

# Orbital Information Encoded in Stream Substructure

## The example of Palomar 5

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Andreas Küpper



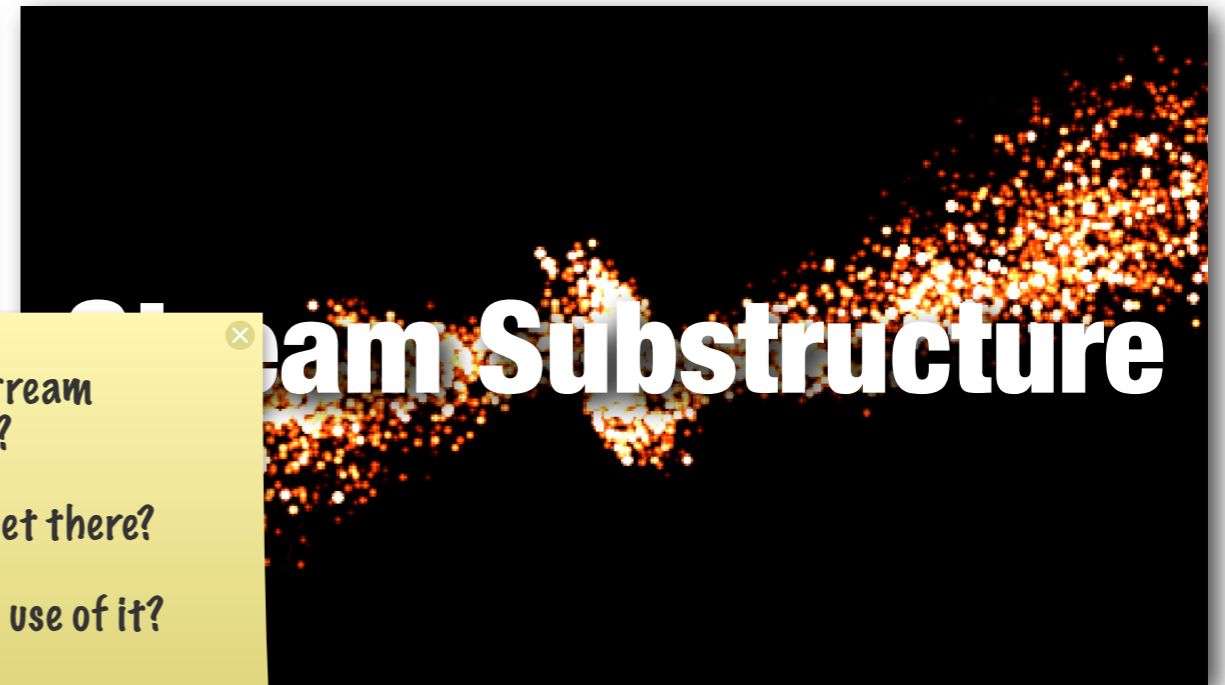
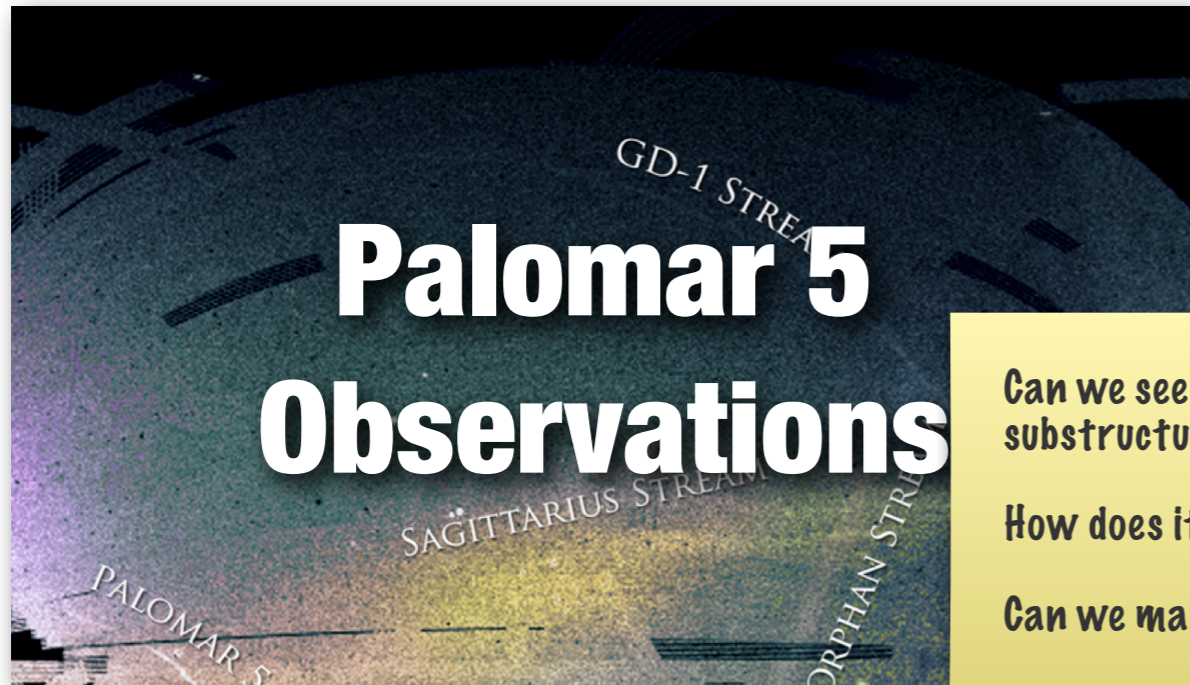
There's more to streams  
than just positions and  
velocities (and  
abundances)



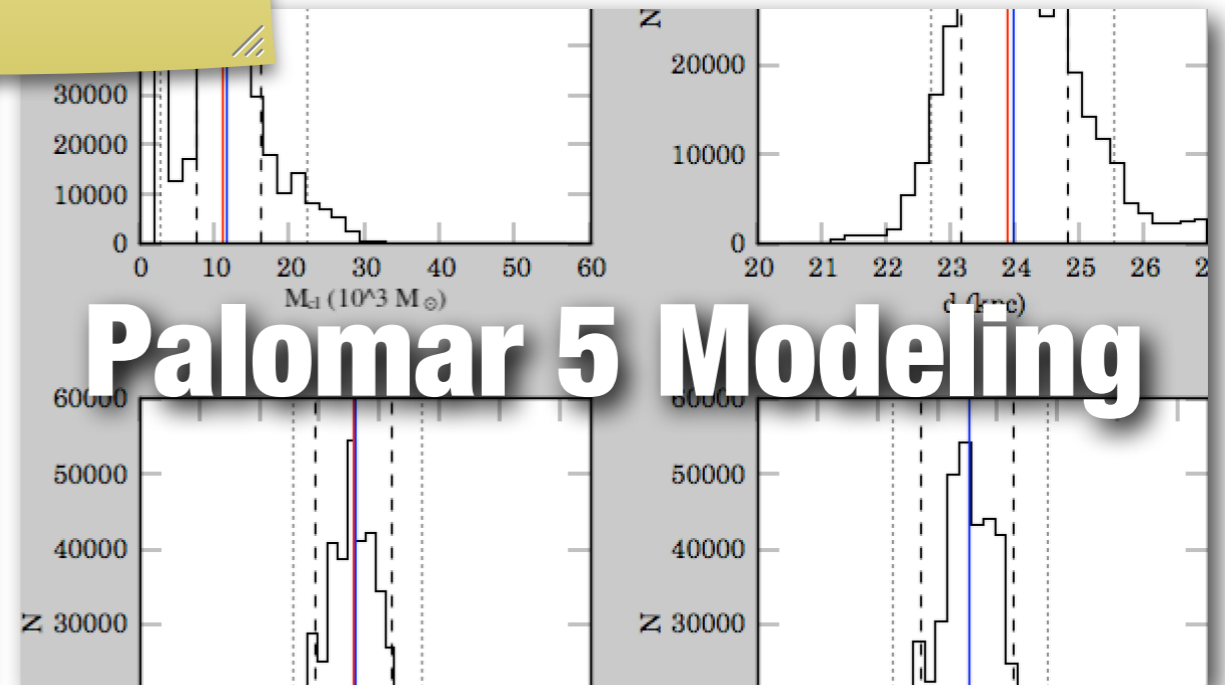
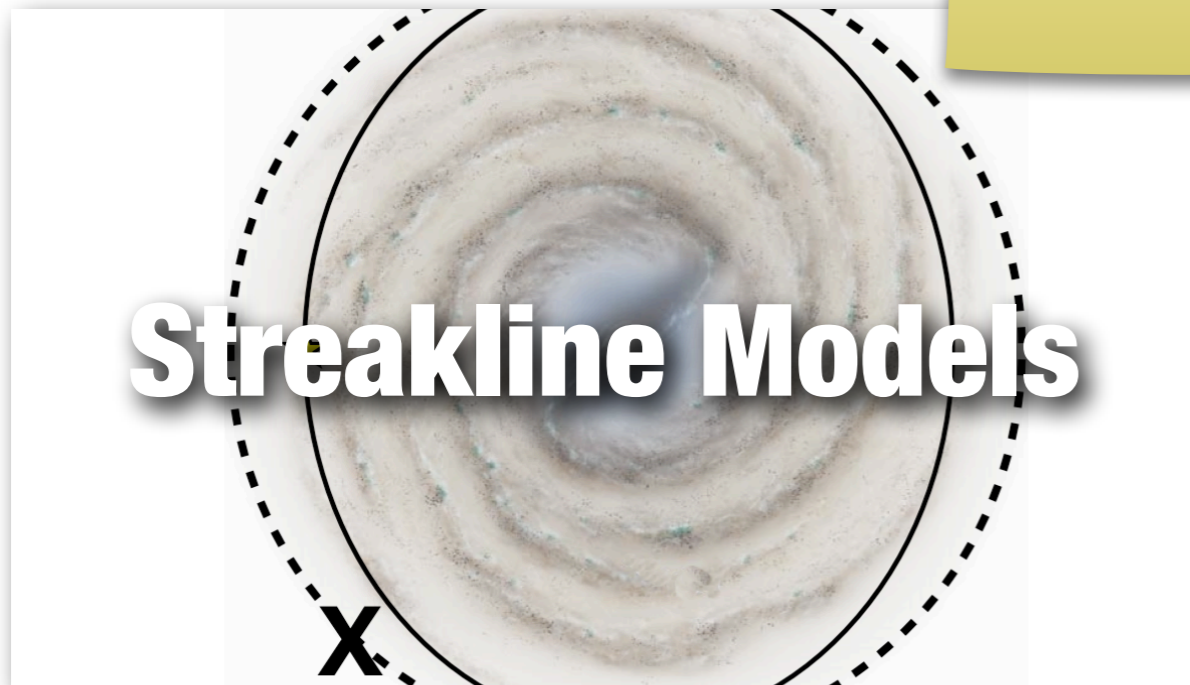
Stream substructure can be used to constrain  
model parameters

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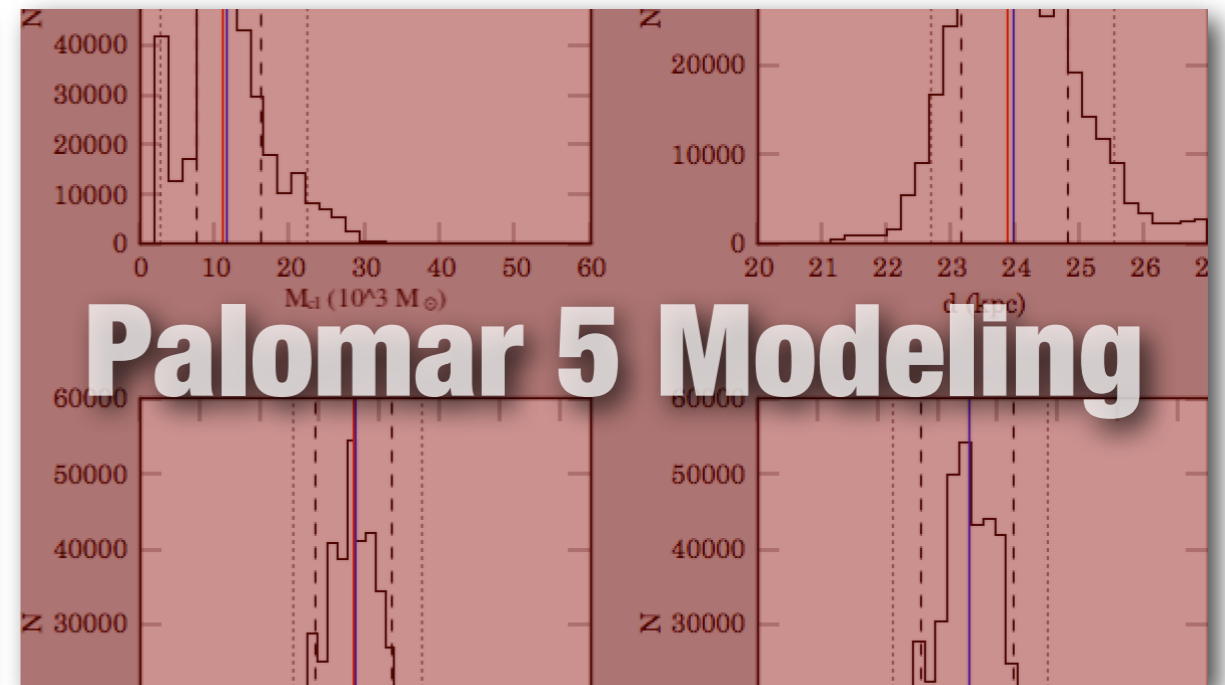
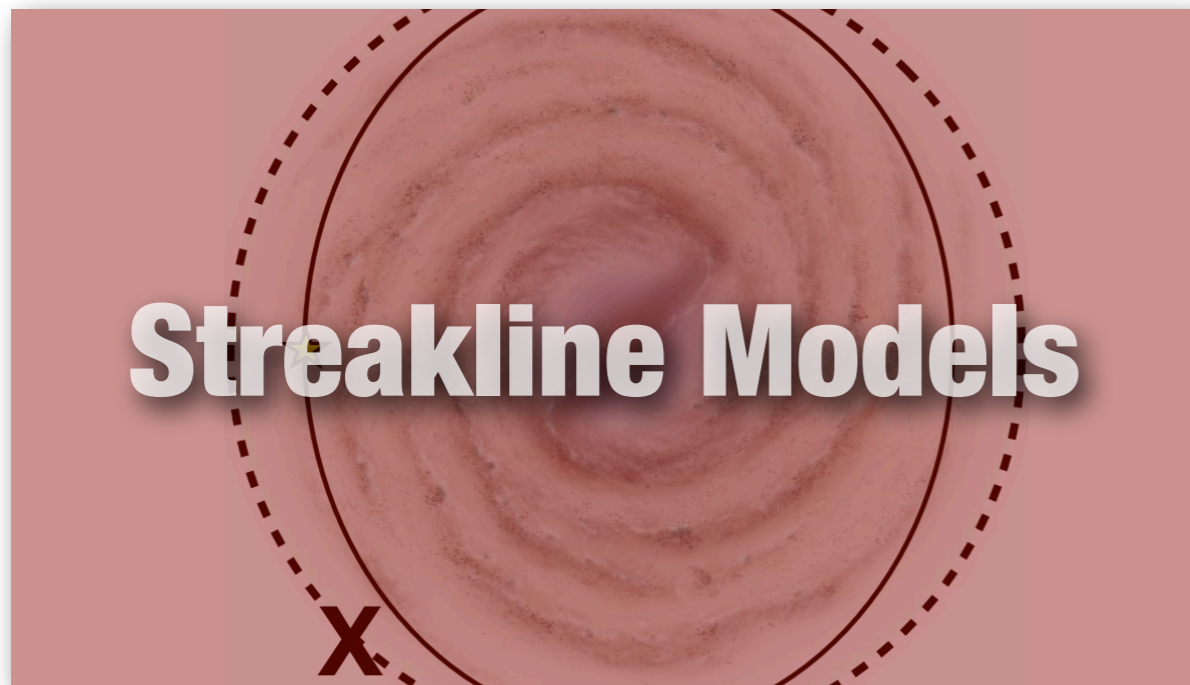
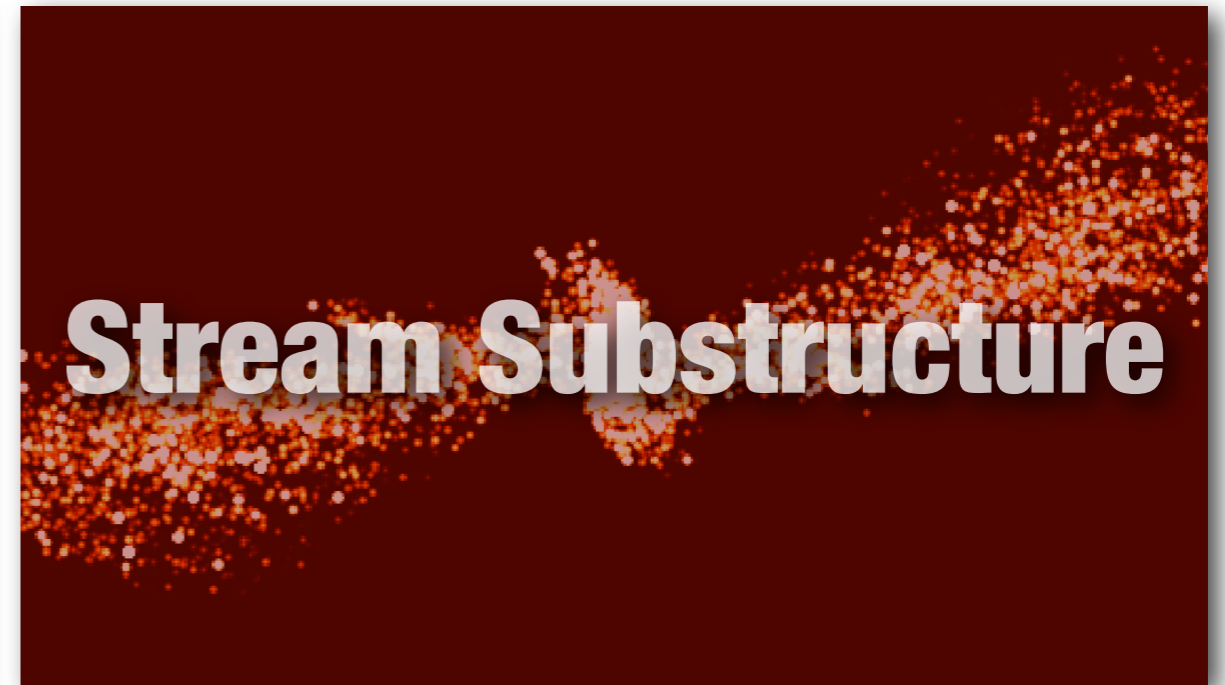
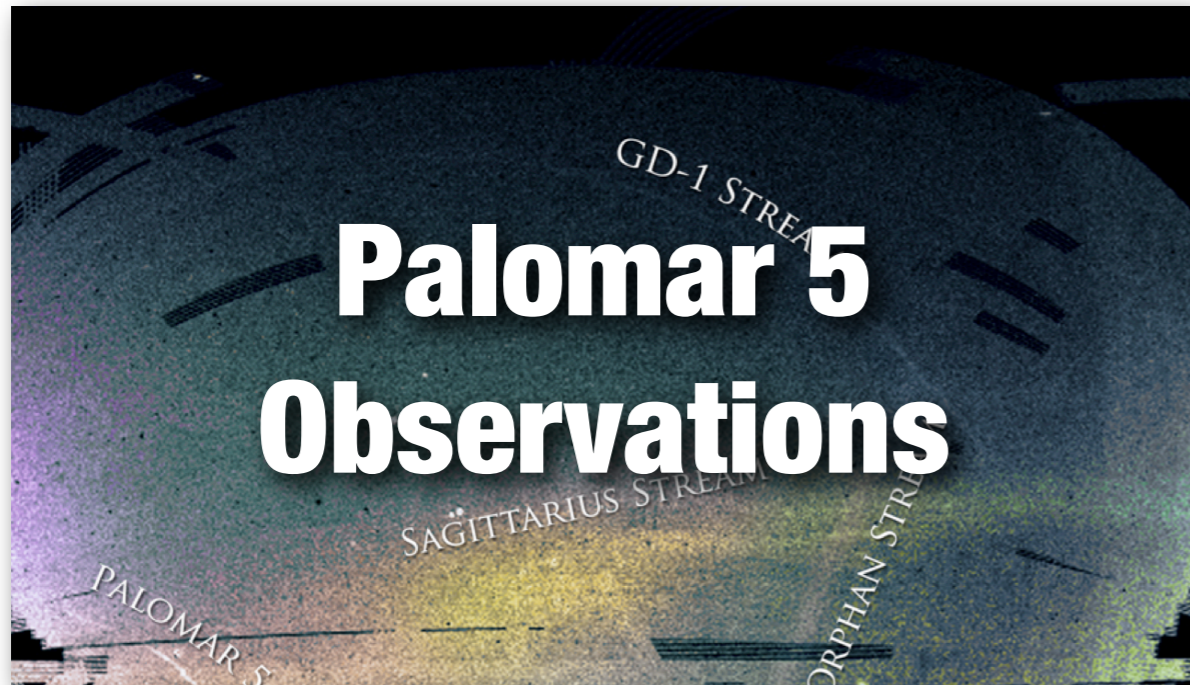
Stream substructure can be used to constrain model parameters



Can we see stream substructure?  
How does it get there?  
Can we make use of it?  
What does it tell us?

