Streams, shells, galactic archeology

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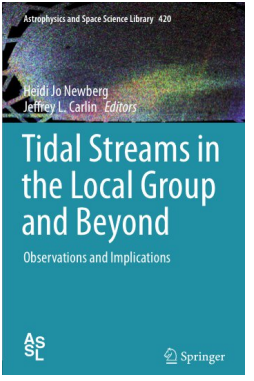
45th Heidelberg Physics Graduate Days, October 2020

Outline

- Stellar systems in a tidal field
- Formation of streams and shells
- Observational evidence for streams
- Detection methods
- Streams as dynamical probes
- Galactic archeology



Motion in the rotating frame

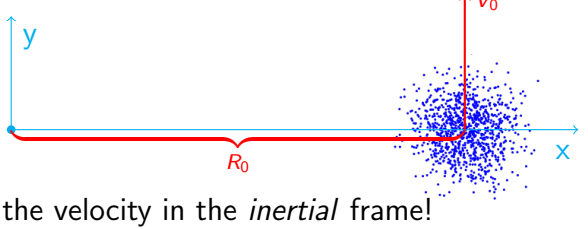
A satellite galaxy or a star cluster on a circular orbit in the host galaxy:

consider a rotating coordinate system so that the x axis points towards the cluster, y is the direction of its motion, and z is the normal to the orbital plane.
$\Phi_\mathrm{h}(\mathbf{x})$ and $\Phi_\mathrm{c}(\mathbf{x})$ are the potentials of the host galaxy and the cluster;
the centre-of-mass position of the cluster is $\{R_0, 0, 0\}$,
its velocity in the inertial frame is $\{0, V_0, 0\}$, where $V_0 = \sqrt{R_0\, \partial\Phi/\partial x\big|_{x=R_0}}$;
$\mathbf{\Omega} \equiv \{0, 0, V_0/R_0\}$ is the angular velocity of the cluster.

$$H_\mathrm{J} = \Phi(\mathbf{x}) + \tfrac{1}{2}\left|\mathbf{p}\right|^2 - \mathbf{\Omega}\cdot\mathbf{L} \qquad (\text{where } \mathbf{L} \equiv \mathbf{x}\times\mathbf{p}, \quad \Phi \equiv \Phi_\mathrm{h} + \Phi_\mathrm{c})$$

Hamilton's equations of motion:

$$\dot{\mathbf{x}} = \quad \mathbf{p} \quad - \mathbf{\Omega}\times\mathbf{x}$$
$$\dot{\mathbf{p}} = -\nabla\Phi - \mathbf{\Omega}\times\mathbf{p}$$



Note that canonical momentum $\mathbf{p}$ is the velocity in the *inertial* frame!

Tidal radius (Jacobi radius, Hill sphere, Roche lobe, . . .)

Note that the energy or angular momentum in the inertial frame

$E \equiv \Phi + \frac{1}{2}\left|\mathbf{p}\right|^2$, $\mathbf{L} \equiv \mathbf{x} \times \mathbf{p}$ are not conserved individually,

but the Jacobi integral $E_\mathrm{J} = E - \mathbf{\Omega} \cdot \mathbf{L}$ is conserved.

It can be written as $E_\mathrm{J} = \Phi_\mathrm{eff} + \frac{1}{2}\left|\dot{\mathbf{x}}\right|^2$,

where the effective potential includes the centrifugal term:

$\Phi_\mathrm{eff}(\mathbf{x}) \equiv \Phi(\mathbf{x}) - \frac{1}{2}\left|\mathbf{\Omega} \times \mathbf{x}\right|^2$.

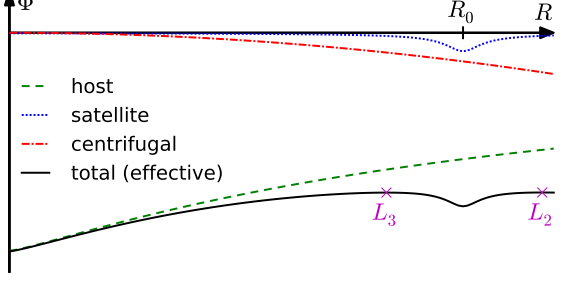
Saddle points of Φ_eff (Lagrange points L_2, L_3) are defined by $\partial\Phi_\mathrm{eff}/\partial x = 0$.

For a pointlike satellite

$\Phi_\mathrm{s} = -\frac{GM_\mathrm{s}}{\sqrt{(x-R_0)^2+y^2+z^2}}$,

two solutions are at $x \approx R_0 \pm R_\mathrm{t}$:

$$R_\mathrm{t} \approx \left[\frac{GM_\mathrm{s}}{\left(\frac{1}{R_0}\frac{\partial\Phi_\mathrm{h}}{\partial x} - \frac{\partial^2\Phi_\mathrm{h}}{\partial x^2}\right)\Big|_{x=R_0}}\right]^{1/3}$$

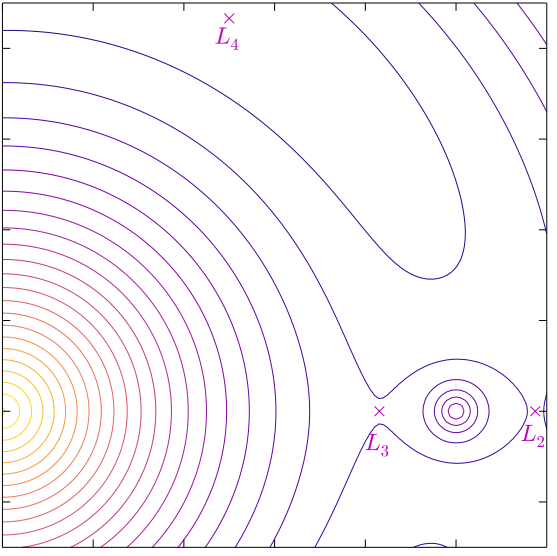


Tidal radius (Jacobi radius, Hill sphere, Roche lobe, . . .)

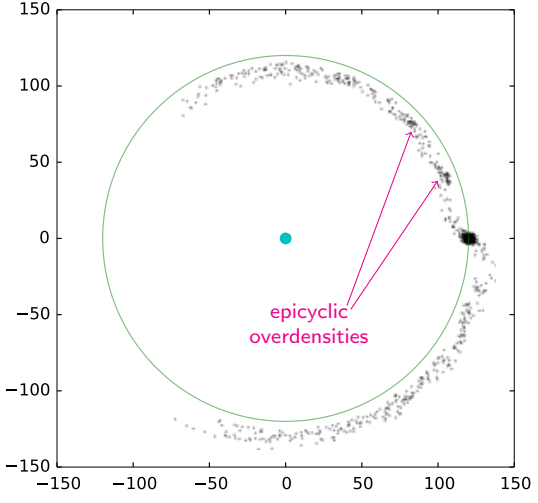
$$R_\mathrm{t} \approx \left[\frac{GM_\mathrm{s}}{\left(\frac{1}{R_0} \frac{\partial \Phi_\mathrm{h}}{\partial x} - \frac{\partial^2 \Phi_\mathrm{h}}{\partial x^2} \right) \Big|_{x=R_0}} \right]^{1/3}$$

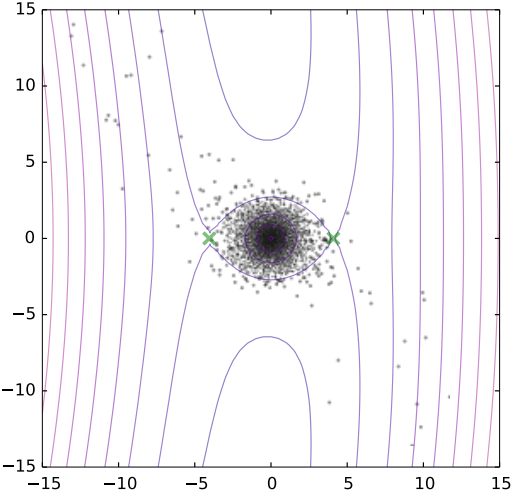
Example:
host system is also a point mass M_h,
then $R_\mathrm{t} \approx R_0 \left(M_\mathrm{s} / [3\, M_\mathrm{h}] \right)^{1/3}$.

More generally:
the denominator in R_t is
$\propto \Omega^2 \propto M_\mathrm{h}(< R_0) \,/\, R_0^3$
(the mean density of the host galaxy within the radius of the orbit R_0), and the mass of the satellite spread over the volume of the Hill sphere is of the same order.



