THE MILKY WAY HALO

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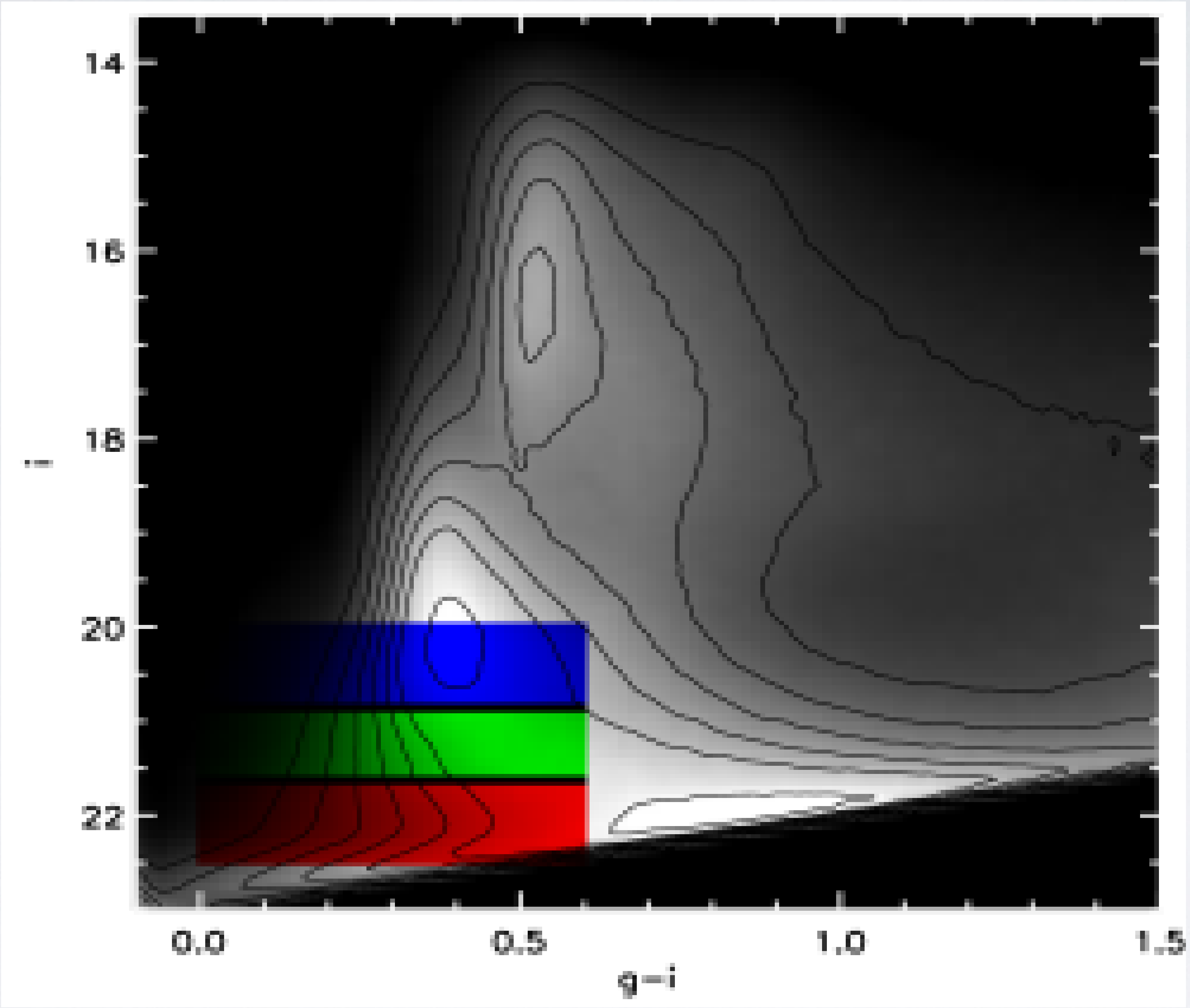
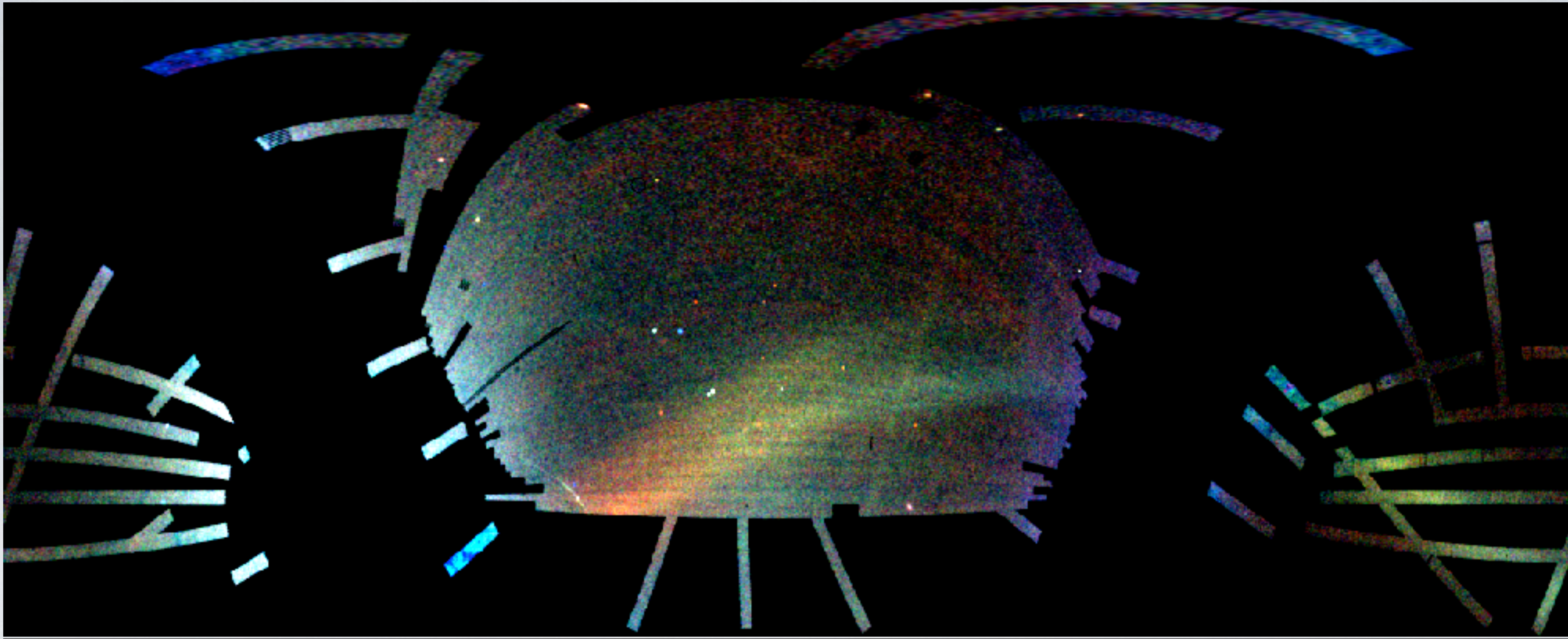
THE STELLAR HALO

The fundamental observation goes back half a century. Eggen, Lynden-Bell & Sandage (1962) noted that :

"The time required for stars in the halo to exchange their energies and angular momenta is very long compared with the age of the Galaxy. Hence, knowledge of their present energy and angular momenta tells us something of the initial conditions under which they formed"

THE FIELD OF STREAMS





Belokurov et al. 2006

THE FIELD OF STREAMS

THE STELLAR HALO

1. The Smooth Component
   - ⋆ the BHB and MSTO populations.
2. The Streams
   - ⋆ the Sgr Stream,
   - ⋆ the GD-1 Stream.
3. The Satellites and the Clouds
   - ⋆ the Hercules-Aquila & Pisces Over-densities,
   - ⋆ the ultra-faints.

THE SMOOTH COMPONENT

Bell et al. (2008) claim a smooth model is a poor representation of the stellar halo of our Milky Way.

