



# Tracing stellar tidal streams in the Galactic halo

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**N-body model “maker”:**

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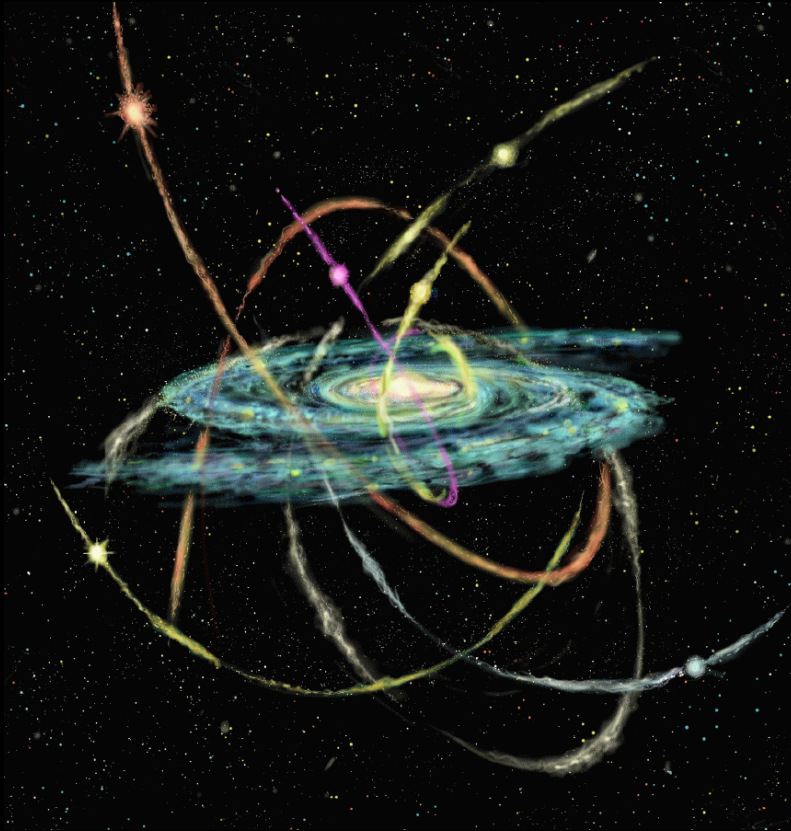
**The SDSS collaboration for Galactic Structure:**

Mario Juric (Princeton), Z. Ivezić (Princeton), H. W.  
Rix (MPIA)

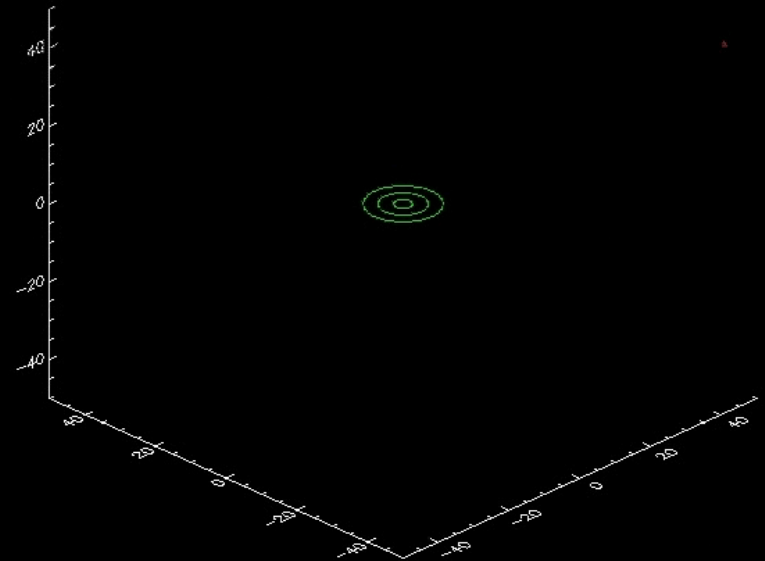
**Also starring:**

E. J. Alfaro (IAA), S. R. Majewski (Virginia Univ), Ignacio  
Trujillo(IAC), R. Jay Gabany (Cosmotography)

# THE MILKY WAY: AN EXCELLENT LABORATORY FOR TESTING GALAXY FORMATION MODELS

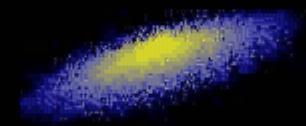
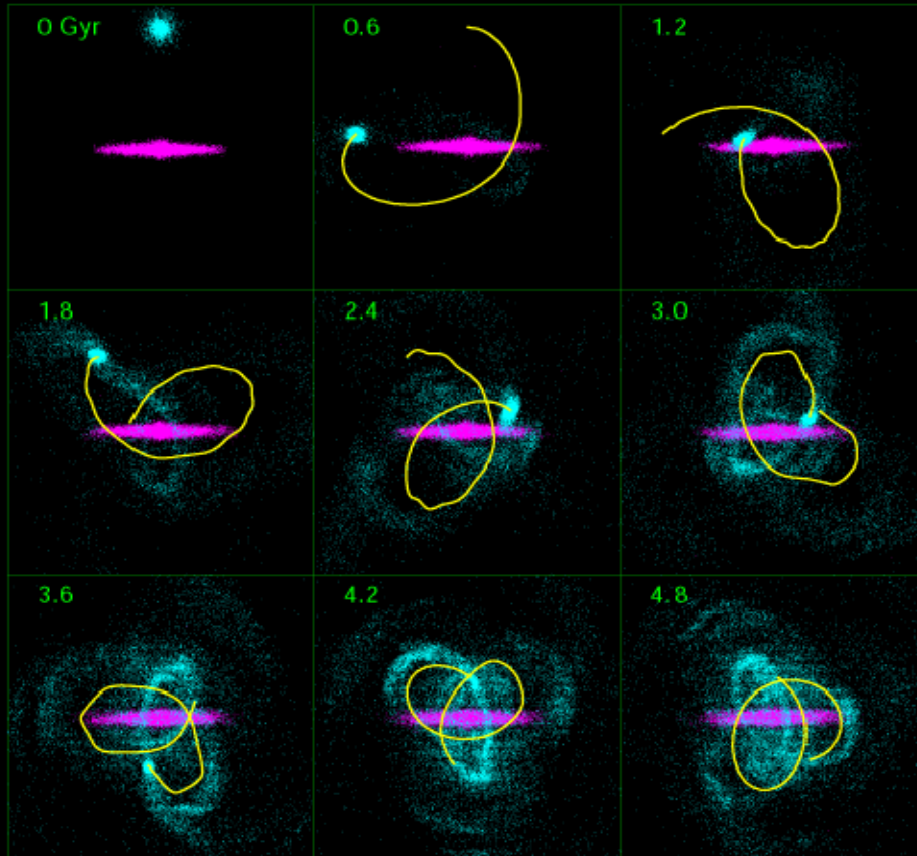


Searle & Zinn (1978)

