Estimating the mass of the Milky Way from the LAMOST Galactic spectroscopic survey

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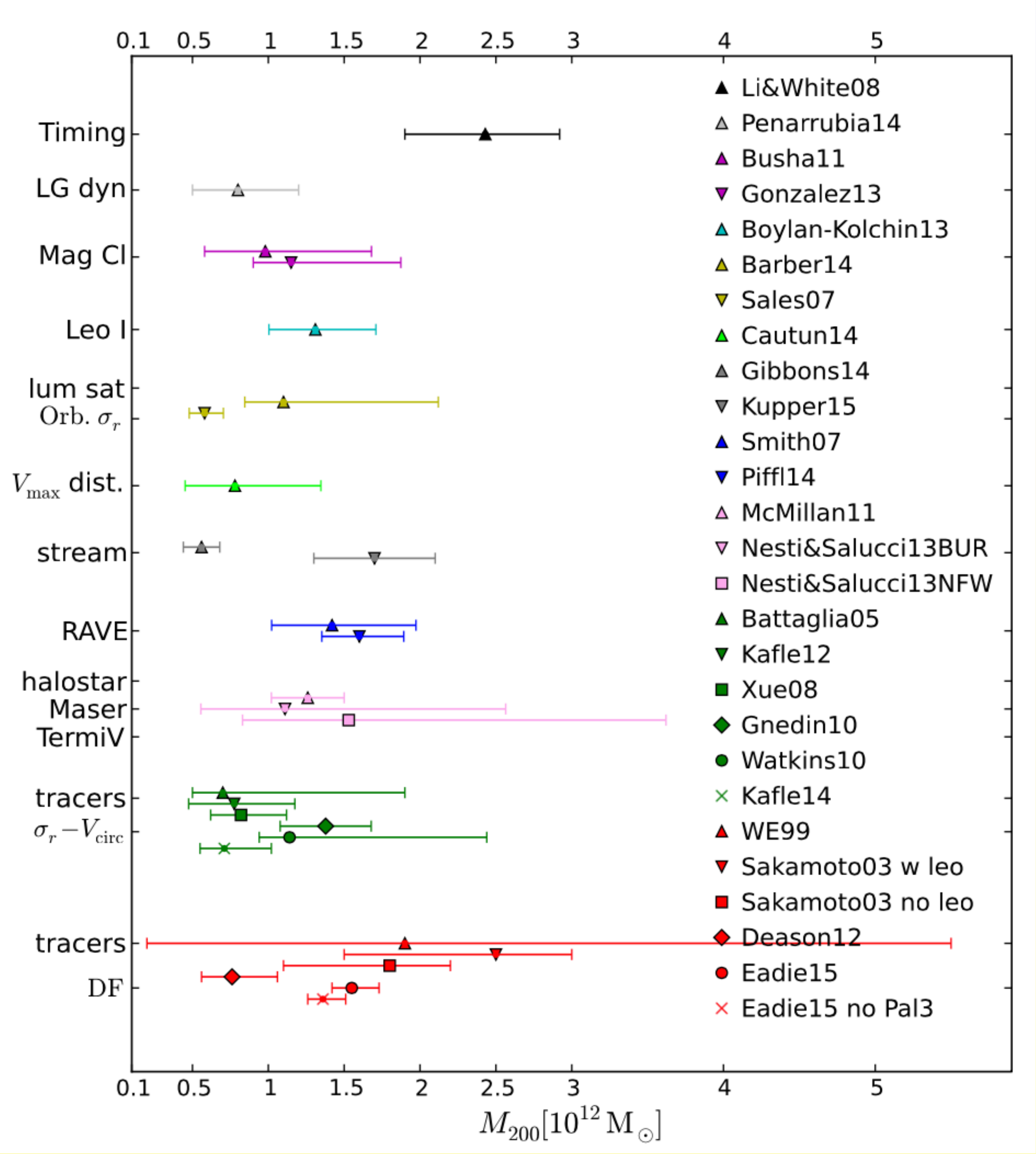
Outline

- **Background**
- **The Galactic rotation curve out to 100 kpc**
- **The Galactic escape velocity curve between 5-14 kpc**
- **Summary & Future prospect**

Background

The mass (profile) of the Milky Way



Wang et al. 2015, MNRAS, 453, 377

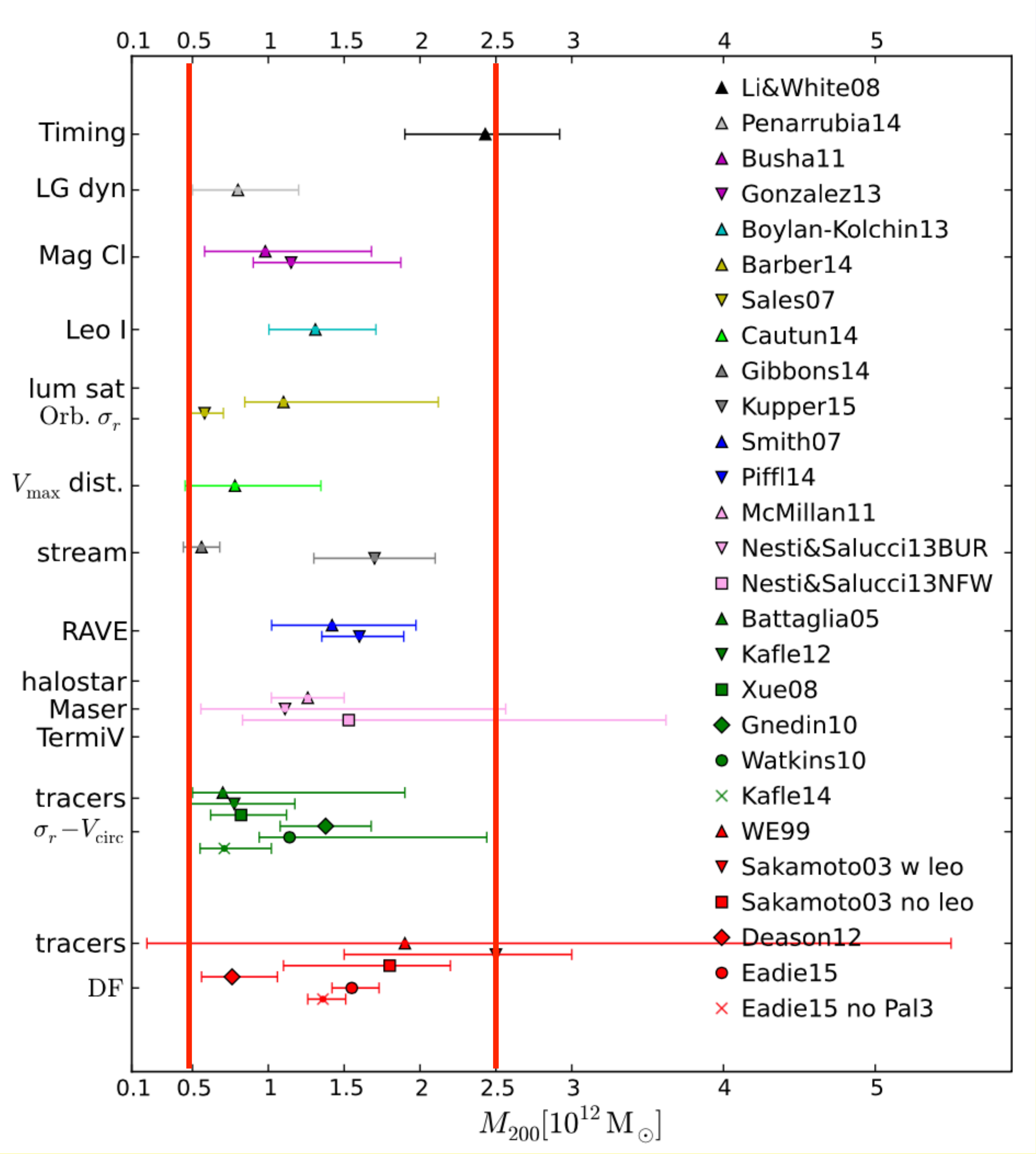
How to estimate the MW's mass?

- Timing argument estimators (e.g. Kahn & Woltjer 1959)
- Modelling of local expansion (Penarrubia et al. 2014)
- Kinematics of bright satellites (e.g. Leo I and Magellanic Clouds; e.g. Sales et al. 2007a,b)
- Kinematics of stellar streams (e.g. Sagittarius stream; e.g. Newberg et al. 2010)
- Galactic rotation curve (e.g. Xue et al. 2008)
- Galactic escape velocity curve (e.g. Smith et al. 2007; Piffl et al. 2014)

Challenges:

- Model dependent (systematics)
- Limited number of tracers (especially the distant one, random errors)
- Incomplete kinematic information

The mass (profile) of the Milky Way



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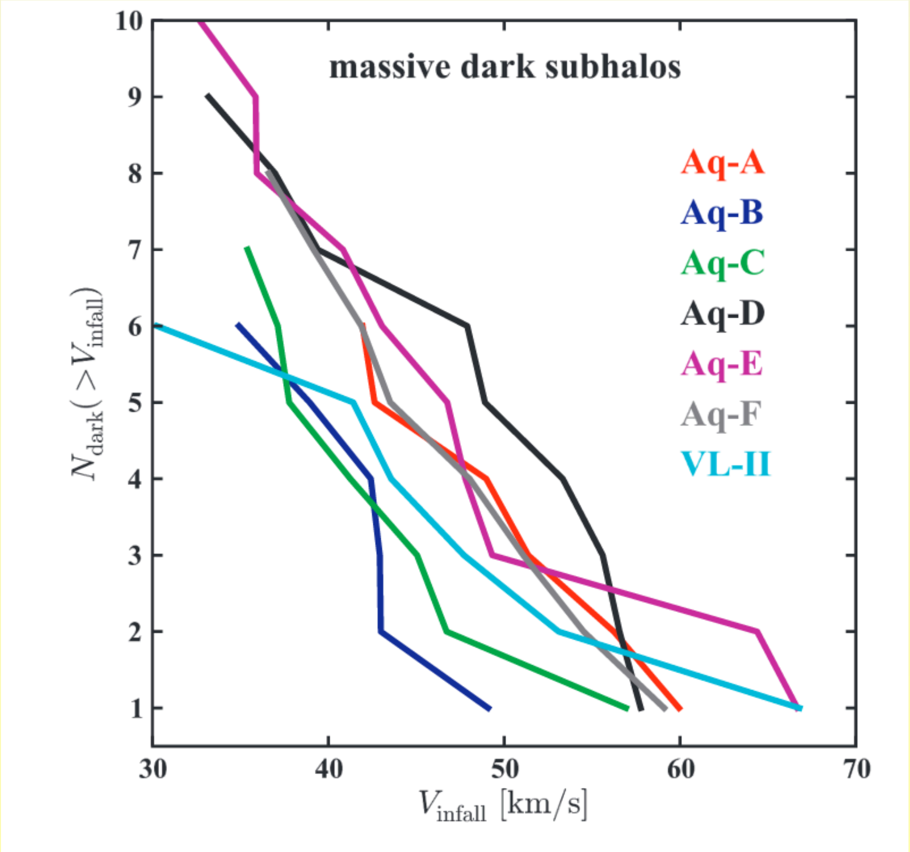
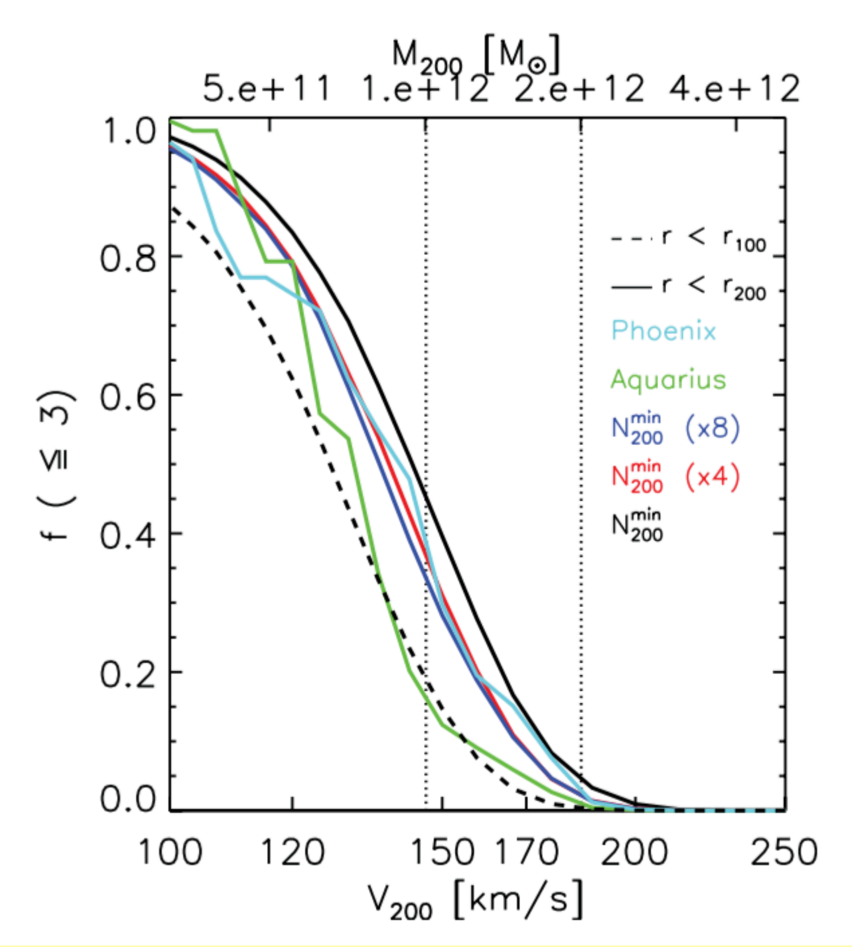
The mass (profile) of the Milky Way

The Milky Way's (MW's) composition, structure, dynamical properties, and formation history are heavily influenced by two important properties: its total mass and mass profile, for examples:

- The missing satellite problem (MSP): the number of subhaloes of a given mass scales directly with the host halo mass (Springel et al. 2008).
- Too big to fail (TBTF): the number of massive subhaloes depends sensitively on the virial mass of the MW.
- Maximal Galactic disk?





Boylan-Kolchin et al. 2011, MNRAS, 415,40 Wang et al. 2012, MNRAS, 424, 2715

Constraining the mass of the Milky Way using LAMOST data

- The Galactic rotation curve out to ~100 kpc (+ data from SDSS/SEGUE & SDSS/APOGEE): Huang et al. 2016, MNRAS, 463, 2623
- The Galactic escape velocity curve: Huang et al. in prep.
- Identifying member stars of (thin) stellar streams (the shape of the dark matter halo): Ongoing
- Surface mass density profile (include the local dark matter density): Ongoing

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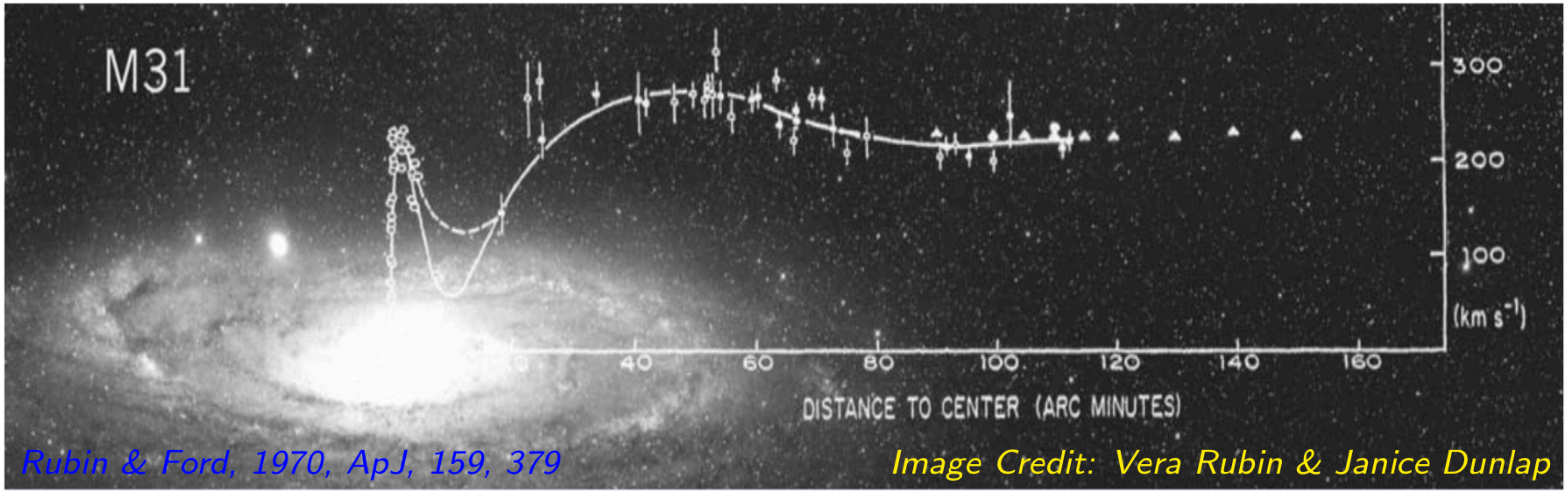
$$V_c^2 = V_{c,\mathrm{disc}}^2 + V_{c,\mathrm{bulge}}^2 + V_{c,\mathrm{halo}}^2 + V_{c,\mathrm{ring}}^2.$$

$$\frac{1}{2}V_{\mathrm{esc}}^2 = |\Phi_{\mathrm{bulge}}| + |\Phi_{\mathrm{discs}}| + |\Phi_{\mathrm{halo}}| + |\Phi_{\mathrm{ring}}|$$

The Galactic rotation curve out to 100 kpc

I. The Milky Way's rotation curve out to 100 kpc

Rotation curves



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.

