Tidal Stripping in Action: The Field of Streams

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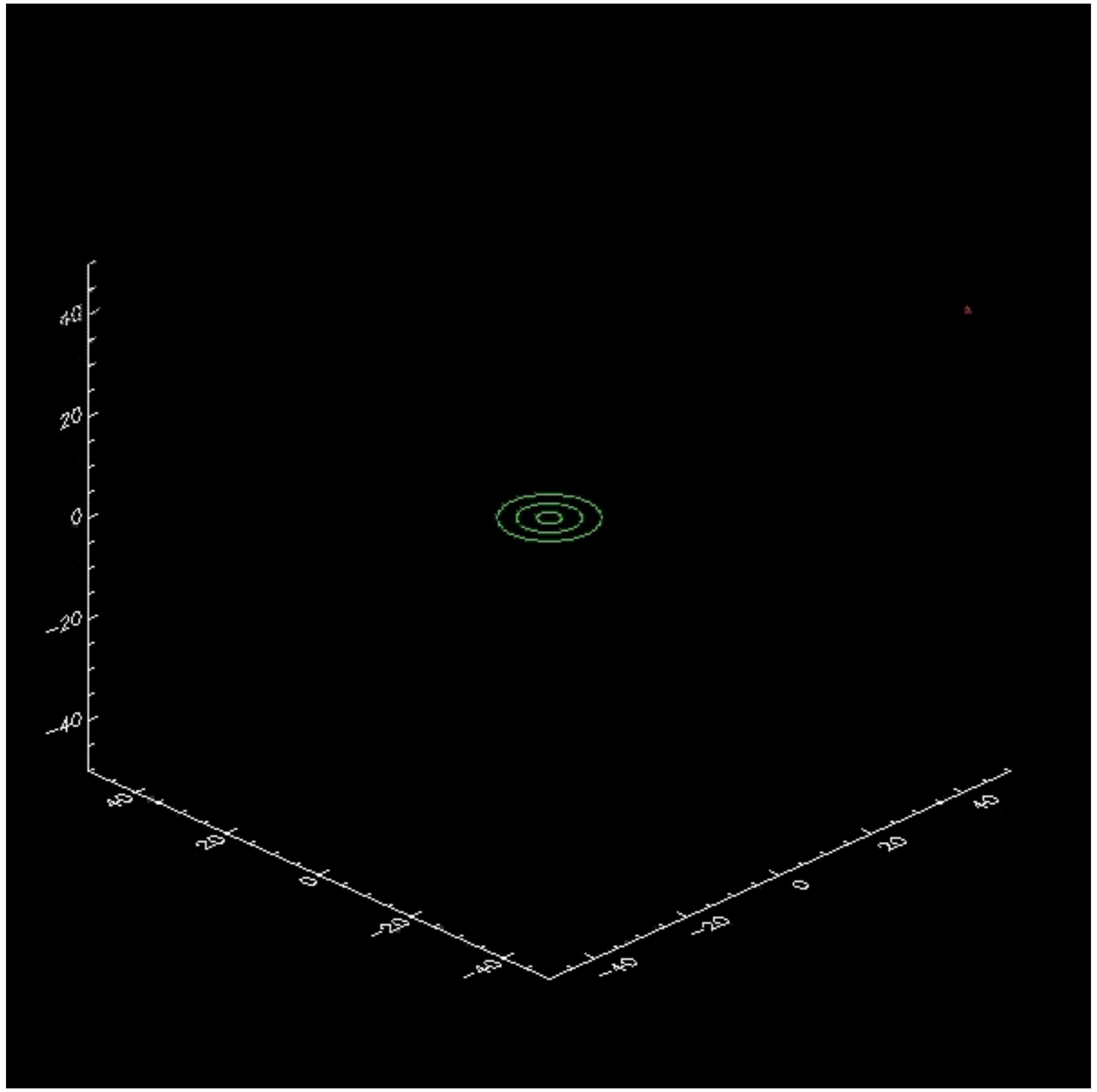
galaxy like our own

is surrounded by
a tangled mess

made of shreds
of smaller objects

Making the mess. On galaxy scales.

Milky Way size Dark Matter halo



computer simulation by Bullock & Johnston 2005

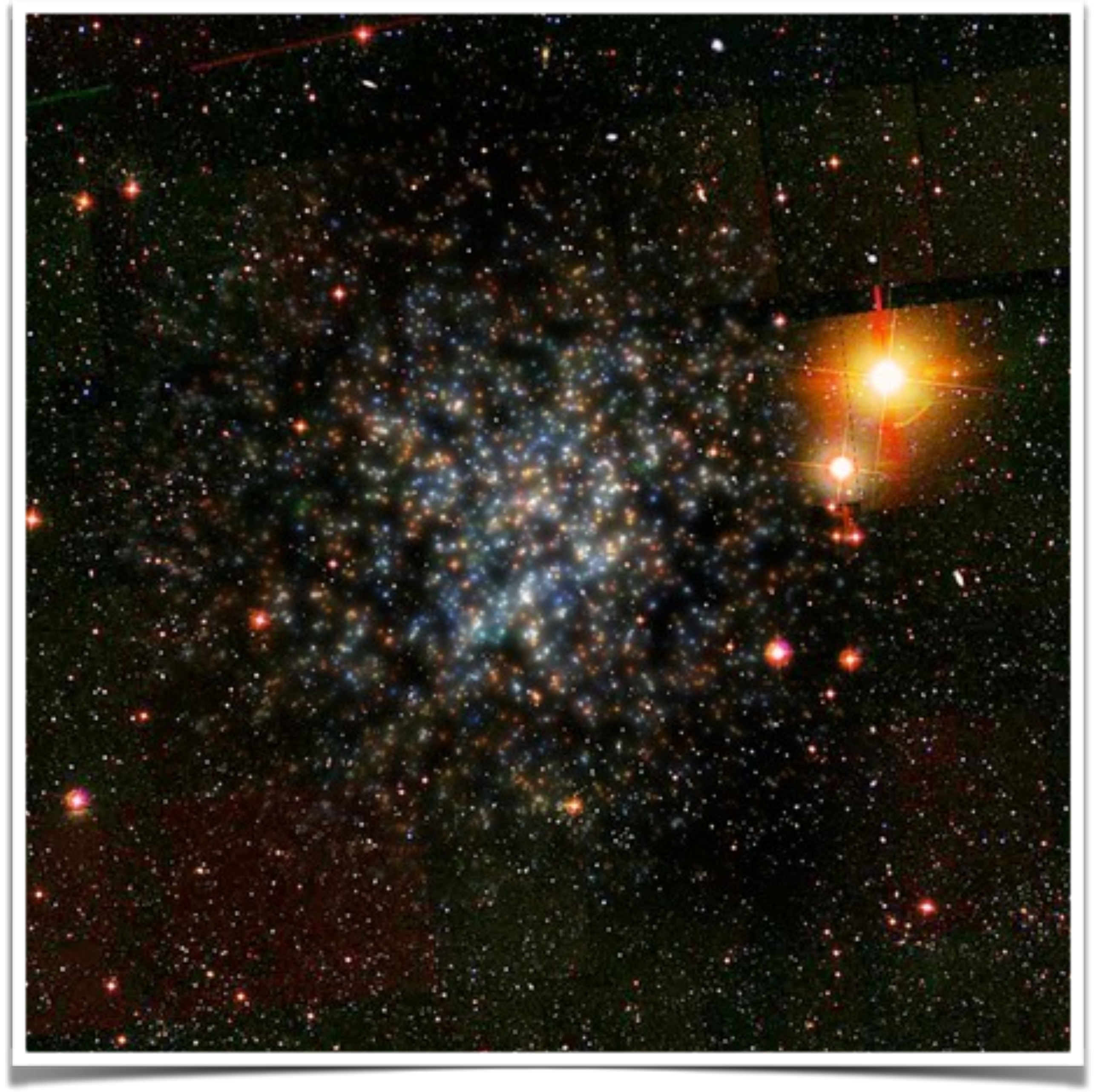
Dwarf galaxies

Invisible galaxies!

Leo I

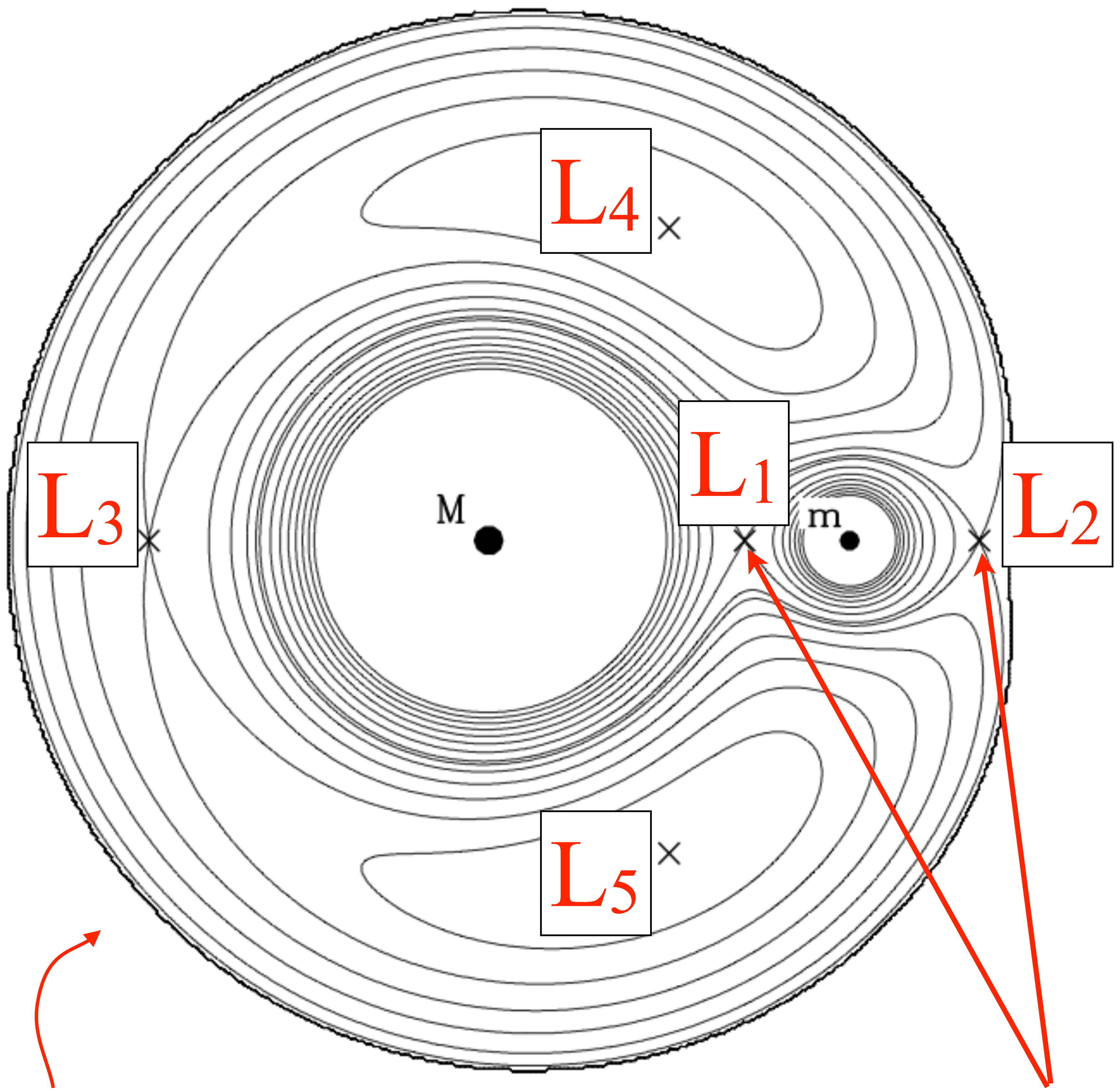
8,000 times fainter
then the Milky Way

Bootes I



2,000,000 times fainter then the
Milky Way

How to unravel a ball of stars



contours of equal effective potential

orbit equation for a test particle in the rotating 2 body system (circular orbit only)

$$\ddot{\mathbf{x}} = -\nabla\Phi - 2\mathbf{\Omega}_{\rm b} \times \dot{\mathbf{x}} - \mathbf{\Omega}_{\rm b} \times (\mathbf{\Omega}_{\rm b} \times \mathbf{x})$$
$$= -\nabla\Phi - 2\mathbf{\Omega}_{\rm b} \times \dot{\mathbf{x}} + |\mathbf{\Omega}_{\rm b}|^2\mathbf{x} - \mathbf{\Omega}_{\rm b}(\mathbf{\Omega}_{\rm b} \cdot \mathbf{x}).$$

Coriolis force

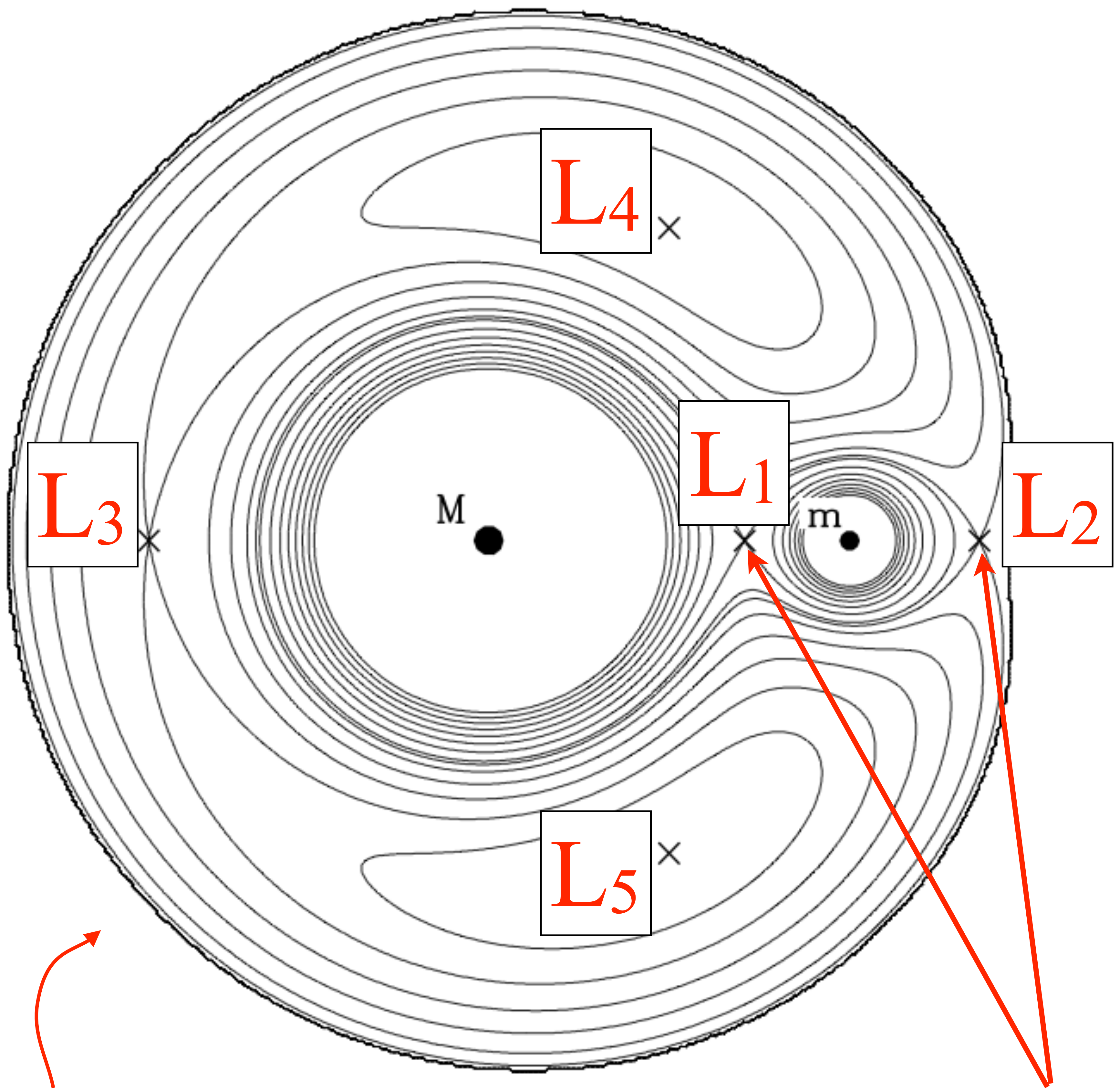
$$\ddot{\mathbf{x}} = -\nabla\Phi_{\rm eff} - 2\mathbf{\Omega}_{\rm b} \times \dot{\mathbf{x}}.$$

effective potential = gravitational attraction + centrifugal repulsion

$$\Phi_{\rm eff}(\mathbf{x}) \equiv \Phi(\mathbf{x}) - \tfrac{1}{2}|\mathbf{\Omega}_{\rm b} \times \mathbf{x}|^2$$
$$= \Phi(\mathbf{x}) - \tfrac{1}{2}\left[|\mathbf{\Omega}_{\rm b}|^2|\mathbf{x}|^2 - (\mathbf{\Omega}_{\rm b} \cdot \mathbf{x})^2\right].$$

stars can climb out through L_1 and L_2

How to unravel a ball of stars



contours of equal effective potential

Condition for a stationary particle around m:

$$x = \pm r_J, \quad \text{where} \quad r_J \equiv \left(\frac{Gm}{4\Omega_0 A_0} \right)^{1/3}$$

