Finding Galactic-halo substructure in the Gaia data

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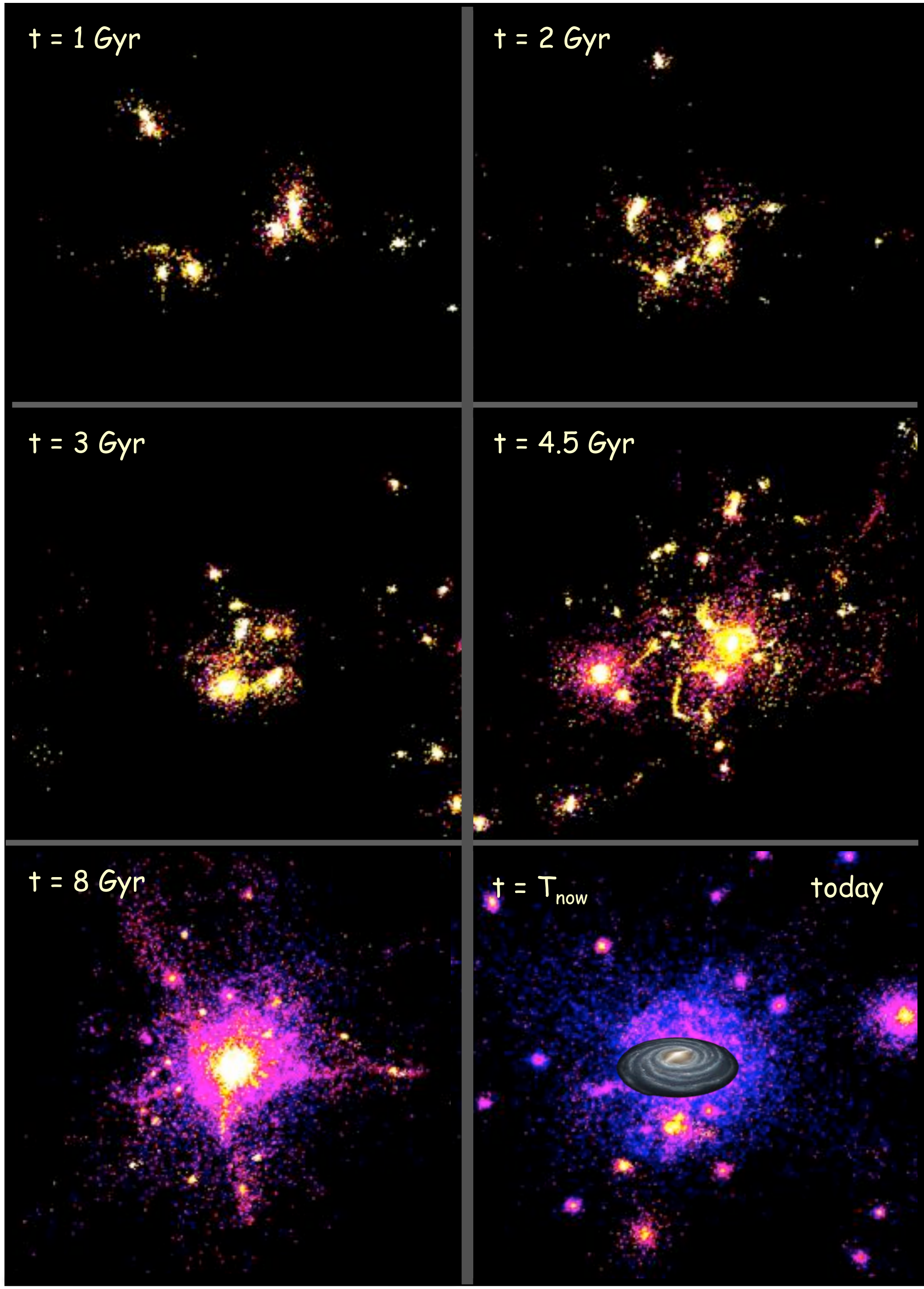
Stellar halo: treasure trove of merger relics

- Cosmological model's characteristic: hierarchical growth: mergers
- Disrupted galaxies/debris naturally in a stellar halo:
  →merger signatures: *Substructures and tidal streams*
- Questions:
  - Were mergers important for galaxies like MW?
  - How often and when did they happen?
  - What were the building blocks?
- Stars are "fossils"
  - Motions, ages, chemical composition trace origin
  - Substructures pinpoint to merger debris
  - Probe force field → mass (gravity)



snapshots: J. Gardner

Testing the cold dark matter paradigm

Is this “picture” correct?

- Are galaxies like the Milky Way and its nearest neighbours embedded in dark matter halos like those predicted by the cosmological model?

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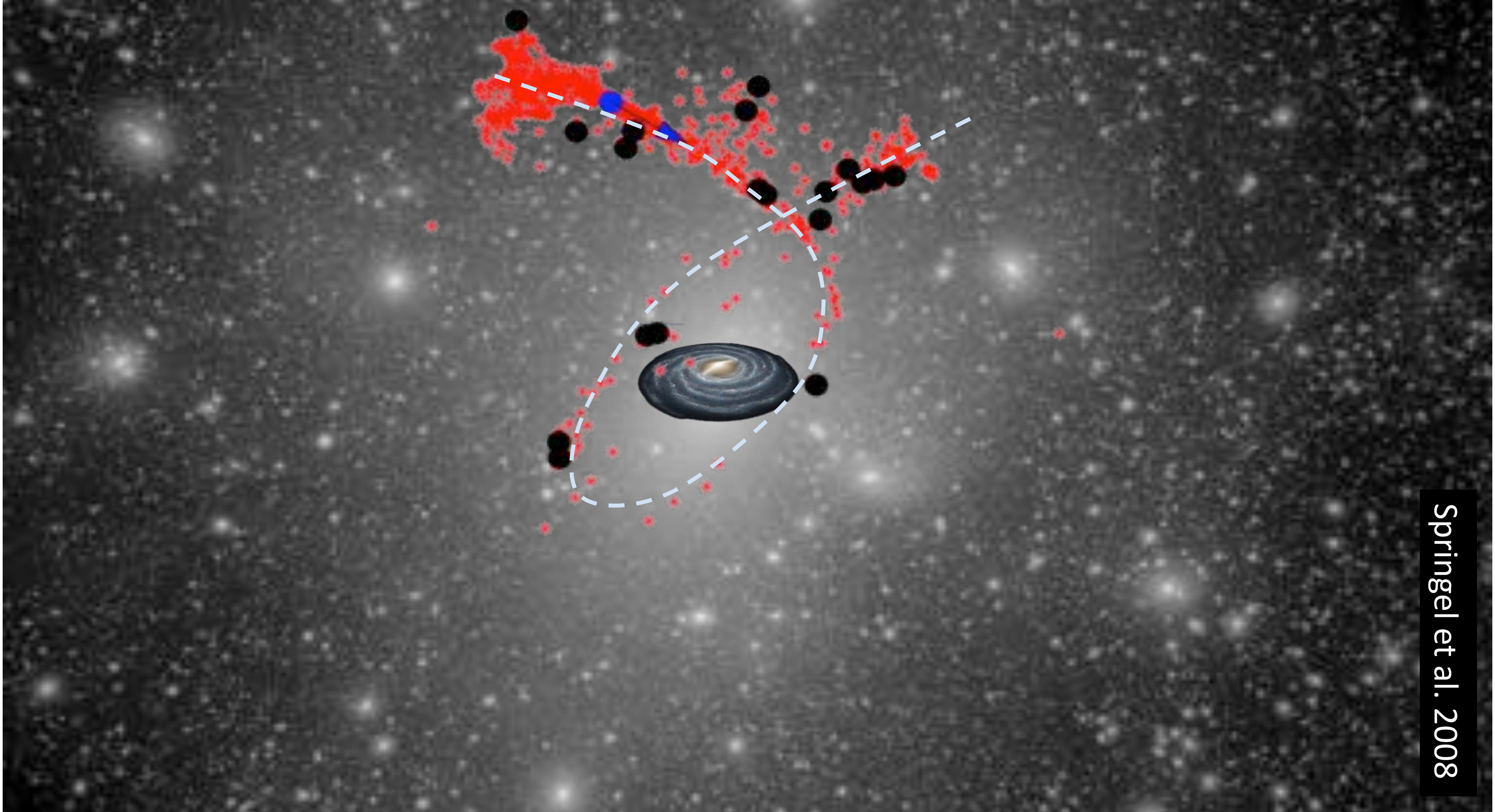
Is this "picture" correct?

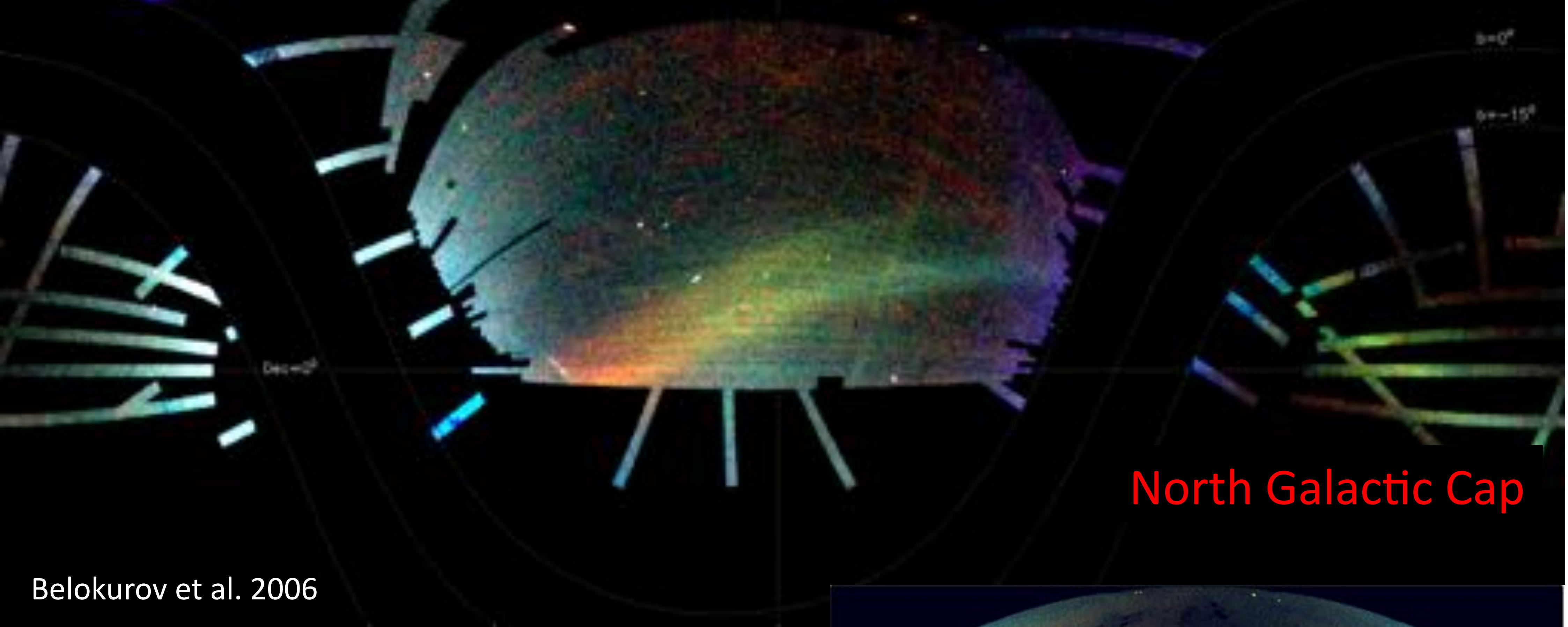
- Are galaxies like the Milky Way and its nearest neighbours embedded in dark matter halos like those predicted by the cosmological model?
- How much dark matter is there?
  - how is it distributed?
  - what is the dark matter?
- Is Gravity correct?

