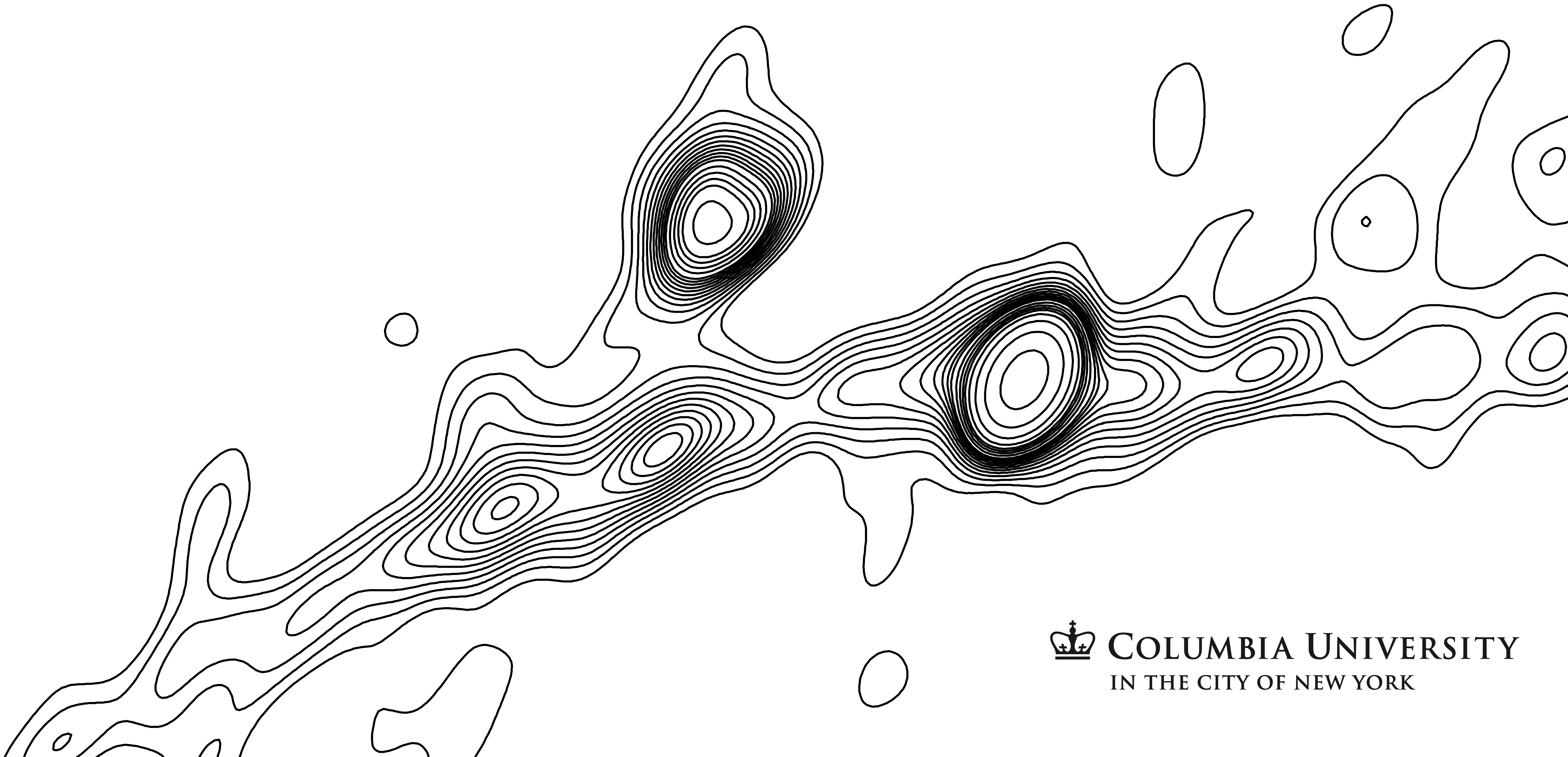
Globular Cluster Streams as Galactic High-Precision Scales

Andreas Küpper



COLUMBIA UNIVERSITY
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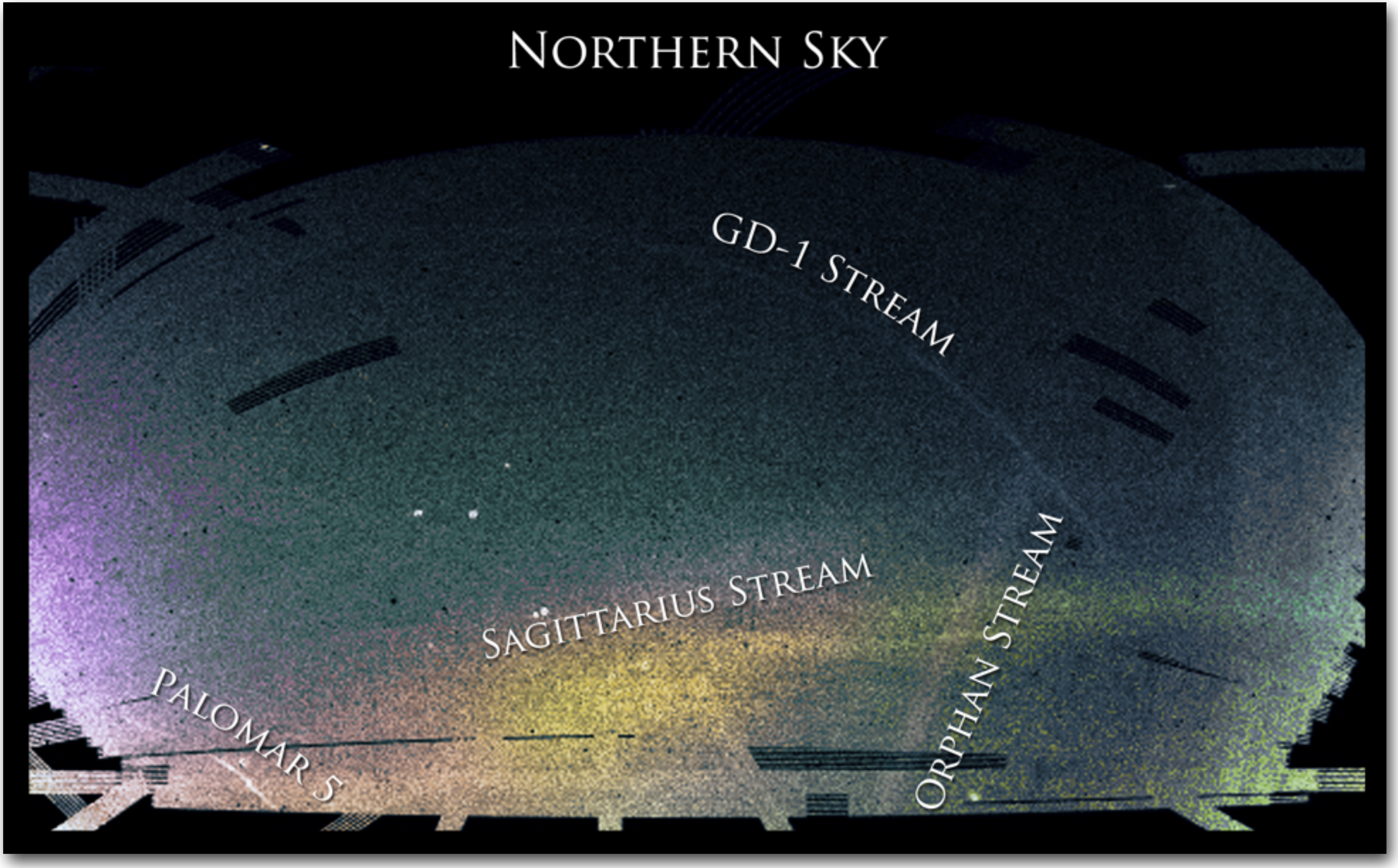
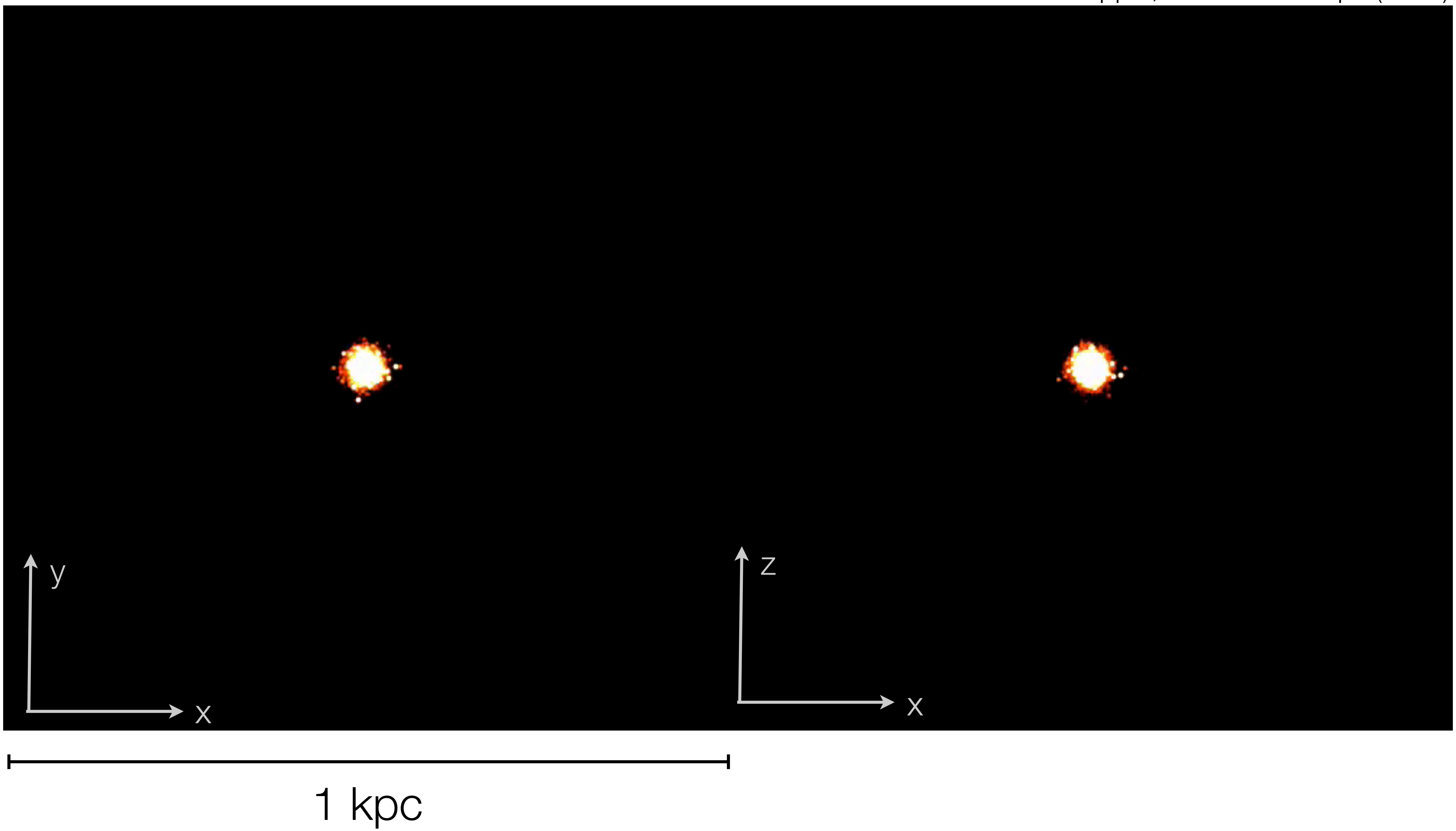
Tidal streams help us understand the parts of the Galaxy which are dark

Bonaca, Geha & Kallivayalil (2012)

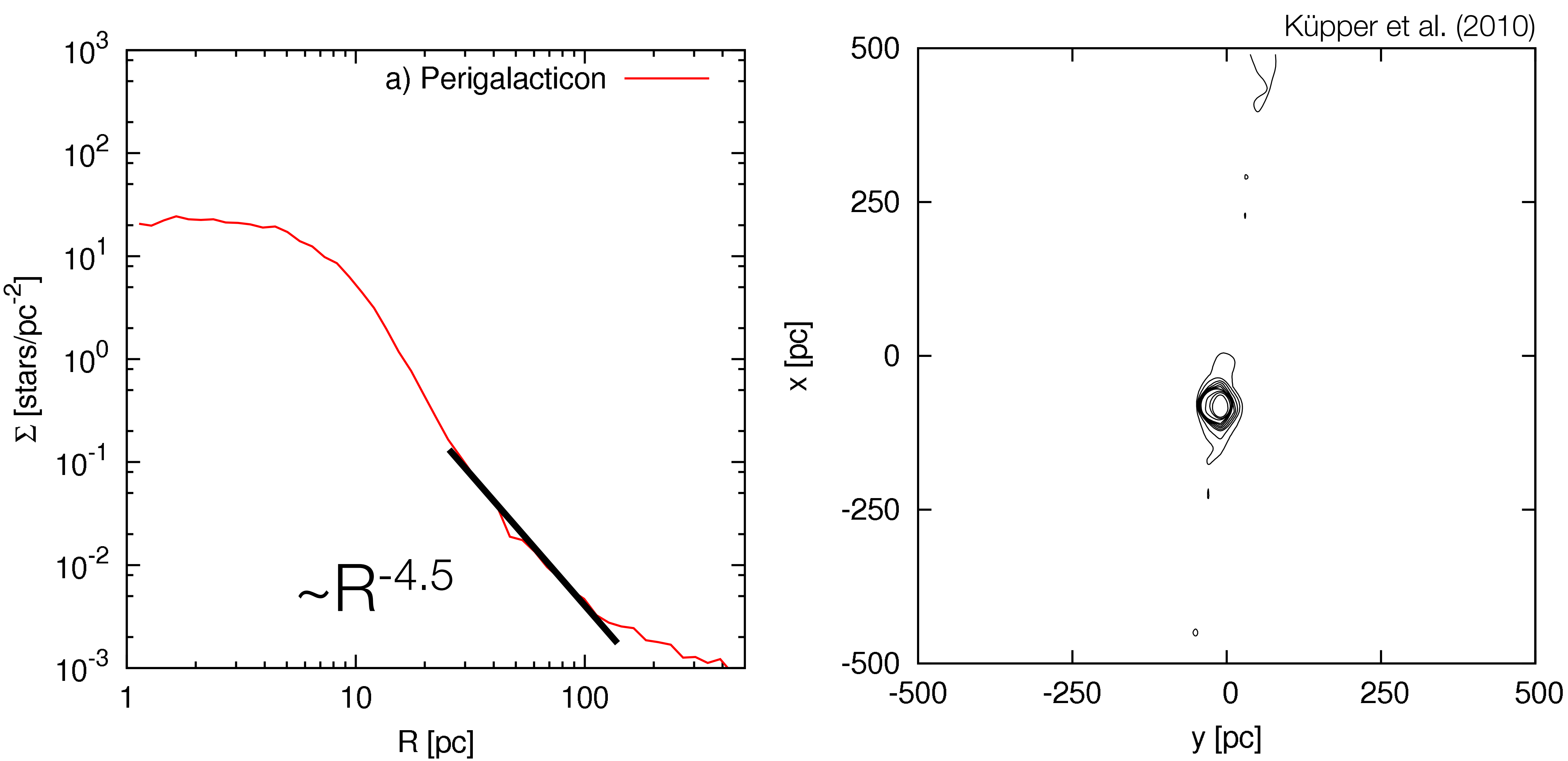


Where does the stream begin, where does the satellite end?

Küpper, Mieske & Kroupa (2011)



The orbital phase has strong influence on the surface density and the appearance of cluster & stream



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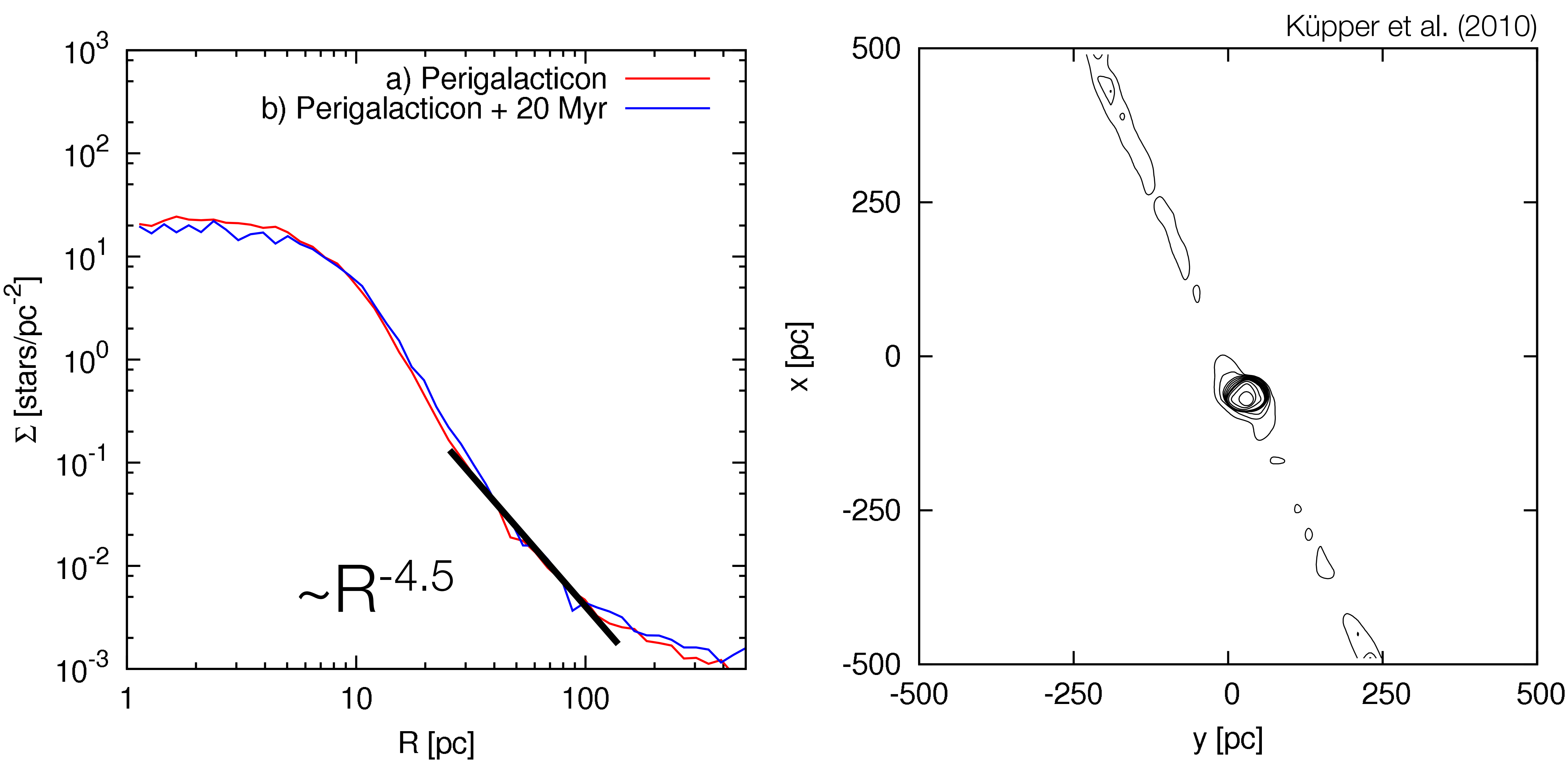

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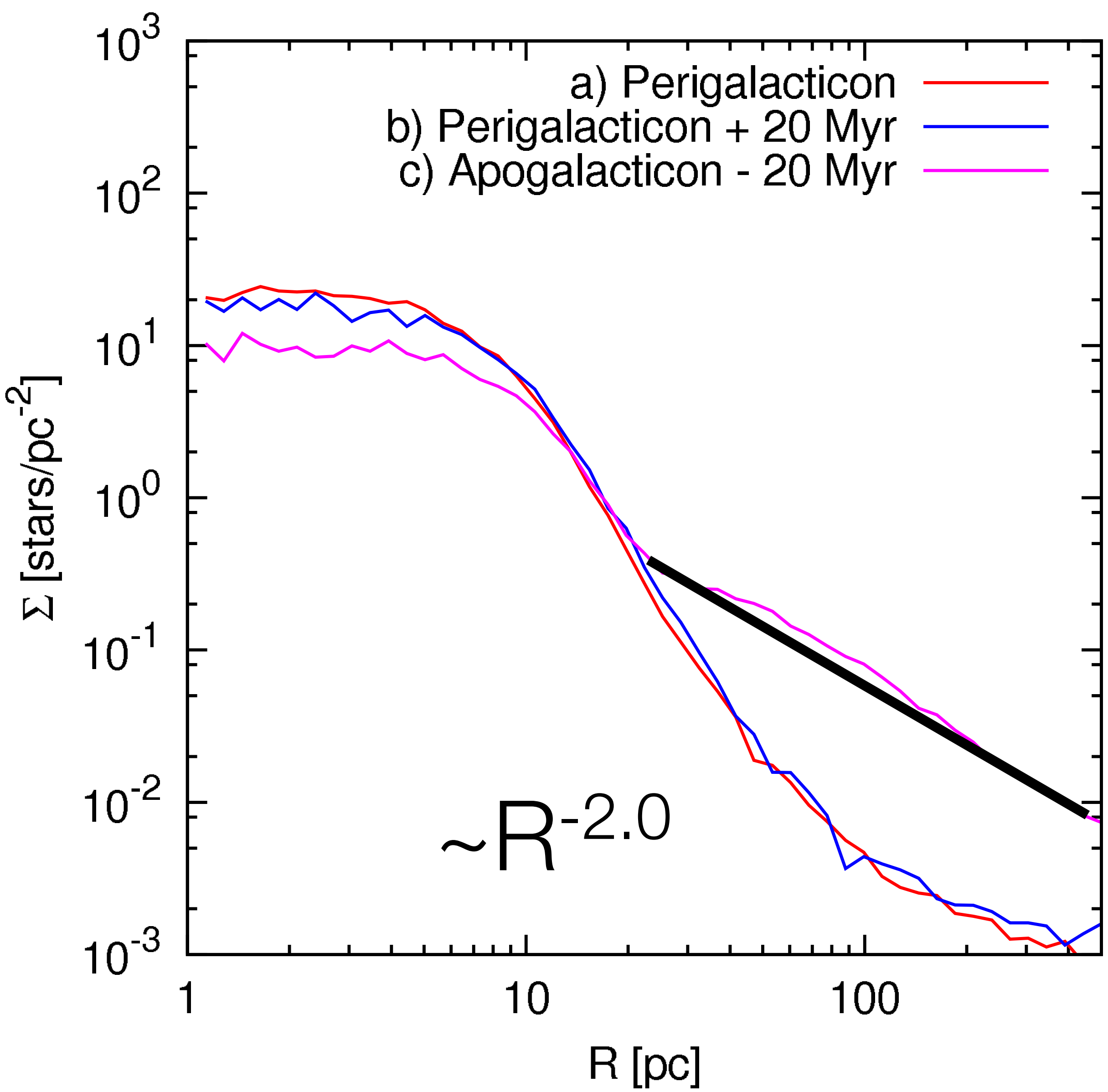
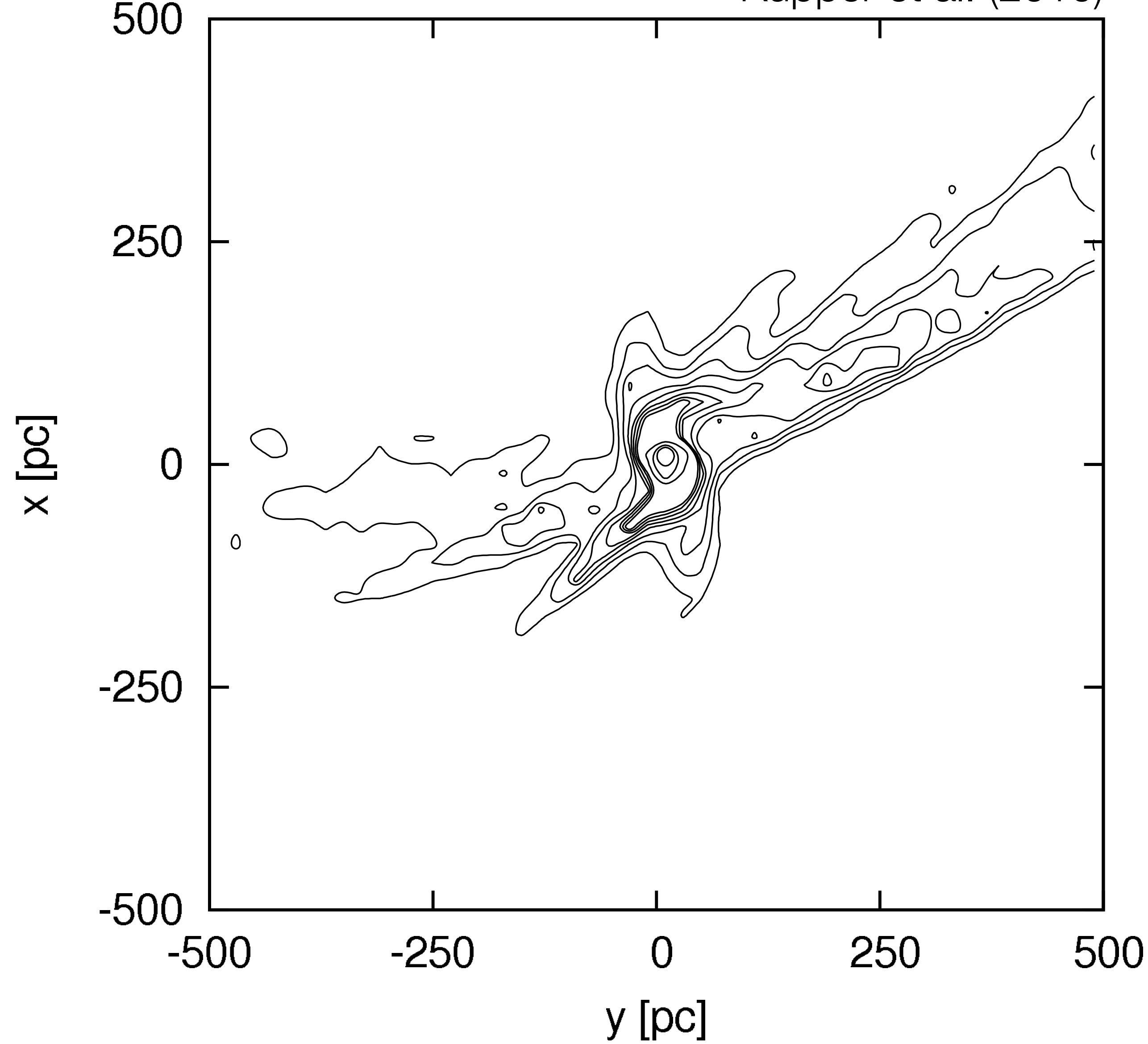


