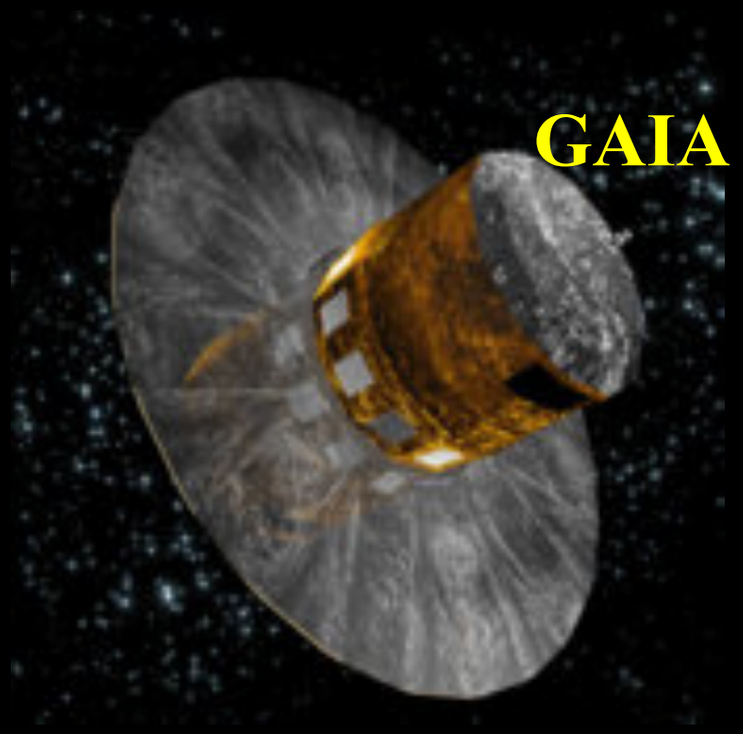
Stream identification in Gaia era:

Identifying and Characterizing the (Stellar) Halo-Substructure in "Integral-of-Motion" Space



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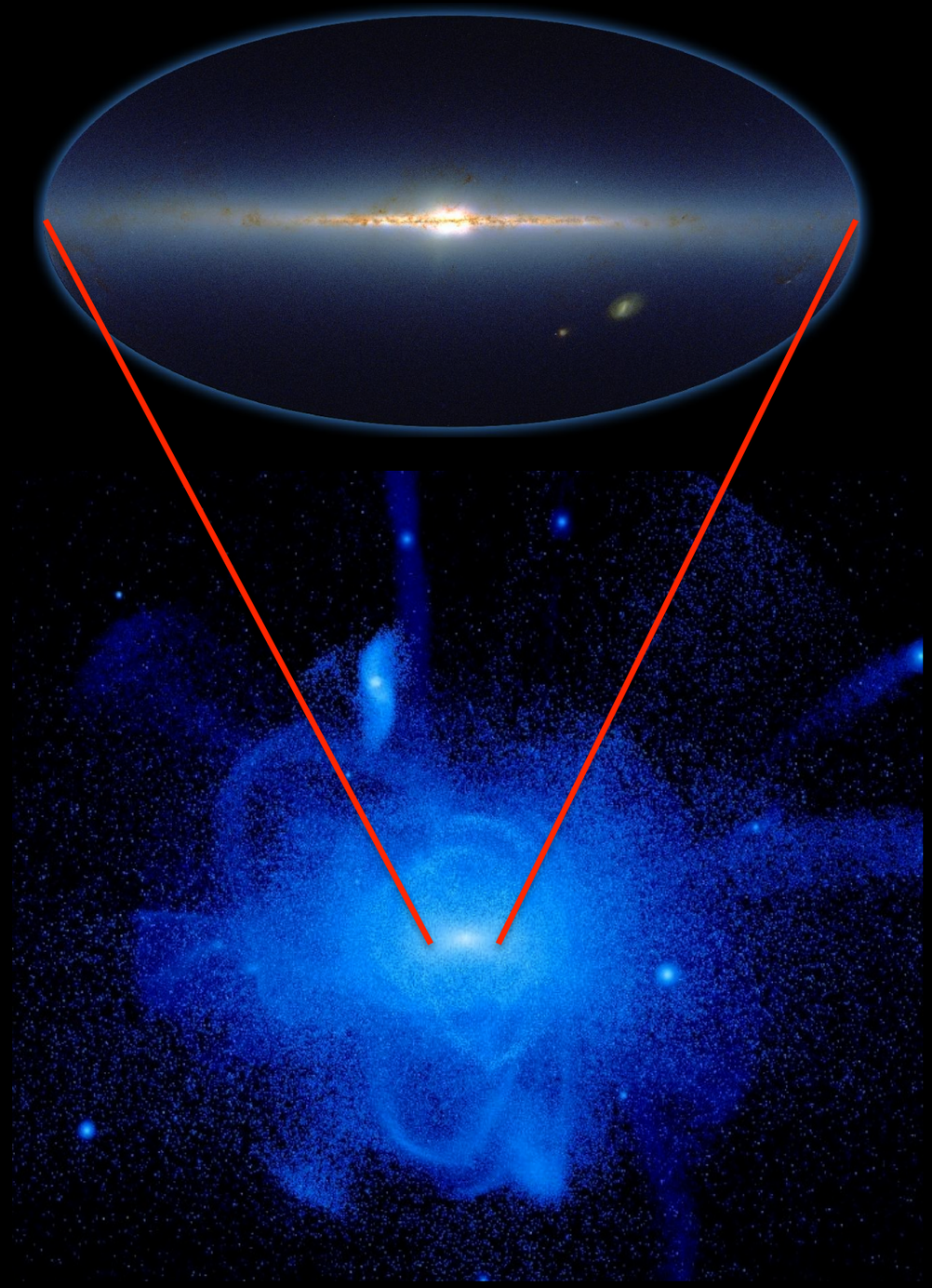
Why identify halo-substructure?

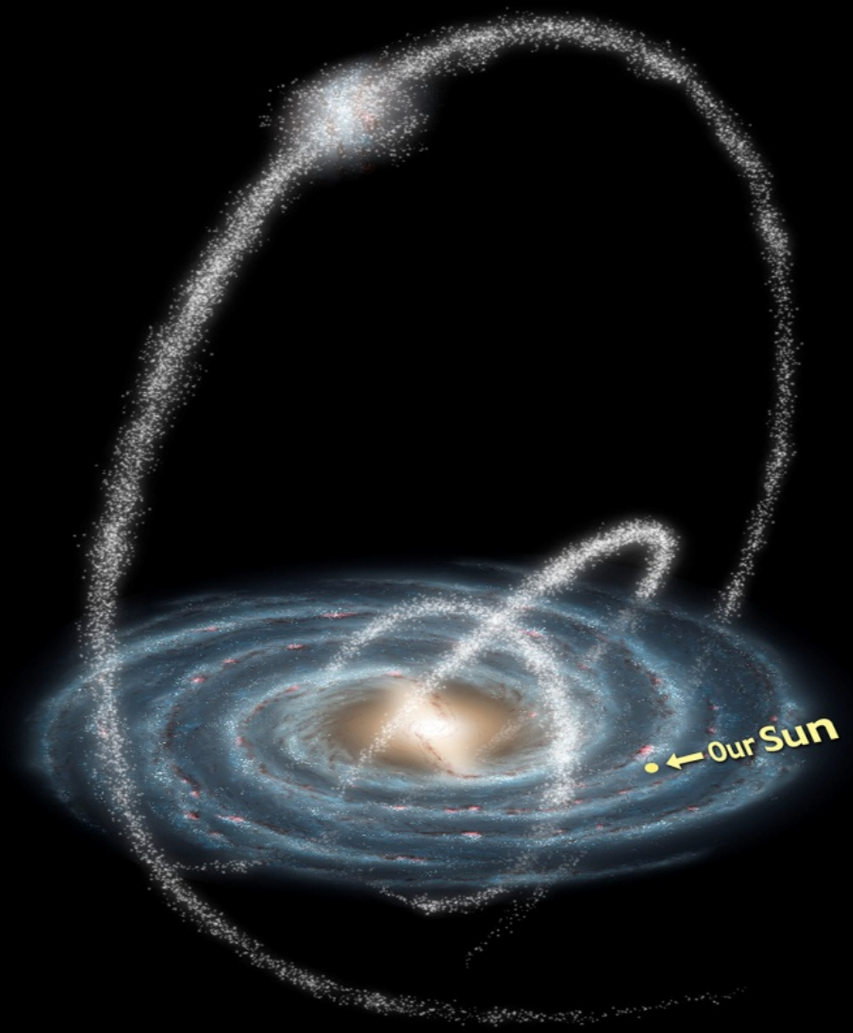
- The Λ cold dark matter (CDM) cosmological model predicts
  - "in-situ" formation (inside)
  - many mergers have occurred (large radii)
  - at large radii: VERY long orbital period (>0.5 Gyr)—> remnants of disrupted satellites are still apparent
  - Therefore, easiest dynamical signatures of the mergers in the halo
- Evidences of spatial substructures have been found in the MW halo.
- Does accretion dominate the Galaxy formation?
- Streams can be used to constrain the mass of the Milky Way.



