Galactic archaeology and dynamics at Groningen

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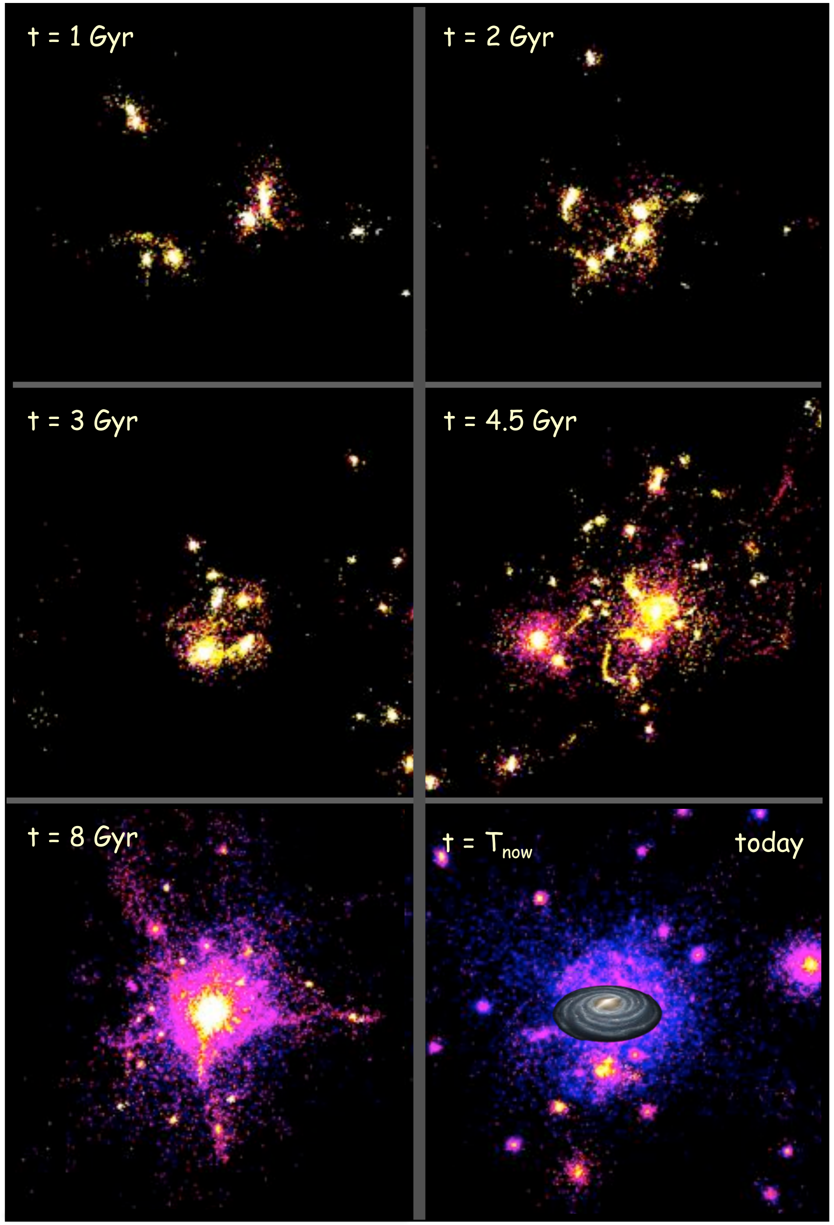
Galactic Archaeology

- Key ingredient of galaxy formation: mergers
    - Were mergers important for galaxies like the Milky Way?
    - How often and when did they happen?
    - What were the building blocks?
- Stars are "fossils"
    - Motions, ages, chemical composition trace origin
    - Substructures pinpoint to debris from accretion events
    - Probe force field ➔ mass (gravity)