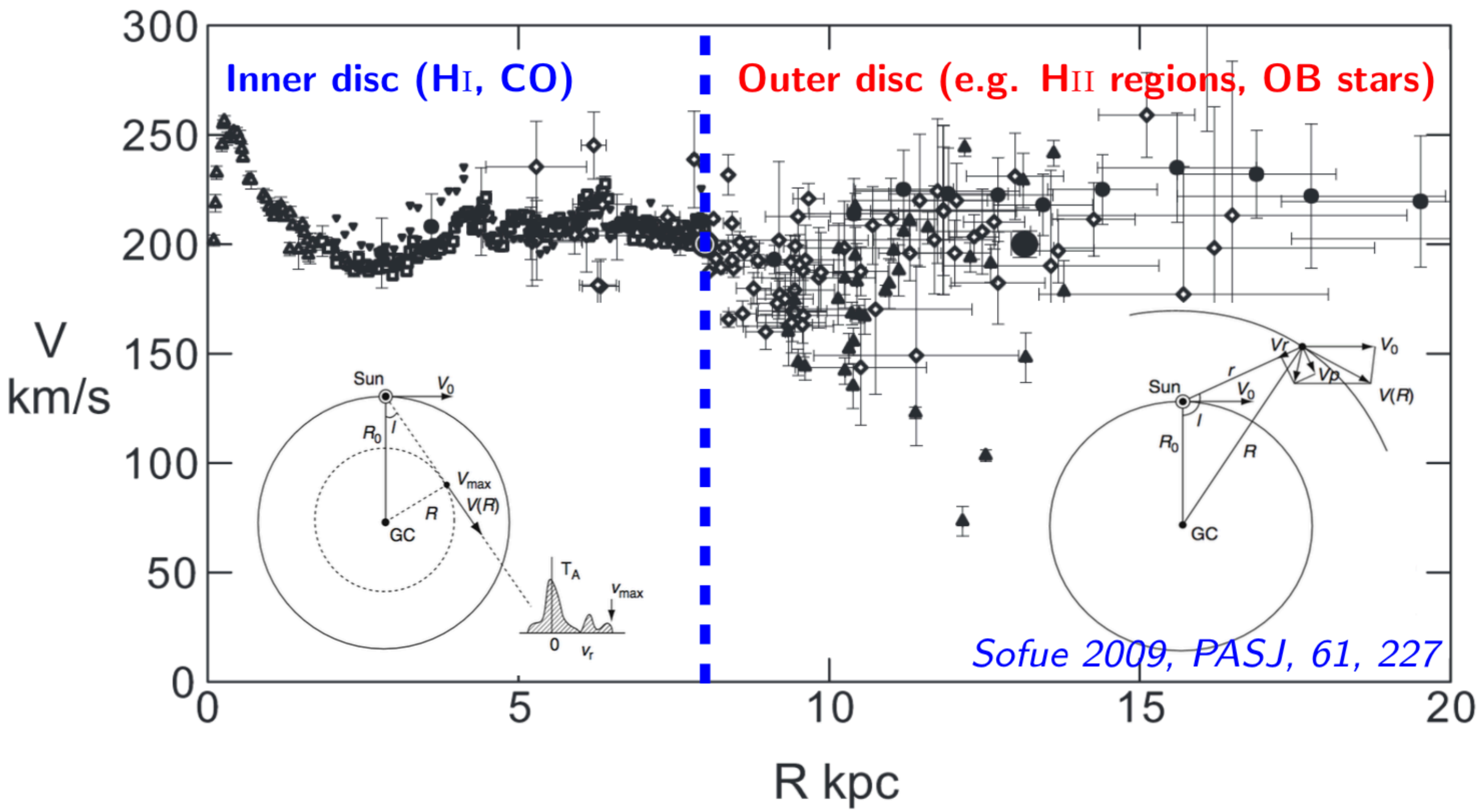
2. Evidence for dark matter

- 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**.

I. The Milky Way's rotation curve out to 100 kpc

Rotation curves of the Milky Way: disc tracers

- Tangent-point method
- Radial velocity & distance analysis



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

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

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

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

Challenges:

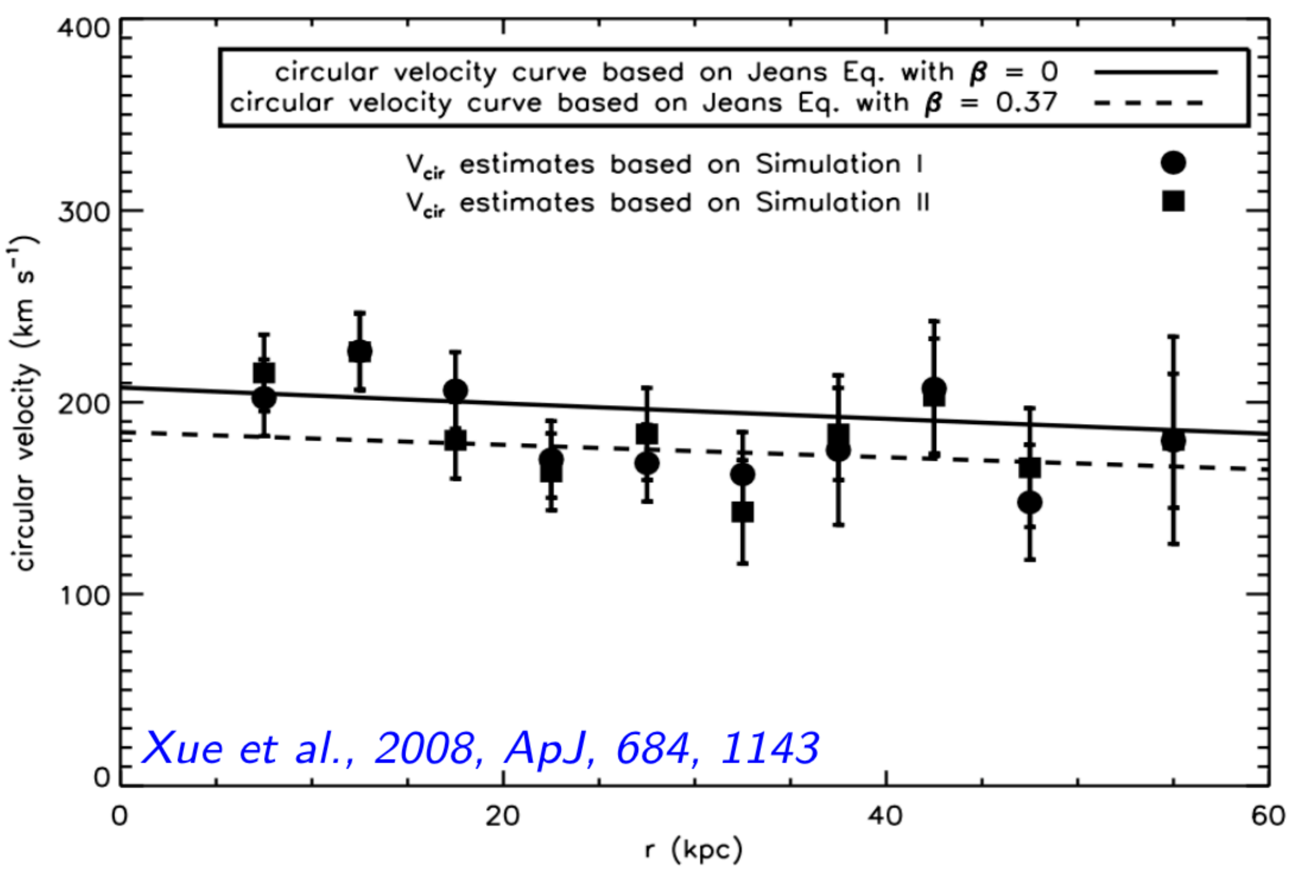
1. **Poorly distance determinations** in the outer Galactic disc
2. **Significant perturbations** by non-axisymmetric structures (e.g. central bar, spiral arms)

Image Credit: R. Hurt

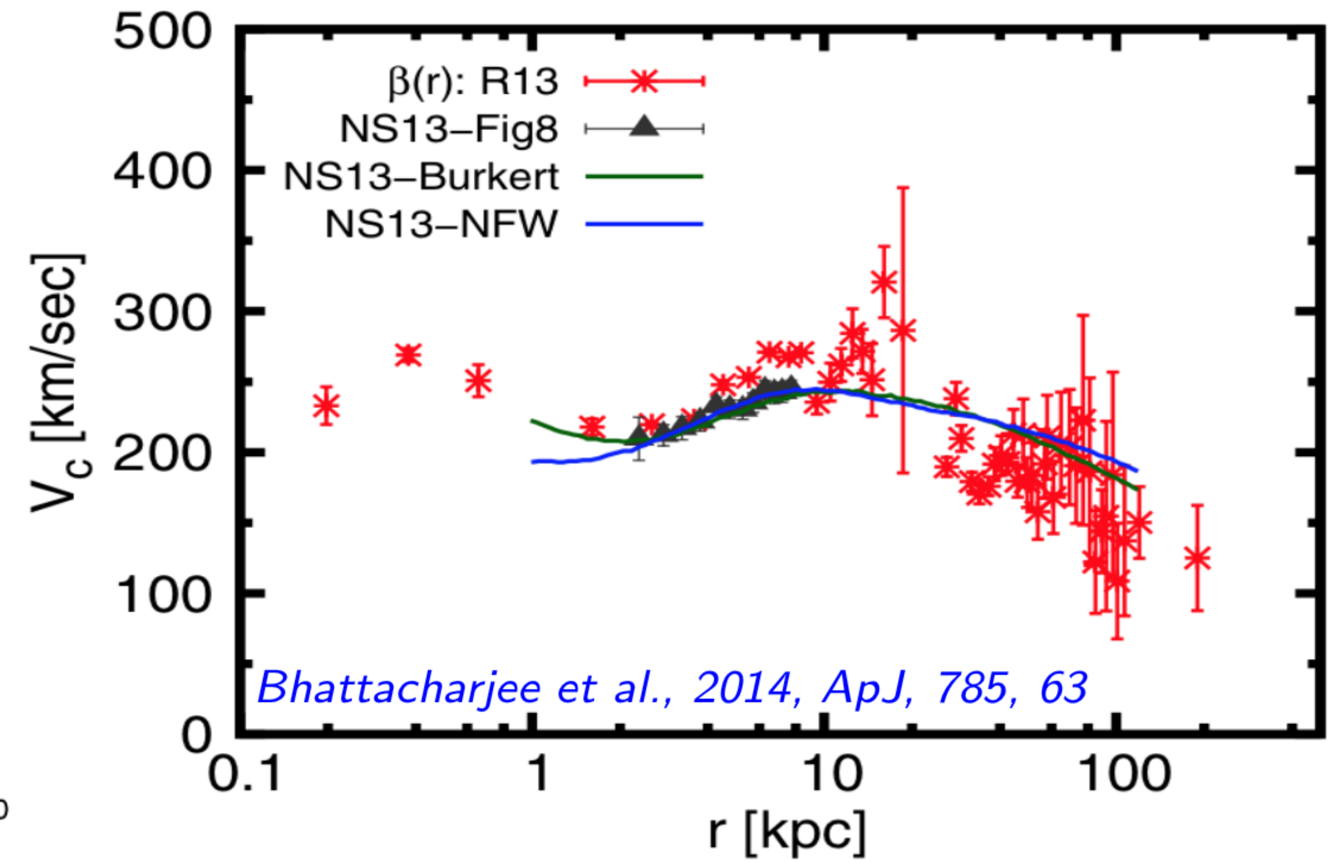
I. The Milky Way's rotation curve out to 100 kpc

Rotation curves of the Milky Way: halo tracers

- **2401 BHB stars**



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



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

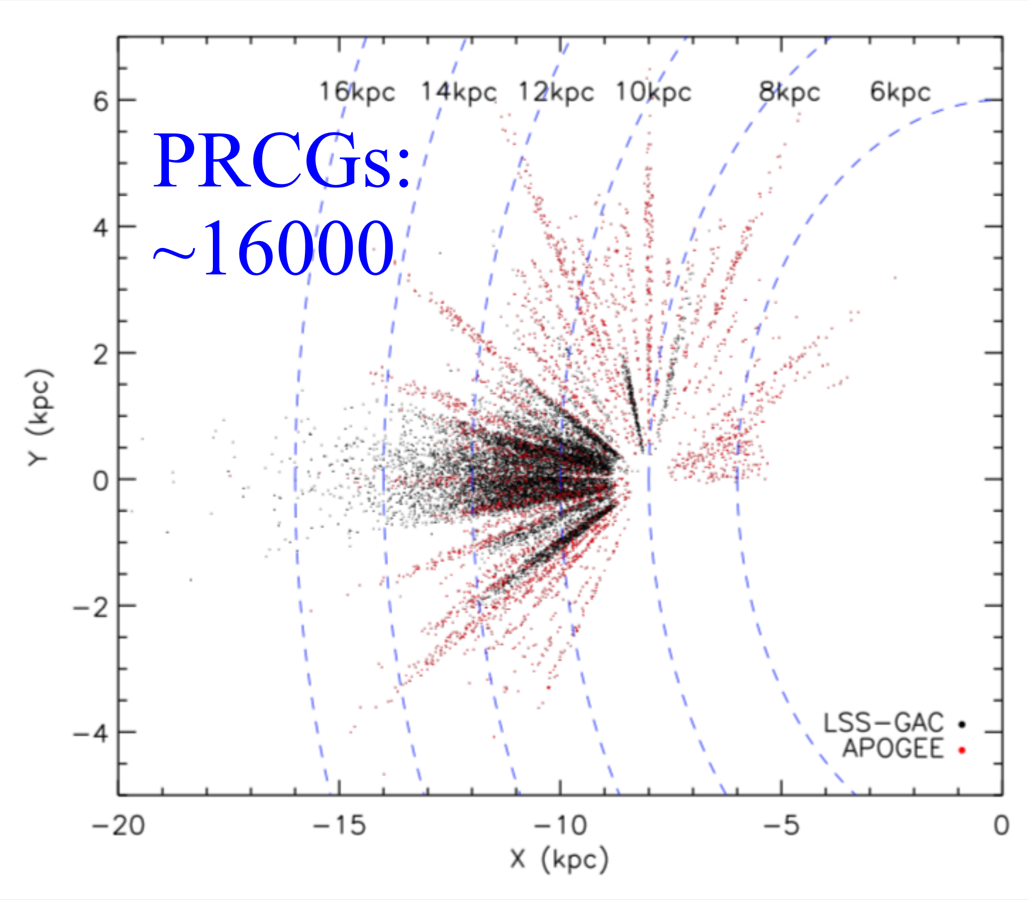
I. The Milky Way's rotation curve out to 100 kpc

Data to construct the the Galactic rotation curve

For the (outer) disk region:

PRCGs: select from the LSS-GAC DR2 (Liu et al. 2014; Yuan et al. 2015) and SDSS-III/APOGEE (Majewski et al. 2015) by Huang et al. (2015b) and Bovy et al. (2014); respectively.

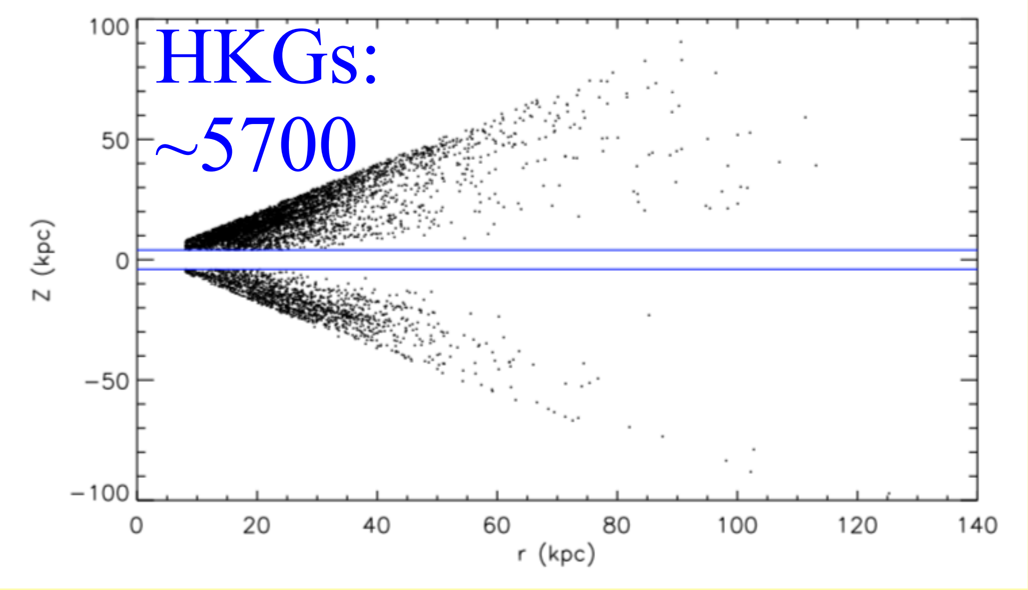
- PRCGs are warm populations: insensitive to the perturbations of non-axisymmetric structures
- PRCGs are standard candles (distance accuracy: 5-10%)



For the halo region:

Halo K giants (HKGs): select from SDSS/SEGUE (Yanny et al. 2009) by Xue et al. (2014).

- HKGs are bright and also span a large range in absolute magnitude (-3 < Mr < 1 mag)



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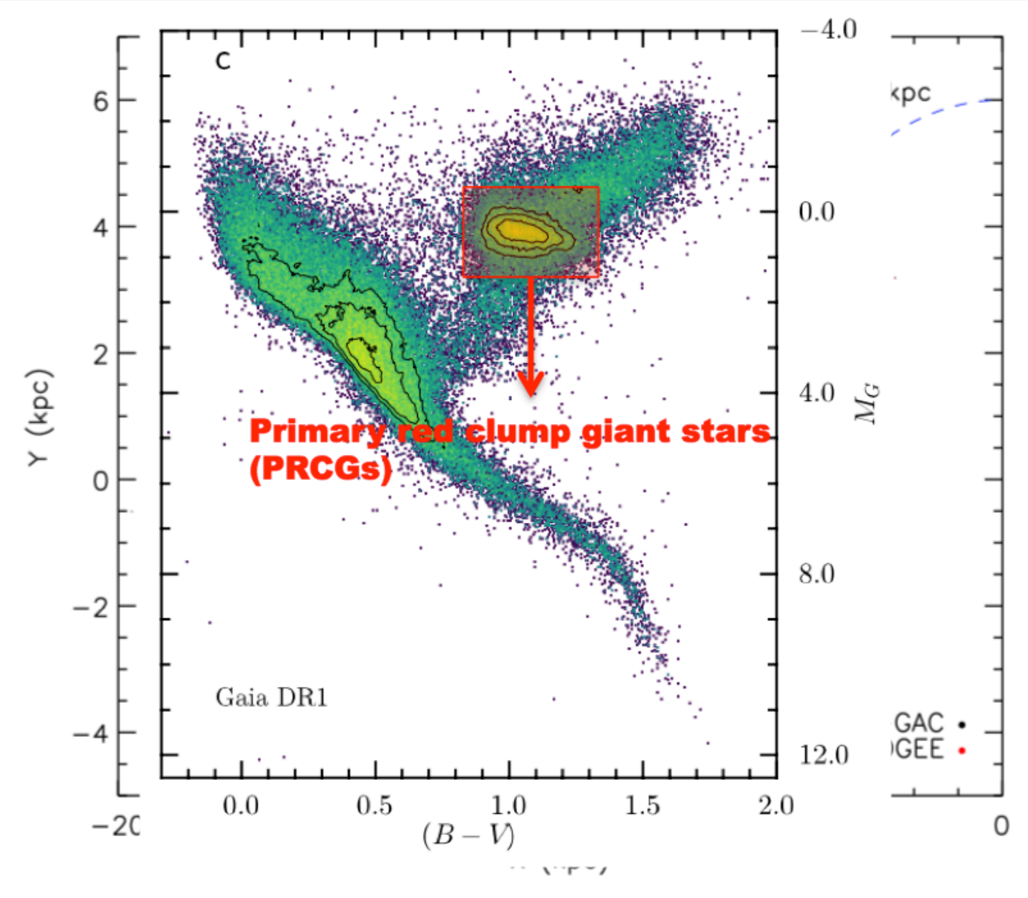

