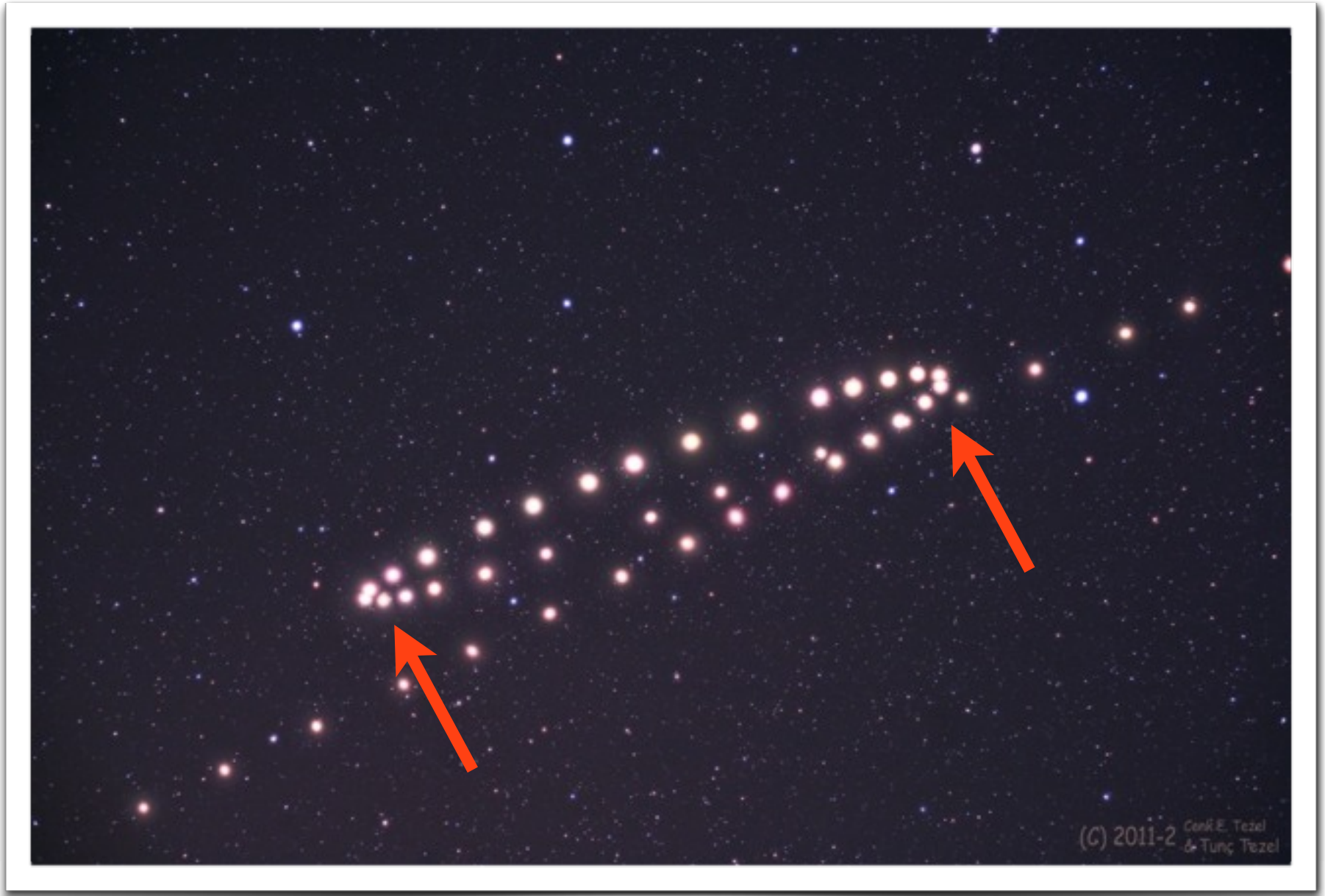
How to weigh the Milky Way using tidal tails of globular clusters

Andreas H.W. Küpper

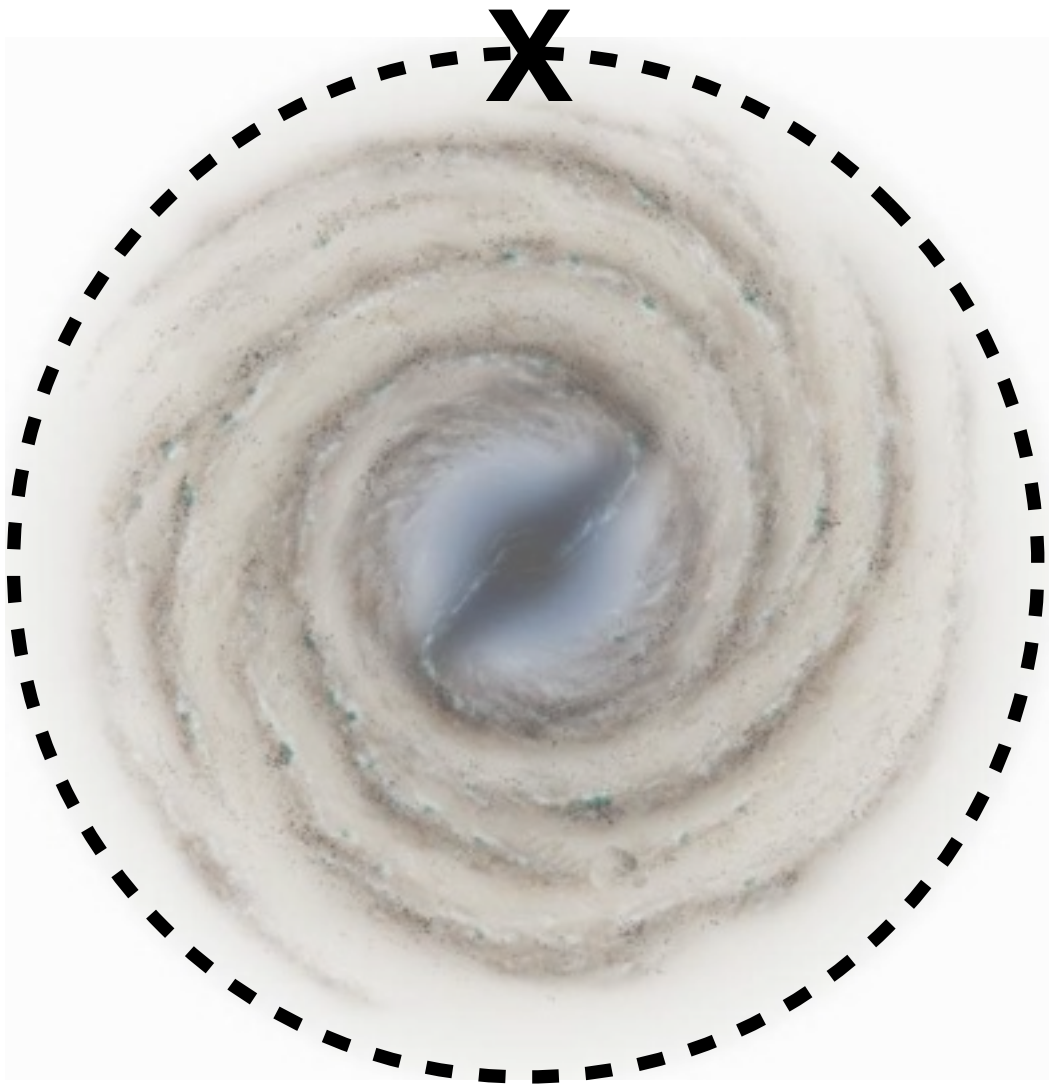
Argelander-
Institut
für
Astronomie

400 years ago people thought that Venus is moving on epicycles around the earth

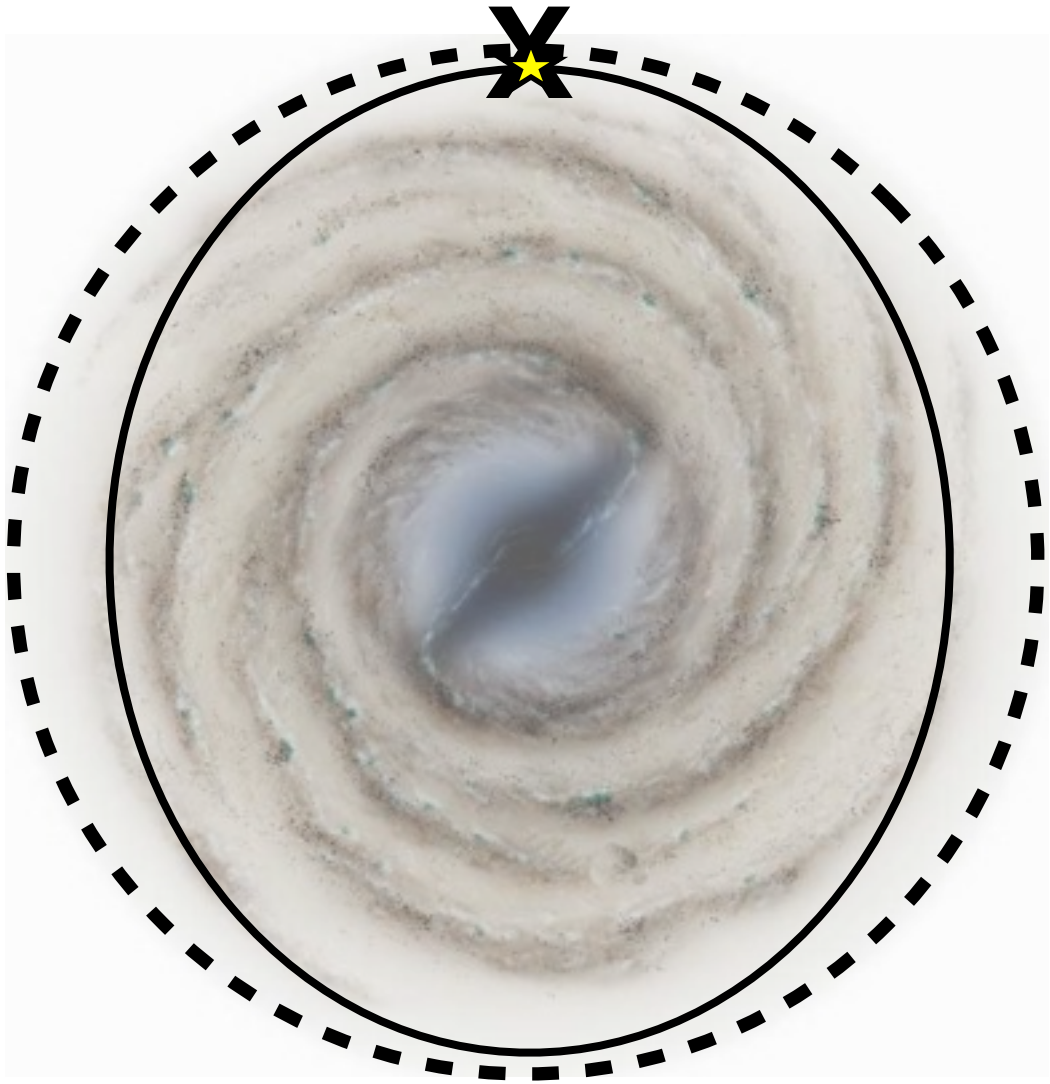
Epicyclic motion causes ‘overdensities‘ and ‘underdensities‘ containing orbital information



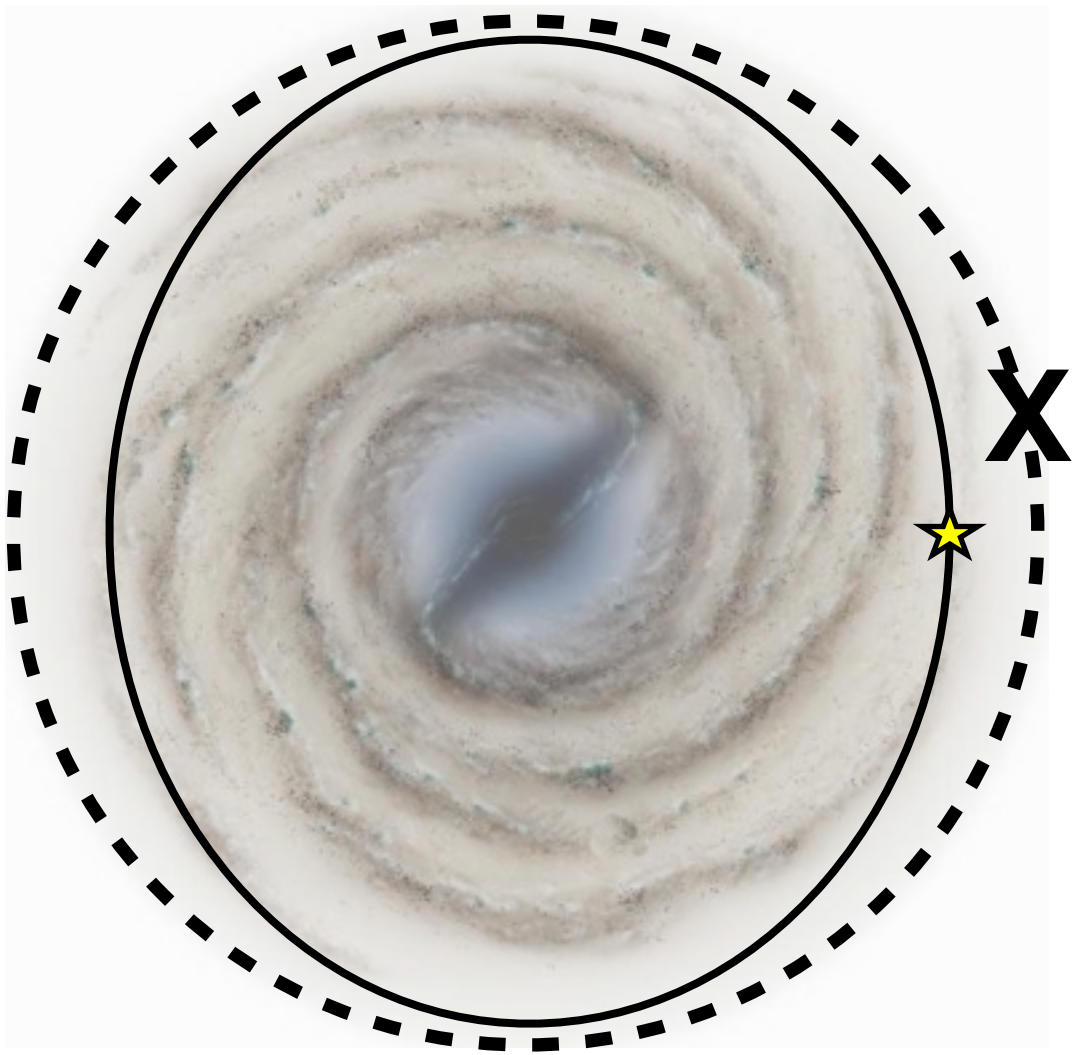
Analogy: consider a star cluster on a circular orbit about a galaxy



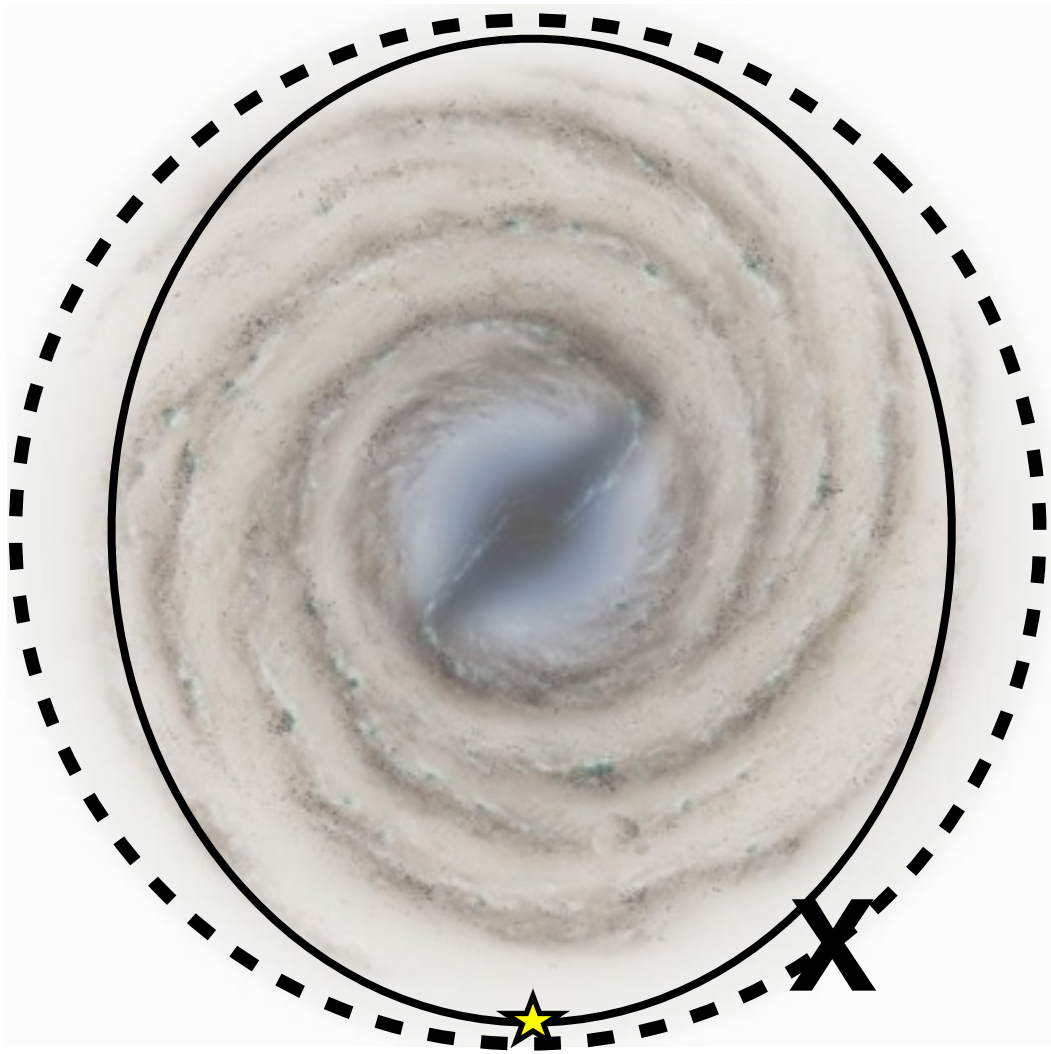
An escaping star with a smaller orbital velocity will be on a slightly eccentric orbit



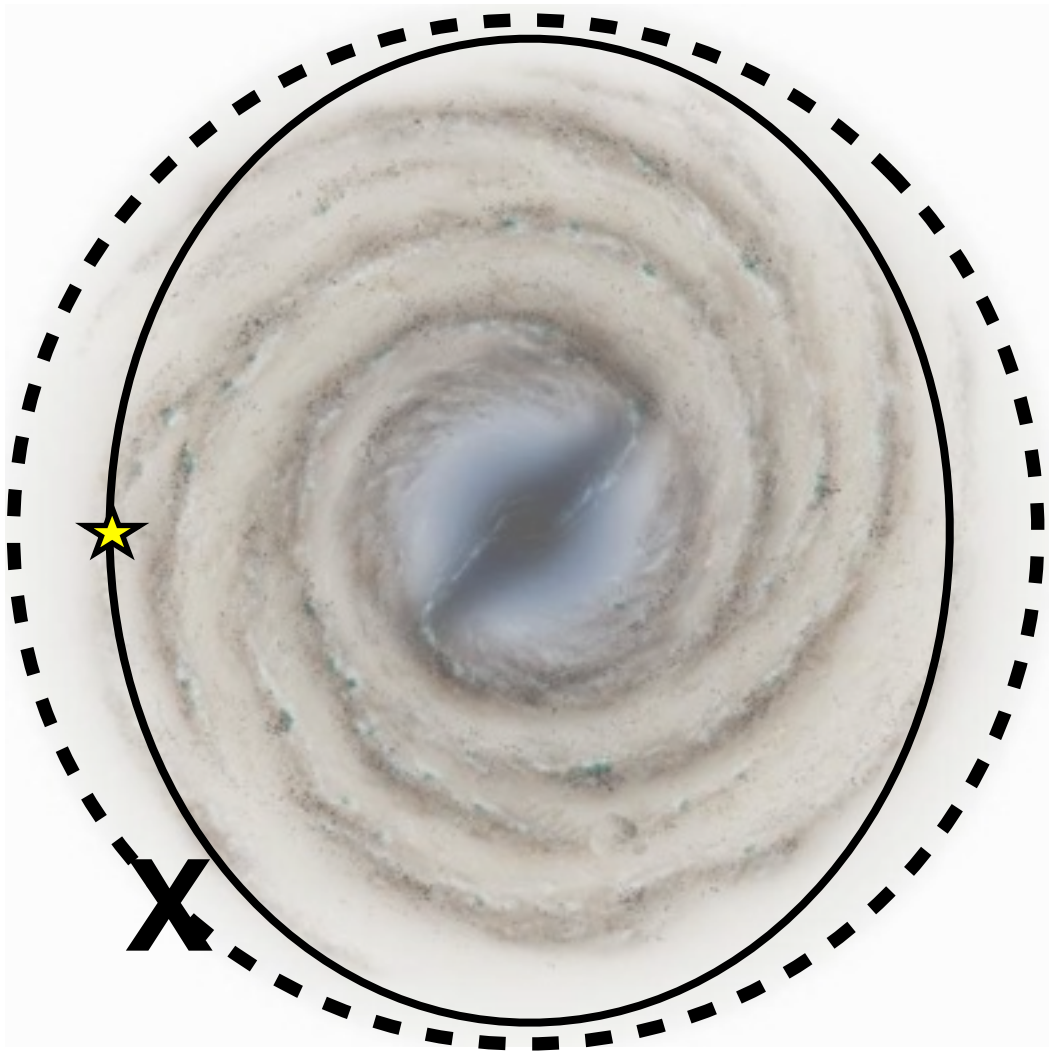
It will move ahead of the cluster and the distance to the cluster orbit will vary periodically



