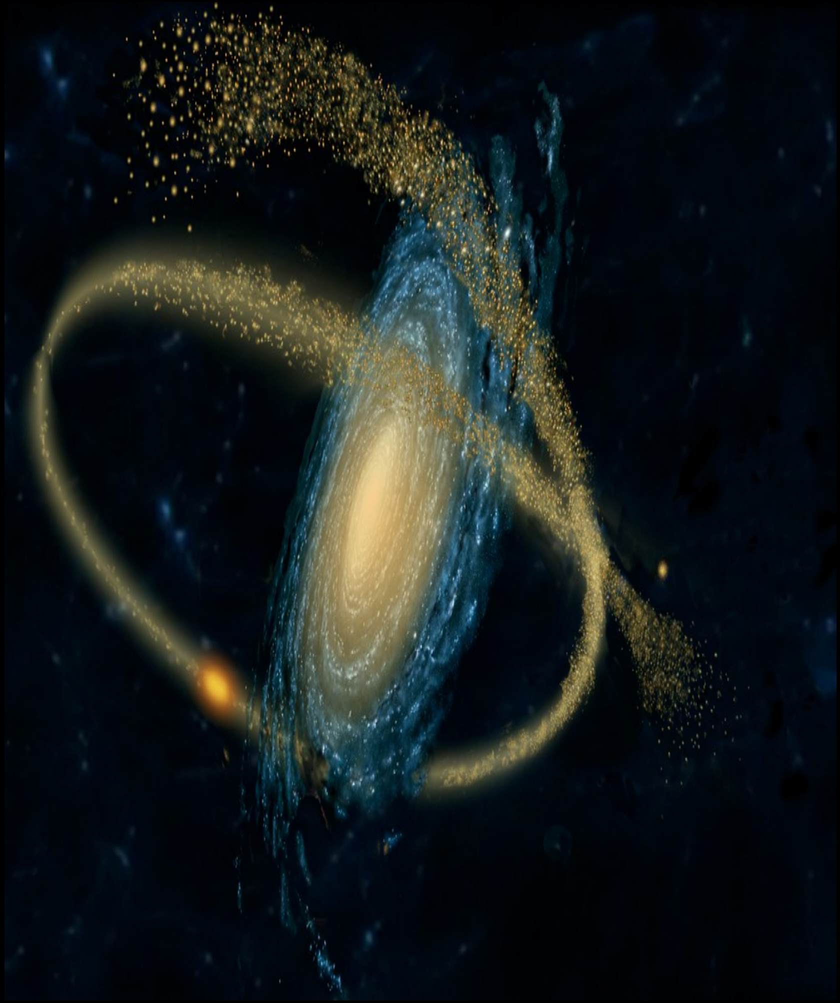
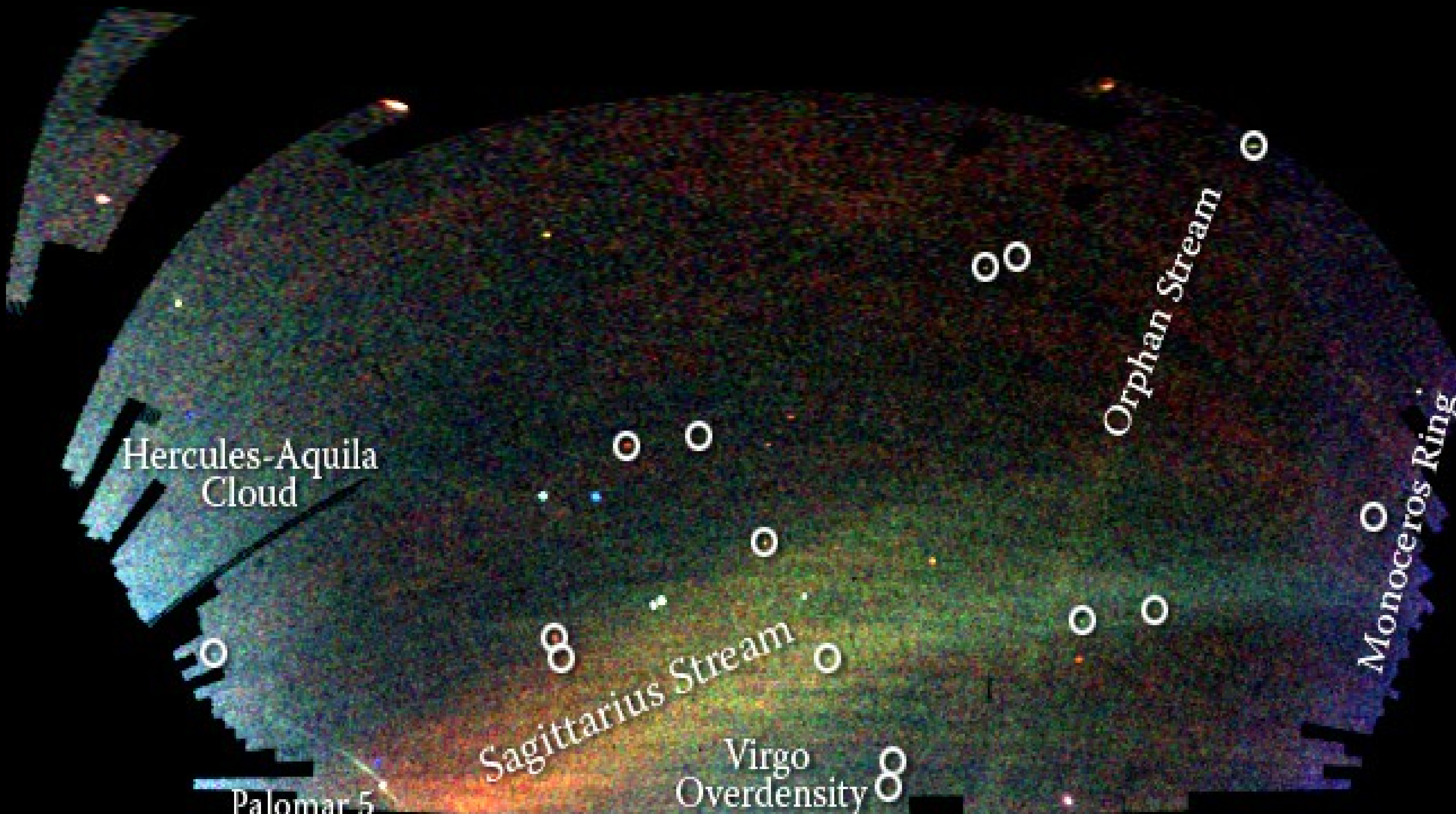
Using stellar streams to probe the galactic potential