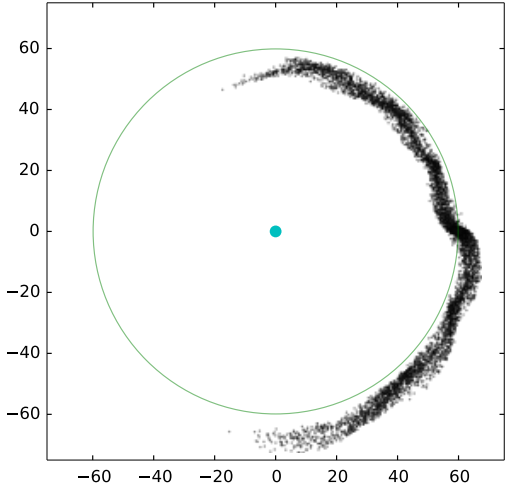
Stellar system in a tidal field

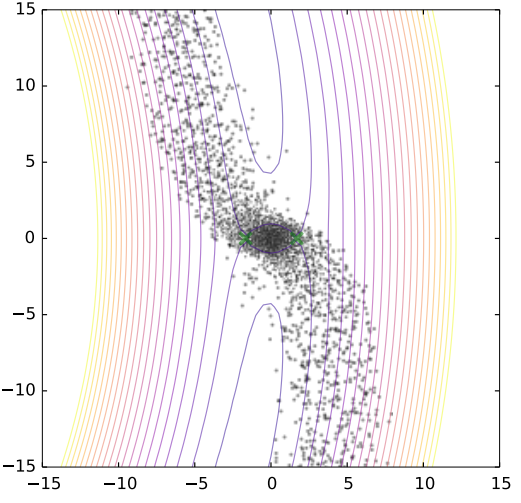




circular orbit, weak tidal stripping

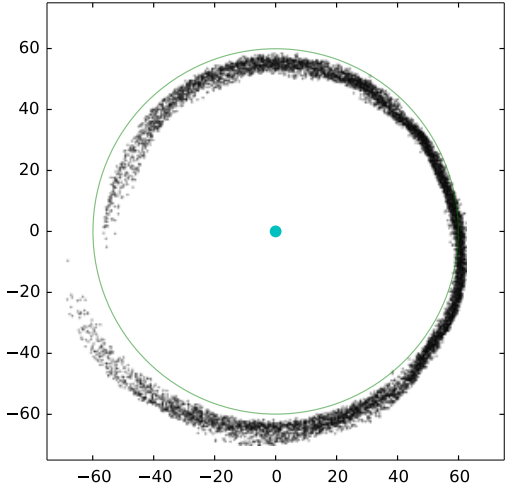
Stellar system in a tidal field

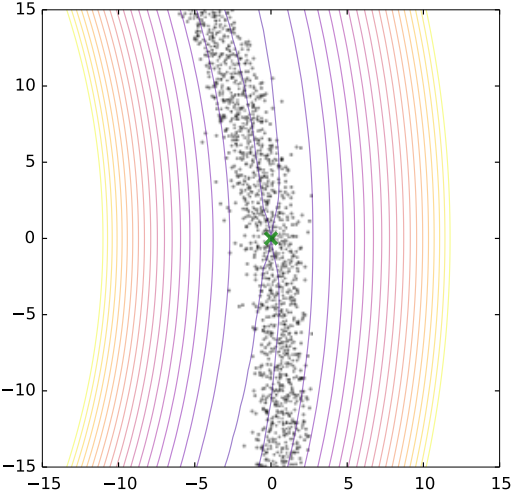




circular orbit, strong tidal stripping

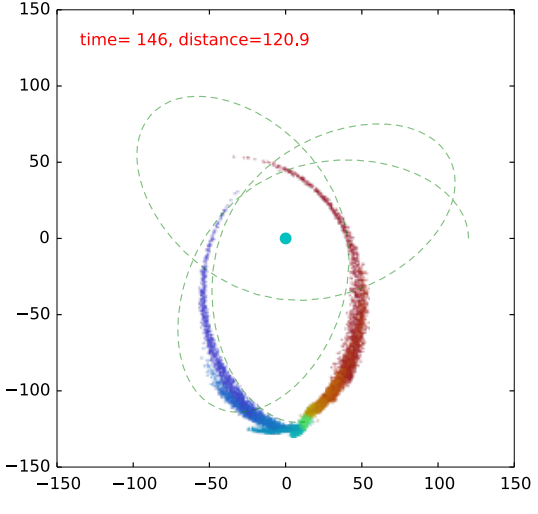
Stellar system in a tidal field

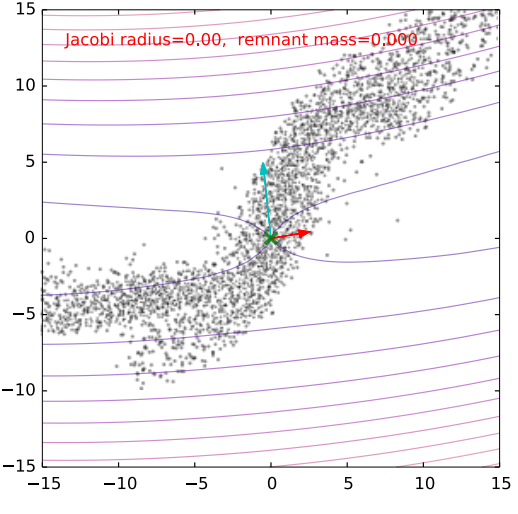




circular orbit, strong tidal stripping leading to a complete disruption

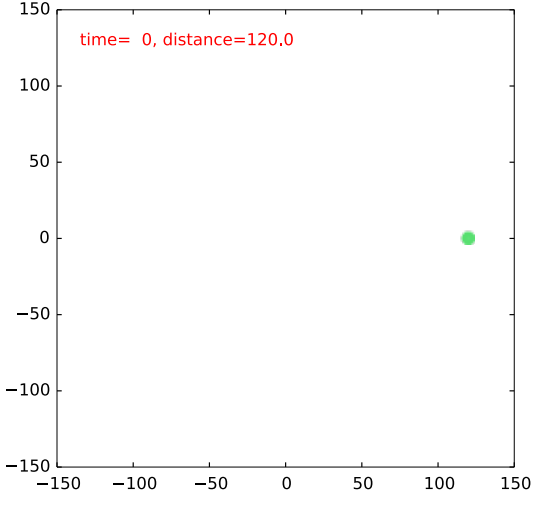
Stellar system in a tidal field

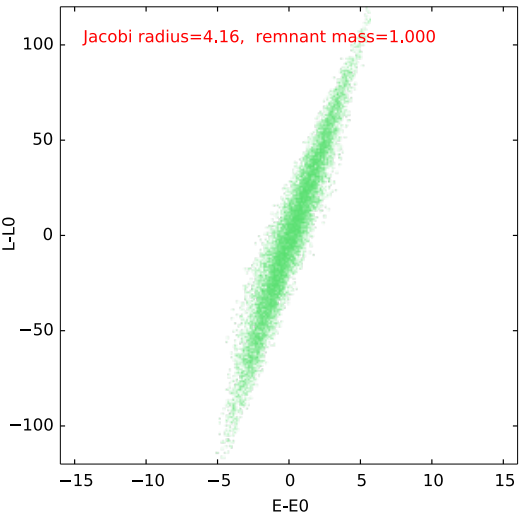




eccentric orbit, bursty stripping in tidal shocks

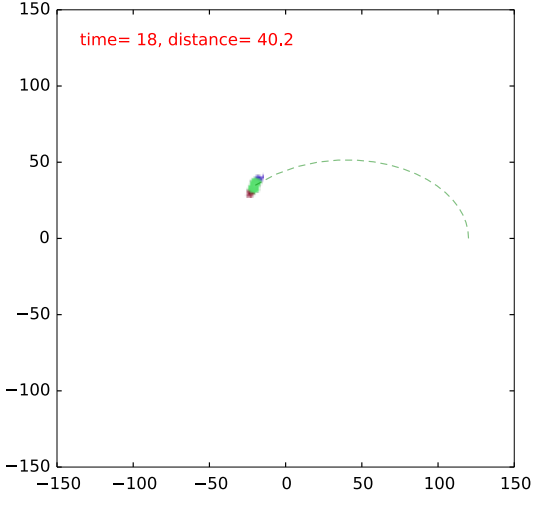
Evolution of tidal debris in the $E - L$ space

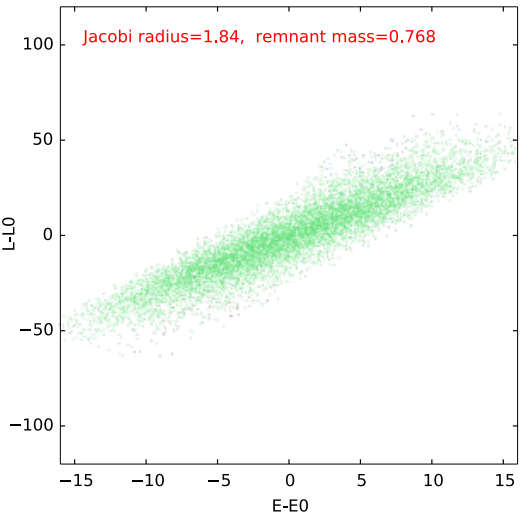




apocentre

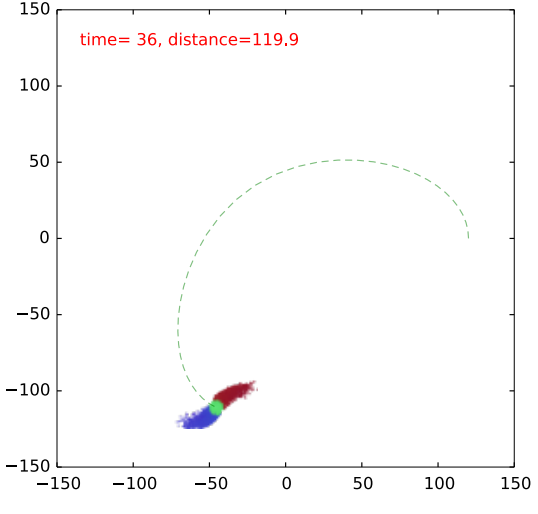
Evolution of tidal debris in the $E - L$ space

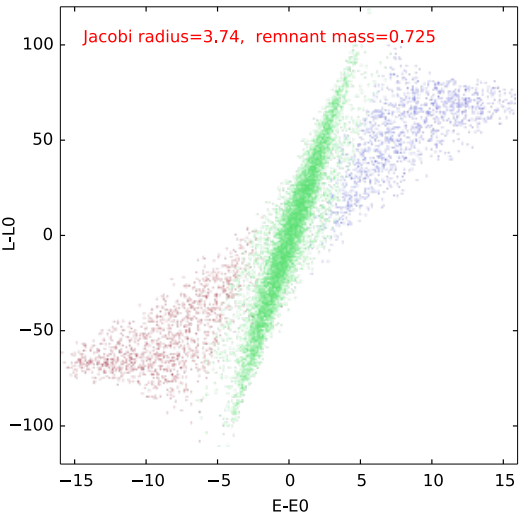




pericentre: tidal shock unbinds some stars

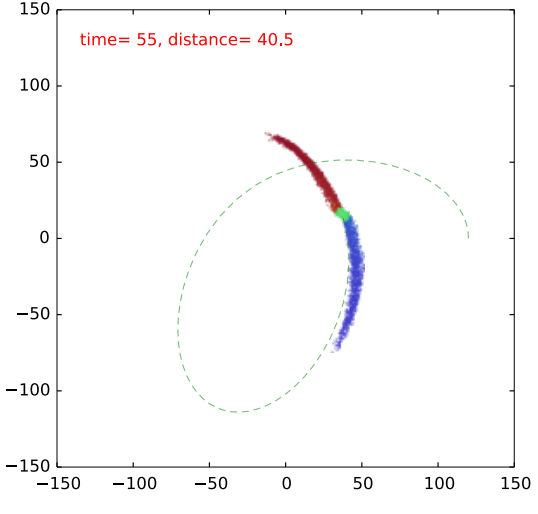
Evolution of tidal debris in the $E - L$ space

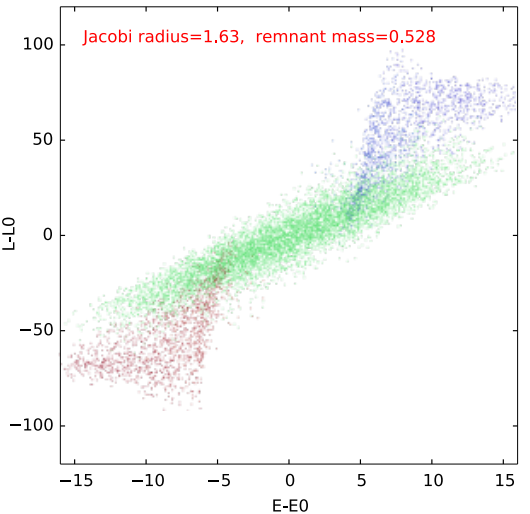




next apocentre: formation of the two tails

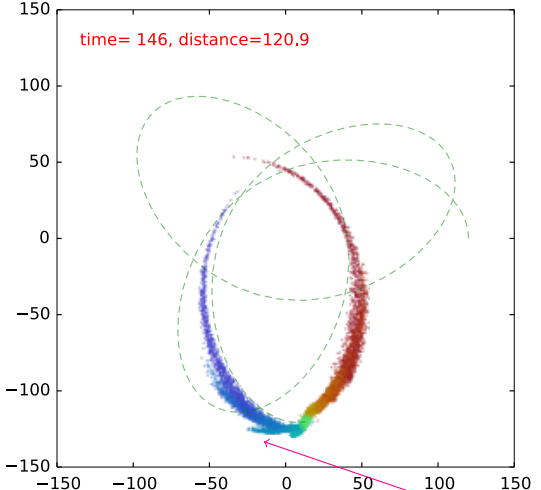
Evolution of tidal debris in the $E - L$ space

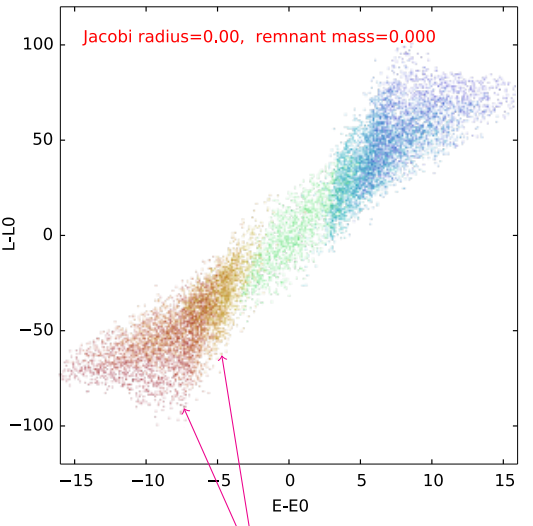




next pericentre: another iteration of stripping

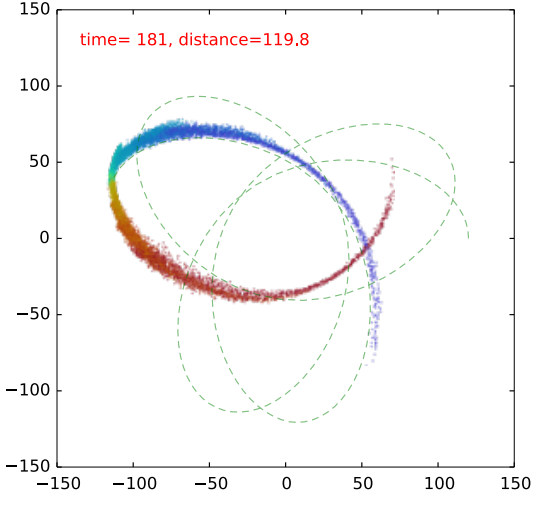
Evolution of tidal debris in the $E - L$ space

