A box full of chocolates:
Structure of the nearby stellar halo with Gaia & RAVE

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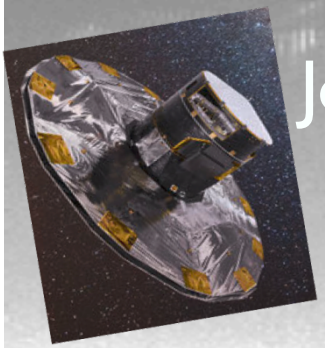

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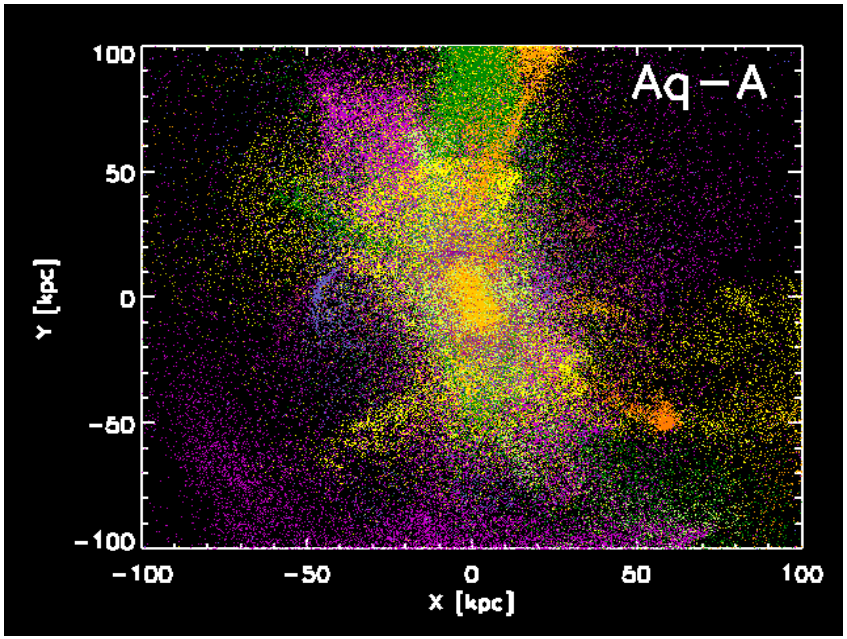
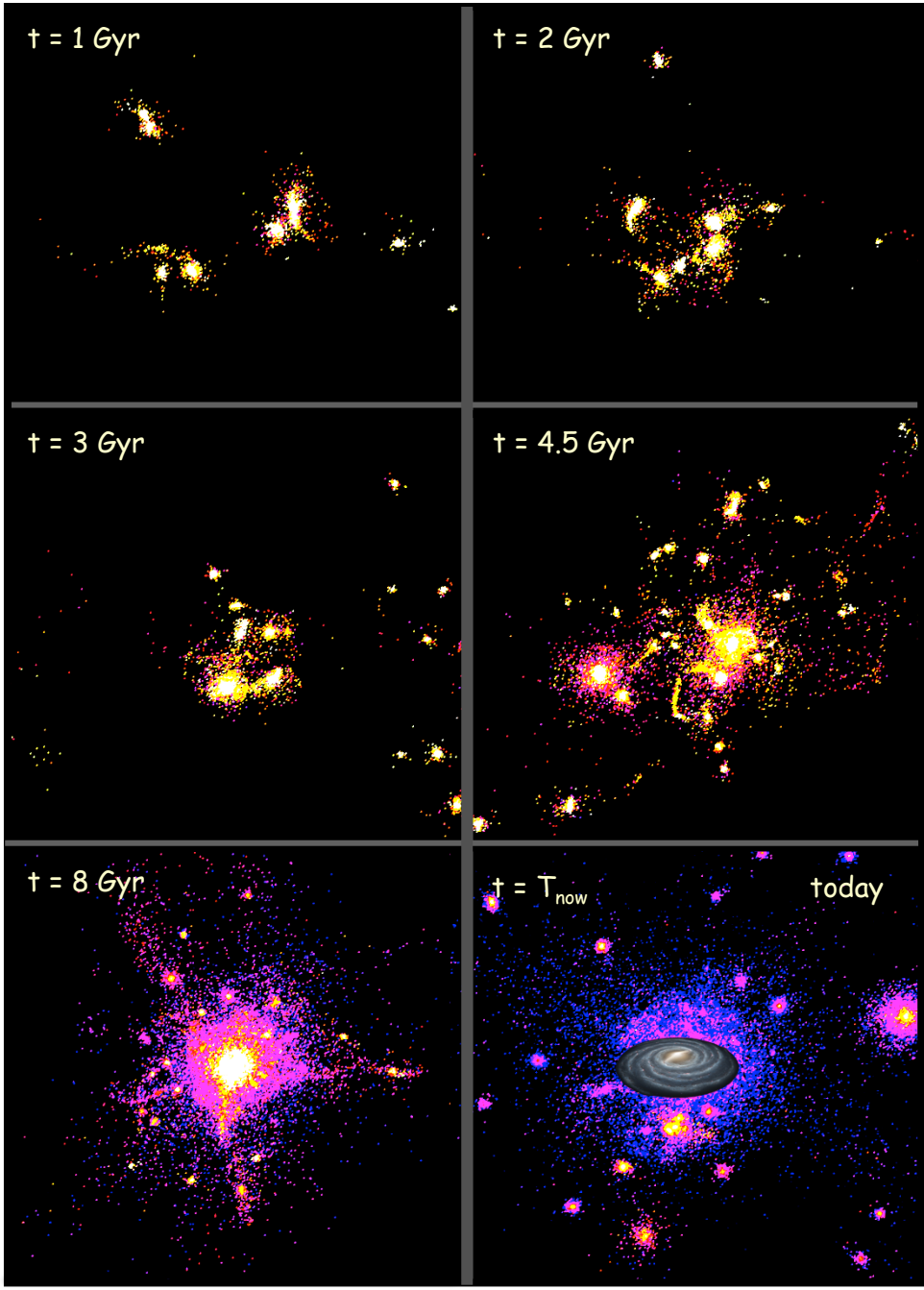
Stellar halo: treasure trove of merger relics

- Cosmological model's characteristic is hierarchical growth: mergers → how important for Milky Way?

- Disrupted galaxies/debris naturally in a stellar halo:
  → merger signatures: *Substructures and tidal streams*