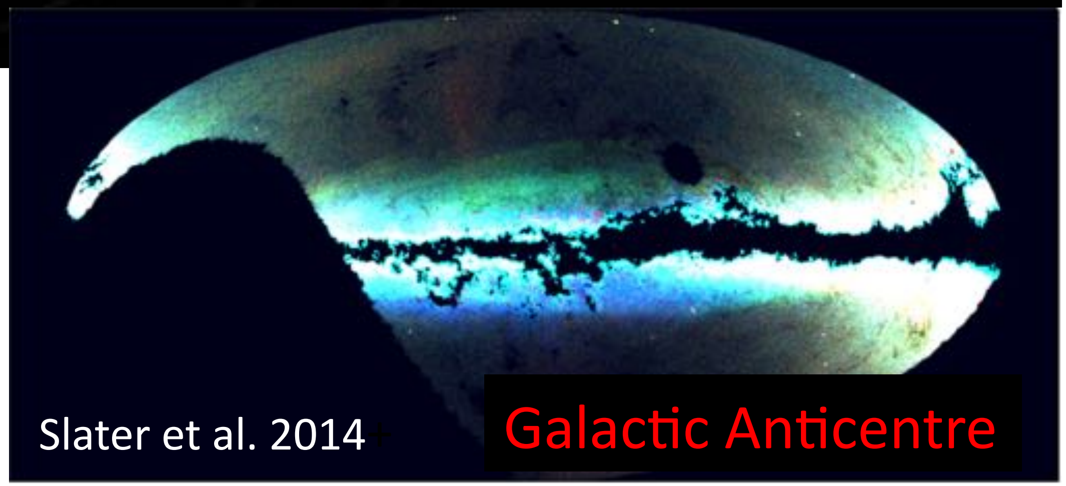
A stream in a dark halo with substructure



Granularity: Hundreds of thousands dark clumps if dark matter particle is cold

The accretion history unveiled so far:
The Galactic halo from SDSS/PanStarrs



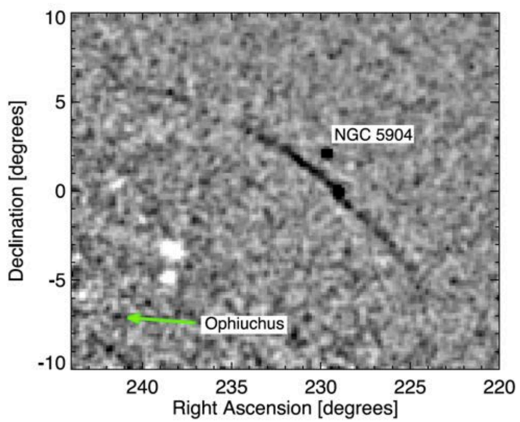


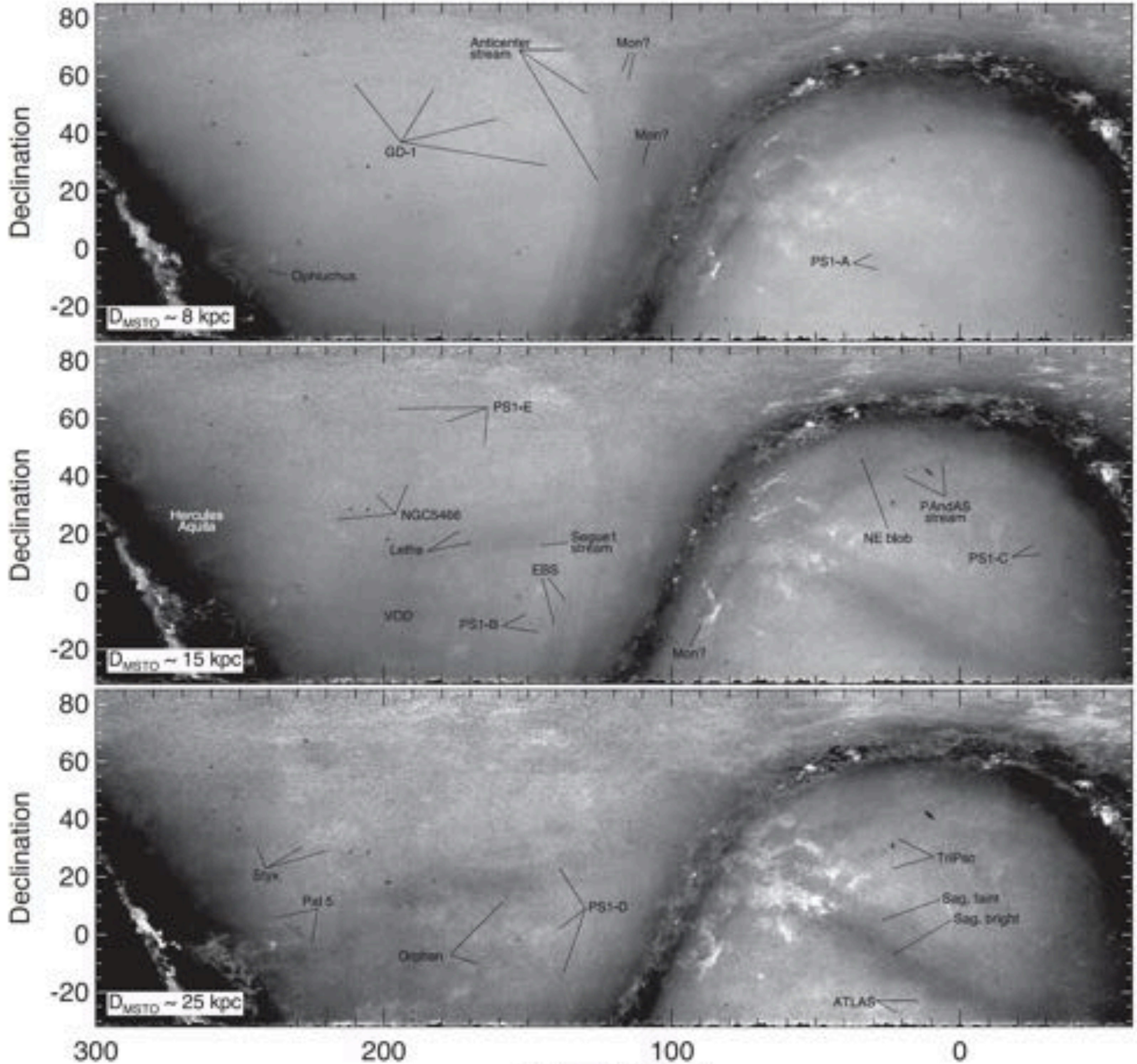
Outer halo: R > 20 kpc

- 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)

PanSTARRS 3π survey

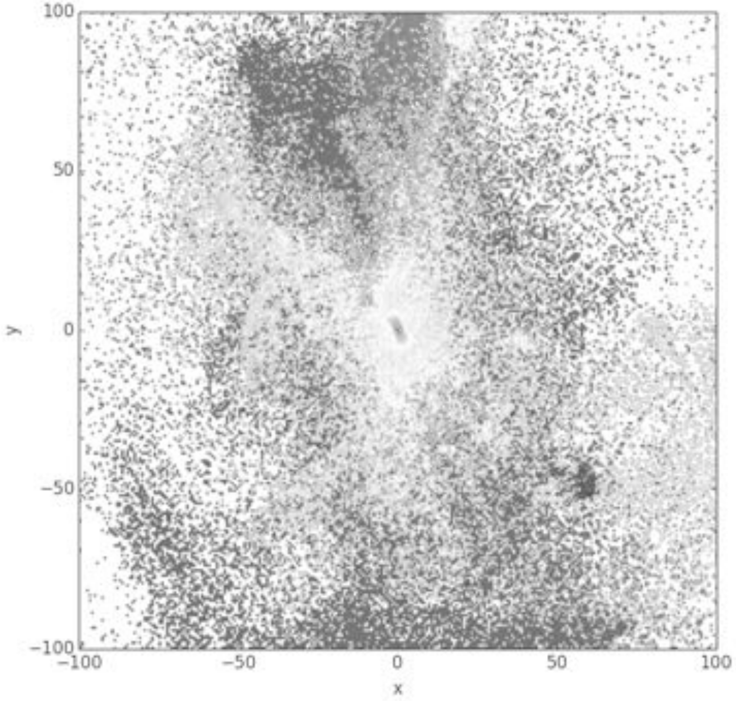
Many narrow streams mapped/discovered.





Bernard et al. (2016)

The relevance of kinematic information



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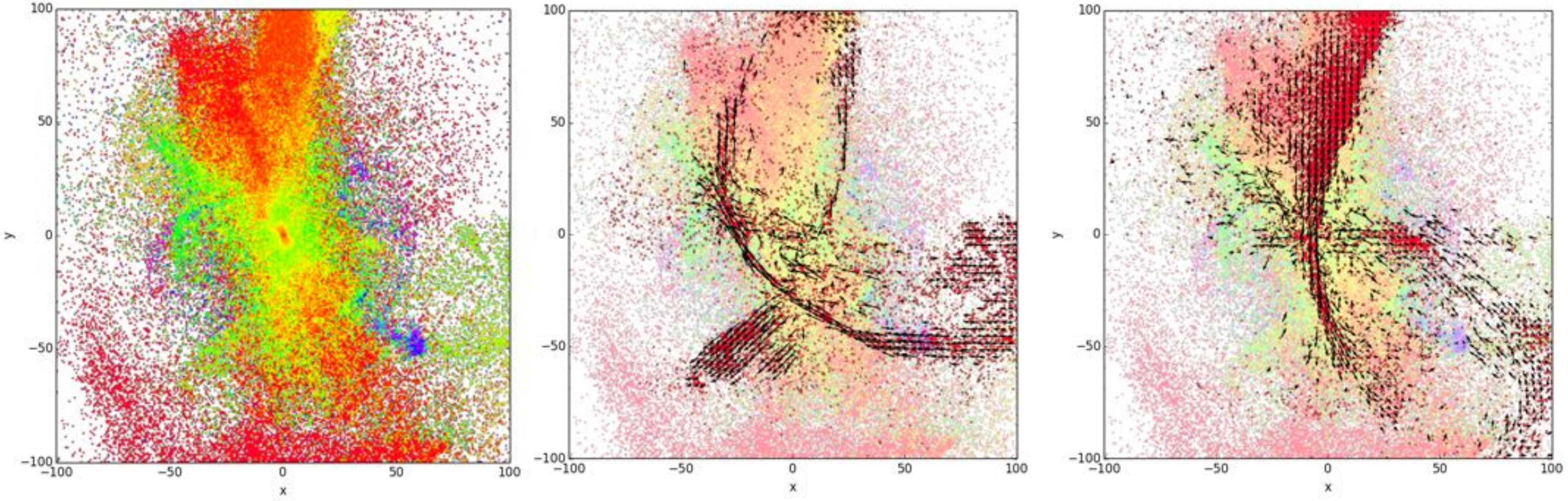


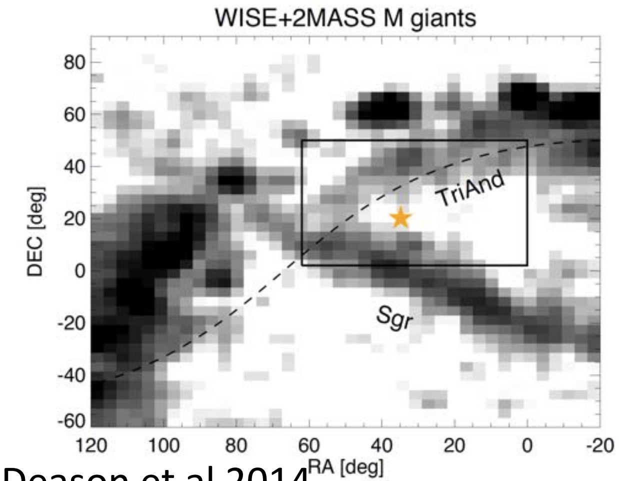
Proper motions from Gaia DR2 (April 2018)

vt=200 km/s → μ~1 – 5 mas/yr (d ~ 10 – 40 kpc)

