Modern stellar dynamics, lecture 11: stellar streams and galactic archeology

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Motion in the rotating frame

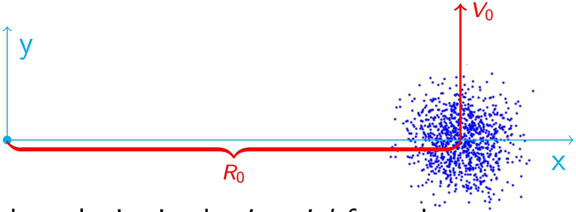
A satellite galaxy or a star cluster on a circular orbit in the host galaxy:

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 $V_0 = \sqrt{R_0\, \partial\Phi/\partial x\big|_{x=R_0}}$;
$\boldsymbol{\Omega} \equiv \{0, 0, V_0/R_0\}$ is the angular velocity of the cluster.

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

Hamilton's equations of motion:

$$\begin{aligned} \dot{\mathbf{x}} &= \quad \mathbf{p} \quad - \boldsymbol{\Omega}\times\mathbf{x} \\ \dot{\mathbf{p}} &= -\nabla\Phi - \boldsymbol{\Omega}\times\mathbf{p} \end{aligned}$$



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:

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

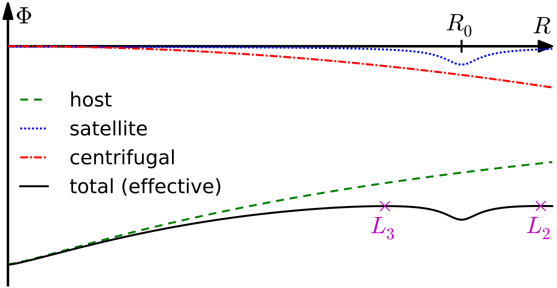
Saddle points of Φ_eff (Lagrange points L_2, L_3) are defined by $\partial\Phi_\mathrm{eff}/\partial x = 0$.

For a pointlike satellite

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

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

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

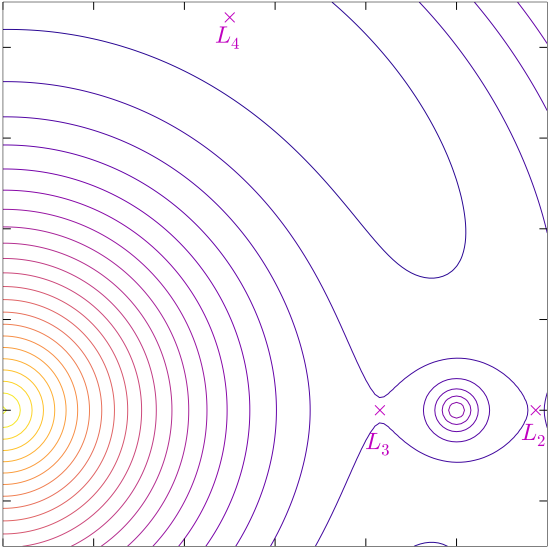


Tidal radius (Jacobi radius, Hill sphere, Roche lobe, ...)

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

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

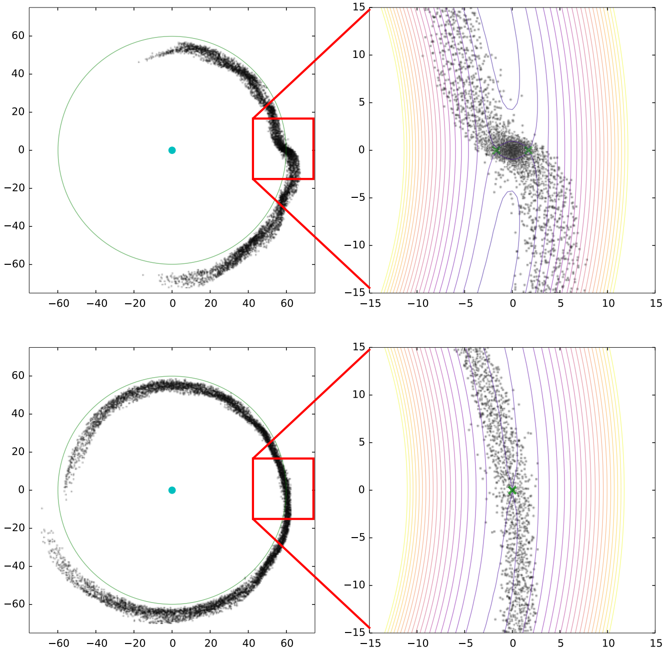
More generally:
the denominator in R_t is
$\propto \, \Omega^2 \, \propto \, M_\mathrm{h}(< R_0) \, / \, R_0^3$
(the mean density of the host galaxy within the radius of the orbit R_0),
and the mass of the satellite spread over the volume of the Hill sphere is of the same order.



