# The Milky Way's rotation curve out to 100 kpc and its constraint on the Galactic mass distribution

Yang Huang

(*LAMOST Fellow, yanghuang@pku.edu.cn*)

Peking University

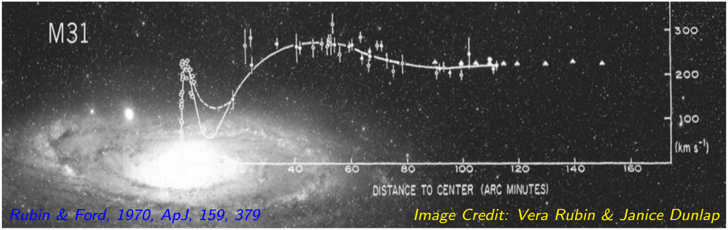
September 19, 2016

Collaborators: Xiaowei Liu (PKU), Haibo Yuan (BNU), Maosheng Xiang (NAOC), Bingqiu Chen (PKU), Huawei Zhang (PKU), Juanjuan Ren (NAOC), Zhijia Tian (PKU), Chun Wang (PKU), Zhiying Huo (NAOC)

# Outline

1. Introduction
2. Data sample
3. Methods, results & discussions
4. Summary

# Rotation curves



*Rubin & Ford, 1970, ApJ, 159, 379*

*Image Credit: Vera Rubin & Janice Dunlap*

*Vera Rubin*

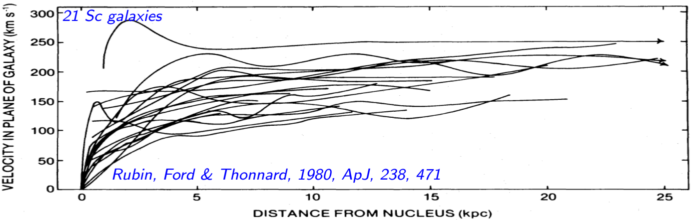
## 1. Mass distribution of galaxies

- $M(R) \propto RV_c^2(R)$
- The rotation curves are important tools in studies of the **structures** and **mass distribution** of galaxies.

## 2. Evidence for dark matter

- In the outer parts of the galaxies, $V_c(R) \propto 1/\sqrt{R}$ if visible components only.
- The flatness of the outer rotation curves implies that the galaxies contain large amounts of unseen matter – **dark matter**.

# Rotation curves



*Rubin, Ford & Thonnard, 1980, ApJ, 238, 471*

### 1. Mass distribution of galaxies

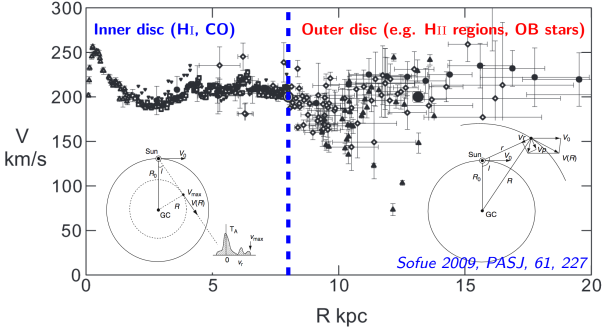
- $M(R) \propto RV_c^2(R)$
- The rotation curves are important tools in studies of the **structures** and **mass distribution** of galaxies.

### 2. Evidence for dark matter

- In the outer parts of the galaxies, $V_c(R) \propto 1/\sqrt{R}$ if visible components only.
- The flatness of the outer rotation curves implies that the galaxies contain large amounts of unseen matter – **dark matter**.

# Rotation curve of the Milky Way: disc tracers

- **Tangent-point method**
- **Radial velocity & distance analysis**



*Sofue 2009, PASJ, 61, 227*

$$V_c(R) = V_c(R_0)\sin(l) + V^{\max}_{r,\mathrm{LSR}}$$

$$R = R_0 \sin(l)$$

$$V_c(R) = \frac{R}{R_0}\left[\frac{V_{r,\mathrm{LSR}}}{\sin(l)\cos(b)} - V_c(R_0)\right]$$

$$R = (d^2 + R_0^2 - 2dR_0\cos(l))^{1/2}$$

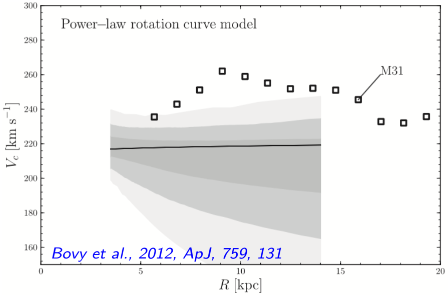
**Challenges:**

1. **Poorly distance determinations** in the outer Galactic disc
2. **Significant perturbations** by non-axisymmetric structures (e.g. central bar, spiral arms)