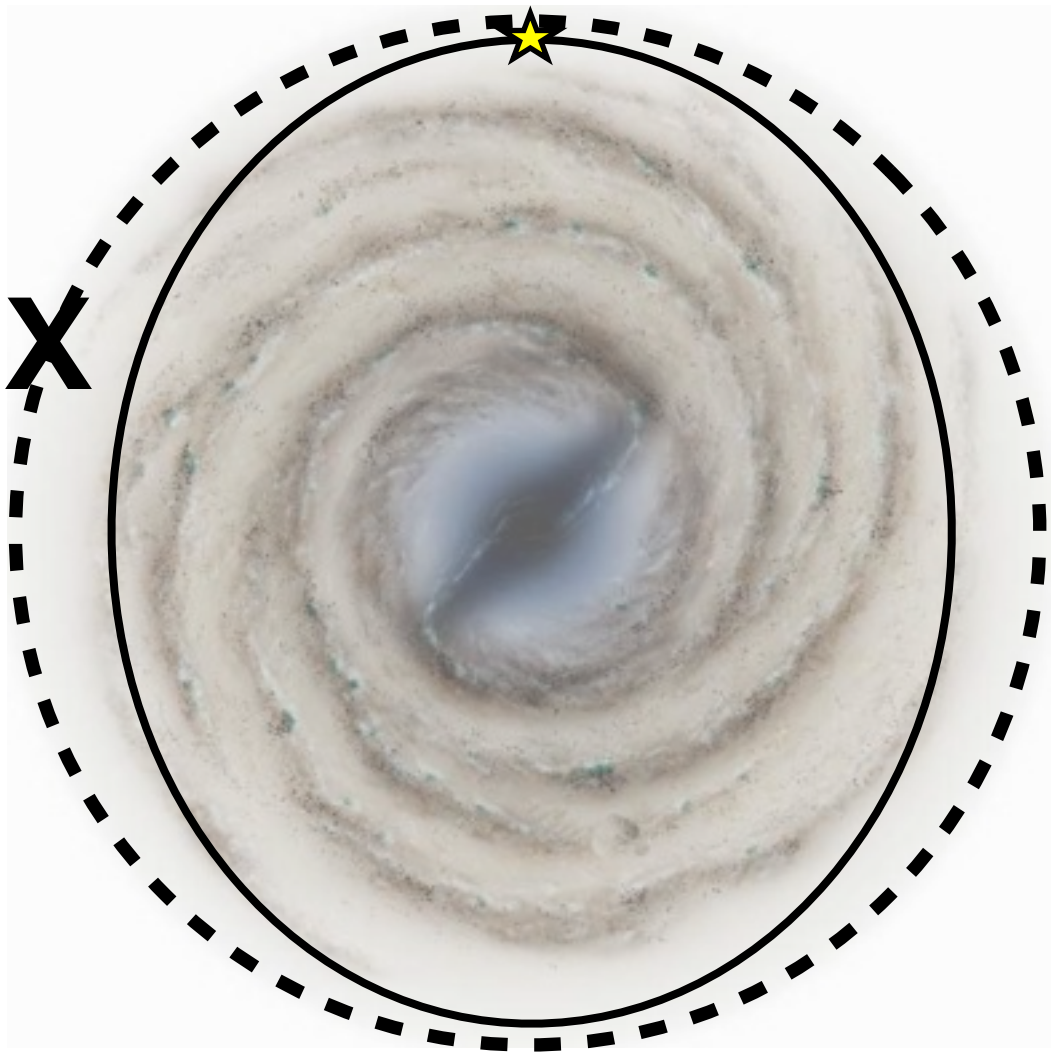
It will move ahead of the cluster and the distance to the cluster orbit will vary periodically



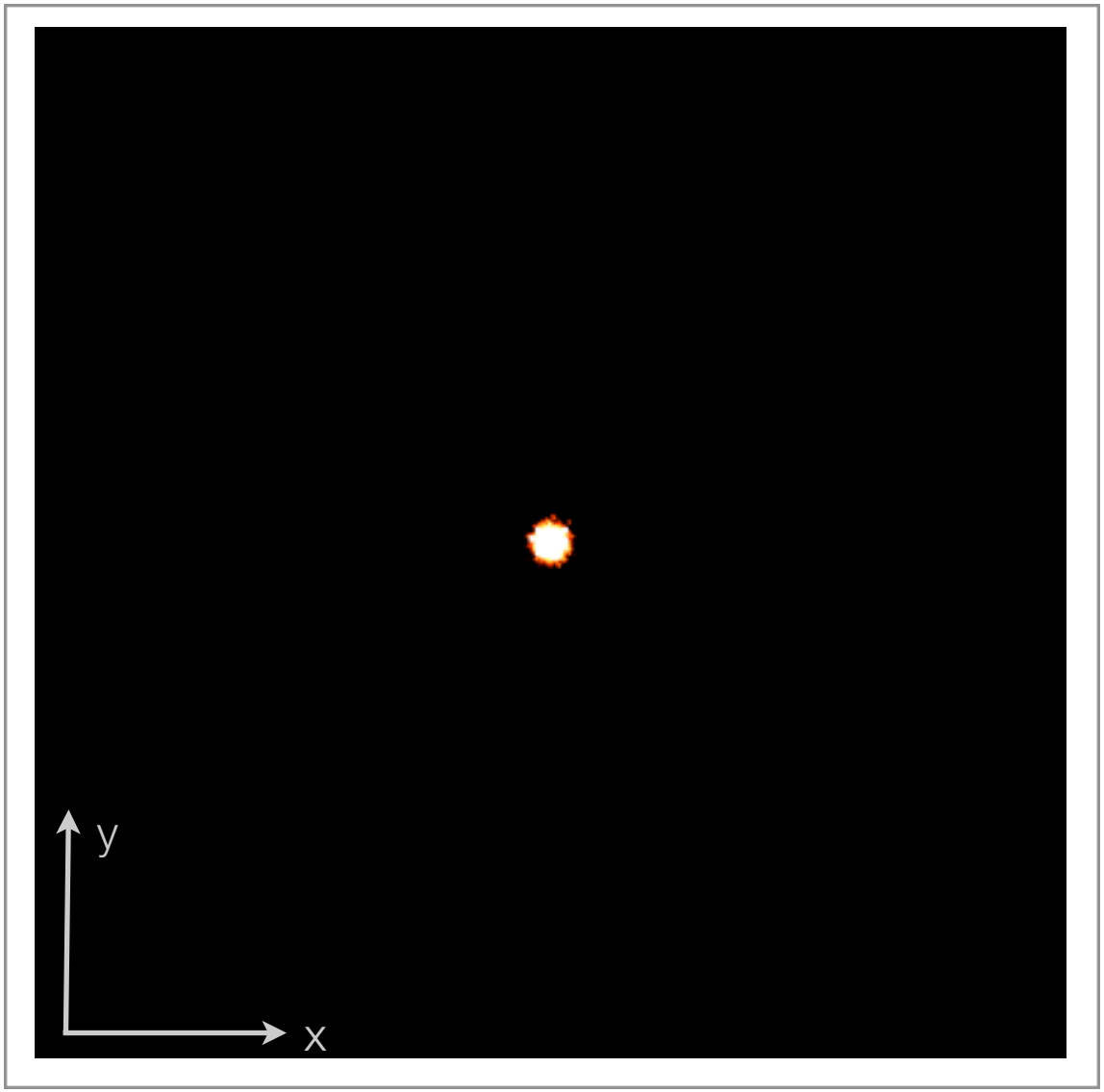
It will move ahead of the cluster and the distance to the cluster orbit will vary periodically



It will move ahead of the cluster and the distance to the cluster orbit will vary periodically

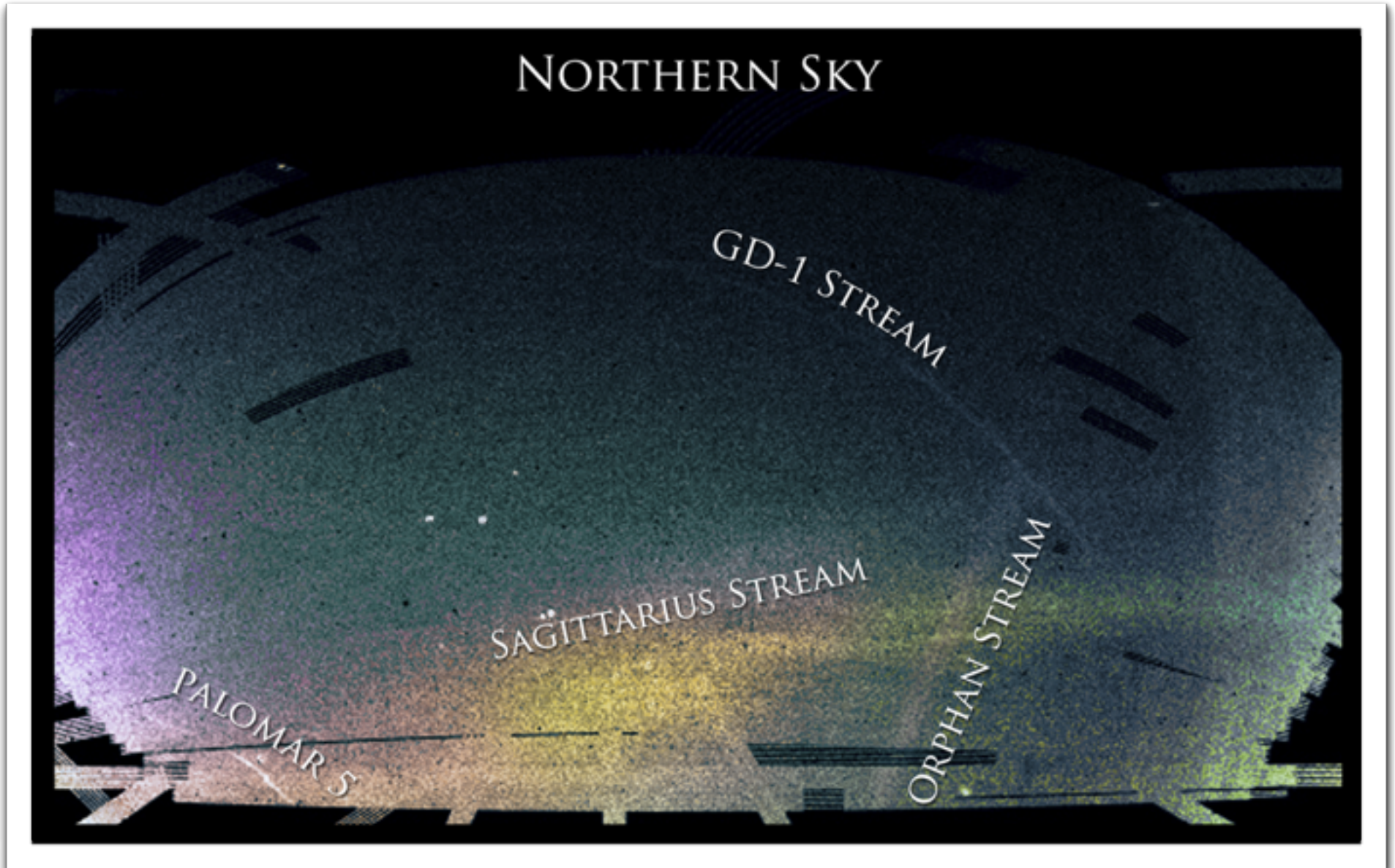


Star clusters produce a continuous stream of stars while they dissolve



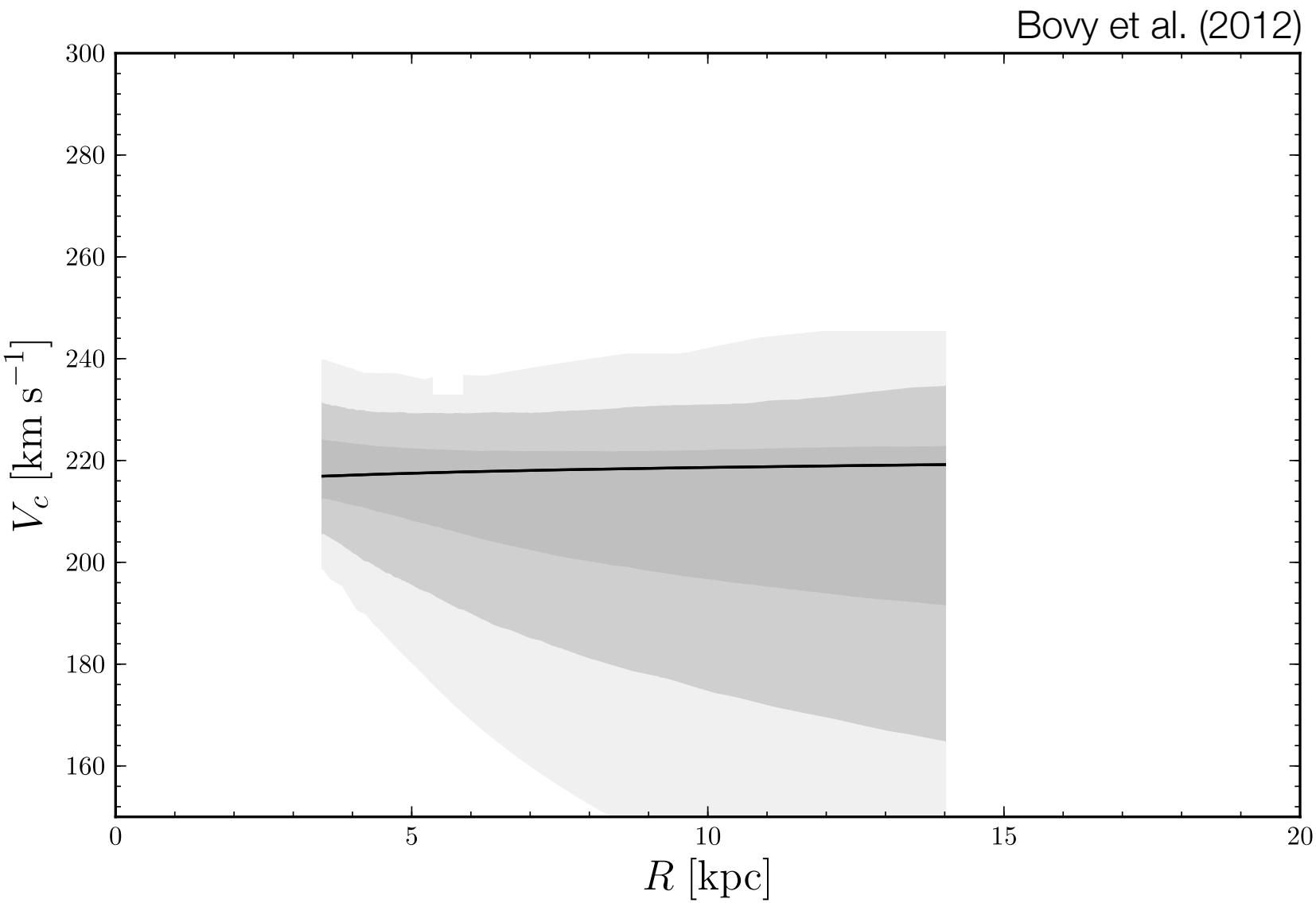
Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

The Milky Way halo is full of stellar substructure from dissolving Galactic satellites

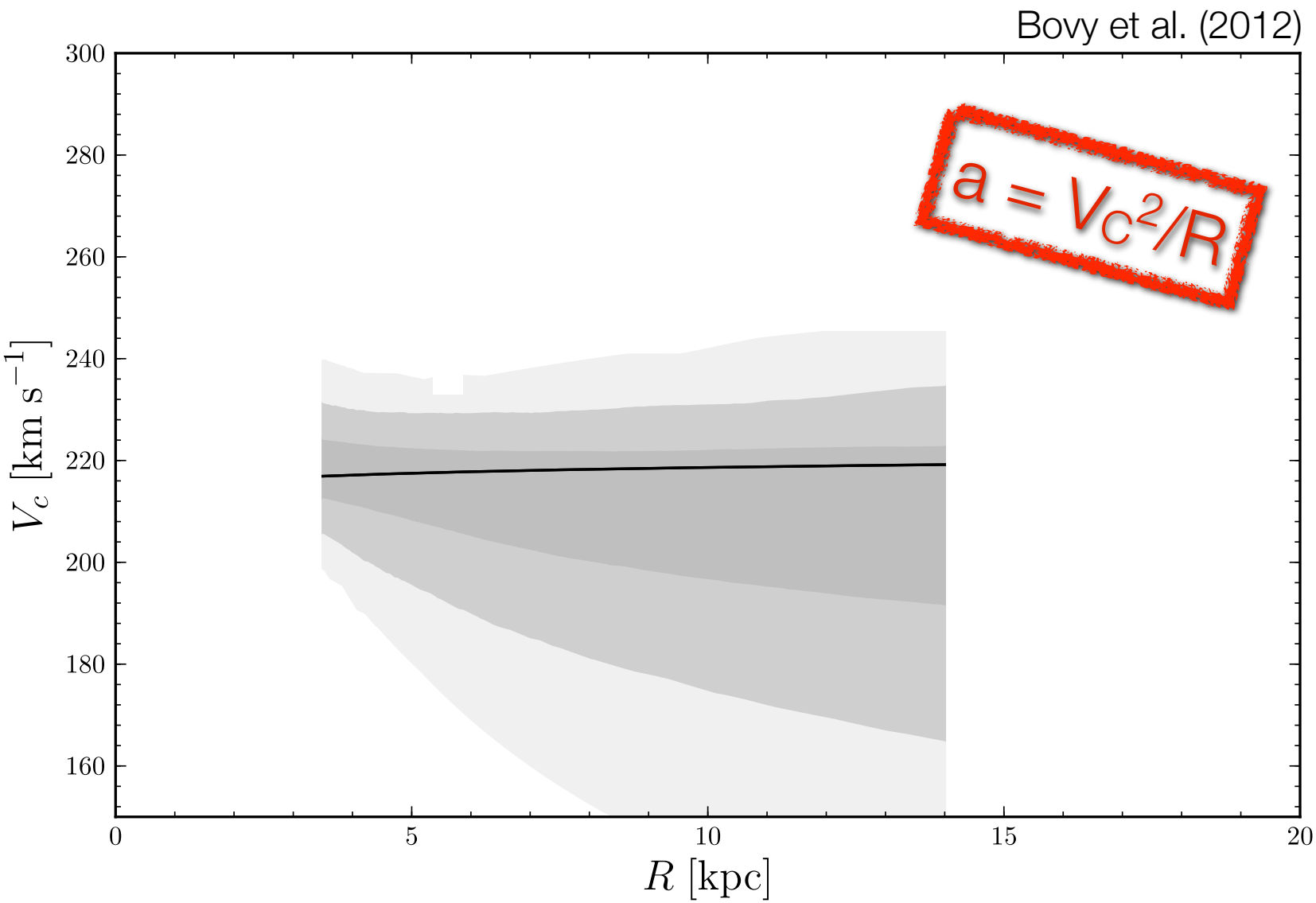


Bonaca, Giguere & Geha (2012)

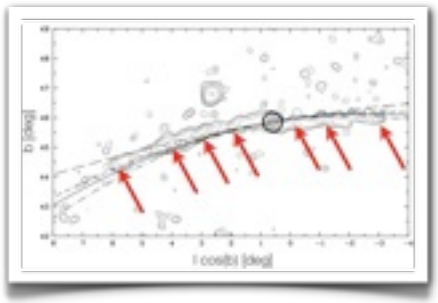
Within the Galactic disk the circular velocity appears to be constant at about 220 km/s



Within the Galactic disk the circular velocity appears to be constant at about 220 km/s

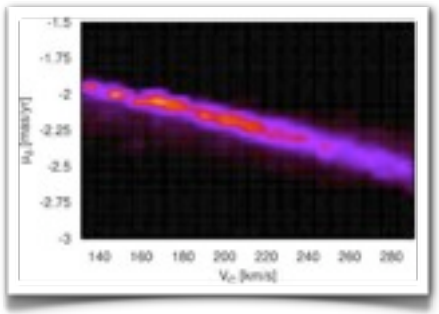


How can we weigh the Milky Way using tidal tails of globular clusters?



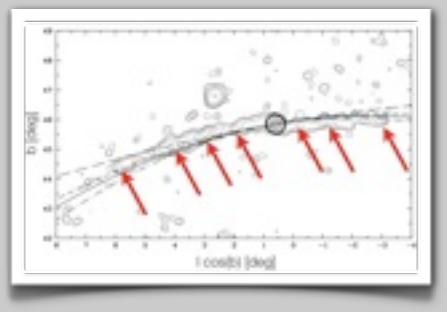
The tidal tails of Palomar 5

Streaklines - a concept from continuum mechanics



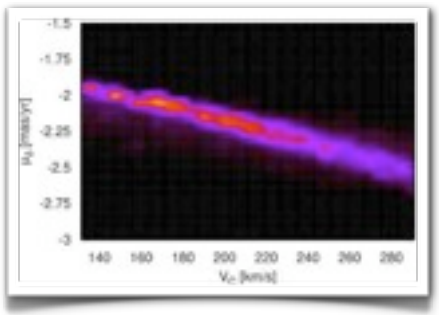
Extracting Palomar 5‘s orbit using streaklines

How can we weigh the Milky Way using tidal tails of globular clusters?



