The Bifurcation of the Sagittarius Stream and the Shape of the Milky Way Halo

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Observational Evidence -
The Bifurcation (overlap of two branches of the tails)
Stream (A) and (B) have almost the same distance. Stream (C) is located behind stream (A).
“Houston - we have a Problem”:

- How can the two streams be so close in position and distance?
  - Is there no peri-centre shift?
  - Is there almost no shift of the object's orbit plane?
  - Is it caused by two objects?
    - No, see LMC & SMC
  - Did Sagittarius collide with another object?
    - Maybe, but that’s not causing a bifurcated stream
Model for Sagittarius:

- Plummer sphere with 1M particles
  - $R_{pl} = 0.35 - 0.5$ kpc ; $R_{cut} = 1.75 - 3.0$ kpc
  - $M_{pl} = 10^8 - 10^9$ $M_{sun}$

- Position today
  - $\alpha = 18^h 55^m 1$ ; $\delta = -30^\circ 29'$
  - $D_{sun} = 25$ kpc ; $v_{rad} = 137$ km/s

- Proper motion
  - HST, Schmidt plates, Law et al. fit & variations

- Orbit followed from -10 Gyr until today
Galactic Models: 1. - ML

- Logarithmic Halo:
  - $V_0 = 186$ km/s
  - $R_g = 12$ kpc

- Miamoto-Nagai Disc:
  - $M_d = 10^{11} M_{\odot}$
  - $b = 6.5$ kpc, $c = 0.26$ kpc

- Hernquist Bulge:
  - $M_b = 3.4 \times 10^{10} M_{\odot}$
  - $a = 0.7$ kpc

\[
\Phi_h = \frac{1}{2} v_0^2 \ln (R^2 + \frac{z^2}{q_\phi} + R_g^2)
\]

\[
\Phi_d = \frac{GM_d}{\sqrt{R^2 + (b + \sqrt{z^2 + c^2})^2}}
\]

\[
\Phi_b = \frac{GM_b}{r + a}
\]
Galactic Models: 2. - DB

- Dehnen & Binney model (1998)
- 3 discs (ISM, thin, thick) double exponential
- 2 spheroids (bulge halo) power law

\[
\rho_d = \frac{\Sigma_d}{2z_d} \exp \left( -\frac{R_m}{R} - \frac{R}{R_d} - \frac{|z|}{z_d} \right)
\]

\[
\rho_s = \rho_0 \left( \frac{m}{r_0} \right)^{-\gamma} \left( 1 + \frac{m}{r_0} \right)^{\gamma-\beta} \exp \left( -\frac{m^2}{r_t^2} \right); m^2 = R^2 + \frac{z^2}{q^2}
\]
'old' trailing arm
'young' leading arm
'Sun'
'Sag GC'
'old' leading arm
'young' trailing arm

D < 20 kpc
B

D > 20 kpc
D

C

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New Zeals for Old Galaxies
Distances
Sequence of increasing initial mass of Sagittarius

Strength of the Bifurcation decreases with increasing mass

\[ M_{\text{Sgr}} \geq 7.5 \times 10^8 \, M_\odot \Rightarrow \]

No Bifurcation
Increasing the mass matches the measured distances better
Spot The Bifurcation!
ML - HST proper motion - $q=0.90$
ML - HST proper motion - q=0.95
ML - HST proper motion - $q=1.00$
ML - HST proper motion - q=1.05
ML - HST proper motion - $q=1.11$
ML - HST proper motion - q=1.25
ML - Schmidt plates PM - $q=0.90$
ML - Schmidt plates PM - q=0.95
ML - Schmidt plates PM - $q=1.00$
ML - Schmidt plates PM - q=1.05

$q_\phi = 1.05$
ML - Schmidt plates PM - $q=1.11$
ML - PM fit by Law et al. - q=0.80
ML - PM fit by Law et al. - $q=0.90$
ML - PM fit by Law et al. - $q=0.95$
ML - PM fit by Law et al. - $q=1.00$
ML - PM fit by Law et al. - \( q=1.05 \)
ML - PM fit by Law et al. - $q=1.11$
ML - PM fit by Law et al. - \( q=1.25 \)
ML - PM fit by Law et al. - $q=1.50$
DB - Schmidt pl. PM + 0.1 - q = 0.90
DB - Schmidt pl. PM+0.1 - q=0.95

