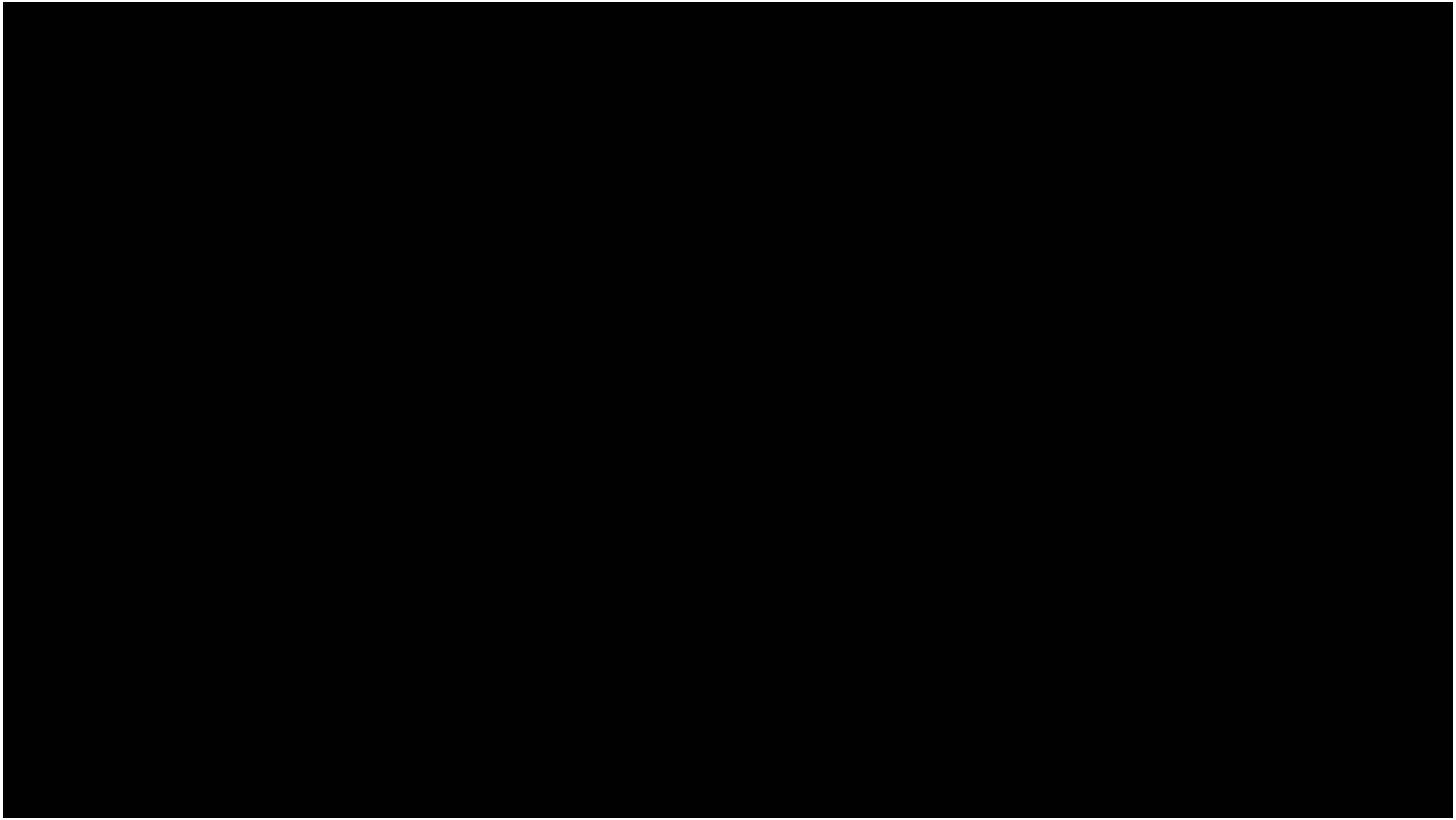
Dwarf encounters with the Milky Way as seen by

RAVE

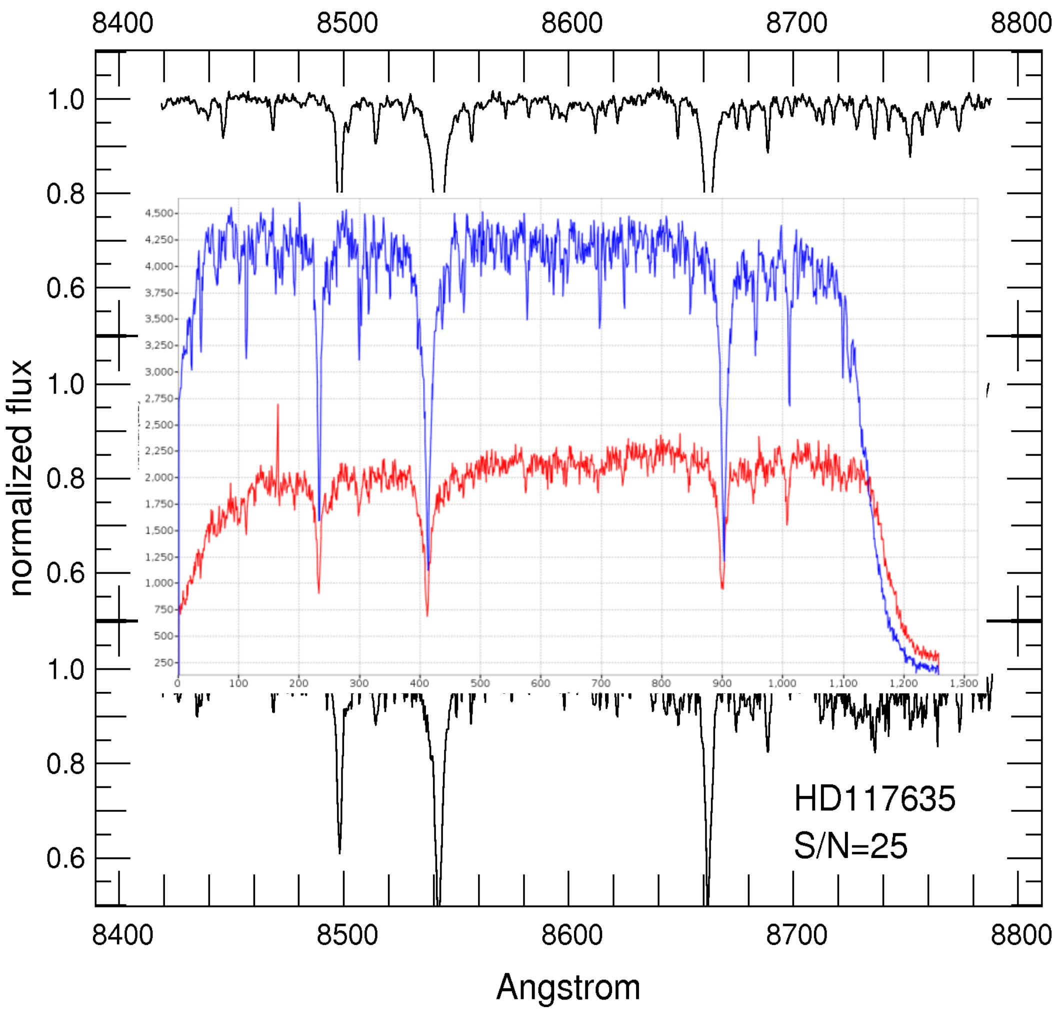
RADIAL VELOCITY EXPERIMENT

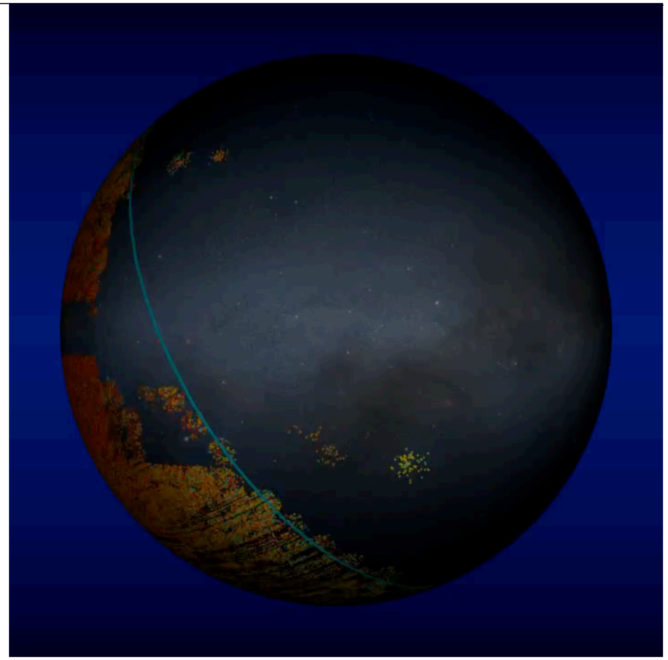
Systematic spectroscopic surveys 2014



RAVE: 574,630 spectra for 483,330 stars

λ range: 8410-8795Å (Gaia)
Resolution R=7500 at 8600Å;





From the RAVE spectra we obtain:

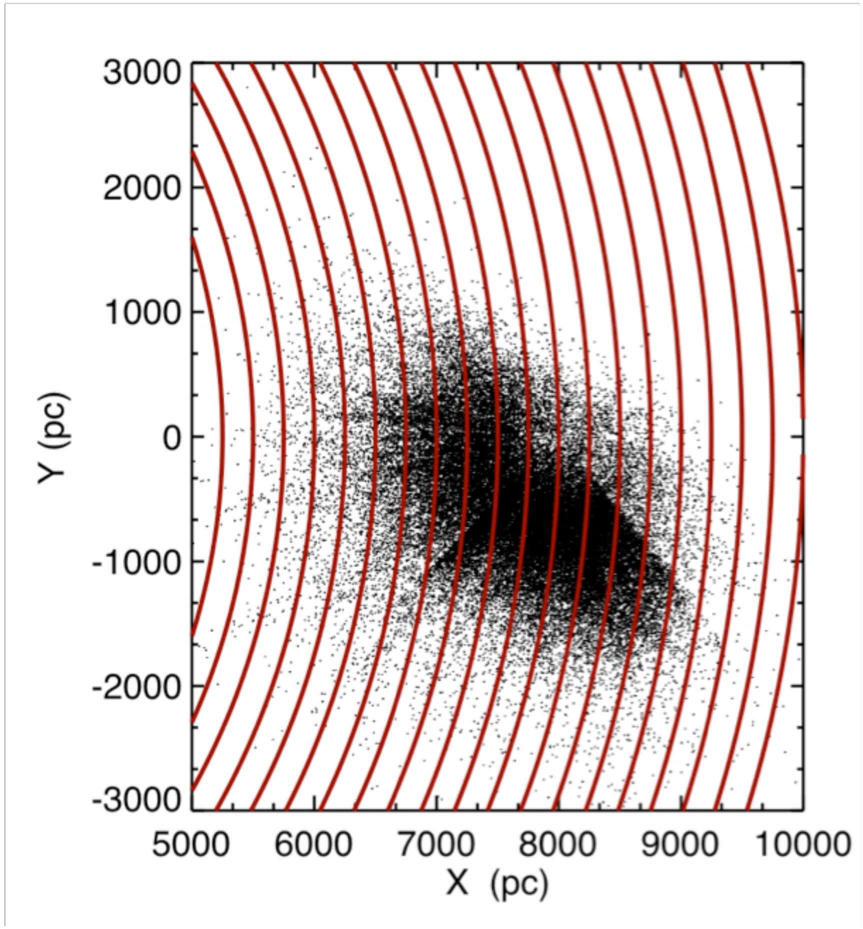
- radial velocities
- stellar parameters
- chemical abundances
- RAVE + photometry
- distances