A stream

- is an association of stars moving along similar orbits,
- was once a globular cluster or dwarf galaxy that has now been torn apart and stretched out along its orbit by tidal.

A schematic view of accretion

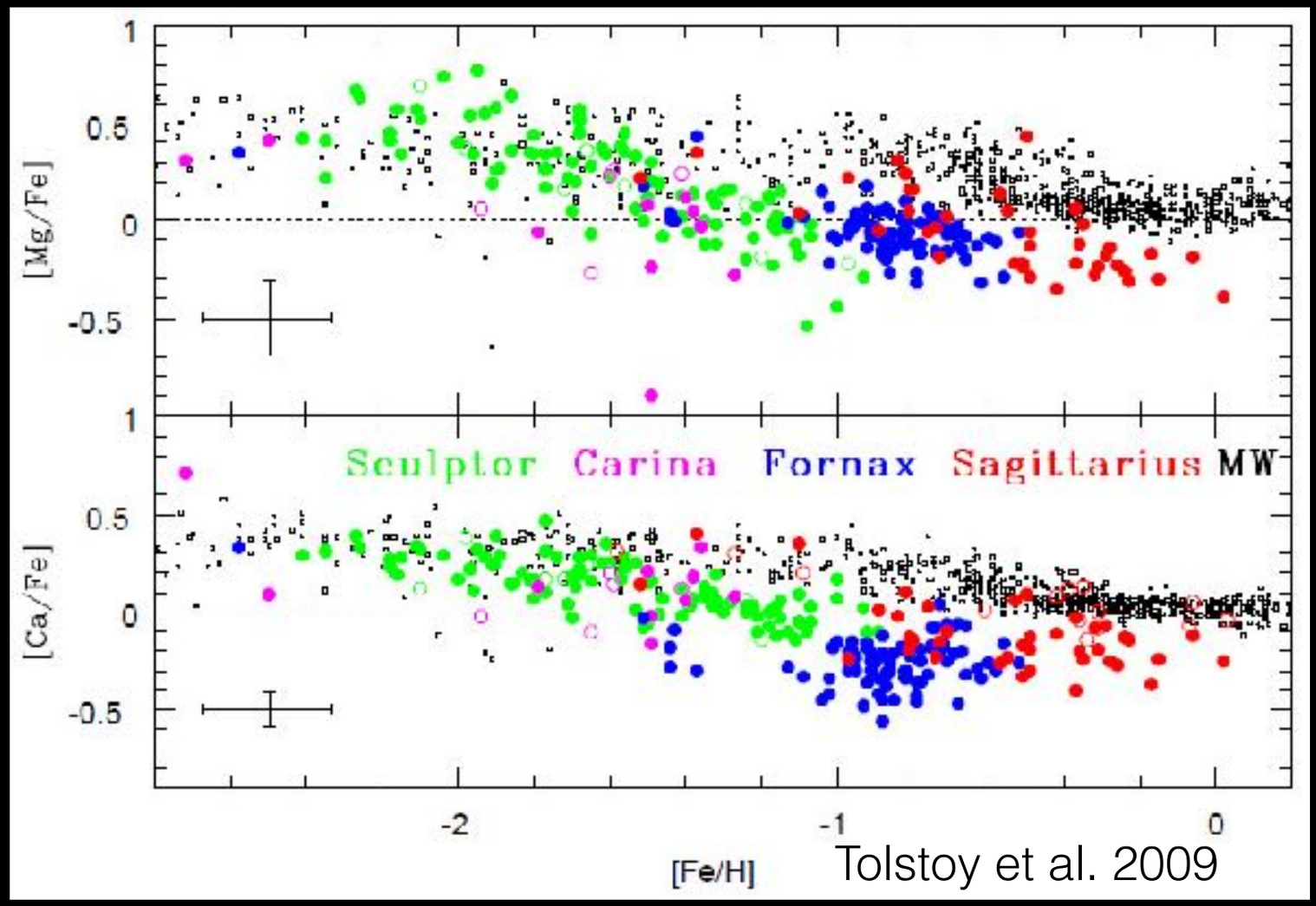


NASA/JPL-Caltech/R. Hurt(SSC/Caltech)

Reconstructing the accretion history of Milky Way

need kinematic tracers with r(α,δ,D), v_{los}, proper motion, and [Fe/H] to

- quantify stellar streams
  - identify steam members
  - isolate different streams
- study the origin of streams
  - [Fe/H]
  - other elements abundance



Tolstoy et al. 2009

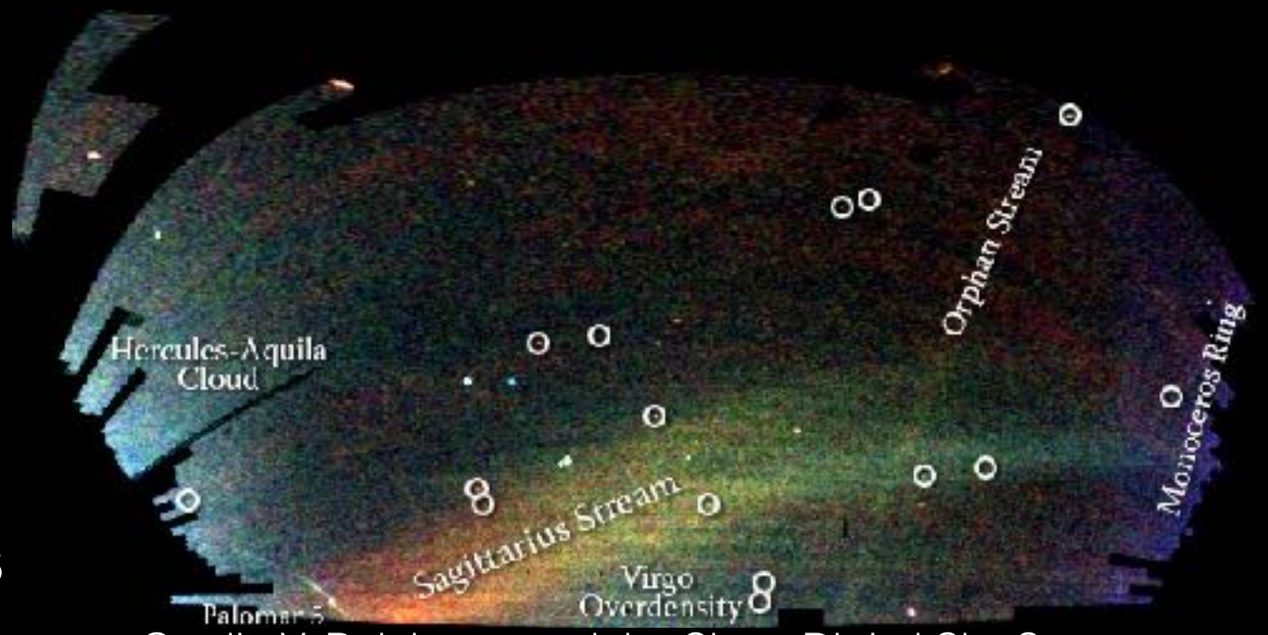
What has been well known for MW halo-substructure?

Galactic Stellar Halo has abundant substructure: *Sagittarius, Virgo stellar stream, Virgo overdensity, Monoceros, Tri-Andromeda, Hercules-Aquila cloud, Pisces overdensity, Orphan stream, Aquarius stream...*

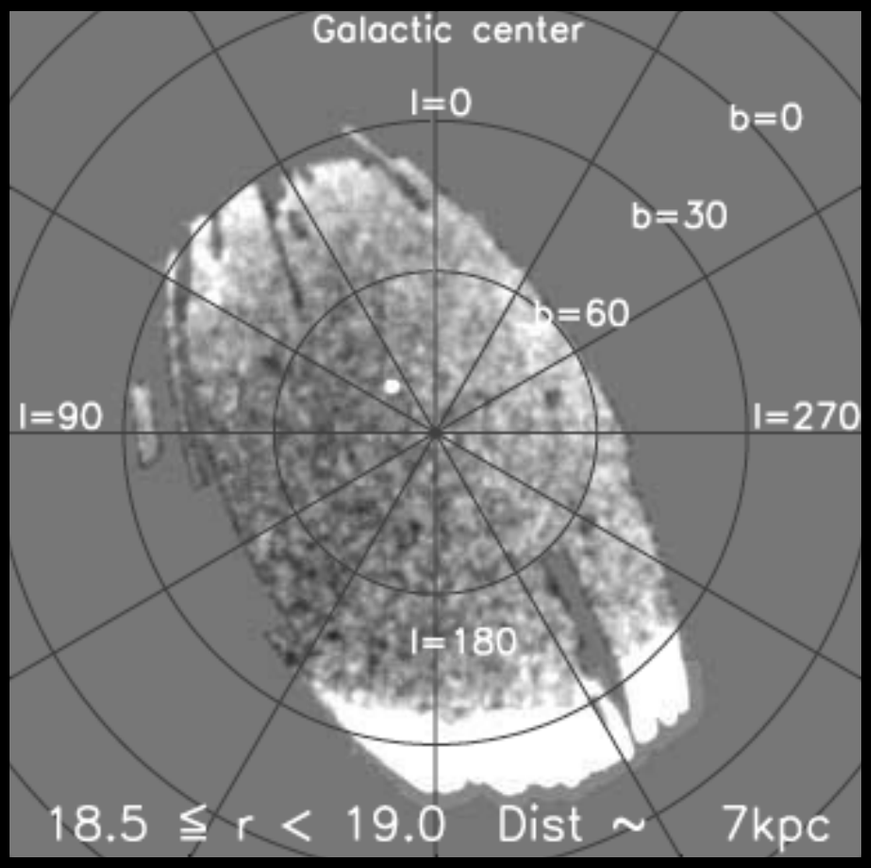
- field of streams
- features differ in different populations