Küpper et al. (2010)



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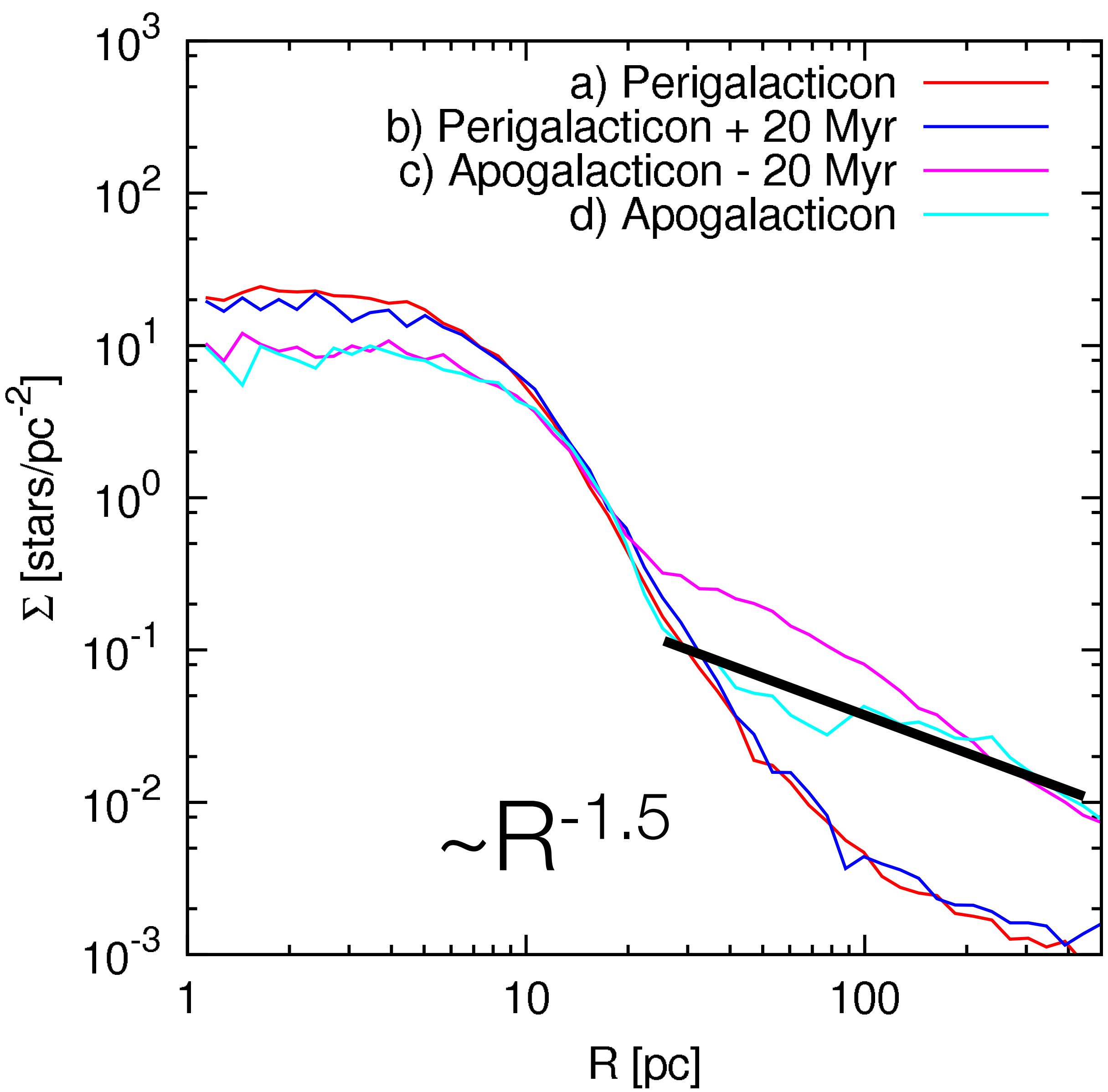
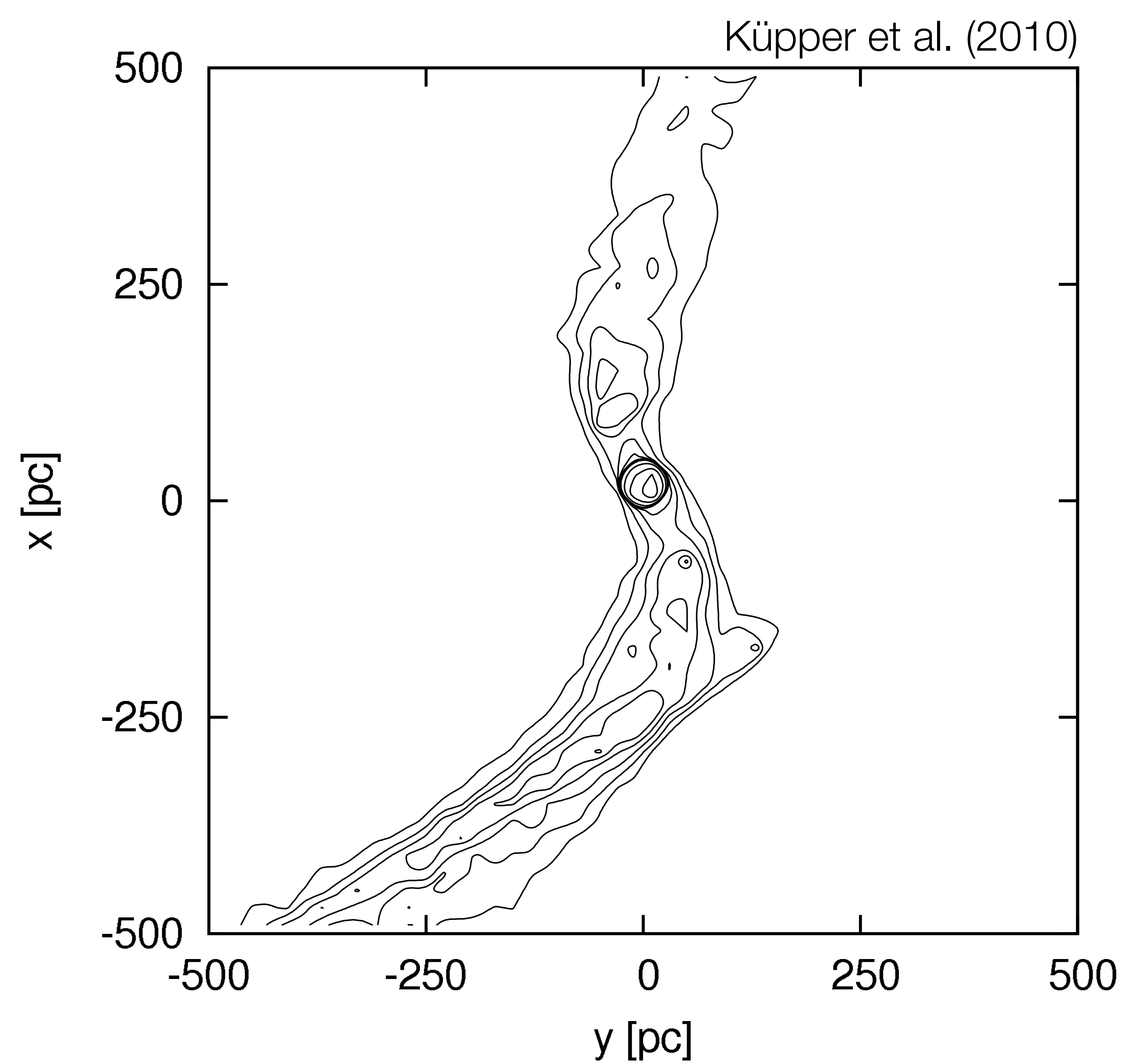
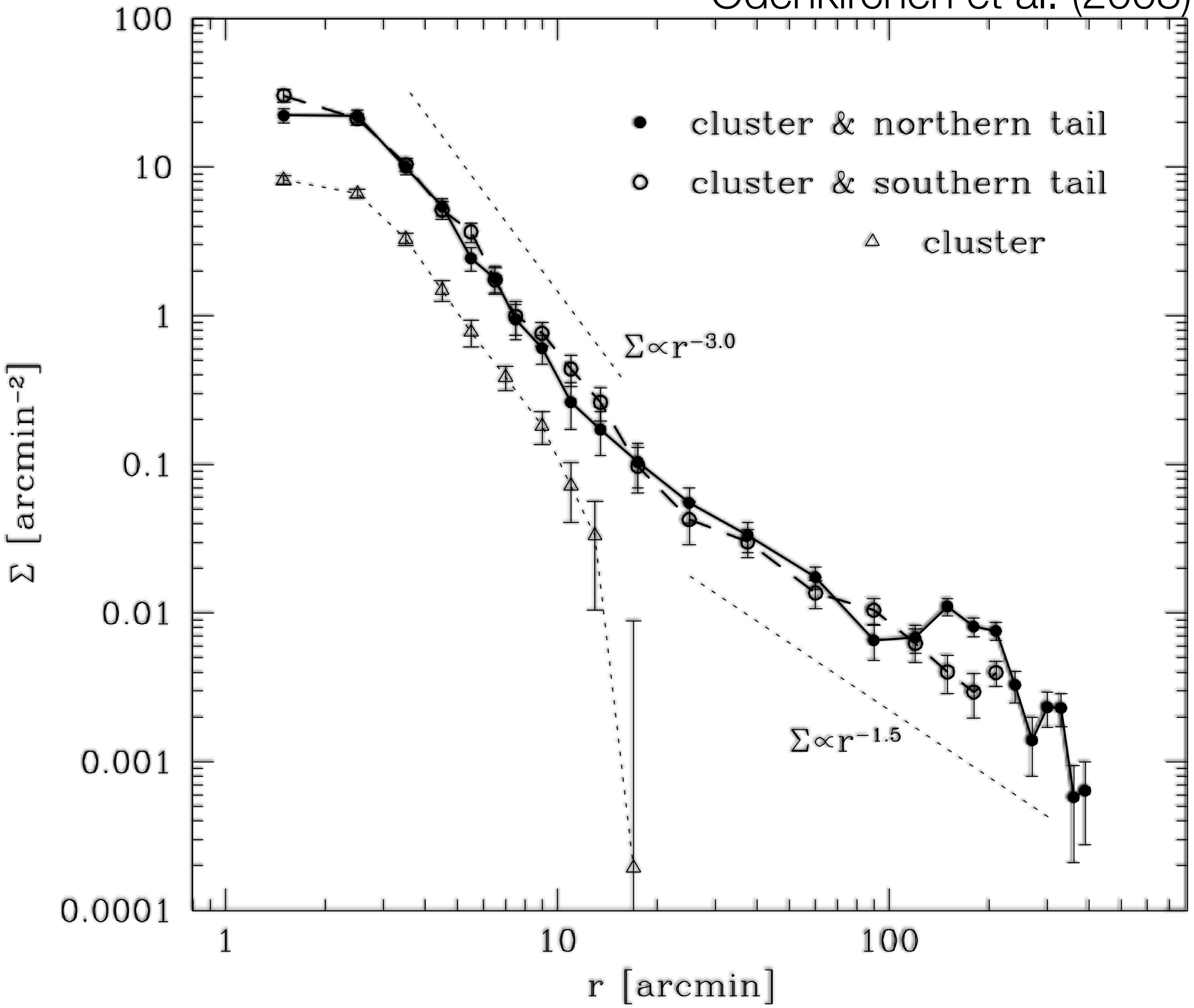


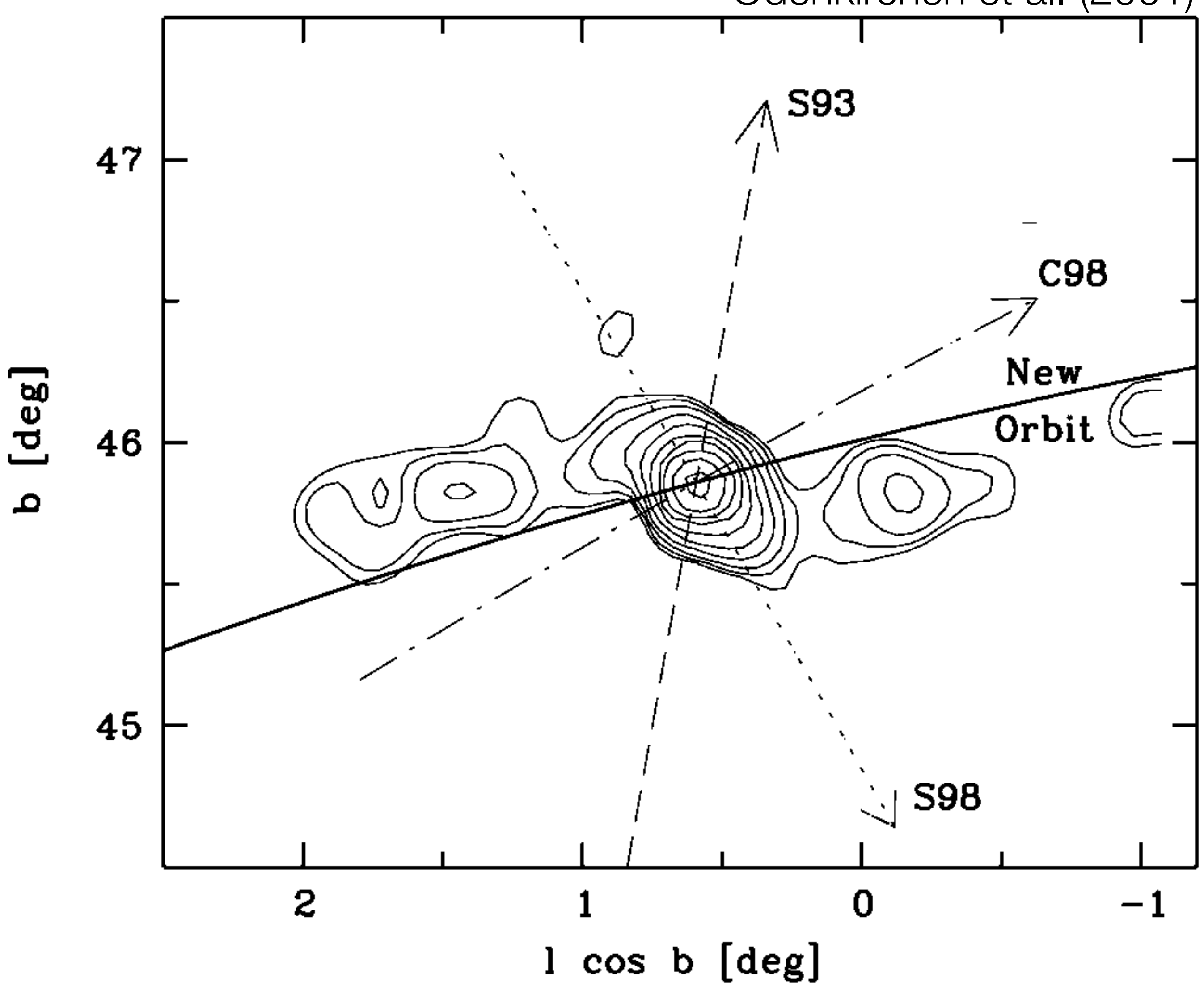


Palomar 5 is a low-mass, low-density clusters in the halo of the Milky Way high above the Galactic disk

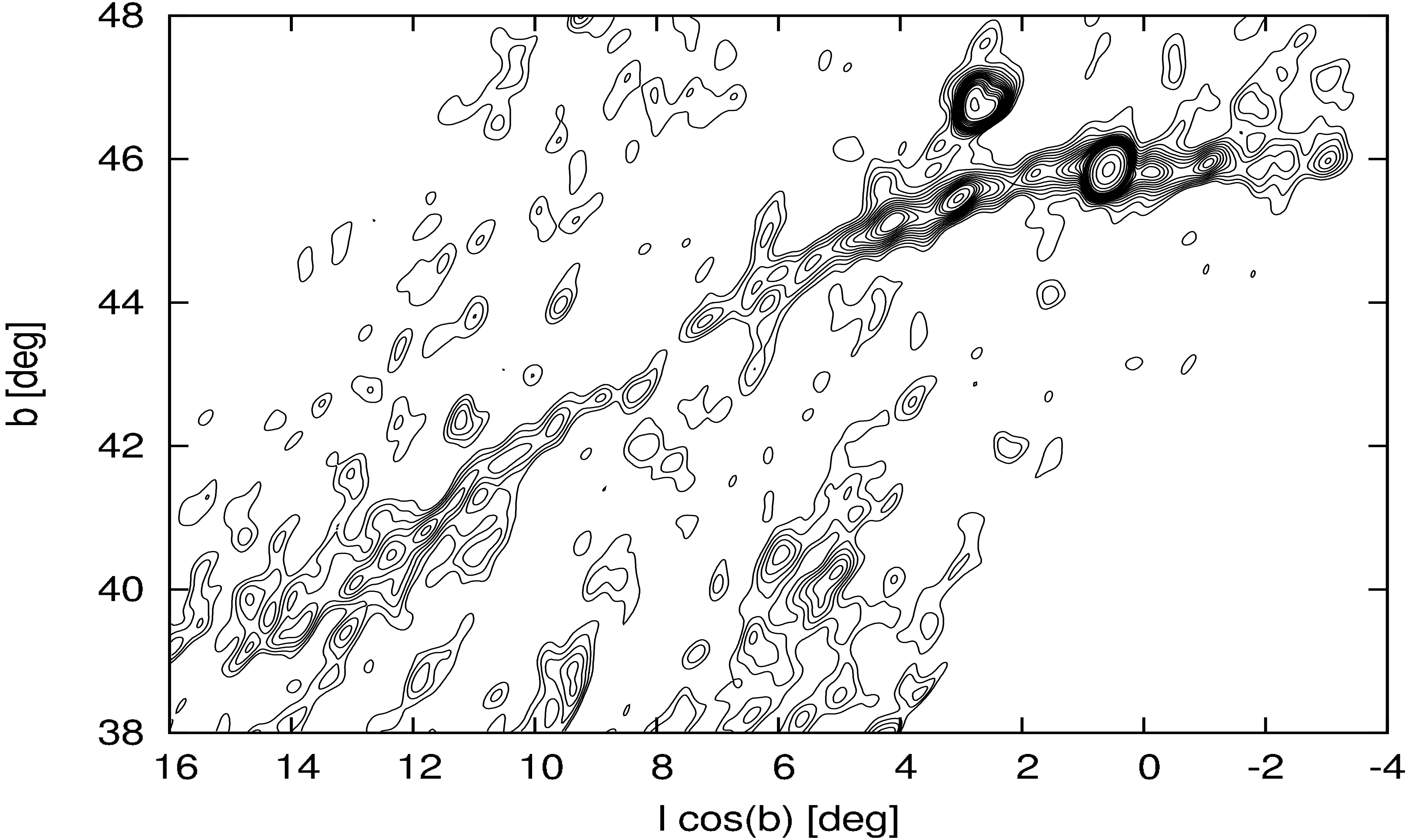
Odenkirchen et al. (2003)



Odenkirchen et al. (2001)

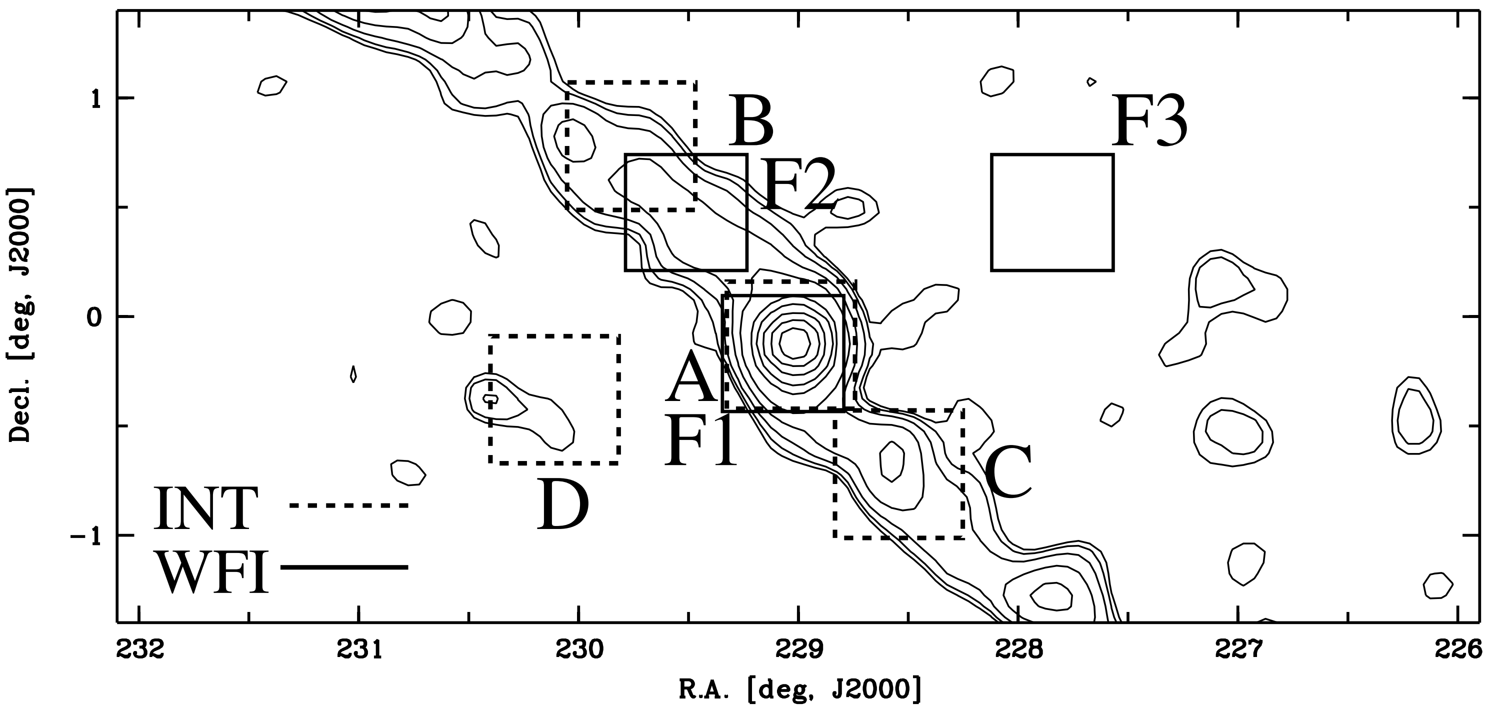


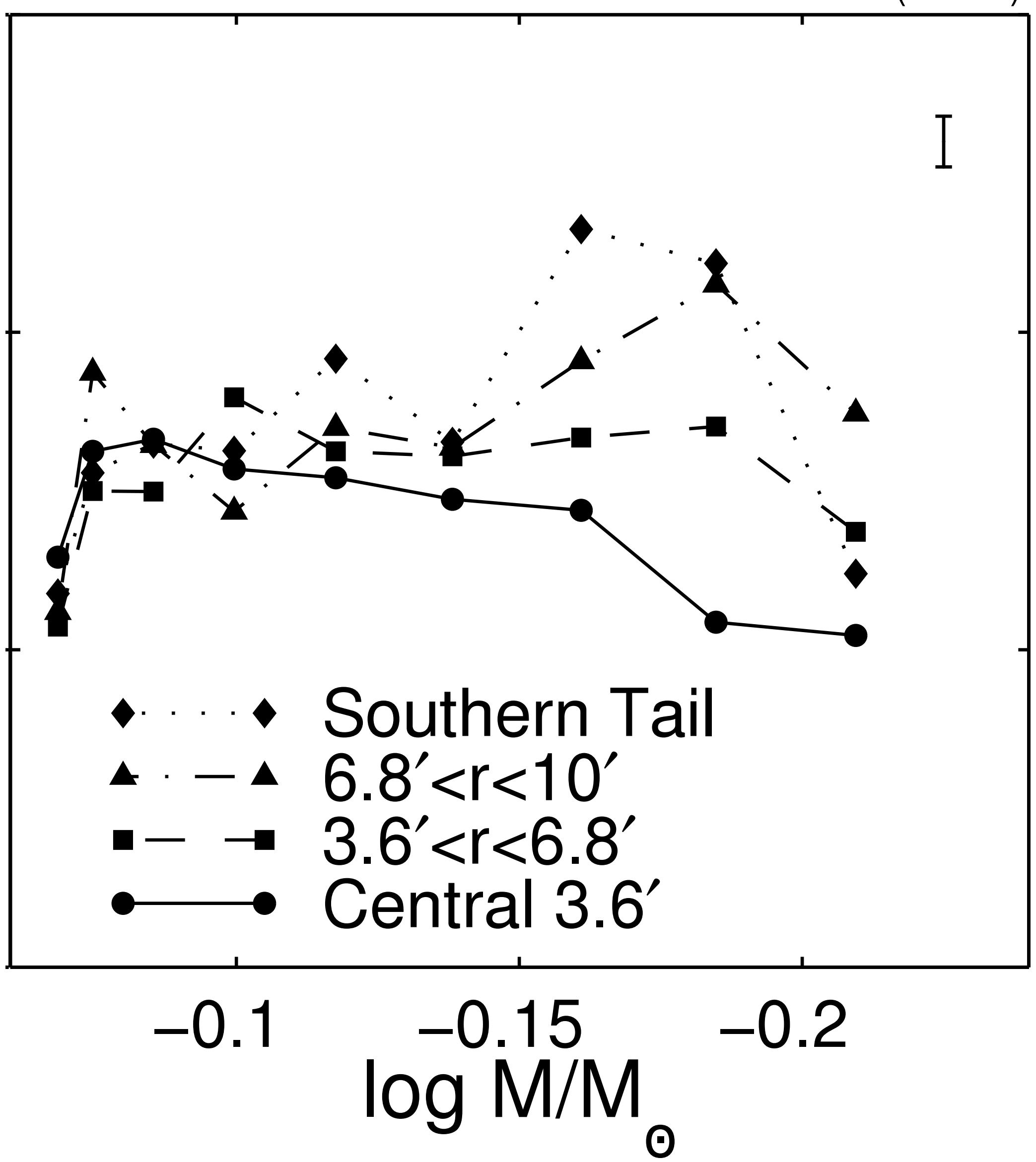
In the last data release it can be traced for > 20 deg, which corresponds to more than 8 kpc