*Image Credit: R. Hurt*

# Rotation curve of the Milky Way: disc tracers

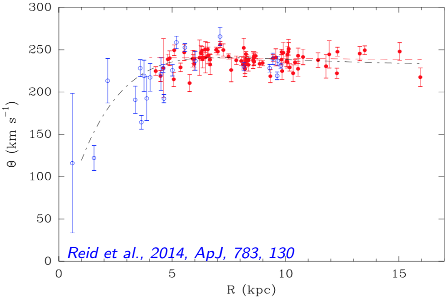
- **3365 APOGEE red giant stars (warm tracers)**



*Bovy et al., 2012, ApJ, 759, 131*

1. **Distance determinations:** **poorly**
2. **Perturbations:** **relatively small**

- **Over 100 masers from BeSSeL survey (cold tracers)**

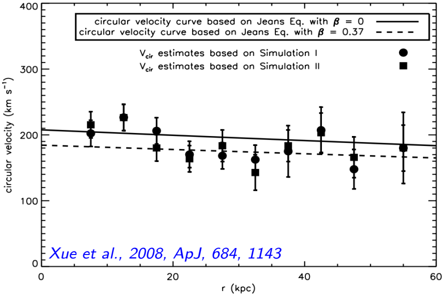


*Reid et al., 2014, ApJ, 783, 130*

1. **Distance determinations:** **accurate**
2. **Perturbations:** **significant**

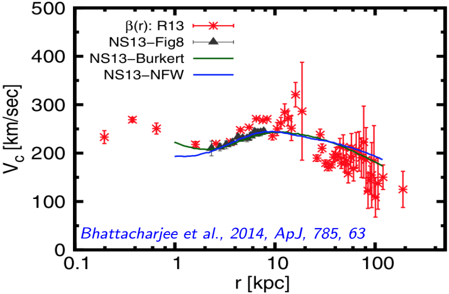
# Rotation curve of the Milky Way: halo tracers

- **2401 BHB stars**



*Xue et al., 2008, ApJ, 684, 1143*

- **1457 BHB stars; 2227 K giants; 16 GCs, 28 FHB stars, 21 dSphs**



*Bhattacharjee et al., 2014, ApJ, 785, 63*

**Challenges:**

1. **The halo density profile:** inner halo & outer halo
2. **The velocity anisotropy parameter $\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$:** not a constant

# Remarks of the current Galactic rotation curve measurements

## 1. Tracers in the inner disc region

- The distribution and kinematics of cold gas are significantly perturbed by central bar in the innermost region (i.e. $R \leq 4 - 4.5\,\mathrm{kpc}$)

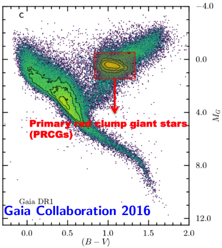
## 2. Tracers in the outer disc region

- Poorly distance determinations
- Significant perturbations (especially for cold tracers)

## 3. Tracers in the halo region

- Halo density profile
- Velocity anisotropy parameter

# Primary red clump giant stars & Halo K giant stars

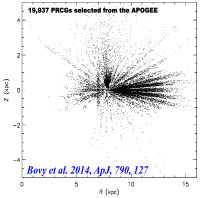


Gaia Collaboration 2016

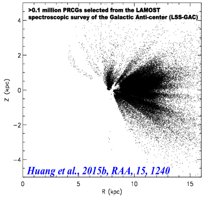
## PRCGs

- **Standard candle:** distance accuracy better than 5–10%
- **Warm population:** relatively insensitive to the perturbations caused by non-axisymmetric structures

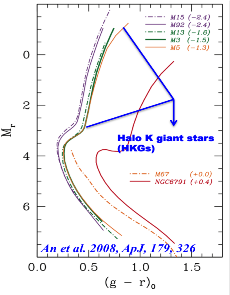
**Select purely ($\geq$90%) PRCGs based on their position in color–metallicity–surface-gravity–effective-temperature space.**