The tidal tails of Palomar 5

Streaklines - a concept from continuum mechanics

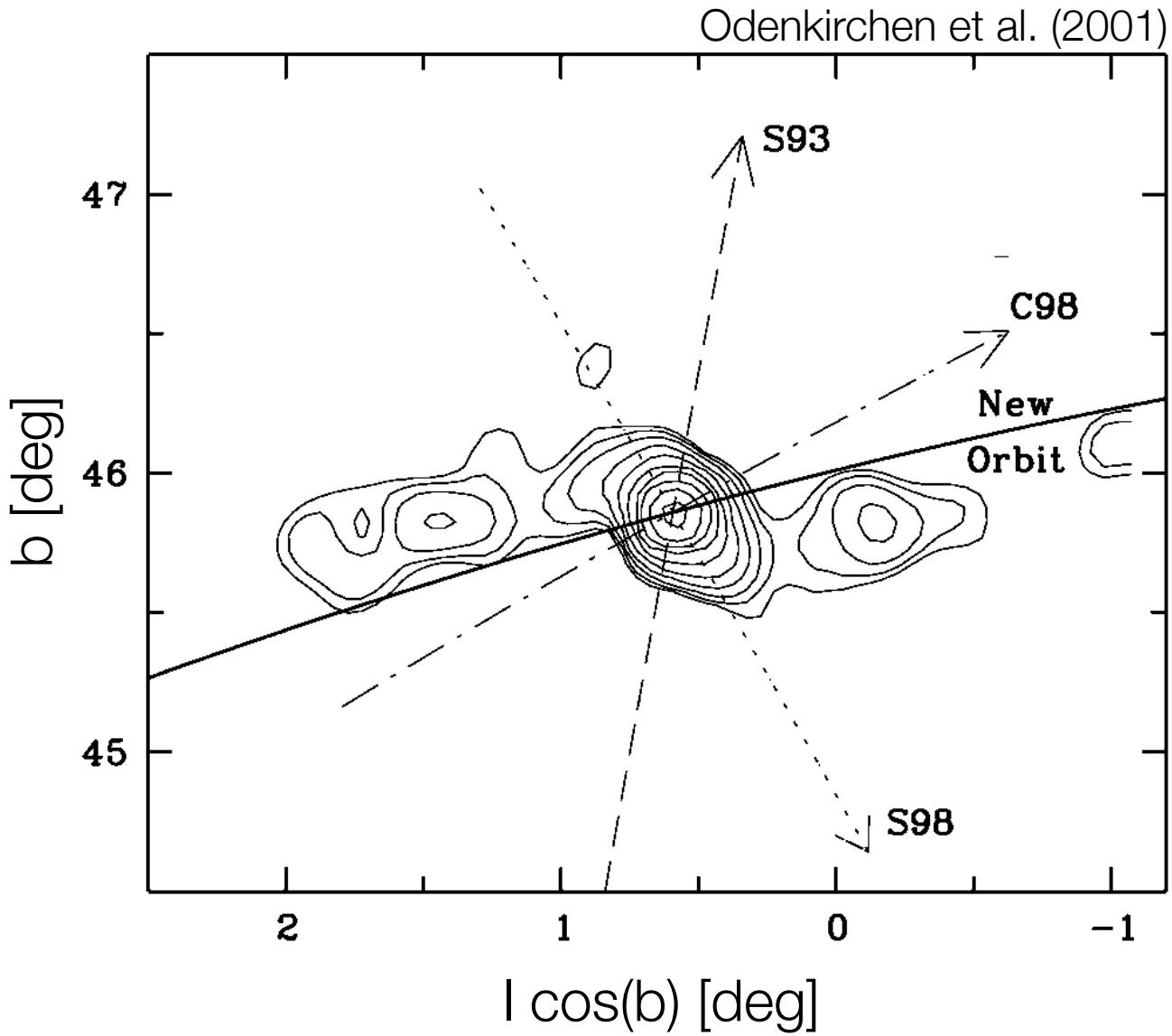


Extracting Palomar 5‘s orbit using streaklines

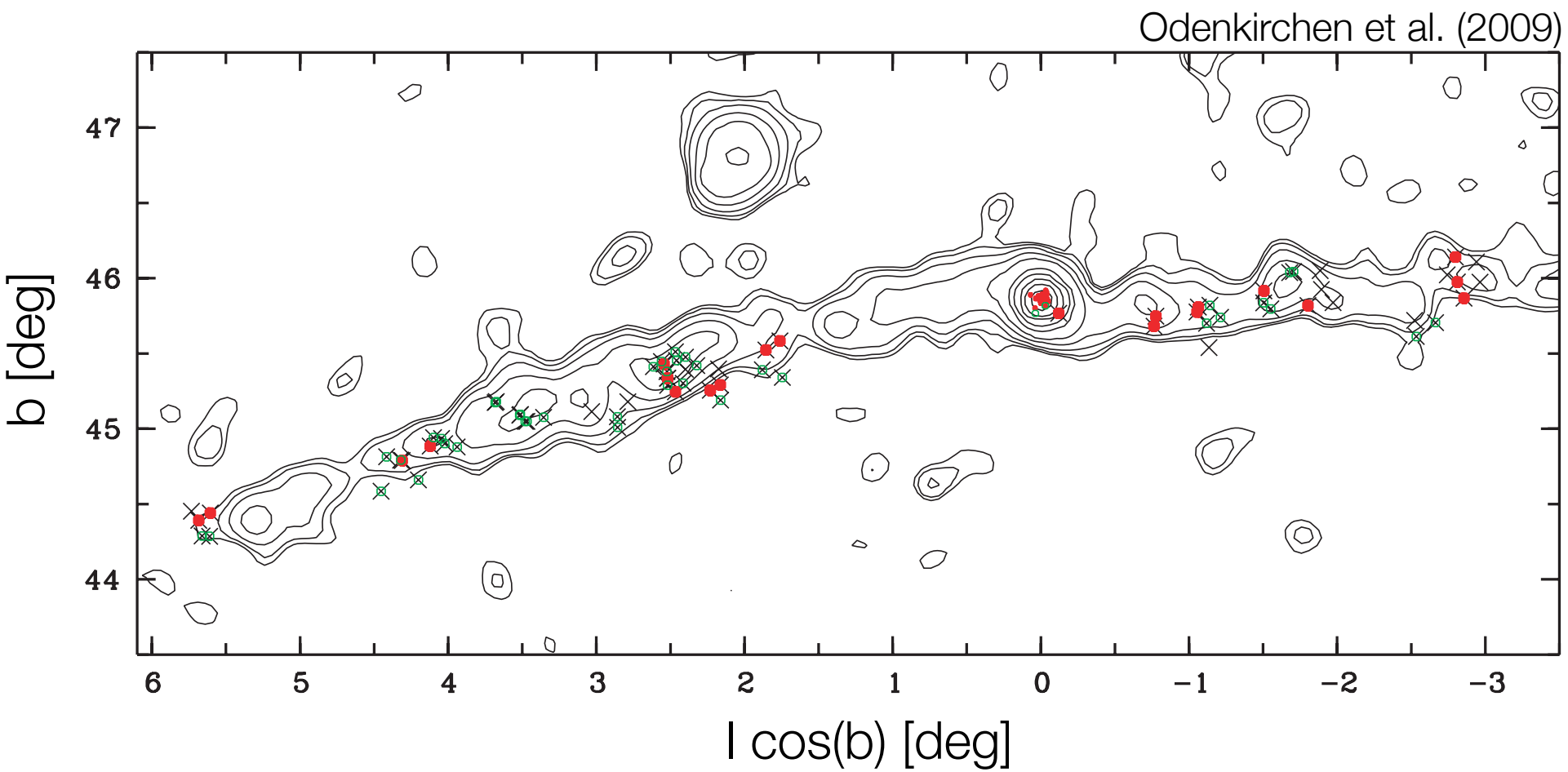
Palomar 5 is a low-mass, low-density clusters in the halo of the Milky Way high above the Galactic disk

- M_V = -5.17 mag
- central density: 1 star/pc^2
- R_{sun} = 23.5 kpc
- R_{GC} = 18.6 kpc, z =16.9 kpc
- extremely depleted in low-mass stars

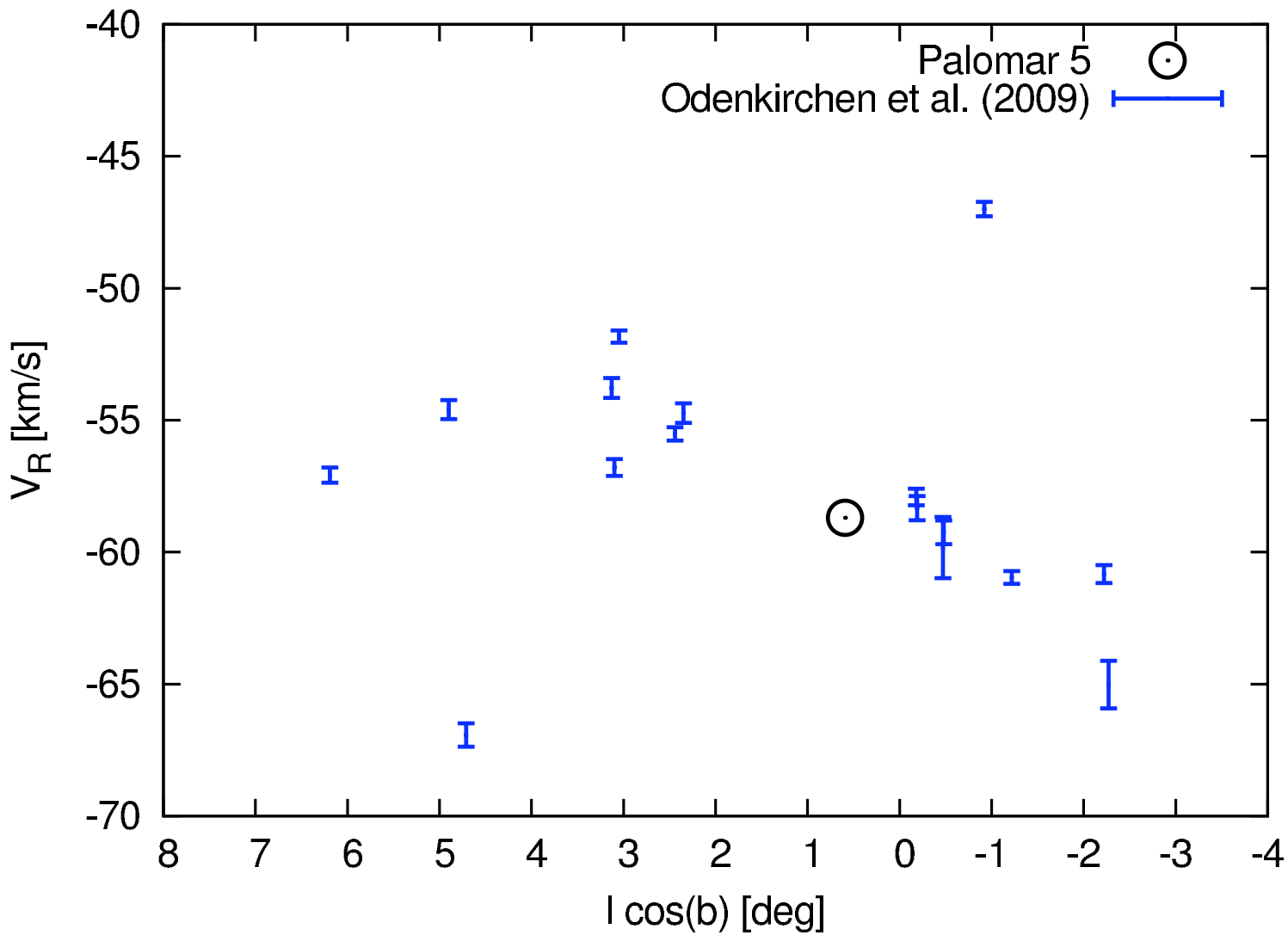
Palomar 5‘s tidal tails constrain its tangential motion on the sky



Radial velocities constrain one additional component of its orbit

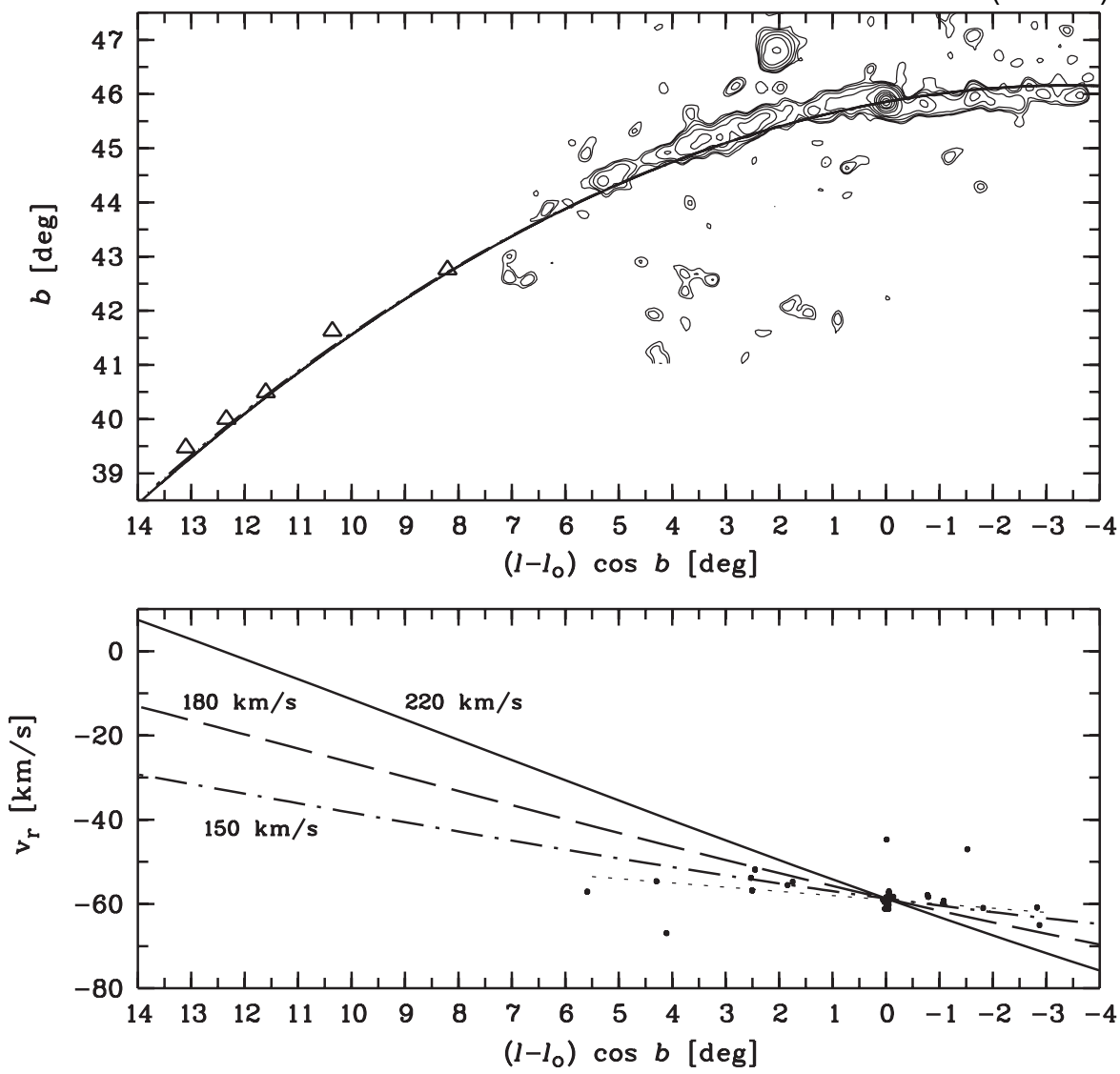


Yet, the velocity gradient is not well constrained



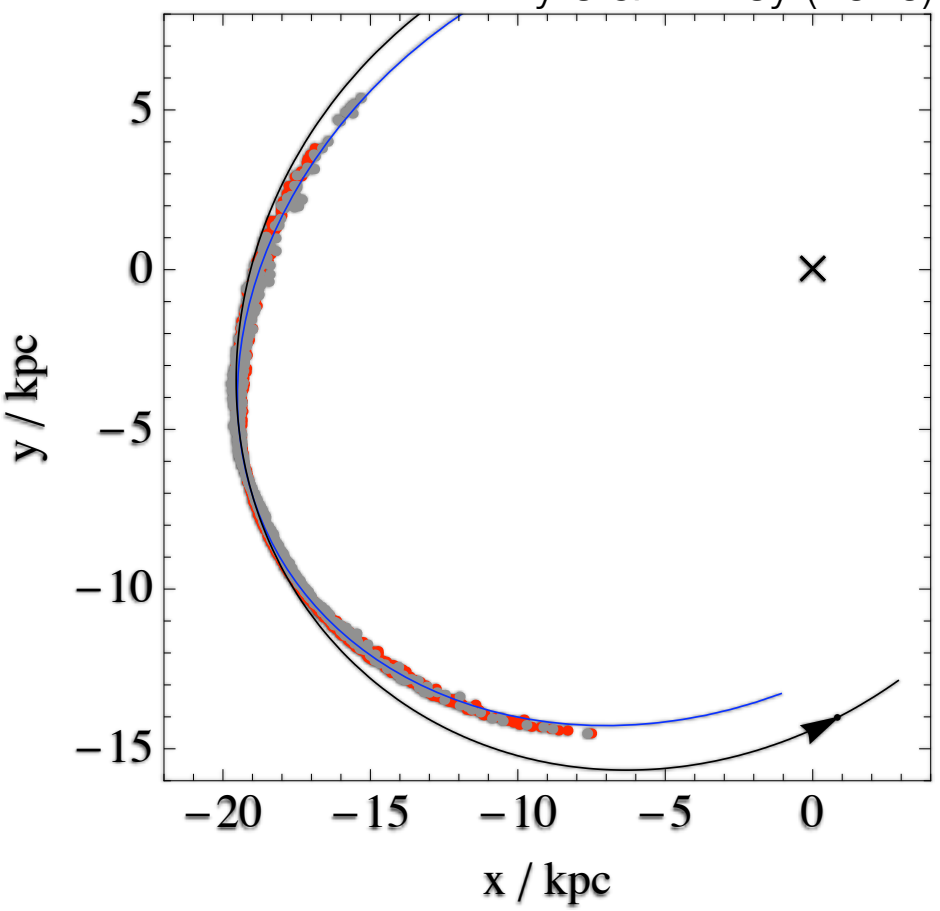
There are many orbital solutions. Radial velocites may help to brake the degeneracy...

Odenkirchen et al. (2009)

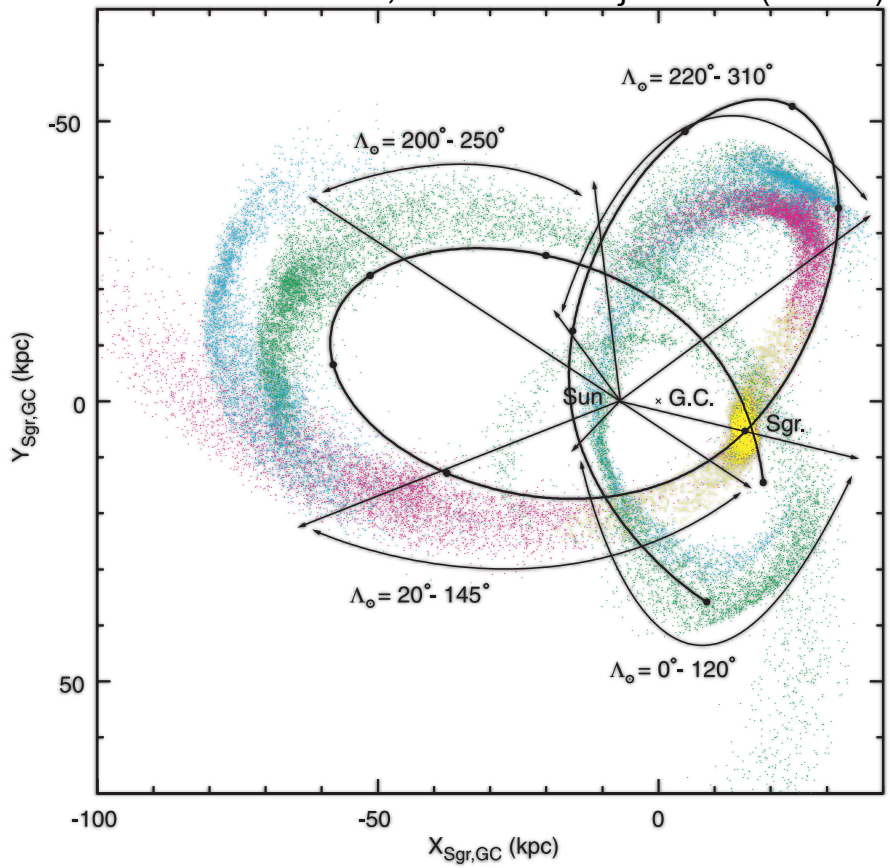


...but it is not straightforward to model the radial gradient and offset from the cluster orbit correctly