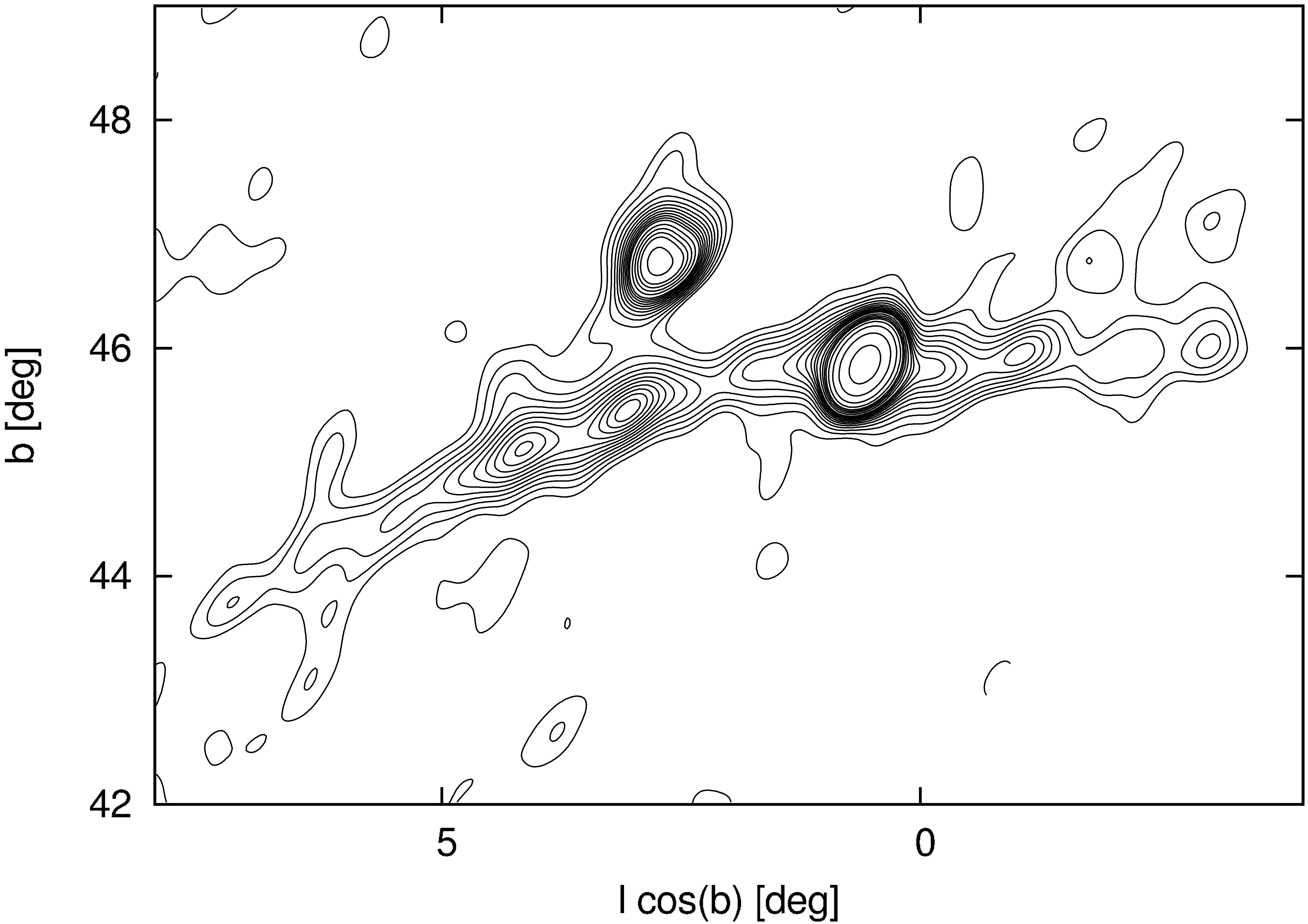
Palomar 5 is dissolving, not being torn apart

Koch et al. (2004)





The stream shows substructure



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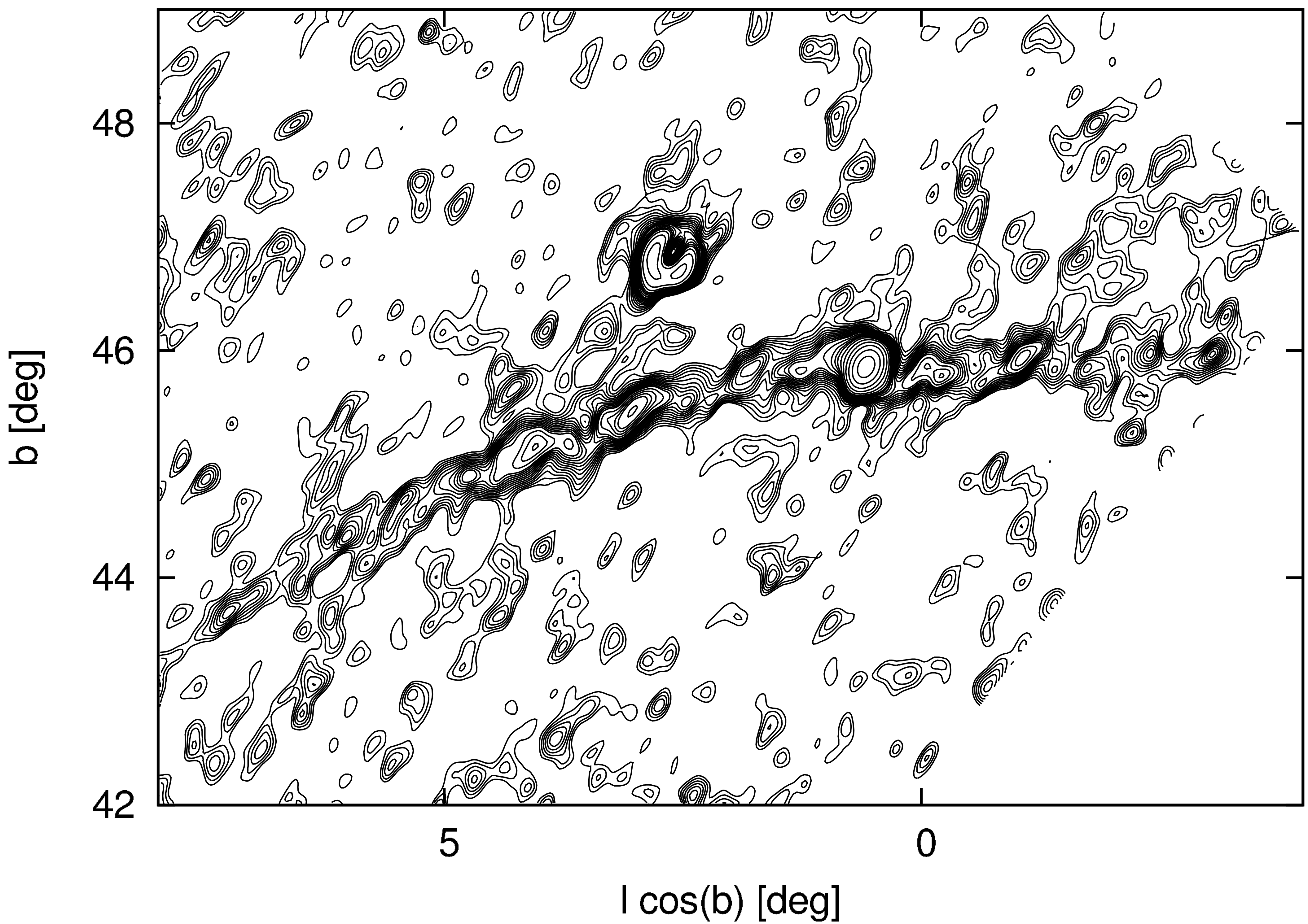
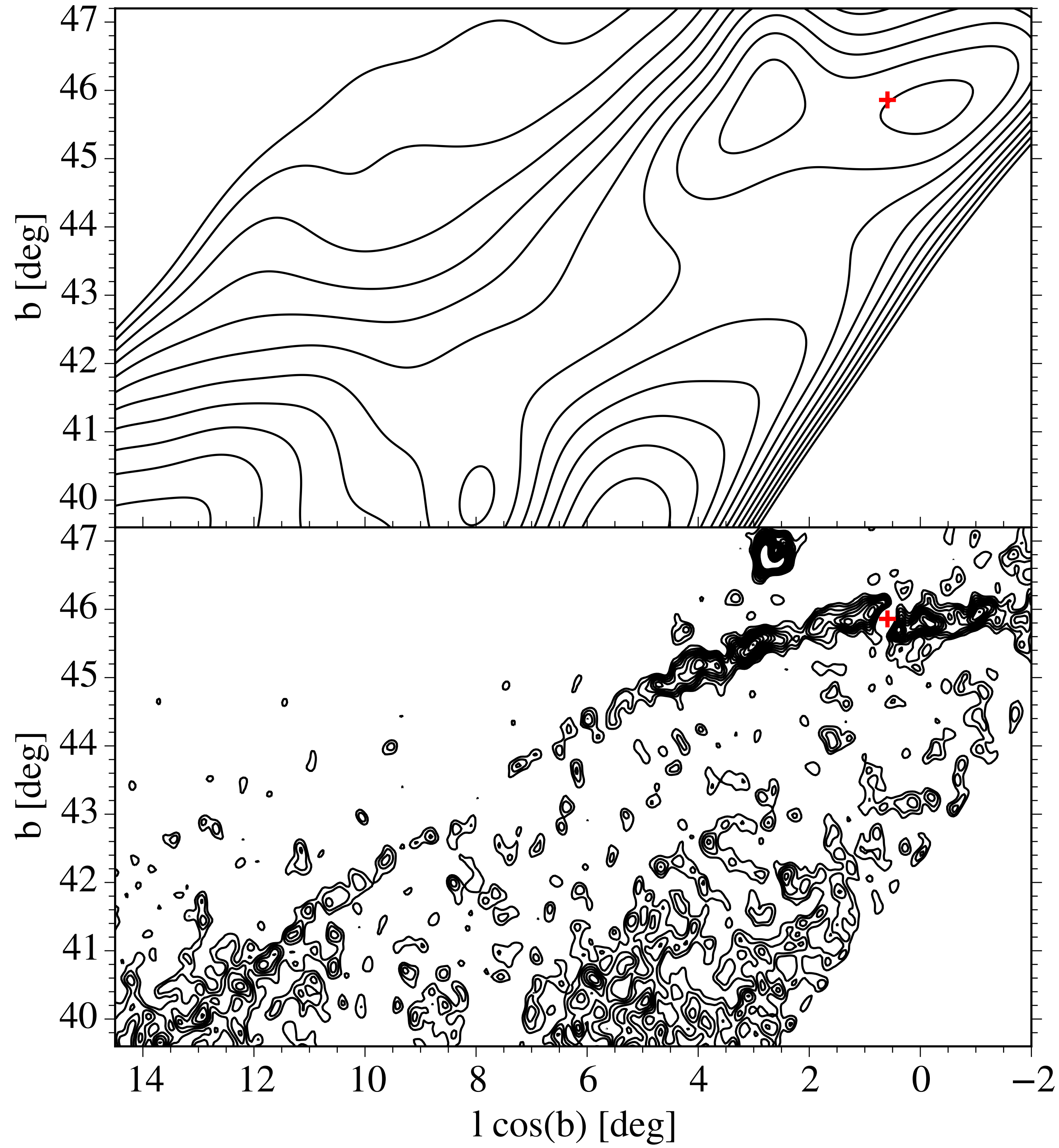
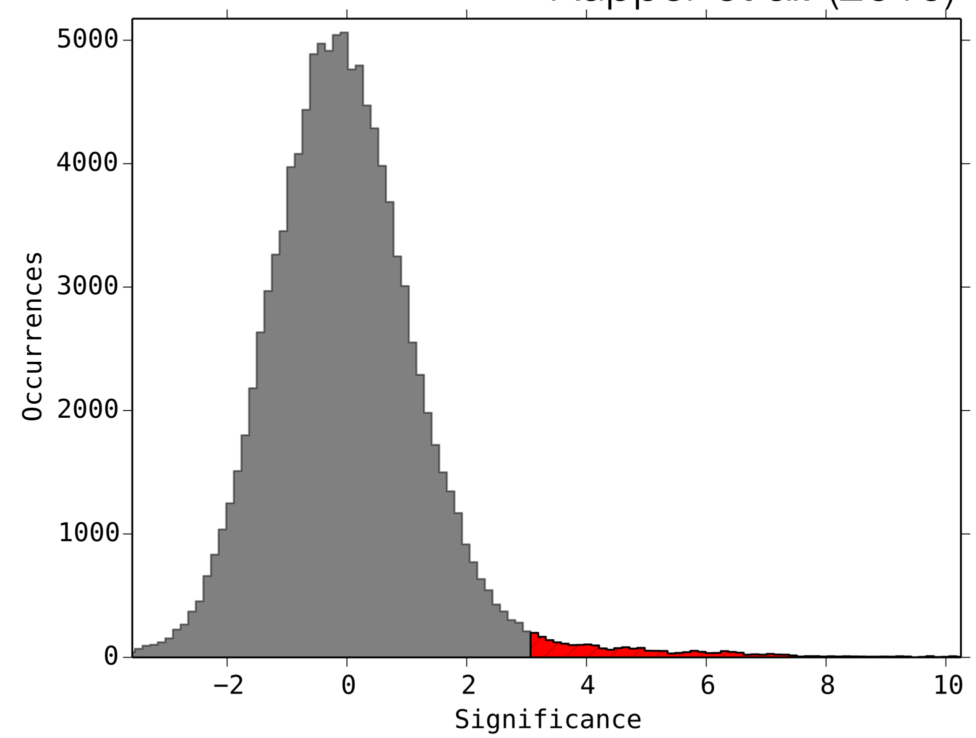


Substructure can be statistically quantified using a difference-of-Gaussian process



Küpper et al. (2015)



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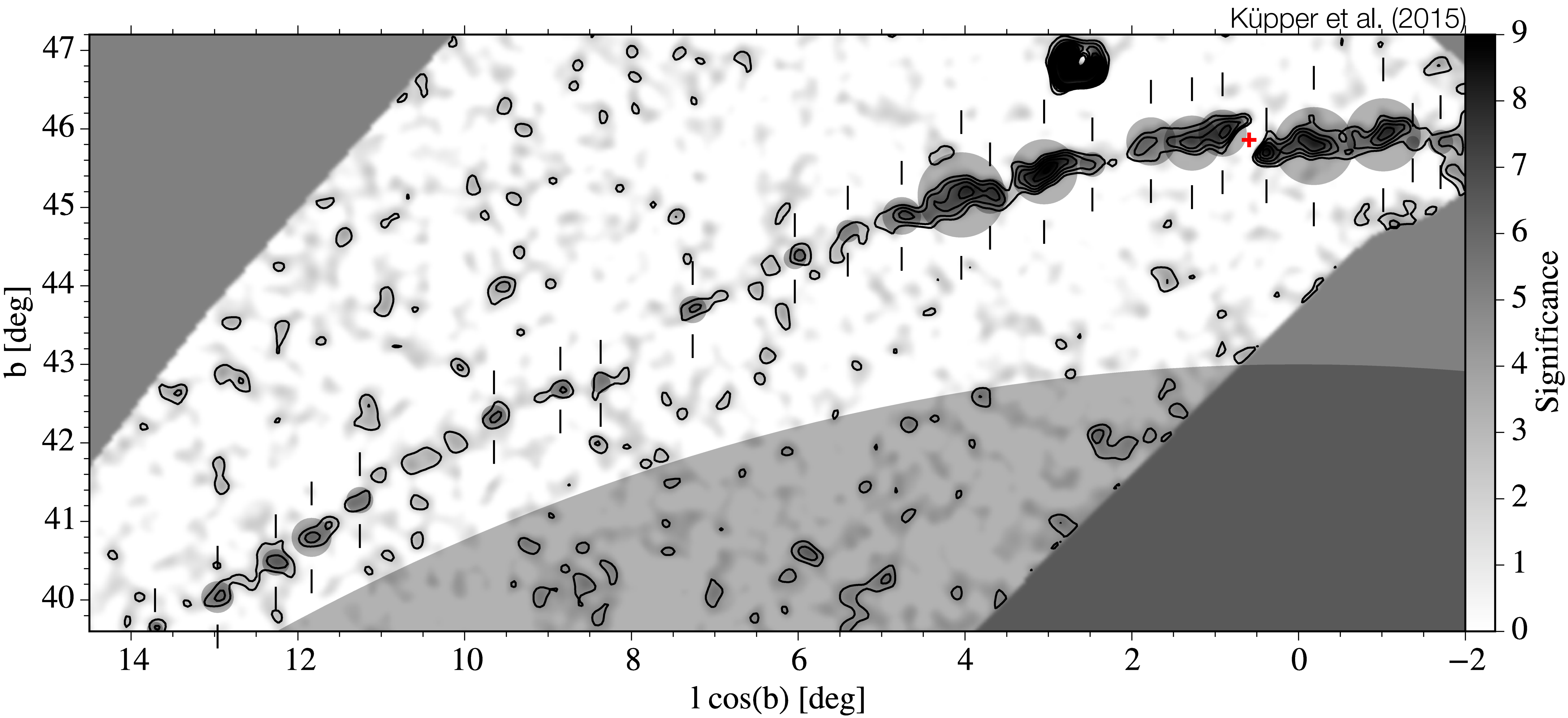
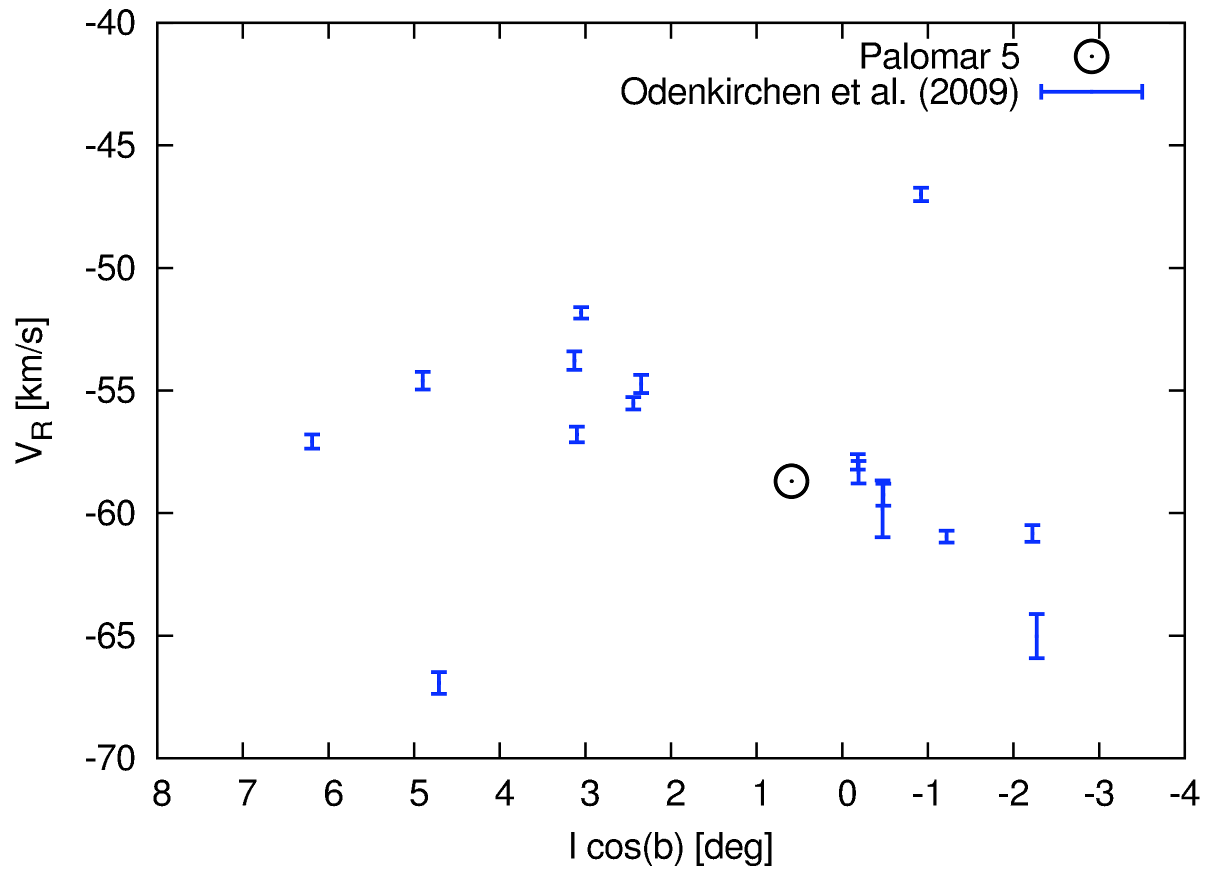
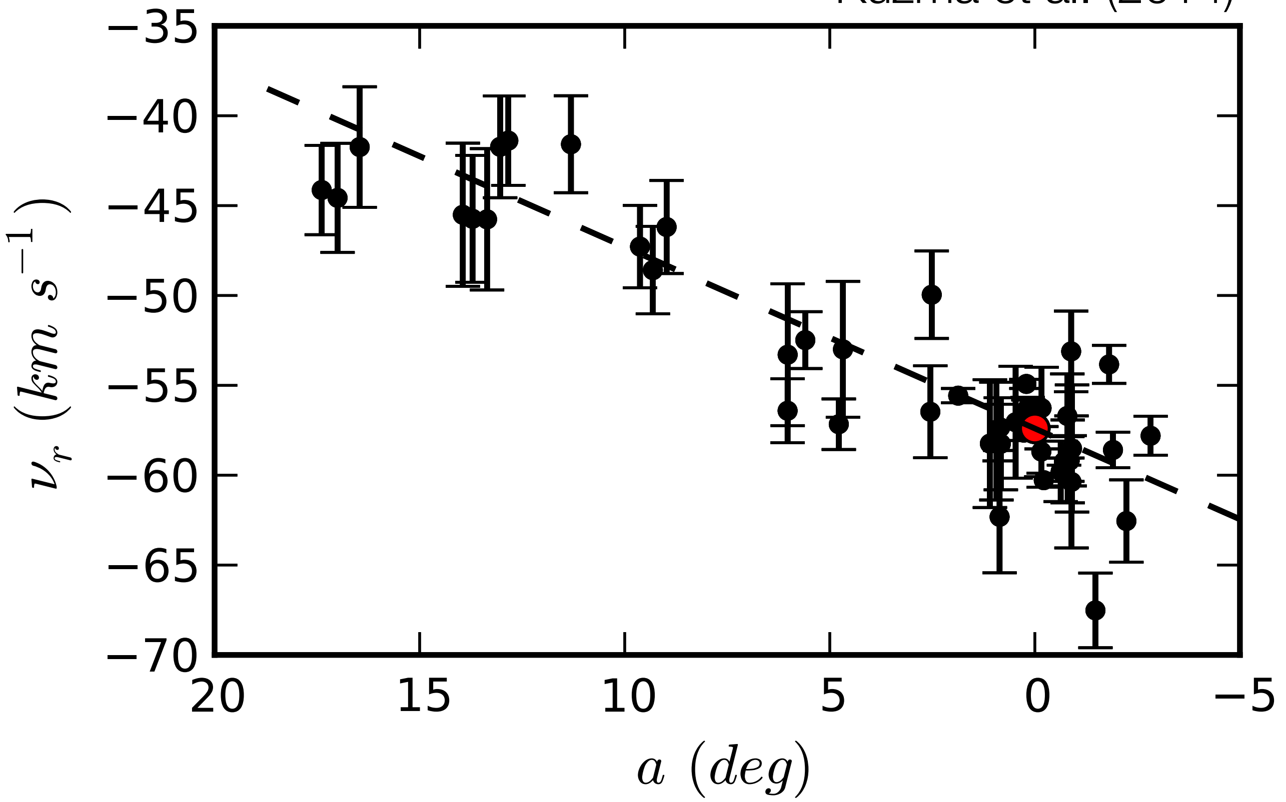