By: Adam Bowden

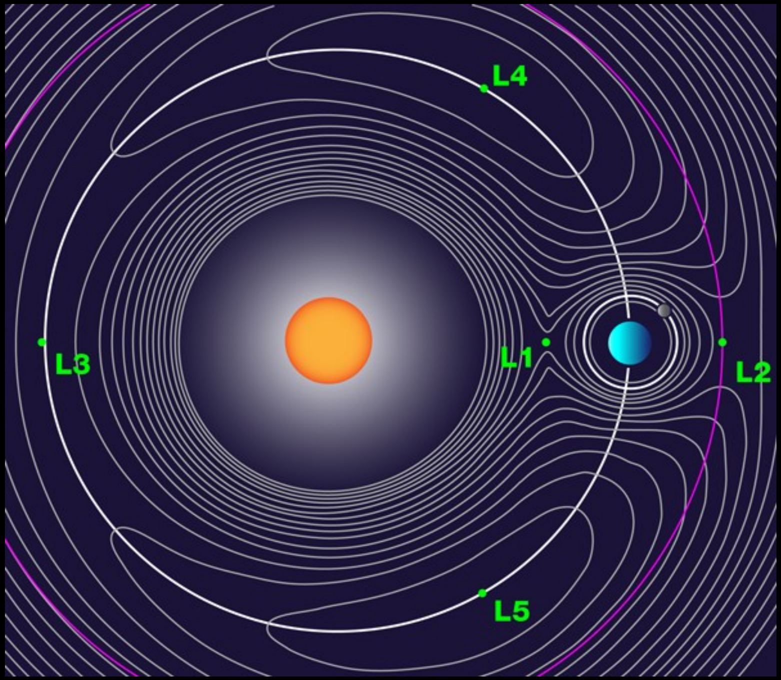


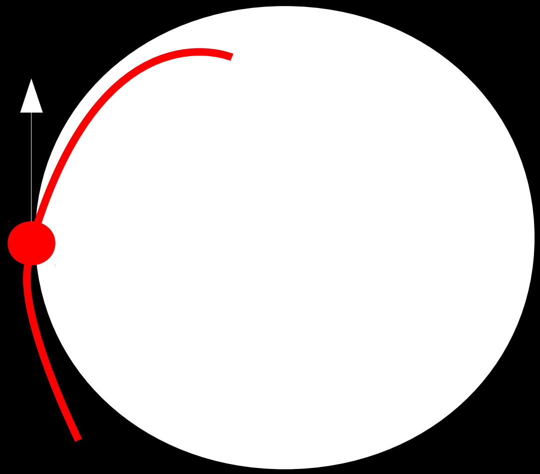


The “Field of Streams” from SDSS data
Image: Belokurov+06

Streams 101

- Stars are stripped from dwarf galaxies or globular clusters by tidal forces.
- Test particles can most easily escape through two Lagrange points, which define a constantly changing tidal radius.





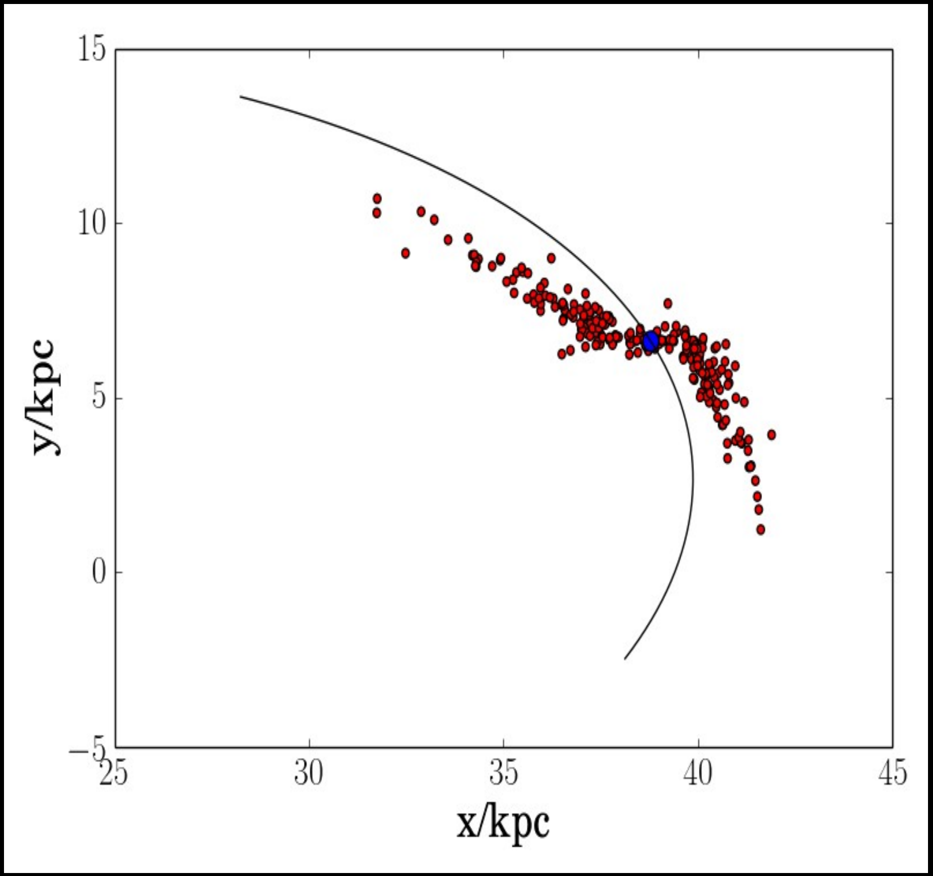
- Outer L-point – Higher E, longer P – trailing stream.
- Inner L-point – Lower E, shorter P – leading stream.

Modelling Streams

- We aim to learn about the halo potential in which the streams form.
- We can extract properties such as mass, flattening and maybe even substructure.