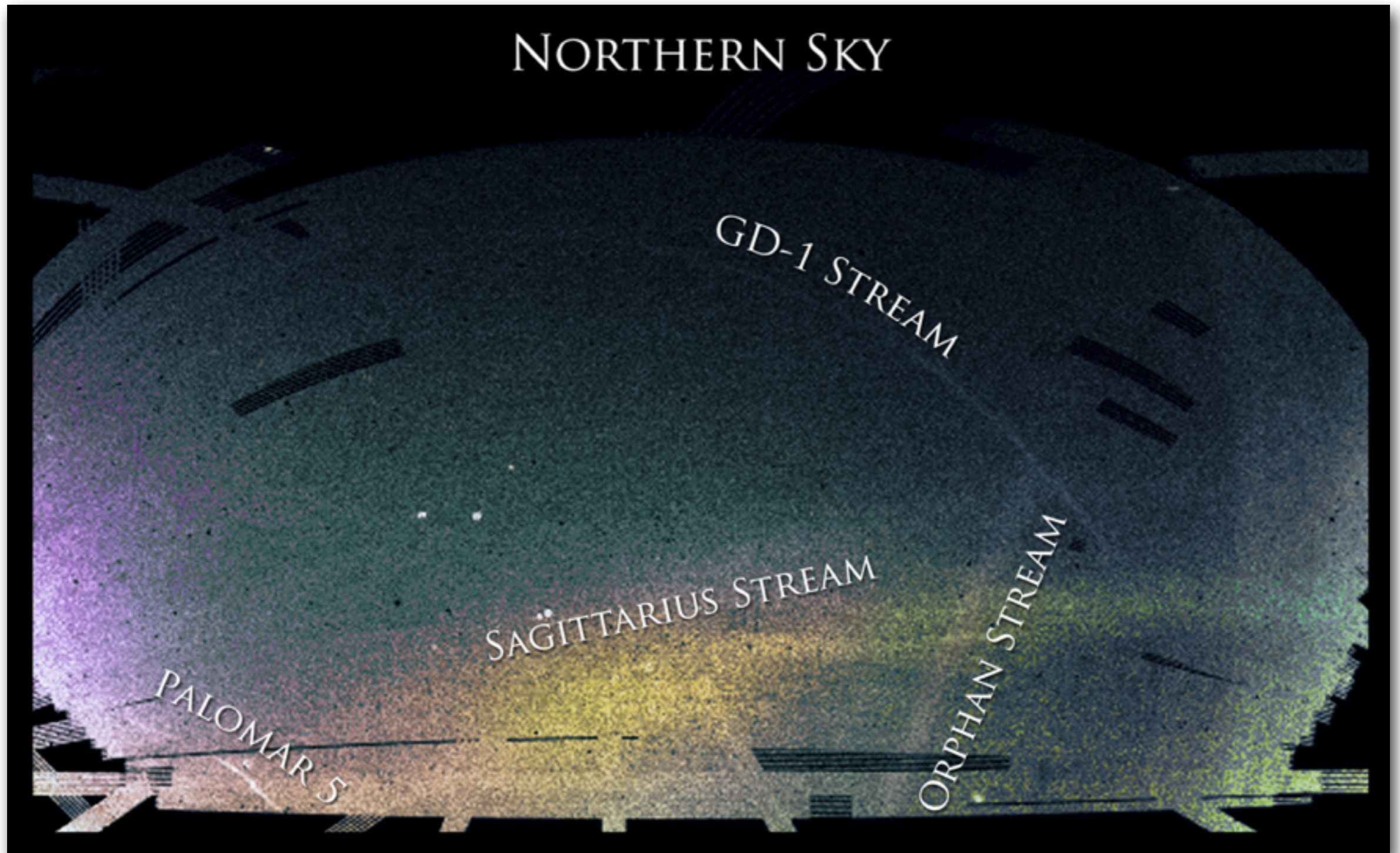


Stream substructure can be used to constrain model parameters



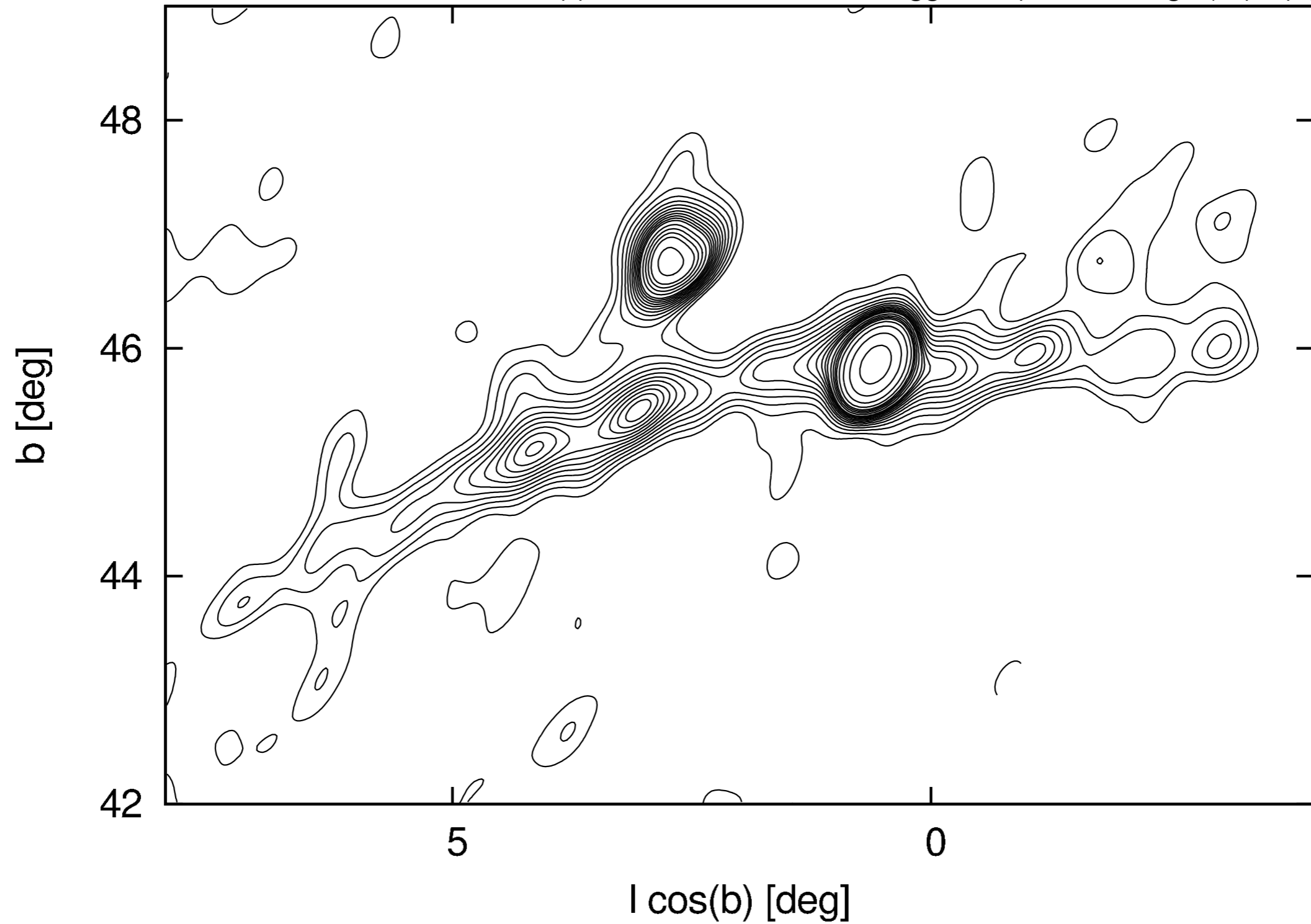
Palomar 5 is a short but prominent globular cluster stream in the SDSS. What can we learn from it?

Bonaca, Geha & Kallivayalil (2012)



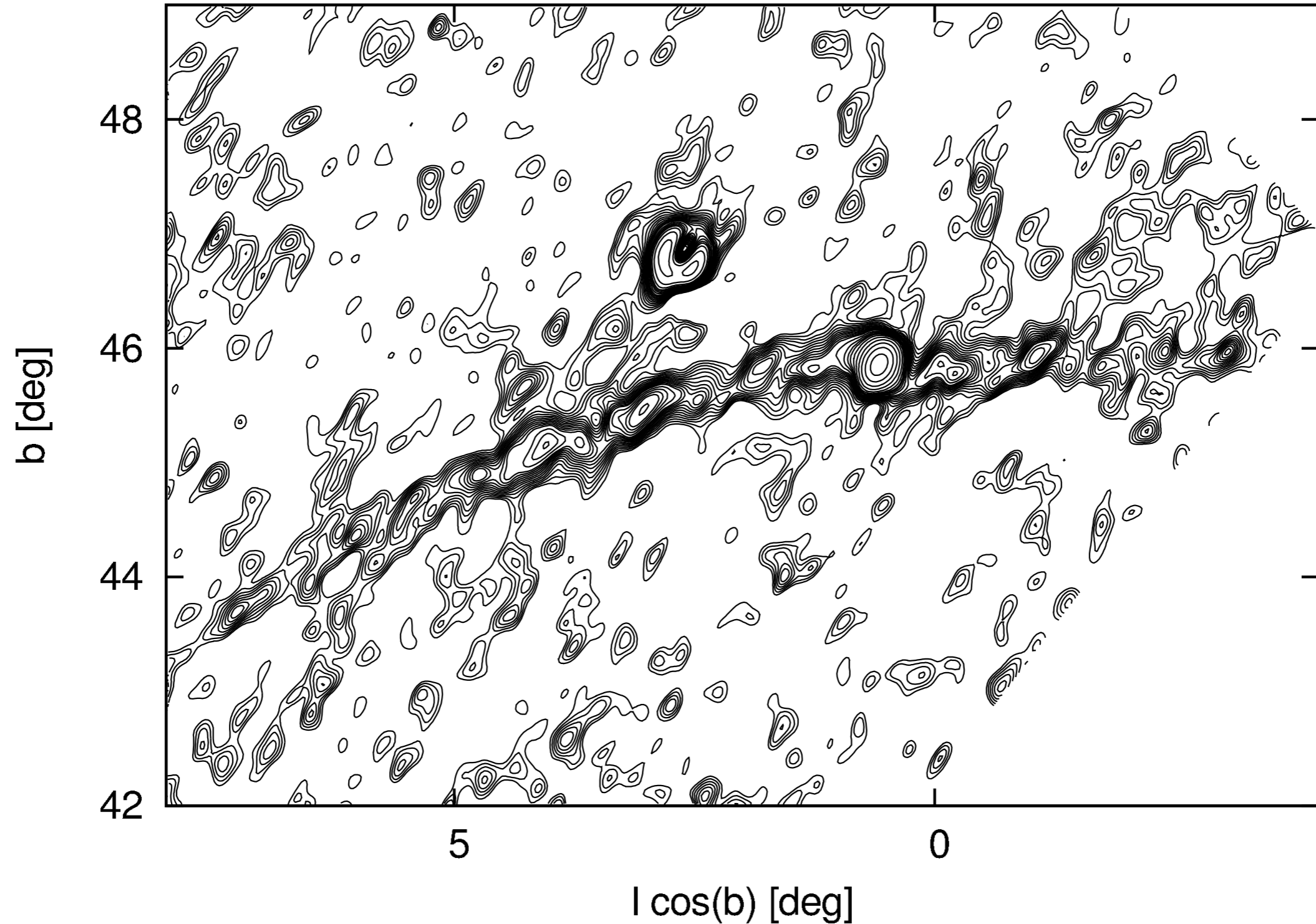
# The Palomar 5 stream shows substructure

Küpper, Balbinot, Bonaca, Hogg, Kroupa & Santiago (in prep.)



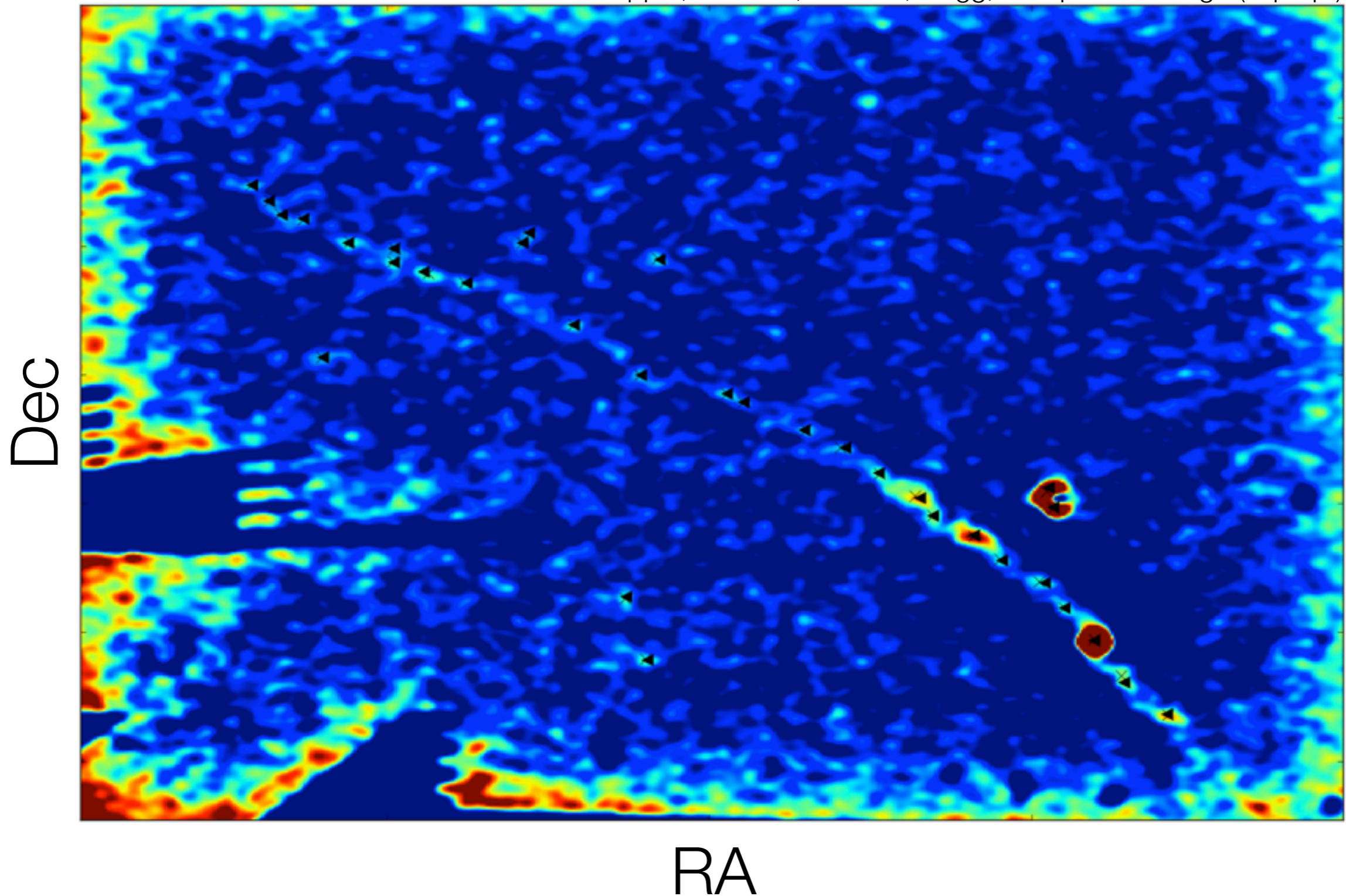
# The Palomar 5 stream shows substructure

Küpper, Balbinot, Bonaca, Hogg, Kroupa & Santiago (in prep.)



Some positions along the stream seem to be preferred over others

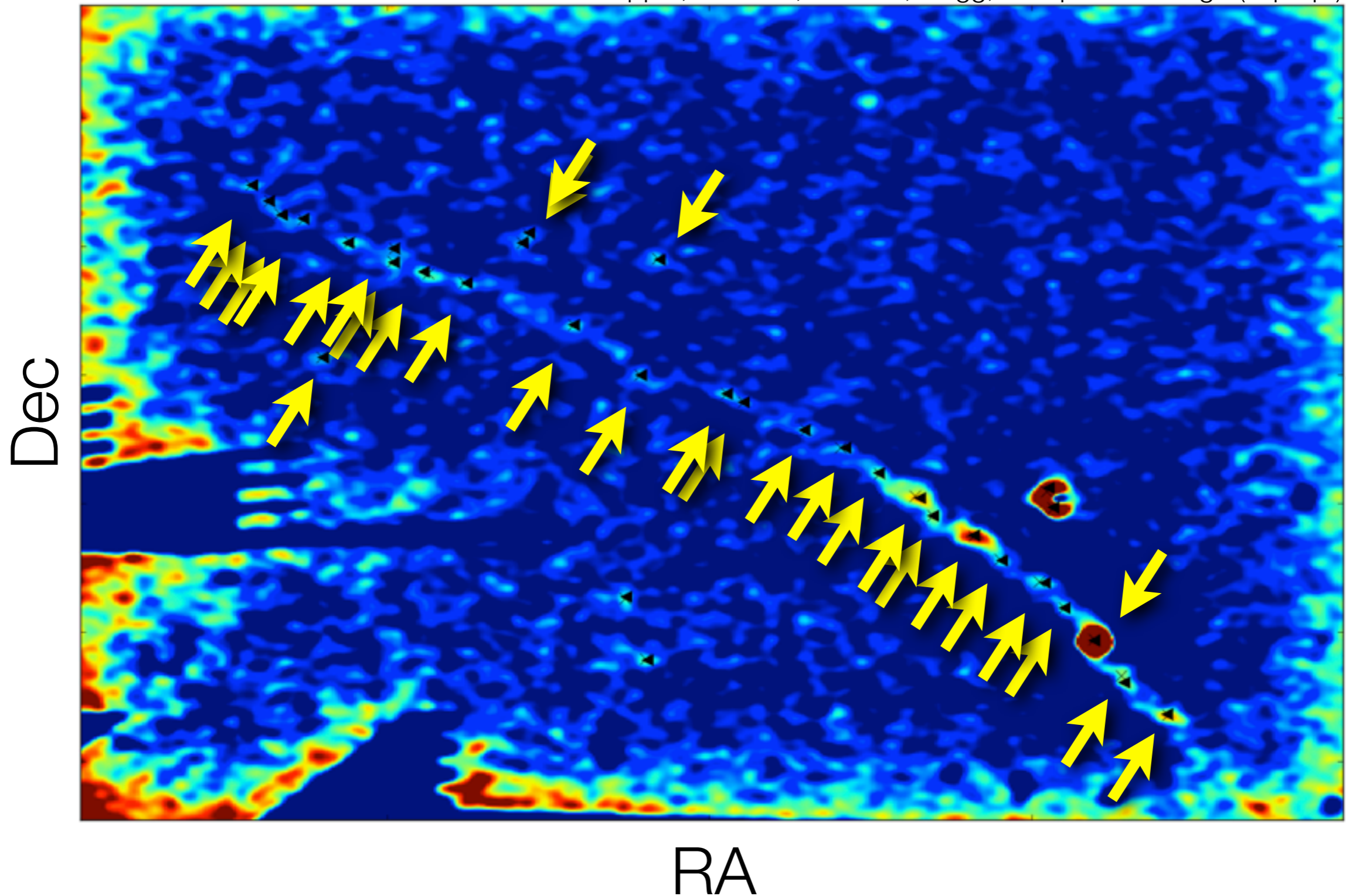
Küpper, Balbinot, Bonaca, Hogg, Kroupa & Santiago (in prep.)