Jacobi or "tidal" radius

For a point mass host:

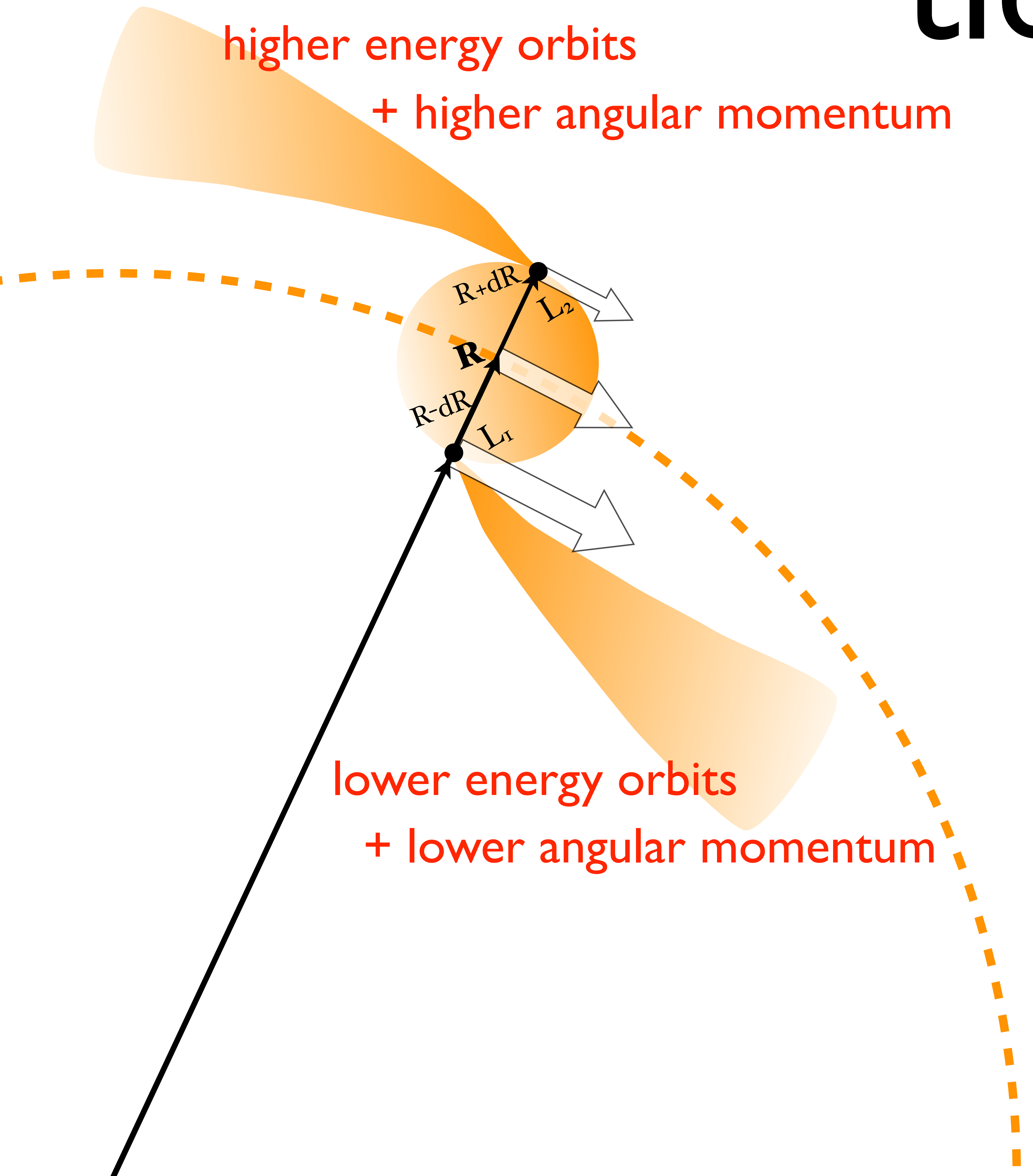
$$r_J = \left(\frac{m}{3M} \right)^{1/3} R_0.$$

stars can climb out through L_1 and L_2

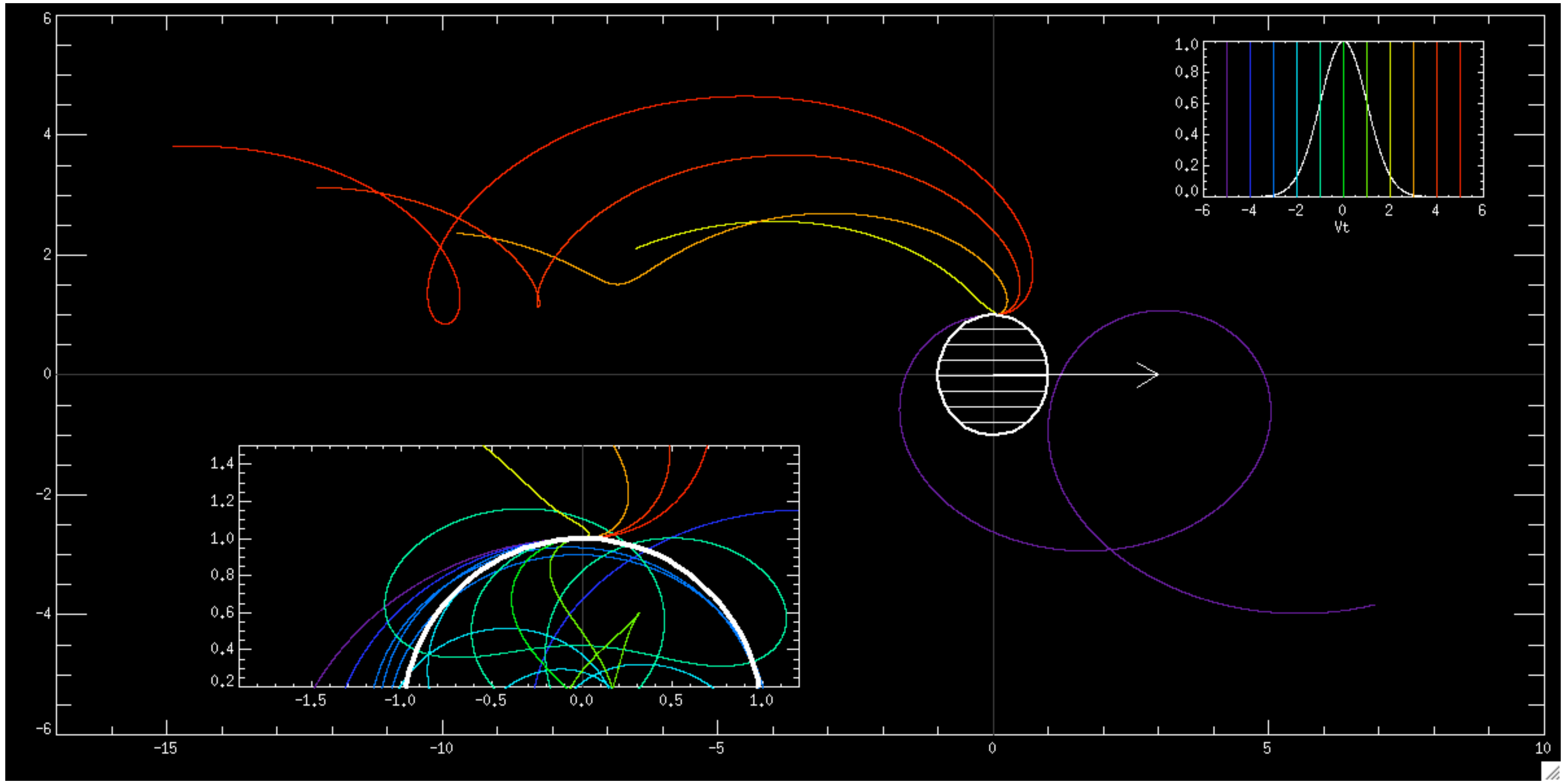
But why would they?