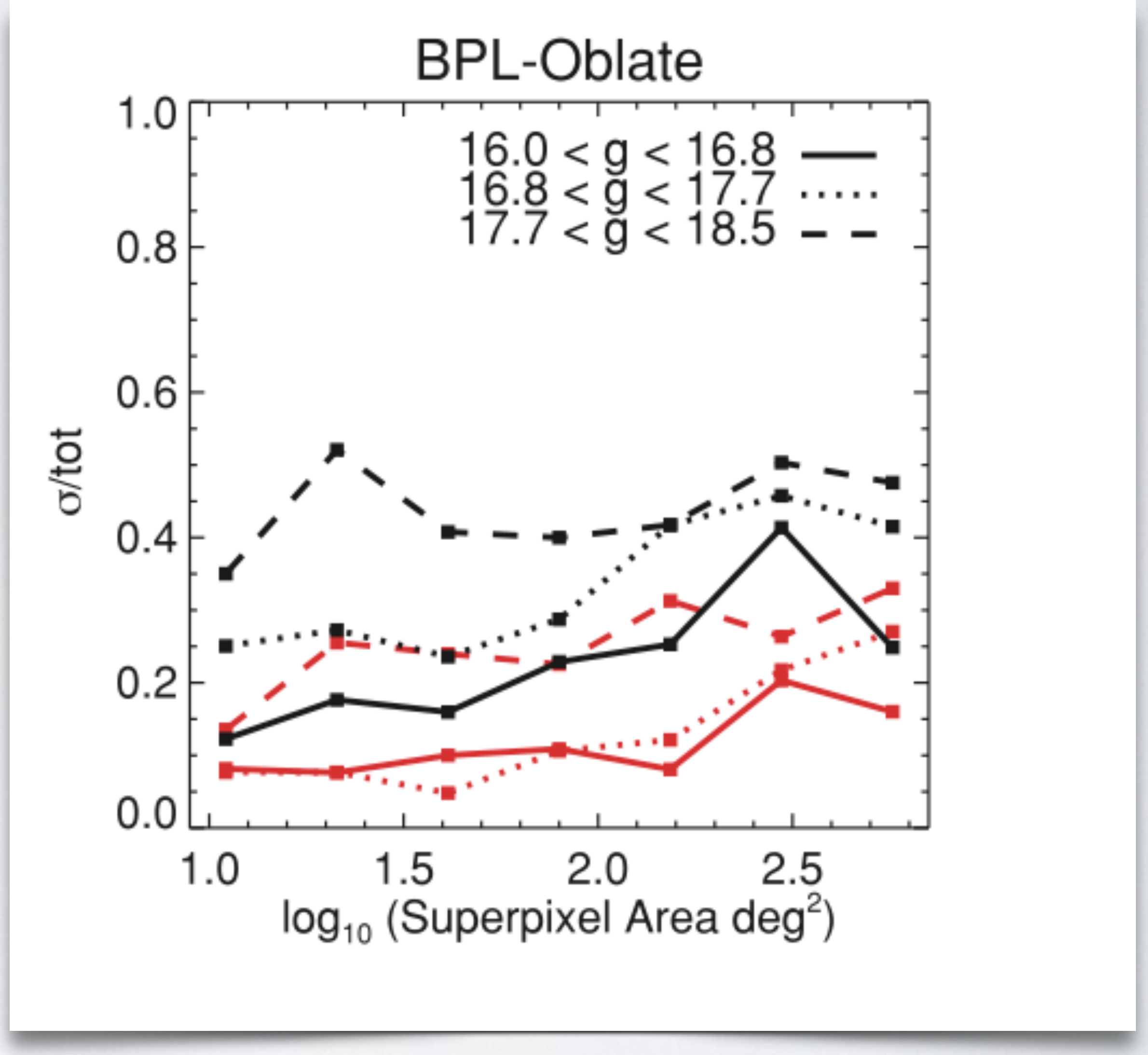
$$\langle \sigma^2 \rangle = \frac{1}{n}\sum_i (D_i - M_i)^2 - \frac{1}{n}\sum_i (M_i' - M_i)^2,$$

$$\sigma/\text{total} = \frac{\sqrt{\langle \sigma^2 \rangle}}{\frac{1}{n}\sum_i D_i},$$

The σ/total of the b > 30° data around the model is >42%; even if the largest substructures are clipped, the values of σ/total are >33%.

THE SMOOTH COMPONENT

Deason et al. (2011) re-visited the problem. On scales smaller than several tens of degrees, σ /tot is in the range $0.05 < \sigma$ /tot < 0.2, indicating that the halo is not dominated by substructure and is relatively smooth.



Deason, Belokurov, Evans 2011

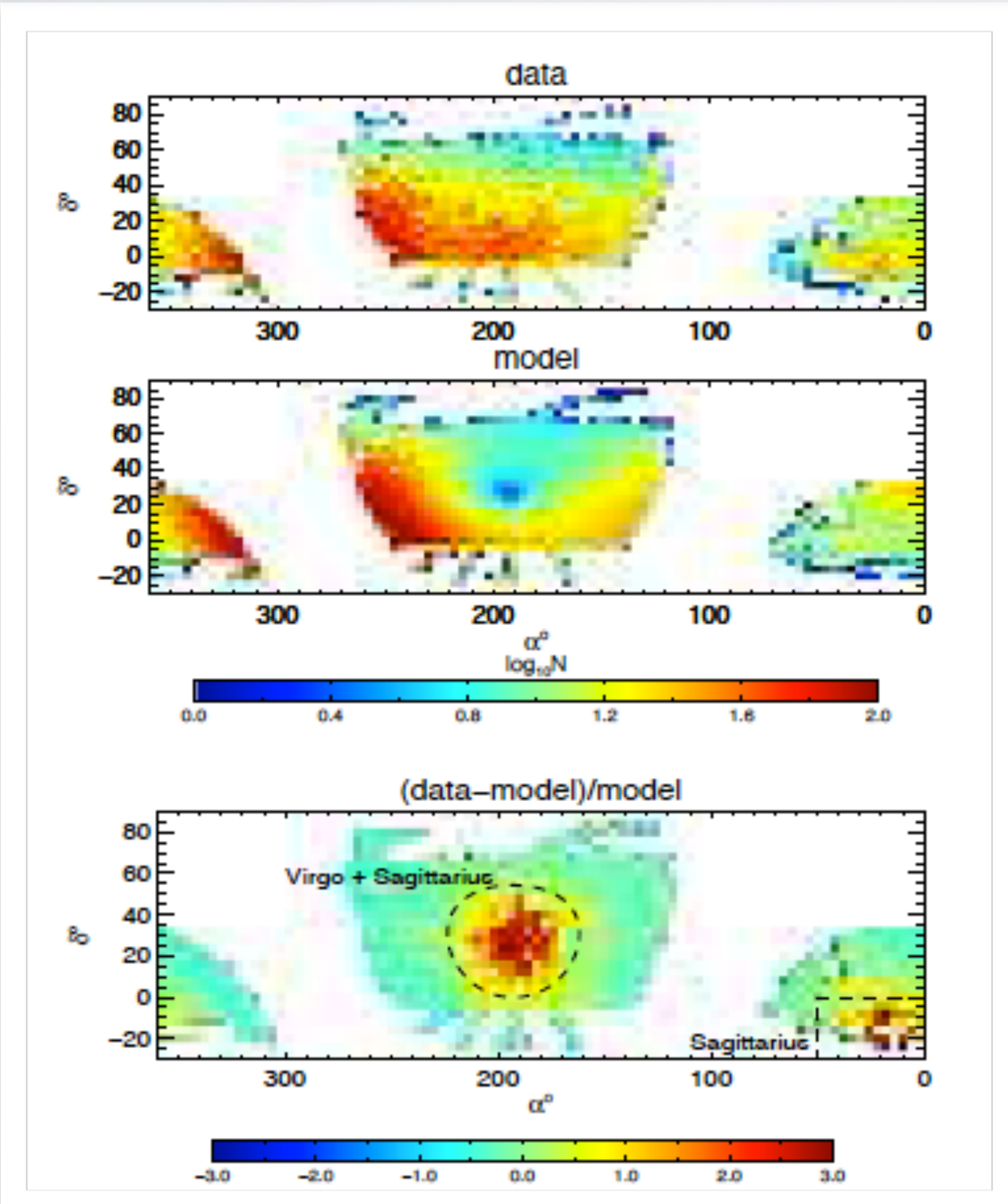
THE SMOOTH COMPONENT

A commonly used model for the stellar halo is an axisymmetric broken power-law

$$\rho(r_q) \propto \begin{cases} r_q^{-\alpha_{\rm in}} & r_q \leq r_{\rm b} \\ r_q^{-\alpha_{\rm out}} & r_q > r_{\rm b}. \end{cases}$$

$$r_q^2 = x^2 + y^2 + z^2 q^{-2}.$$

THE SMOOTH COMPONENT



Deason, Belokurov, Evans 2011

The smooth component is well described by an oblate double power-law density, with a flattening q ~ 0.6, inner power-law ~2.3 ±0.1, outer power-law ~ 4.6 ±0.2 and break radius ~ 27 ±1 kpc.

THE SMOOTH COMPONENT

The problem has also been examined by a number of authors (Juric et al. 2008, Bell et al. 2008, Watkins et al. 2009, Sesar et al. 2010, Faccioli et al. 2014).

The most recent study by Pila-Diez et al. (2015) uses much deeper pencil-beam INT/CFHT data on halo MSTO stars. They find a flattening of 0.65, an inner power-law index of 2.5 ±0.04, an outer-power law index of 4.8 ±0.04 and a break radius of 19.5 ±0.4 kpc.

THE SMOOTH COMPONENT

Three dimensional kinematics of halo stars have been studied by Smith et al. (2009) and Bond et al. (2010).

Smith et al. (2009) extracted ~1800 halo sub-dwarfs with SDSS spectra and proper motions extracted from the multi-epoch SDSS photometry for Stripe 82.