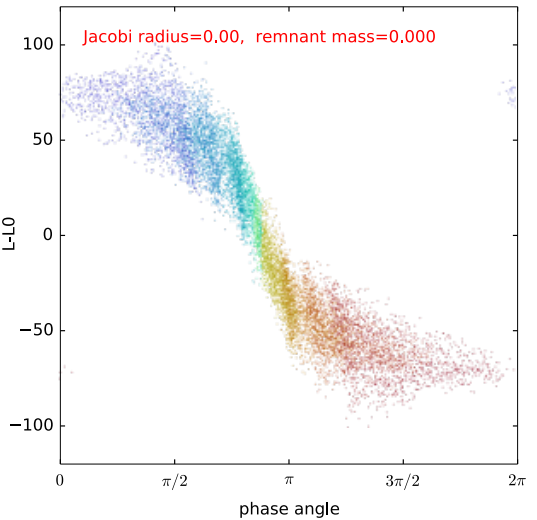




each stripping episode produces a "feather" and a "wedge" in each tail

Evolution of tidal debris in the action – angle space



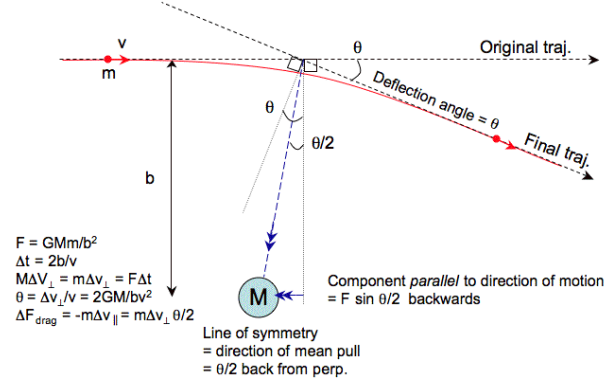


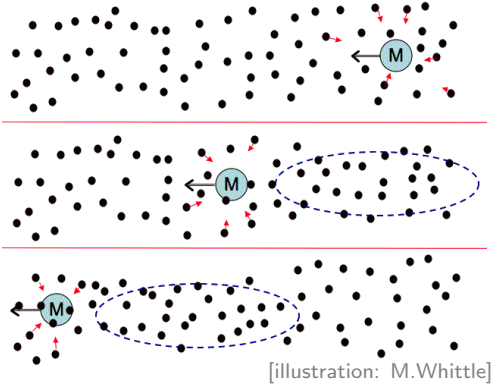
Dynamical friction

A moving massive object creates a trailing density wake, which slows it down. Standard expression in an infinite homogeneous medium [Chandrasekhar 1943]:

$$\frac{\mathrm{d}v_M}{\mathrm{d}t} = -\frac{4\pi\, G^2\, M\, \rho\, \ln\Lambda}{v_M^2}\left[\mathrm{erf}\left(\frac{v_M}{\sqrt{2}\,\sigma}\right) - \frac{\sqrt{2}\,v_M}{\sqrt{\pi}\,\sigma}\,\exp\left(-\frac{v_M^2}{2\,\sigma^2}\right)\right]$$

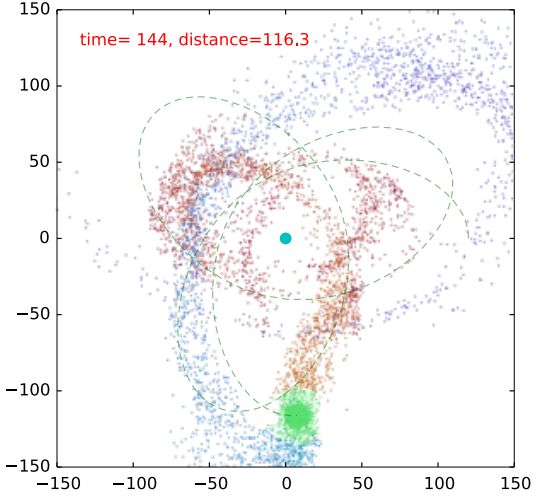
M, v_M – mass and velocity of the object; ρ, σ – density and velocity dispersion of the field stars; $\ln\Lambda \simeq \mathcal{O}(1)$ – Coulomb logarithm.

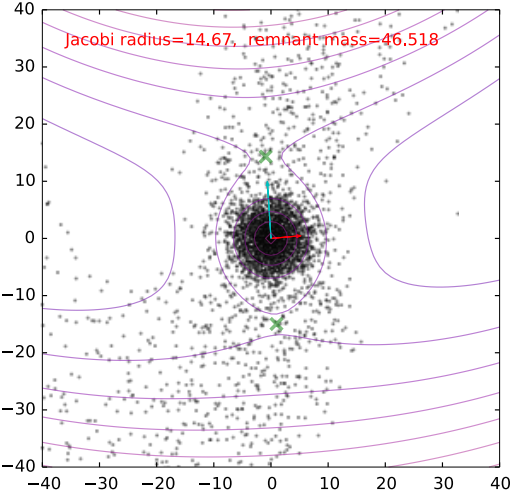




[illustration: M.Whittle]

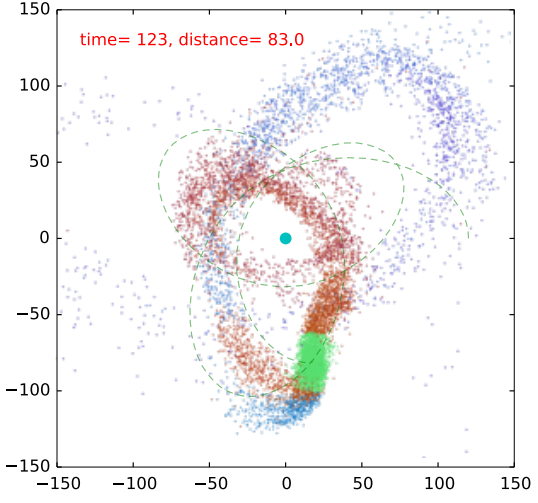
Tidal stripping is accelerated by dynamical friction

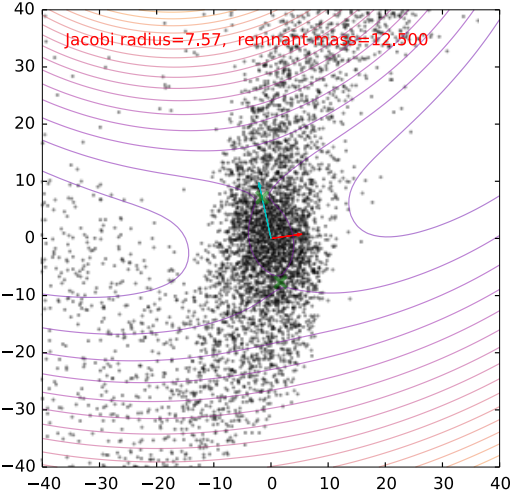




massive satellite, ignoring dynamical friction

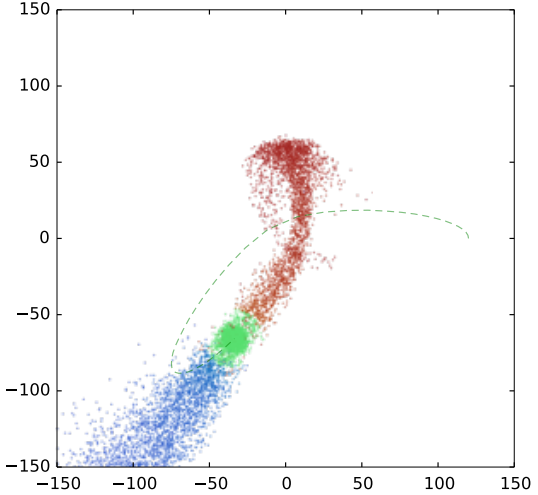
Tidal stripping is accelerated by dynamical friction

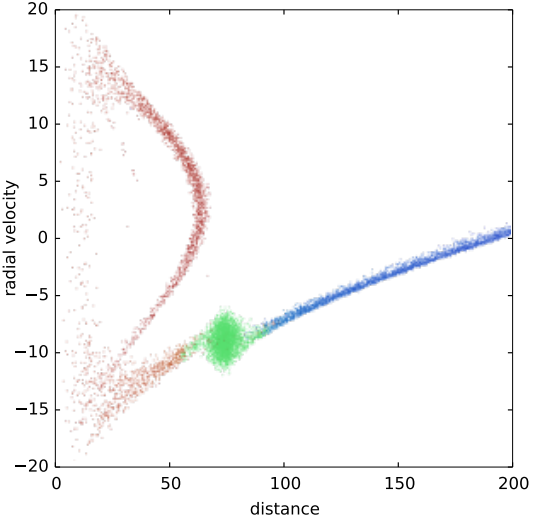




massive satellite with dynamical friction

Formation of shells in head-on collisions





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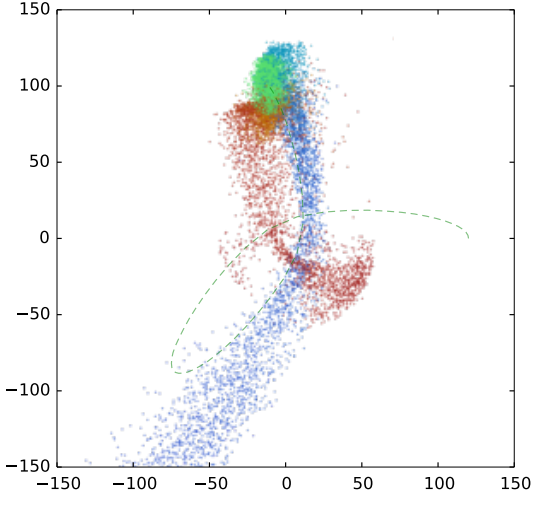