- Two- and three-body interactions
- Time varying potential
- Disk/bulge shocks

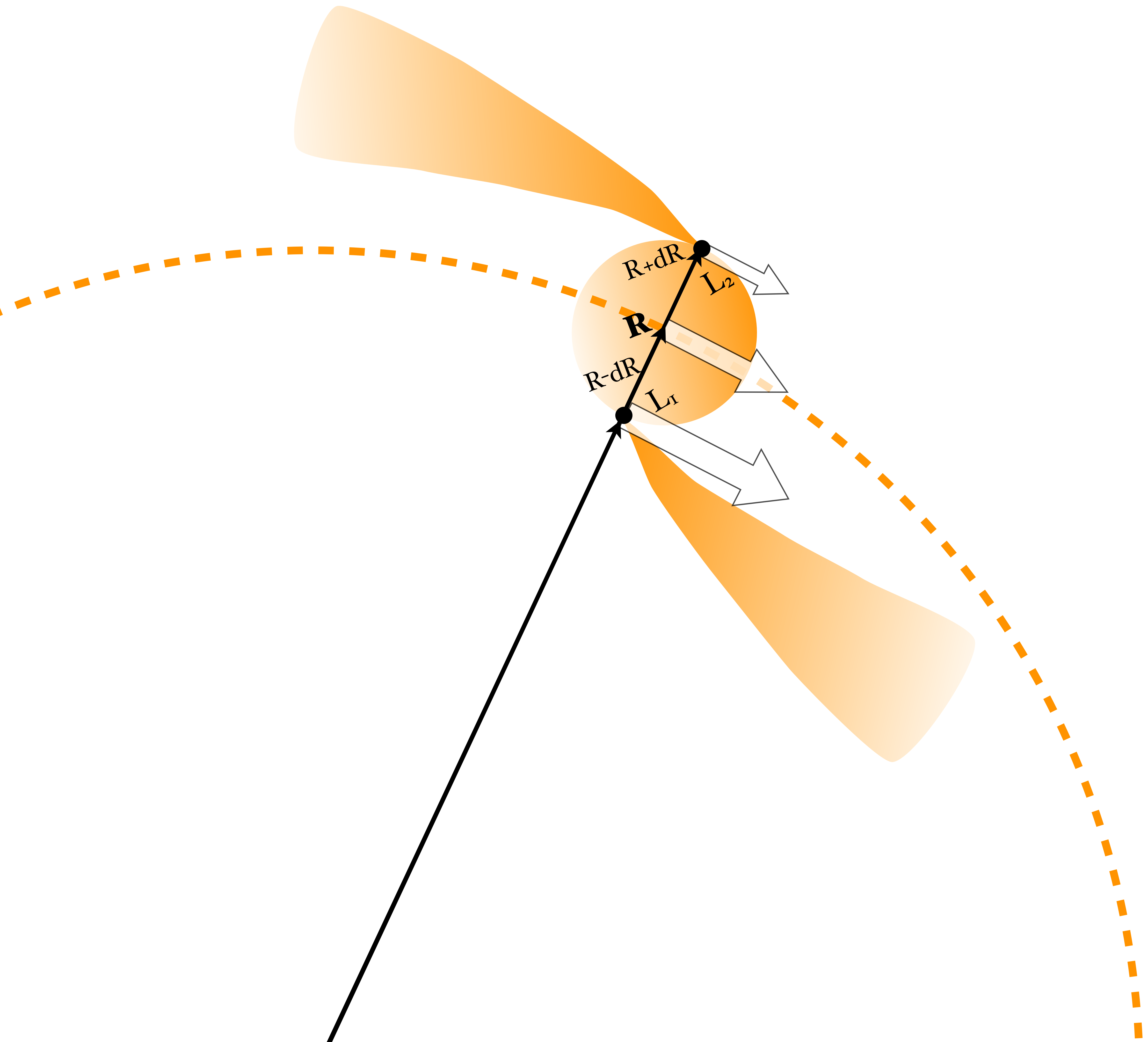
Stream formation during tidal stripping

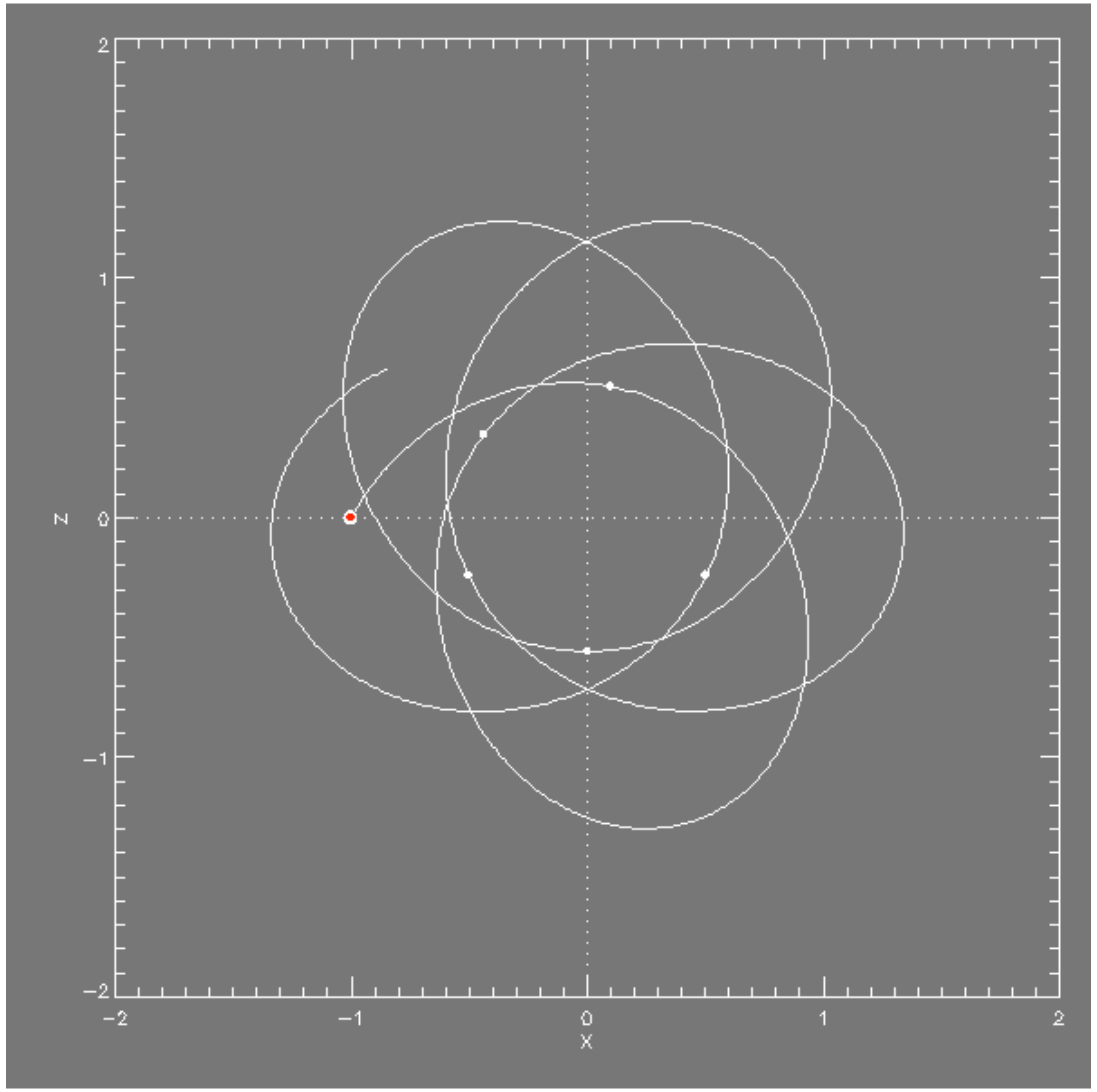


Trailing tail formation through Lagrange 2

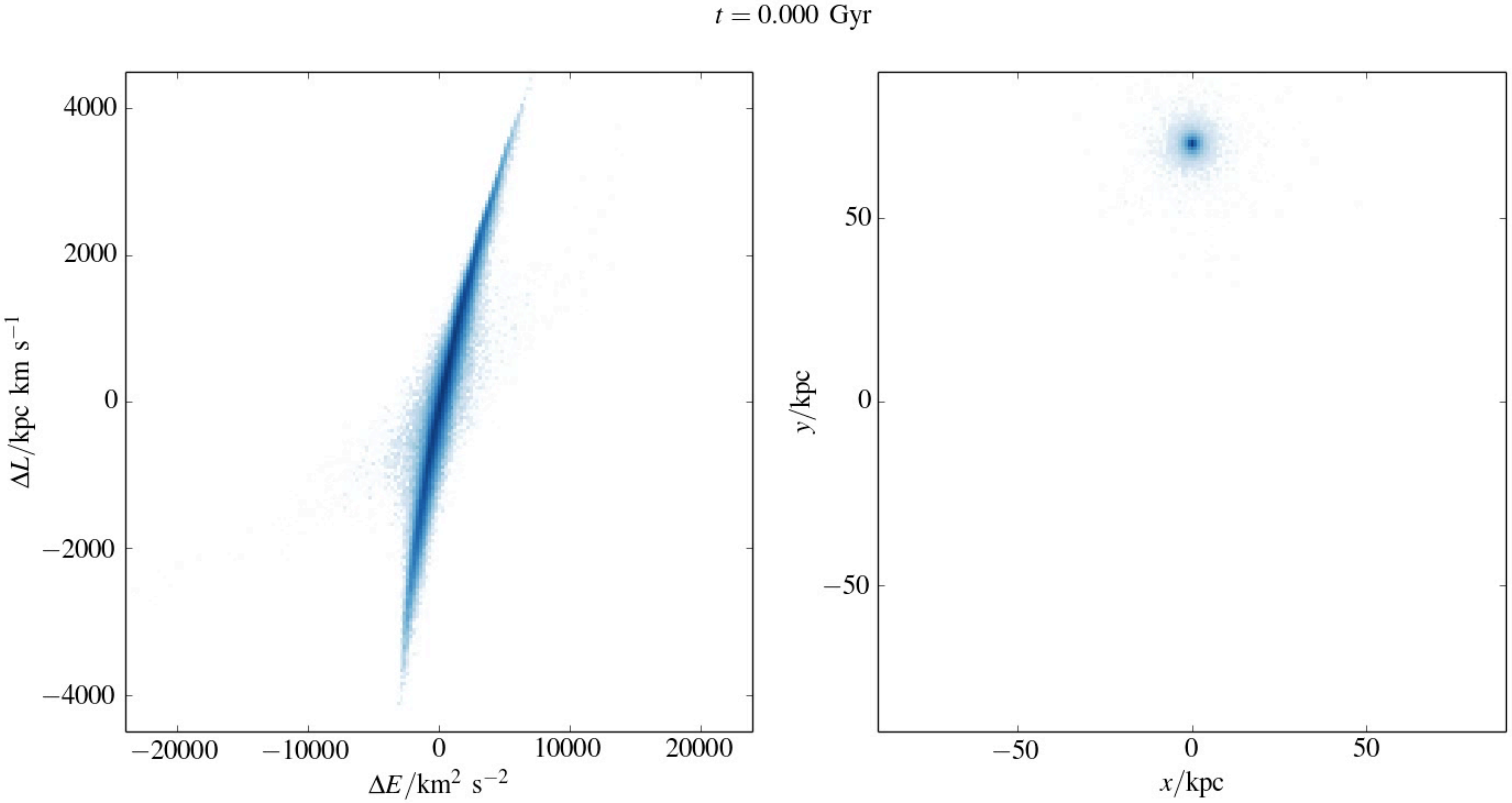


Tidal stream formation

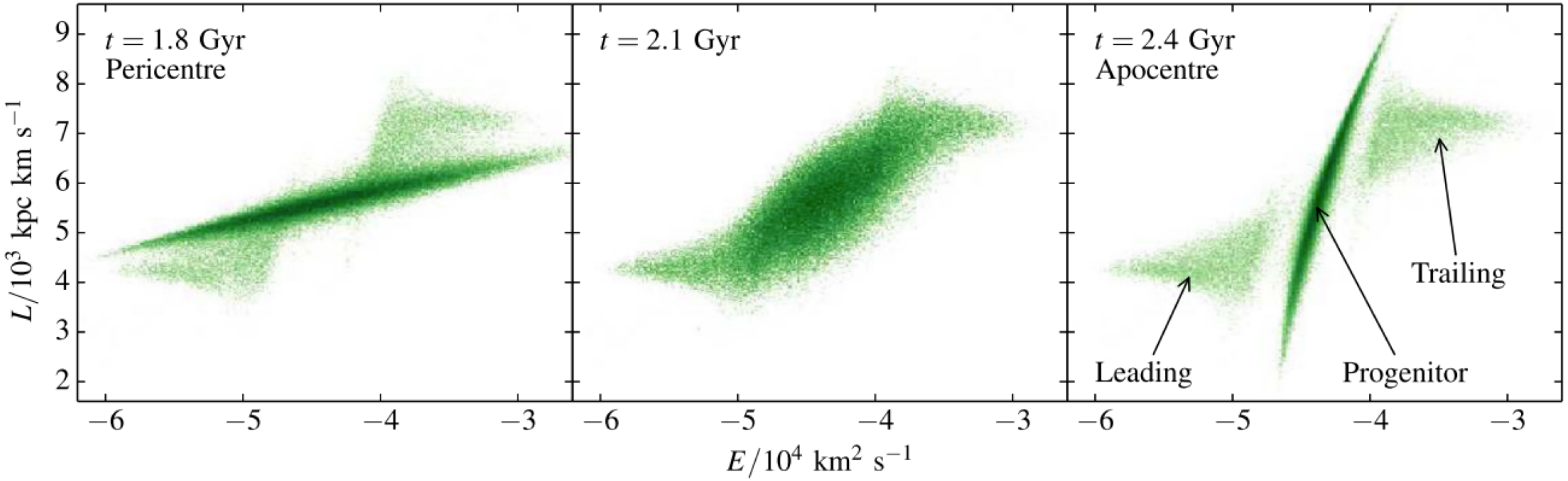




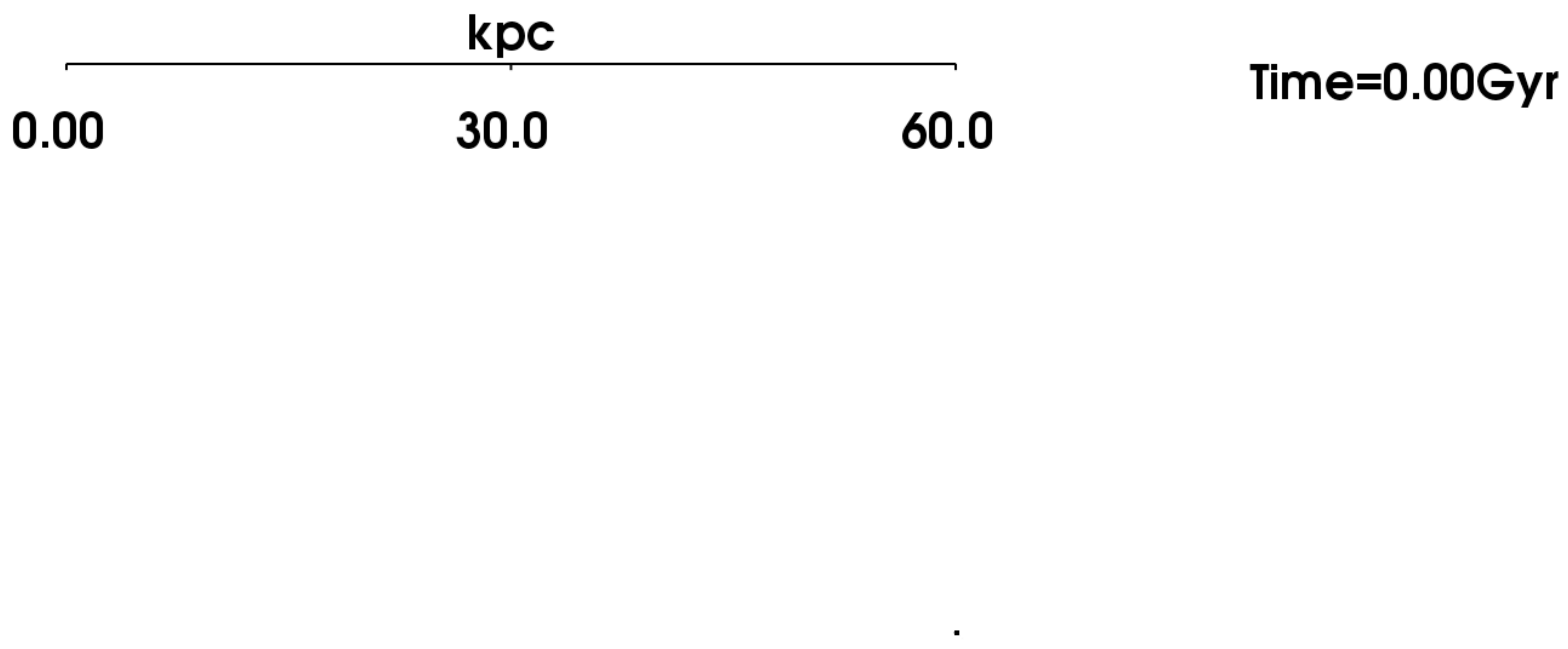
Energy and angular momentum



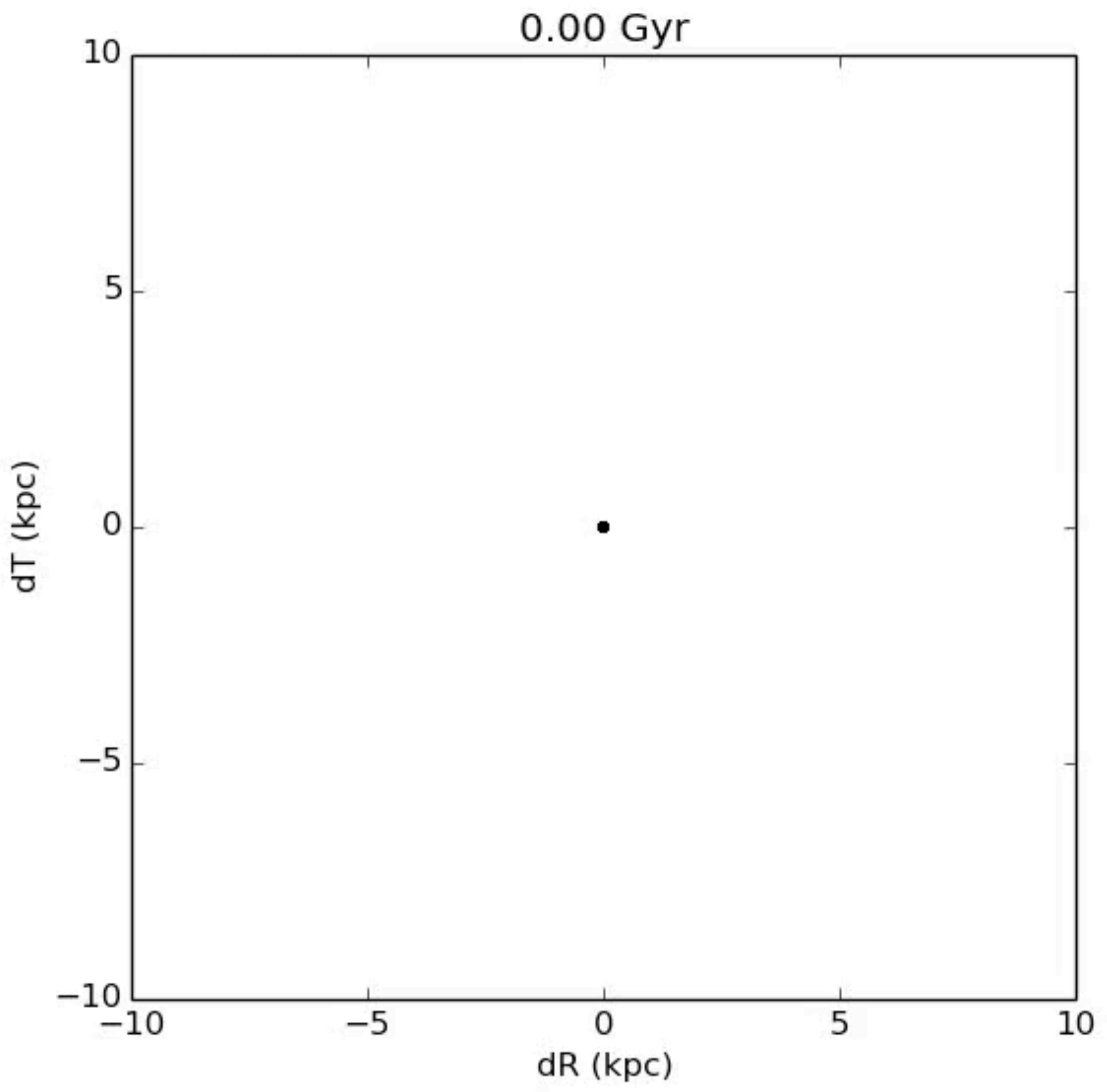
Tidal debris in E,L space



A simulation of tidal disruption

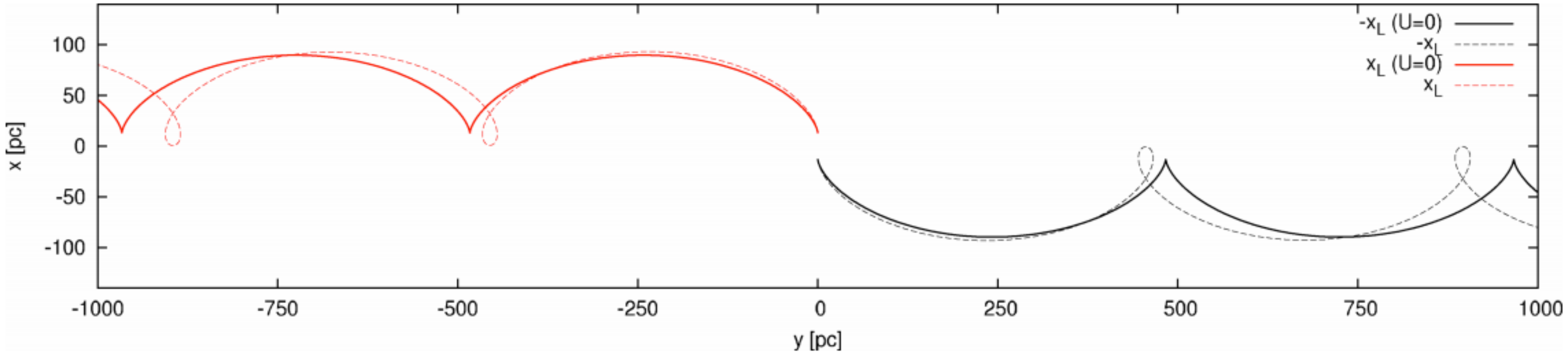


Disruption from the cluster's point of view

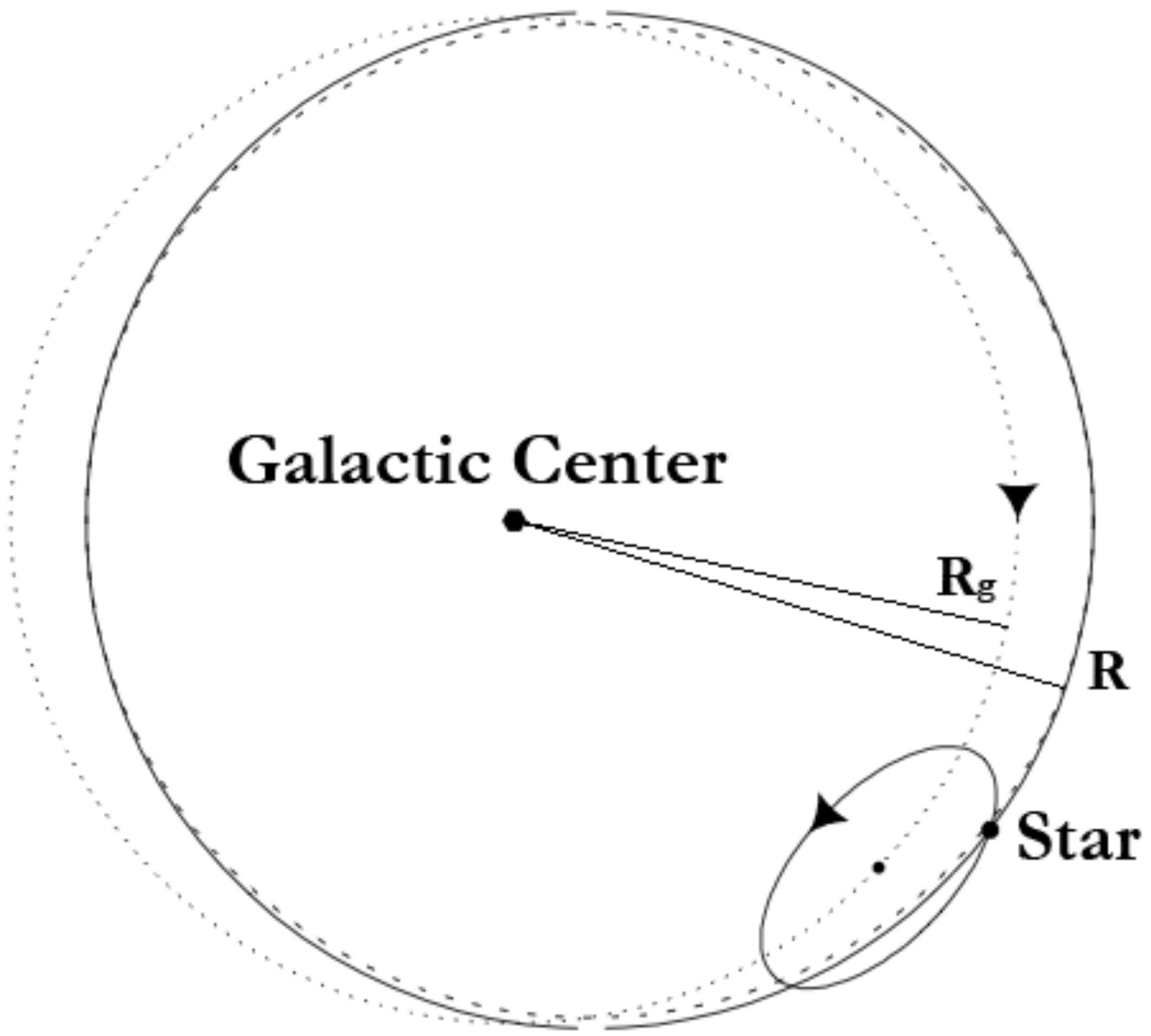


Why are the tidal tails so wrinkled?