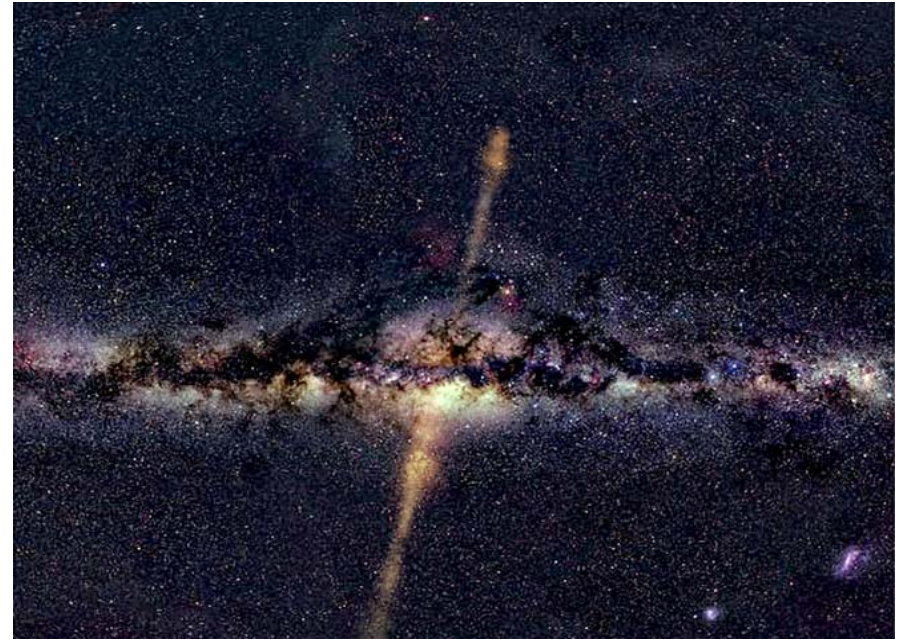


Hierarchical galaxy formation in CMD cosmology (present)

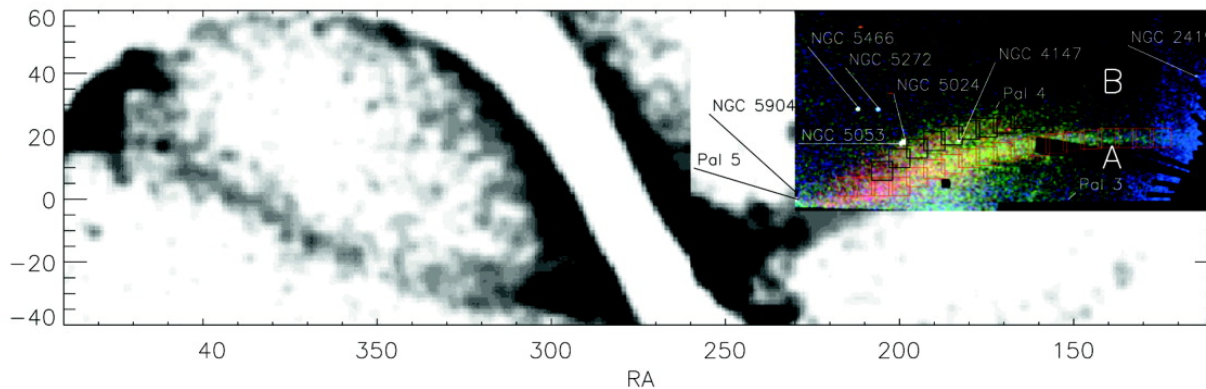
# The ghost of a dwarf galaxy: Stellar Tidal Streams



# THE SAGITTARIUS TIDAL STREAM



Martinez-Delgado et al. 2001



Majewski et al. 2003

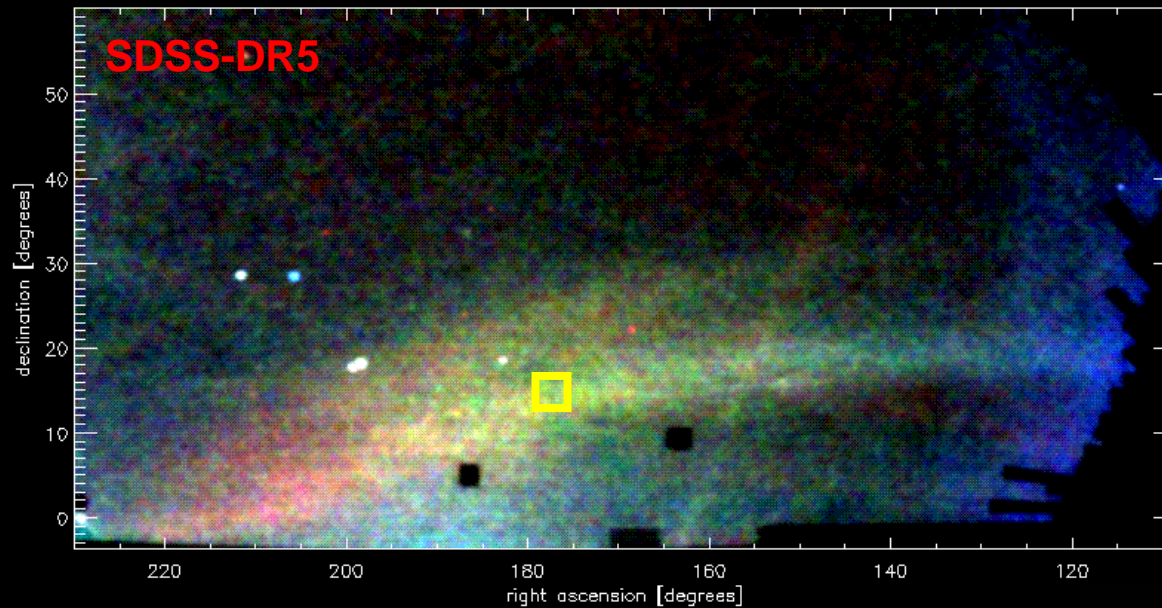
Belokurov et al. 2006

AN ALL SKY VIEW OF  
THE SGR STREAM!!

$M_V = -13.3$ ;  $M/L \sim 25$

15% mass in tidal stream !

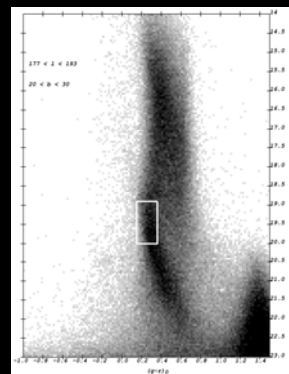
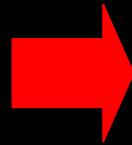
# Galactic Tidal Streams



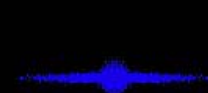
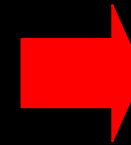
Belokurov et al. 2006



