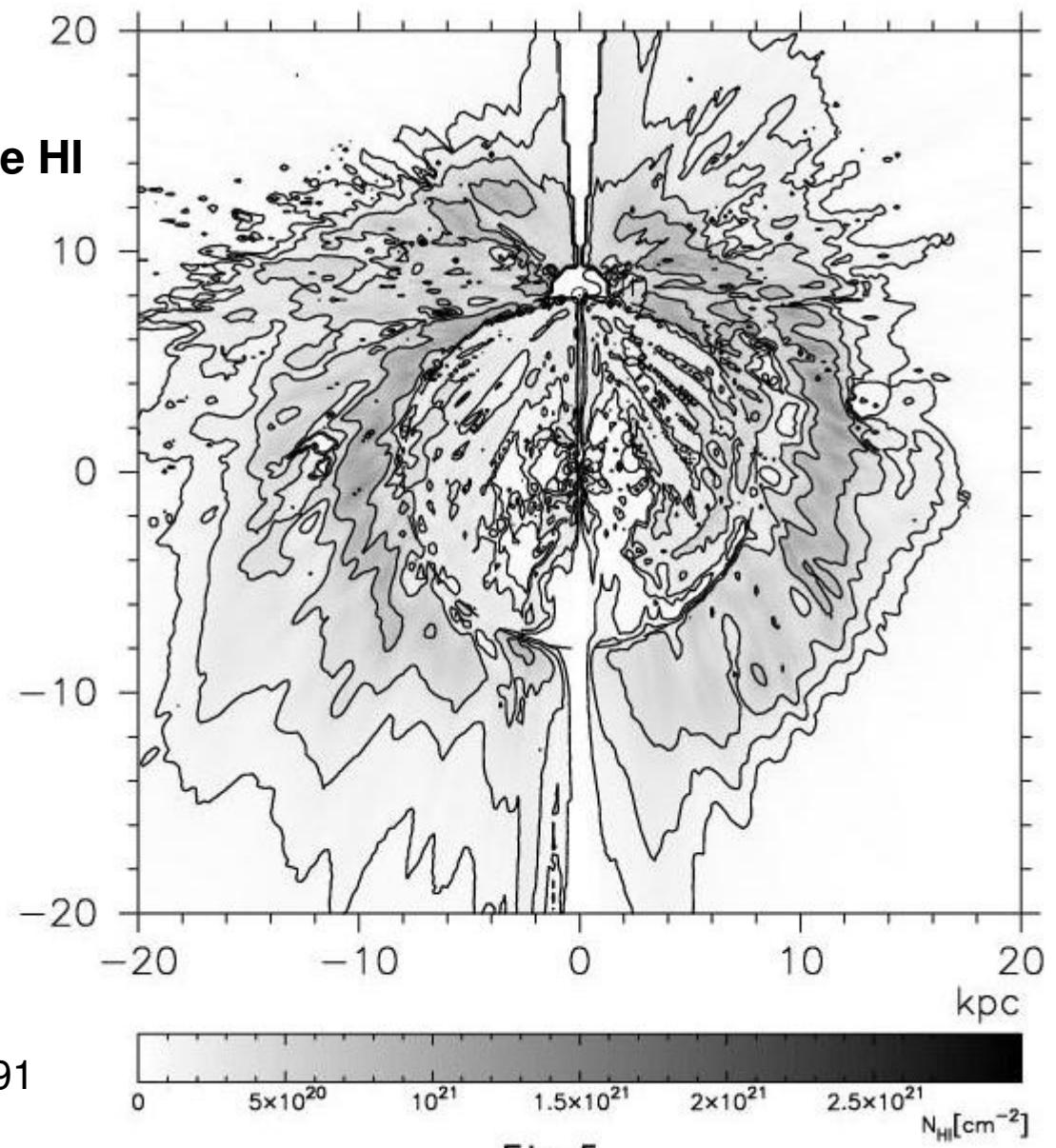
**Figure 1.** Plan view of the Milky Way showing the locations of high-mass star forming regions (HMSFRs) with trigonometric parallaxes measured by the VLBA, VERA, and the EVN. The Galactic center (red asterisk) is at (0,0) and the Sun (red Sun symbol) is at (0.8,34). HMSFRs were assigned to spiral arms based primarily on association with structure seen in  $\ell$ - $V$  plots of CO and H I emission (and not based on the measured parallaxes): inner Galaxy sources, yellow dots; Scutum arm, cyan octagons; Sagittarius arm, magenta hexagons; Local arm, blue pentagons; Perseus arm, black squares; Outer arm, red triangles. Open circles indicate sources for which arm assignment was unclear. Distance error bars are indicated, but many are smaller than the symbols. The background gray disks provide scale, with radii corresponding in round numbers to the Galactic bar region ( $\approx 4$  kpc), the solar circle ( $\approx 8$  kpc), co-rotation of the spiral pattern and Galactic orbits ( $\approx 12$  kpc), and the end of major star formation ( $\approx 16$  kpc). The short COBE “boxy-bar” and the “long” bar (Blitz & Spergel 1991; Hammersley et al. 2000; Benjamin 2008) are indicated with shaded ellipses. The solid curved lines trace the centers (and dotted lines the  $1\sigma$  widths) of the spiral arms from the log-periodic spiral fitting (see Section 3 and Table 2). For this view of the Milky Way from the north Galactic pole, Galactic rotation is clockwise.