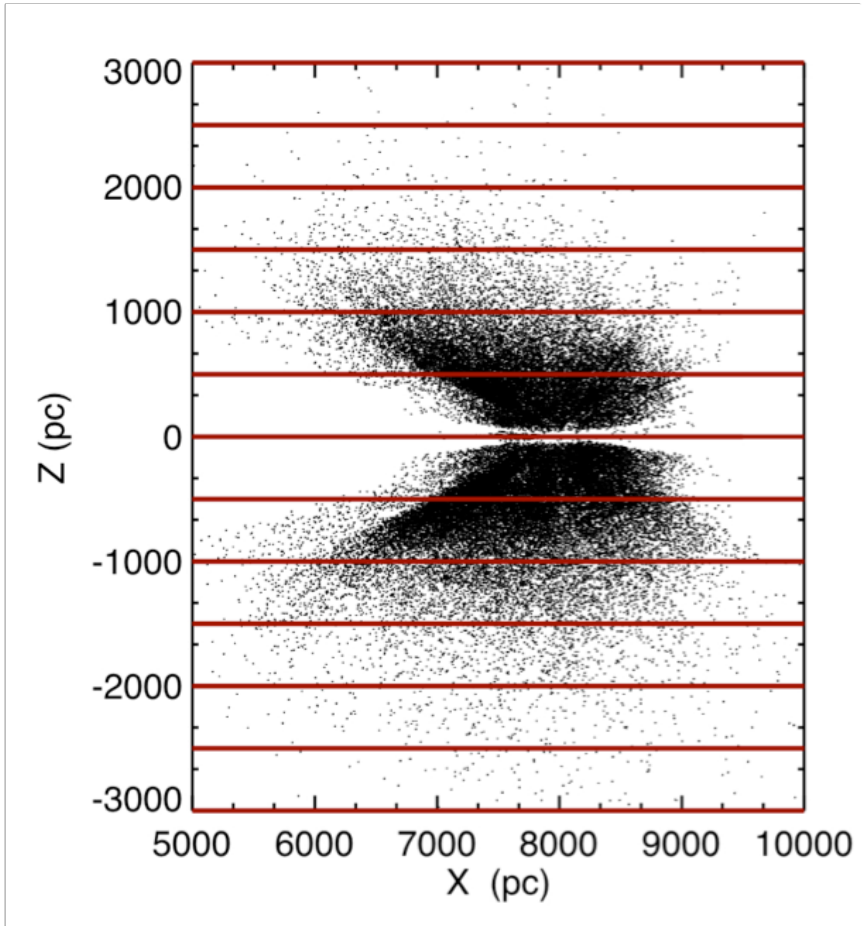
Signatures of Accretion with RAVE

- The Wobbly Galaxy (Willams et al 2013)
- Accretion events
  - Aquarius stream (Williams et al 2011)
  - Tidal debris from Globular Clusters (Kunder et al 2014, Anguiano et al, 2014)
  - relation between velocity dispersion and abundances (Minchev et al 2014)
- Mass of the Milky Way (Piffl et al 2014a, 2014b)
- What comes next?

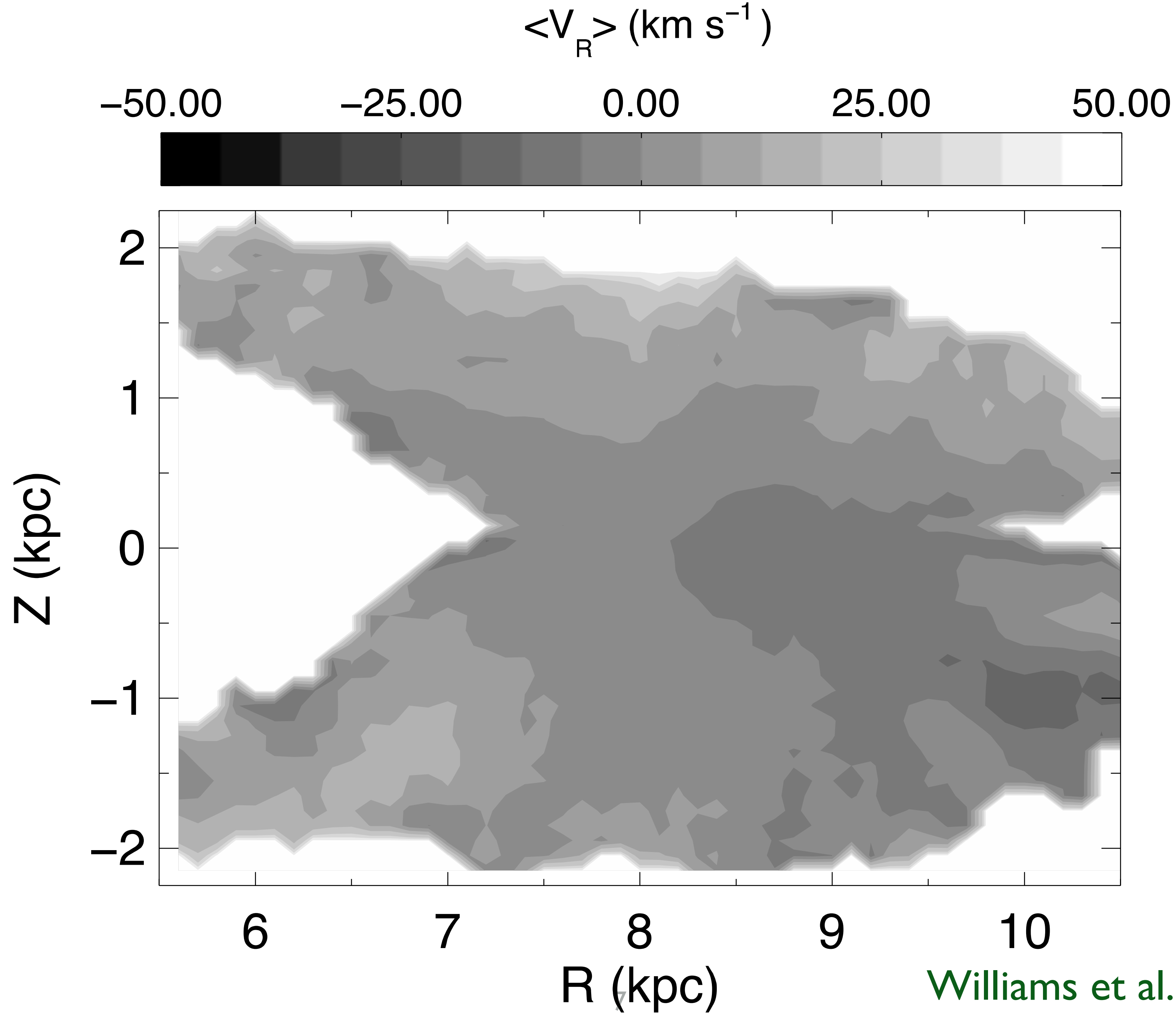
Dissecting the Milky Way

- cut into 250pc wide rings in R, 500pc thick slices in Z
- use only samples with adequate sample size
- a few restrictions on the velocities and their errors