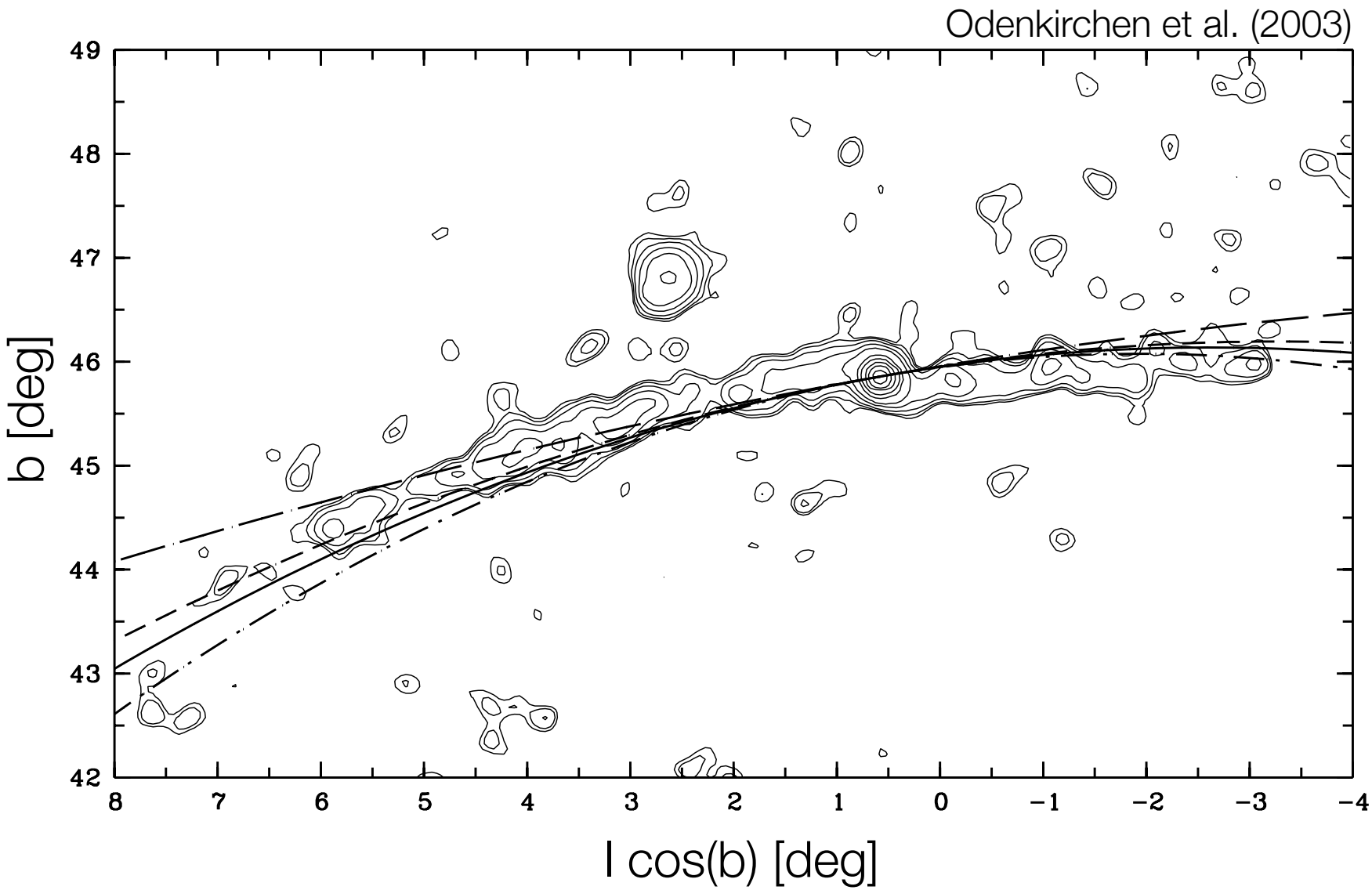
Eyre & Binney (2010)



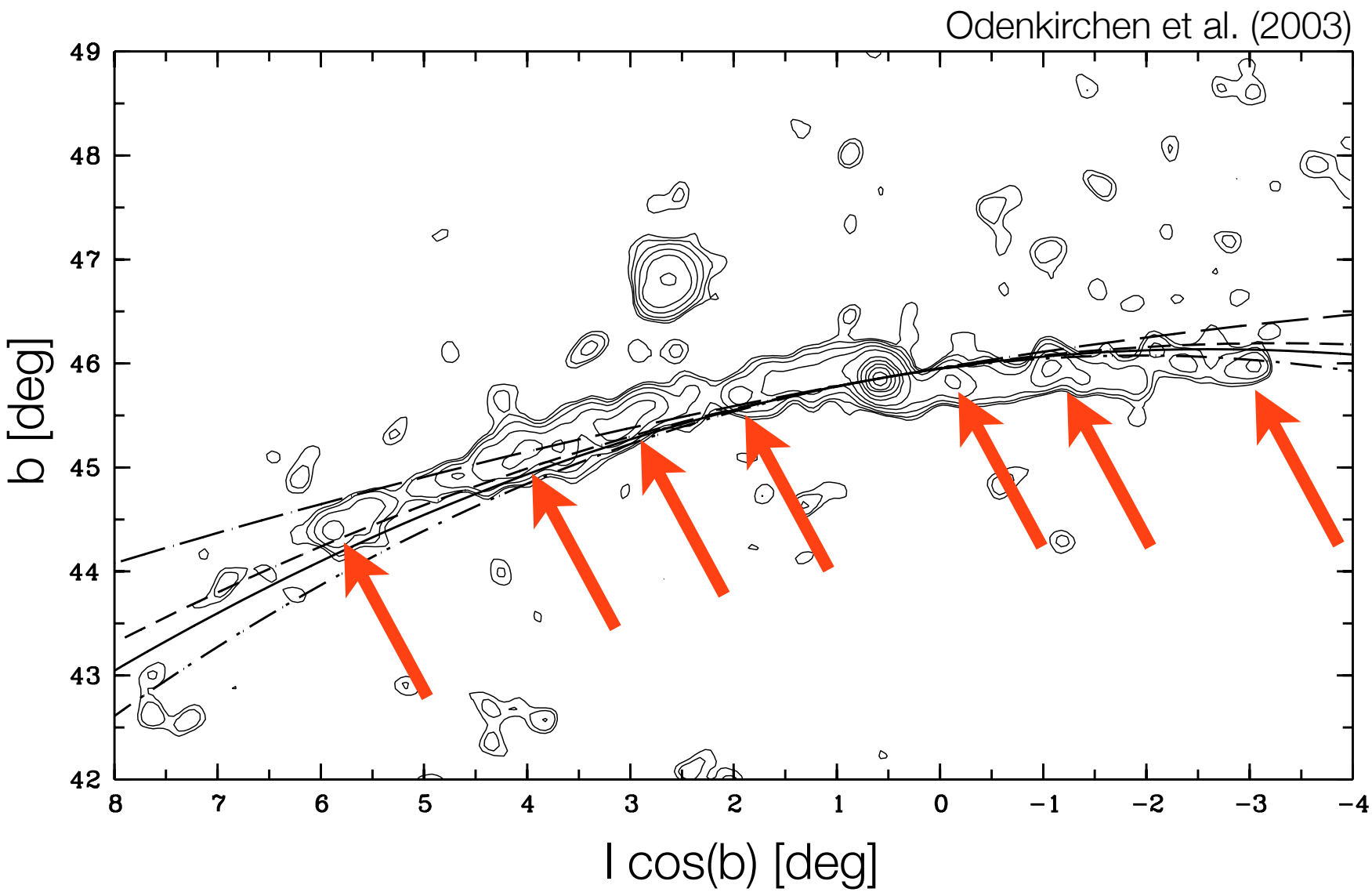
Johnston, Law & Majewski (2005)



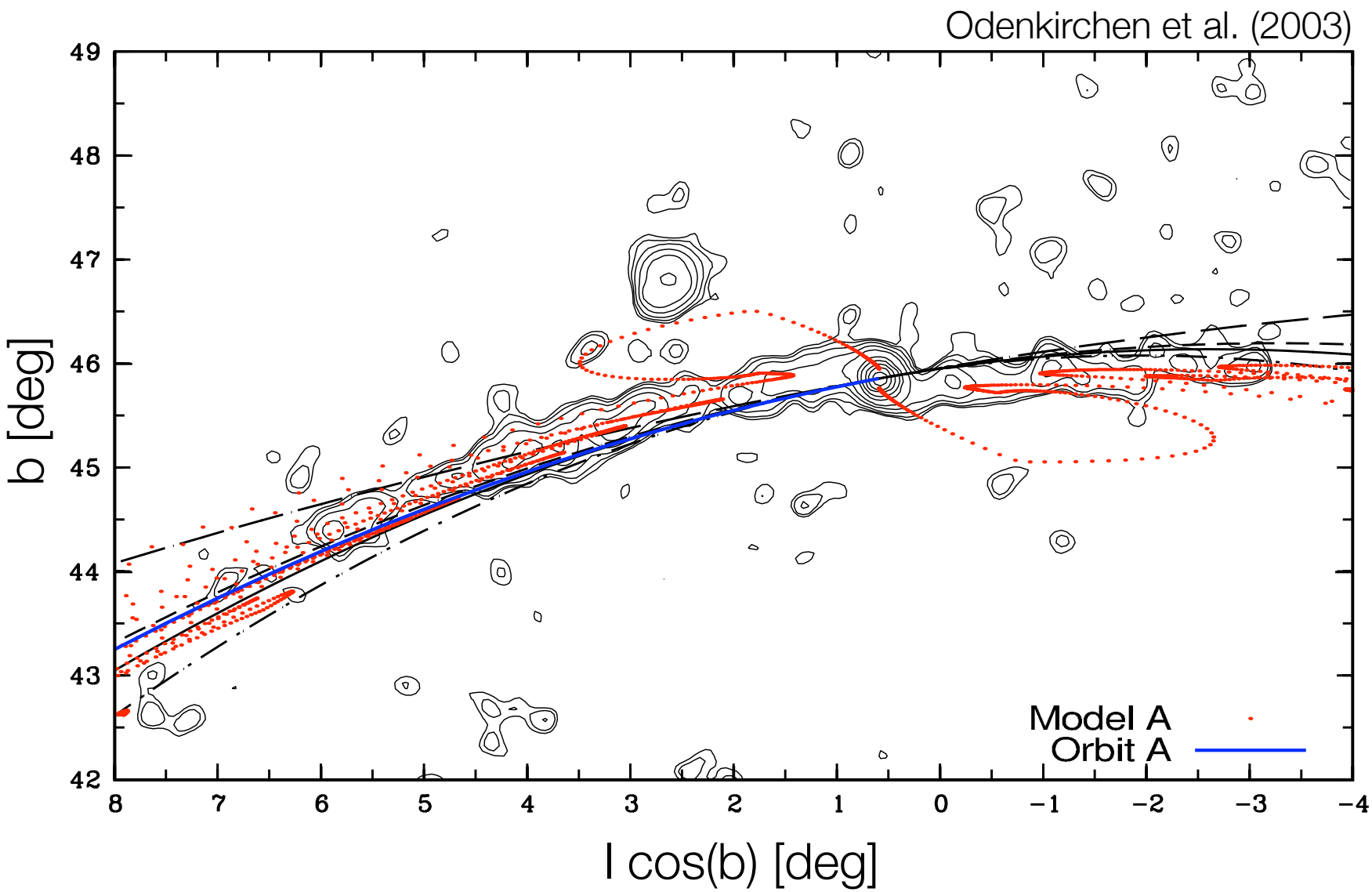
Palomar 5‘s tidal tails show epicyclic overdensities which contain additional orbital information



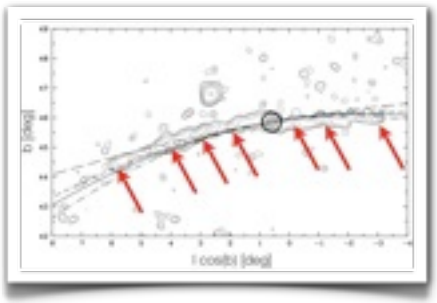
Palomar 5‘s tidal tails show epicyclic overdensities which contain additional orbital information



We found an orbital solution that reproduces all observational constraints

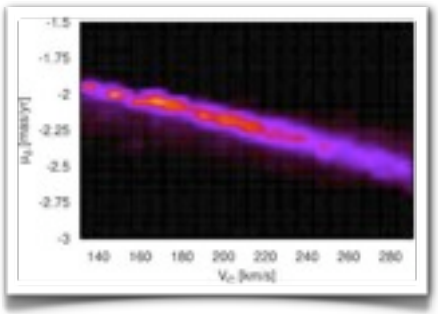


How can we weigh the Milky Way using tidal tails of globular clusters?



The tidal tails of Palomar 5

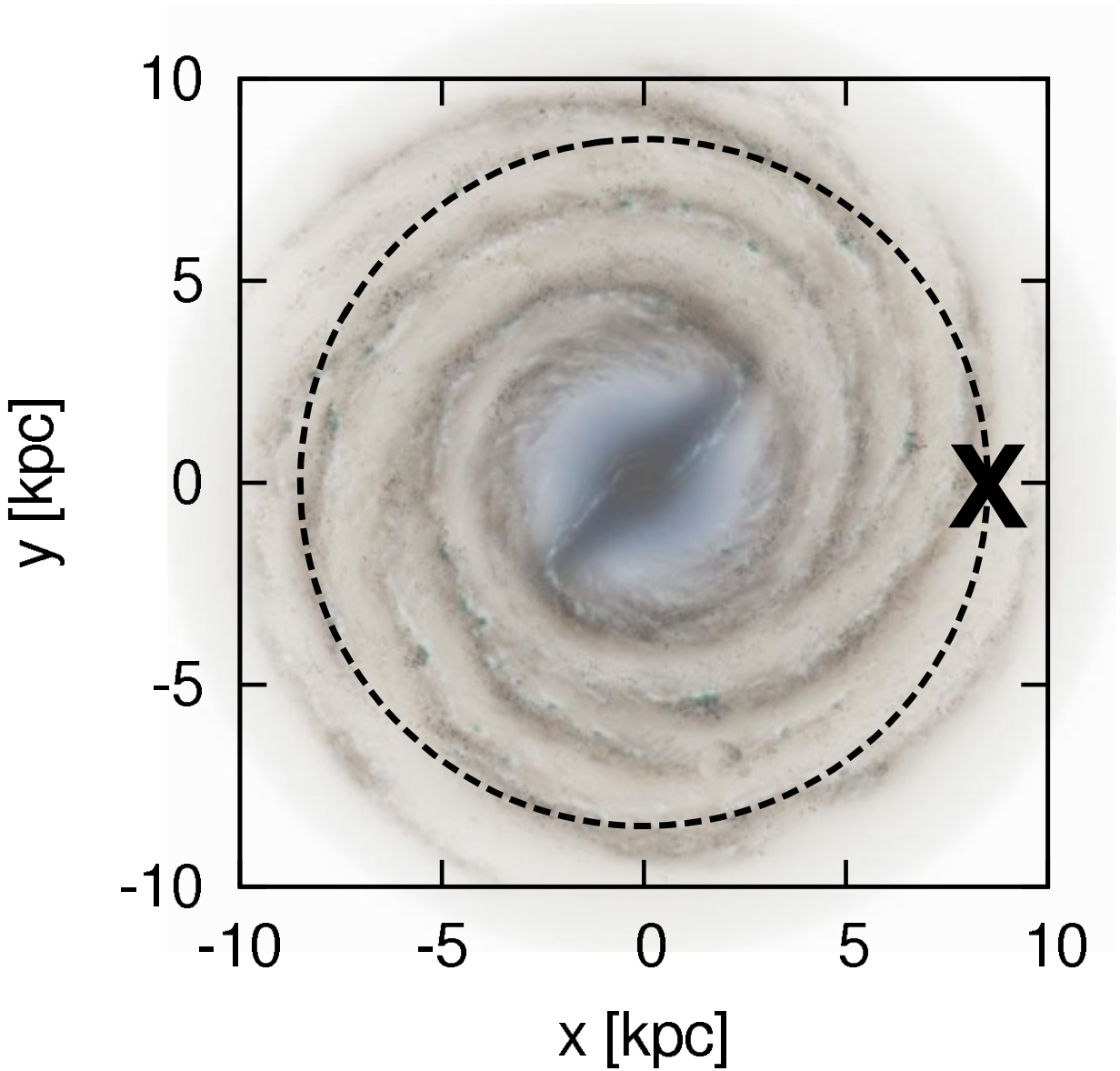
Streaklines - a concept from continuum mechanics



Extracting Palomar 5‘s orbit using streaklines

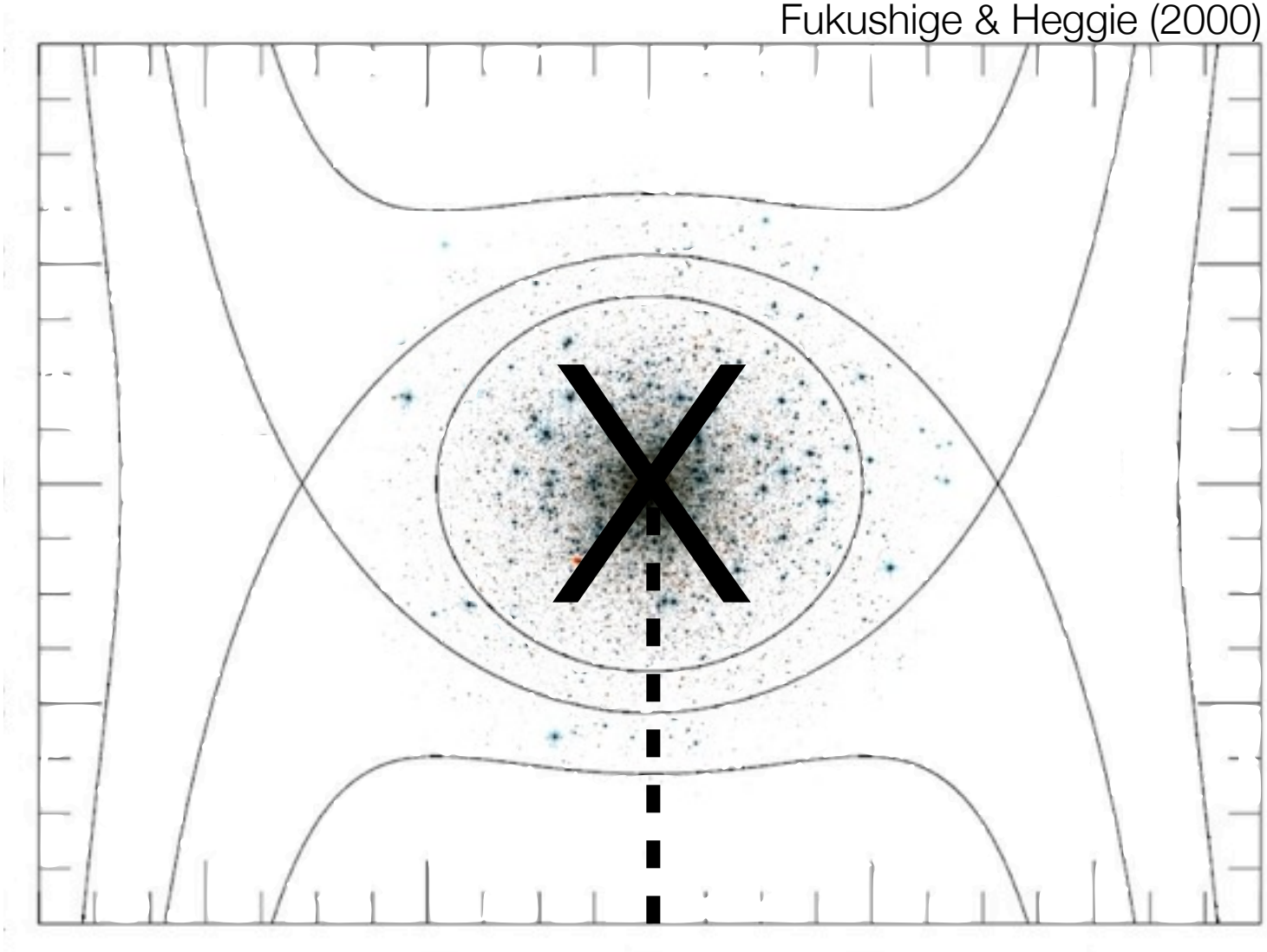
Streaklines or streamlines are often used to visualise the flow of air or water around an object

We can use this concept for studying trajectories of escaping stars within tidal tails

