Modeling the Debris of Globular Clusters

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Andreas

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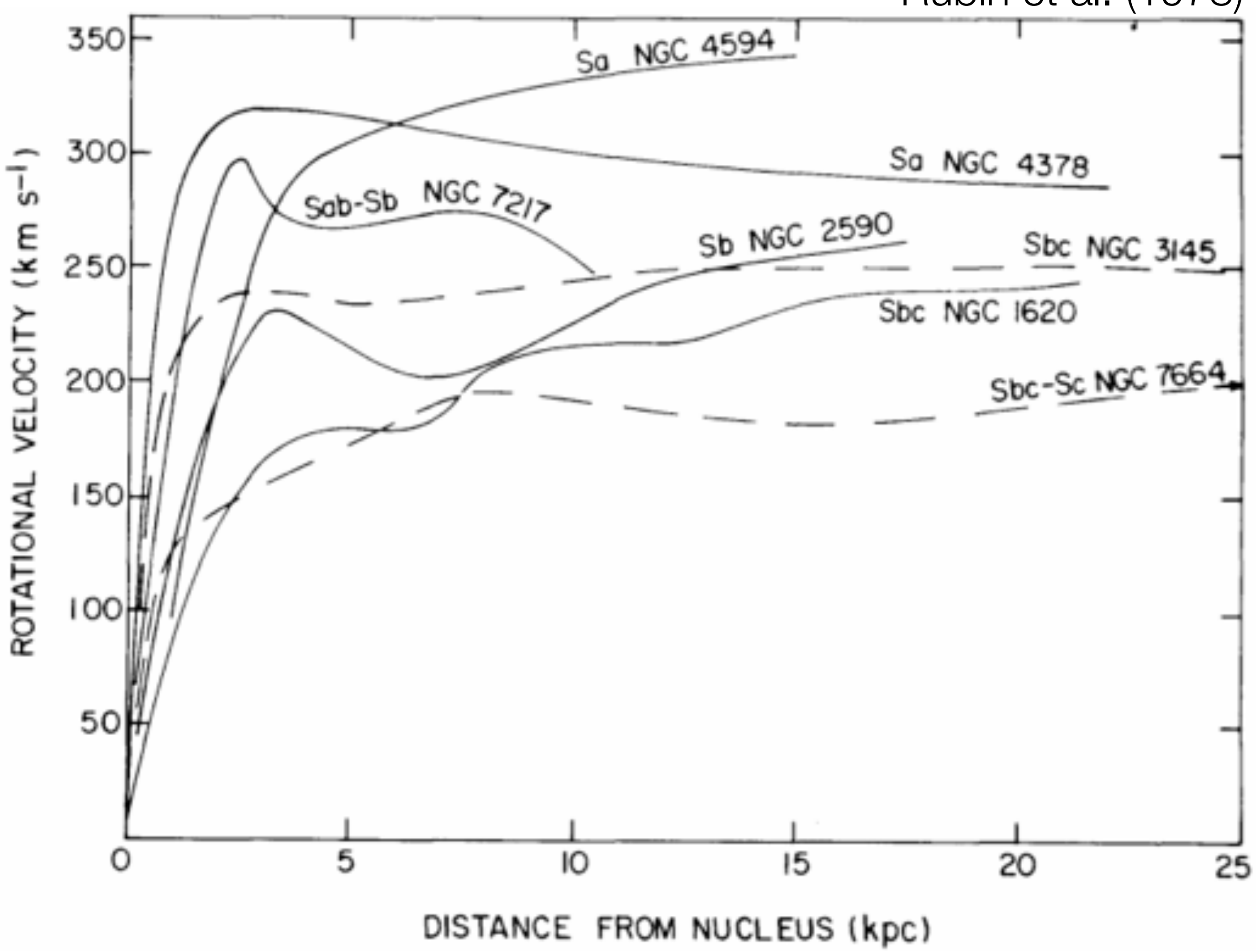
Since the 70's it is apparent that spiral galaxies have some form of dark halo component

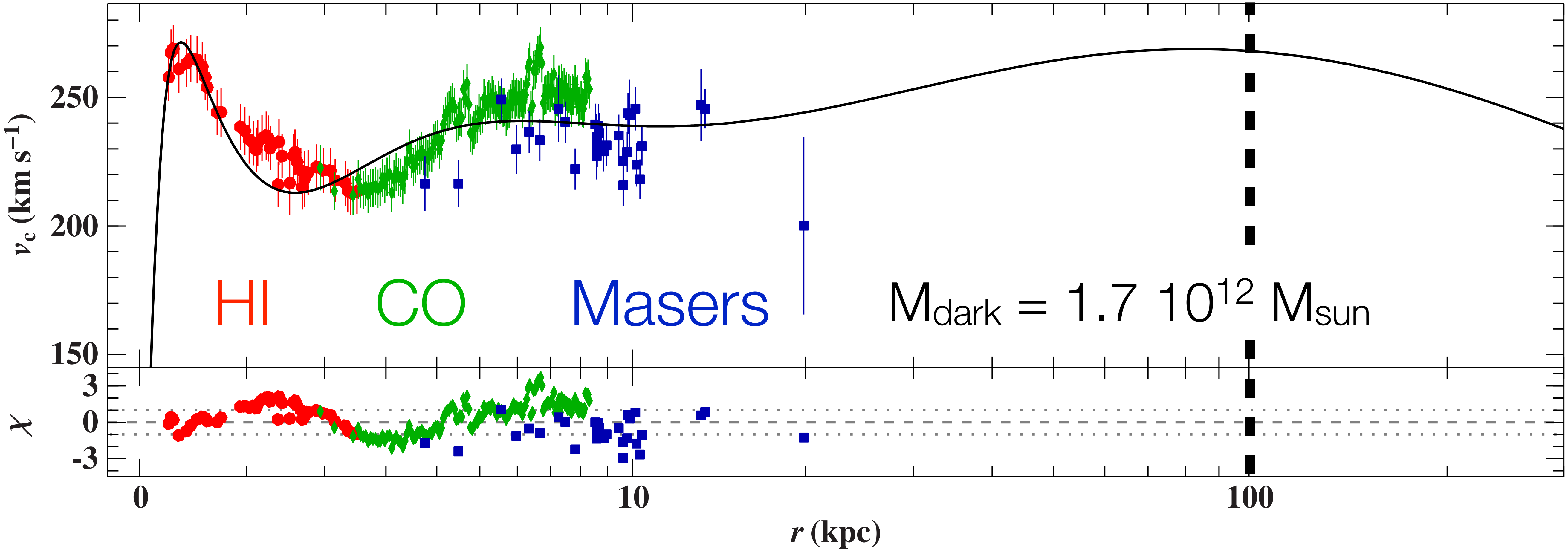
Image credit: American Institute of Physics

Rubin et al. (1978)

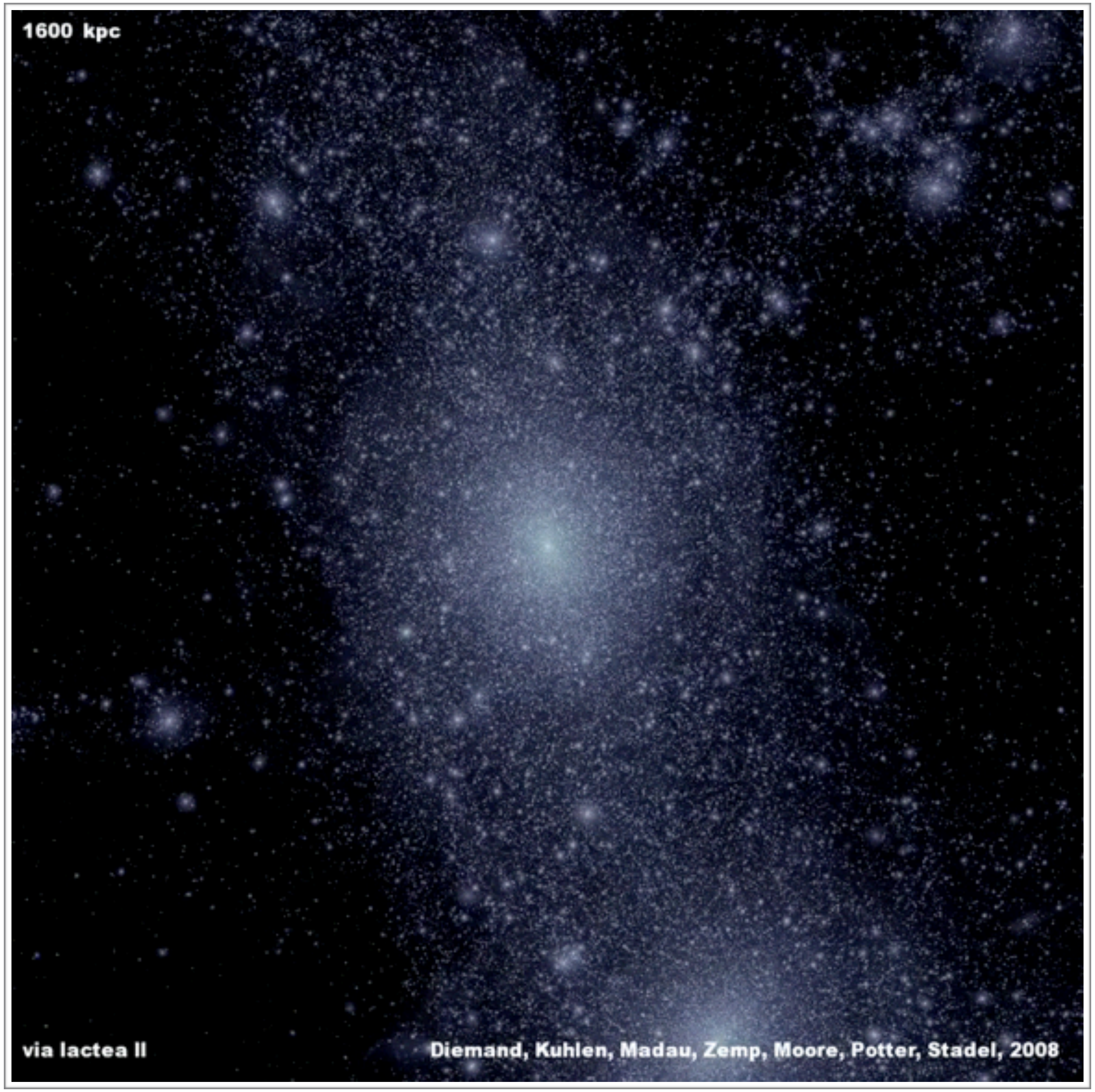


The rotation curve of the Galactic disk requires some form of dark component

Irrgang et al. (2013)

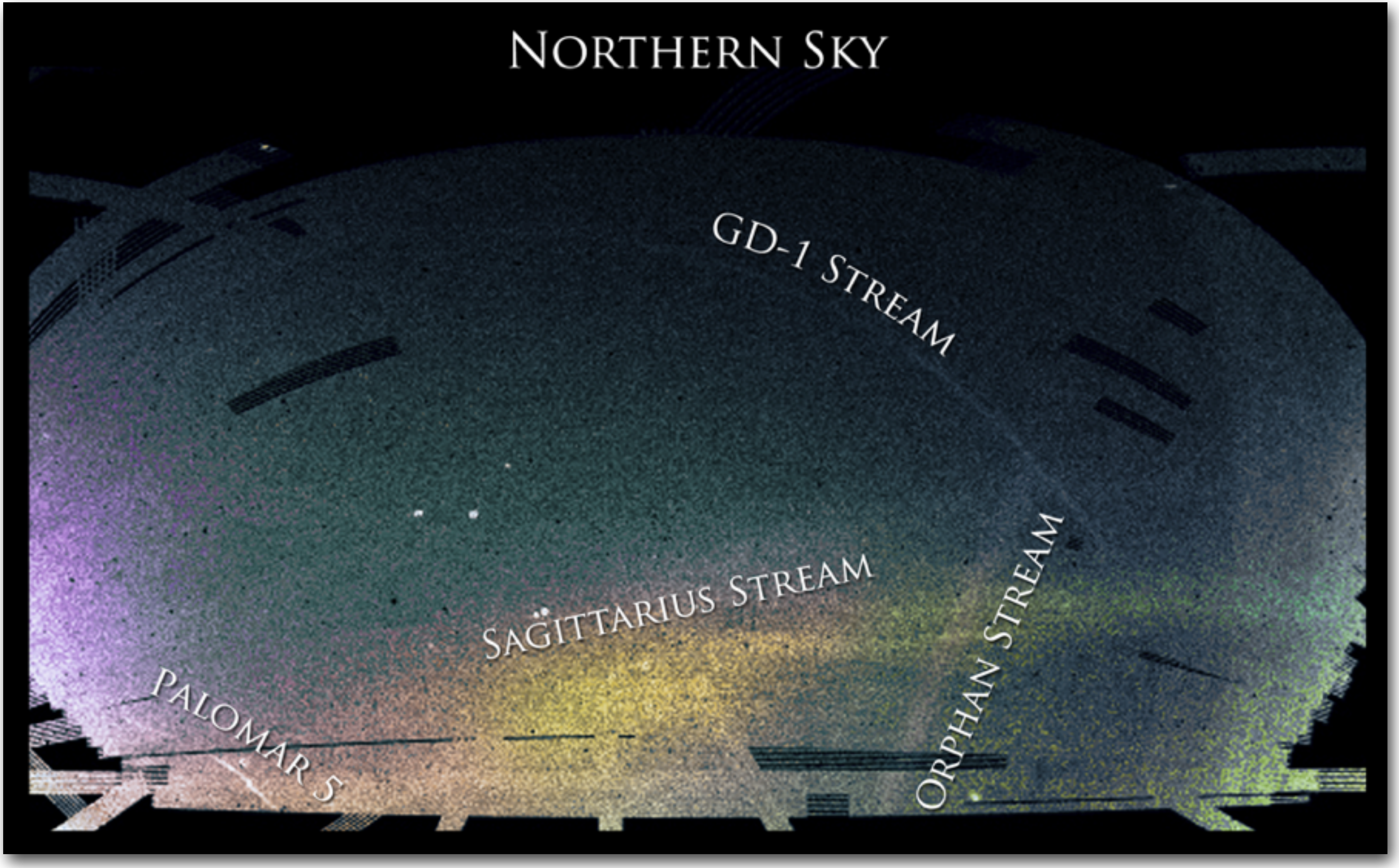


Dark matter halos in LCDM are complex and mostly triaxial structures



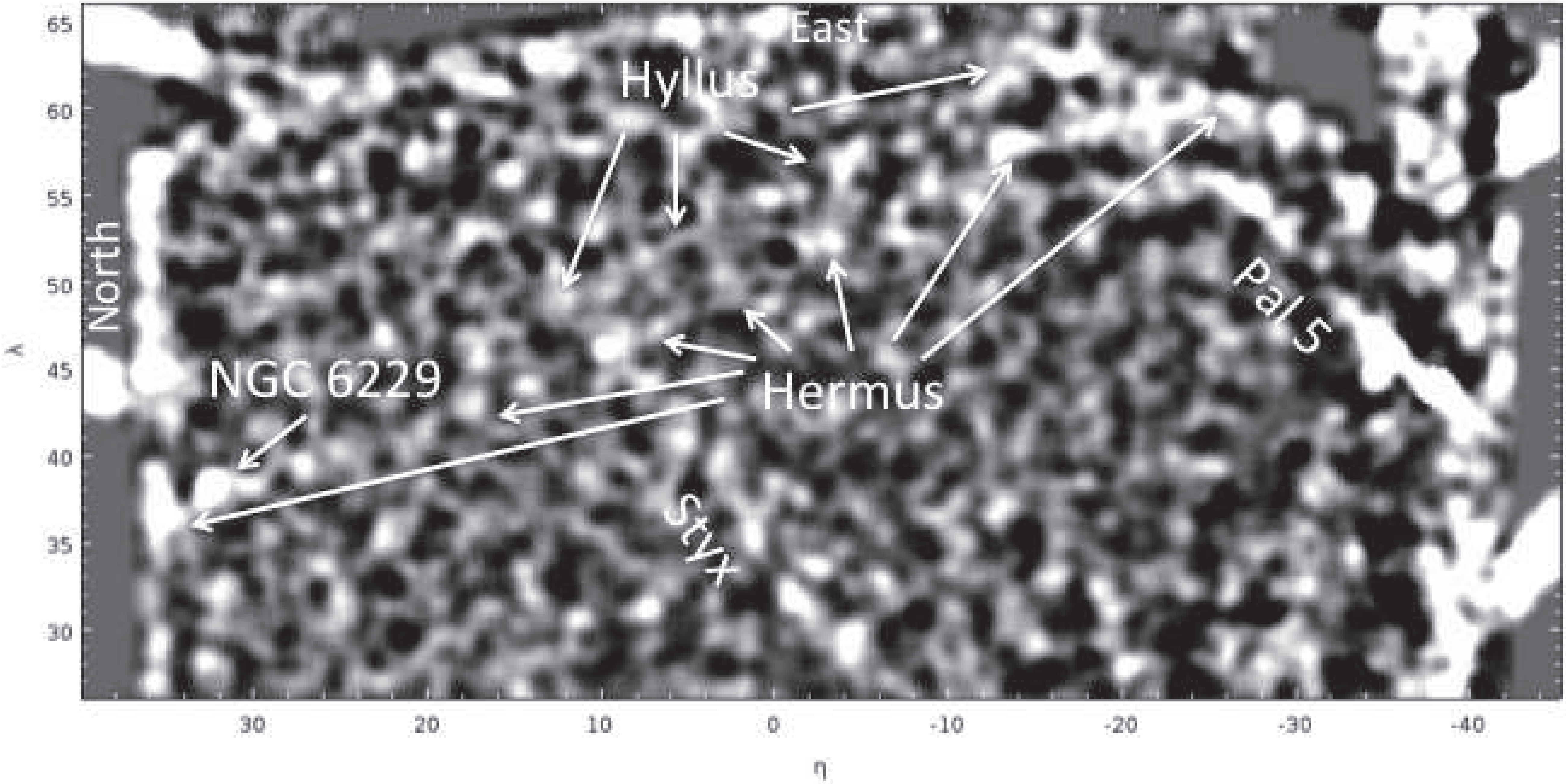
Tidal streams help us understand the parts of the Galaxy which are dark in more detail

Bonaca, Geha & Kallivayalil (2012)

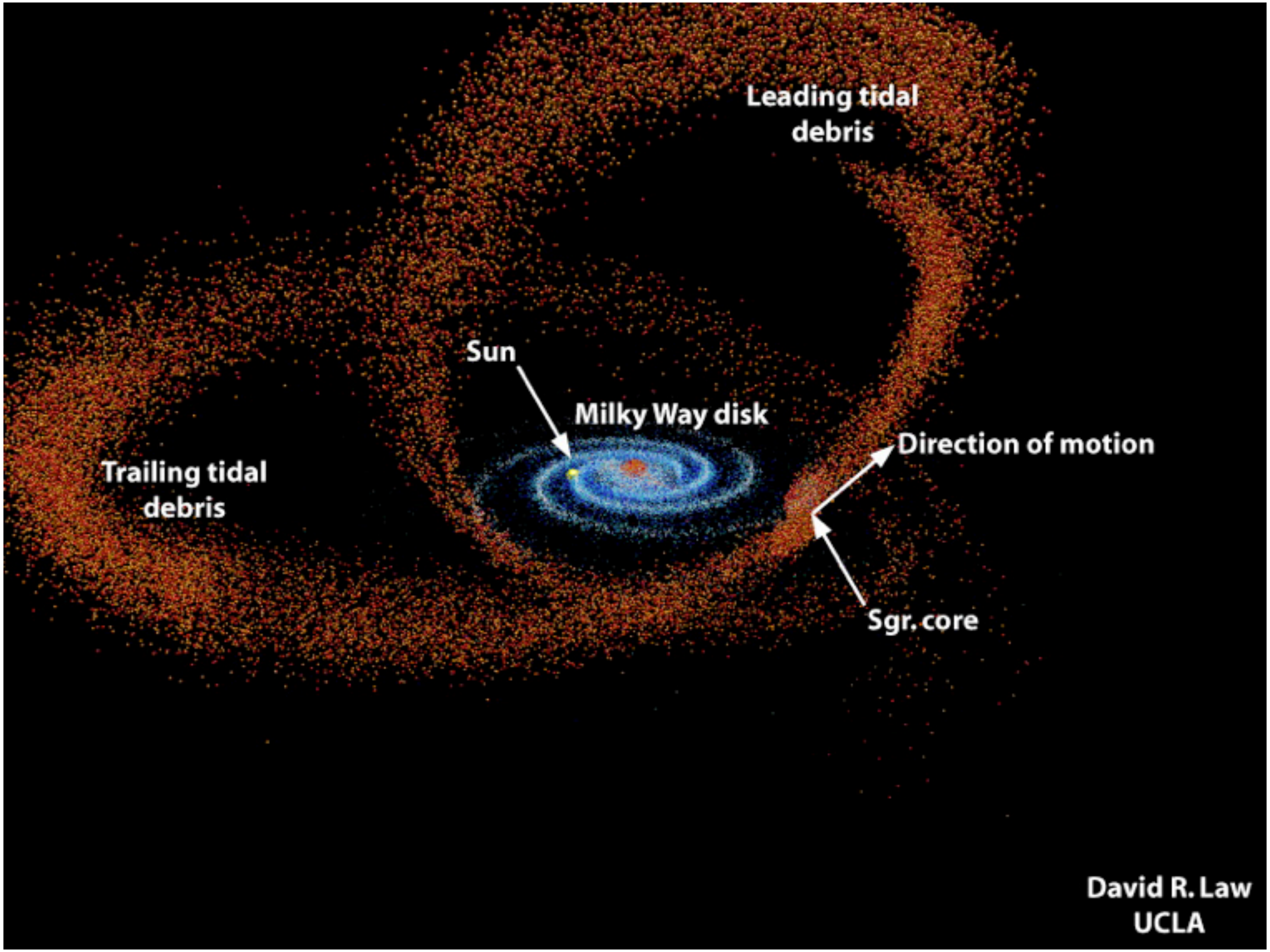


Tidal streams help us understand the parts of the Galaxy which are dark in more detail

Grillmair (2014)