The found that the velocity ellipsoid was aligned in spherical polar co-ordinates to excellent accuracy (< 1°) and $(\sigma_r, \sigma_\theta, \sigma_\phi) = (142, 77, 81)$ kms^{-1}

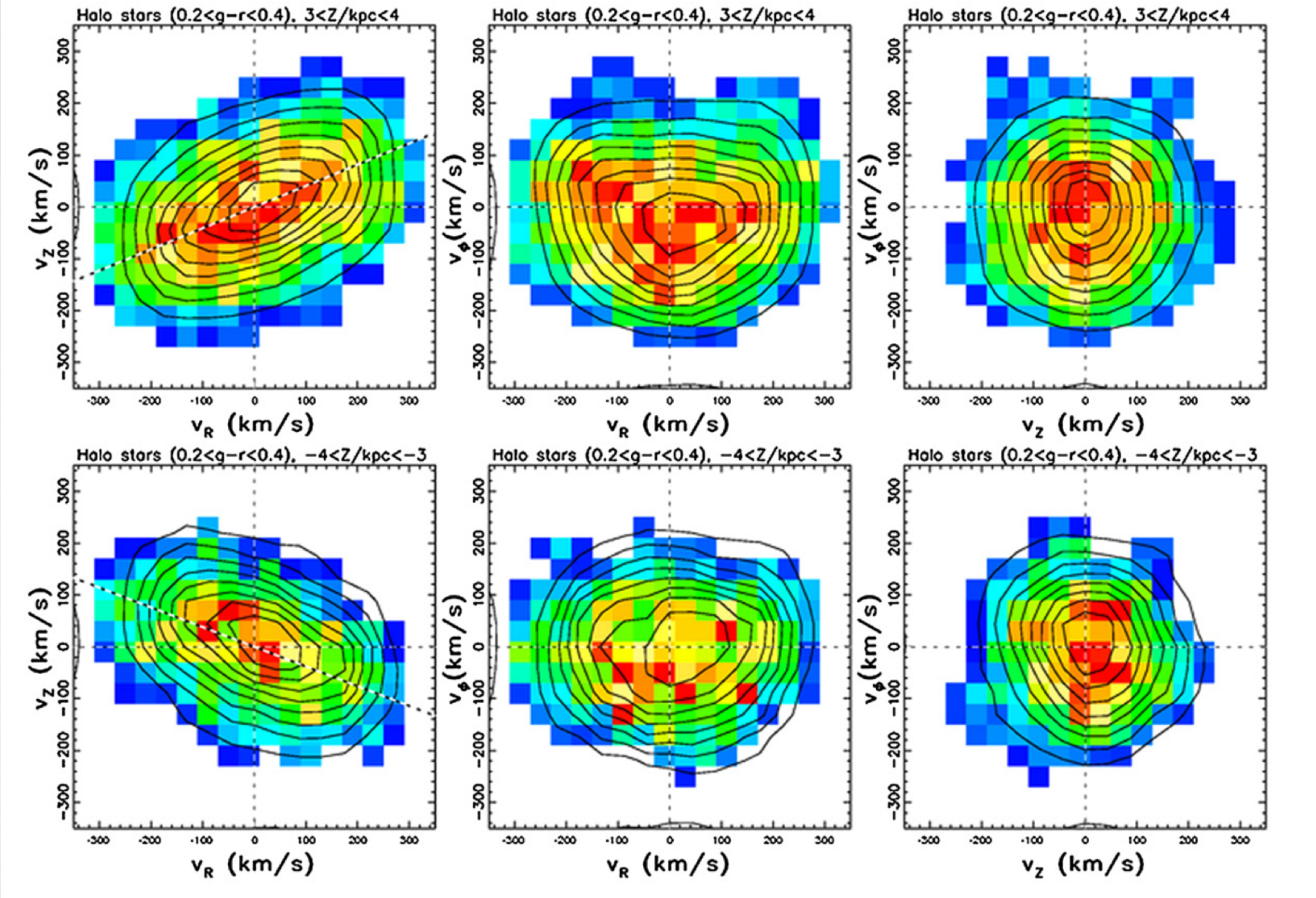
THE SMOOTH COMPONENT

Bond et al's sample is 47,000 colour & metallicity-selected halos stars with heliocentric distances within ~10 kpc in both the Northern and Southern Galactic hemispheres. They use SDSS spectra and POSS photometry.

The velocity dispersion tensor is aligned in the spherical polar coordinate system to very good accuracy (< 5°). The shape is approximately invariant with (σ_r, σ_θ, σ_Φ)= (141, 75, 85) kms^{-1}

This is in excellent agreement with an earlier study of halos subdwarfs by Smith et al.

THE SMOOTH COMPONENT



Bond et al. 2010

THE SMOOTH COMPONENT

Smith et al. (2009) showed spherical alignment at heliocentric distance < 5 kpc along the 2500 deg^2 of Stripe 82. Bond et al. (2010) showed spherical alignment is good at distances < 10 kpc over much of the Northern and Southern Galactic hemispheres.

But this is a surprising result!

How come the halo stars always know where the Galactic Centre is?

THE SMOOTH COMPONENT

The DF has form $F(v_r^2, v_\theta, v_\Phi; r, \theta, \Phi)$.

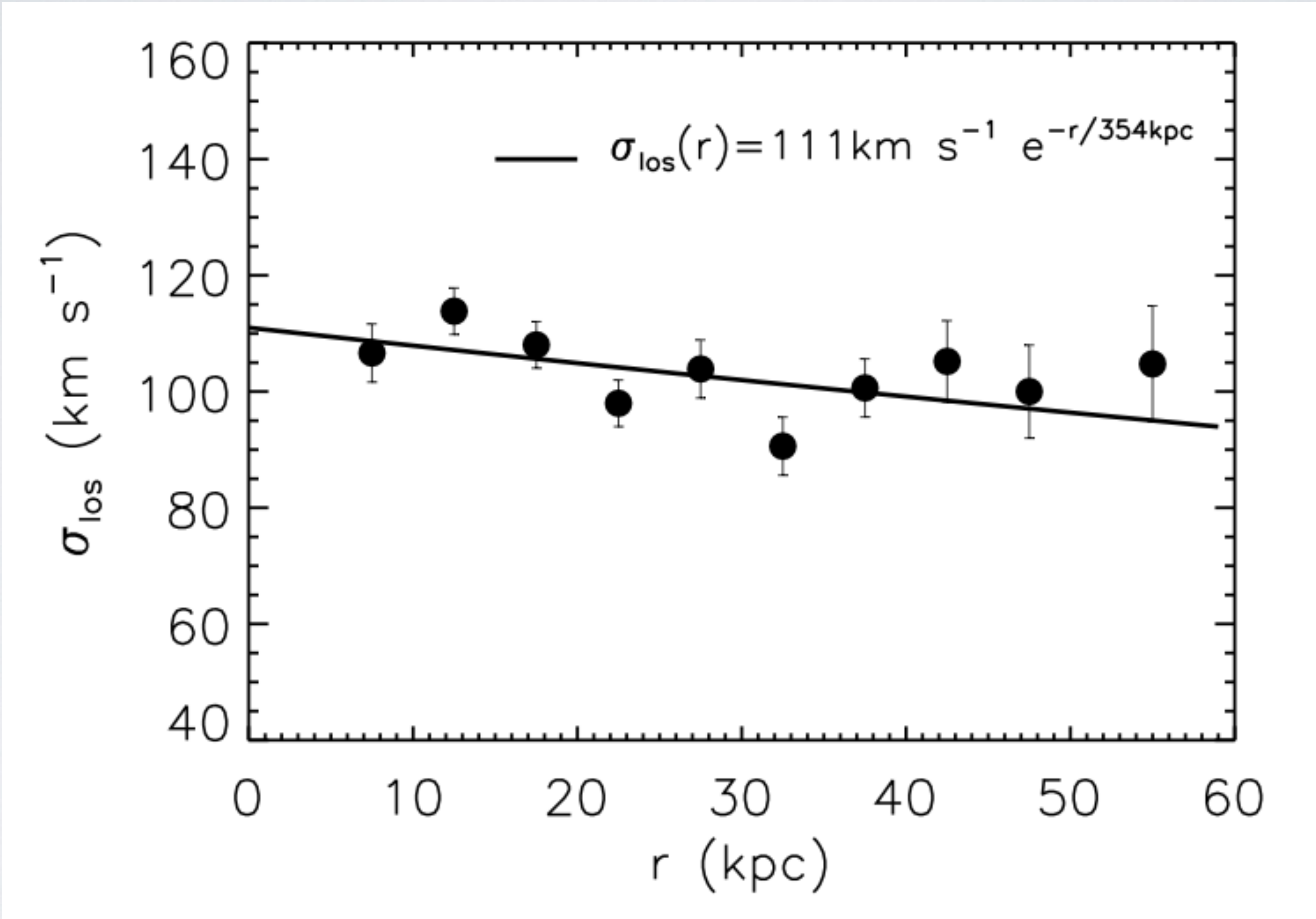
Now eliminate v_r^2 using the Hamiltonian. The DF becomes $F(H, v_\theta, v_\Phi; r, \theta, \Phi)$.

The Poisson Bracket of the DF with the Hamiltonian must vanish (Jeans Theorem). which implies $F(H, v_\theta, v_\Phi; \theta, \Phi)$.

So, the r coordinate has separated off, which implies the potential is spherical.