Stellar system in a tidal field

Consider a stellar system (star cluster or a satellite galaxy) on a circular orbit around the host galaxy. Stars outside the Hill sphere are no longer bound and form a two-arm tidal stream, with the leading arm closer to the host galaxy's centre and spreading ahead of the satellite orbit, and the trailing arm lagging behind and staying at larger distance.

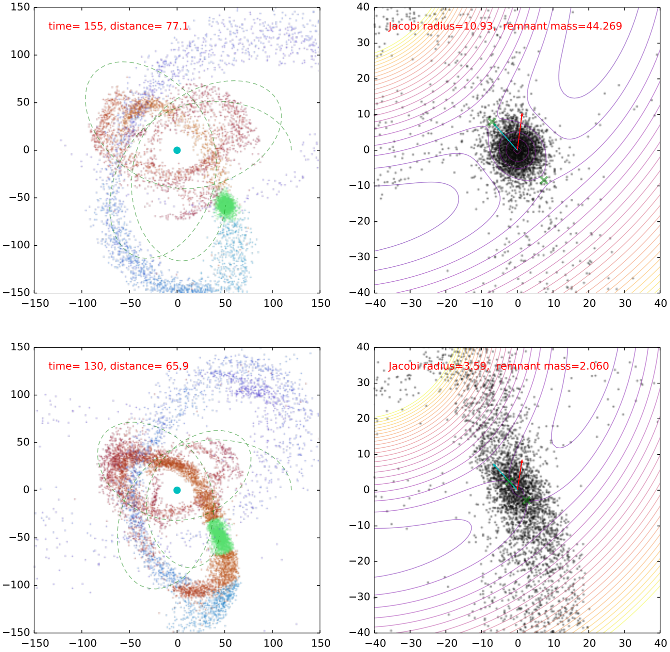
As the stars escape through the Largange points, the mass of the satellite decreases, and so does the Hill radius. Eventually the satellite will be completely disrupted, if its central density is below the critical value (the mean density of the host galaxy within the satellite orbit).



Stellar system in a tidal field

In the case of eccentric orbits, the simple rotating frame picture remains qualitatively valid, but with the Hill radius varying along the orbit and reaching minimum at pericentre. Thus the satellite undergoes most stripping from "tidal shocks" during pericentre passages.

A massive satellite further experiences dynamical friction in the host galaxy, which shrinks its orbit and accelerates tidal disruption even further.

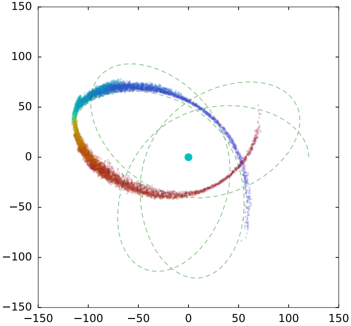


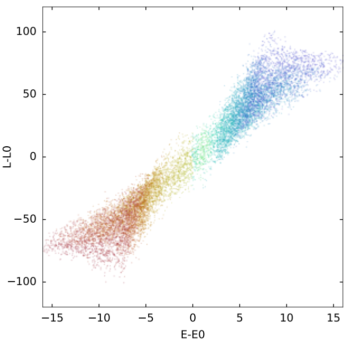
Evolution of tidal debris in the $E - L$ and action–angle spaces

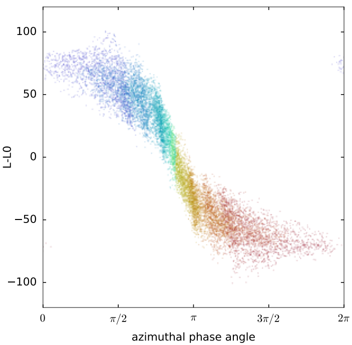
The stars in the leading/trailing arm have lower/higher energy and angular momentum than the progenitor, producing a characteristic "bow-tie" structure in the $E - L$ space.