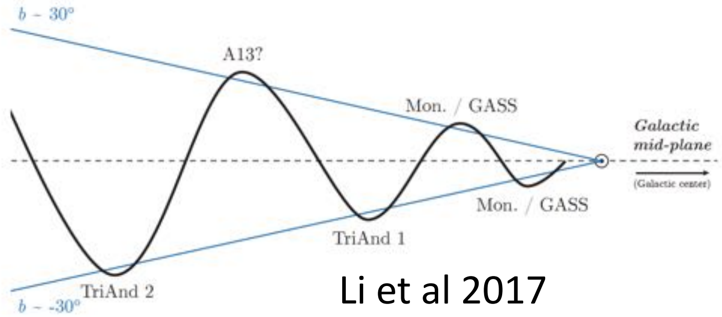
expected error: σ_μ ~ 0.1mas/yr (G ~ 17)

→ Trace substructures, outlier removal, and map MW potential

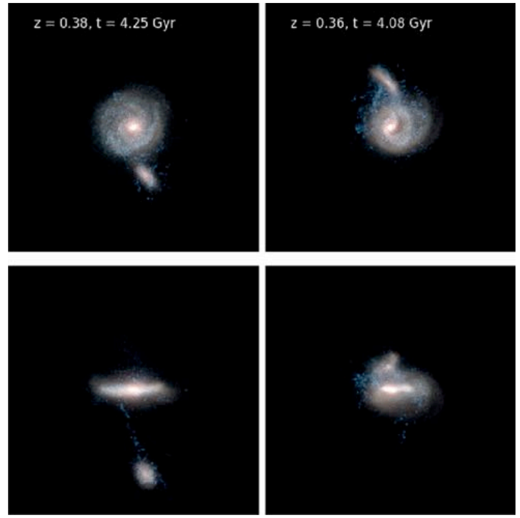
Not all substructure is accreted – does pinpoint to interactions and mergers

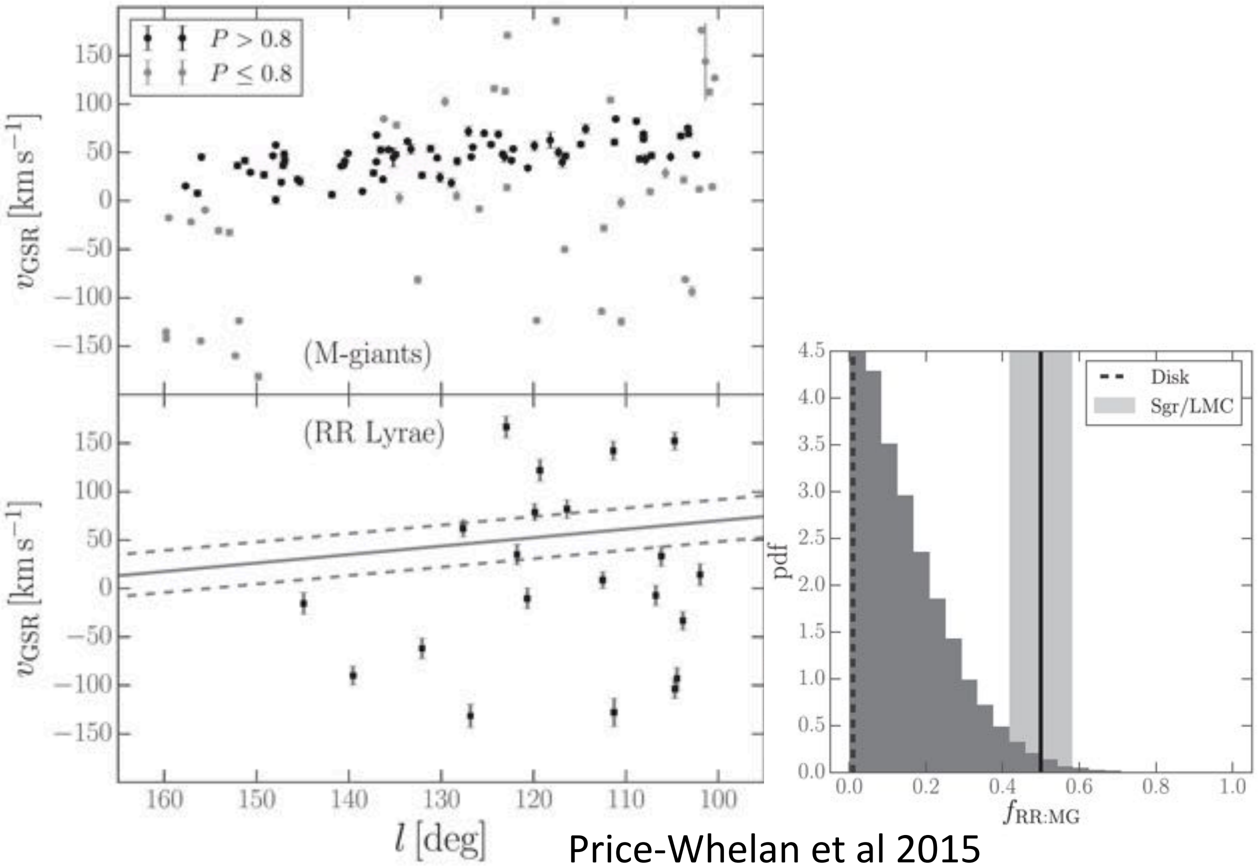


Deason et al 2014

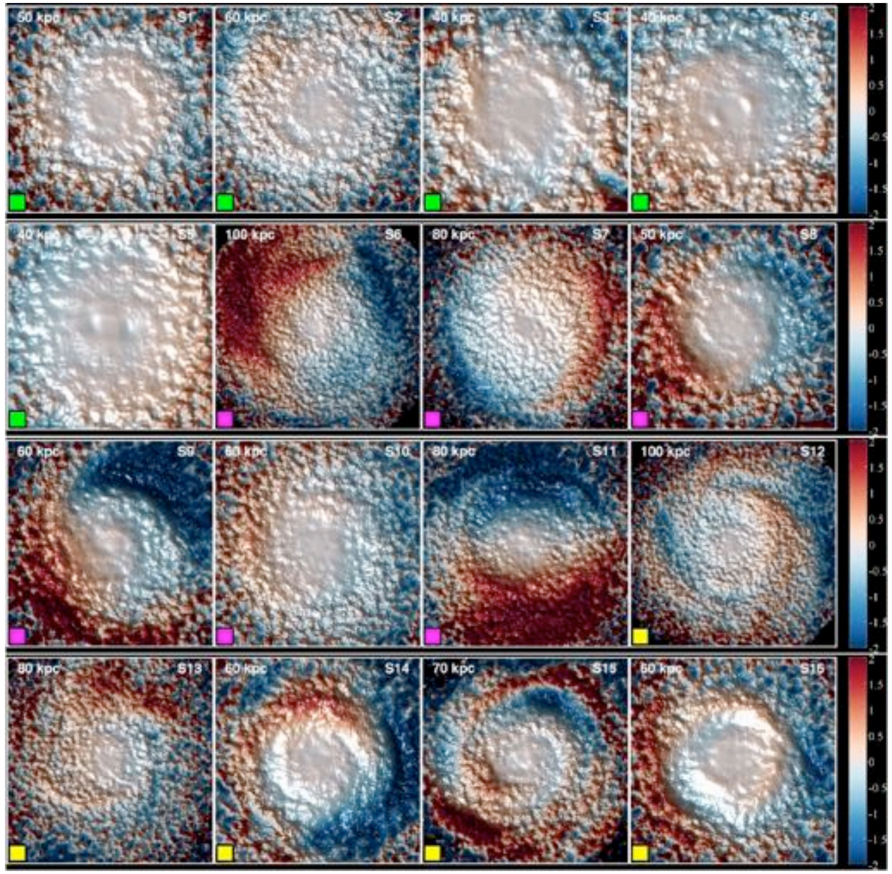


Li et al 2017



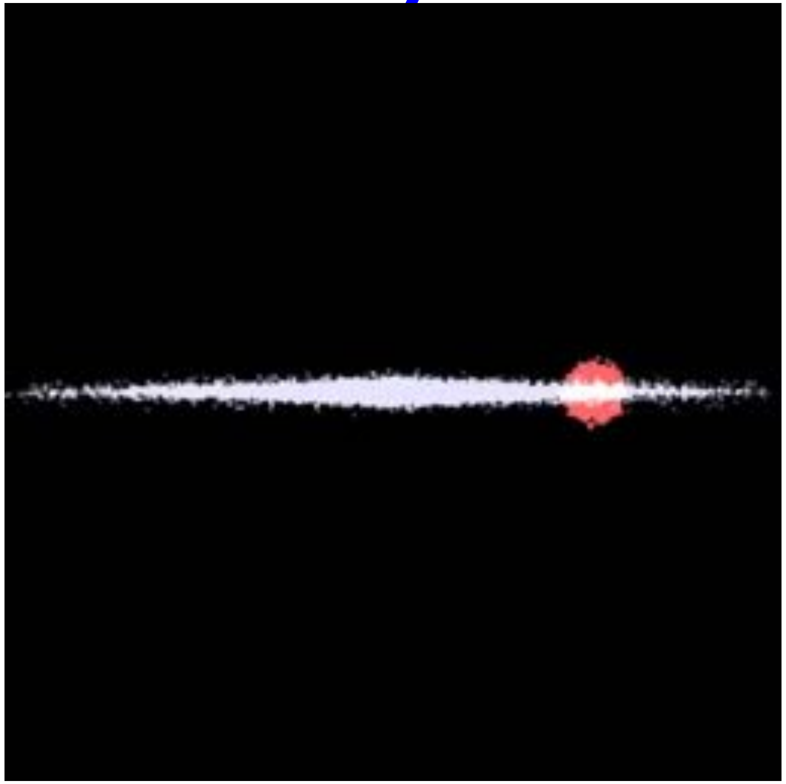


Price-Whelan et al 2015



Gomez et al. (2016, 2017)

Nearby halo

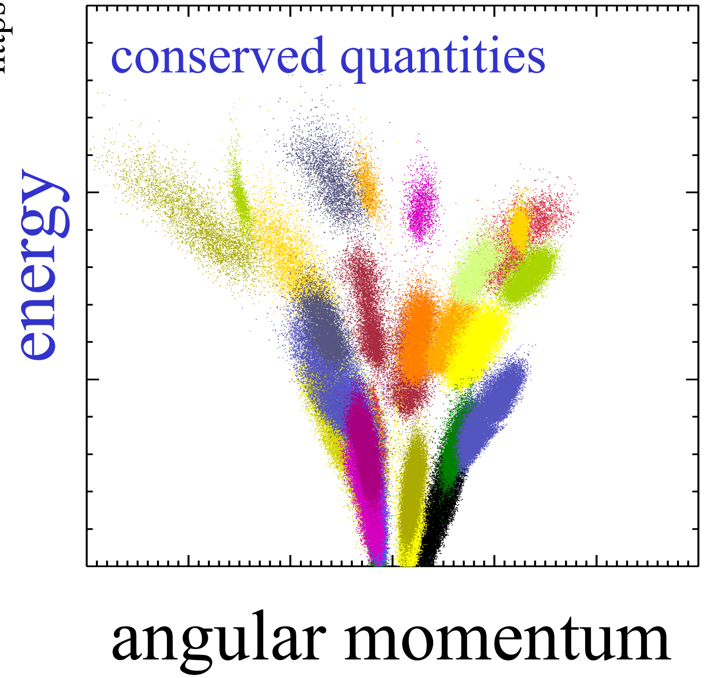


https://www.astro.rug.nl/~ahelmi/research/gaia/movie.html

Memory of origin: retained in the motions

- 100s of streams should cross Sun's vicinity
- So far.. not much evidence (small samples)