Evans & Lynden-Bell 2015

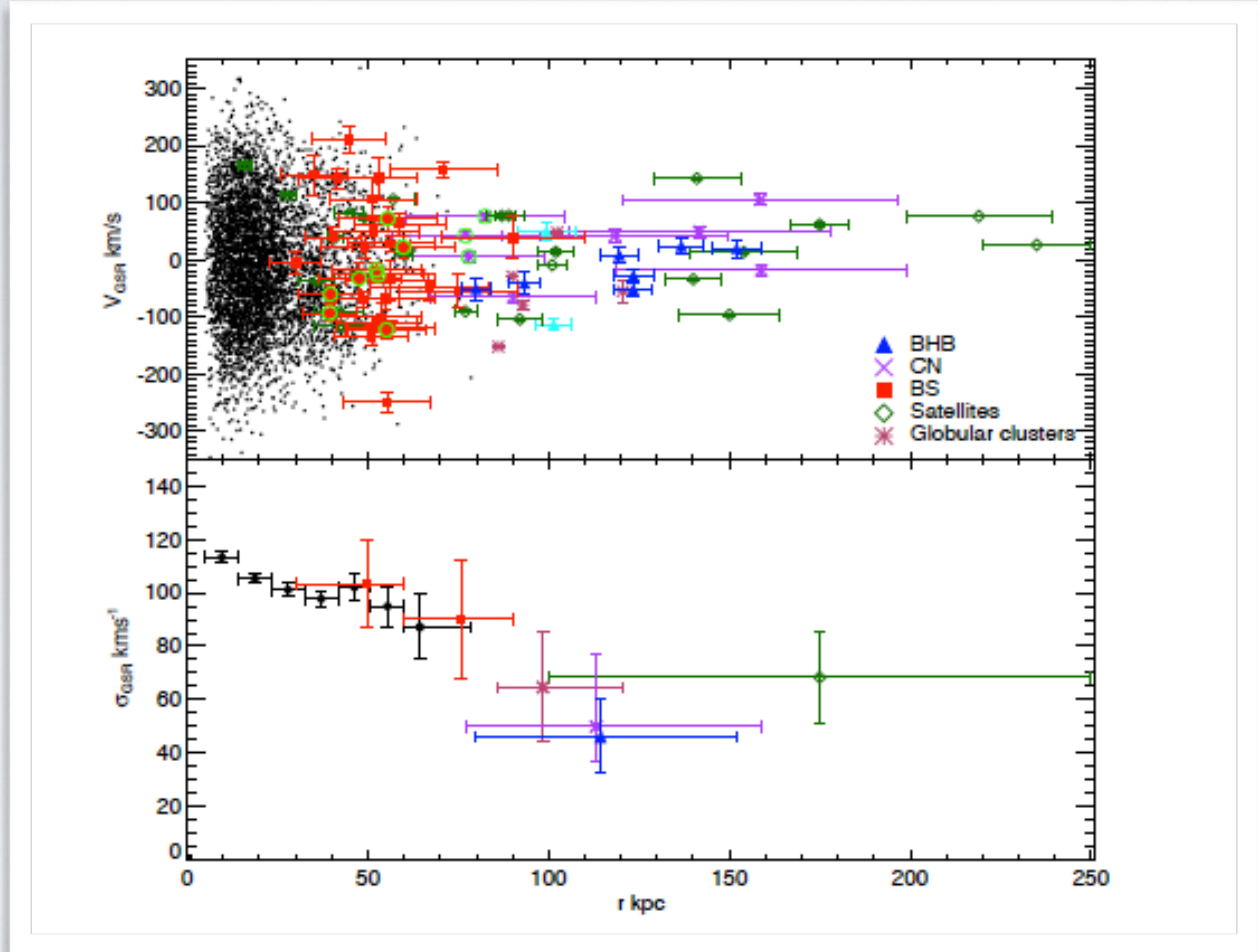
THE SMOOTH COMPONENT



Xue et al. 2008

~2000 BHBs from SDSS

THE SMOOTH COMPONENT



~30 tracers beyond 80 kpc

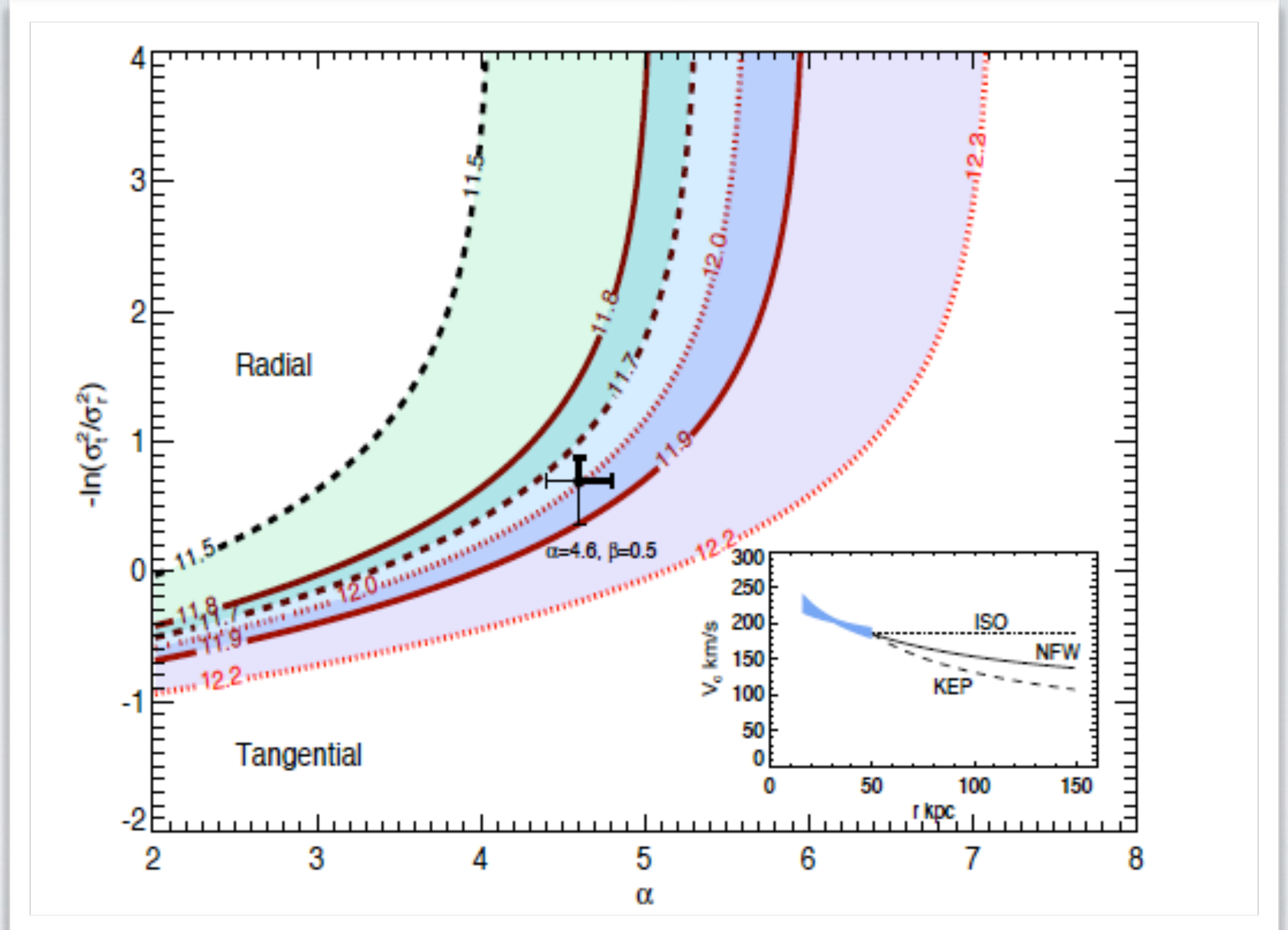
Deason et al. 2012

THE SMOOTH COMPONENT

$$M = \frac{C}{G}\langle v_r^2 r^\gamma \rangle, \quad C = (\gamma + \alpha - 2\beta)\, r_{\mathrm{out}}^{1-\gamma}$$

Mass enclosed by a tracer population with density $\rho \sim r^{-\alpha}$, $\psi \sim r^{-\gamma}$ and velocity anisotropy β

THE SMOOTH COMPONENT



Estimated mass within 150 kpc

THE SMOOTH COMPONENT

1. The Stellar Halo *May* Have a Smooth Component.
2. The Density Law is a Broken Power-Law.
3. The Velocity Dispersion Tensor is Spherically Aligned within ~10 kpc
4. The Radial Velocity Dispersion Profile is Falling Beyond ~ 20 kph