Streams resolved  
in stars. SB~30.5  
mag/arcsec<sup>2</sup>

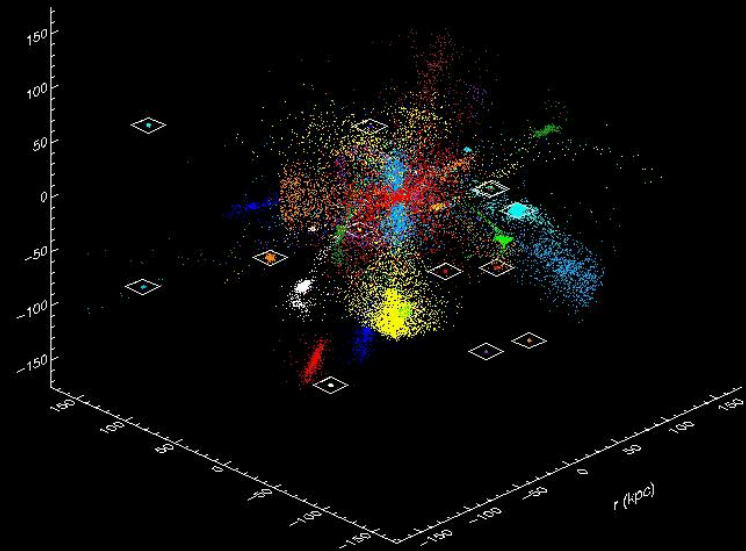
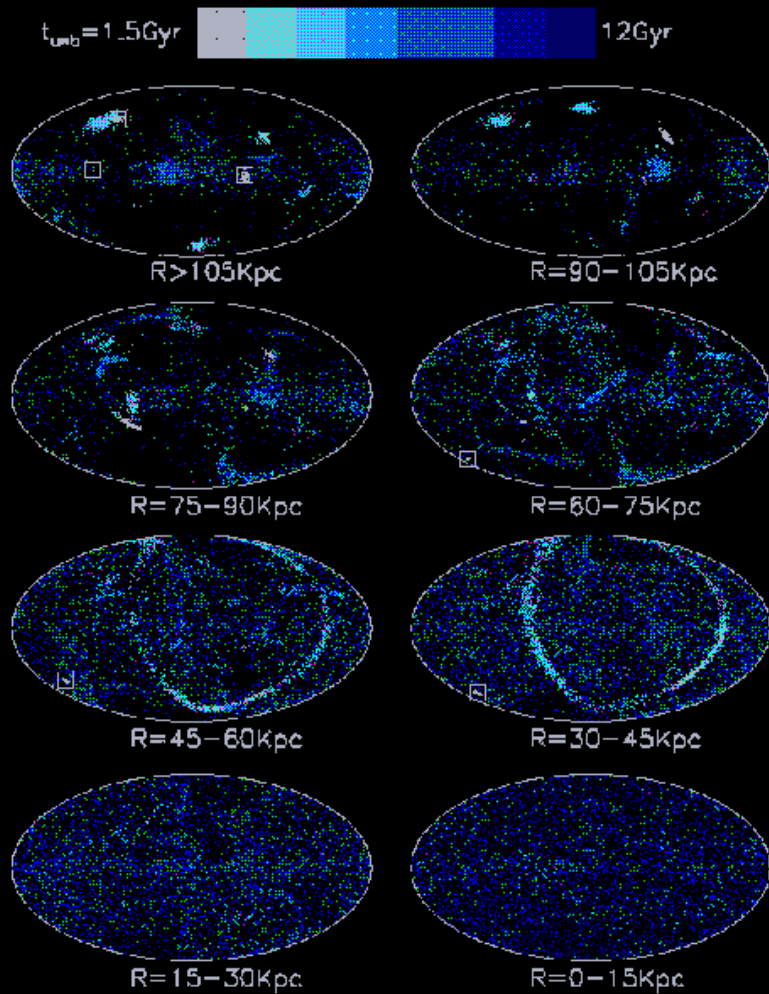


CMD provides positions,  
distances, targets for Vr



N-body simulations  
build the dynamical  
history of the stream

# GALACTIC ARCHAEOLOGY



How many merger events  
can be identified in the  
Galactic halo today?

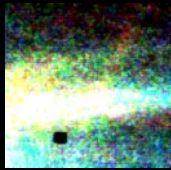
# Milky Way tidal stream census 2007



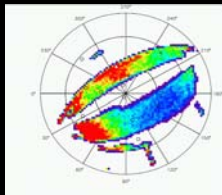
**Sagittarius tidal stream**



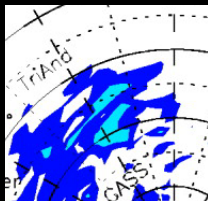
**Monoceros/Anticenter tidal stream**



**Orphanat stream**



**Virgo tidal stream ??**



**Tri/And tidal stream ??**



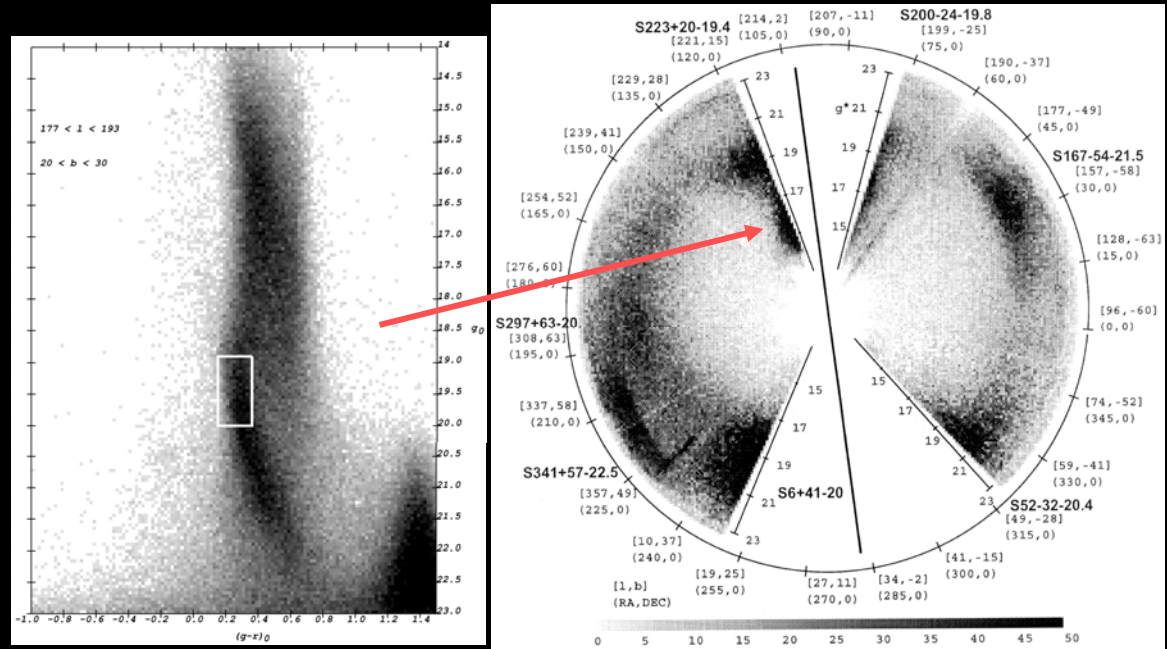
# The Monoceros tidal stream

A giant stellar ring surrounding the Milky Way disk at 16 kpc (Newberg et al. 2002)

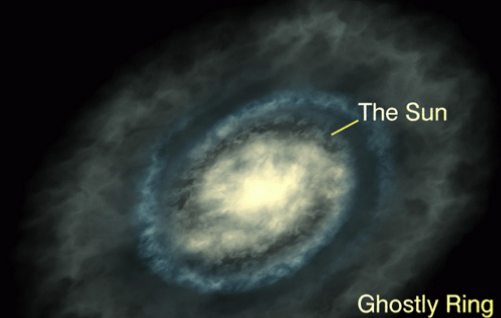
Only visible at low galactic latitude ( $|b| < 25$ )

Tidal stream detected before the discovery of its parent galaxy.

The nature of low-latitude stellar structure is controversial: Galactic feature or satellite accretion?