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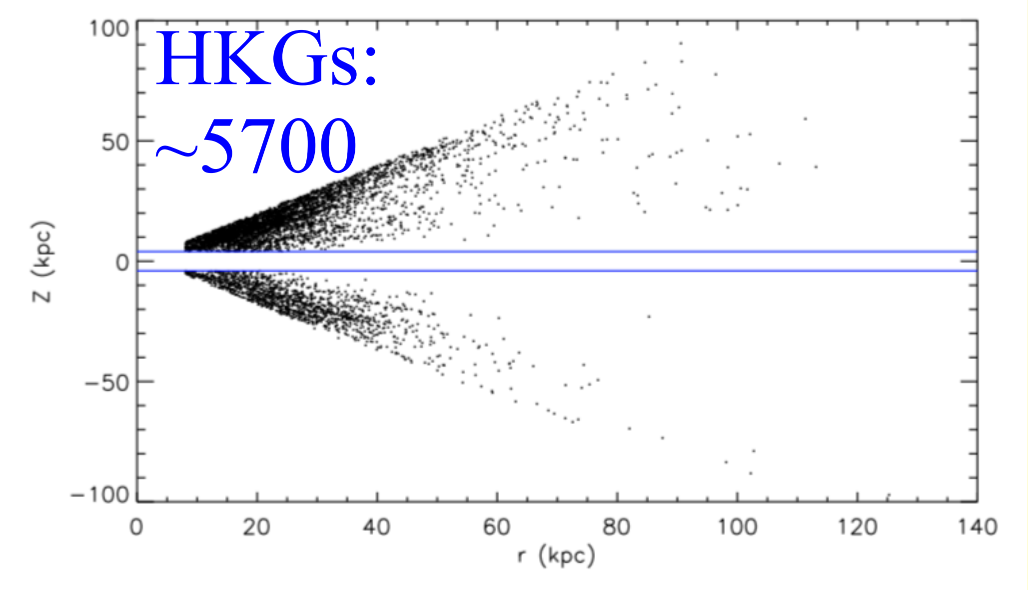
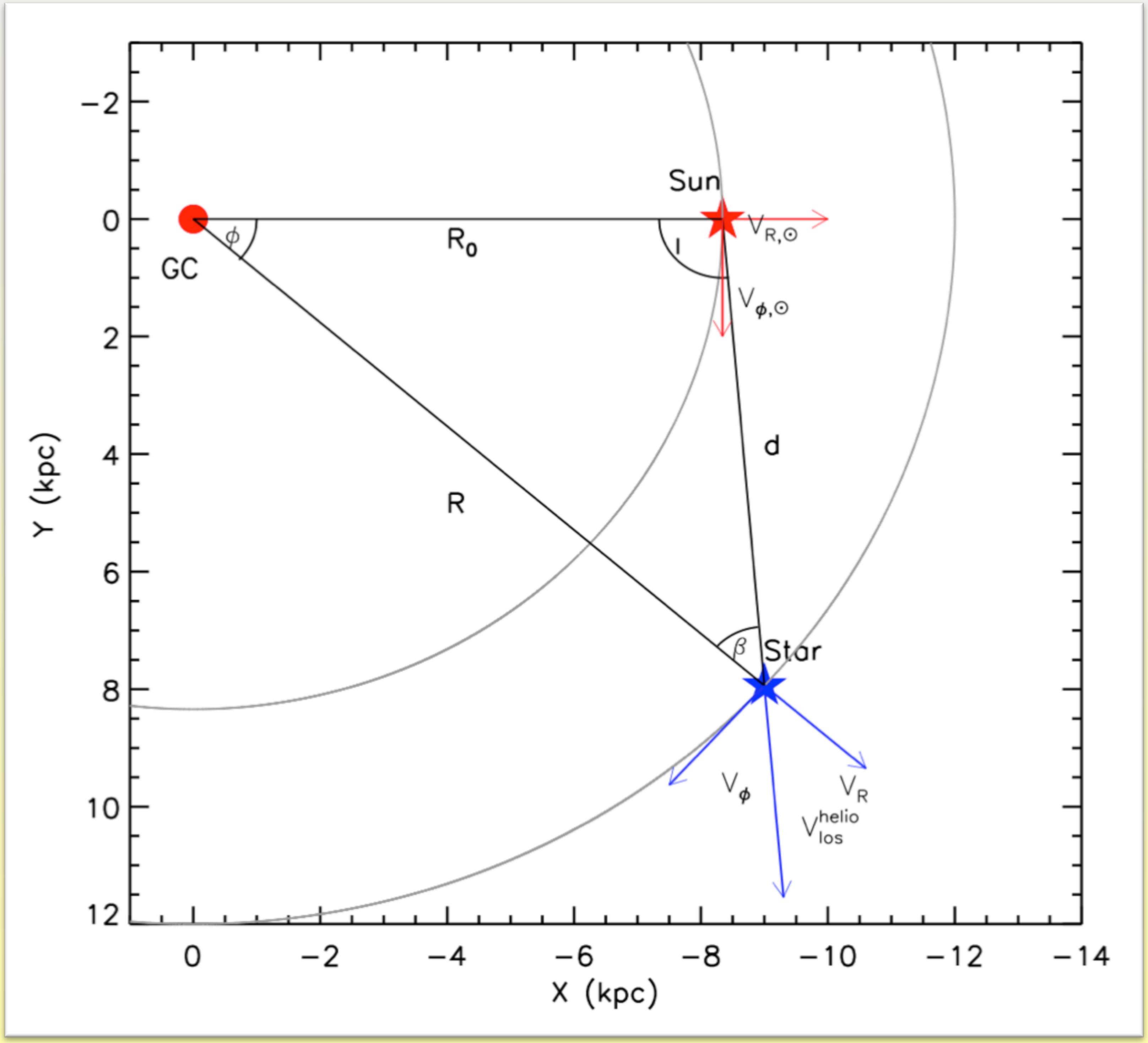


I. The Milky Way's rotation curve out to 100 kpc

Galactic rotation curve for outer disk region with PRCG sample



Kinematic model

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

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

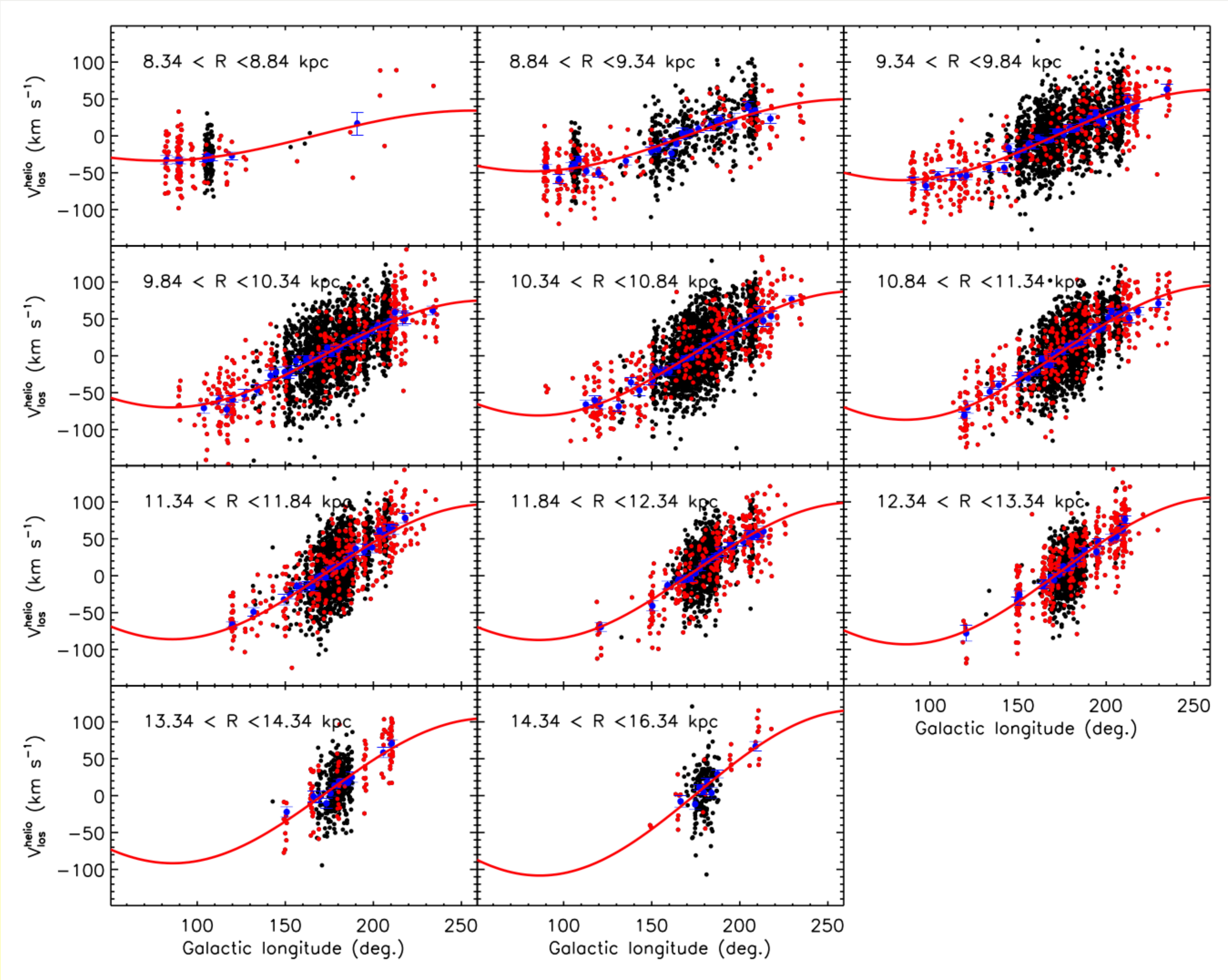
$$\beta = \sin^{-1}\left(\frac{R_0}{R}\sin l\right).$$

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

$R_{\rm d}$ (kpc)	2.5	–
σ_ϕ^2/σ_R^2	0.5	–
R_σ (kpc)	16.40	this work
σ_{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

I. The Milky Way's rotation curve out to 100 kpc

Galactic rotation curve for outer disk region with PRCG sample



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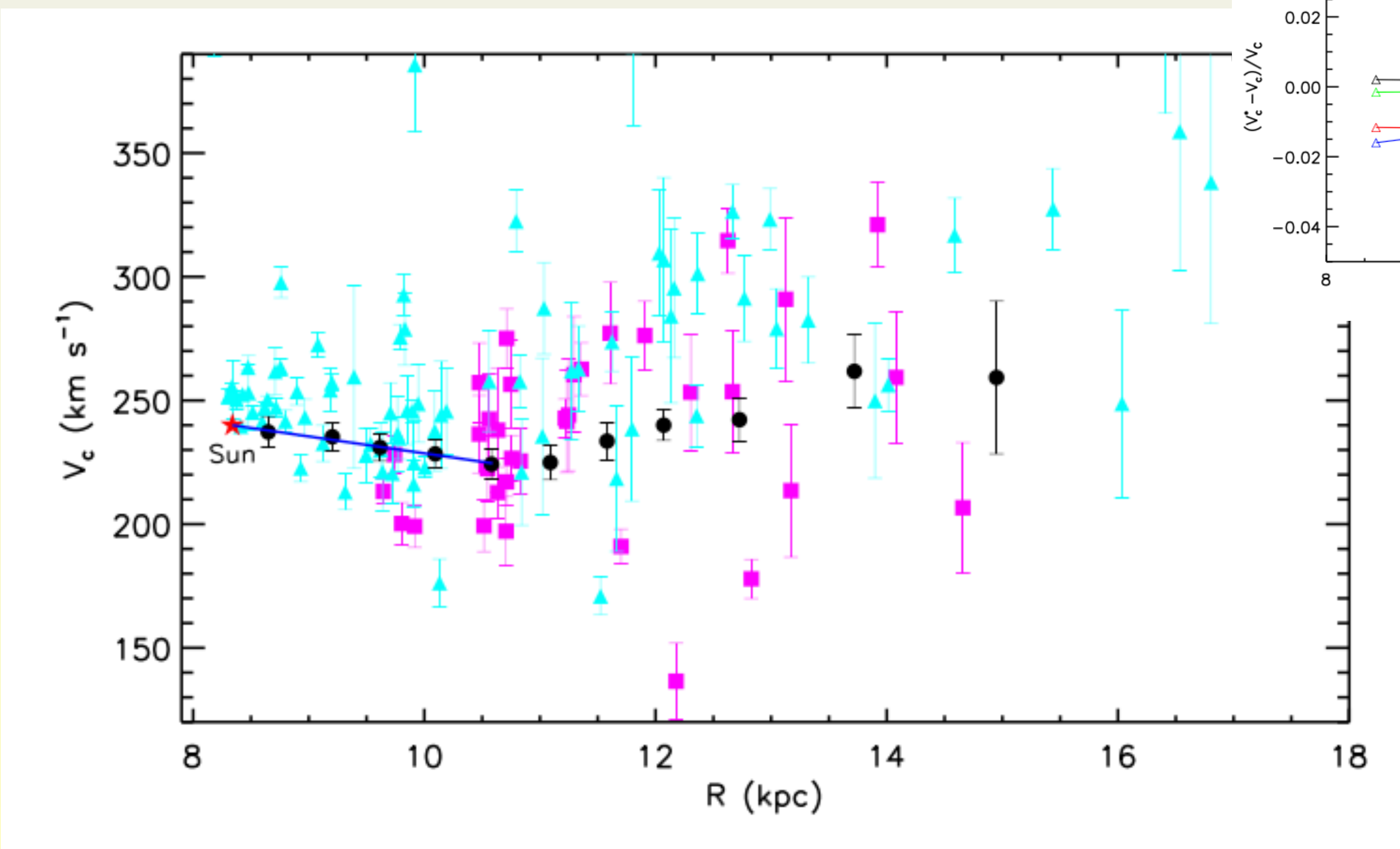
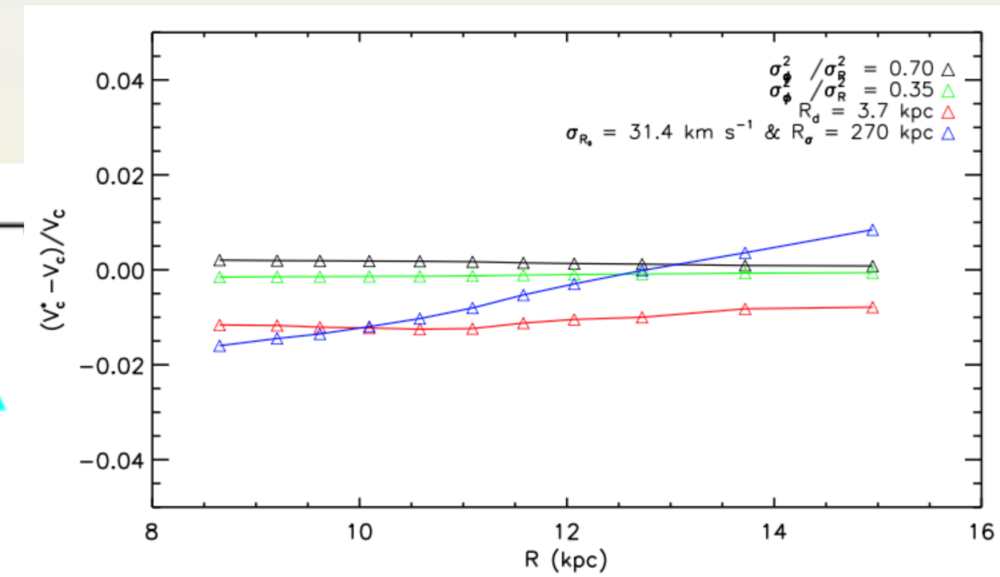




The systematic errors of RC resultant as a consequence of our adopted canonical values of parameters are likely to be smaller than 2 per cent(~5km/s).

I. The Milky Way's rotation curve out to 100 kpc

Galactic rotation curve for halo region with halo HKG sample

Spherical Jean equation (Jeans 1915):

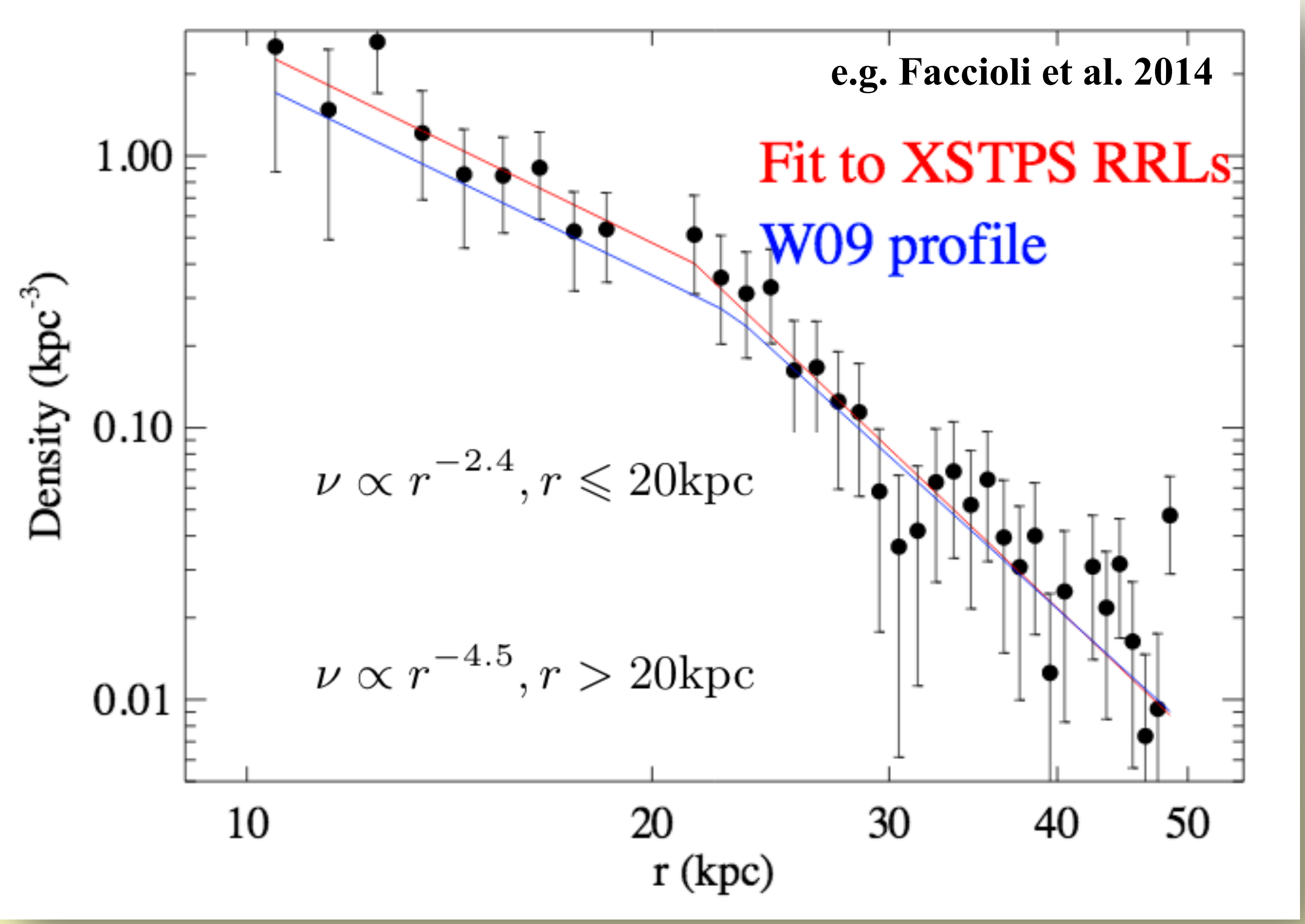
$$V_c^2(R) = -\sigma_r^2\left(\frac{d\,\mathrm{ln}\nu}{d\,\mathrm{ln}r} + \frac{d\,\mathrm{ln}\sigma_r^2}{d\,\mathrm{ln}r} + 2\beta\right),$$