THE STREAMS

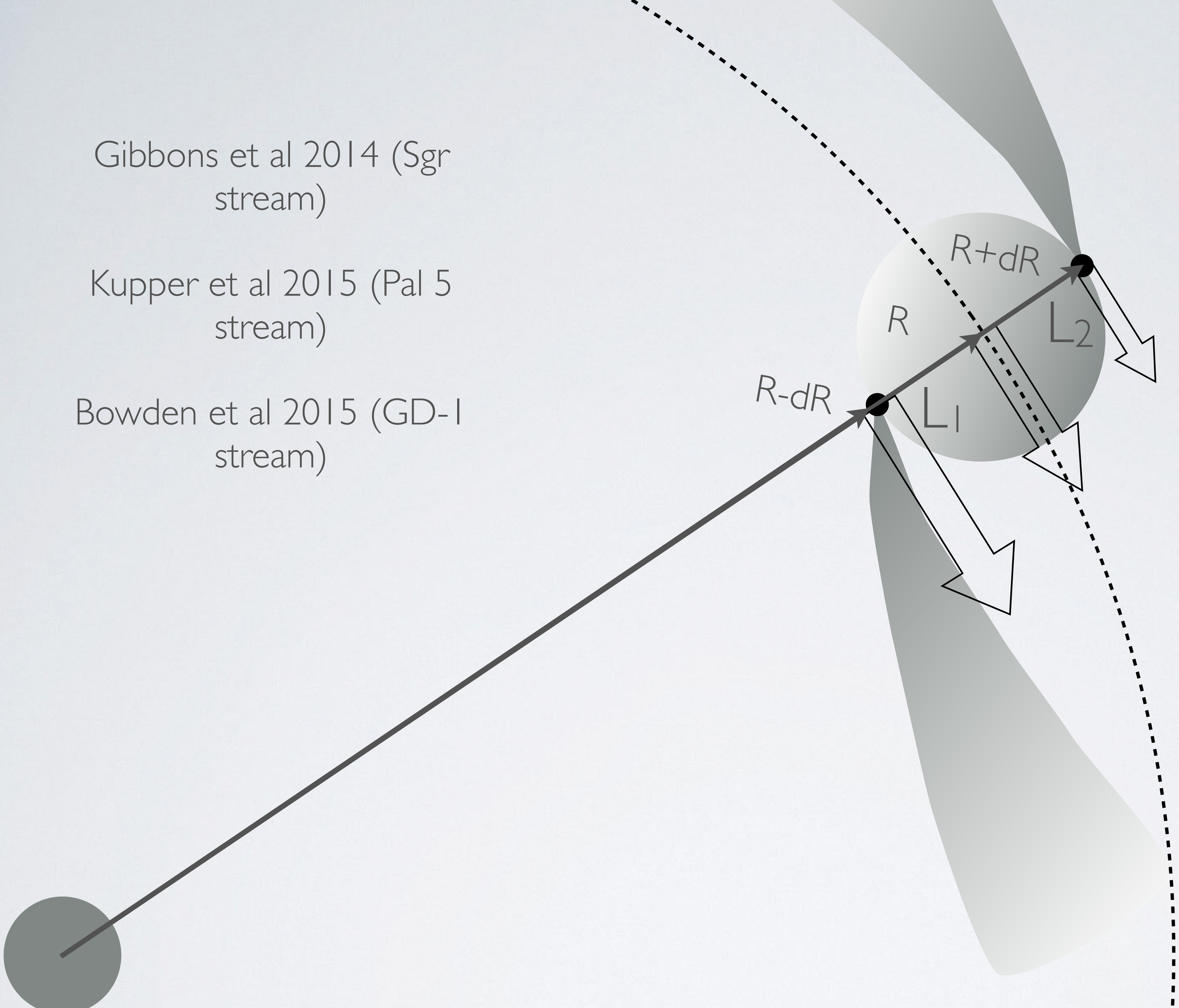
"*The tidal debris delineates the orbit of a long-gone satellite galaxy. like a ghost haunting the past abode of a murdered victim. We may look for streams among the globular clusters and small satellite galaxies like the meteor streams along old cometary paths in the Solar system*" (Lynden-Bell & Lynden-Bell 1995)

Just as meteor streams are the gravestones of the short-period comets, so tidal streams in the mark the death throes of dying satellite galaxies.

Gibbons et al 2014 (Sgr stream)

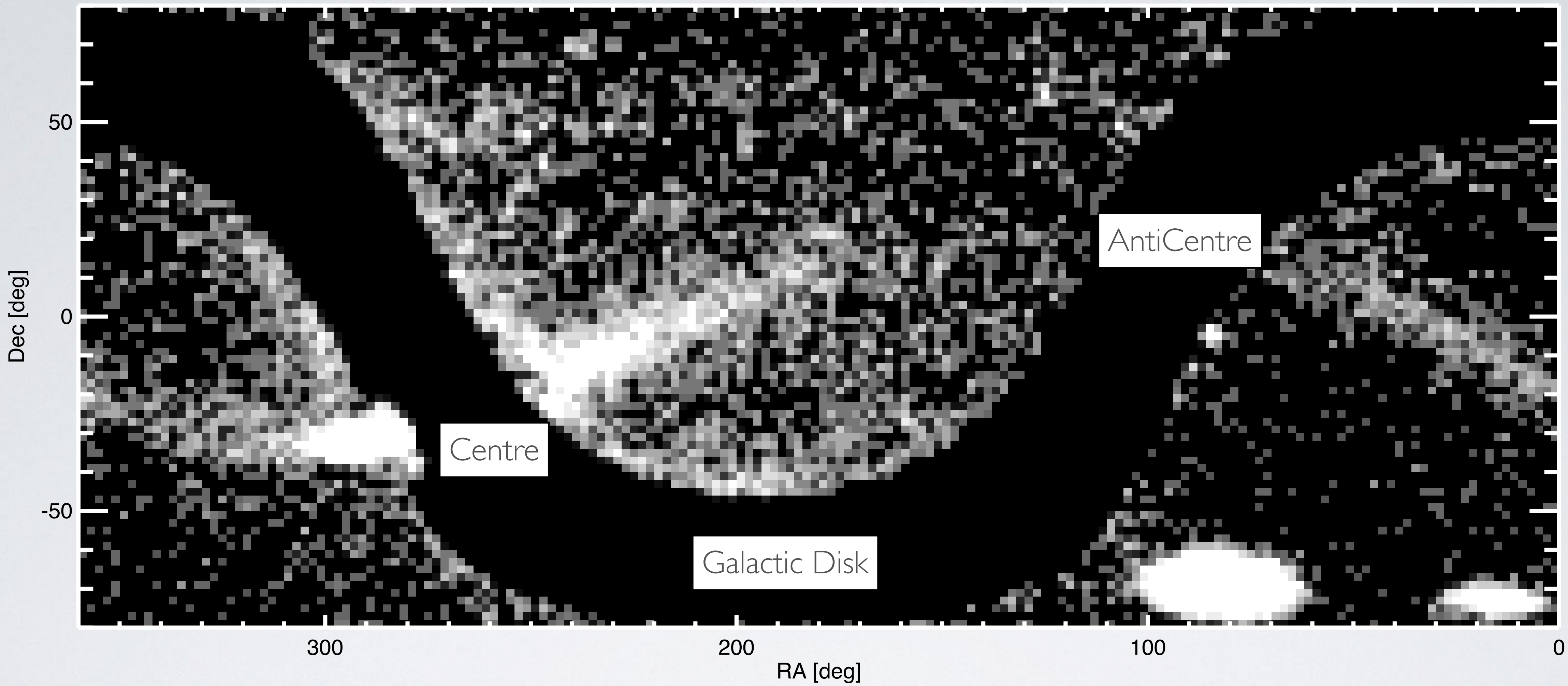
Kupper et al 2015 (Pal 5 stream)

Bowden et al 2015 (GD-1 stream)