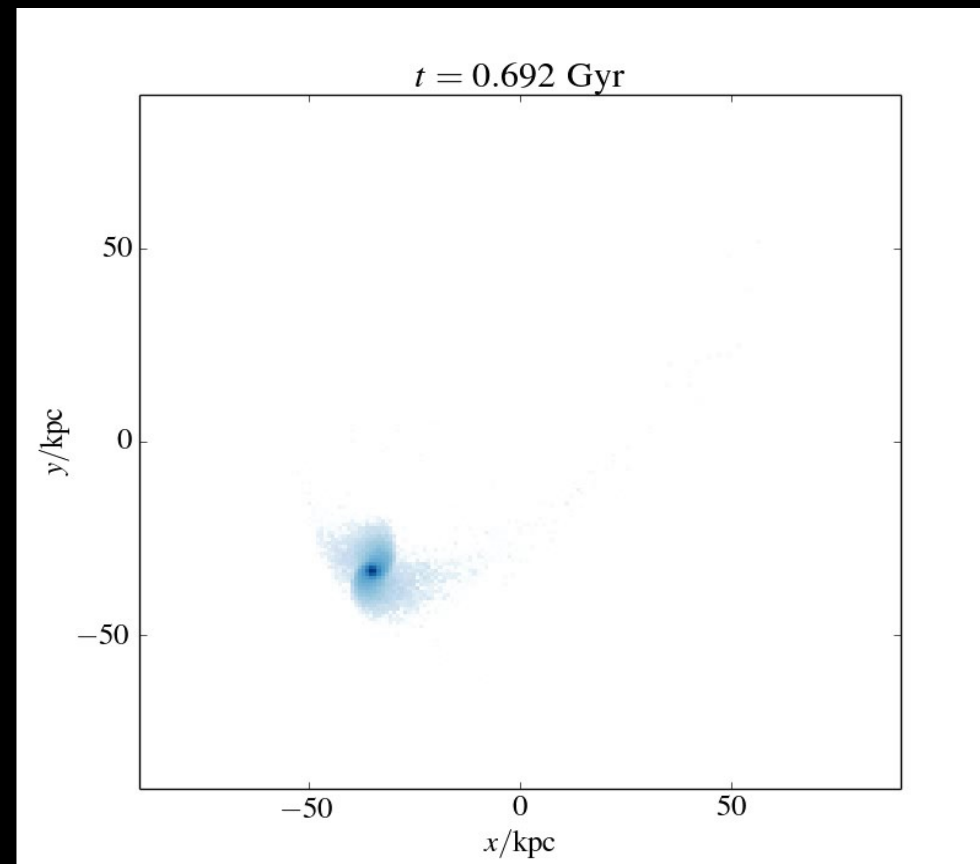
Orbit modelling

- To first order, streams look like orbits and can be fit as such.
- With this assumption, potential properties can be constrained simply.
- Alas, it's not quite that simple.



N-body simulations

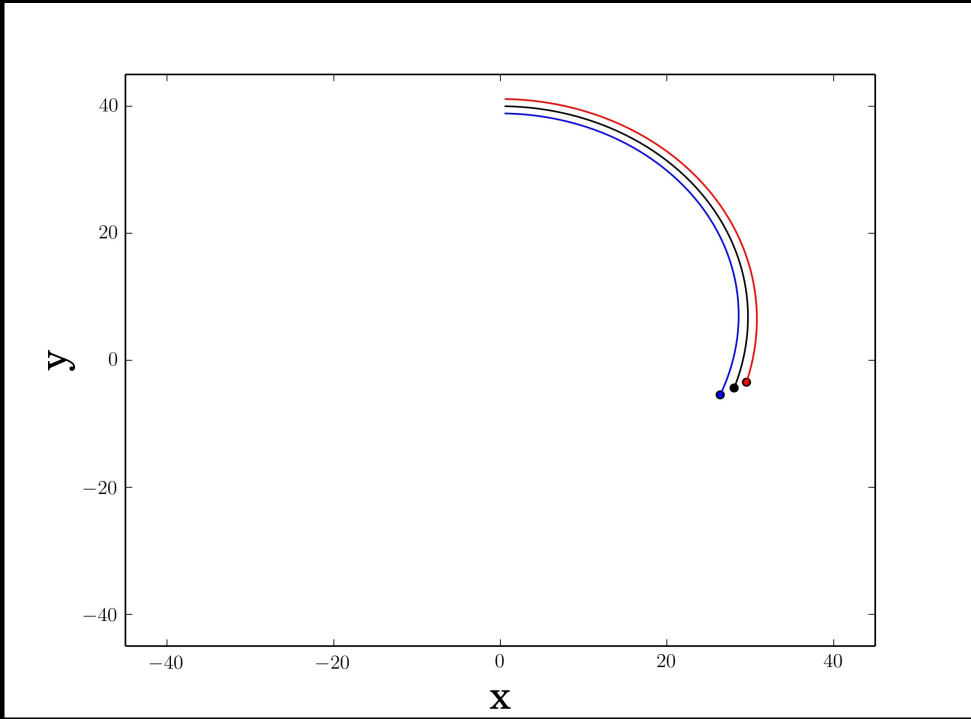
- N-body codes allow us to fully model a disrupting cluster.
- Good for providing insight into the disruption process.
- Too computationally intensive for parameter exploration.