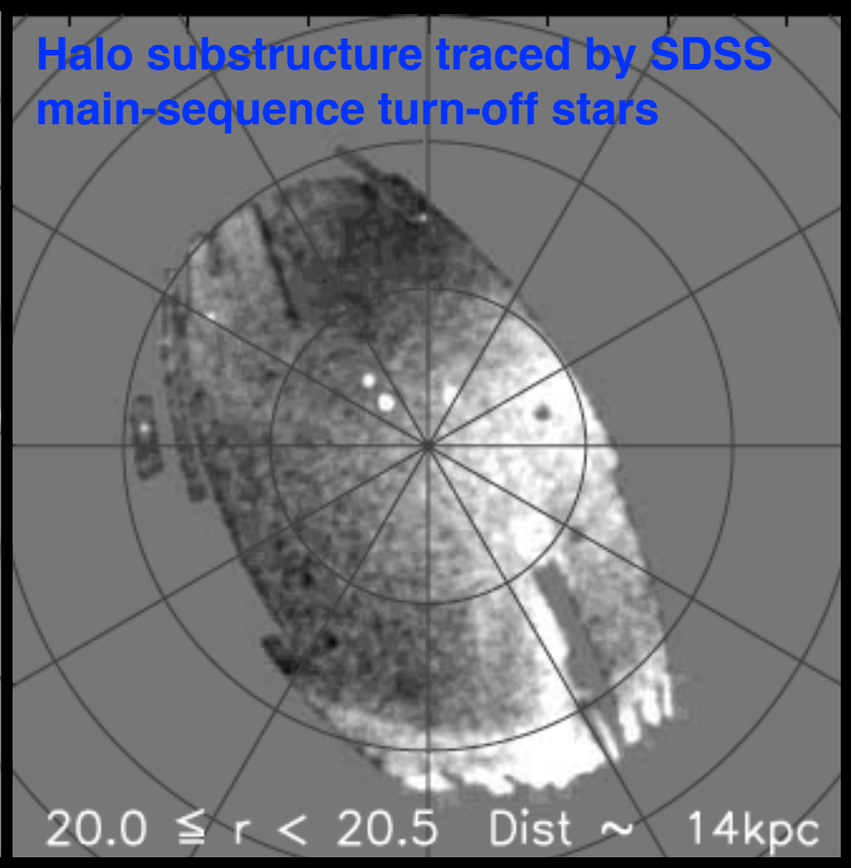
  Ibata+ 2001, Majewski+ 1996, 2003, Bell+ 2008
- position-velocity(4D) substructure

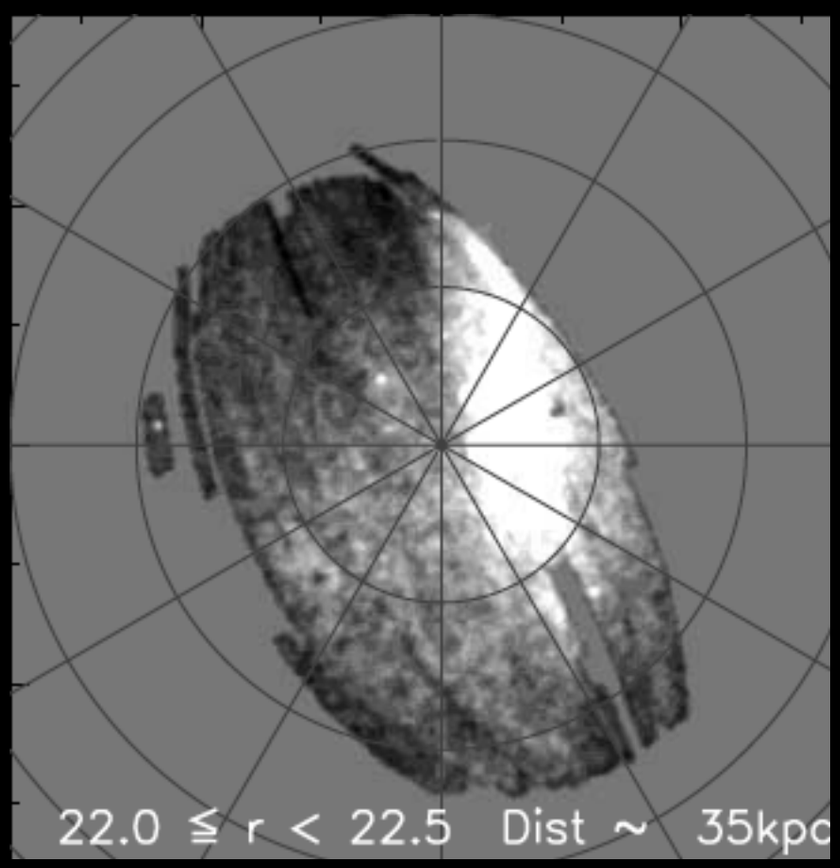
  Starkenburg+ 2009, Xue+ 2011, Janesh+ 2016



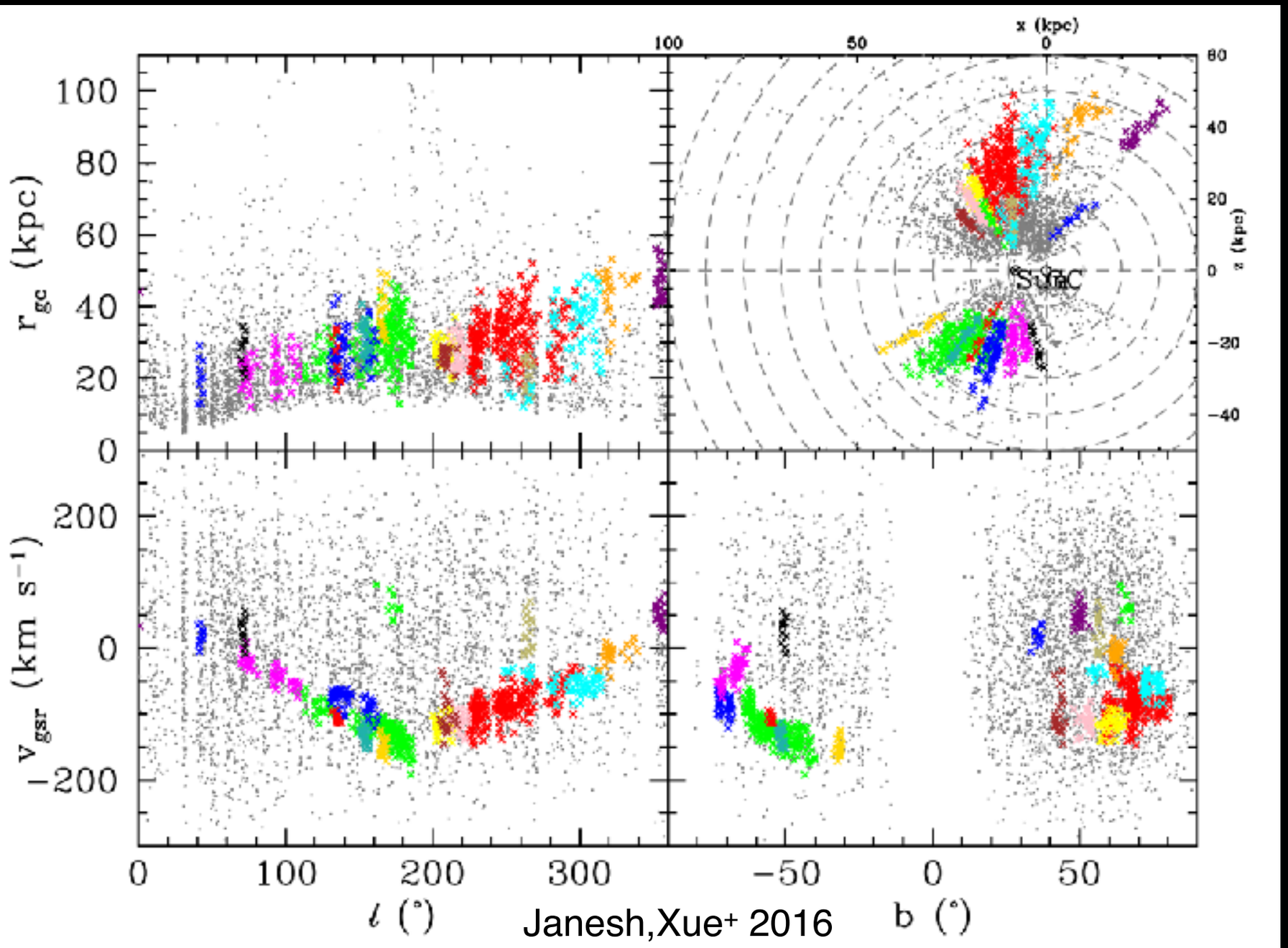
Credit: V. Belokurov and the Sloan Digital Sky Survey