snapshots: J. Gardner

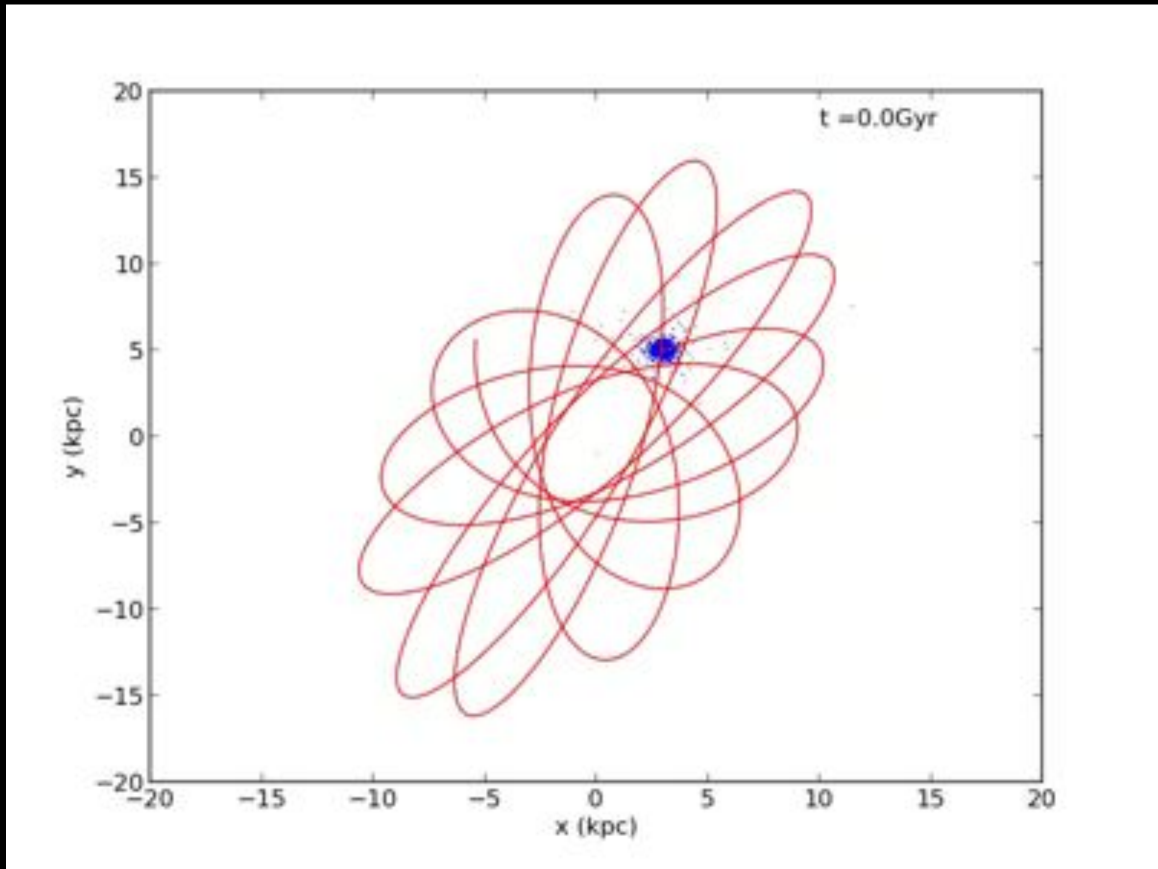
Testing the cold dark matter paradigm

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?
- How much dark matter is there?
  - how is it distributed?
  - what is the dark matter?
- Is Gravity correct?

Streams, orbits and gravitational potentials

As satellite galaxy disrupts, stars delineate nearly an orbit

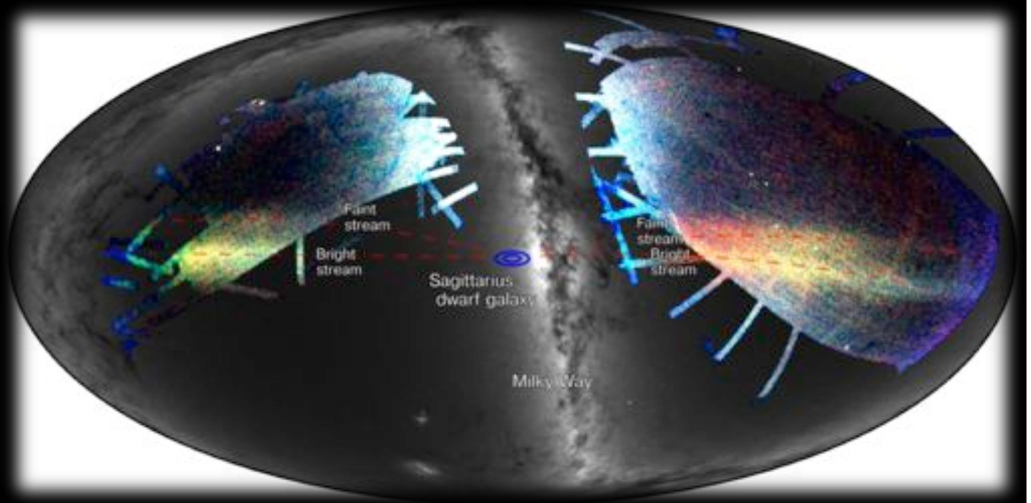


M. Hutten* (2014)

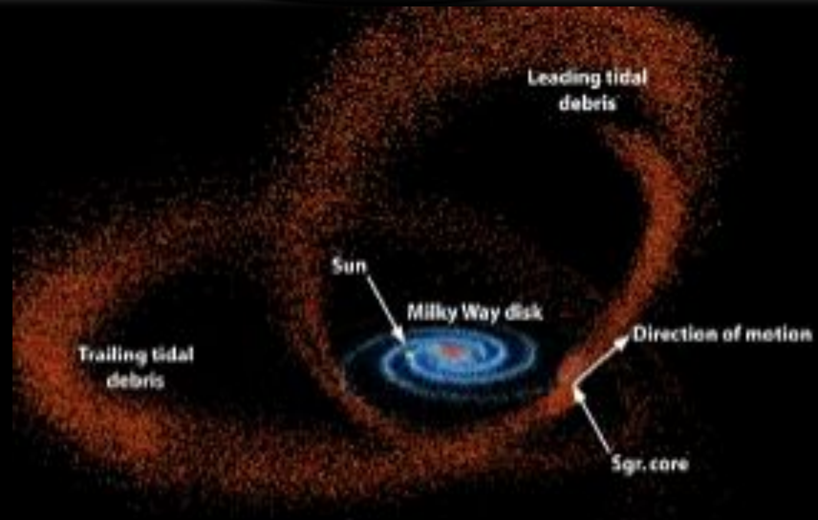
•undergraduate student in Groningen, followed Galactic Dynamics