we estimate the distance to the Galactic center,  $R_0$ , to be  $8.34 \pm 0.16$  kpc, a circular rotation speed at the Sun,  $\Theta_0$ , to be  $240 \pm 8$  km s $^{-1}$ , and a rotation curve that is nearly flat (i.e., a slope of  $-0.2 \pm 0.4$  km s $^{-1}$  kpc $^{-1}$ ) between Galactocentric radii of  $\approx 5$  and 16 kpc..

**Table 3** Estimated Parameters of the Milky Way Model

Component	Parameter	Value
Bulge	Half-mass scale radius	$R_b \sim 0.3 \text{ kpc}$
	Mass	$M_b \sim 1.5 \times 10^{10} M_\odot$
Disk	Scale radius	$R_d \sim 4.0 \text{ kpc}$
	Central mass density	$\Sigma_{dc} \sim 1.2 \times 10^3 M_\odot \text{ pc}^{-2}$
	Mass	$M_d \sim 1.2 \times 10^{11} M_\odot$
Dark matter halo	Scale radius	$R_h \sim 5.0 \text{ kpc}$
	Central volume mass density	$\rho_{hc} \sim 0.01 M_\odot \text{ pc}^{-3}$
	Mass in <u><math>r = 20 \text{ kpc}</math> sphere</u>	$M_h(20 \text{ kpc}) = 1.0 \times 10^{11} M_\odot$
Total Galaxy mass	Mass in <u><math>r = 20 \text{ kpc}</math> sphere</u>	$M_{\text{total}}(20 \text{ kpc}) = 2.3 \times 10^{11} M_\odot$