Substructure identification in position-velocity space



Janesh,Xue+ 2016

$$\delta_{4d}^2 = w_\phi \phi_{ij}^2 + w_v (v_i - v_j)^2 + w_d (d_i - d_j)^2,$$

Friends-of-friends works by drawing a circle around each point, with a radius of 4distance=0.03 (Maximum physical size $\boldsymbol{\theta}$=5.4°, $\boldsymbol{\Delta}$d=6kpc, $\boldsymbol{\Delta}$v=15km/s)

Colors:
The friends-of-friends groups with >= 10 members

How can we identify a stream as a group?

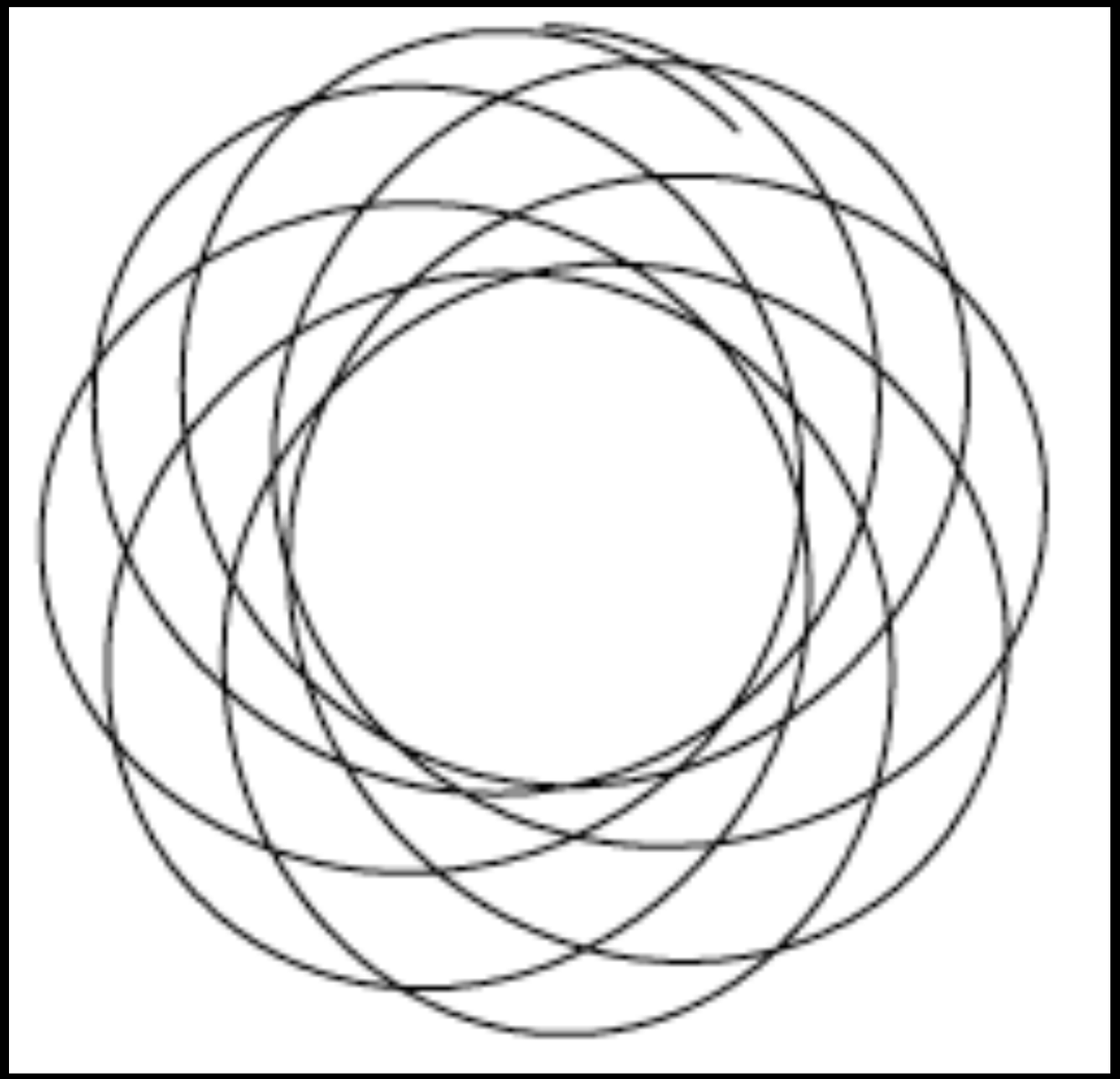
- K giants belonging to Sgr streams, Orphan streams, Cetus Polar stream, and other unknown substructures are identified.

What is the right coordinates to identify substructure?

Integral-of-Motion Space

- Assume the gravitational potential that stars in the MW halo (> 20 kpc) feel is spherical
- The orbit of a star in spherical potential can be characterized by 4 classical integrals-of-motion
  - energy
  - angular momentum vector
- In the same period, the direction of apocenter can be taken as another integral-of-motion
- 5 integrals-of-motion in total

The orbit of a star in spherical potential



Identifying the Halo-Substructure in I.o.M. space

1. About the two components (V_l, V_b) of the tangential velocity V_T

   - Before Gaia: we know a prior of their probabilities that can be described by a Gaussian with mean at 0 and width of 120 km/s

   - Gaia DR2: we know proper motions with δ_{pm}=0.072 mas/yr@G=18

2. In spherical potential $\Phi_{tot}(r)$, there are 4 classical integrals-of-motion
   - The energy and the angular momentum vector, (E, L_x, L_y, L_z)
   - Transfer them to eccentricity, semi-major axis, the direction of the orbital pole, and the direction of apocenter, (e,a,l_{orbit},$b_{orbit,}$$l_{apo}$)

3. The orbit-space-probability-distribution of each star i, p_i
   - Randomly sample a set of tangential velocities (V_l, V_b) from the prior or true distribution
   - In given spherical potential, calculate a set of integrals of motion (e,a,l_{orbit},$b_{orbit,}$$l_{apo}$) —> the orbit-space-probability-distribution p_i