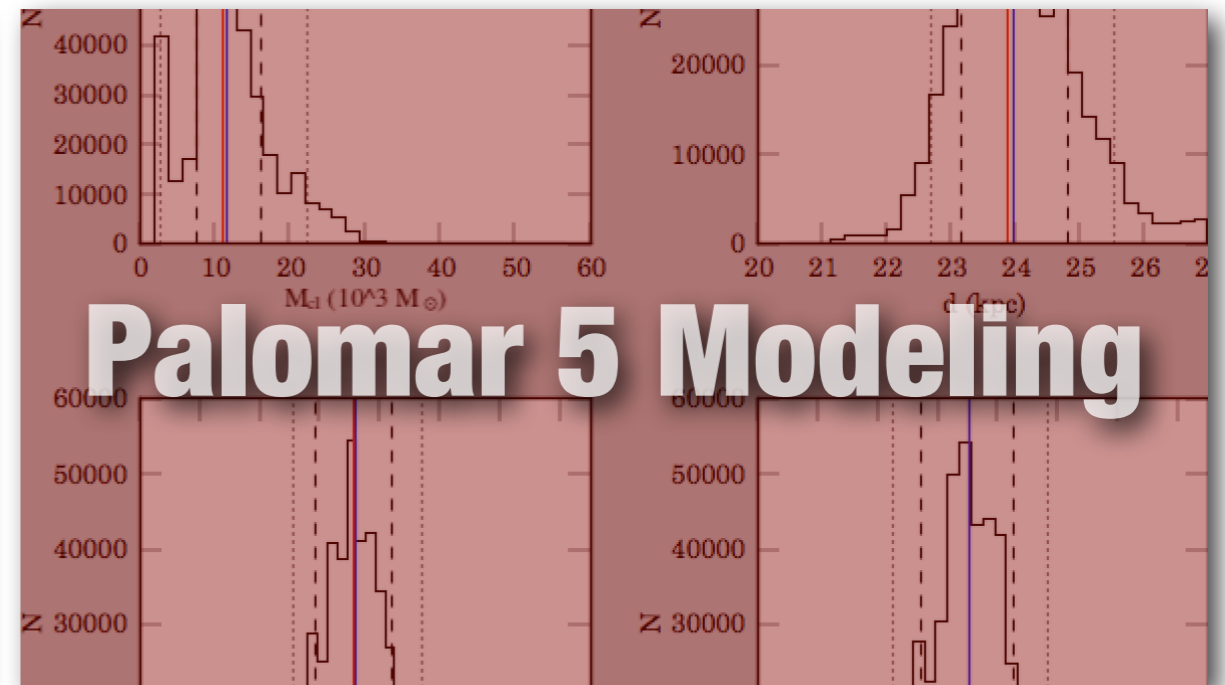
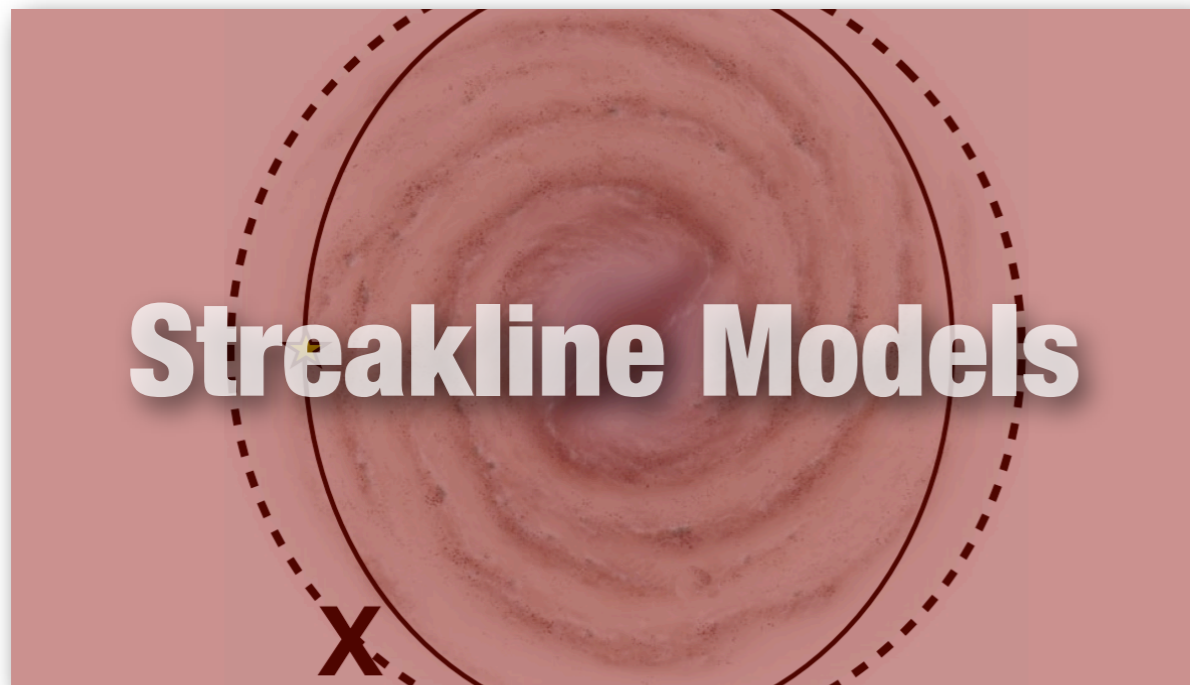
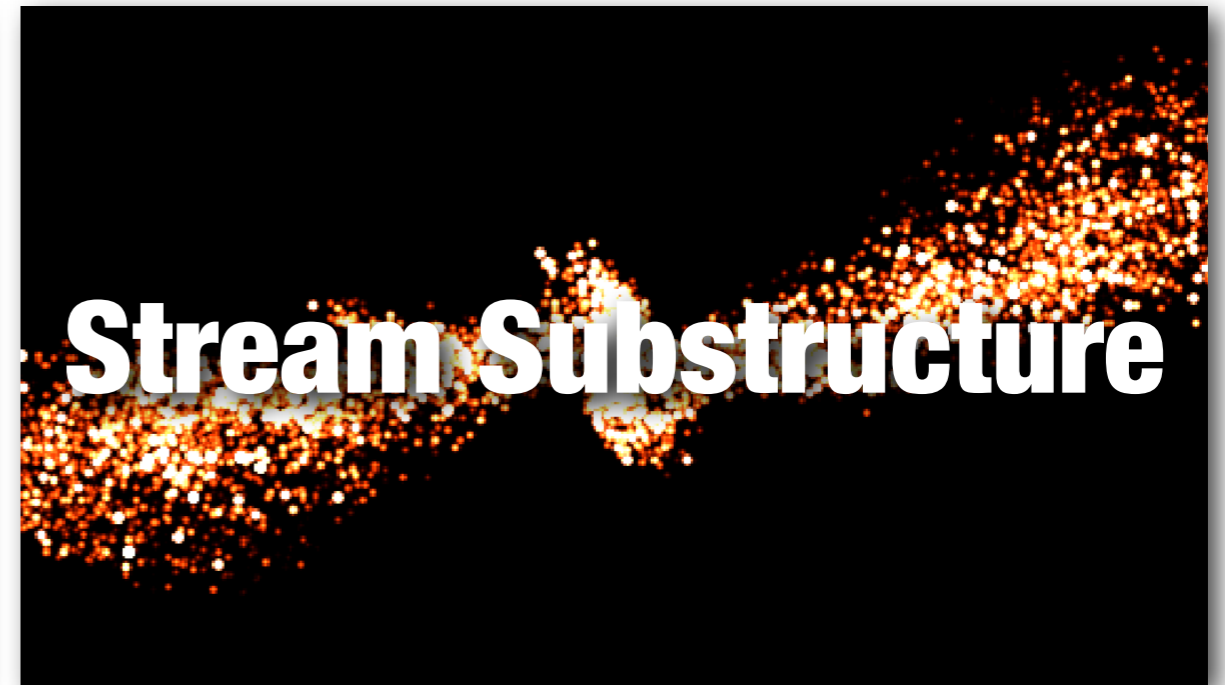
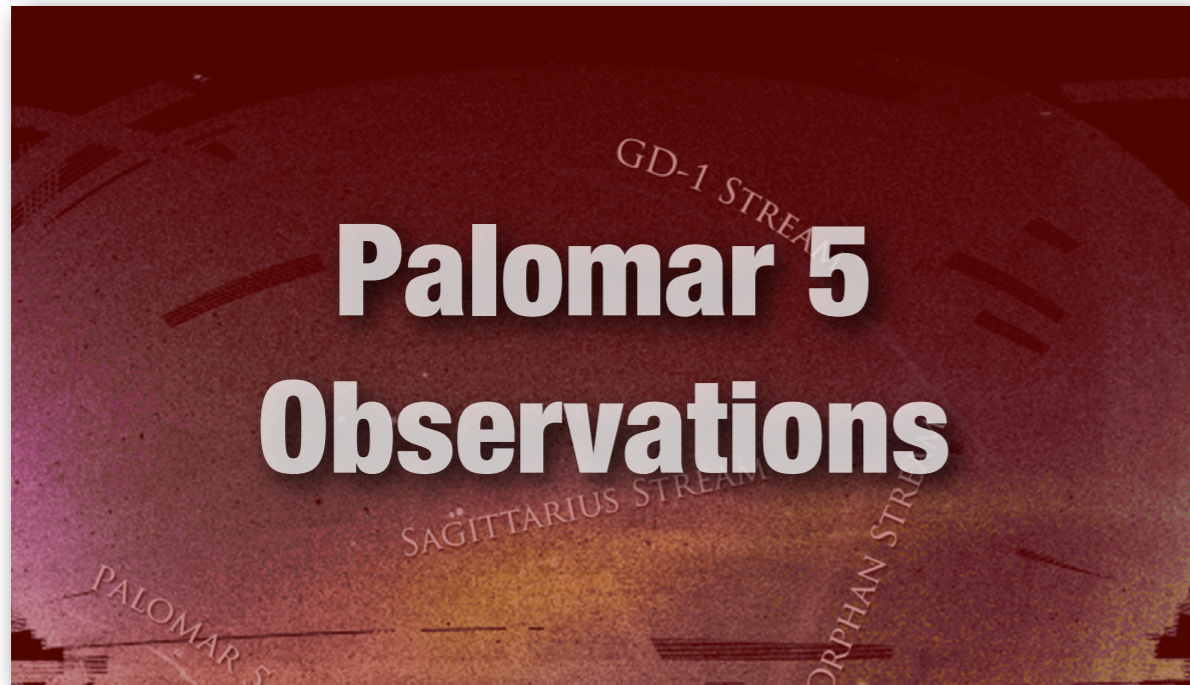


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Küpper, Balbinot, Bonaca, Hogg, Kroupa & Santiago (in prep.)

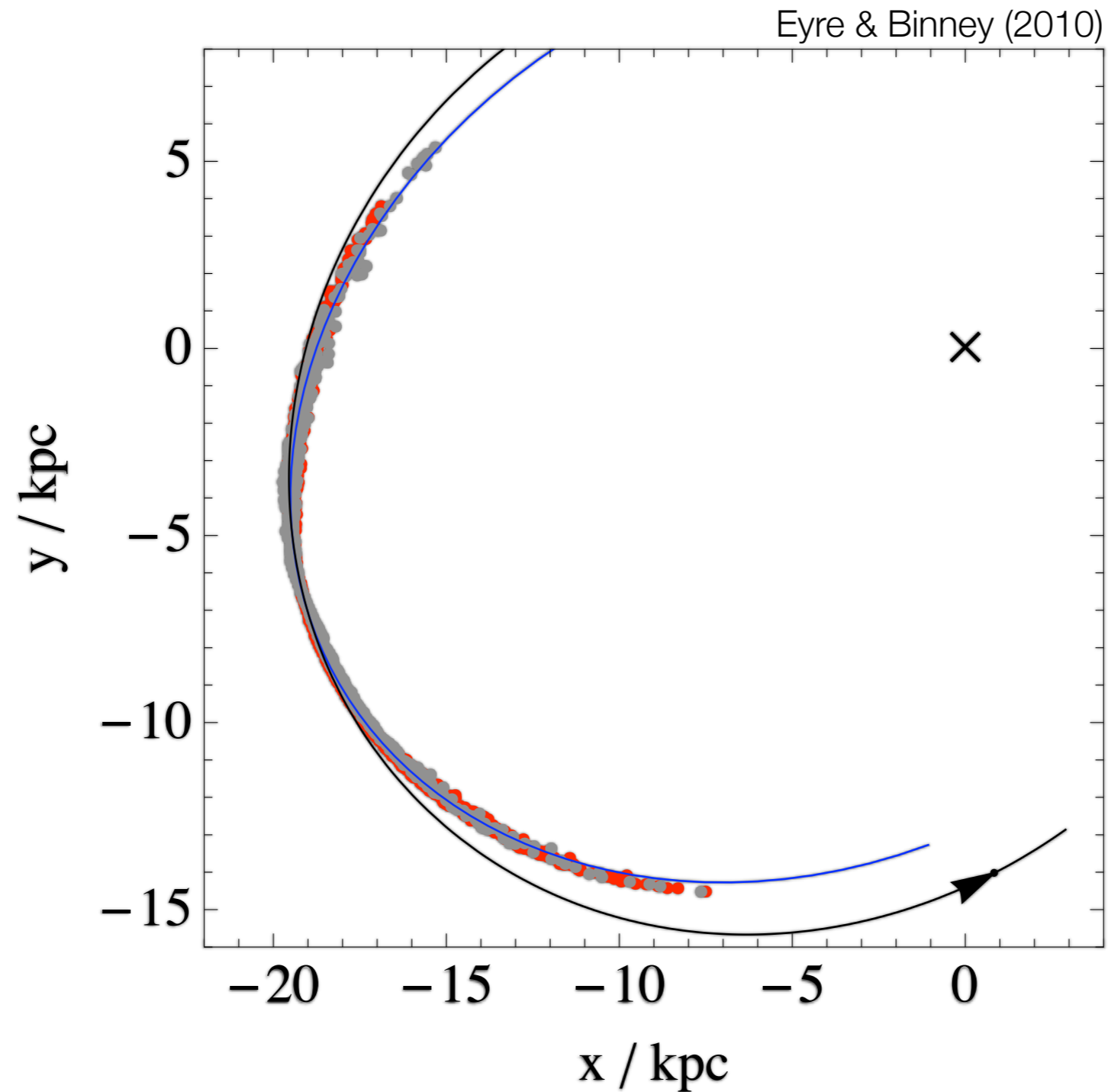


Stream substructure can be used to constrain model parameters

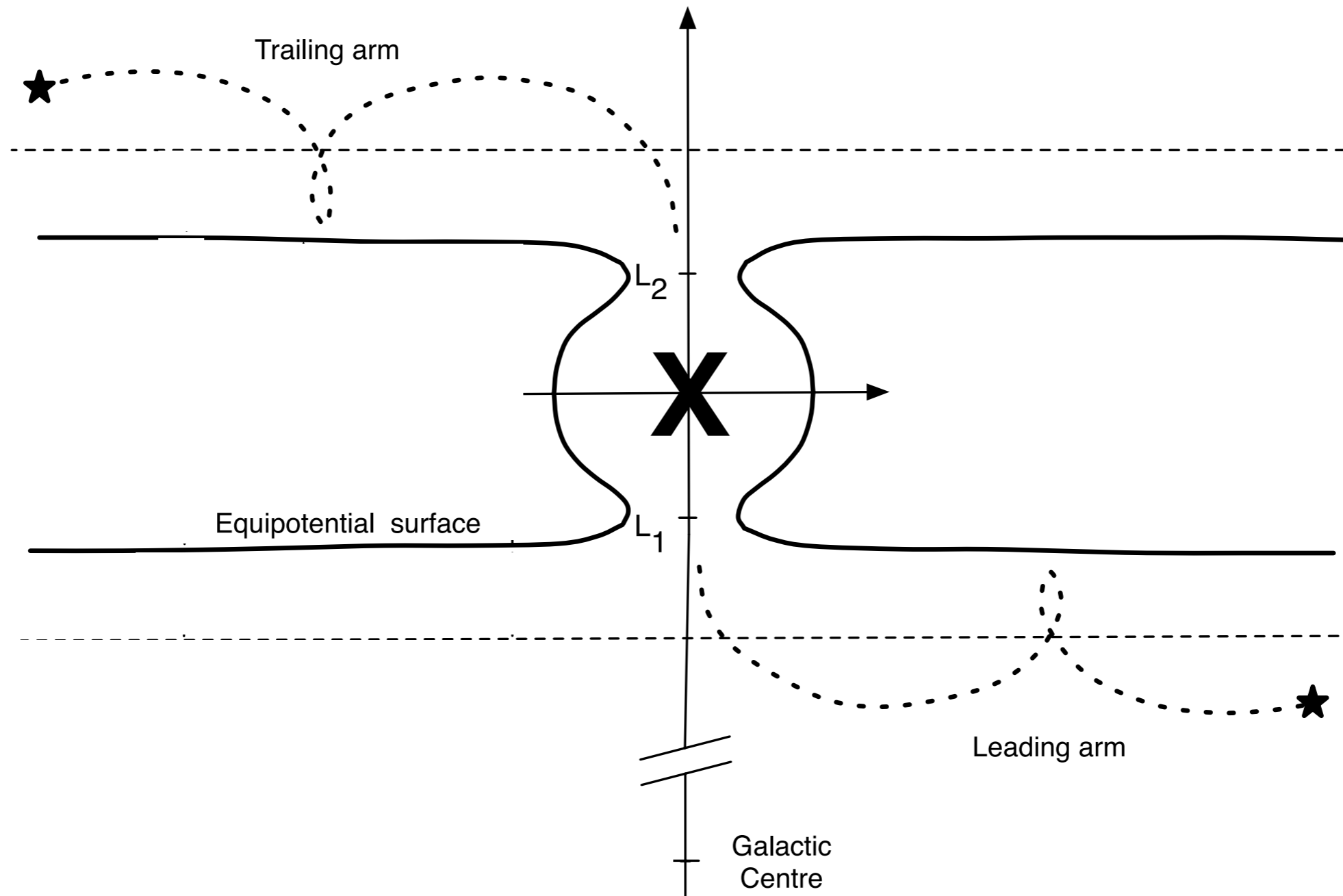


Stream stars have an offset with respect to the cluster orbit

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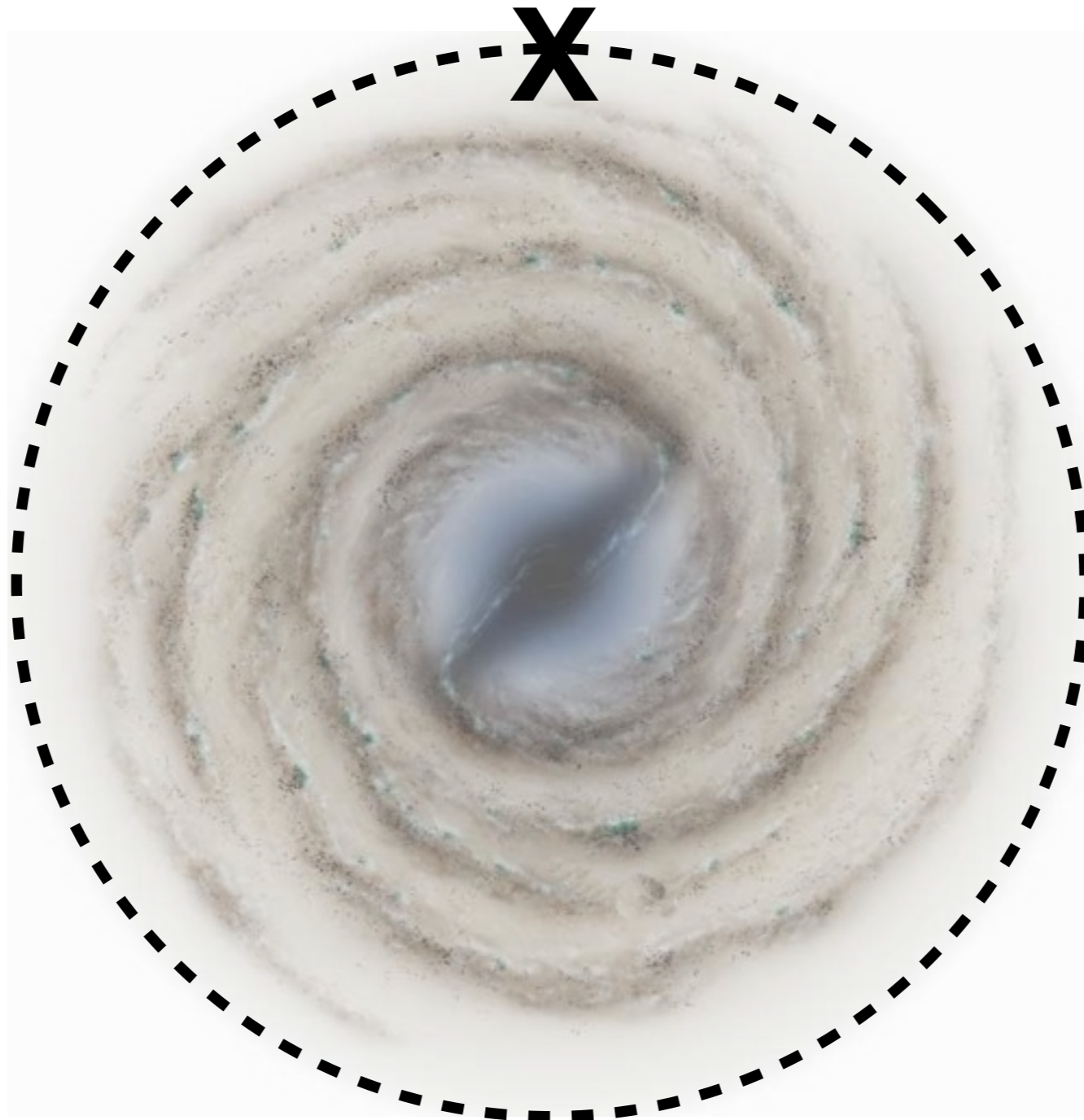


# Stars escape through the Lagrange points and move non-linearly along the stream



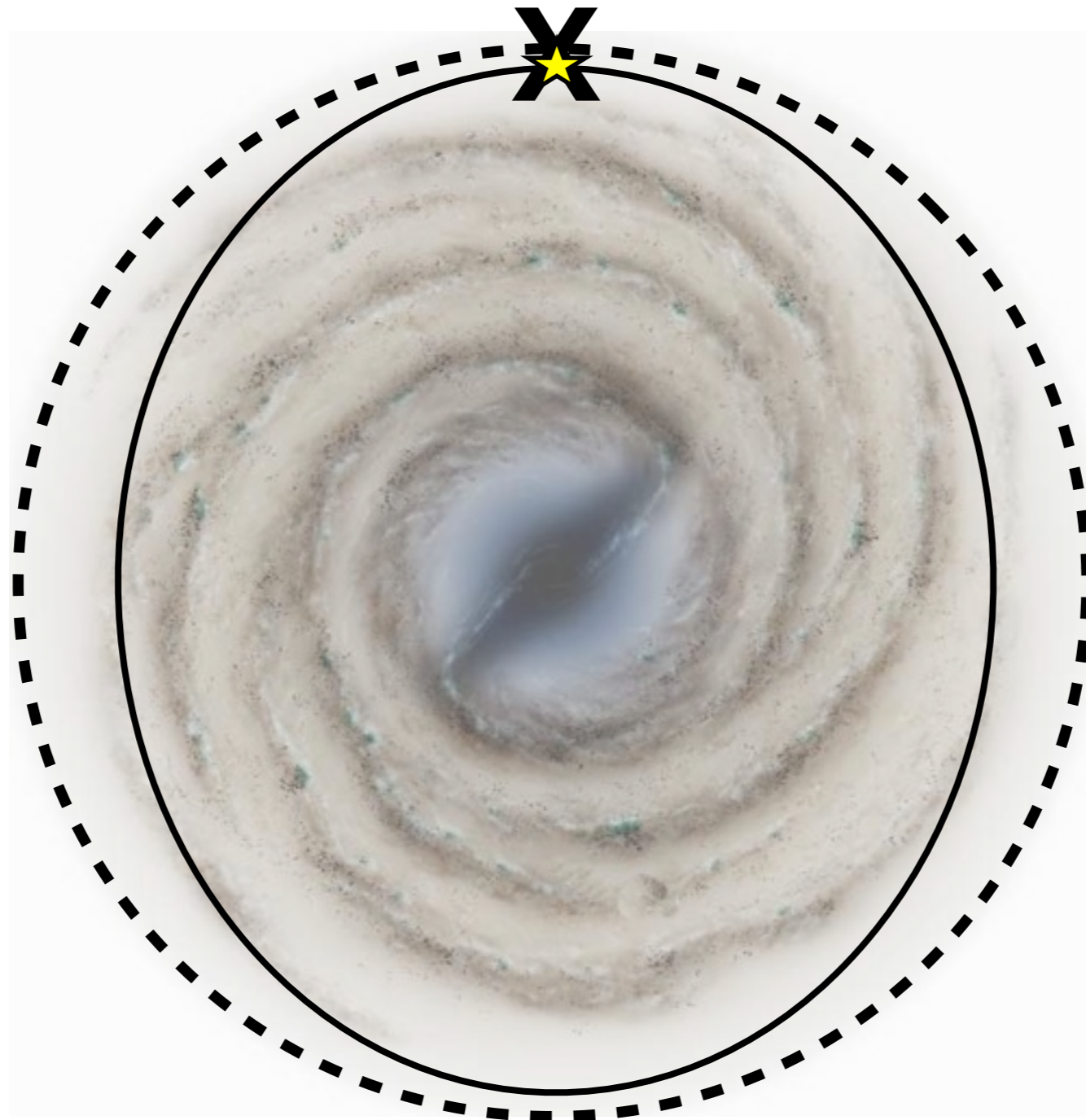
Stream substructure tells us something about the offset from the streams stars to the cluster orbit