The Milky Way's dark halo shape and Sgr stream

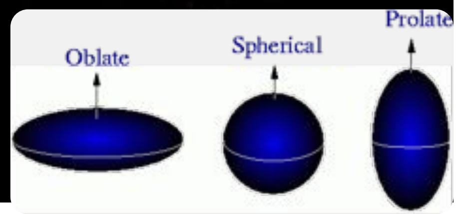
- If halo is spherical, motion is in a plane
  - Deviations, if any, tell us shape
    - in CDM halos are triaxial at large radii



- PUZZLES from models of Sgr stream in axisymmetric potentials
  - *Precession signal* (non-spherical halo): clearly favour OBLATE (Johnston et al. 2005)
  - *Radial velocities*: clearly favour PROLATE (Helmi 2004)

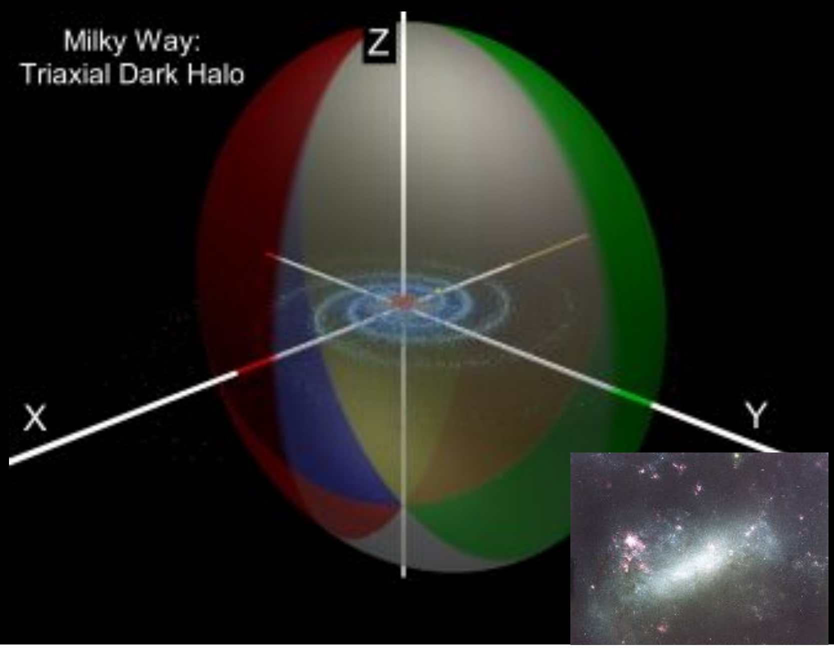


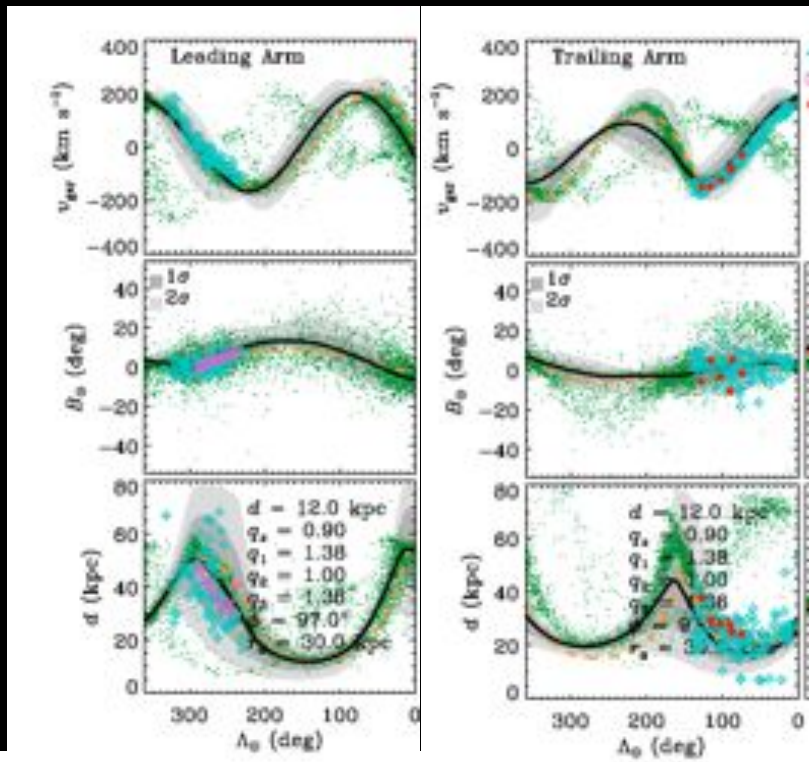
Law et al. 2005



Solution: A triaxial halo?