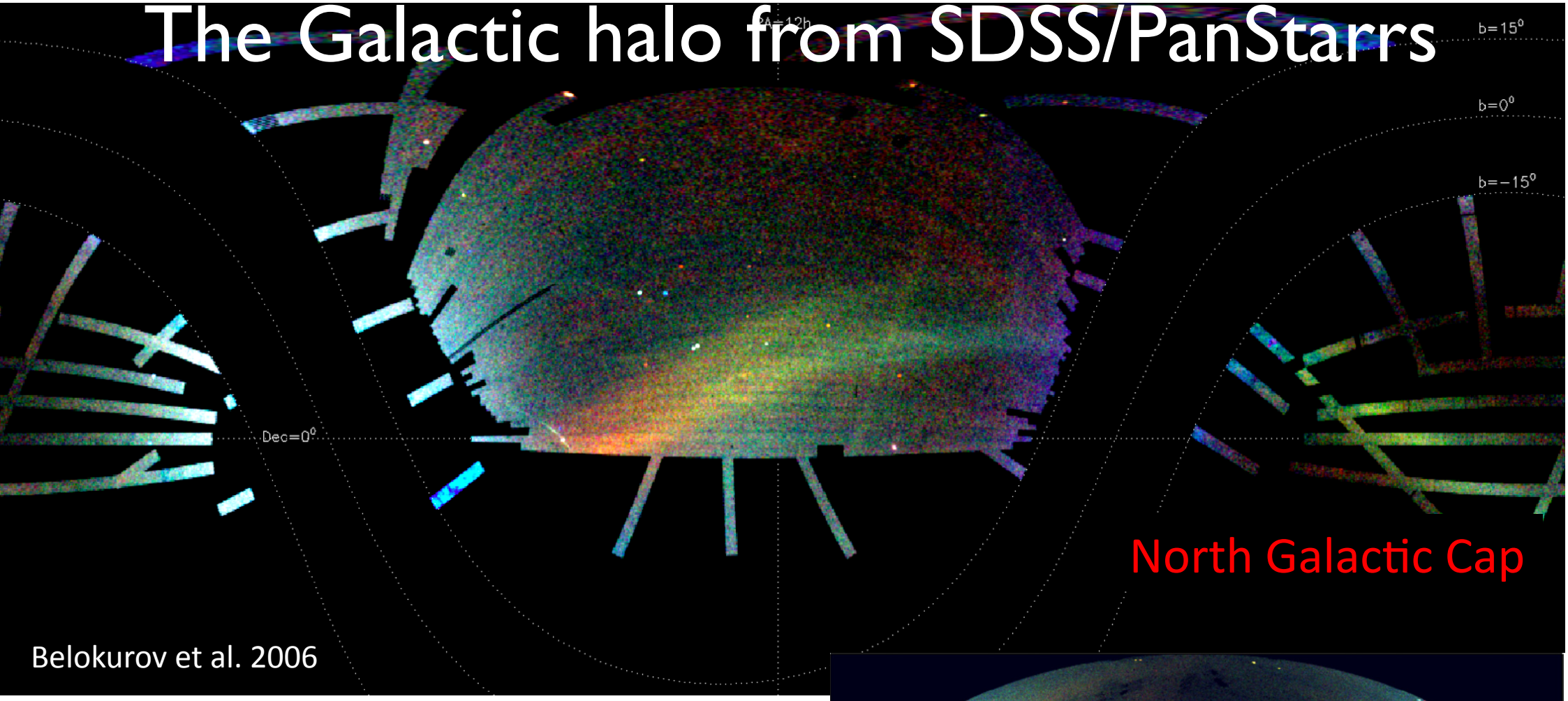




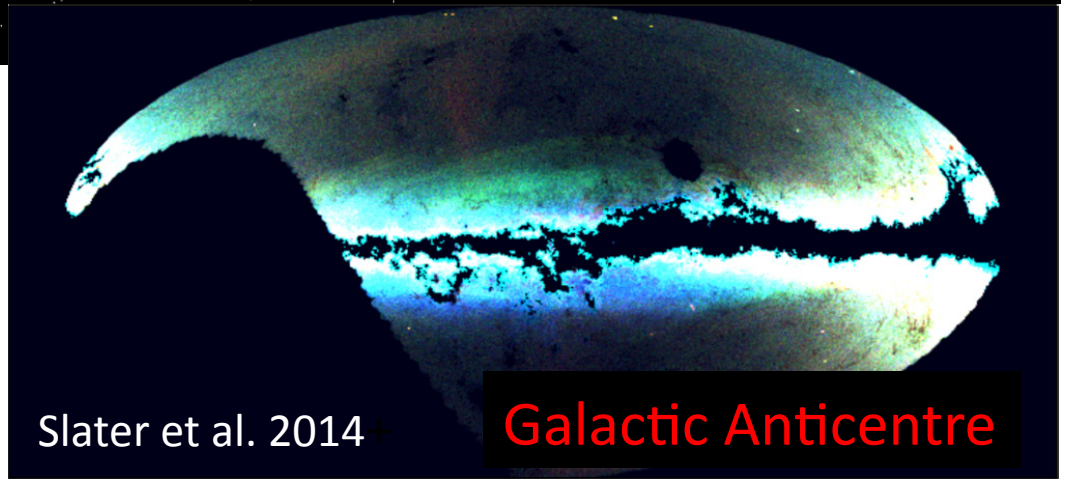
snapshots: J. Gardner

The accretion history unveiled so far:

The Galactic halo from SDSS/PanStarrs



Belokurov et al. 2006



Slater et al. 2014

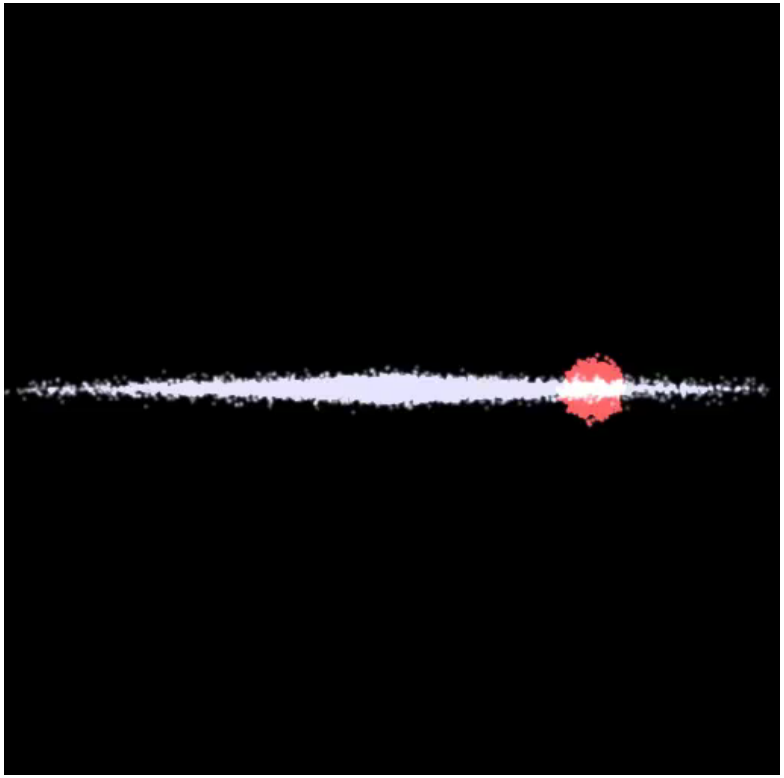
Outer halo: R > 20 kpc

- Clear evidence of substructure
- Limited to high-surface brightness features (progenitors/time of events)
- Qualitatively consistent with expectations from ΛCDM (Helmi et al. 2011; Deason et al. 2014)

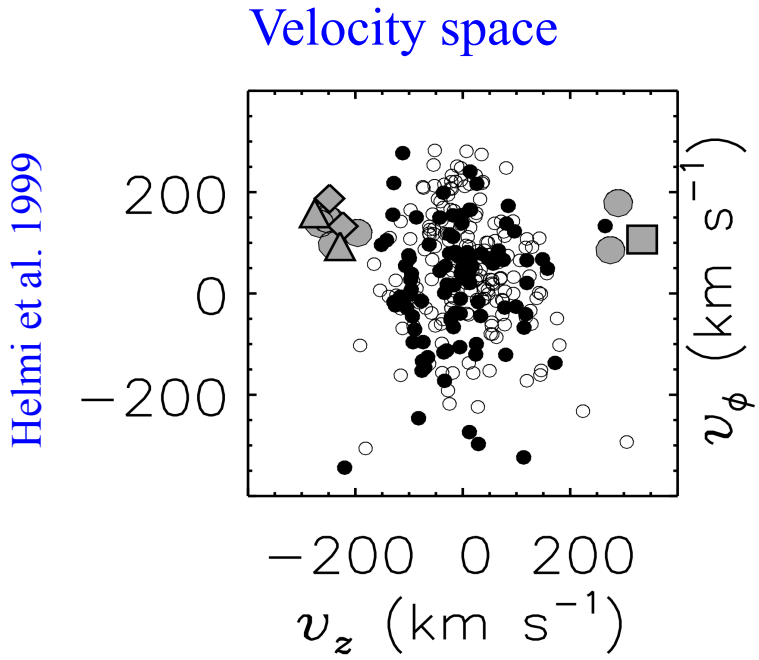
Nearby halo

Memory of origin: retained in the motions

- 100s of streams should cross Sun's vicinity
- So far.. two streams near the Sun from a galaxy disrupted very early on and a few more "hints" (Smith 2016)



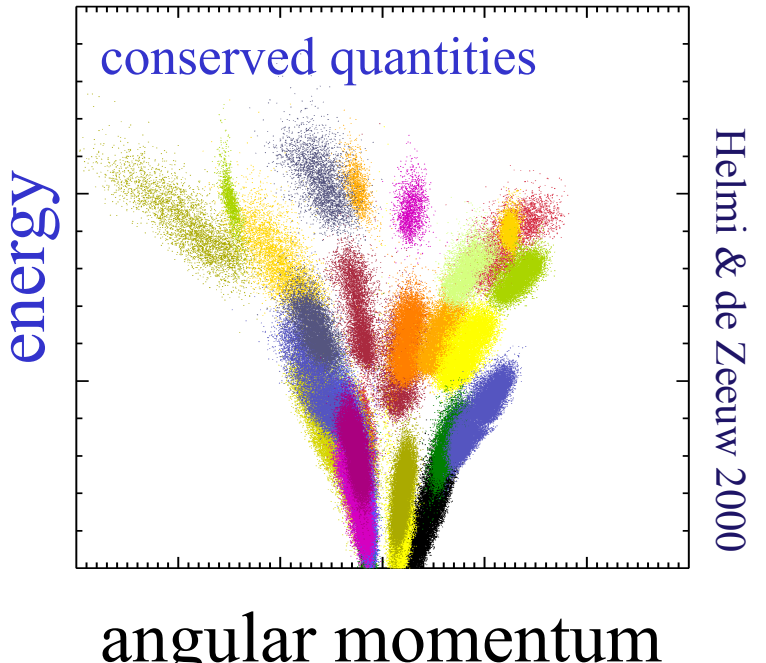
The movie can be found at
https://www.astro.rug.nl/~ahelmi/research/gaia/movie.html



Many more hiding…

How to find these?