- How to find more? → Clustering in conserved quantities

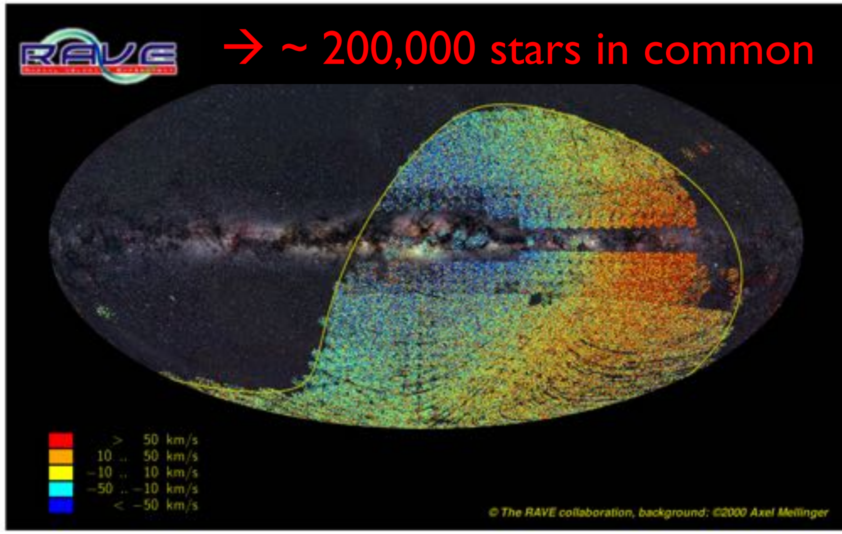


Helmi & de Zeeuw 2000

Construction of a halo sample: TGAS x RAVE

Jovan Veljanoski

Maarten Breddels



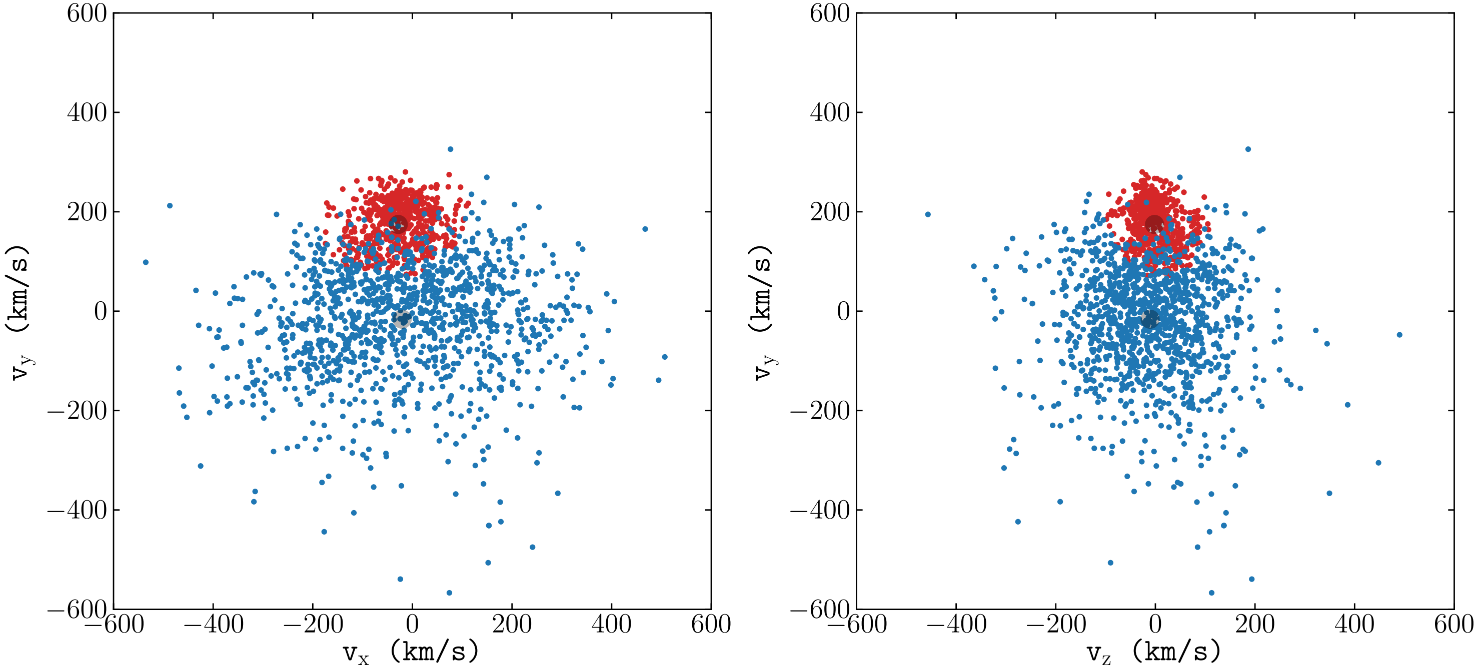
- TGAS dataset is significant improvement, but need full phase-space information → cross-match to RAVE survey
- RAVE: spectra for 500k stars in southern sky: v_{los}, [M/H], spectrophotometric distance/parallax
  (with TGAS priors, McMillan et al. 2017)

•<u>Metallicity cut $[M/H]_{cal}$ < -1 dex</u> to select preferentially halo

•Remove stars with disk-like kinematics

•2-Gaussian decomposition

→ sample of 1307 genuine halo stars



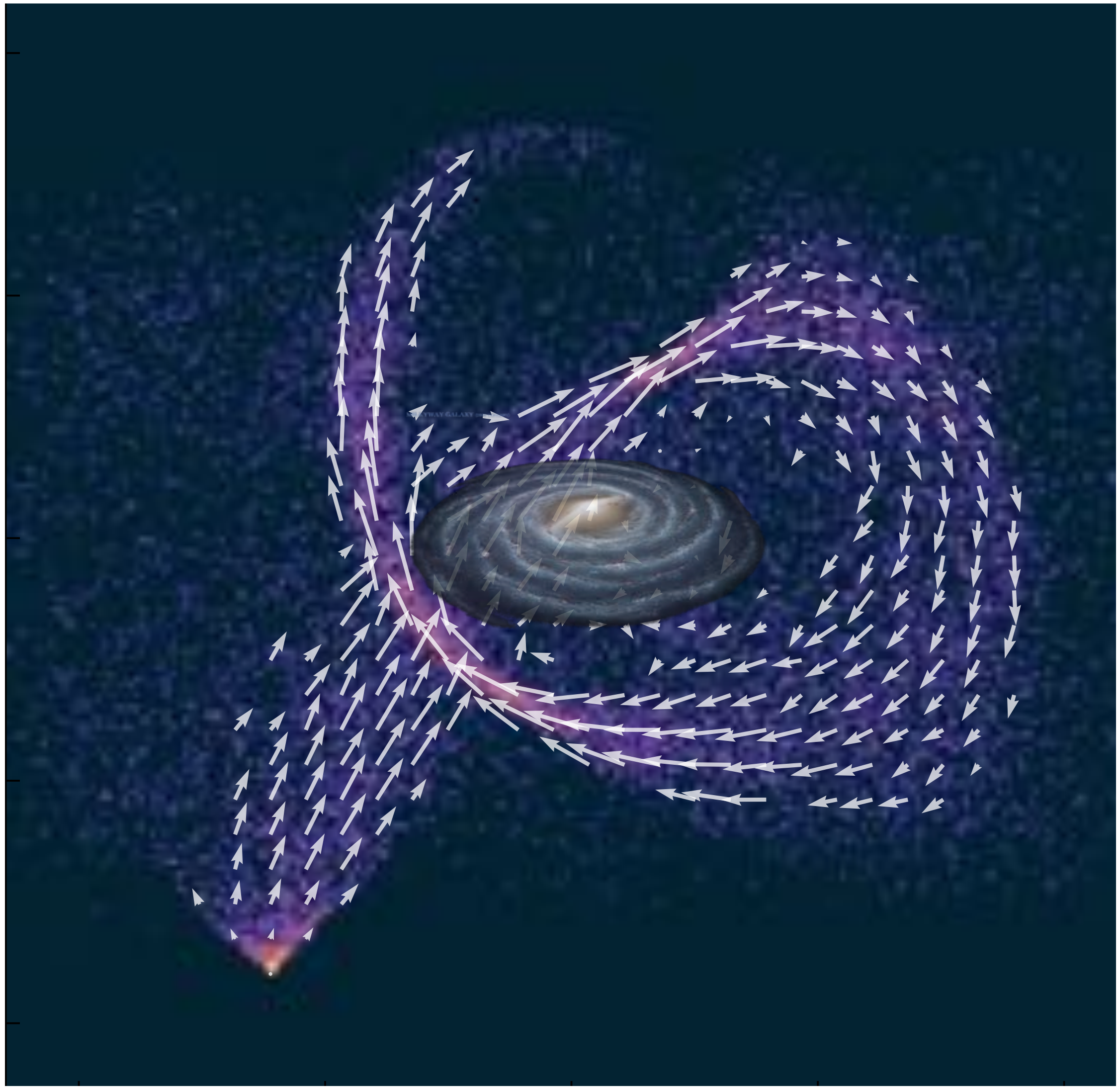
Helmi, Veljanoski, Breddels et al. (2017), Veljanoski et al. (in prep)