- Model by Law & Majewski (2010)
  - ✓ Positions on the sky (hence precession) and radial velocities
- However, it is odd…nearly oblate shape
  - – Symmetry plane: yz, i.e. perpendicular to the disk → not a stable configuration/nor intuitive physically
    - Constraints on inner shape weak: can accommodate an oblate flattened inner halo (Vera-Ciro & Helmi 2013)
  - – Why long axis along y?
    - LMC provides additional significant torque → effective potential is sum of contribution of triaxial MW halo + LMC → *indistinguishable so far*

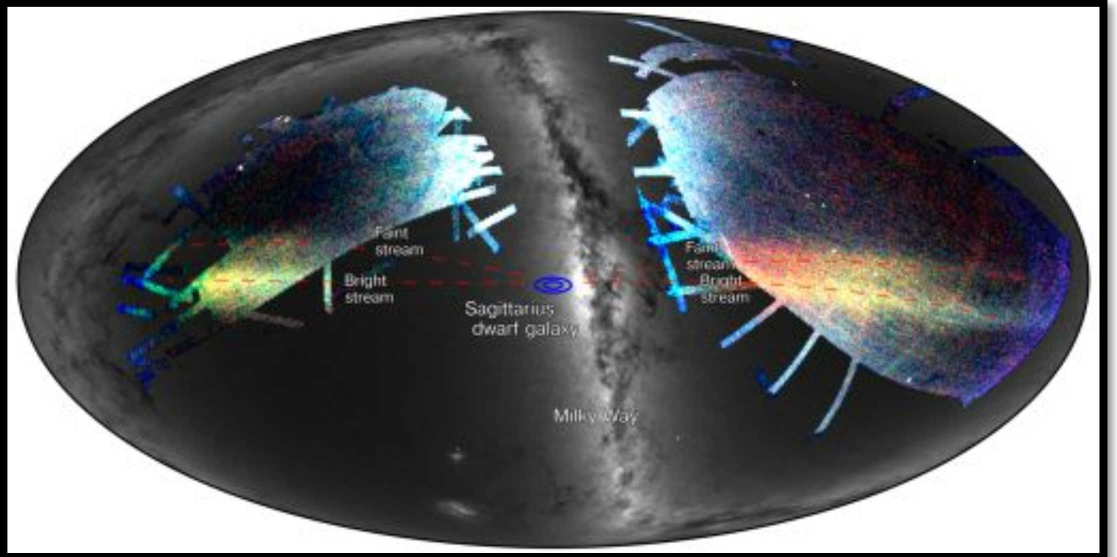


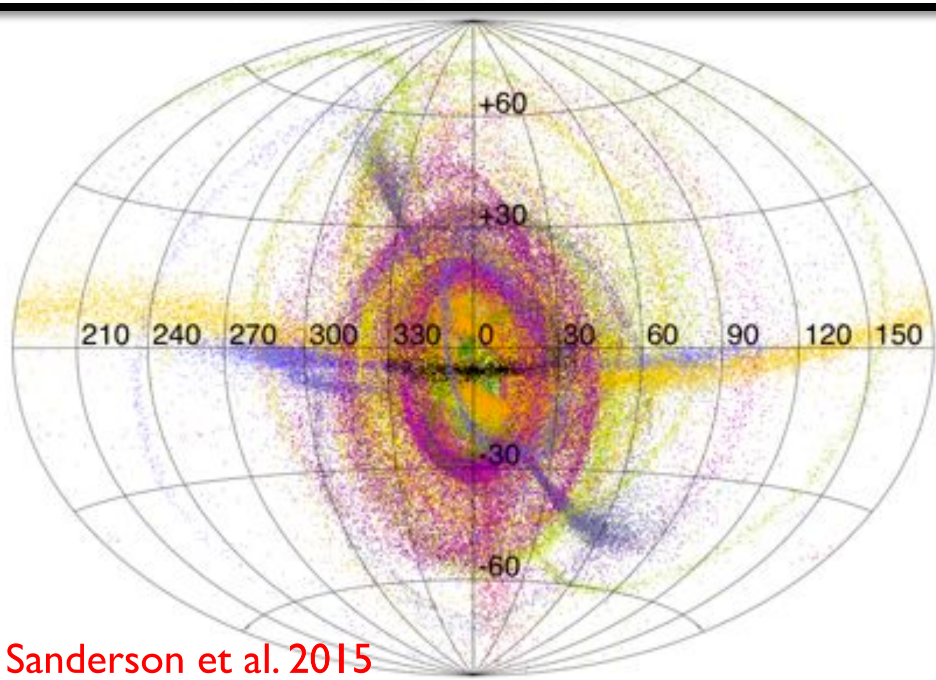


Vera-Ciro & Helmi, 2013

The stellar halo and its many streams

- With Gaia: many streams with different orbital properties
- Should be used simultaneously to constrain potential
- What is best way to do this?