A Ring around the Milky Way

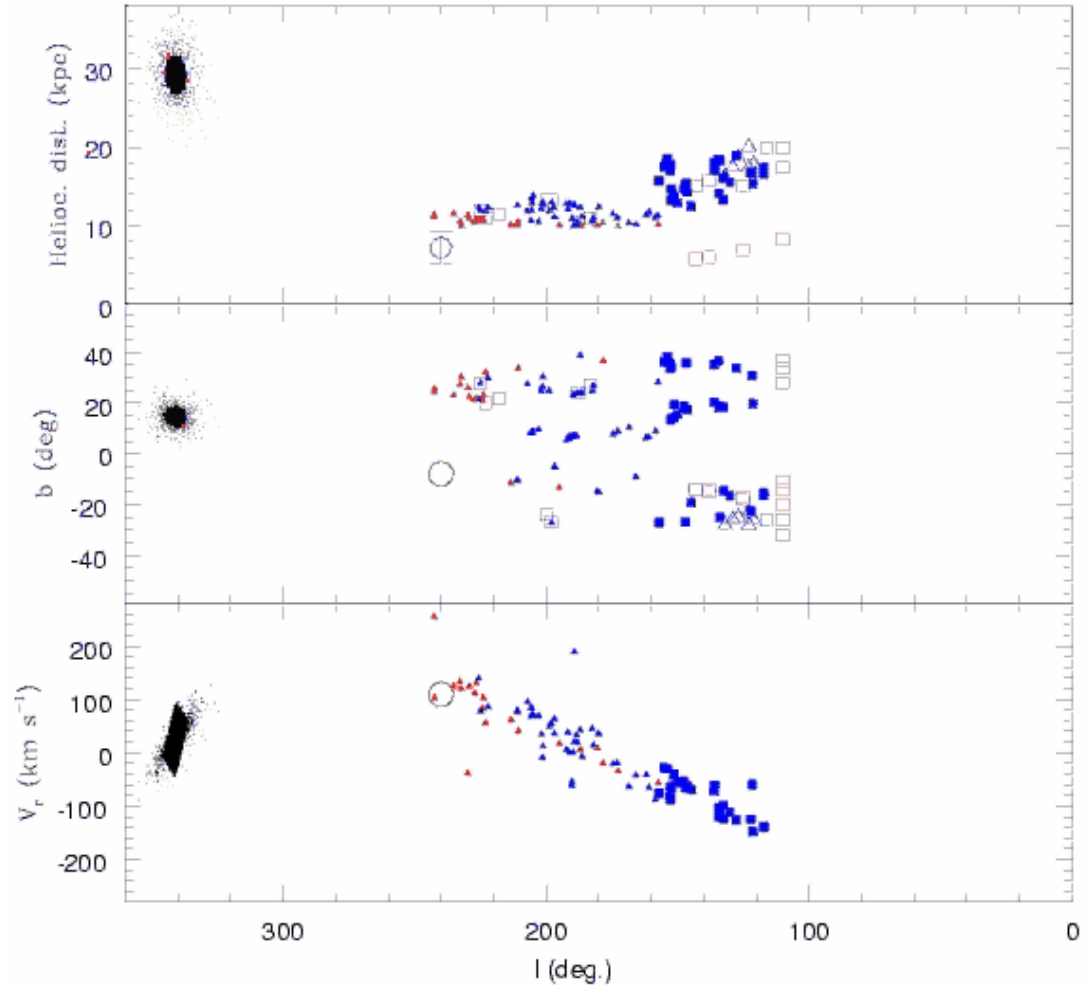


# A comprehensive model of the Monoceros Stream

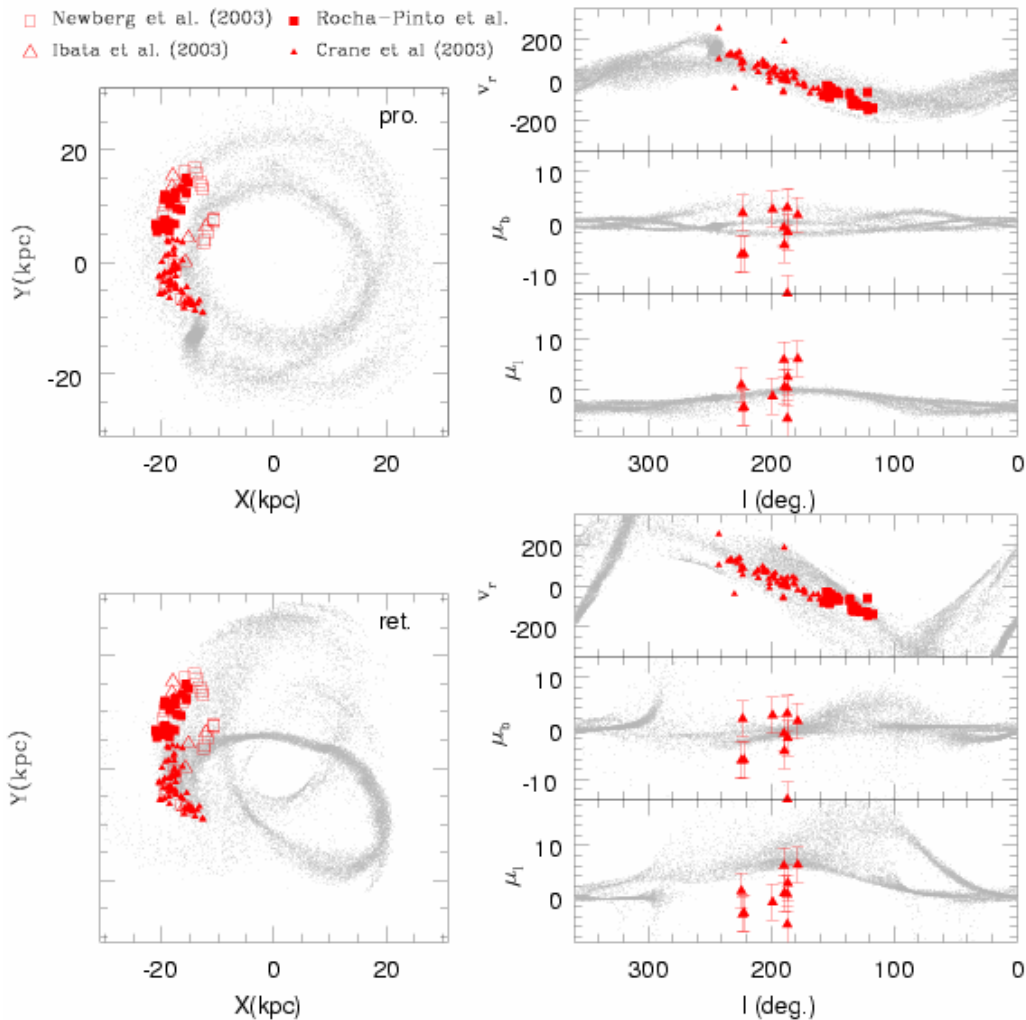
An extraordinary observational effort in the last year for different groups to trace this stream.

Best orbit obtained using semi-analytical model from fitting to position, distance and velocities of stream stars (151200 simulations)

N-body simulation for the best orbit, including dynamical friction included



Observational data consistent with a huge tidal stream disrupted in the last 2.9 Gyr