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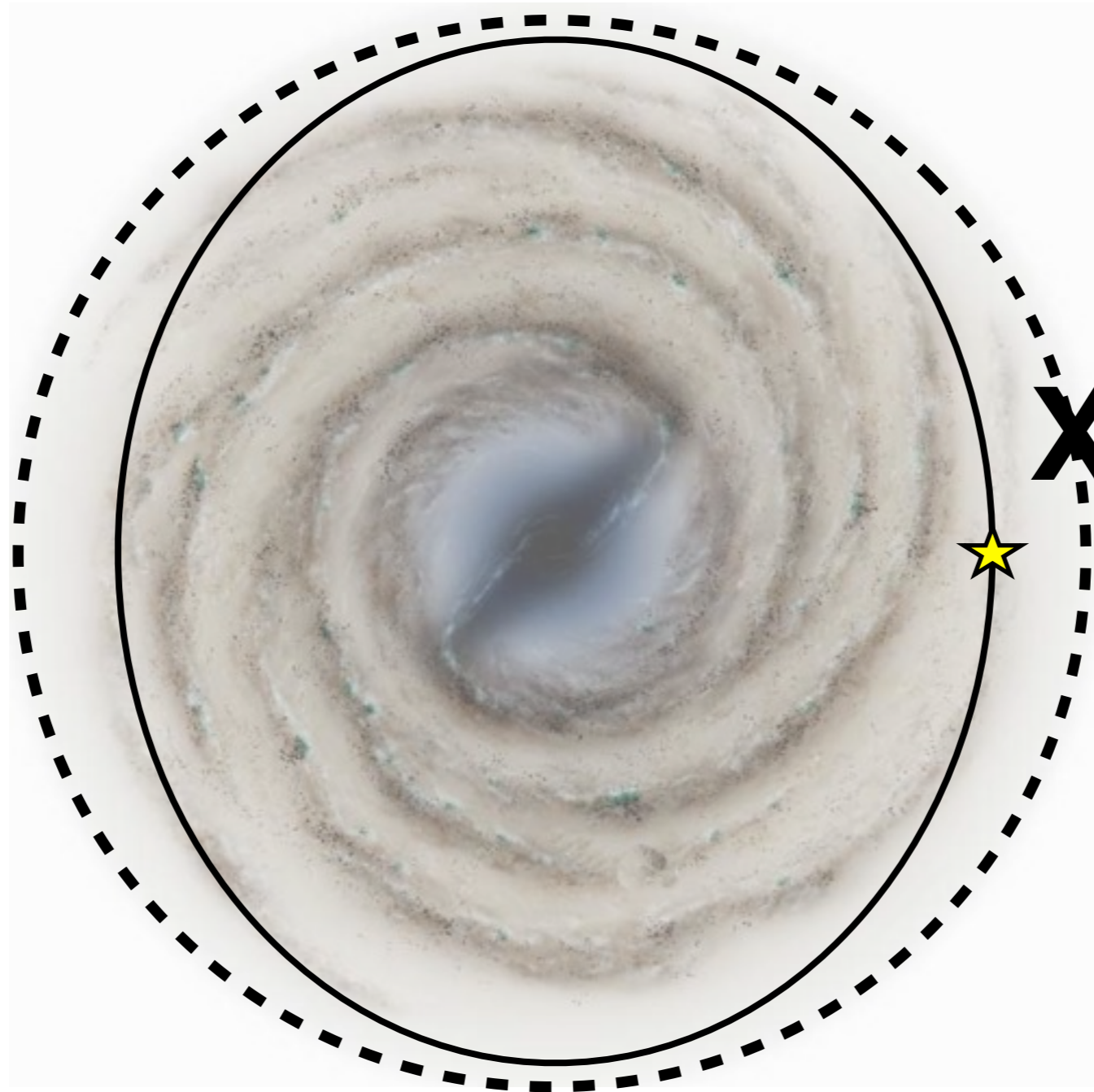
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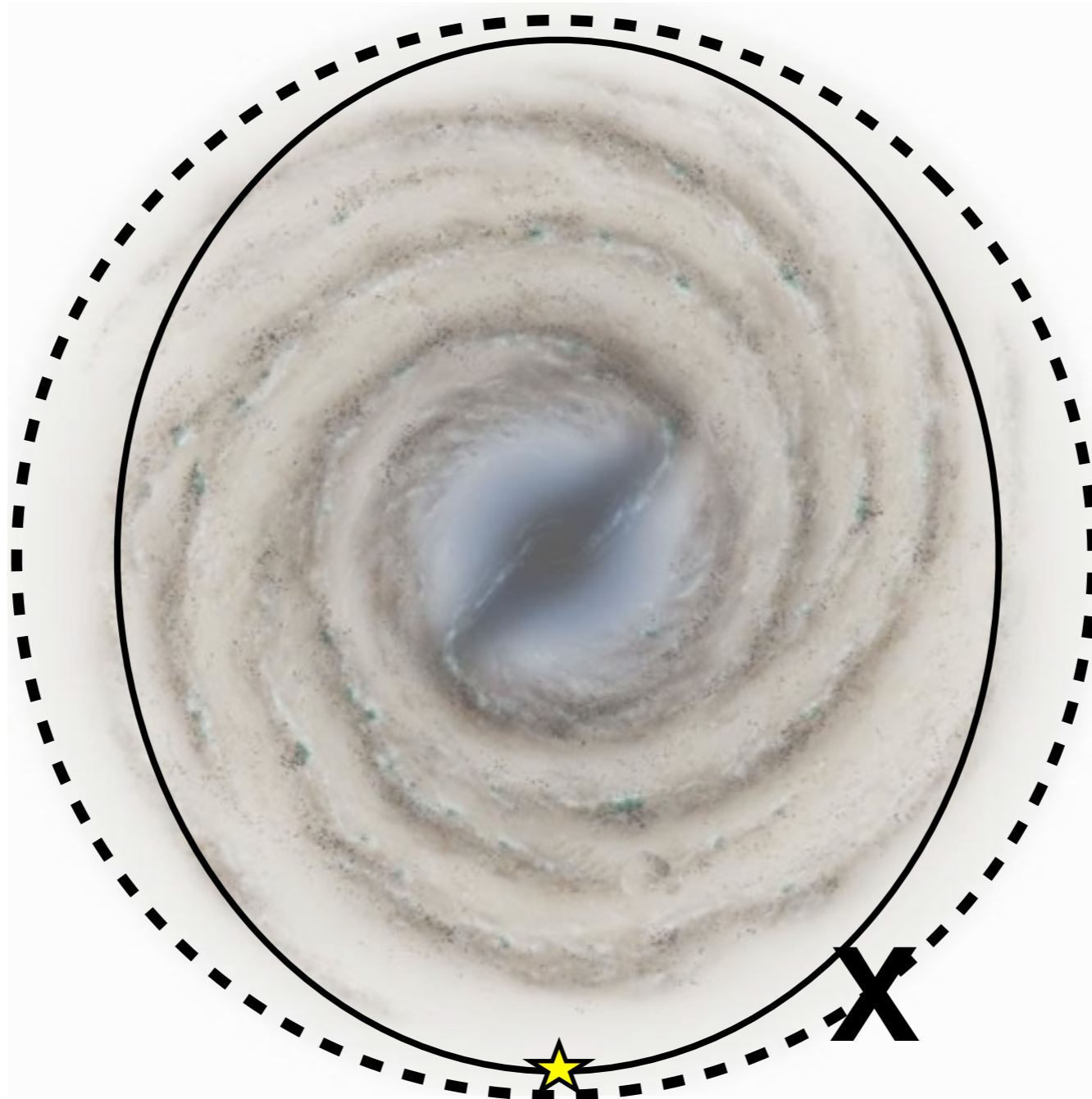
Stream substructure tells us something about the offset from the streams stars to the cluster orbit

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Stream substructure tells us something about the offset from the streams stars to the cluster orbit

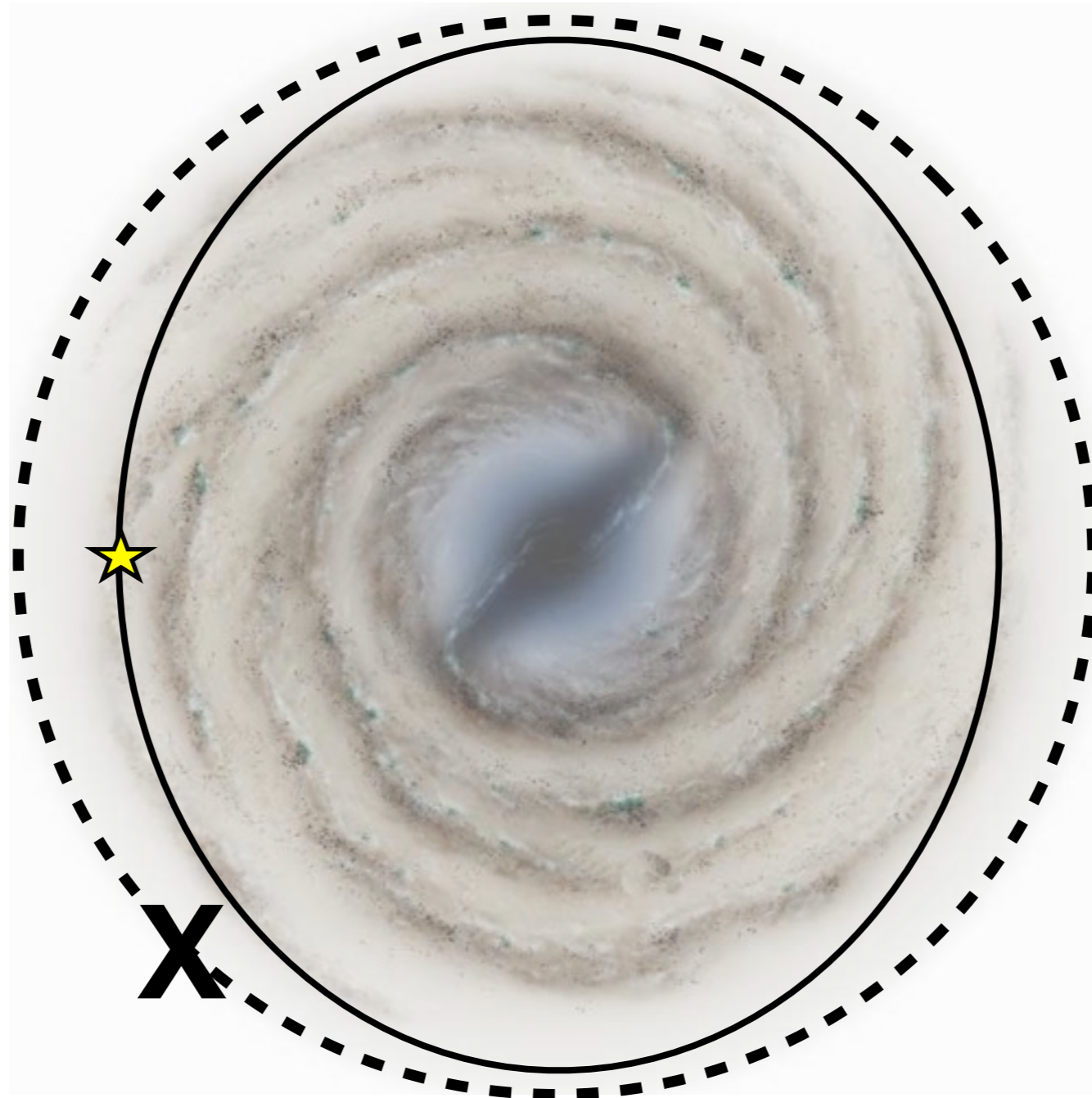
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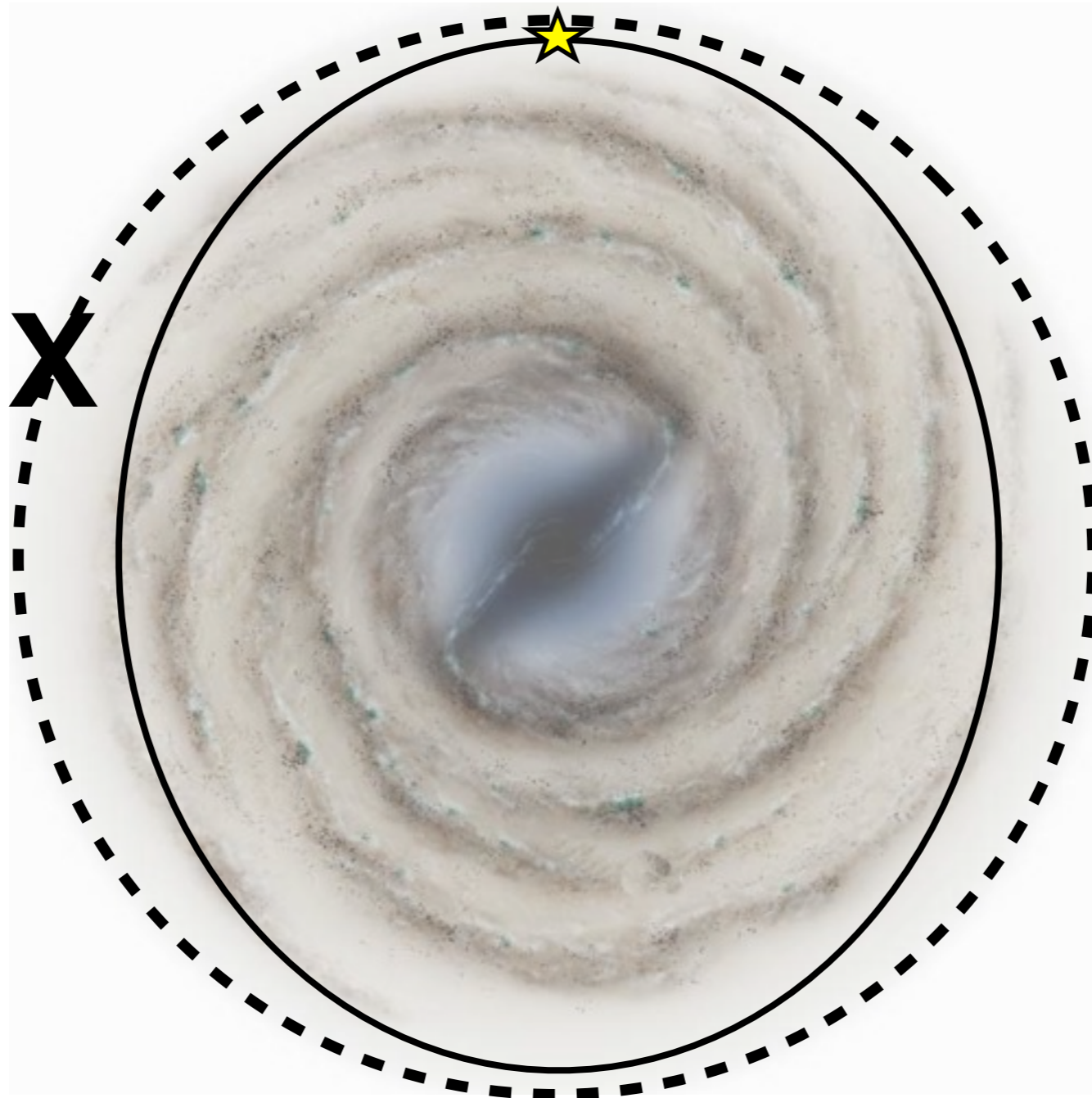
Stream substructure tells us something about the offset from the streams stars to the cluster orbit

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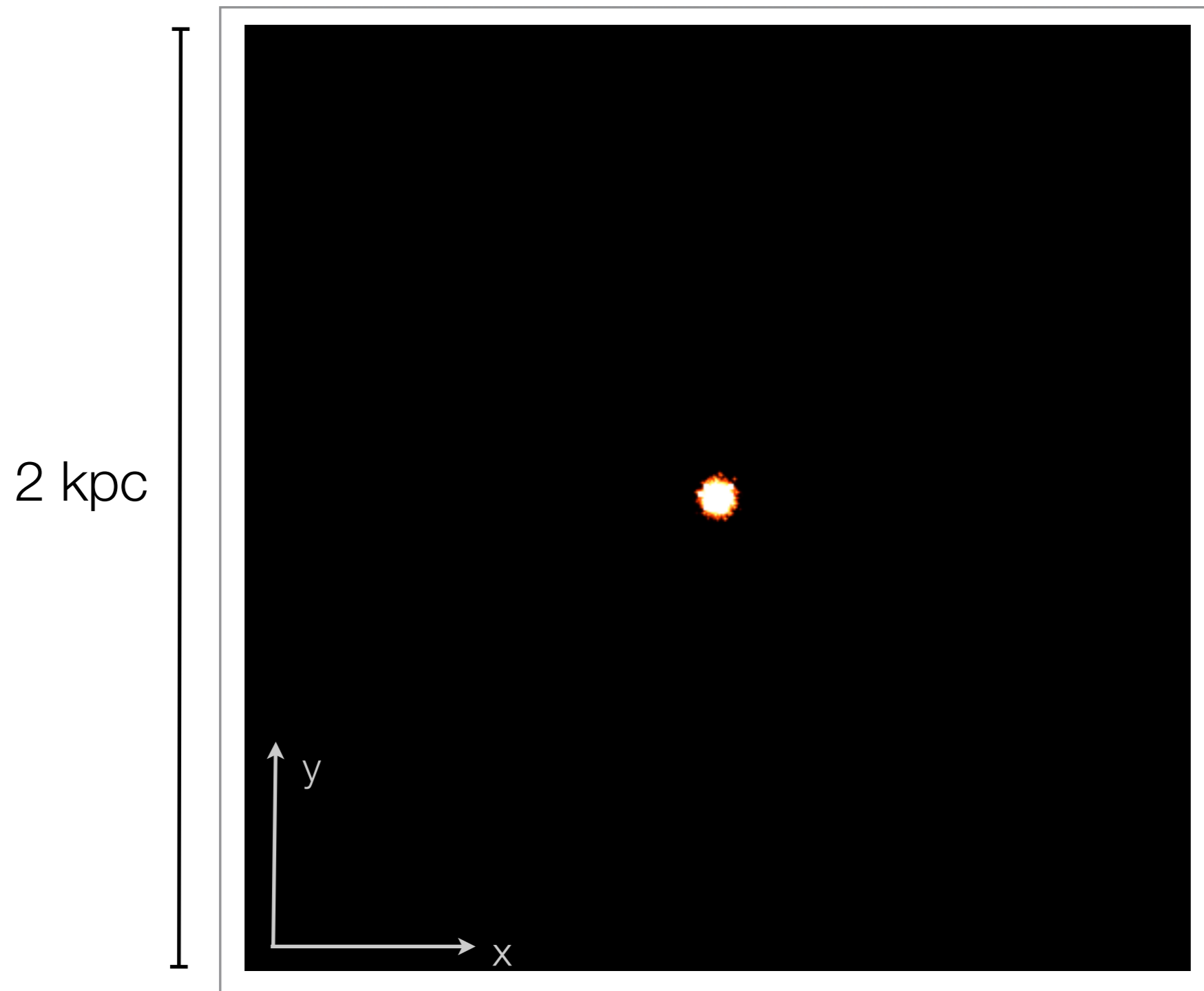
Stream substructure tells us something about the offset from the streams stars to the cluster orbit

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Star clusters produce a continuous stream of stars while they dissolve which creates an epicyclic pattern

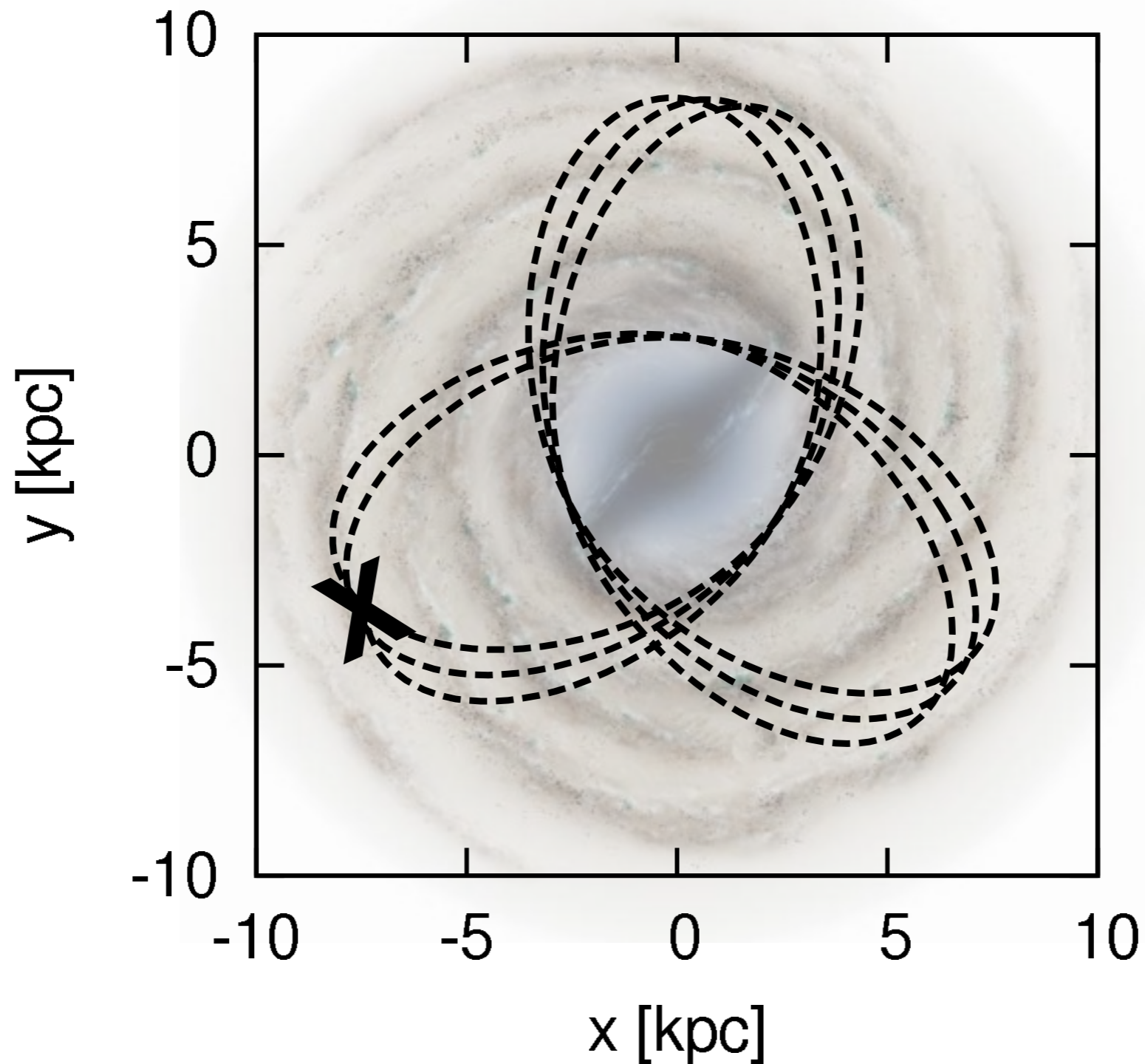
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Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