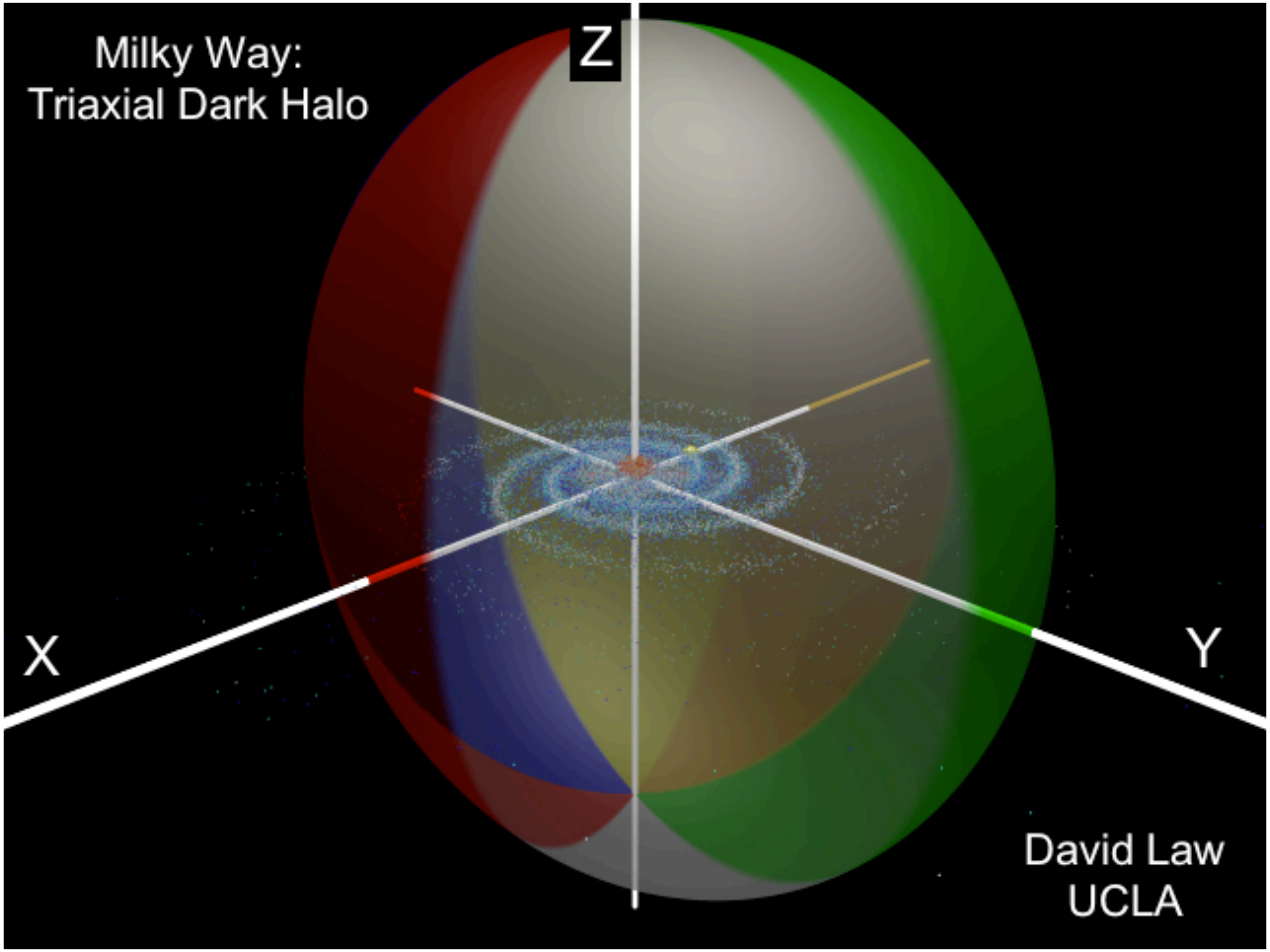


Sagittarius was the first stream used for probing the Milky Way's dark halo

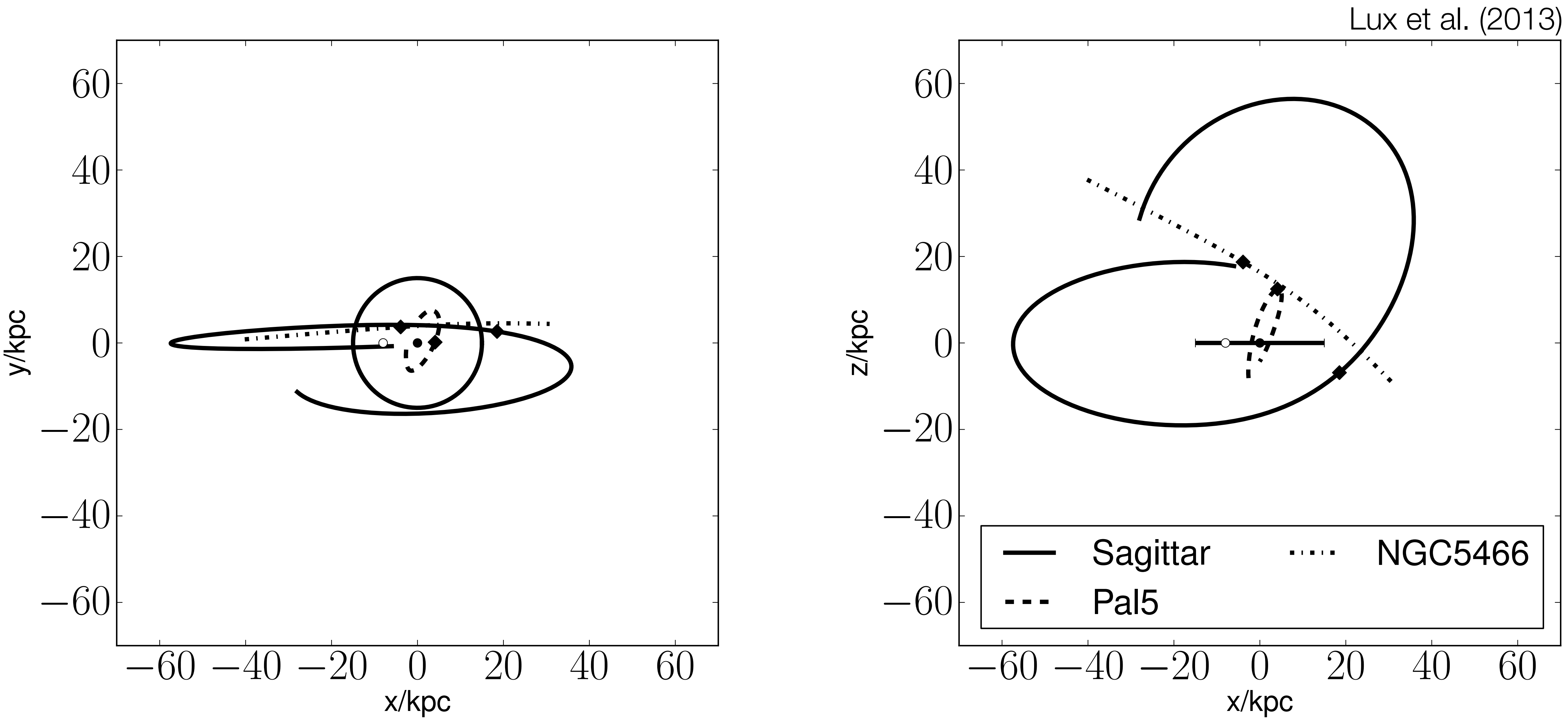


Models of the stream prefer a triaxial halo with the intermediate axis aligned with the disk z-axis

Law & Majewski (2010)



Different streams probe different parts of the Galaxy



1	Modeling Streams
2	Palomar 5 Observations
3	Modeling Palomar 5

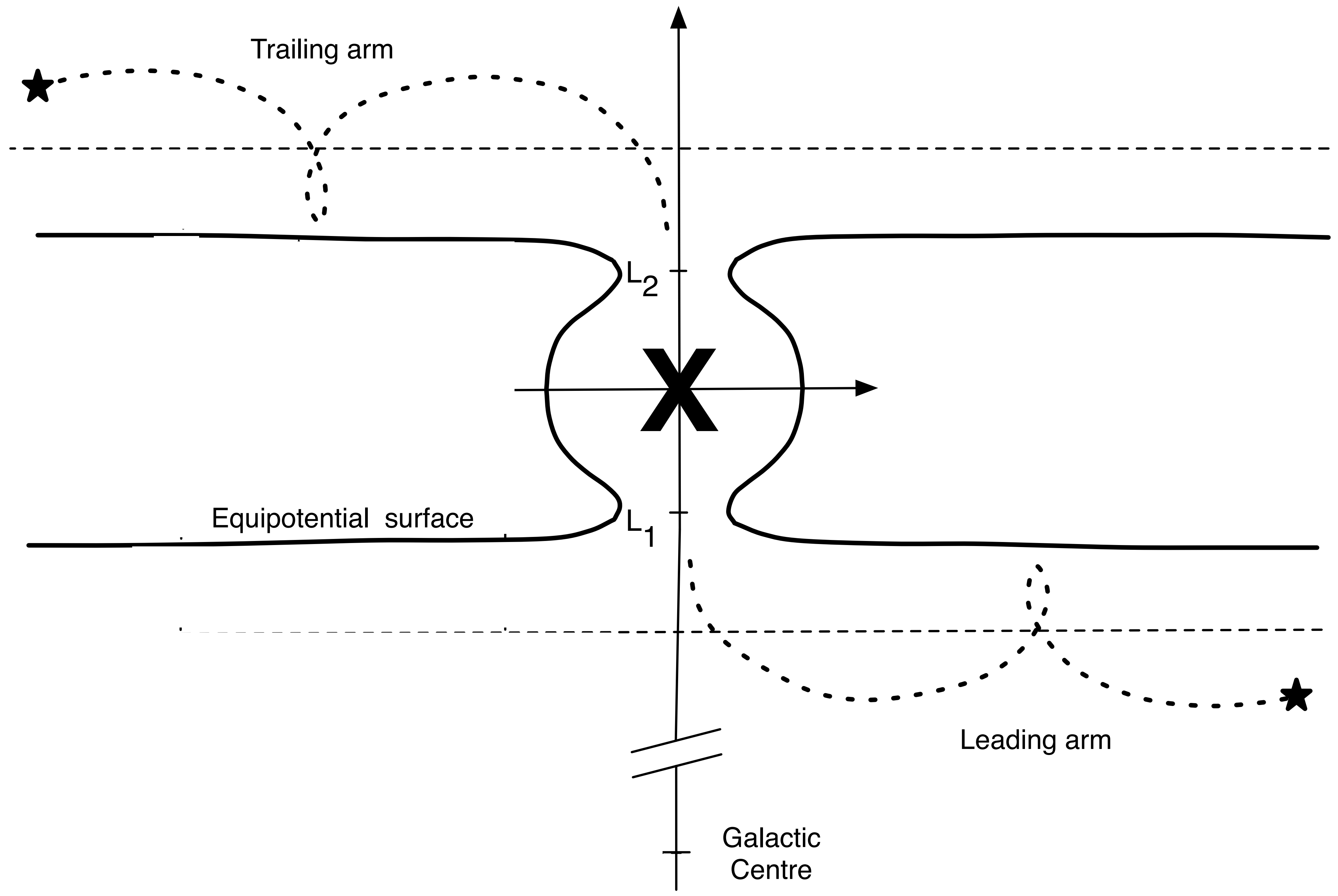
Modeling of Streams

Orbit Fitting	low accuracy	fast
Orbit Fitting with some offset		
Restricted three-body		
Collisionless simulations		
Direct N-body simulations	high accuracy	slow

Modeling of Streams

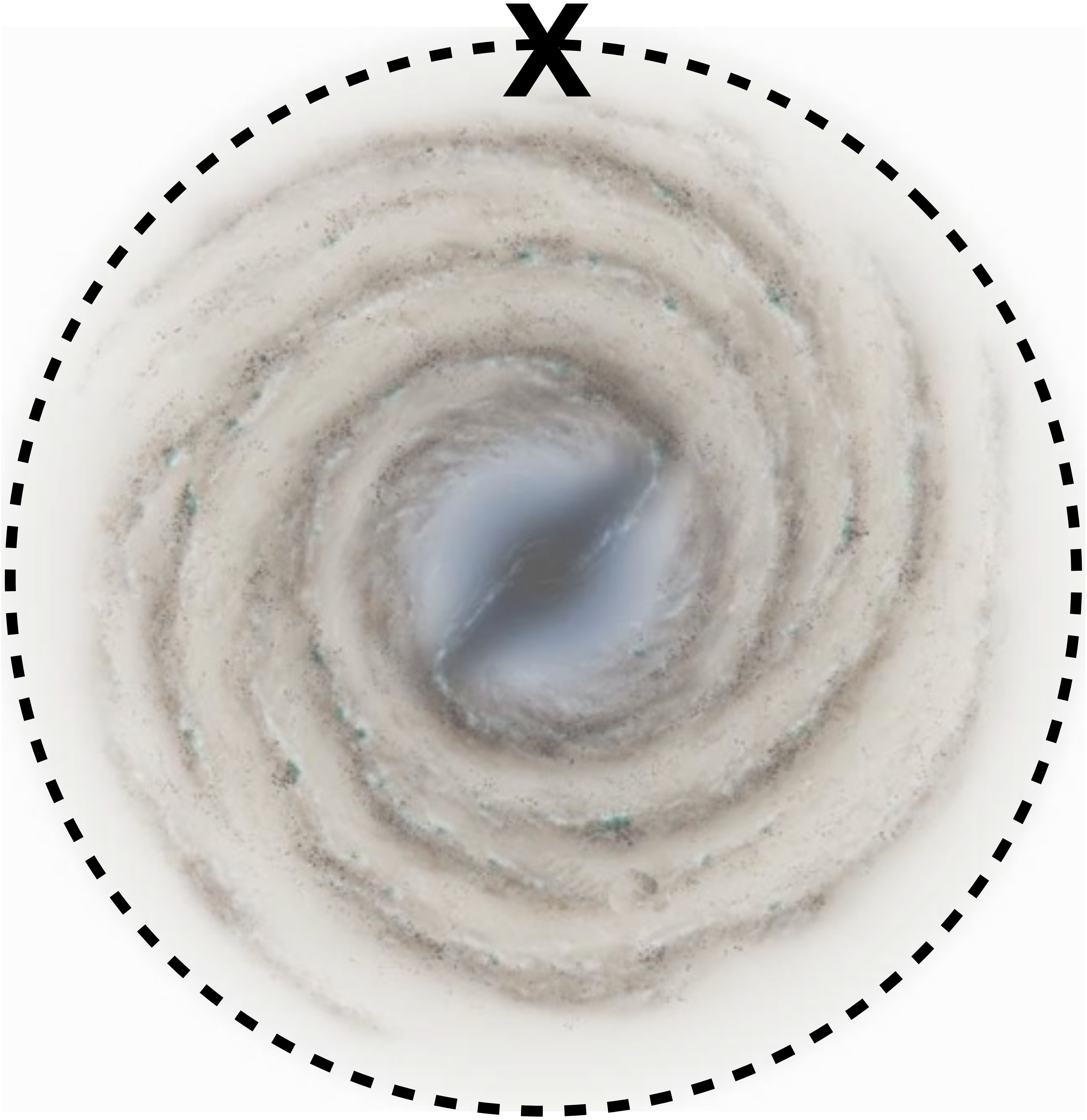
Orbit Fitting	low accuracy	fast
Orbit Fitting with some offset		
Restricted three-body	Streakline modeling	
Collisionless simulations		
Direct N-body simulations	high accuracy	slow

Stars escape through the Lagrange points with low offset velocities

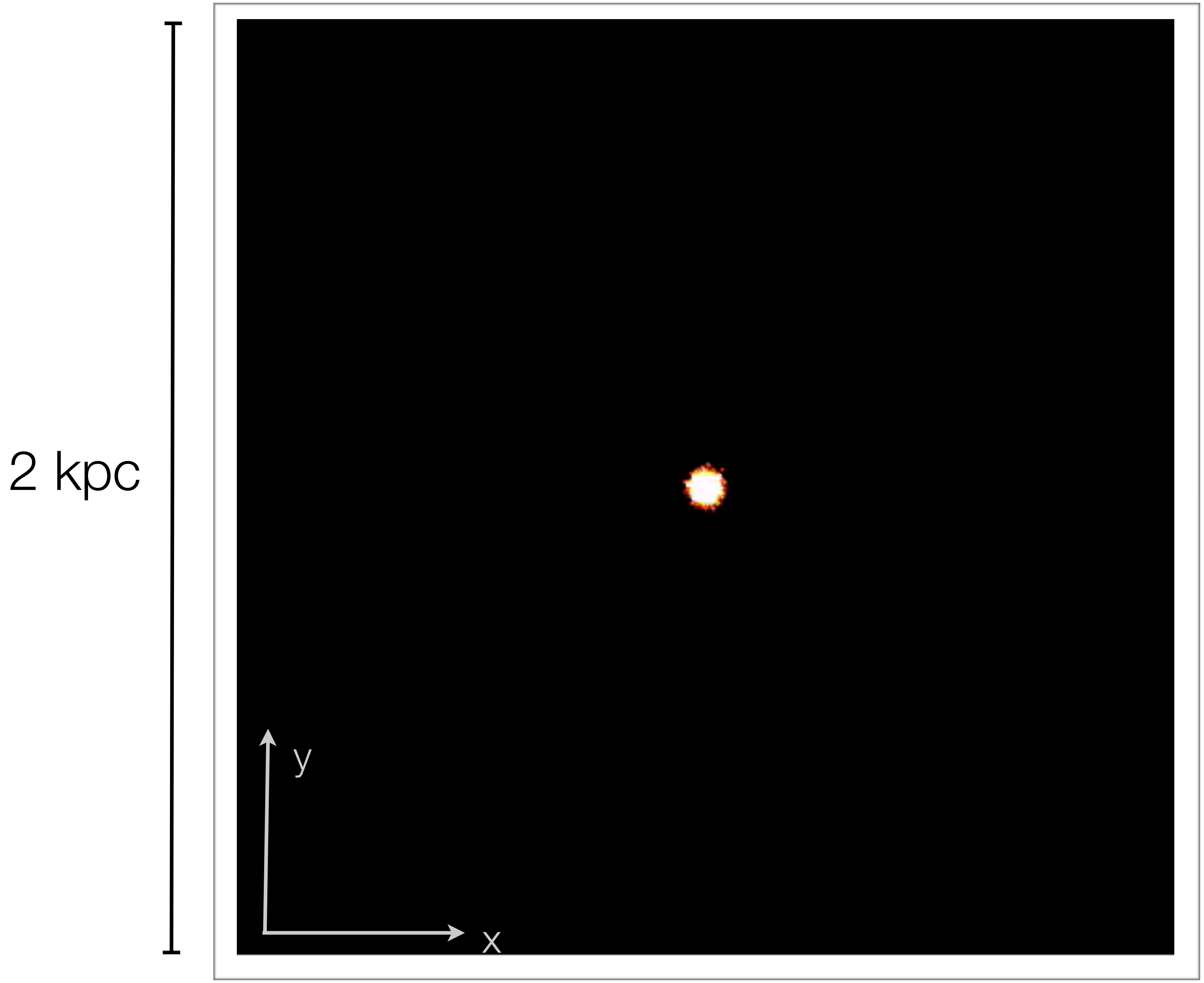


Just, Berczik, Petrov & Ernst (2009)

Simplest case: circular orbit

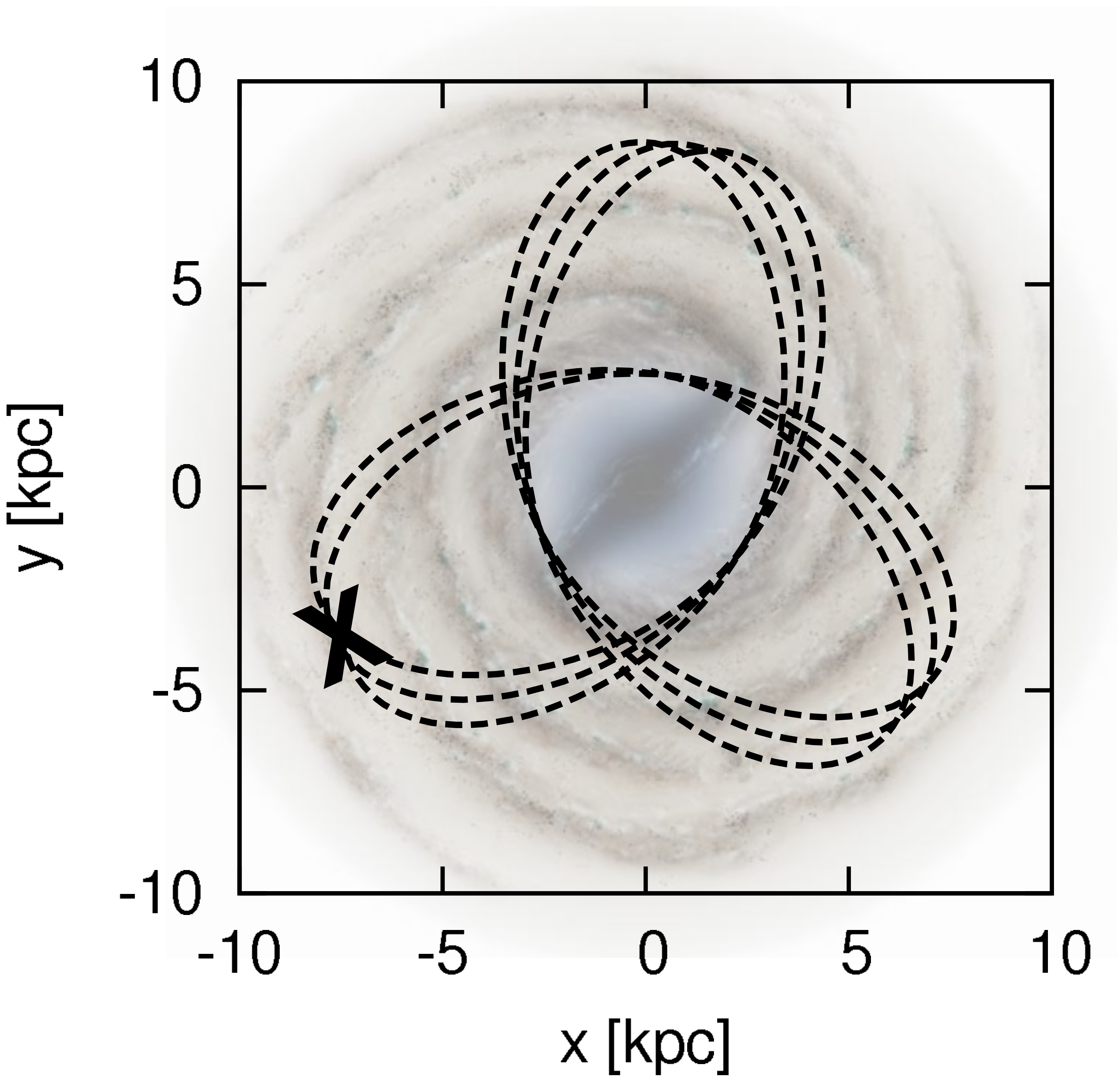


Star clusters produce a continuous stream of stars

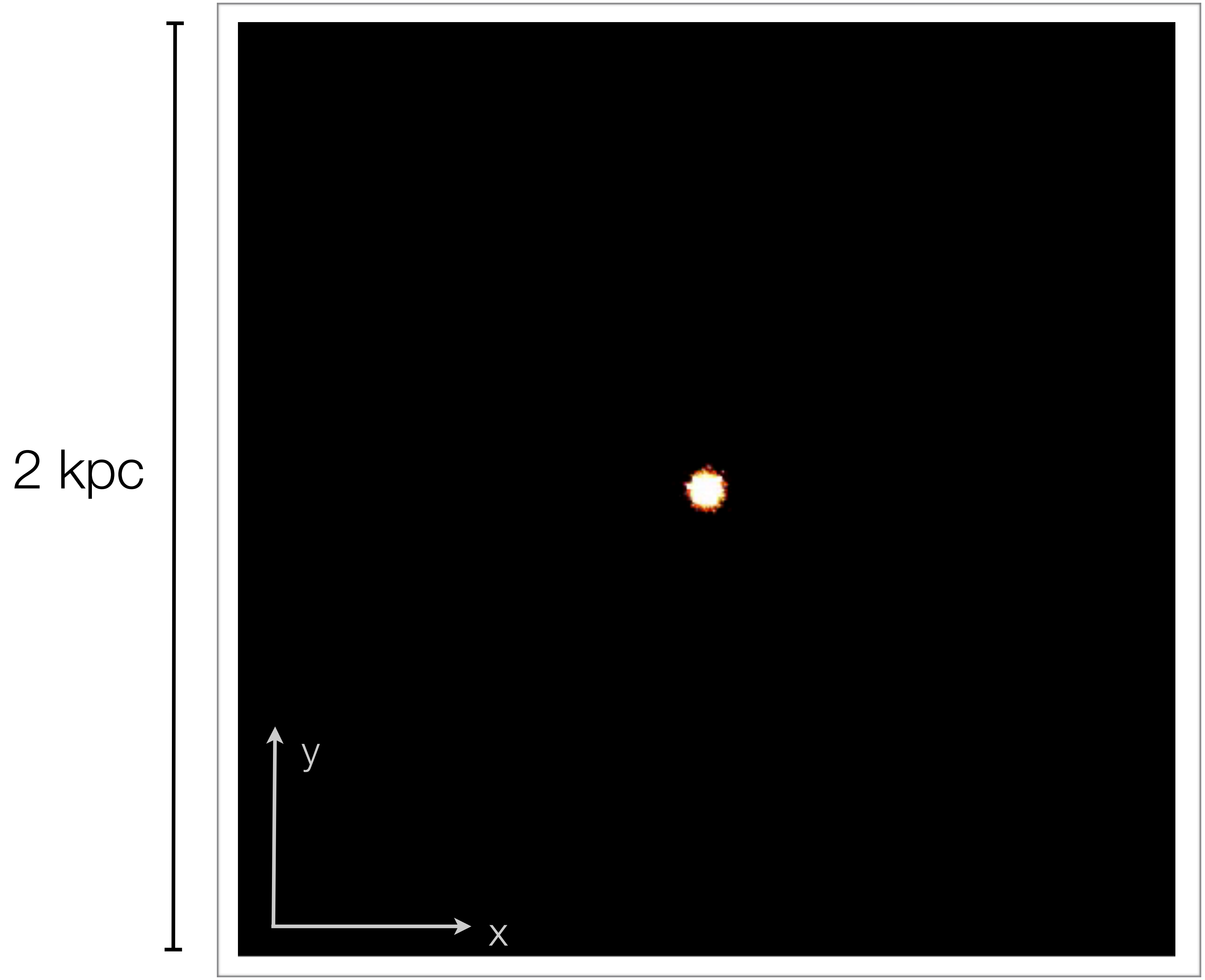


Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

Stream overdensities also form in streams of clusters on eccentric orbits



Ideally we would like to make a full N-body run for each parameter combination

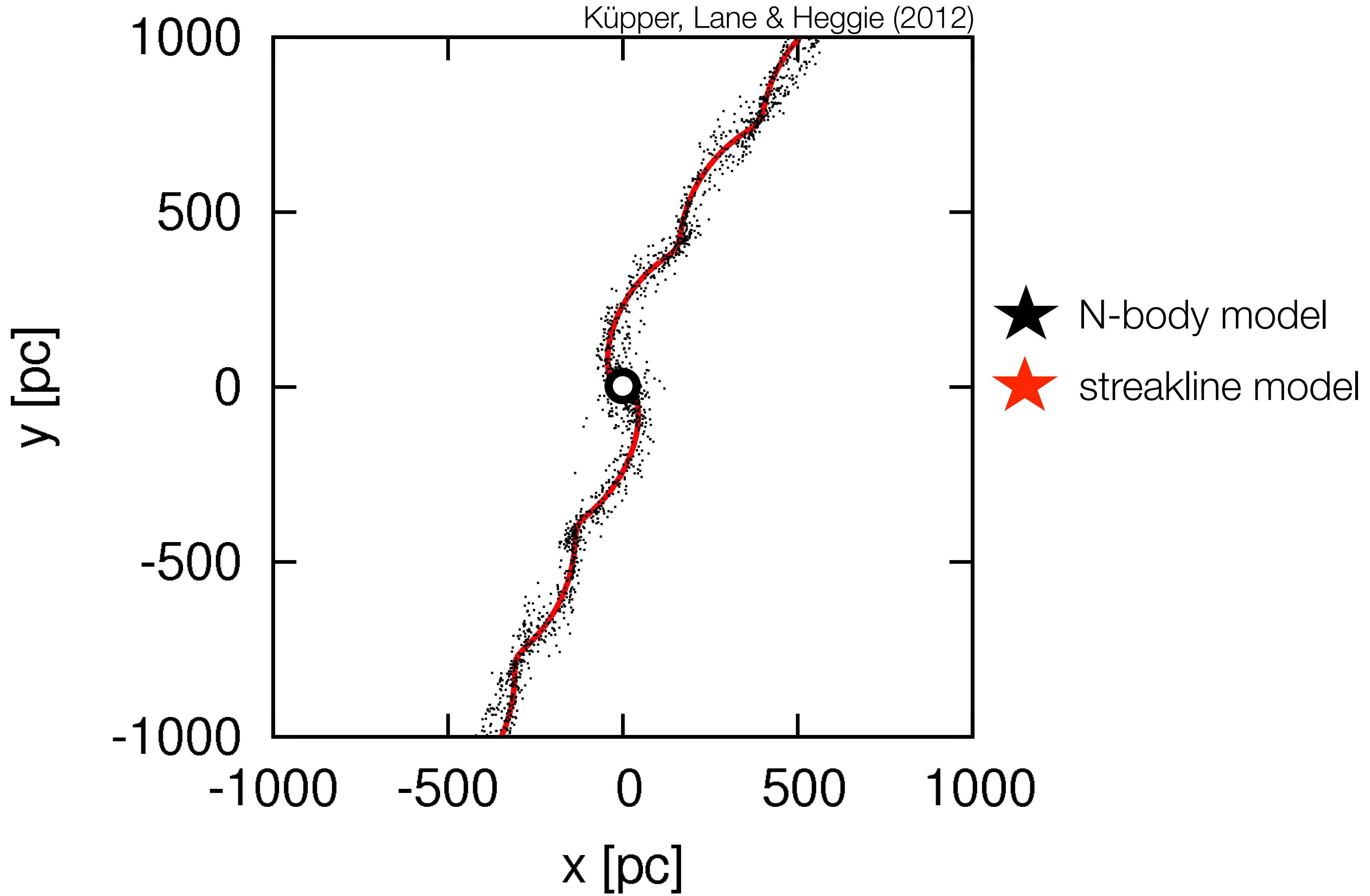


Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

A streakline visualizes the flow of particles in a stream due to progenitor orbit and surrounding medium