17 (+ 47) radial velocities have been measured along the tidal stream

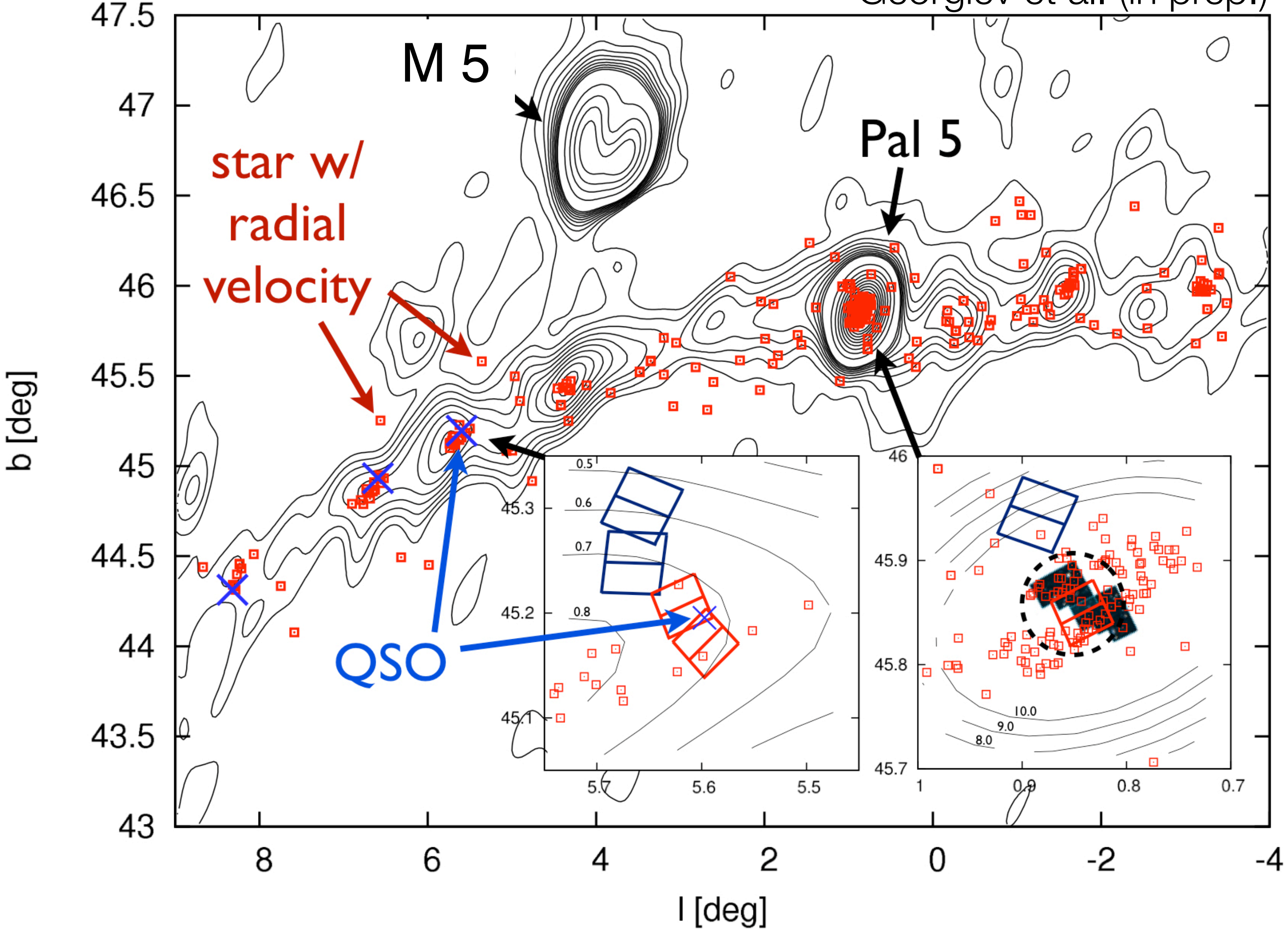


Kuzma et al. (2014)

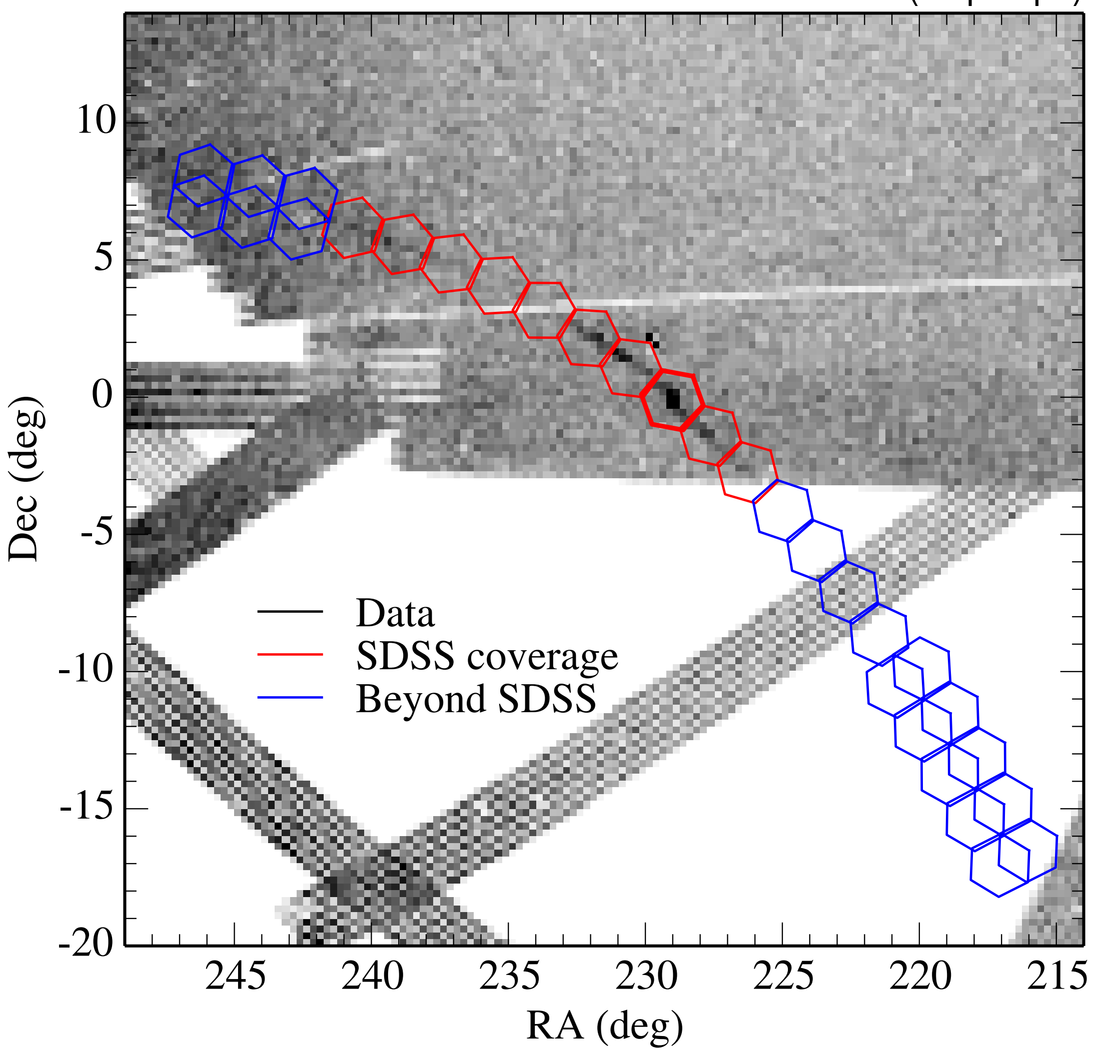


More data is coming soon

Georgiev et al. (in prep.)

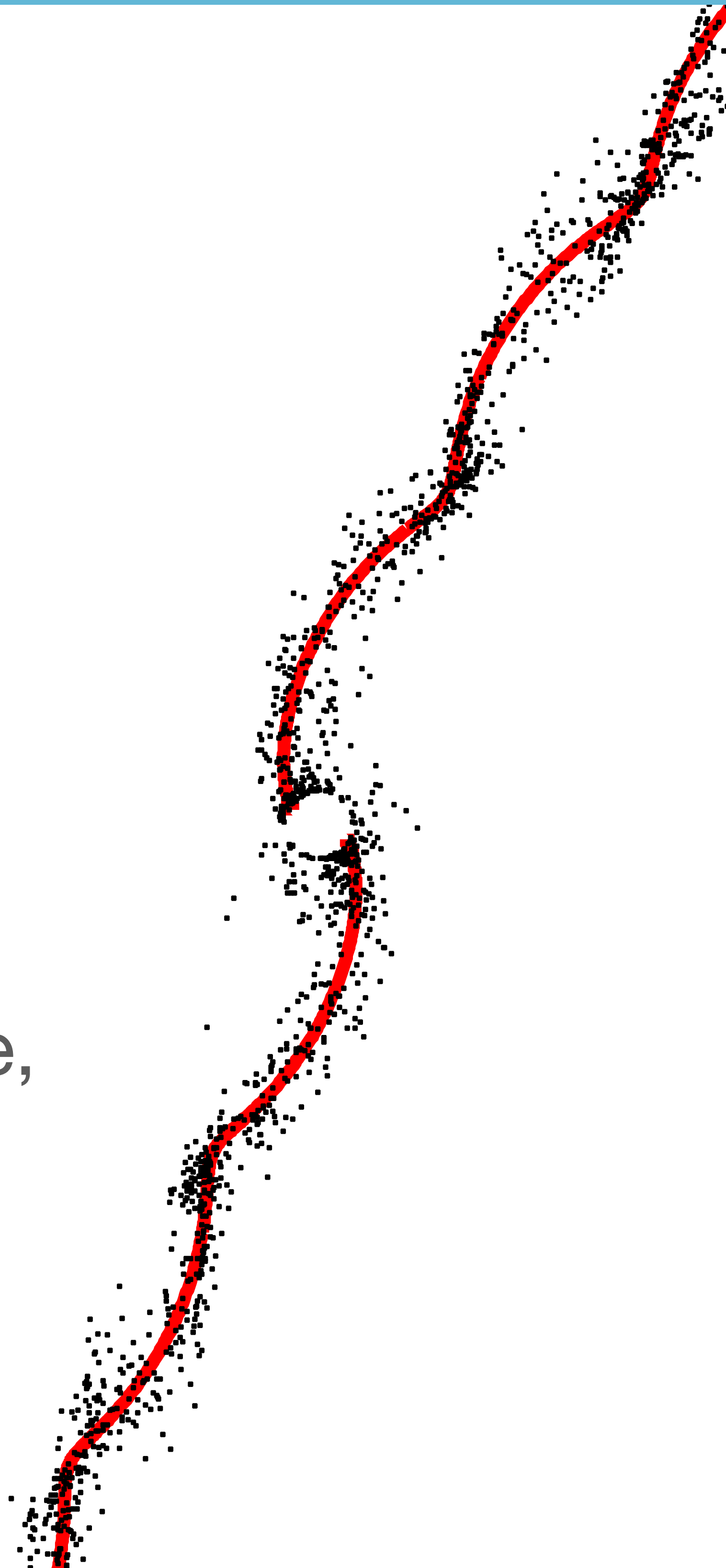


Bonaca et al. (in prep.)

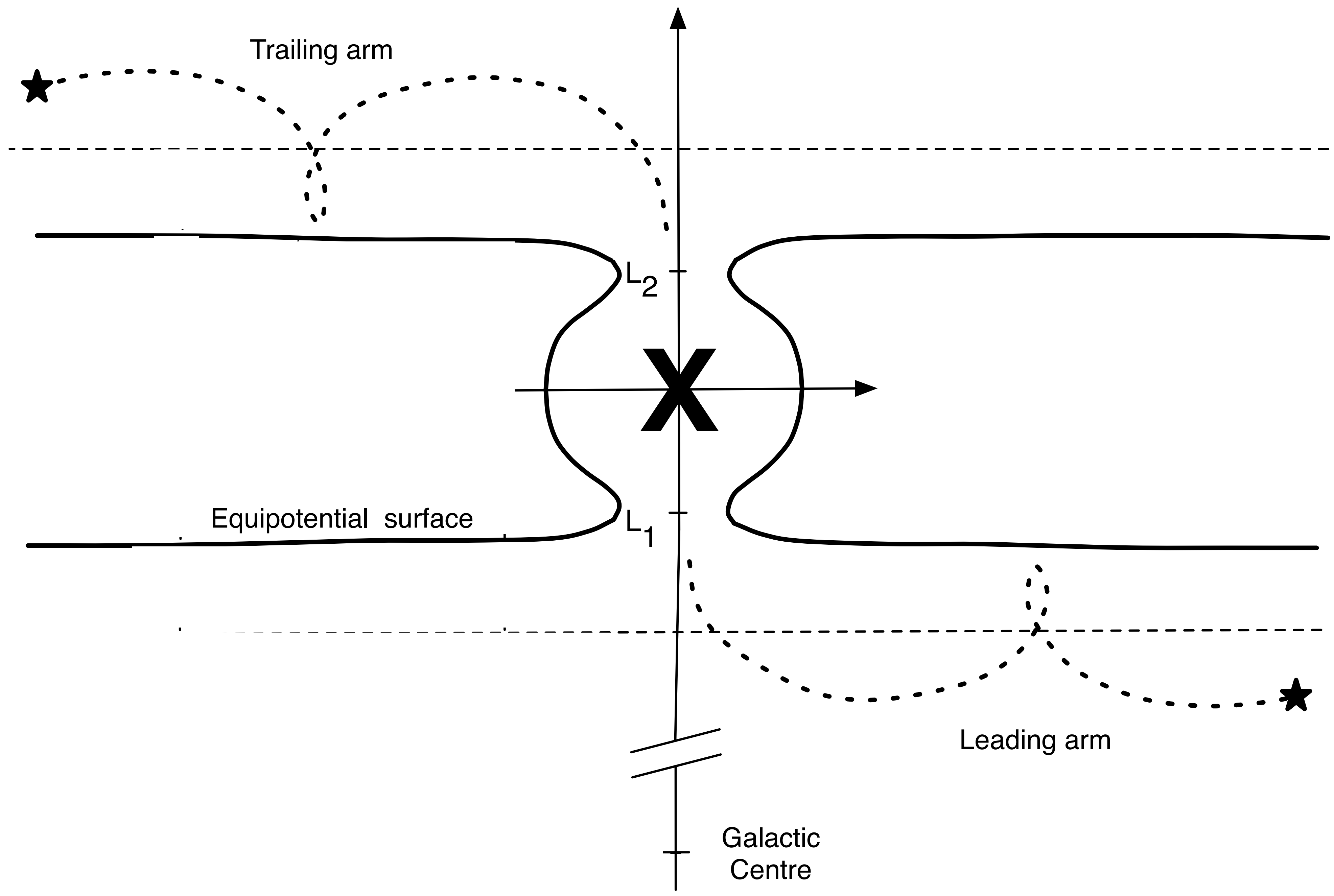


Several modeling techniques have been developed in recent years

- Orbit fitting (Buist, Deg, Koposov)
- Actions, Angles & Frequencies (Bovy, Sanders)
- Rewinding orbits (Price-Whelan)
- Entropy minimization (Peñarrubia, Sanderson)
- Energy conservation (Hattori)
- Streakline/particle spray (Odenkirchen, Varghese, Bonaca, Amorisco, Fardal, Gibbons, …)



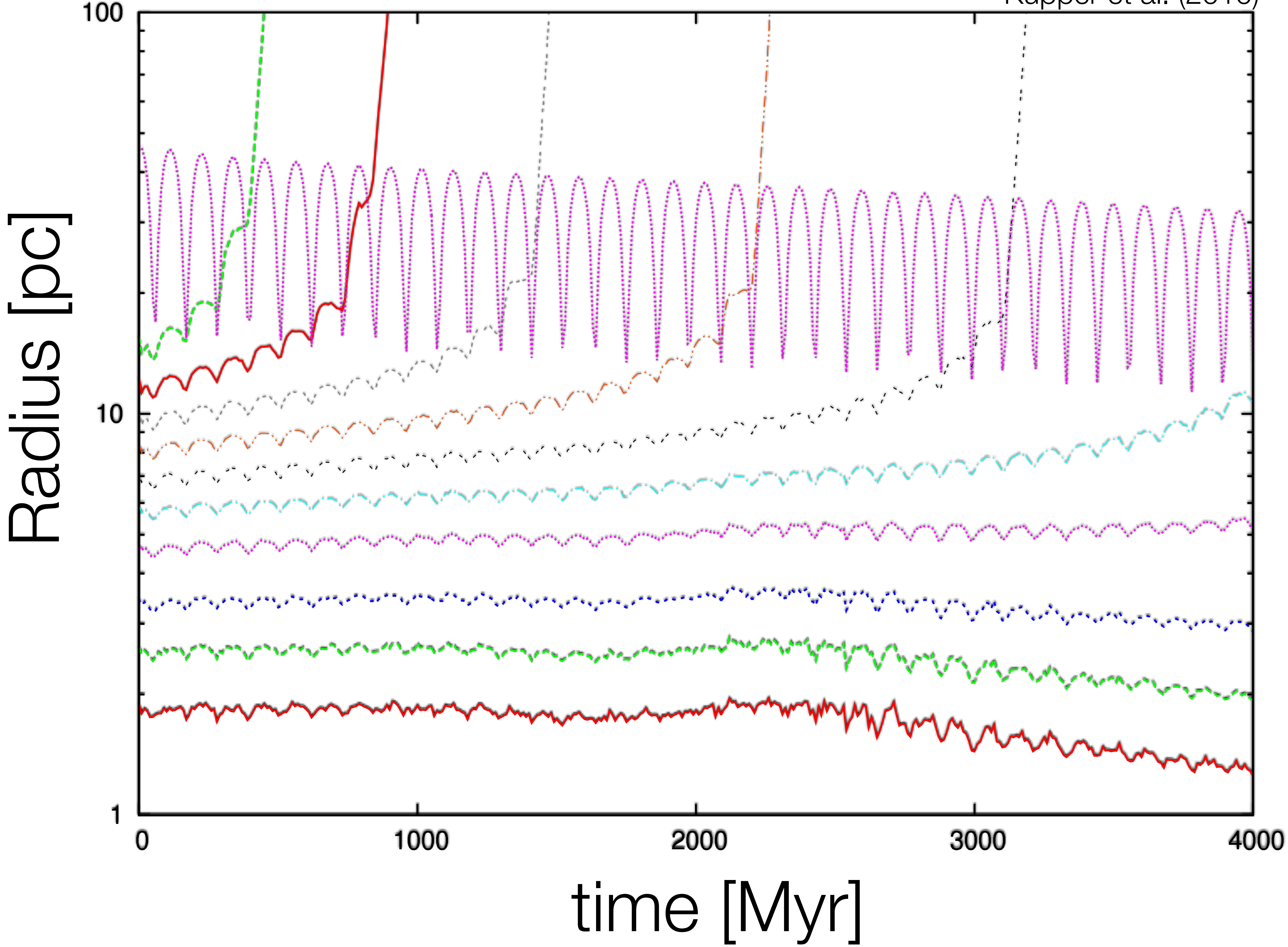
Stars escape through the Lagrange points with low offset velocities



Just, Berczik, Petrov & Ernst (2009)

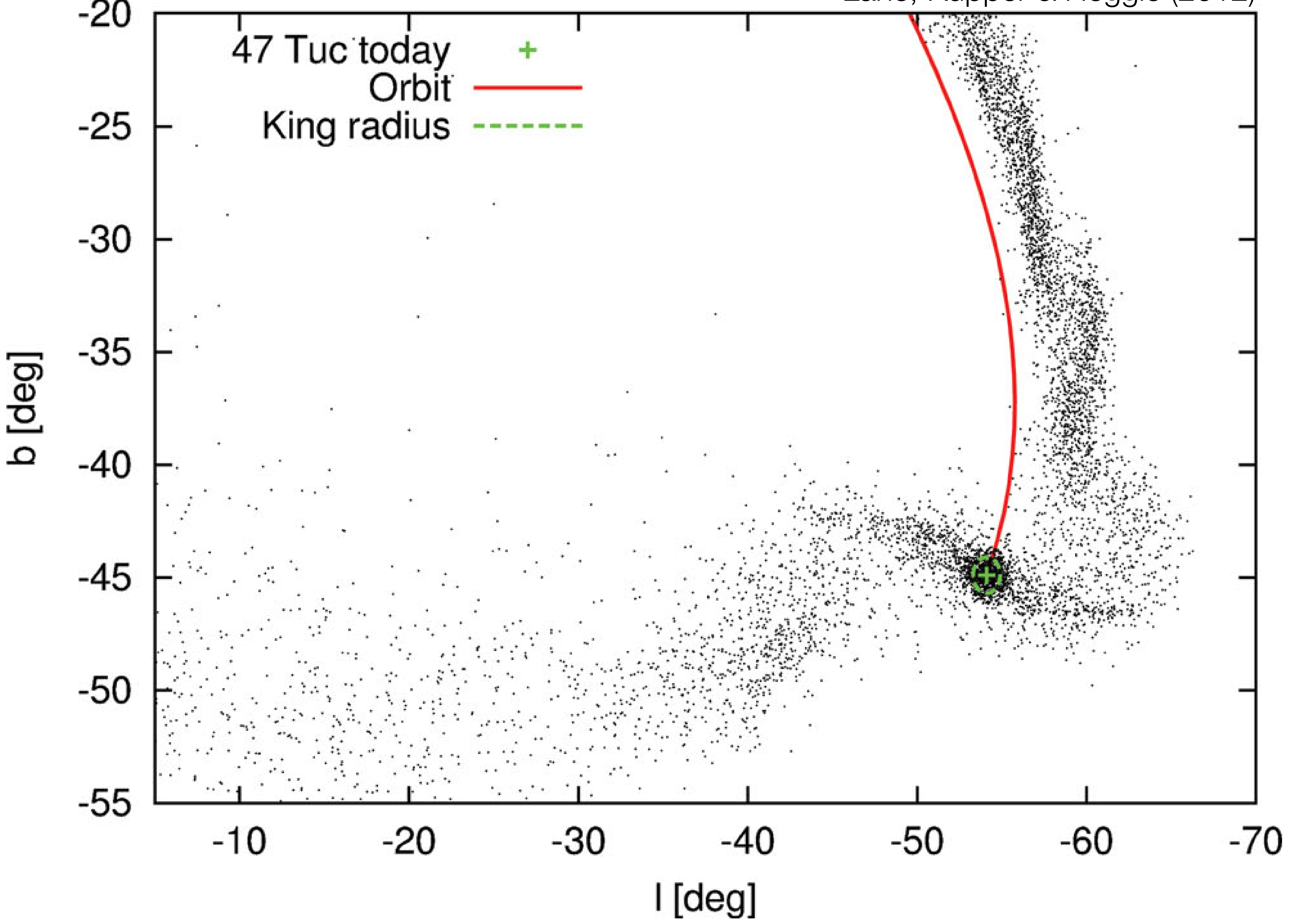
Stars escape from the Jacobi radius - if they can