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

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

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

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



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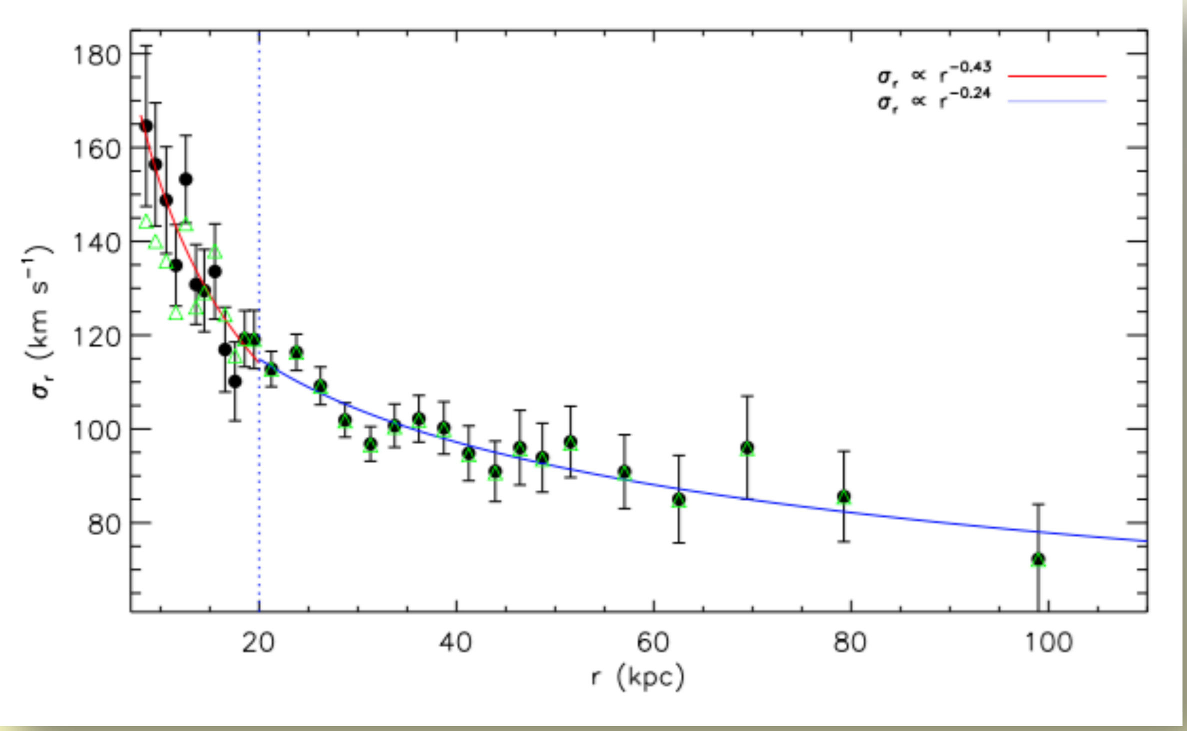
For the radial velocity dispersion, again a double power-law distribution is assumed:



I. The Milky Way's rotation curve out to 100 kpc

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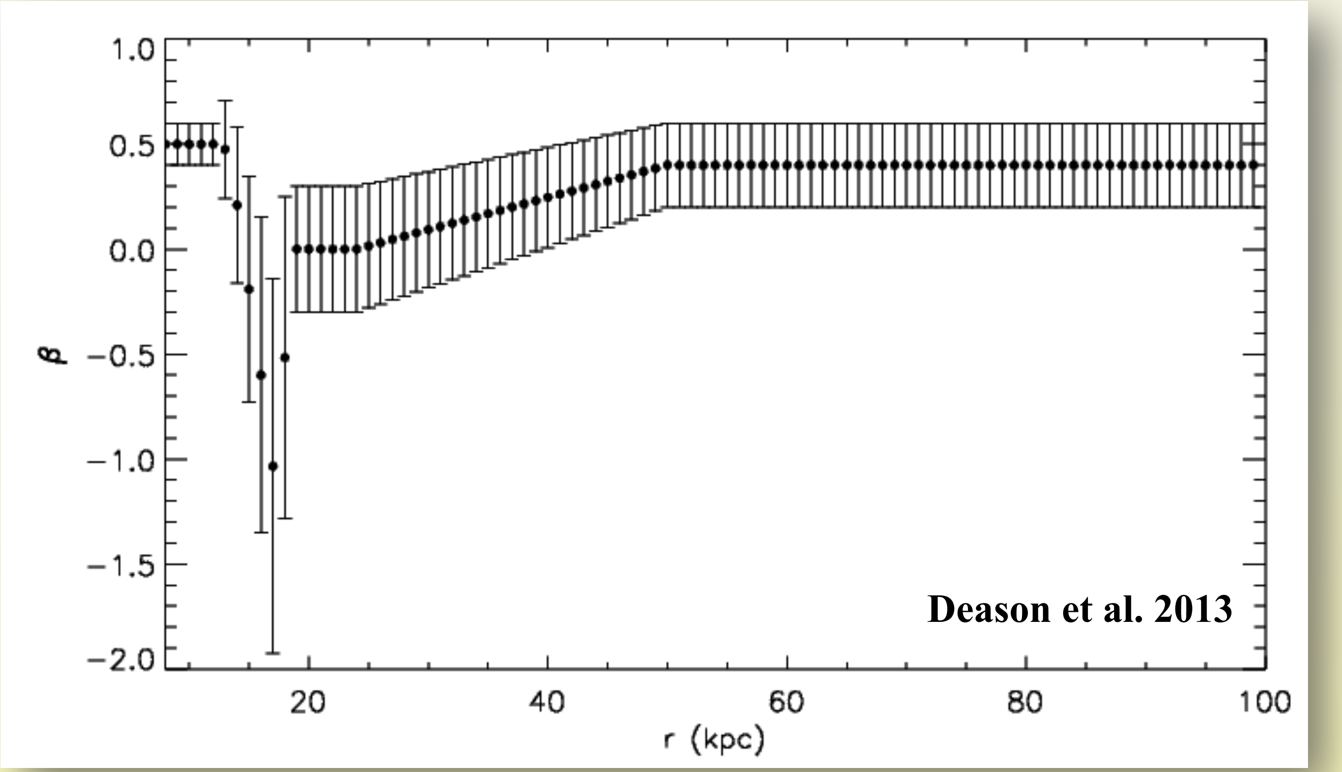
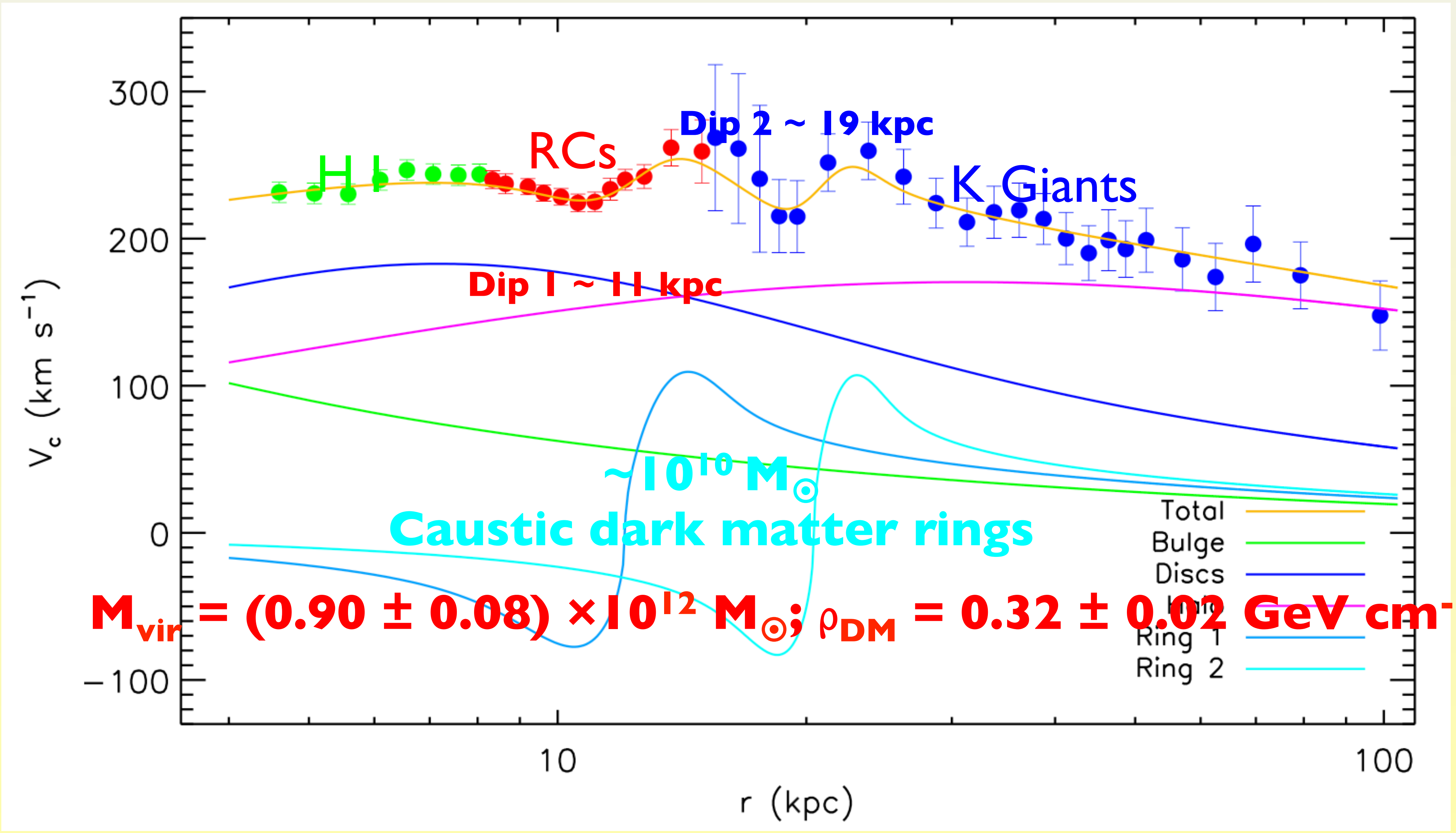
For the anisotropy parameter, adopted from the current literature available:



I. The Milky Way's rotation curve out to 100 kpc

- **Hitherto the most accurate Galactic rotation curve extending to 100 kpc based on 12000 selected from LSS-GAC DR2 and 4000 selected from APOGEE low Galactic latitude (|b| < 3°) primary red clump stars, and 6000 halo K giants selected from SDSS**
- **The data establish the existence of two localized dips in the rotation curve, at 11 and 19 kpc, respectively**



I. The Milky Way's rotation curve out to 100 kpc

McMillan 2011

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

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

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

NFW profile

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

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

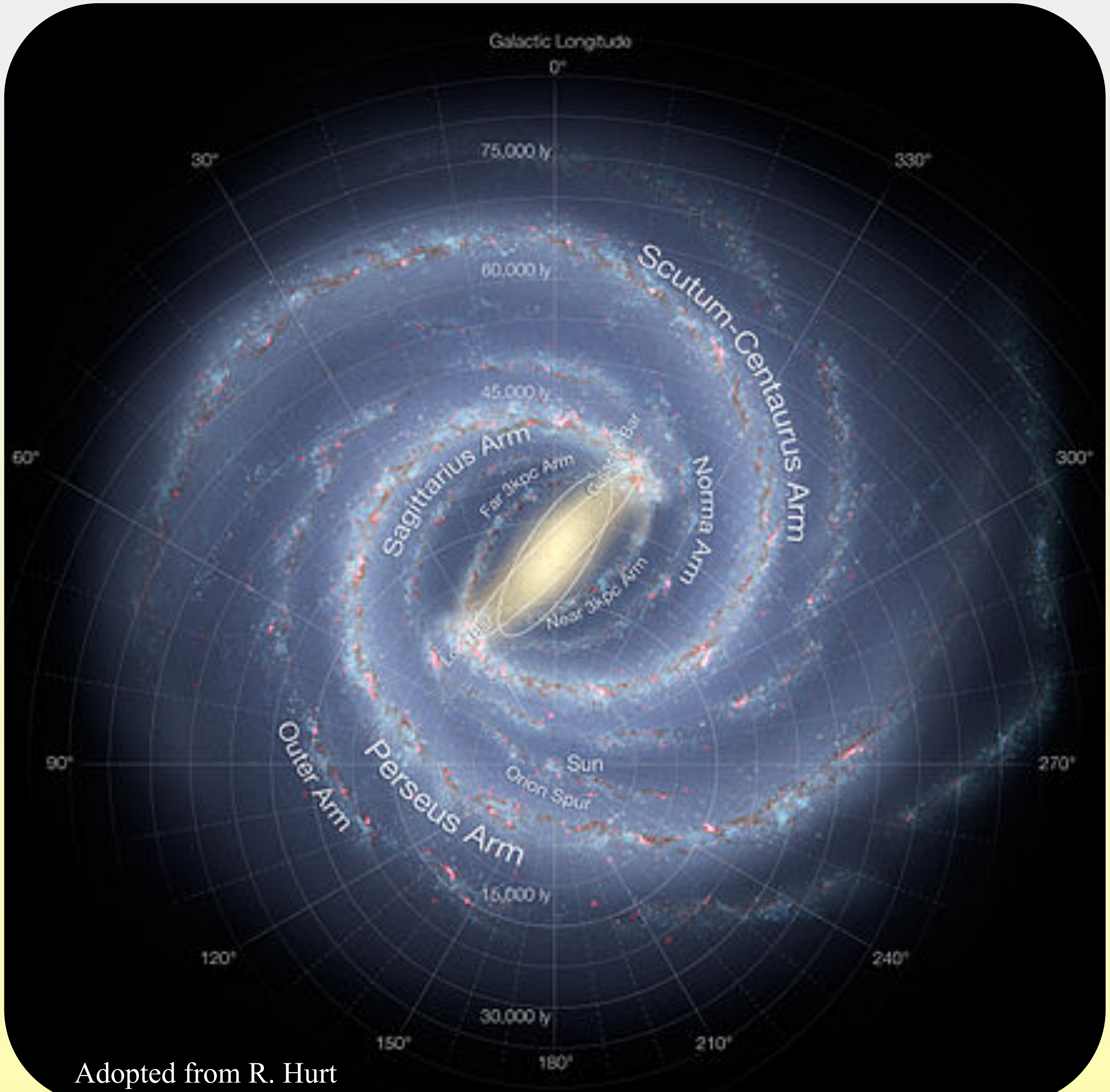
$$\Sigma(R) = \Sigma_{0,ring} \exp[-\frac{(R-R_{ring})^2}{2\sigma_{ring}^2}].$$

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

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

The Galactic escape velocity curve between 5-14 kpc

II. The Galactic escape velocity curve between 5-14 kpc



The Galactic escape speed at a position ***r*** is hence defined as the minimum speed needed for an object to escape the gravity at that position of the Galaxy.

Specially, we call the escape speed at solar position as local escape speed.

The determination of the escape speed is very **important** for, e.g. Galaxy trek, constraining the mass distribution of the Milky Way.

II. The Galactic escape velocity curve between 5-14 kpc

Table 1. Measurements of the local escape velocity in the literature.

Source	$V_e(R_0)$ ($\mathrm{km\,s^{-1}}$)	Method
Oort (1928)	$\geqslant 65 + \Theta_0$	Keplerian method
Schmidt (1956)	> 280	
Schmidt (1965)	380	
Caldwell & Ostriker (1981)	640 ± 96	Highest velocity star in the solar neighborhood
Alexander (1982)	> 450	
Sandage & Fouts (1987)	> 450	
Carney, Latham & Laird (1988)	> 500	
Cudworth (1989)	> 475	
Leonard & Tremaine (1990) LT90	450 - 650	Velocity distribution of local high velocity stars
Kochanek (1996) K96	489 - 730	
Smith et al. (2007) S06	544^{+64}_{-46}	
Pifil et al. (2014) P14	533^{+54}_{-41}	

II. The Galactic escape velocity curve between 5-14 kpc

Methodology

$$L(v_{||}) = \frac{(v_{\rm esc} - |v_{||}|)^{k+1}}{\int_{v_{\rm min}}^{v_{\rm esc}} {\rm d}v\,(v_{\rm esc} - |v_{||}|)^{k+1}} = (k+2)\frac{(v_{\rm esc} - |v_{||}|)^{k+1}}{(v_{\rm esc} - v_{\rm min})^{k+2}}$$

$$f_{\rm r}(v_{\rm r}\,|\,v_{\rm esc}, k) \propto (v_{\rm esc} - v_{\rm r})^{k+1}.$$

Used by LT90 & P14

$$f_{\rm r}(v_{\rm r}\,|\,v_{\rm esc}, k) \propto \left(v_{\rm esc}^2 - v_{\rm r}^2\right)^{k+1}.$$

Used by K96 & S07

Challenges:

- Distribution function of stellar velocities around $v_{\rm esc}$
  - **Taylor series expansion**
  - **The exponent index k**
- The high velocity star (**halo populations**) **sample** defined by $v_{\rm GSR} > v_{\rm min}$

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Disk contaminations

- The high velocity star (**halo populations**) **sample** defined by $v_{\rm GSR} > v_{\rm min}$