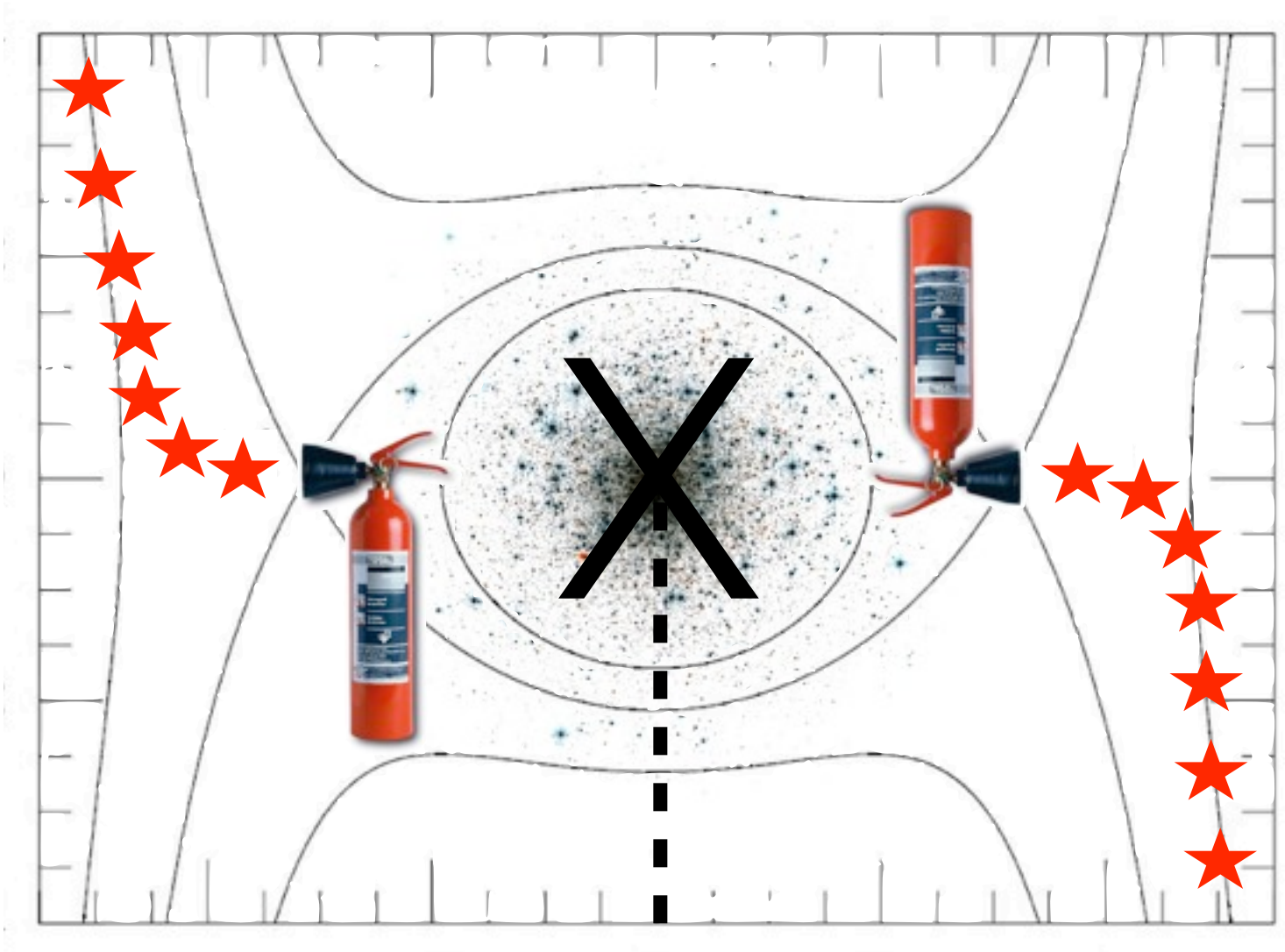


Stars escape from a cluster through the Lagrange points into the tidal tails

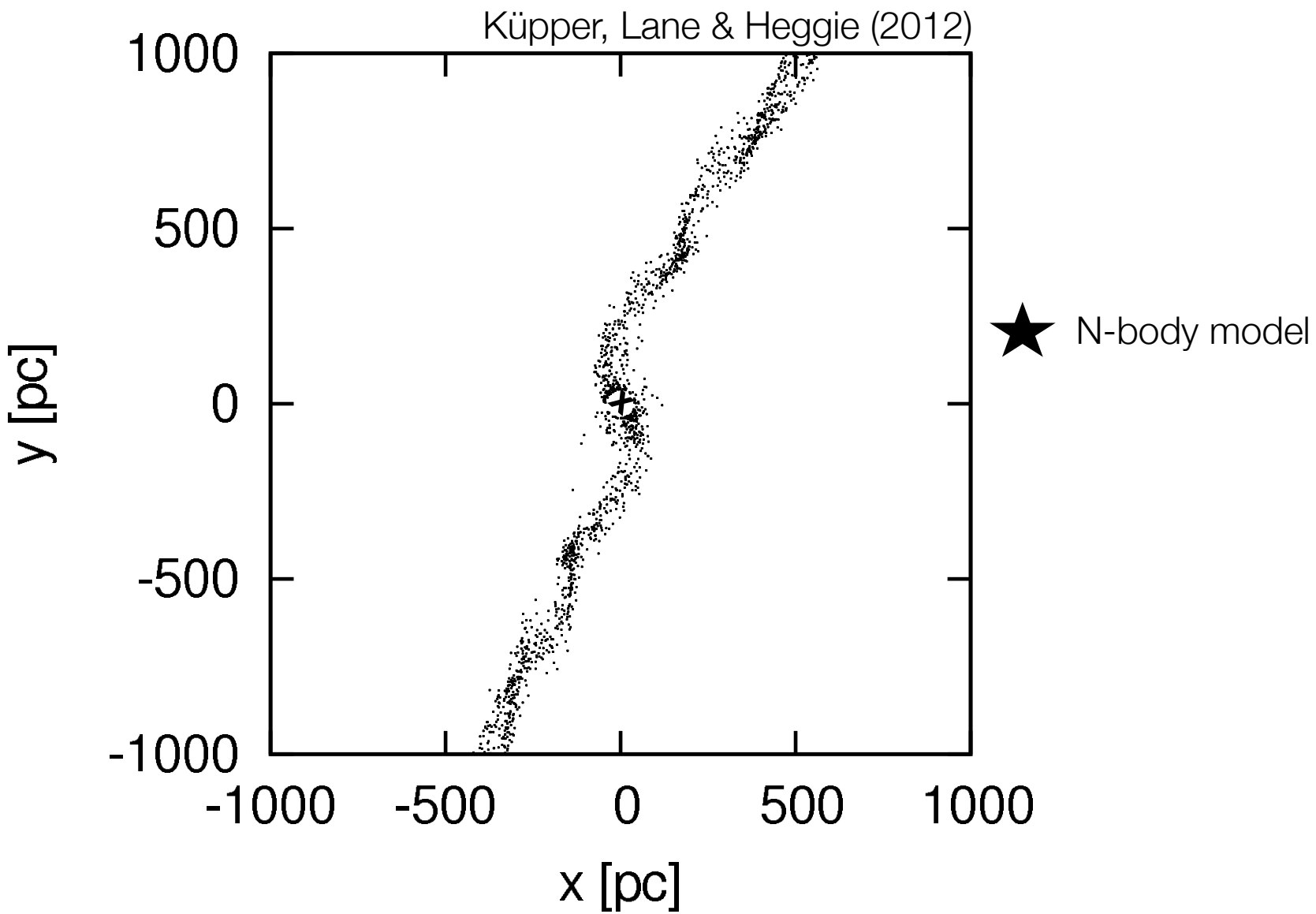
Fukushige & Heggie (2000)



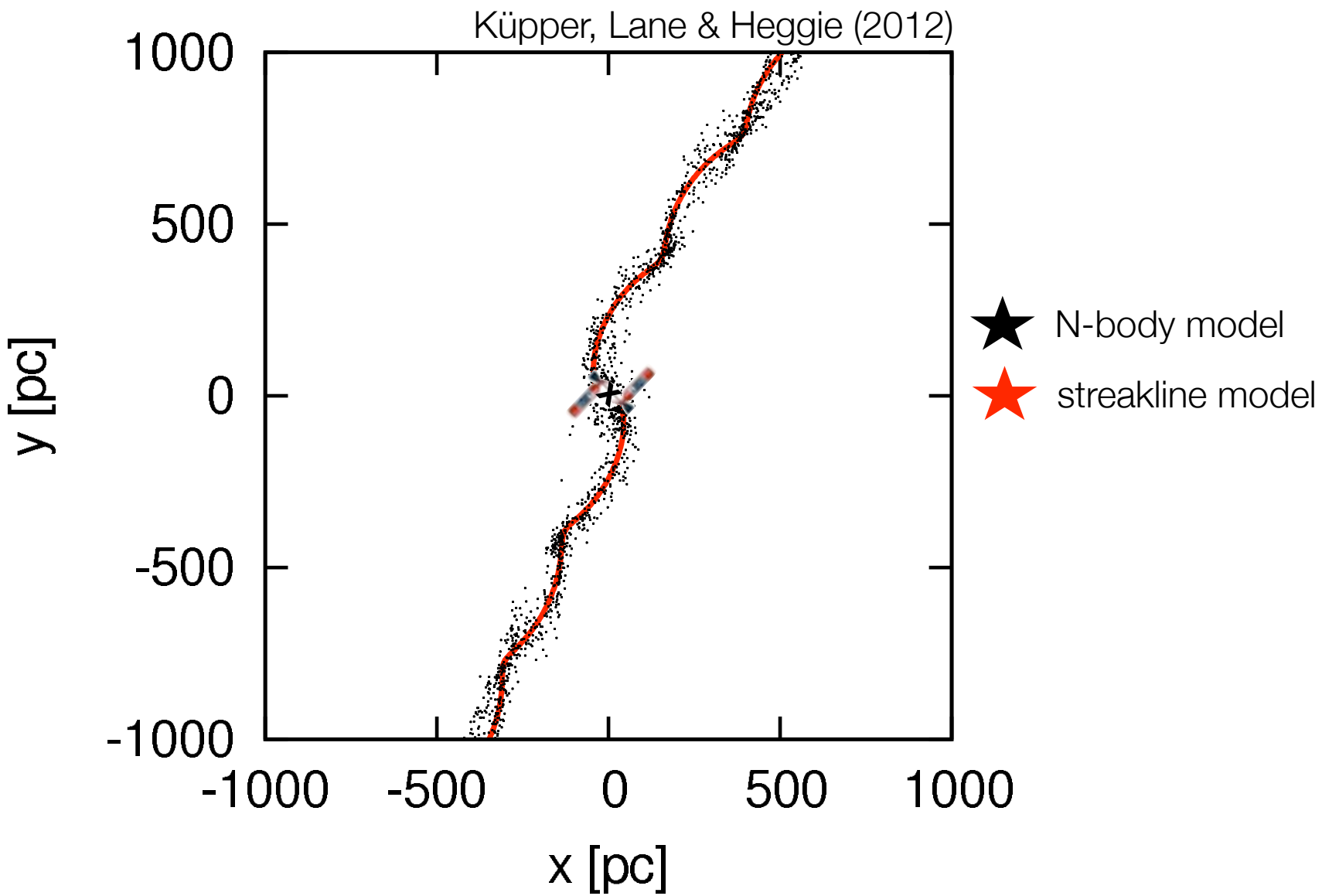
We release test particles from the Lagrange points and see where they end up after some time



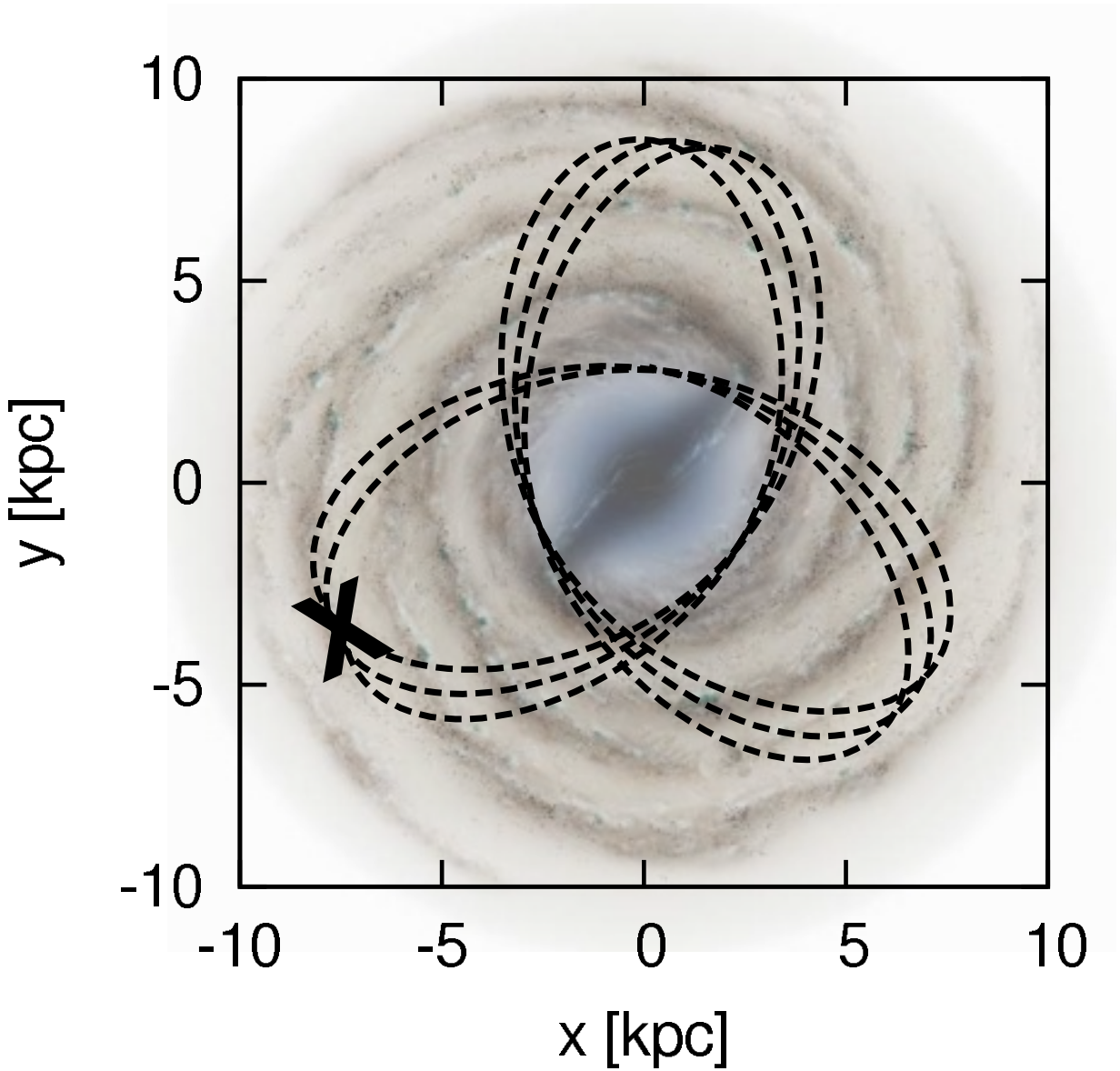
In N-body simulations we clearly see epicyclic overdensities



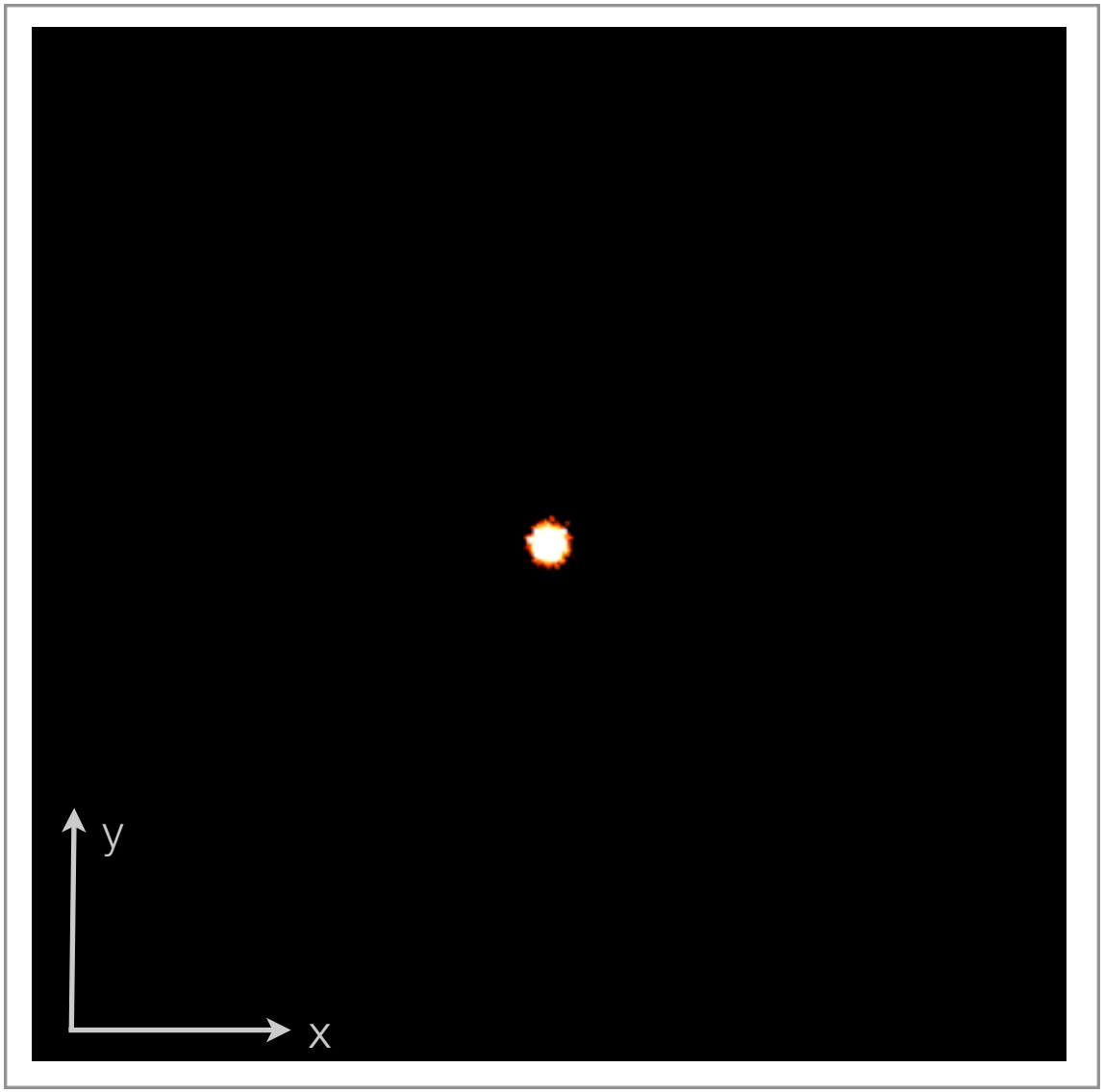
Our streakline model can reproduce the shape of the tails and the positions of the overdensities



Streaklines are particularly useful for clusters on eccentric orbits

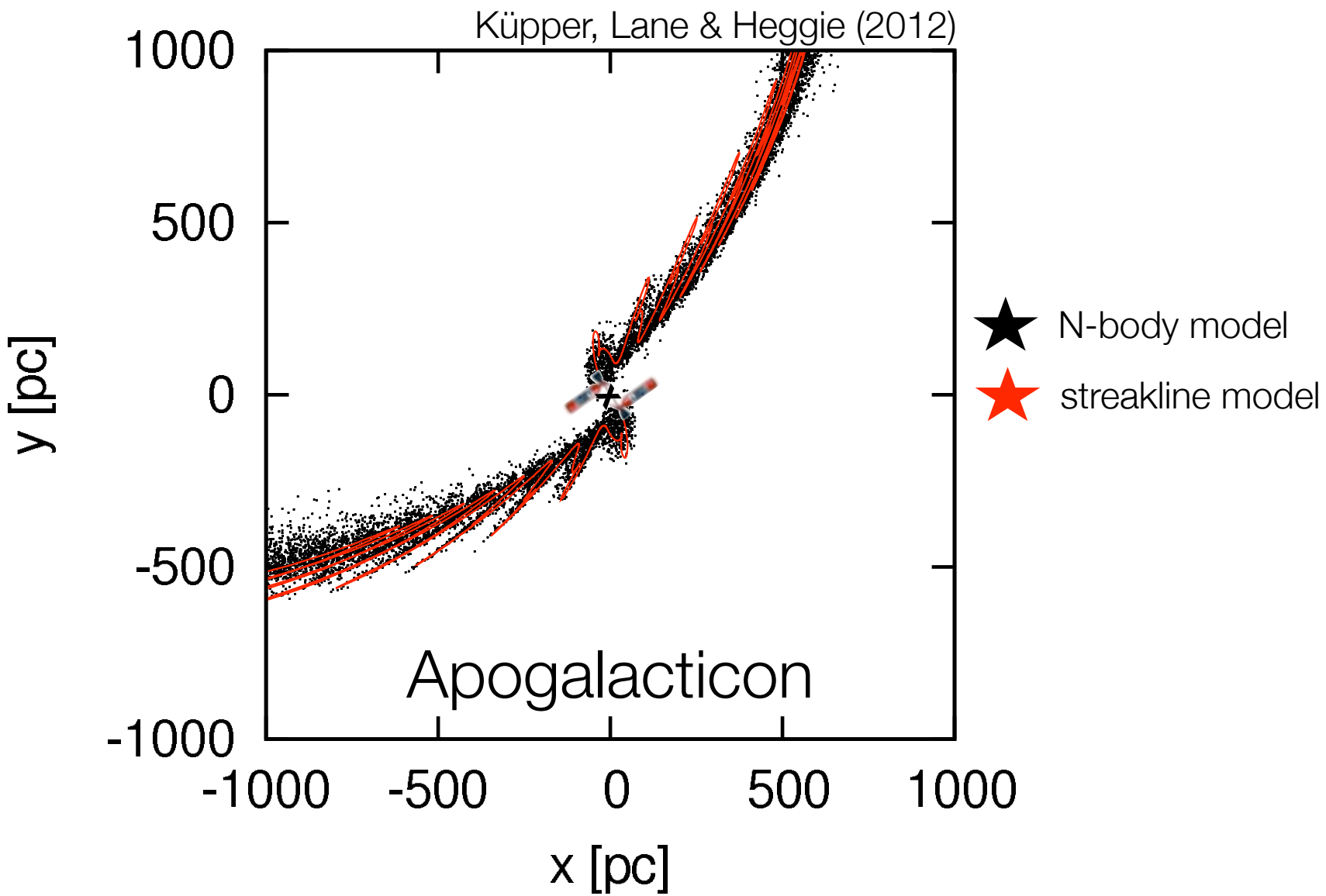


N-body computations of clusters with an orbital eccentricity of 0.5 show complex behaviour