- Clustering in conserved quantities
- A good dataset



Construction of a halo sample: TGAS x RAVE

- TGAS dataset is significant improvement, but need full phase-space information
  → cross-match to RAVE
- RAVE survey obtained spectra for 500k stars in southern sky: radial velocity; metallicity; spectrophotometric distance/parallax

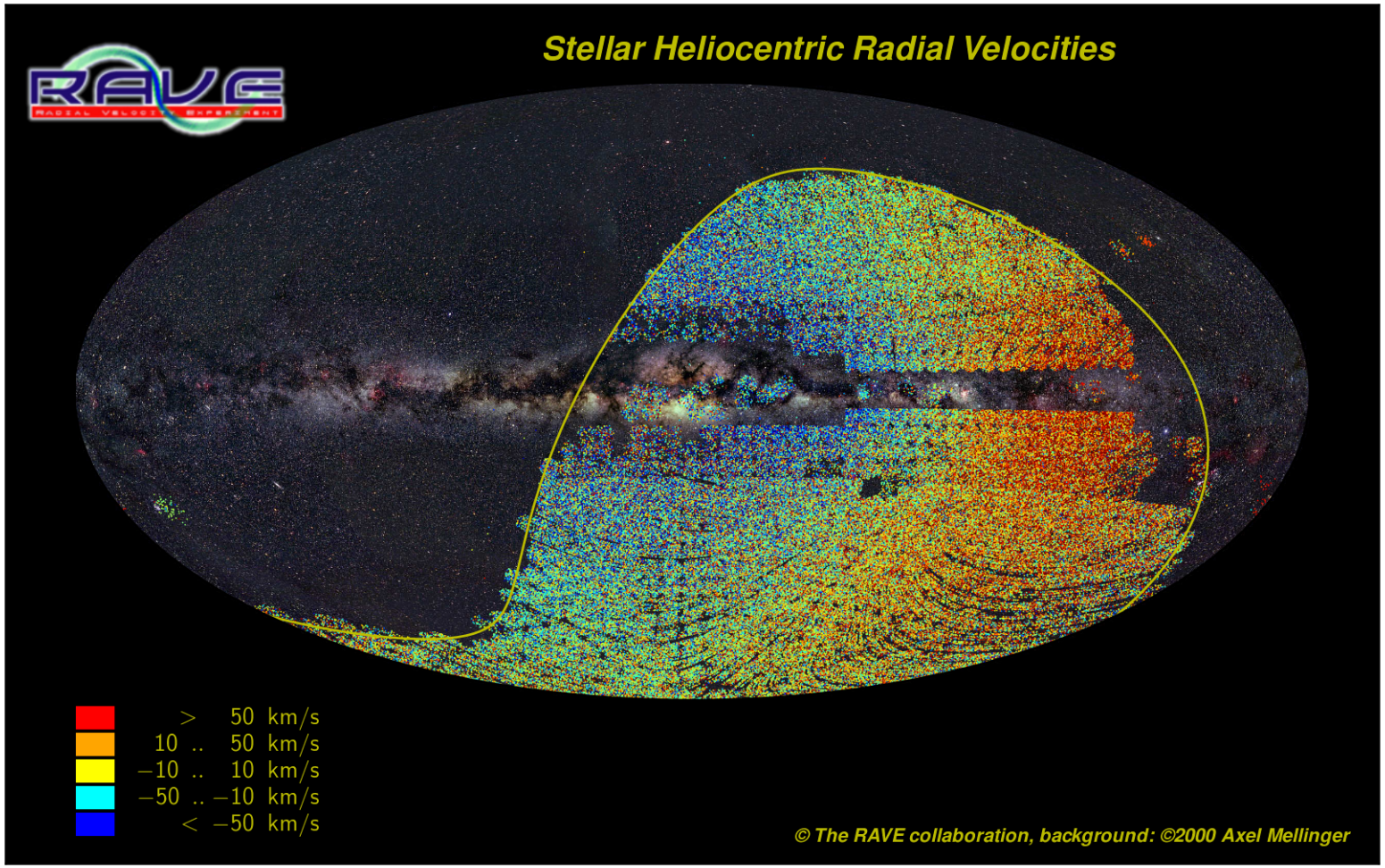
→ 210,263 stars in common

Quality criteria for reliable parallaxes, RV and metallicity

-RAVE flags for reliable l.o.s. velocity and atmospheric parameters (SNR > 20, algoConv ≠ 1, ε_{RV} < 10 km/s, CorrCoeff > 10)

-Use TGAS or RAVE parallax depending in smallest relative parallax error

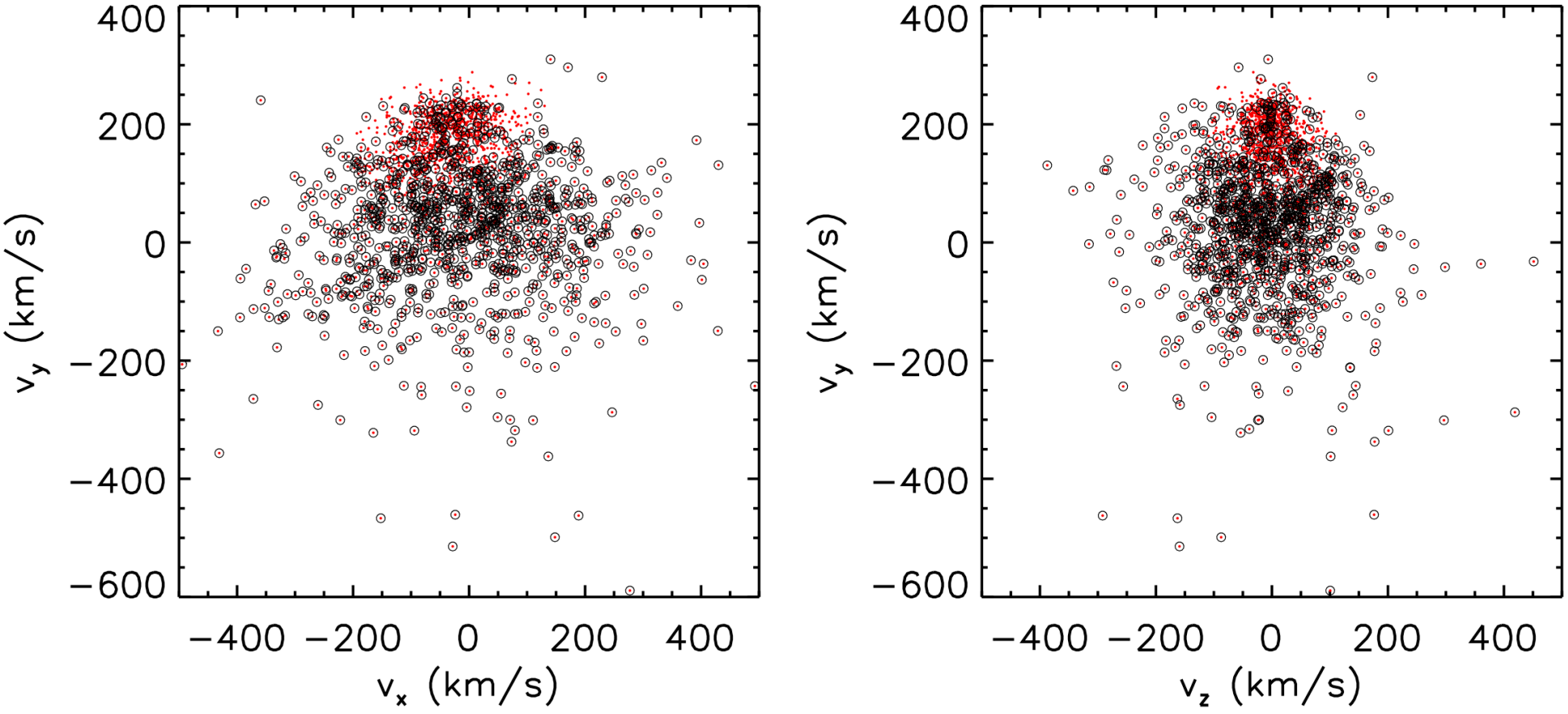
-Only stars with $\varepsilon_{\varpi}/\varpi$ < 0.3 and distance>100 pc



Construction of a halo sample

- Metallicity cut [M/H] < -1.5 dex to select preferentially halo → selects of 2,013 stars
- Still contains stars with disk-like kinematics
- Fit 2 Gaussians in velocity and determine probability for each star to belong to either component → assign to halo or disk