Sanderson et al. 2015

Streams in action-angle space

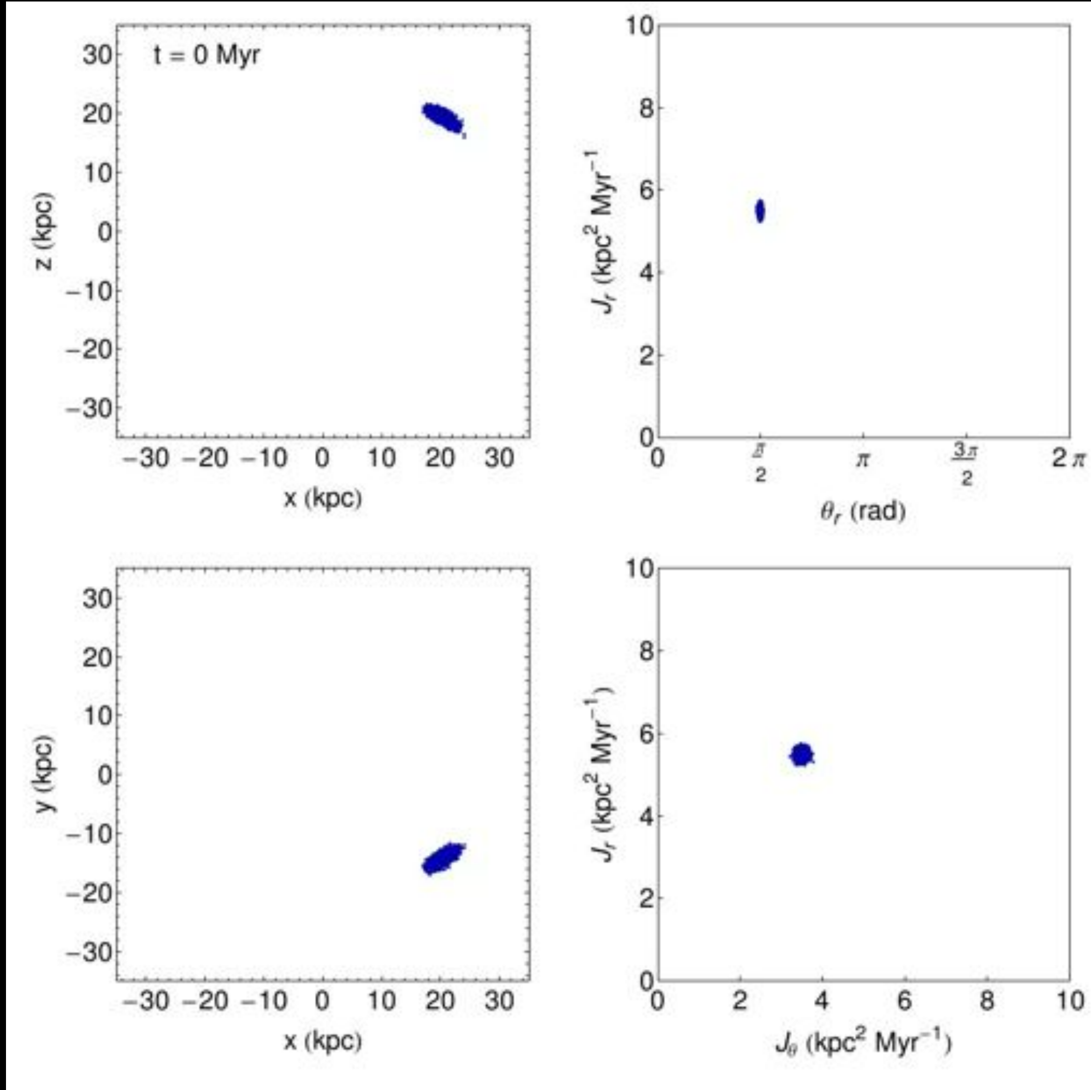
- Action-angle evolution is simple:

  $$\theta = \theta_0 + \Omega(J)\, t$$
  $$J = J_0$$

  - streams spread out in angle but maintain the actions

- Actions should be clustered
  - even if potential changed with time

- Maximal clustering in the right potential
  - We assume functional form
  - Characterized by 2 parameters: mass M and scale radius b