Statistical tests and searches of substructure

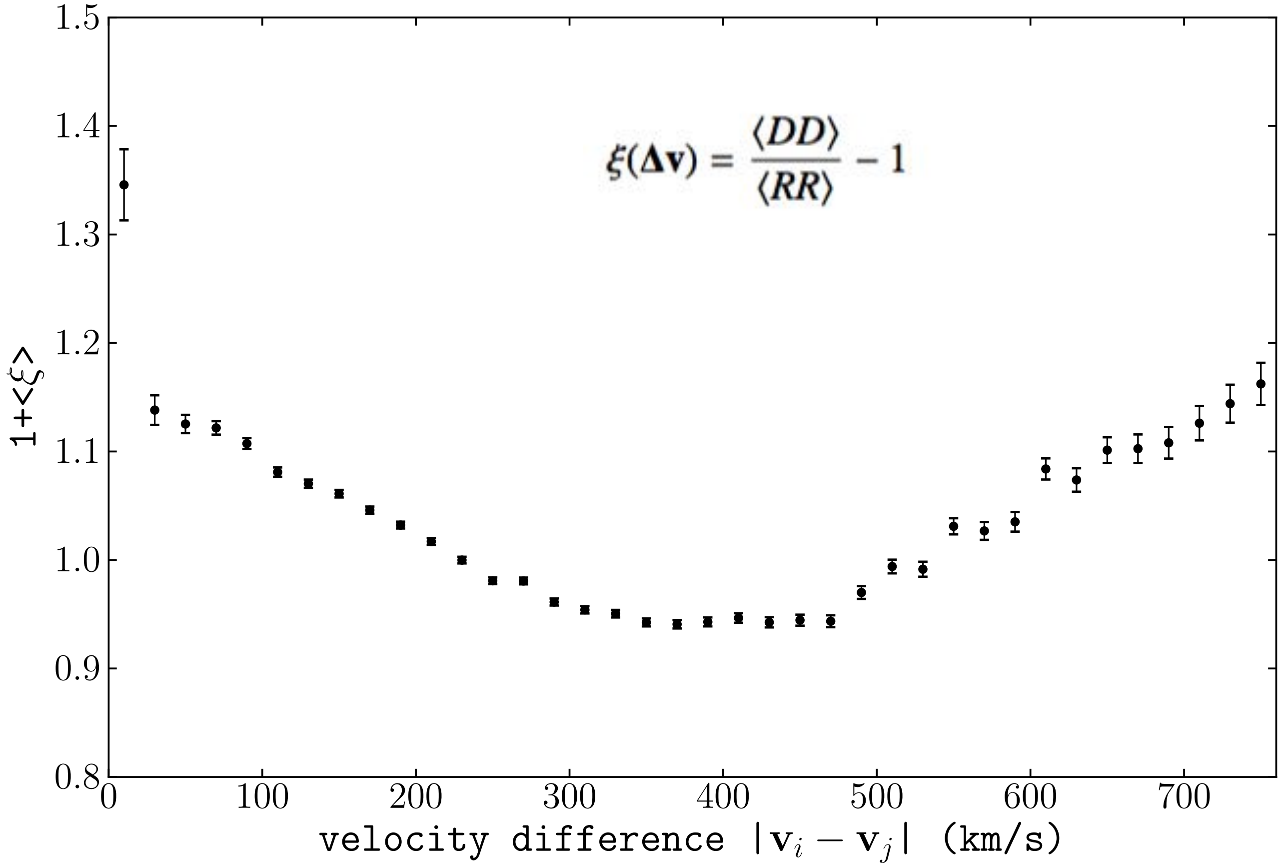
Models predict

- 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

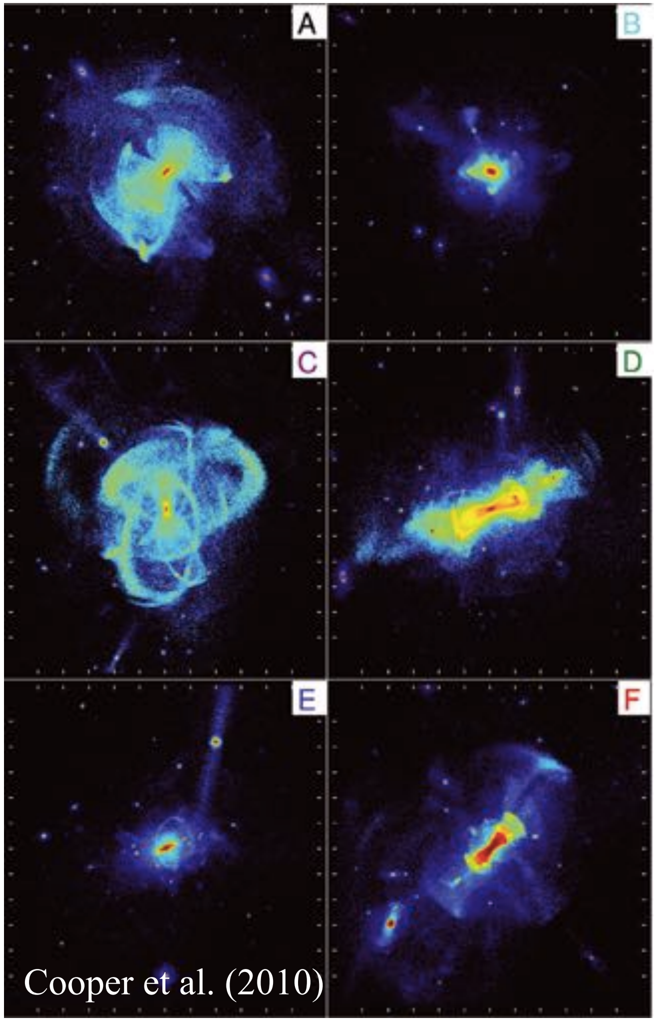


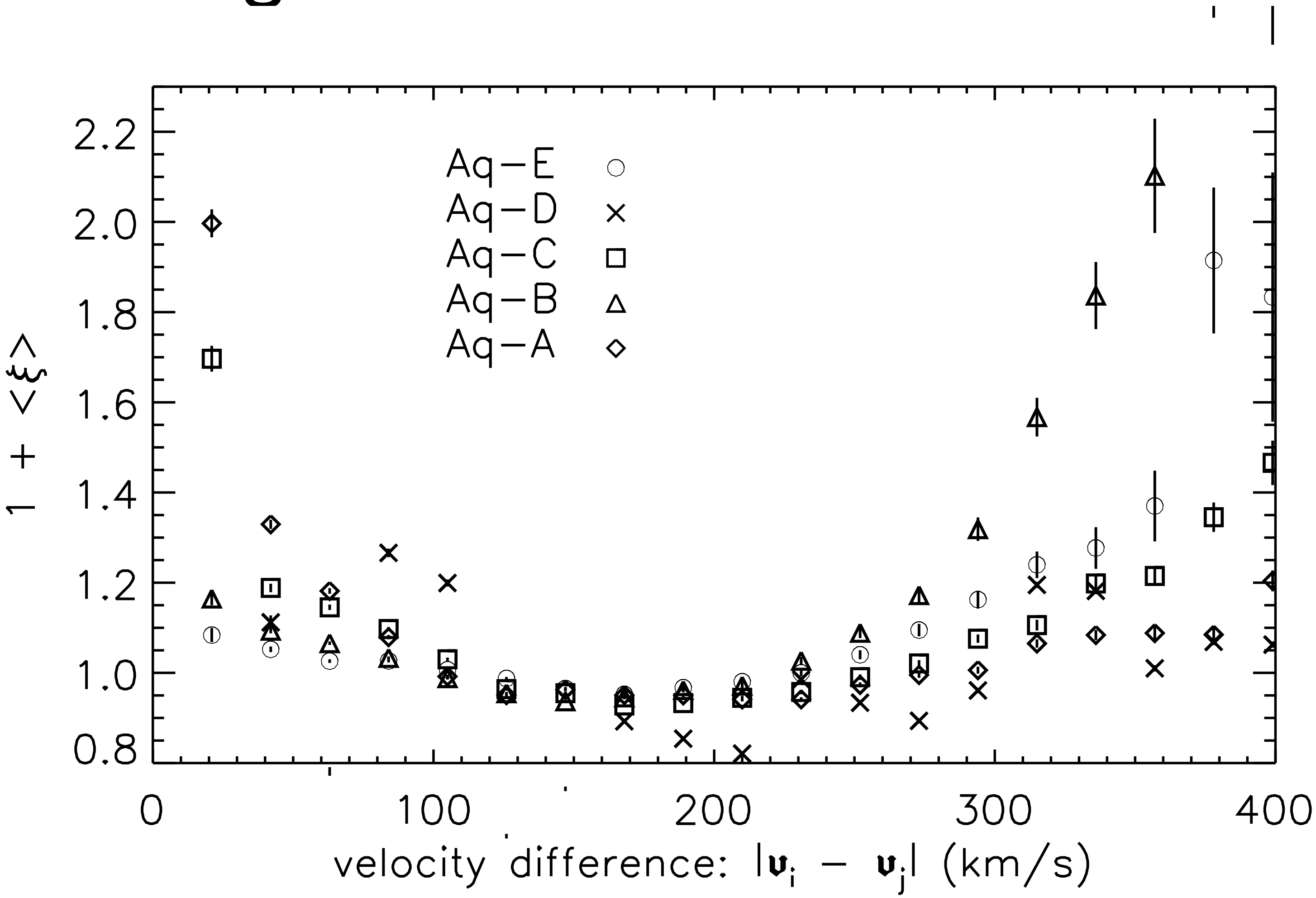
Helmi, Veljanoski et al. (2017)

- Very significant excess of pairs in data compared to random/smooth
  - for Δ < 20 km/s, 5.5σ (120 pairs of stars in excess)
  - for 20 < Δ < 40 km/s: 8.8σ (328 pairs in excess)

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

The amount of substructure: comparison to cosmological simulations

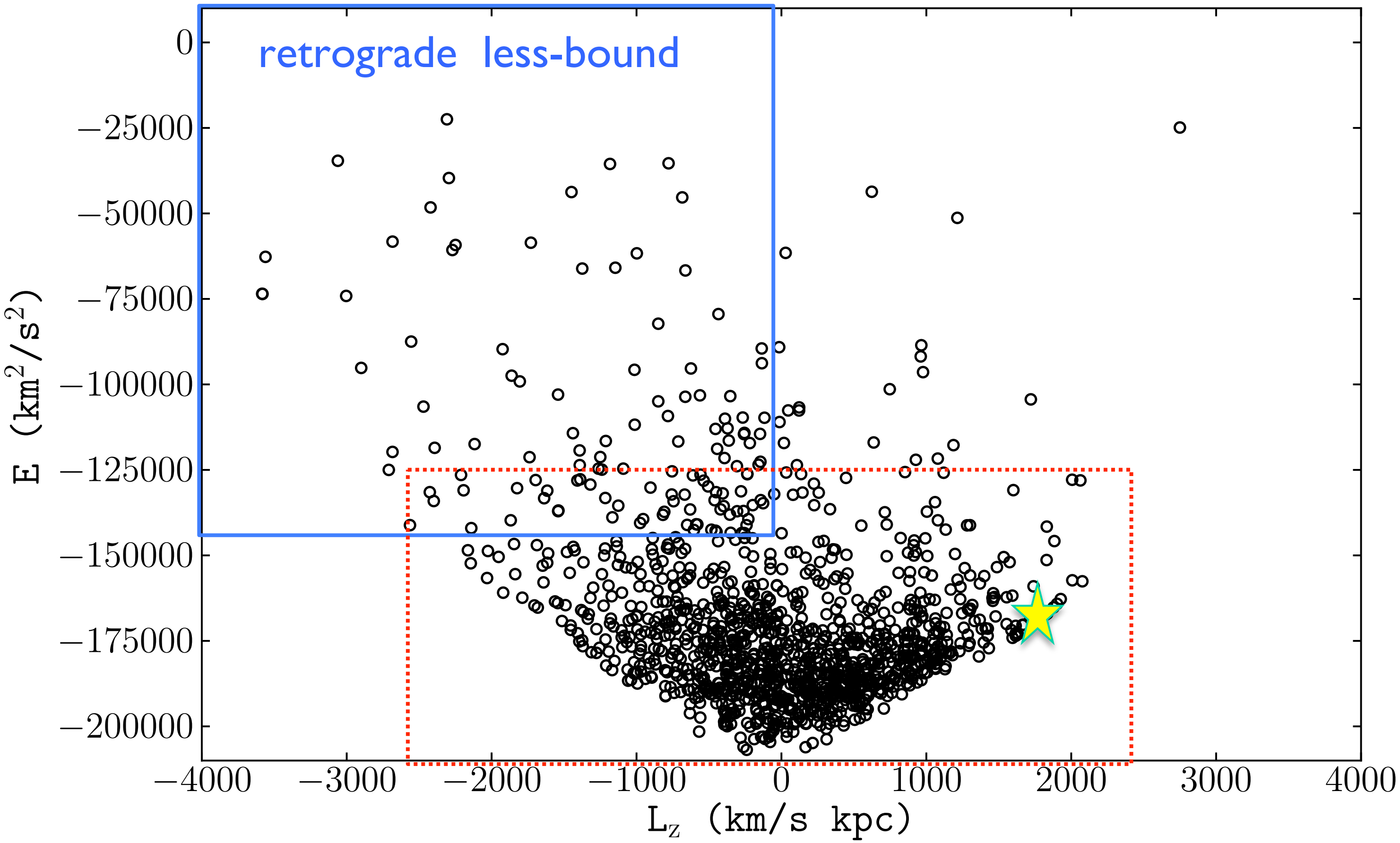




- Simulations of halos purely built via accretion show *excess on small and large separations of similar amplitude*
  - some variation from halo to halo