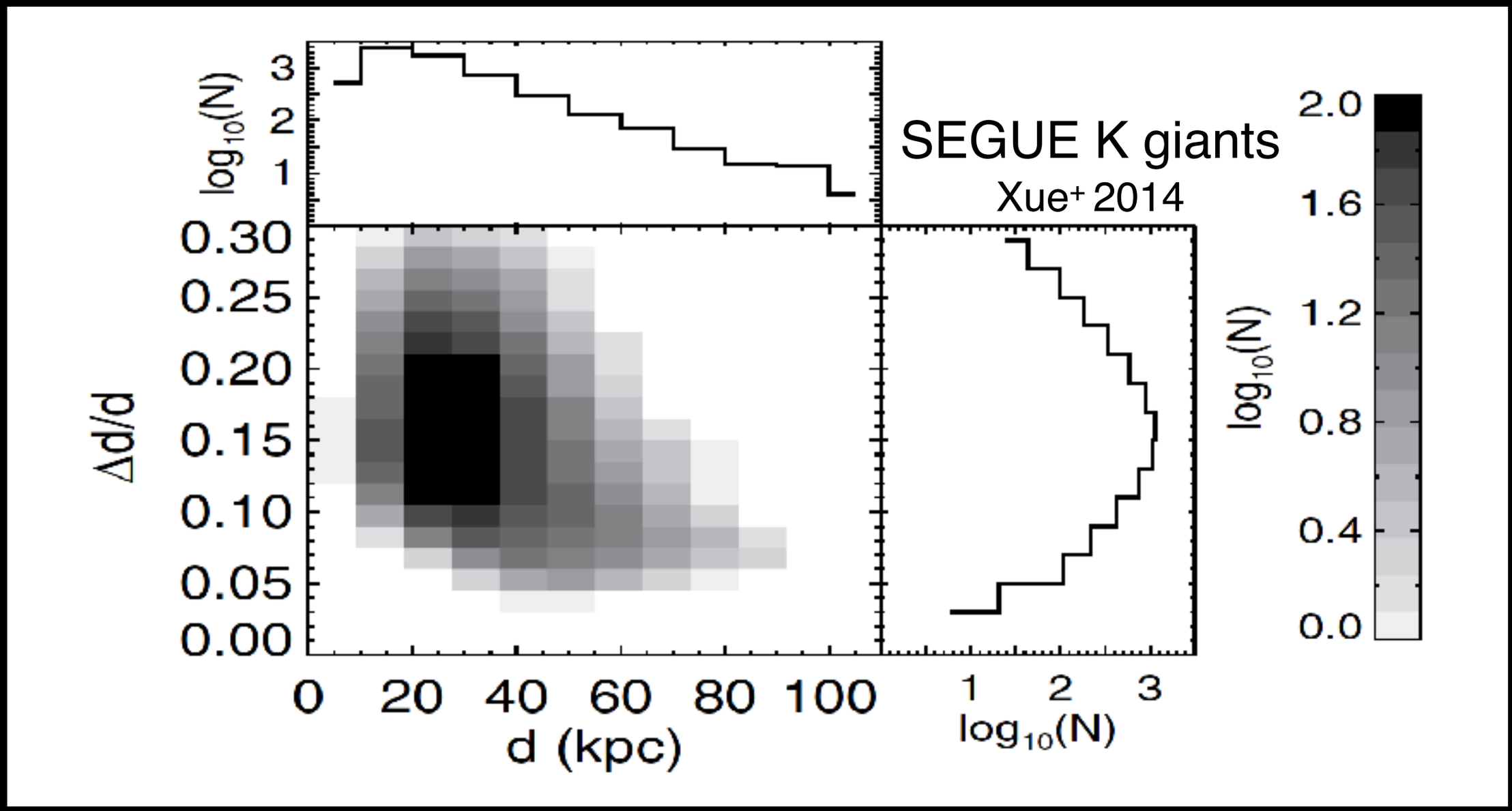
4. Orbit-likelihood-distance+FoF
   - Define the orbit-likelihood-distance between two stars as $LD_{ij} = D_{ij}-0.5*(D_{ii}+D_{jj})$, where $D_{ij} = -\ln(\mathrm{sum}(p_i*p_j))$
   - Apply FoF to identify groups

Mock data

- in SEGUE-2 plates
- the smooth halo
  - about 2200 stars
  - follows similar number density profile, selection function, line-of-sight velocity distribution, magnitude distribution as the SEGUE-2 K giants (Xue+ 2015)
  - the tangential velocities (V_l,V_b) are randomly drawn from 2D Gaussian with mean at 0 and width of 120 km/s
- 10 streams
  - about 200 stars in total
  - produced using galpy's orbit-integration code
- Distance and velocity errors of SEGUE KGs are added.

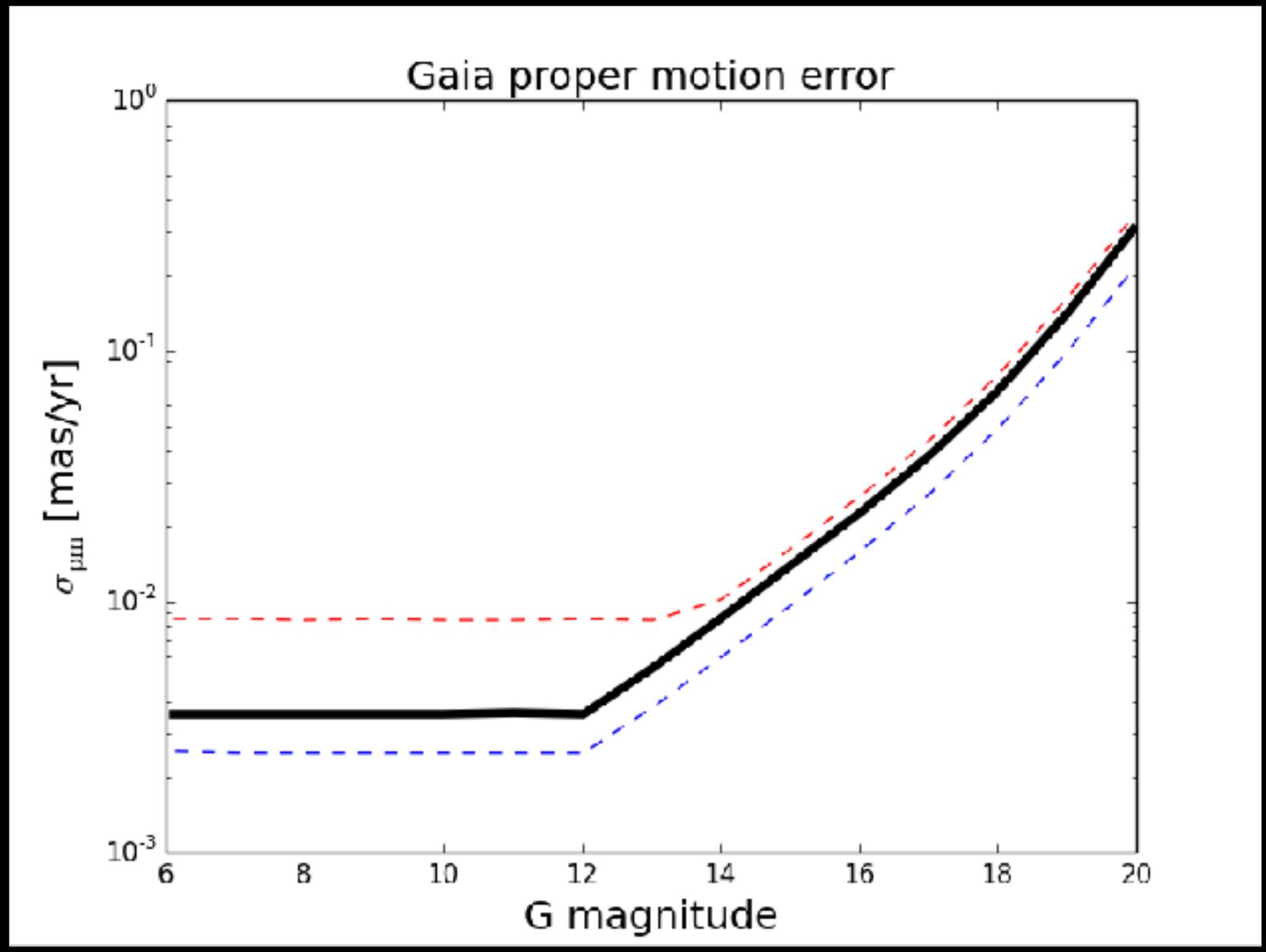
Errors of observables

- Errors of line-of-sight velocities: δv_{los}~7km/s
- A typical error of 15% in distances