Final sample: 1113 "halo" stars

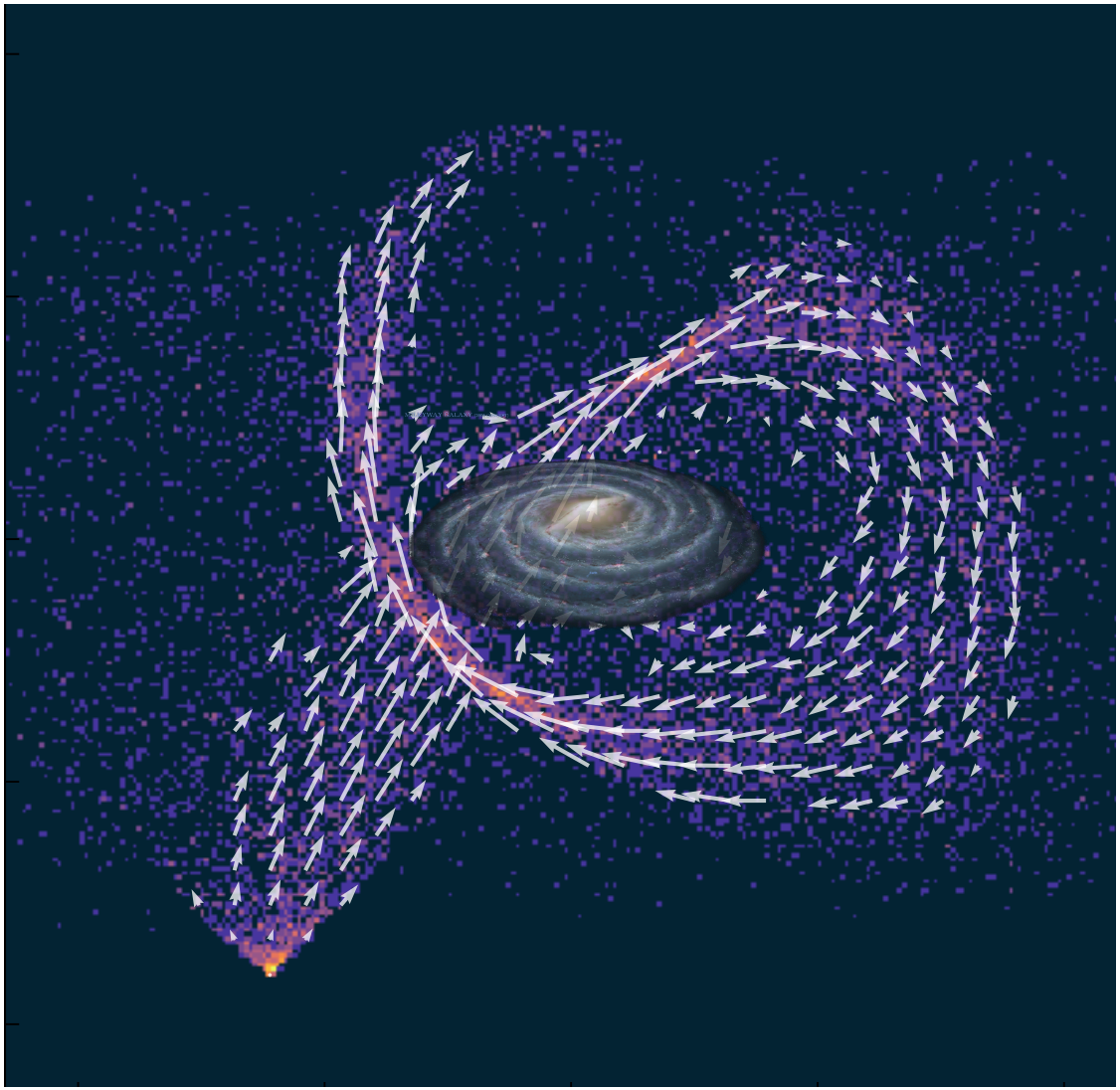


Statistical tests and searches of substructure

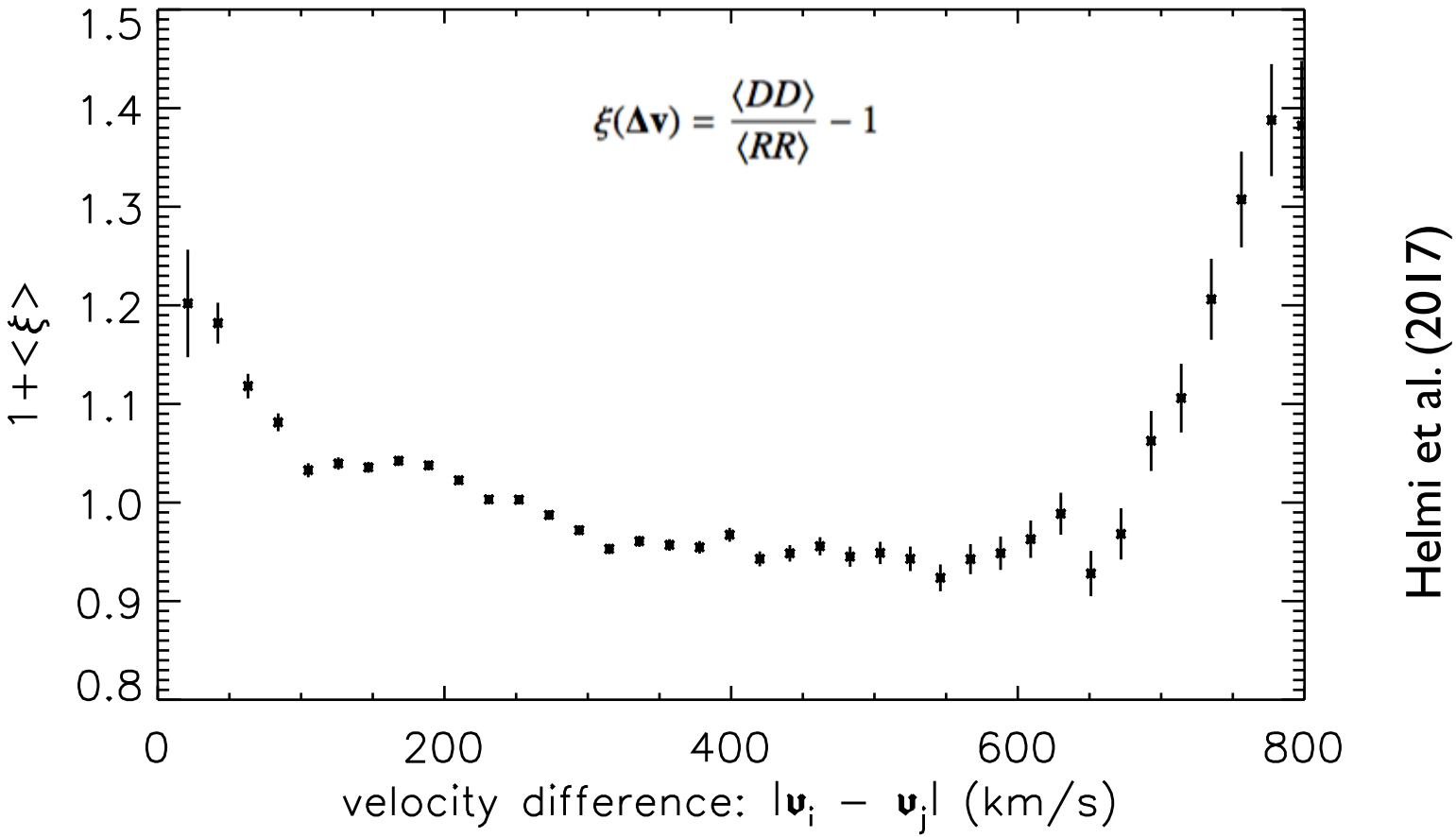
Models predict

- several hundred moving groups or streams in Solar Neighbourhood
  → we search for excess clustering in velocity space with a correlation function

- substructure to be more easily apparent in Integrals of Motion space
  → we characterise the distribution, degree of clustering and establish significance



Velocity correlation function

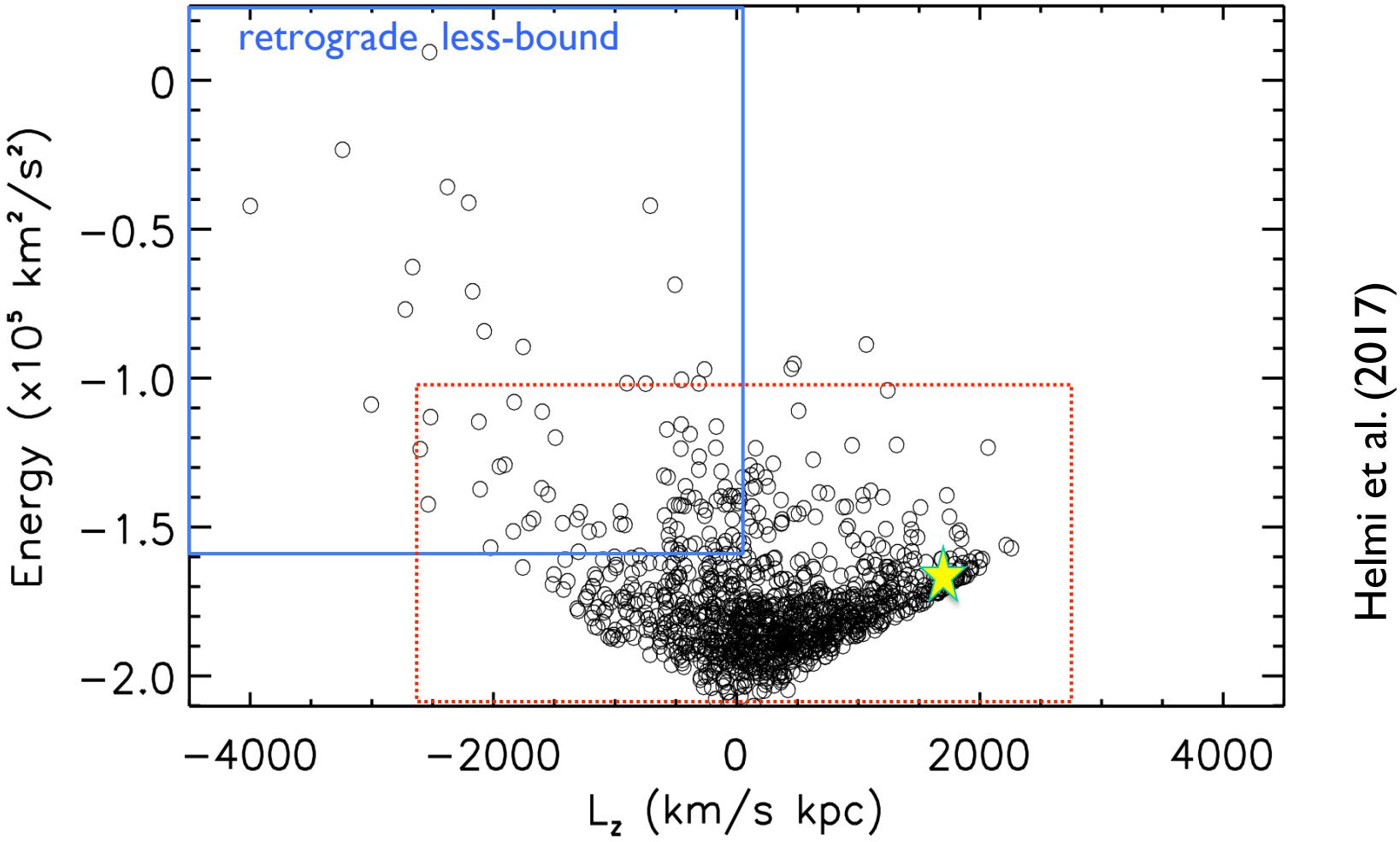


Helmi et al. (2017)