→ Milky Way halo consistent with being fully built via accretion

Integrals of motion - space

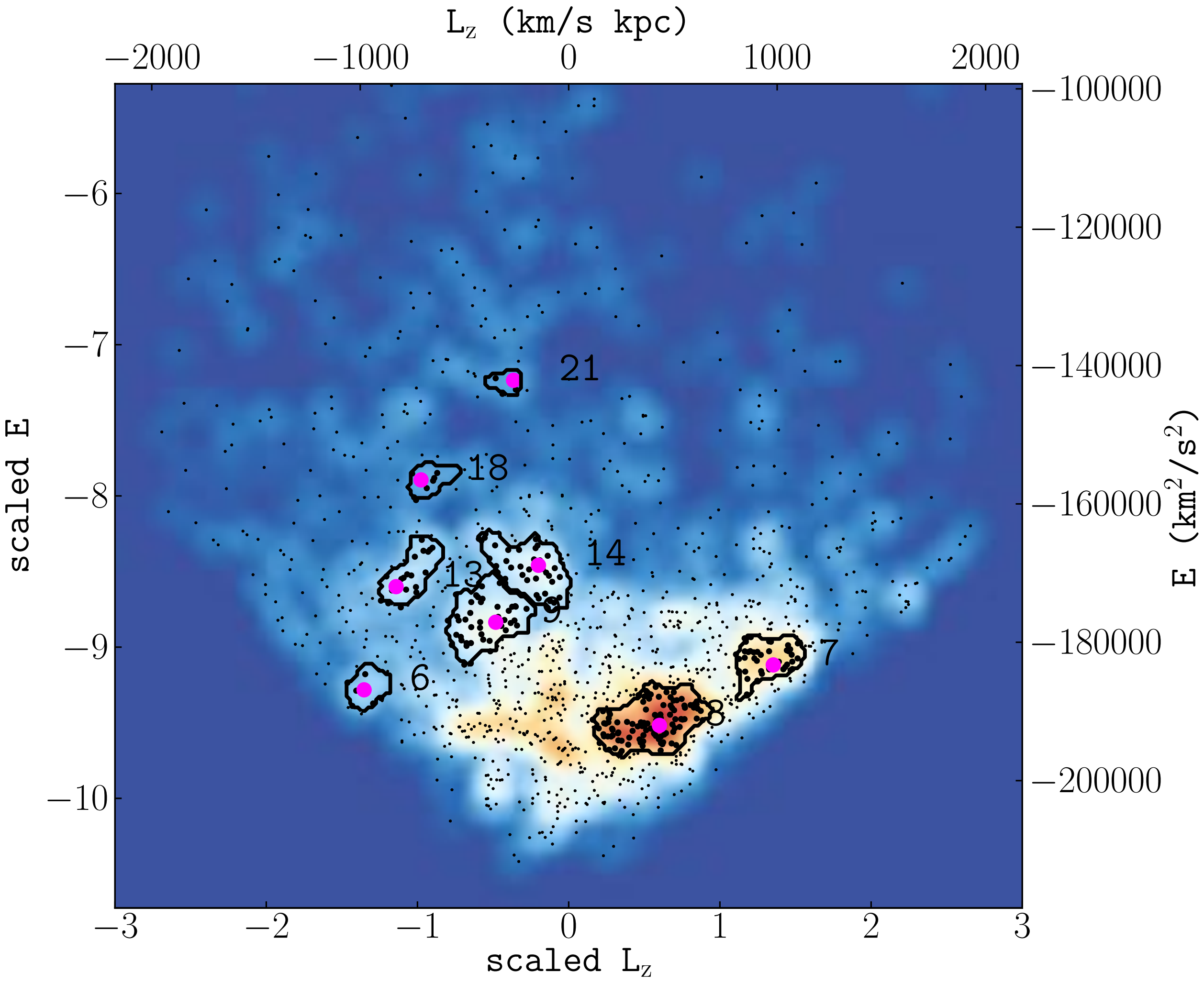


Helmi, Veljanoski et al. (2017)

→ very retrograde motions: 73% of all stars (for $E > -1.3\times10^5$ km^2/s^2)

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

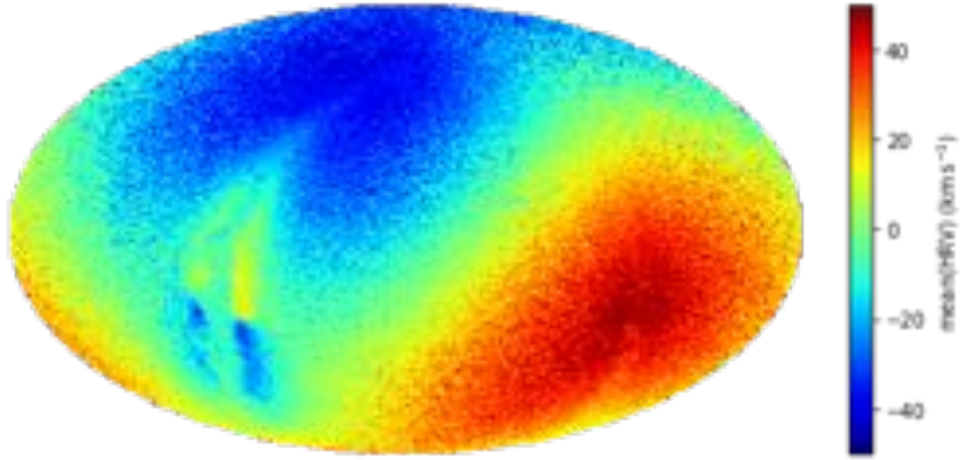
Integrals of motion – space

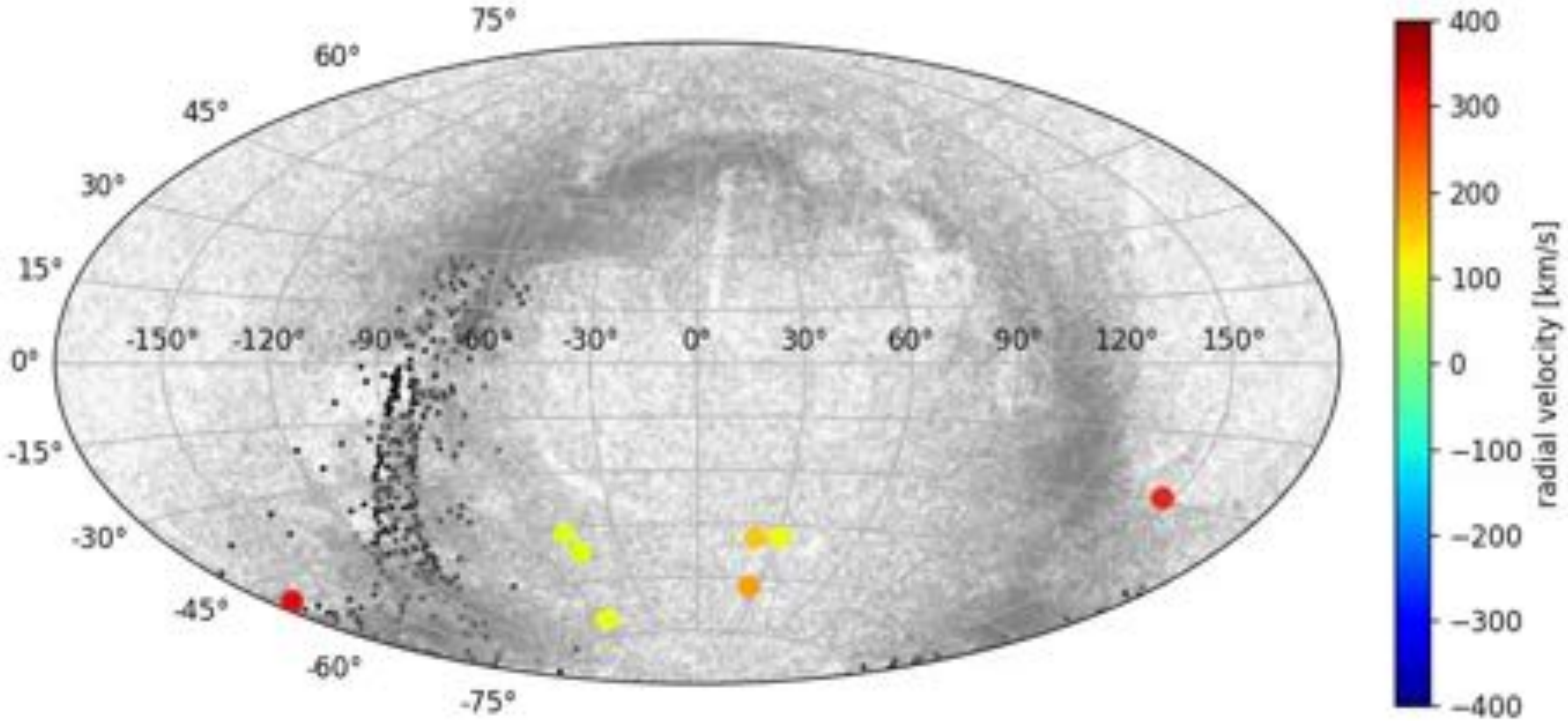


- •Statistical comparison to smooth distributions allows identification of overdensities in E vs Lz
- •Structures at Lz ~-500 km/s kpc could be related to OmegaCen debris (Dinescu 2002)
- •VelHel-6: stars with disk-like kinematics but counter-rotating

see also Myuoung et al. (2017)

Helmi, Veljanoski, Breddels et al. (2017), Veljanoski et al. (in prep)


40
20
0
−20
−40


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
400
300
200
100
0
−100
−200
−300
−400
radial velocity [km/s]