## Mapa de densidad superficial de HI



Nakanishi & Sofue 2003, PASJ 55, 191

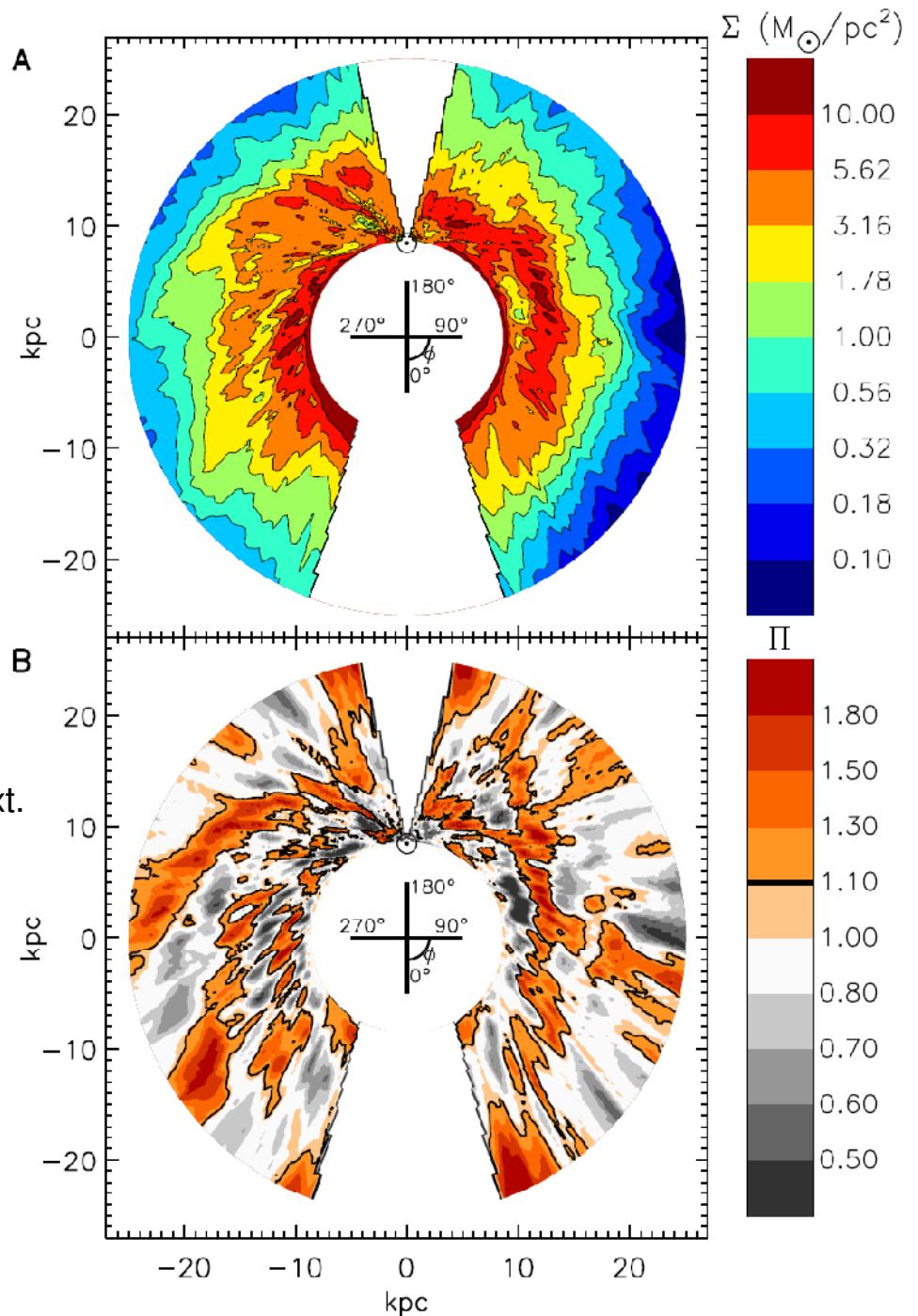
Fig 5

## Mapa de densidad superficial de HI vs. mapa de perturbaciones en la densidad superficial de HI (solo $R > R_0$ )

Figure A: Contour plot of the surface density  $\Sigma (R, \phi)$ . The location of the Sun is marked at (0, 8.5 kpc) by the solar symbol  $\odot$ . The regions excluded due to unreliable distances are the large blank wedges near the Sun-Galactic center line ( $\pm 15^\circ$ ).

Figure B: Contour plot of  $\pi (R, \phi)$ , as defined in the text. Colored regions are overdense compared to the local median, whereas grayscale regions are underdense.

Levine et al. 2006, Science 312, 1773



## Mapa de perturbaciones en la densidad superficial de HI - estructura espiral

Figure A: The same contour plot as in Fig. 1, with a four armed logarithmic spiral fit overplotted. The fitting method is described in the text. Other fits that connect different features are possible.

Figure B: The same contour plot as in Fig. 1, with the four armed symmetric spiral model overplotted. The solid lines represent the model over its claimed range of validity; the dashed lines are an extension beyond that range. The unlabeled short line near the Sun is the local Orion arm. The width of the model arms is arbitrary.

Levine et al. 2006, Science 312, 1773