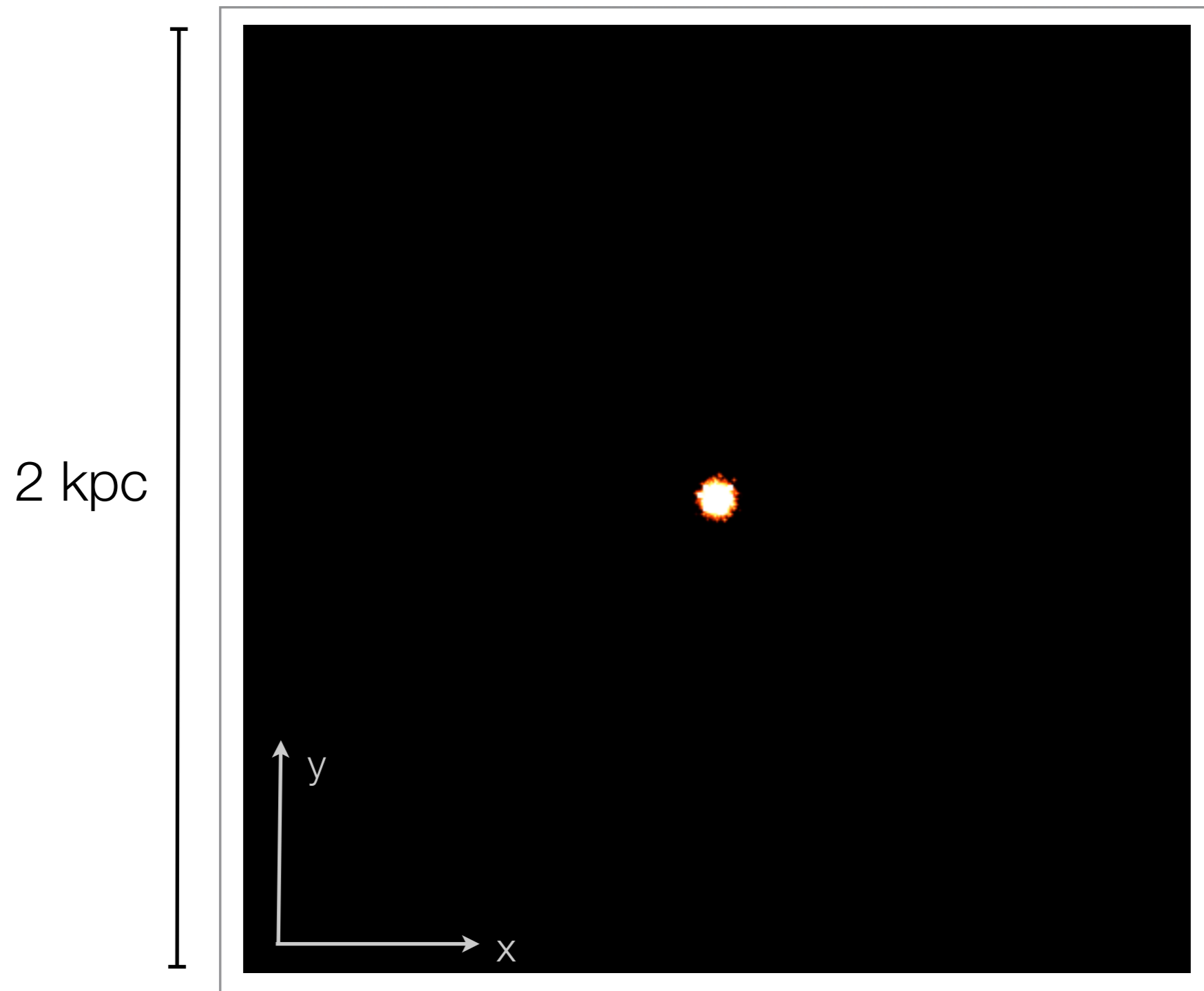
Stream overdensities also form in streams of clusters on eccentric orbits

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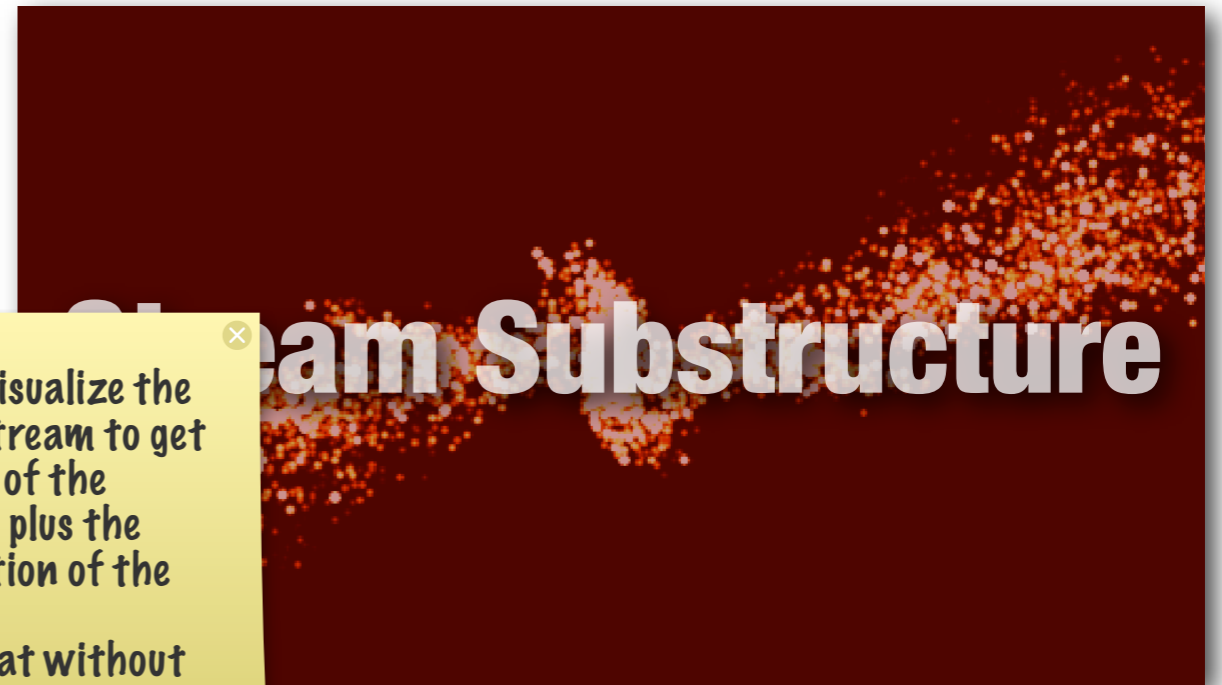
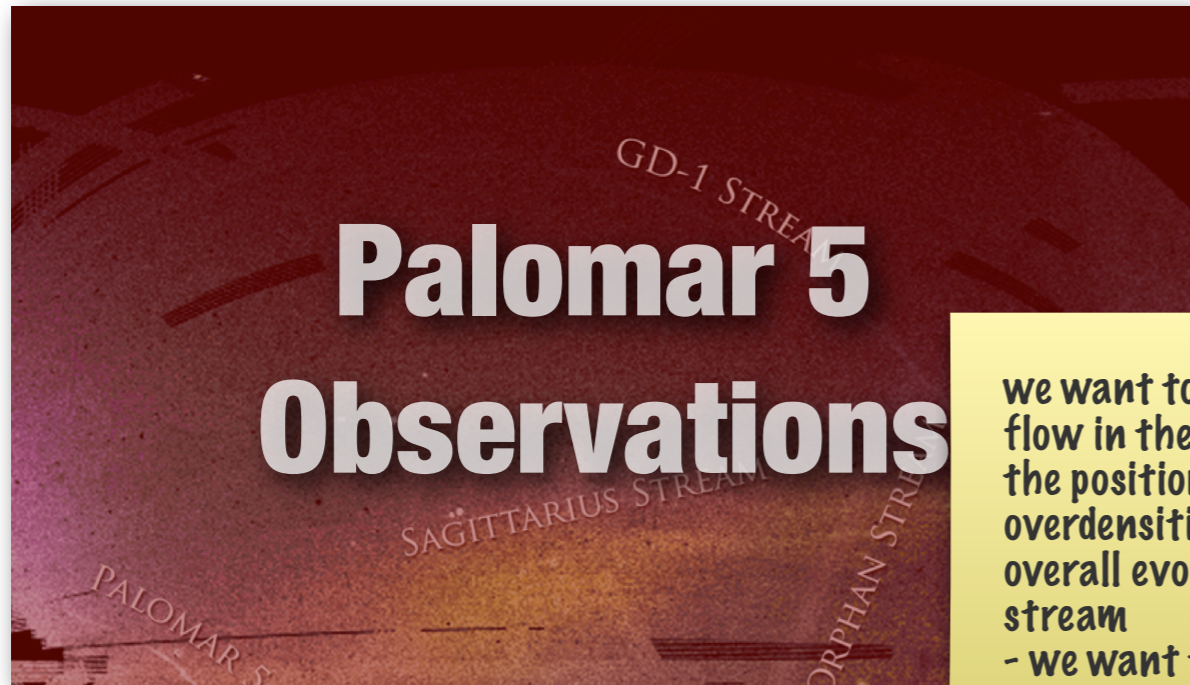
N-body computations of clusters on eccentric orbits show complex behavior of the overdensities

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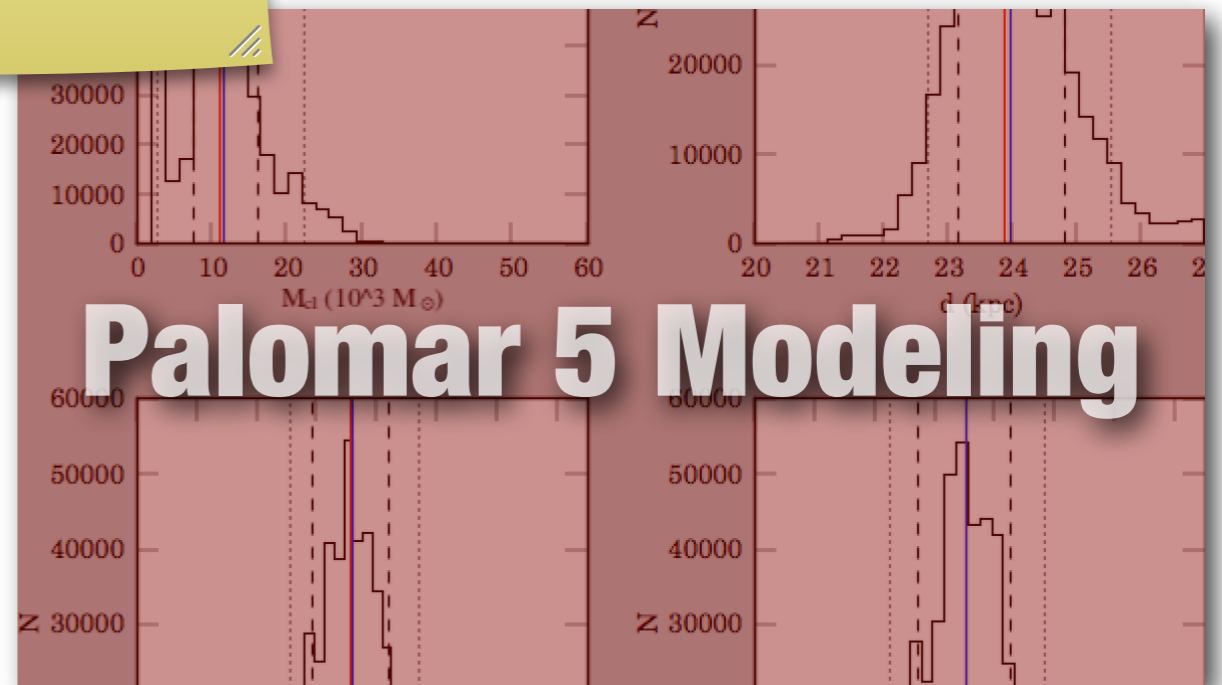
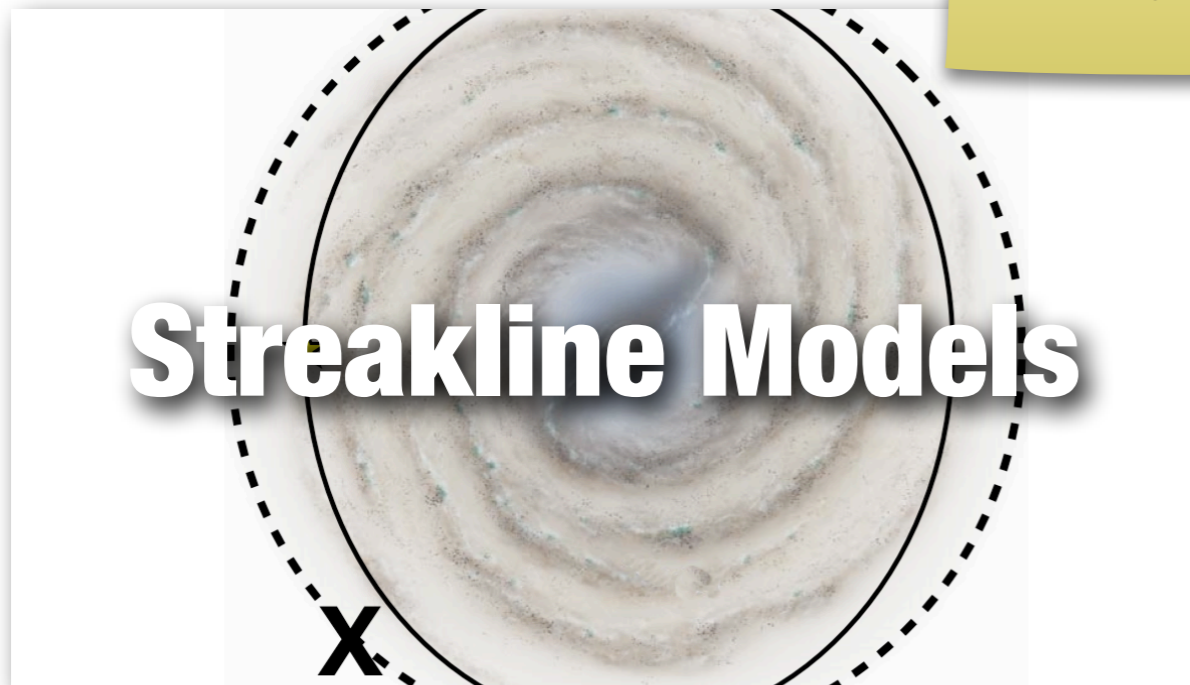


Simulation from Küpper, Kroupa, Baumgardt & Heggie (2010)

# Stream substructure can be used to constrain model parameters



we want to visualize the flow in the stream to get the positions of the overdensities plus the overall evolution of the stream  
- we want that without referring to Nbody sims



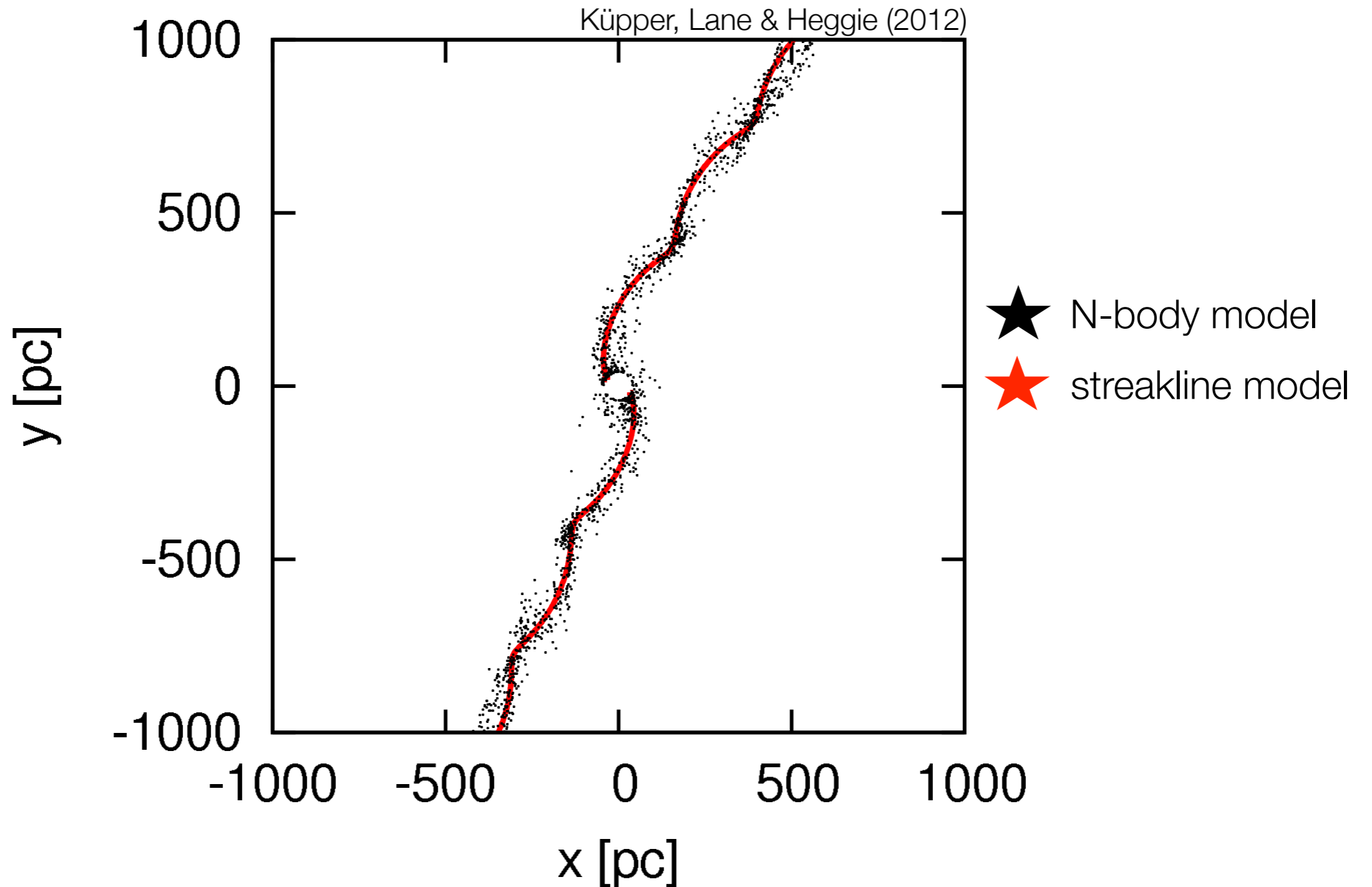
A streakline visualizes the flow of particles in a stream due to progenitor orbit and surrounding medium

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

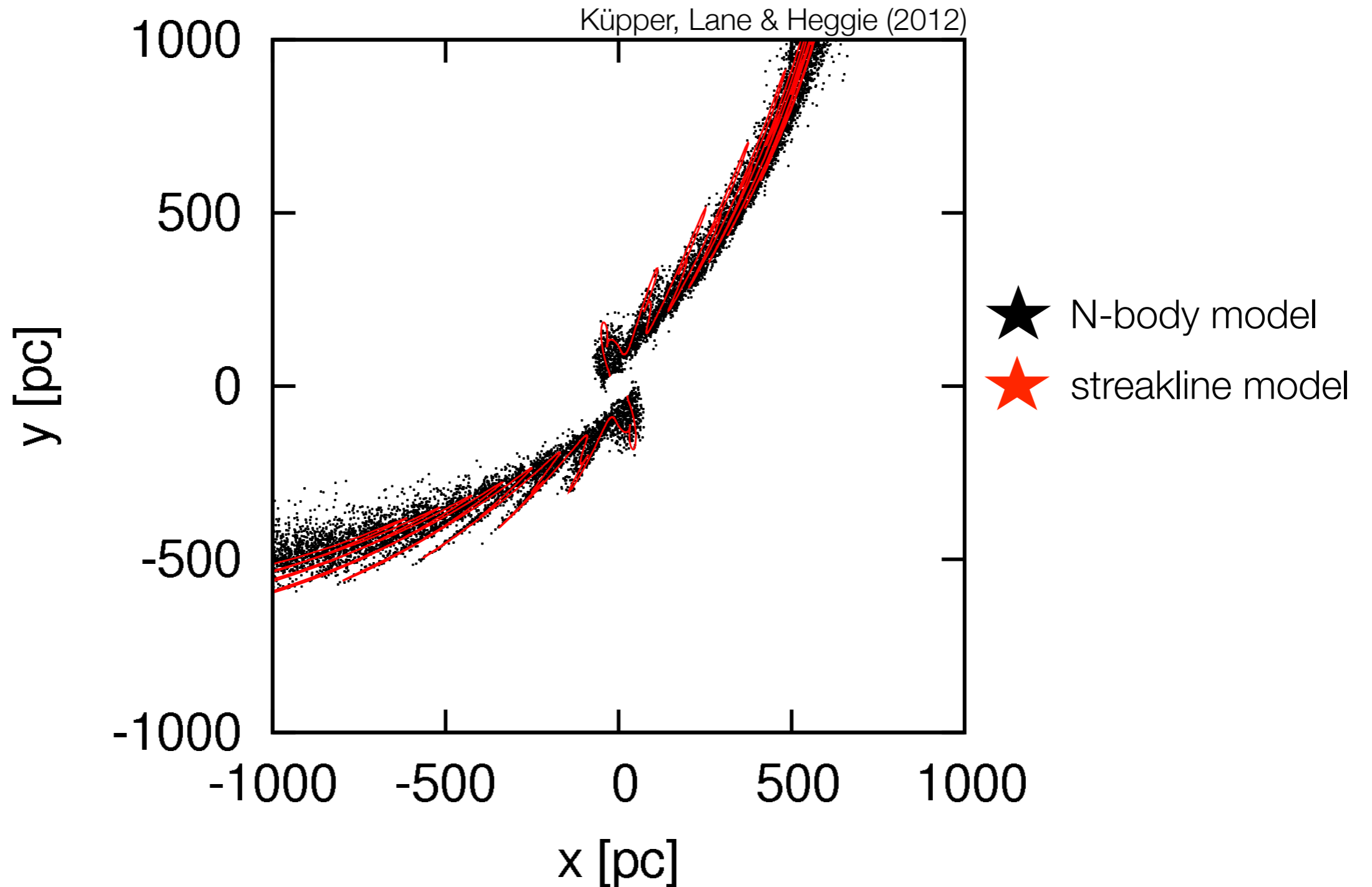
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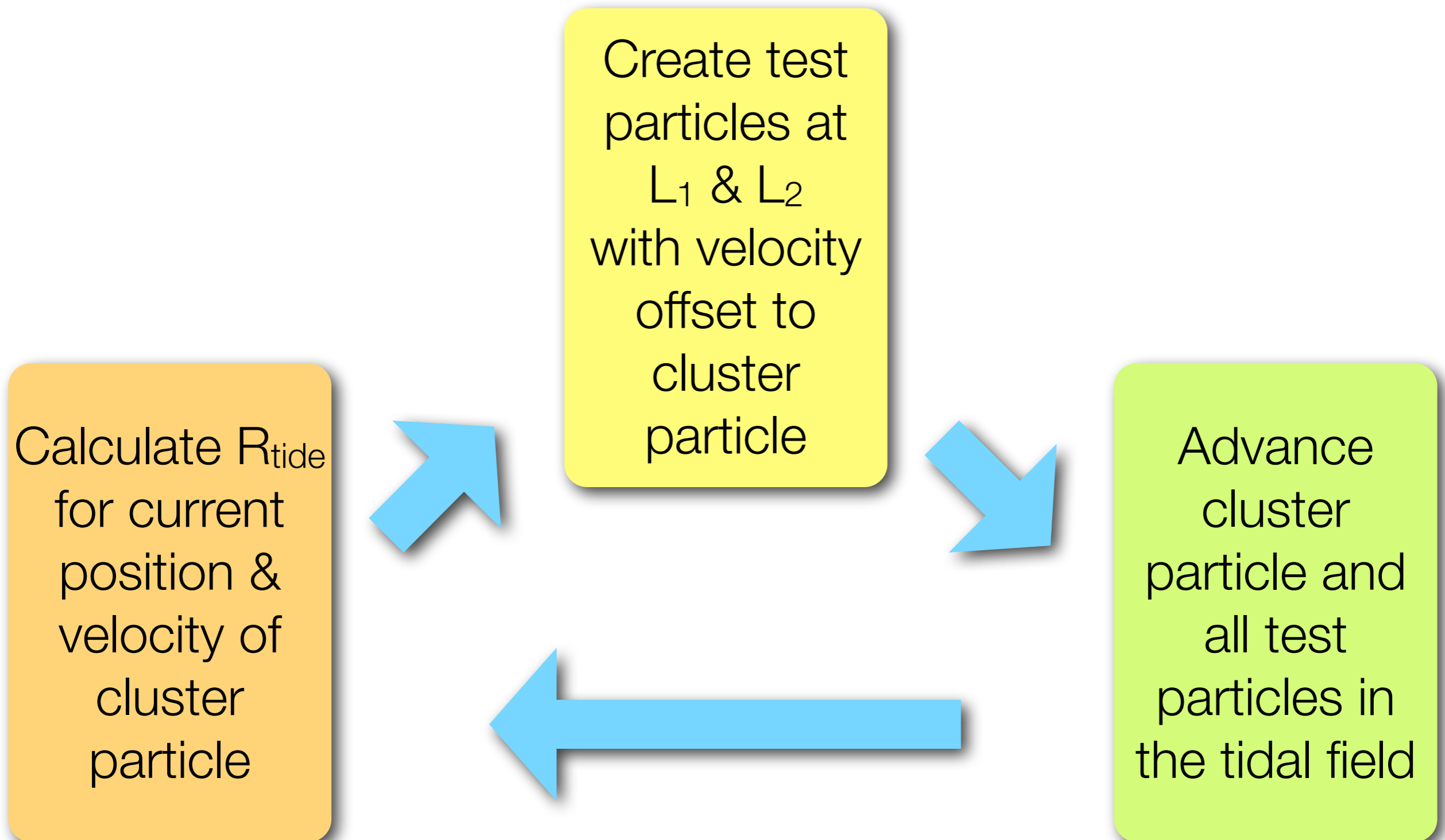
# Streakline models approximate full N-body simulations at low computational cost