mimic Gaia's proper motion errors

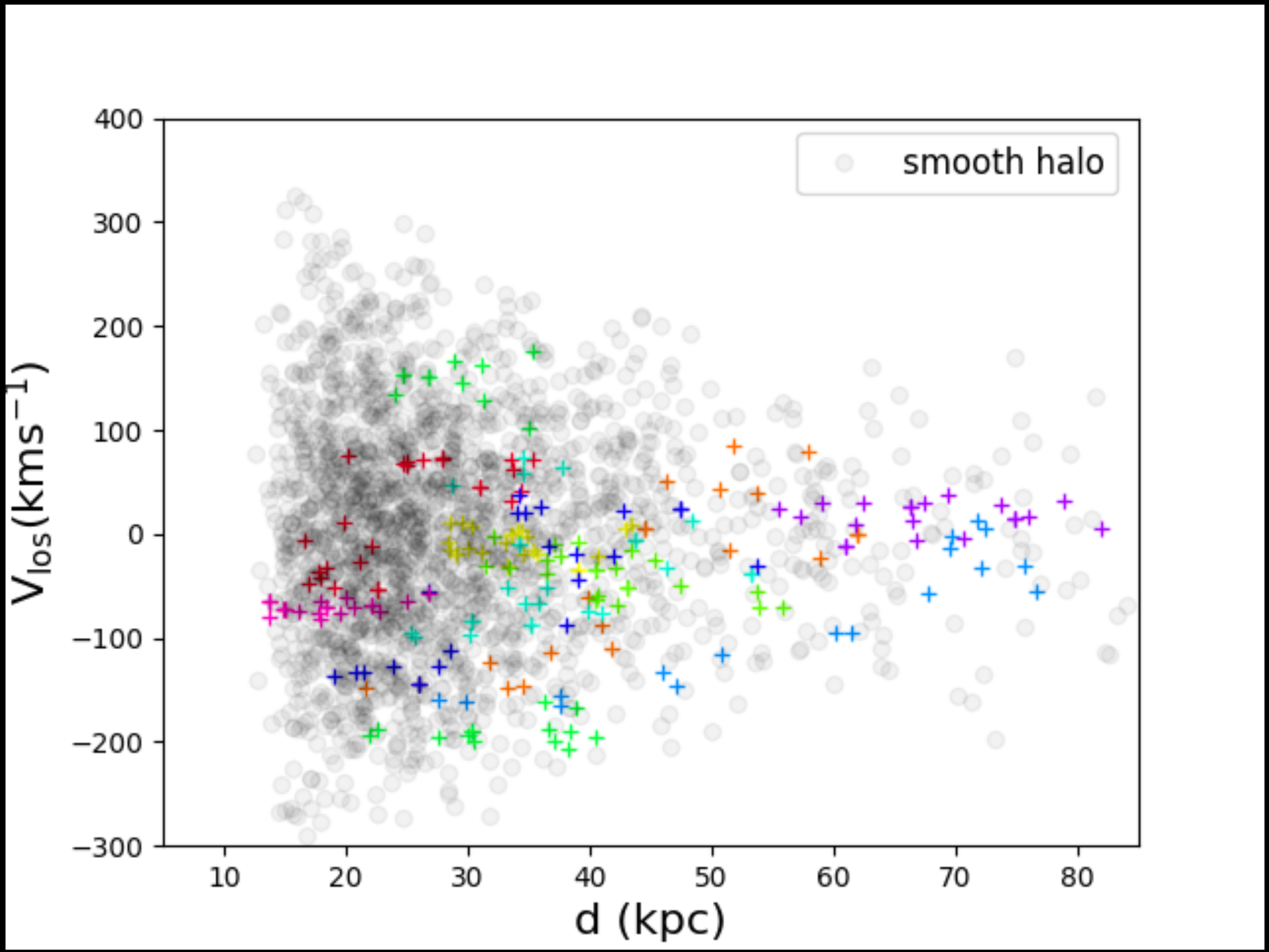
- Link σ_{pm} to mock stars by apparent magnitude r
- $V_T = k*d*pm$
- Ideal case:
  $\sigma_{vt} = k*d*\sigma_{pm}$
  $= |\sigma_{pm}/pm|*V_T$



True case: $(\sigma_{vt})^2=[(\sigma_{pm}/pm)^2+(\sigma_d/d)^2]*(V_T)^2$

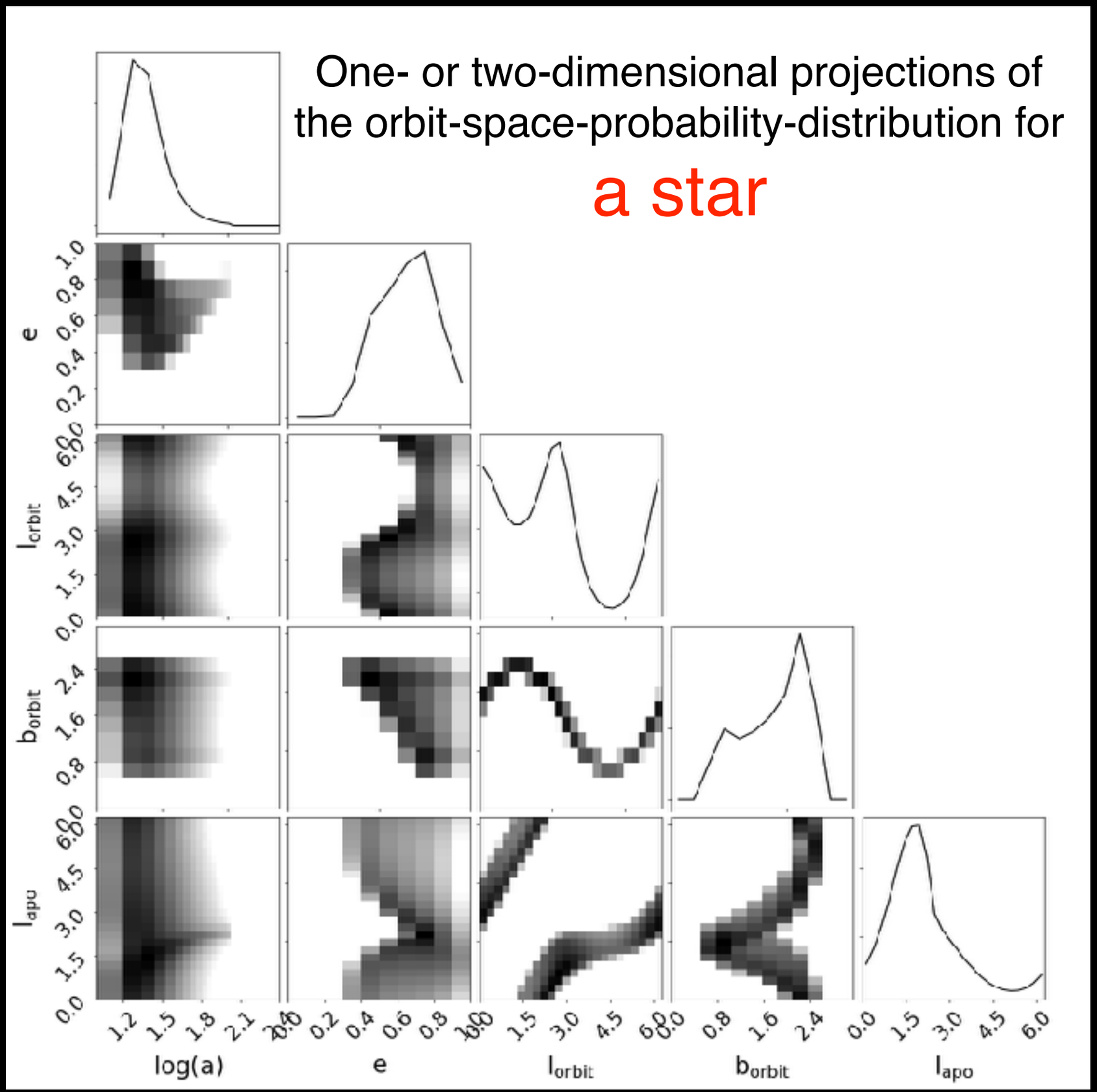
Mock data

It is difficult to see the substructure by eyes!



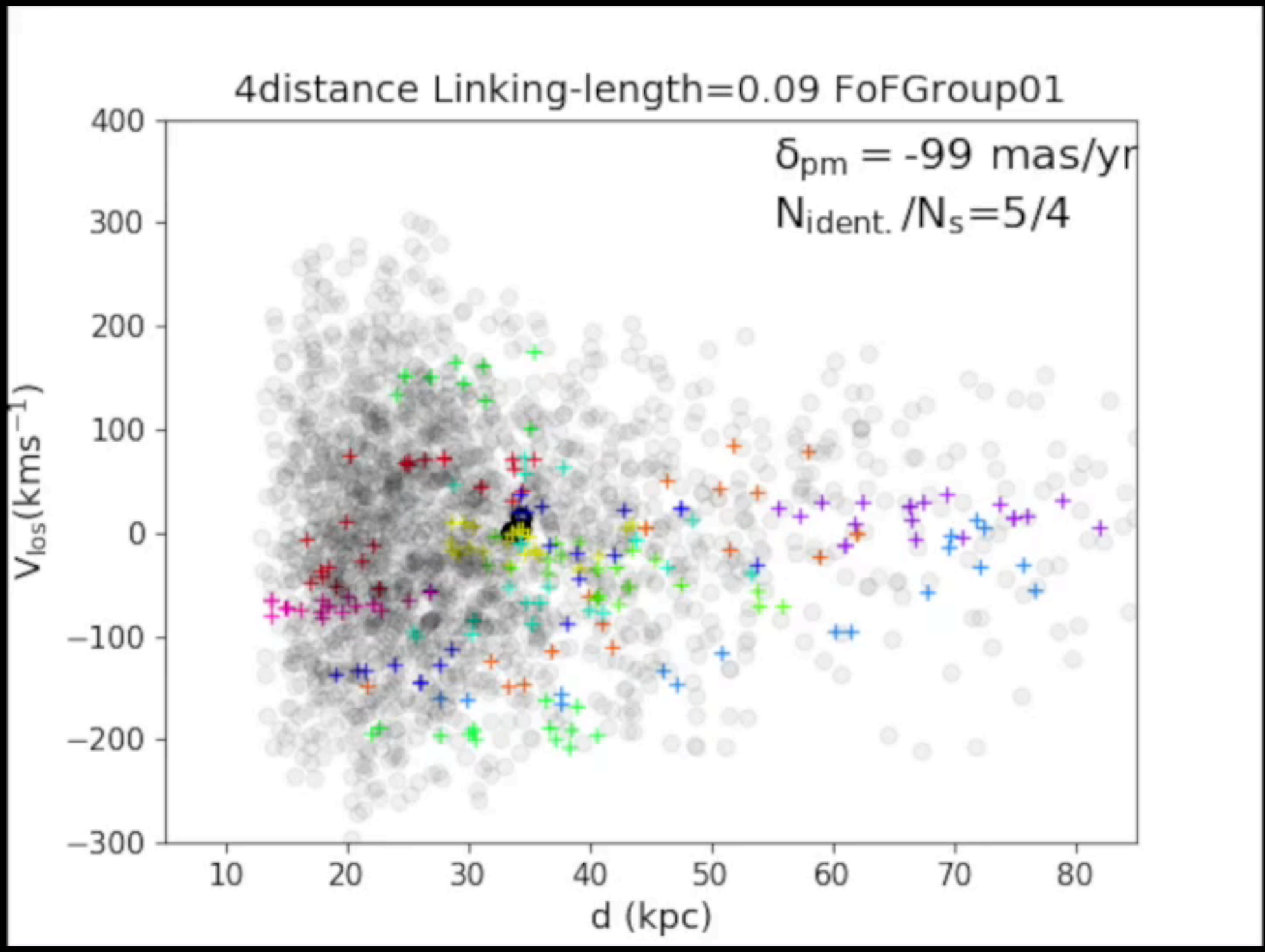
If only a prior of V_T is available for halo stars, is it helpful on the stream identification?