Orbits of stars released from Lagrange points relative to progenitor



Epicycles!



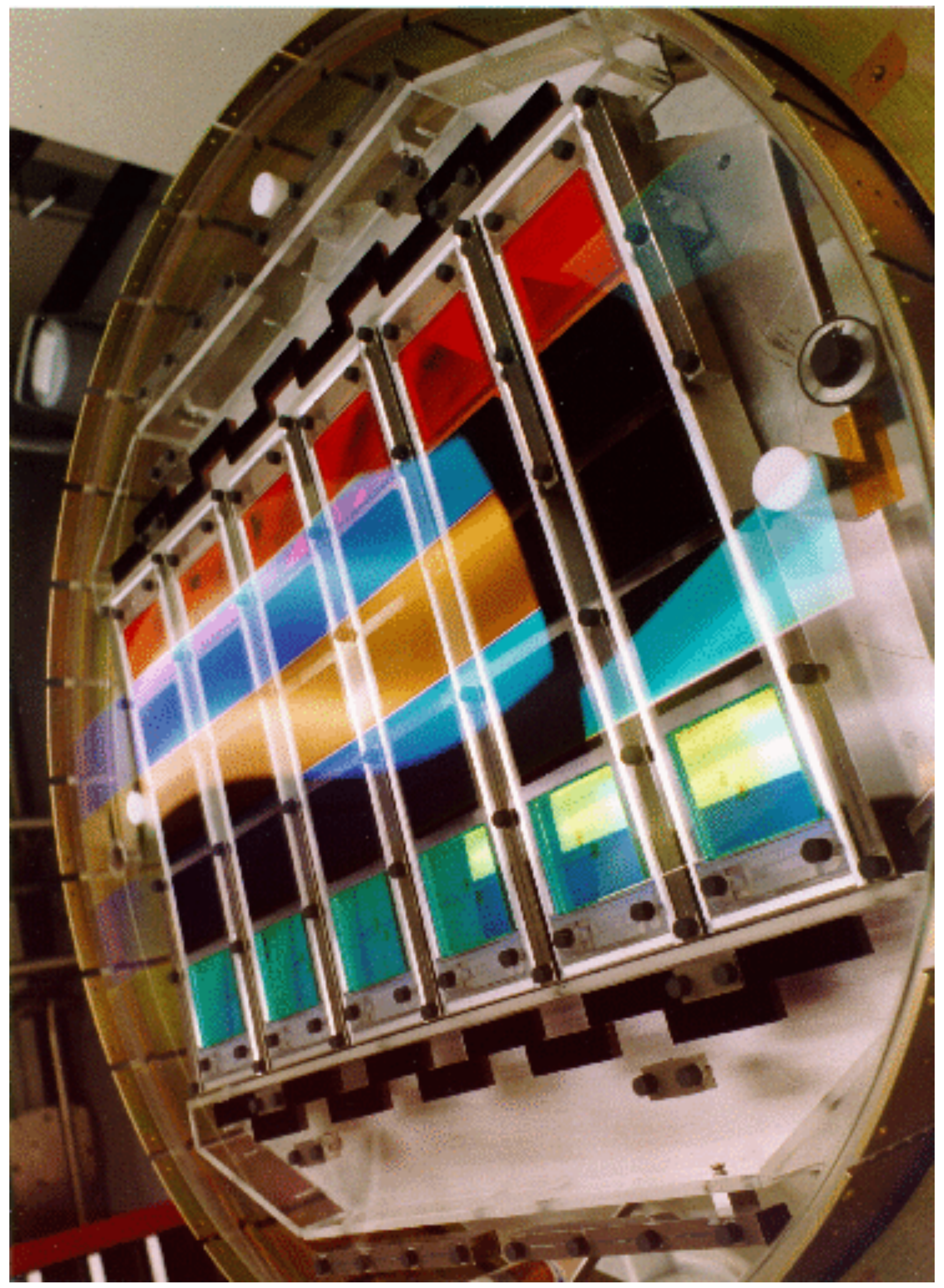
Conclusions

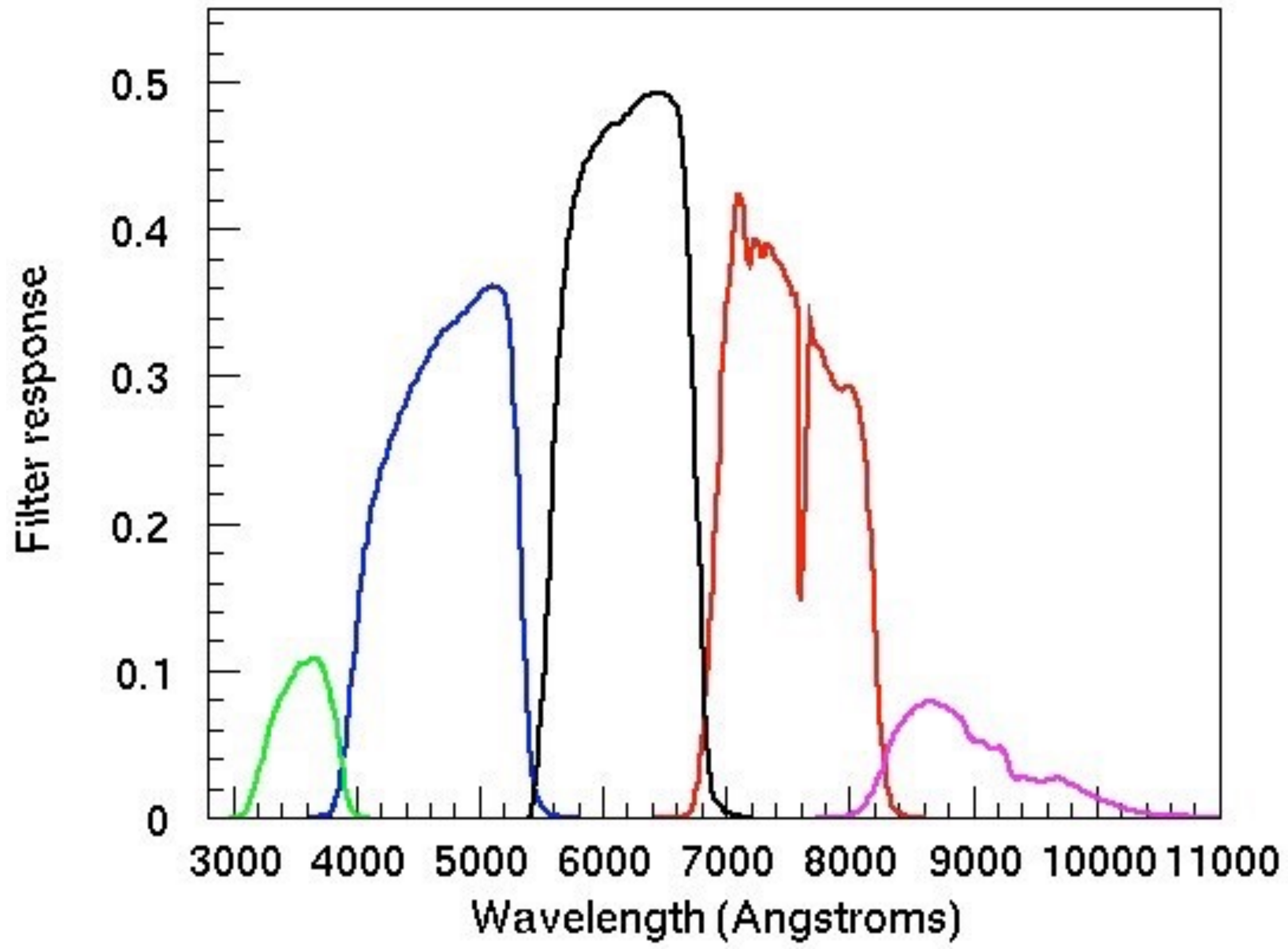
1. Stellar streams look like bent, wrinkled versions of orbits!
2. Around the disk of our galaxy, there should be a diffuse halo built from the debris of destroyed satellites

Do we see anything
of this sort
in the Galaxy?


Sloan Digital Sky Survey
2.5m telescope
Apache Point Observatory
New Mexico, USA

Measuring the sky the SDSS way





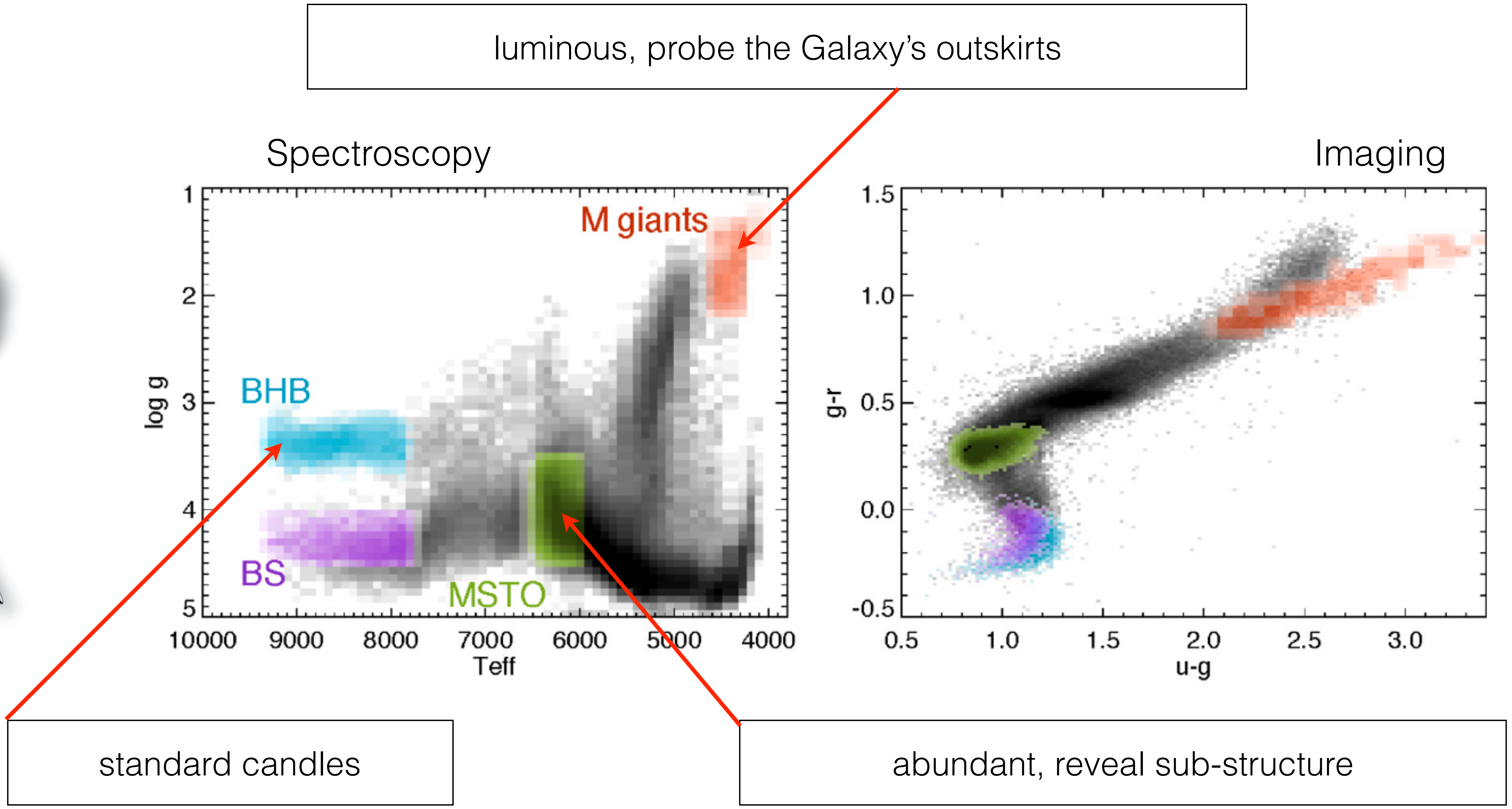
Drift scanning. Let the image slide through the focal plane as the Earth rotates. Read out the CCD in sync with the rate of rotation.

Doing science the SDSS way

- All images are reduced automatically
- All data is released to everyone who wants to use it
- Hundreds of millions of objects are measured on 1/4 of the sky