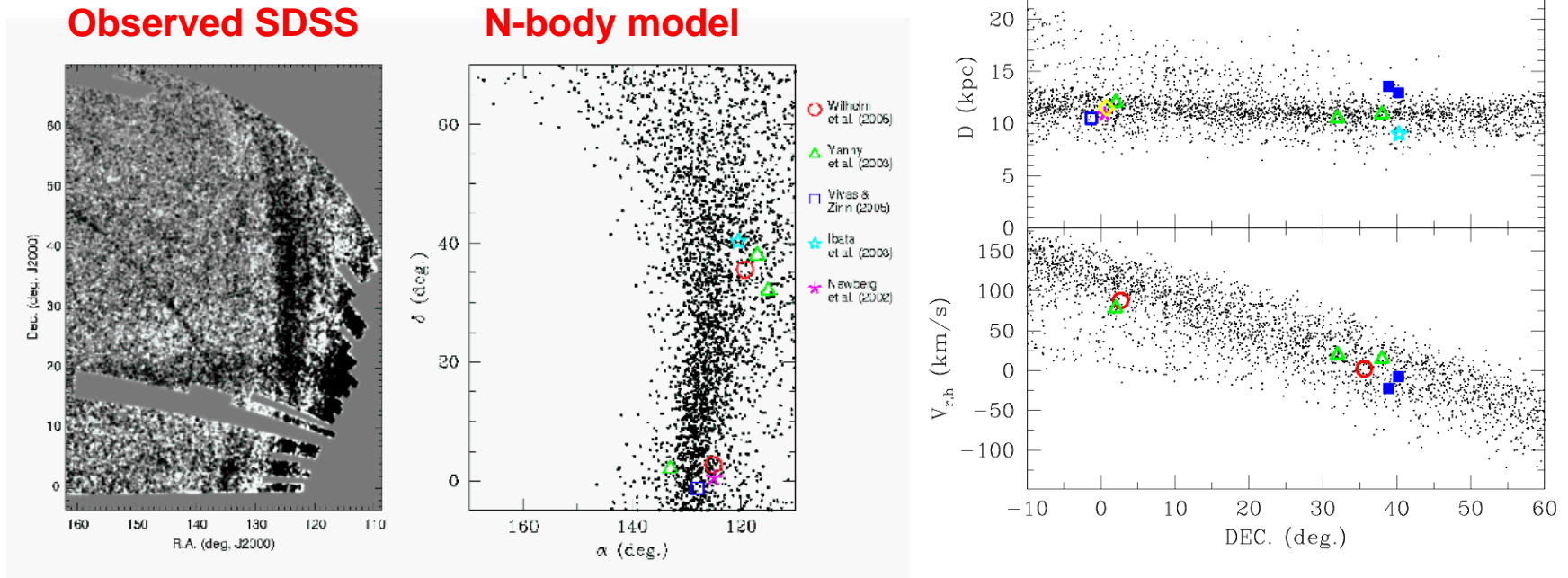
Radial velocities are not enough to constrain the sense of motion of the orbit: Proper motions from SDSS were used to constrain orbital motion

**A low inclined ( $i=20 \pm 5^\circ$ ), almost circular ( $e=0.10 \pm 0.05$ ), **PROGRADE** orbit**

Distance and kinematical data are not enough to constrain the position of the main body of the parent galaxy: progenitor can be in  $100 > l > 200$

**Peñarrubia, Martínez-Delgado, Rix et al. 2005**

# The Galactic Anticenter Stream?



Grillmair (2006) reports the discovery of a coherent 60°-long unknown tidal stream in the Galactic Anticenter.

However, we find an excellent agreement with the Monoceros tidal stream N-body model: the first panoramic view of this outer stellar ring (Peñarrubia, Martínez-Delgado & Rix 2007)

# TIDAL DEBRIS IN VIRGO

Large scale photometric surveys report the presence of extended over-densities in Virgo

- The Virgo Stellar Stream - RR Lyrae clump (QUEST)  
- MS turnoff stars (SDSS)

Vivas 2002; Newberg et al. 2002; Duffau et al. 2006

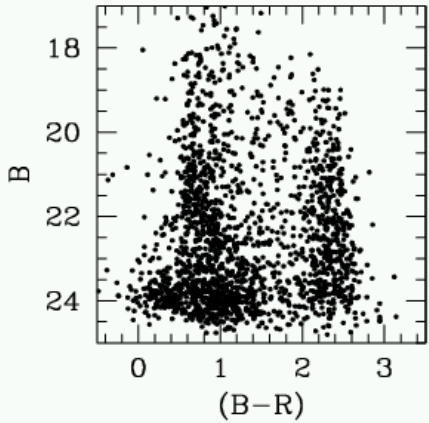
- The Virgo “over-density” - MS stars (SDSS)

Juric et al. 2006

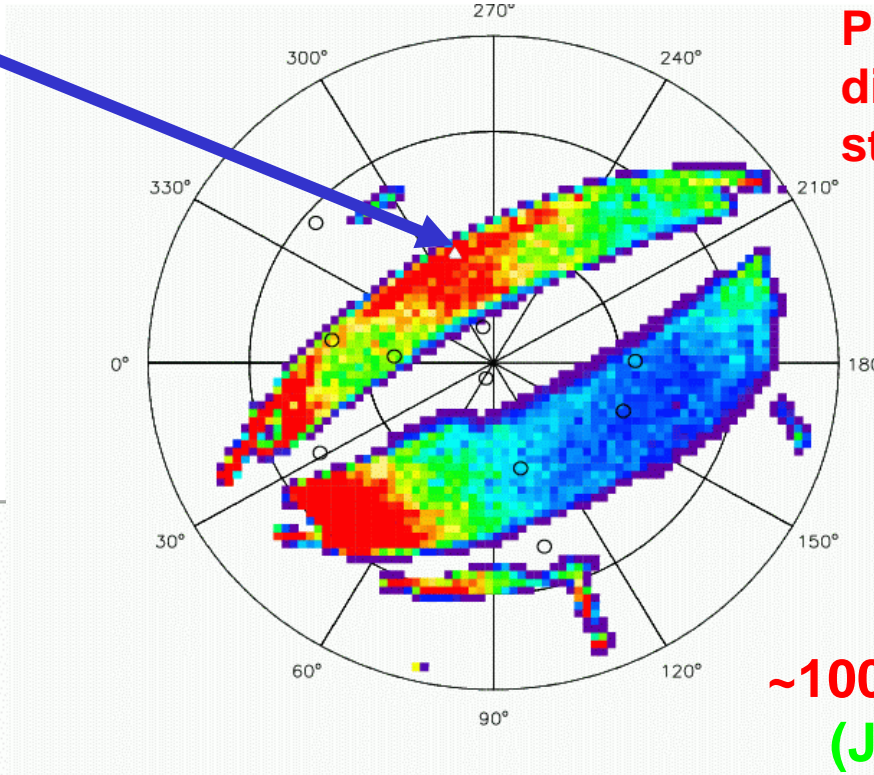
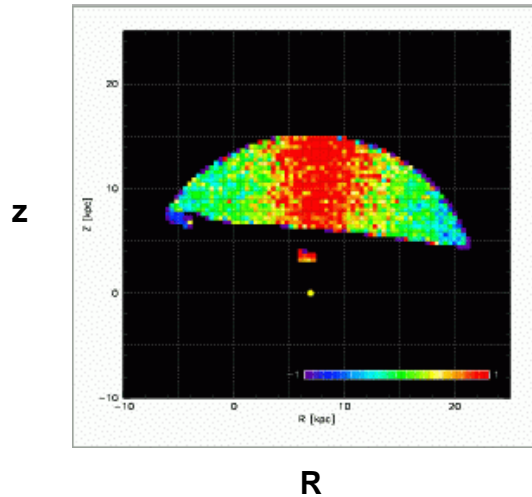
Similar position, but different distances and structure.

Are these populations tracing a huge tidal debris of a new satellite? Or a mix of debris from different systems?