Case I: no proper motions, but only a prior of V_T



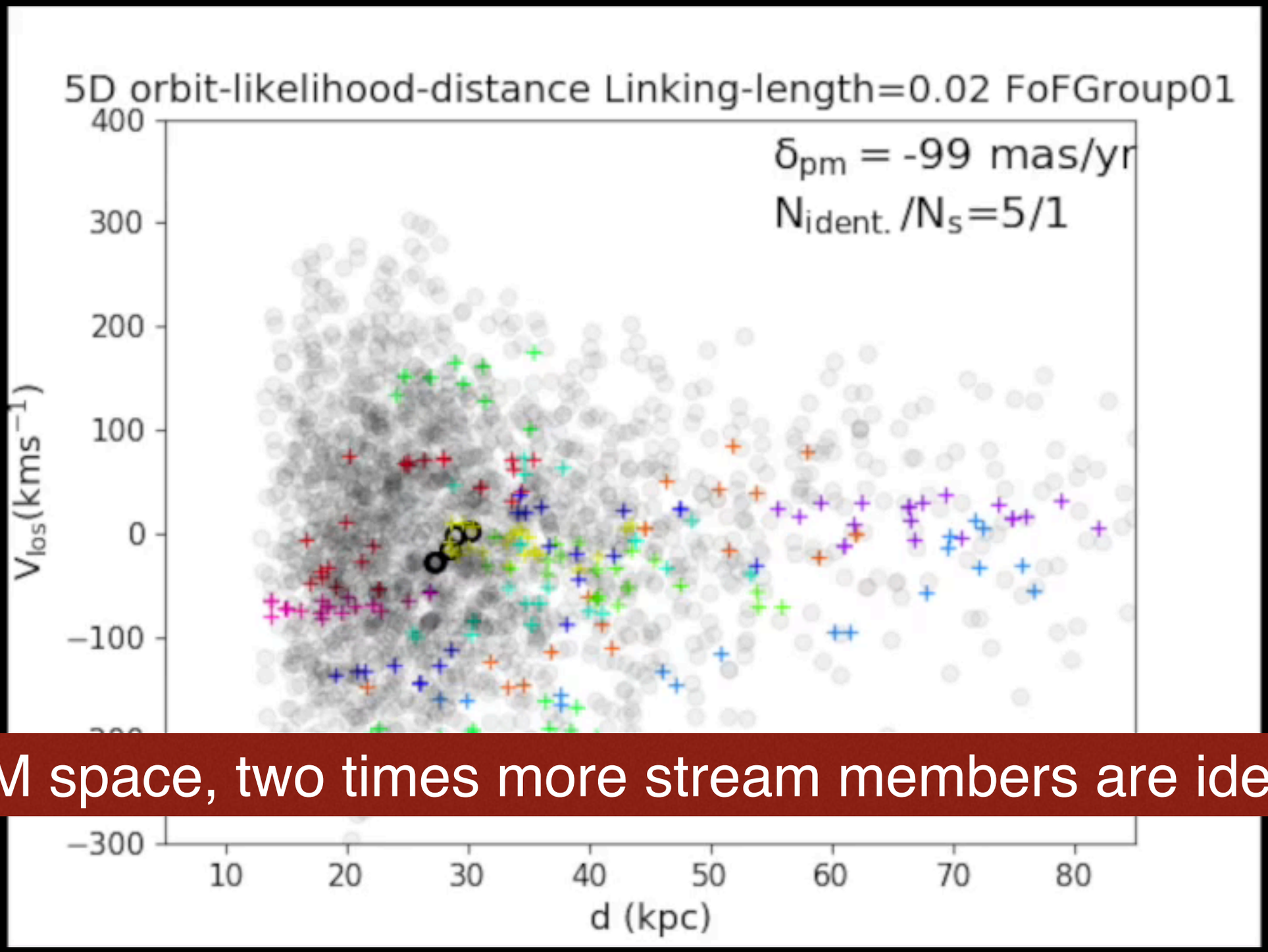
Case I: no proper motions, but only a prior of V_T

identify stream members in 4D velocity-position space



Case I: no proper motions, but only a prior of V_T

identify stream members in I.O.M space



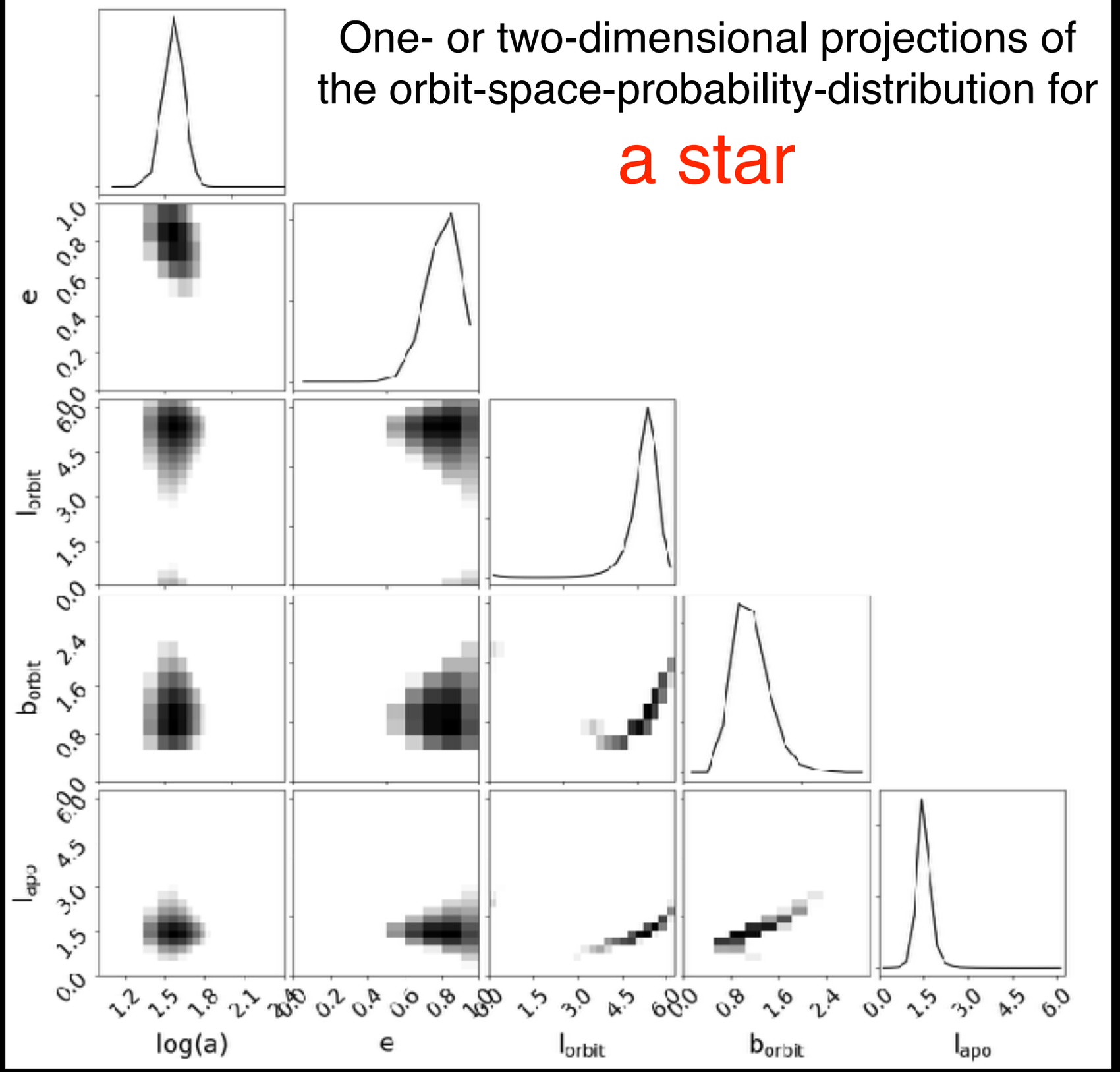
In I.O.M space, two times more stream members are identified!