- Very significant excess of pairs in data compared to random/smooth:
  for $\Delta < 20$ km/s, 3.7σ (82 pairs of stars); for $20 < \Delta < 40$ km/s: 8.8σ

- Also for very large separations, there is a significant excess

Integrals of motion - space

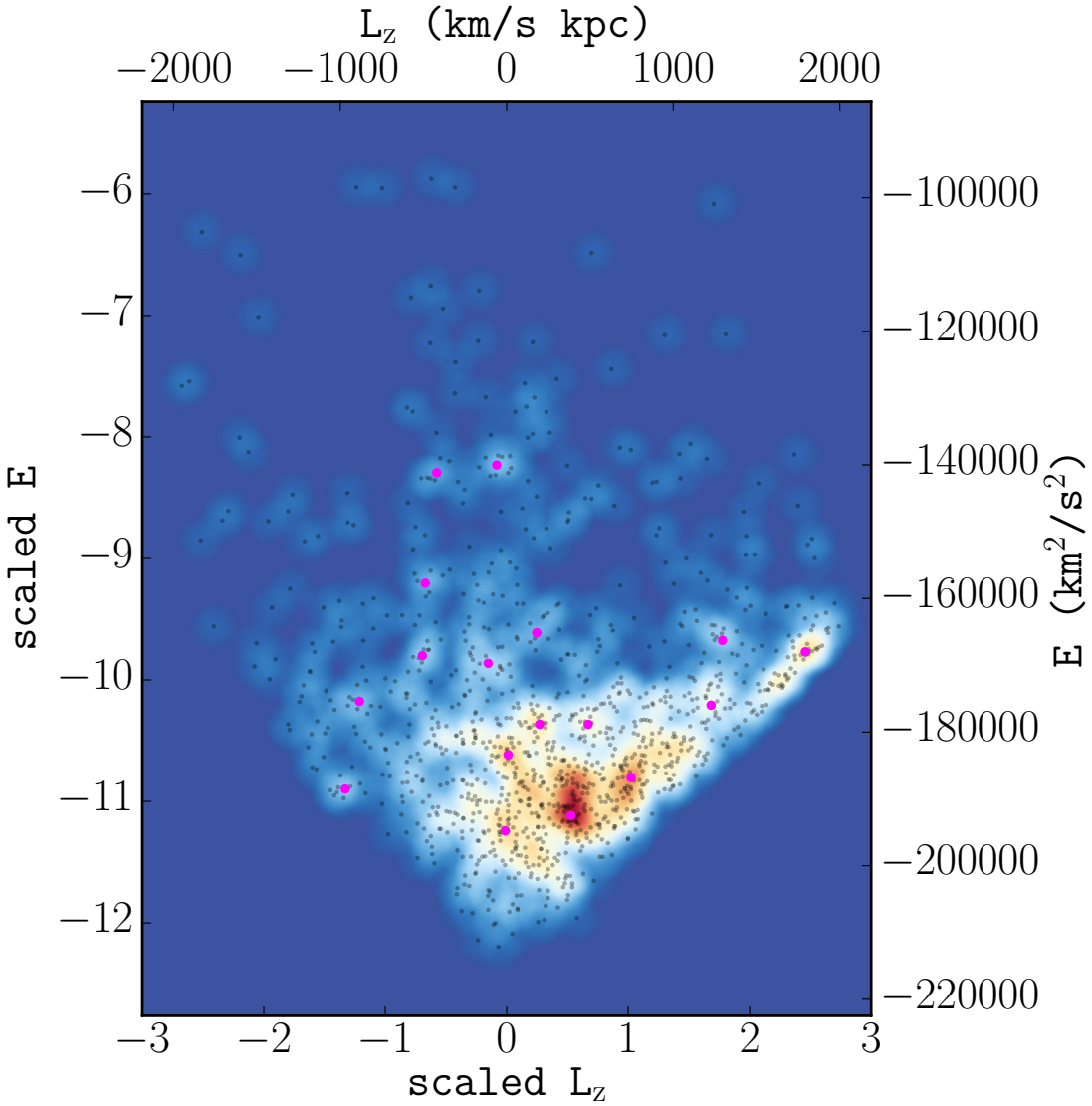


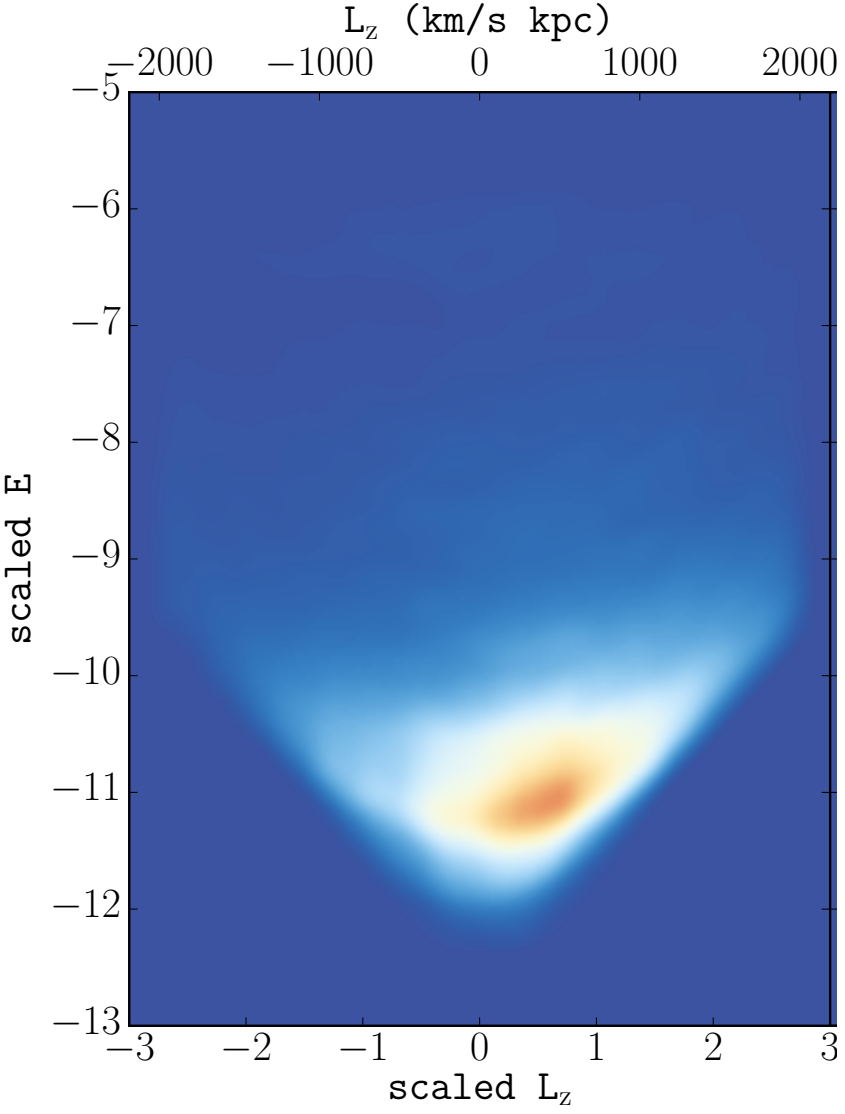
- Less bound halo stars → very retrograde motions: 73% (for $E > -1.3 \times 10^5$ km^2/s^2)

  In randomised (re-shuffled) smooth distributions the probability of having so many loosely bound counter-rotating stars is < 0.1%