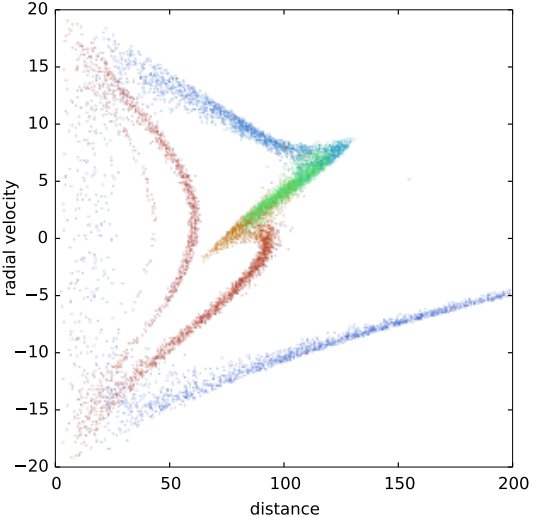

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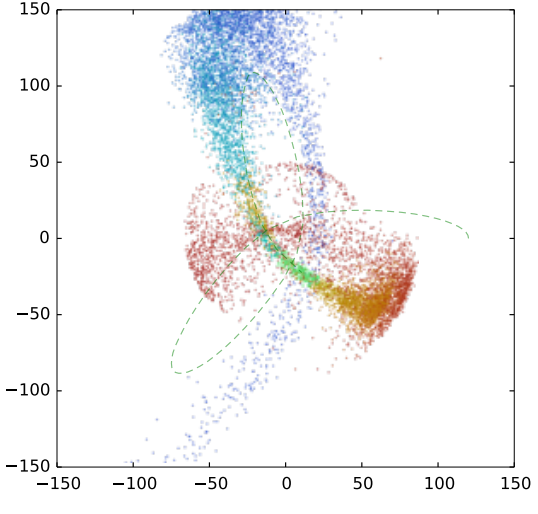
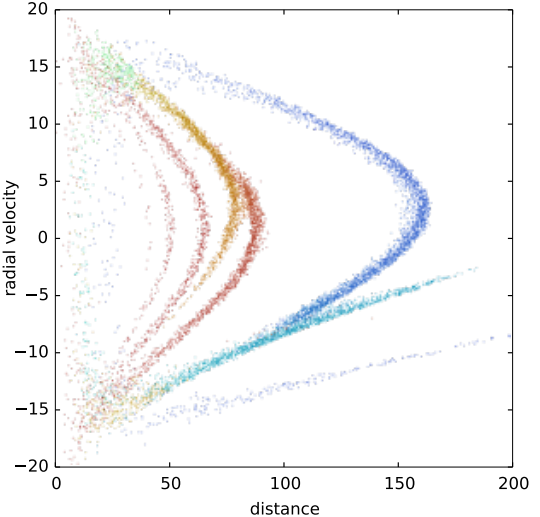
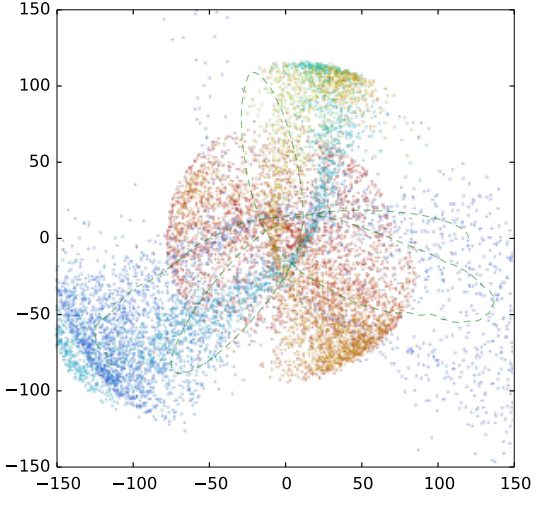
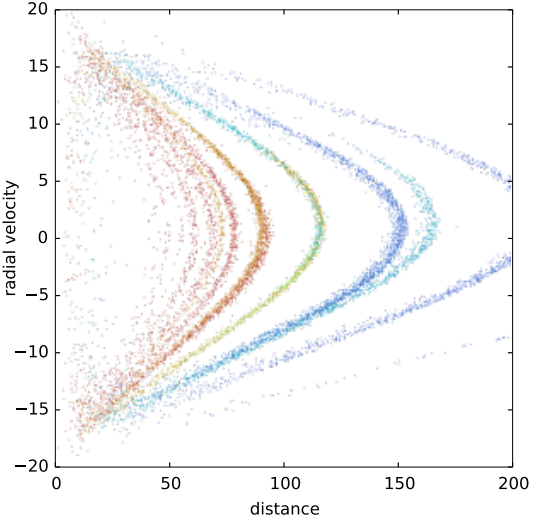




Formation of shells in head-on collisions





Shells and streams in external galaxies: NGC 5907

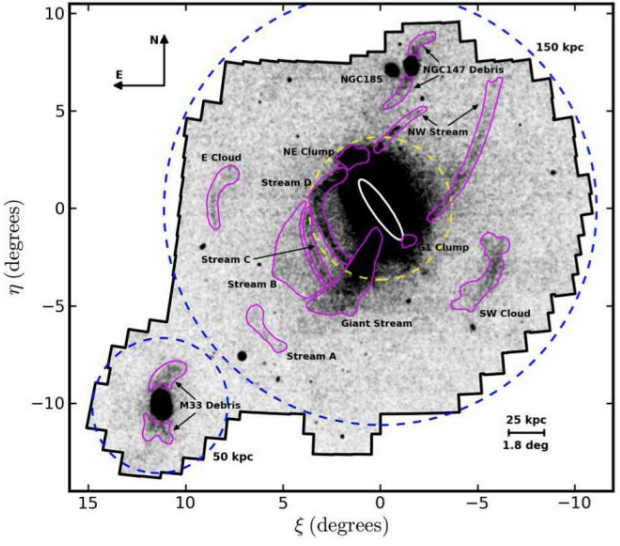
[credit: J.Gabany]

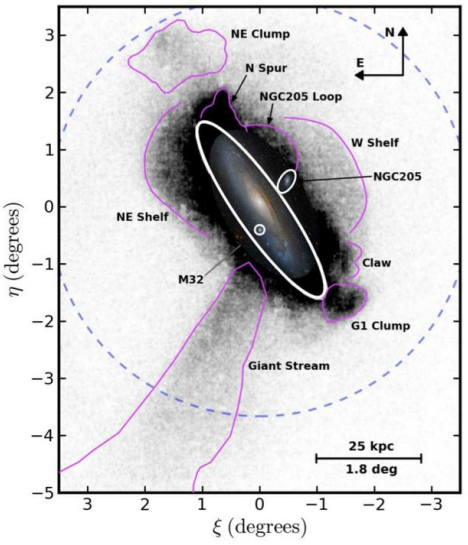
Shells and streams in external galaxies: NGC 474

[view in Aladin]

[credit: P.-A.Duc, J.-C.Cuillandre]

Shells and streams in external galaxies: M 31 (Andromeda)

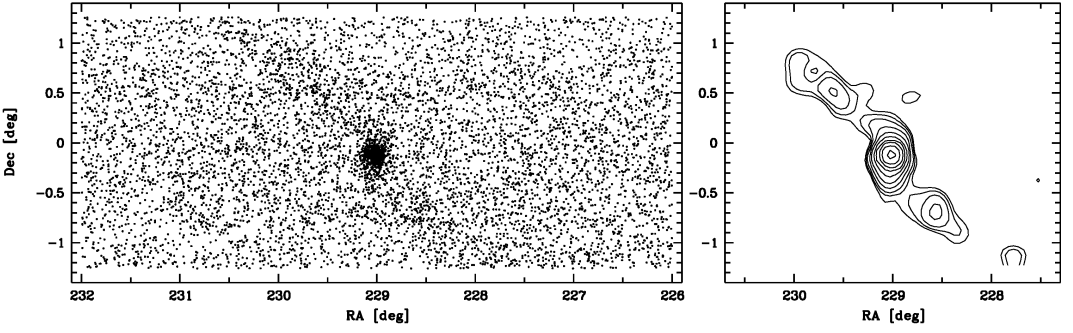




[credit: A.Ferguson, PAndAS survey]

Streams in the Milky Way

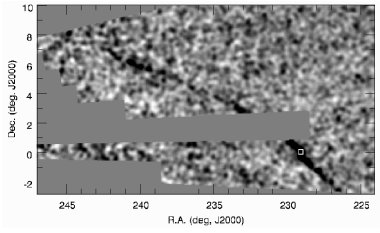
Globular cluster Pal 5



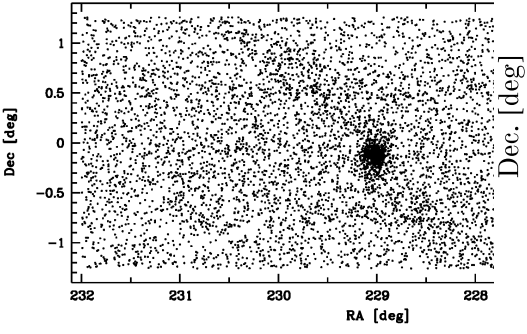
[Odenkirchen+ 2001] – SDSS commissioning data

Streams in the Milky Way

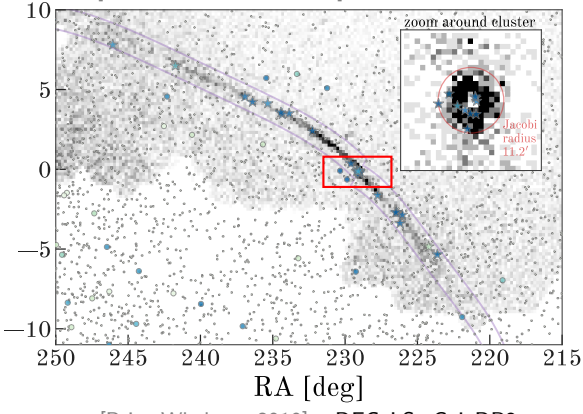
Globular cluster Pal 5



[Grillmair&Dionatos 2006] – SDSS DR4



[Odenkirchen+ 2001] – SDSS commissioning data

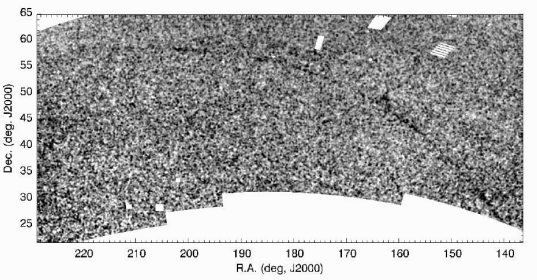


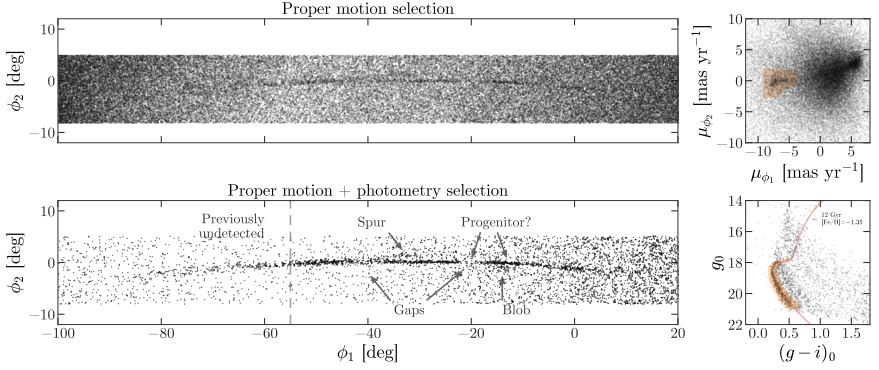
[Price-Whelan+ 2019] – DECaLS+GaiaDR2

Streams in the Milky Way

A cold stream with no known progenitor:

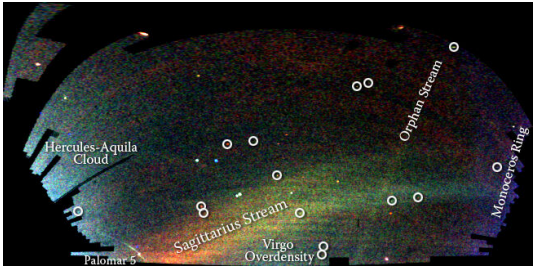
GD-1 [Grillmair&Dionatos 2006] – SDSS



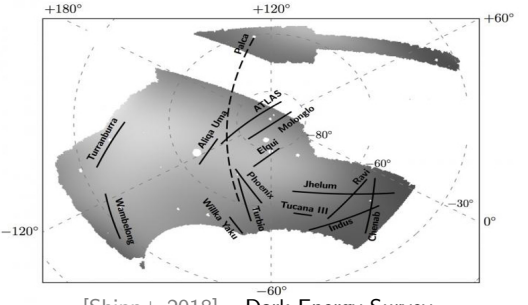


[Price-Whelan&Bonaca 2018] – PanSTARRS+GaiaDR2

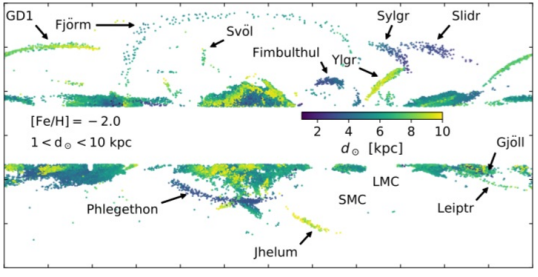
Streams in the Milky Way



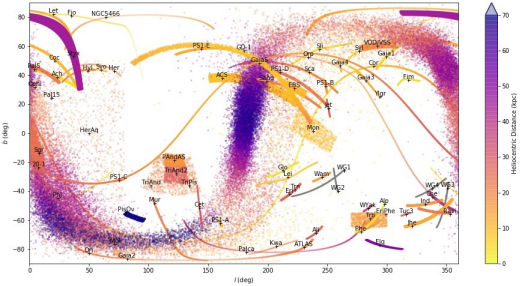
[Belokurov+ 2006] – SDSS field of streams



[Shipp+ 2018] – Dark Energy Survey



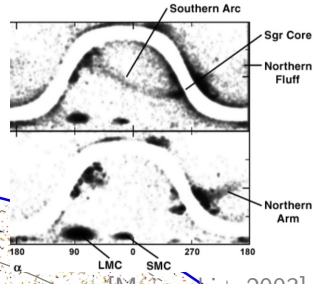
[Ibata+ 2018] – GaiaDR2



GalStreams database [C.Mateu+]

Sagittarius: the King of Streams

colour selection corresponding to M giants in 2MASS



[Majewski+ 2003]

leading arm

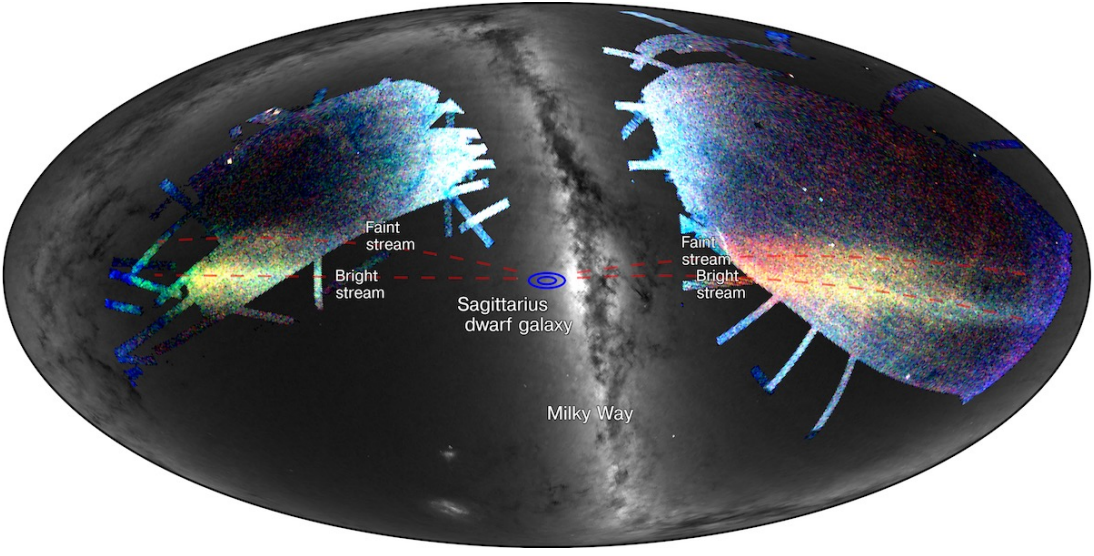
trailing arm

Ks mag.

11 12 13 14

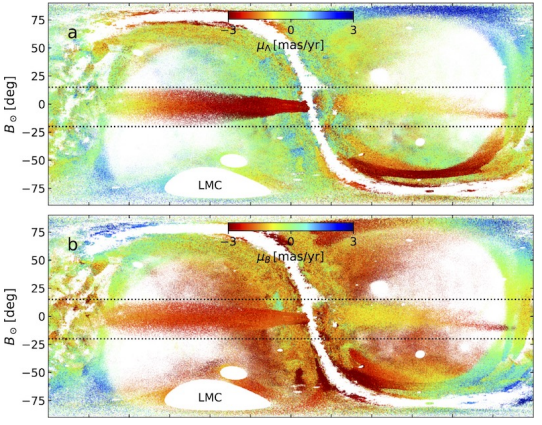
Sagittarius: the King of Streams

colour selection in SDSS: stream bifurcation [Belokurov+ 2006; Koposov+ 2012]

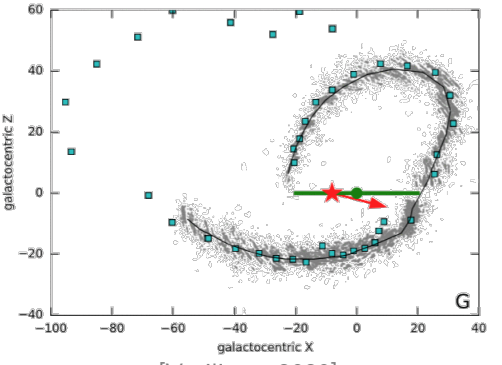


Sagittarius: the King of Streams

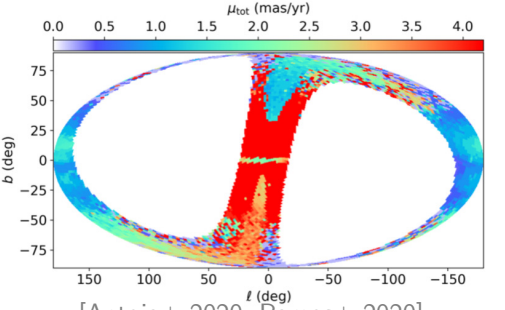
All-sky panorama of the stream provided by Gaia DR2



[Ibata+ 2020]



[Vasiliev+ 2020]



[Antoja+ 2020; Ramos+ 2020]

How to find stuff, part 0: look at your data

LETTERS TO NATURE VOL 370 · 21 JULY 1994

A dwarf satellite galaxy in Sagittarius

R. A. Ibata*, G. Gilmore* & M. J. Irwin†

* Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA, UK
† Royal Greenwich Observatory, Madingley Road, Cambridge CB3 OEZ, UK

We have detected a large, extended group of comoving stars in the direction of the Galactic Centre, which we interpret as belonging to a dwarf galaxy that is closer to our own Galaxy than any other yet known. Located in the constellation of Sagittarius, and on the far side of the Galactic Centre, it has not previously been seen because of the large number of foreground stars (in the Milky Way) in that direction. Following convention, we propose to call it the Sagittarius dwarf galaxy. Its properties are similar to those of the eight other dwarf spheroidal companions to the Milky Way, and it is comparable in size and luminosity to the largest of them—the Fornax system. The Sagittarius dwarf is elongated towards the plane of the Milky Way, suggesting that it is undergoing some tidal disruption before being absorbed by the Milky Way.

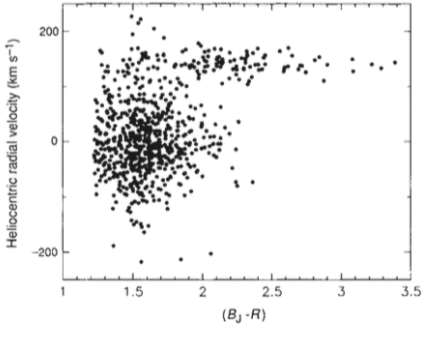


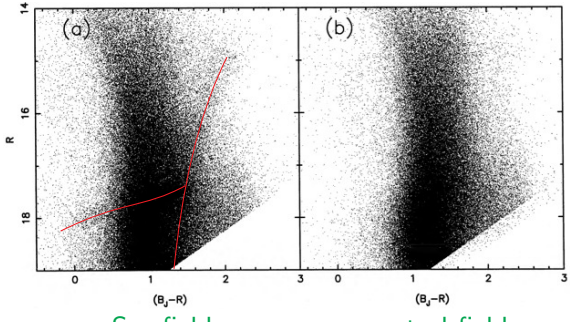
FIG. 1 The heliocentric radial velocity–colour distribution for three selected regions at Galactic coordinates $l=5°$, $b=-12°$, $-15°$ and $-20°$. The population with mean velocity of 0 km s^{-1} and dispersion 70 km s^{-1} is the expected Galactic bulge. There is a clear excess of stars at a common velocity of ~140 km s^{-1} extending to (B_J-R) colours >3. This feature does not appear in any of the other regions for which spectroscopy has been obtained. The excess of stars is most prominent at $l=5°$, $b=-15°$ but is also unambiguously present in the other two regions.

How to find stuff, part 0: look at your data

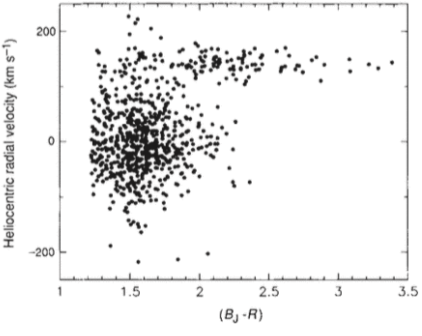
LETTERS TO NATURE VOL 370 · 21 JULY 1994

A dwarf satellite galaxy in Sagittarius

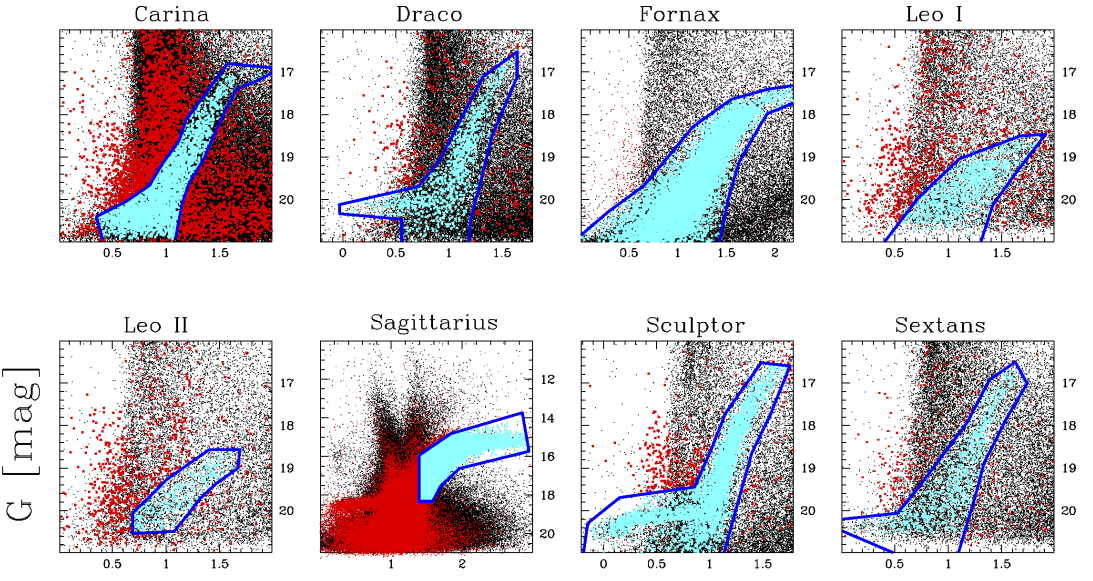
R. A. Ibata*, G. Gilmore* & M. J. Irwin†



Sgr field control field



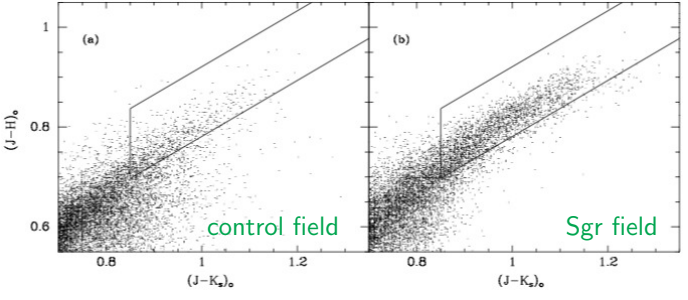
How to find stuff, part I: simple filters



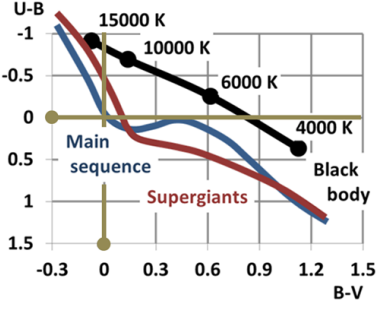
[Gaia Collaboration: Helmi+ 2018]

How to find stuff, part I: simple filters

If the distance is not known:
try different magnitude offsets for the CMD filter,
or use a colour–colour filter optimized for selecting giant stars



[Majewski+ 2003]



[source: Wikipedia]

How to find stuff, part II: matched filters

Improve the signal-to-noise ratio by boosting the parts of the CMD filter (or any other data dimension) where the contrast between the object and the foreground is stronger (e.g., Rockosi+ 2002 for Pal 5).