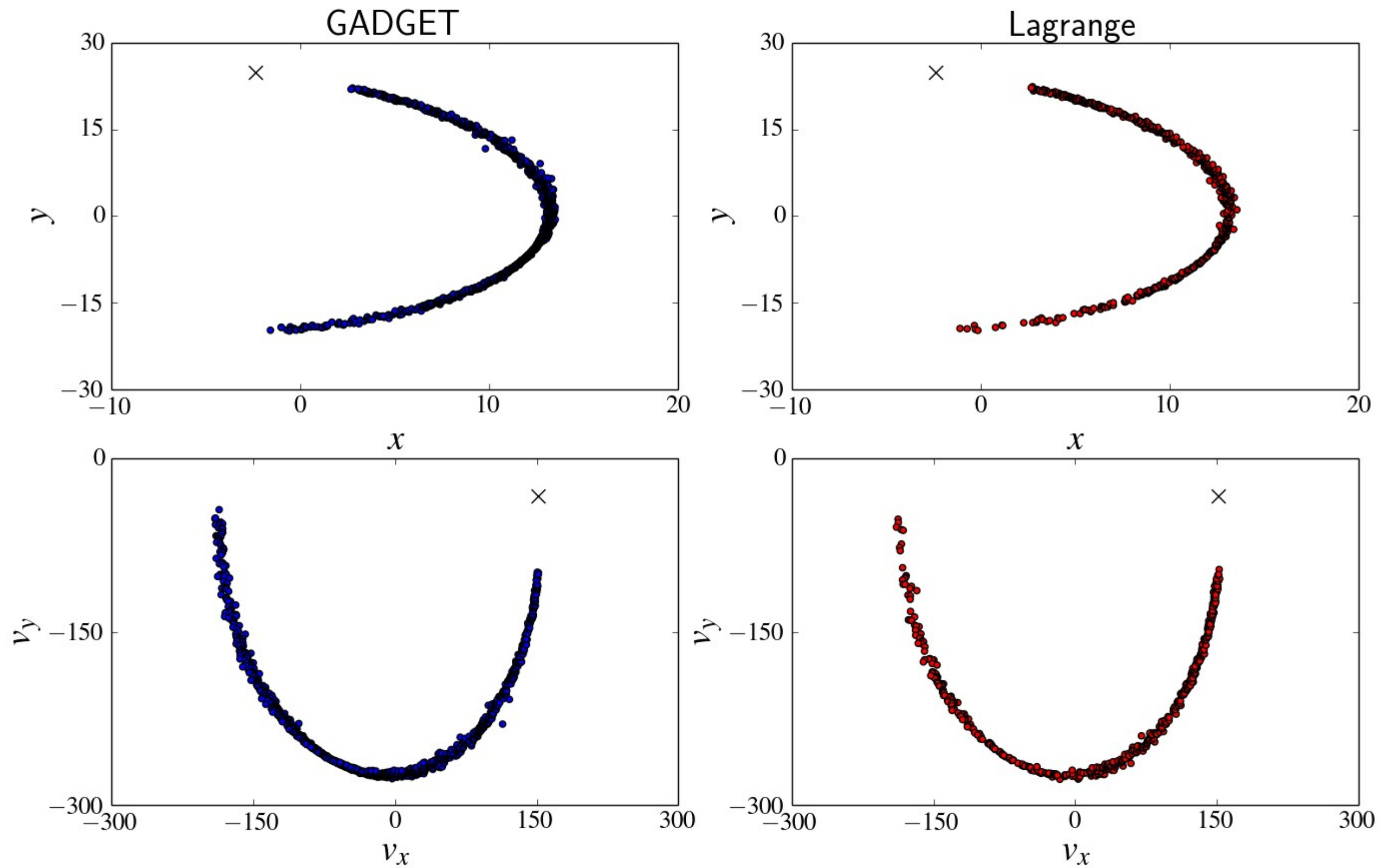


Movie: Gibbons

A better method

- We can generate stars at Lagrange points as the progenitor orbits (see Varghese 2011, Kuepper 2012).
- These stars, given appropriate initial conditions, then orbit in the combined potential of host and progenitor.





Comparison of streams produces using N-body simulations and Lagrange point stripping

How to strip

- Tidal radius is defined as $$r_t = \left(\frac{GM_{sat}}{\Omega^2 - \frac{d^2\Phi}{dr^2}} \right)^{\frac{1}{3}}$$

- This is fine for spherical potentials – for mildly aspherical potentials we approximate as spherical.

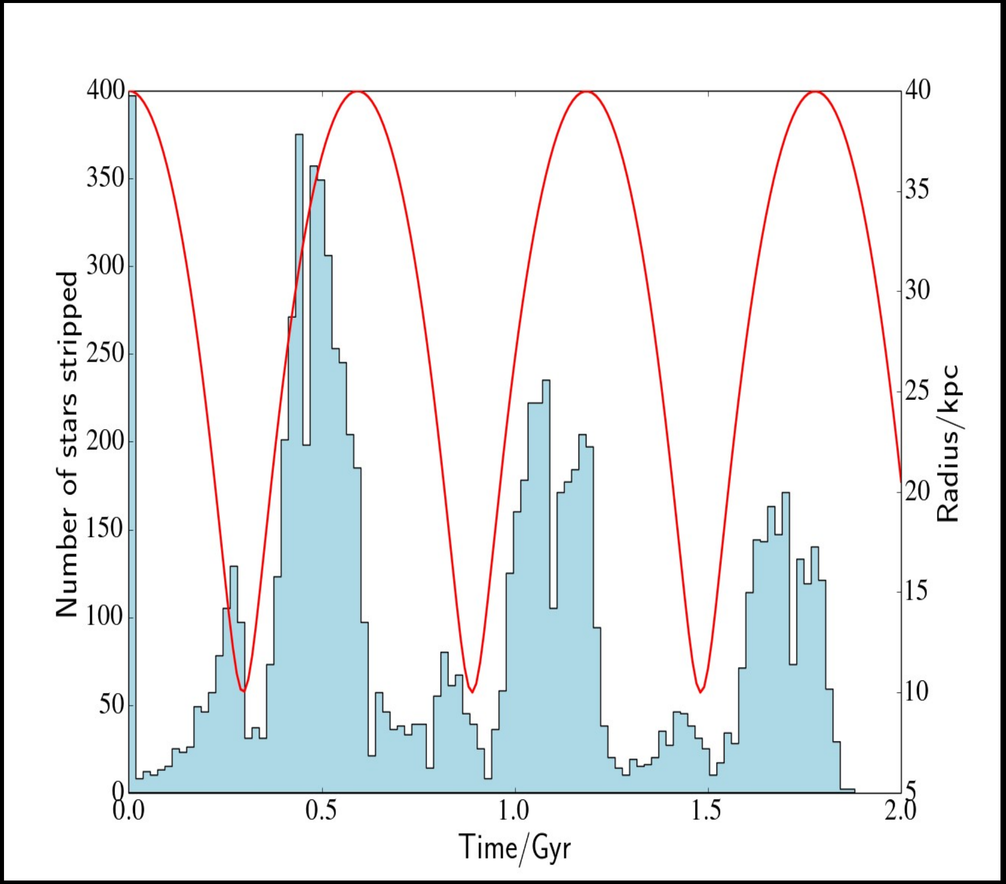
- We strip stars at 1.2 times the tidal radius, to ensure the majority escape.

How to strip

- Base velocity is determined by the satellite – we match radial velocities.
- Tangential velocity we could match to either the satellite velocity **or** satellite angular velocity.
- Kuepper (2012) found heuristically that somewhere between these two values is best.
- Scatter representing satellite velocity dispersion is also added.

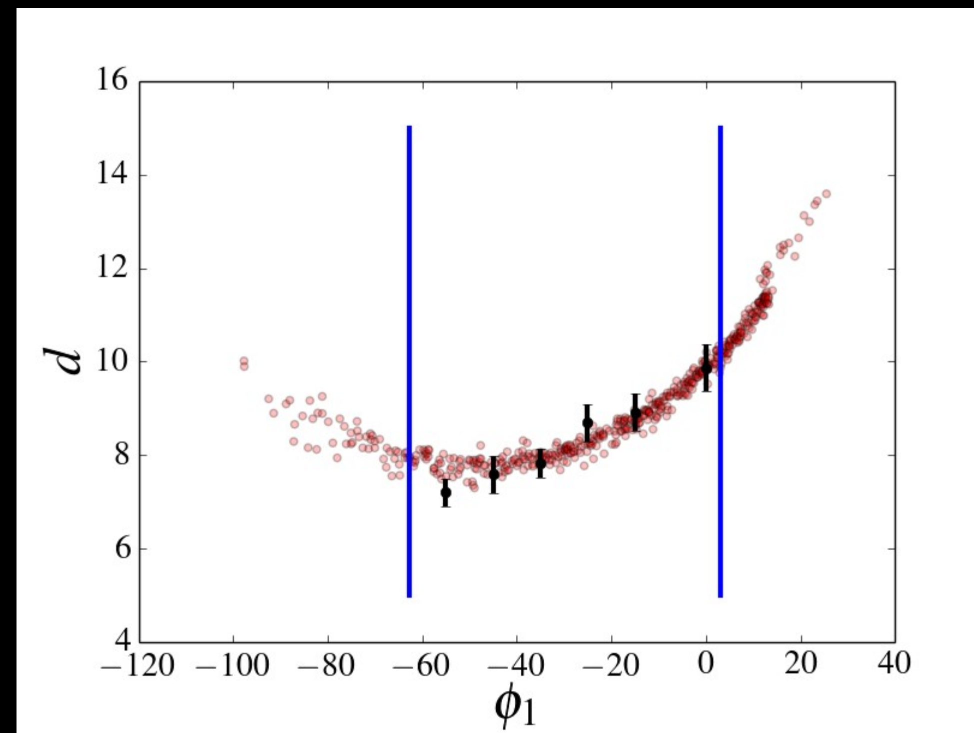
When to strip

- Disruption is complicated.
- Tidal radius shrinks and grows as the progenitor orbits – excess stars are lost near pericentre.
- This affects density along the stream.
- Density is also affected by epicyclic motions and dark matter substructure.
- We fit the stream's mean track, not the density, letting us strip uniformly in time.