Integrals of motion - space

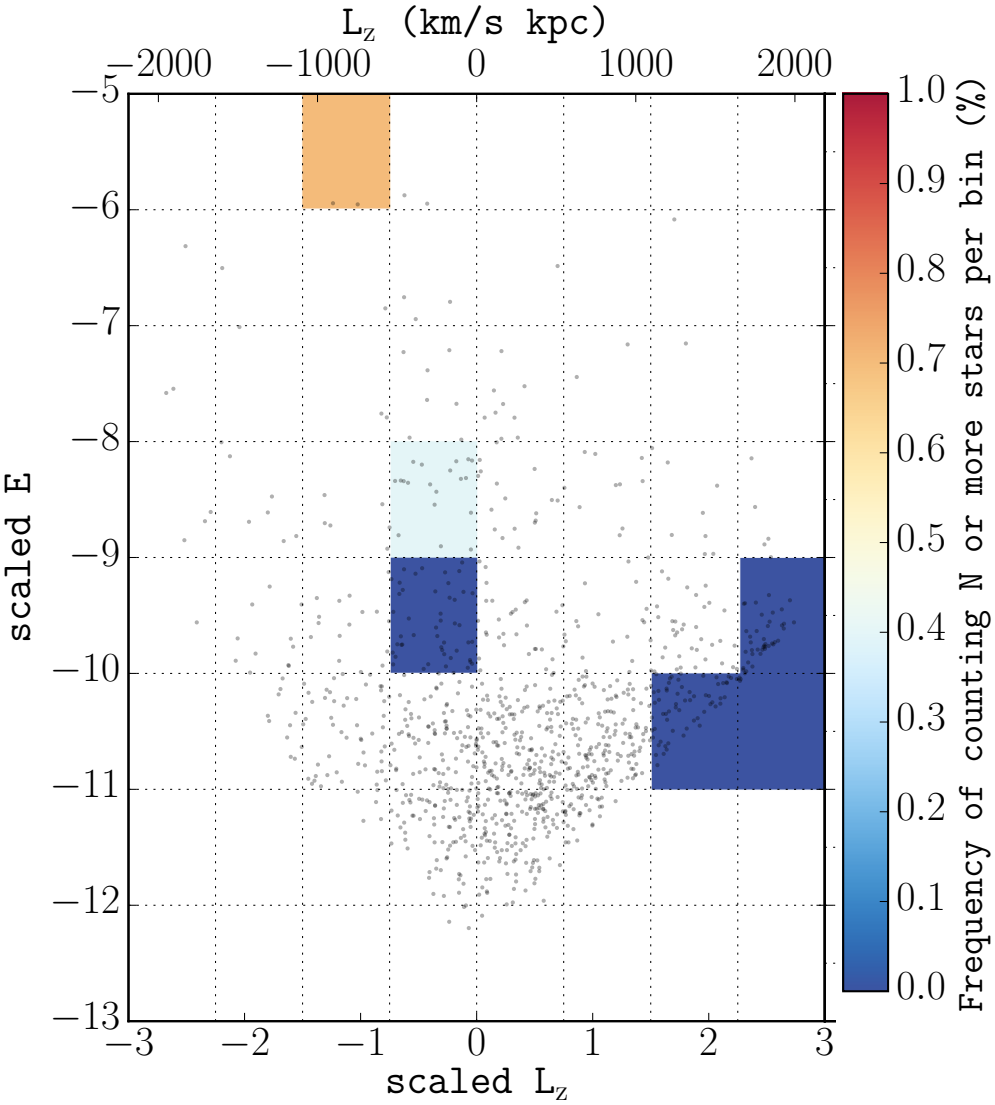
- Distribution is not smooth for more bound halo
- Significance of peaks/overdensities via comparison to randomised (re-shuffled) sets

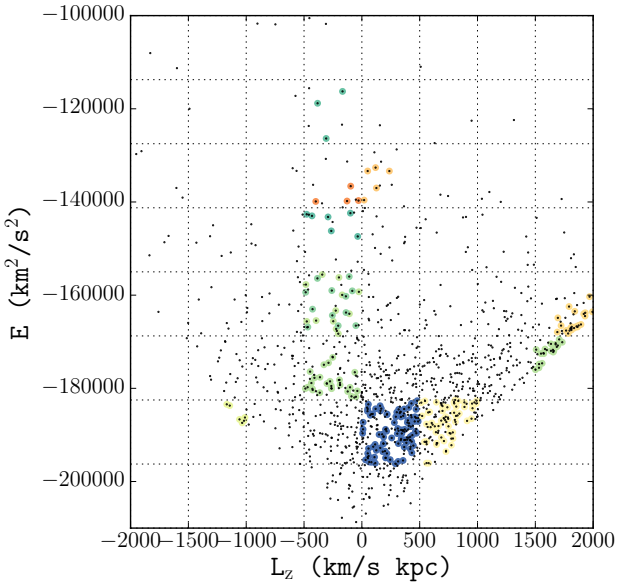


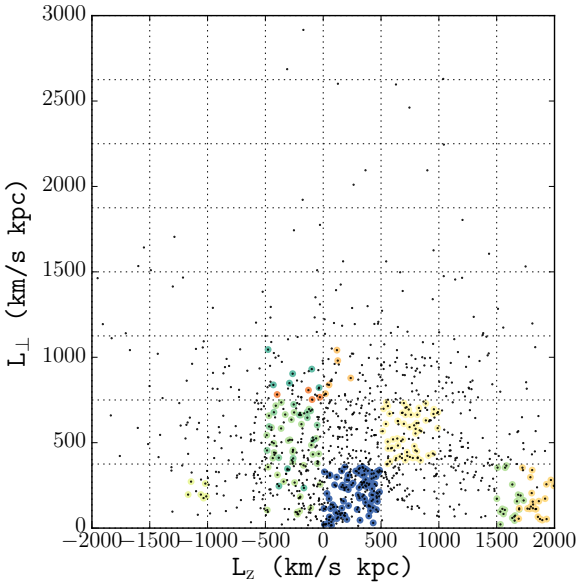


For significance via comparison to randomised sets

- how often do we find in the "smooth" sets as many stars as in the data at given location in IoM space
- in 2D and in 3D (now including also Lperp = $(Lx^2 + Ly^2)^{1/2}$)





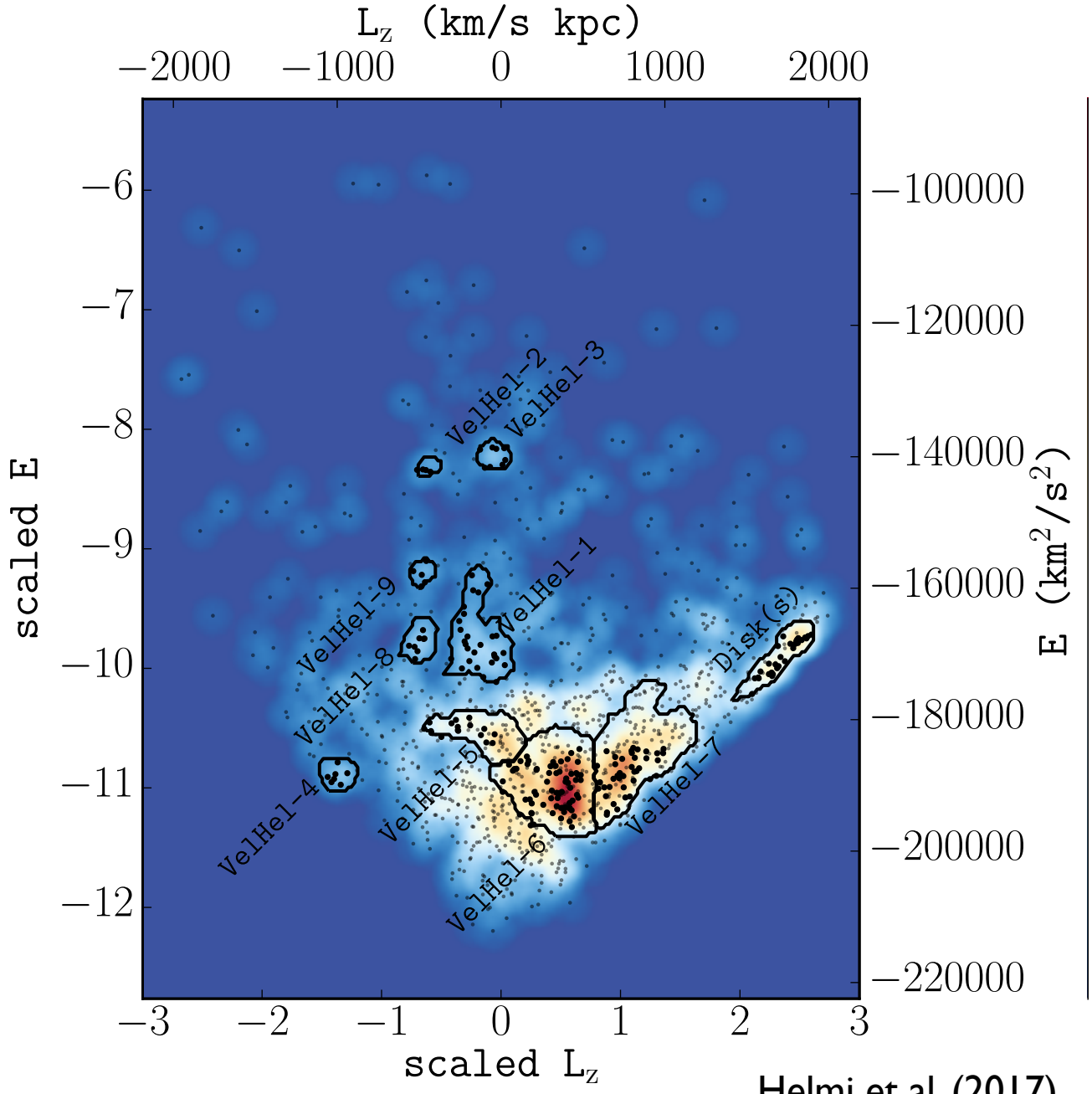


Consider bins where the probability is less than 1% (strict criterion excludes false positives)