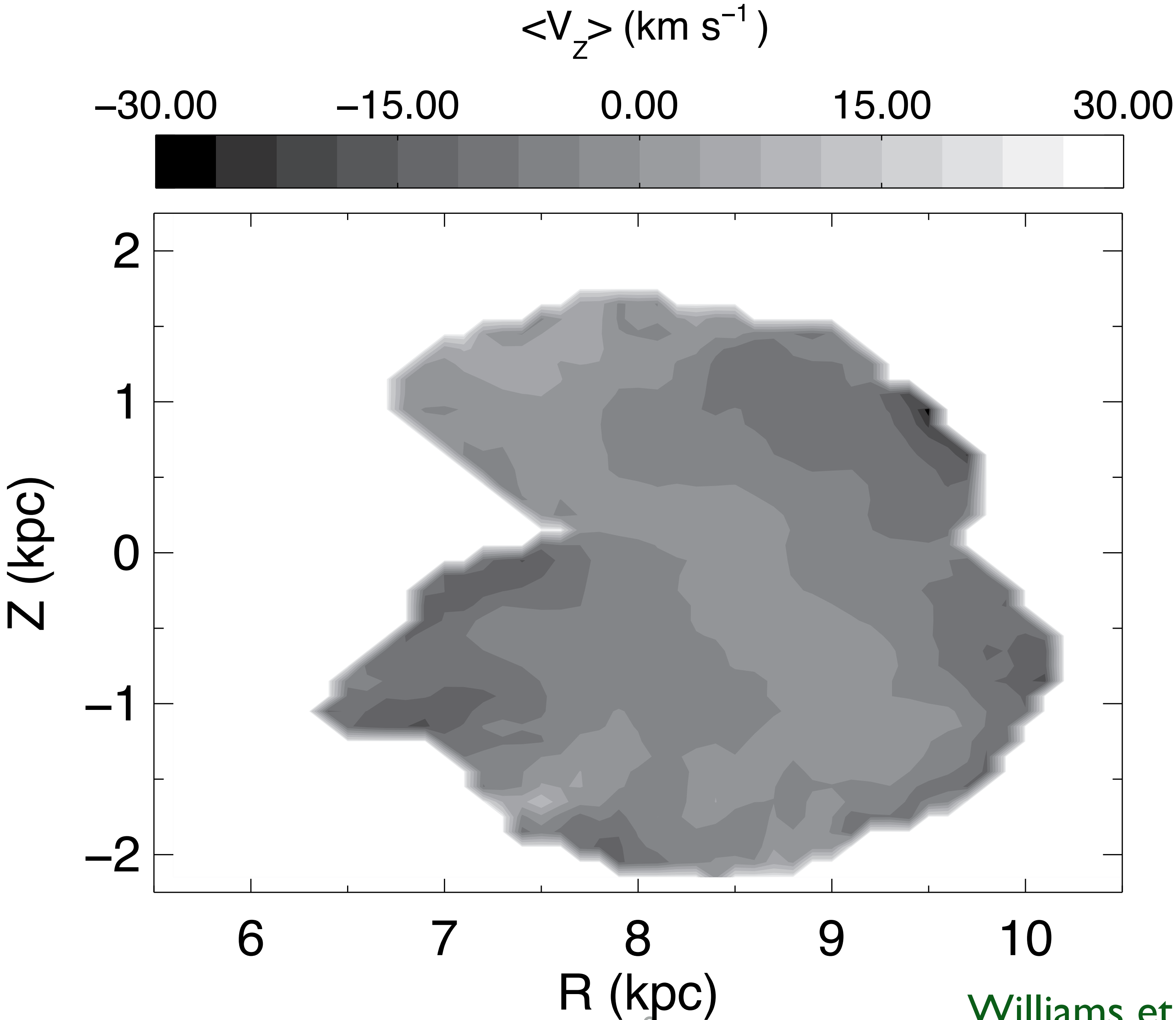


Radial Streaming Velocity



Williams et al., 2013

Radial Streaming Velocity



Williams et al., 2013

Real effect or a systematic artifact of the data?

- Proper motion errors
- Distance errors (e.g. misidentified RC stars; RC normalization, systematics …)
- Local Standard of Rest velocities
- Comparison to other surveys

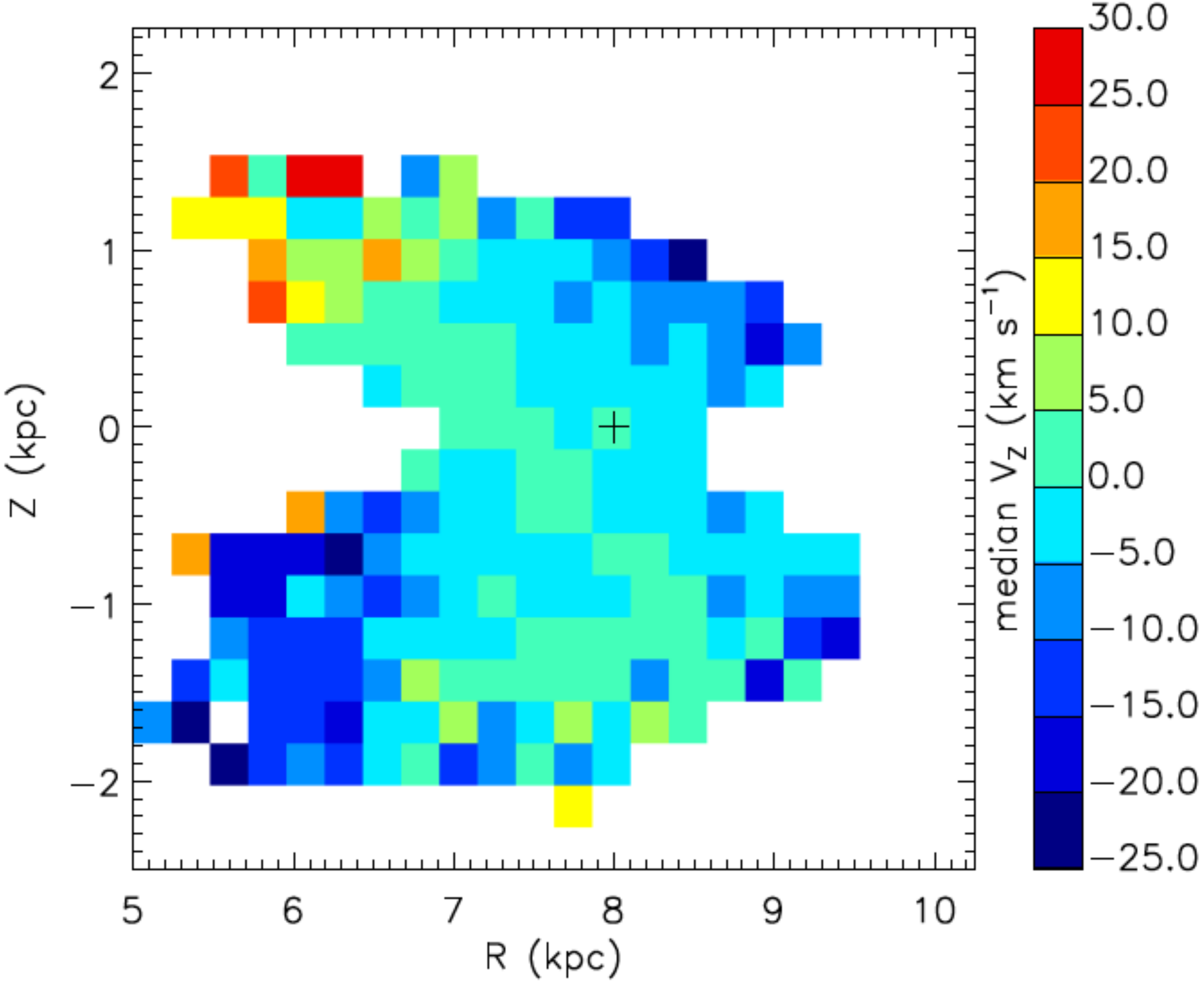
Real effect or a systematic artifact of the data?

- Proper motion errors
  - Systematic differences between UCAC3 and SPM4
  - Signal less pronounced in SPM4
  - In order to explain asymmetries by p.m. systematics
    - 90<RA<270: $\Delta\mu_{RA}$= -2 (mas/yr) × dist (kpc)
    - RA<90 or RA>270: μ_{RA}= +1 (mas/yr) × dist (kpc)
  - Asymmetry is also visible in radial (p.m. independent) analysis

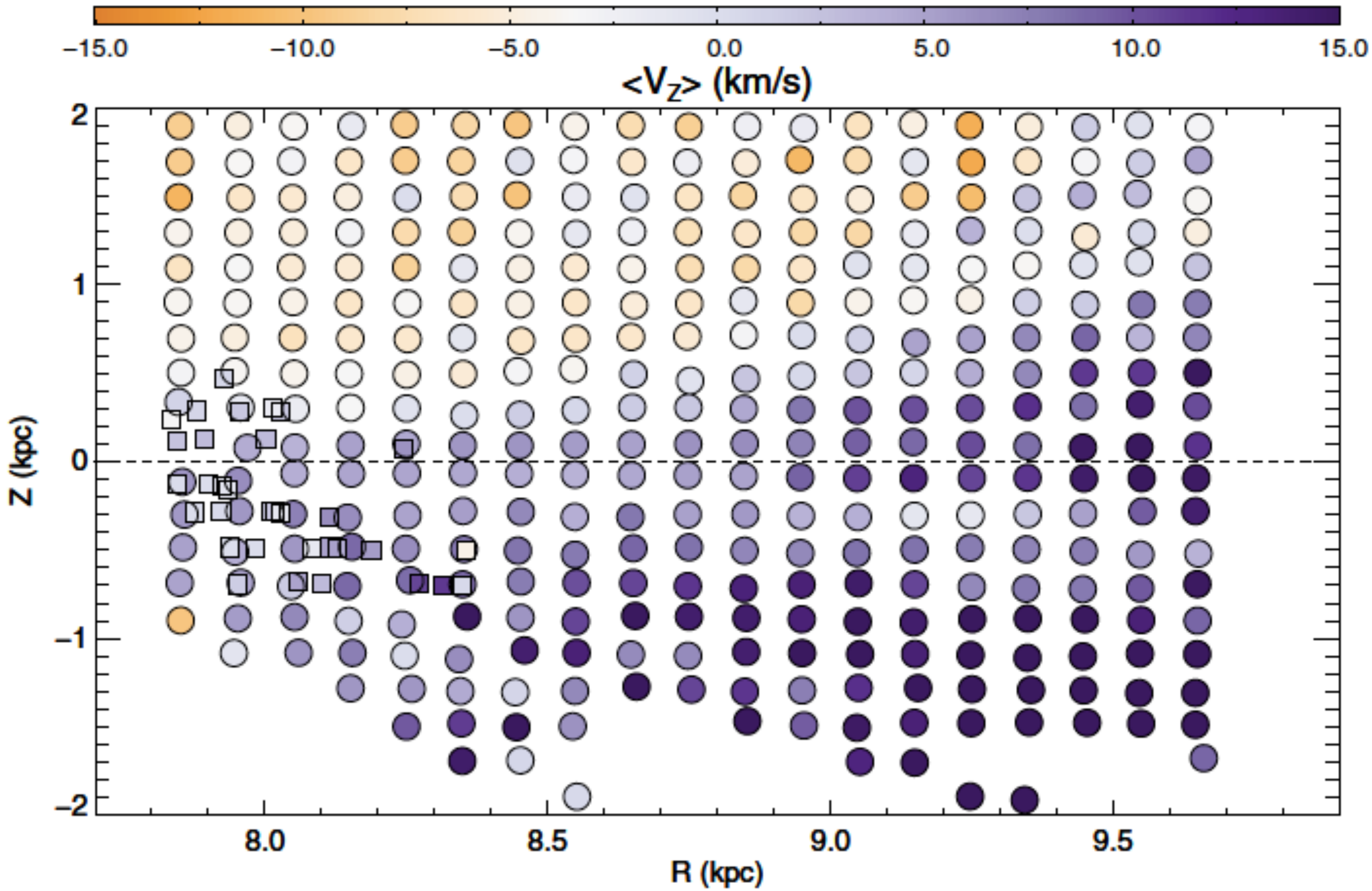
Real effect or a systematic artifact of the data?