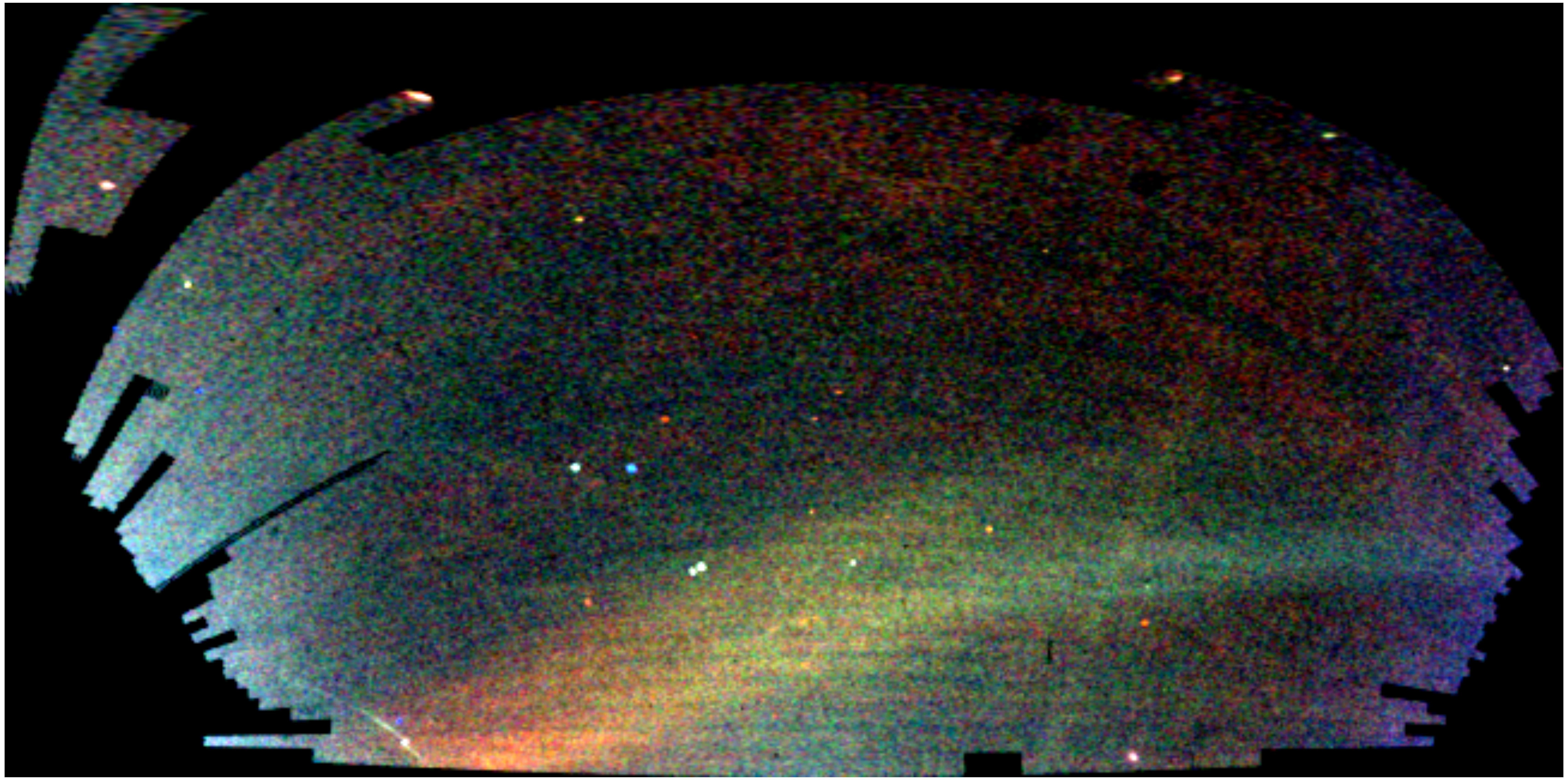
Data mining

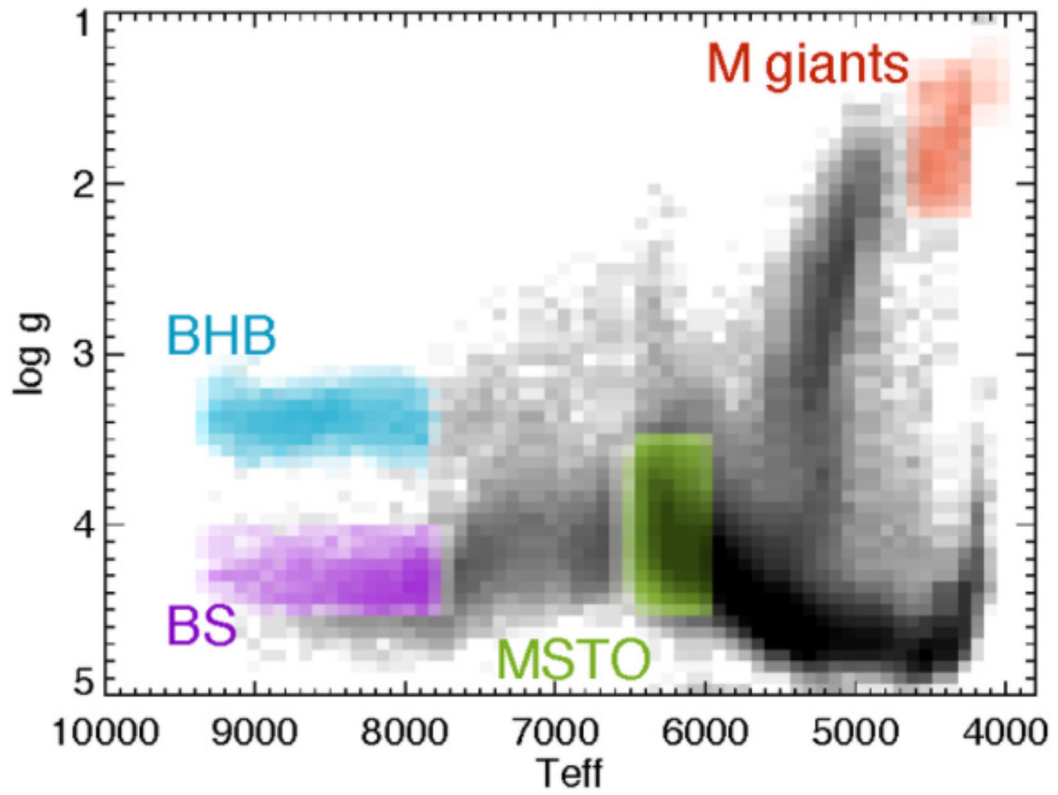
Swiss Army knife approach to stellar pops

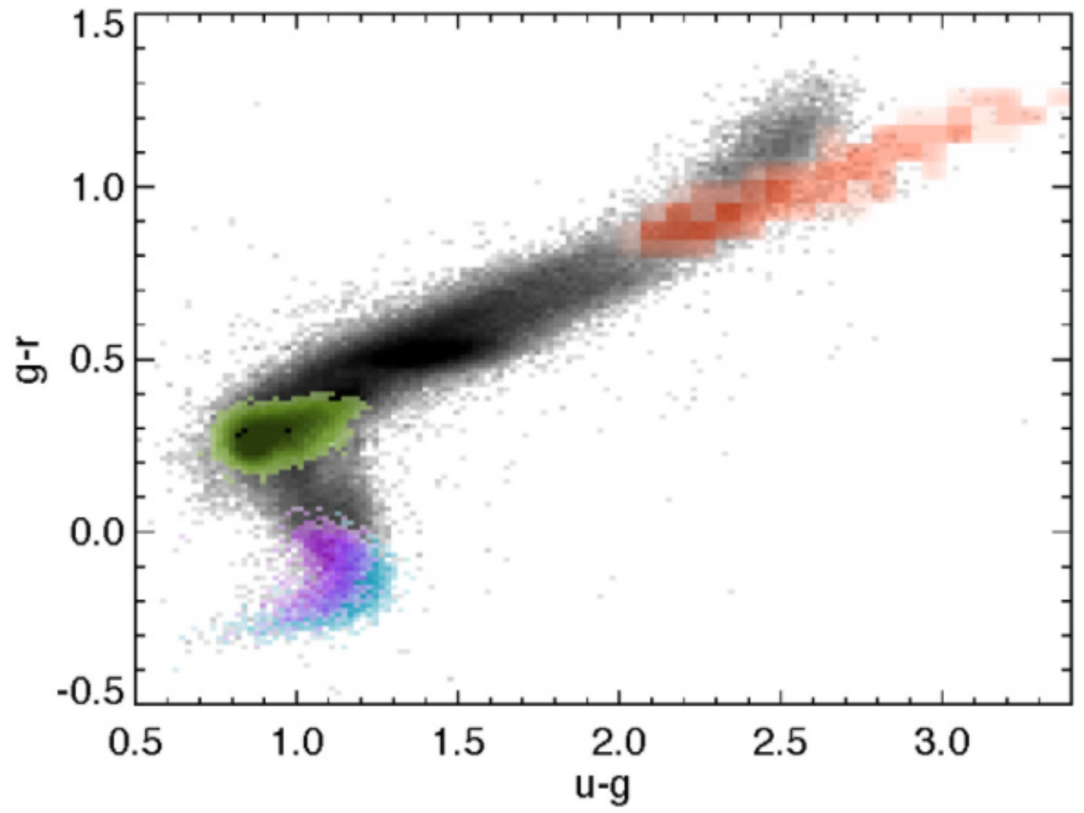


Do we see these in the Galaxy?

Milky Way stellar halo in the SDSS DR9 with MSTO stars “Field of Streams”

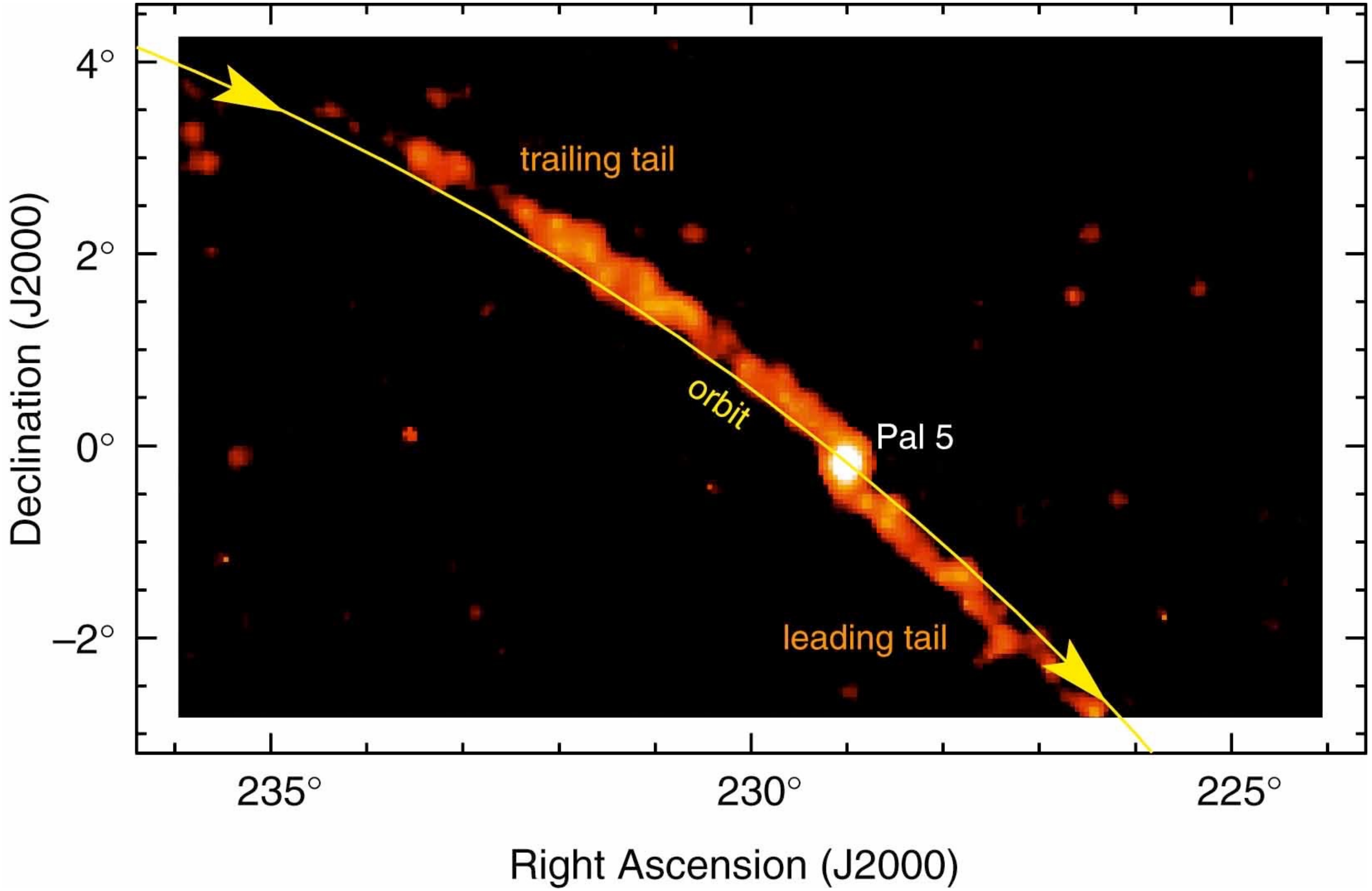




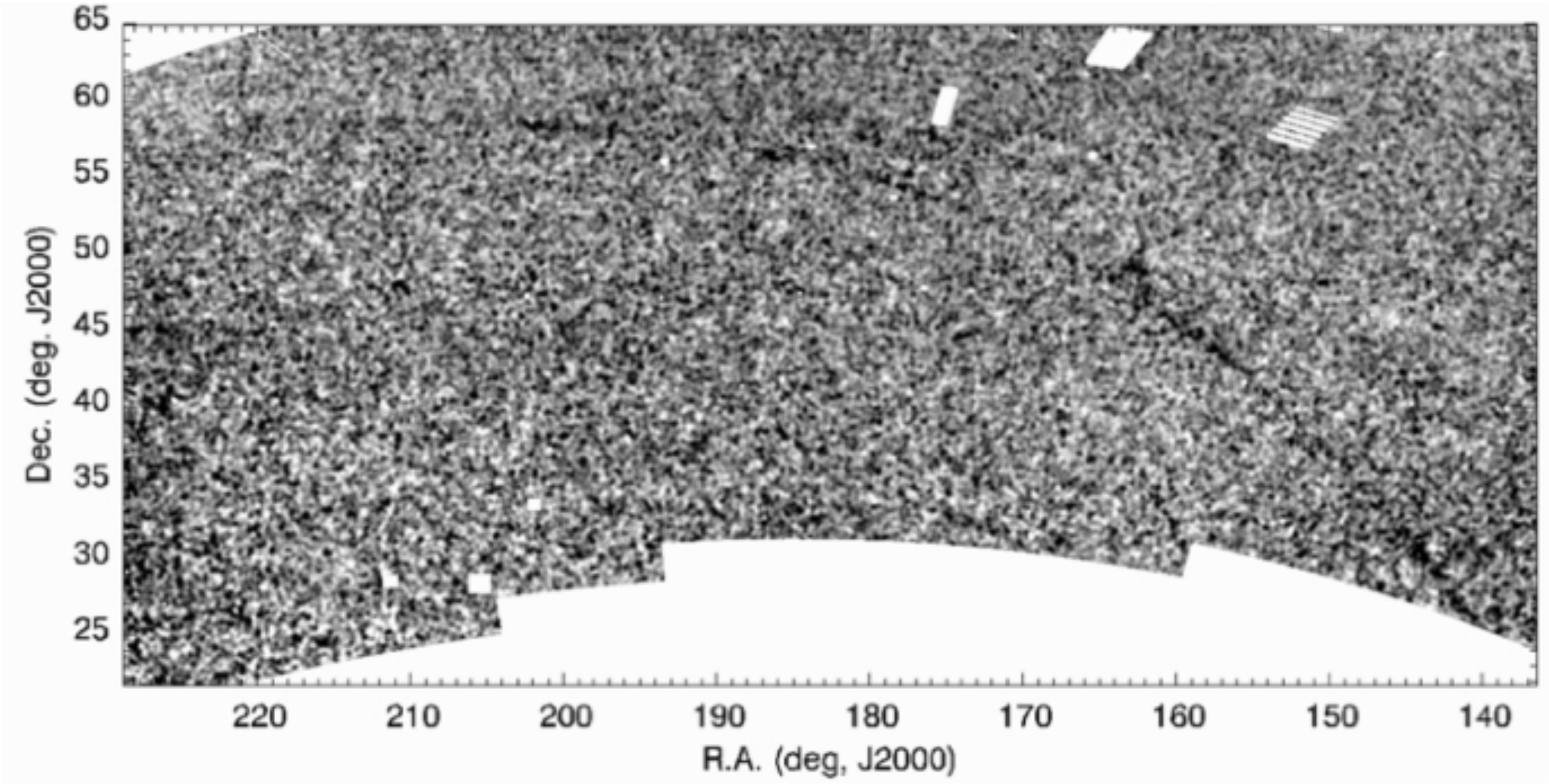


Examples of globular cluster tails

Palomar 5 globular cluster tails by Odenkirchen et al 2003

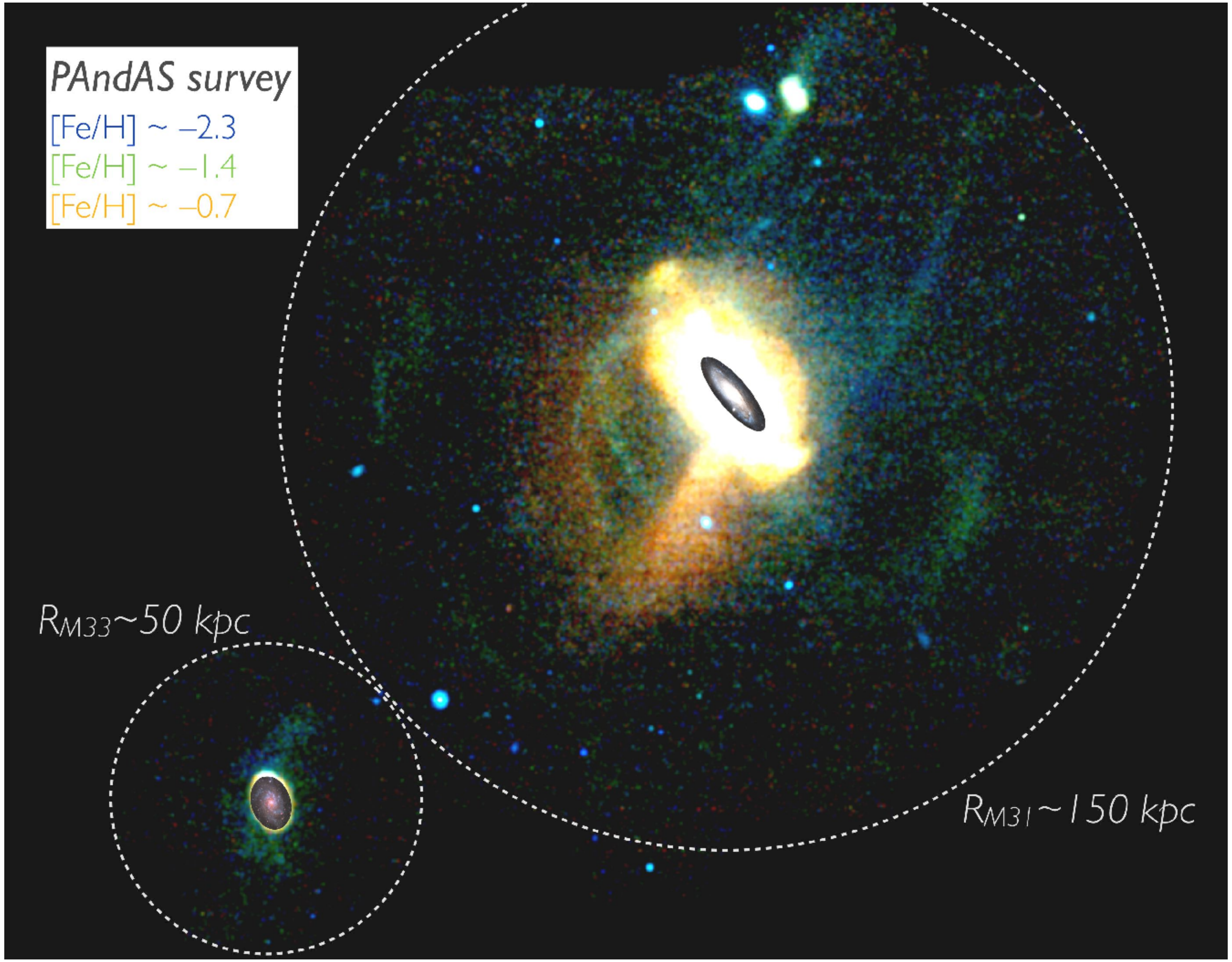


GD1 stream, no known progenitor



Grillmair & Dionatos, 2006

In other galaxies?