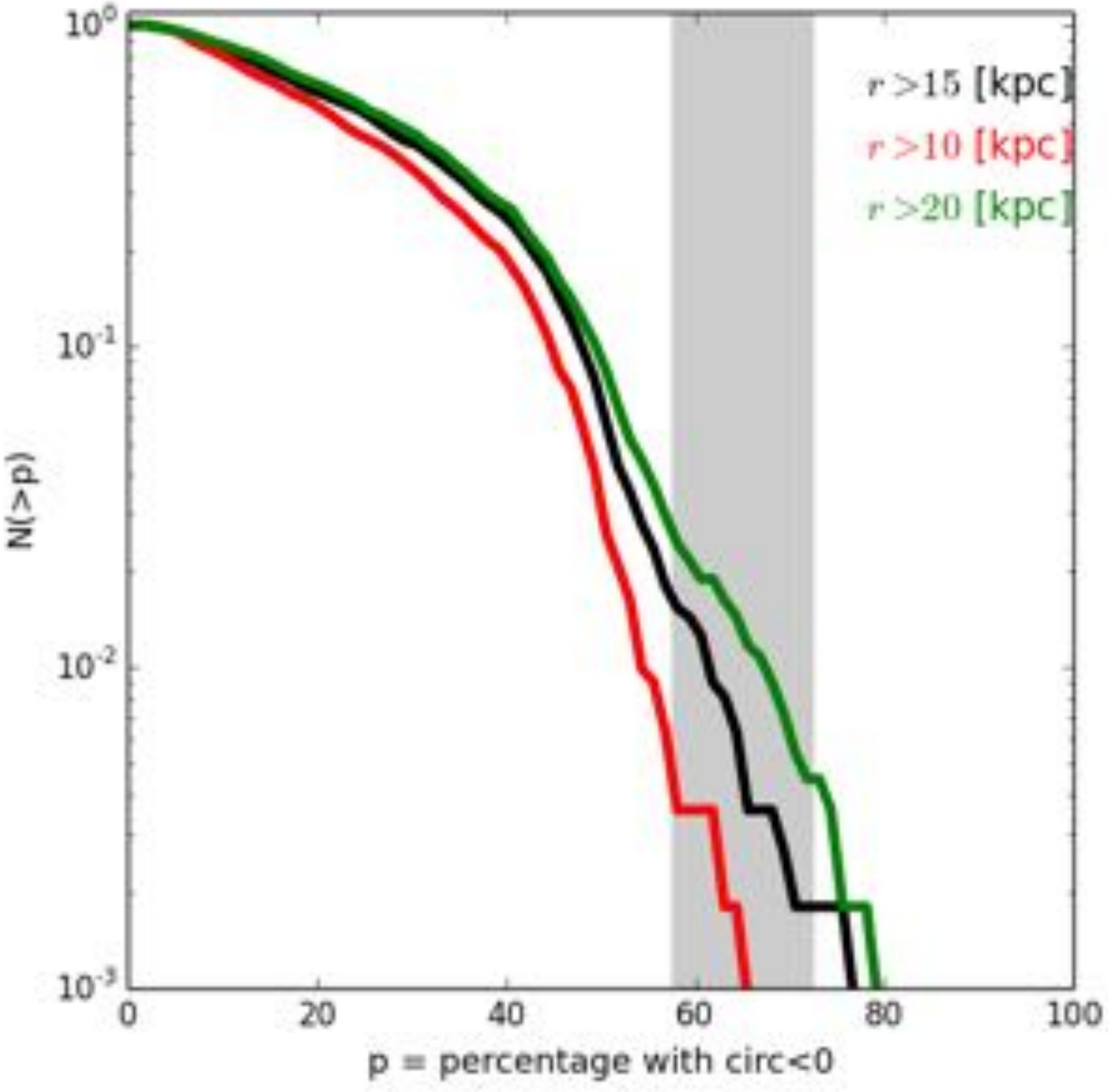
The retrograde halo in context

- Not common in cosmological simulations

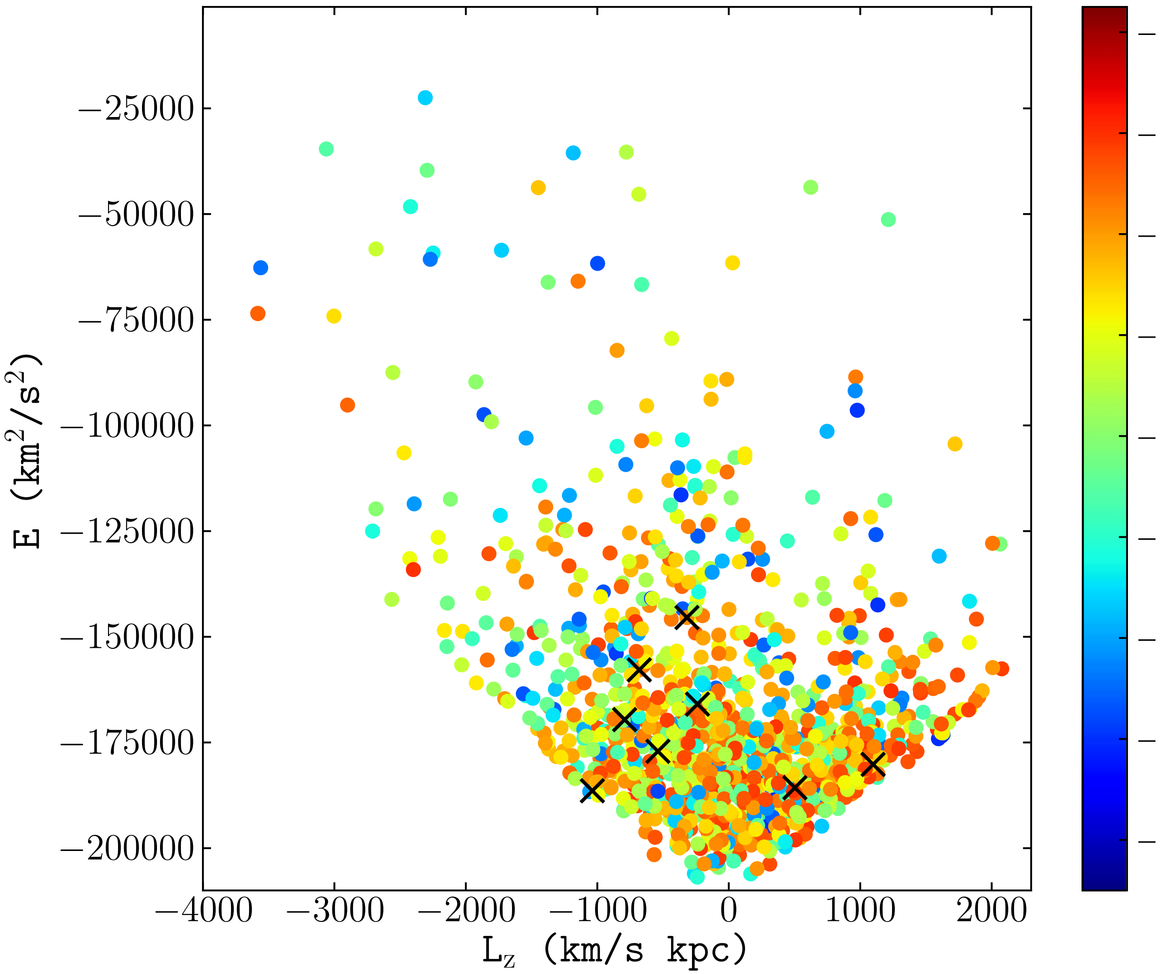
  (e.g. Illustris; Vogelsberger et al. 2014)

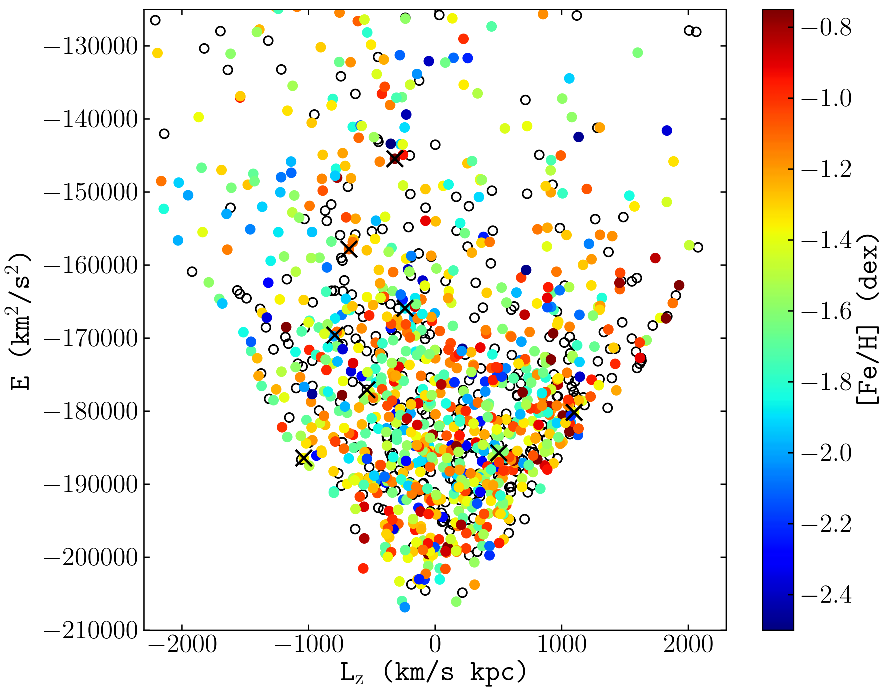
- Less than 1% of MW-mass galaxies have more than 60% of the less bound stars on retrograde orbits

  (here defined as r > 15 kpc)



Chemical abundances

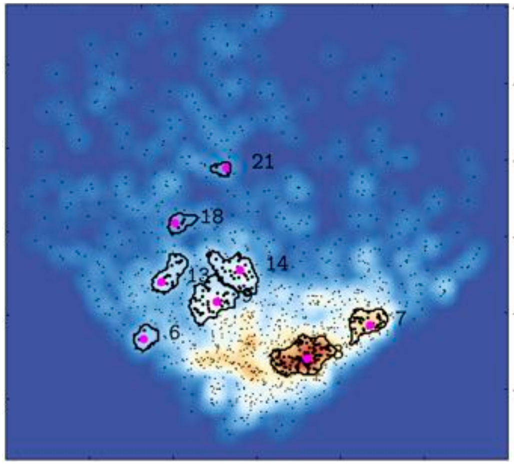


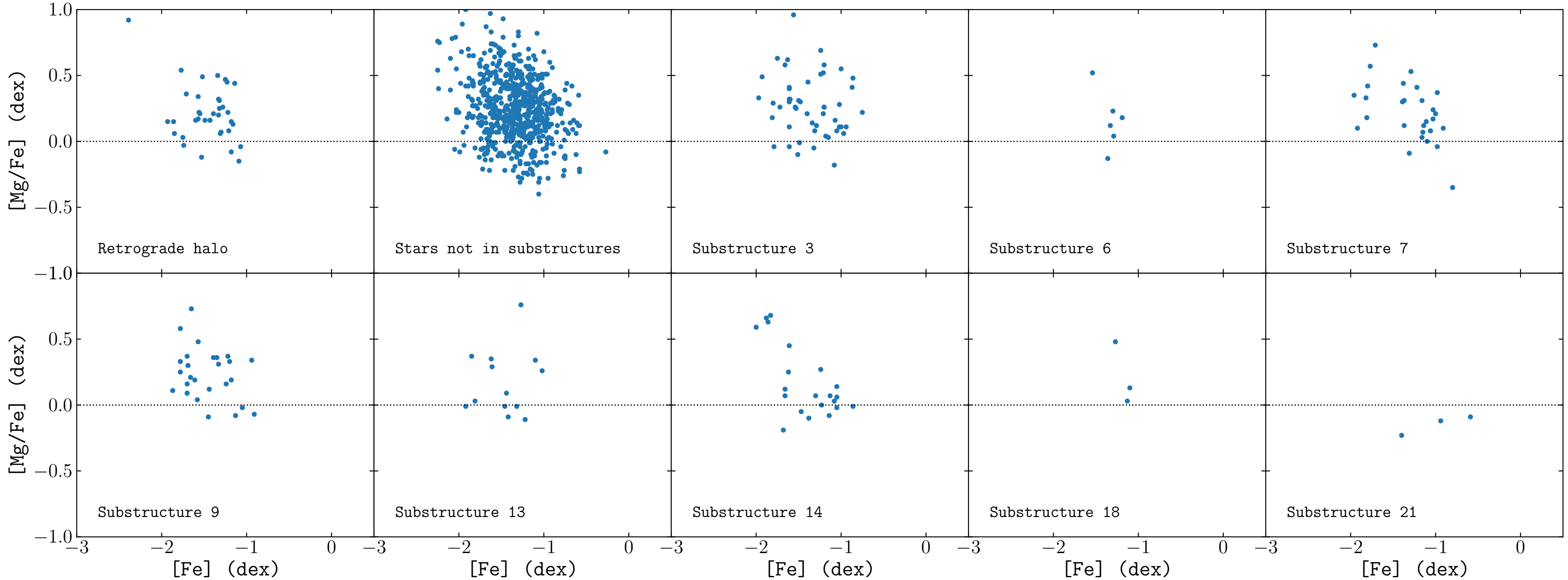


Veljanoski (in prep)

- C. Boeche chemical pipeline, not all stars have detailed abundances (SNR > 20, McMillan sample)
- Stars with Lz < 0 on average lower metallicity, both [M/H] and [Fe/H]
- May be some clumpiness (?)