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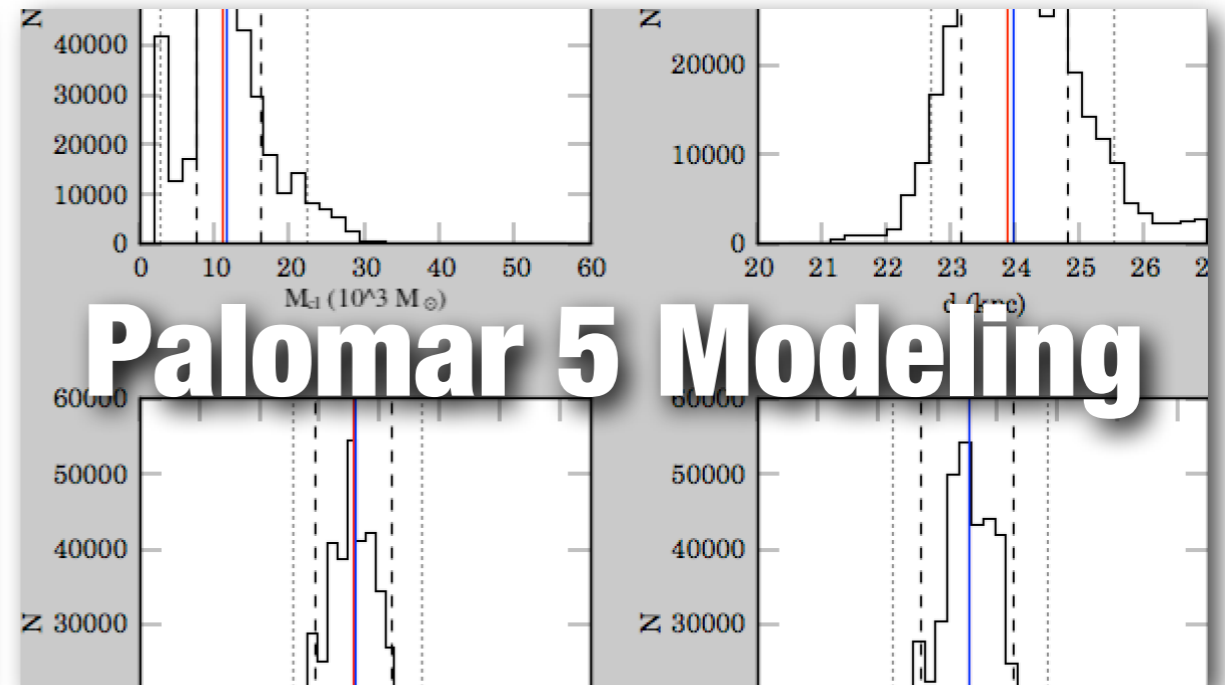
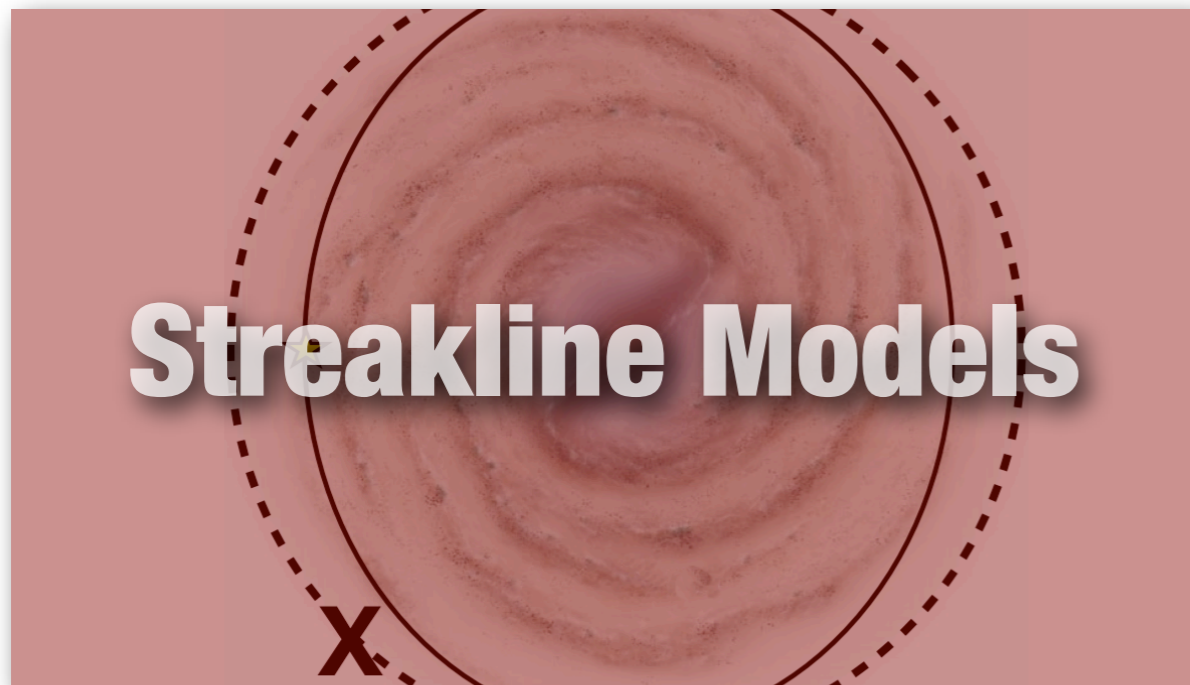
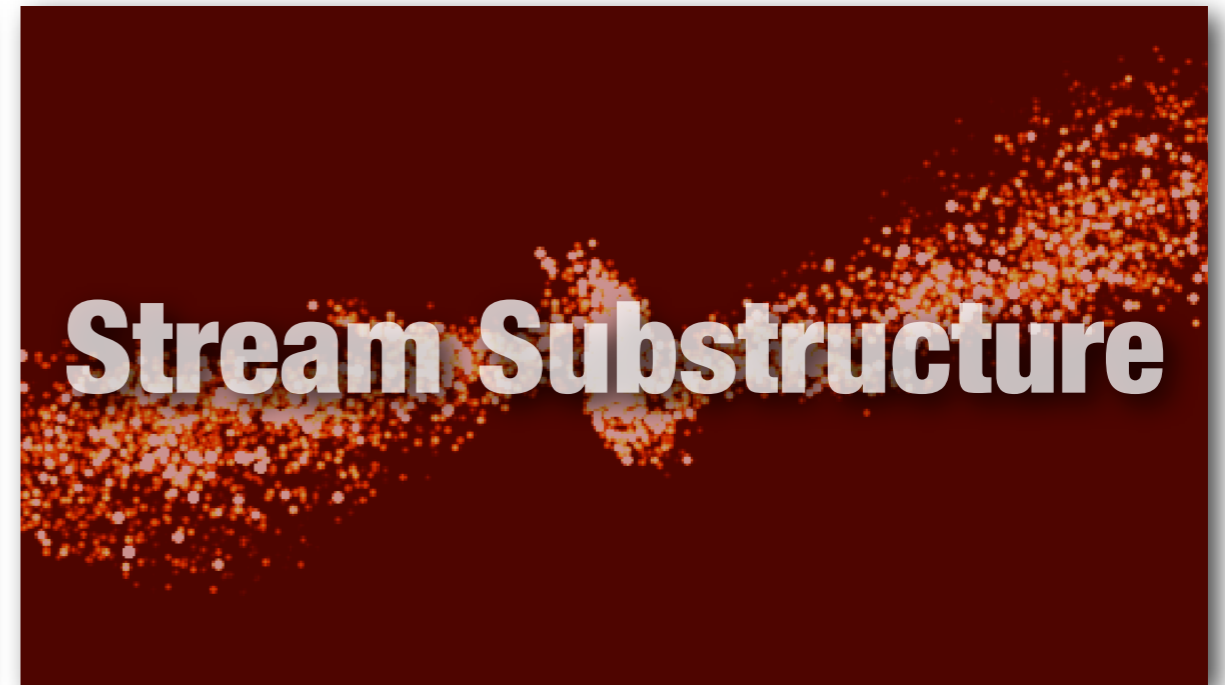
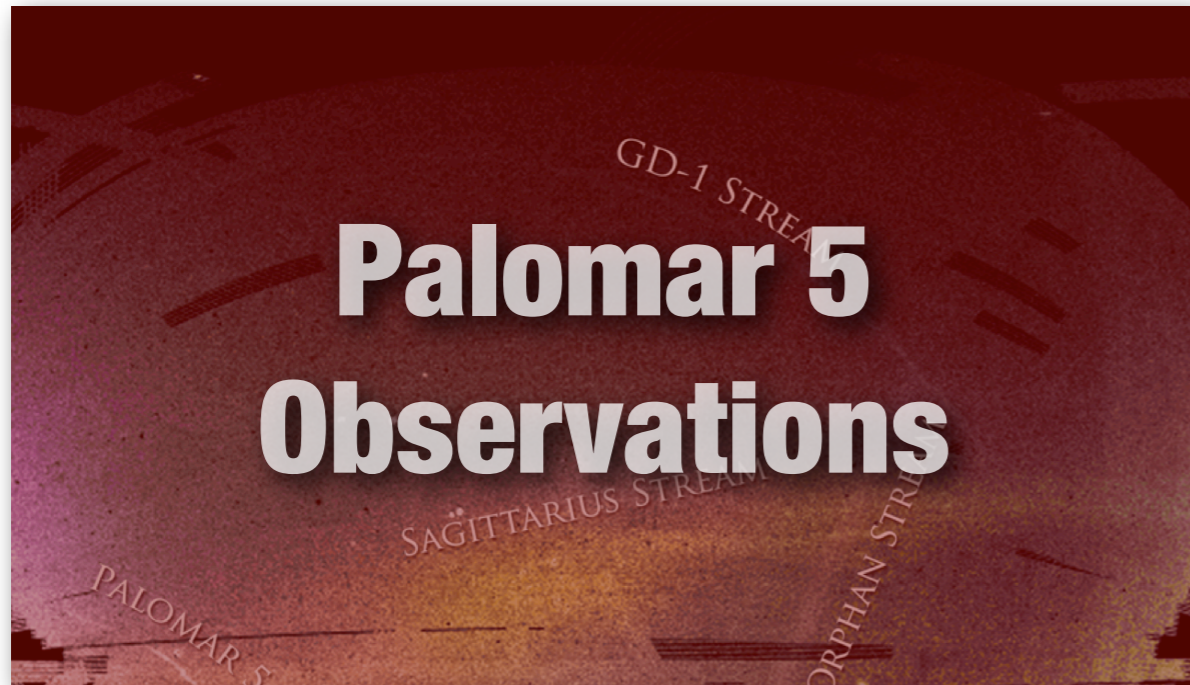


# Generating a streakline to visualize the flow of stars in a stream is simple

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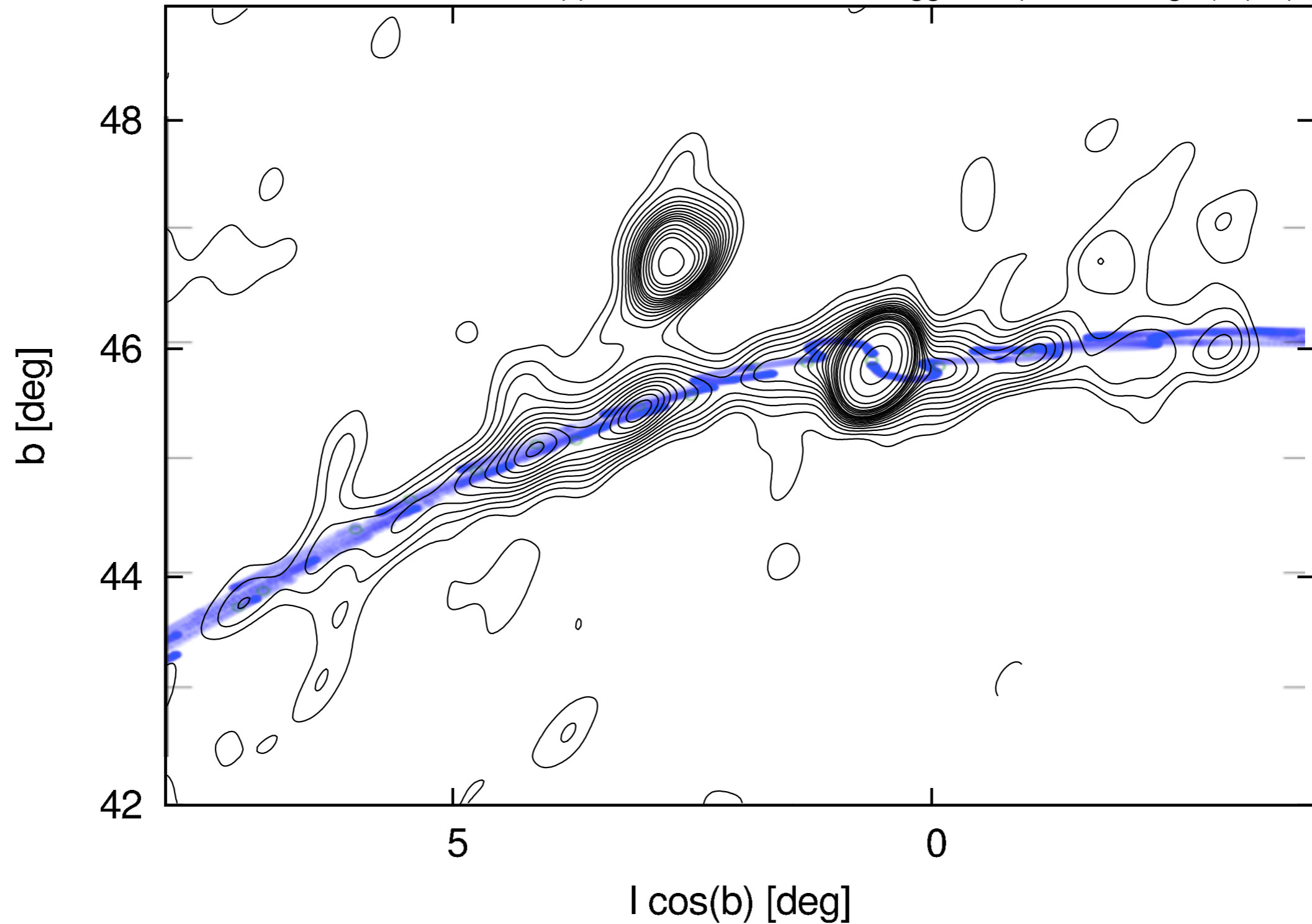


Stream substructure can be used to constrain model parameters



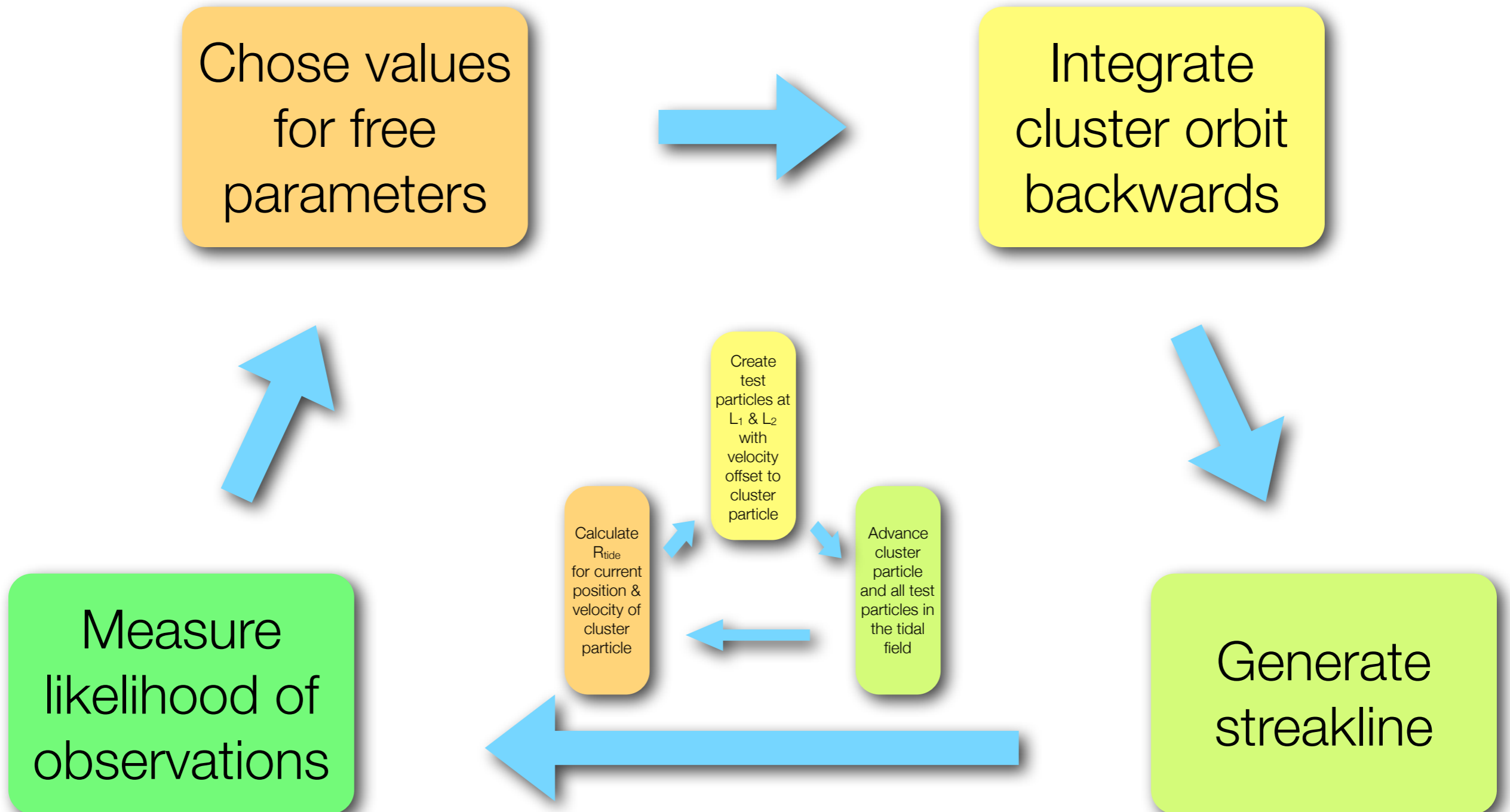
We can find a streakline model that reproduces the observed substructure

Küpper, Balbinot, Bonaca, Hogg, Kroupa & Santiago (in prep.)