THE MAKING OF STREAMS

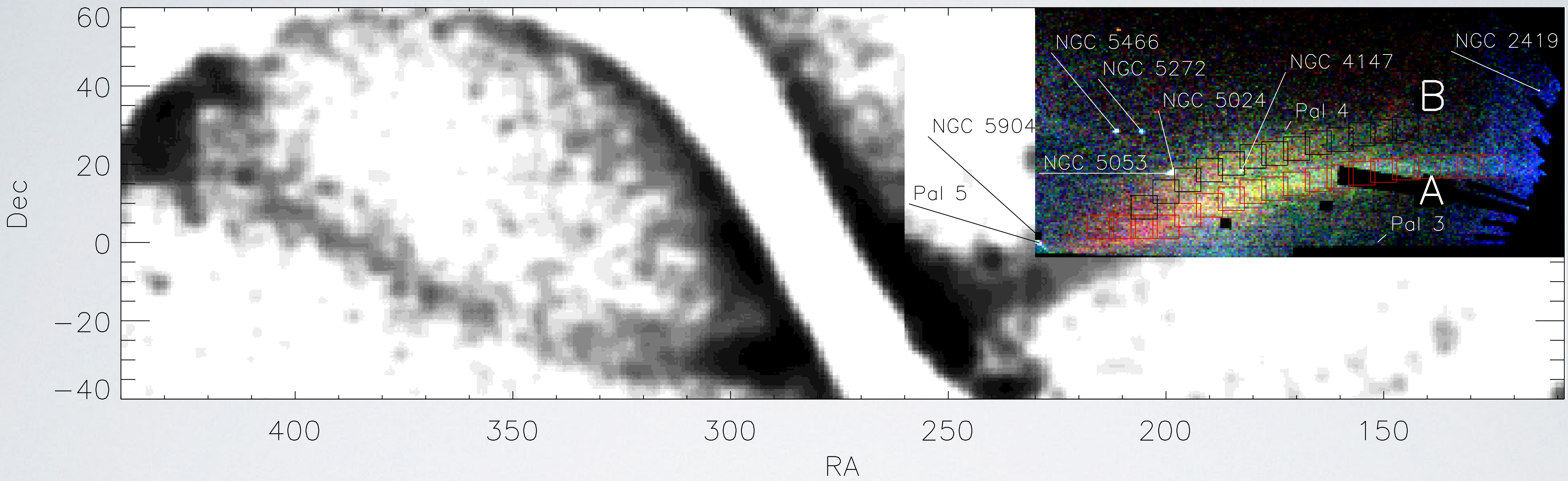
M giants as seen by 2MASS



Majewski et al., 2003

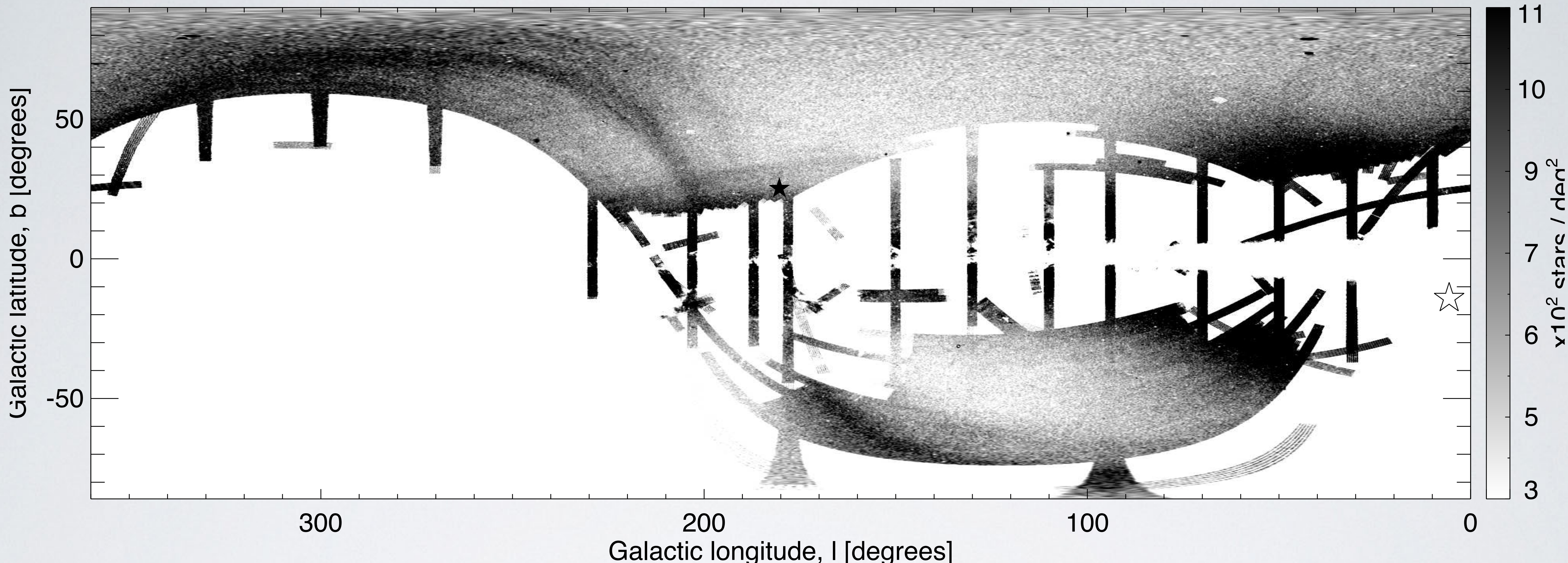
THE SAGITTARIUS STREAM

Traced by 2MASS (2 Micron All-Sky Survey) throughout the Southern Galactic hemisphere.



THE SAGITTARIUS STREAM

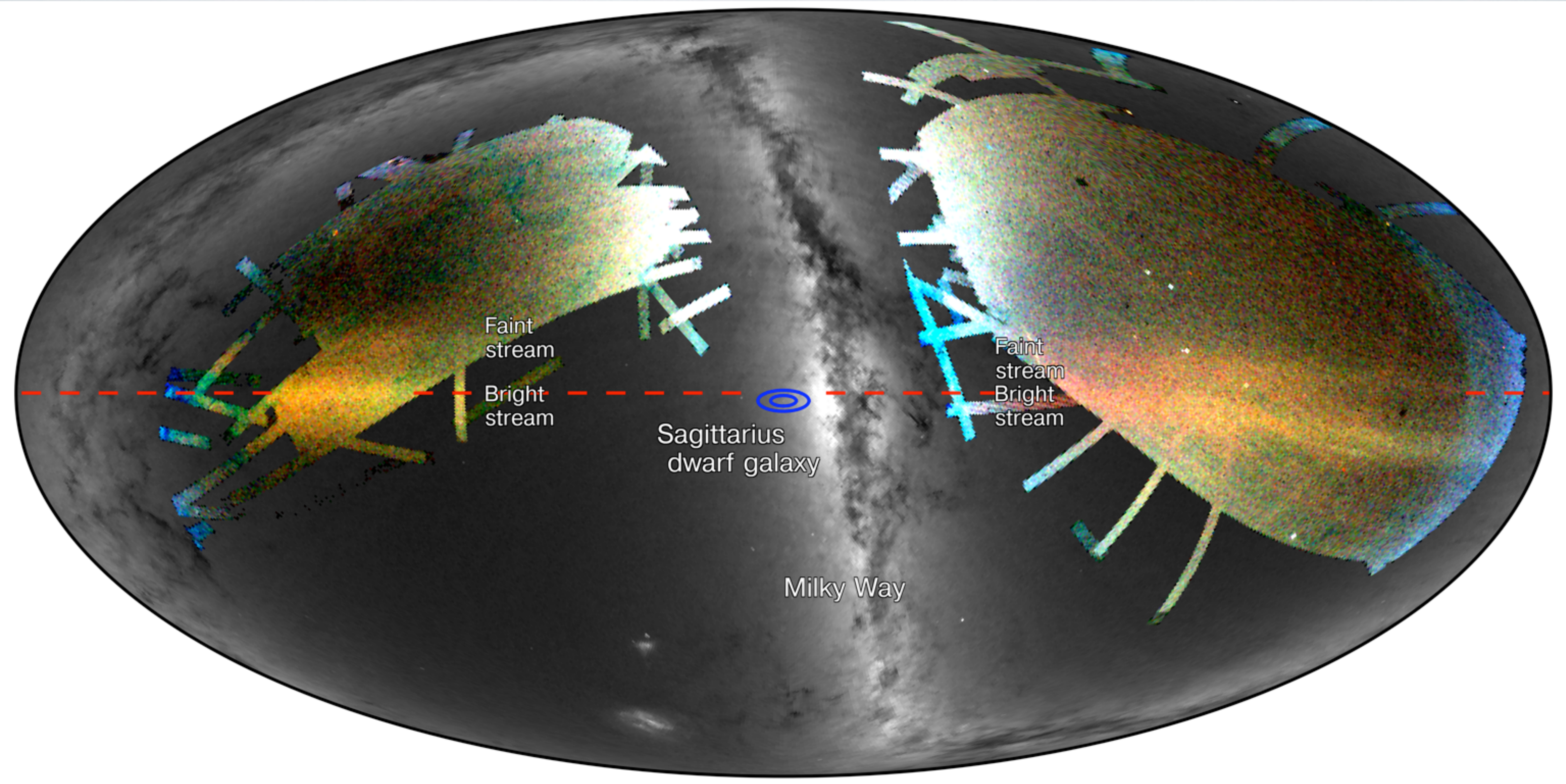
The Field of Streams completes the picture in the North



Koposov et al 2012

The Sgr stream in the South as delineated by MSTO stars with 0 < g-i < 0.7. Everywhere we look we see two streams with similar heliocentric distances!

THE SAGITTARIUS STREAM



THE SAGITTARIUS STREAM

The Sgr Stream provides ~ 20 % of all the debris of the stellar halo. including multiple huge tidal streams and probably 20 or so globular clusters.

By building luminosity profiles along the streams, and adding to the luminosity of the remnant, we can compute the luminosity of the progenitor galaxy as $\sim 1.4 \times 10^8$ $L_\odot$, comparable to the present-day Small Magellanic Cloud (Niederste-Ostholt et al. 2010).

THE SAGITTARIUS STREAM

One possibility is rotation, as is expected if the progenitor is a dIrr (Penarrubia et al. 2010, 2011)

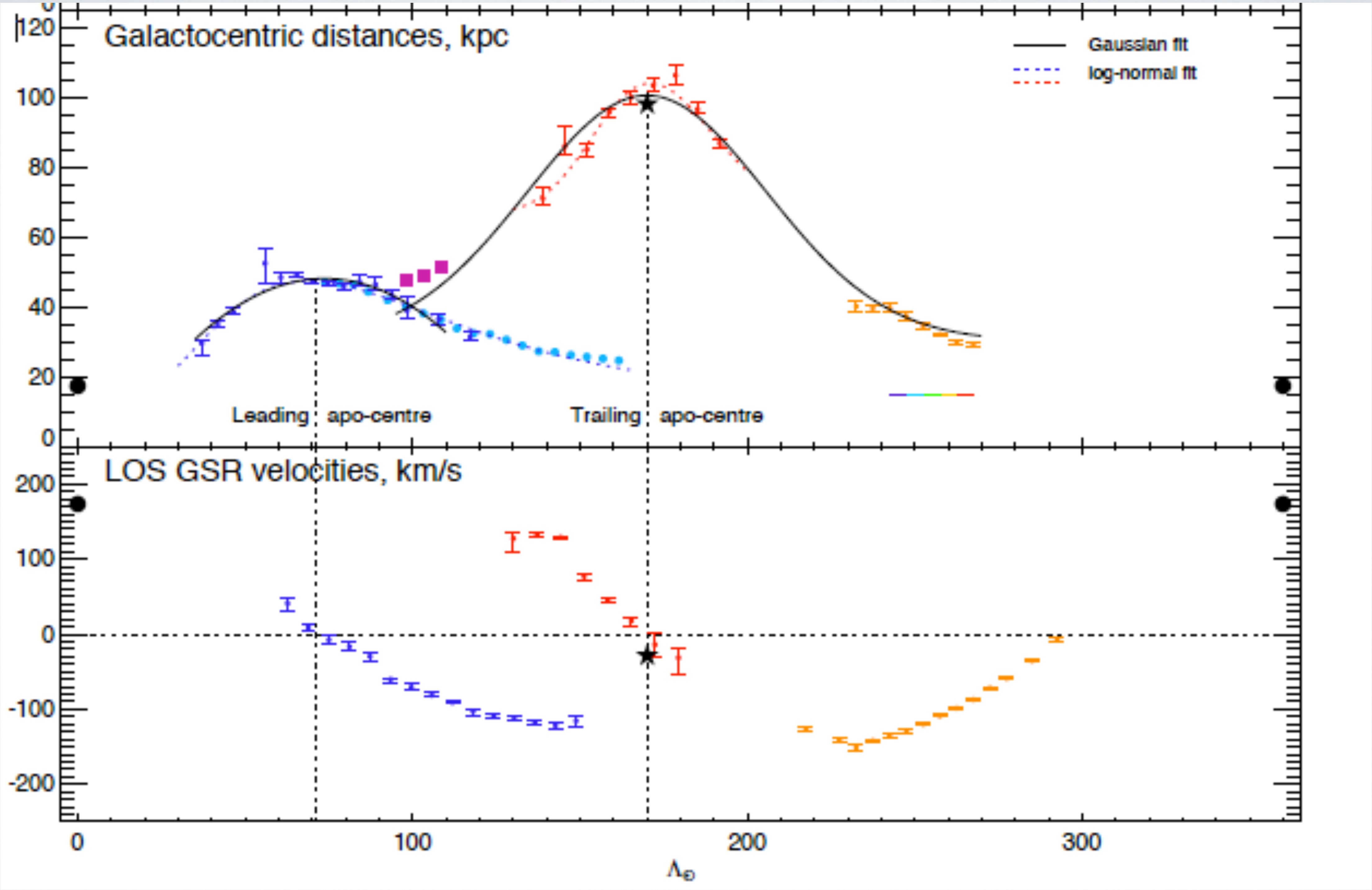
Another possibility is group infall, as is happening to the Magellanic Clouds at the present time. If two bound objects fall in, there may be two streams and two corpses (NGC 2419?).