Chemical abundances: substructures





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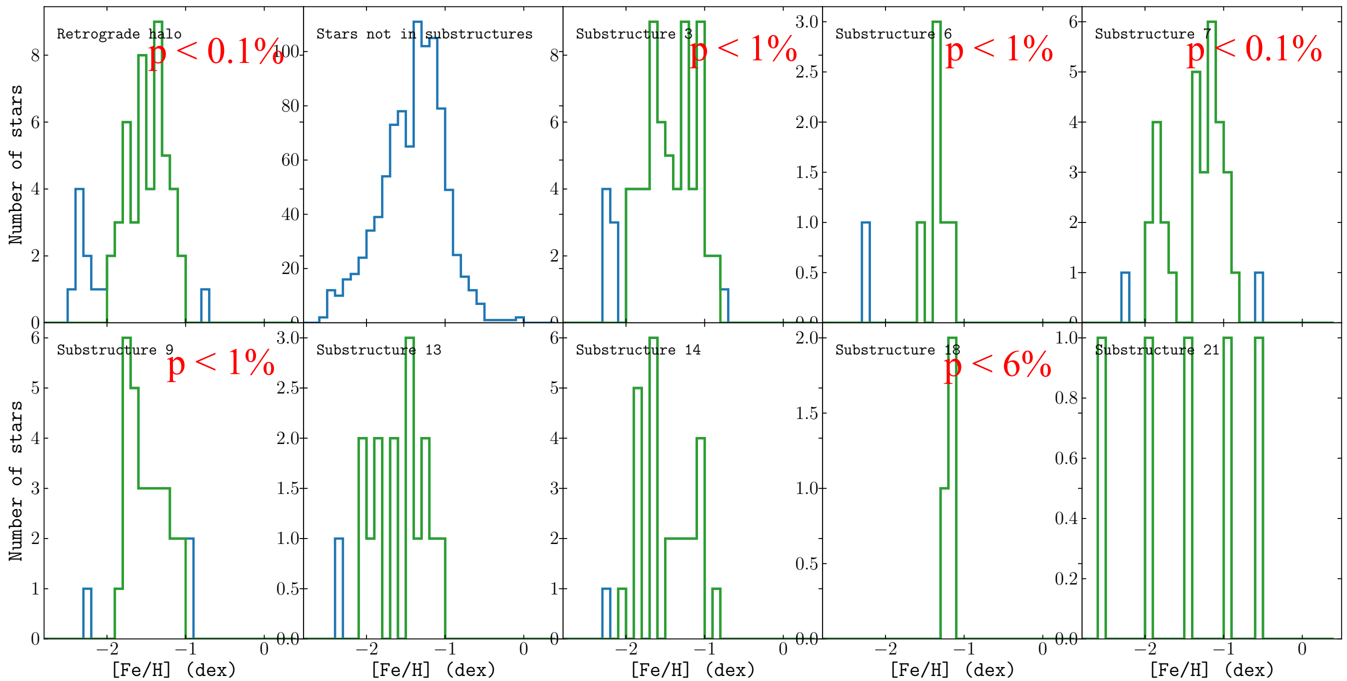


Probabilities drawn from overall population can be relatively small

Similar behaviour in e.g. [Mg/Fe]

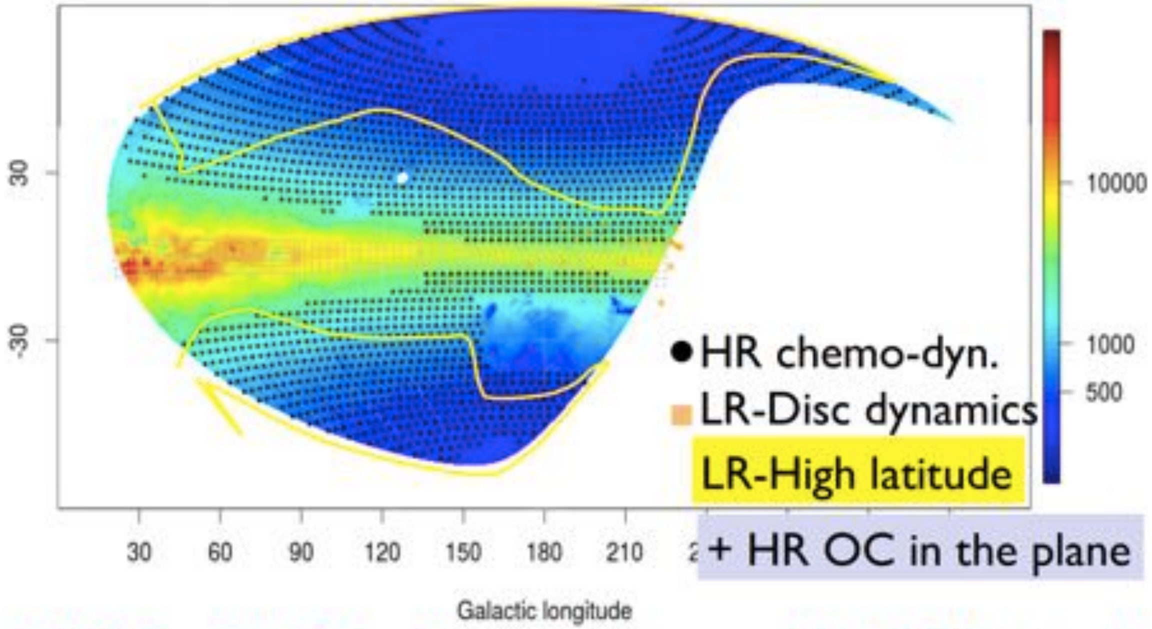
Generally limited by number of stars

Galactic Archaeology surveys with

@WHT

PI – GA surveys:
Vanessa Hill

WEAVE-GA surveys at glance

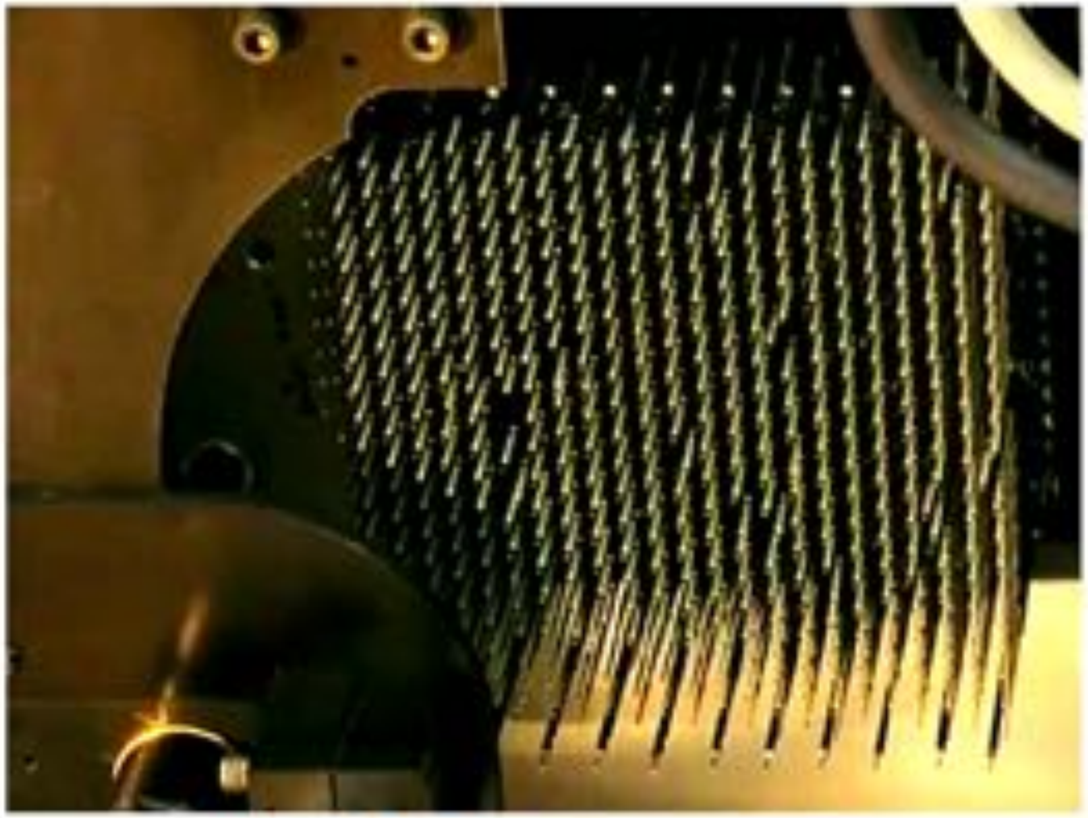


WEAVE - GA ~3-4 million stars to unravel the MW history !

4MOST

de Jong, et al. " 4MOST: the 4-metre Multi-Object Spectroscopic Telescope project at preliminary design review", *Proc. SPIE* 9908 (2016)

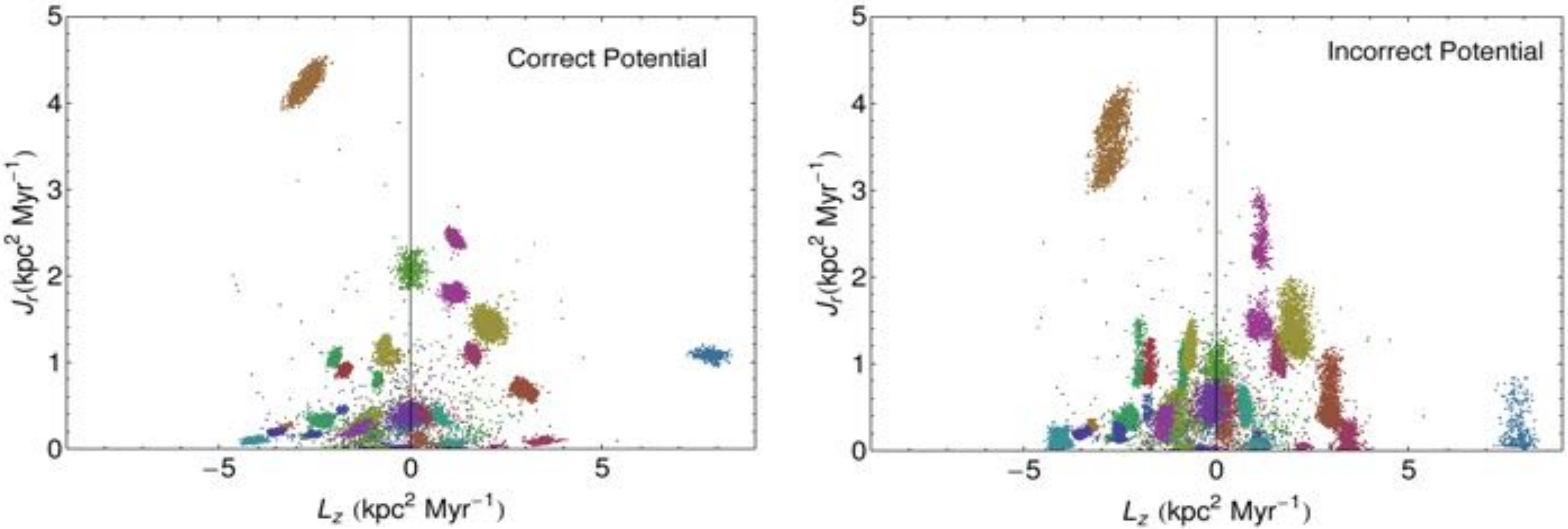
- 2400 fibres (1600 LR & 800 HR)
- First light 2022
- 5+5 years
- high-resolution spectra for more than 2 million stars



ESO VISTA 4 meter telescope on Paranal

Clustering in integrals of motion (e.g. actions) maximal for right gravitational potential

(DR2)



Sanderson et al. (2014, 2016)

Summary

- Halo substructure is useful for dynamics (dark matter) and merger history

- Photometric surveys mapped large structures in the outer halo
- TGAS x RAVE: excess of close velocity pairs and IoM space rich in substructure
  - at level consistent with cosmological simulations of halos purely built via accretion
  - Less-bound halo stars predominantly retrograde (significance > 99.9%)
  - Many overdensities for more bound halo

- What's coming:
  - DR2 (April 2018) will be fantastic: proper motions and parallaxes for 1 billion stars!
  - 4MOST and WEAVE: spectroscopic follow
  - 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
  - constraints on characteristic mass and scale of Milky Way