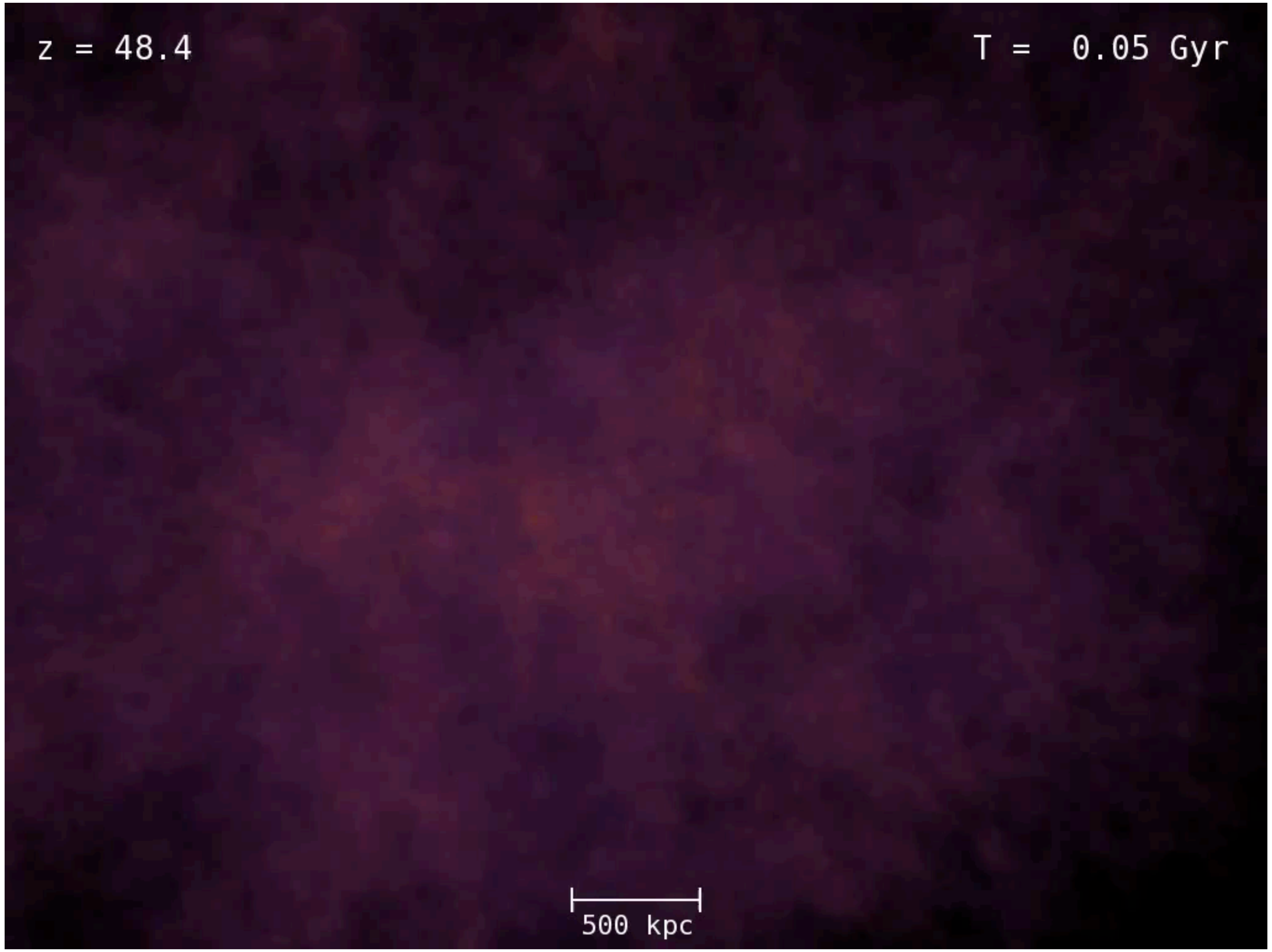
M31

Other other galaxies?

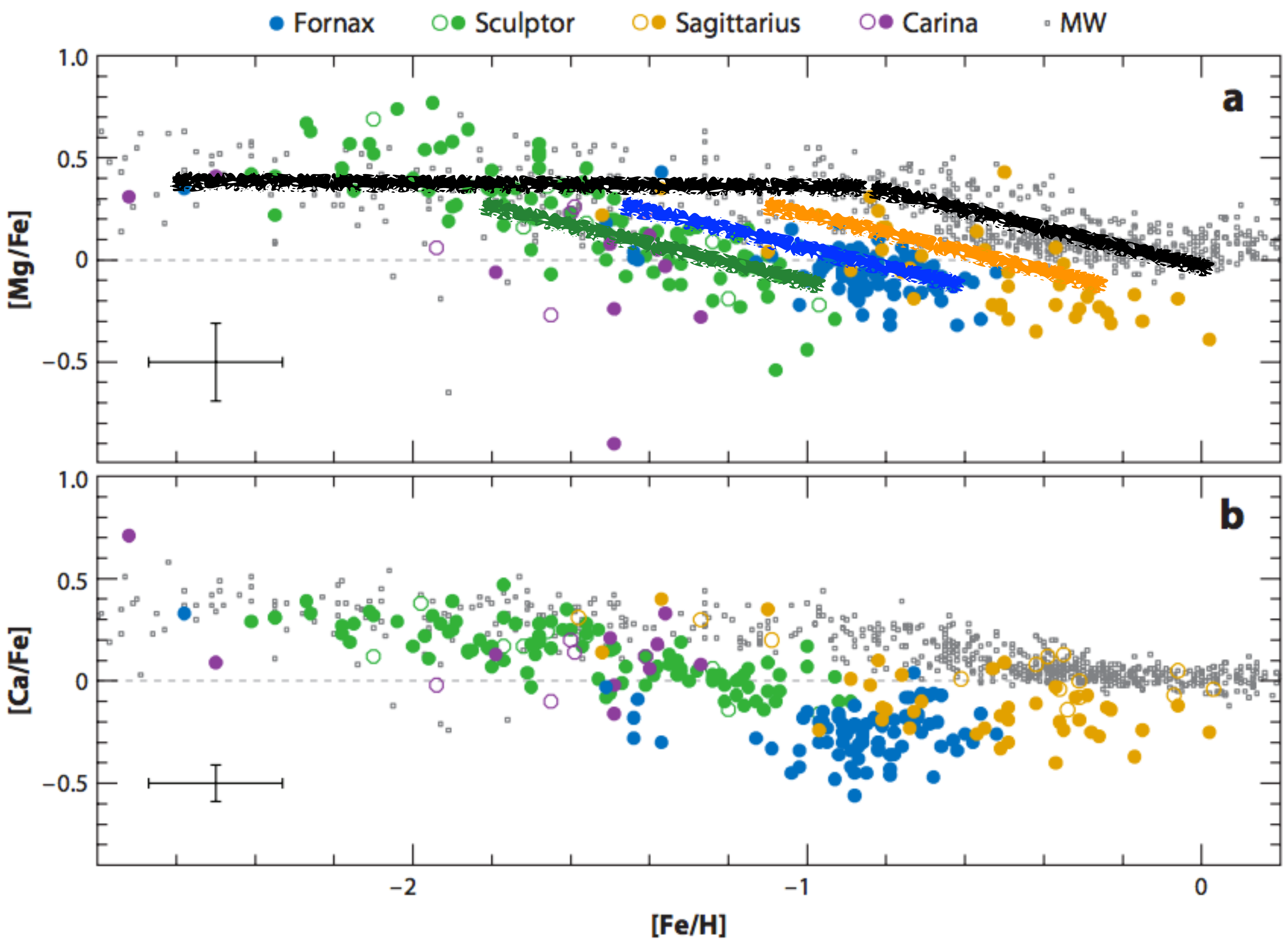
Why care about stellar streams?

- Confirmation of the hierarchical nature of structure formation
- Study of long gone satellites
- Gauge the mass distribution in the Galaxy
- Measure the lumpiness of the dark matter distribution

Cosmological zoom-in simulation

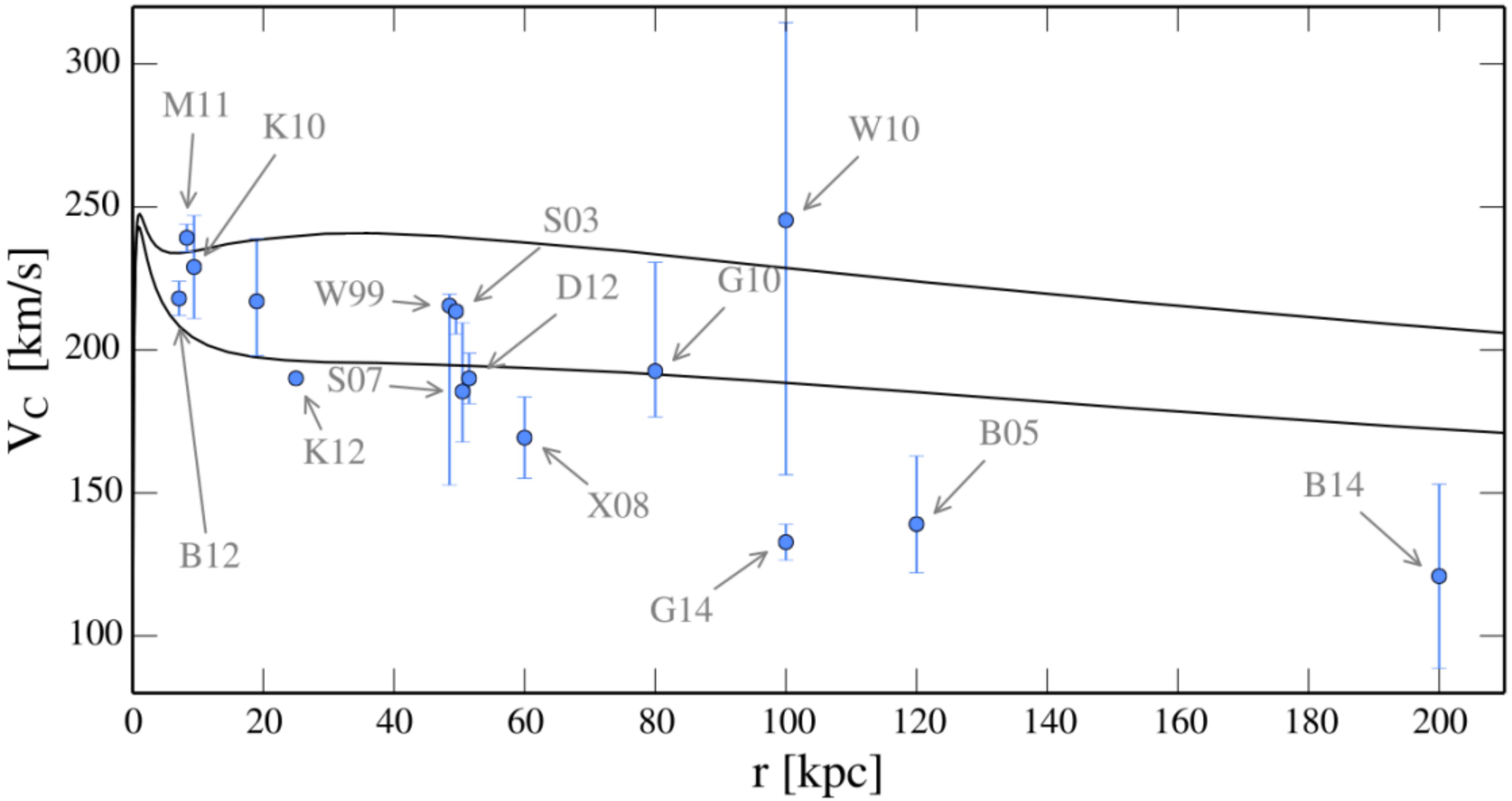


Perished satellites did not exactly look like those that survived



Tolstoy et al 2010

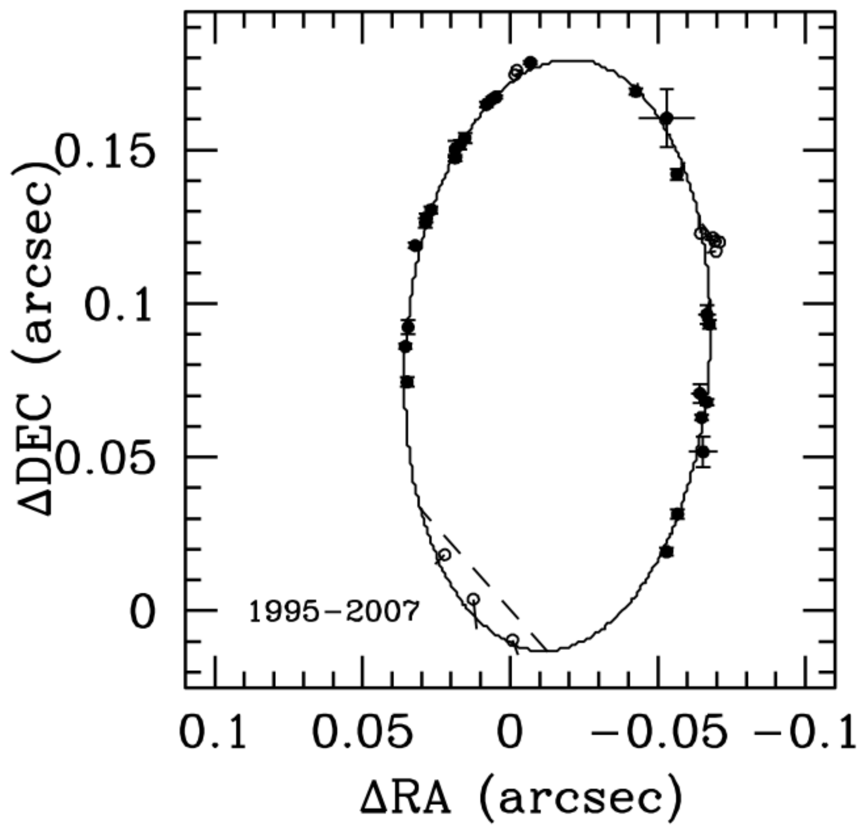
Do we know the mass of the Galaxy?