$$r_J = \left(\frac{GM}{\Omega^2 - \partial^2\Phi/\partial R^2} \right)^{1/3}$$

Streakline models approximate full N-body simulations at low computational cost



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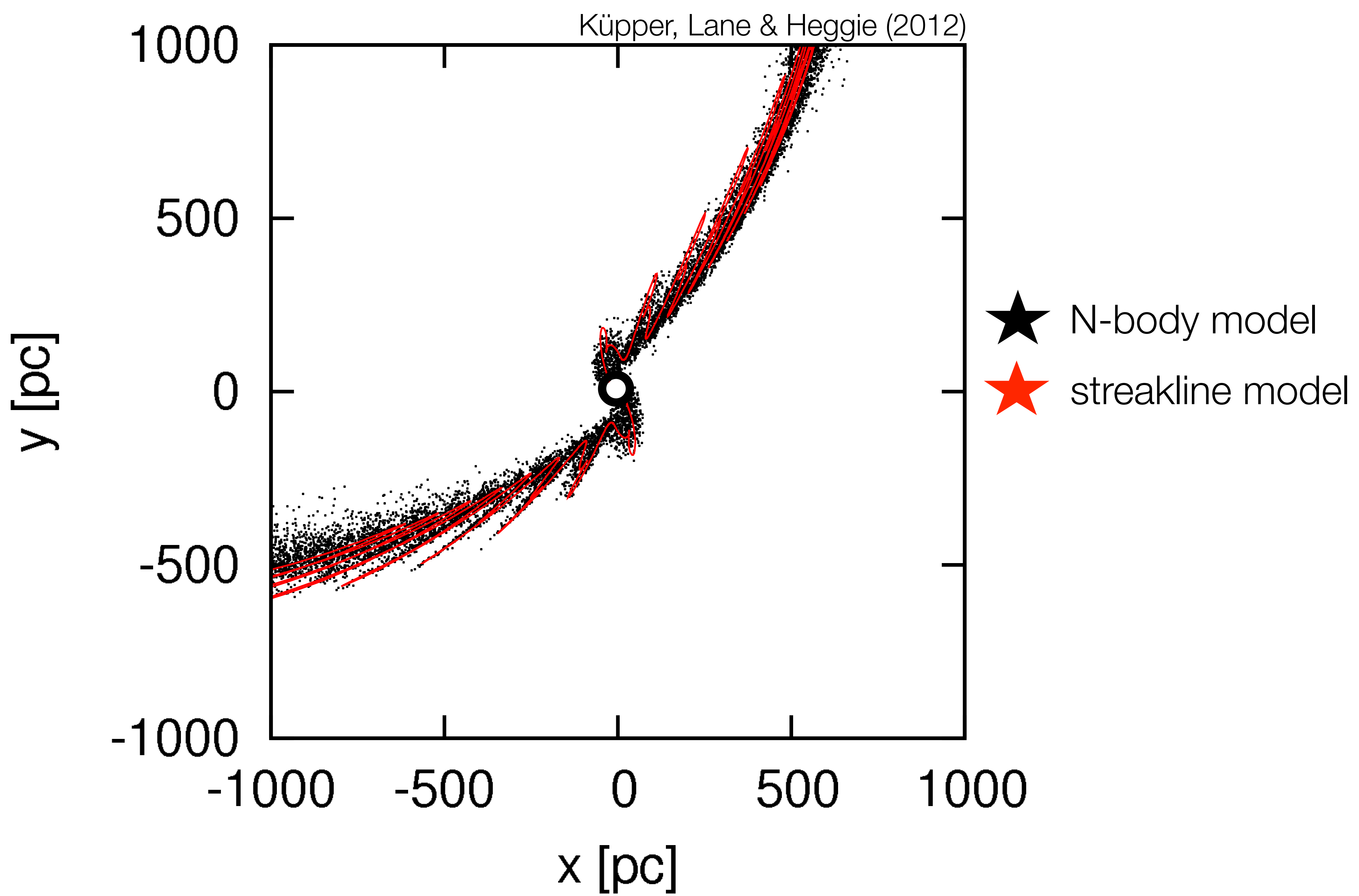

2	Palomar 5 Observations
3	Modeling Palomar 5

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
- r_h = 20-30 p
- central density: 1 star/pc^2
- R_{sun} = 23.6 kpc
- R_{GC} = 18.6 kpc, z =16.9 kpc
- extremely depleted in low-mass stars

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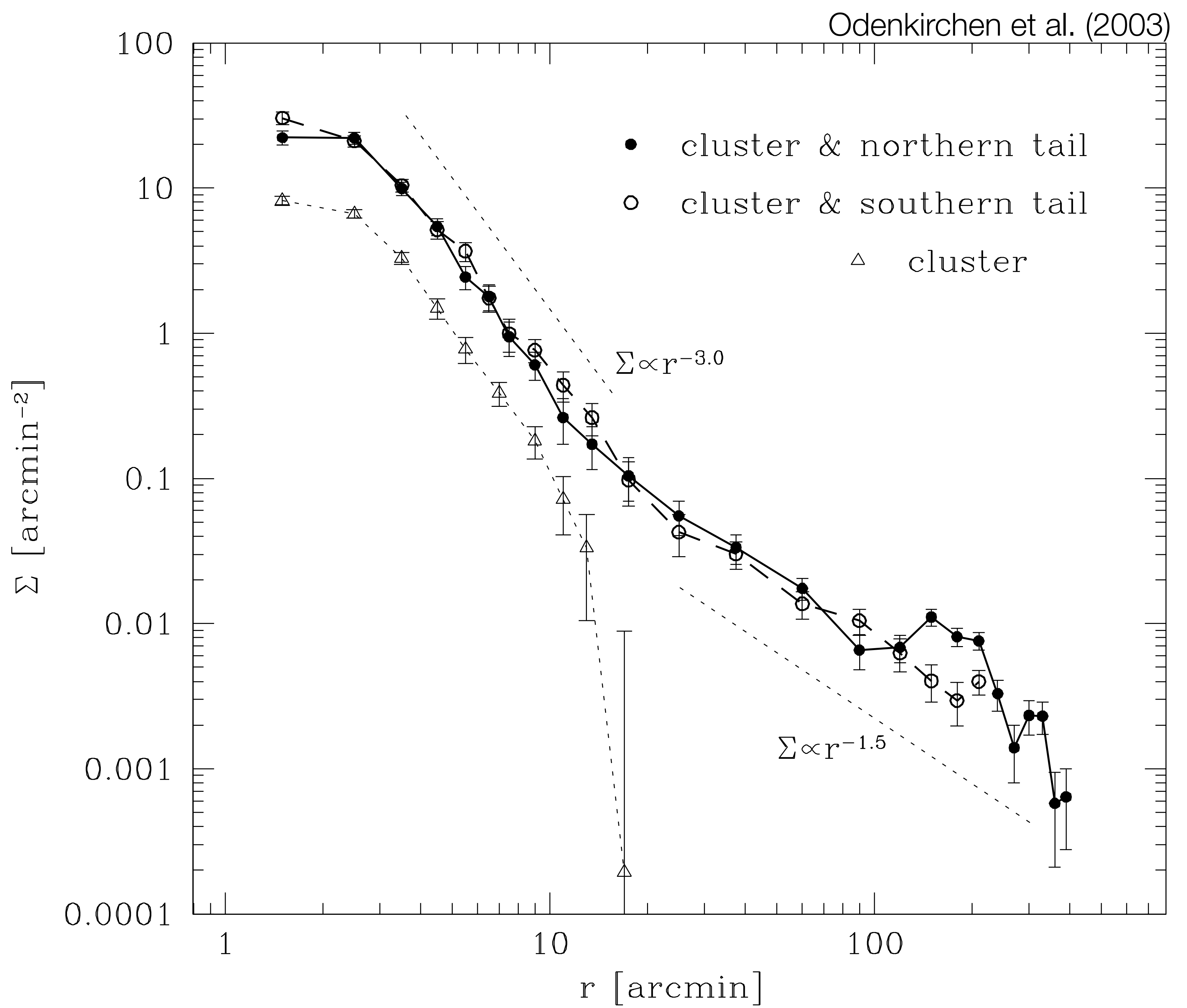
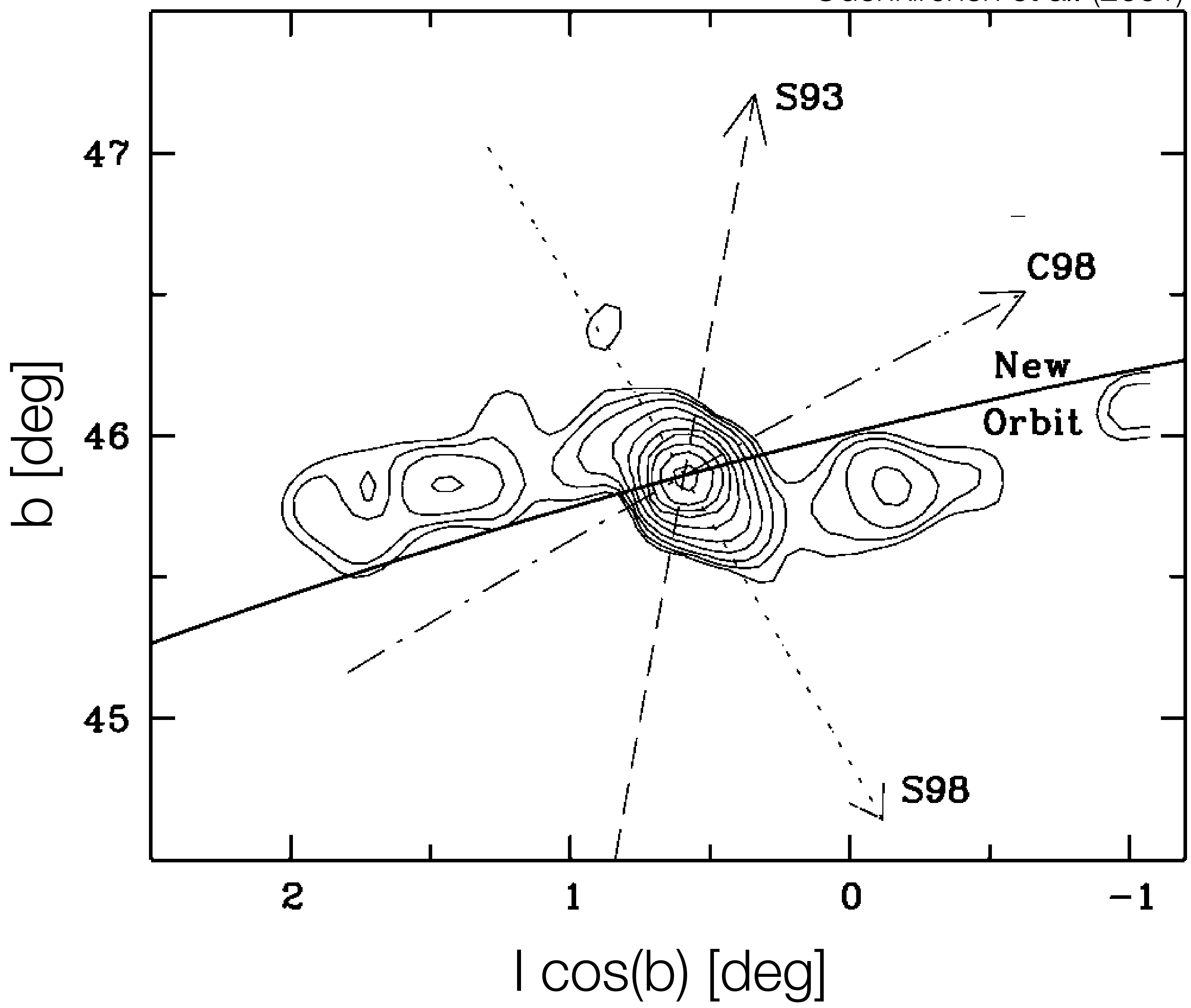
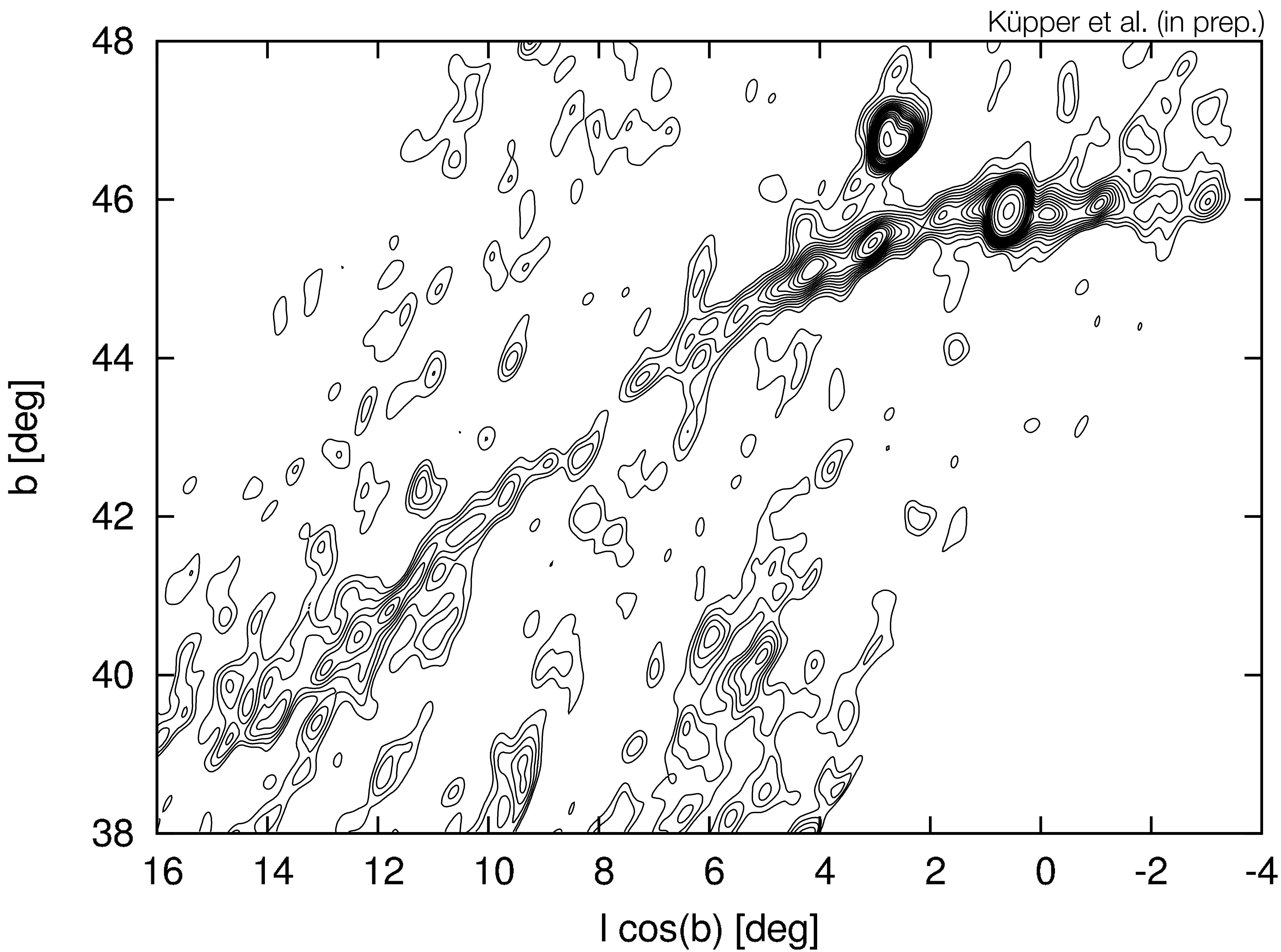


Its tidal tails were detected in the first data release of SDSS

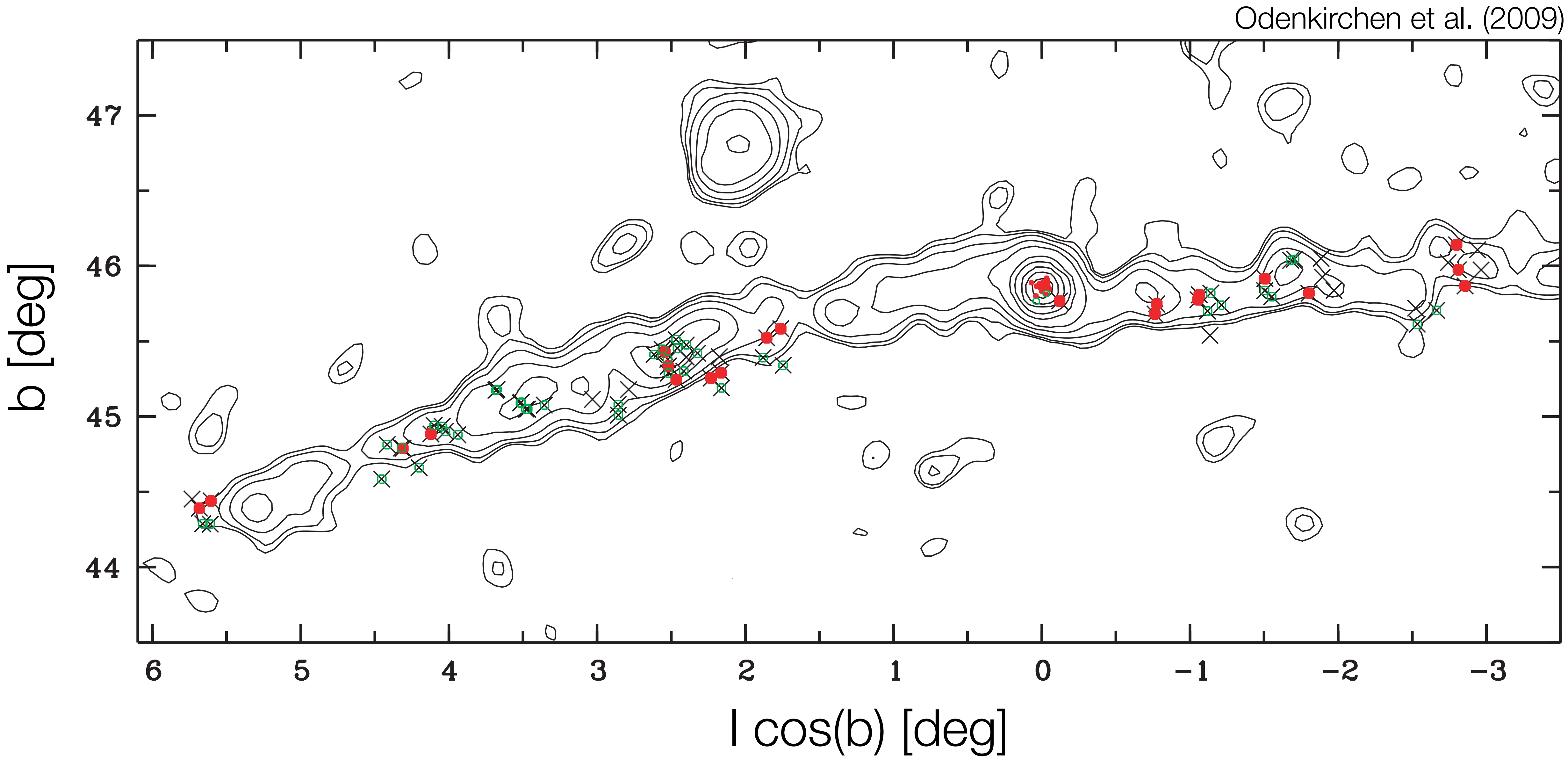
Odenkirchen et al. (2001)