Bovy et al. 2014, ApJ, 790, 127



Huang et al., 2015b, RAA, 15, 1240

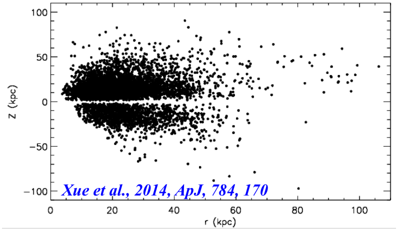


An et al. 2008, ApJ, 179, 326

## HKGs

- **Intrinsically bright and also span about 4 mag in $r$-band absolute magnitude ($-1$ to 3 mag in $M_r$): cover a large distance range**
- **Abundantly observed in SDSS/SEGUE**

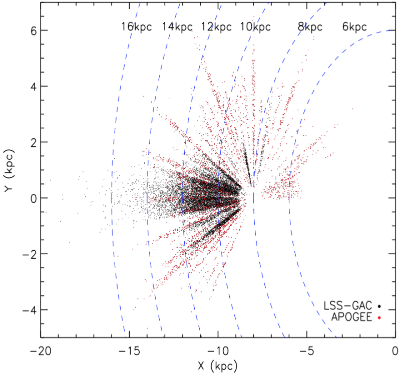
**6036 K giant stars selected from the SDSS/SEGUE with unbiased distance (typical precision $\sim$ 16 per cent).**



Xue et al., 2014, ApJ, 784, 170

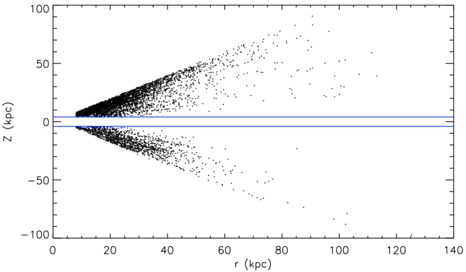
# The final sample

## PRCG sample



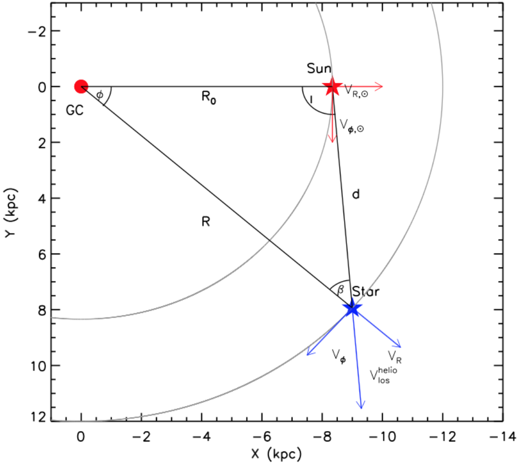
- **To ignore the vertical motions and to minimize the contamination of halo stars, we have restricted the PRCG sample to stars of $|b| \leq 3^\circ$ and [Fe/H]$\geq -1.0$.**
- **Finally, 15,634 PRCGs are left (11,572 from LSS-GAC and 3792 from APOGEE).**

## HKG sample



- **To exclude possible contamination from the disc population, we have selected only those HKGs of $|z| \geq 4$ kpc.**
- **Finally, 5733 HKGs are left.**

# Rotation curve from PRCG sample



## Kinematical model

$$\overline{V}_{\rm los}^{\rm helio} = \overline{V}_\phi(R)\sin\beta - V_{\phi,\odot}\sin l + \overline{V}_R(R)\cos\beta + V_{R,\odot}\cos l,$$

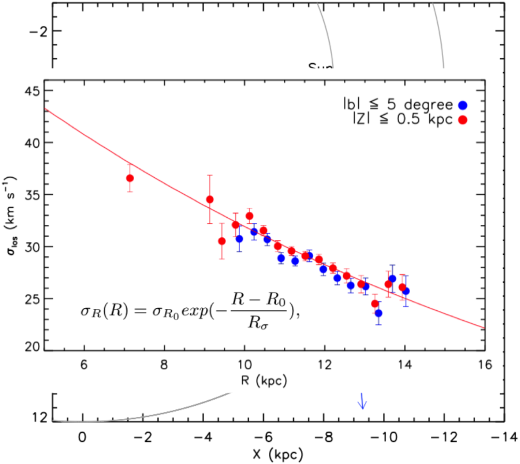
$$\overline{V}_\phi(R) = V_c(R) - V_a(R).$$