- Proper motion errors
- Distance errors (e.g. misidentified RC stars; RC normalization)
  - Signal visible also with other distance estimators (Zwitter et al 2011, Burnett et al, 2011, Binney 2013)
  - Systematic overestimation of distances by 25-50% would be required
  - Structures in V_R and in particular in V_φ are incompatible with distance errors required for the V_Z behavior
  - Misidentification of red clump stars:
    - MC simulations: contamination ≈ 40% by first ascent giants
    - adds noise, however no systematic shift
  - Similar structures found with SEGUE (?) and LAMOST

Vertical Velocities with Binney-distances

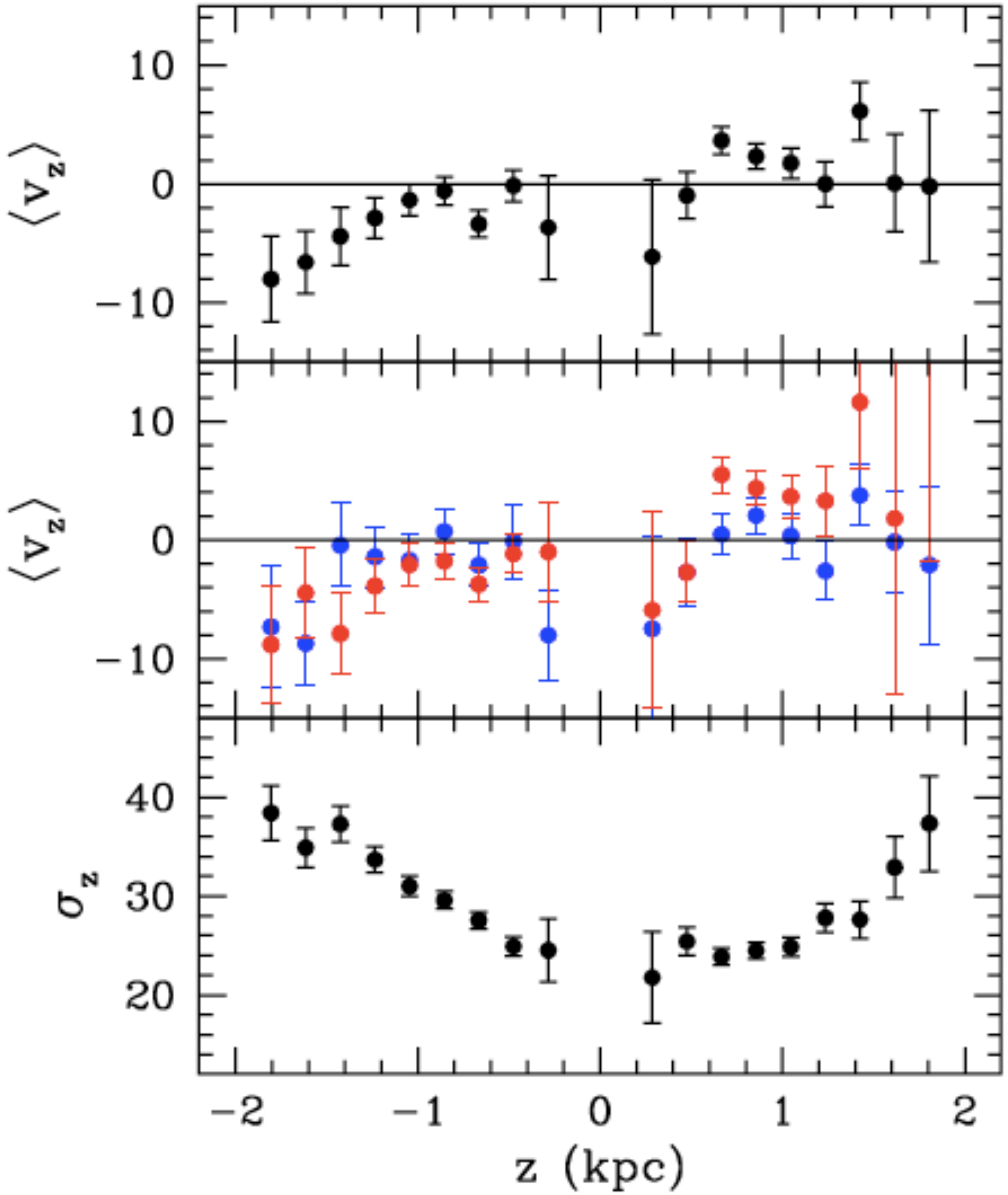


Wobbly Galaxy with LAMOST



Carlin et al. 2013

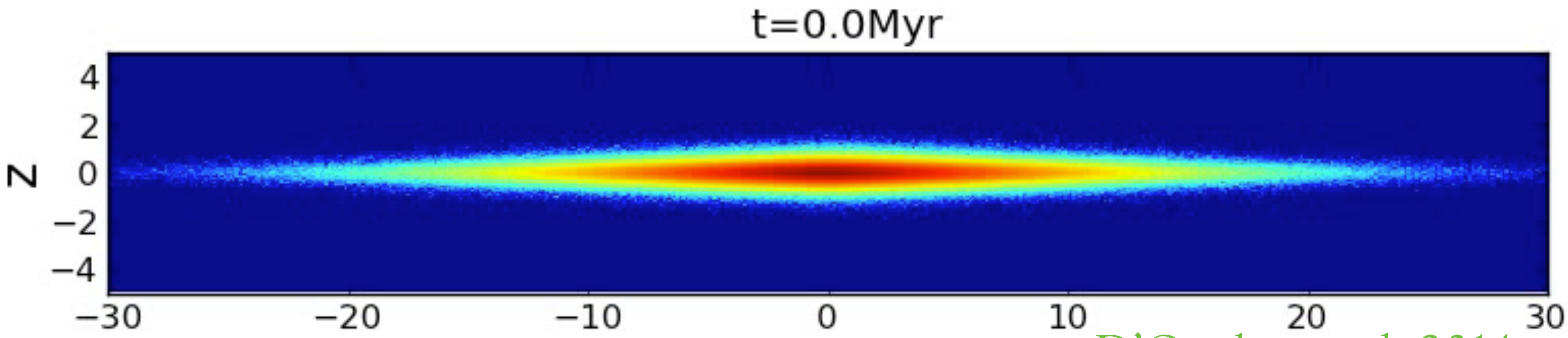
Wobbly Galaxy with SDSS



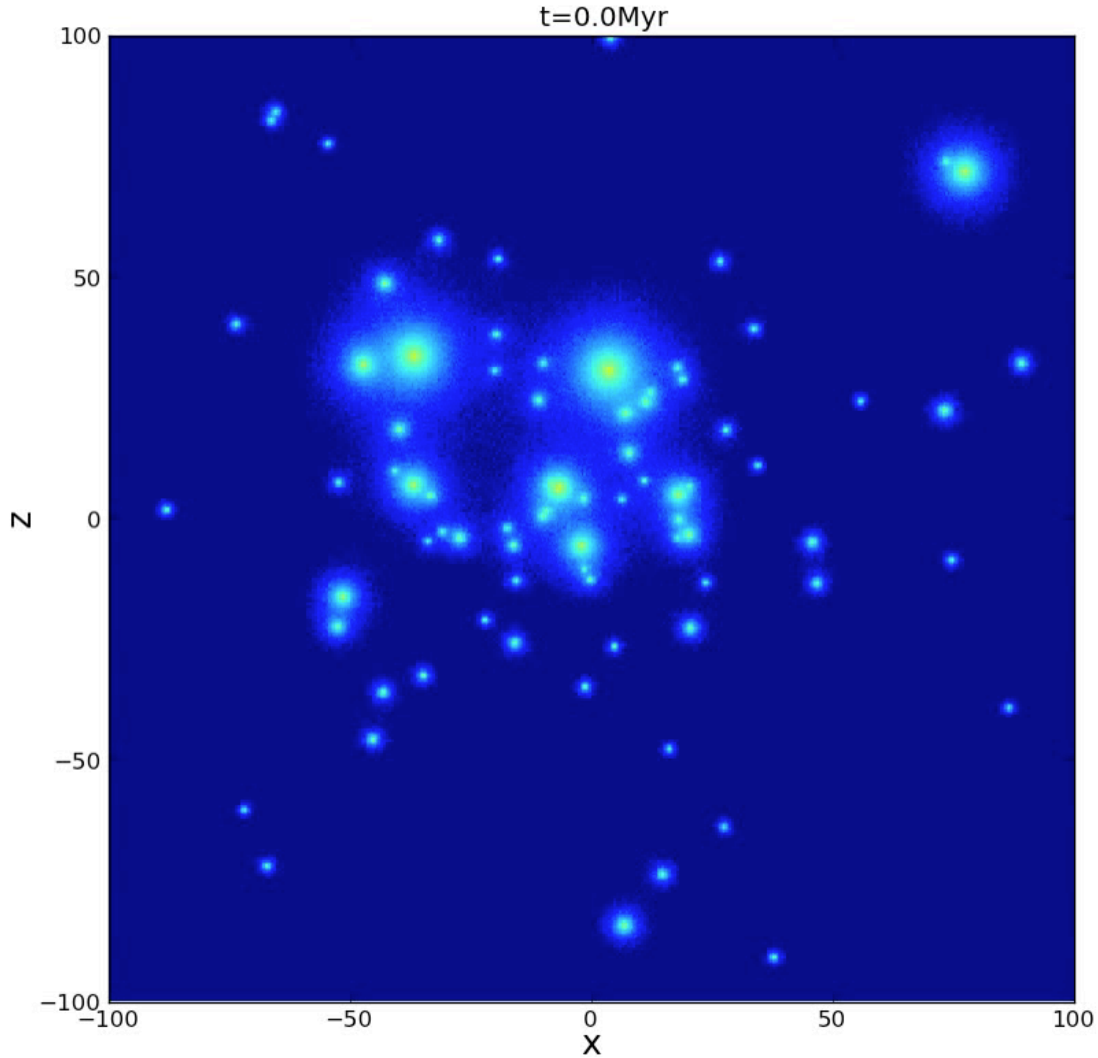
Widrow et al et al. 2012

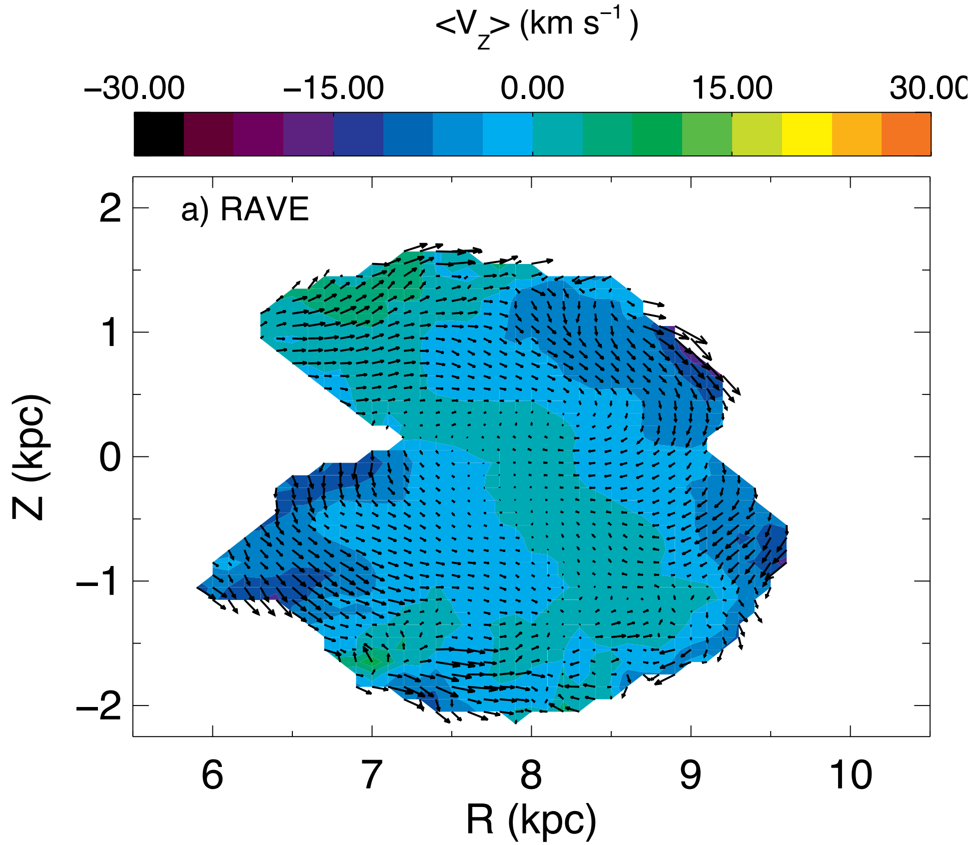
Real effect or a systematic artifact of the data?

- Proper motion errors
- Distance errors (e.g. misidentified RC stars; RC normalization)
- Local Standard of Rest velocities
  - Schönrich (2012): somewhat larger value for $U_\odot$ of 14 km/s than from GCS
  - Effect on asymmetry: only result in an overall shift