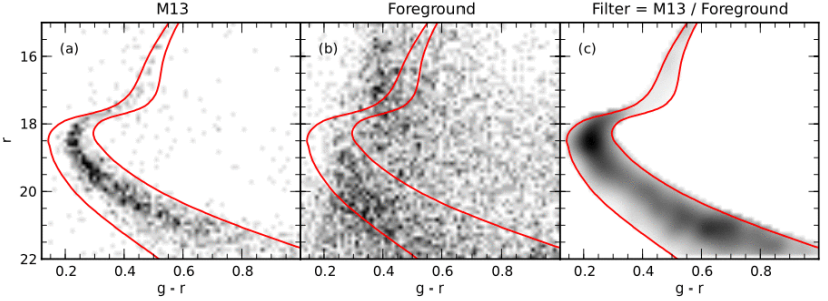


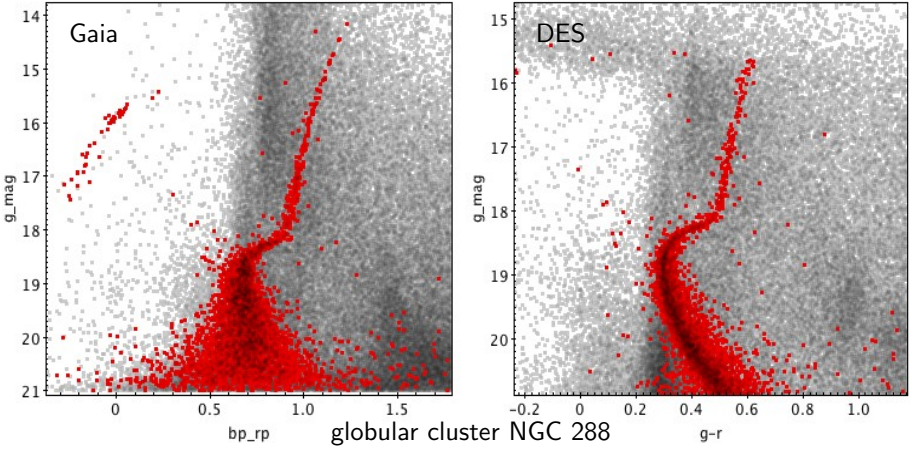
Figure 1. Steps in creating an M13-based filter for selection of old, metal-poor stars: the left panel shows a Hess diagram of SDSS stars detected in the inner region of globular cluster M13, while that of a surrounding area, representative of Milky Way foreground, is given in the middle panel. A ratio of the two produces the desired filter, which preferentially selects stars that are in the region of the color–magnitude diagram with the greatest contrast between M13 and Milky Way stellar populations. In order to reduce clumpiness, the filter is smoothed (right panel). The resulting filter is most heavily weighted near the main-sequence turnoff. Red lines, derived from an isochrone matching the M13 population, trace the width of the filter on all three panels.

[Bonaca+ 2012]

How to find stuff, part II: matched filters

Improve the signal-to-noise ratio by boosting the parts of the CMD filter (or any other data dimension) where the contrast between the object and the foreground is stronger (e.g., Rockosi+ 2002 for Pal 5).

Note: high-quality and deep photometry is crucial here! (and elsewhere)

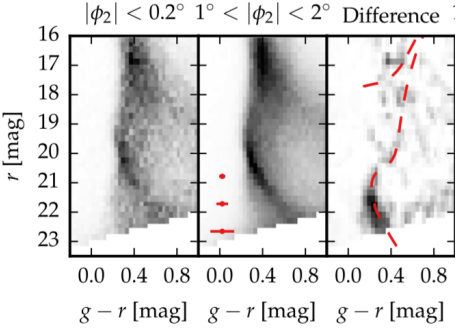


globular cluster NGC 288

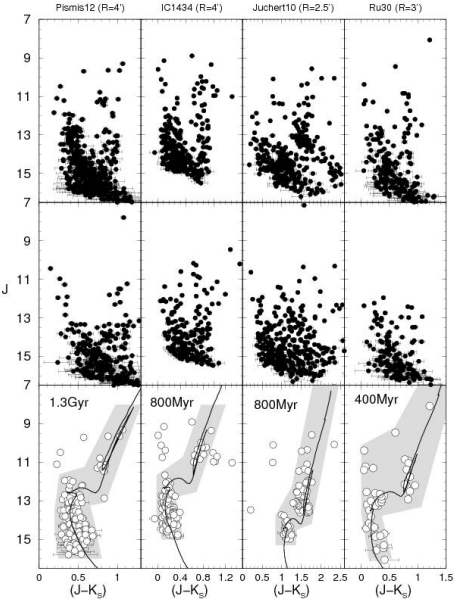
How to find stuff, part III: statistical decontamination

Clean up the CMD by "subtracting" the background population at the level of individual objects, without binning them first.

For each star in the field of interest, find a close analogue (in terms of CMD location) in the control field, and if found, remove this star with some probability.



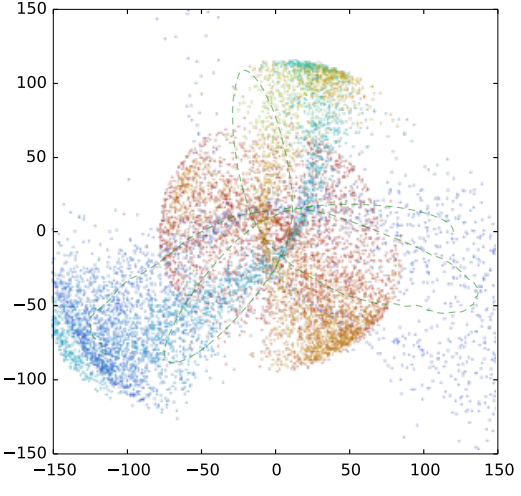
binned (Hess difference): [Jethwa+ 2017]



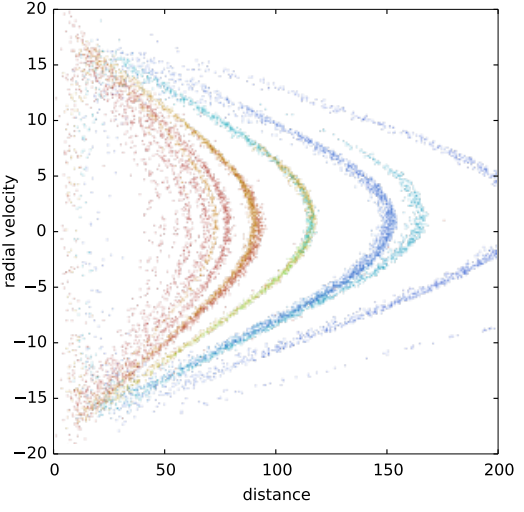
unbinned: [Bica&Bonato 2011]

How to find stuff, part IV: unsharp masking

Example: finding shells by looking for apocentre turnaround points

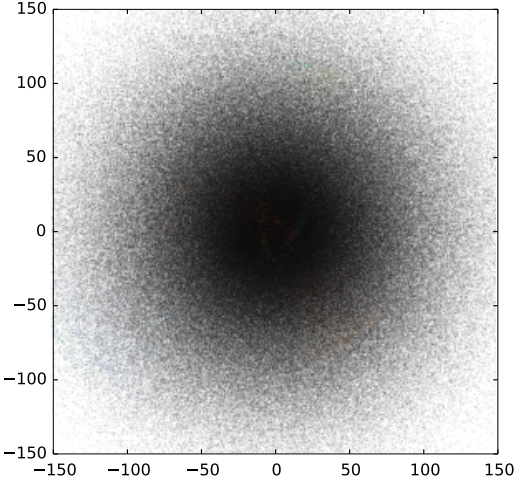


disrupted satellite in r vs v_r space

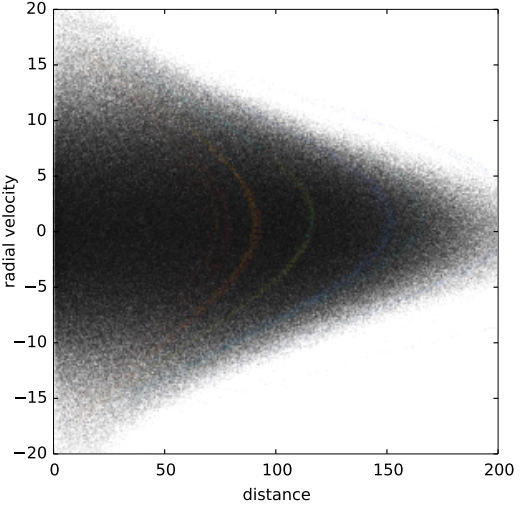


How to find stuff, part IV: unsharp masking

Example: finding shells by looking for apocentre turnaround points

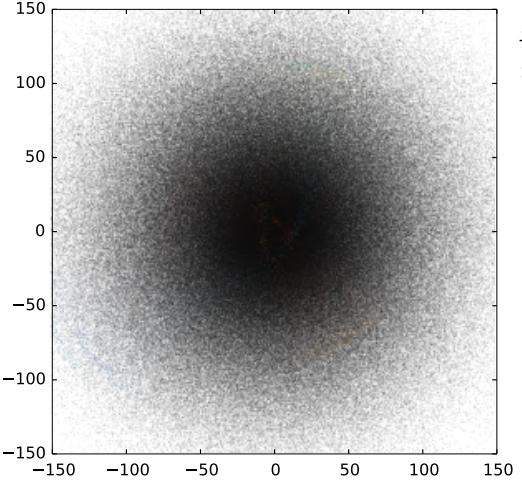


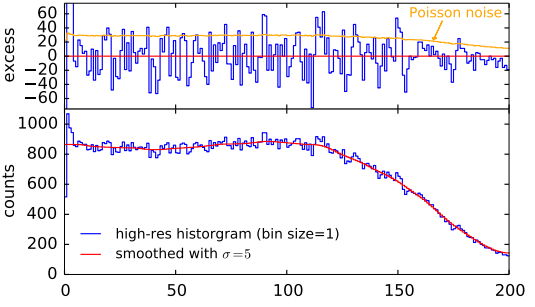
all stars including the foreground

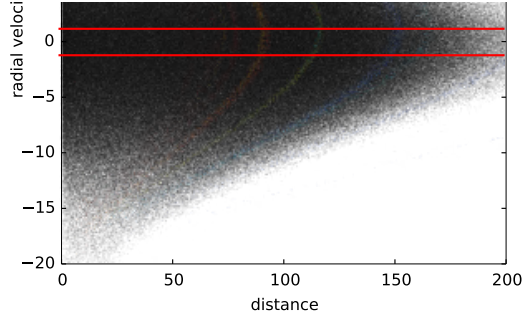


How to find stuff, part IV: unsharp masking

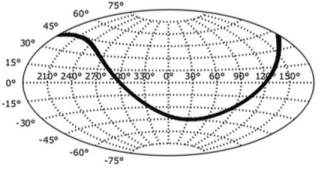
Example: finding shells by looking for apocentre turnaround points