Another possibility is that -- just as meteors have spread into different streams through evolution in the Solar system -- so debris from the Sagittarius torn off at different pericentric passages may suffer different amounts of precession in the Galaxy.

NGC 2419 the largest globular cluster in the Milky Way -- already suggested as the core of a dwarf galaxy by Cohen & Kirby (2012)

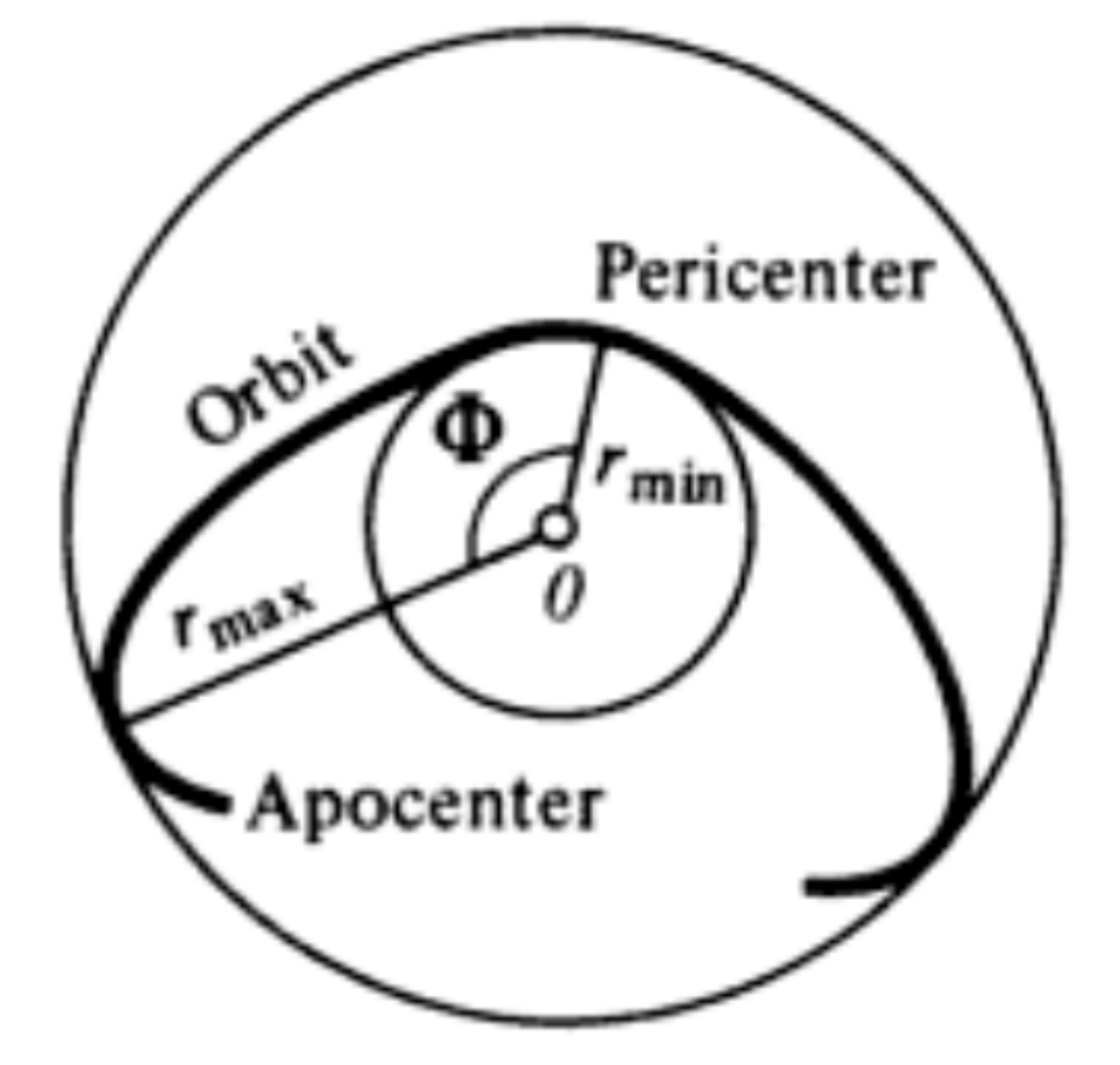
KINEMATICS OF SGR STREAM

Belokurov, et al 2013



The apocentre of the leading tail (trailing tail) is at 48(102) kpc. The angular difference between apocentres is 93º.

MECHANICS 101



The angle **Φ** is related to the potential

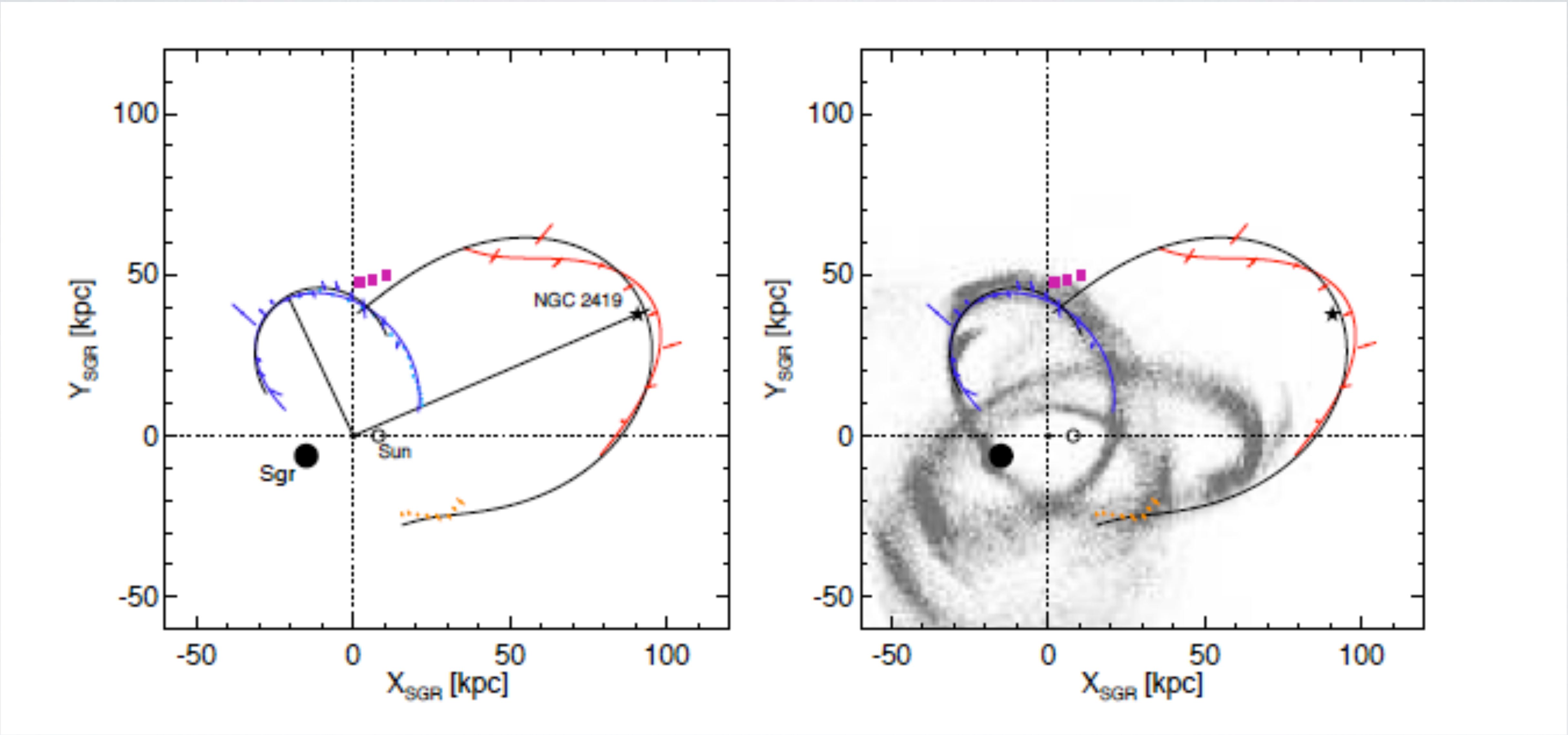
$$\Phi = \pi(\psi'/[3\psi' + \psi''])^{1/2}$$

For a power-law $\psi \sim r^{-\gamma}$, it is independent of radius

$$\Phi = \pi/\sqrt{(2-\gamma)}.$$

For a flat rotation curve **Φ≈** 120°

KINEMATICS OF SGR STREAM



Belokurov, Koposov, Evans et al 2013

In Law & Majewski's (2010) disruption model, the angle between apocentre & pericentre is 123°. For the data, it is 134°.