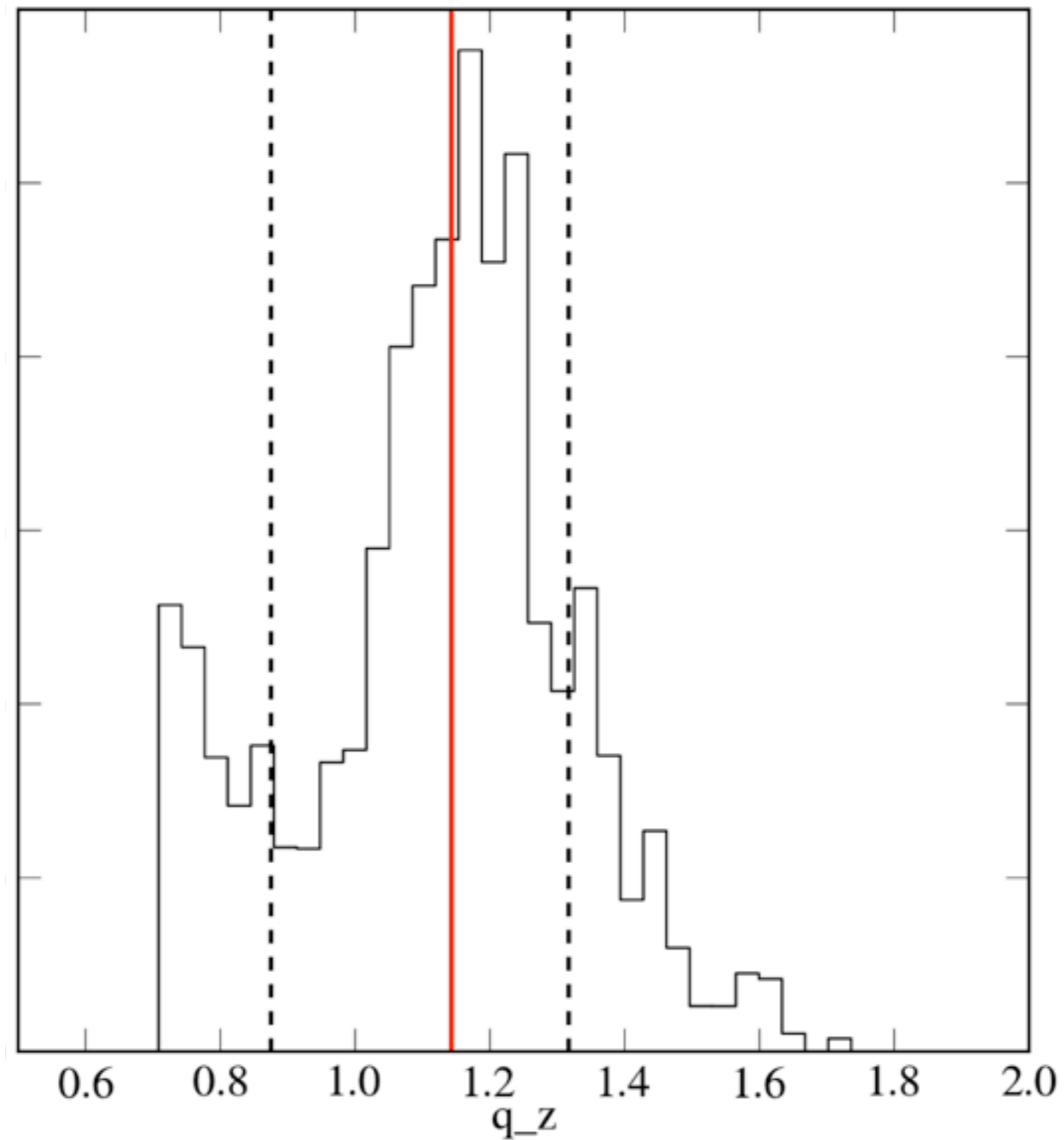
# Bayesian modeling of Palomar 5 using *emcee*

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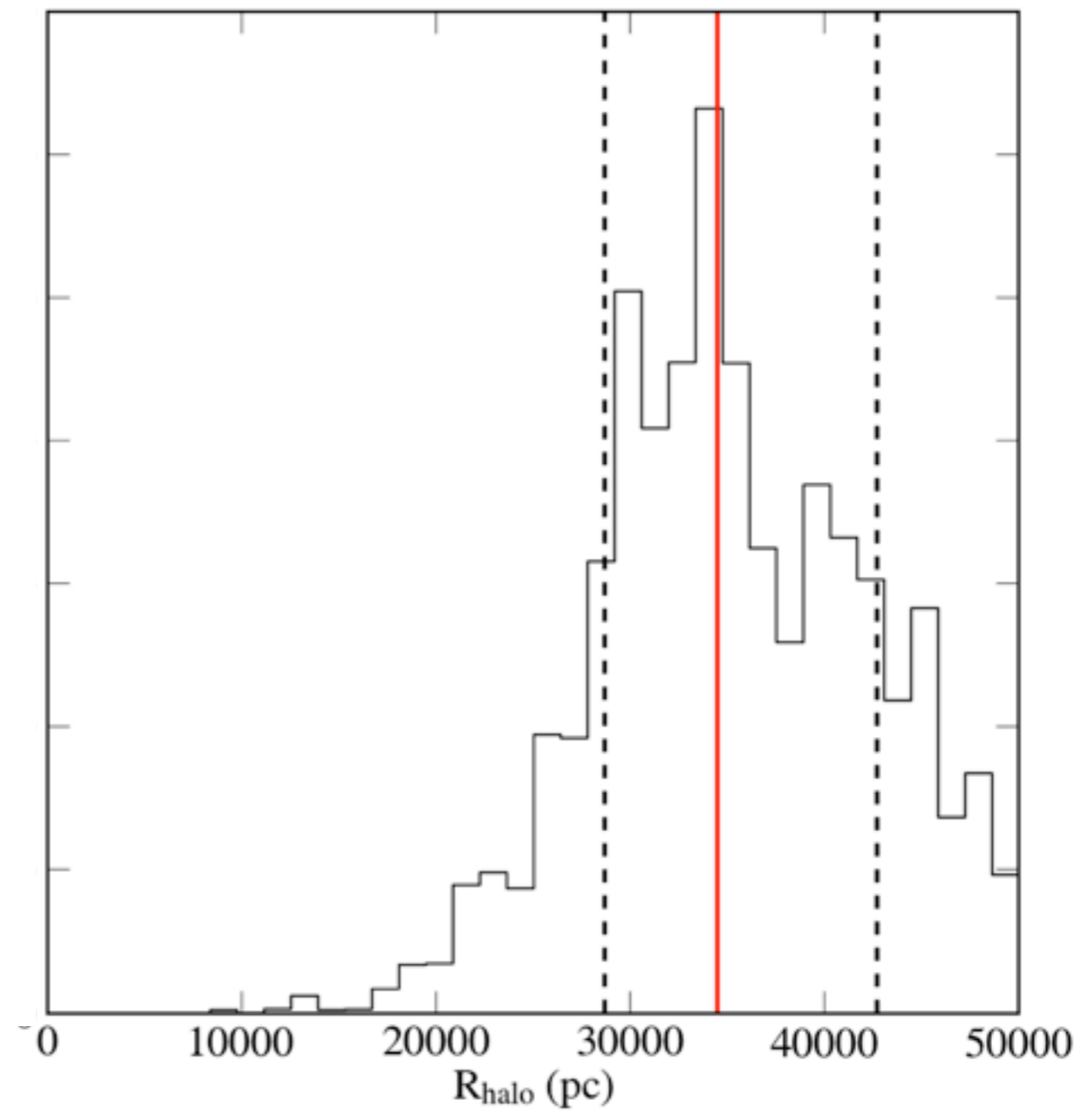
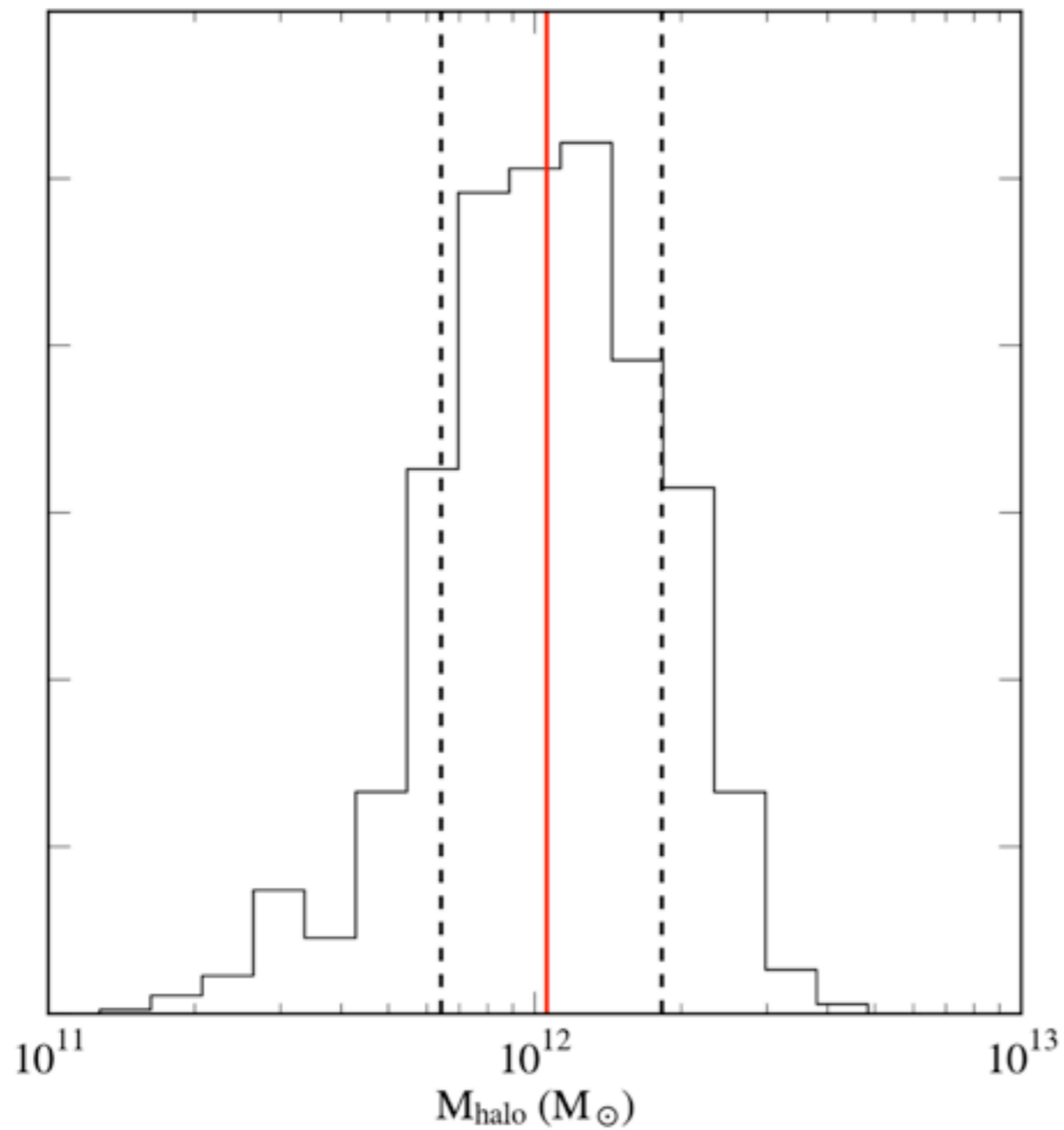
# Modeling of Palomar 5 constrains halo shape to be slightly prolate

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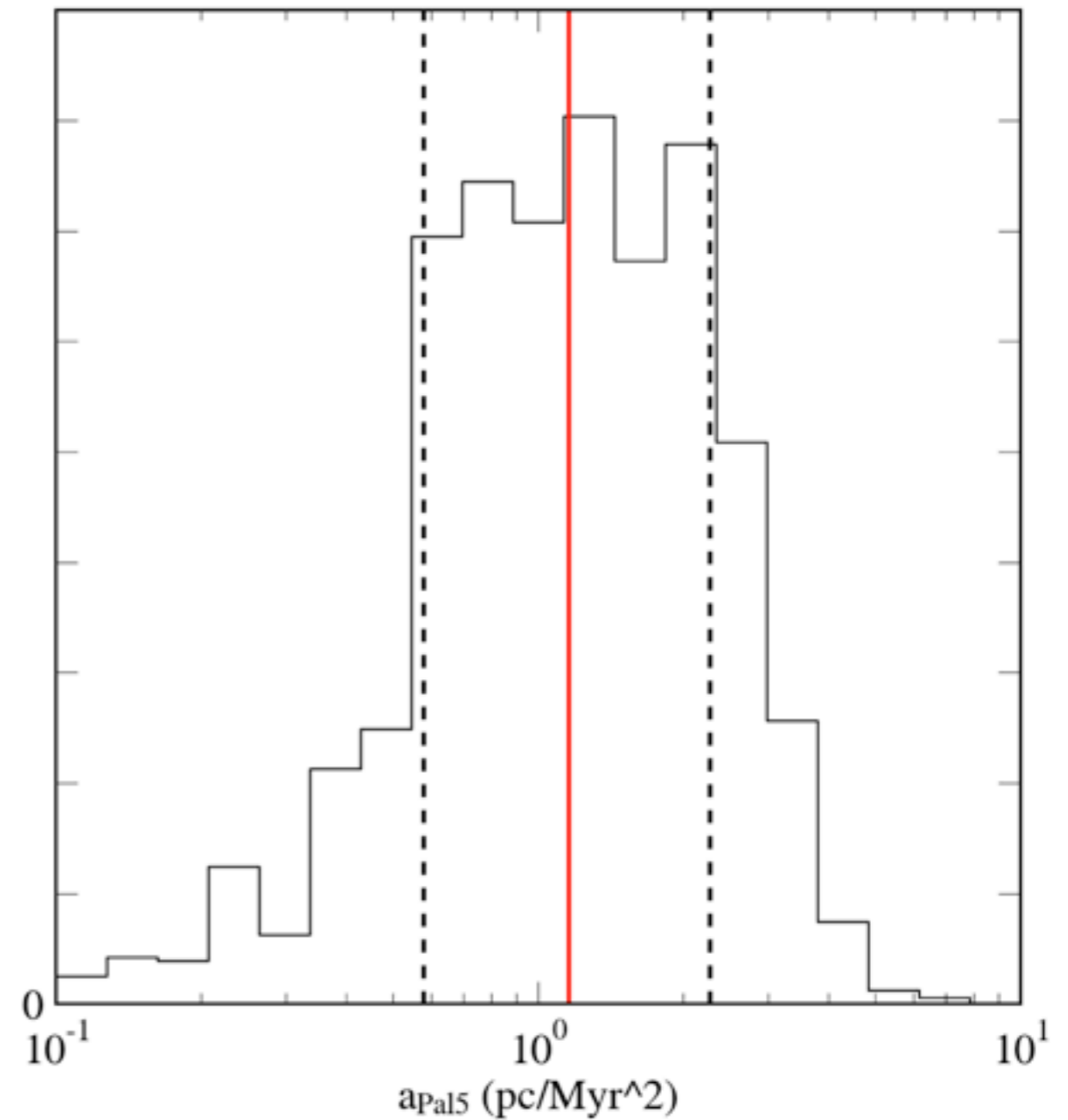
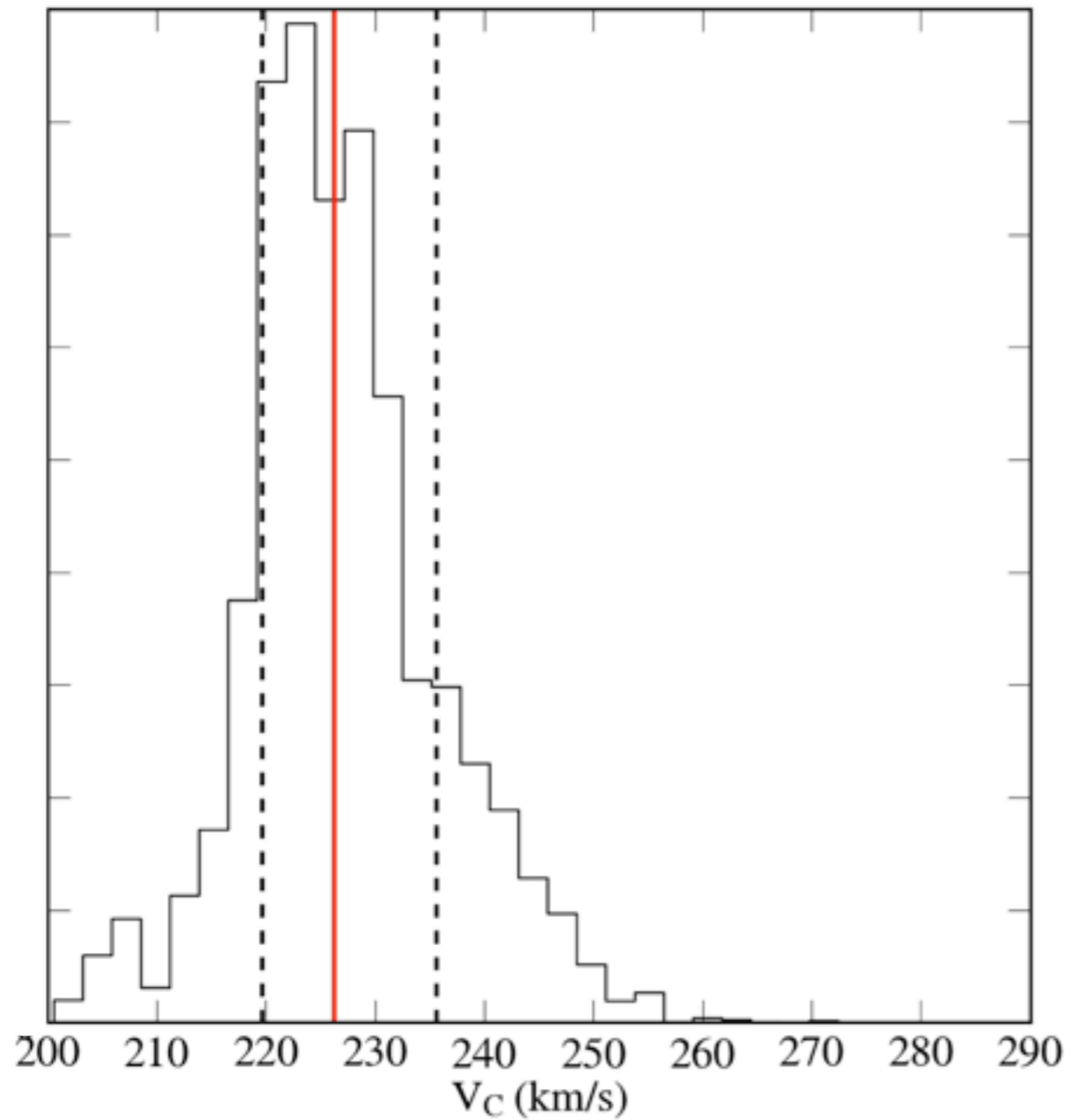
# Modeling of Palomar 5 stream substructure constrains NFW halo parameters

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Gives consistent values for circular velocity at solar circle and very low acceleration at Pal 5