Sample size

Radial velocity error

The choice of $v_{\rm min}$

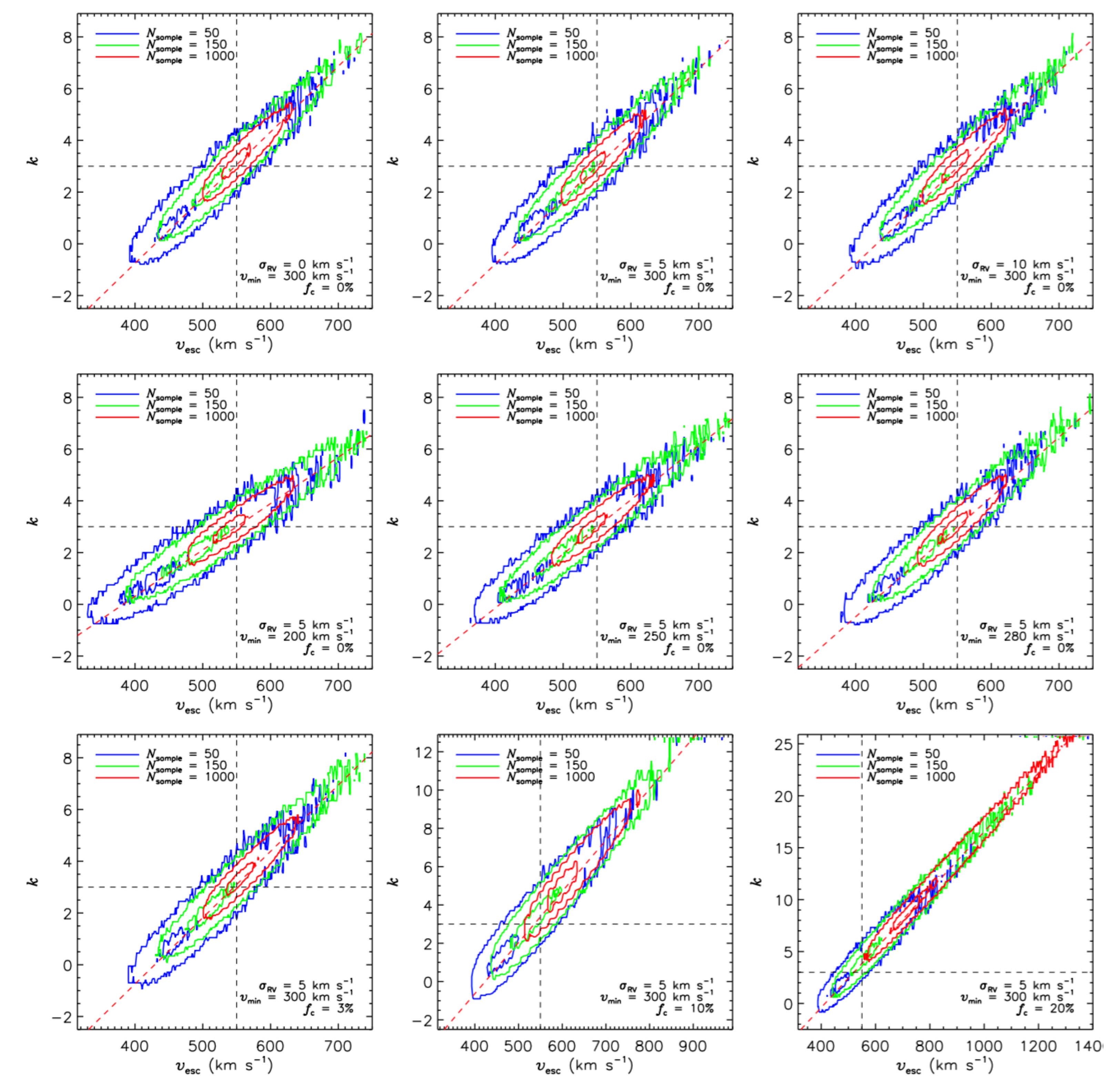
II. The Galactic escape velocity curve between 5-14 kpc

General behavior of the method

Radial velocity error

Different v_{min}

Contaminations



- **The radial velocity errors** (at least for most of current surveys) have **minor effect** in the determination of v_{esc}
- Only sample size larger than **500**, you can determine v_{esc} and v_{min} simultaneously; otherwise you need a **proper prior of k**
- The larger value of v_{min}, the weaker the degeneracy between v_{esc} and k; but also the smaller the sample size
- The disk contaminations must be controlled , at least, smaller than **5%**

II. The Galactic escape velocity curve between 5-14 kpc

General behavior of the method

The bases to a reliable estimate of v_{esc} based on the current method

- **A proper knowledge of *k* if the sample size is not large enough (say smaller than 500)**
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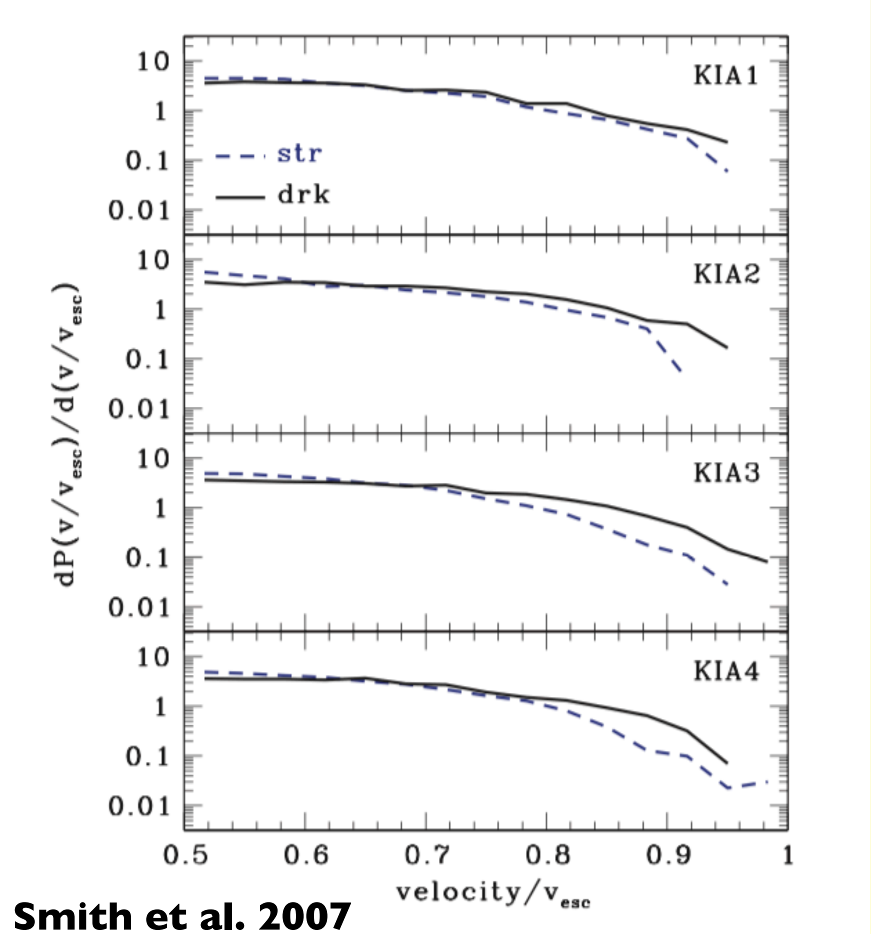

Smith et al. 2007

- $k = 1 - 3$ used by LT90
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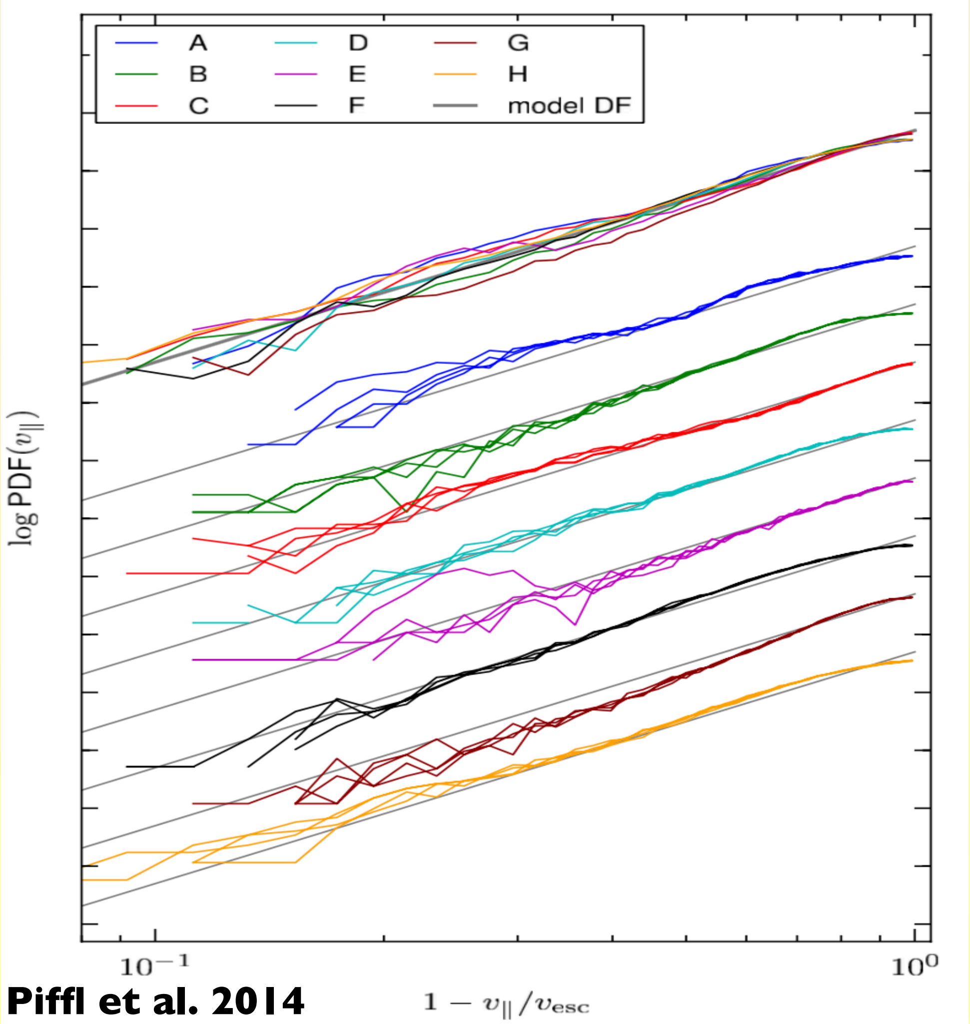

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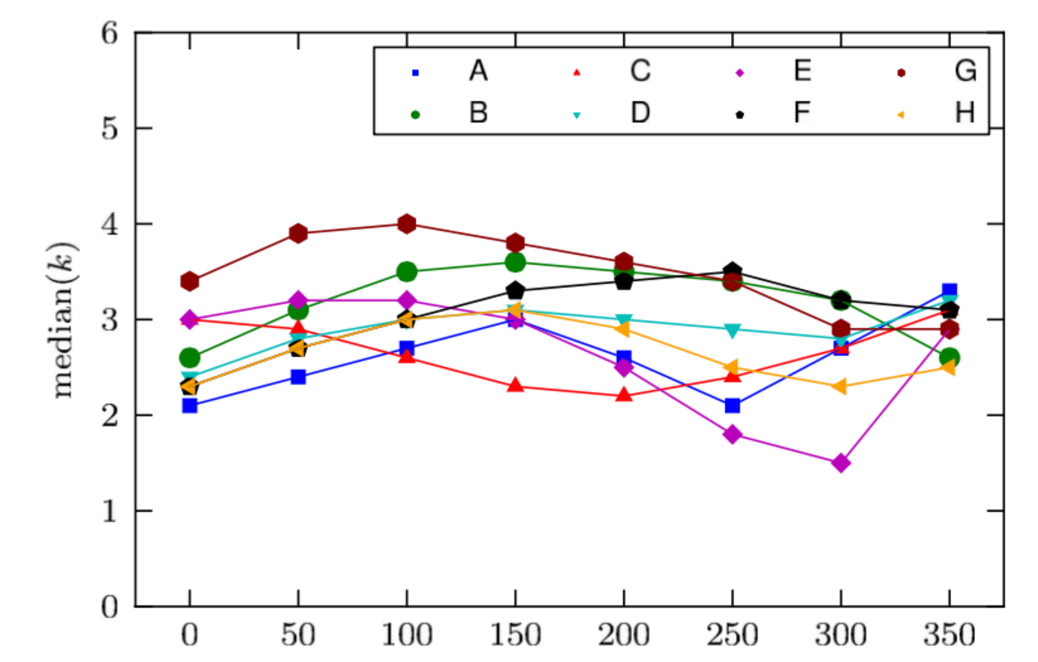
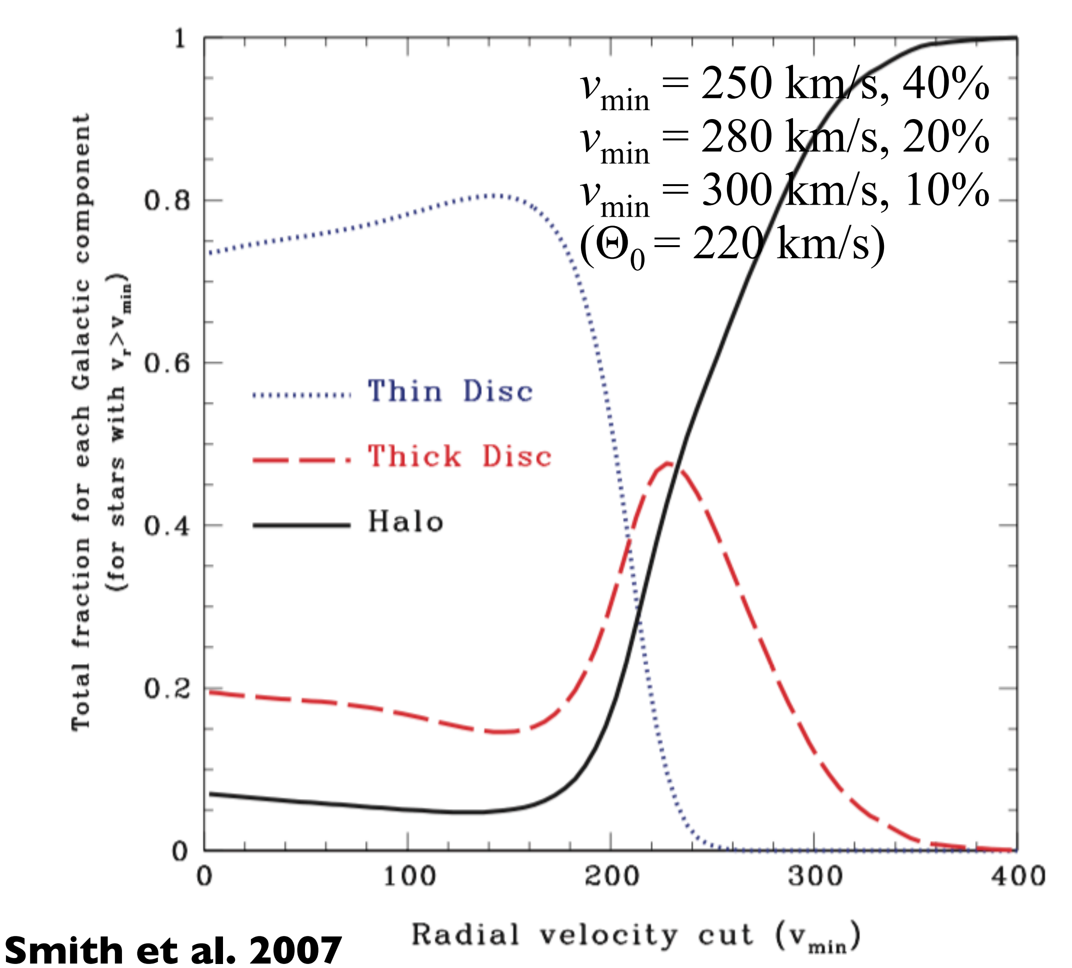


Piffl et al. 2014



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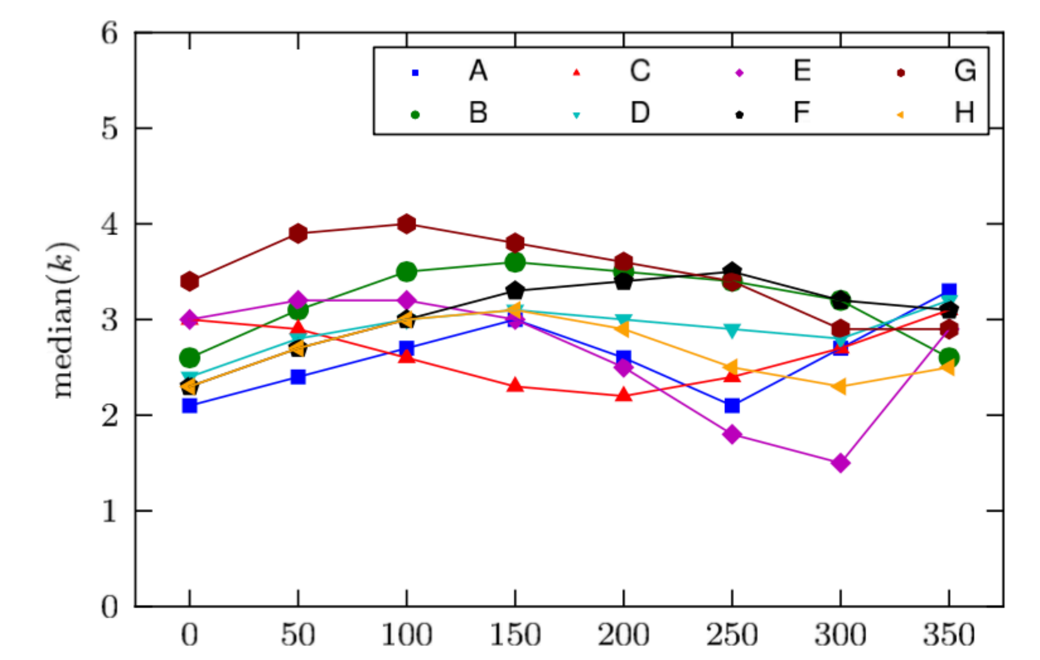

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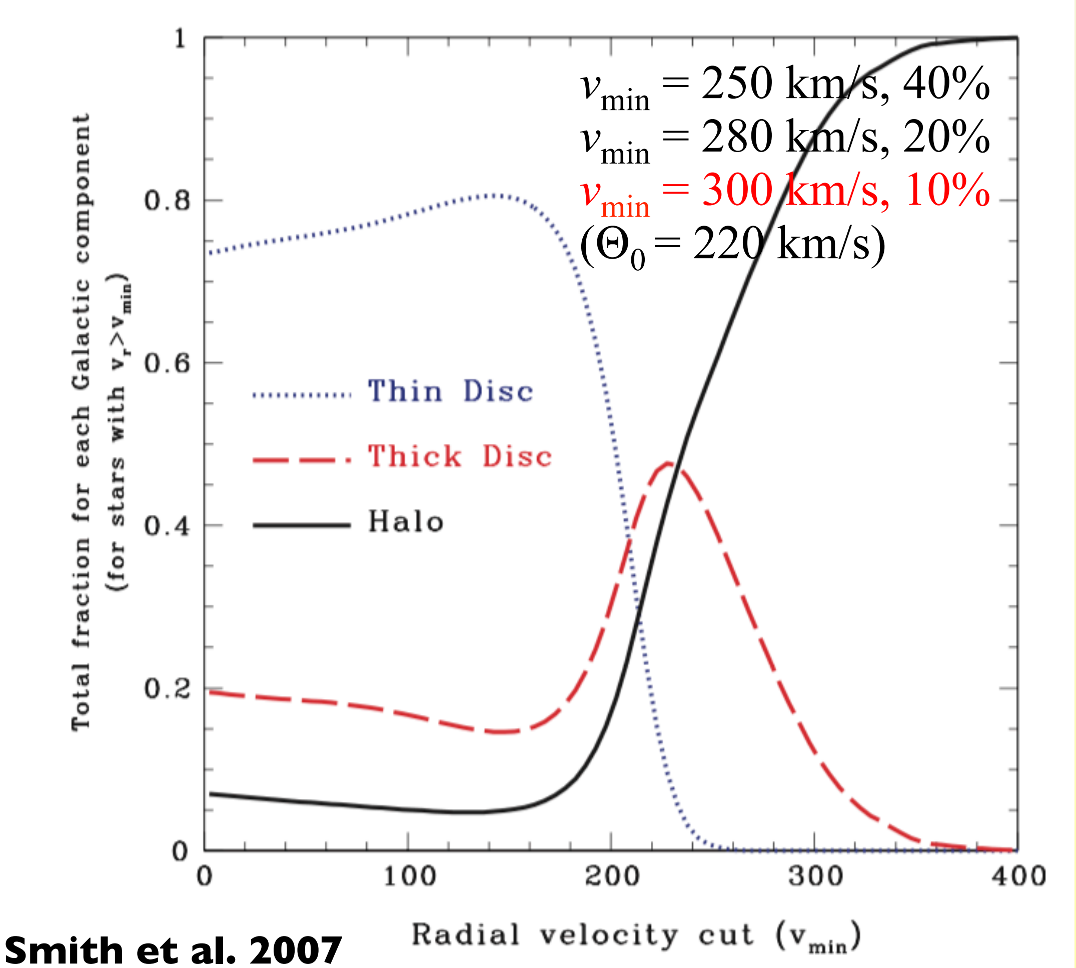

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The current (local) high (radial) velocity star sample:

- Leonard & Tremaine (1990): 15 stars with V_{GSR} > 250 km/s
- Kochanek (1996): 31 stars with V_{GSR} > 250 km/s (10 stars with V_{GSR} > 300 km/s)
- Smith et al. (2007): 33 stars with V_{GSR} > 300 km/s
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Given the enormous number of spectra observed by LAMOST, it is very promising to build a sample with the largest number of high radial velocity stars.