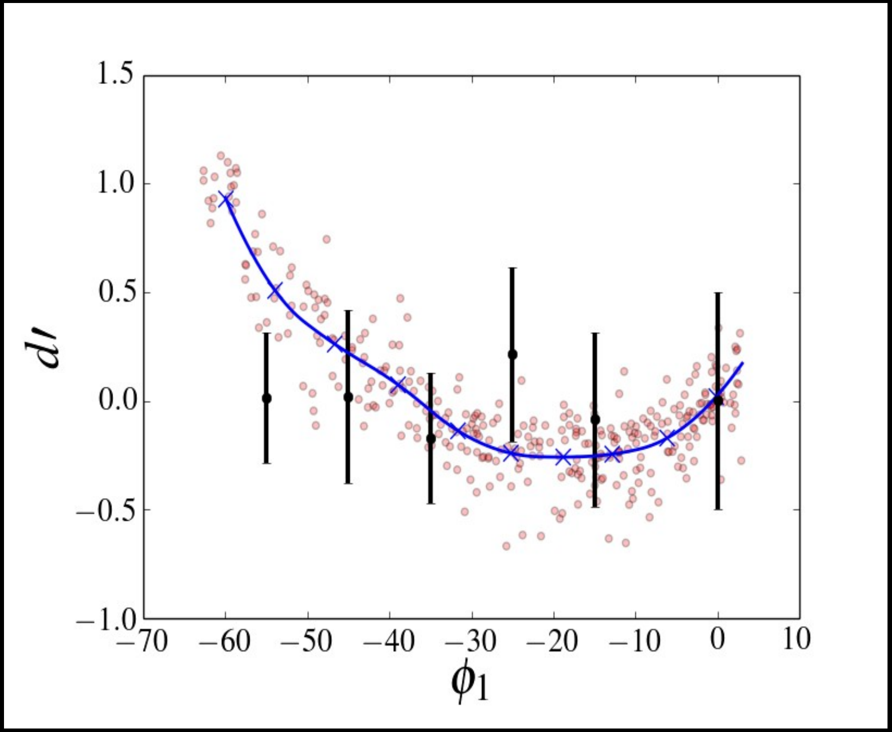
Comparing Streams

- Having made a stream, we need a way of assessing the fit.
- After converting to observable co-ordinates, we make some cuts.
- Stars which return to within 0.8 tidal radii are removed.
- The outlying 2% of stars at either end are also cut.
- If the stream does not cover the range of the data, we can discard it.



Finding the stream track

- We need to fit a line through a set of points.
- We bin stars to minimize variation.
- Bins must have at least 10 stars, and cover at least 0.1 radians.
- We fit in co-ordinates that trace the stream data, to reduce curvature.



The likelihood value

- Where the spline passes the observations gives us a chi-squared value for the fit.
- Our likelihood function for the stream is therefore

$$\ln \mathcal{L} = -\chi^2 = -\sum_i \frac{(x_{model,i} - x_{data,i})^2}{2\sigma_i^2}$$

Parameter exploration: MCMC

- One method of exploring a parameter space is using Markov chain Monte Carlo (MCMC) methods.
- We use the open source *emcee* code (Foreman-Mackey 2013).

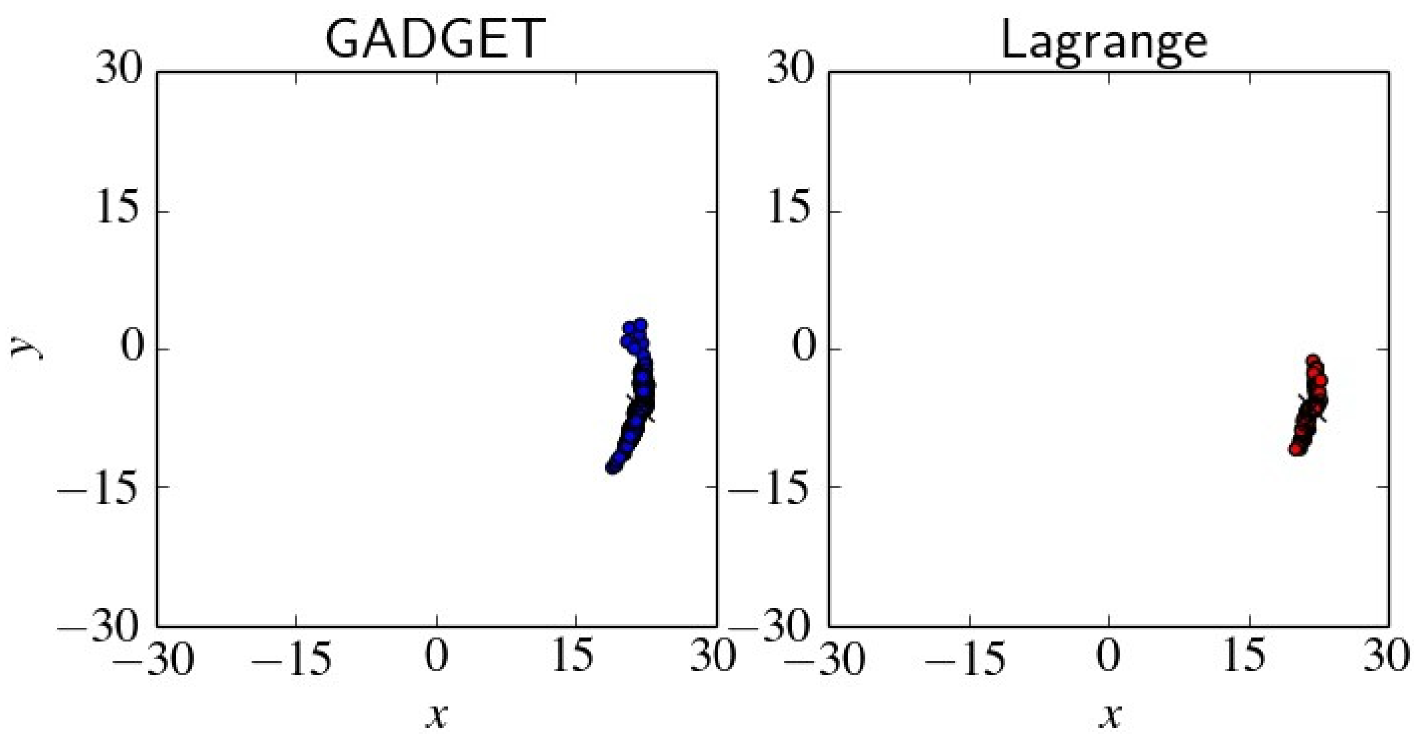
Parameter	Description
V	Potential parameters
R, z	Progenitor position
v_r, v_t, v_z	Progenitor velocity
M_s, a_s, σ_s	Progenitor properties
t_d	Disruption timescale