# The Virgo stellar over-density: a new Milky Way satellite?



Martinez-Delgado et al. 2006



Photometric parallax  
distances of 48 million  
stars (Juric et al. 2006)

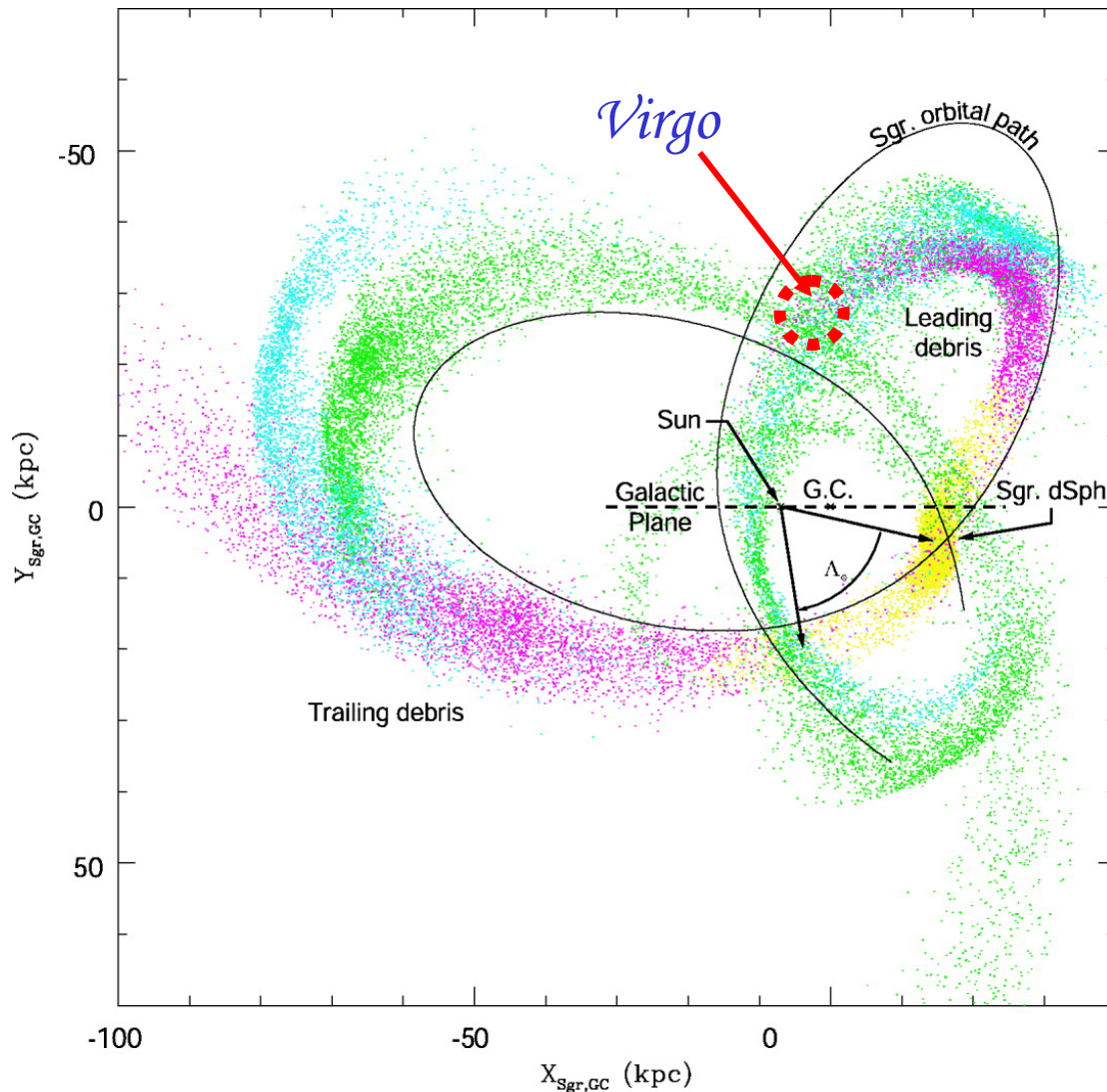
~1000 square degrees  
(Juric et al. 2006)

**The largest stellar lump ever reported in the  
outer halo!!!**

PRESS RELEASE January 9<sup>th</sup>, 2006:

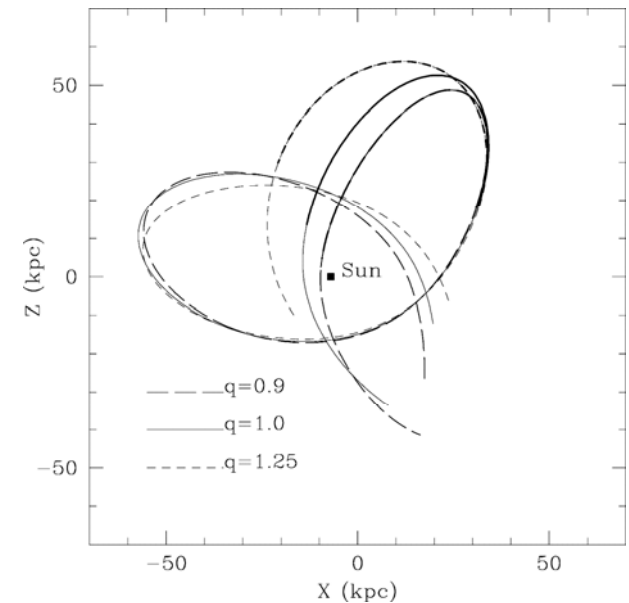
**“The SDSS reveals a new Milky Way neighbor”**

# Tidal debris from Sagittarius dwarf?



Law et al. 2005

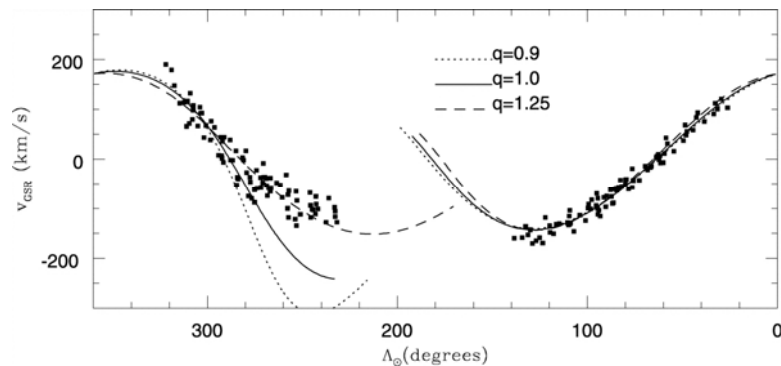
Stellar over-densities in Virgo were associated with a cross of Sgr tidal tails at 20 kpc predicted by theoretical models...but never observed...



# What is the best Sgr stream model?

Sgr tidal stream has been used to constrain the shape of the dark matter halo of the Milky Way (Johnston et al. 2005; Helmi 2004; Law et al. 2005; Martinez-Delgado et al. 2004)

But there is not a perfect model!:



Radial velocities of the Sgr leading arm can only be fitted with a prolate halo model (Helmi 2004)

Johnston et al. (2005) find prolate halos cannot reproduce the precession rate in the youngest pieces of the Sgr stream (excluding models with  $q > 1$ )

For our comparison, we will explore both cases:  
**q=0.8 (oblate halo)**      **q=1.4 (prolate halo)**