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



17 radial velocities have been measured along the tidal stream



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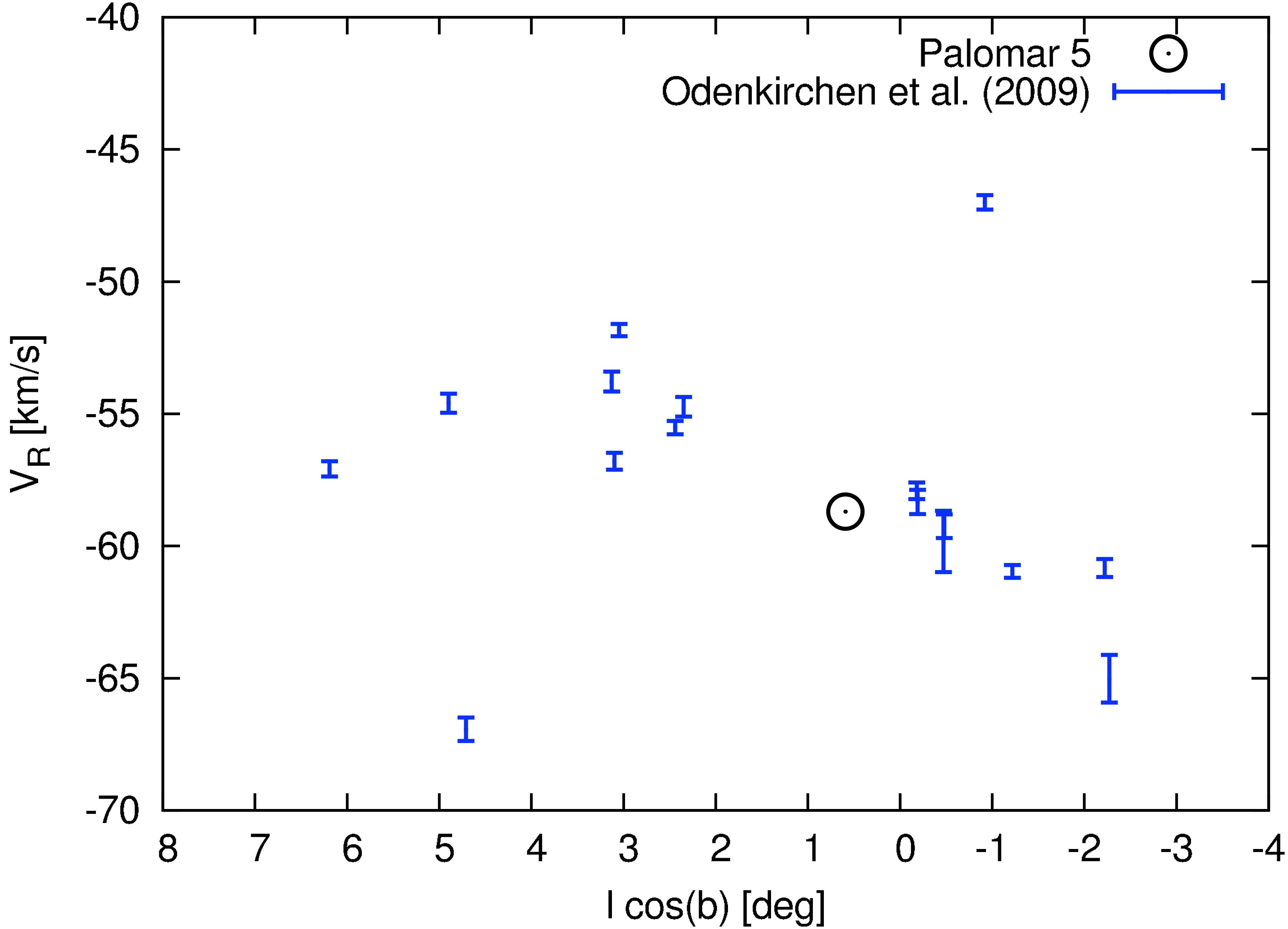
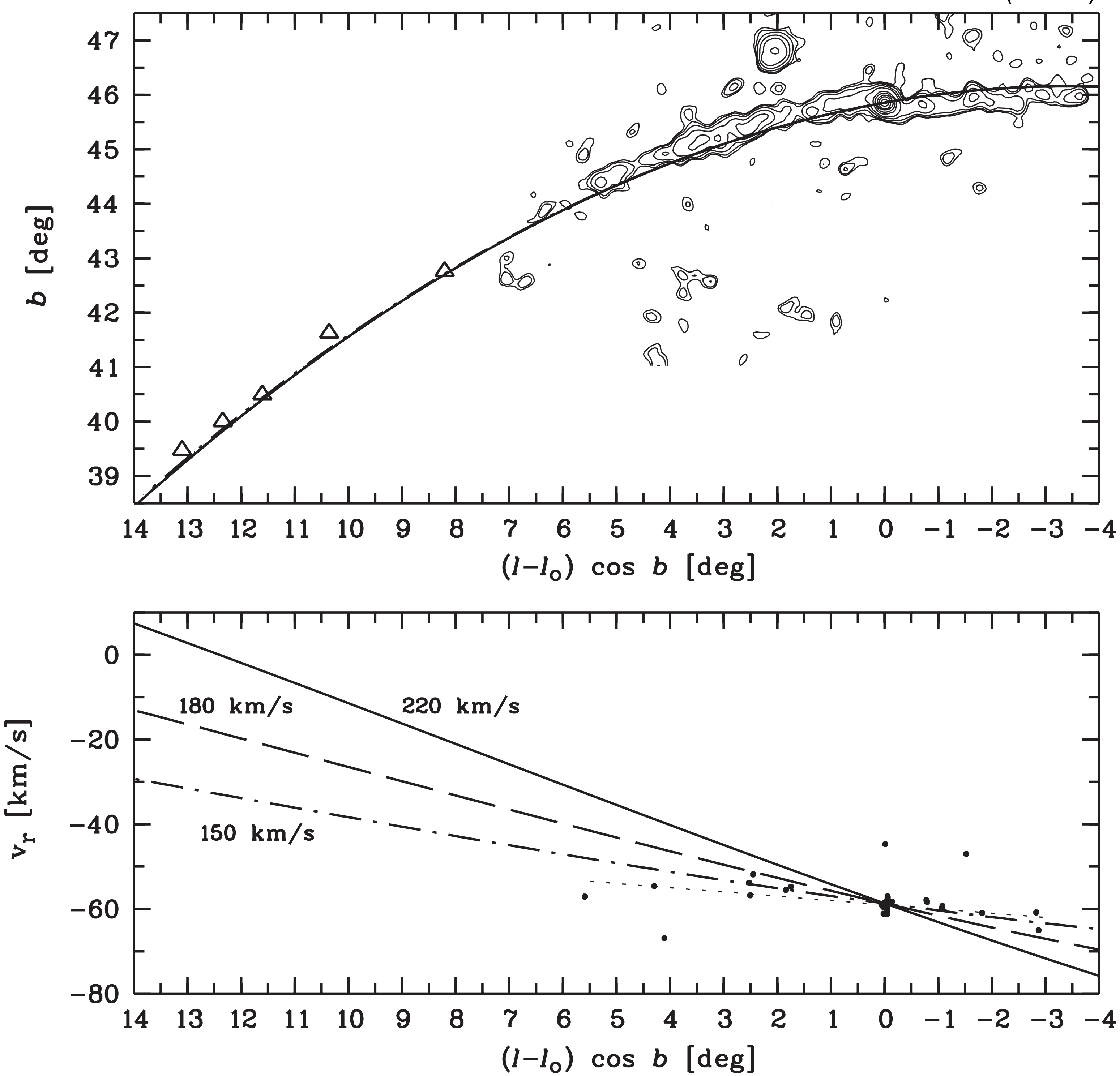


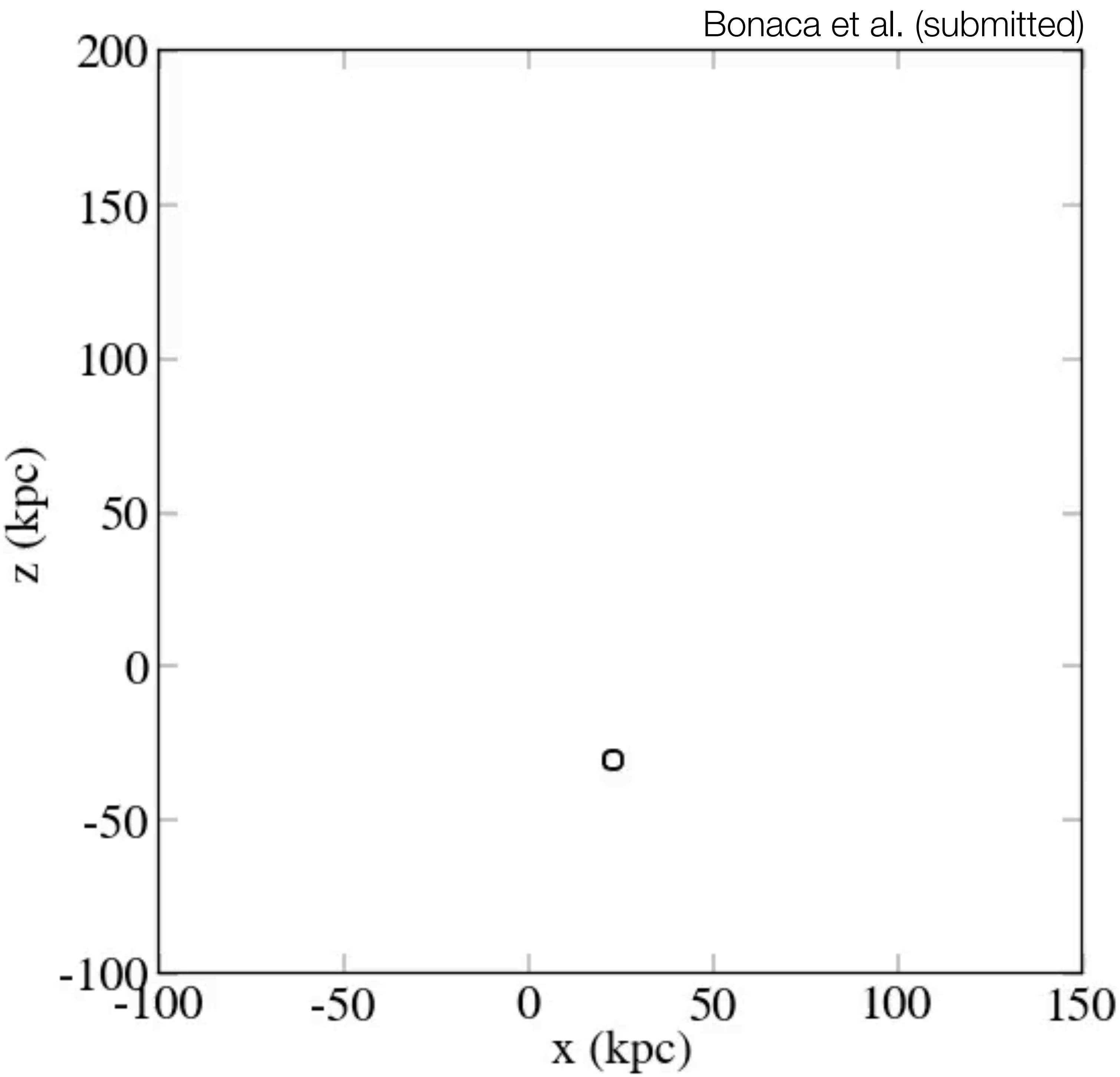
Fitting orbits to streams is highly degenerate and produces biased results

Odenkirchen et al. (2009)

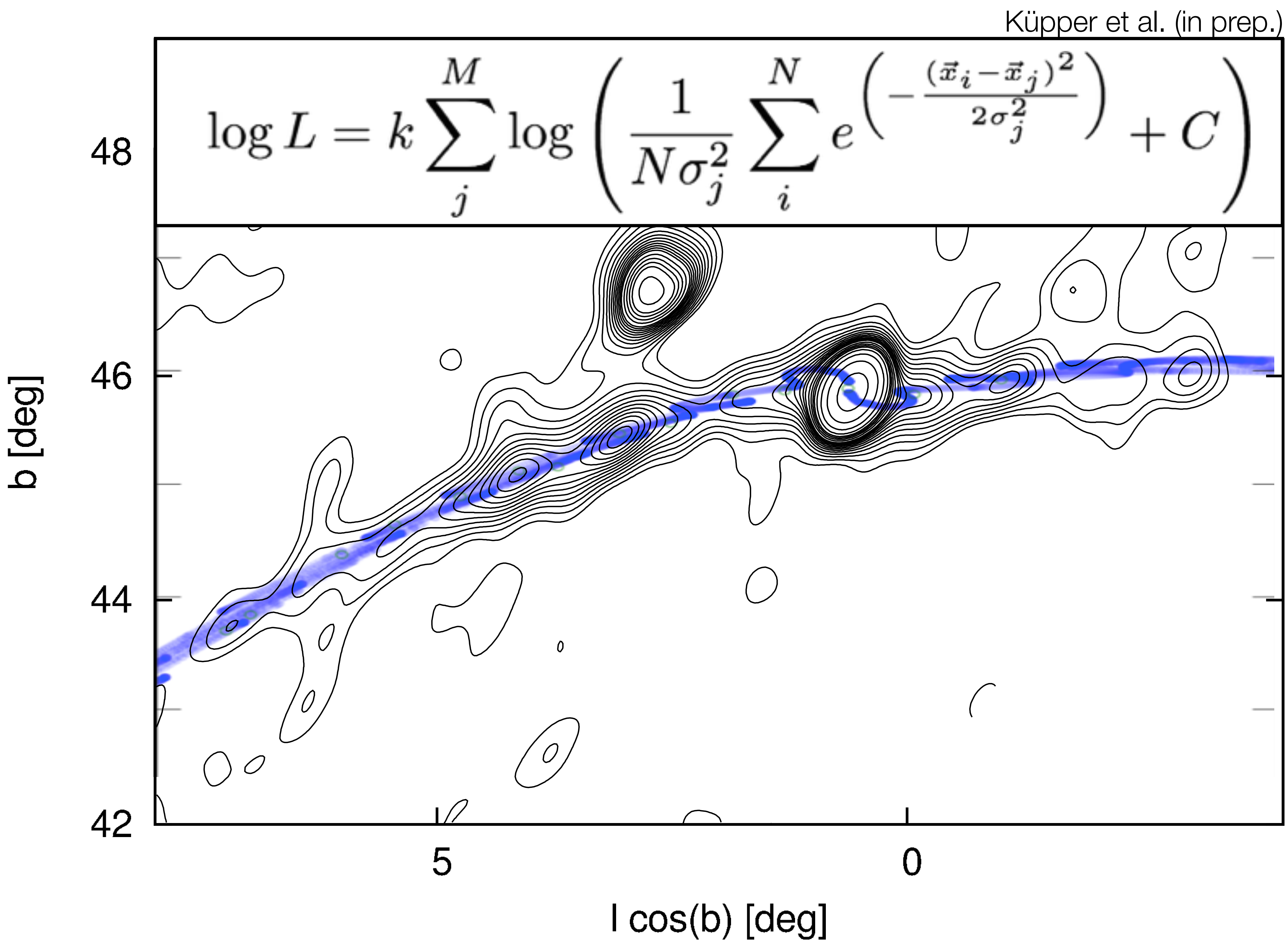


3 Modeling Palomar 5

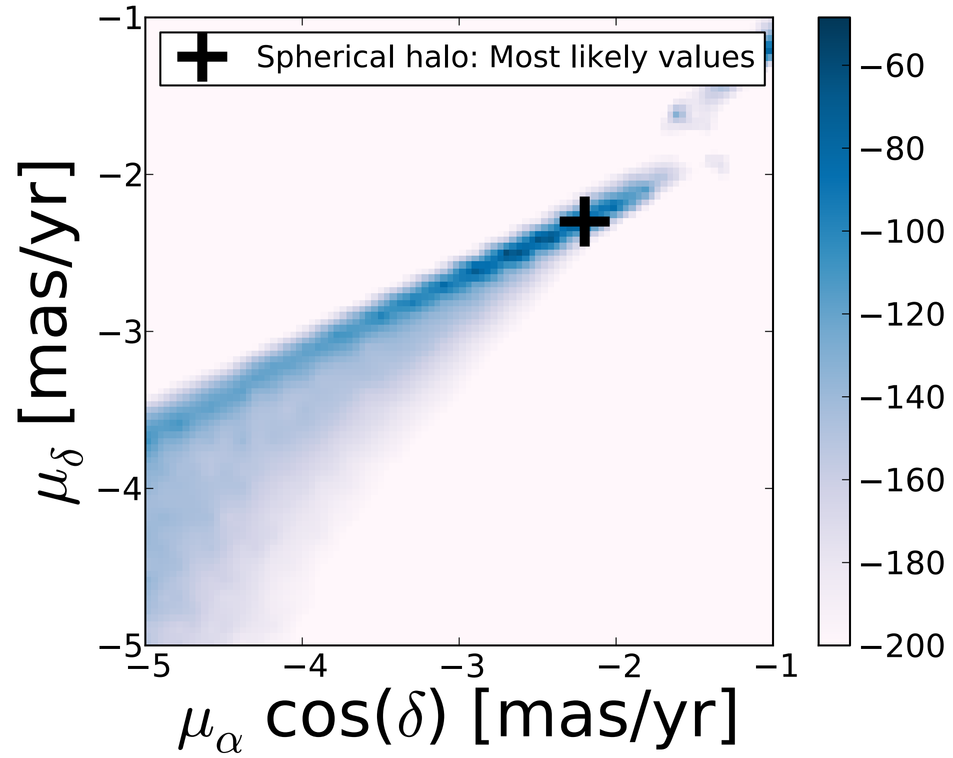
Streakline models make extensive parameter-space search in arbitrary potentials possible



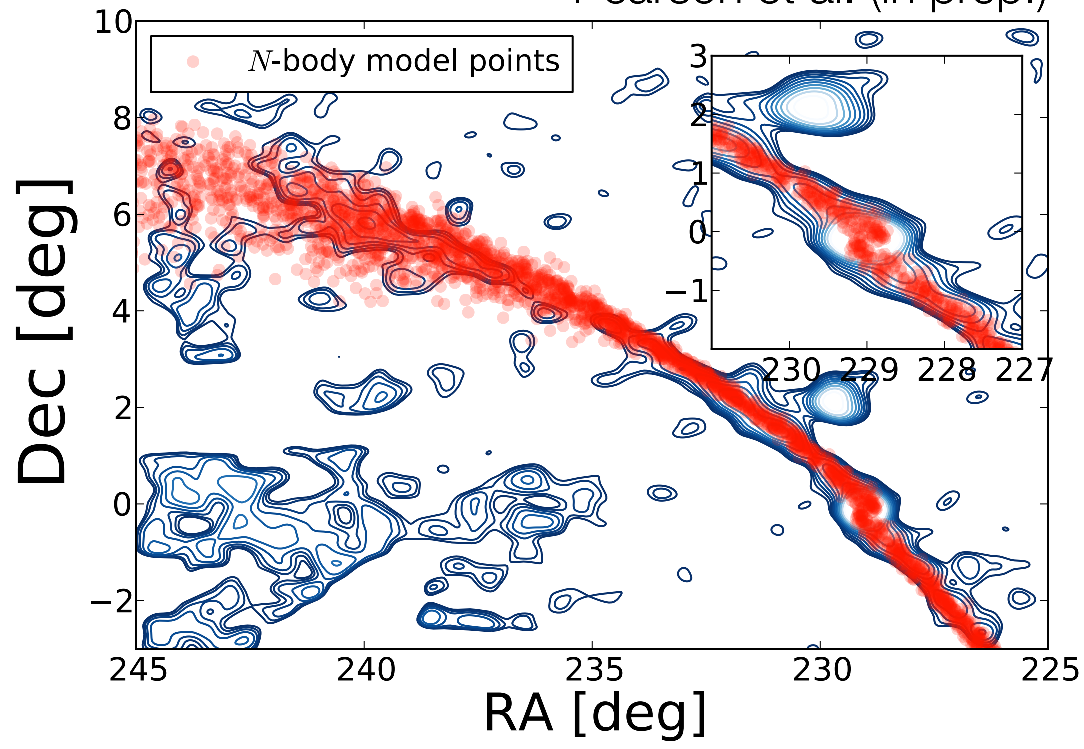
Produce a streakline model and compare it to the data via an appropriate likelihood function



The Palomar 5 stream is very thin - thinner than expected in a very triaxial potential



Pearson et al. (in prep.)



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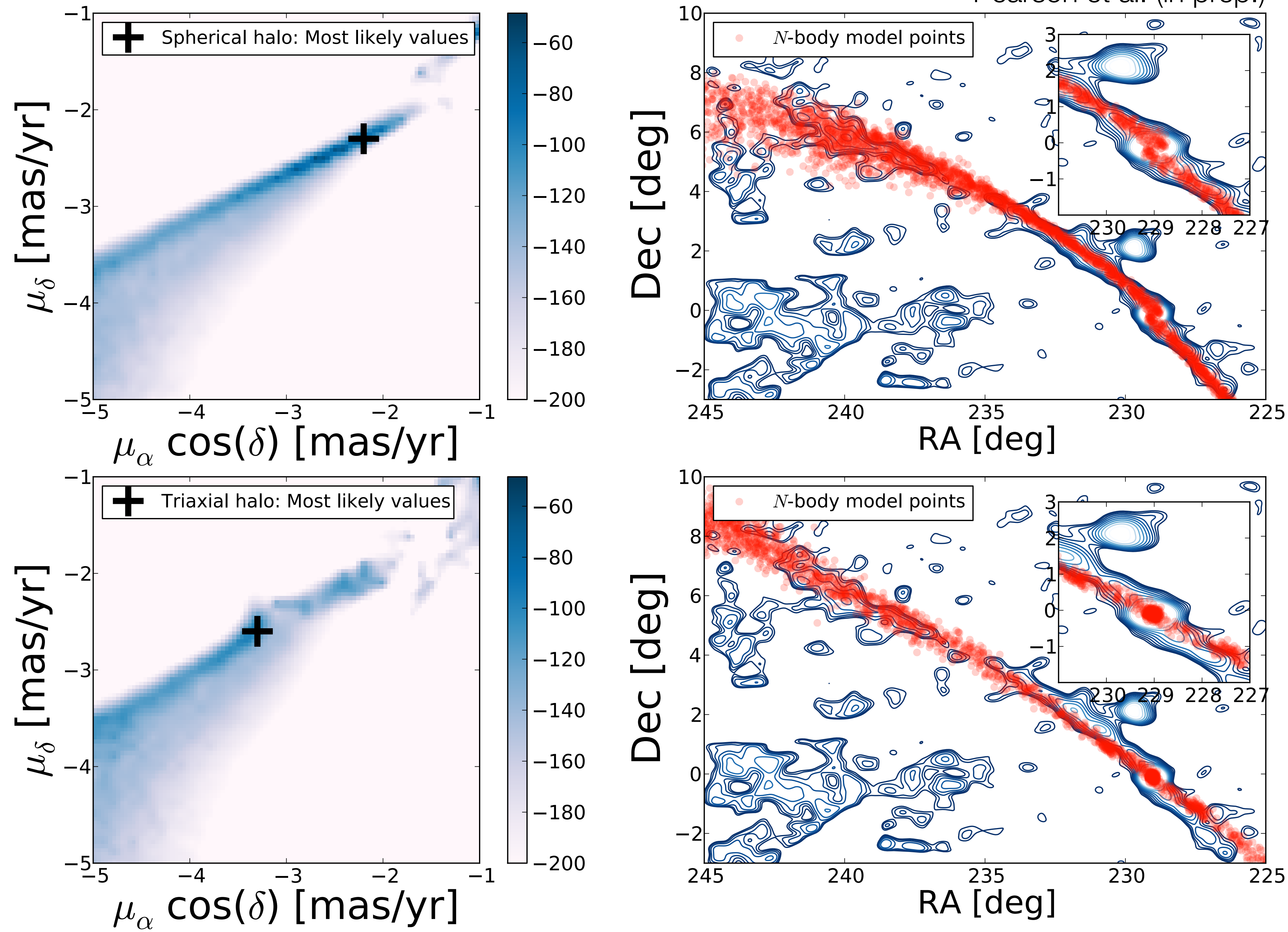

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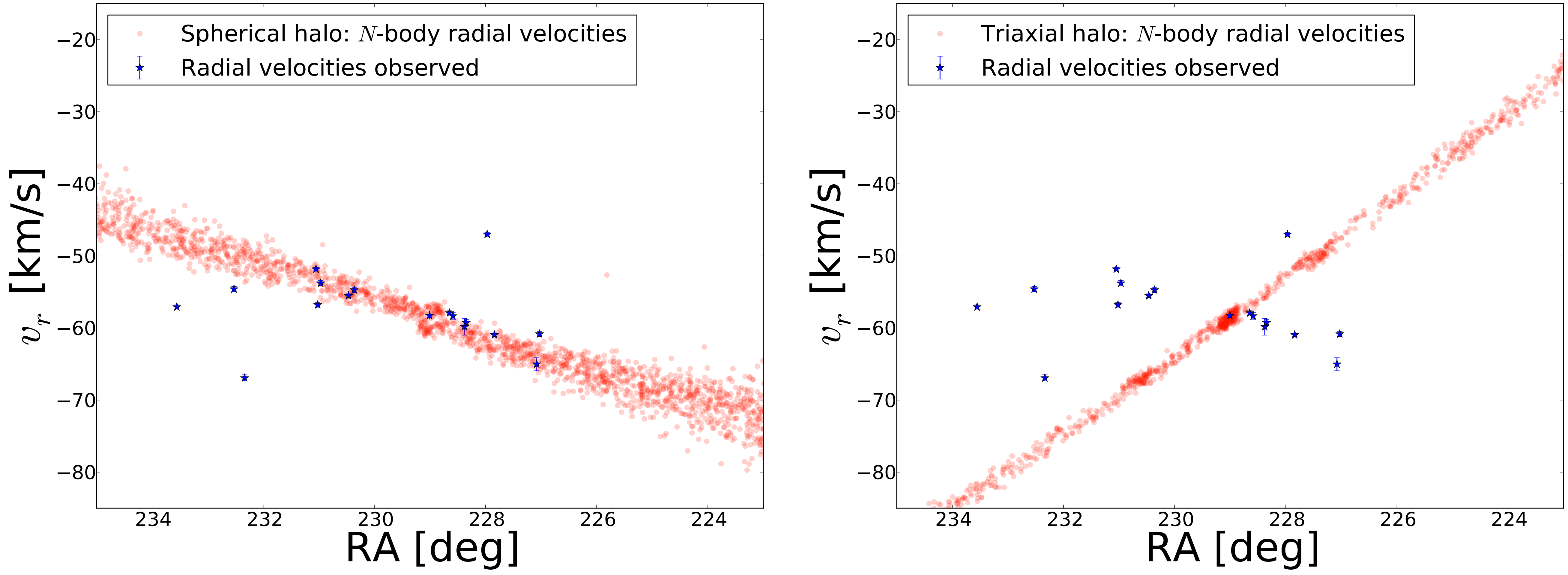
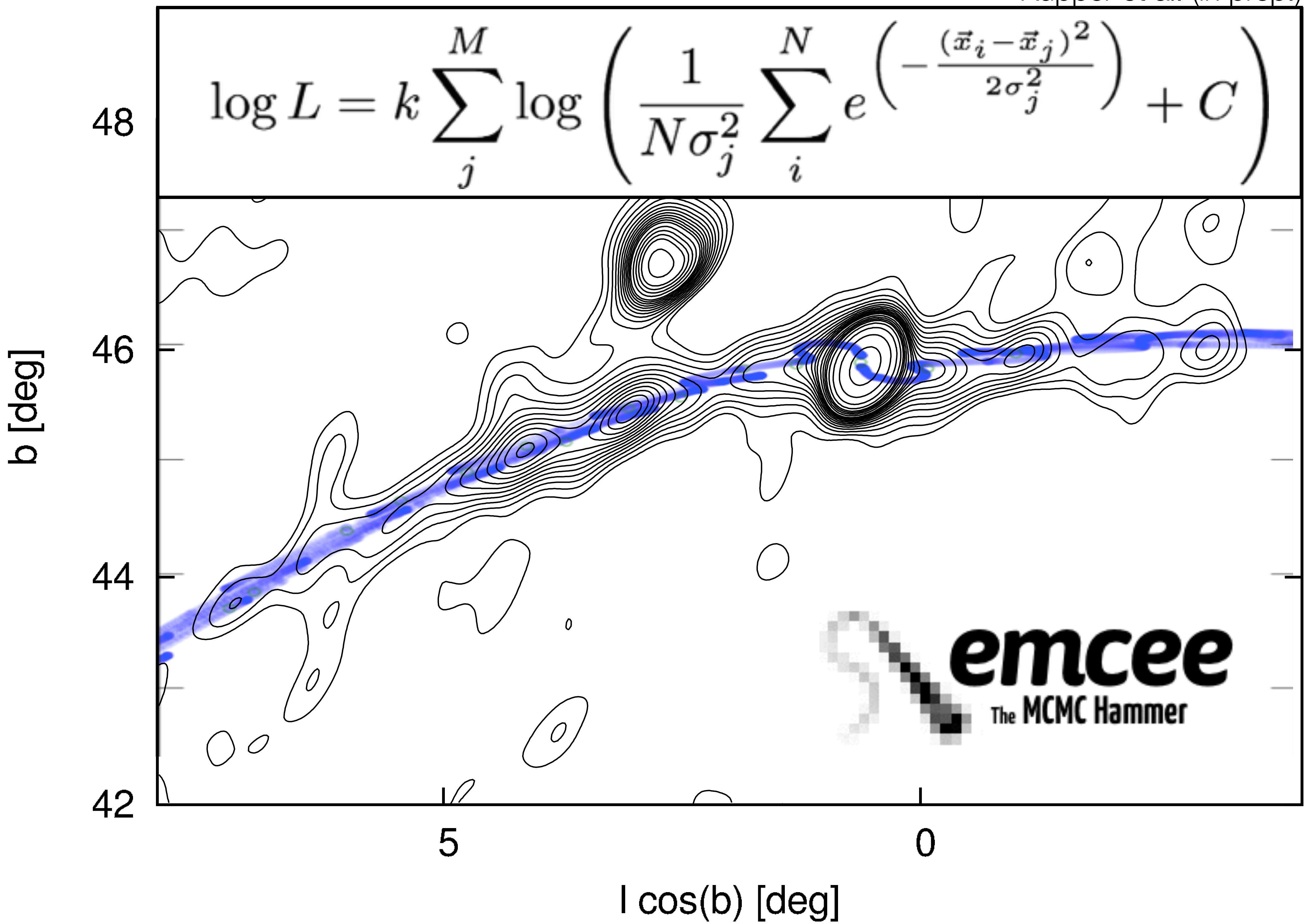


Use MCMC to walk through parameter space

Küpper et al. (in prep.)