II. The Galactic escape velocity curve between 5-14 kpc

Data

Up to 2016/06, a total of ~7 million spectra with SNR (4650 Å) > 10

- **Objtype: 'star'**
- **Have stellar parameters (Teff, logg, [Fe/H], RV) measured by LSP3**
- **3500 < Teff < 6500 K (FGK stars)**
- **Unique star (if multiple, choose the one with highest SNR)**

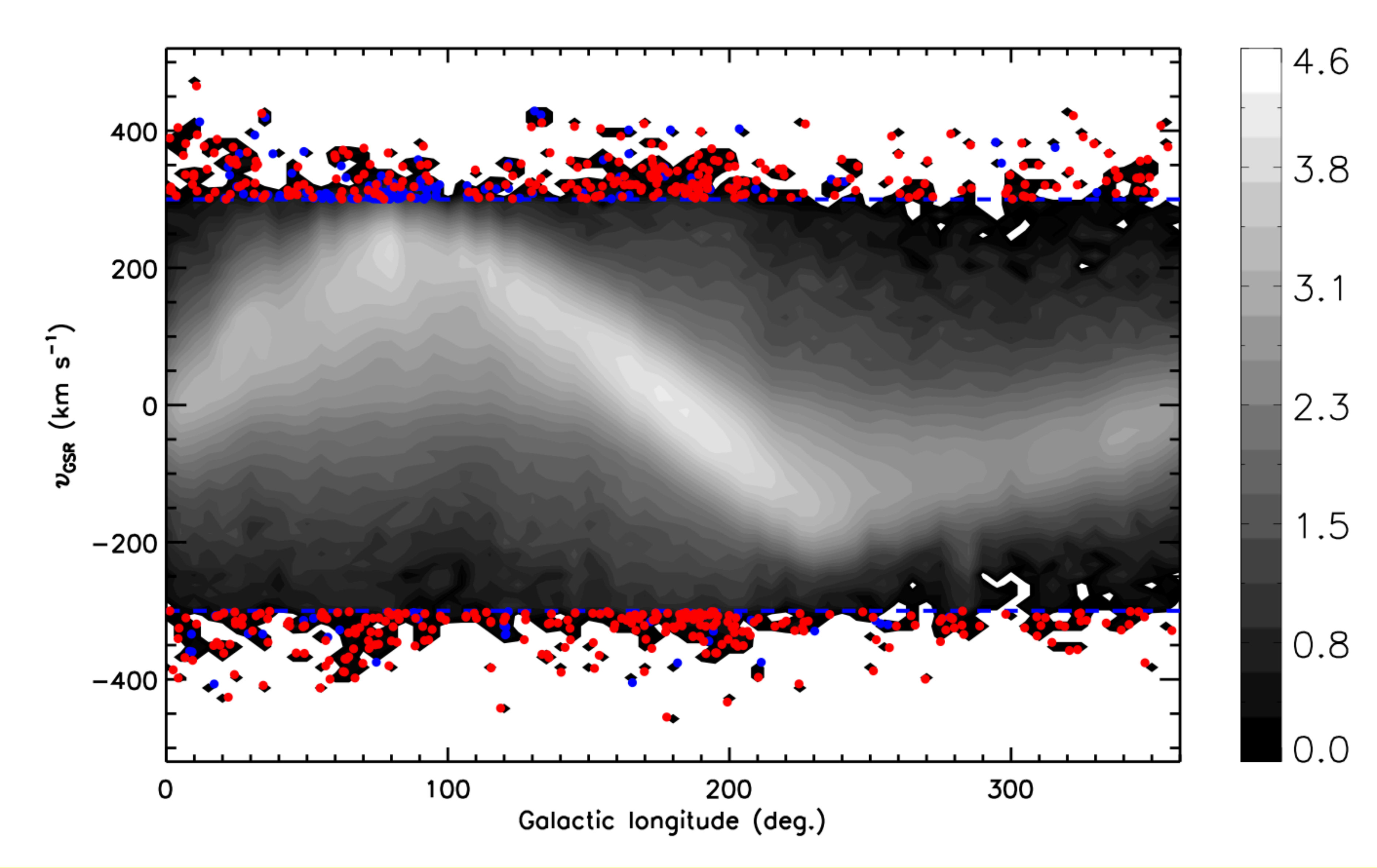
~4.1 million stars left

- **|Vgsr| >= 300 km/s**
- **Variable/Binary stars and other peculiar objects (e.g. GC) are removed**
- **Careful eye check**

Finally, 692 stars left

II. The Galactic escape velocity curve between 5-14 kpc

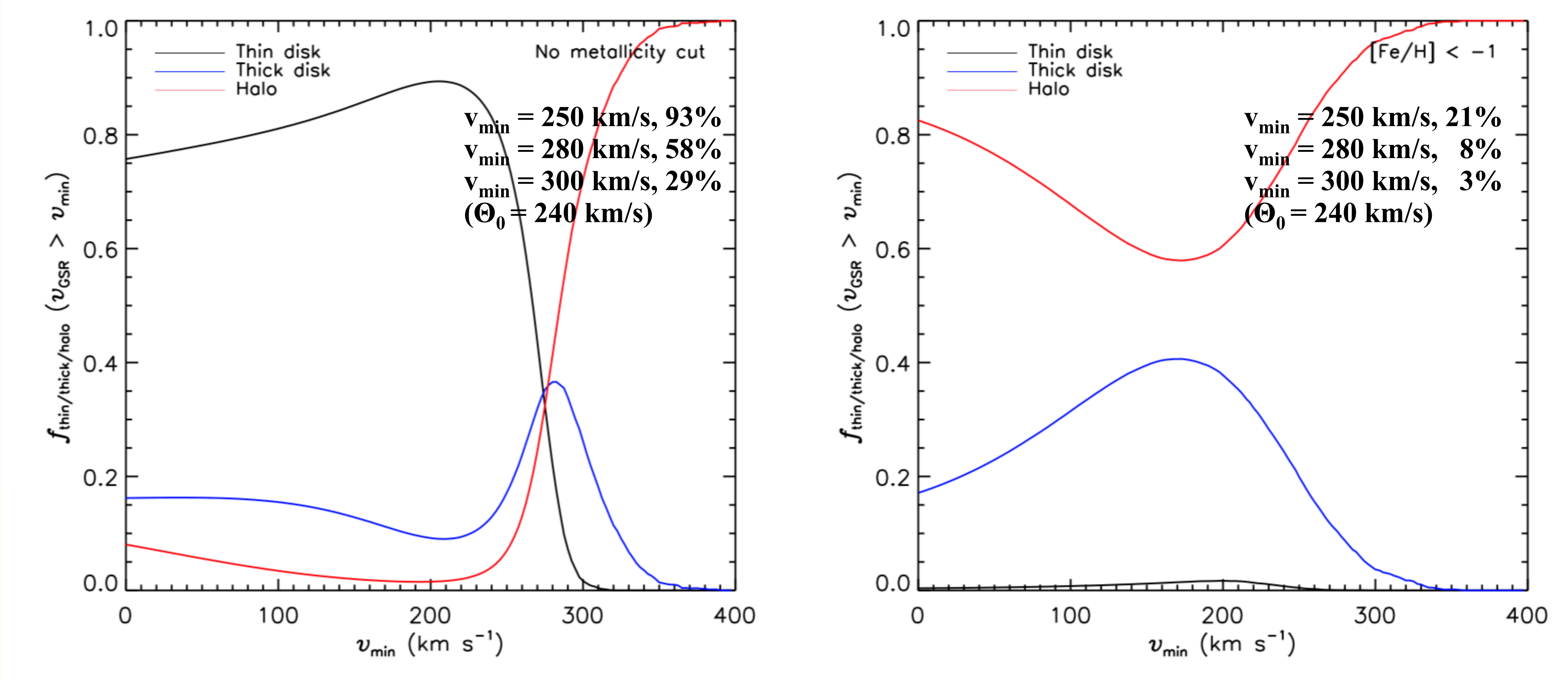
Data



II. The Galactic escape velocity curve between 5-14 kpc

Data: contaminations

Toy model with [Fe/H] information:
(5 < R< 14 kpc, -2.5 < Z < 2.5 kpc)



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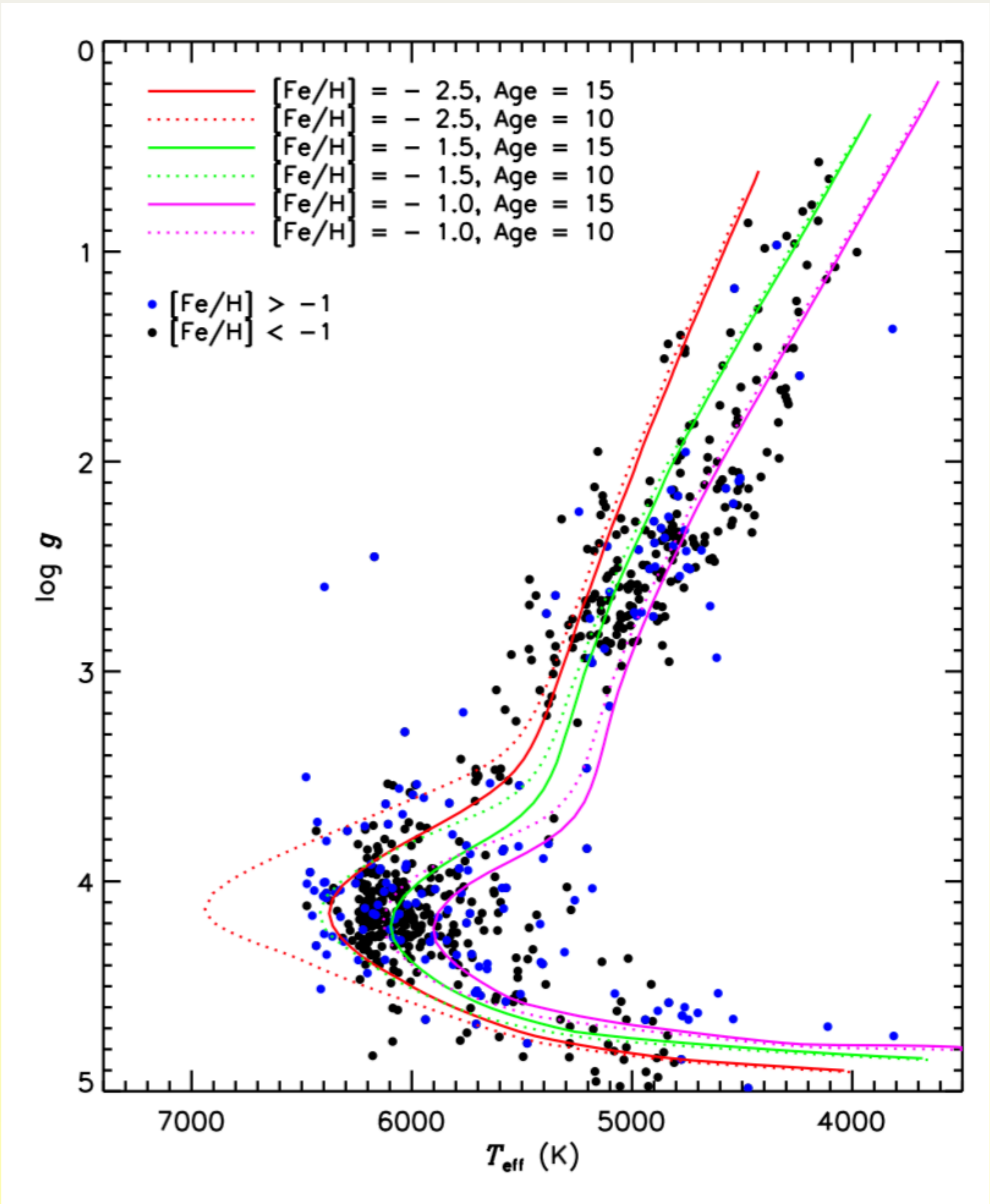
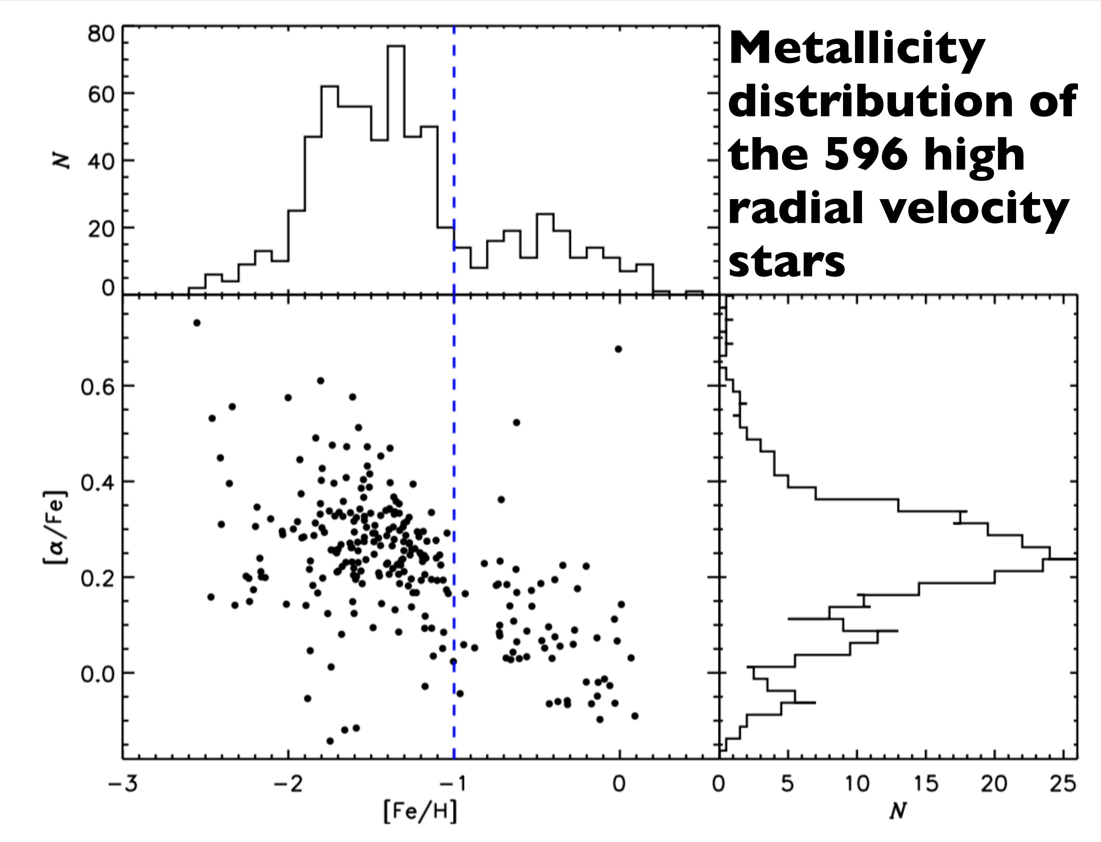
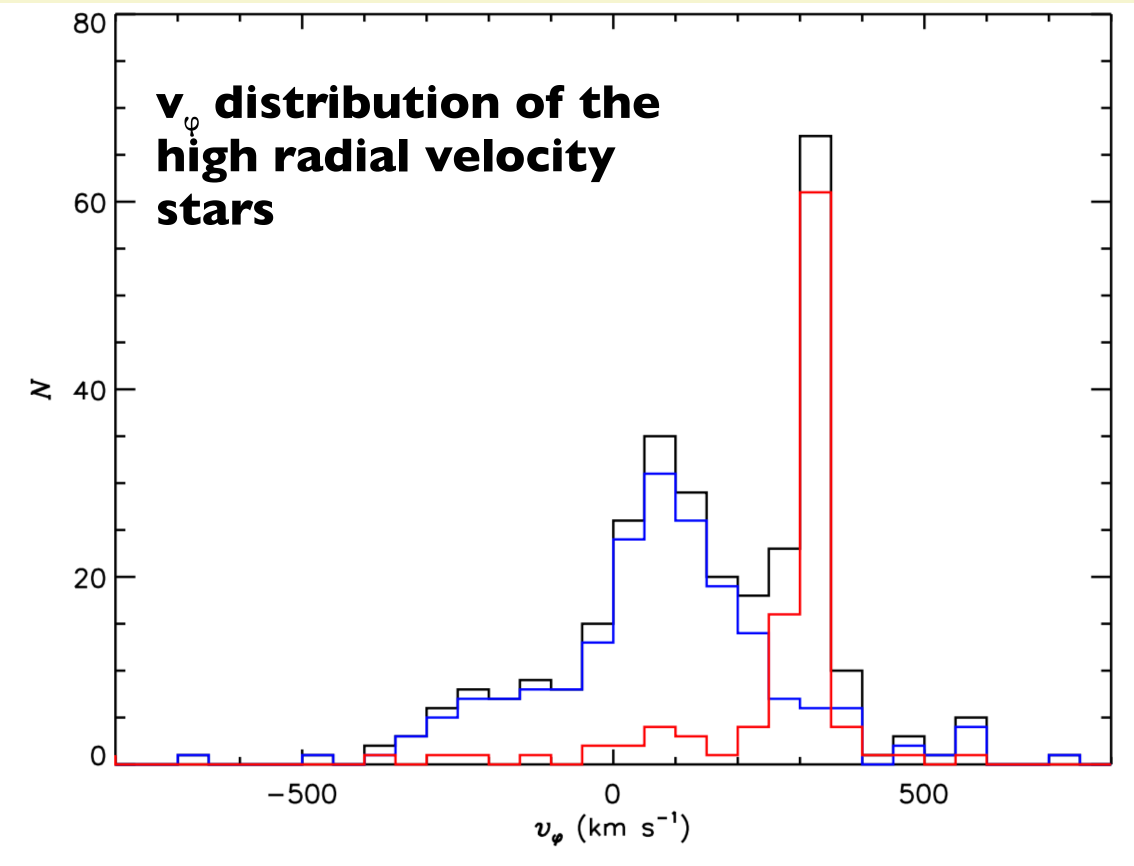
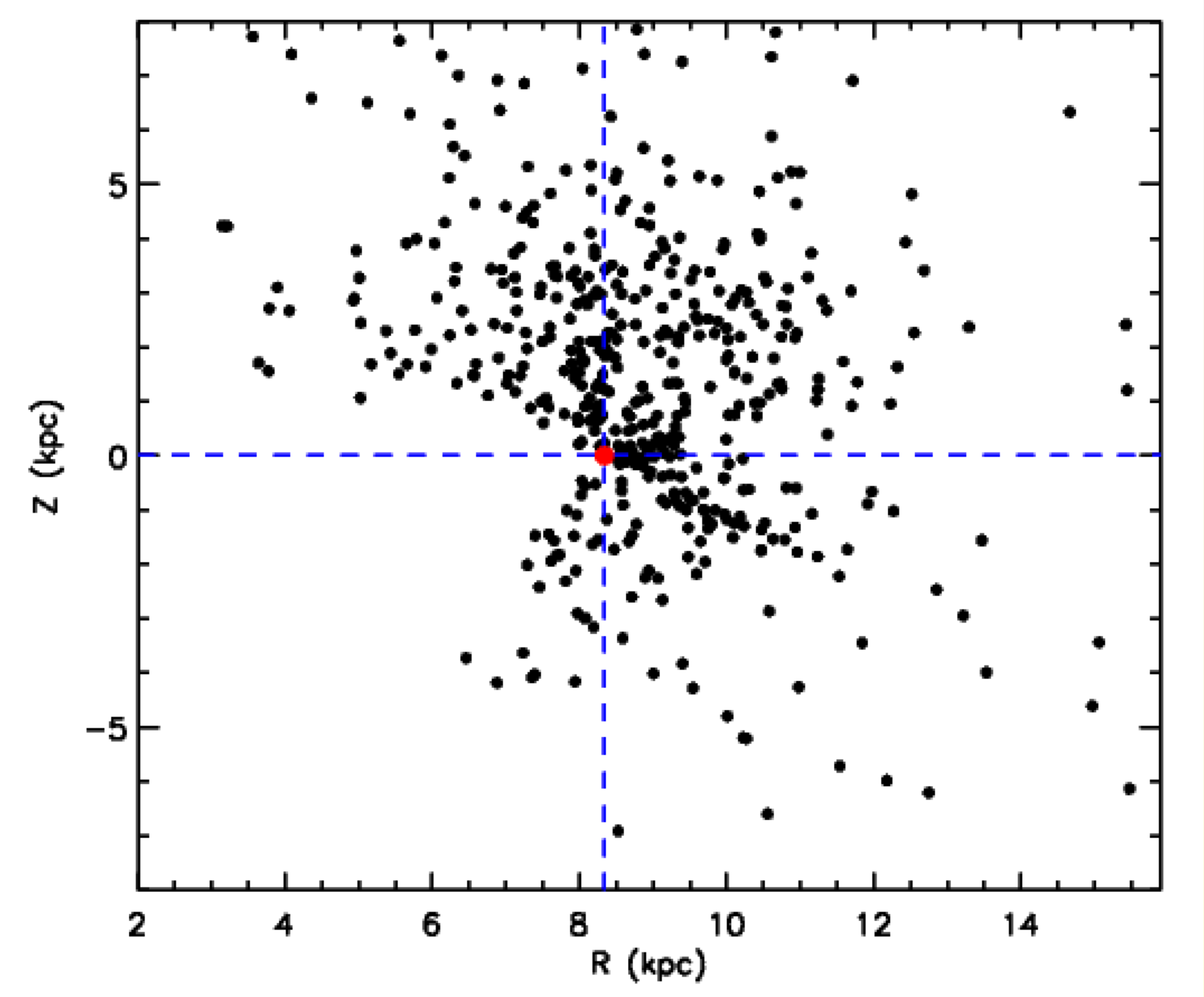