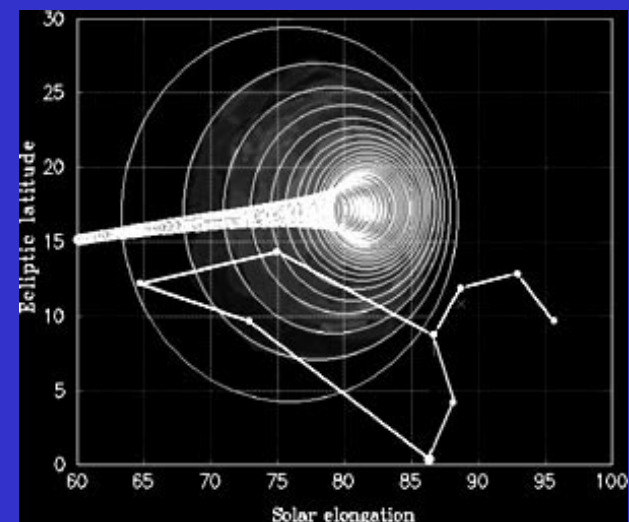
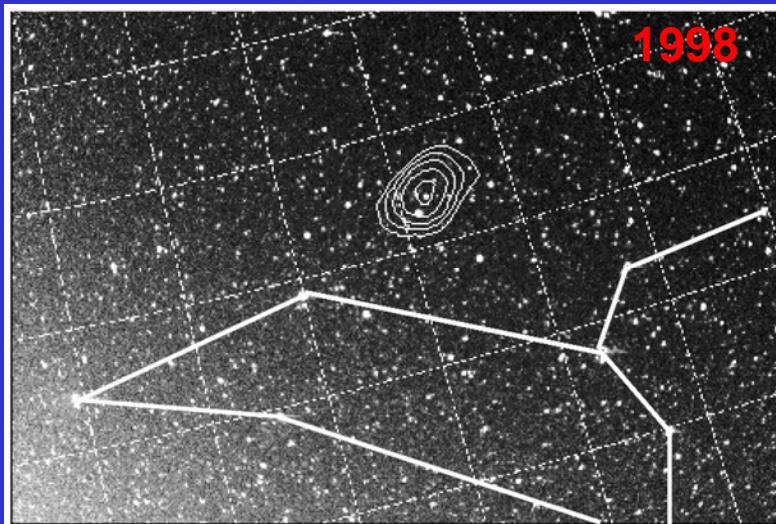
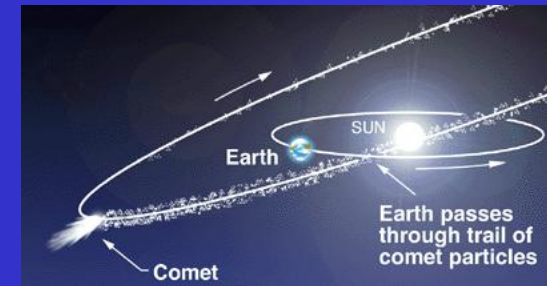
**We have not include any data of Virgo in these simulations**



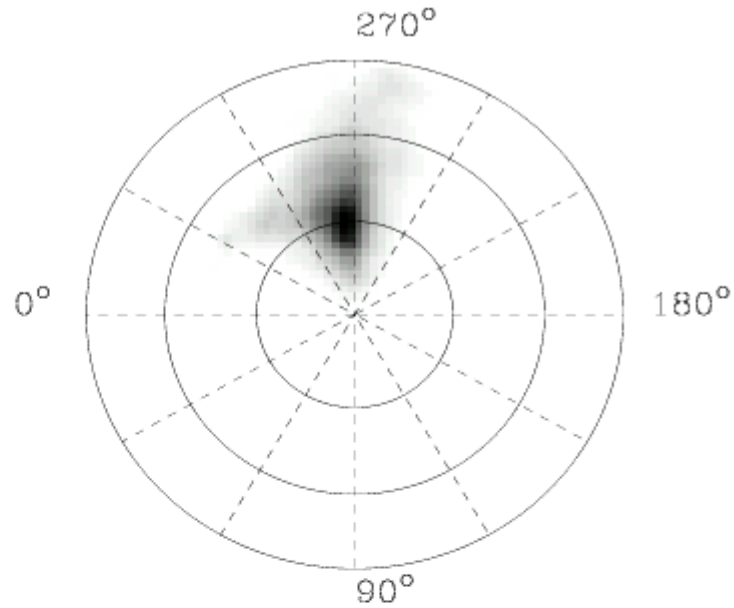
# A meteor shower analogy



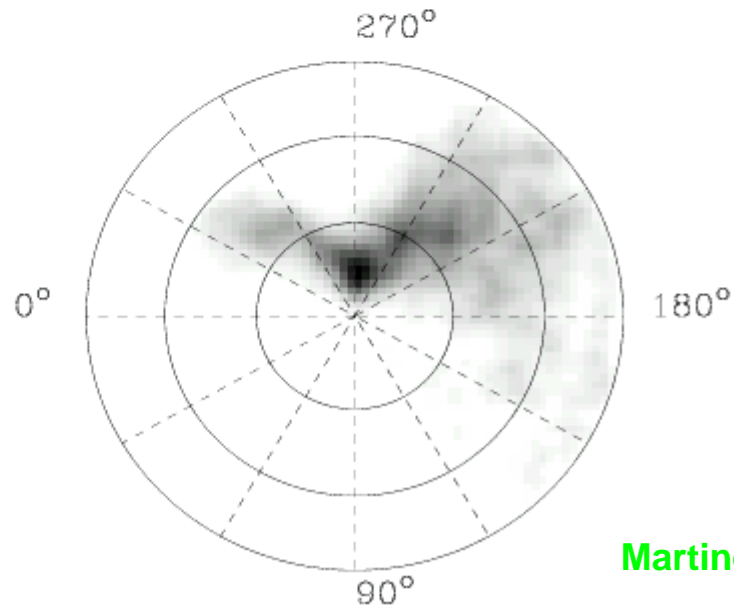
During the 1883 Leonids meteor storm, some observers reported a huge light glow in the sky: the signature of the meteoroids stream closing to the Earth seen in projection!!!