NO! It carries an uncertainty of 200%

Best measured mass in the Galaxy

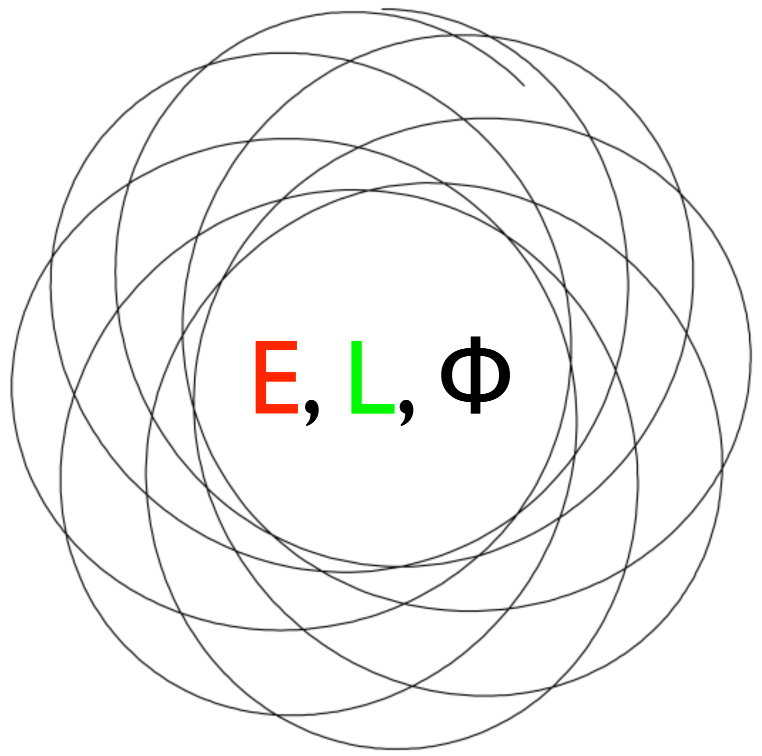
Point mass
$4.1 \pm 0.6\ 10^6\ M_\odot$



Ghez et al 2008

S02 star, 0.0005 pc
away from the Galactic BH

Any spherically symmetric density



Binney & Tremaine

Orbit can be described as a precessing ellipse

Your Universe

Needs non-baryonic

Dark Matter

The Astrophysical Journal Supplement Series, 192:16 (19pp), 2011 February

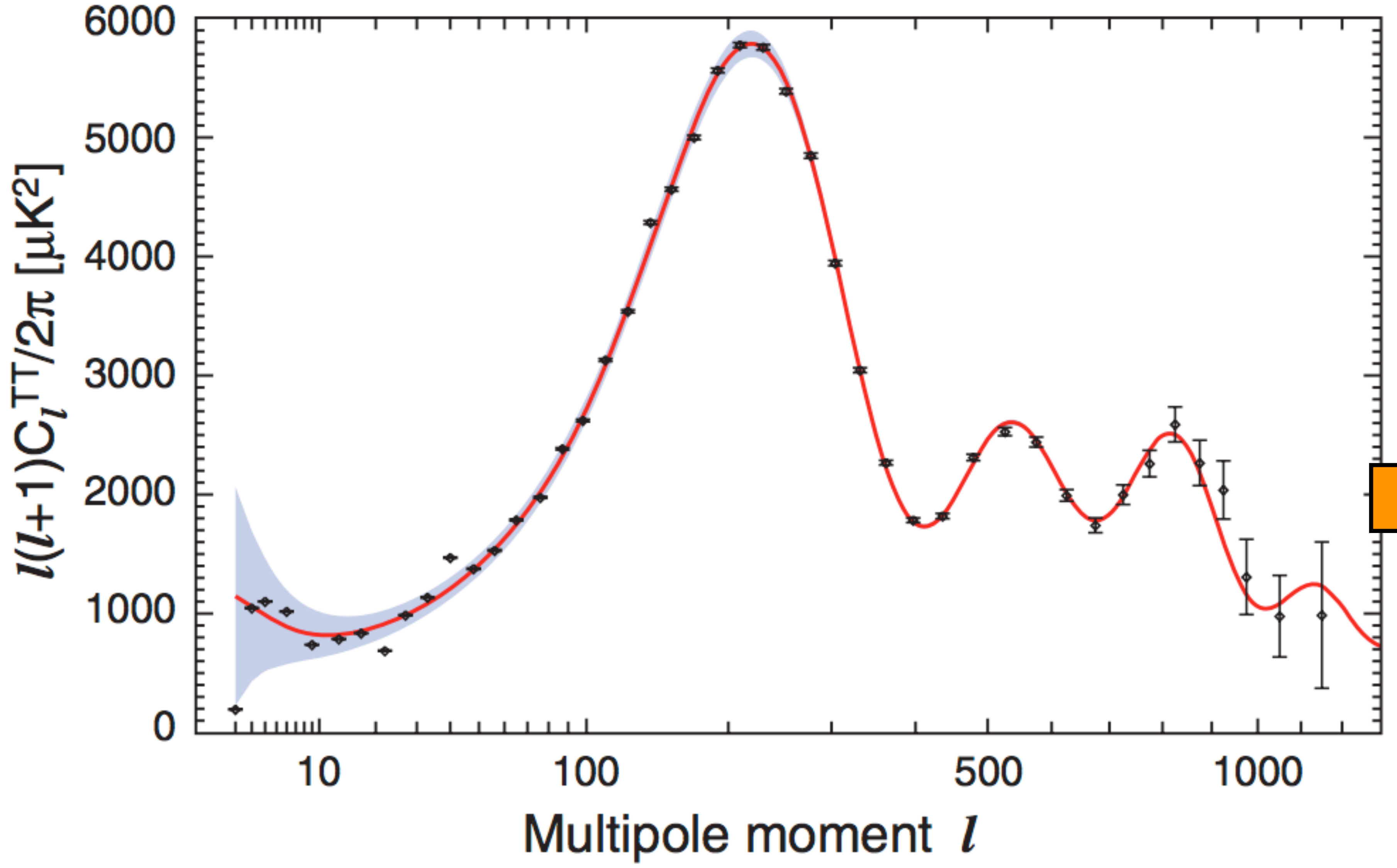
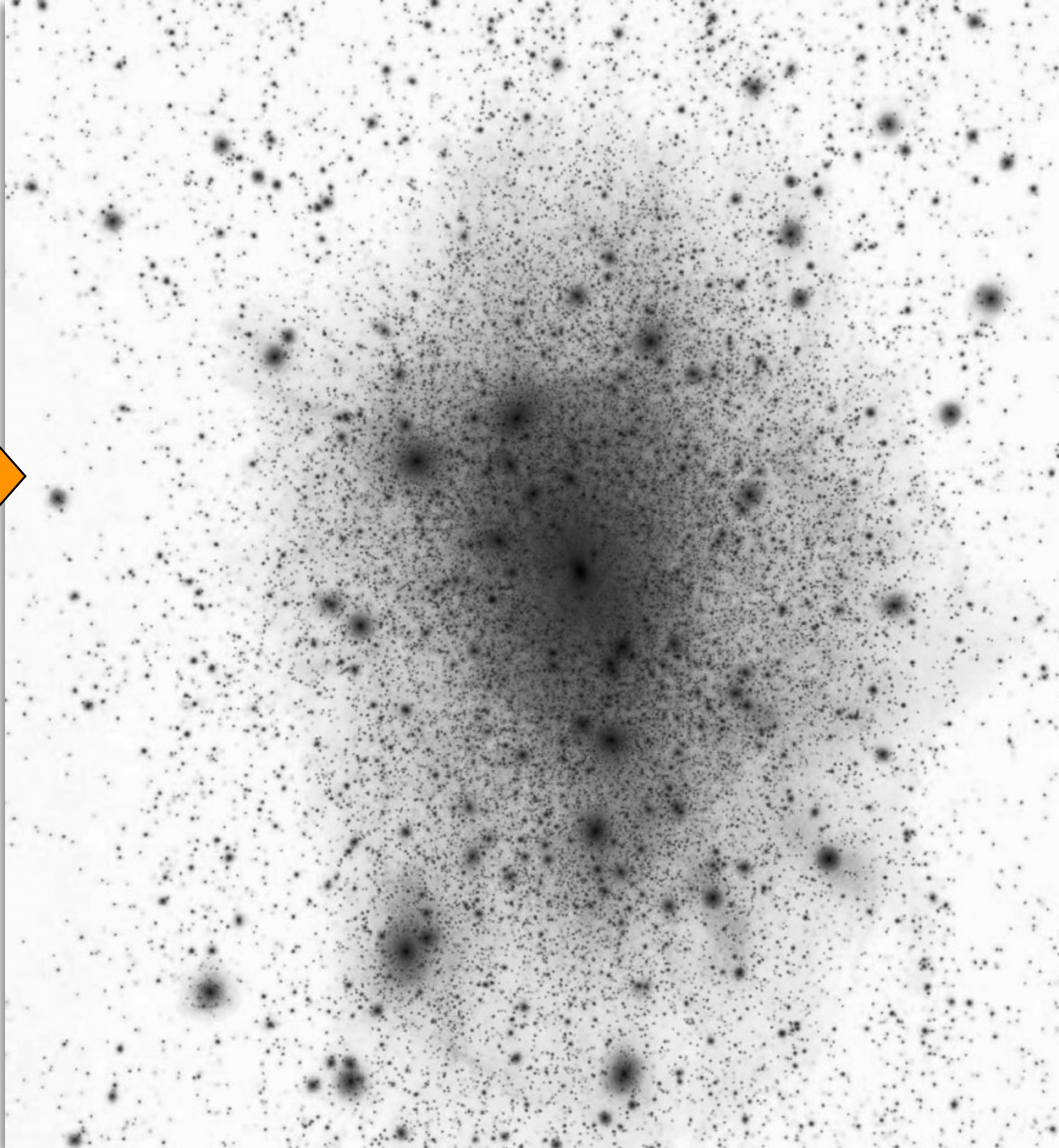
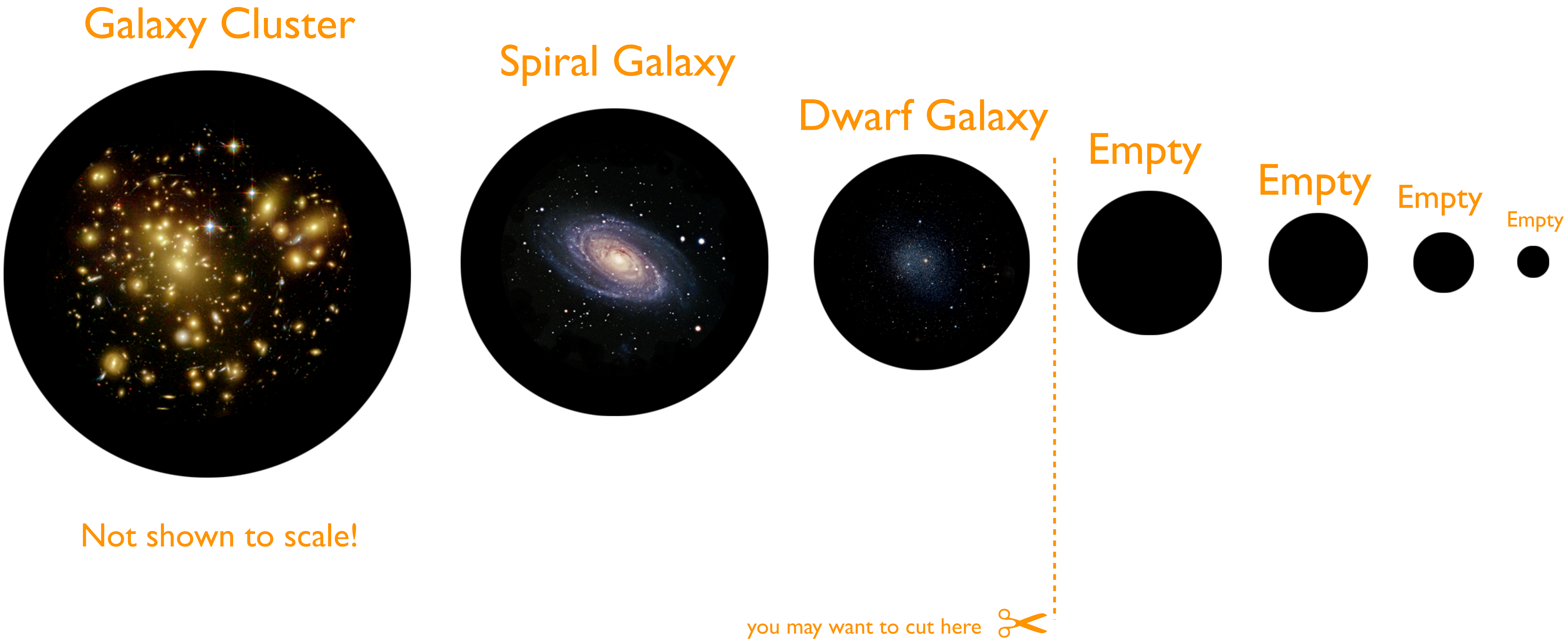


Figure 1. Seven-year temperature (TT) power spectrum from *WMAP*. The third acoustic peak and the onset of the Silk damping tail are now well measured by *WMAP*. The curve is the ΛCDM model best fit to the seven-year *WMAP* data: $\Omega_b h^2 = 0.02270$, $\Omega_c h^2 = 0.1107$, $\Omega_\Lambda = 0.738$, $\tau = 0.086$, $n_s = 0.969$, $\Delta^2_{\mathcal{R}} = 2.38 \times 10^{-9}$, and $A_{SZ} = 0.52$. The plotted errors include instrument noise, but not the small, correlated contribution due to beam and point source subtraction uncertainty. The gray band represents cosmic variance. A complete error treatment is incorporated in the *WMAP* likelihood code. The points are binned in progressively larger multipole bins with increasing l; the bin ranges are included in the seven-year data release.

Komatsu et al, 2011



Lumps of Cold Dark Matter



DM sub-halos create gaps in streams

Data

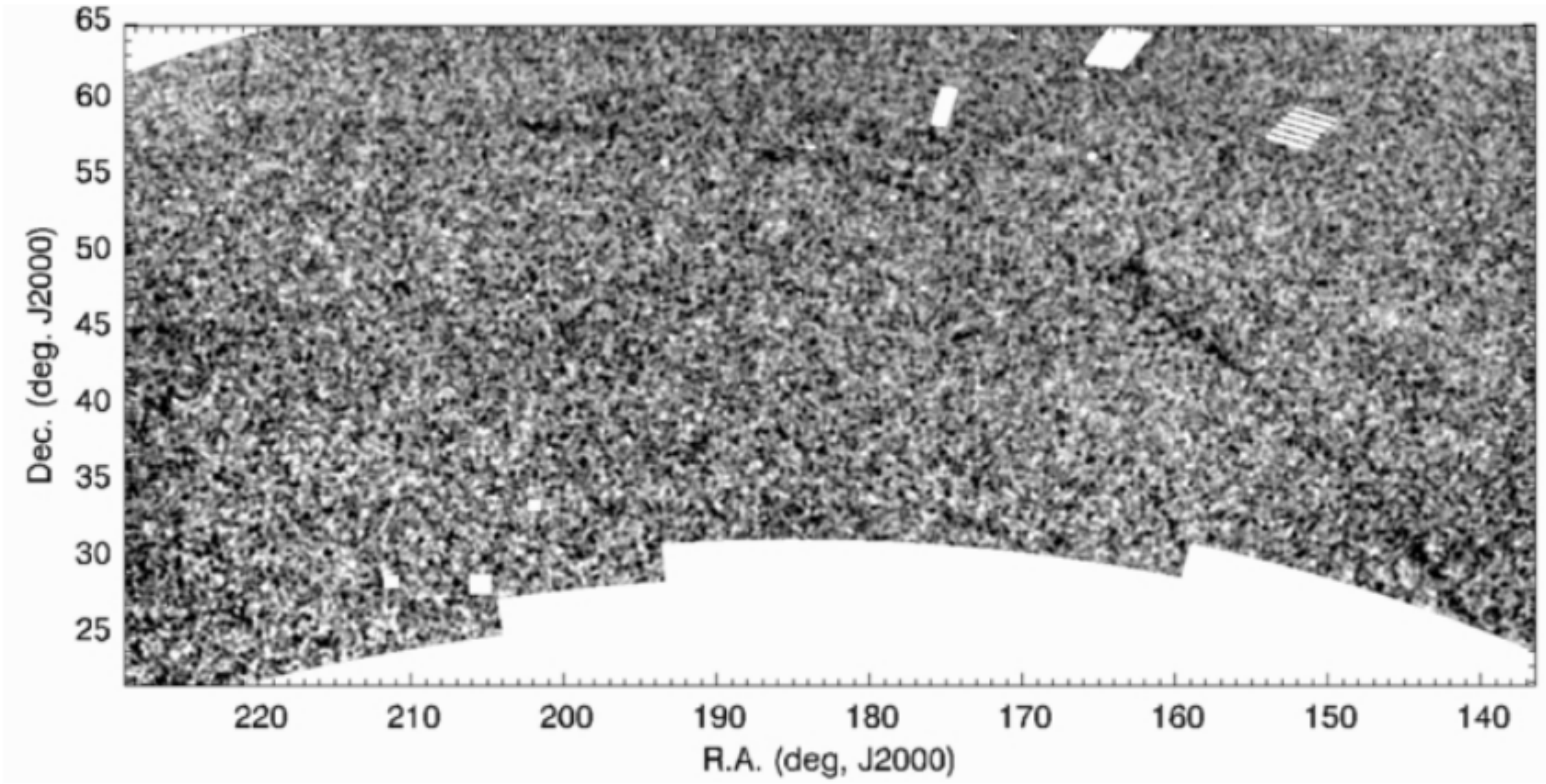


FIG. 1.—Smoothed, summed weight image of the SDSS field after subtraction of a low-order polynomial surface fit. Darker areas indicate higher surface densities. The weight image has been smoothed with a Gaussian kernel with $\sigma = 0\overset{\circ}{.}2$. The white areas are either missing data, clusters, or bright stars that have been masked out prior to analysis.