$$\beta = \sin^{-1}(\frac{R_0}{R}\sin l).$$

$$V_a(R) = \frac{\sigma_R^2(R)}{2V_c(R)}[\frac{\sigma_\phi^2(R)}{\sigma_R^2(R)} - 1 + R(\frac{1}{R_d} + \frac{2}{R_\sigma}) - \frac{R}{\sigma_R^2(R)}\frac{\partial\overline{V_R V_Z}}{\partial Z}],$$

| | | |
|---|---|---|
| $R_{\rm d}$ (kpc) | 2.5 | – |
| $\sigma_\phi^2/\sigma_R^2$ | 0.5 | – |
| $R_\sigma$ (kpc) | 16.40 | this work |
| $\sigma_{R_0}$ (km s$^{-1}$) | 35.32 | this work |
| $R_0$ (kpc) | 8.34 | Reid et al. 2014 |
| $\Omega_\odot$ (km s$^{-1}$ kpc$^{-1}$) | 30.24 | Reid et al. 2004 |
| $V_{\rm R,\odot}$ (km s$^{-1}$) | −7.01 | Huang et al. 2015b |

# Rotation curve from PRCG sample



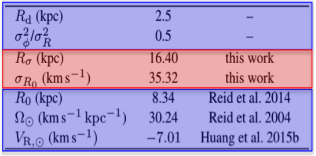
## Kinematical model

$$\overline{V}^{\rm helio}_{\rm los} = \overline{V}_\phi(R)\sin\beta - V_{\phi,\odot}\sin l + \overline{V}_R(R)\cos\beta + V_{R,\odot}\cos l,$$

$$\overline{V}_\phi(R) = V_c(R) - V_a(R).$$

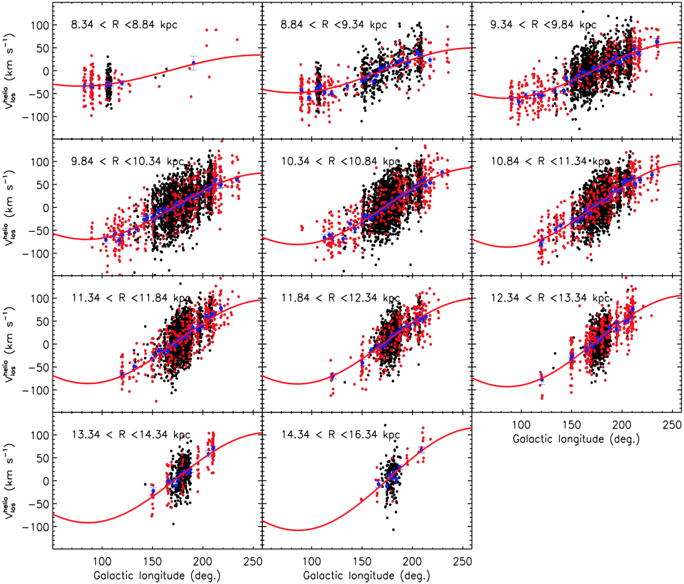
$$\beta = \sin^{-1}(\frac{R_0}{R}\sin l).$$

$$V_a(R) = \frac{\sigma_R^2(R)}{2V_c(R)}[\frac{\sigma_\phi^2(R)}{\sigma_R^2(R)} - 1 + R(\frac{1}{R_d} + \frac{2}{R_\sigma}) - \frac{R}{\sigma_R^2(R)}\frac{\partial \overline{V_R V_Z}}{\partial Z}],$$

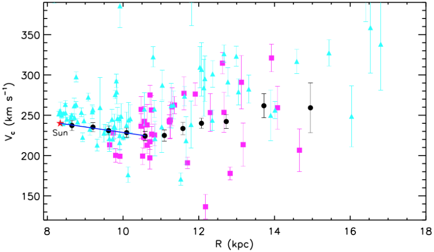


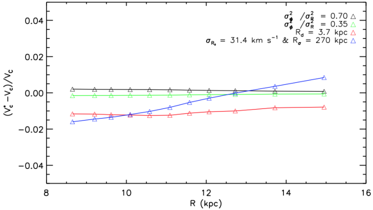
| | | |
|---|---|---|
| $R_{\rm d}$ (kpc) | 2.5 | – |
| $\sigma_\phi^2/\sigma_R^2$ | 0.5 | – |
| $R_\sigma$ (kpc) | 16.40 | this work |
| $\sigma_{R_0}$ (km s$^{-1}$) | 35.32 | this work |
| $R_0$ (kpc) | 8.34 | Reid et al. 2014 |
| $\Omega_\odot$ (km s$^{-1}$ kpc$^{-1}$) | 30.24 | Reid et al. 2004 |
| $V_{R,\odot}$ (km s$^{-1}$) | −7.01 | Huang et al. 2015b |