II. The Galactic escape velocity curve between 5-14 kpc

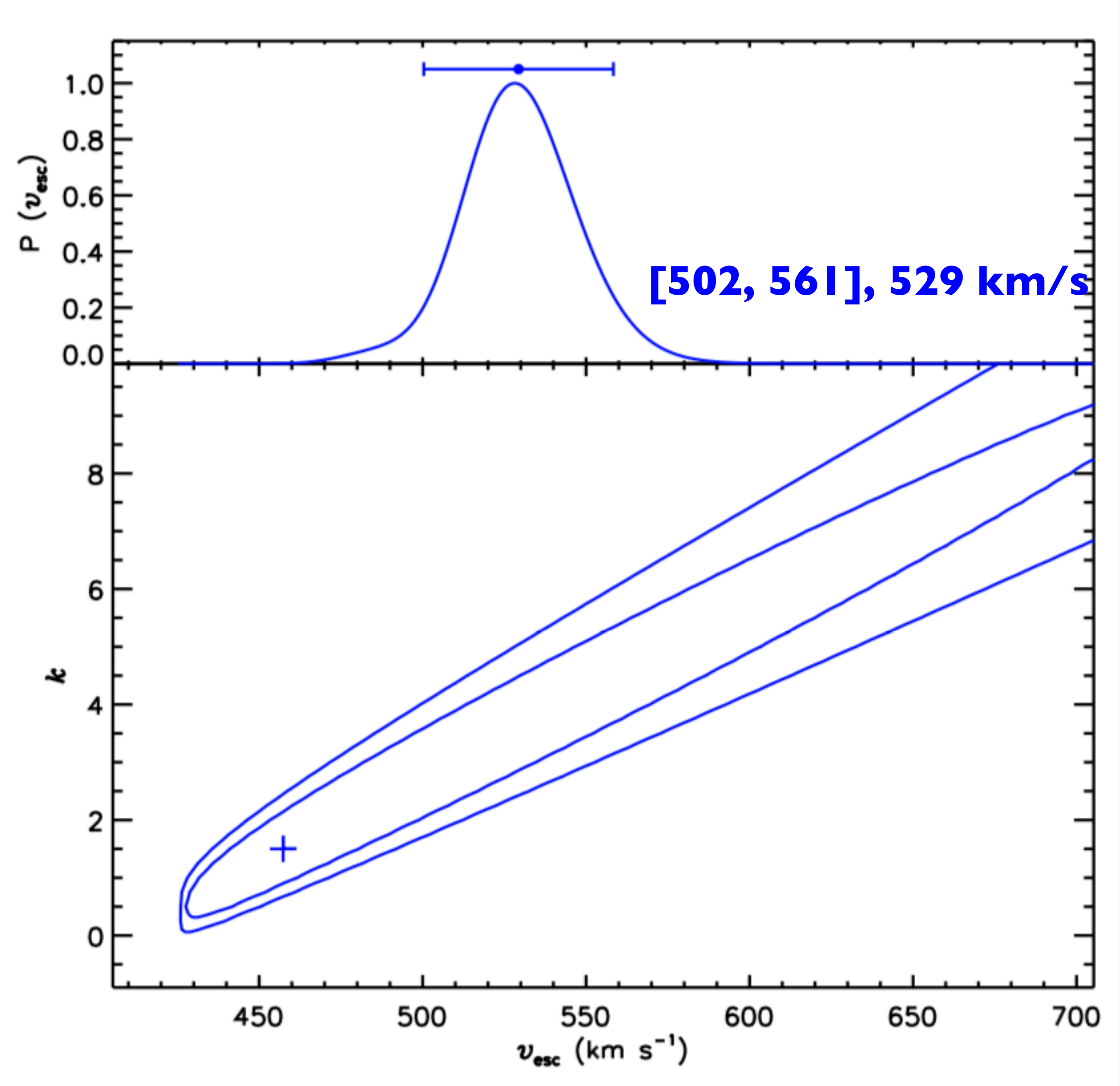
Data: final sample – 527 stars



- $k = 2.3 – 3.7$ (predicted by P14 using 8 cosmological simulations)
- $v_{min} = 300$ km/s
- Contaminations: in the level of 3%
- Sample size: 527 stars

II. The Galactic escape velocity curve between 5-14 kpc

Results & discussion



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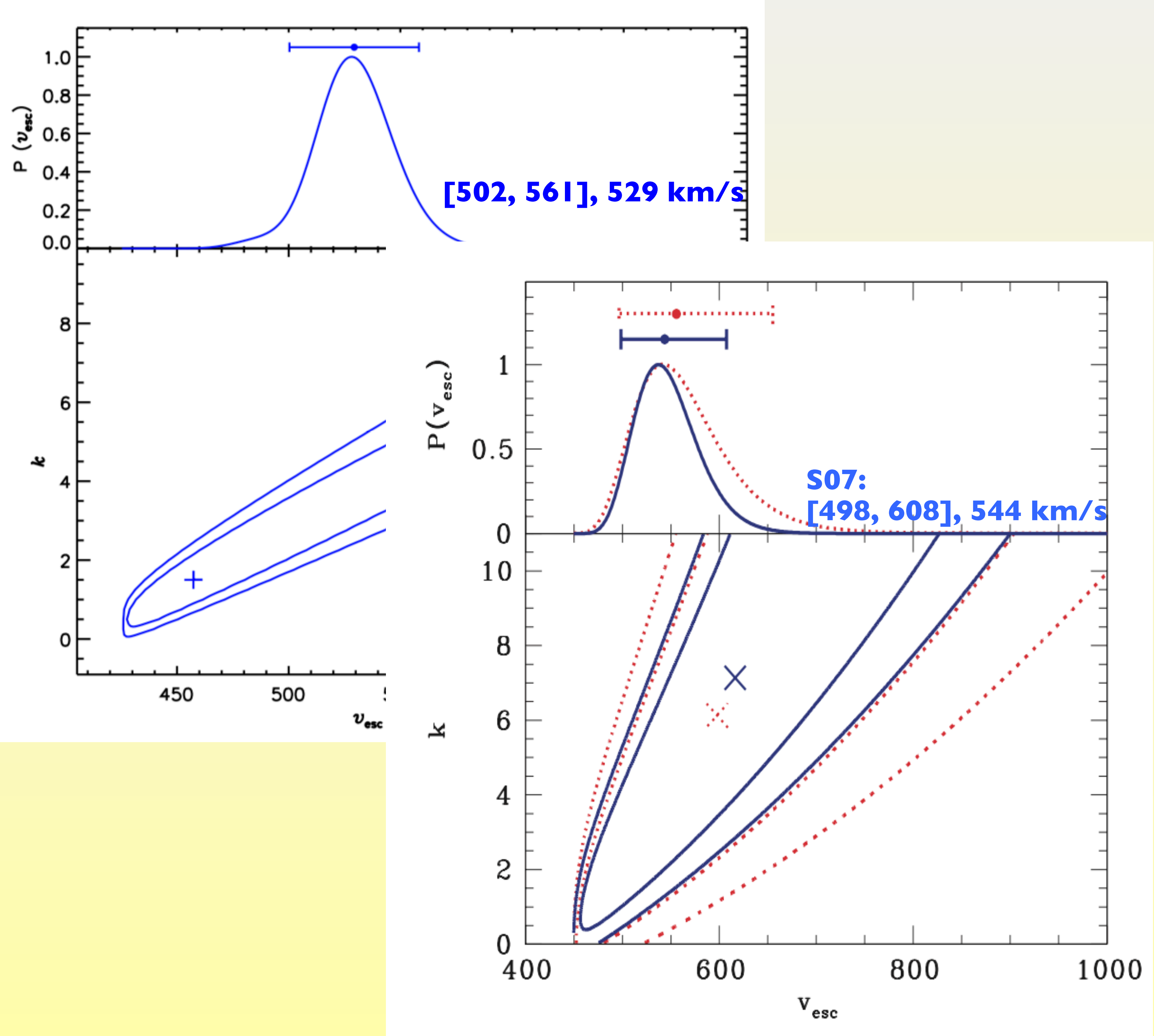
Results & discussion



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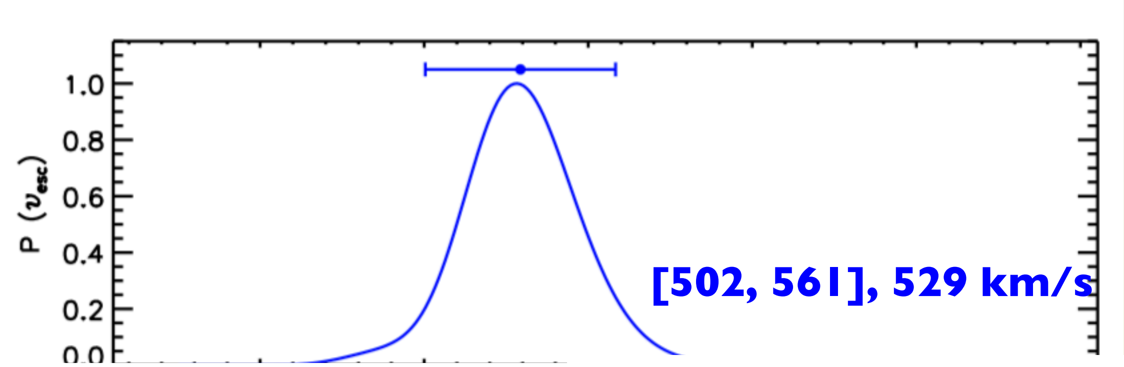