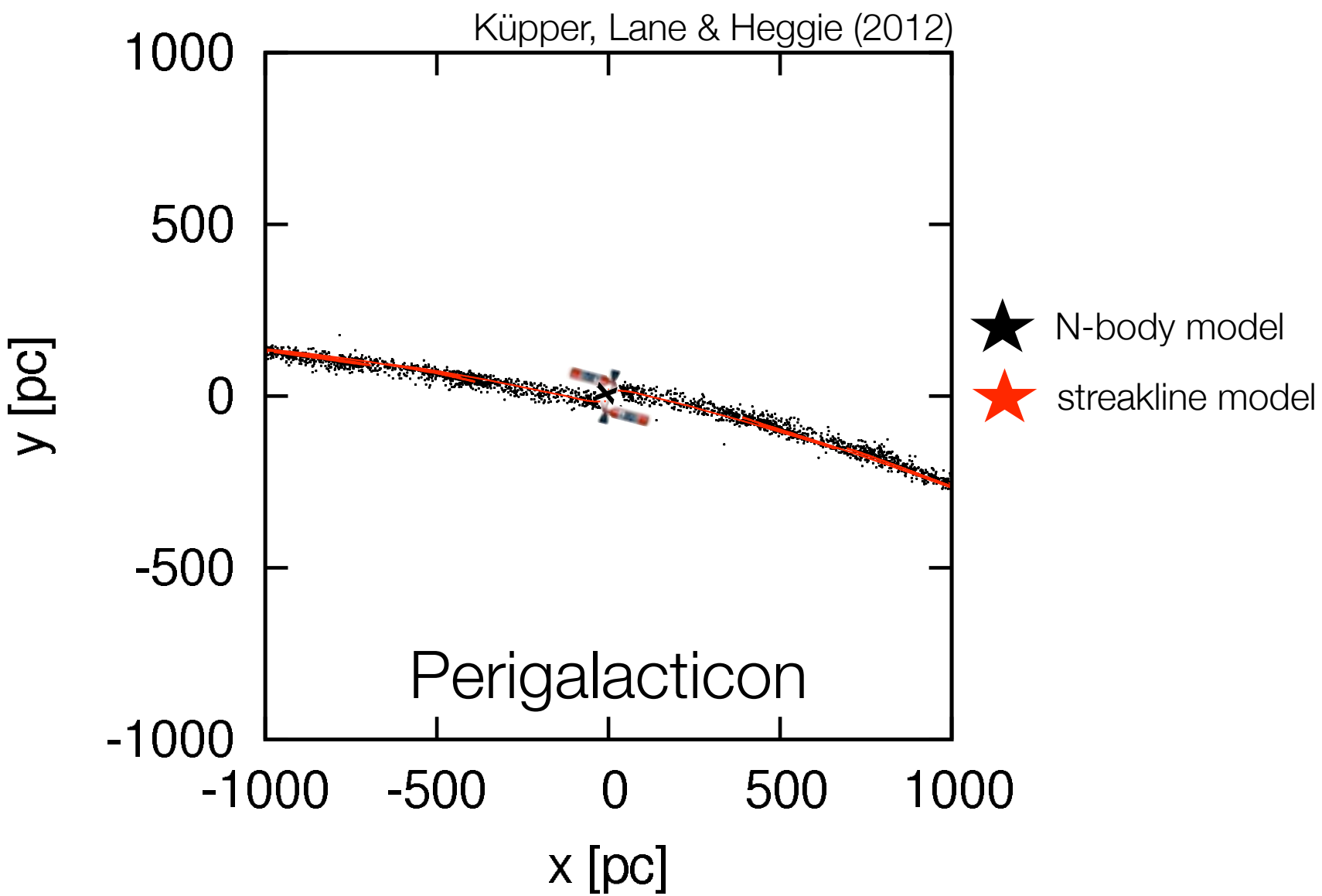


Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

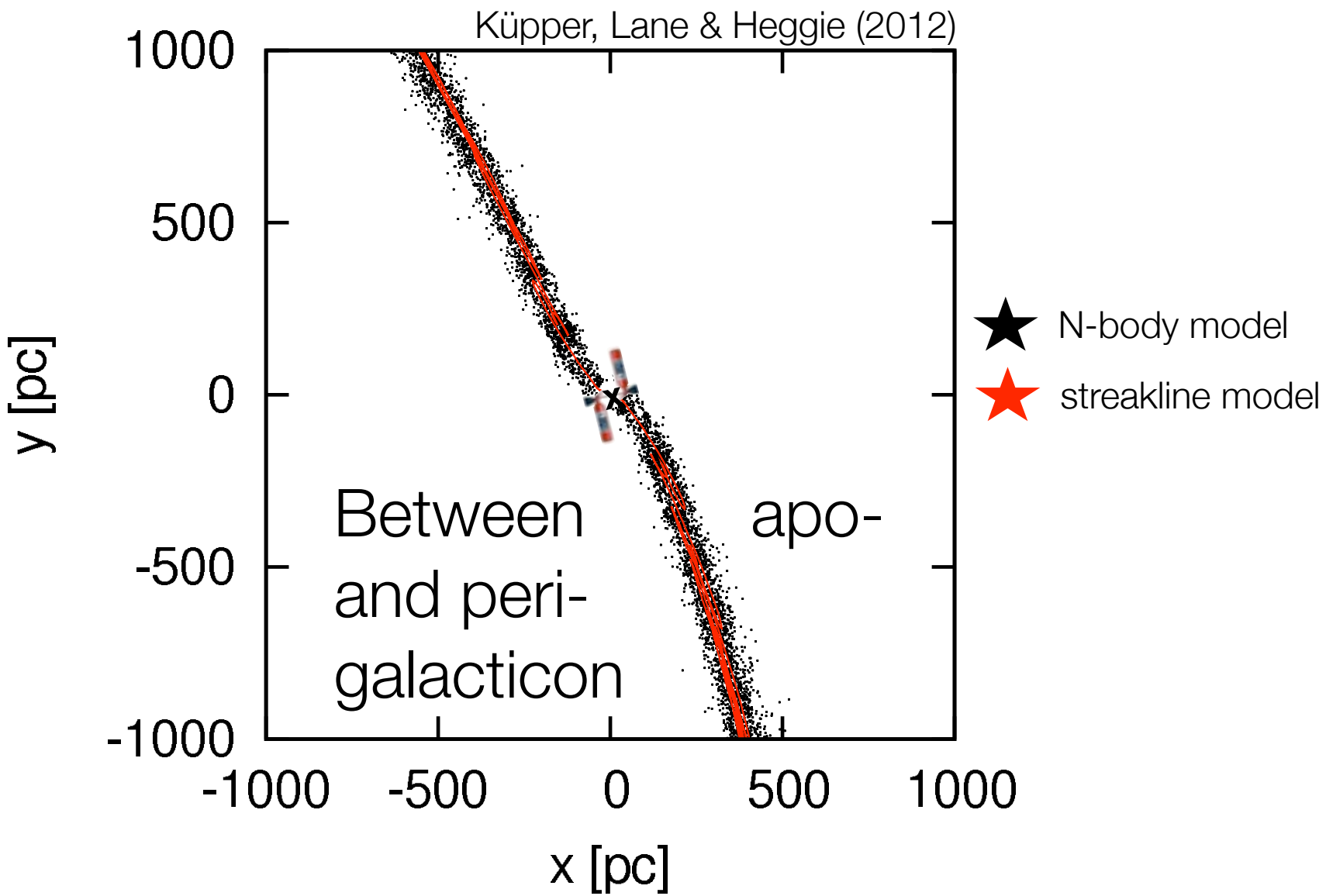
Again, our simple model can reproduce the shape of the tails and the positions of the overdensities



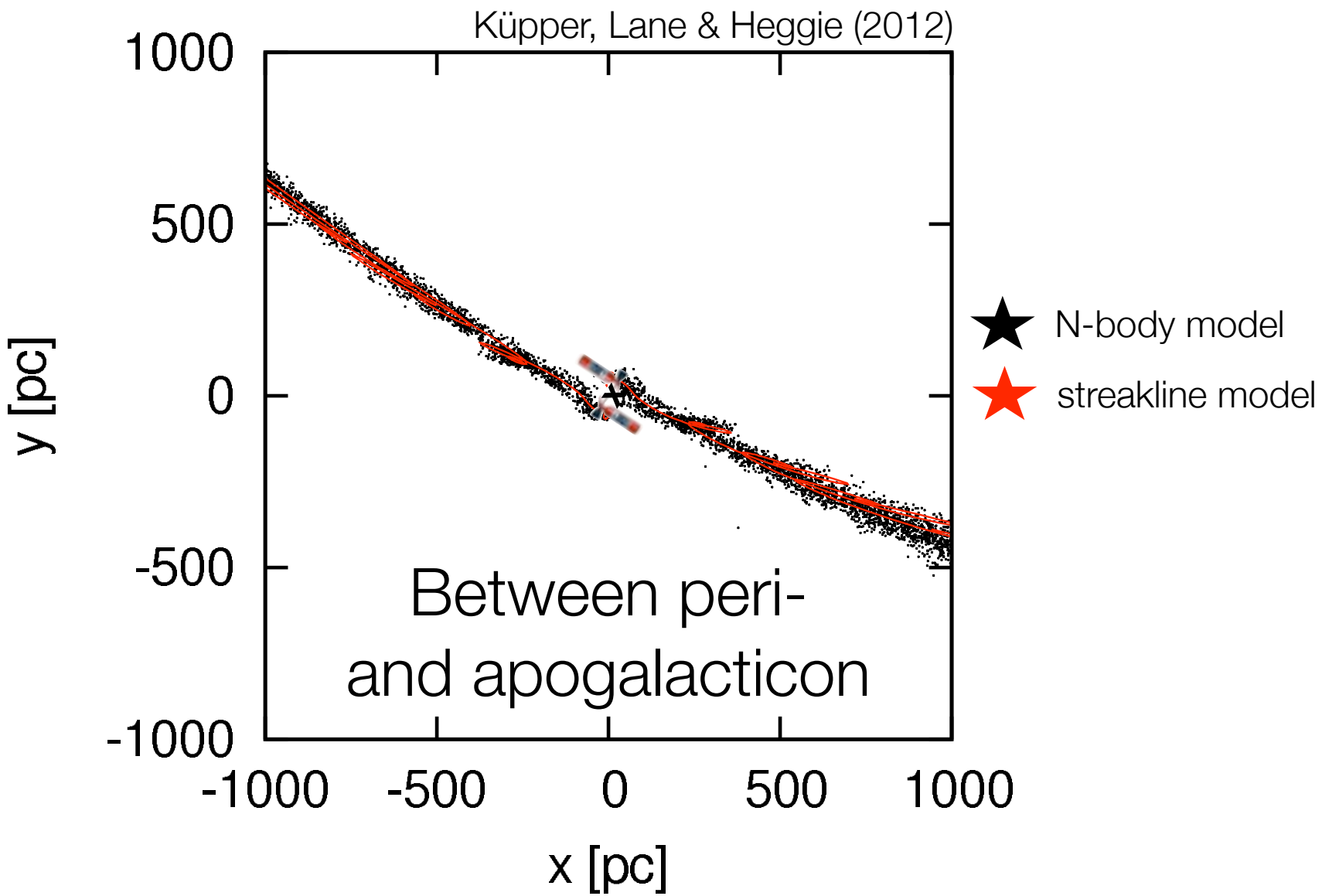
Again, our simple model can reproduce the shape of the tails and the positions of the overdensities



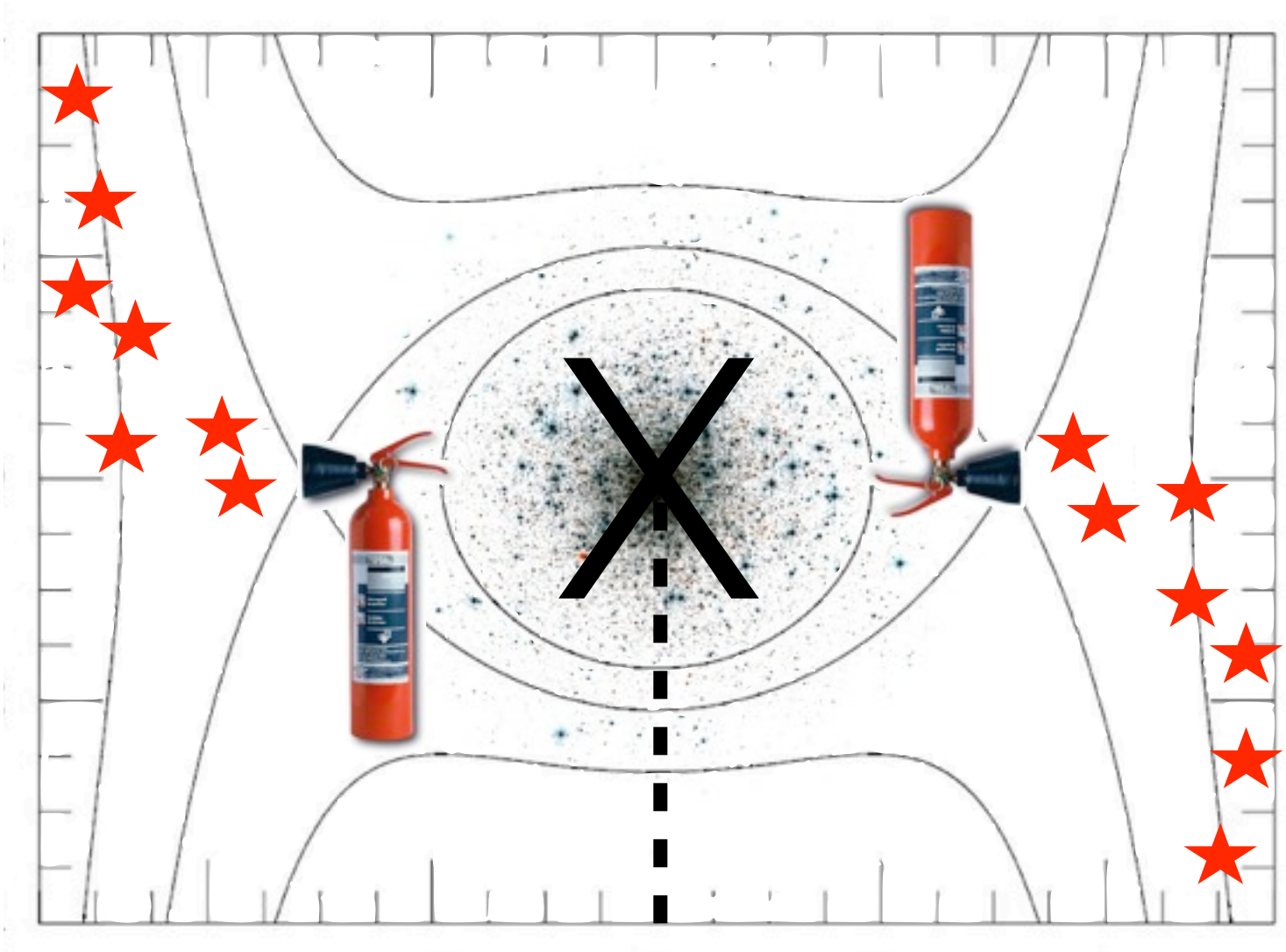
Again, our simple model can reproduce the shape of the tails and the positions of the overdensities



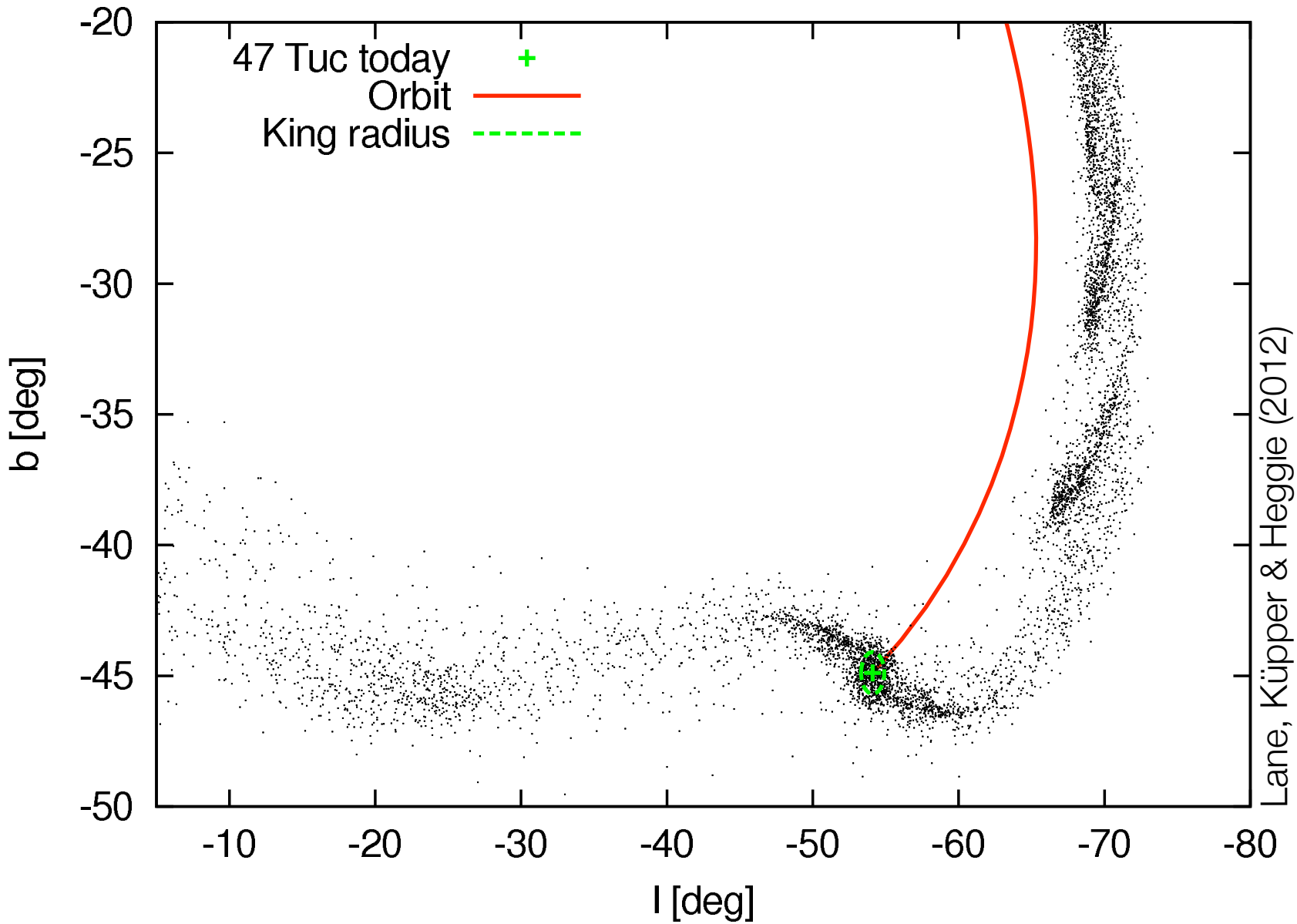
Again, our simple model can reproduce the shape of the tails and the positions of the overdensities



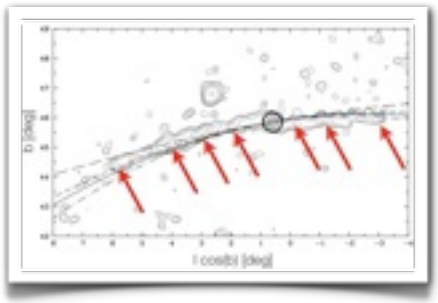
By adding a little scatter to the test particles we can emulate tidal tails



This method can be used to predict shapes of tidal tails without the need for N-body simulations

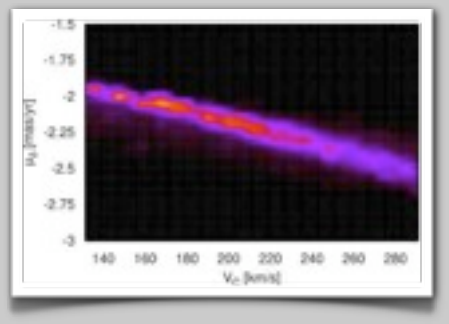


How can we weigh the Milky Way using tidal tails of globular clusters?



The tidal tails of Palomar 5

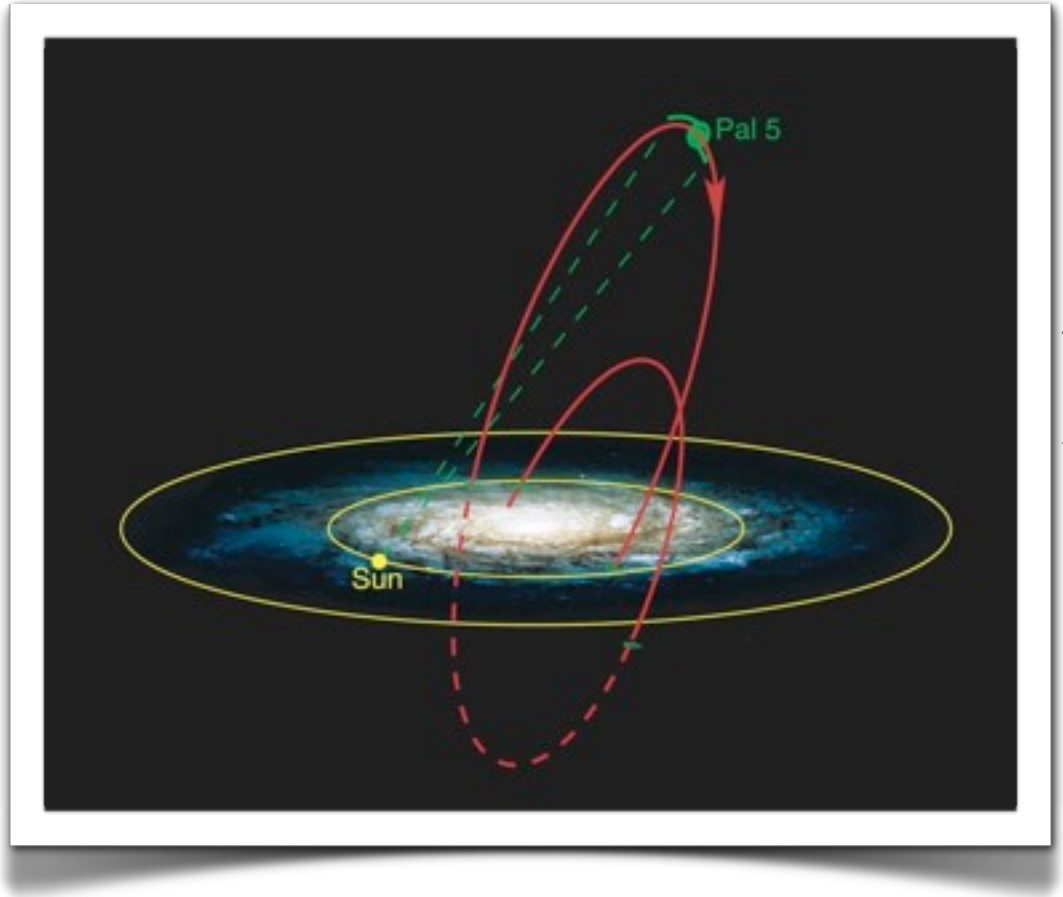
Streaklines - a concept from continuum mechanics



Extracting Palomar 5‘s orbit using streaklines

Modeling Palomar 5 involves many free parameters, so full N-body modeling is out of reach!