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DB - Schmidt pl. PM+0.1 - q=1.00
DB - Schmidt pl. PM+0.1 - q=1.05
DB - Schmidt pl. PM+0.1 - q=1.11
DB - PM fit by Law et al. - q=0.90

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New Zeals for Old Galaxies
DB - PM fit by Law et al. - $q=0.95$
DB - PM fit by Law et al. - q=1.00
DB - PM fit by Law et al.- q=1.05

q=1.05

RA [deg]

DEC [deg]
DB - PM fit by Law et al. - q=1.11
DB - Schmidt plates PM - q=1.00
What’s your result?

- You should have spotted 7 simulations which show a bifurcation and maybe a few very weak ones.
- All simulations with bifurcation have $0.95 \leq q \leq 1.05$.
Miamoto-Nagai + logarith. halo - Dehnen-Binney model

$q = 0.9$

$q = 0.95$

$q = 1.0$

$q = 1.05$

$q = 1.11$
Conclusions

- Bifurcation only appears in spherical or almost spherical halos
  \[ Q_\phi(20 \text{ kpc}) \approx 0.95 - 0.97 \]
- Higher masses blur out the bifurcation but decrease the distance error
  \[ M_{Sgr} \leq 5 \times 10^8 \, M_{\text{sun}} \]
- HST proper motion does not reproduce the bifurcation in any Galactic model
Is this the end of this talk?

No!
Some more results from our group …
The North Galactic Cap as Seen by SDSS: A “Field of Streams”...and Dots

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Canes Venatici I

Appears “normal”, yet contains two kinematic components, $\sigma \sim 14 \text{ km s}^{-1}$ and $\sigma < 2 \text{ km s}^{-1}$ (Ibata et al. 2006)
Boötes

Bizarre morphology, measured $\sigma \sim 7$ km s$^{-1}$ (Muñoz et al. 2006); paper in prep: Keck, AAT data
Ursa Major II

Bizarre; associated with Orphan stream? (Complex A?)
Reproduction of Orphan Stream & UMa II
Comparing the kinematics of the different models

One component: before, while & after dissolution

Two component
But wait, there are more...

- 4 more probable dwarfs and a likely globular:
  - Coma
  - CanVen II
  - Segue 1
  - Hercules
  - Leo IV
Some Implications

- Numbers: 8 MW dwarfs (including UMa I) have been found to date, in SDSS data covering ~20% of the sky ⇒ tens more likely remain undiscovered.

- Properties: Ultra-low luminosities (-3.8 ≥ M_V ≥ -7.9) and surface brightnesses (μ_V < 27 mag arcsec^2), odd morphologies ⇒ are these truly dwarf galaxies or massive star clusters? Are these a distinct class of object?

Hobbit Galaxies?
Mind the Gap?

And XI, XII, XIII

MV vs. Log(r_h)
Leo T: A New Type of Dwarf?

- $M_V \sim -7.1$,
- $\mu_V \sim 26.9$ mag arcsec$^{-2}$
- $(m - M)_0 \sim 23.1$, ~420 kpc
- Recent < 1 Gyr star formation -- blue loop/MS stars

SDSS data
INT Data
The Smallest Star-Forming Galaxy?

- Not dead yet: stars formed within past few $\times 10^8$ yr
- HIPASS: Coincident H I, $RV_\odot \sim 35$ km/s (+ GMRT...)
- if @ 450 kpc, $\sim 2 \times 10^5 M_\odot$ in H I ($M_{HI}/M_* \sim 1$, cf. Local Group dIrrs)
- Is Leo T the tip of a Local Group “free floating” iceberg?
Now I'm really finished

I promise!

No seriously...

No seriously...

I'm not joking - this is the end...