Example fit – Making a stream

- We disrupted a 250,000 solar mass Plummer sphere with an 8 pc scale radius for 6.5 Gyr using GADGET.
- The host potential was

$$\Phi(R, z) = \frac{v_0^2}{2} \ln(R^2 + \frac{z^2}{q^2}),$$

  with circular speed 220 km/s and flattening 0.9.
- We took fake observations of this stream and fit them using our method.


GADGET
Lagrange
30
15
0
−15
−30
−30
−15
0
15
30
x
y

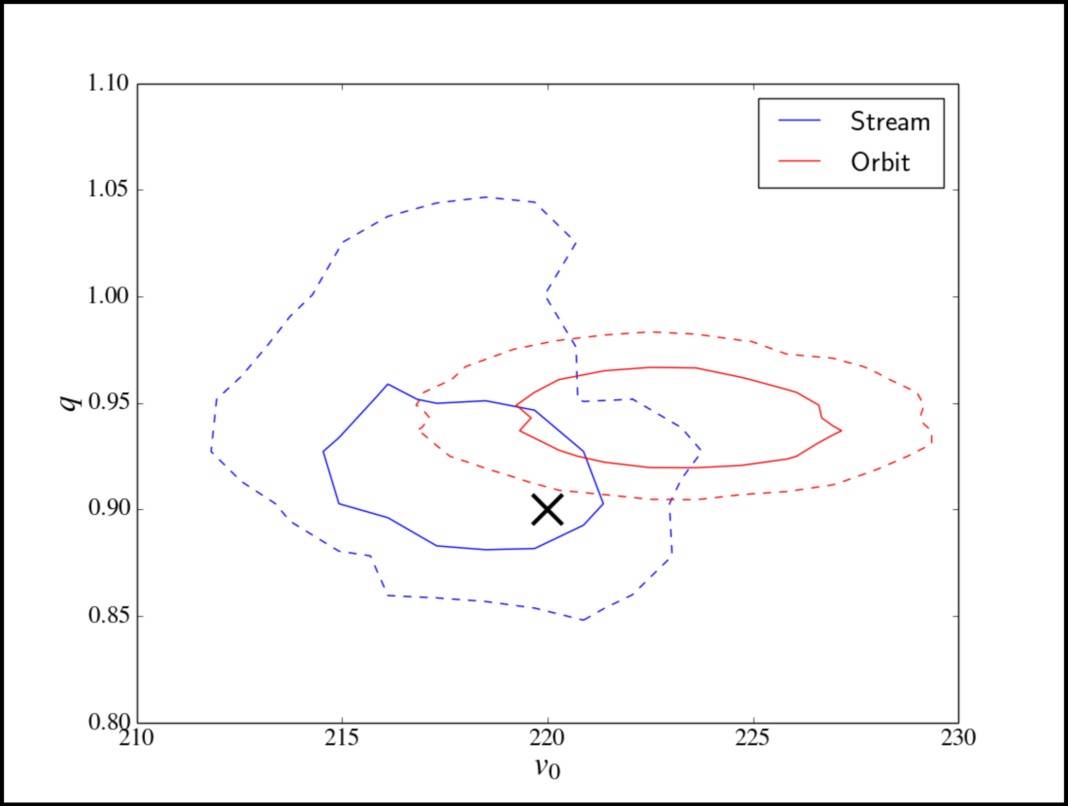
Example fit - Results

- We recover the correct normalization and flattening to within 1σ.

$$v_0 = 218.0^{+2.1}_{-1.6};\ q = 0.921^{+0.017}_{-0.024}$$

- Orbit fitting does not.

$$v_0 = 223.1^{+2.3}_{-2.6};\ q = 0.943^{+0.012}_{-0.018}$$



GD-1

- GD-1 is a dynamically cold tidal stream.
- It spans ~60º on the sky at roughly 14 kpc from the galactic centre.
- It covers a small range of galactocentric distances