Küpper et al. (2010)



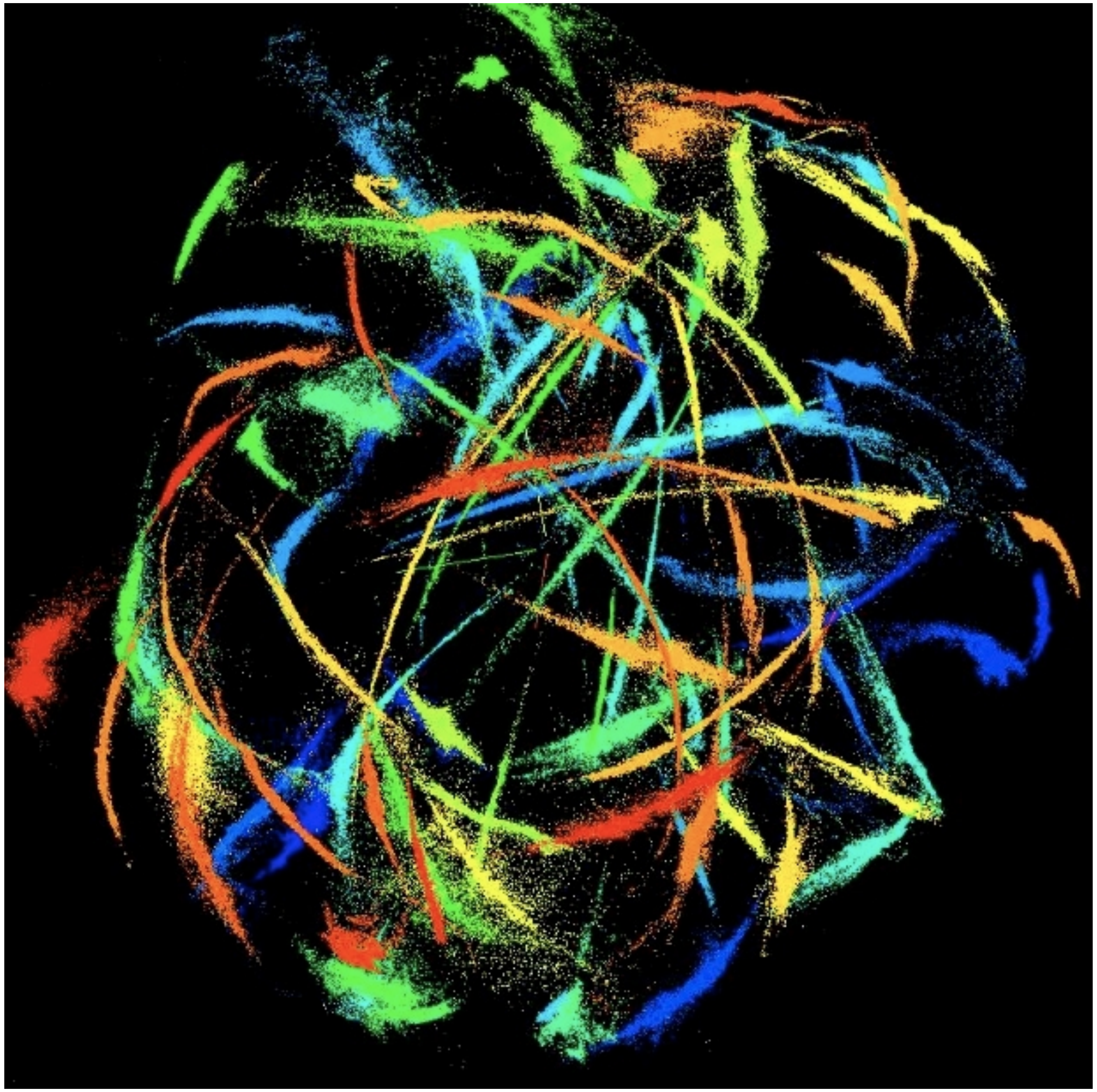
Streaklines can be used to predict shapes of streams

Lane, Küpper & Heggie (2012)



Streaklines can be easily inserted into simulations of structure formation

Küpper & Diemand (in prep.)

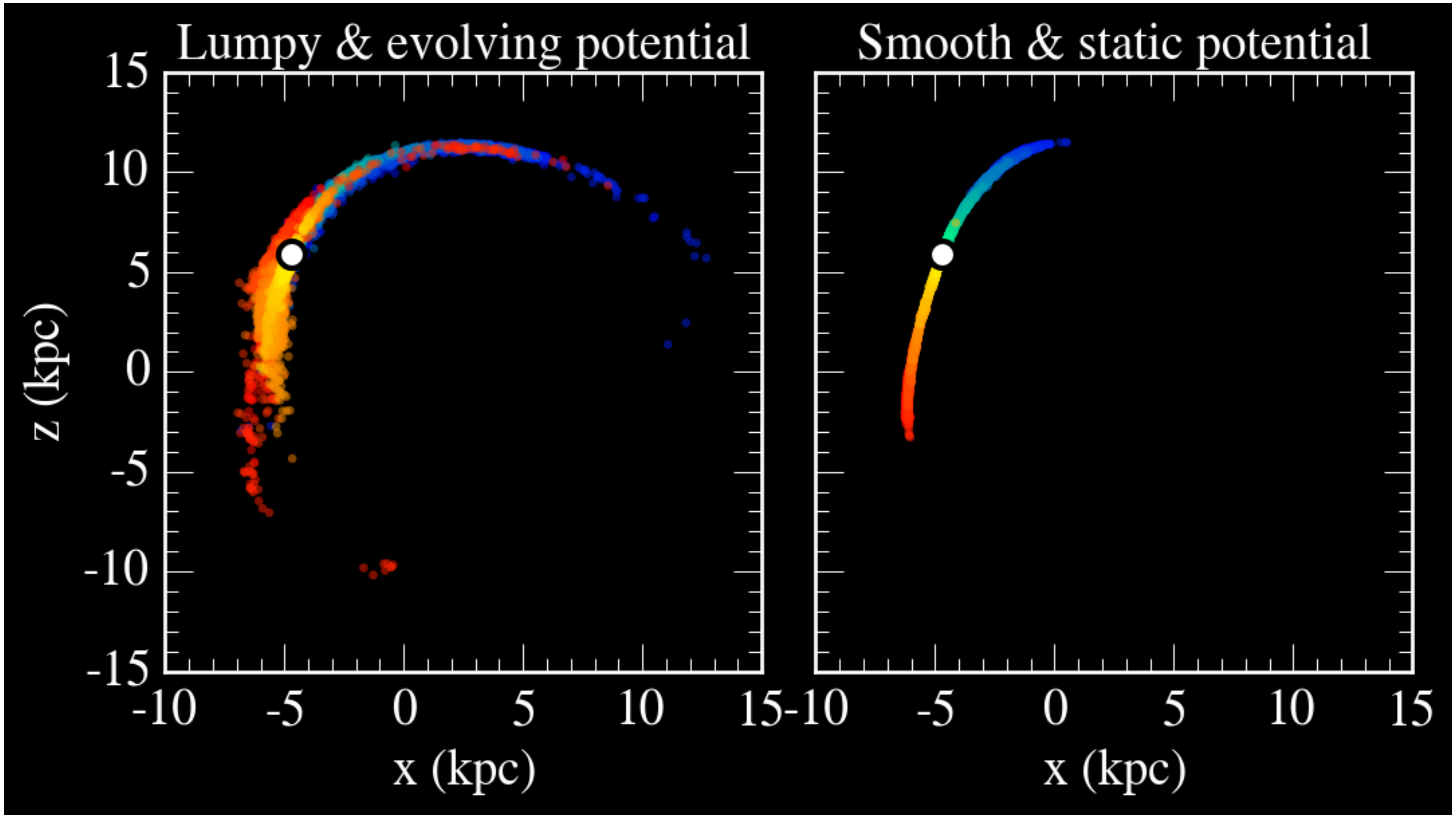


Via Lactea Cauda

- 1.1 billion DM particles
- 1280 cluster particles
- 120,000 stream particles each
- data publicly available soon

Can we approximate a live halo with a static, analytic parametrization?

Bonaca et al. (2014)



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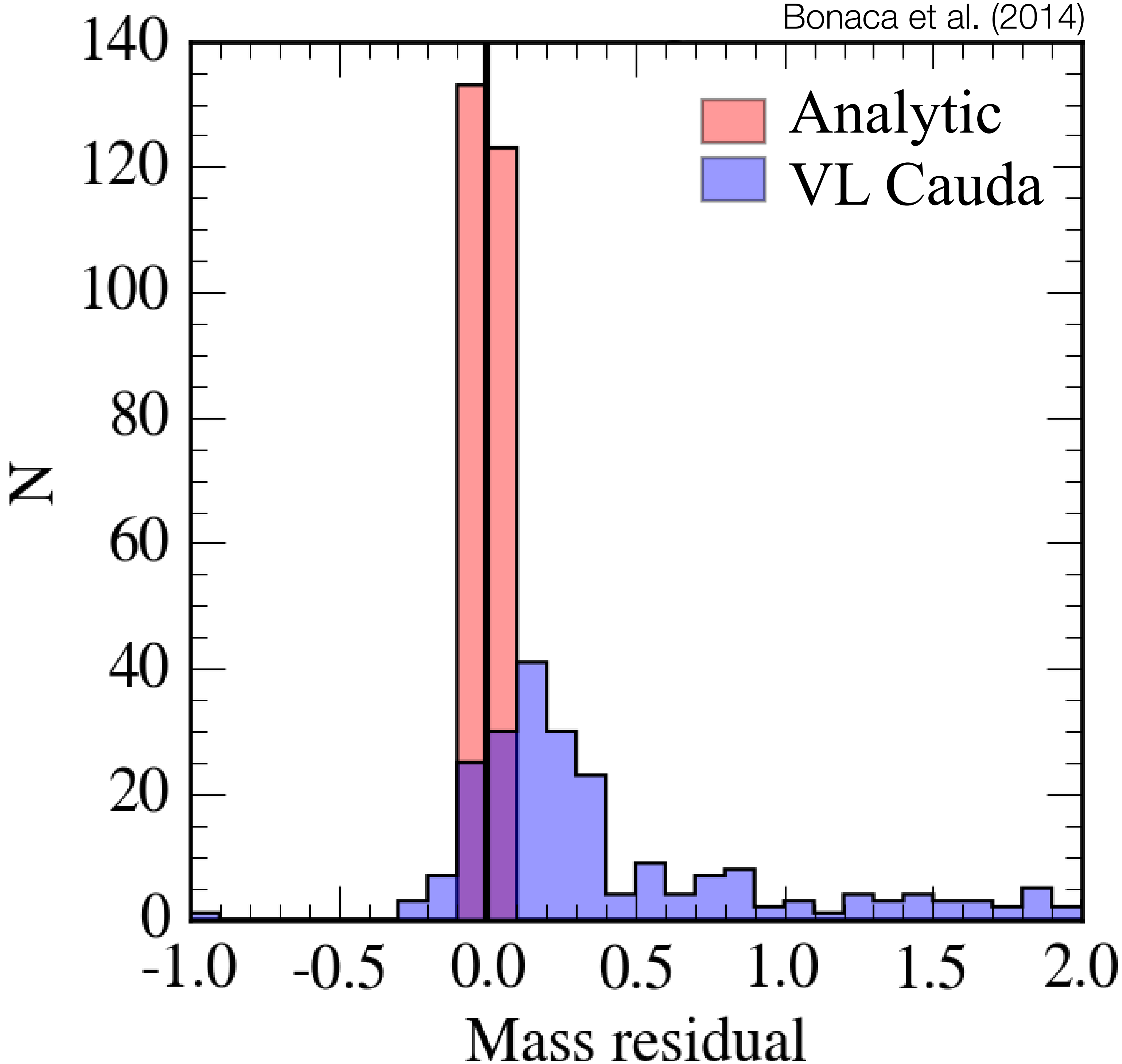
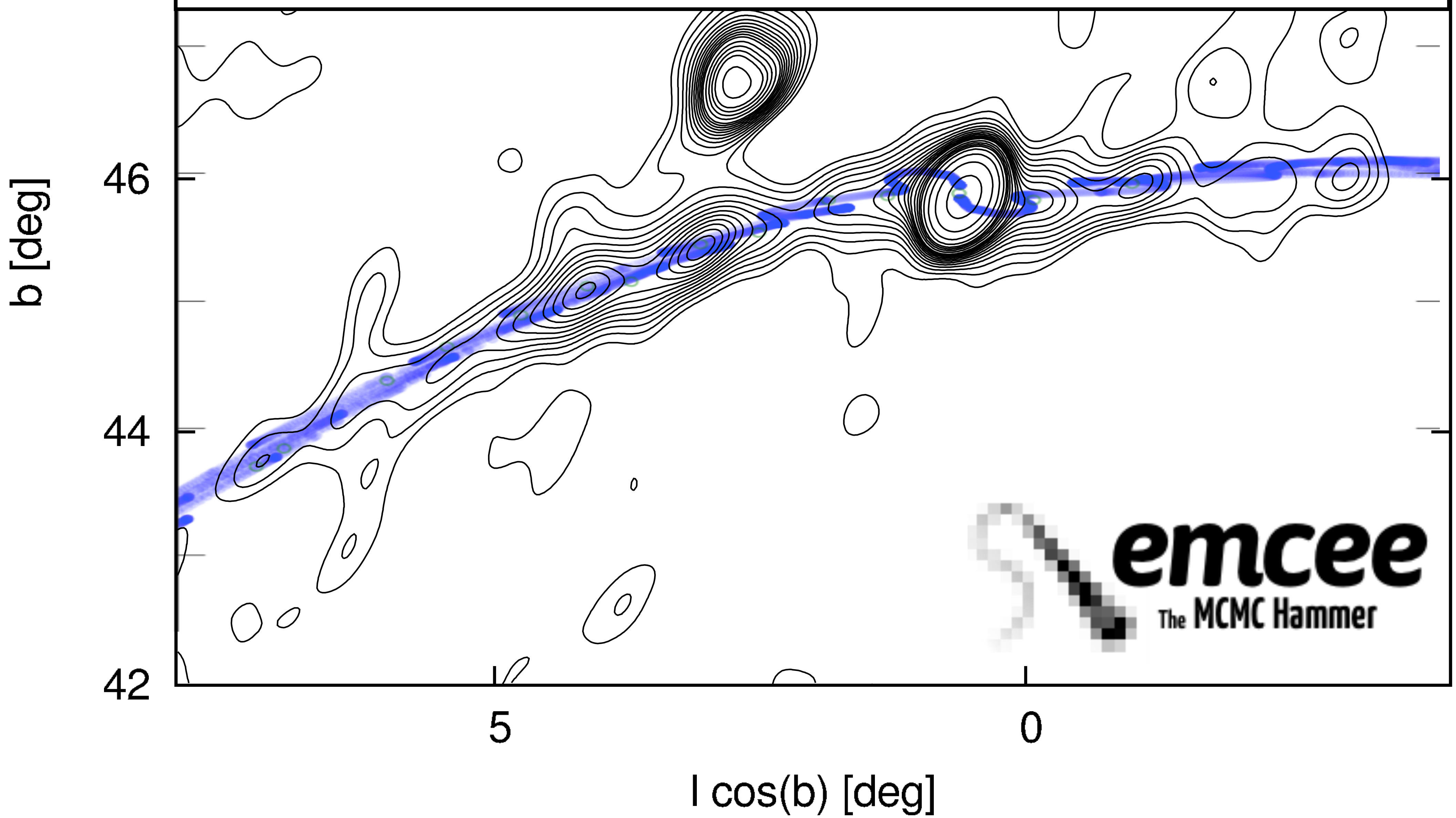


Ana Bonaca (Yale)

10^7 stream realizations for inference with MCMC using 10^5 CPU hours on Columbia's Yeti cluster

Küpper et al. (2015)

$$\log L = k \sum_{j}^{M} \log \left(\frac{1}{N\sigma_j^2} \sum_{i}^{N} e^{\left(-\frac{(\vec{x}_i - \vec{x}_j)^2}{2\sigma_j^2}\right)} + C \right)$$



Our streakline modeling has 10 free parameters

NFW halo scale mass

NFW halo scale radius

NFW halo flattening

Solar distance to Galactic center

Solar transverse velocity

distance Sun-Palomar 5

Palomar 5 proper motion RA

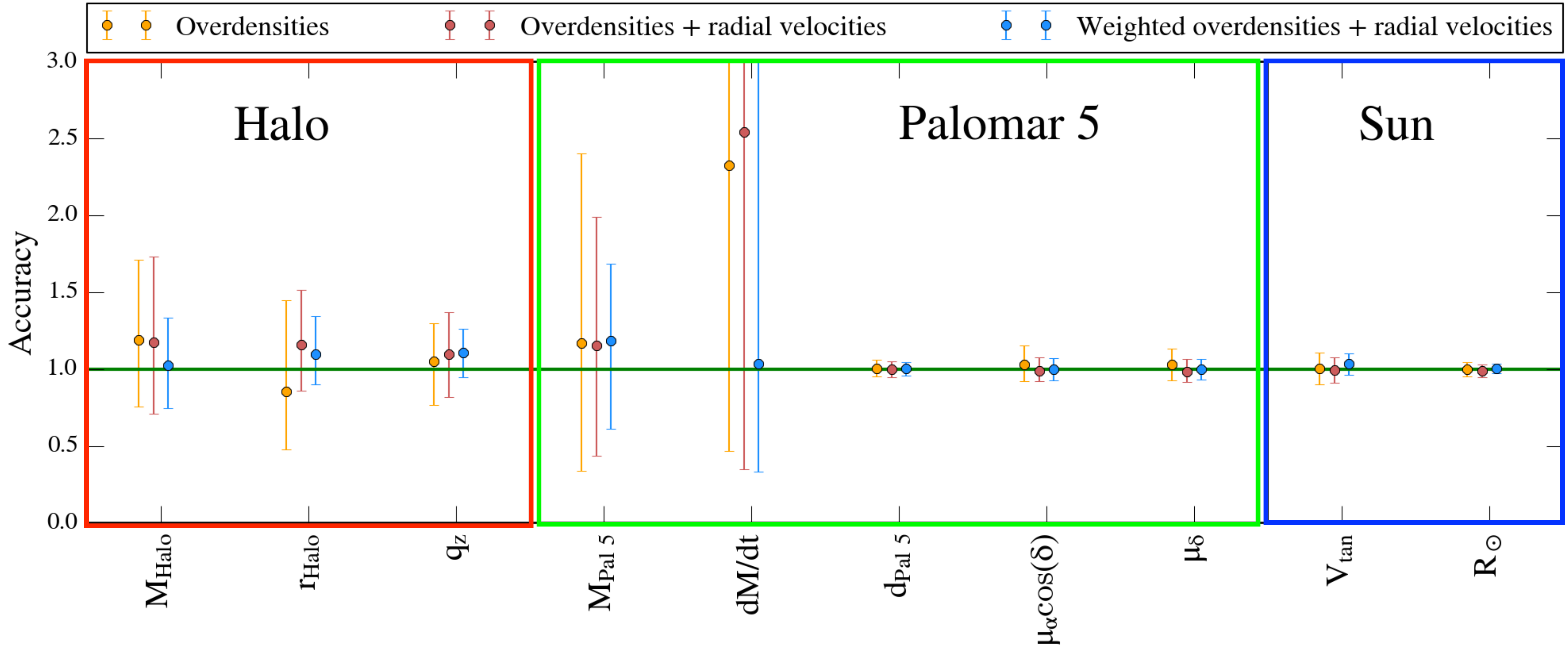
Palomar 5 proper motion Dec

present-day mass of Palomar 5

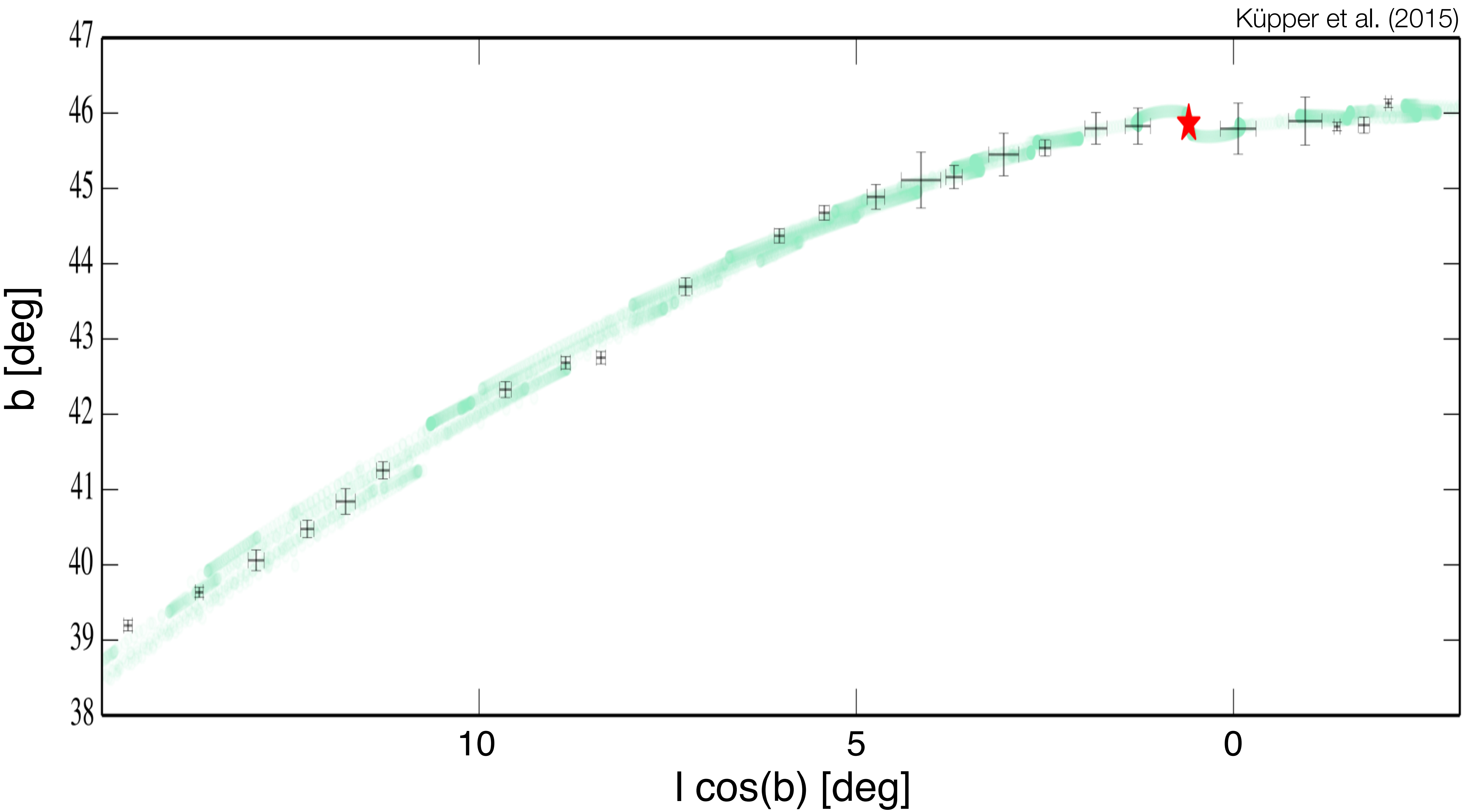
mean mass-loss rate of Palomar 5

If applied to an N-body simulation our method recovers all values with high accuracies