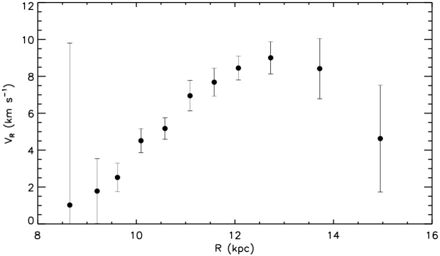
# Rotation curve from PRCG sample



# Rotation curve from PRCG sample







## Discussion:

- **The systematic errors of rotation curve resultant as a consequence of our adopted canonical values of parameters are likely to be smaller than 5 km/s.**
- **The newly derived RC shows a prominent dip at R∼11 kpc.**
- **The possibility that the derived RC is affected by the non-axisymmetric structures cannot be ruled out.**

# Rotation curve from HKG sample

Spherical Jeans equation:

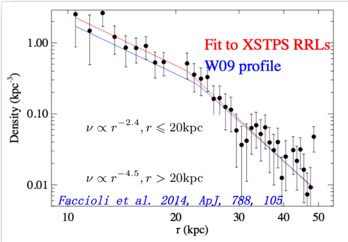
$$V_c^2(R) = -\sigma_r^2\left(\frac{d\,\ln\nu}{d\,\ln r} + \frac{d\,\ln\sigma_r^2}{d\,\ln r} + 2\beta\right),$$

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

$$\sigma_r = \frac{\sigma_{\rm GSR}}{\sqrt{1 - \beta A(r)}},$$

$$A(r) = \frac{r^2 + R_0^2}{4r^2} - \frac{(r^2 - R_0^2)^2}{8r^3 R_0}\ln\left|\frac{r + R_0}{r - R_0}\right|.$$

For the stellar density, a double power-law distribution is assumed:



*Faccioli et al. 2014, ApJ, 788, 105*

# Rotation curve from HKG sample

Spherical Jeans equation:

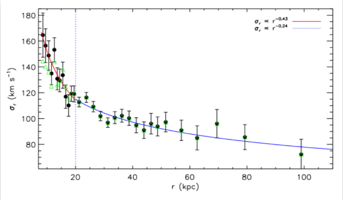
$$V_c^2(R) = -\sigma_r^2\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right),$$

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

$$\sigma_r = \frac{\sigma_{\rm GSR}}{\sqrt{1-\beta A(r)}},$$

$$A(r) = \frac{r^2 + R_0^2}{4r^2} - \frac{(r^2 - R_0^2)^2}{8r^3 R_0}\ln\left|\frac{r+R_0}{r-R_0}\right|.$$

The radial velocity dispersion profile is derived from the observed line-of-sight velocity dispersion:



# Rotation curve from HKG sample

Spherical Jeans equation:

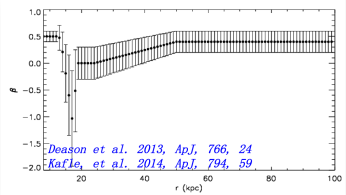
$$V_c^2(R) = -\sigma_r^2\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right),$$

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

$$\sigma_r = \frac{\sigma_{\rm GSR}}{\sqrt{1-\beta A(r)}},$$

$$A(r) = \frac{r^2 + R_0^2}{4r^2} - \frac{(r^2 - R_0^2)^2}{8r^3 R_0}\ln\left|\frac{r+R_0}{r-R_0}\right|.$$

For the anisotropy parameter, adopted the results available in the literature:



*Deason et al. 2013, ApJ, 766, 24*
*Kafle, et al. 2014, ApJ, 794, 59*

# Rotation curve from HKG sample

Spherical Jeans equation:

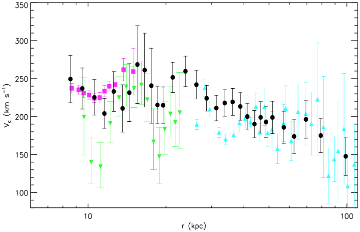
$$V_c^2(R) = -\sigma_r^2\left(\frac{d\,\ln\nu}{d\,\ln r} + \frac{d\,\ln\sigma_r^2}{d\,\ln r} + 2\beta\right),$$