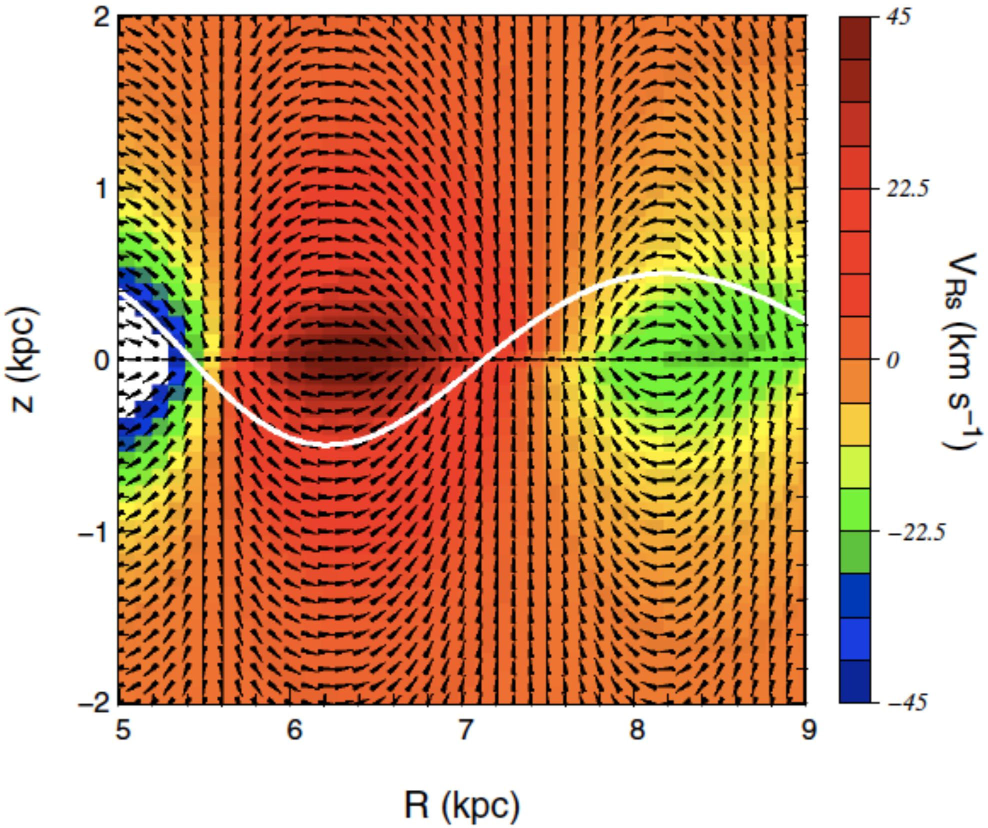
D'Onghia et al. 2014

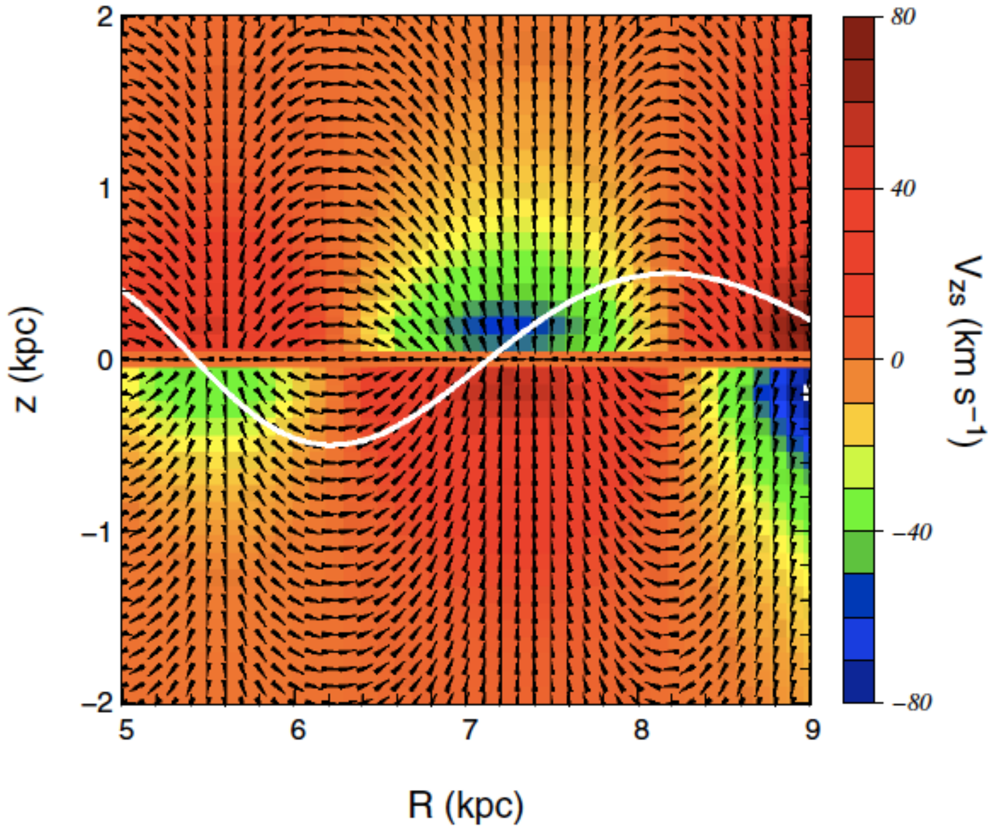




Williams et al. 2013

Radial and vertical flows induced by galactic spiral arms

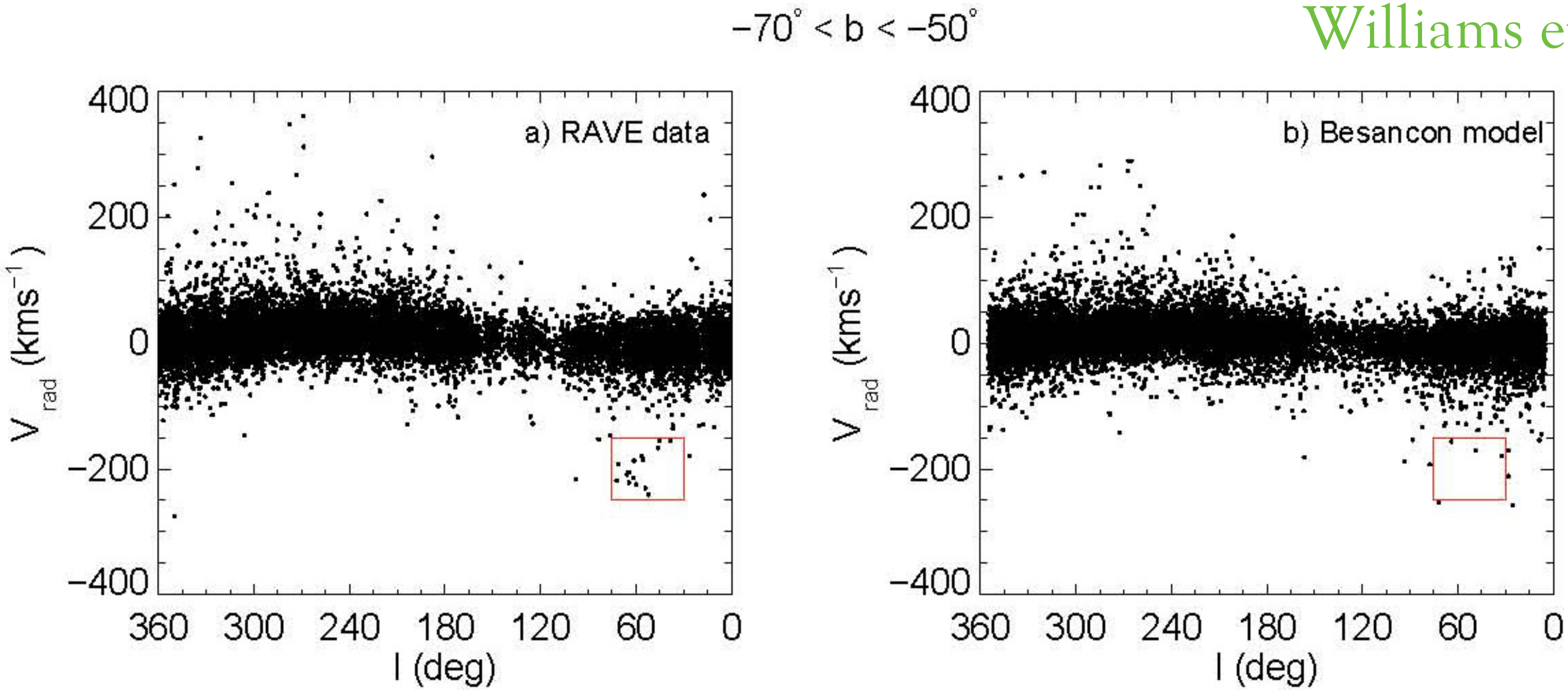


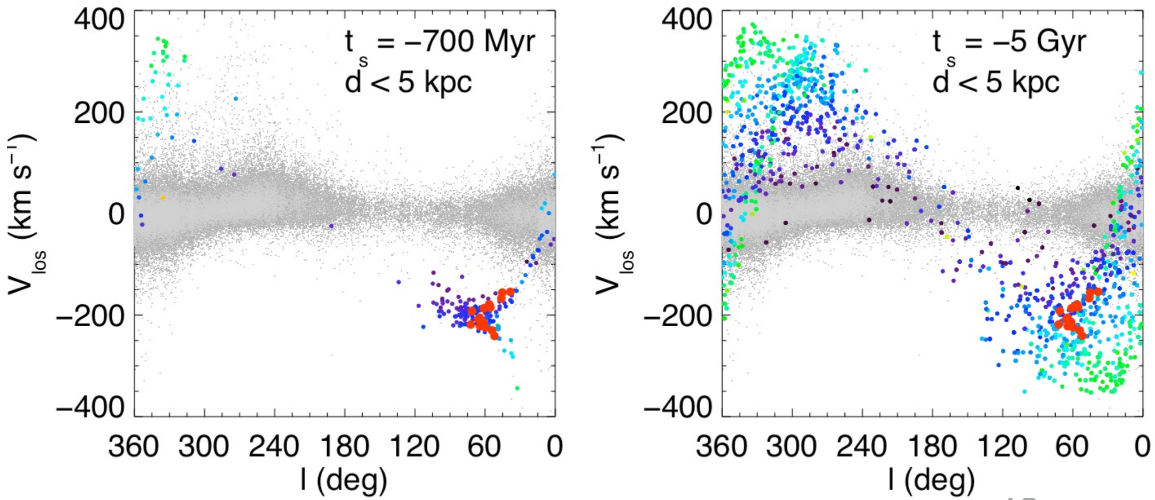


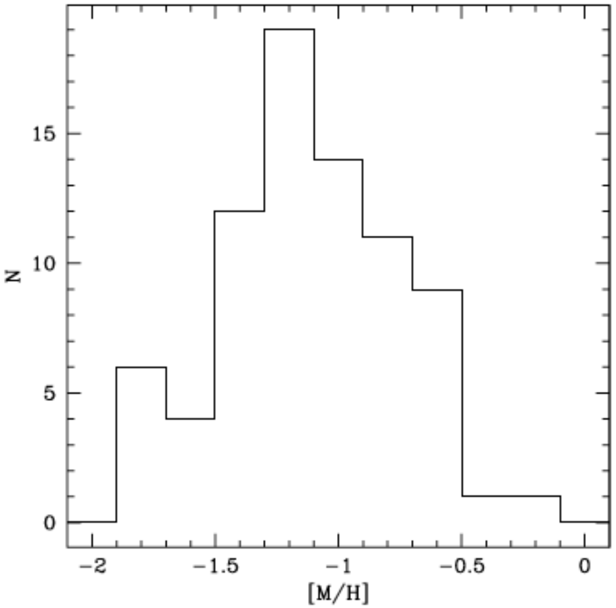
Faure et al. 2014

Aquarius stream update

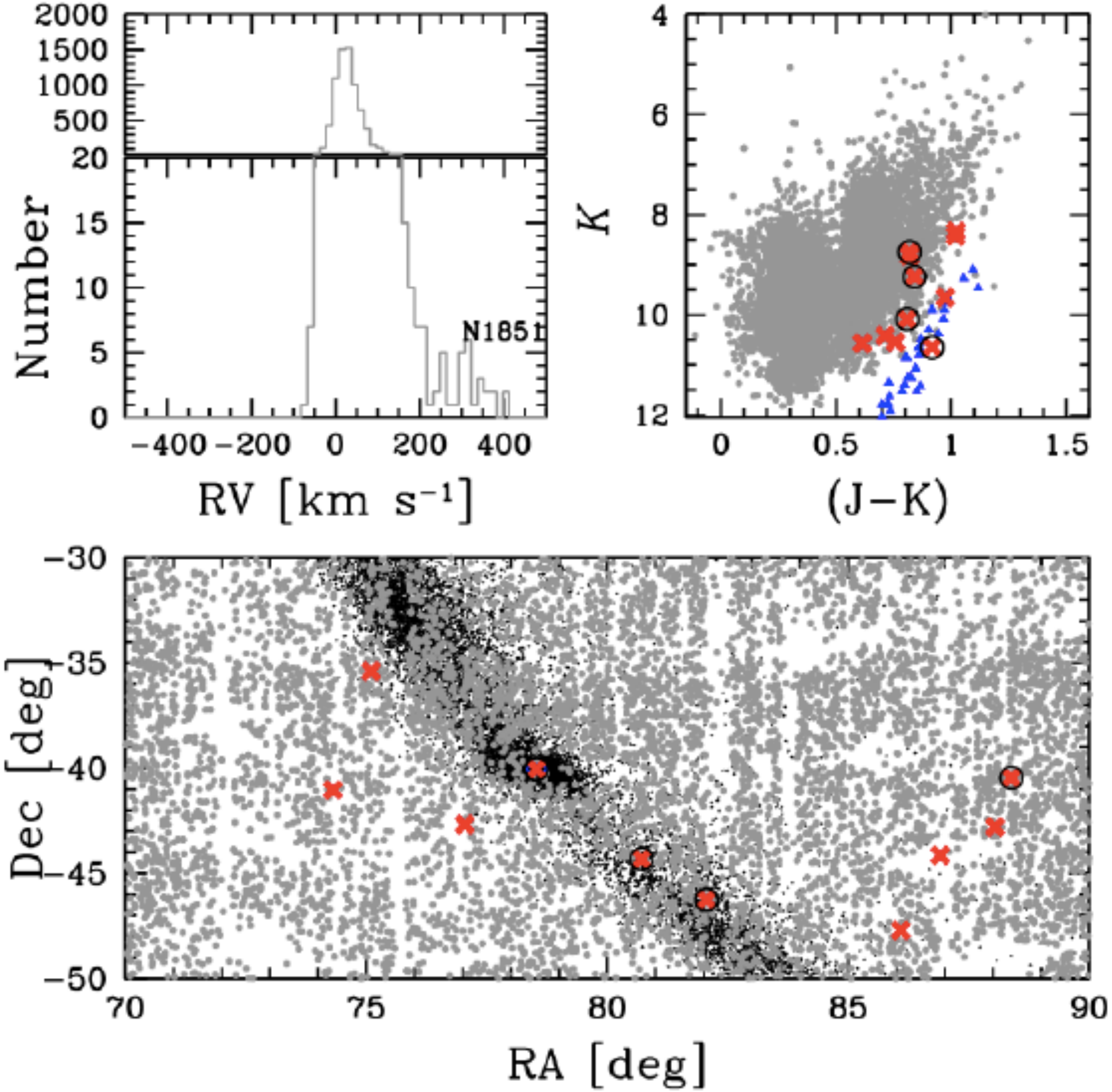
Williams et al. 2011







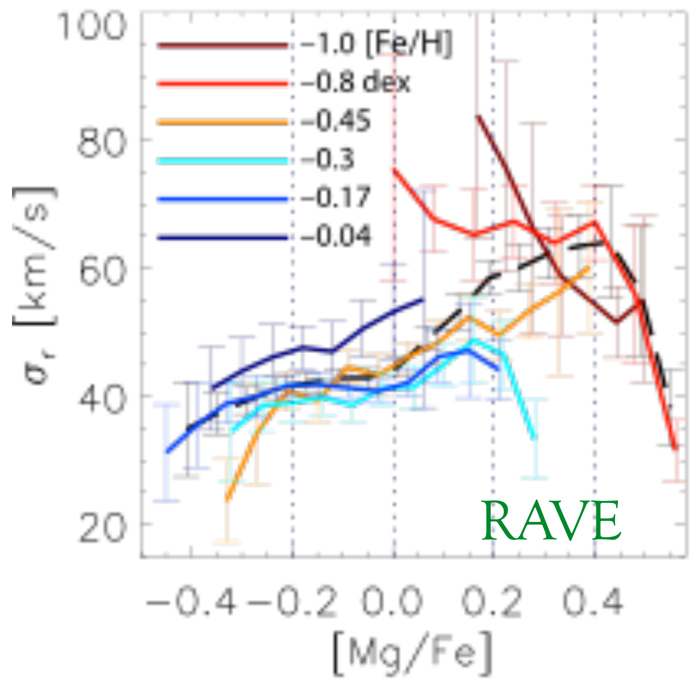
Tidal debris from Globular Clusters

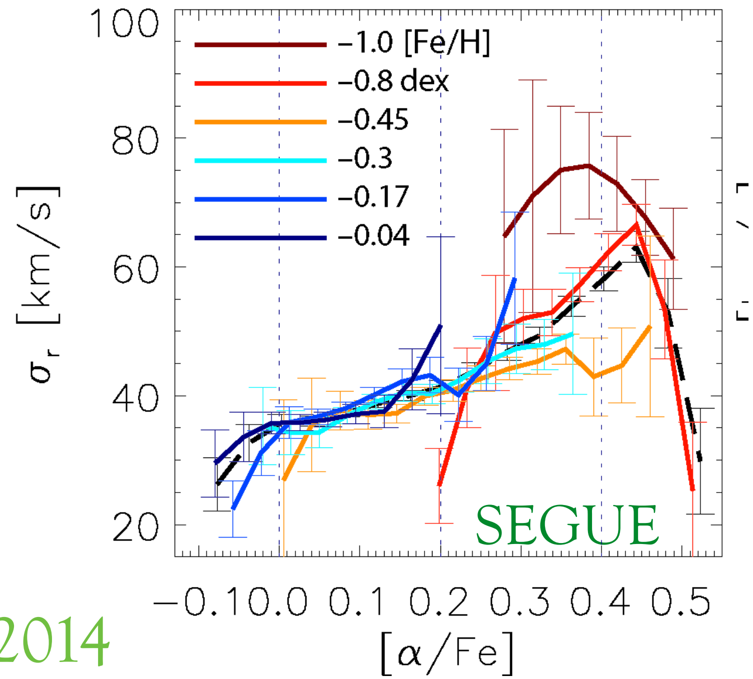


Kunder et al, 2014, see Poster Angiano et al, 2014

Chemo-kinematic signature of MW formation

- More metal poor and alpha enriched (i.e. older stars) are expected to have higher velocity dispersions in the MW disk owing to heating
- RAVE data show that the most metal-poor, alpha-enhanced stars display a surprising reversal of this trend (red lines)
- Similar signature also identified in SEGUE dwarfs
- Minchev et al (2014) can explain these trends with a model that brings cold, old stars from the inner Milky Way to the Solar neighborhood by merger induced stellar radial migration