The gradual spreading of the stream is caused by the variation of the orbital frequency with energy: stars in the leading/trailing arm have higher/lower frequency than the progenitor and move faster/slower in the angle space, stretching further with time.

Thus, strictly speaking, stars in a stream do not follow the same orbit, but rather on a family of nearby orbits with well-defined gradient of parameters determined by the properties of the progenitor.

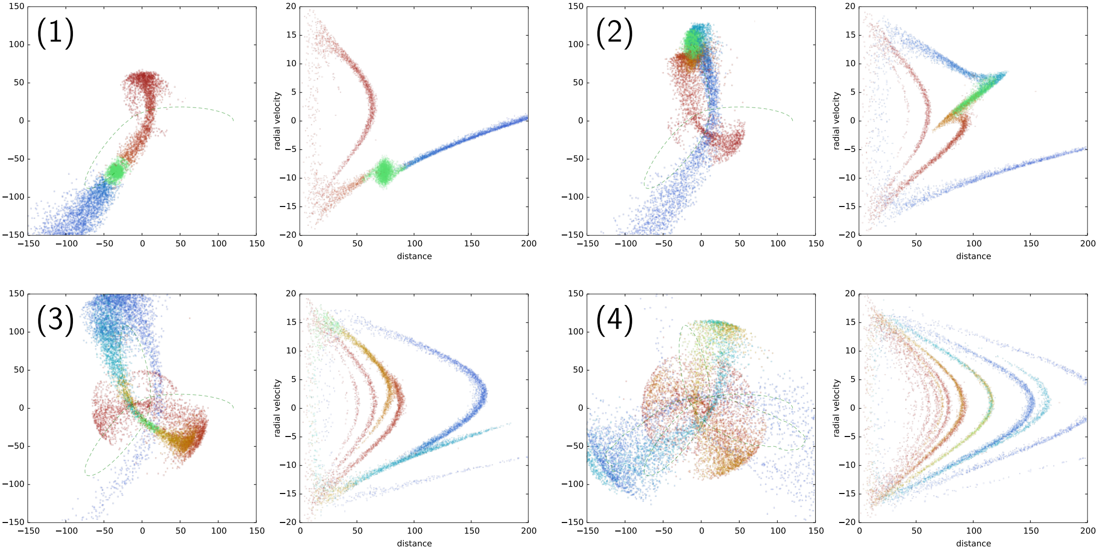




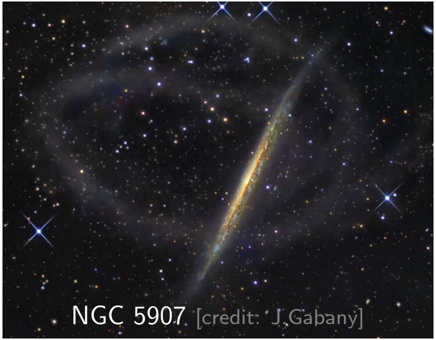


Formation of shells in head-on collisions

Each pericentre passage close to the host galaxy's centre produces a shell-like feature in the configuration space and a wedge-like structure in the $r - v_r$ space.