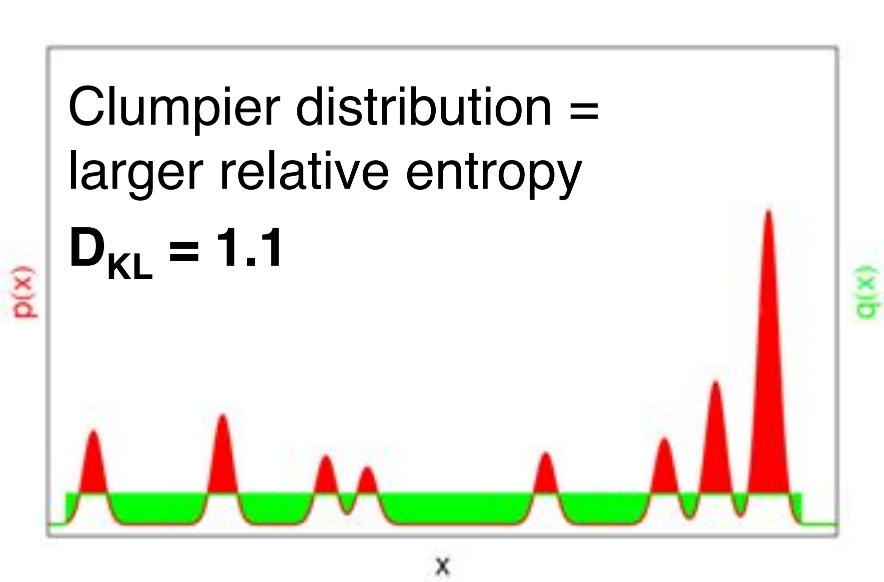


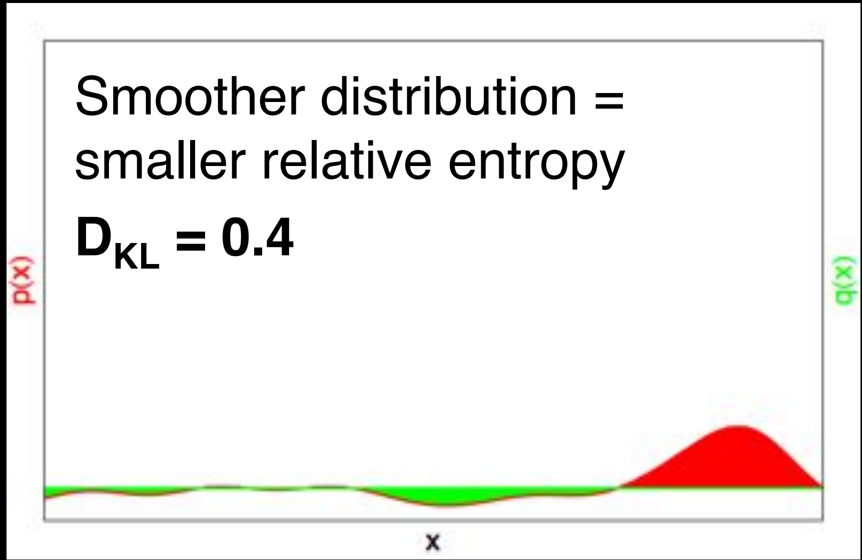
Sanderson et al. 2015

Relative clustering in action-angle space: Kullback-Leibler Divergence

- Quantify clustering using Kullback-Leibler divergence (KLD)
  - p(x) is df of actions in right potential, and q(x) is comparison distribution

$$D_{KL}(p||q) = \int \ln\left(\frac{p(x)}{q(x)}\right) p(x)\,dx$$





Sanderson et al. 2015

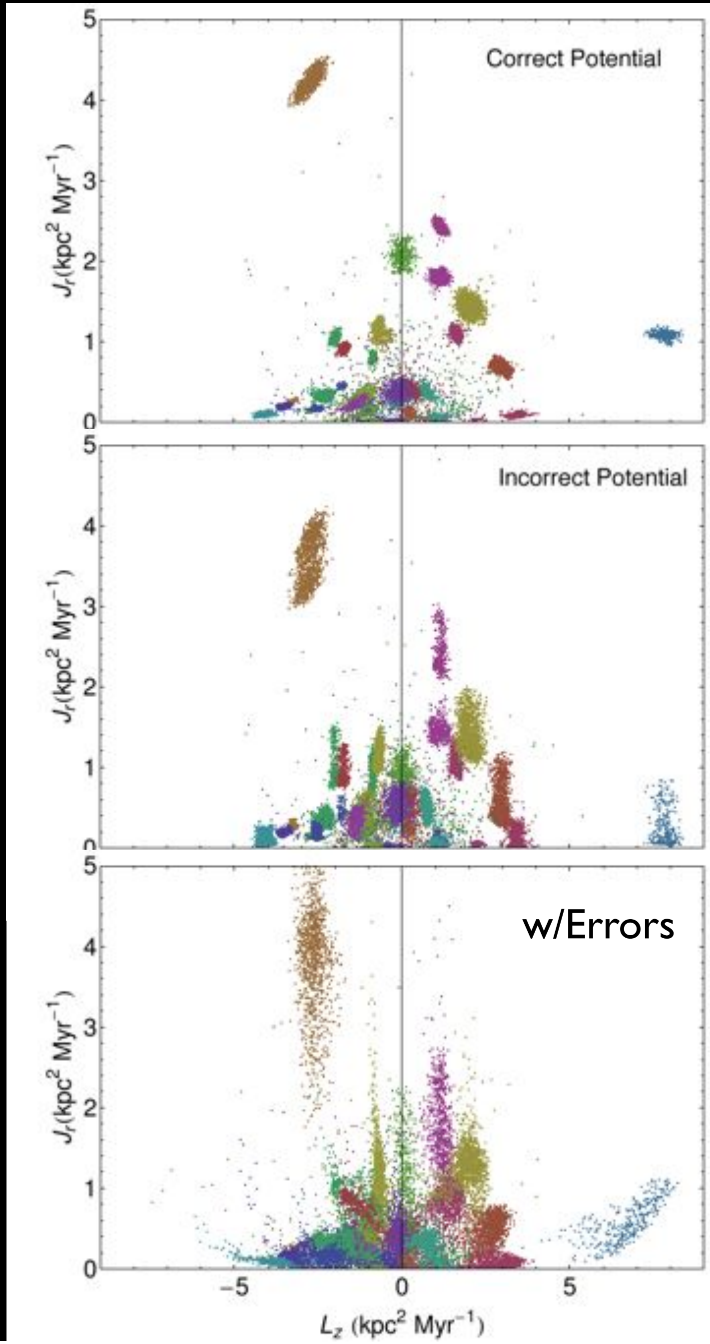
Stellar halo from streams: action-angle space

Sanderson et al. (2015)