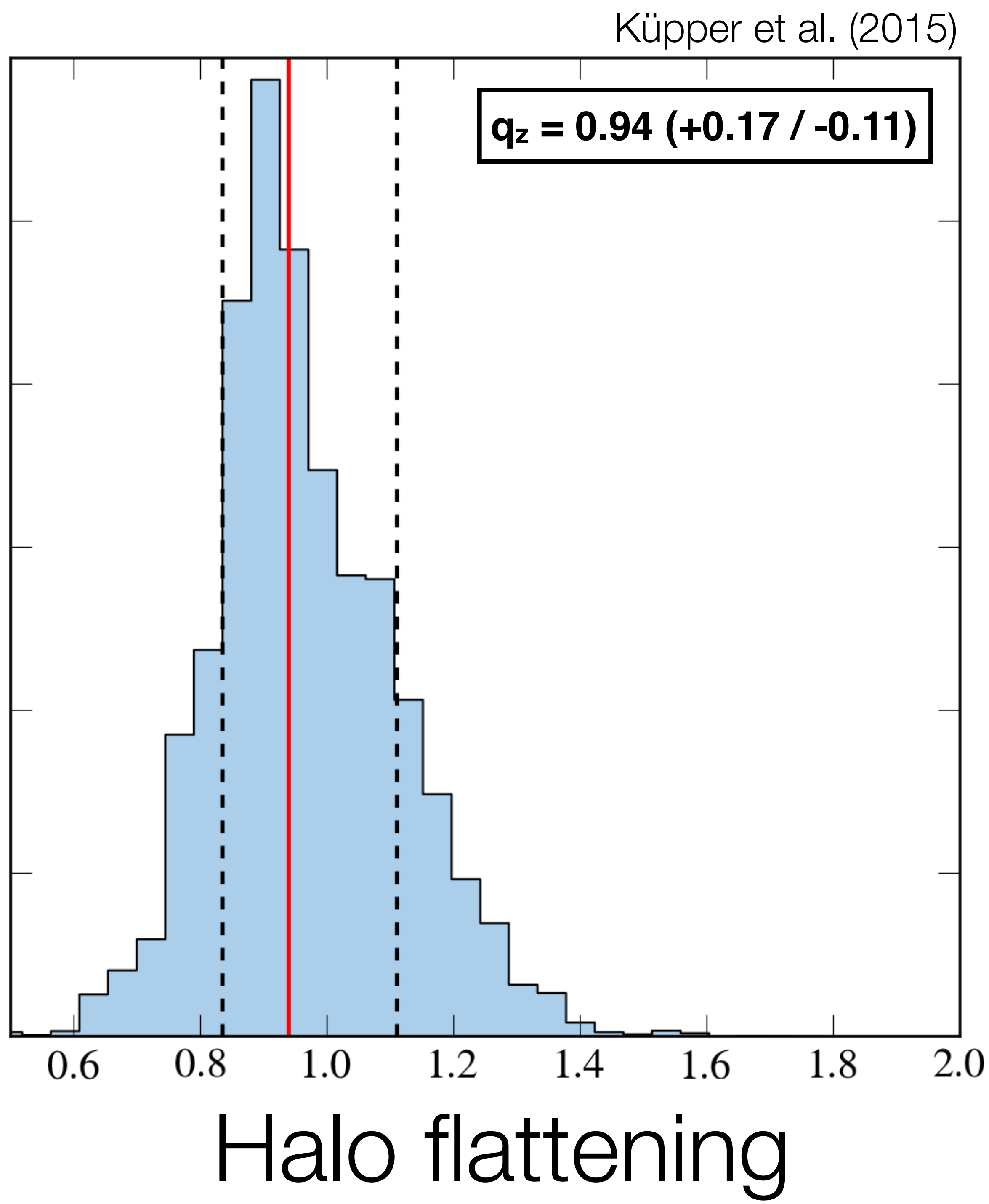
Küpper et al. (2015)



Best-fit streakline models recover overdensity pattern

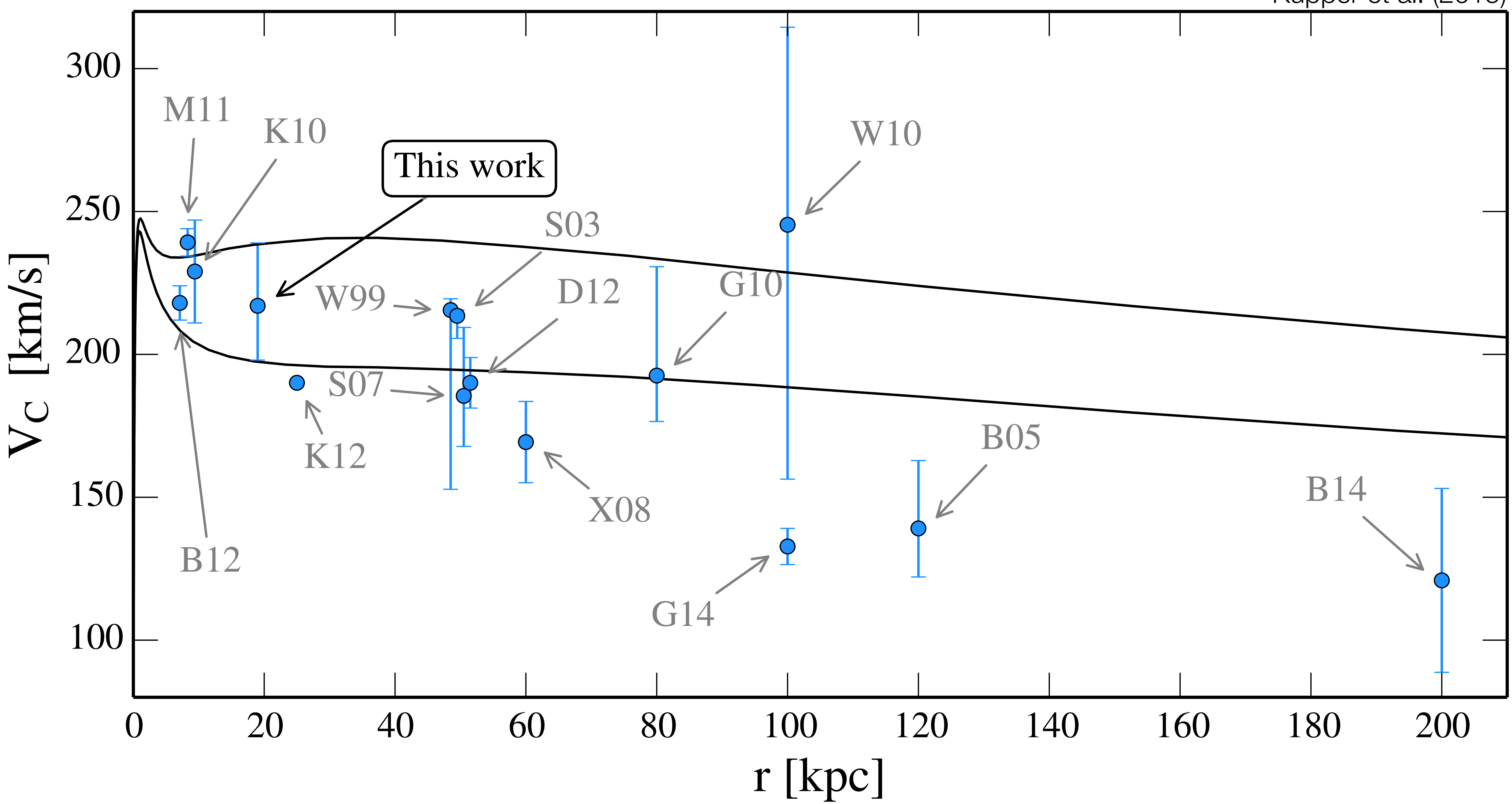


Halo at 19 kpc is slightly oblate

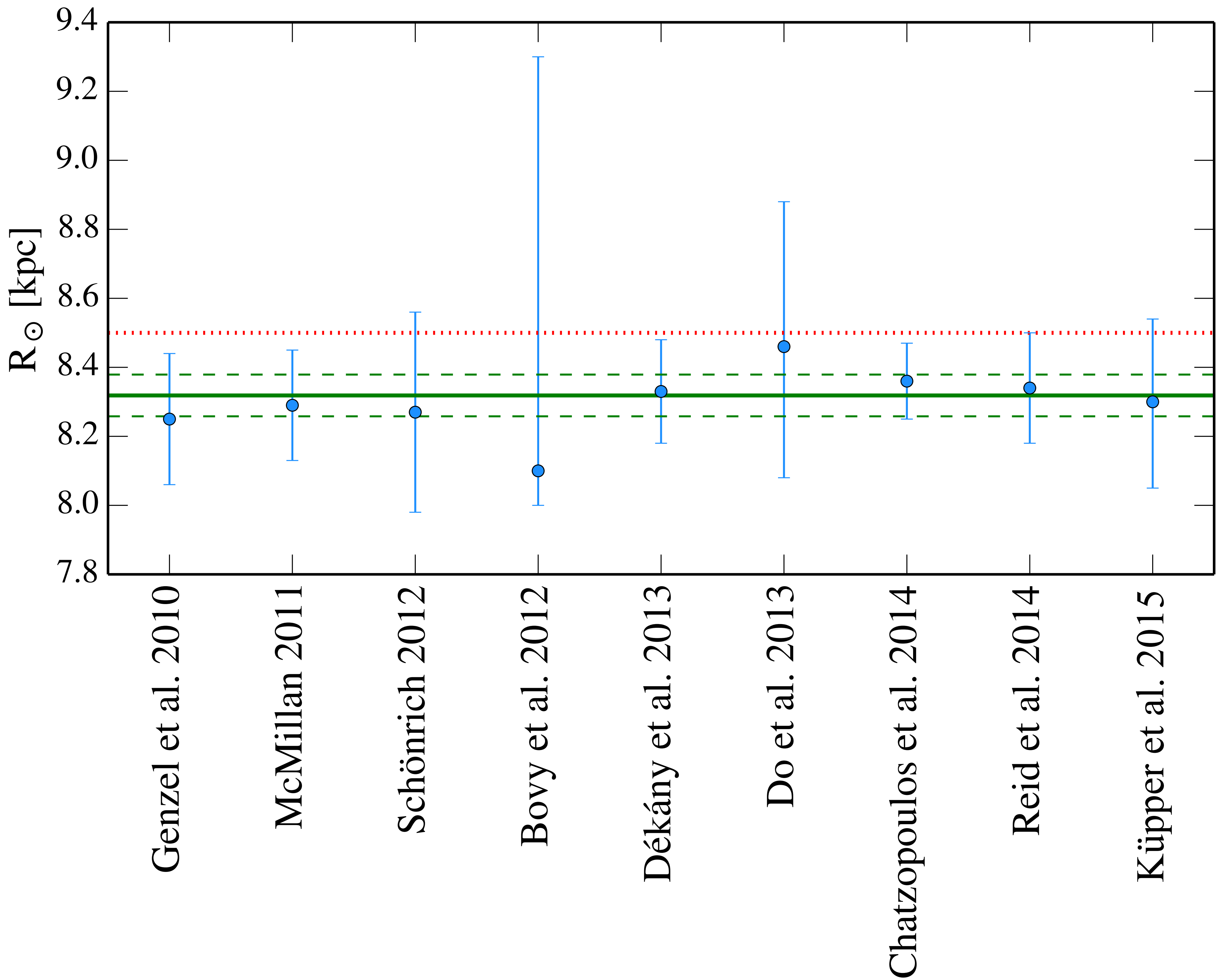


Circular velocity in the disk at 19 kpc is 221 km/s

Küpper et al. (2015)

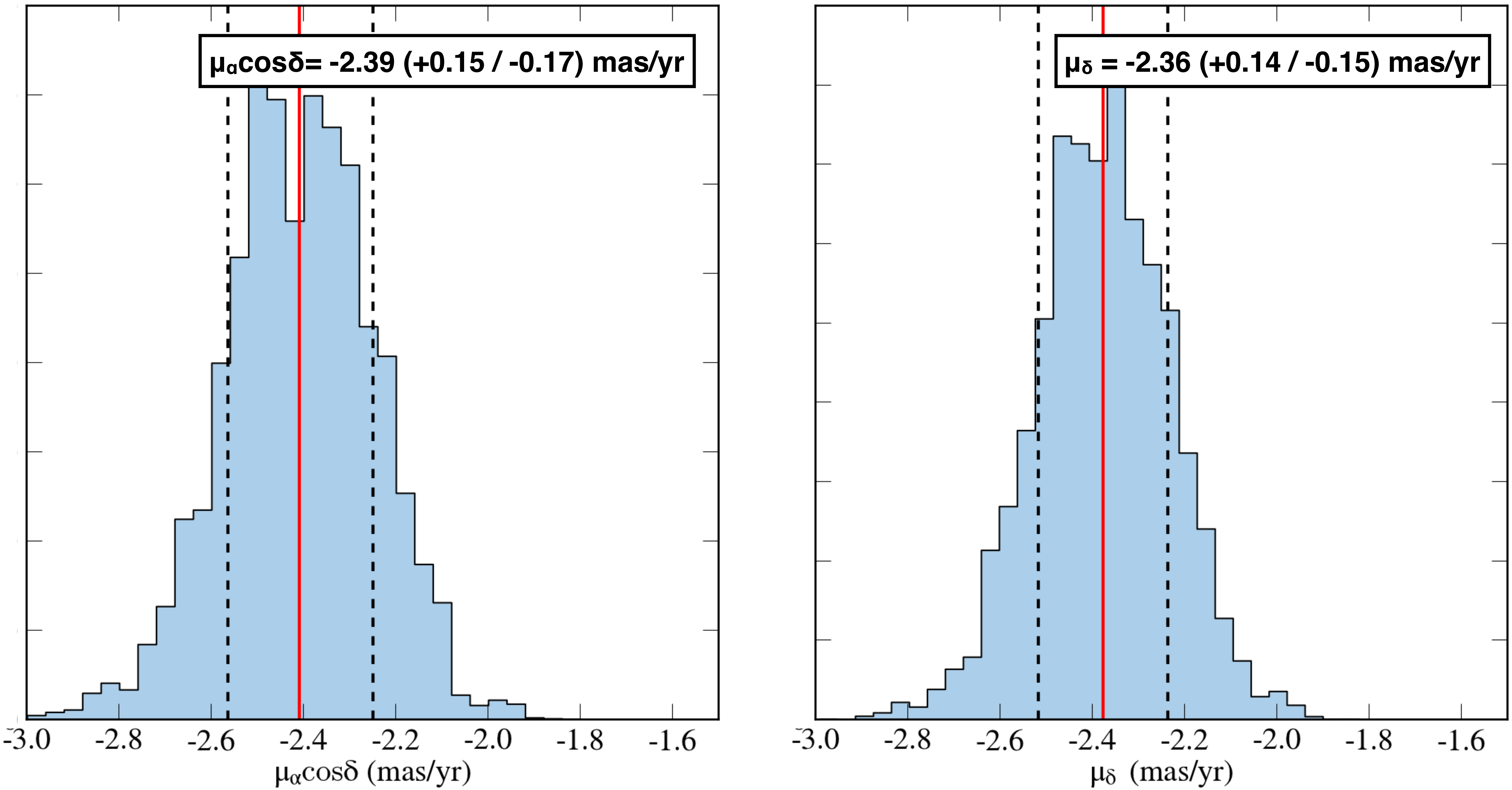


Solar parameter results are in agreement with other methods, e.g., masers, NSC, Sgr A*, bulge



We predict proper motions of Palomar 5

Küpper et al. (2015)



Take-home messages

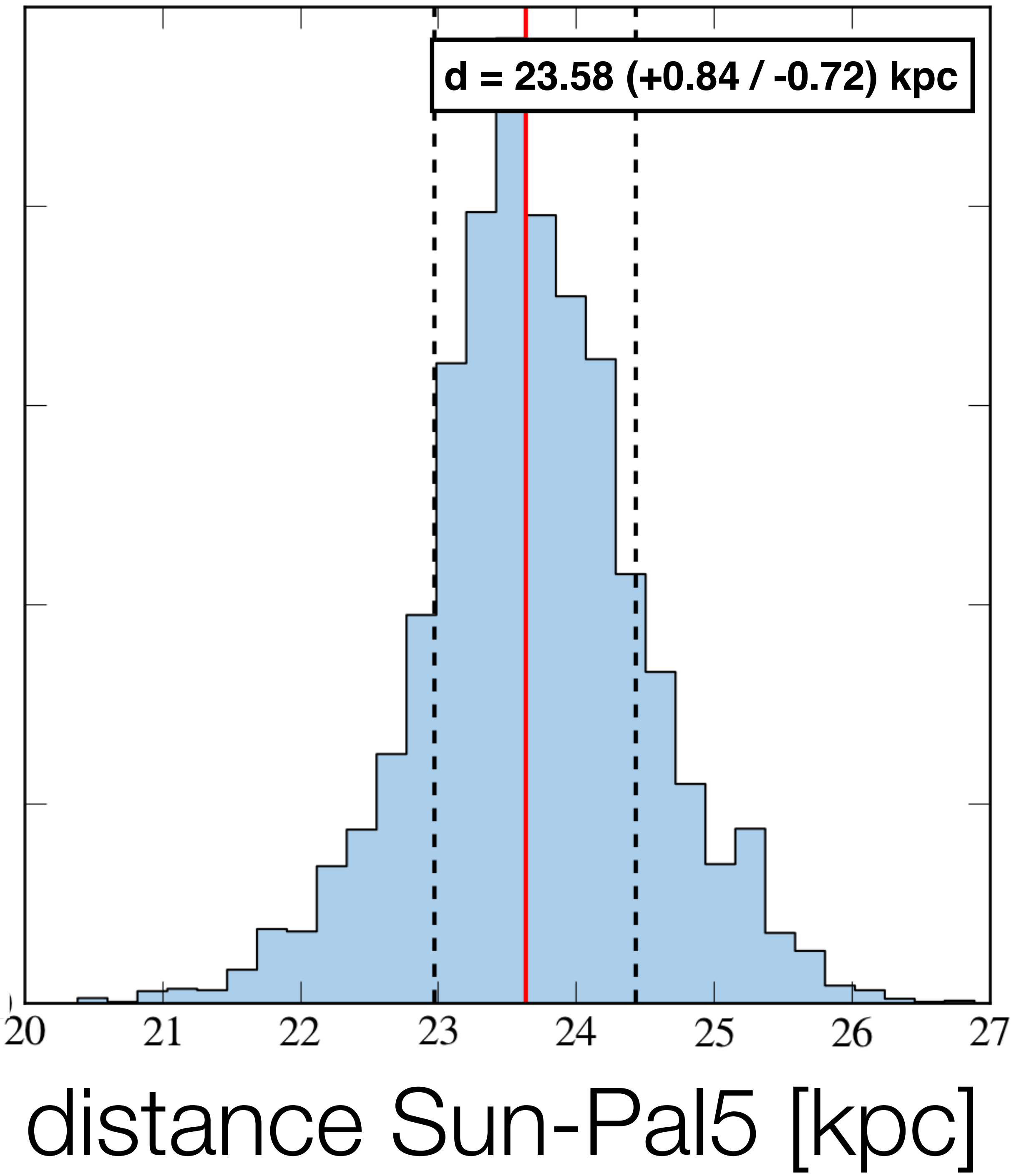
- ★ Globular cluster streams are high-precision scales
- ★ MW dark halo potential is nearly spherical within 19 kpc
- ★ "Circular velocity" at 19 kpc is about 217 km/s
- ★ Distance Sun-Galactic Center is 8.3 kpc

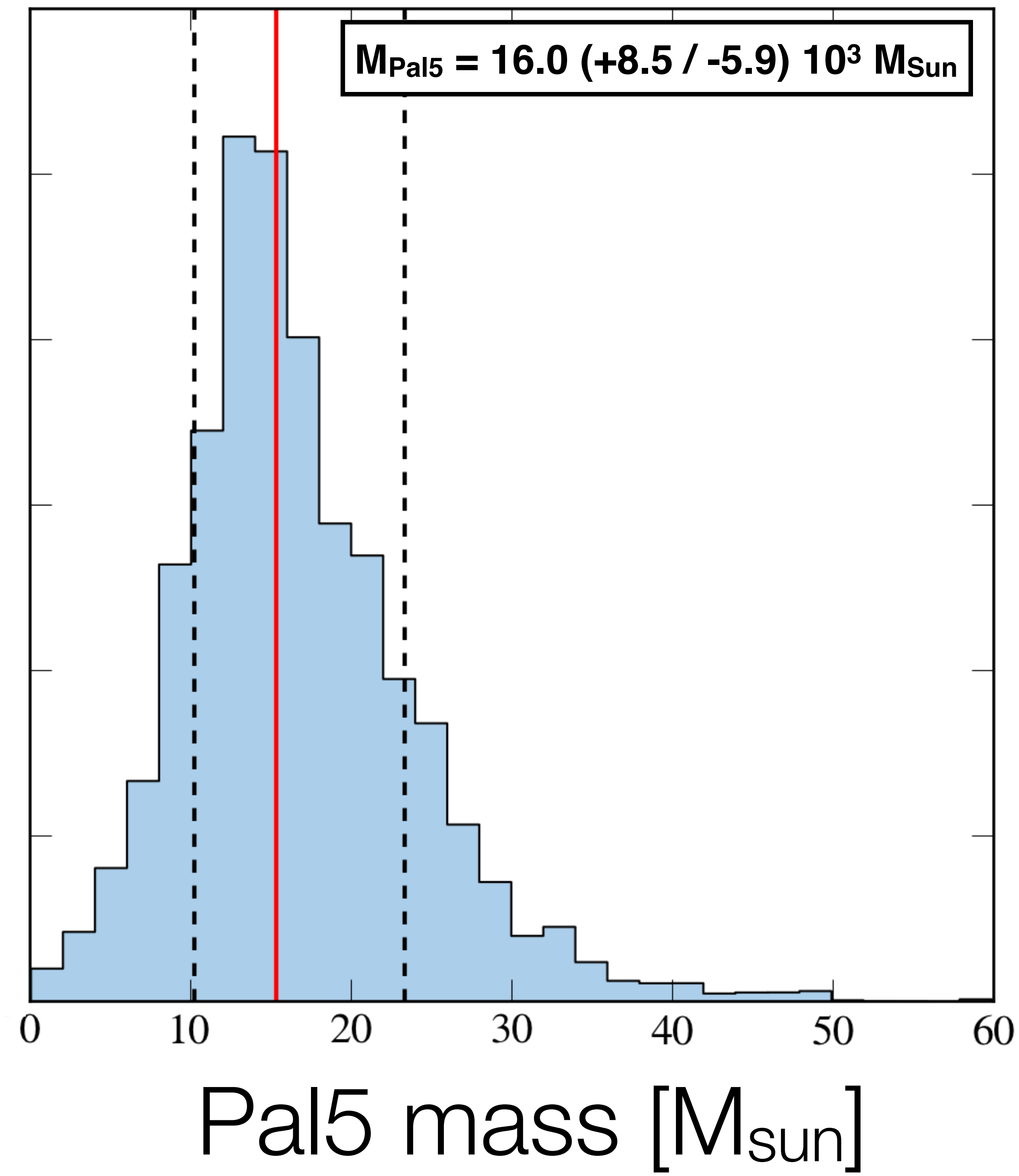
VL Cauda

Bonus material

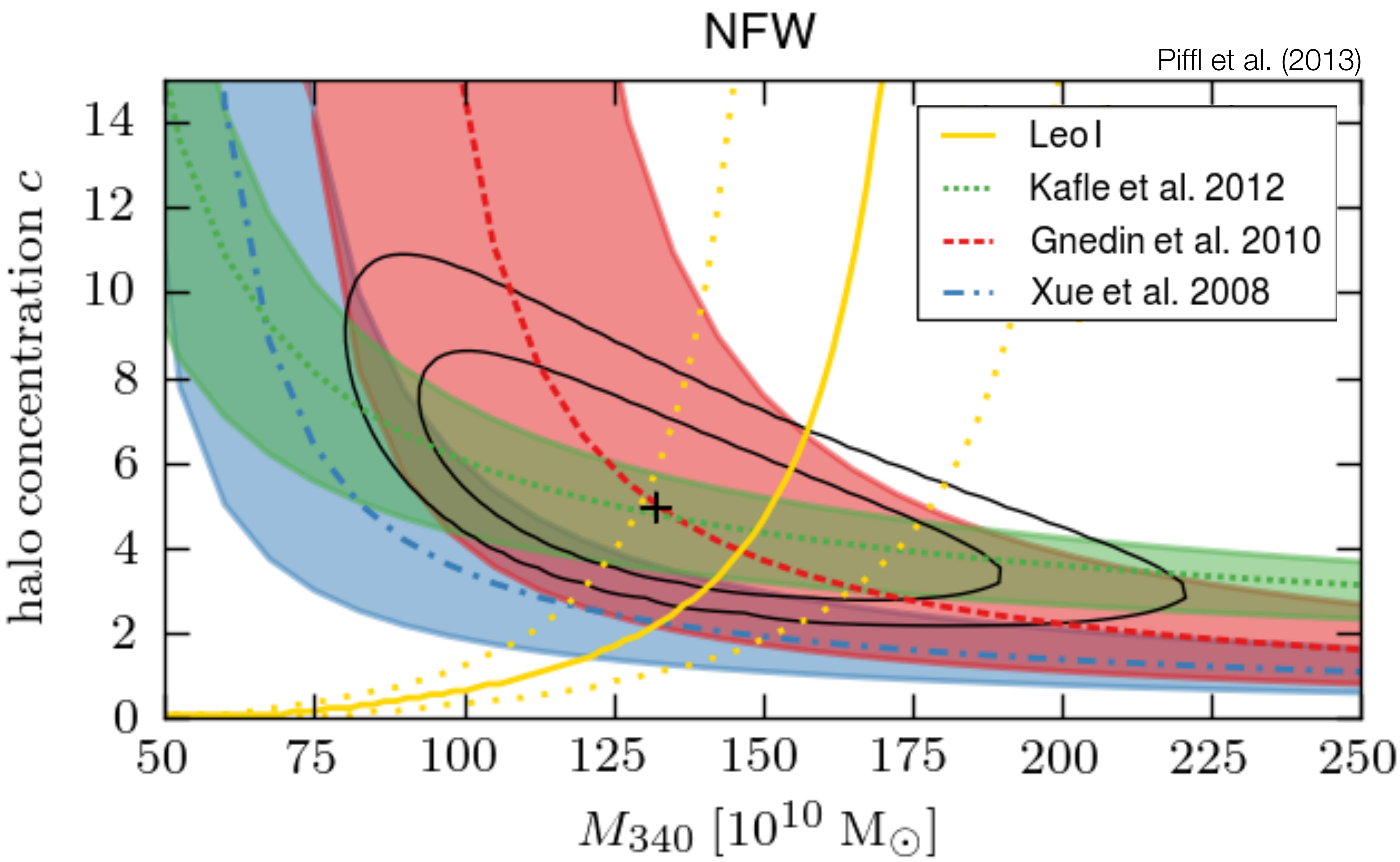
We get estimates & uncertainties on additional cluster parameters independent of other methods