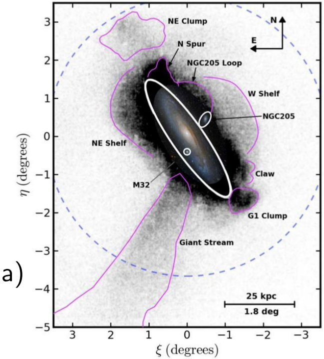


Shells and streams in external galaxies

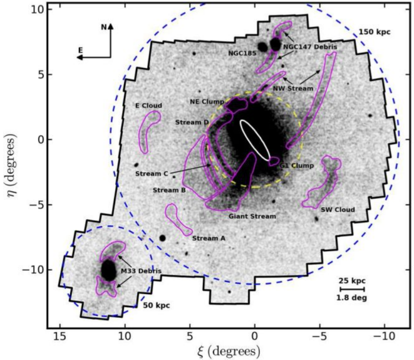


NGC 5907 [credit: J.Gabany]

NGC 474 [credit: P.-A.Duc, J.-C.Cuillandre]

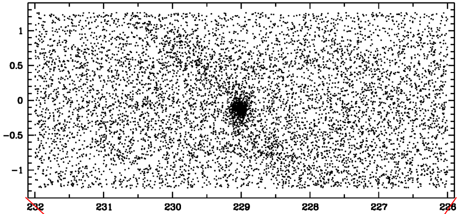


M 31 (Andromeda)
[credit: A.Ferguson, PAndAS survey]

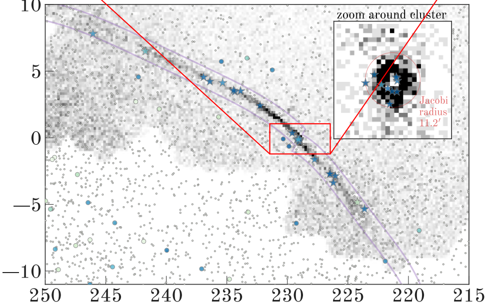


Streams in the Milky Way

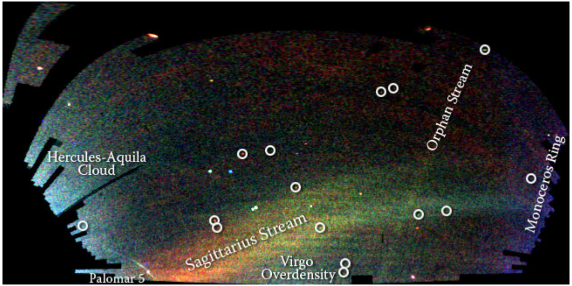
Globular cluster Palomar 5



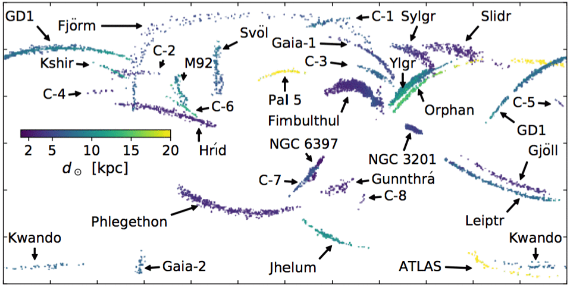
. . . in 2001 [Odenkirchen et al.]



. . . in 2019 [Price-Whelan et al.]



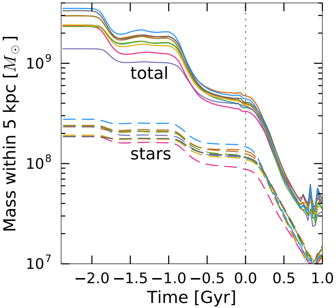
field of streams in SDSS survey [Belokurov+ 2006]

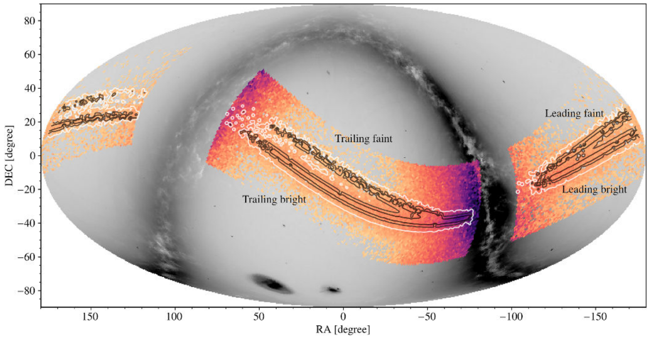


census of streams in *Gaia* EDR3 [Ibata+ 2020]