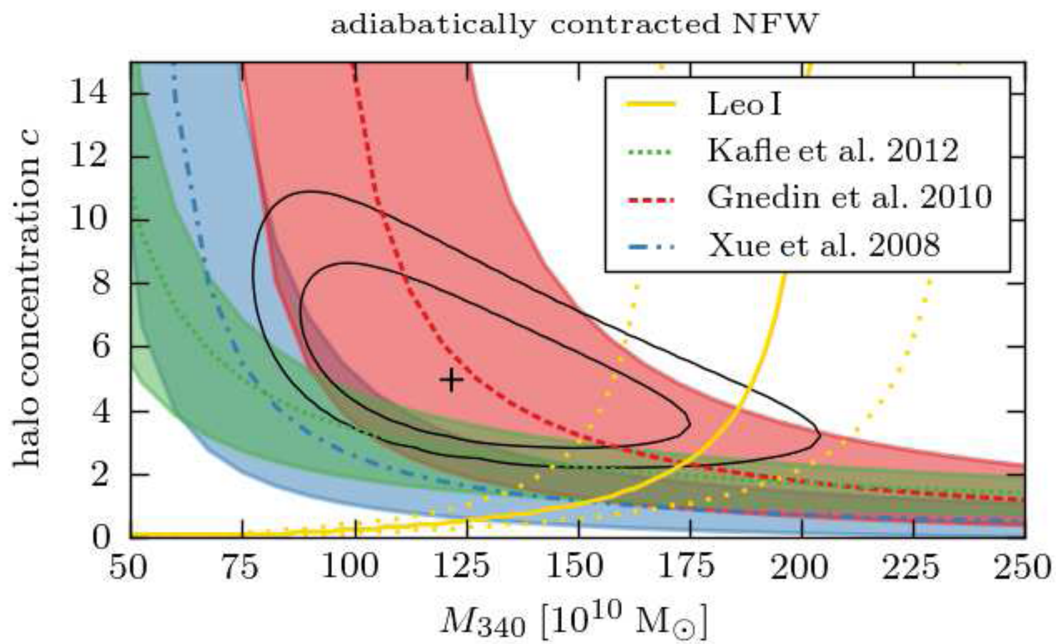




Minchev et al. 2014

Escape speed of the Milky Way at the Solar Circle

- Leonard & Tremaine (1990):
  - consider distribution function f(E)
  - $f \rightarrow 0$ as $E \rightarrow \Phi(r_{vir}) \Rightarrow n(v) \propto (v_{esc}\text{-}v)^k$
- Consequently for line of sight:
  $$n(v_{||}) \propto (v_{esc} - v_{||})^{k+1}$$
- Dependence verified via cosmological simulations
- Measure distribution $n(v_{||})$ for high velocity stars with RAVE on counterrotating orbits
- Piffl et al (2014a):
  $493\text{km/s} < v_{esc} < 587\text{km/s}$
  $1.1\times10^{12}M_\odot < M_{200} < 2.1\times10^{12}M_\odot$

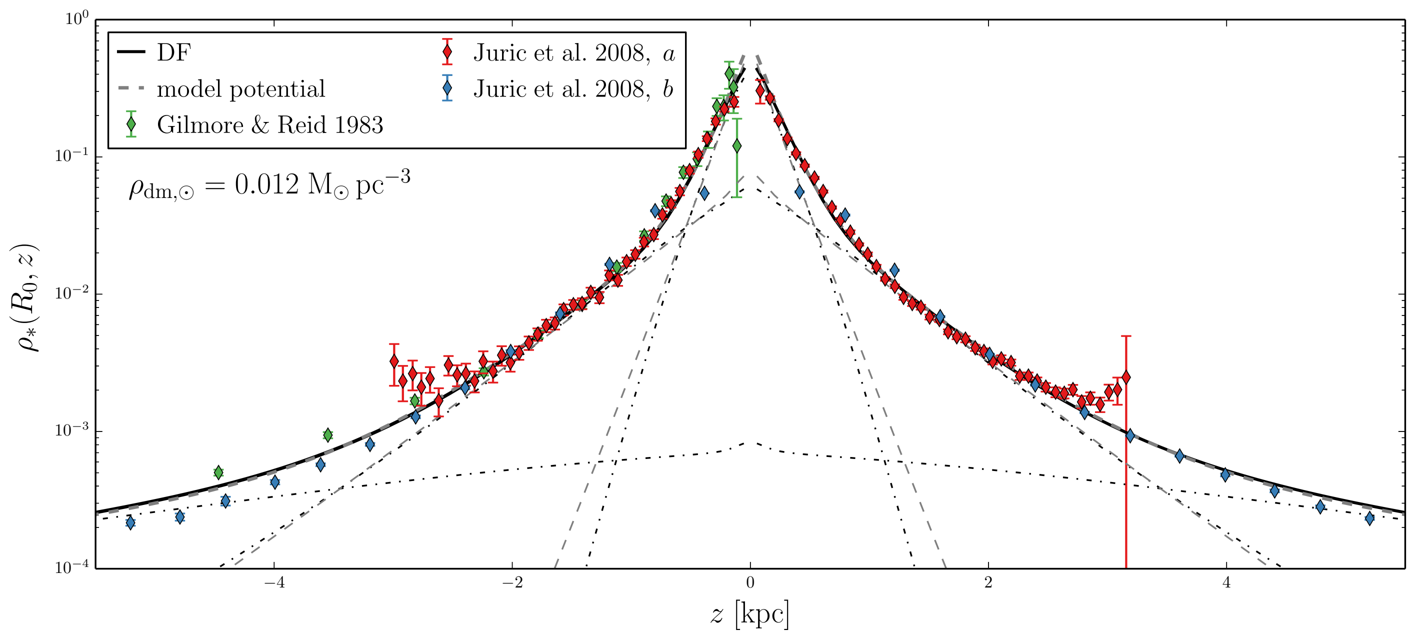


How to compare simulations and survey data?

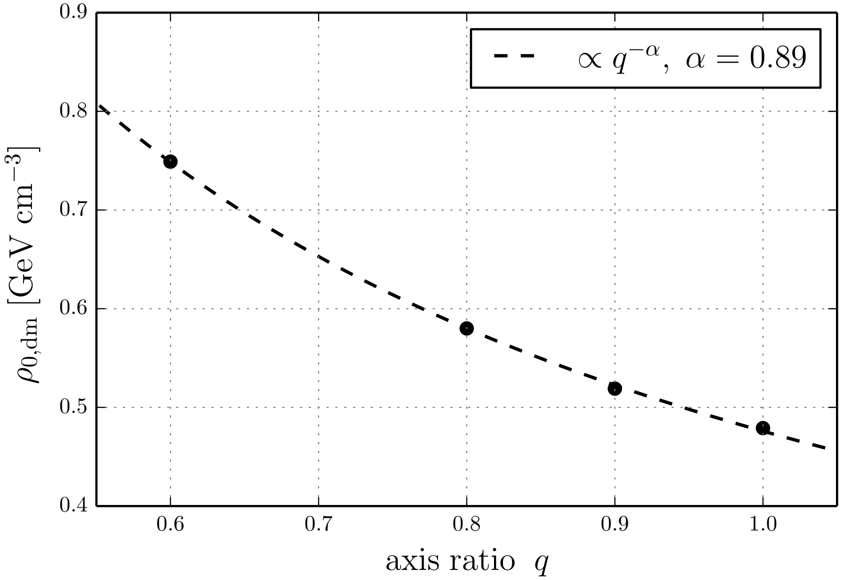
- Without the assumption of equilibrium any DF in (x,v) is consistent with a potential Φ
- Equilibrium probably a reasonable assumption for MW, good starting point
- we know there are non-equilibrium features (spiral arms, warps, tidal streams, wobbling disk)
  $\Longrightarrow$ should show up as differences to equilibrium model
- describe simulations and observations as pdf and see to what extent pdfs are consistent with each other

Dark mass in the solar neighborhood (Piffl et al 2014)

- Mass Model:
  - three exponential disks
  - flattened bulge
  - NFW dark matter halo
- Binney 2012 model for kinematics (incl. stellar halo)
- Model fit to vertical RAVE data