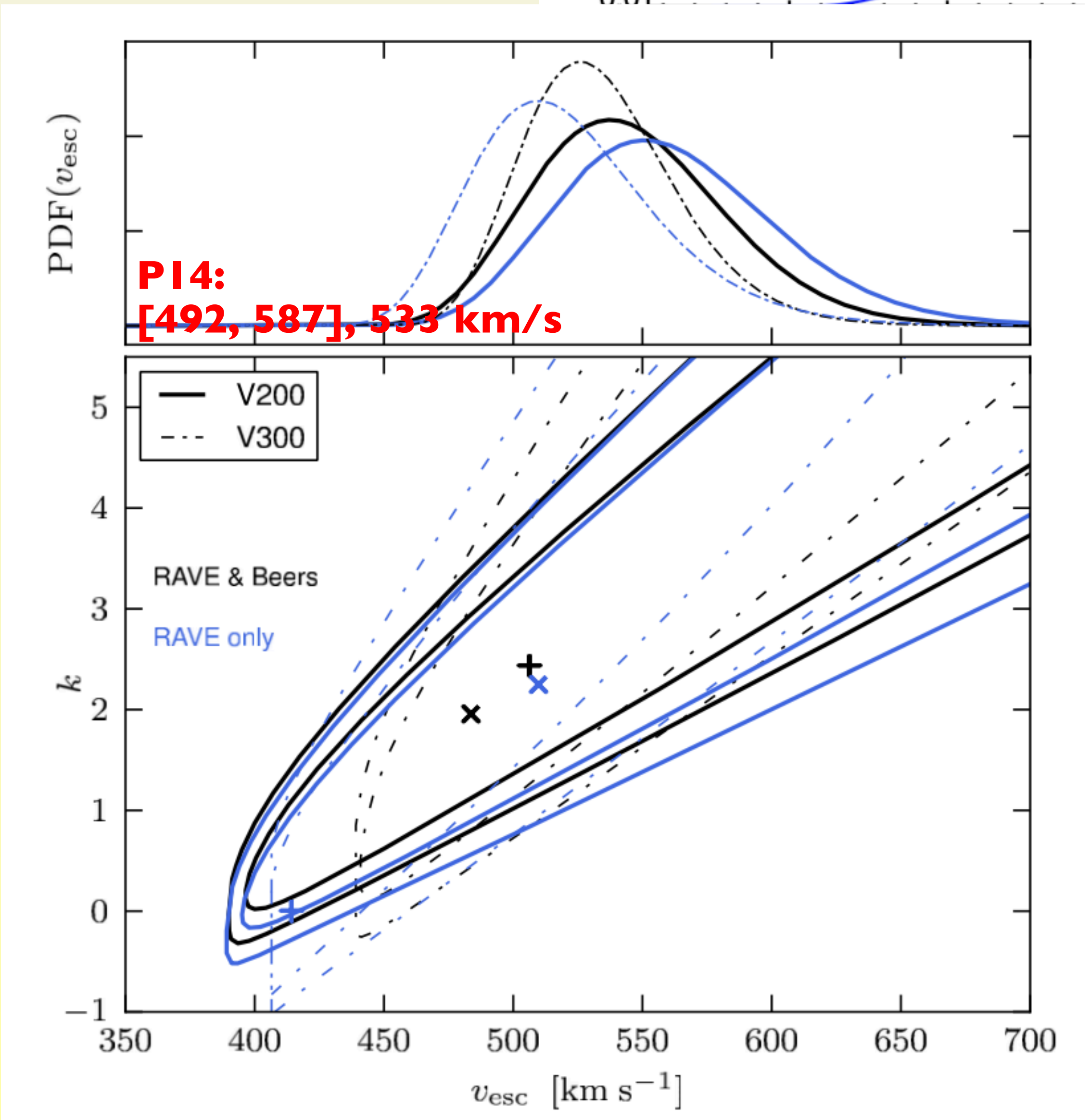

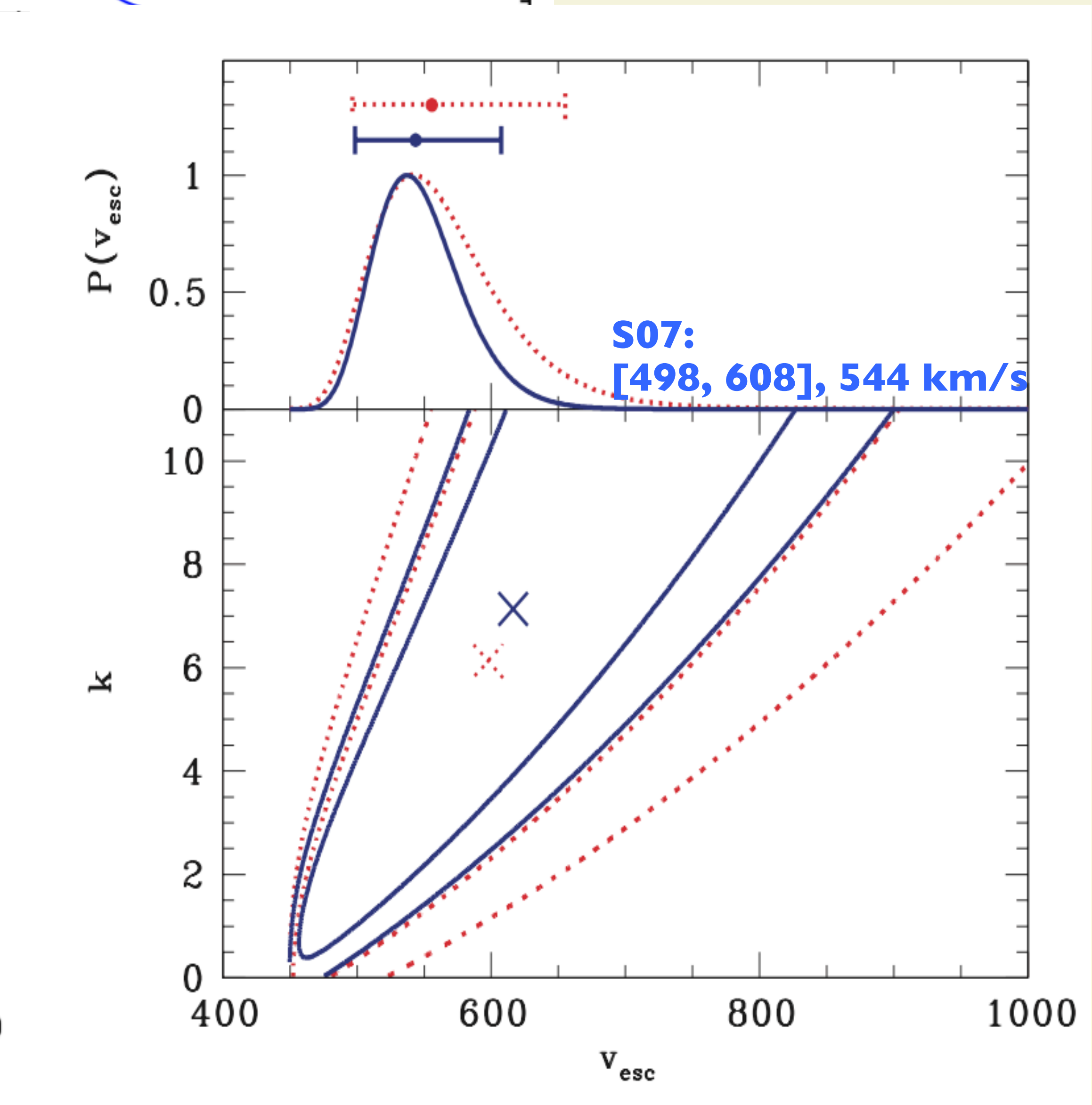

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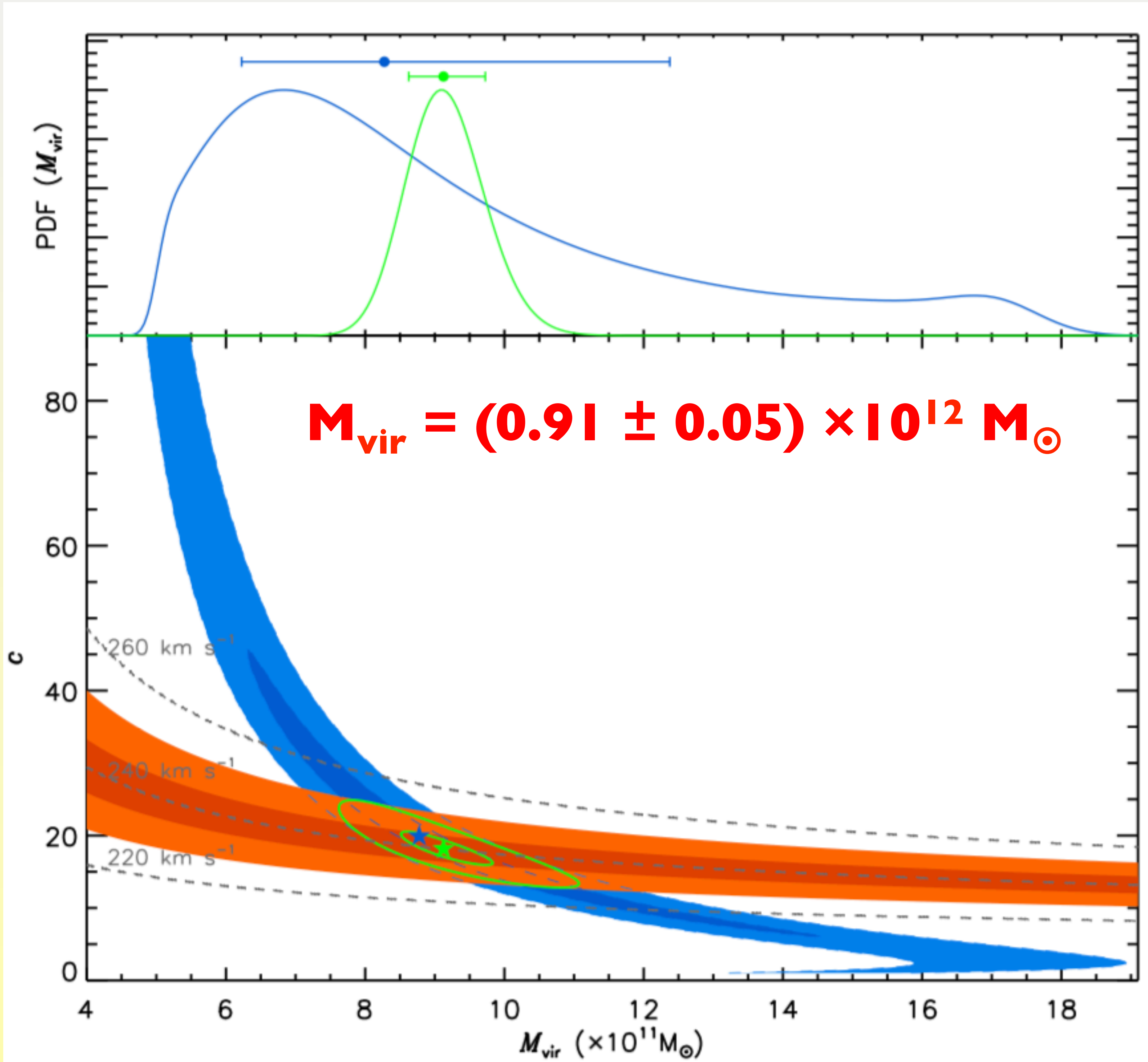


Fitting the escape velocity curve

- Hernquist bulge
- Exponential disc
- NFW halo

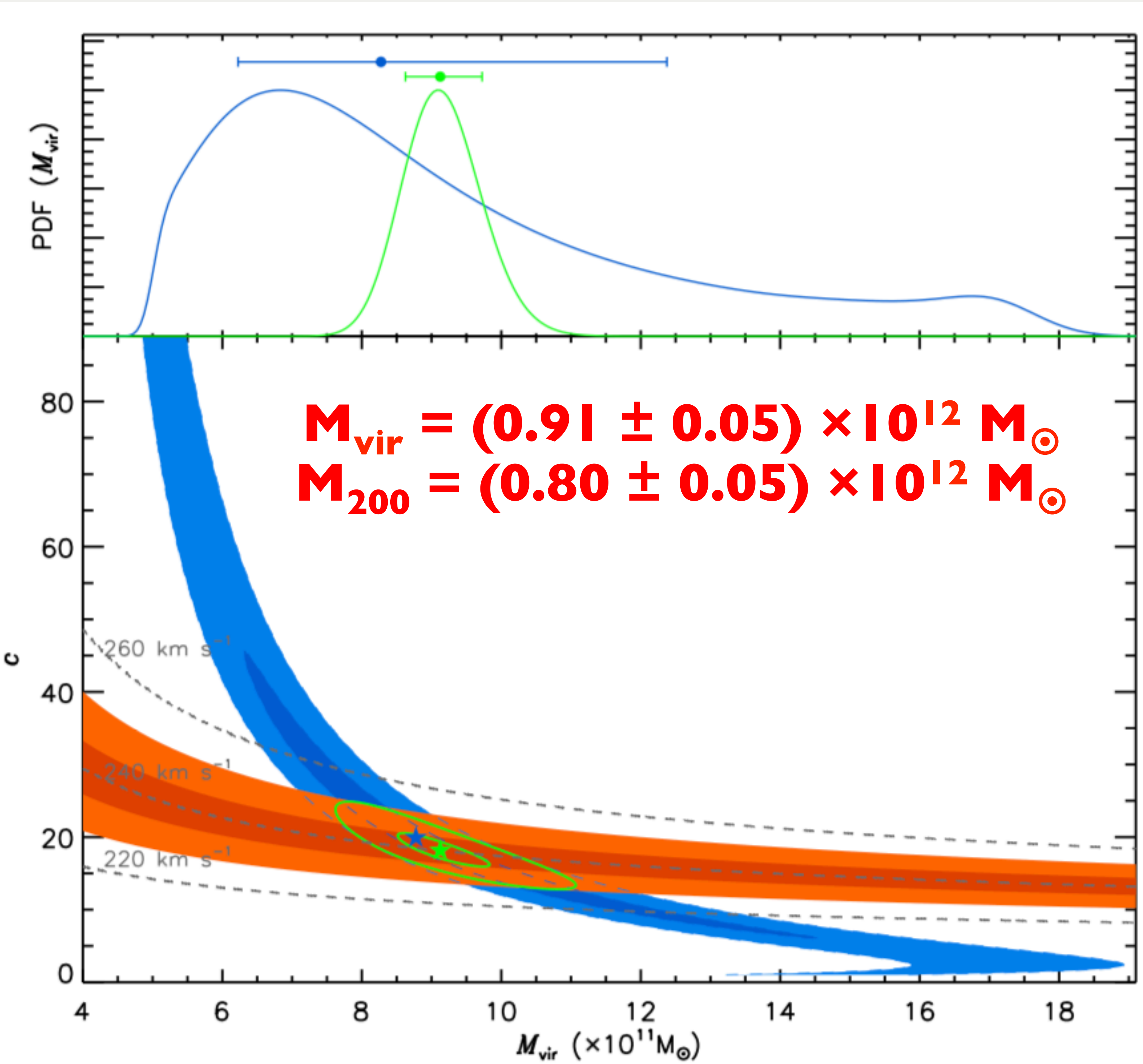
Galactic baryonic components	Parameter	Value
Bulge	$M_b(\times 10^{10} M_\odot)$	1.5
	r_b (kpc)	0.6
Disc	$M_d(\times 10^{10} M_\odot)$	5.0
	R_d (kpc)	2.5
	Z_d (kpc)	0.3

	Parameter	Value 1[a]	Value 2[b]
DM halo	c	$22.73^{+24.40}_{-13.55}$	$18.18^{+2.05}_{-1.90}$
	$M_{vir}(\times 10^{12} M_\odot)$	$0.83^{+0.41}_{-0.21}$	$0.91^{+0.06}_{-0.05}$
	R_{vir} (kpc)	$248.96^{+36.00}_{-22.50}$	$257.46^{+5.50}_{-5.00}$
	c_{200}	$17.01^{+18.62}_{-10.29}$	$13.55^{+1.56}_{-1.44}$
	$M_{200}(\times 10^{12} M_\odot)$	$0.73^{+0.30}_{-0.16}$	$0.80^{+0.05}_{-0.04}$
	R_{200} (kpc)	$186.37^{+22.55}_{-15.15}$	$191.96^{+3.66}_{-3.35}$
Circular speed	$v_c(R_0)$ (km s^{-1})	248^{+30}_{-30}	–

[a] Without $v_c(R_0)$ prior
[b] With $v_c(R_0)$ prior

II. The Galactic escape velocity curve between 5-14 kpc

Results & discussion



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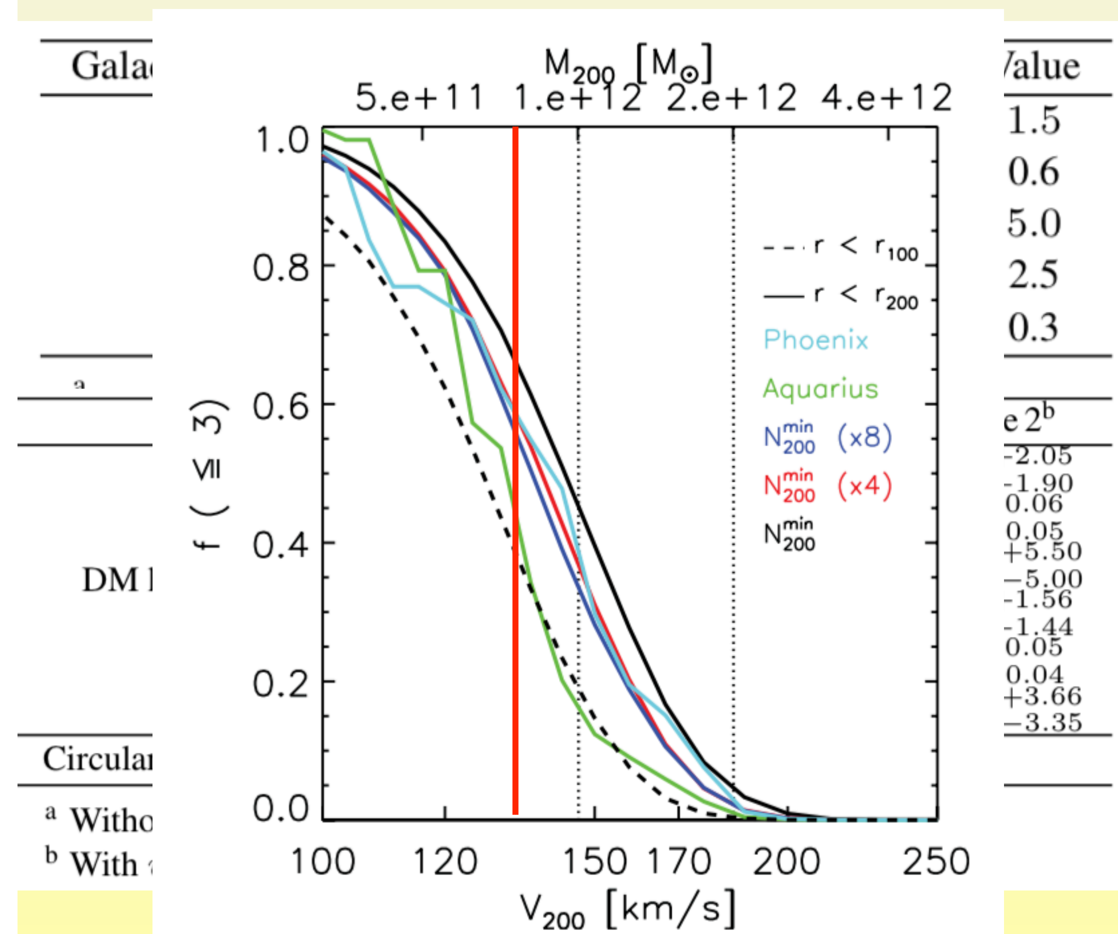

Wang et al. 2012, MNRAS, 424, 2715

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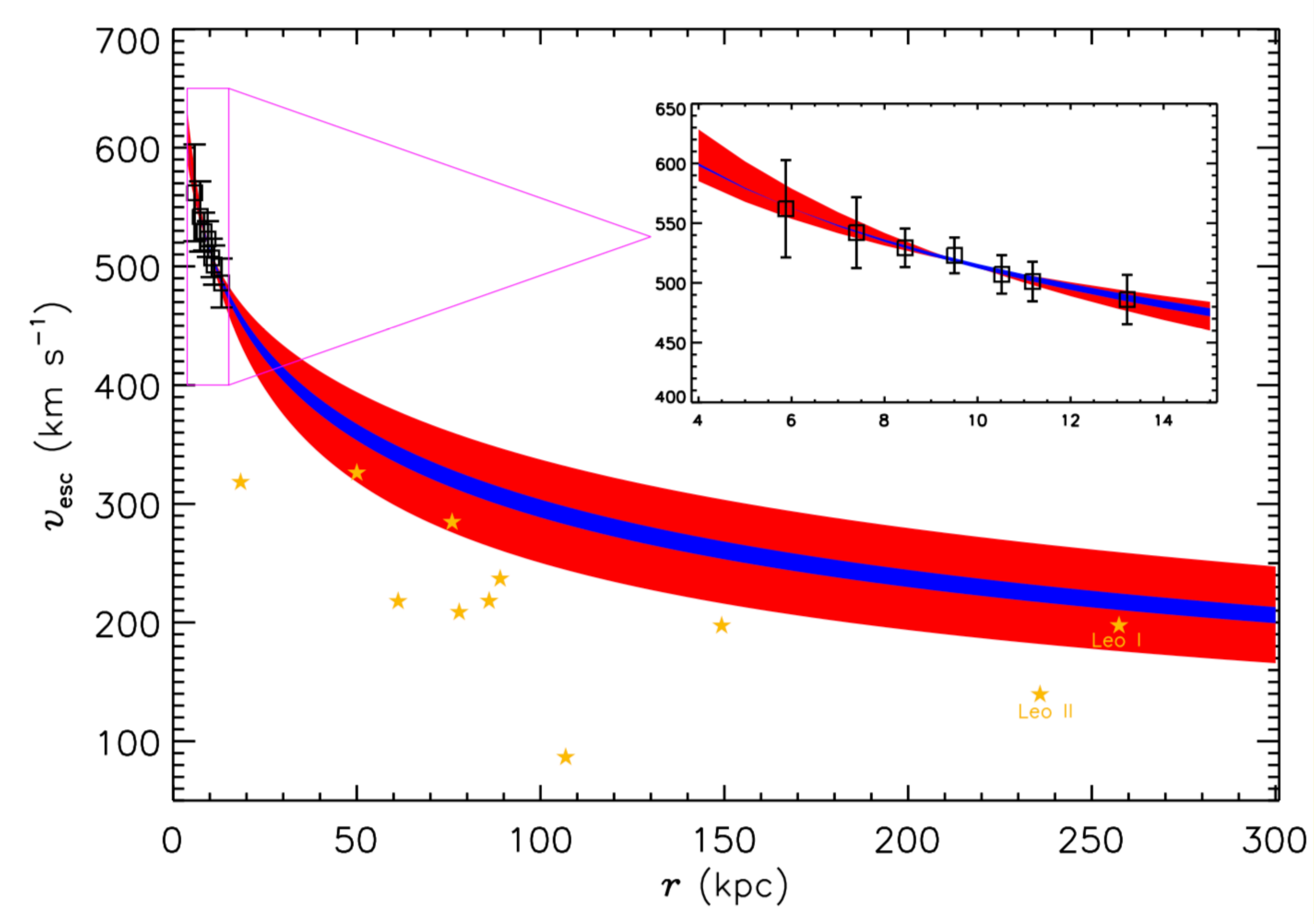

Summary & Future prospect

Constraining the mass of the Milky Way using LAMOST data

- We have derived the Galactic rotation curve out to ~100 kpc and find M_{vir} = (0.90 ± 0.08) $\times 10^{12}$ $M_{\odot}$, ρ_{DM} = 0.32 ± 0.02 GeV cm^{-3} (Huang et al. 2016, MNRAS, 463, 2623)

- We have derived the Galactic escape velocity curve between 5 and 14 kpc. The local Galactic escape velocity is about 523±17 km/s. Using this curve, we again find M_{vir} = (0.91± 0.05) $\times 10^{12}$ $M_{\odot}$ (Huang et al. in prep.).

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- Identifying member stars of (thin) stellar streams (the shape of the dark matter halo)
- Surface mass density profile (include the local dark matter density)
- Other available constraints

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Accurate mass distribution of our Milky Way

Thank You!


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