Out of the 17 peaks/overdensities, <u>10 are significant</u>

Integrals of motion – space

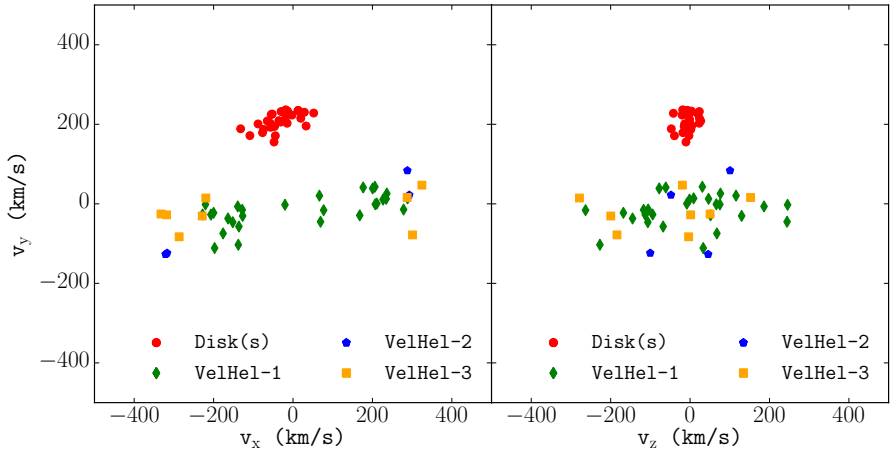
- Disk: low metallicity stars in this component (thick disk tail, e.g. Kordopatis et al 2014)
- VelHel-4: stars with disk-like kinematics but counter-rotating
- Structures at Lz ~-500 km/s kpc could be related to OmegaCen debris (Dinescu 2002)

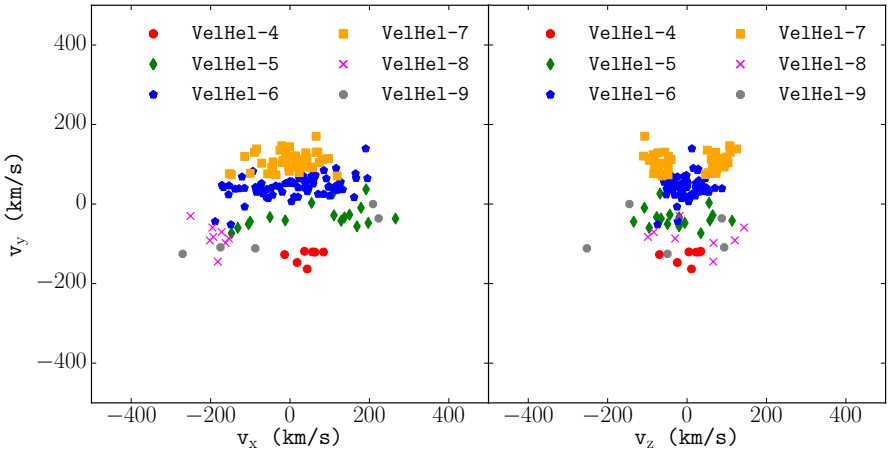


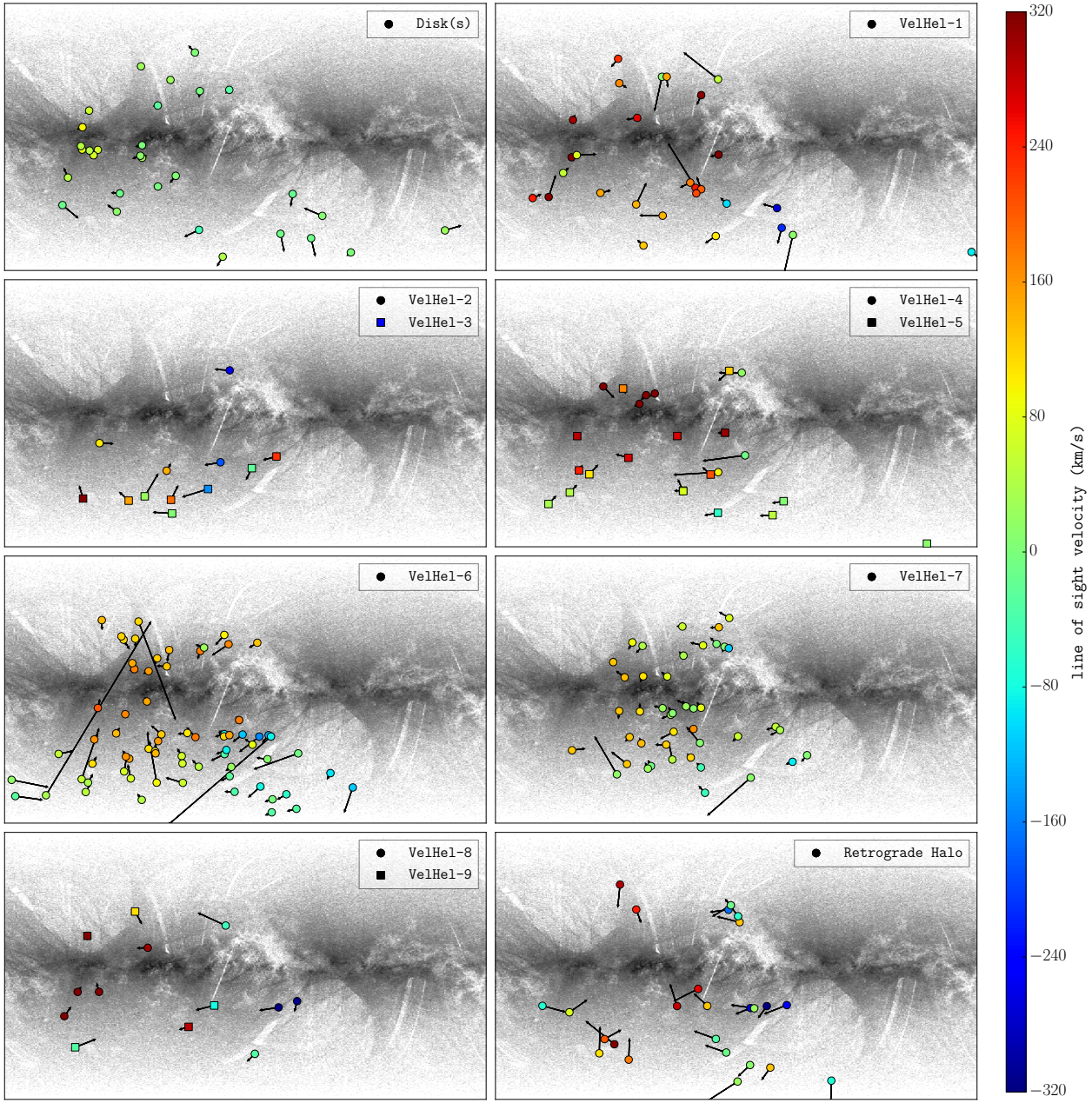
Helmi et al. (2017)