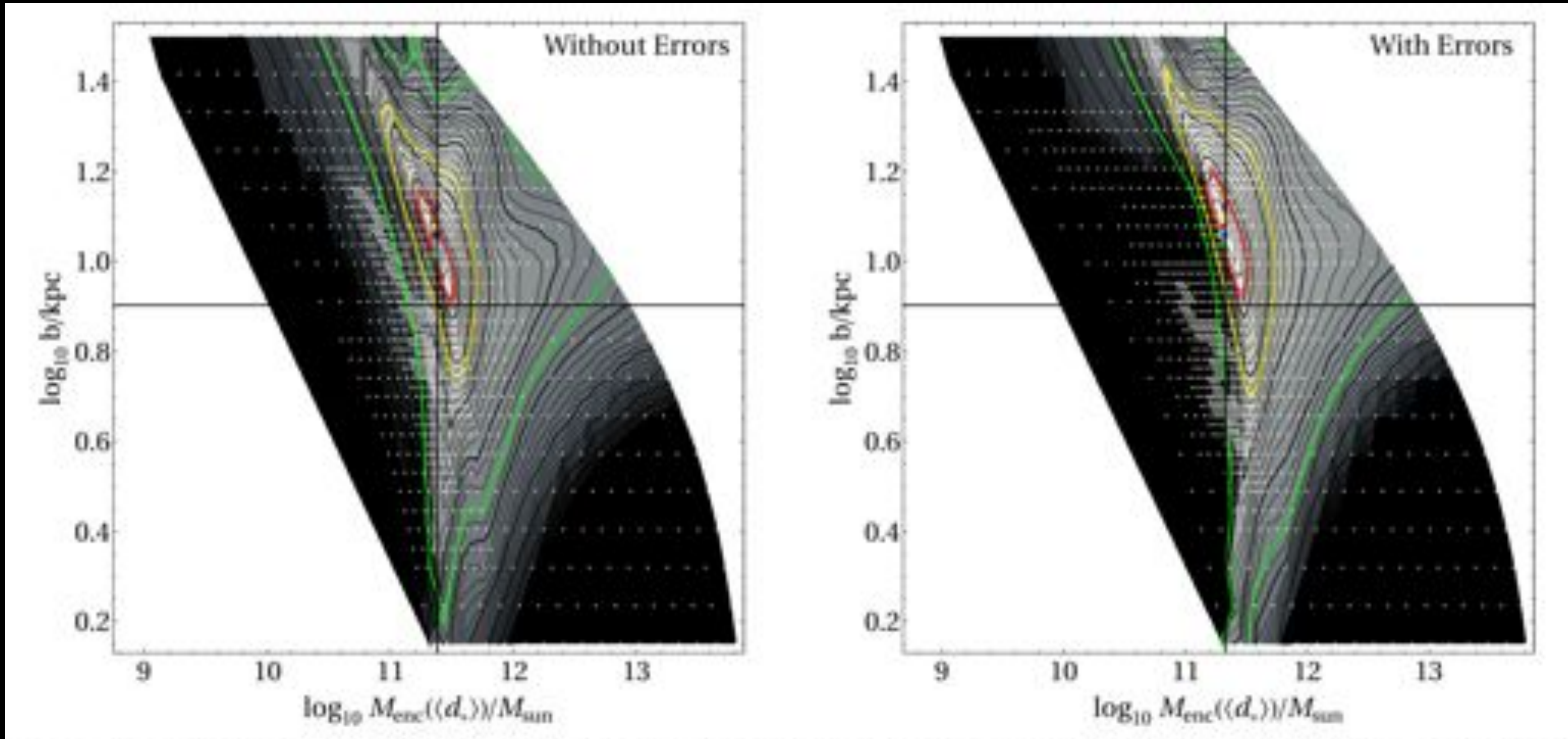
- Stellar halo built up from disrupted satellites
  - realistic mass function and orbital properties
  - Host (MW) potential assumed to be a spherical isochrone
  - 2 characteristic parameters: mass M and scale radius b

- Action-clustering maximally apparent for right potential

- Gaia errors blur quantities but clustering still present



D_{KL} and constraints on characteristic parameters

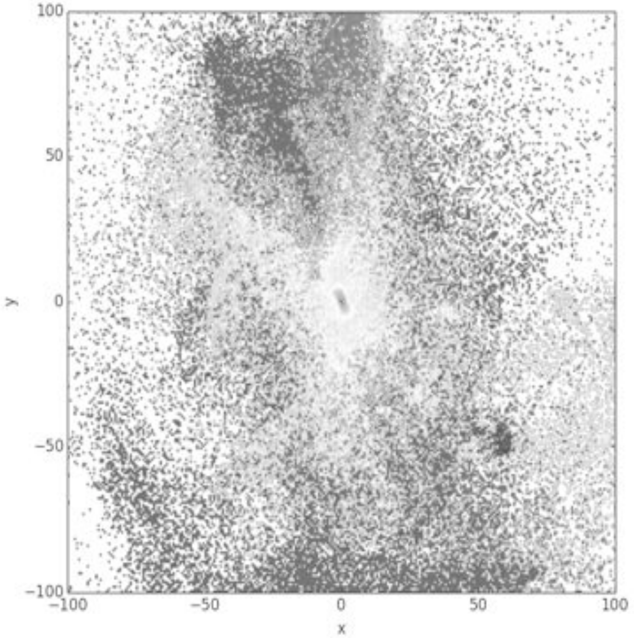


Sanderson et al. 2015

D_{KL} = 0.5 (1σ) 2(2σ), 4.5(3σ) confidence

- Recovered enclosed mass is within 3% of the input value, ~ 30% uncertainty
- Scale radius is biased high, within 2σ contour, 20% uncertainty
  - More stars at larger distances (e.g. WEAVE and 4most) reduce the biases significantly and lead to tighter estimates of the parameters