Our forward modeling has 11 free parameters

NFW halo scale mass

NFW halo scale radius

NFW halo flattening

distance Sun-Galactic center

solar transverse velocity

distance Sun-Palomar 5

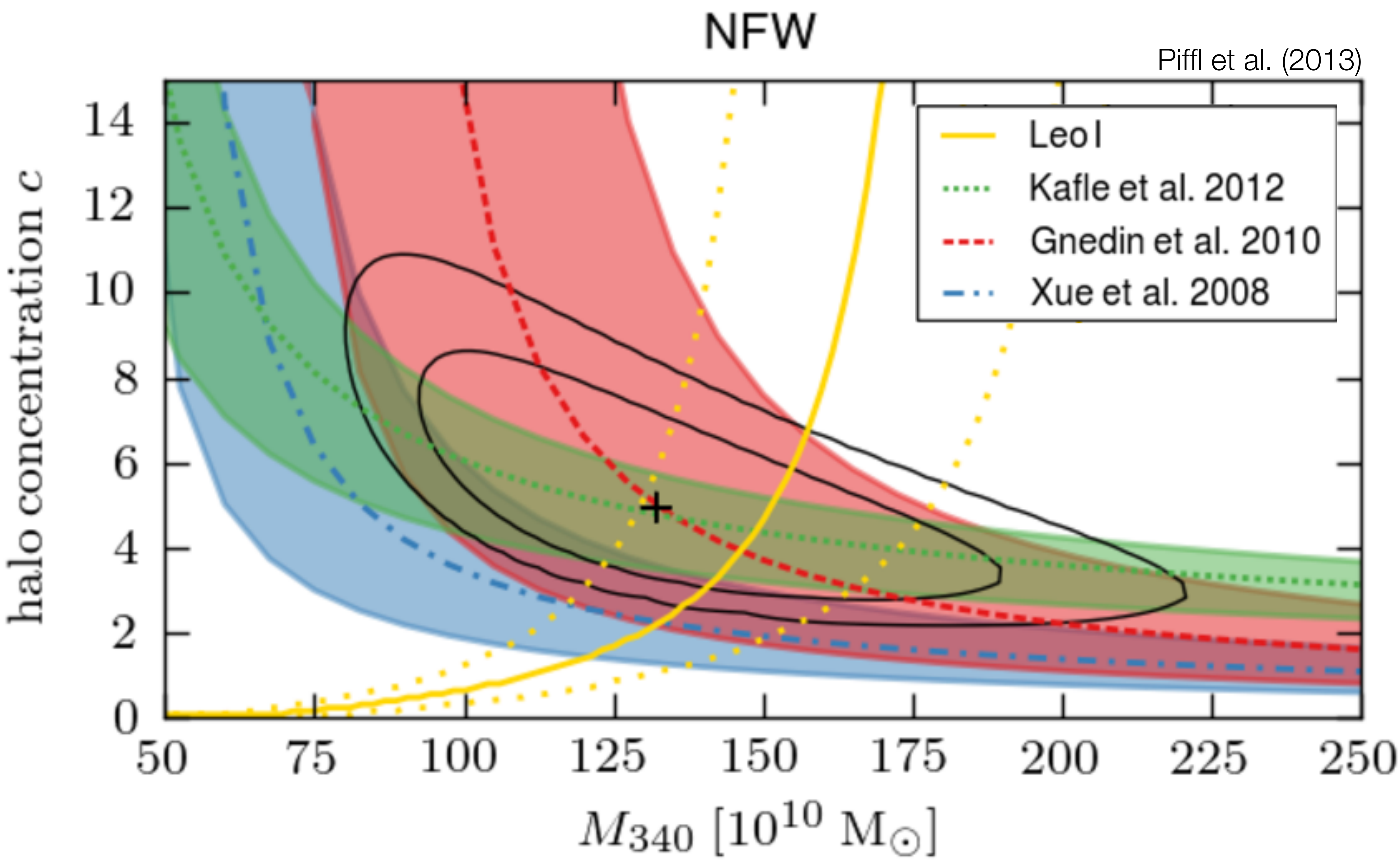
2 proper motion components

present-day mass of Palomar 5

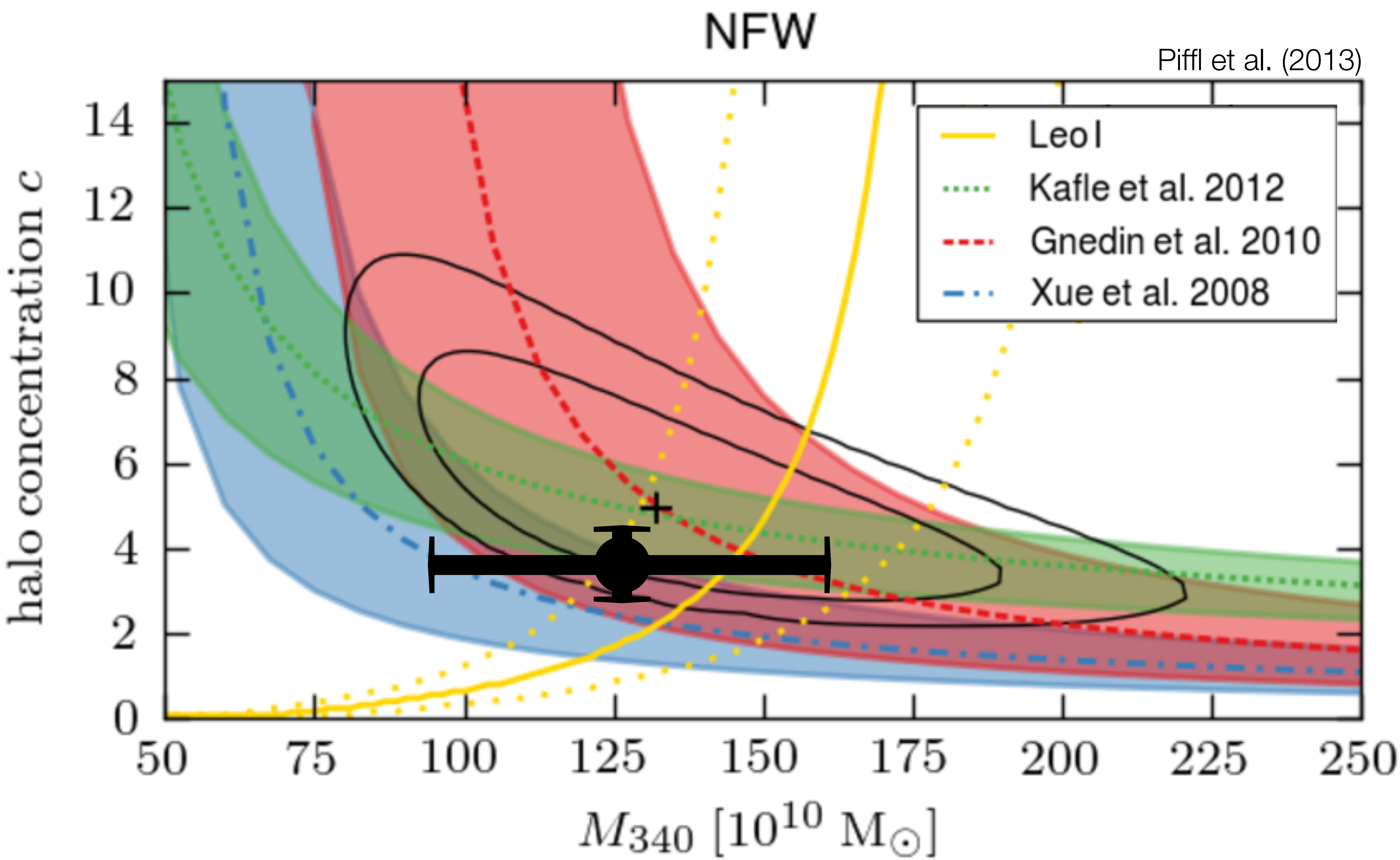
mean mass-loss rate of Palomar 5

integration time

Other methods use tracers in the Galactic halo

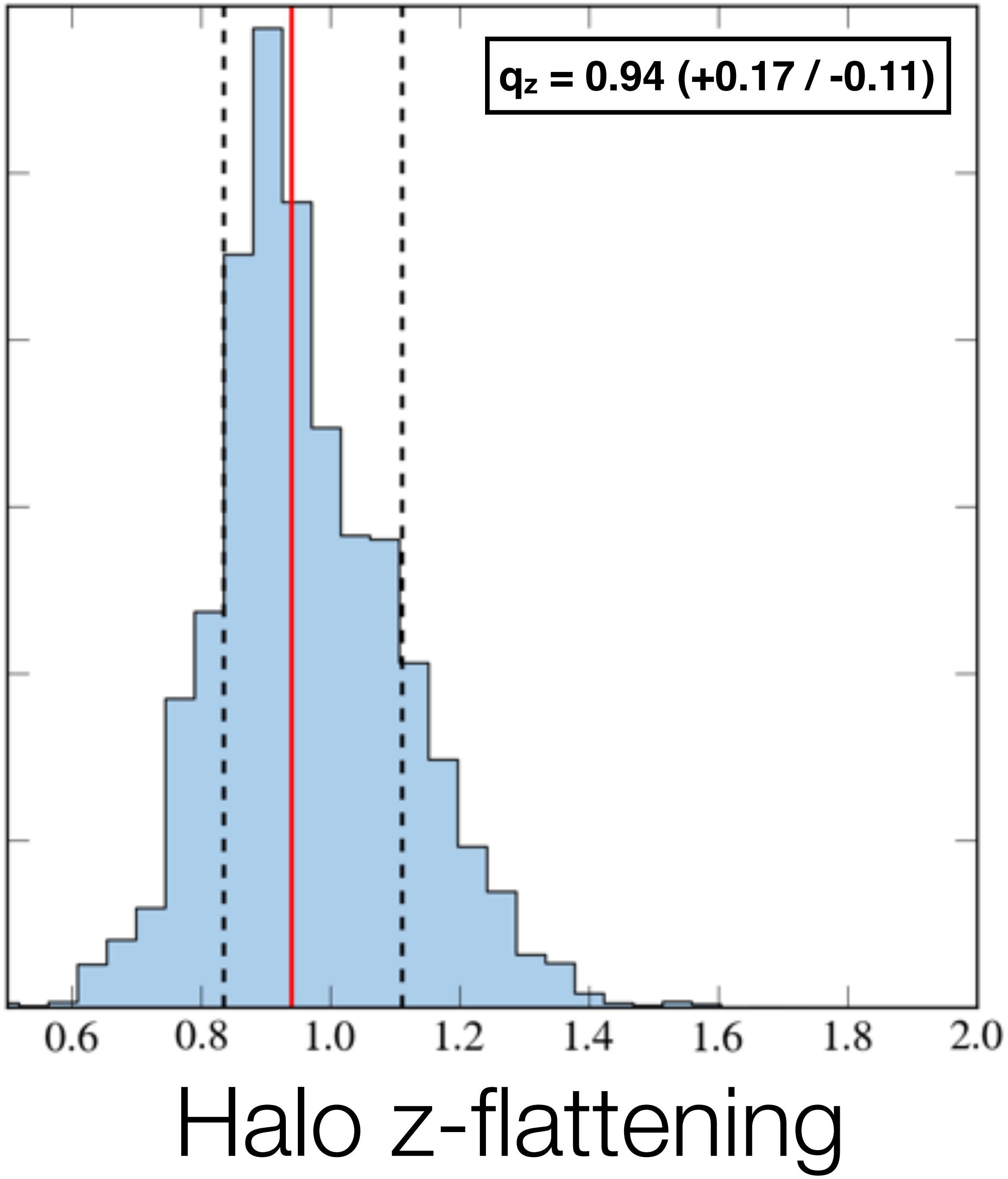


Palomar 5 measurement in excellent agreement with other methods



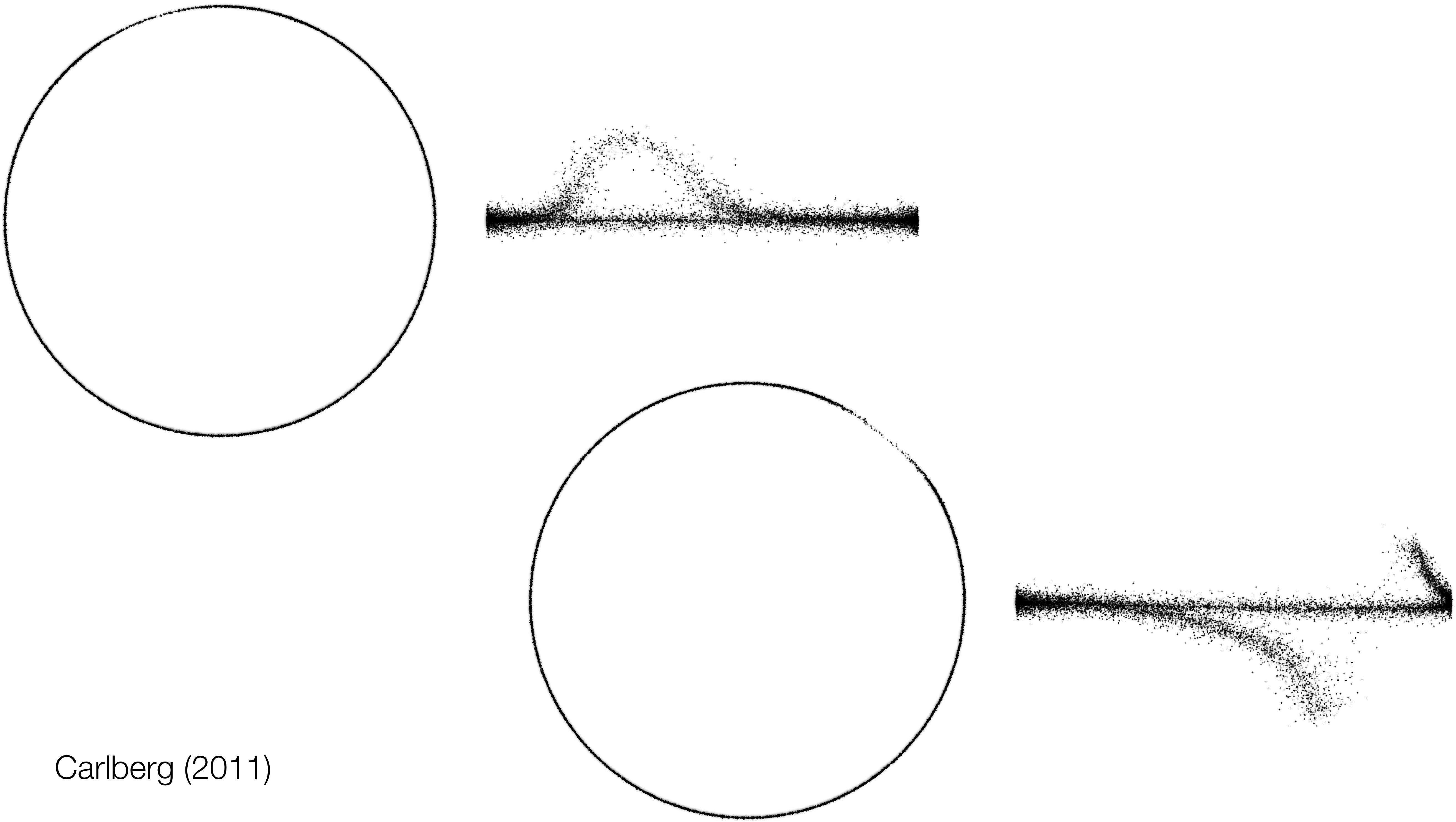
Halo shape may be slightly oblate

Küpper et al. (in prep.)

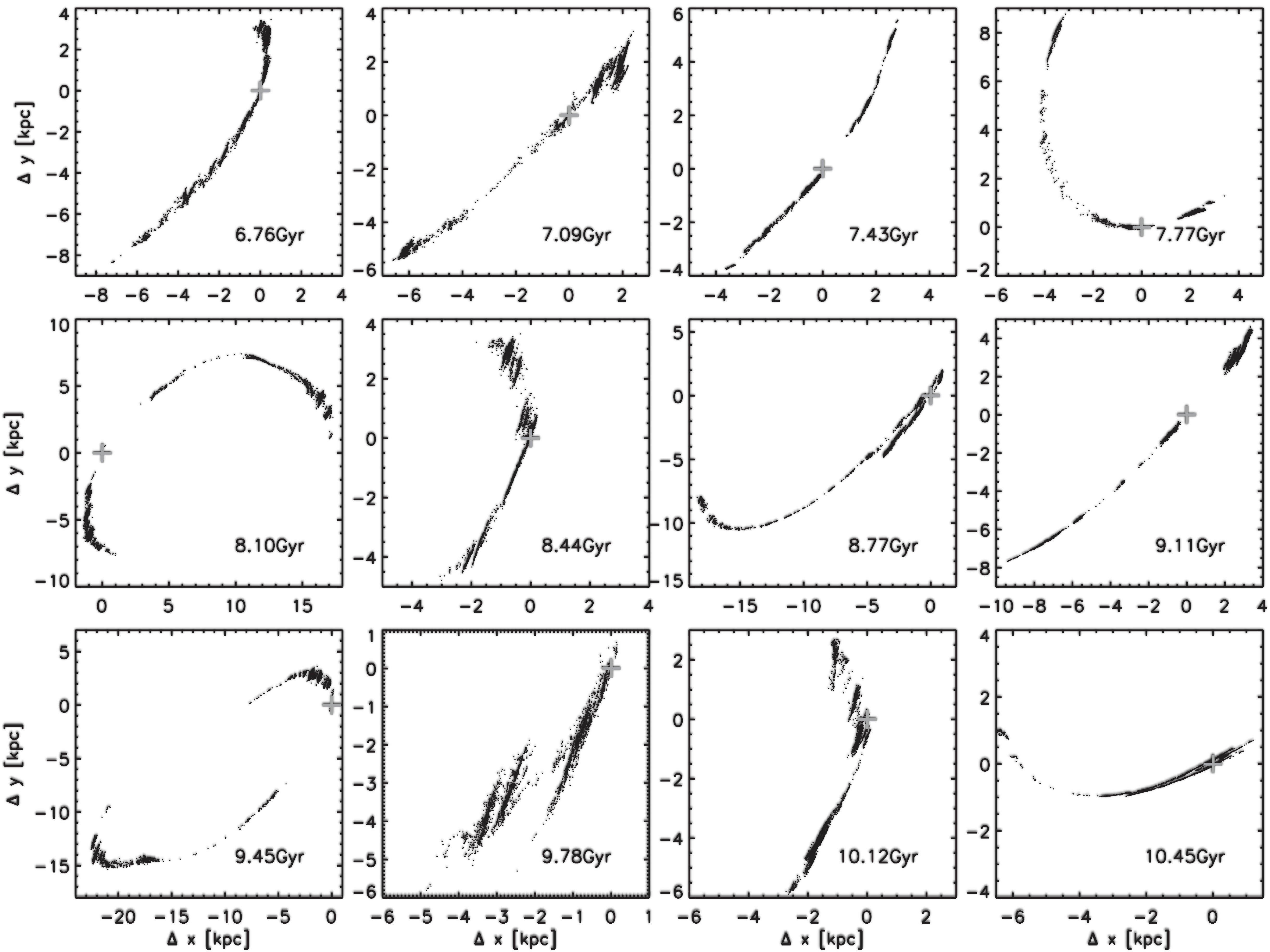


- ★ Globular cluster streams are high-precision scales
- ★ Streakline models make large parameter-space studies possible
- ★ Dark halo is close to being spherical in the inner 25 kpc

Tidal tails of star clusters are perfect detectors of dark matter substructure in the halo

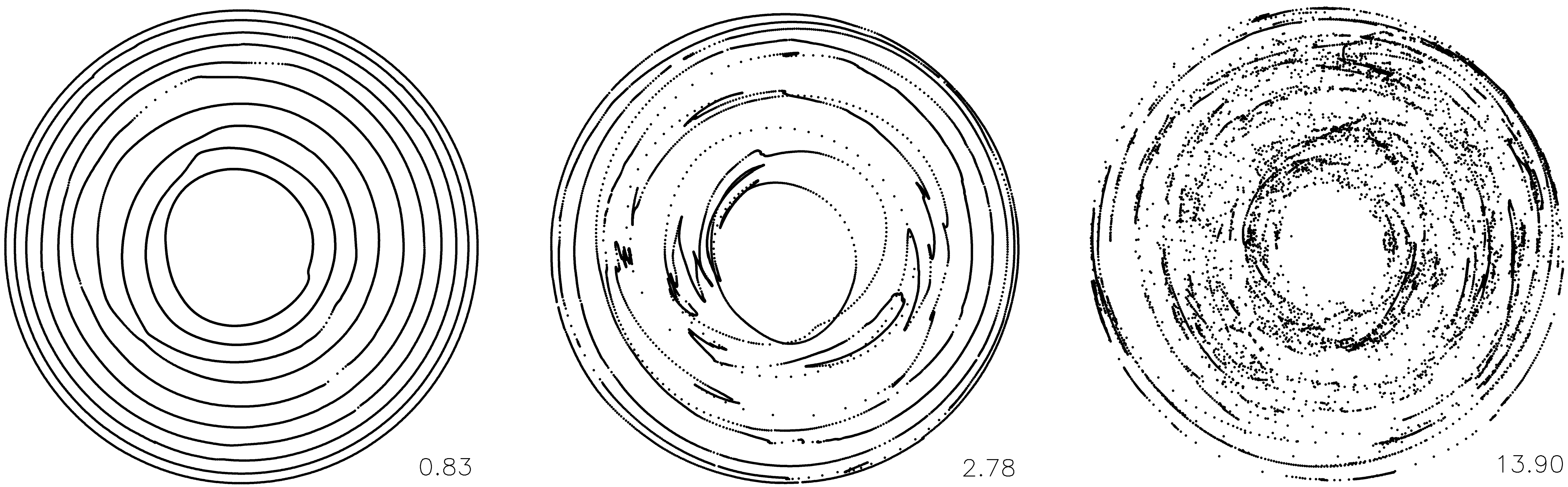


Carlberg (2011)



Yoon, Johnston & Hogg (2011)