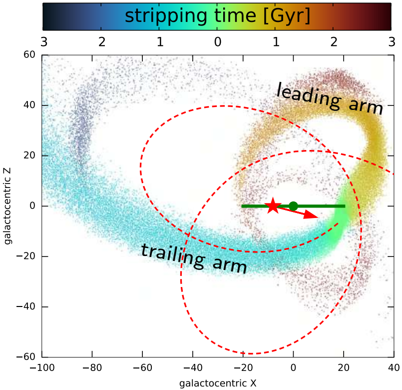
Sagittarius: the King of Streams

Sgr galaxy is the 3rd largest Milky Way satellite, but it was discovered only recently [Ibata+ 1994], being hidden behind the Galactic bulge. Its proximity to the Milky Way produces an enormous tidal stream stretching across the entire sky, first mapped out by the 2MASS survey [Majewski+ 2003] and more recently by SDSS and Gaia. The original stellar mass of the Sgr galaxy was $\sim 2\times10^8\,M_\odot$, half of it still resides in the remnant; the total mass was $\gtrsim 10^{10}\,M_\odot$, but over 95% of it has been already stripped, and the remnant is likely to be disrupted in the next Gyr.



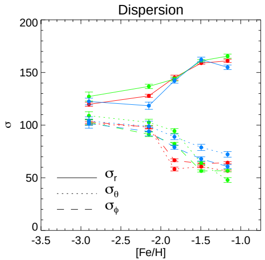


[Ramos+ 2022]



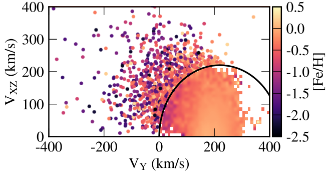
[Vasiliev+ 2021]

Traces of past accretion events: velocity and chemical spaces

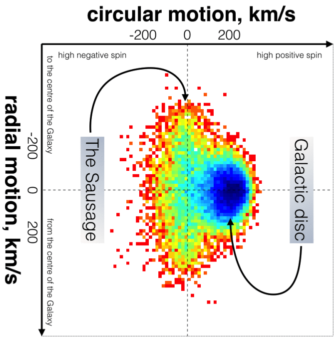


Stars and globular clusters accreted in the early days of the Milky Way history can be identified even at present time thanks to their peculiar chemical and kinematic properties.

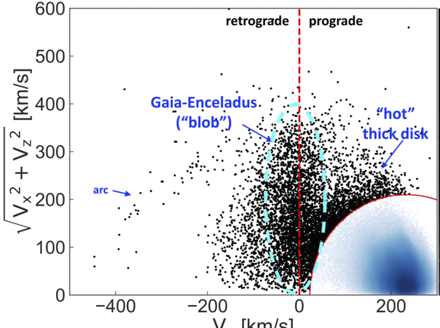
In recent years it became clear that a major fraction of metal-rich halo in the Solar neighbourhood has strongly radial orbits, tracing a nearly head-on collision with a massive satellite some 8 – 10 Gyr ago.



[Bonaca+ 2017]



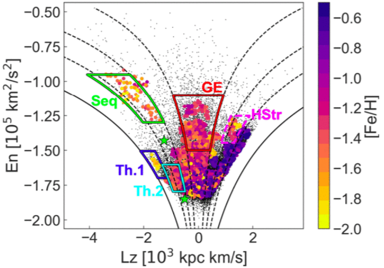
[Belokurov+ 2018]



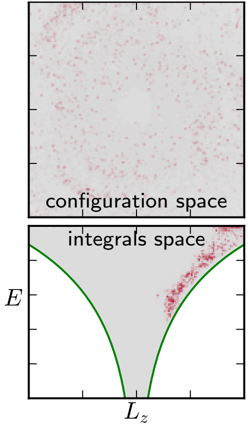
[Helmi+ 2018]