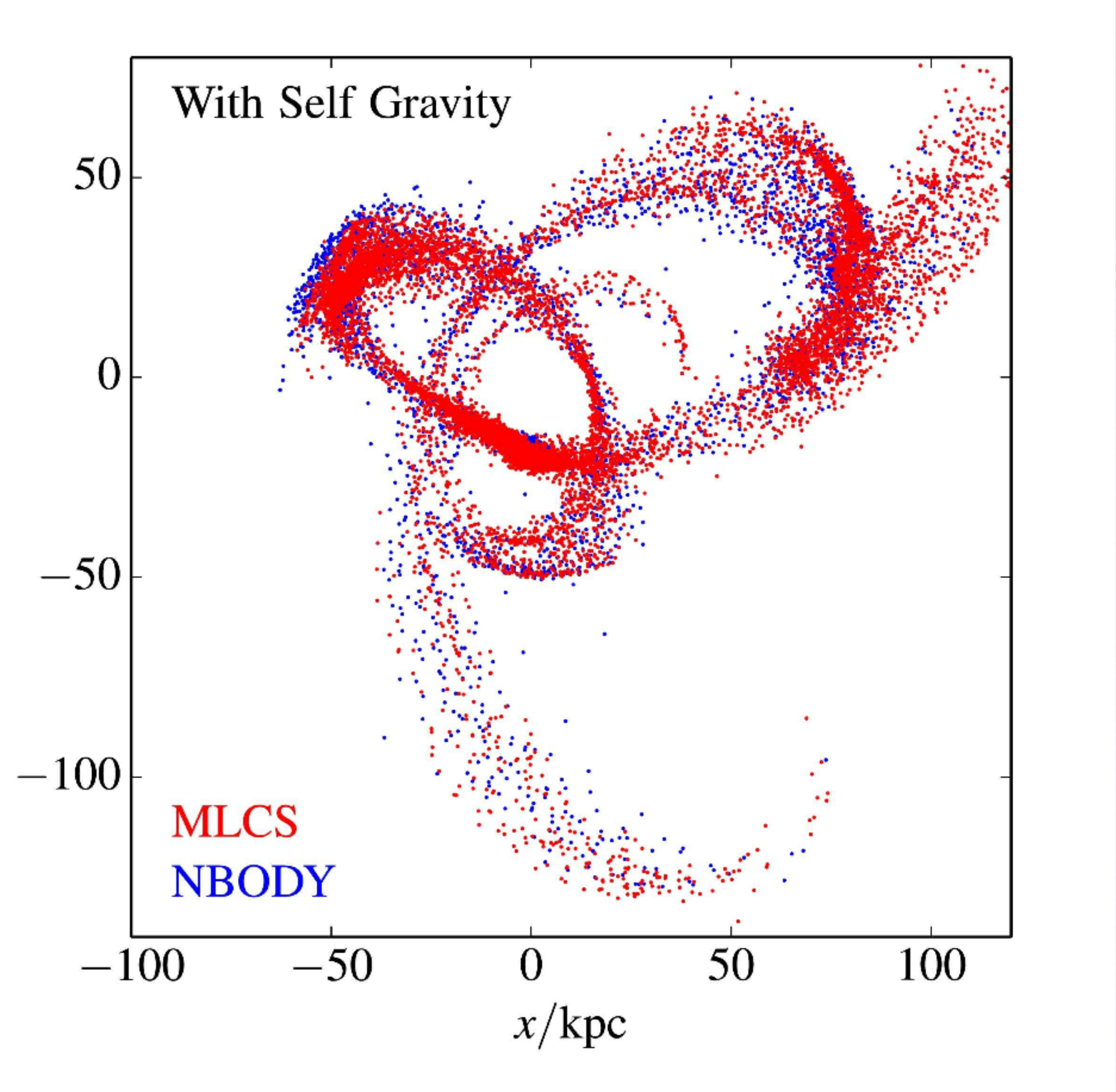
KINEMATICS OF SGR STREAM

- This simple argument is open to a number of objections..The most potent is that a stream is not an orbit. Material is stripped at the two Lagrange points, which lie along the line joining the progenitor to the Galactic centre, with a range of energy and angular momenta.

- Gibbons et al (2014) developed a way of mimicking N body experiments by following clouds of test particles released at Lagrange radii and integrating in the combined potential of the host and the progenitor.

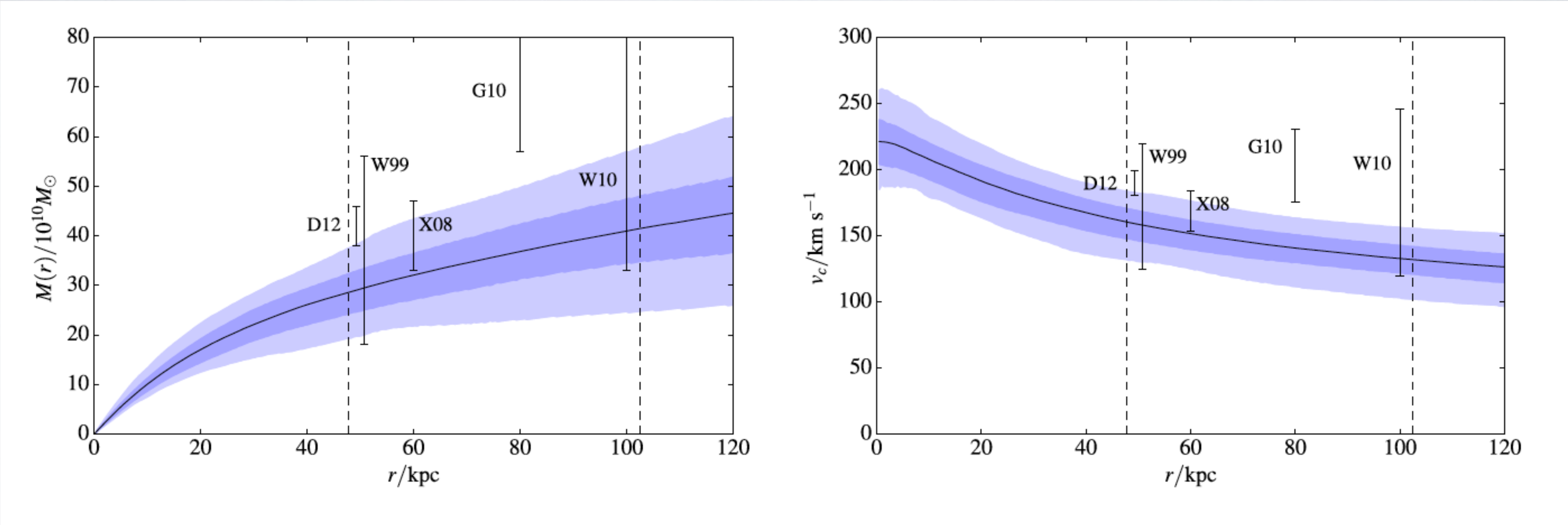
- Constrain 3 gravitational potential parameters while marginalising over 10 nuisance parameters (progenitor's initial conditions and structural parameters).

KINEMATICS OF SGR STREAM



Gibbons et al, 2014

MASS OF THE MILKY WAY



Gibbons et al, 2014

The cumulative mass profile flattens at ~ 40 kpc. If the profile does not change slope beyond 100 kpc, then the mass of the Milky Way should be low, 5-8 x $10^{11} M_\odot$

MASS OF THE MILKY WAY

- The Sgr stream says that the mass of the Milky Way is ~5-8 x $10^{11} M_\odot$ within 200 kpc.

- This is consistent with the kinematics of halo stars (~10^{12} $M_\odot$), and with the kinematics of the satellite galaxies if Leo I is unbound (~1.4 ±0.3 x10^{12} $M_\odot$).

- This is also consistent with the kinematics of the satellites at the fringes of Local Group (Diaz et al 2014) which finds 8 ± 5 x $10^{11} M_\odot$.

- This largely removes the 'Too Big To Fail' problem.

CONCLUSIONS

If there is a smooth component of the halo, then it must be possible to find a consistent solution for the density and the kinematics using an action-based DF (c.f. Williams & Evans 2015, Posti et al. 2015).

Stream modelling is now very fast. Most streams are not as enormous as the Sgr stream, and so their ability to constrain the potential is slight (c.f. Bowden et al 2015 on GD-1). Streams must be folded in with other data, such as the rotation curve or Oort's constants, to provide real constraints on the Galactic potential.