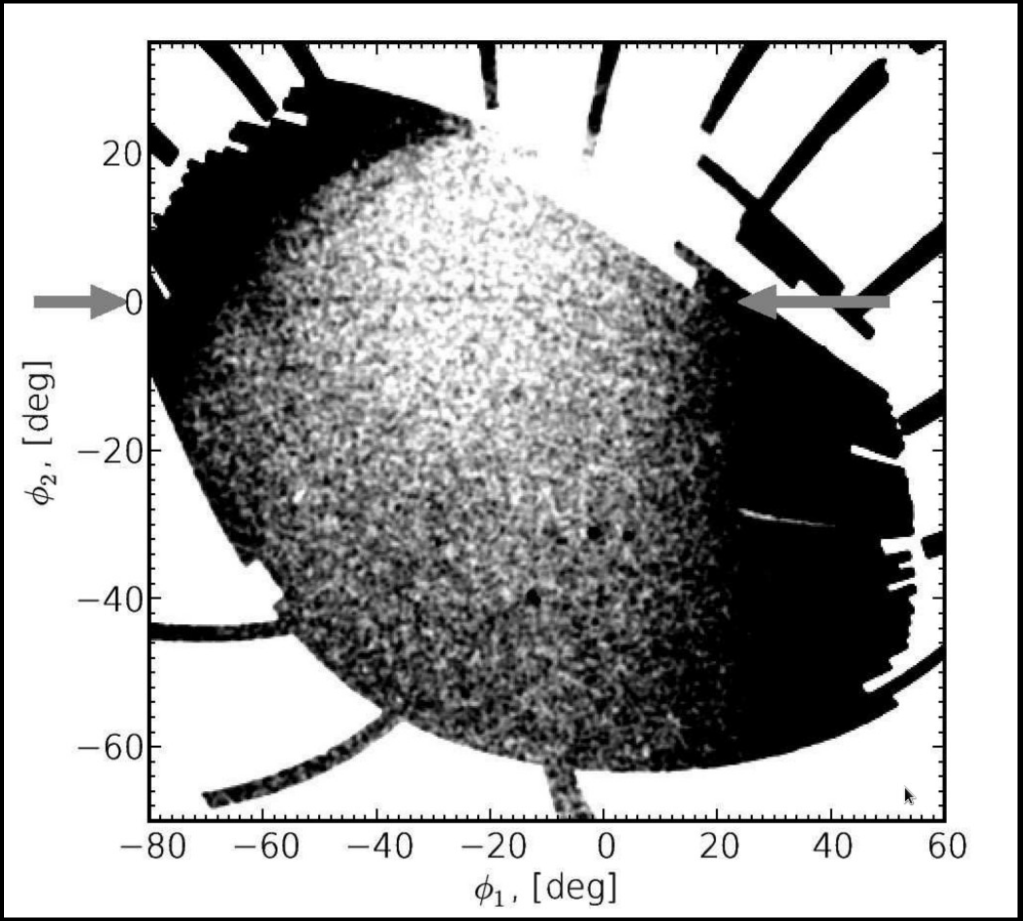


Image: Koposov, Rix & Hogg (2010)

Our fitting

- Our data is 6-d.
- 5 dimensions come from SDSS photometry.
- Radial velocities combine SDSS and Calar Alto data.
- We don't know if the stream is leading or trailing, so we fit each separately.

		Parameter		
5	$\leq$	R/kpc	$\leq$	35
−30	$\leq$	z/kpc	$\leq$	30
−100	$\leq$	v_r/kms^{-1}	$\leq$	200
−50	$\leq$	v_t/kms^{-1}	$\leq$	350
−200	$\leq$	v_z/kms^{-1}	$\leq$	0
130	$\leq$	v_0/kms^{-1}	$\leq$	290
0.5	$\leq$	q	$\leq$	1.5
$10^{4.5}$	$\leq$	$M_s/M_\odot$	$\leq$	$10^{5.5}$
1	$\leq$	a_s/pc	$\leq$	10
0.5	$\leq$	$\sigma_s/\mathrm{kms}^{-1}$	$\leq$	2.5
2	$\leq$	$t_d/\mathrm{kpckm}^{-1}\mathrm{s}$	$\leq$	5

GD-1: results

- Trailing stream

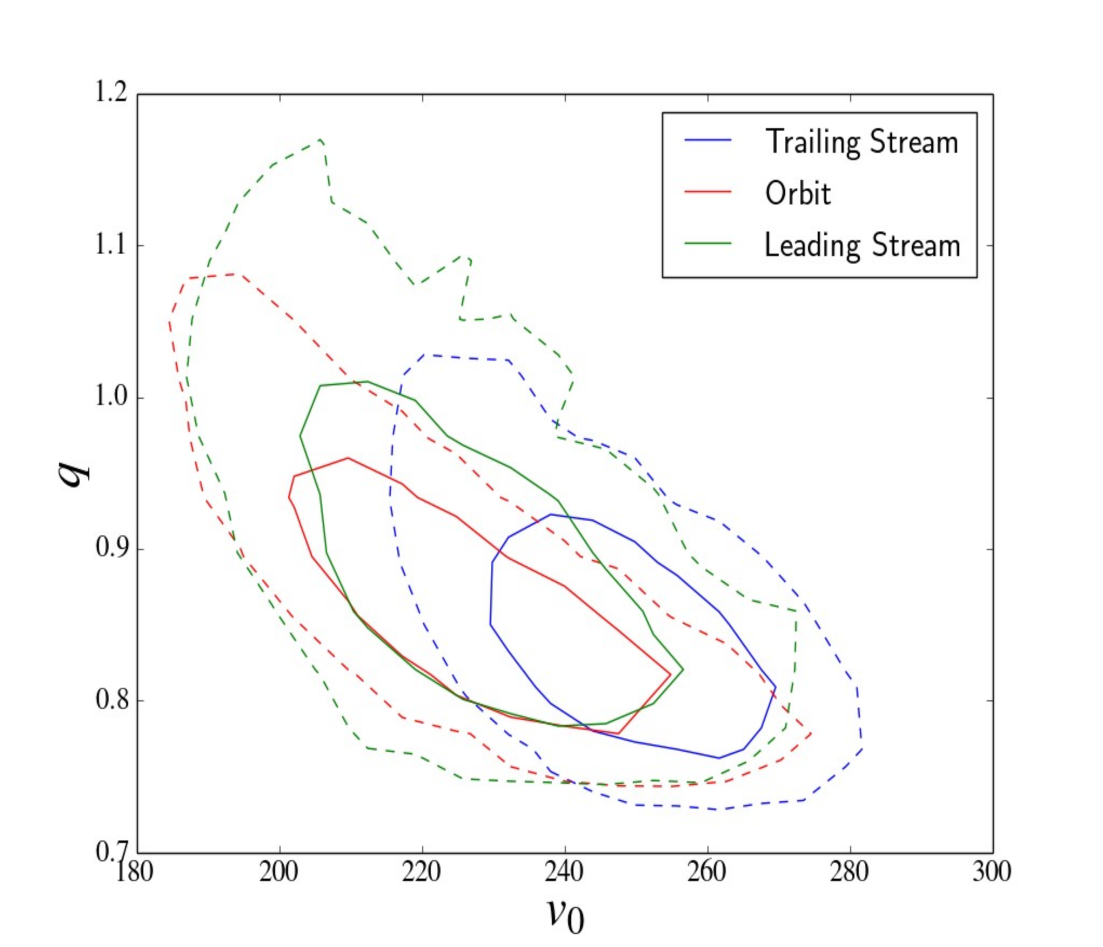
$$v_0 = 247.1^{+14.9}_{-12.3};\ q = 0.850^{+0.036}_{-0.066}$$