When Gaia DR2 good proper motions are available for halo stars, what happens?

Case II: With Gaia DR2 proper motions

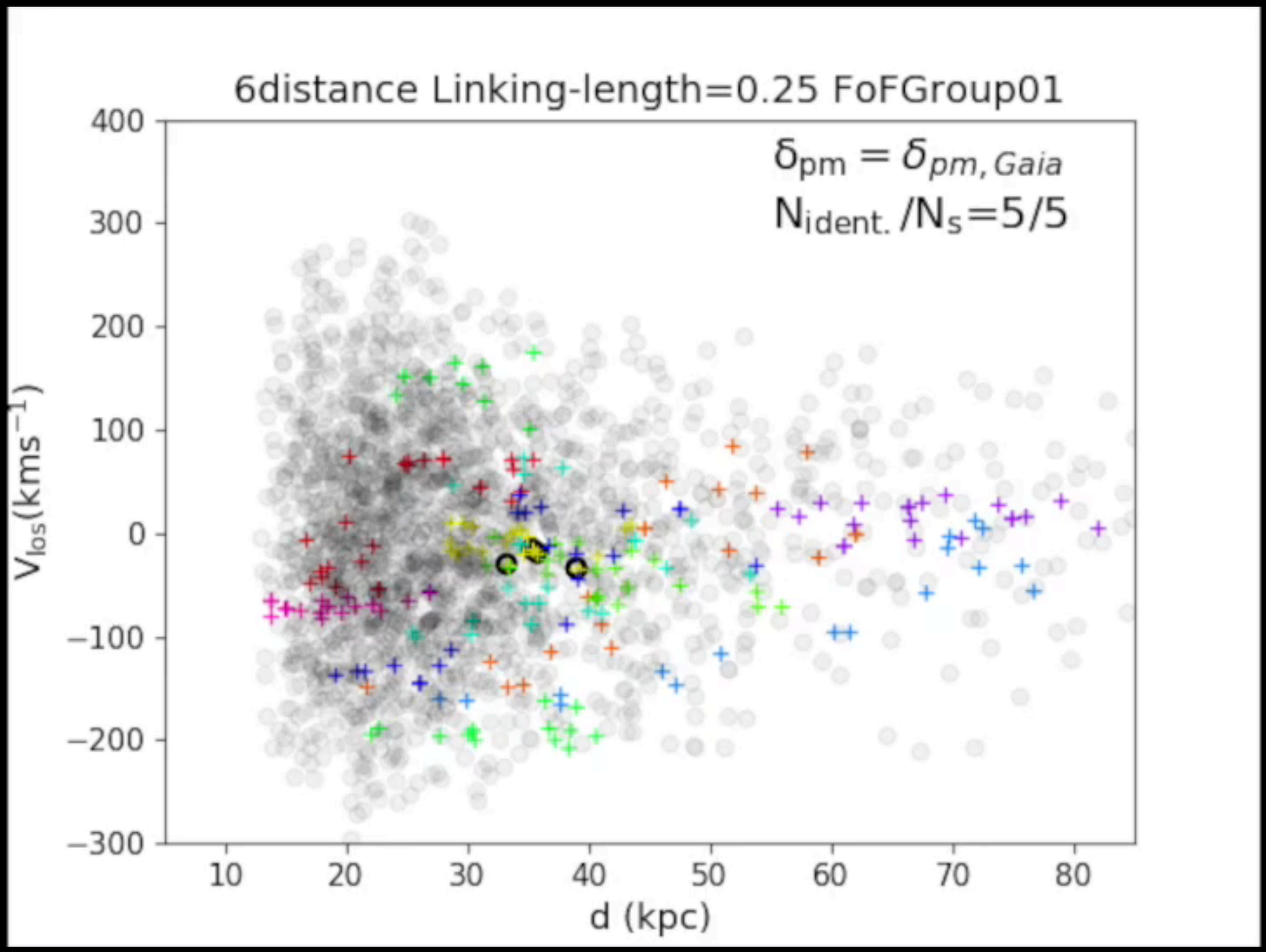
One- or two-dimensional projections of the orbit-space-probability-distribution for

a star



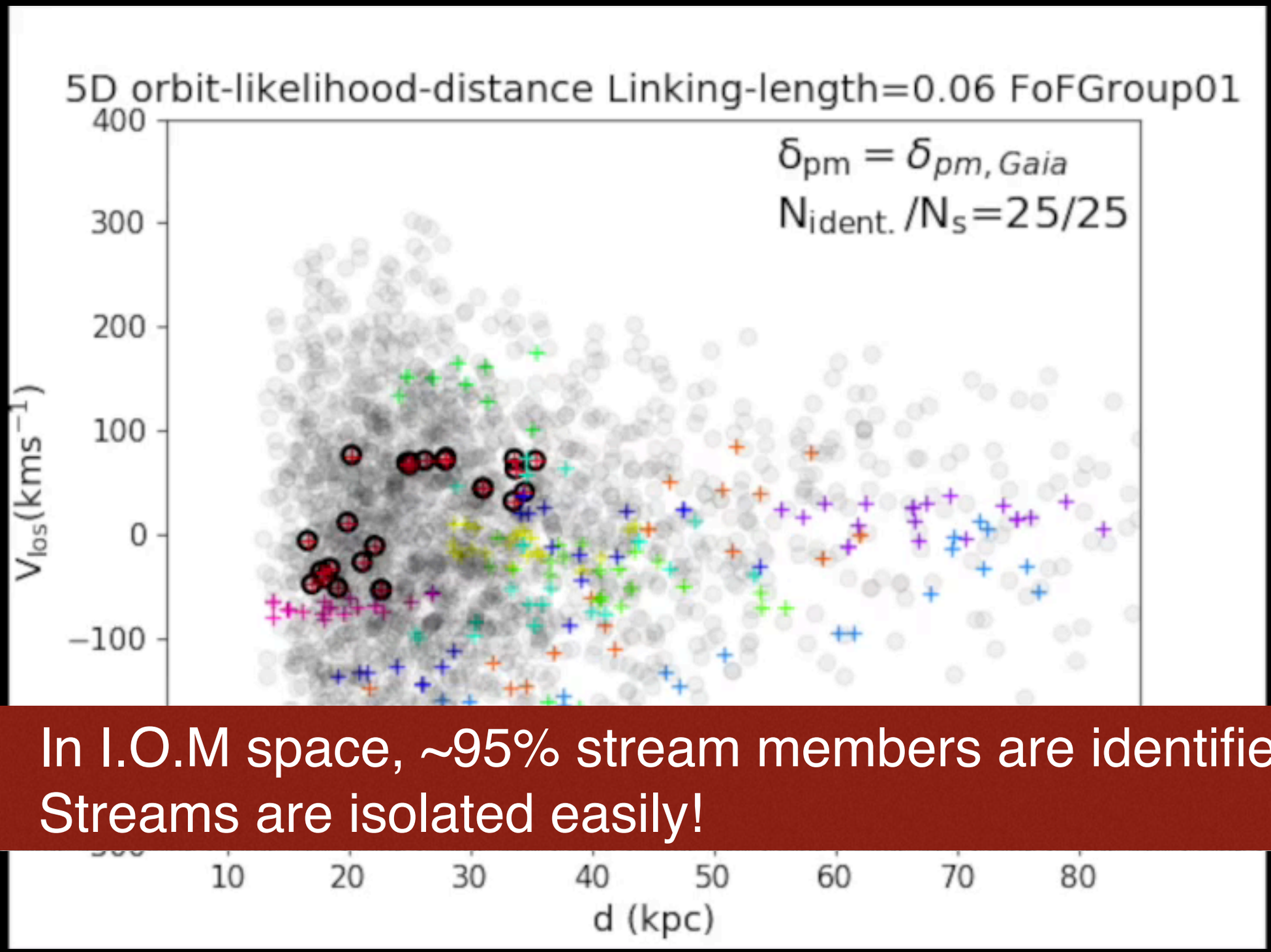
Case II: With Gaia DR2 proper motions

identify stream members in 6D velocity-position space



Case II: With Gaia DR2 proper motions

identify stream members in I.O.M space



- In I.O.M space, ~95% stream members are identified!
- Streams are isolated easily!

Summary

- I.O.M space is the right set of coordinates to identify substructure.
- Gaia’s proper motion will help to identify ~95% of distant stream members. Especially, a stream can be identified as one group.