Küpper et al. (2015)

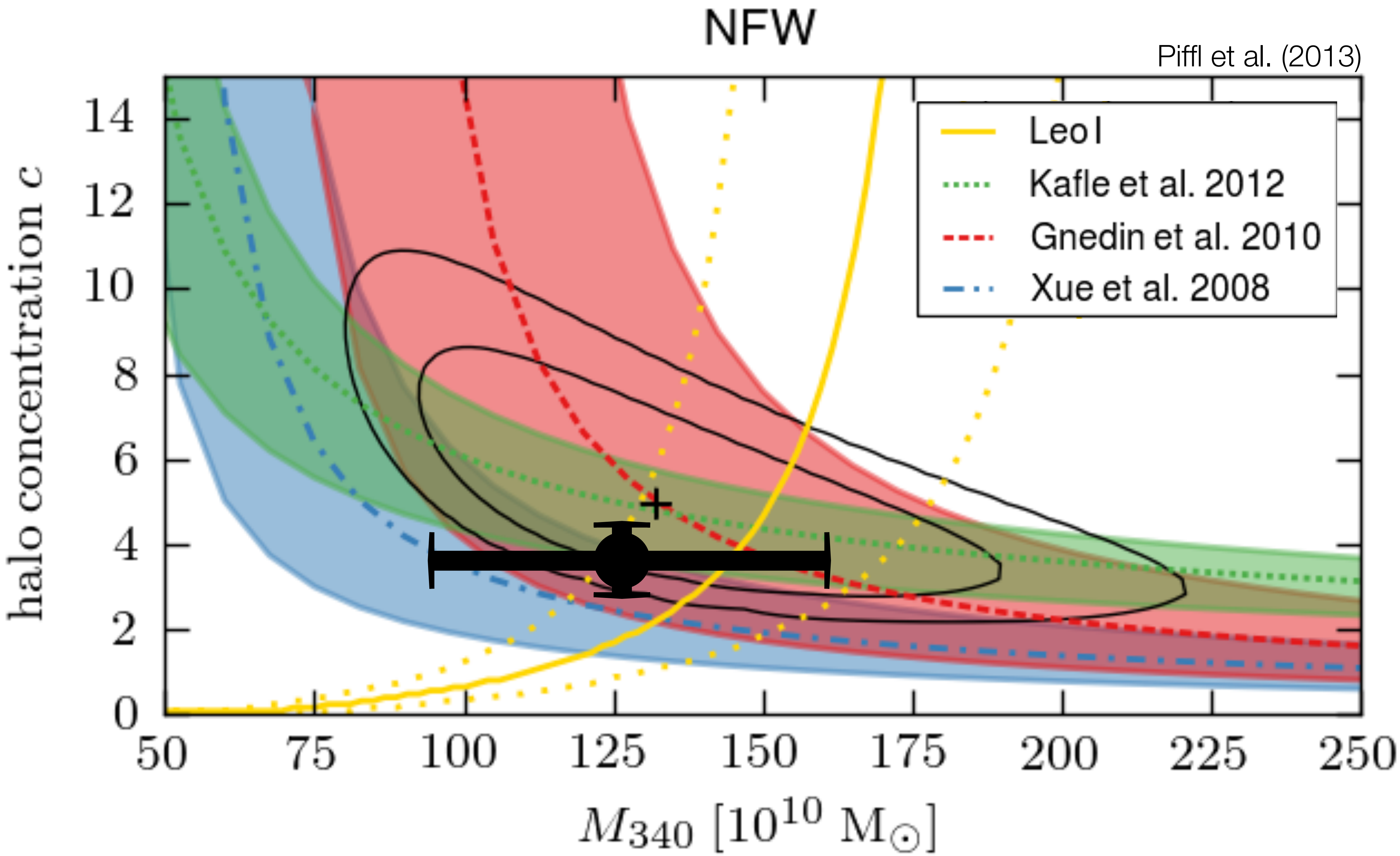




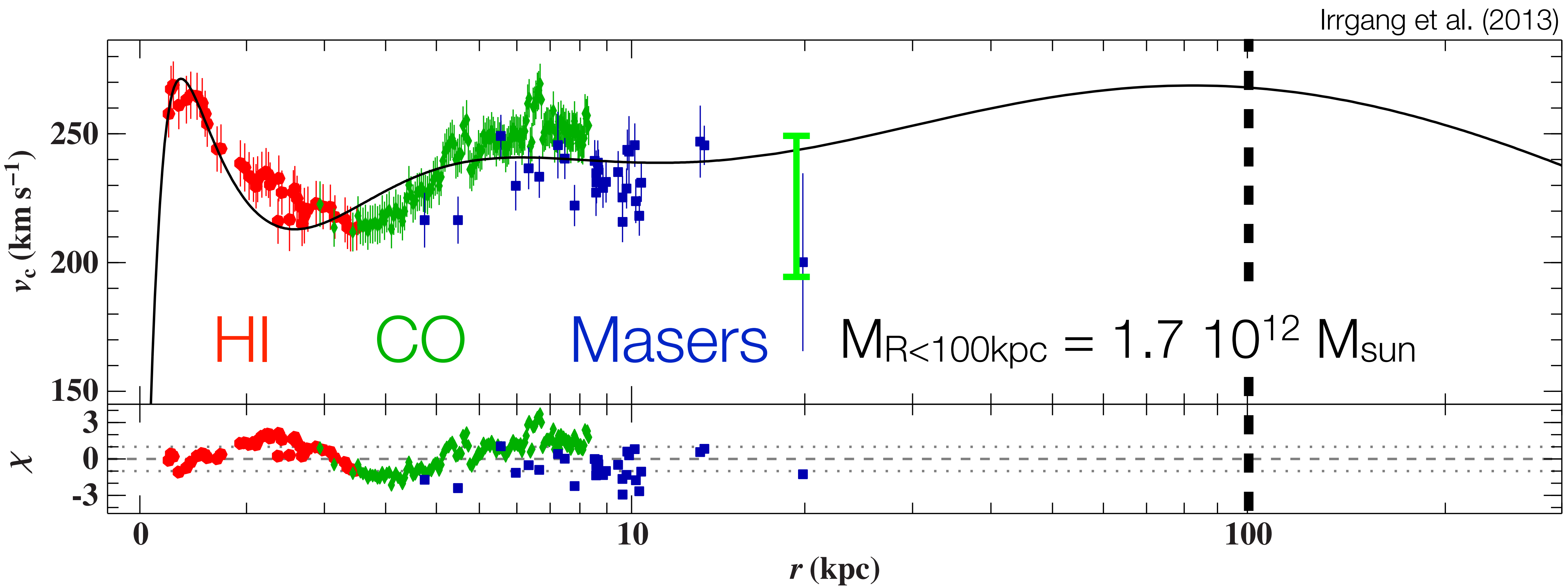
Other methods use tracers in the Galactic halo



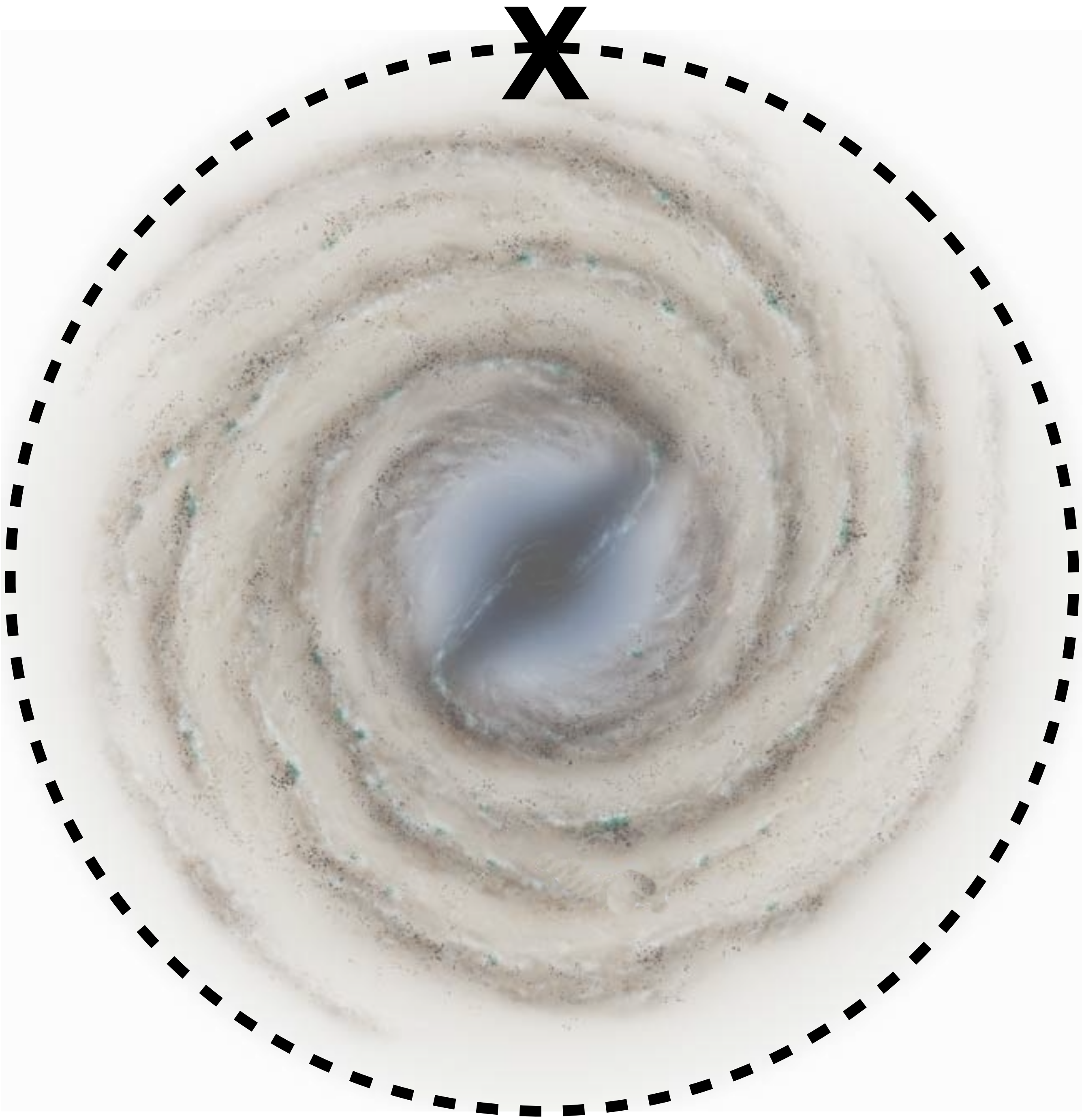
Palomar 5 measurement in excellent agreement with other most other methods



Circular velocity in the halo at 19 kpc is 217 km/s



Orbital offset causes apparent epicyclic motion



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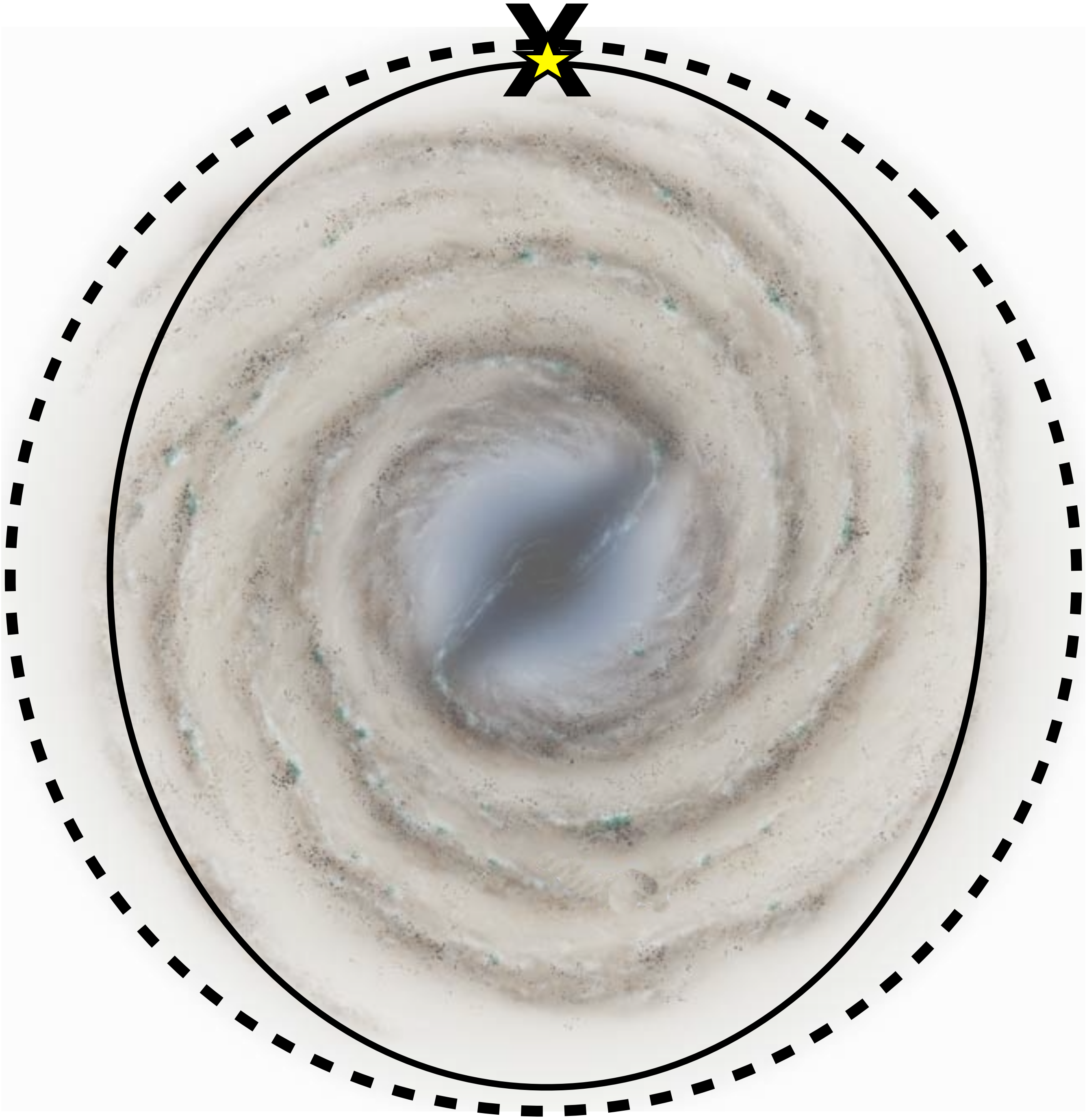

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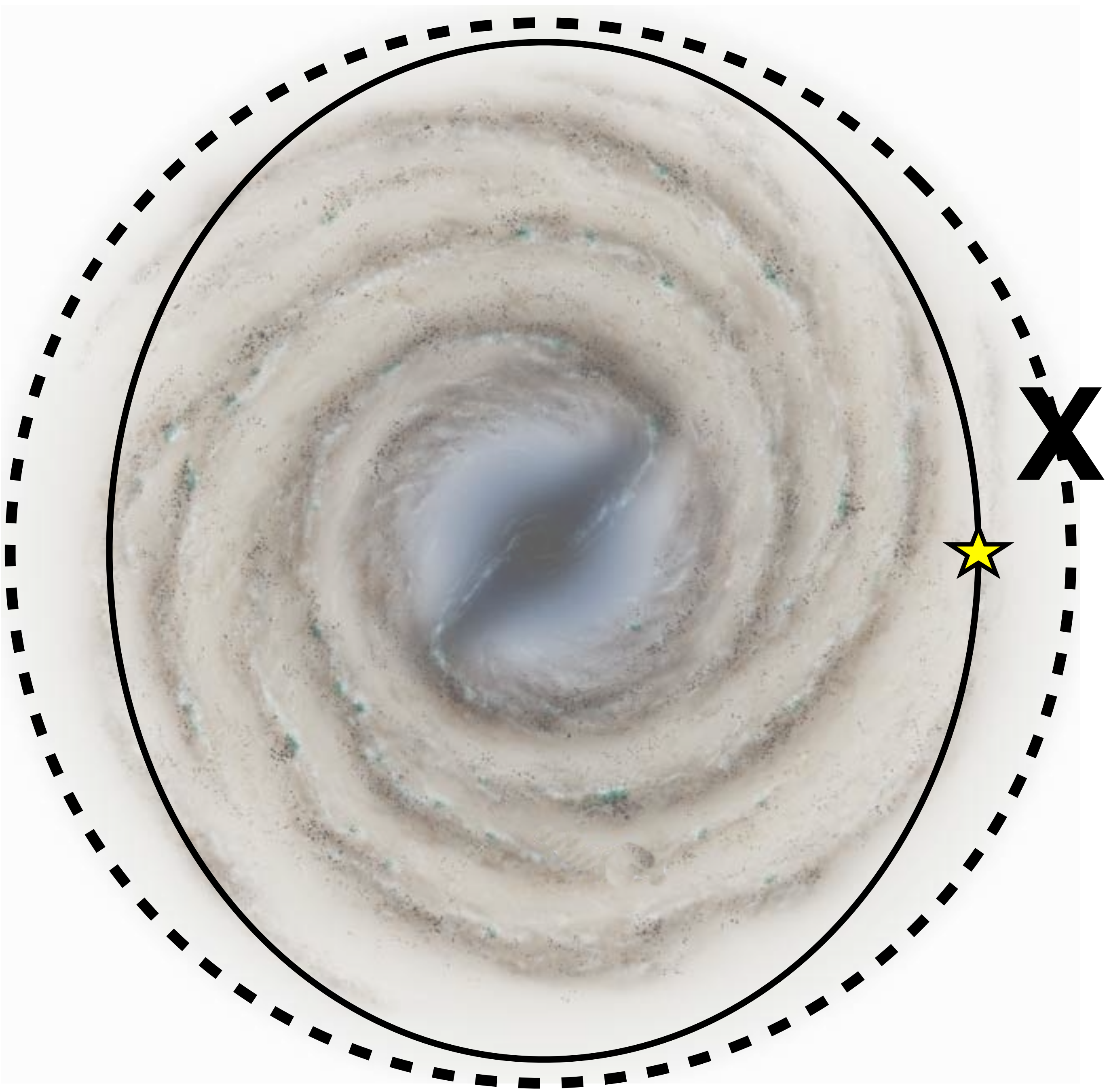

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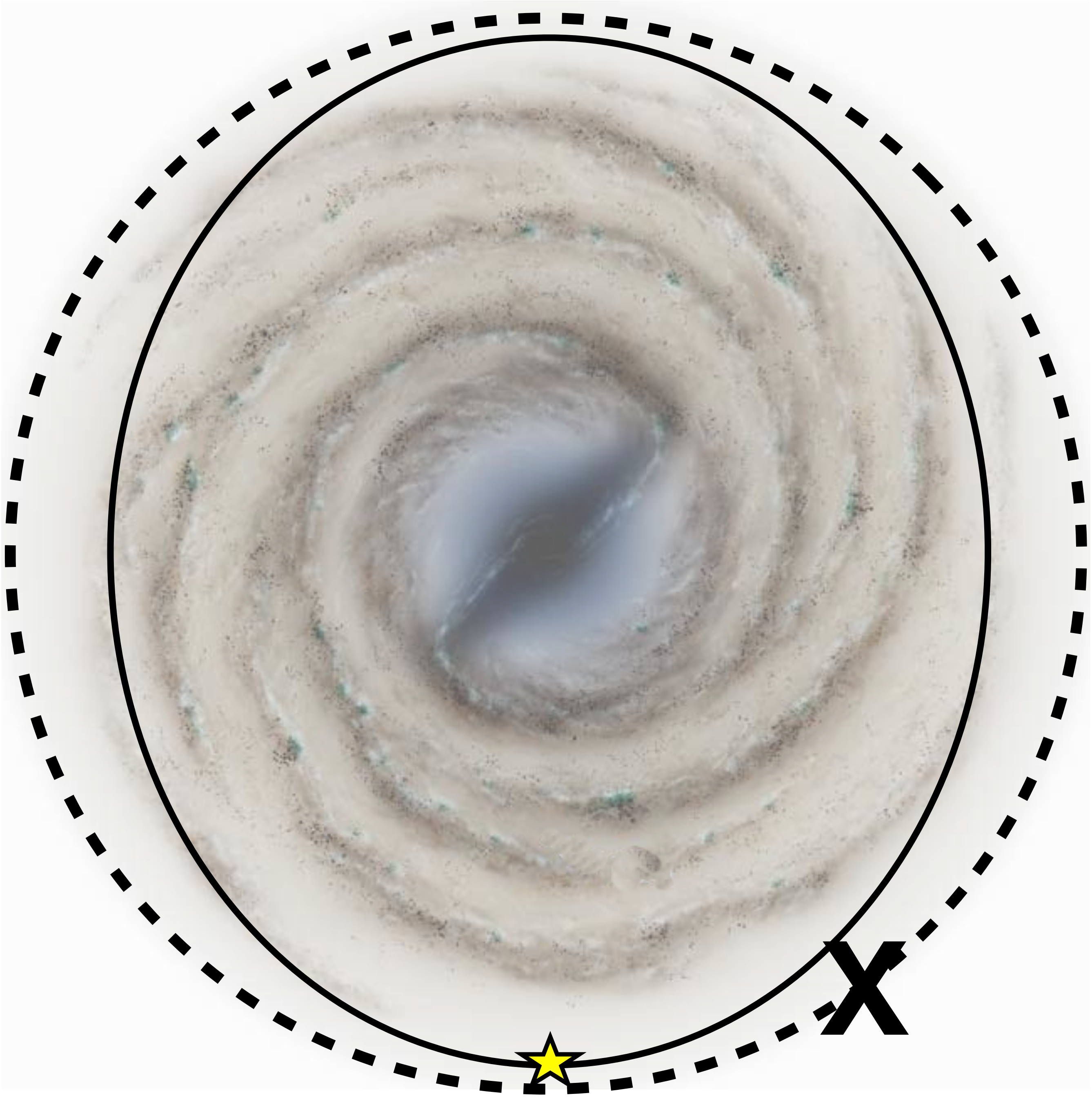

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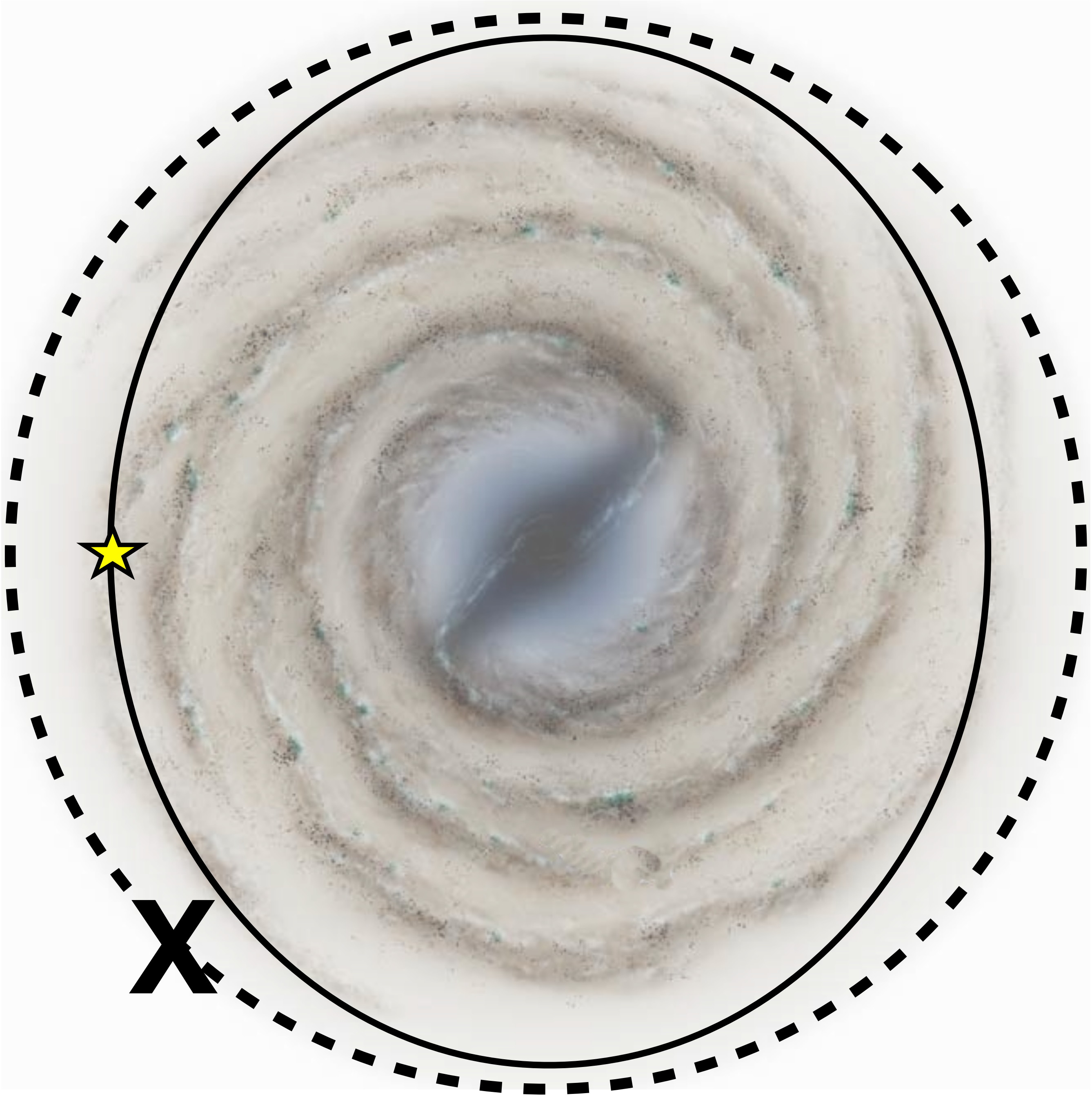