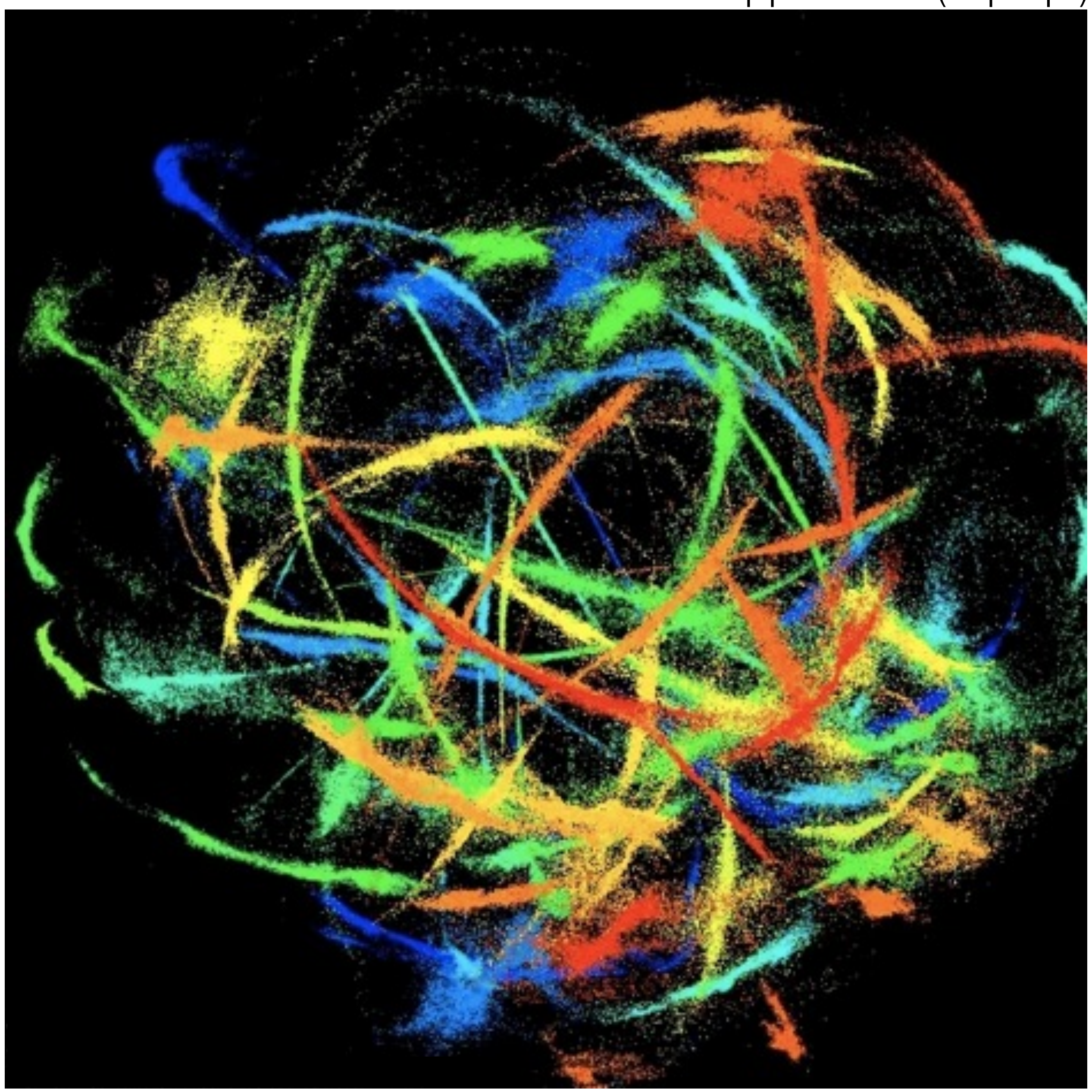
Tidal tails of star cluster should be easily heated by passages of dark matter subhaloes



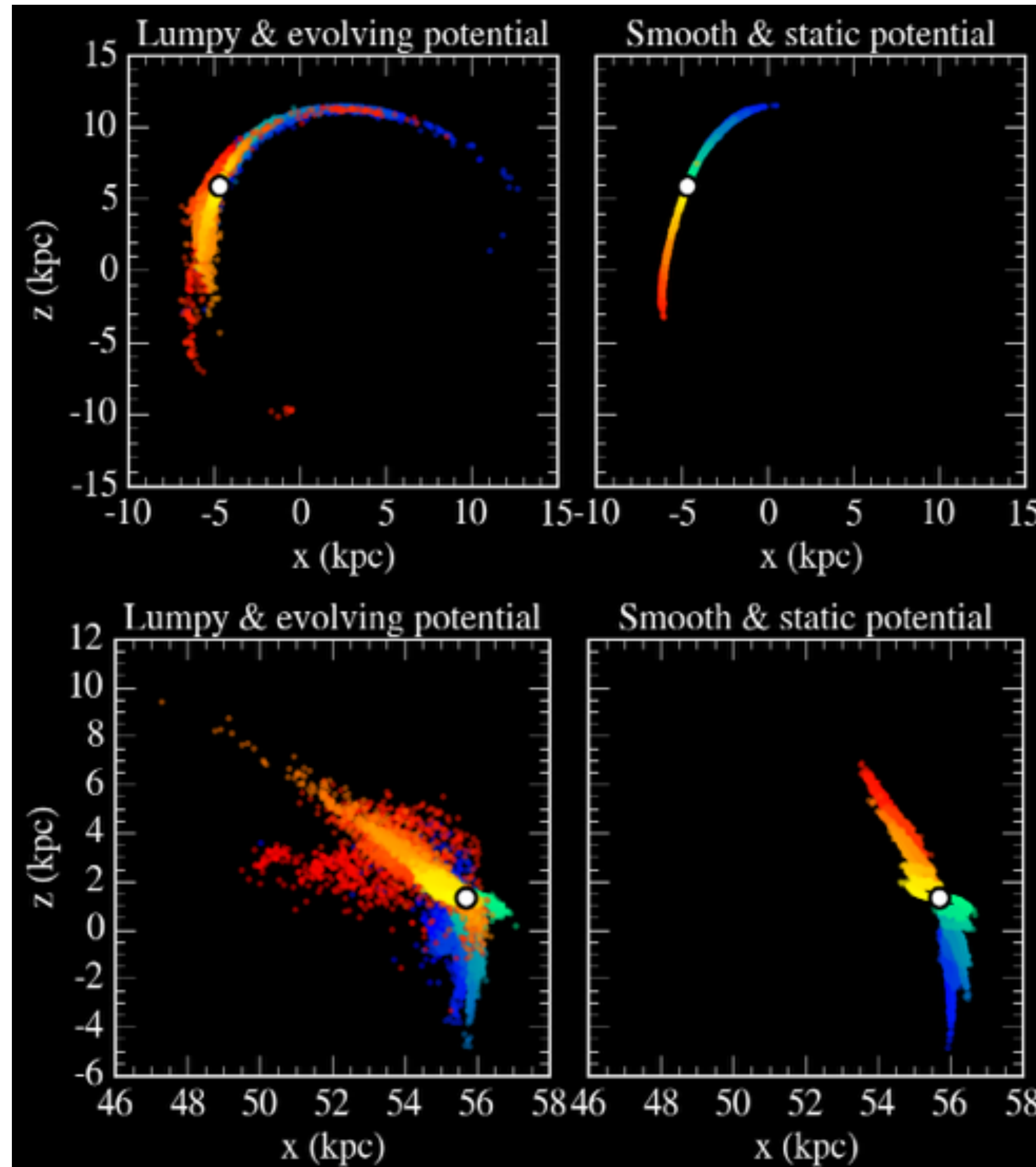
Carlberg (2009)

Streaklines can be used to insert tidal streams into cosmological simulations

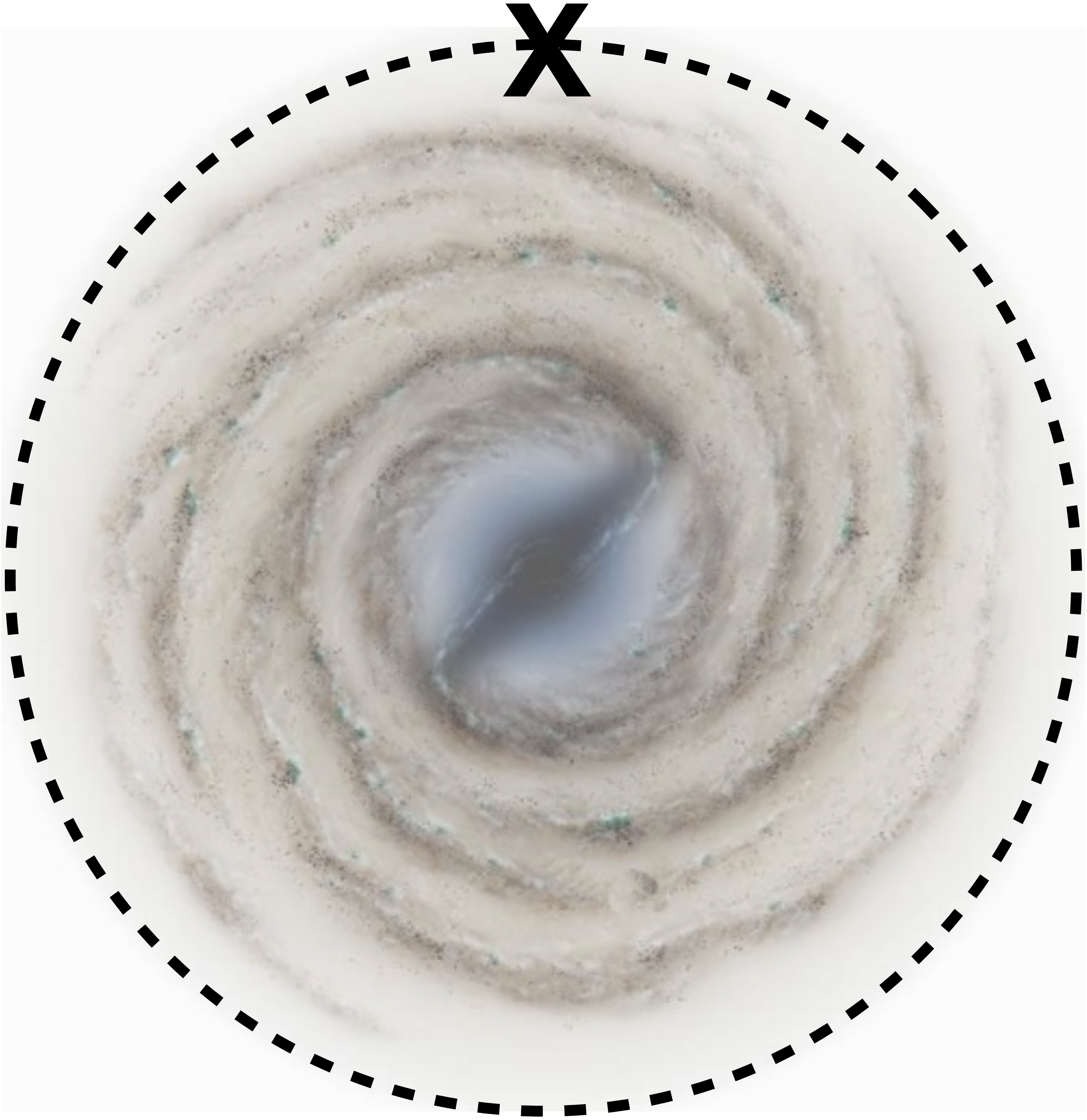
Küpper et al. (in prep.)



Bonaca et al. (submitted)



Orbital offset causes apparent epicyclic motion



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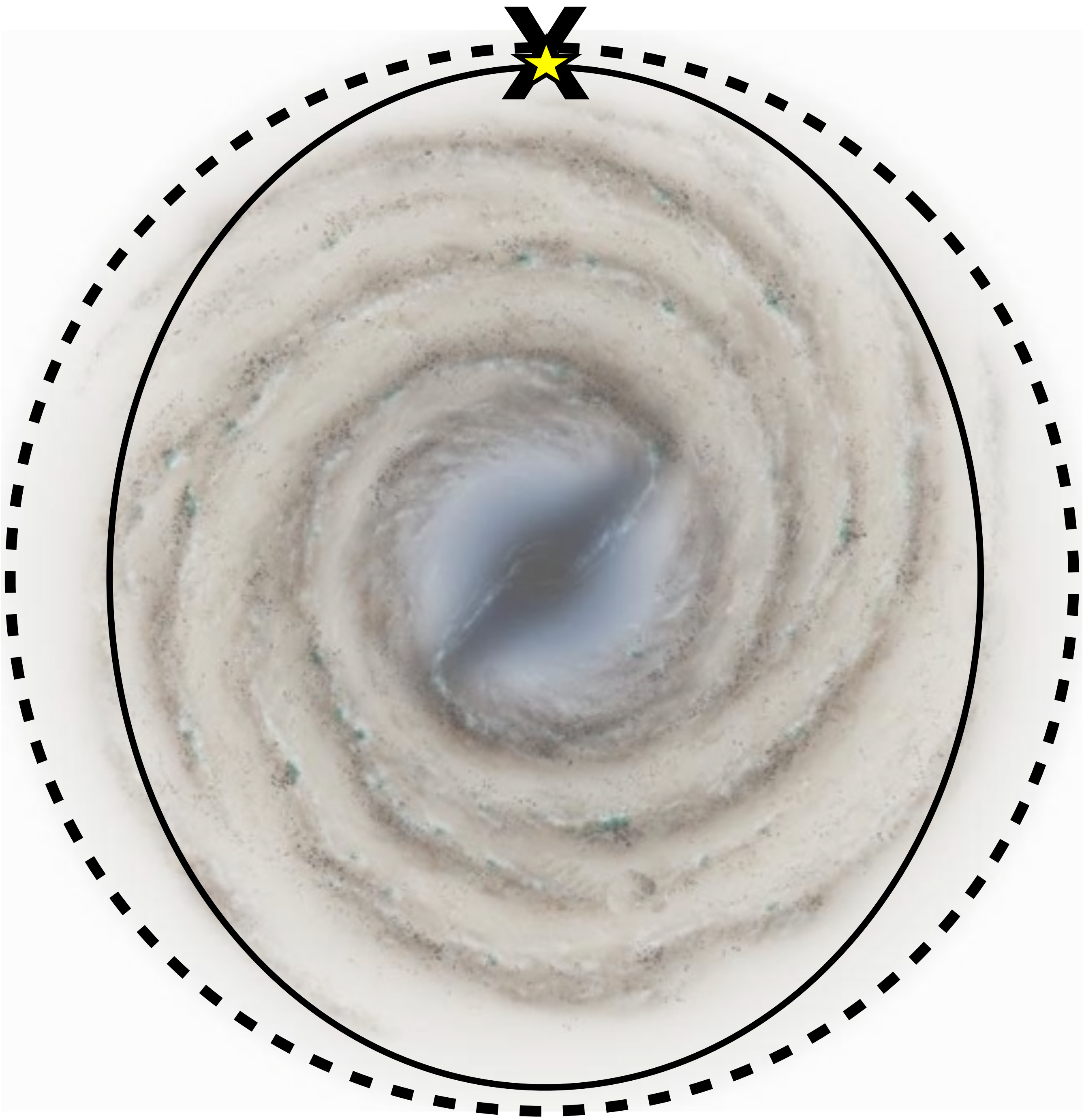

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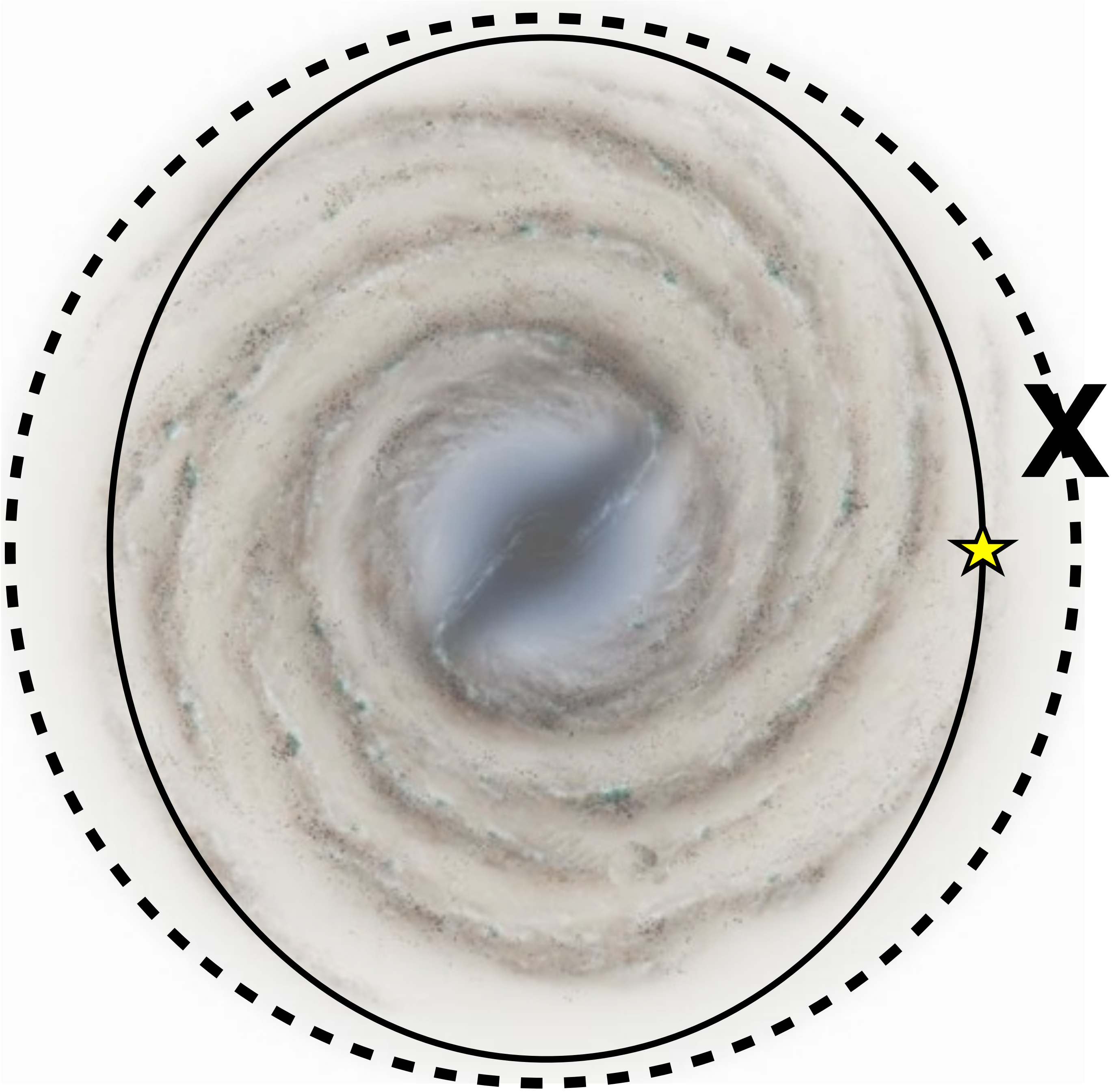

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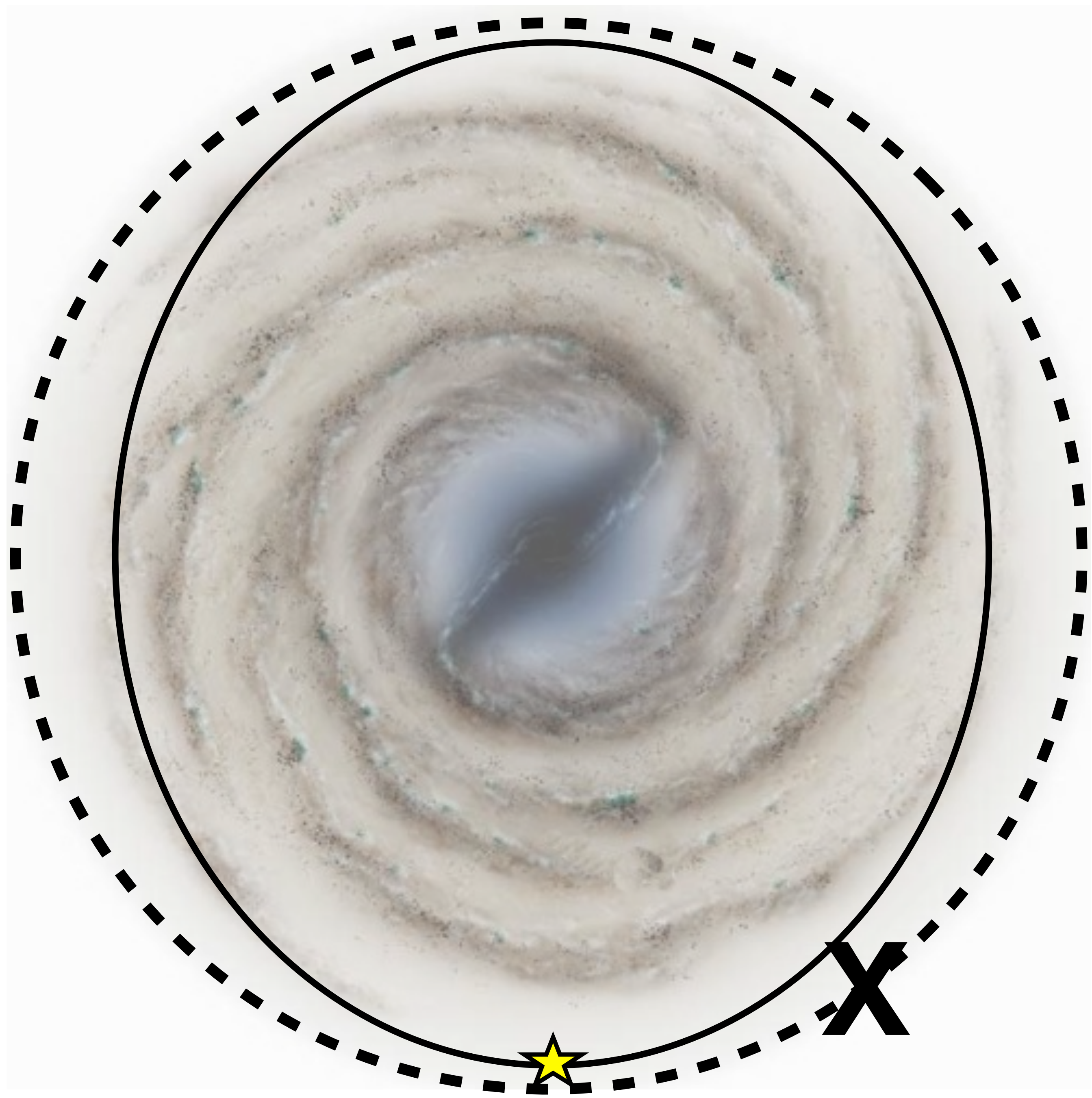

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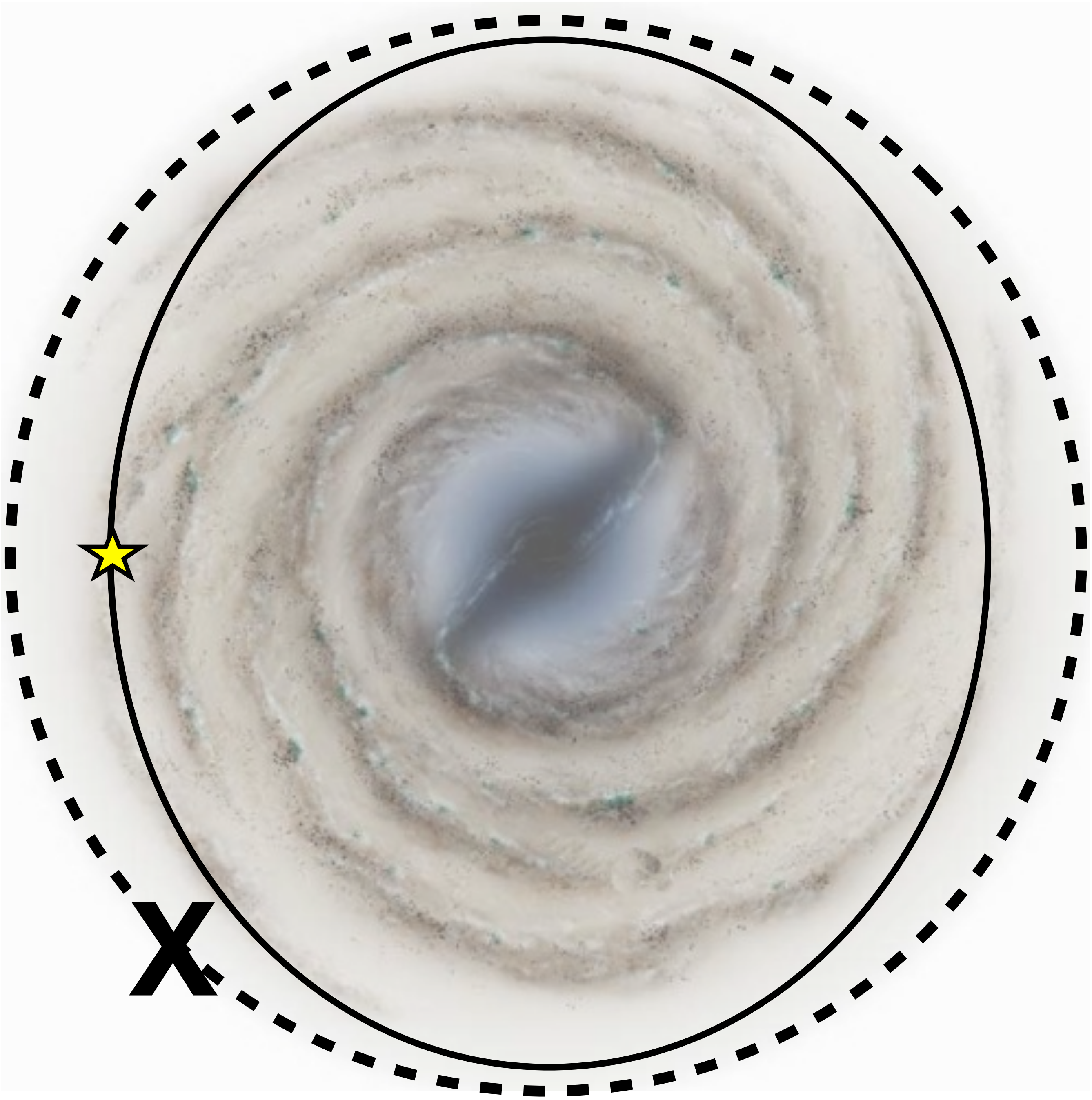