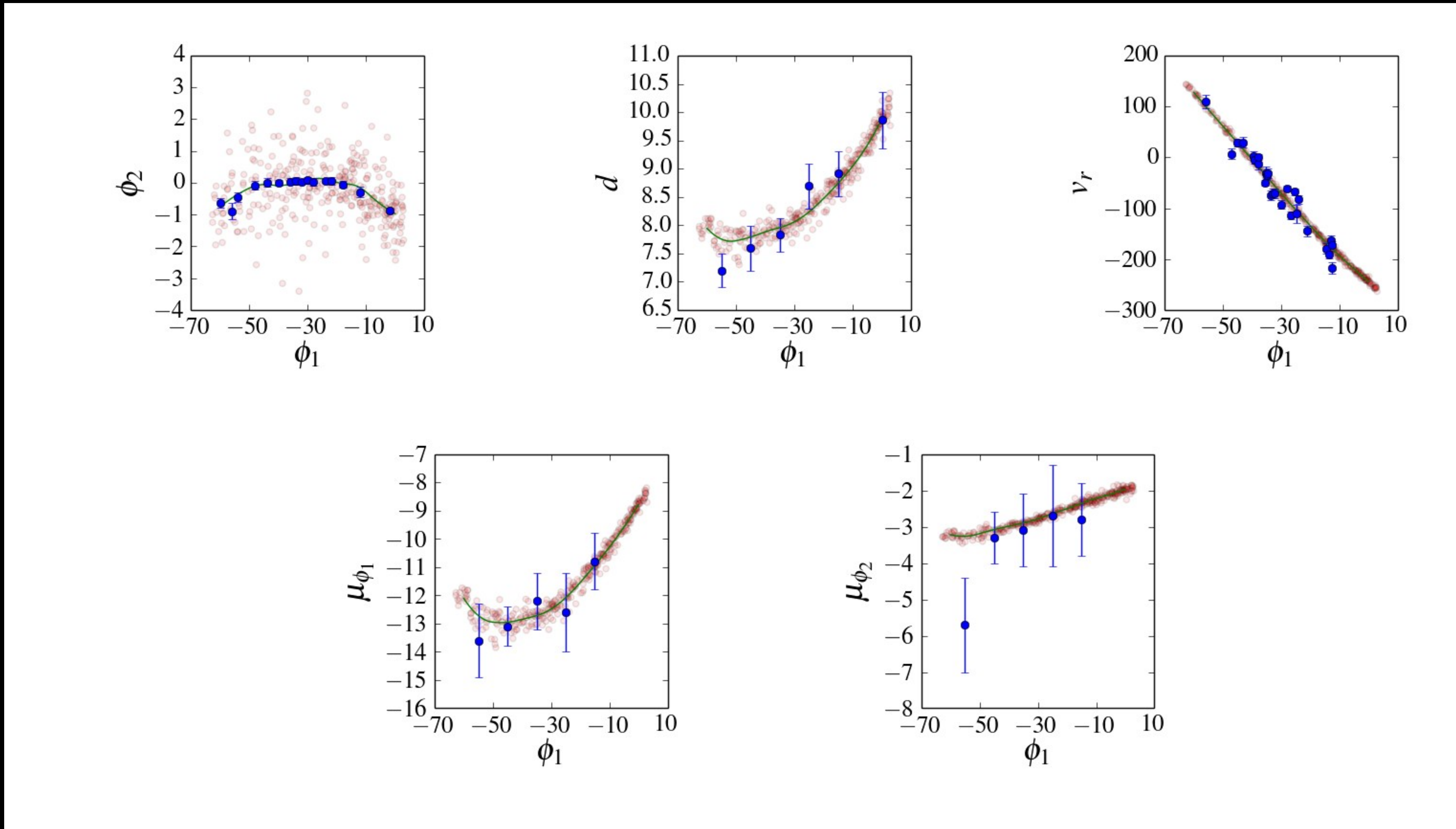
- Leading stream

$$v_0 = 226.9^{+16.0}_{-15.6};\ q = 0.897^{+0.047}_{-0.090}$$

- Orbit

$$v_0 = 225.5^{+18.3}_{-17.3};\ q = 0.873^{+0.029}_{-0.083}$$





An example fit of GD-1 as a leading stream.

Caveats

- The form of the galactic potential is unknown – our form is likely fine for GD-1, but not other streams.
- We only constrain a small region of space.
- Presently, we assume the LSR is given by our model; perhaps an independent prior is better.
- Stripping is not uniform in time, so we cannot use any density information.
- Various properties (of satellite and host) may be time varying.

The future

- The next step is to fit other (and multiple) streams, providing constraints at various radii.
- Future datasets (e.g. GAIA) will provide even more information.

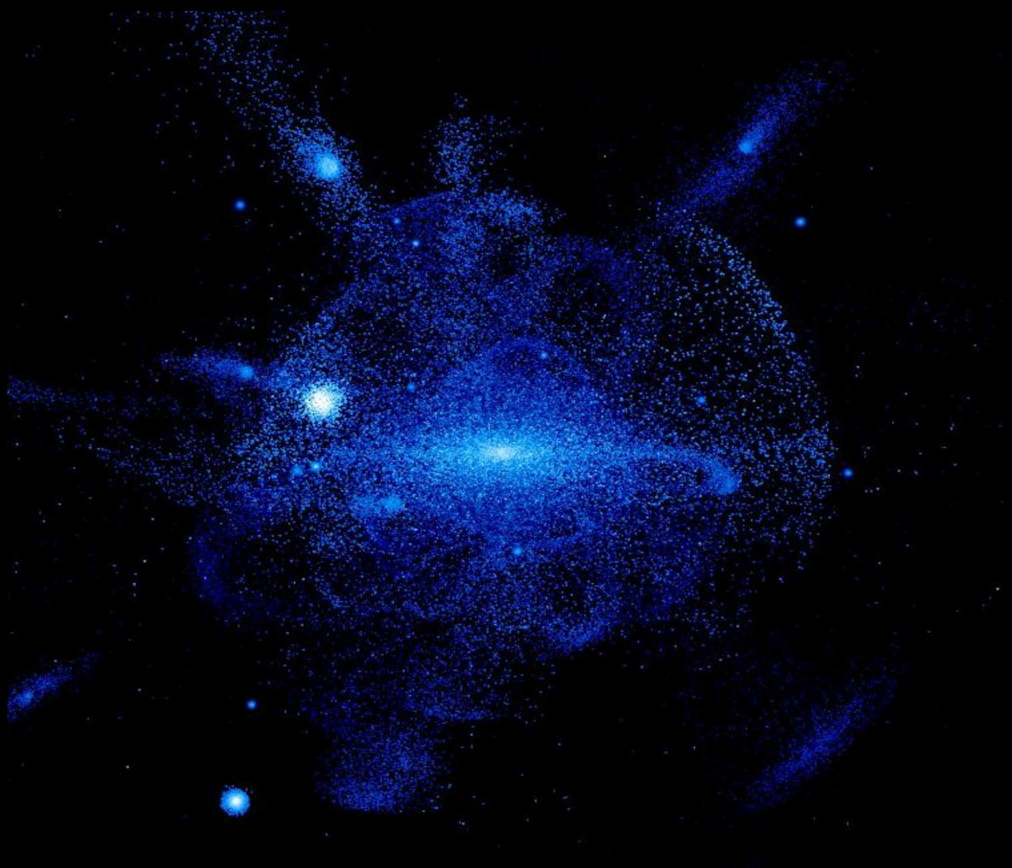


Image: Bullock & Johnston (2005)

Conclusions

- Tidal streams provide an excellent method of probing the galactic halo.
- The Lagrange point stripping method lets us model streams quickly and effectively.
- Results for GD-1 are consistent with but different to orbit modelling.
- GD-1 favours flattened haloes, without ruling out spherical models.