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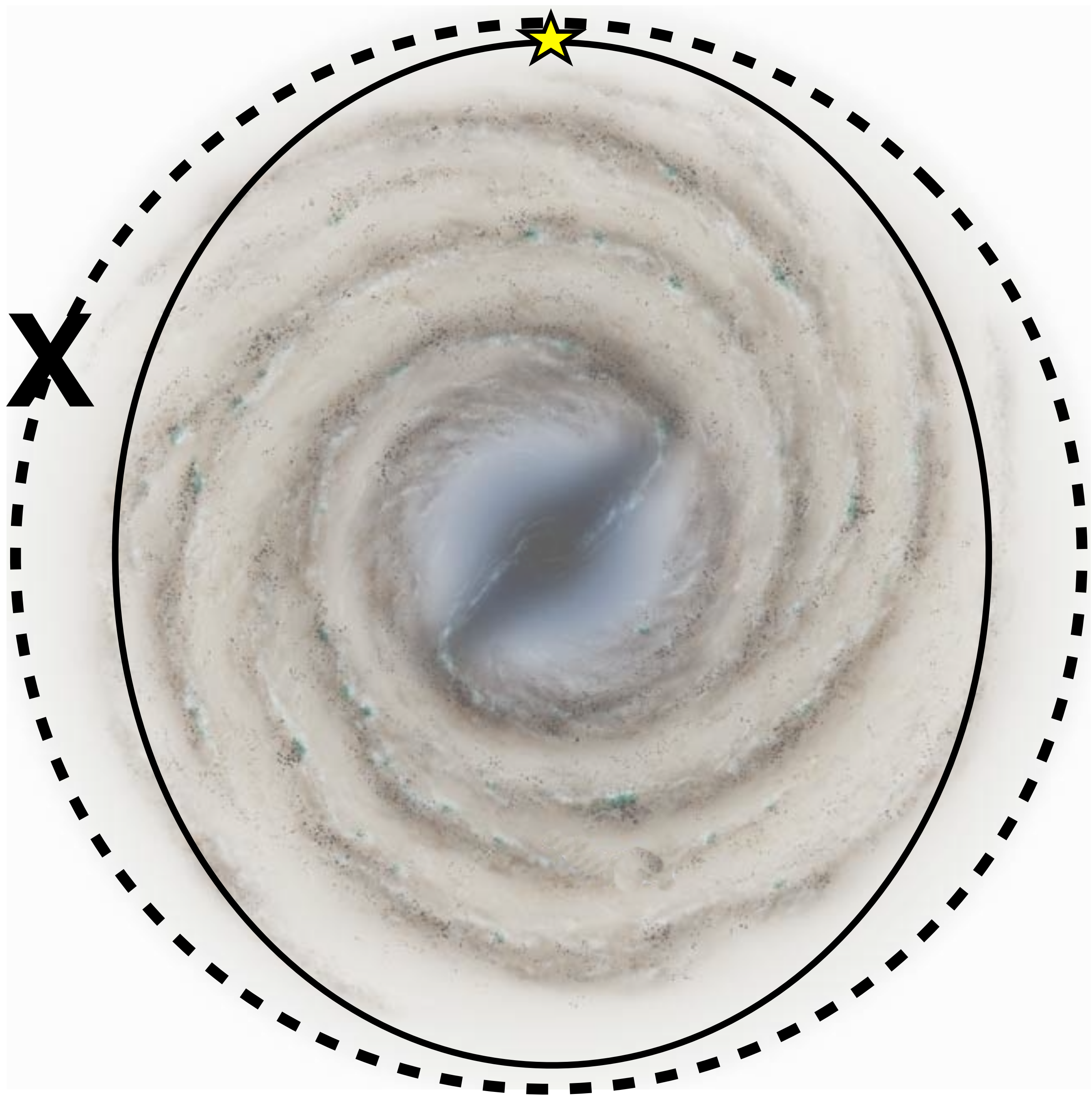
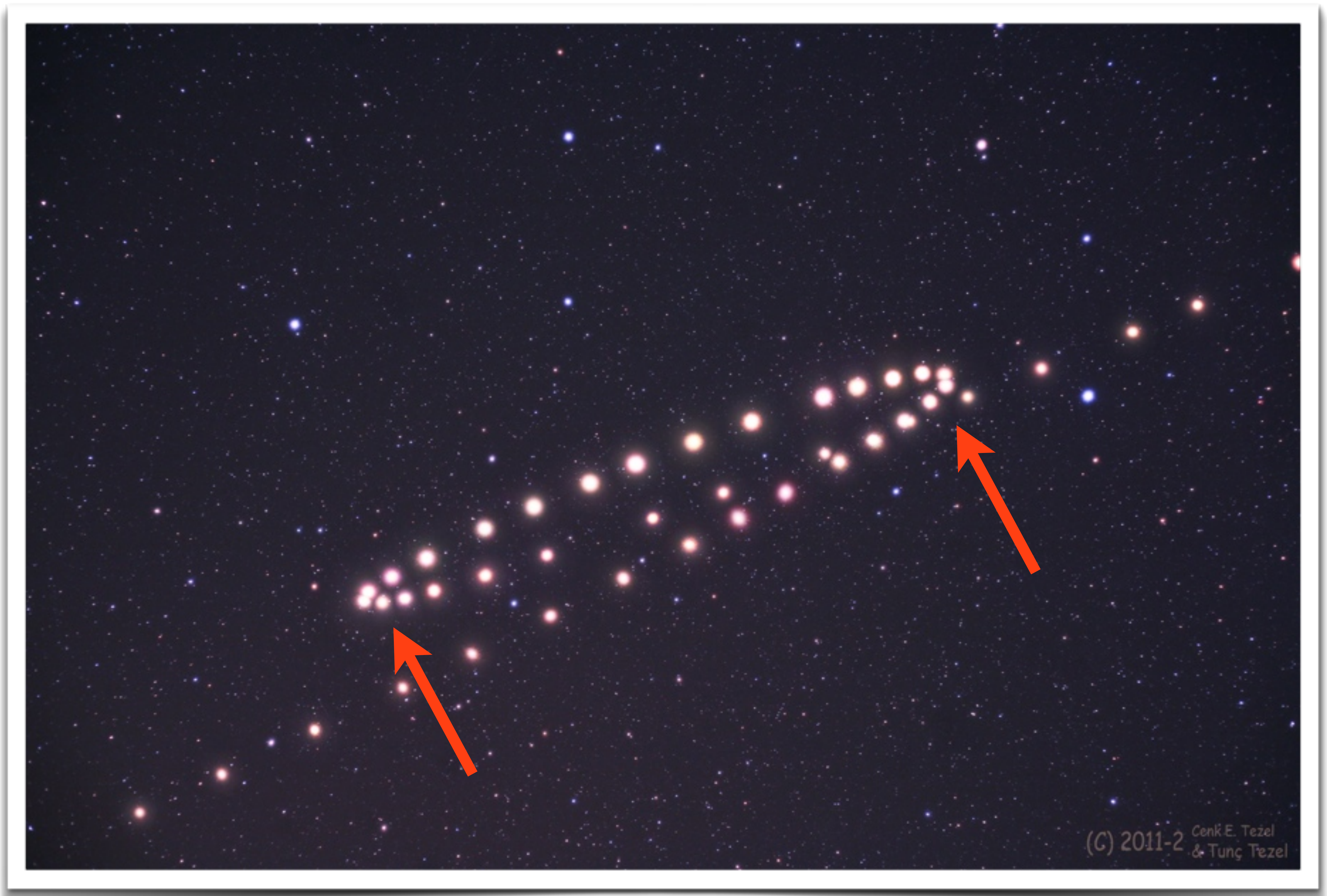
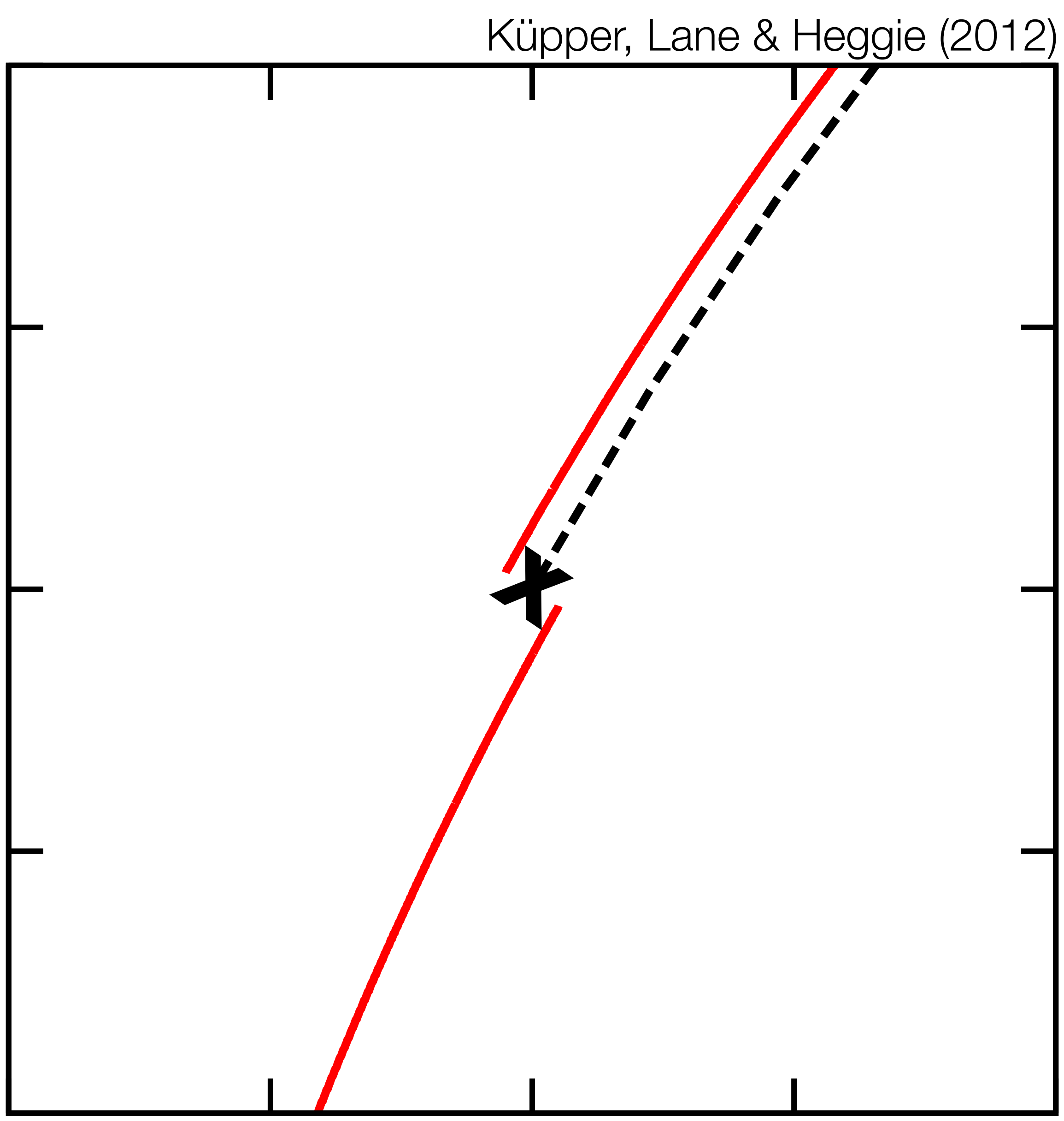


Different orbits cause different epicyclic patterns

Epicyclic motions cause apparent overdensities and underdensities containing orbital information



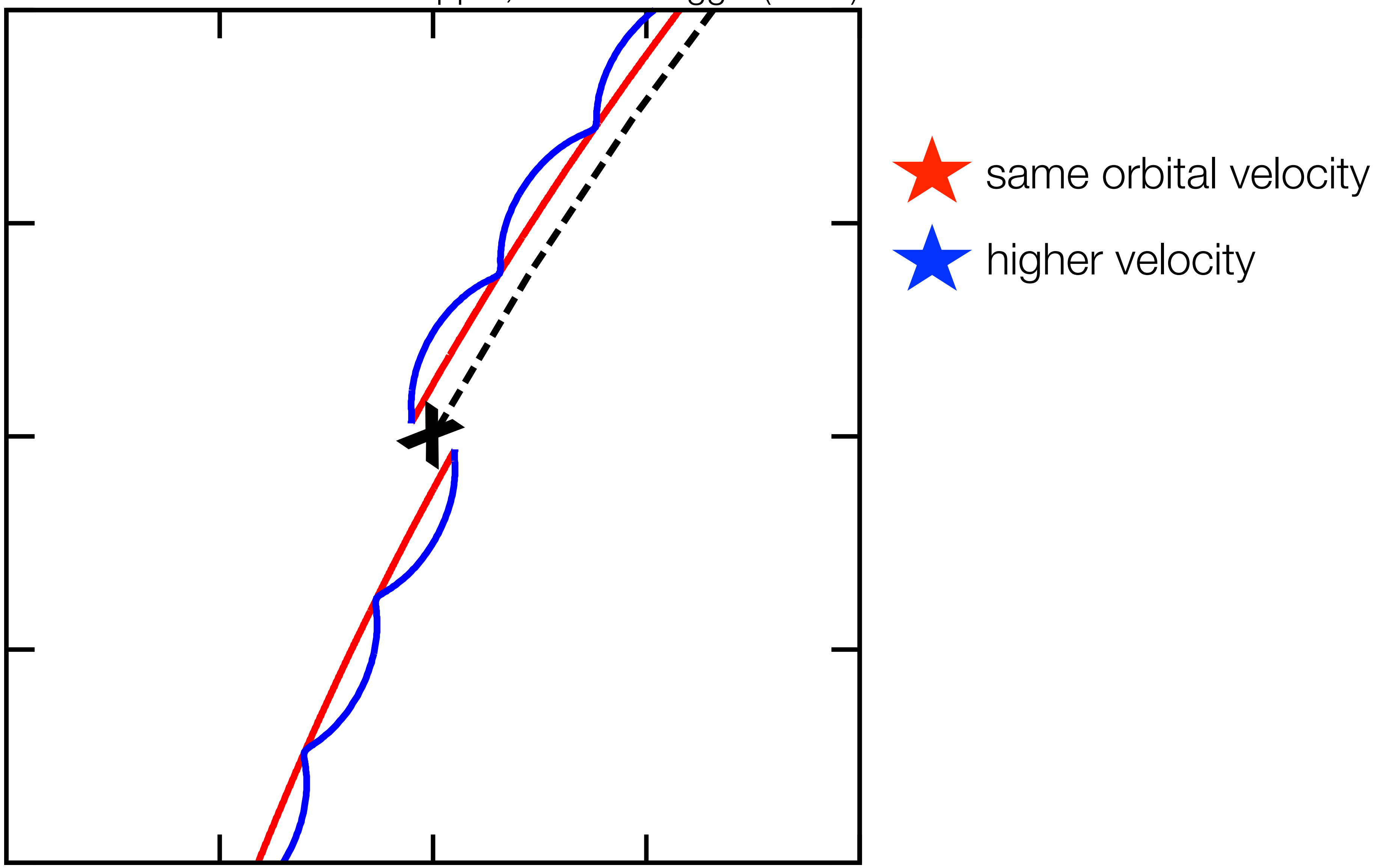
Appearance of streaklines depends crucially on the choice of radial offset and velocity offset



★ same orbital velocity

Appearance of streaklines depends crucially on the choice of radial offset and velocity offset

Küpper, Lane & Heggie (2012)



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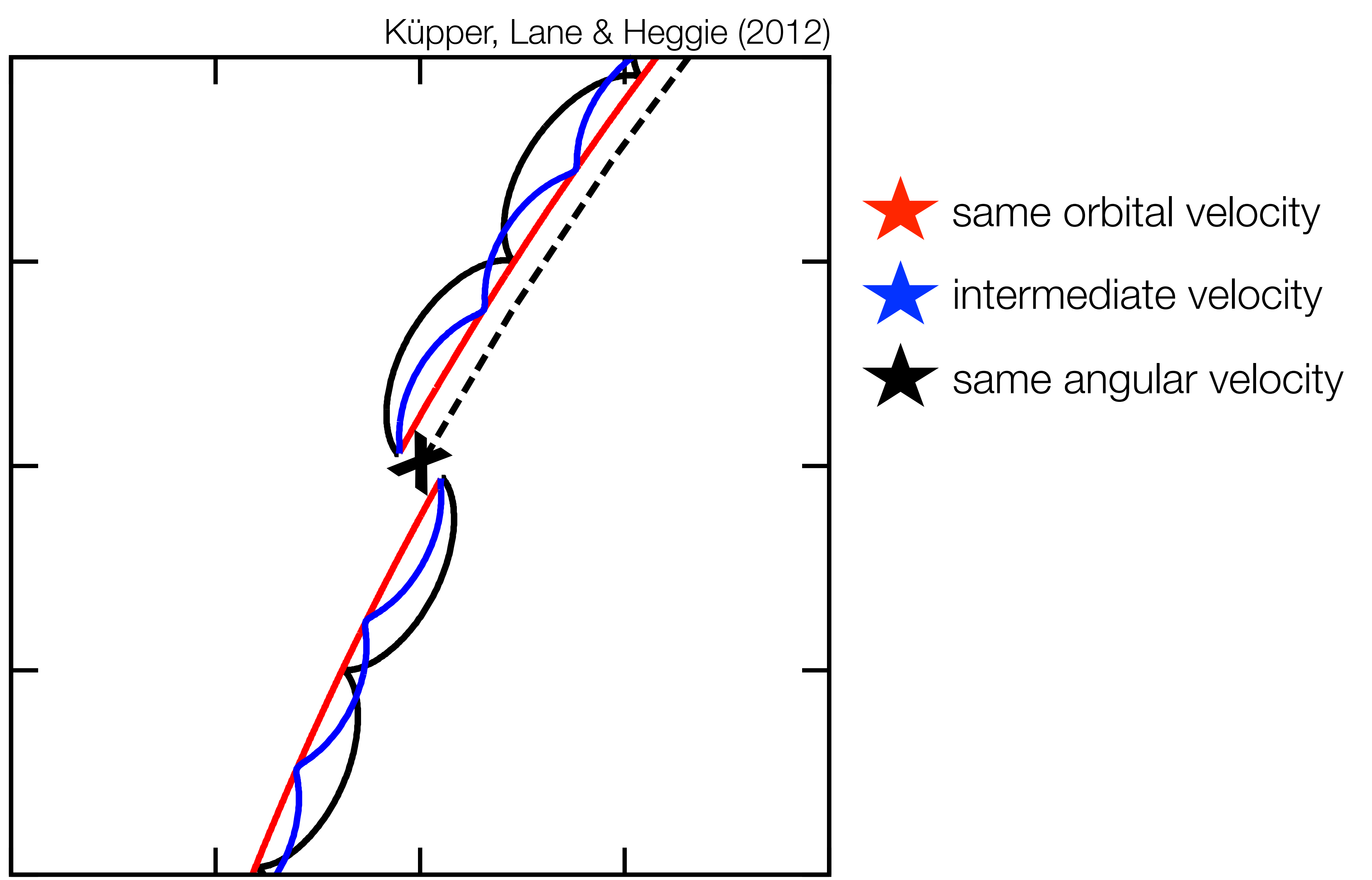
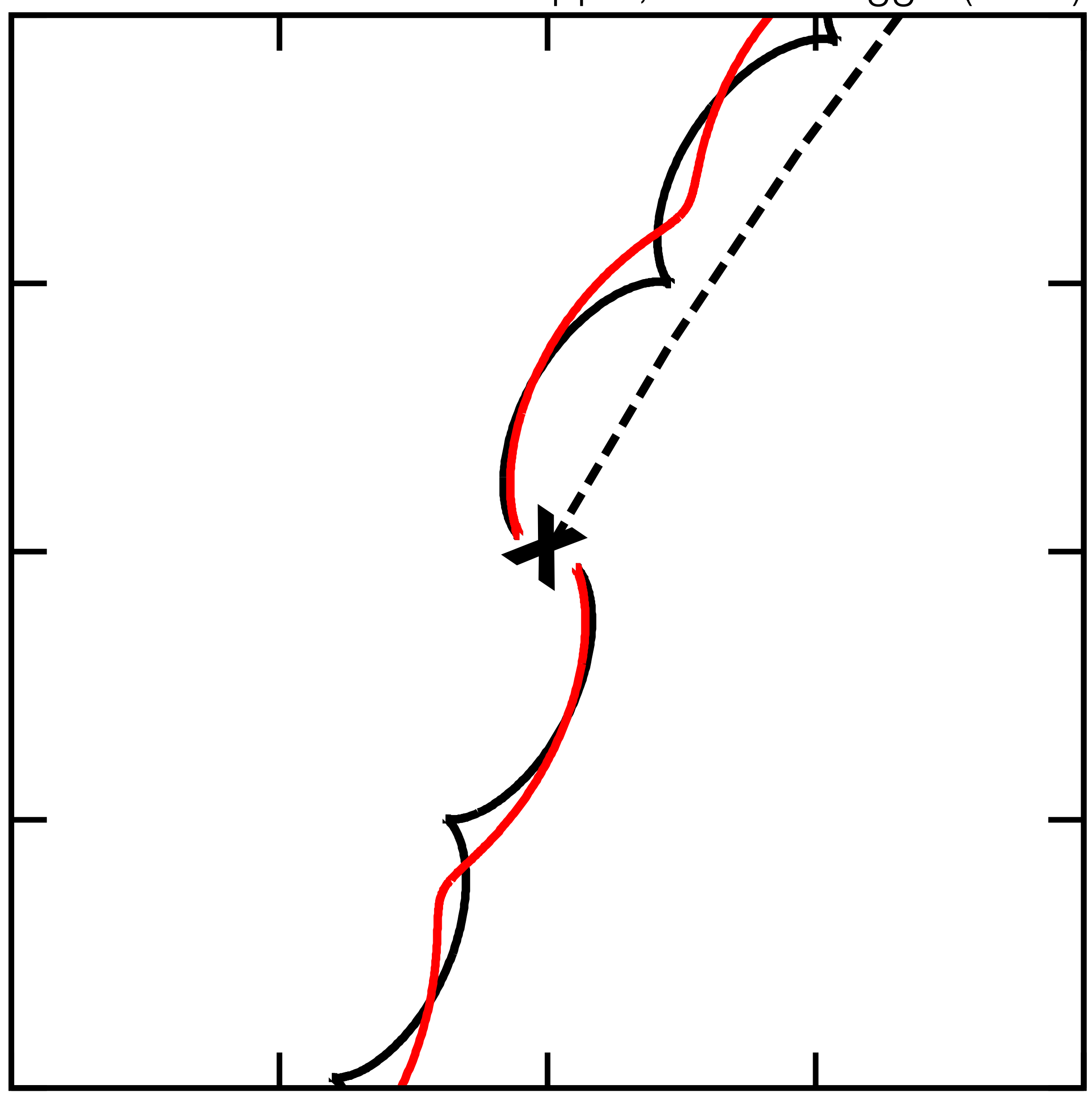


Appearance of streaklines also depends on whether the cluster mass is taken into account or not

Küpper, Lane & Heggie (2012)



★ same angular velocity (w/o cluster mass)

★ same angular velocity (with cluster mass)