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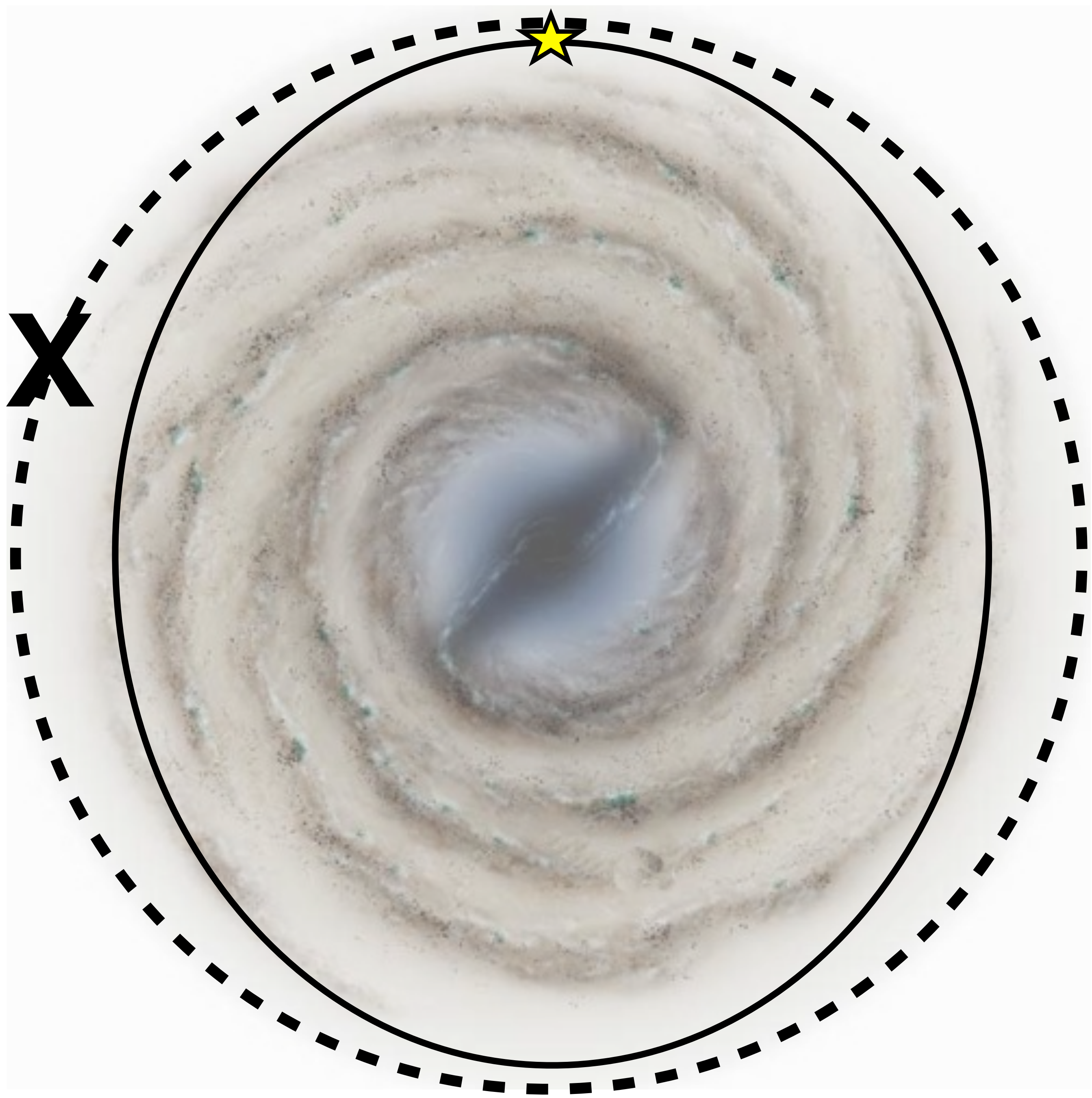
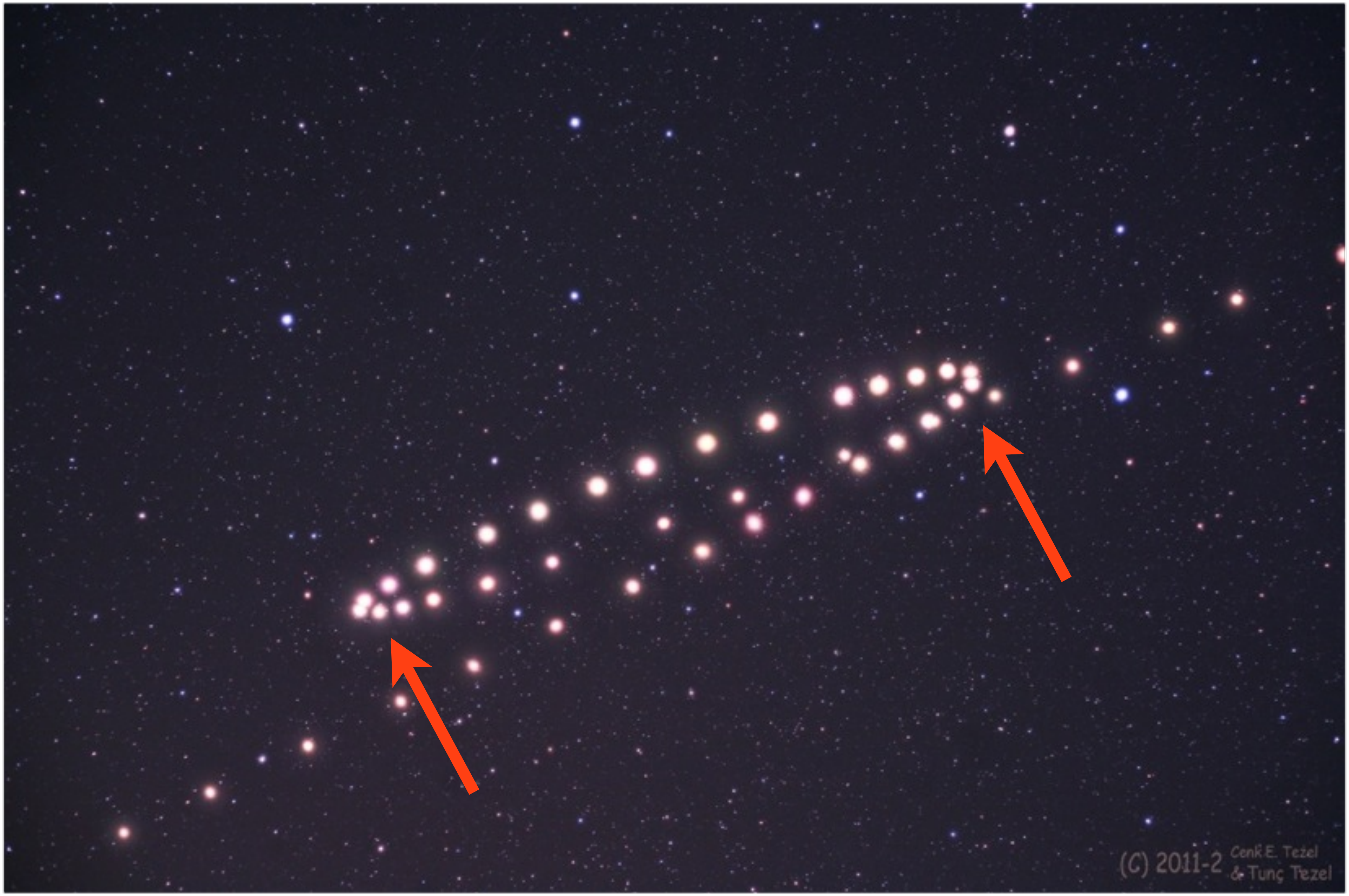


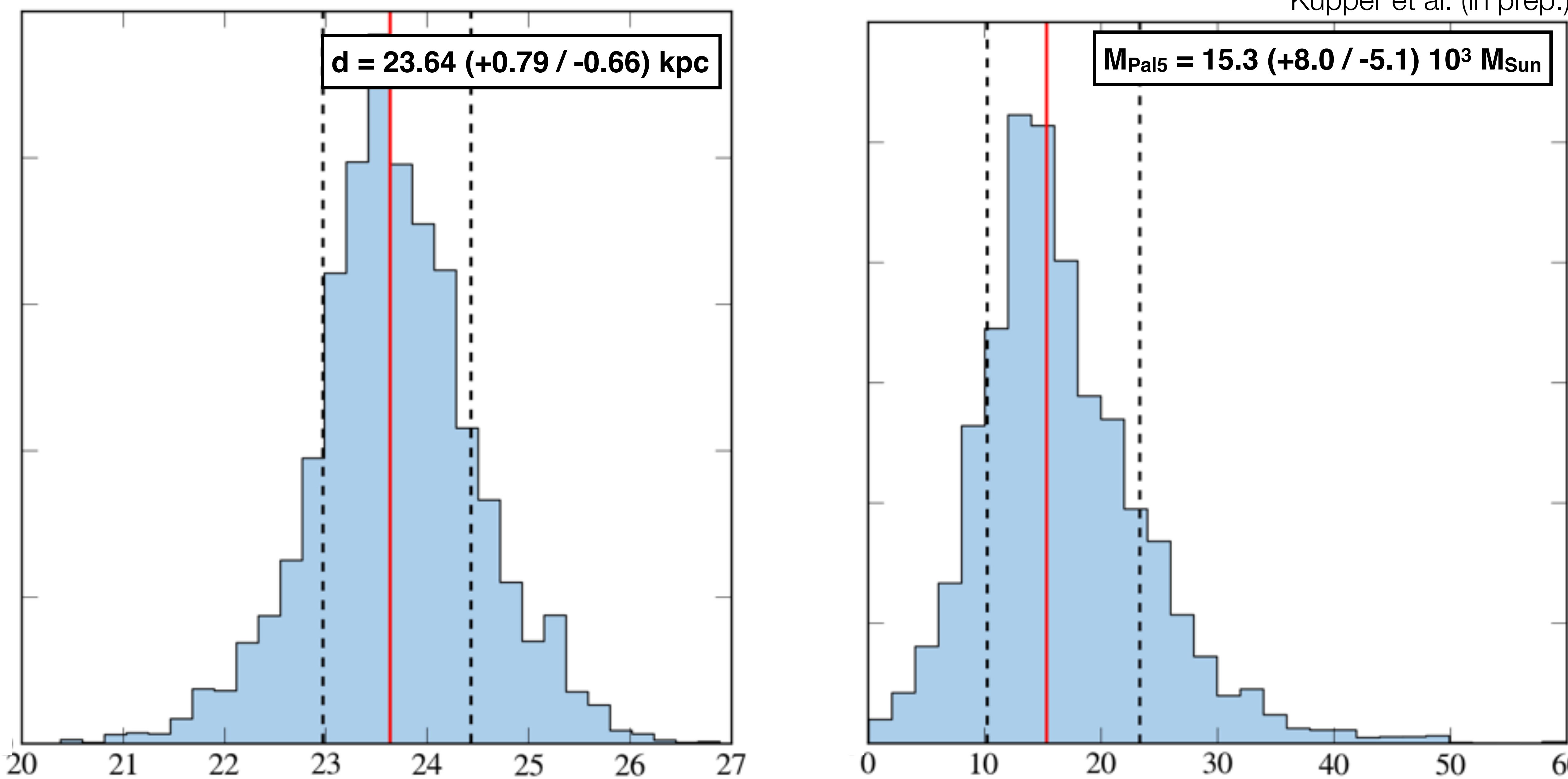
Different orbits cause different epicyclic patterns

Epicyclic motions cause apparent overdensities and underdensities containing orbital information



We get information on additional cluster parameters independent of other methods

Küpper et al. (in prep.)

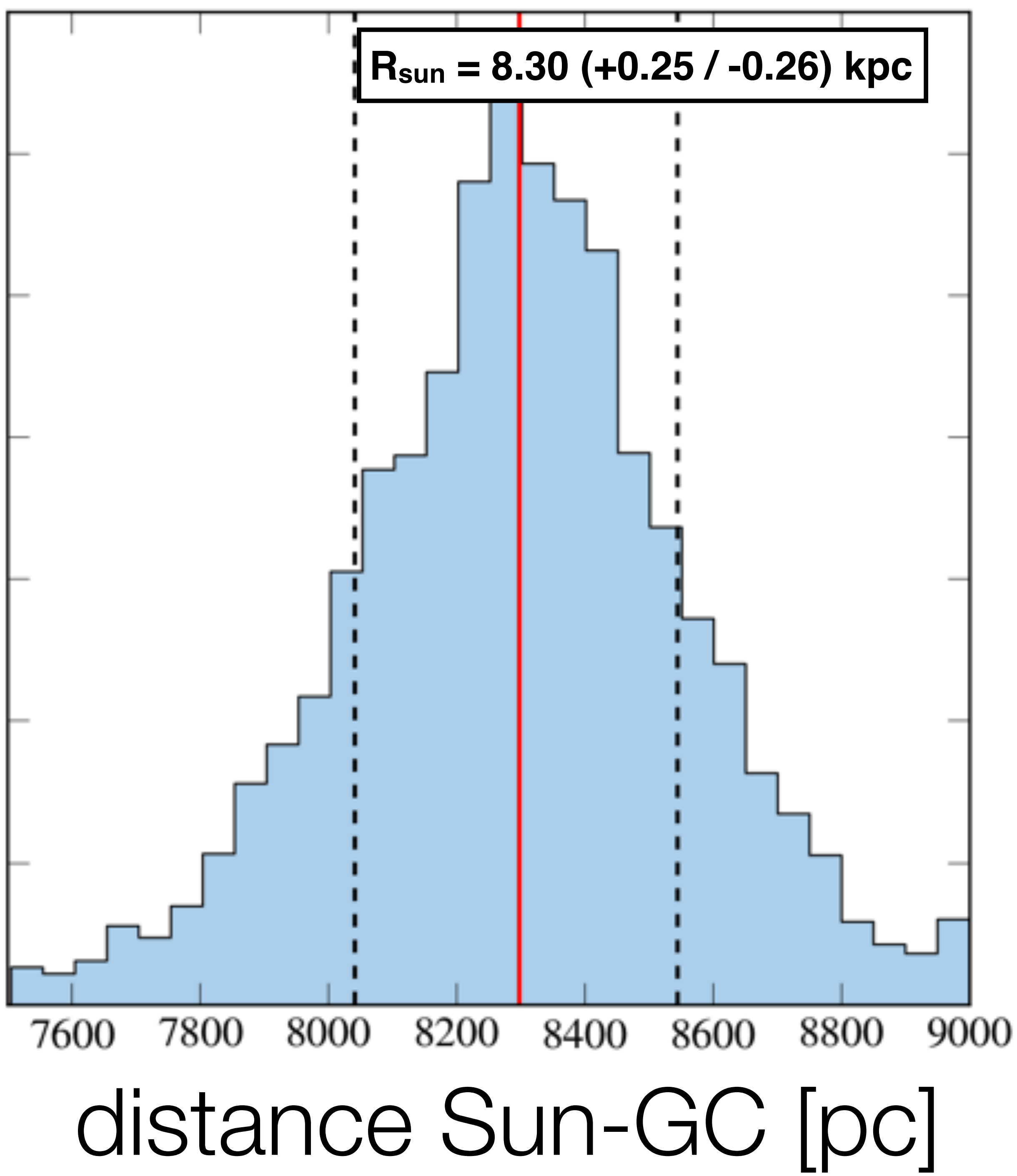


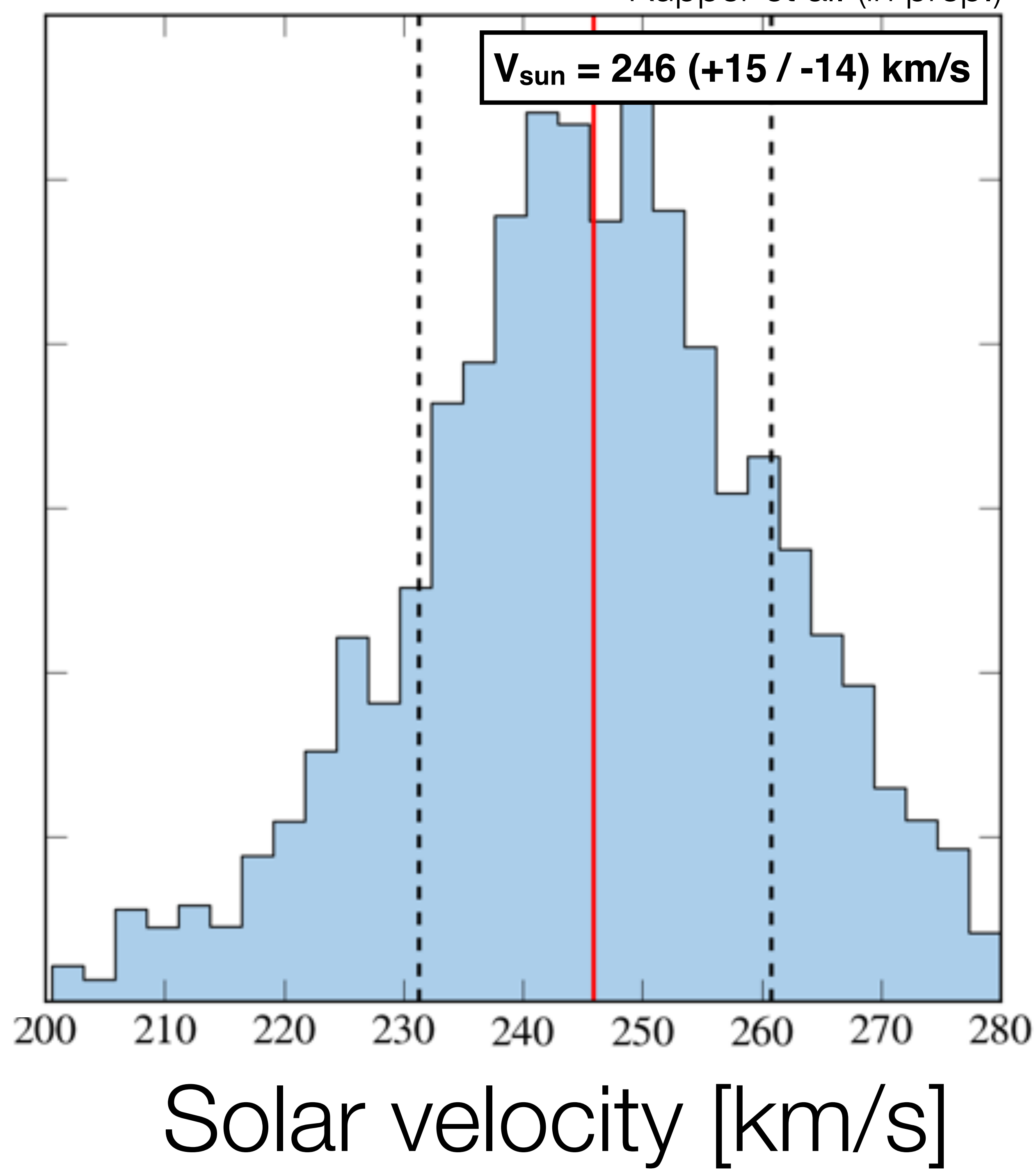
distance Sun-Pal5 [kpc]

Pal5 mass [M_{sun}]

Solar parameters are in agreement with other methods: 8.34 kpc & 243 km/s (Reid et al. 2014)

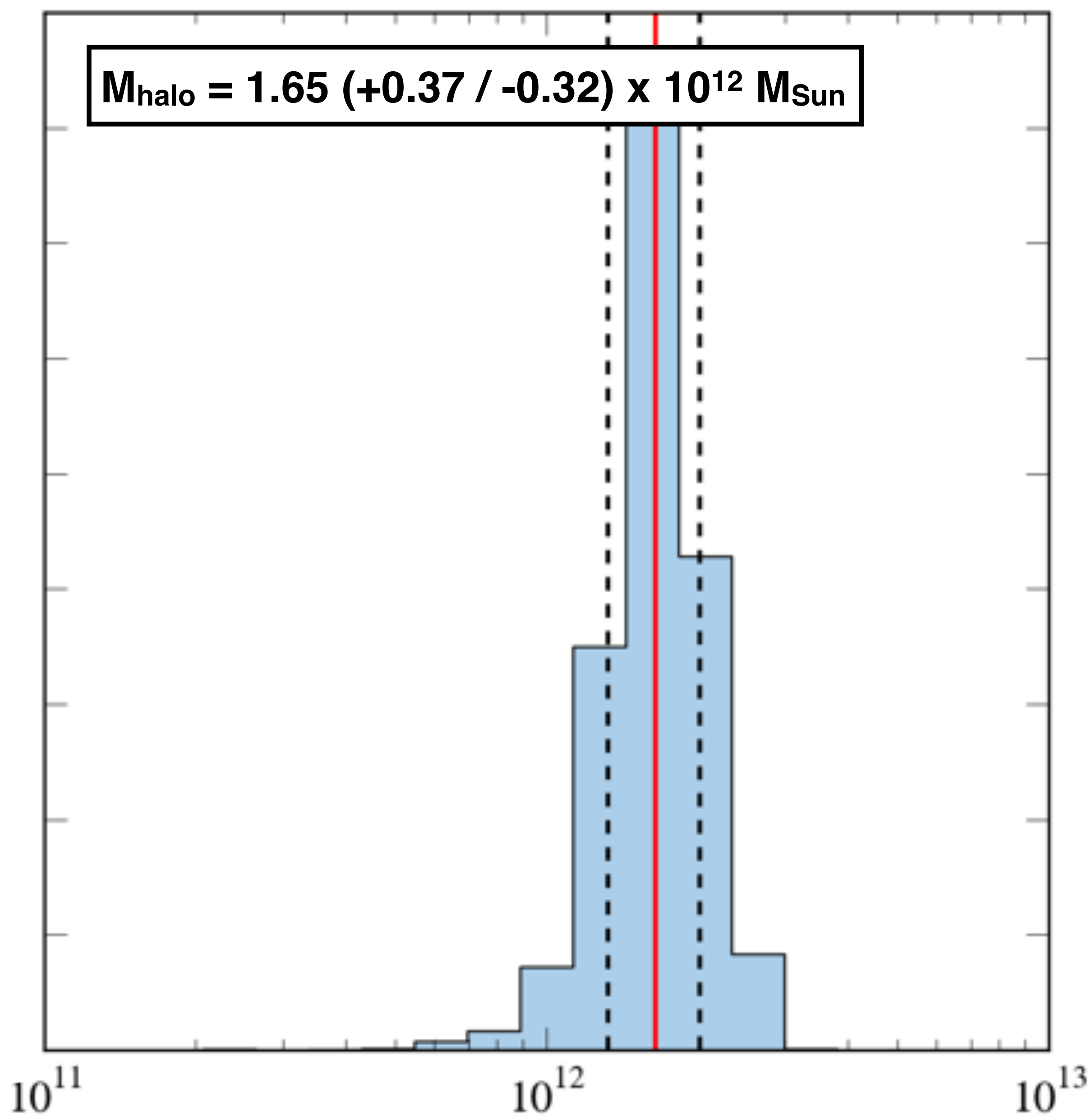
Küpper et al. (in prep.)