The structures in velocity space

Not single structures, but several clumps or moving groups







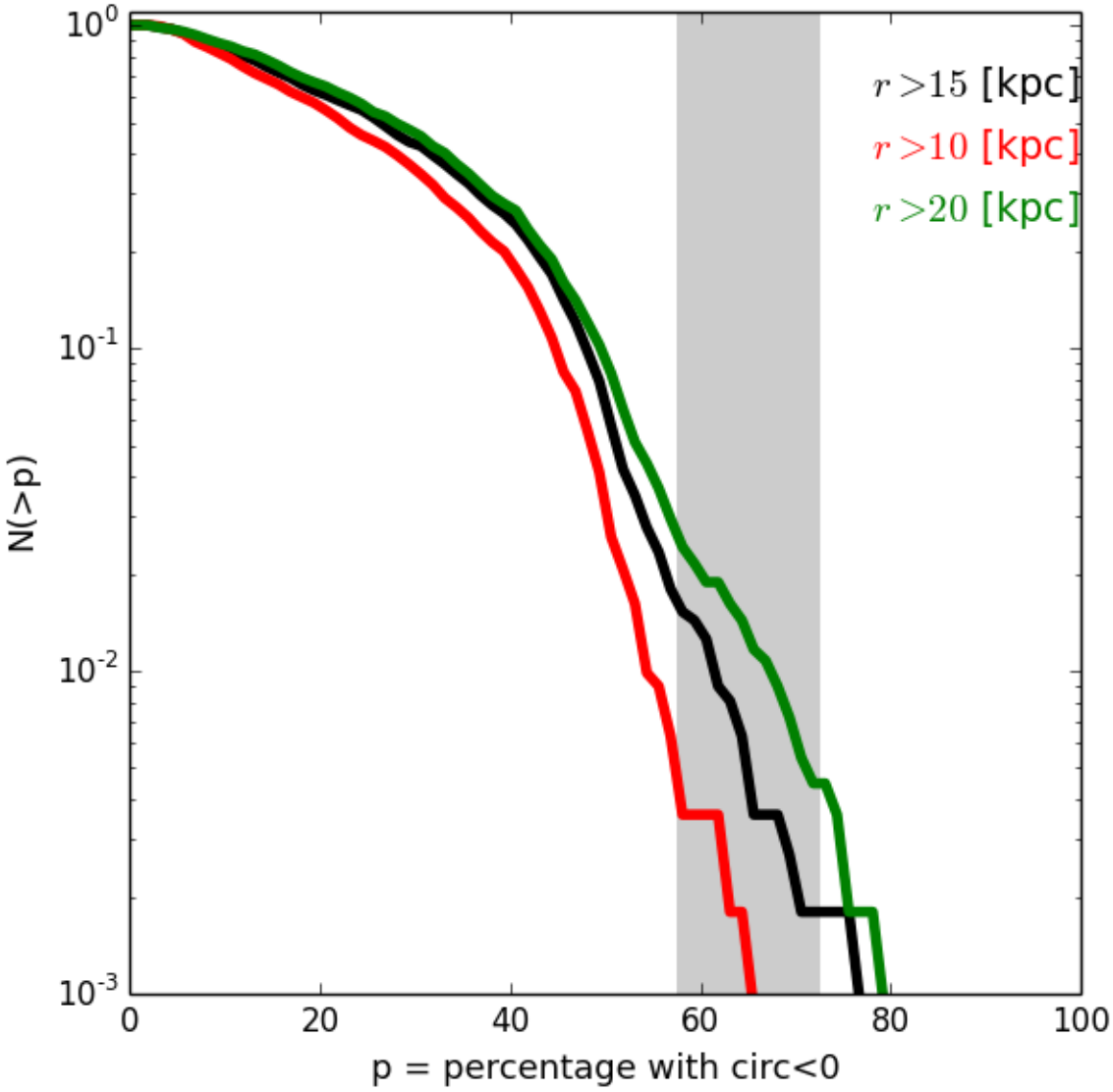
The retrograde halo in context

- Not common in cosmological simulations

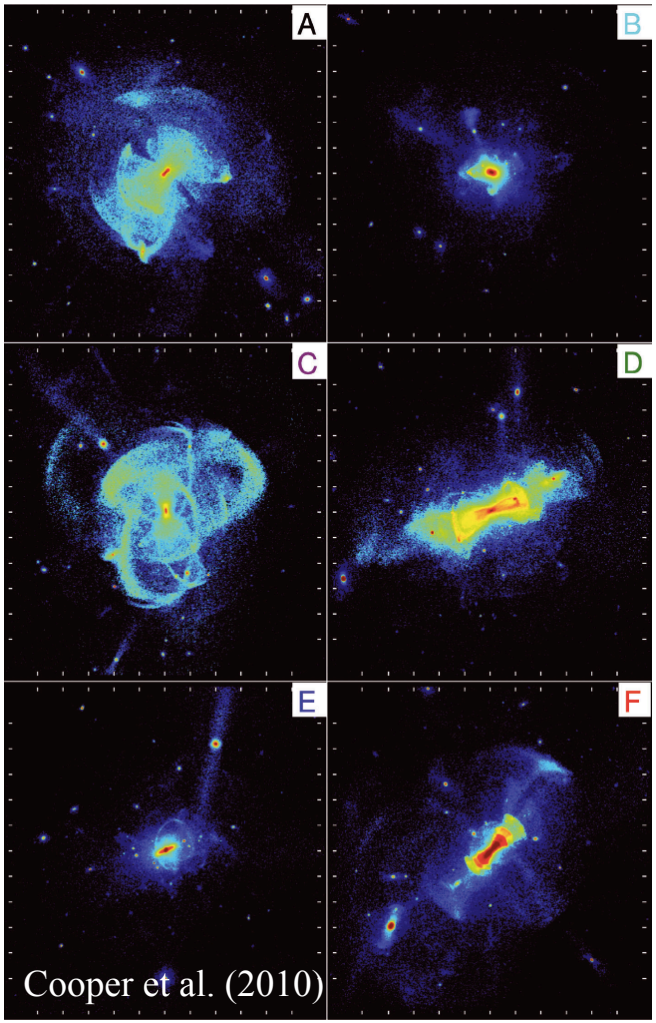
  (e.g. Illustris; Vogelsberger et al. 2014)

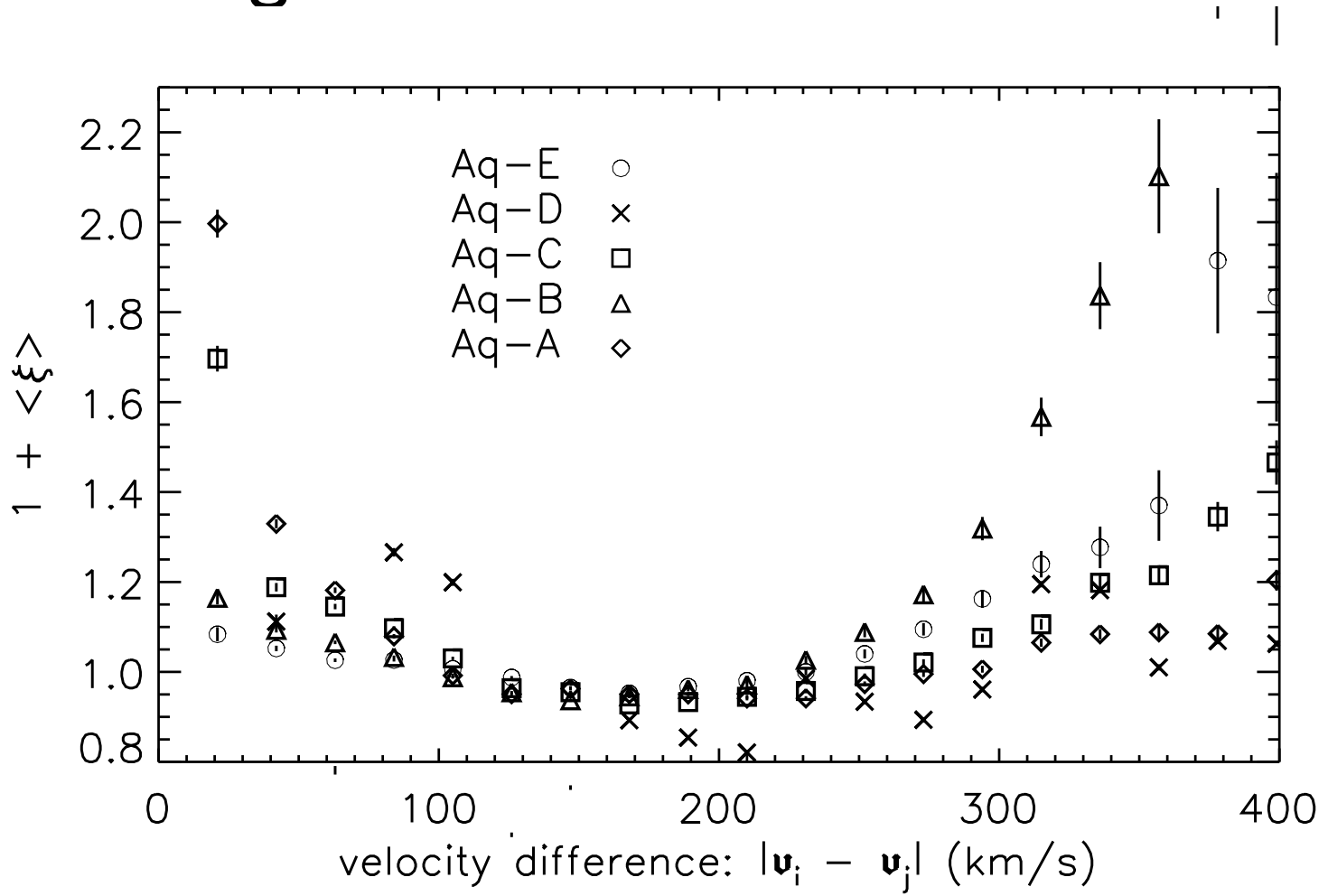
- Less than 1% of MW-mass galaxies have more than 60% of the less bound stars on retrograde orbits

  (here defined as r > 15 kpc)



The amount of substructure: comparison to cosmological simulations





- Simulations of halos purely built via accretion show *excess on small and large separations of similar amplitude*
  - some variation from halo to halo

  → Milky Way halo consistent with being fully built via accretion

Summary

- Sample of over 1,000 halo stars (based on metallicity) with full phase-space coordinates from Gaia and RAVE

- Velocity correlation function reveals significant excess of small scale structure
  - at level consistent with cosmological simulations of halos purely built via accretion

- Integrals of motion space is very rich in structure
  - Less-bound halo stars predominantly retrograde (significance > 99.9%)
  - Ten significant overdensities for more bound halo

- Next steps:
  - Characterization of the stars in the structures found, e.g. chemical abundances, ages
  - Numerical simulations for orbits, infall times, link to other structures in the halo
  - Use the full TGAS sample (10 x larger), i.e. without radial velocity information to identify other structures (poster J. Veljanoski)