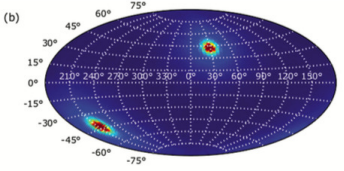




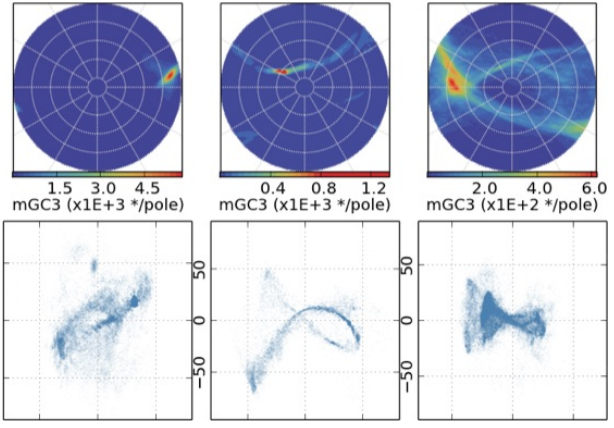


How to find stuff, part V: search for orbital segments





Great circle cell count (GC3) method [Johnston+ 1996] and its extensions to kinematic datasets (nGC3, mGC3)



[Mateu+ 2011, 2017]

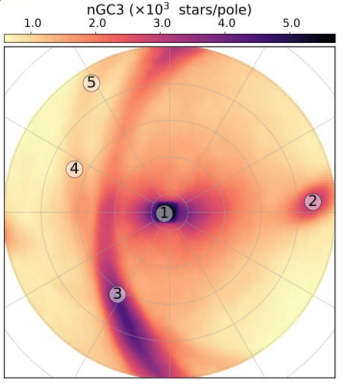
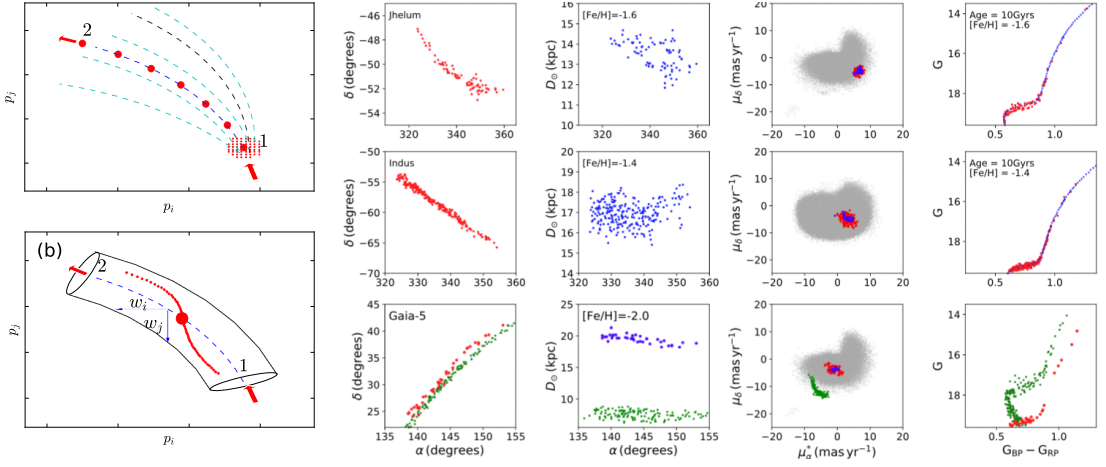


Fig. 1. Pole Count Map of the RR Lyrae catalogue described in Sect. 2. The Galactic disc produces the large concentration at (1), while the peaks (3),(4), and (5) are related to the Large and Small Magellanic clouds. The prominent signal on the right, (2), is caused by the Sgr stream.

[Ramos+ 2020]

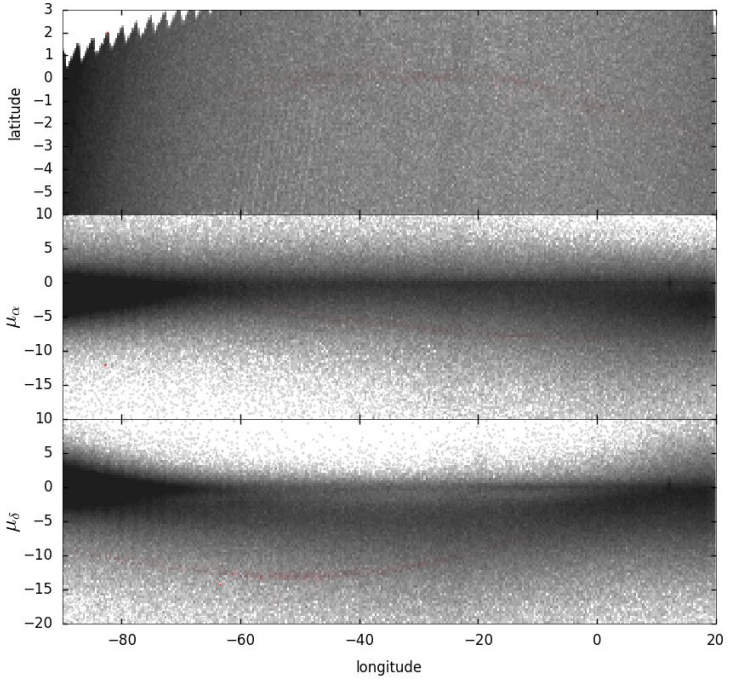
How to find stuff, part V: search for orbital segments

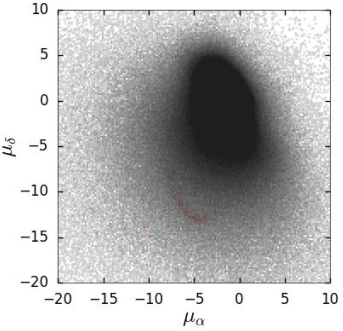
STREAMFINDER: consider all possible orbits emanating from a given star and count the number of other stars aligned with the orbit segment [Malhan&Ibata 2018]

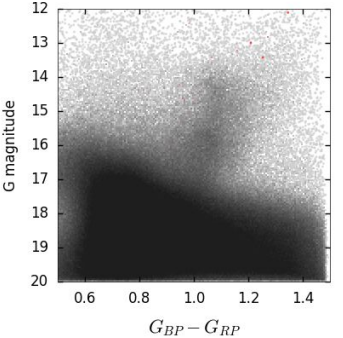


[Malhan+ 2018]