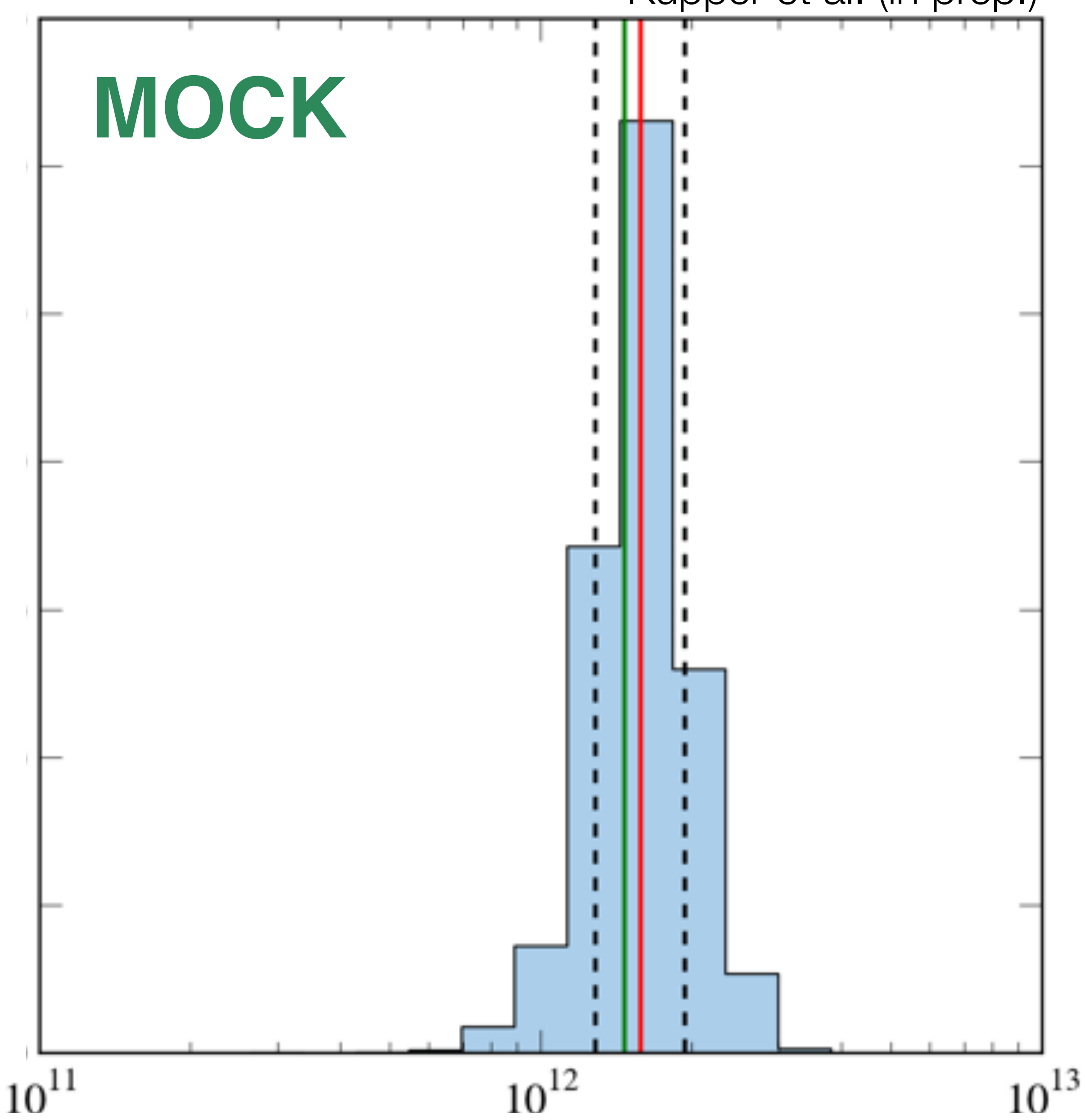




Probabilistic modeling of Palomar 5 constrains the NFW halo scale parameters

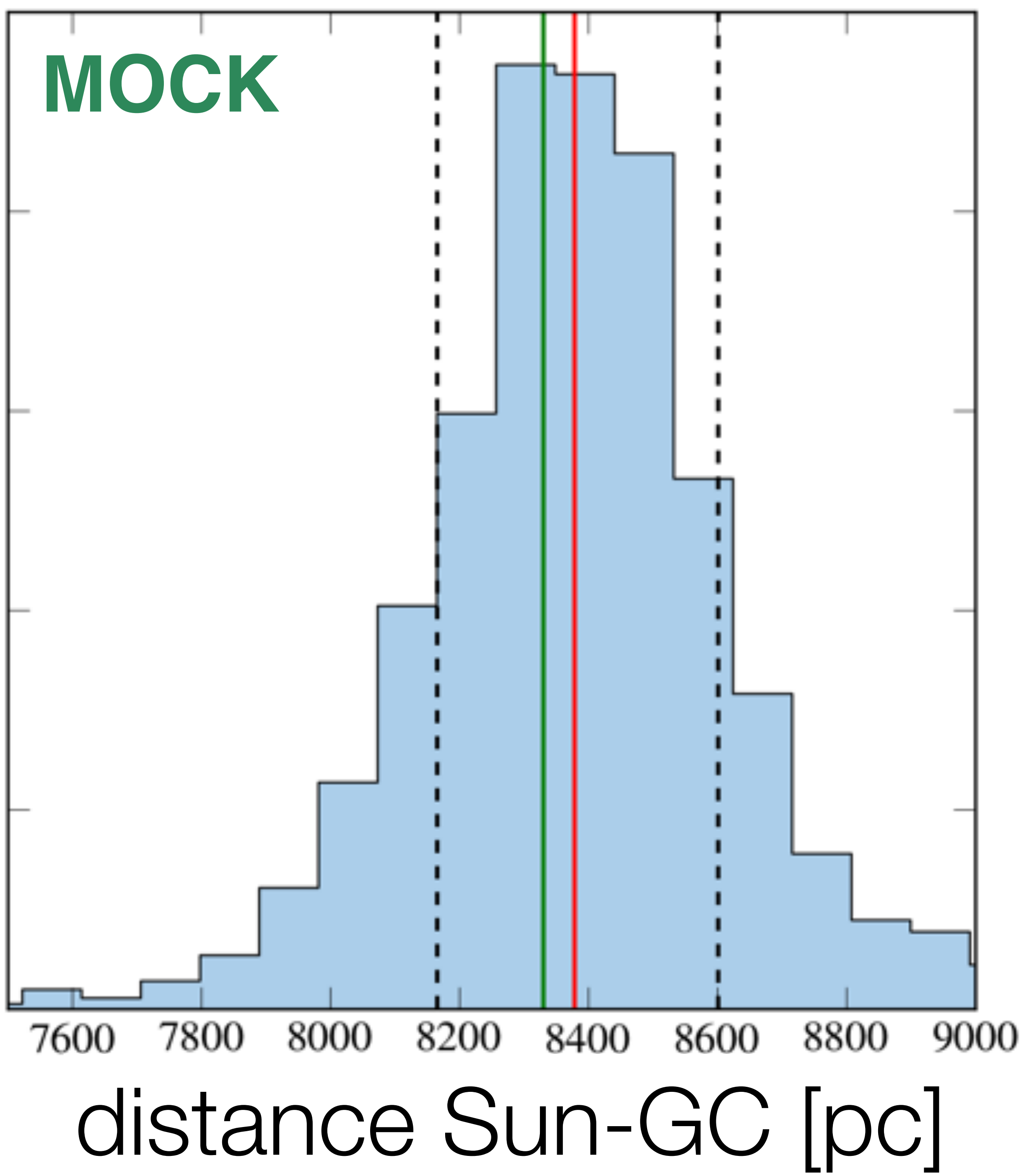
Küpper et al. (in prep.)

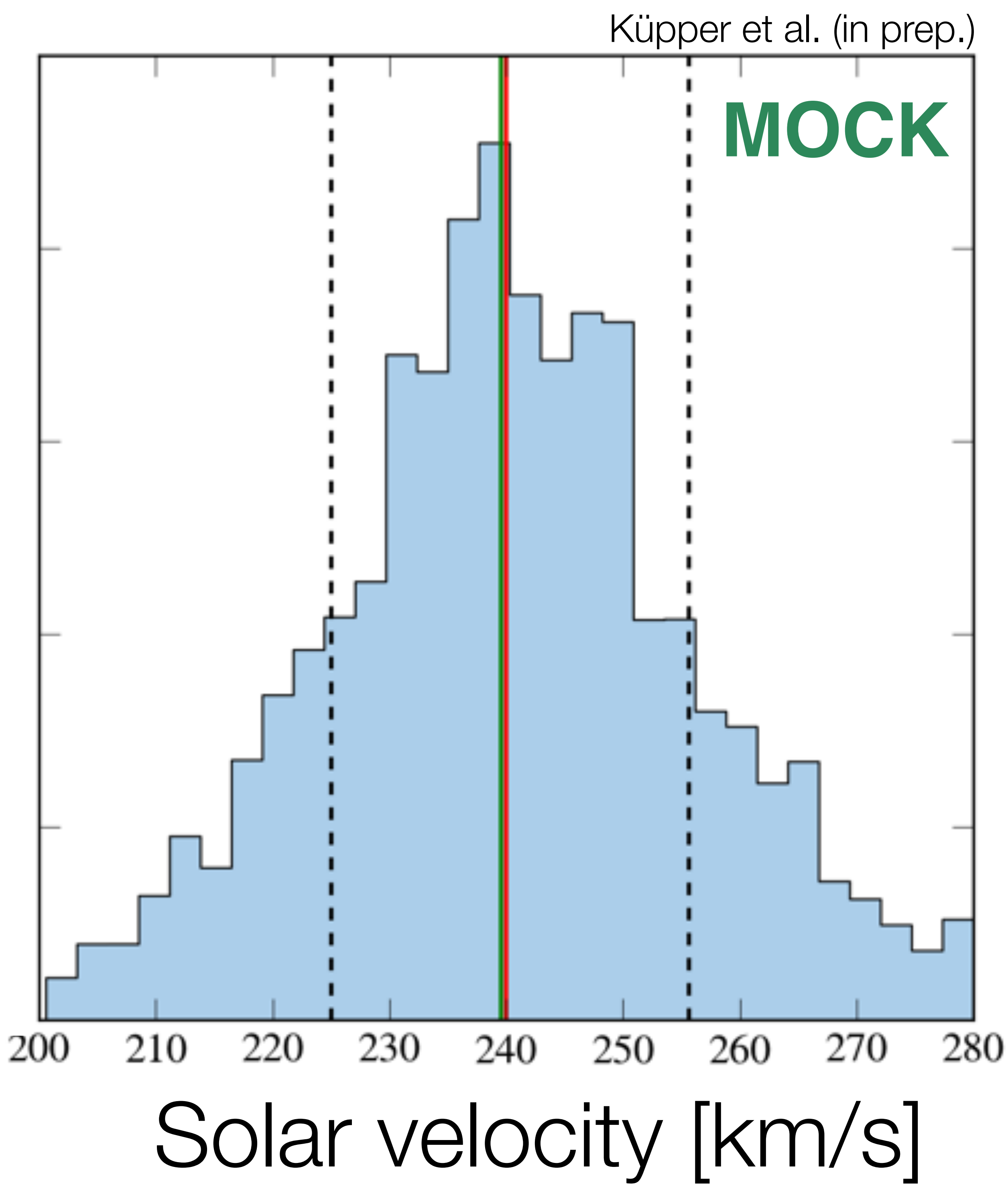




Halo scale mass [M_{sun}]

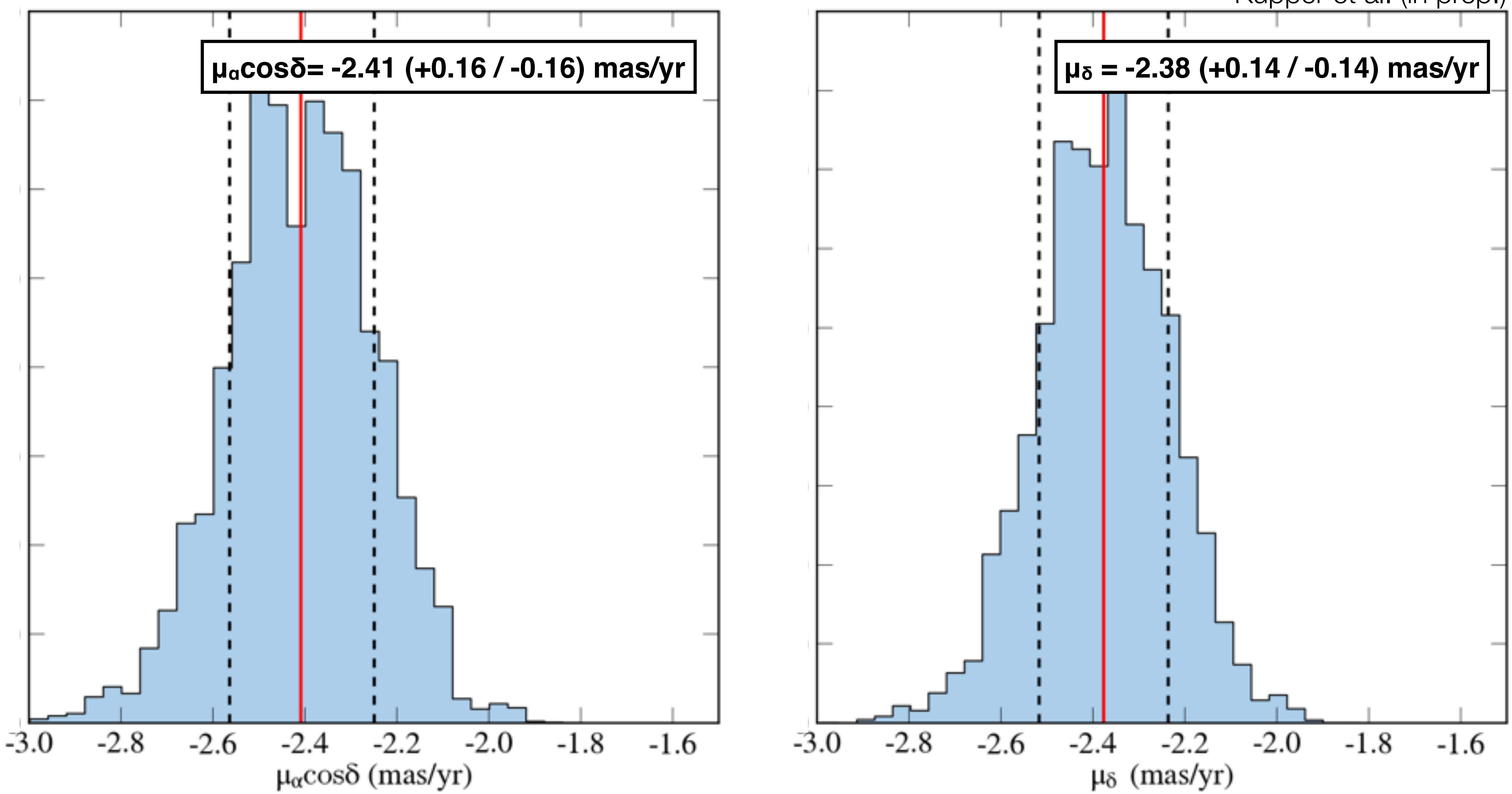
Solar parameters are powerfully constrained



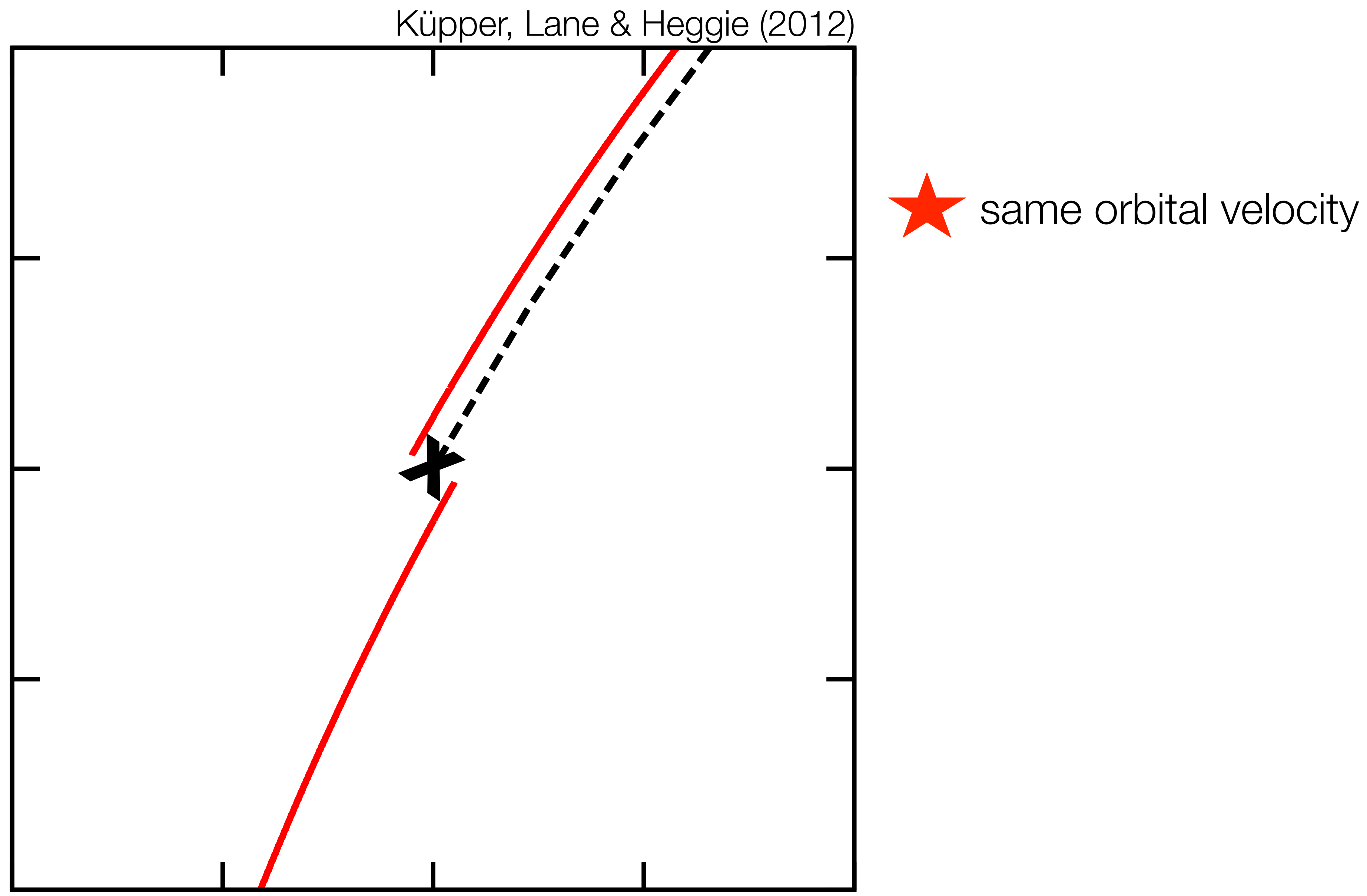


We predict proper motions of Palomar 5

Küpper et al. (in prep.)



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



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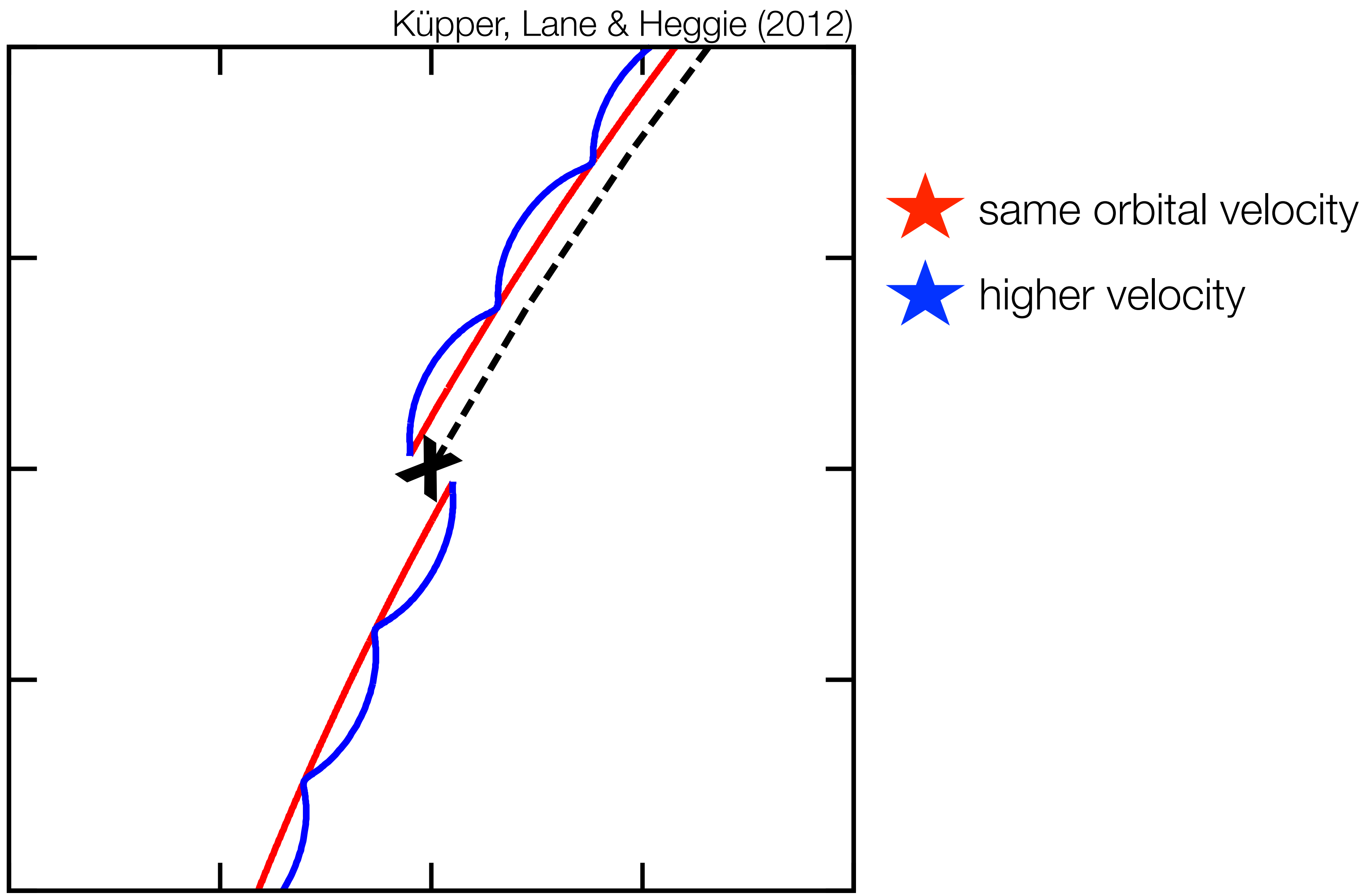

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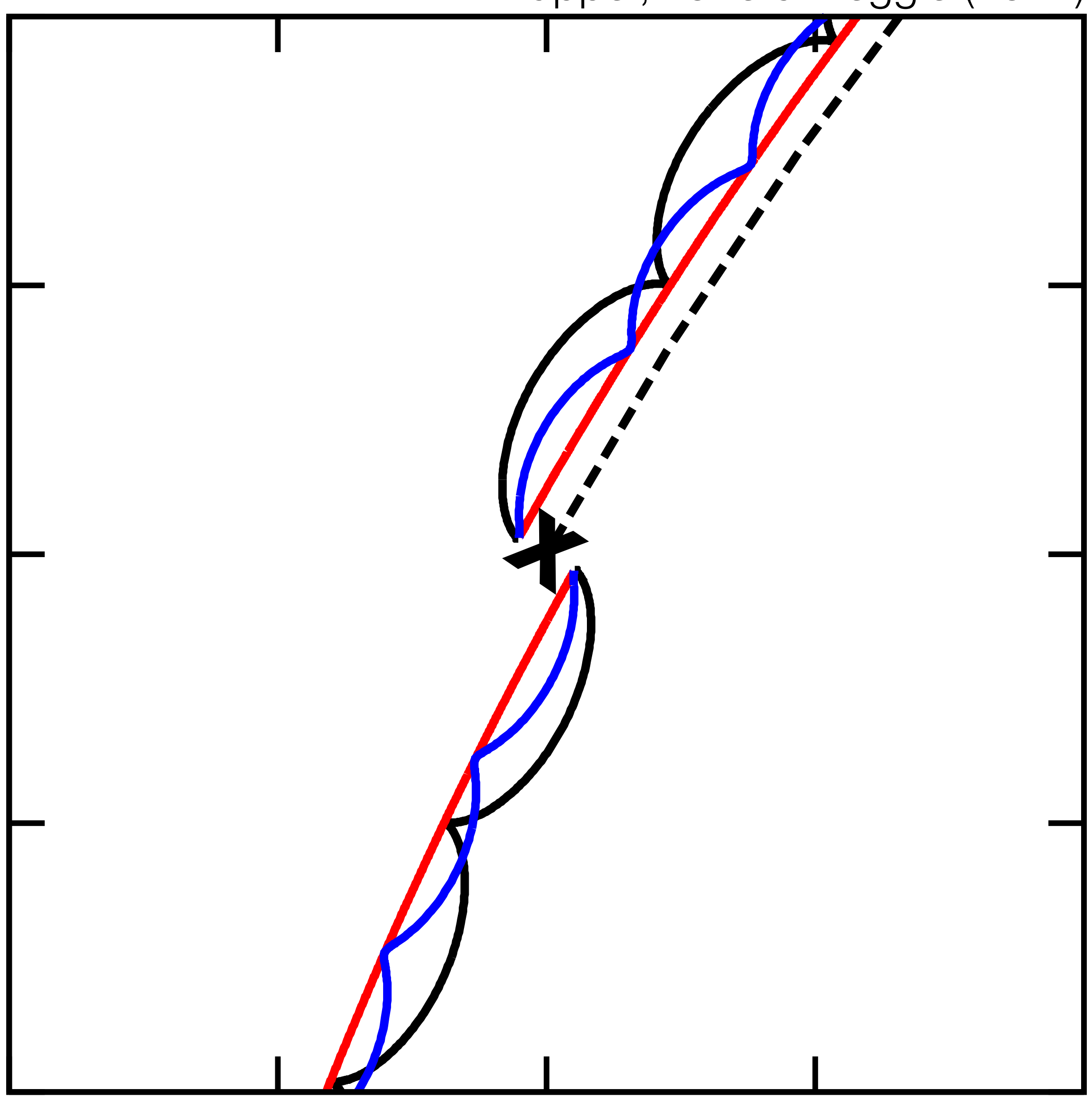
Küpper, Lane & Heggie (2012)



same orbital velocity

intermediate velocity

same angular velocity

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

Küpper, Lane & Heggie (2012)