- Galaxy model
  - ➡ mass of dark halo
  - ➡ flattening/triaxiality
- Cluster model
  - ➡ mass
  - ➡ mass loss rate
- Orbital parameters
  - ➡ proper motion
  - ➡ distance
- Solar parameters
  - ➡ distance to Galactic Center
  - ➡ Solar motion



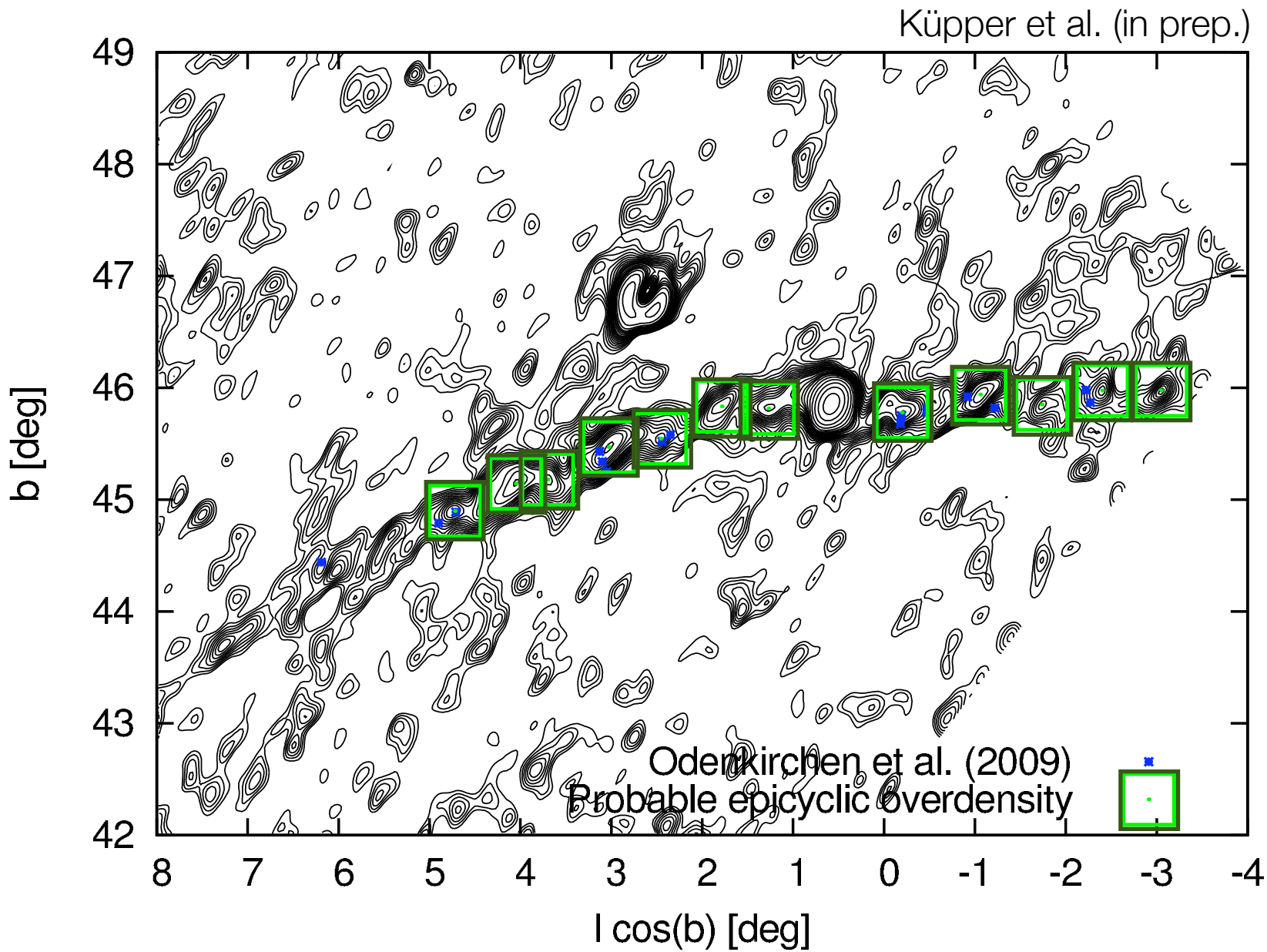
Odenkirchen et al. (2003)

A grid-based parameter study is still demanding even when using streakline models

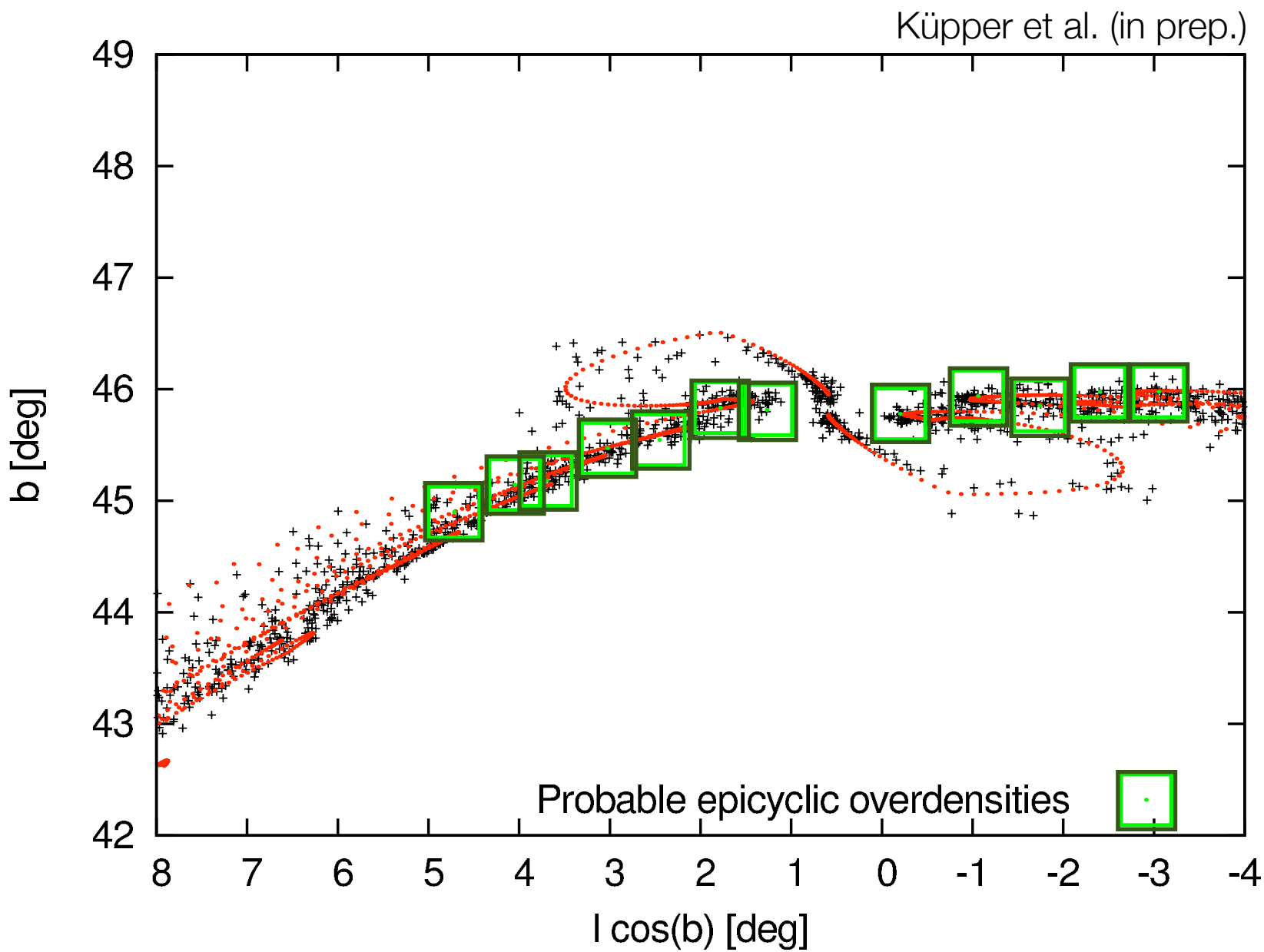
- Galaxy model
  - ➡ circular velocity between 130 - 290 km/s, spherical halo
- Cluster model
  - ➡ mass between 5000 and 40,000 M_{sun}, no mass loss
- Orbital parameters
  - ➡ $\mu_\alpha \cos(\delta)$ & μ_δ between -1.5 and -3 mas/yr, distance fixed
- Solar parameters
  - ➡ fixed

➡ 238,328 models

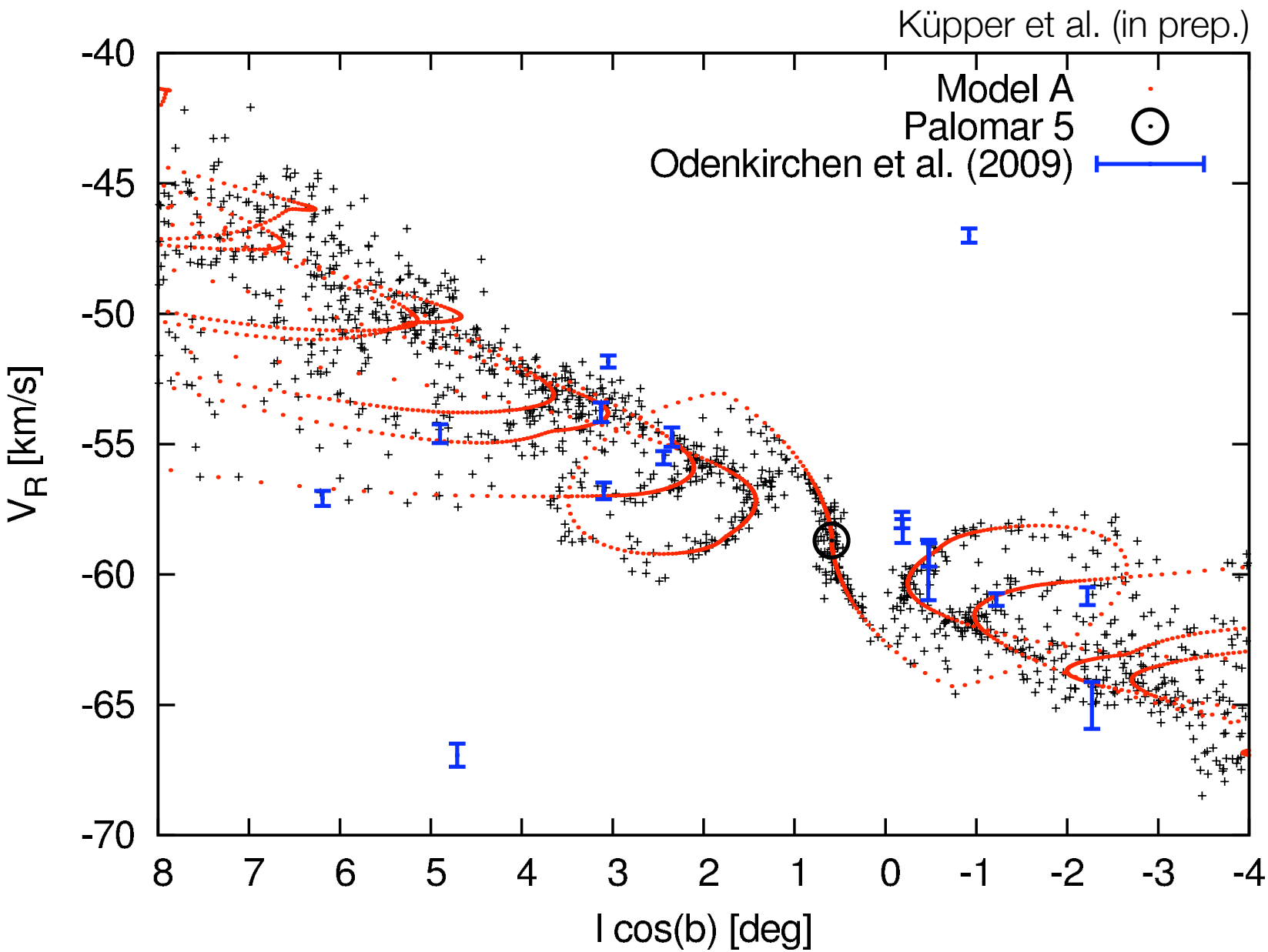
Most important question: how to judge what a good model is



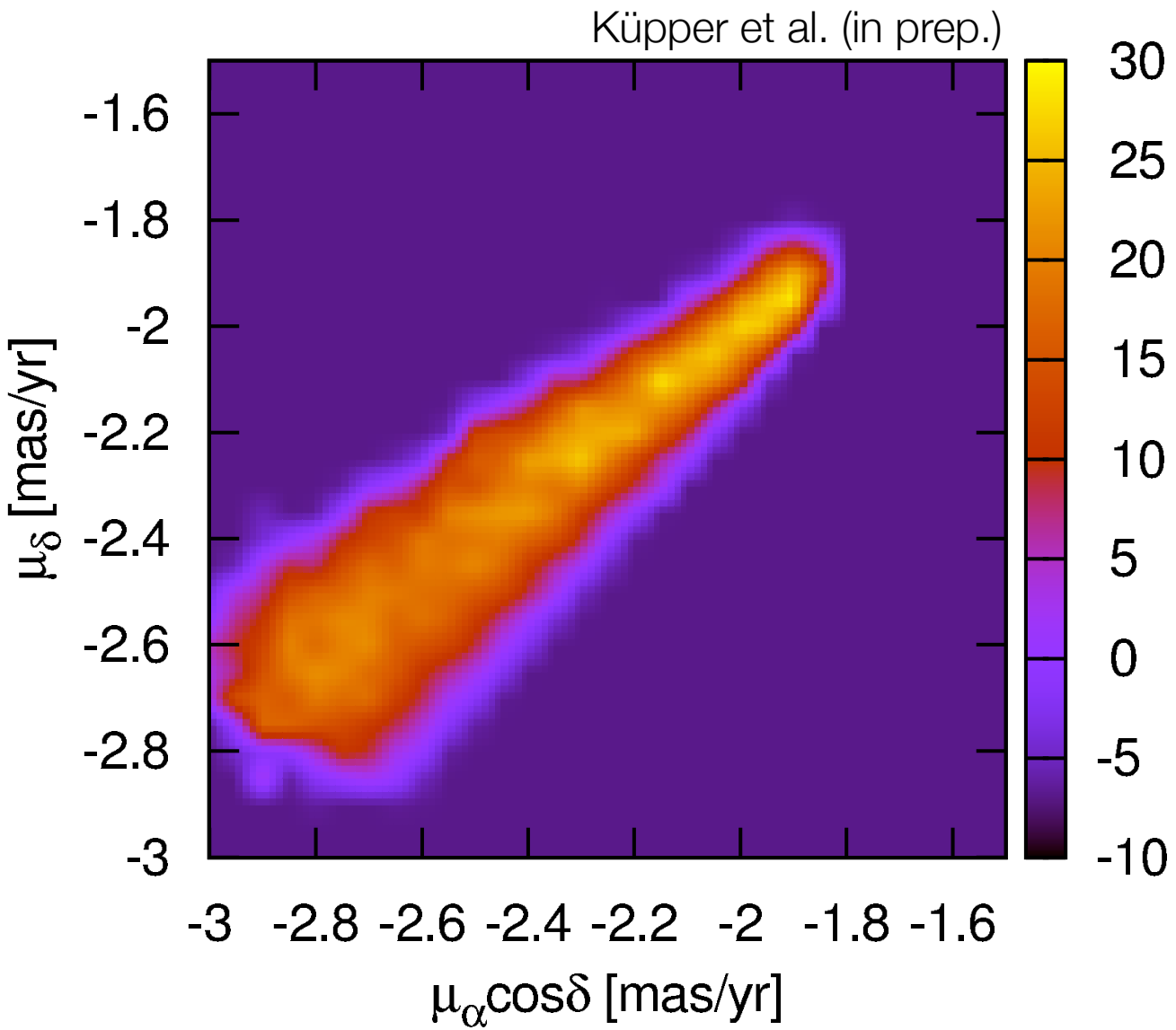
Epicyclic substructure helps us to identify the best-fitting model



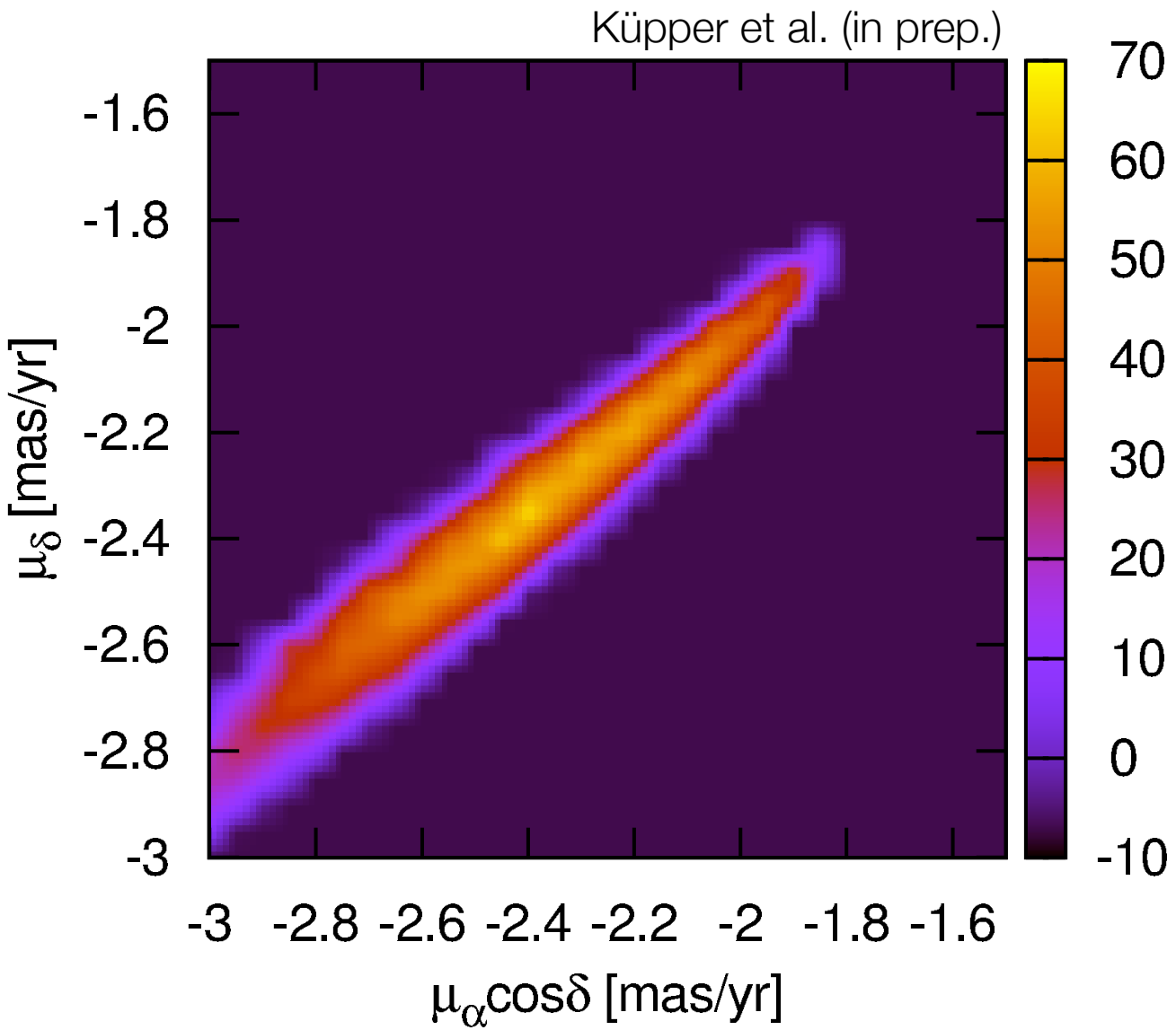
The streakline models help us to interpret the observed scatter in the velocity gradient



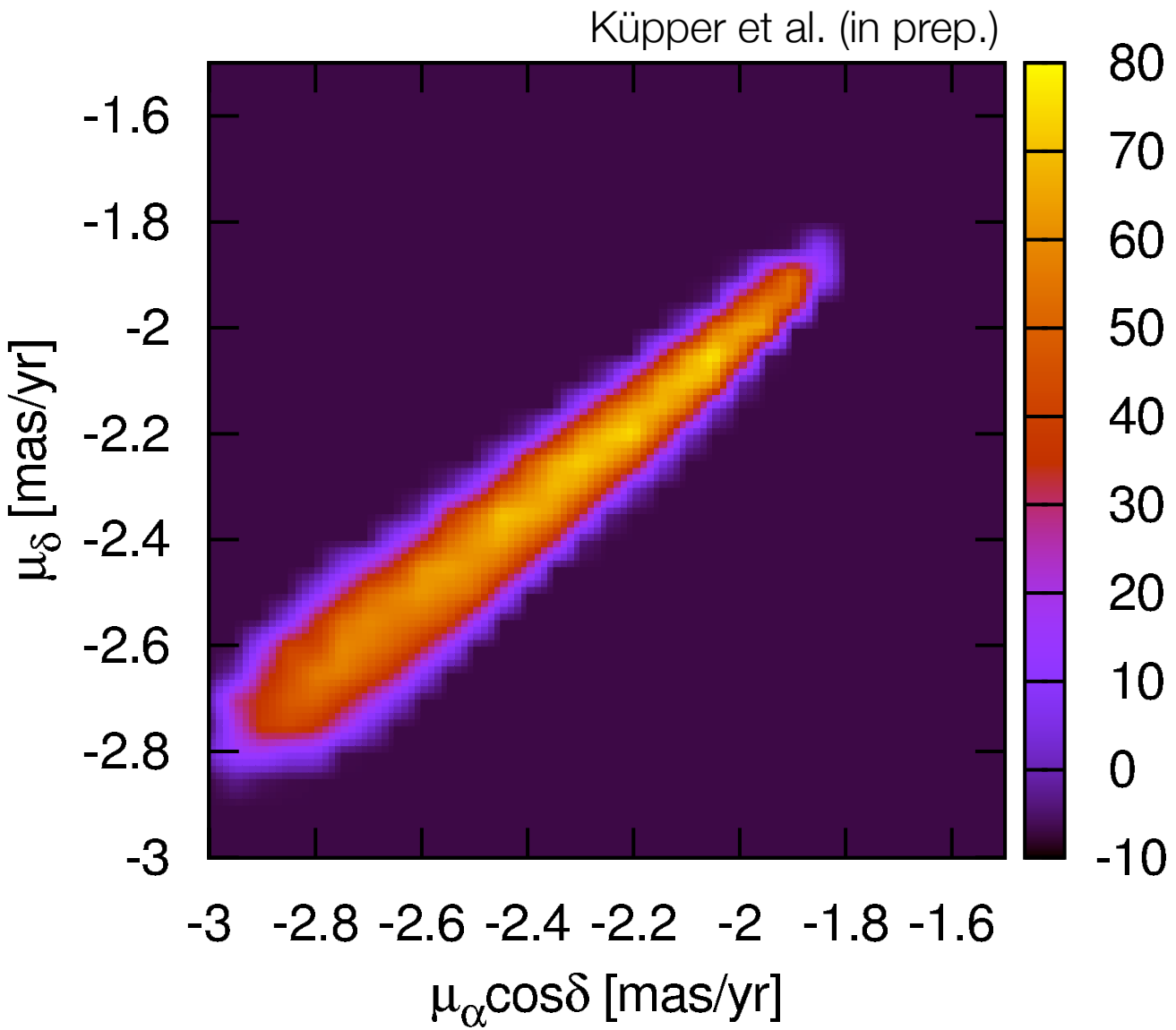
From the set of models we get a prediction for the proper motion