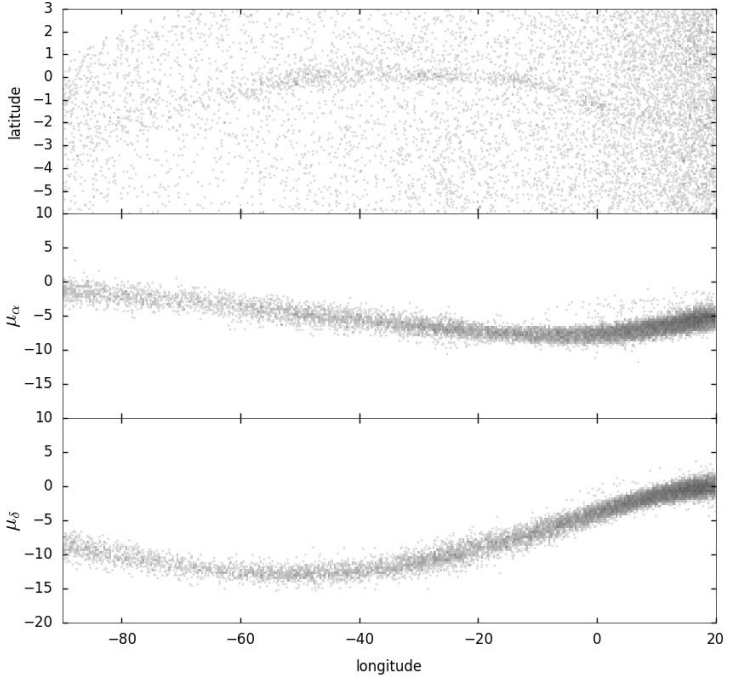
Finding streams with Gaia

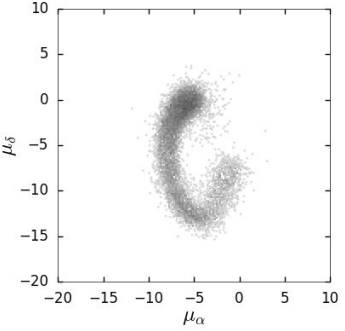


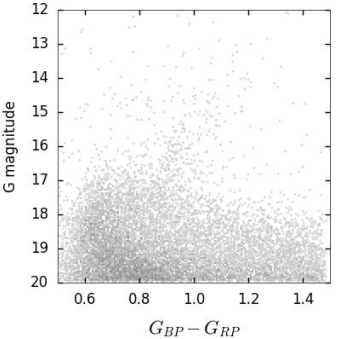




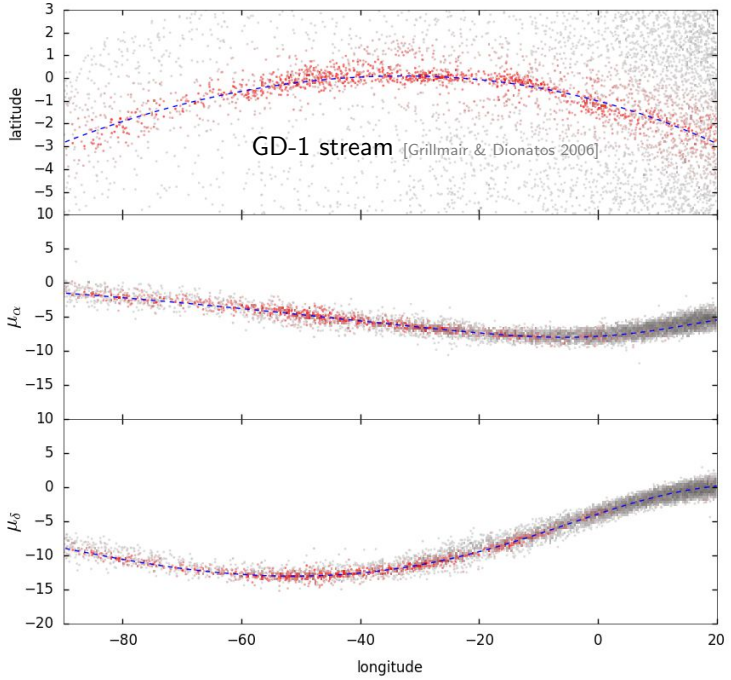
Finding streams with Gaia

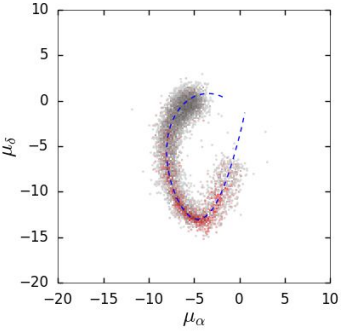


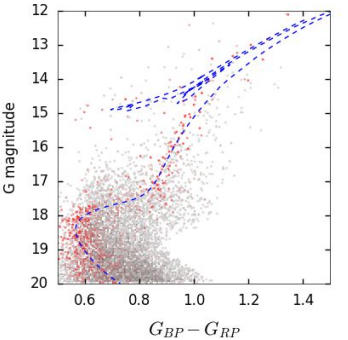




Finding streams with Gaia

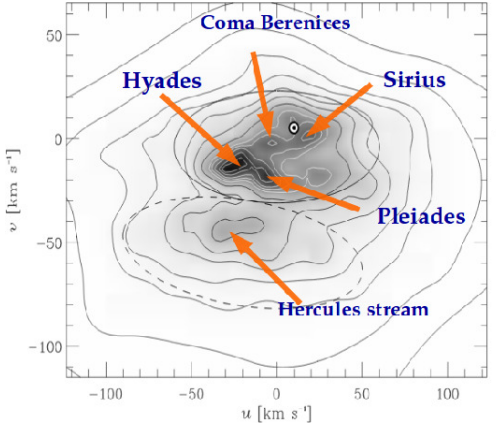




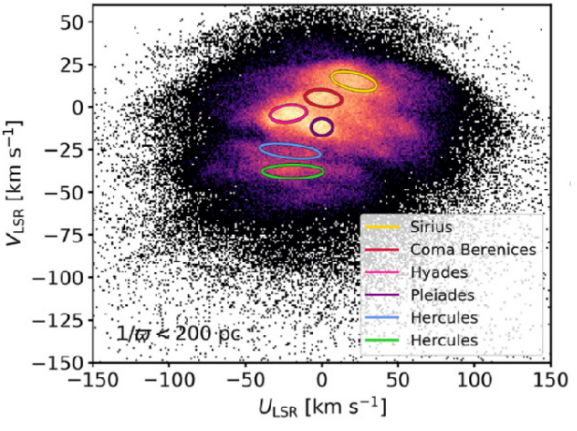


How to find stuff, part VI: structures in the velocity space

"Moving groups" in the Solar neighbourhood:
believed to be associated with non-axisymmetric features in the Galactic disc (bar, spiral arms), not with accreted structures

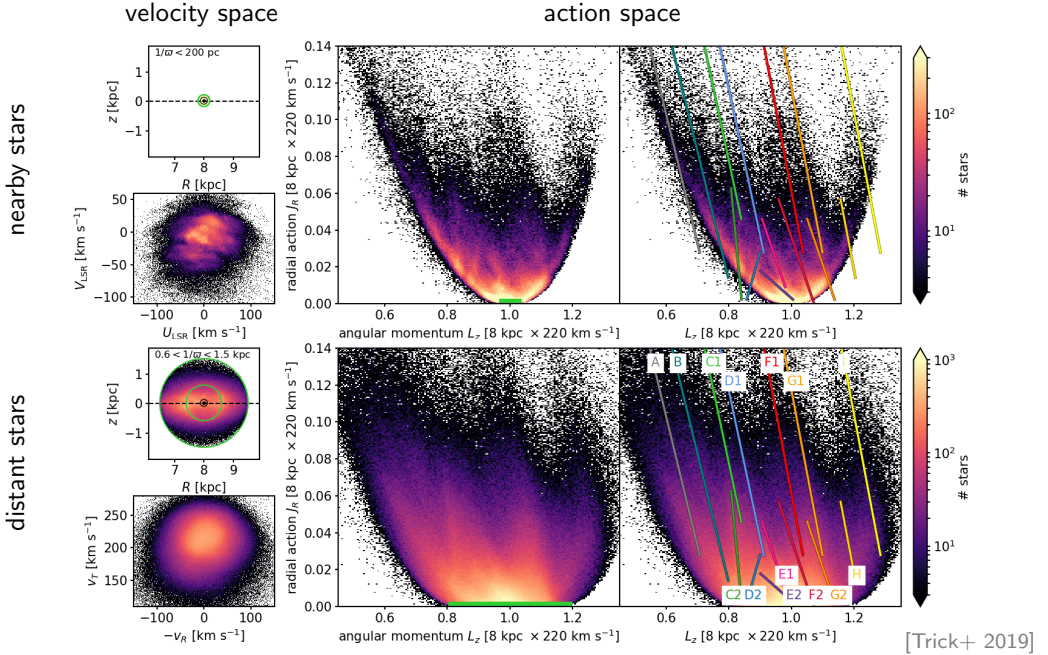


[Dehnen 2000]



[Trick+ 2019]

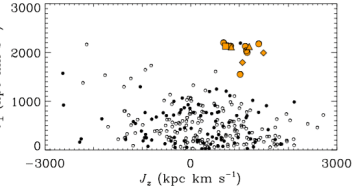
How to find stuff, part VI: structures in the velocity space



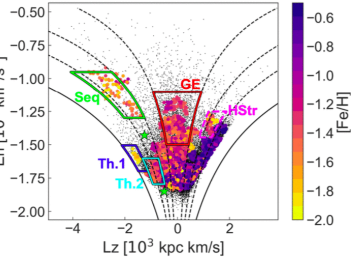
[Trick+ 2019]

How to find stuff, part VII: structures in the integral space

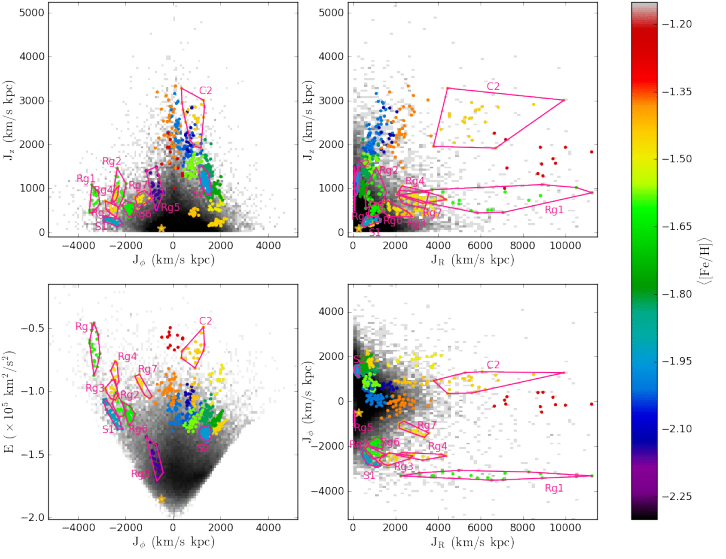
$E : L_z$, $L_\perp : L_z$, $J_r : J_\phi$, ...



[Helmi+ 1999]



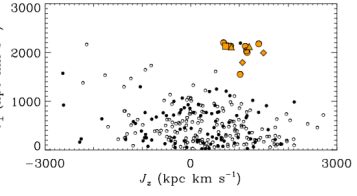
[Koppelman+ 2019]



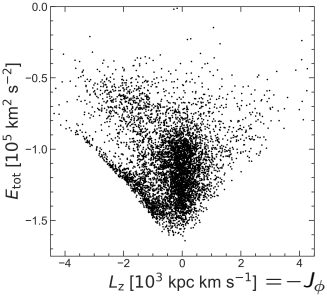
[Myeong+ 2018]

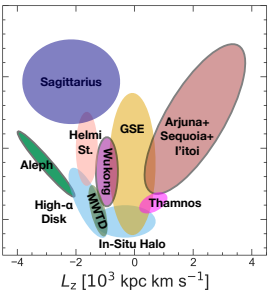
How to find stuff, part VII: structures in the integral space

$E : L_z$, $L_\perp : L_z$, $J_r : J_\phi$, ...

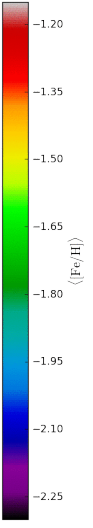


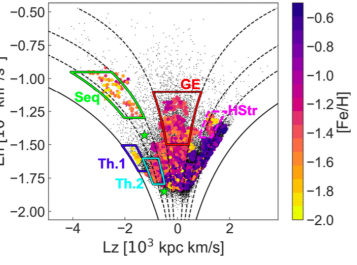
[Helmi+ 1999]



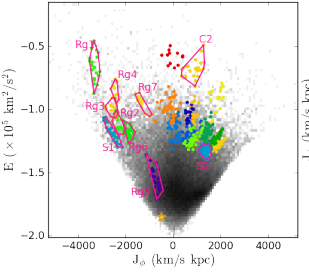


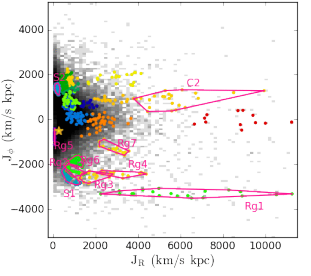
[Naidu+ 2020]





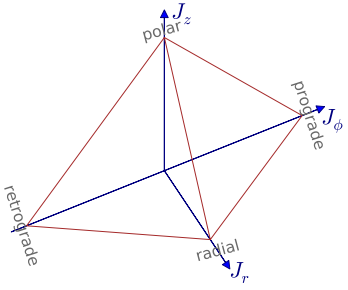
[Koppelman+ 2019]

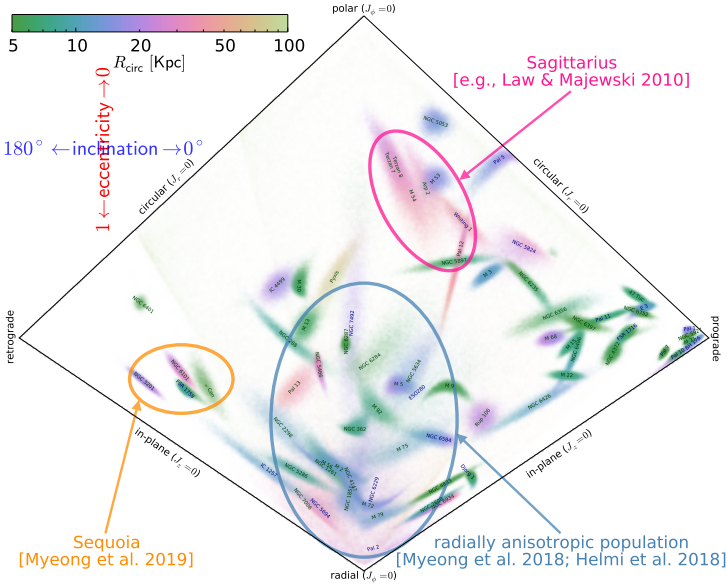




[Myeong+ 2018]

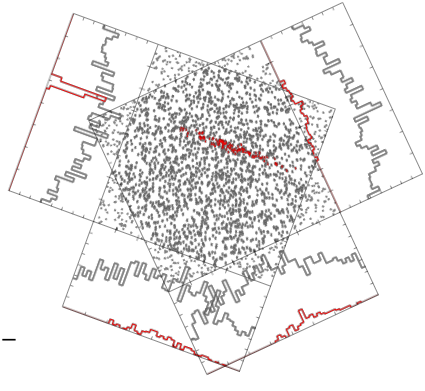
How to find stuff, part VII: structures in the integral space





[Vasiliev 2019]

How to find stuff: summary



- choose the right projection:
  streams are thin in two out of three dimensions
- subtract the smooth background:
  decontamination, unsharp masking
- if possible, use a curvilinear projection:
  methods based on orbit fitting or integrals of motion –
  the results do depend on the potential!
- use as many dimensions of data as possible:
  contrast increases with the number of dimensions –
  colours, chemistry, ...
- don't be afraid to throw away much of your data,
  if this increases contrast