$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

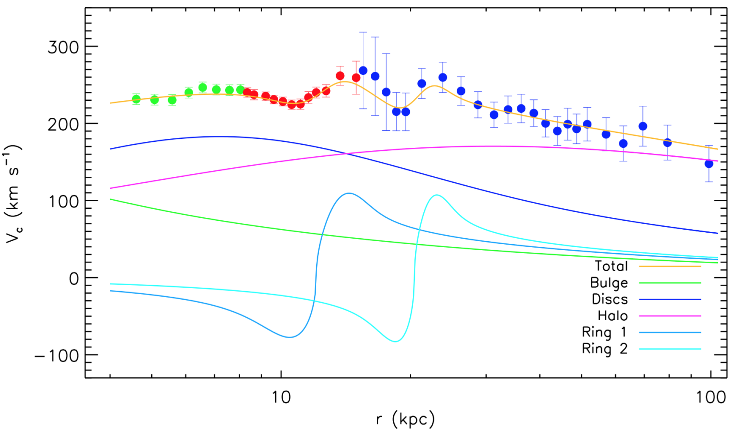
$$\sigma_r = \frac{\sigma_{\rm GSR}}{\sqrt{1-\beta A(r)}},$$

$$A(r) = \frac{r^2+R_0^2}{4r^2} - \frac{(r^2-R_0^2)^2}{8r^3 R_0}\ln\left|\frac{r+R_0}{r-R_0}\right|.$$

The final rotation curve for the halo region:



# Combined rotation curve & Galactic mass distribution



# Combined rotation curve & Galactic mass distribution

$$\rho(R,Z) = \frac{\rho_0}{m^\gamma(1+m)^{\beta-\gamma}} \exp[-(mr_0/r_t)^2],$$

$$m(R,Z) = \sqrt{(R/r_0)^2 + (Z/qr_0)^2},$$

$$\Sigma(R) = \Sigma_{\rm d,0} \exp(-\frac{R}{R_{\rm d}} - \frac{R_{\rm hole}}{R}),$$

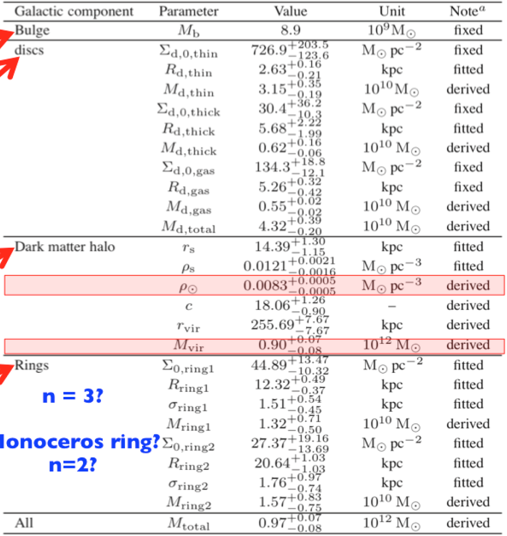
**NFW profile**

$$\rho(r) = \frac{\rho_s}{(r/r_s)[1+(r/r_s)^2]}$$

$$\rho_s = \frac{\rho_{\rm cr}\Omega_{\rm m}\delta_{\rm th}}{3} \frac{c^3}{\ln(1+c) - c/(1+c)}$$

$$\Sigma(R) = \Sigma_{\rm 0,ring} \exp[-\frac{(R-R_{\rm ring})^2}{2\sigma^2_{\rm ring}}].$$