Kinematics for large numbers of halo stars: crucial



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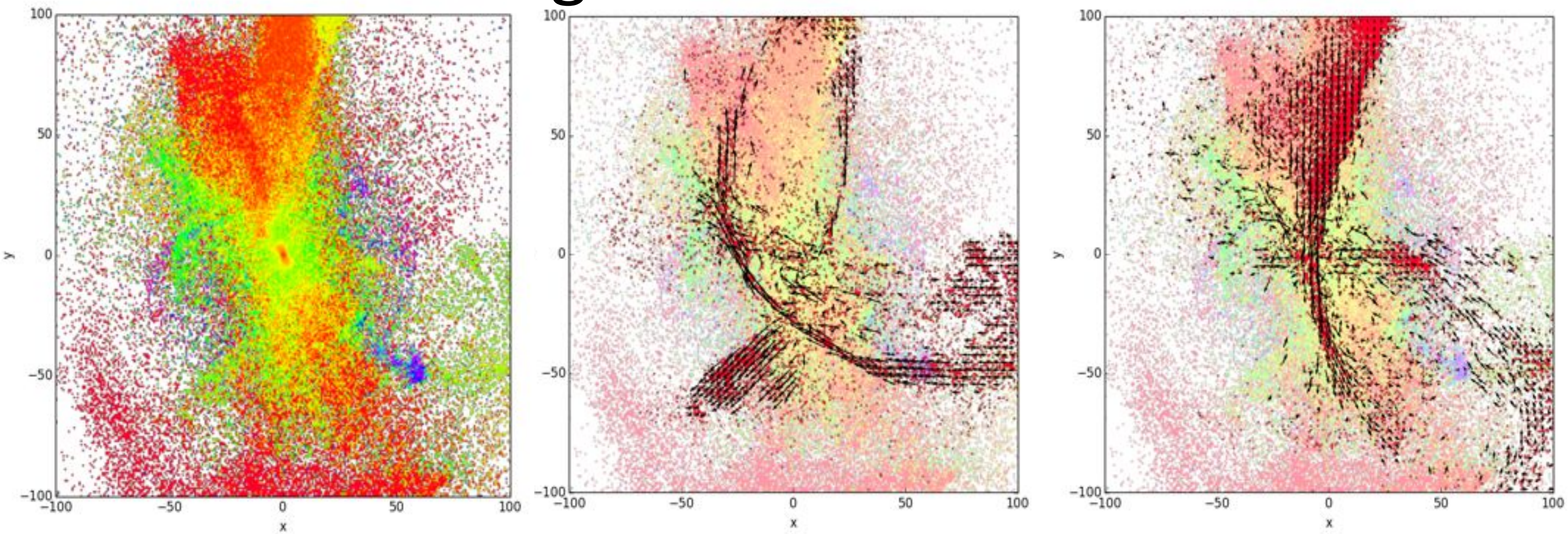
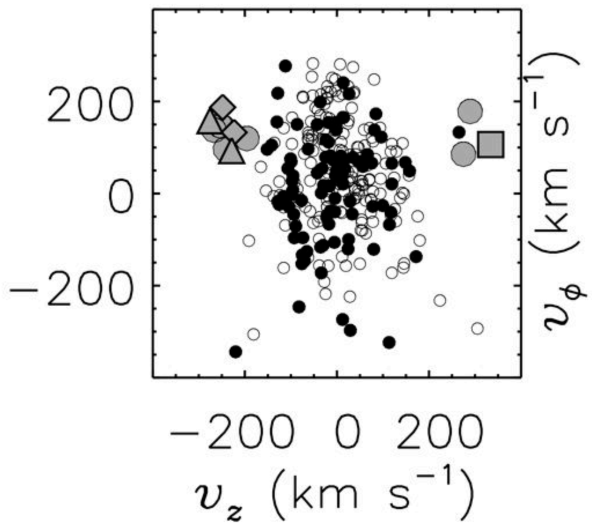


M. Breddels

Velocity space near the Sun

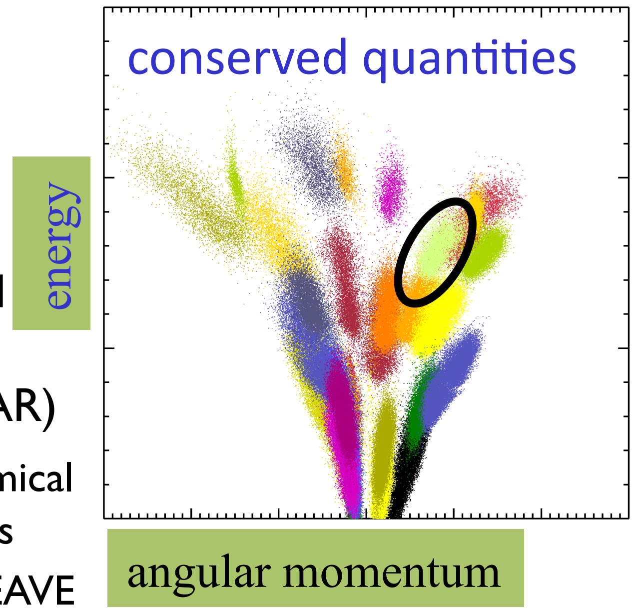
Helmi et al. 1999



100s more predicted and possibly hiding…

How to find these? Gaia!

- Clustering in conserved quantities; algorithms in phase-space (ROCKSTAR)
- Follow-up: SFH and chemical evolution of building blocks → FLAMES, 4MOST & WEAVE



Helmi & de Zeeuw 2000


Tjitske Starkenburg
Hao Tian
Hans Buist
Maarten Breddels
Jovan Veljanoski
Jorrit Hagen