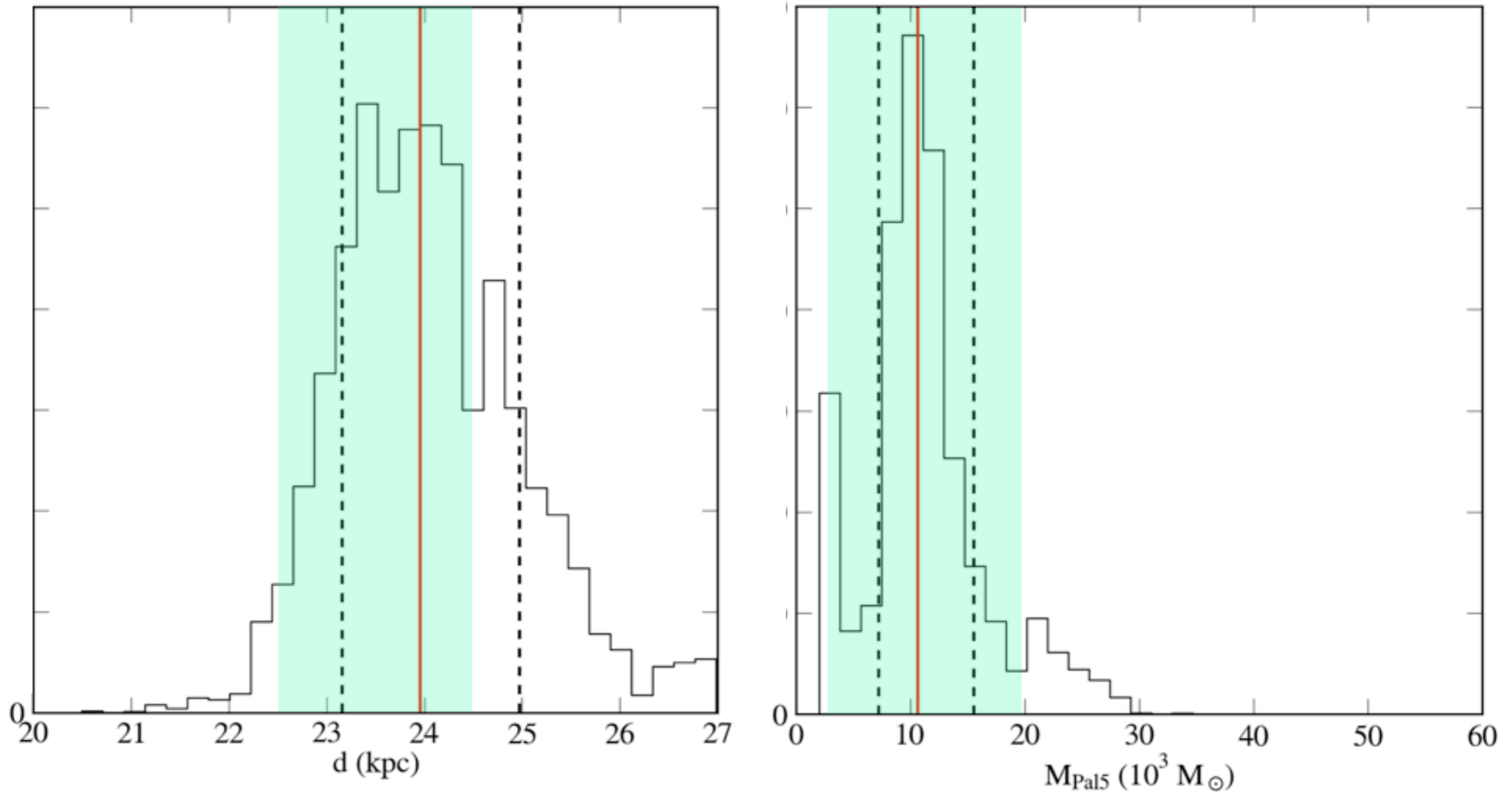
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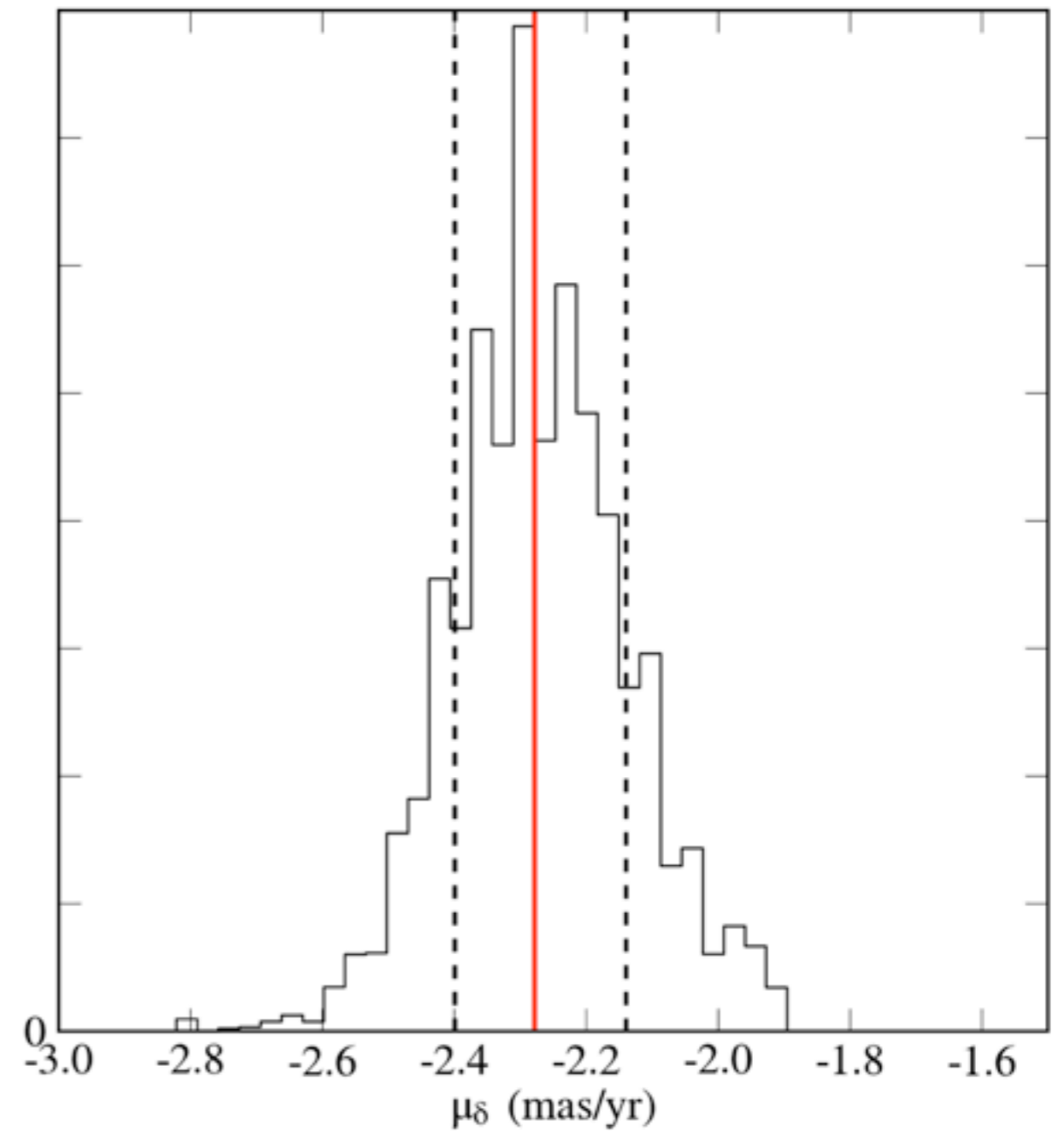
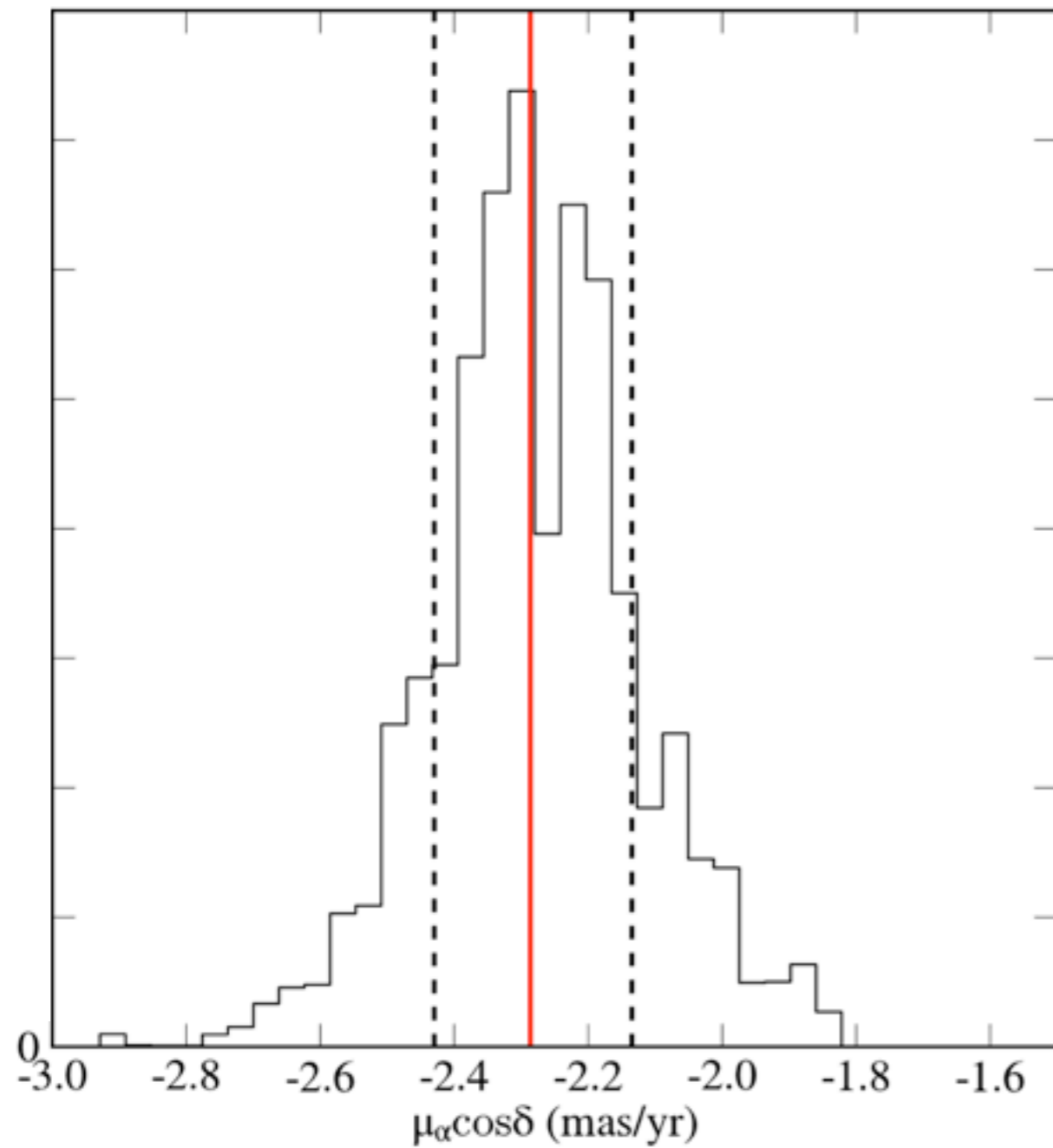
We get information on additional cluster parameters independent of other methods

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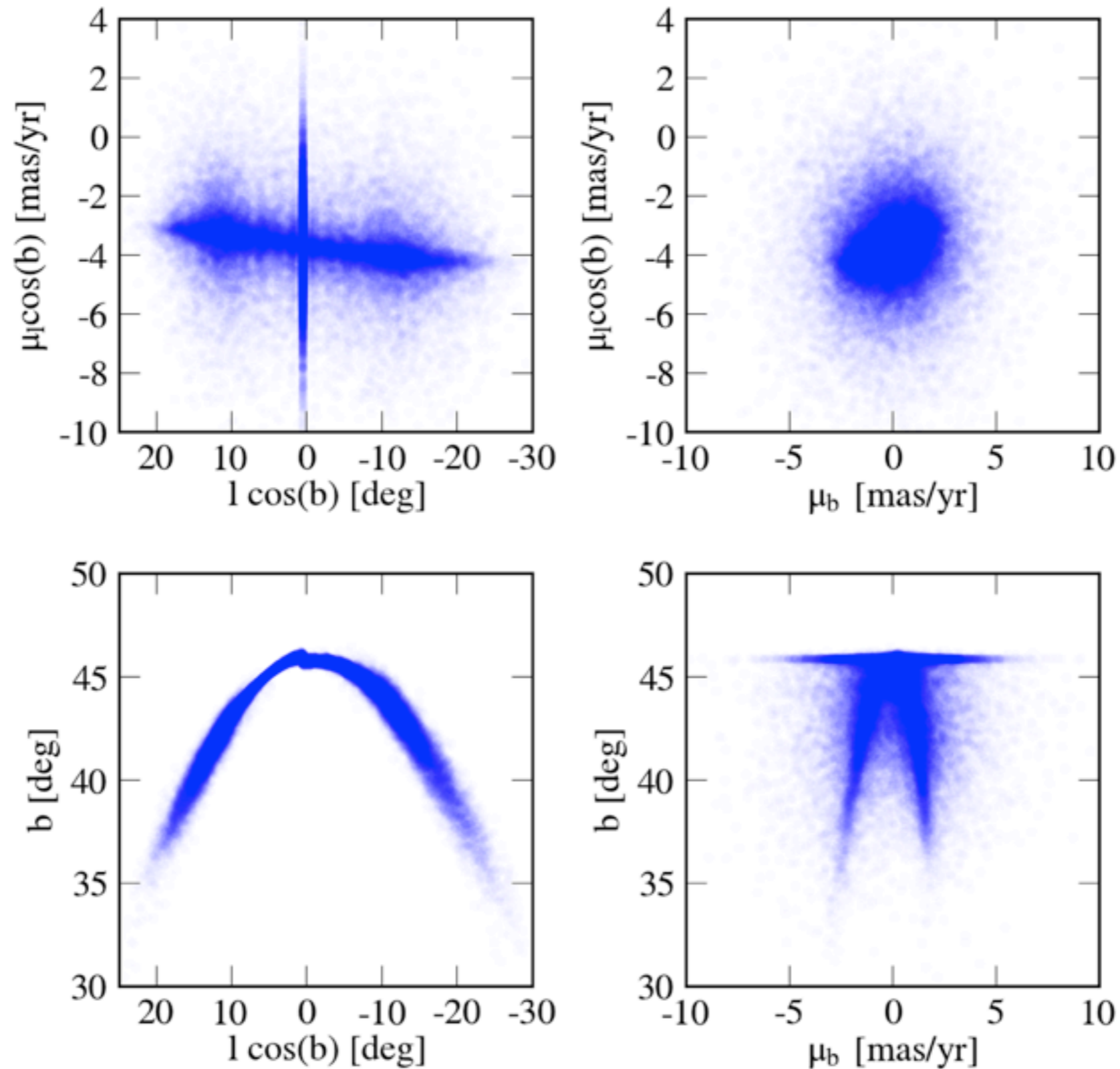


We get information on additional cluster parameters independent of other methods

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# Gaia's view of Palomar 5



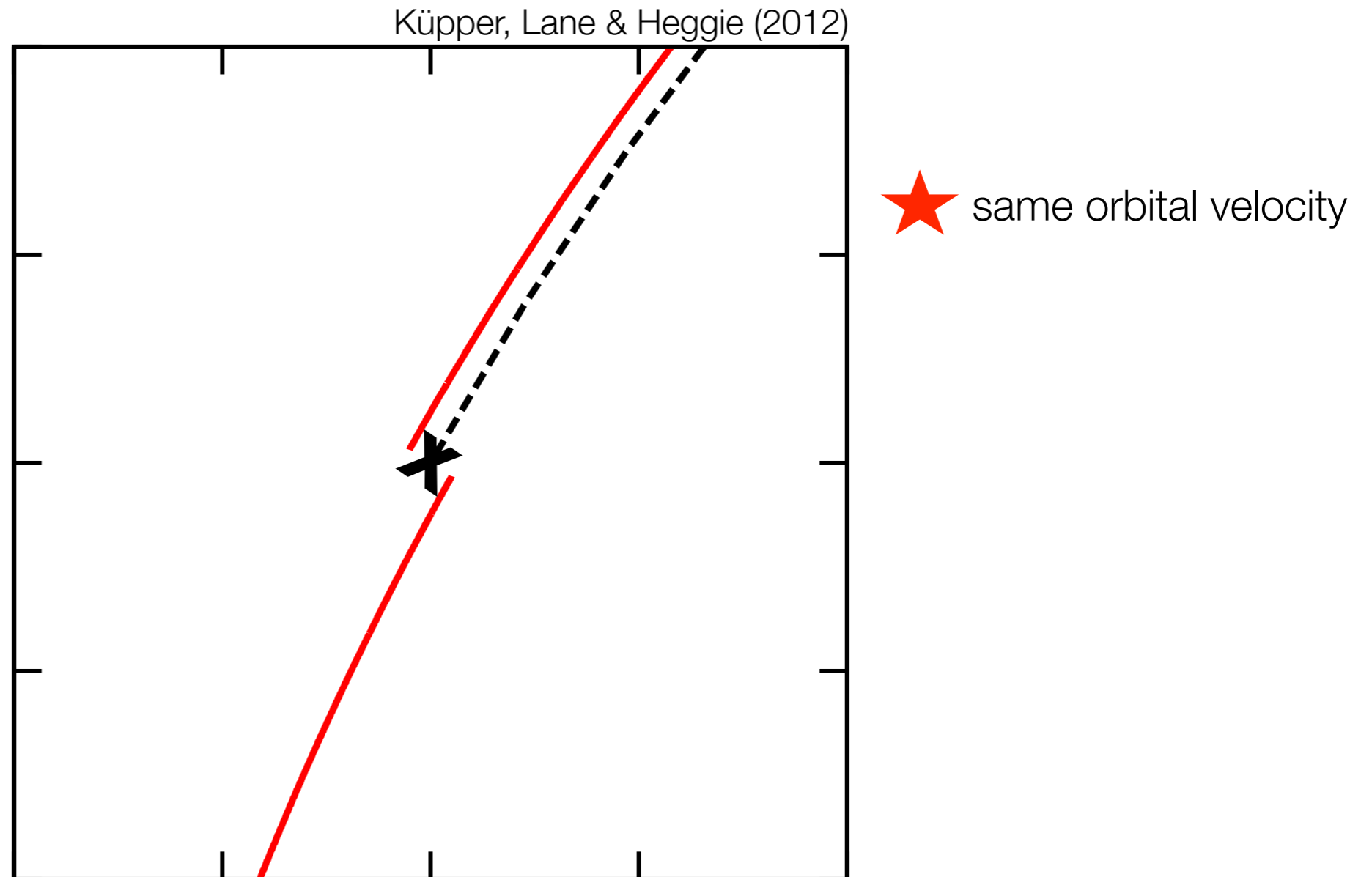
# Stream substructure can be used to constrain model parameters

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- ★ There is more to streams than just positions and velocities
- ★ Palomar 5 stream shows evidence for epicyclic substructure
- ★ Streakline models can reproduce substructure pattern
- ★ Bayesian modeling constrains Palomar 5's orbit & Galaxy potential
- ★ Method enables independent estimates of Palomar 5's mass & distance

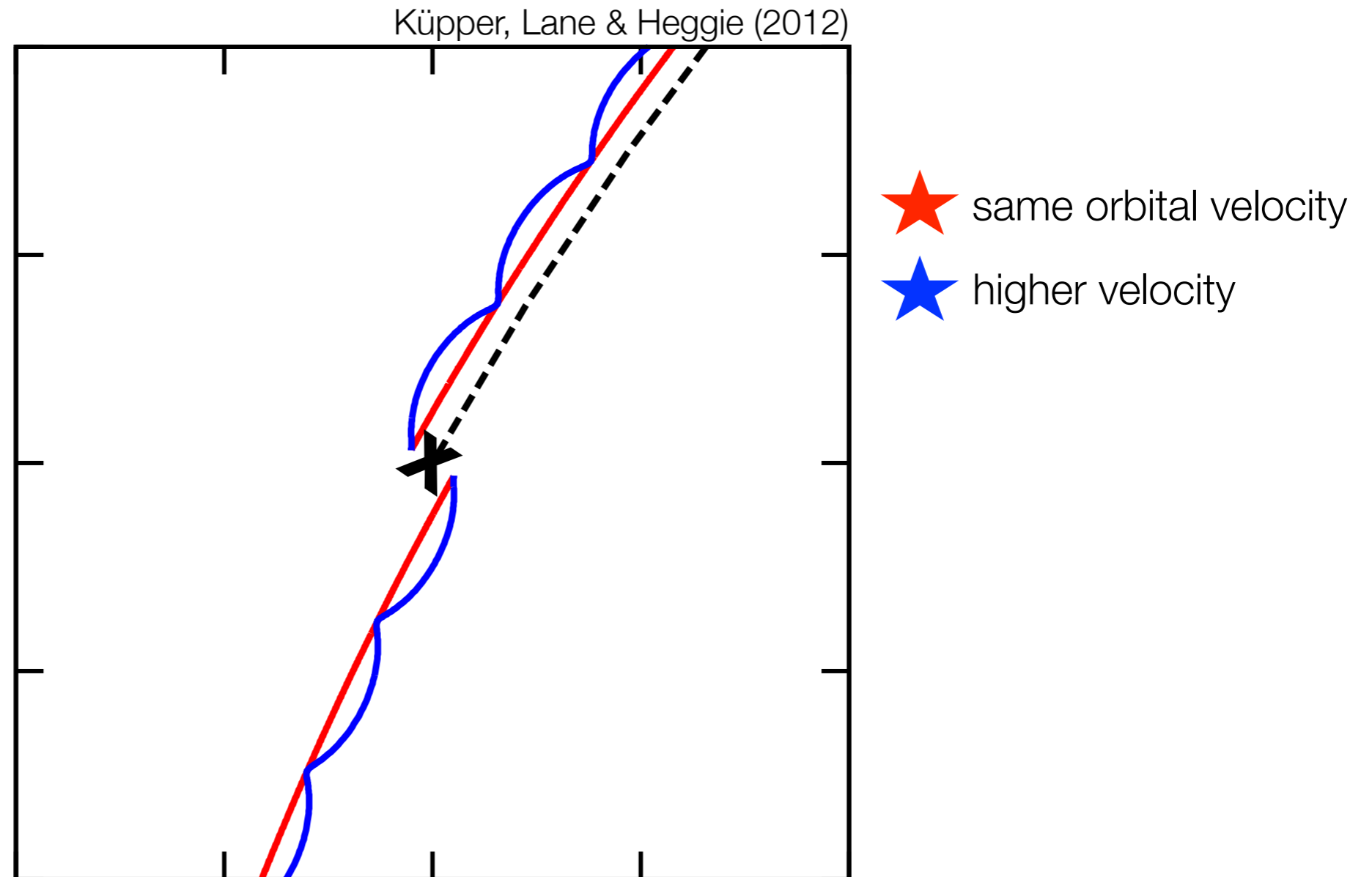
# Appearance of streaklines depends crucially on the choice of radial offset and velocity offset

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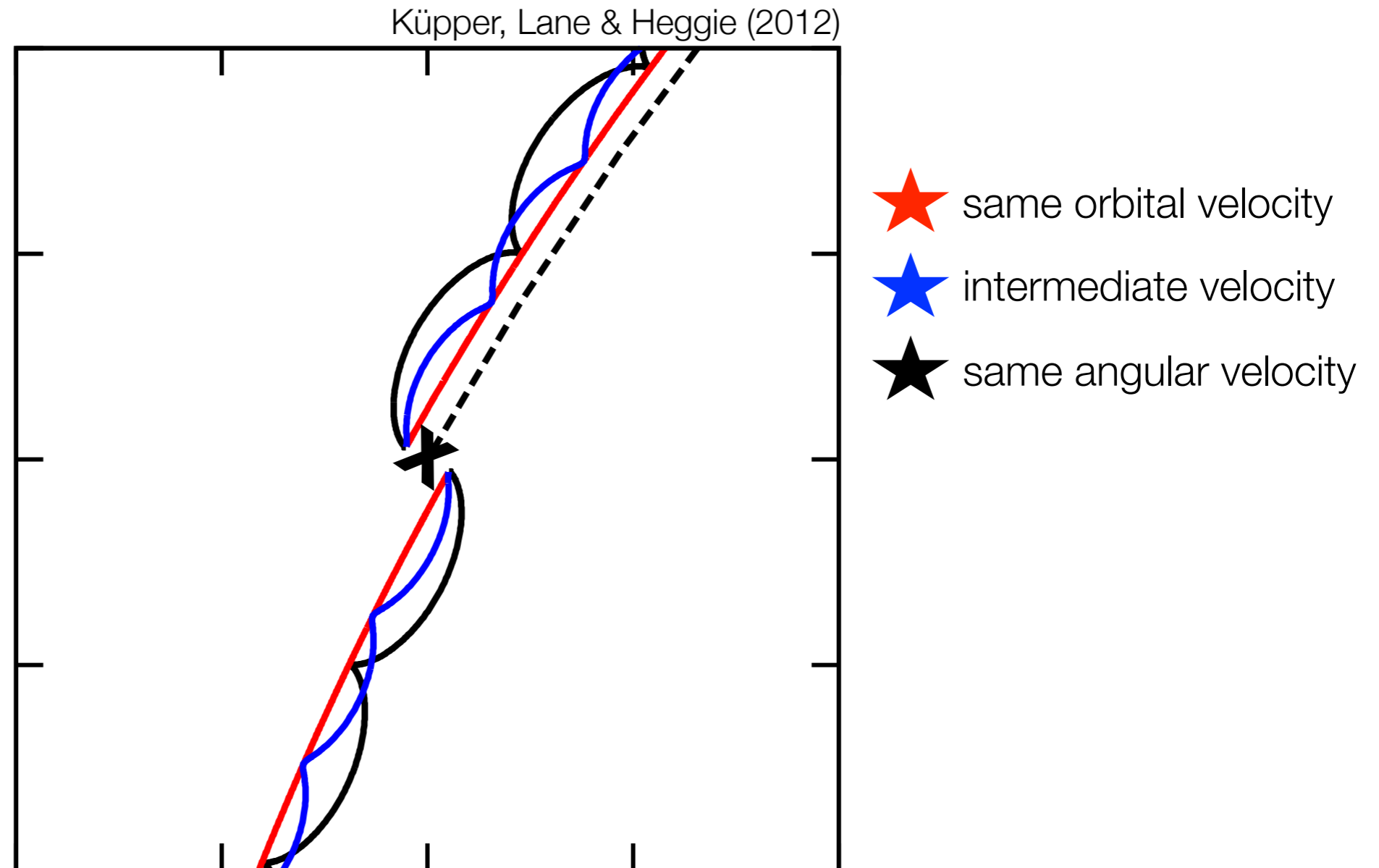
# Appearance of streaklines depends crucially on the choice of radial offset and velocity offset

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

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

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