**Caustic dark matter rings:
An ~ 40kpc/n for n=1,2,3,...
(Natarajan & Sikivie 2007)**



| Galactic component | Parameter | Value | Unit | Note[a] |
|---|---|---|---|---|
| Bulge | $M_{\rm b}$ | 8.9 | $10^9\,{\rm M}_\odot$ | fixed |
| discs | $\Sigma_{\rm d,0,thin}$ | $726.9^{+203.5}_{-123.6}$ | ${\rm M}_\odot\,{\rm pc}^{-2}$ | fixed |
| | $R_{\rm d,thin}$ | $2.63^{+0.16}_{-0.21}$ | kpc | fitted |
| | $M_{\rm d,thin}$ | $3.15^{+0.35}_{-0.19}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| | $\Sigma_{\rm d,0,thick}$ | $30.4^{+36.2}_{-10.3}$ | ${\rm M}_\odot\,{\rm pc}^{-2}$ | fixed |
| | $R_{\rm d,thick}$ | $5.68^{+2.22}_{-1.99}$ | kpc | fitted |
| | $M_{\rm d,thick}$ | $0.62^{+0.16}_{-0.06}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| | $\Sigma_{\rm d,0,gas}$ | $134.3^{+18.8}_{-12.1}$ | ${\rm M}_\odot\,{\rm pc}^{-2}$ | fixed |
| | $R_{\rm d,gas}$ | $5.26^{+0.32}_{-0.42}$ | kpc | fixed |
| | $M_{\rm d,gas}$ | $0.55^{+0.02}_{-0.02}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| | $M_{\rm d,total}$ | $4.32^{+0.39}_{-0.20}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| Dark matter halo | $r_{\rm s}$ | $14.39^{+1.30}_{-1.15}$ | kpc | fitted |
| | $\rho_{\rm s}$ | $0.0121^{+0.0021}_{-0.0016}$ | ${\rm M}_\odot\,{\rm pc}^{-3}$ | fitted |
| | $\rho_\odot$ | $0.0083^{+0.0005}_{-0.0005}$ | ${\rm M}_\odot\,{\rm pc}^{-3}$ | derived |
| | $c$ | $18.06^{+1.26}_{-0.90}$ | – | derived |
| | $r_{\rm vir}$ | $255.69^{+7.67}_{-7.67}$ | kpc | derived |
| | $M_{\rm vir}$ | $0.90^{+0.07}_{-0.08}$ | $10^{12}\,{\rm M}_\odot$ | derived |
| Rings | $\Sigma_{\rm 0,ring1}$ | $44.89^{+13.47}_{-10.32}$ | ${\rm M}_\odot\,{\rm pc}^{-2}$ | fitted |
| | $R_{\rm ring1}$ | $12.32^{+0.49}_{-0.37}$ | kpc | fitted |
| | $\sigma_{\rm ring1}$ | $1.51^{+0.54}_{-0.45}$ | kpc | fitted |
| | $M_{\rm ring1}$ | $1.32^{+0.71}_{-0.50}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| | $\Sigma_{\rm 0,ring2}$ | $27.37^{+19.16}_{-13.69}$ | ${\rm M}_\odot\,{\rm pc}^{-2}$ | fitted |
| | $R_{\rm ring2}$ | $20.64^{+1.03}_{-1.03}$ | kpc | fitted |
| | $\sigma_{\rm ring2}$ | $1.76^{+0.97}_{-0.74}$ | kpc | fitted |
| | $M_{\rm ring2}$ | $1.57^{+0.83}_{-0.75}$ | $10^{10}\,{\rm M}_\odot$ | derived |
| All | $M_{\rm total}$ | $0.97^{+0.07}_{-0.08}$ | $10^{12}\,{\rm M}_\odot$ | derived |

**n = 3?**

**Monoceros ring?
n=2?**

- The Galactic rotation curve between 8 and 100 kpc in Galactocentric radius has been constructed using PRCG samples selected from the LSS-GAC and the APOGEE surveys, combined with a sample of halo K giants selected from the SDSS/SEGUE.
- The newly constructed rotation curve has a generally flat value of 240 km/s within a Galactocentric radius r of 25 kpc and then decreases steadily to 150 km/s at r$\sim$100 kpc. On top of this overall trend, the RC exhibits two prominent localized dips, one at r$\sim$11 kpc and another at r$\sim$19 kpc. The dips could be explained by assuming the existence of two massive (dark) matter rings in the Galactic plane.
- From the newly constructed RC, combined with other data, we have built a mass model of the Galaxy, yielding a virial mass of the Milky Way's dark matter halo of $0.9 \times 10^{12} \mathrm{M}_{\odot}$ and a local dark matter density, $\rho_{\mathrm{DM,sun}} = 0.32 \pm 0.02$ GeV cm$^{-3}$.
- More details, see *Huang et al. 2016, MNRAS, in press (arXiv: 1604.01216)*.


LAMOST与银河 ©Jin Ma 2012
2012.08.22 Nikon D90 + 10-24mm, F3.5, 14x30s, ISO2500
WWW.KARAJIN.COM

*Thank You!*