ICAL JOURNAL, 731:58 (15pp), 2011 April 10

Simulations

YOON, JOHNSTON, & HOGG

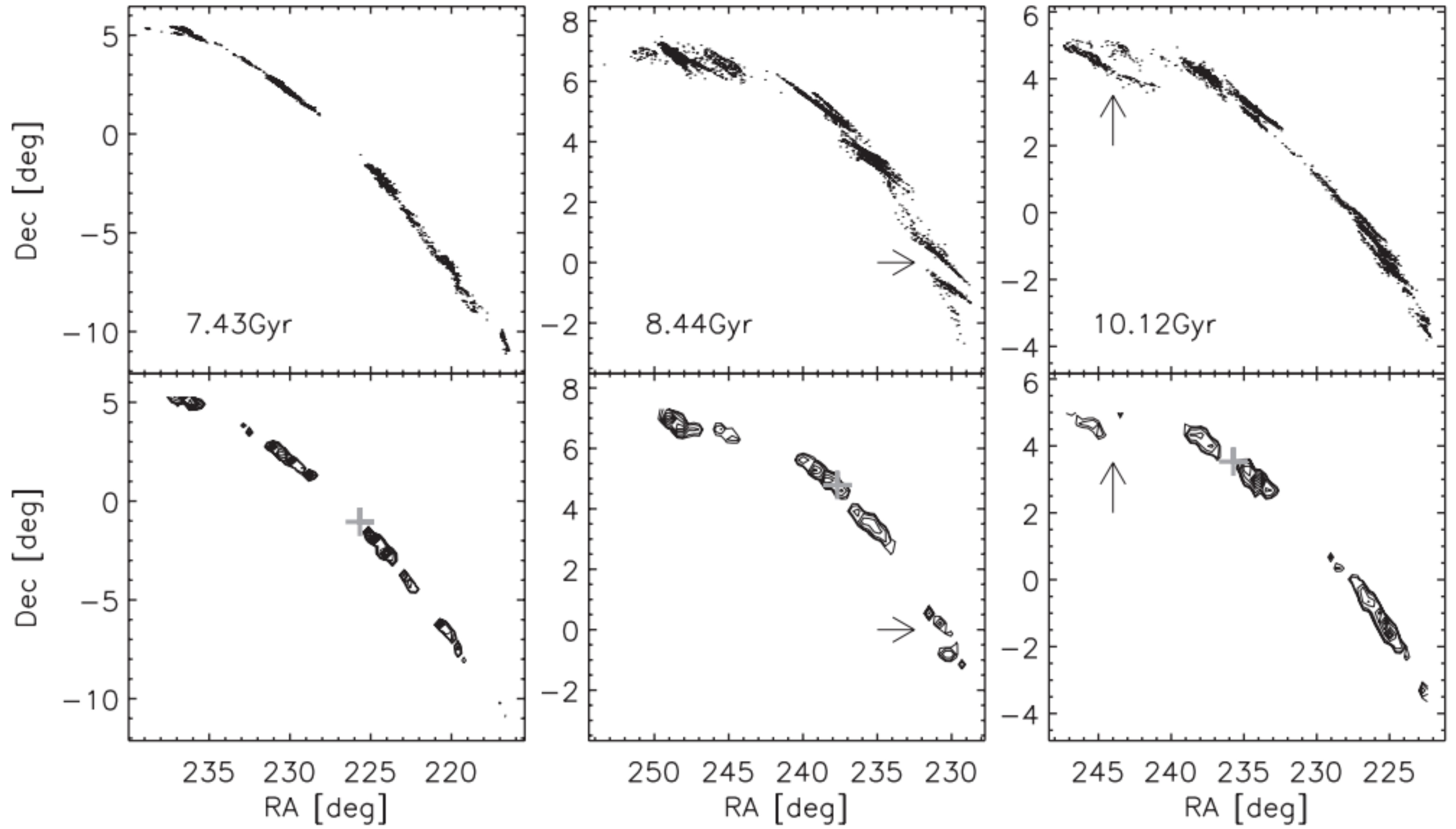
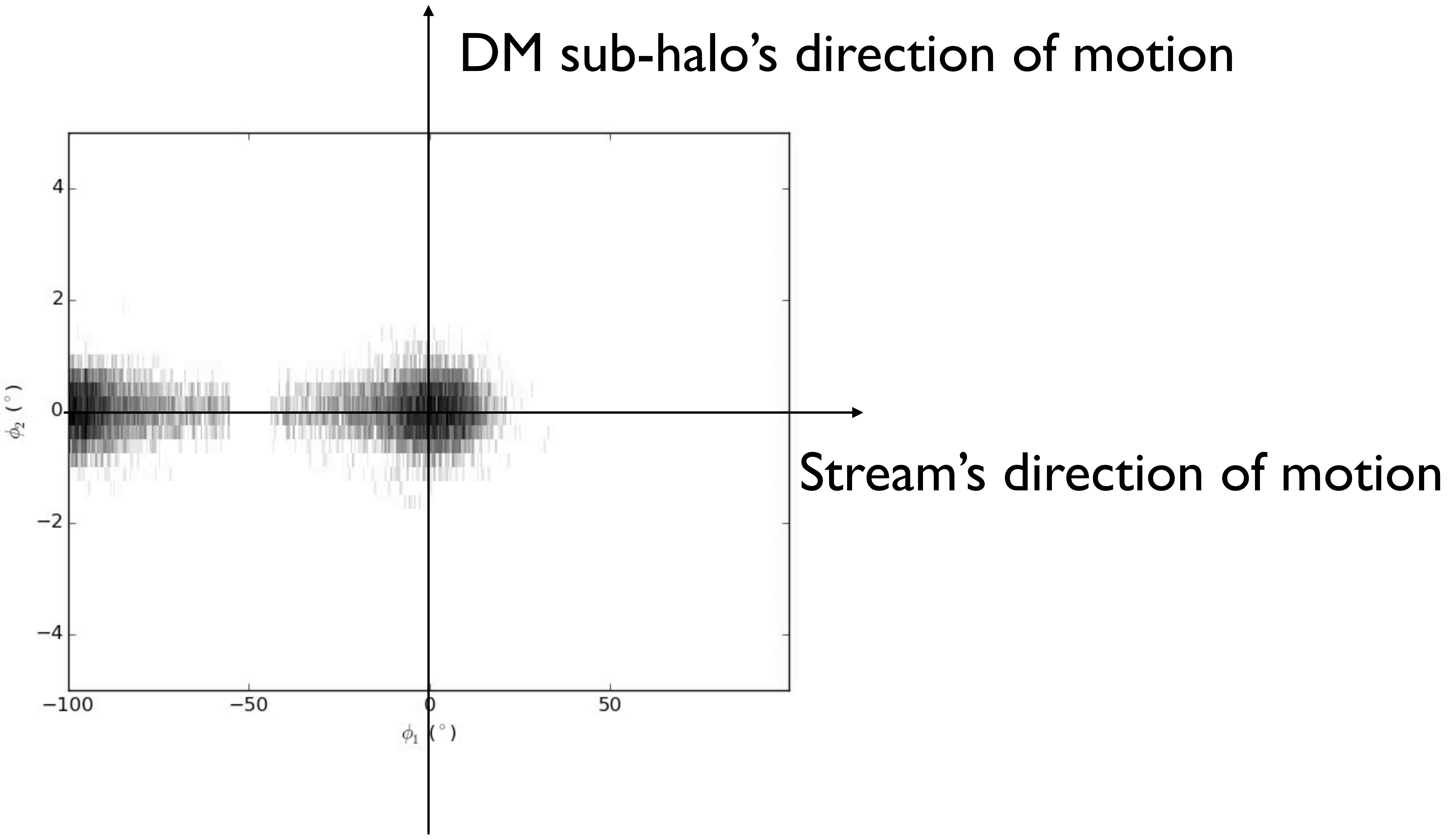
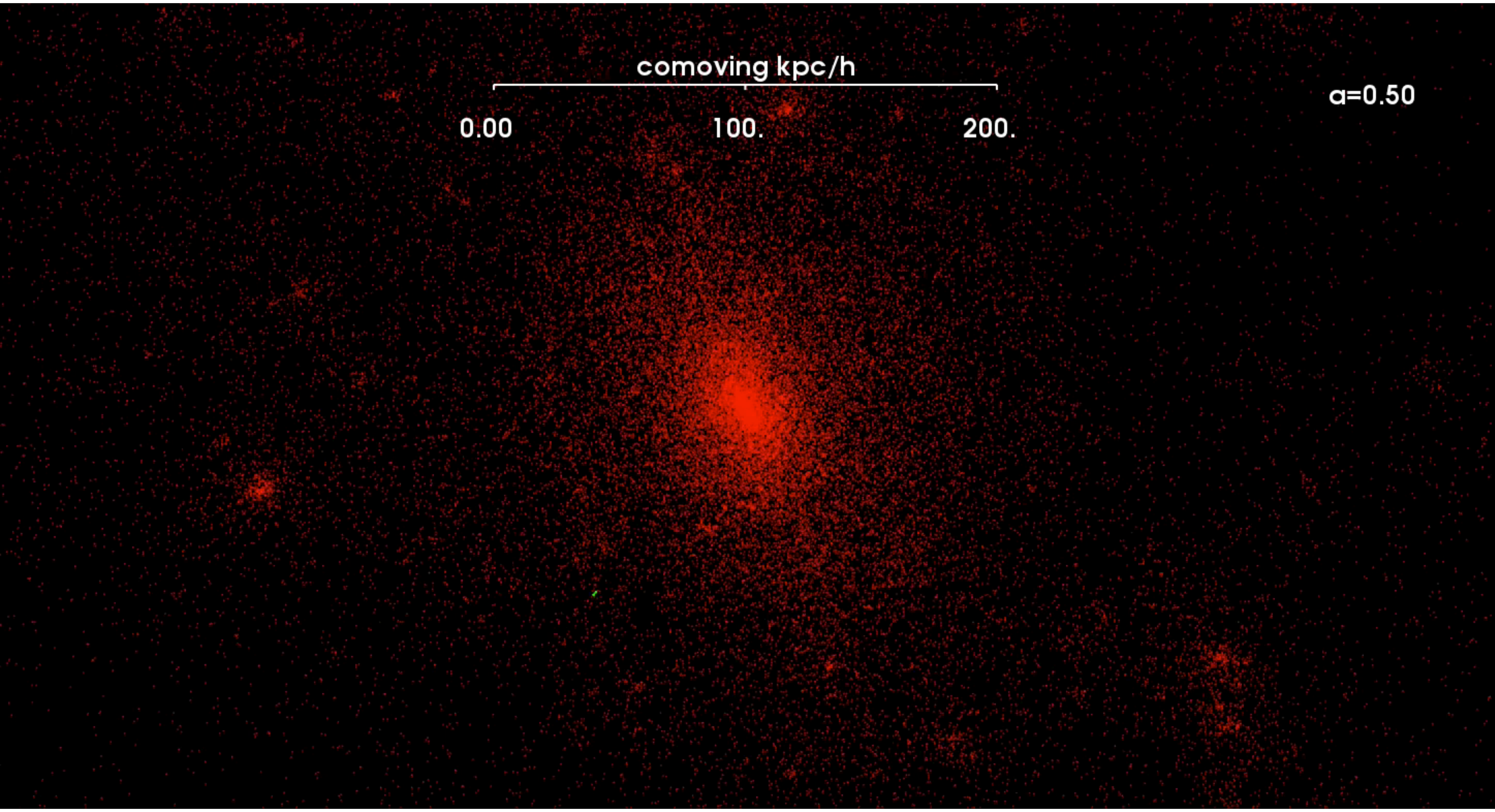


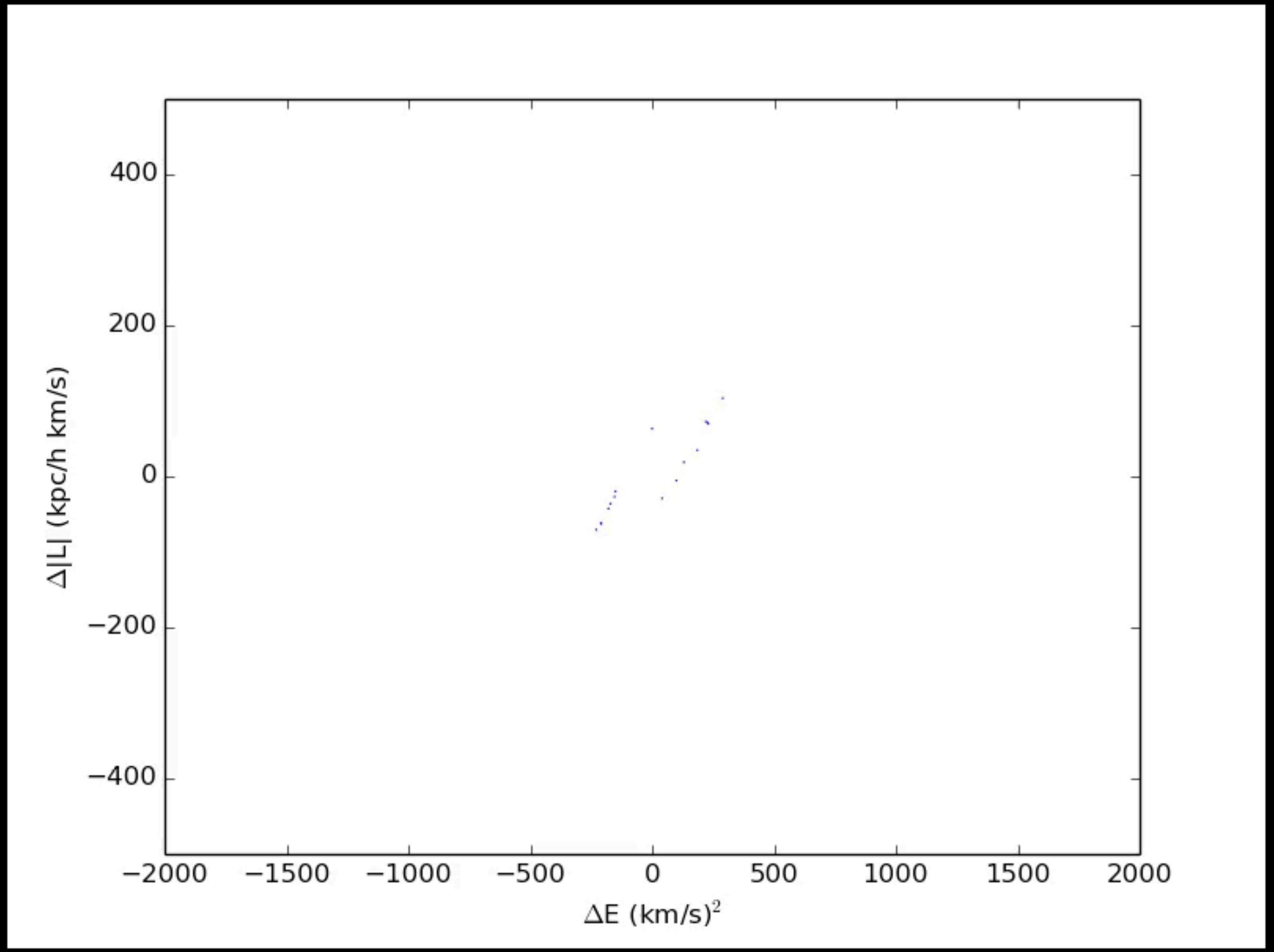
Figure 11. Particle distribution (upper panels) and surface density maps (lower panels) for three model streams from Figure 9 projected onto the plane of the sky. In the particle plots, many slanted gaps are found which are in some cases still apparent in the contour maps (indicated by arrows).

DM sub-halos create gaps in streams



Cosmological simulation of stream interaction with sub-structure





The End