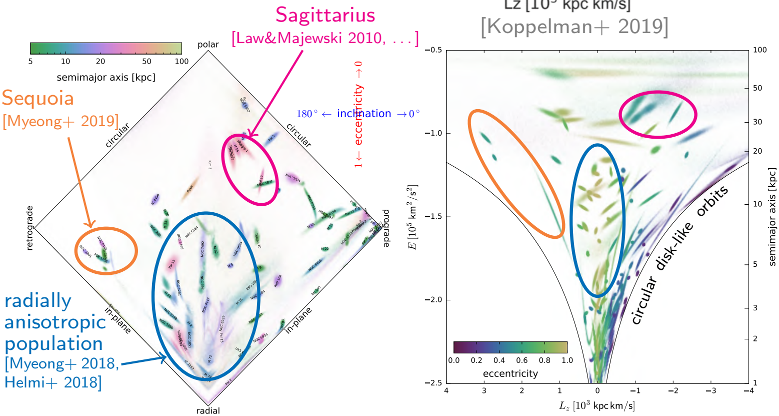
Traces of past accretion events: orbits/integrals space

"Old" debris that have been phase mixed and are not discernible in the position–velocity space anymore, can still be identified in the space of integrals of motion (energy and L_z, or actions). However, this requires that the potential used to compute the integrals is close to the true one. Moreover, significant perturbations in the potential may destroy the coherent appearance of debris in the integrals space.



[Koppelman+ 2019]

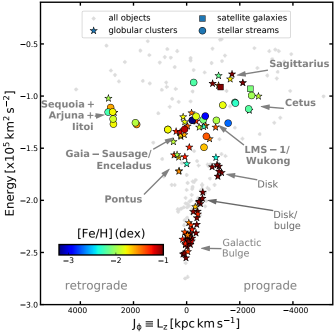




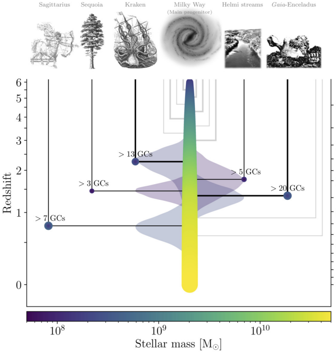
Traces of past accretion events

"Galactic archeology" is a burgeoning field of research, aimed at reconstructing the accretion history of the Milky Way and properties of the disrupted galaxies from the analysis of the distribution of globular clusters, streams and halo stars in the spaces of integrals of motion and chemical features.

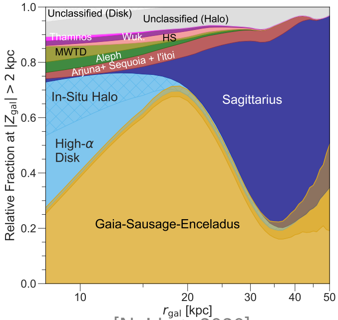
It appears that most of the halo beyond 10 – 20 kpc is accreted from a couple of major progenitors, but the detailed classification, attribution and naming differ between studies.



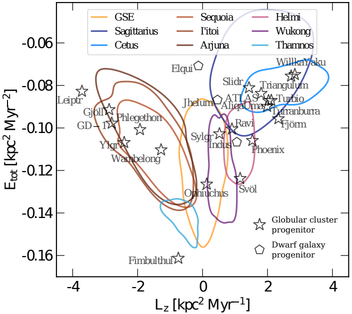
[Malhan+ 2022]



[Kruijssen+ 2020]



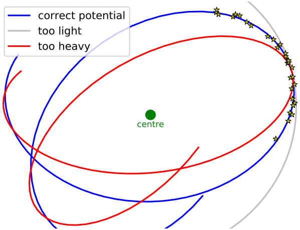
[Naidu+ 2020]



[Bonaca+ 2020]

Summary: what do we learn from streams and tidal debris?

- use stream orbits as probes of Galactic gravitational potential



stars in the stream travel along the same orbit, orbit depends on the Galactic potential $\Longrightarrow$ can measure the mass distribution

- untangle the assembly history and reconstruct the chemical and dynamical evolution of the Galaxy

$\Longrightarrow$