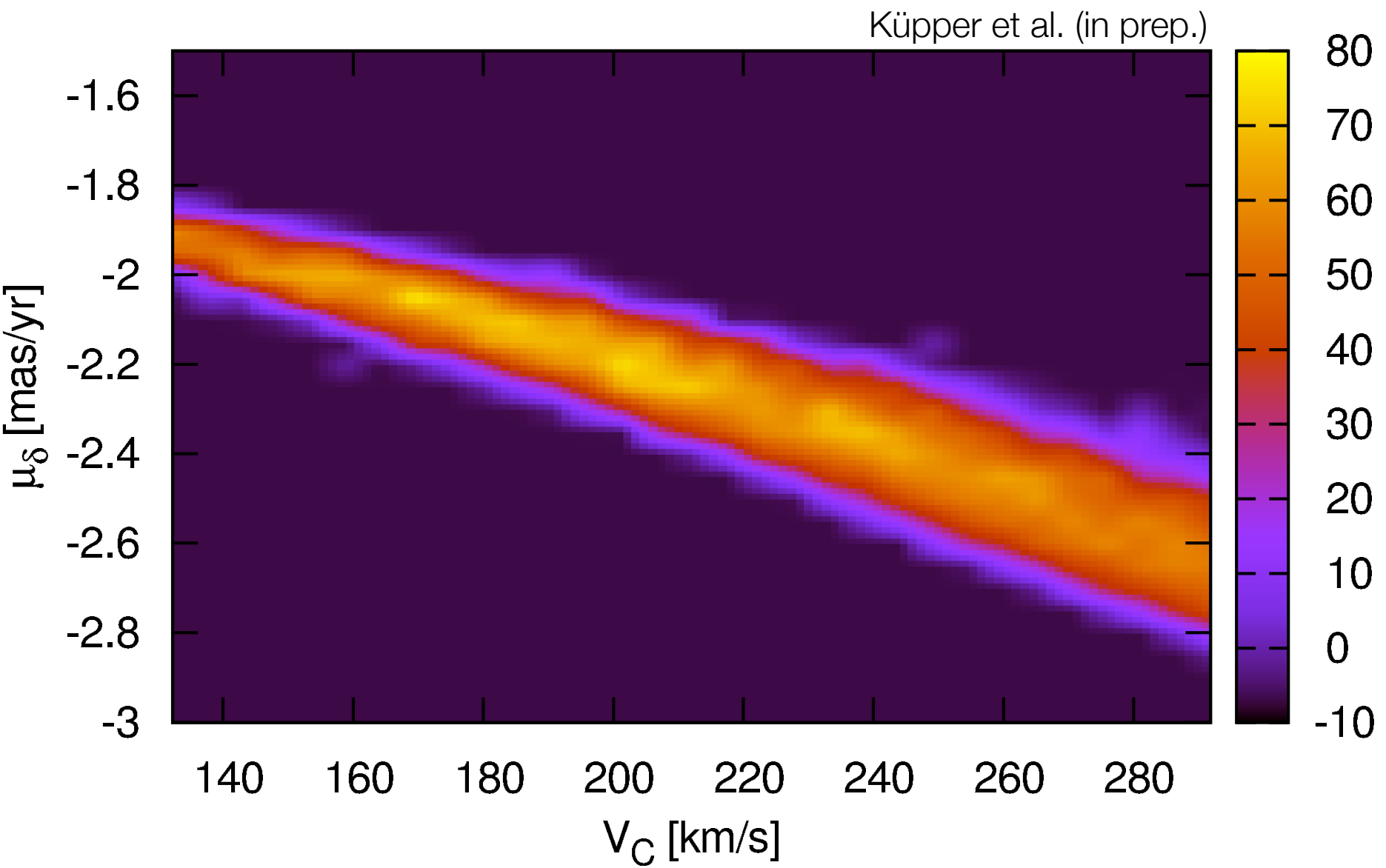
From the set of models we get a prediction for the proper motion



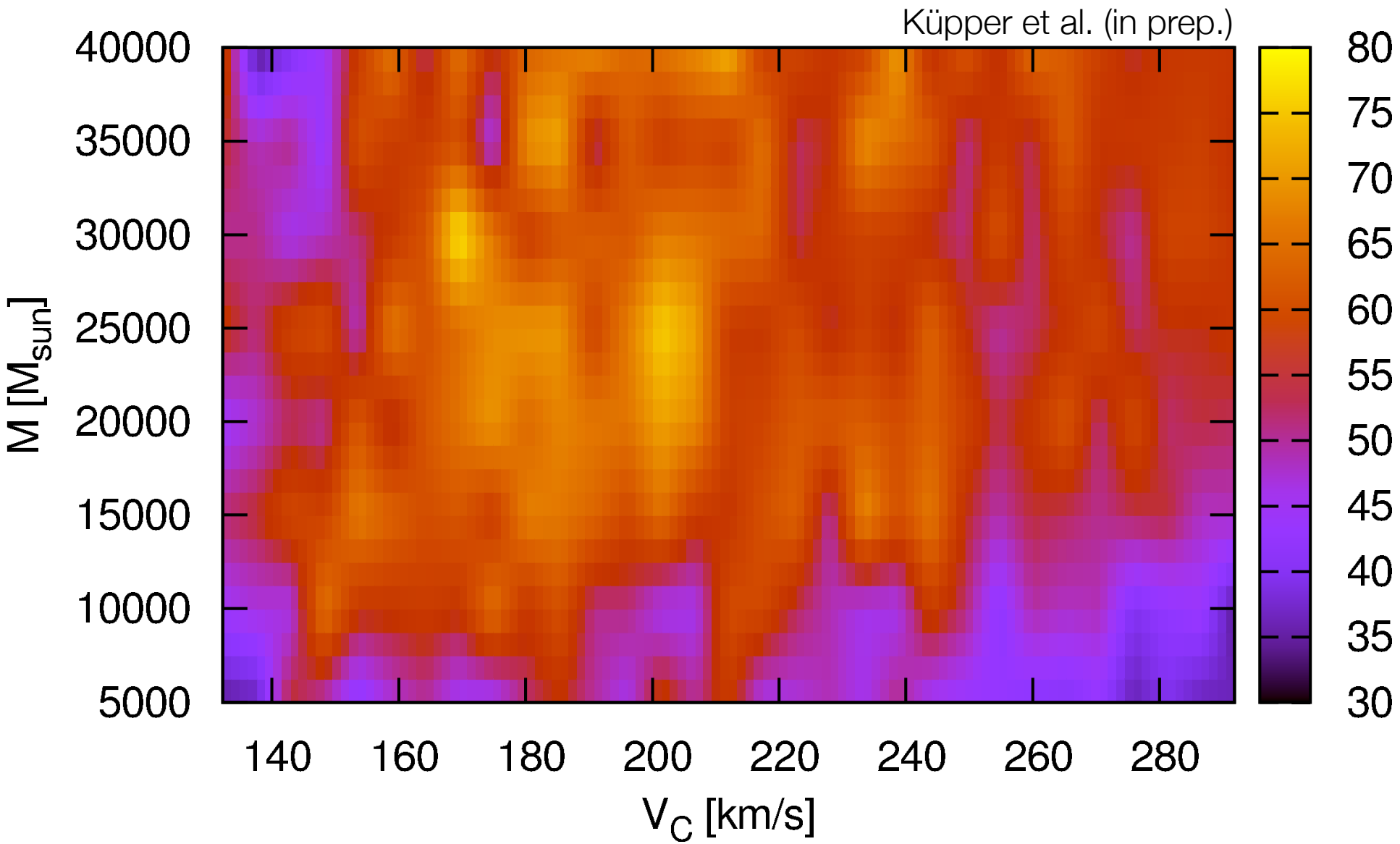
From the set of models we get a prediction for the proper motion



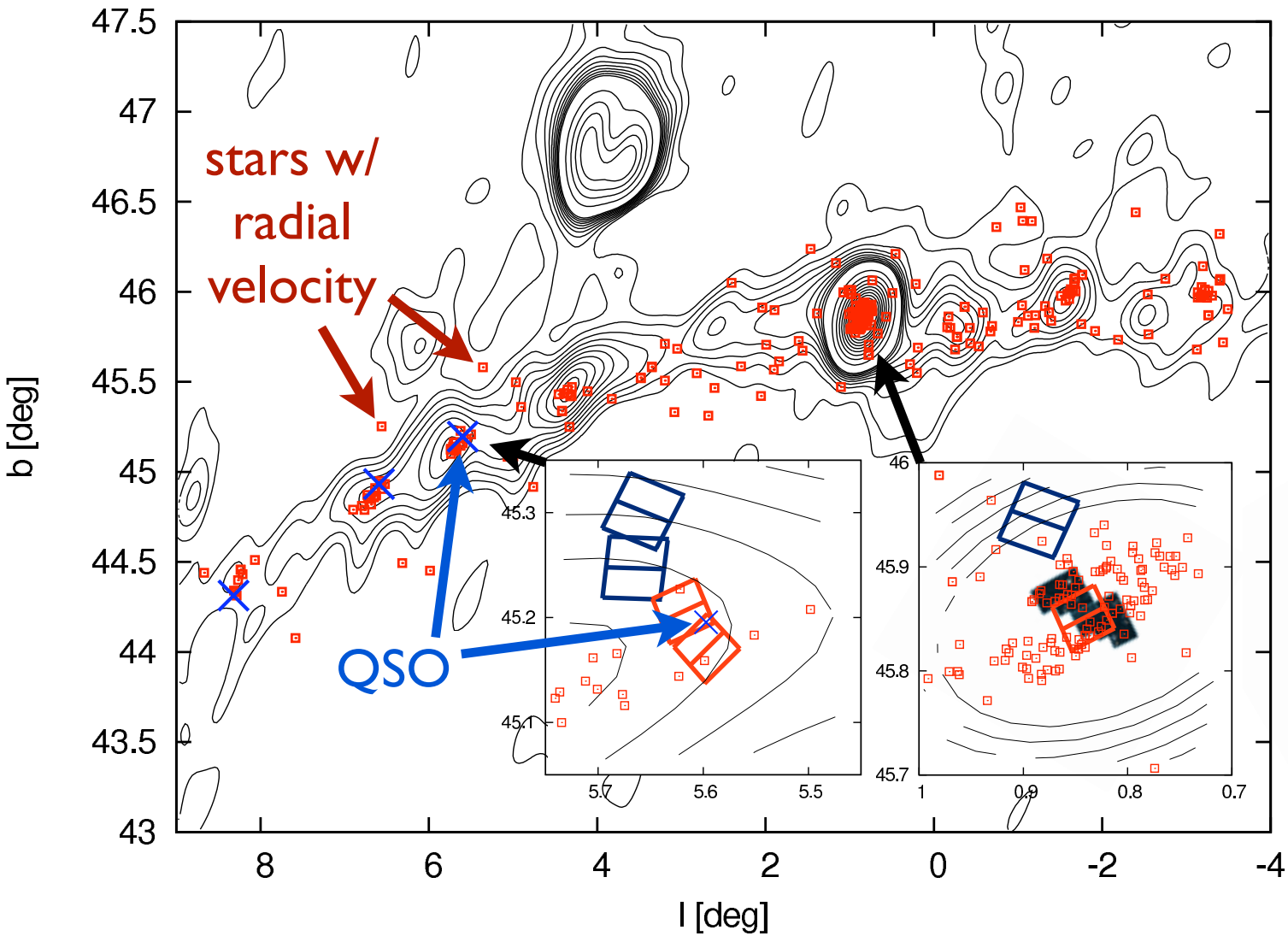
And we also get an estimate of the Galactic circular velocity at Palomar 5‘s galactocentric distance



Finally, we get an independent estimate of Palomar 5‘s mass



Most restricting factor is the quality of the available data - but there is more data to come...

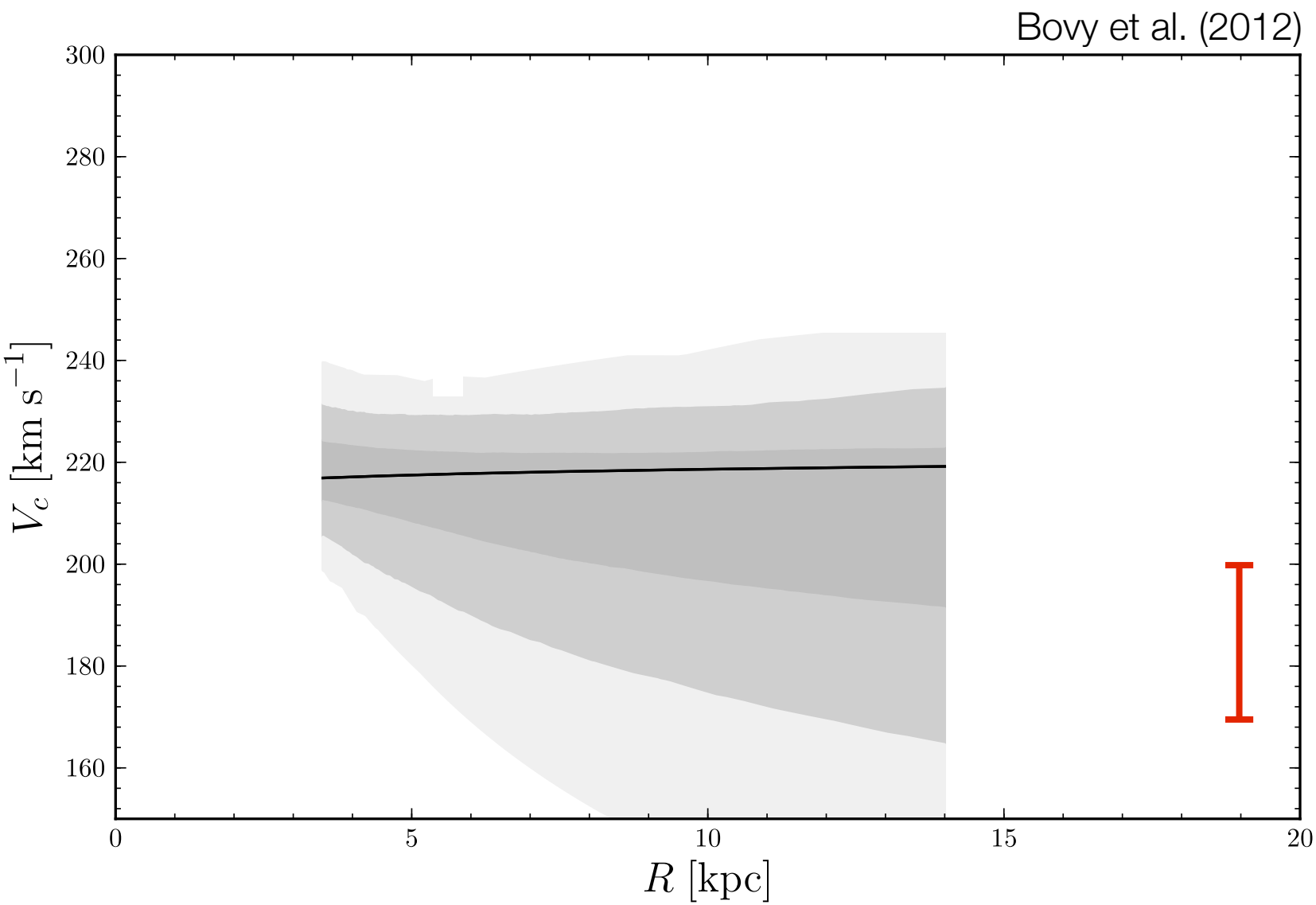


WFC3 fields

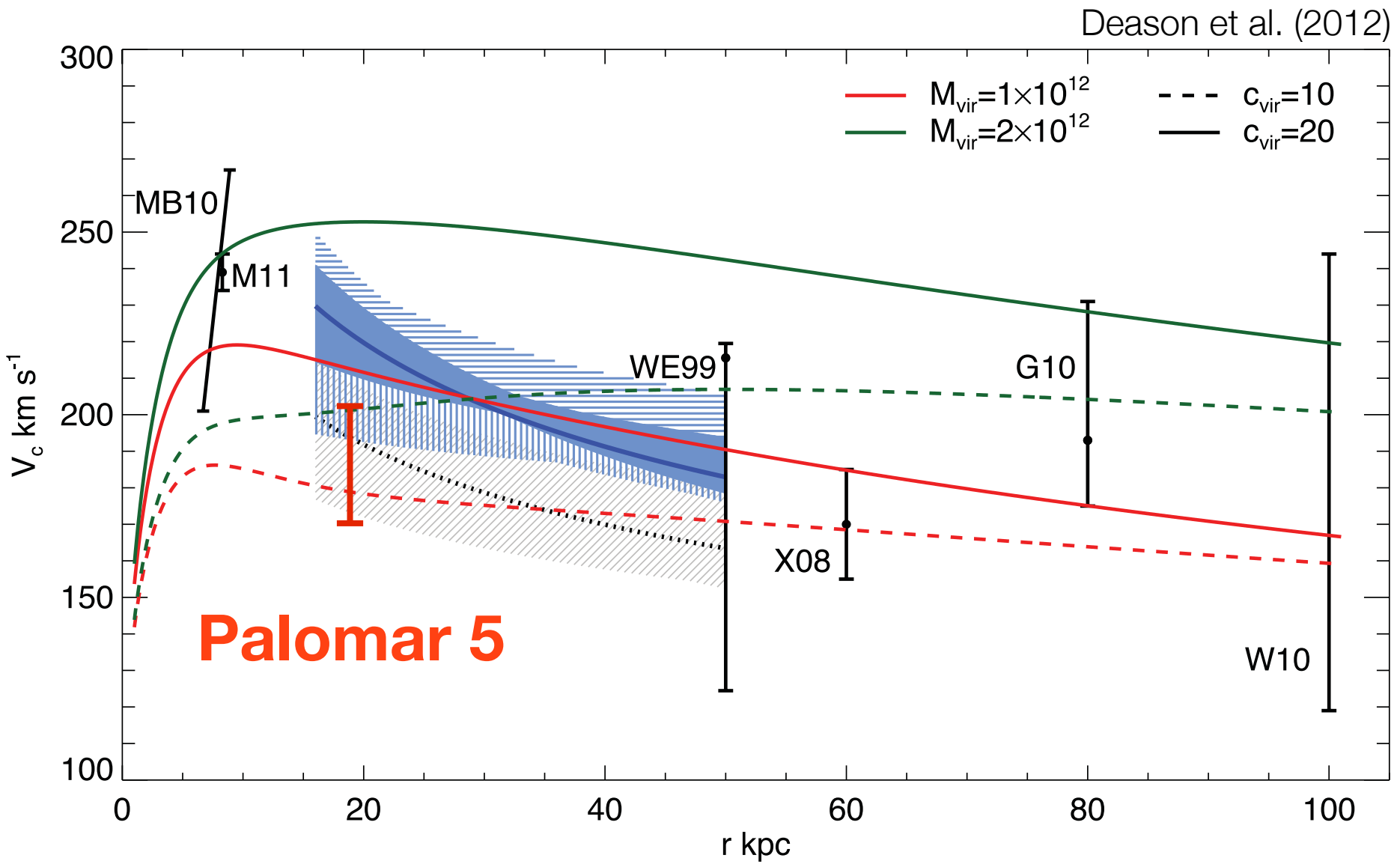
ACS fields
(in parallel)

Cycle 6
WFPC2 fields

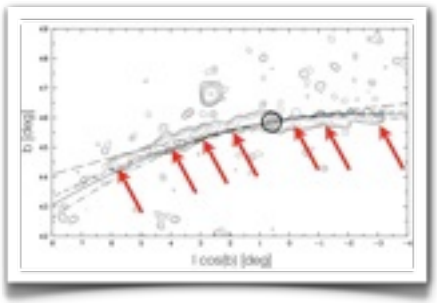
In the solar neighbourhood we observe a circular velocity of 220 km/s



Are lower circular velocities preferred in the halo? Is the Galactic potential flattened?

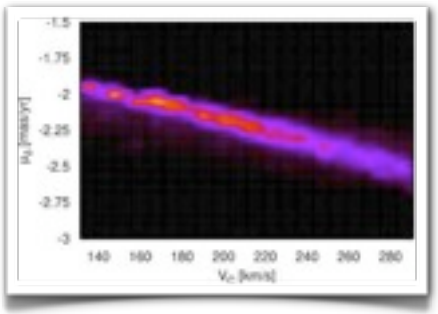


We can locally weigh the Milky Way with tidal tails of globular cluster by applying streakline modeling



- Palomar 5‘s tidal tails show epicyclic overdensities

- Streaklines can be used as quick models of tidal tails



- Circular velocity at Pal 5‘s position is 170-200 km/s