Results



Model potential parameters		
$\Sigma_{0,\rm thin}$	570.7	$M_\odot\,pc^{-2}$
$\Sigma_{0,\rm thick}$	251.0	$M_\odot\,pc^{-2}$
$R_{\rm d}$	2.68	kpc
$z_{\rm d,thin}$	0.20	kpc
$z_{\rm d,thick}$	0.70	kpc
$\Sigma_{0,\rm gas}$	94.5	$M_\odot\,pc^{-2}$
$R_{\rm d,gas}$	5.36	kpc
$\rho_{0,\rm dm}$	0.01816	$M_\odot\,pc^{-3}$
$r_{0,\rm dm}$	14.4	kpc
DF parameters		
$\sigma_{r,\rm thin}$	33.9	$km\,s^{-1}$
$\sigma_{z,\rm thin}$	24.9	$km\,s^{-1}$
$R_{\sigma,r,\rm thin}$	9.0	kpc
$R_{\sigma,z,\rm thin}$	9.0	kpc
$\sigma_{r,\rm thick}$	50.5	$km\,s^{-1}$
$\sigma_{z,\rm thick}$	48.7	$km\,s^{-1}$
$R_{\sigma,r,\rm thick}$	12.9	kpc
$R_{\sigma,z,\rm thick}$	4.1	kpc
$F_{\rm thick}$	0.460	
$F_{\rm halo}$	0.026	

$$\varrho_{\rm DM} = 0.0126 \times q^{-0.89} M_\odot\,pc^{-3} \pm 10\%$$

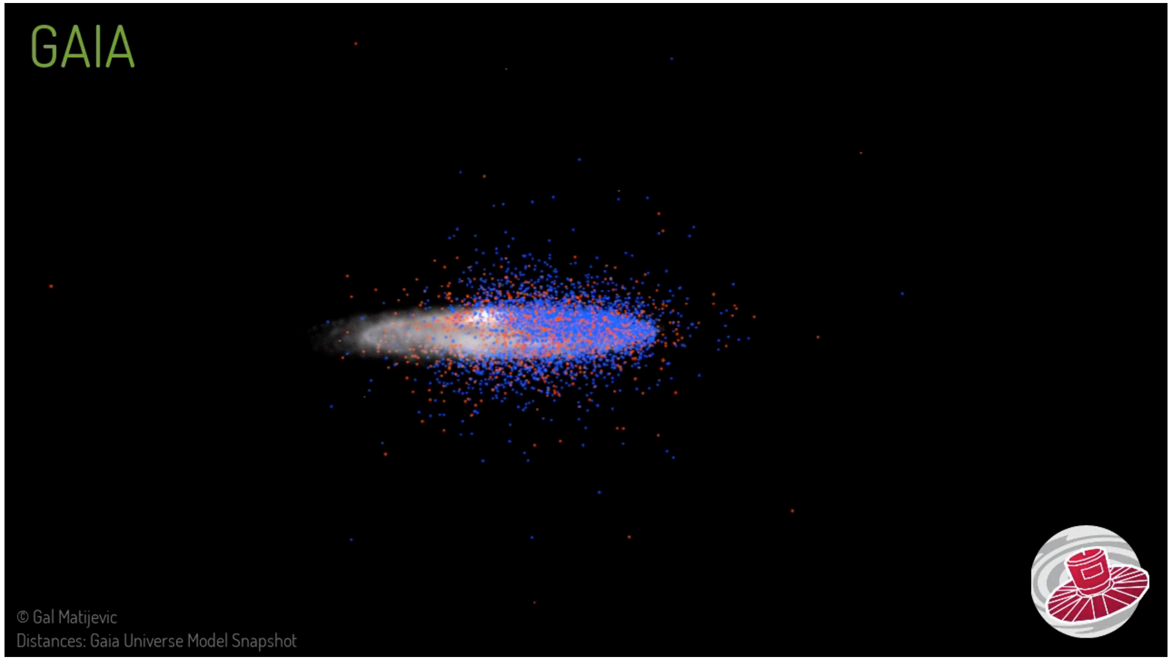
$$\Sigma_{\rm DM}(< 0.9{\rm kpc}) = (69 \pm 10)\,M_\odot\,pc^{-2}$$

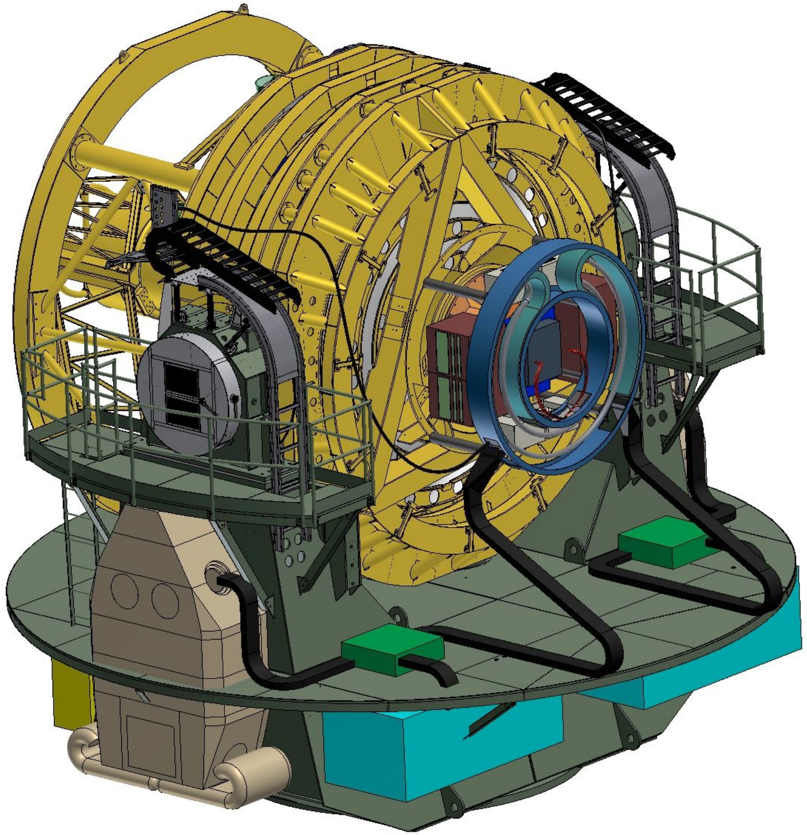
$$M_{\rm DM}(< R_0) = (6.0 \pm 0.9) \times 10^{10}\,M_\odot$$

$$M_{\rm vir} = (1.3 \pm 0.1) \times 10^{12}\,M_\odot$$

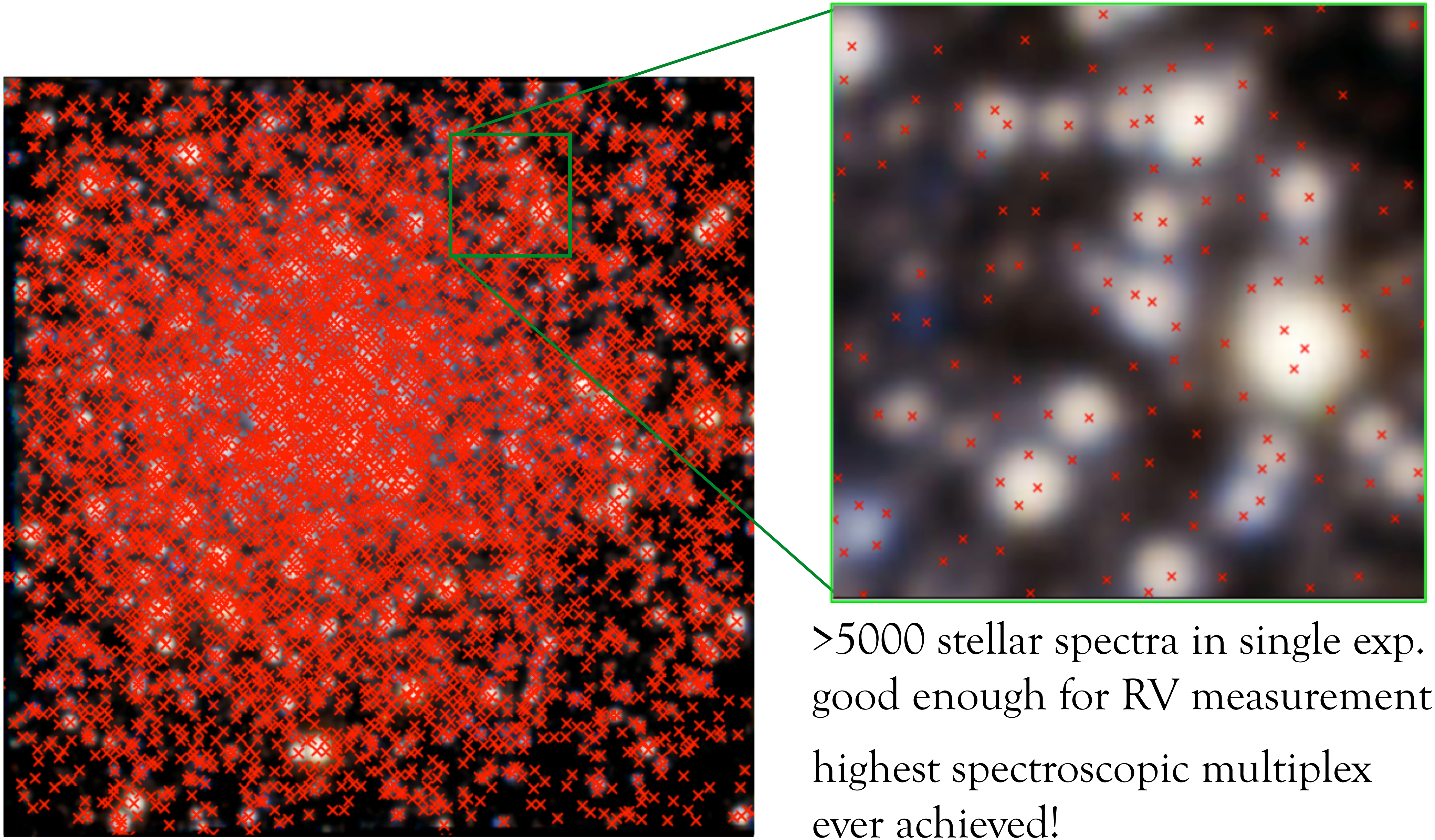
- 45% of the radial force at R_0 provided by baryons
- Bienamyé et al (2014): RAVE stars towards Galactic Pole, red clump distances: $\varrho_{\rm DM}(R=R_0,z=0) = 0.0143 M_\odot pc^{-3}$

What comes next?





Crowded Field 3D Spectroscopy with MUSE: Globular Cluster NGC 6266



>5000 stellar spectra in single exp.
good enough for RV measurement

highest spectroscopic multiplex
ever achieved!

S. Kamann / data from MUSE Commissioning 2014

Summary

- We have exquisite data sets for near field cosmology (CGS, RAVE, SEGUE, APOGEE), many are public
- RAVE survey: more than 574,000 spectra taken
- Detection of large-scale asymmetries of the velocity field in the solar neighborhood
  - Apparent asymmetry above vs below the plan (wave?)
  - number of merger signatures even in the local suburb
- Local escape speed: relatively low Milky Way DM halo mass confirmed
- How to compare advanced (simulation) models to data? we are already data rich and model poor!
- Next major step: Gaia & 4MOST; MUSE