$$q_h = 0.8$$



$$q_h = 1.4$$



$(l, b)_{\text{obs}} \sim (290, 65)$

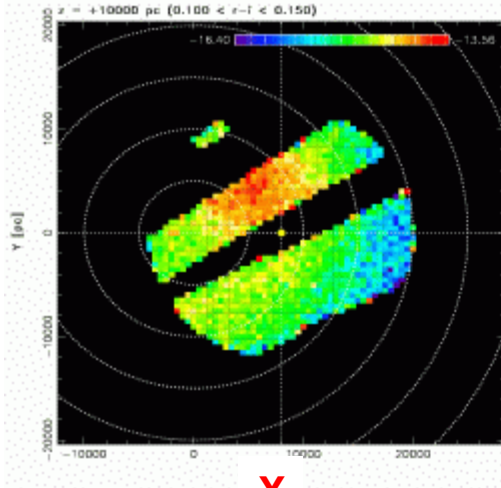
Martinez-Delgado et al. 2007

# *SDSS* tomography

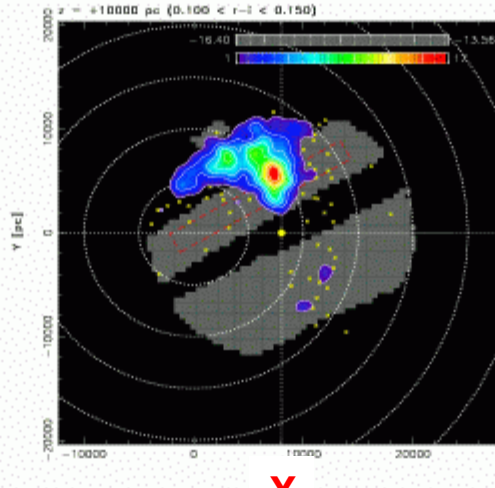
$$q_h = 0.8$$

$$q_h = 1.4$$

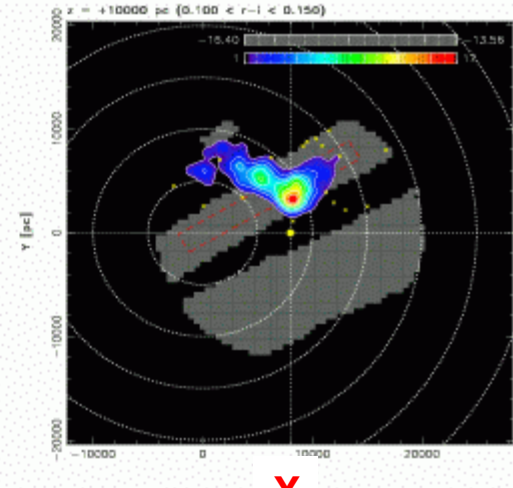
Y



X

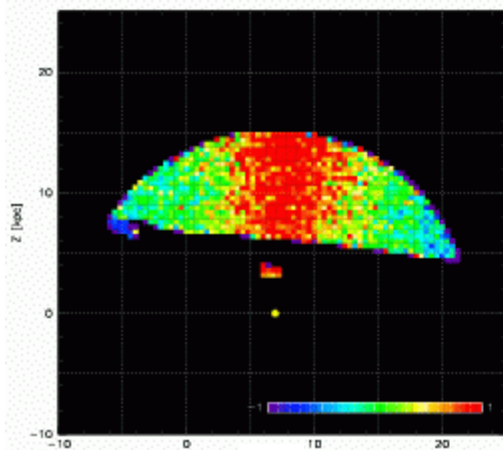


X

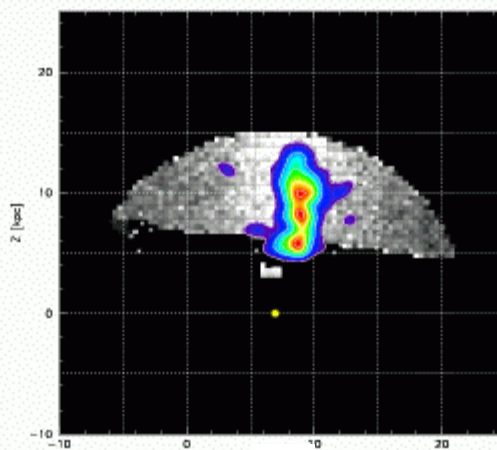


X

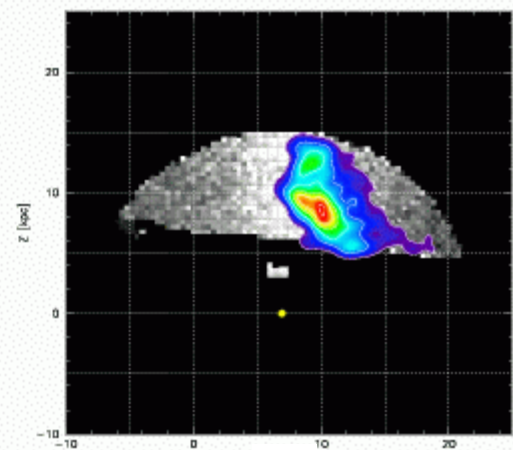
Z



R

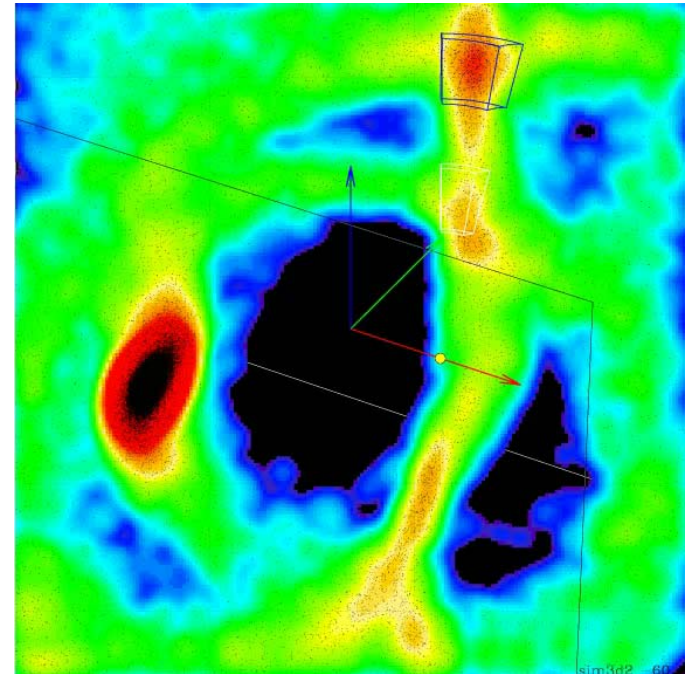
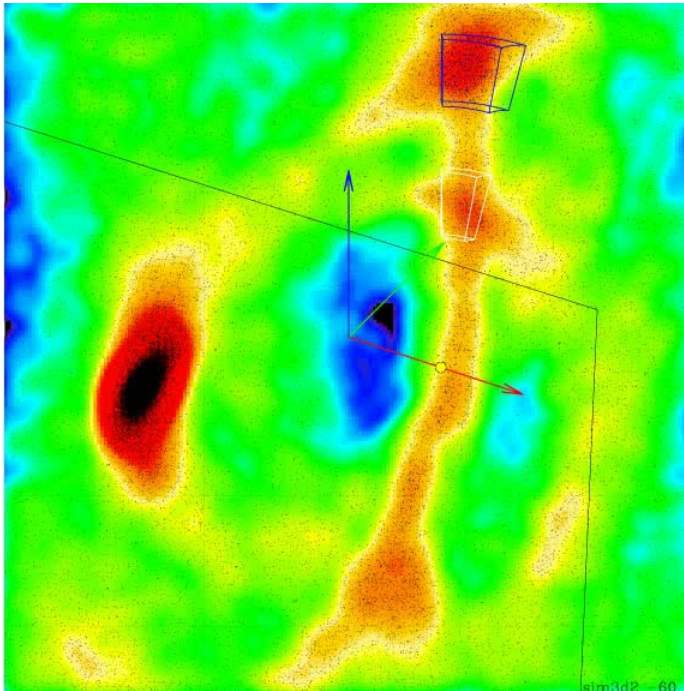
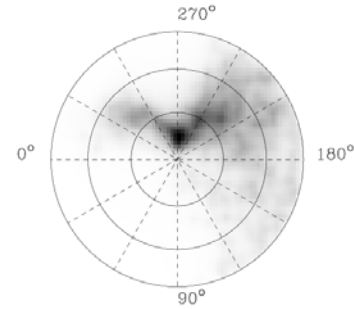
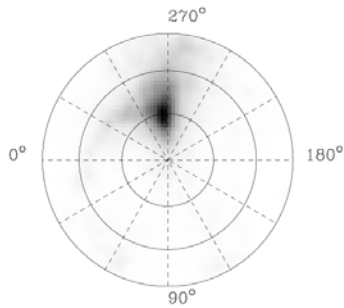


R



R

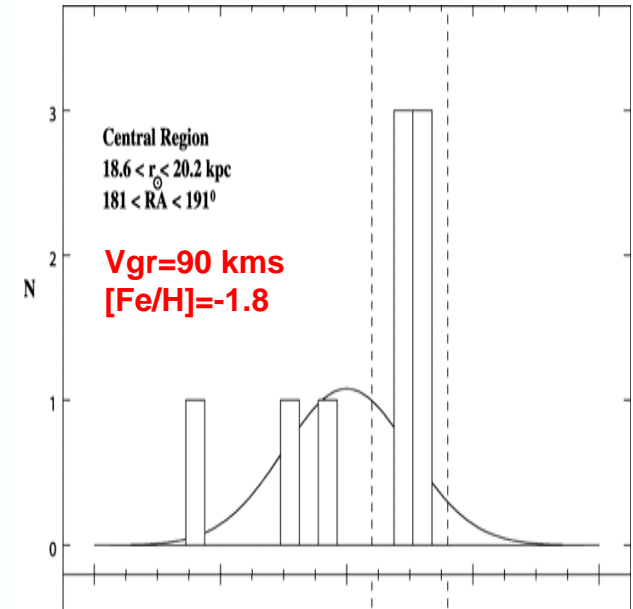
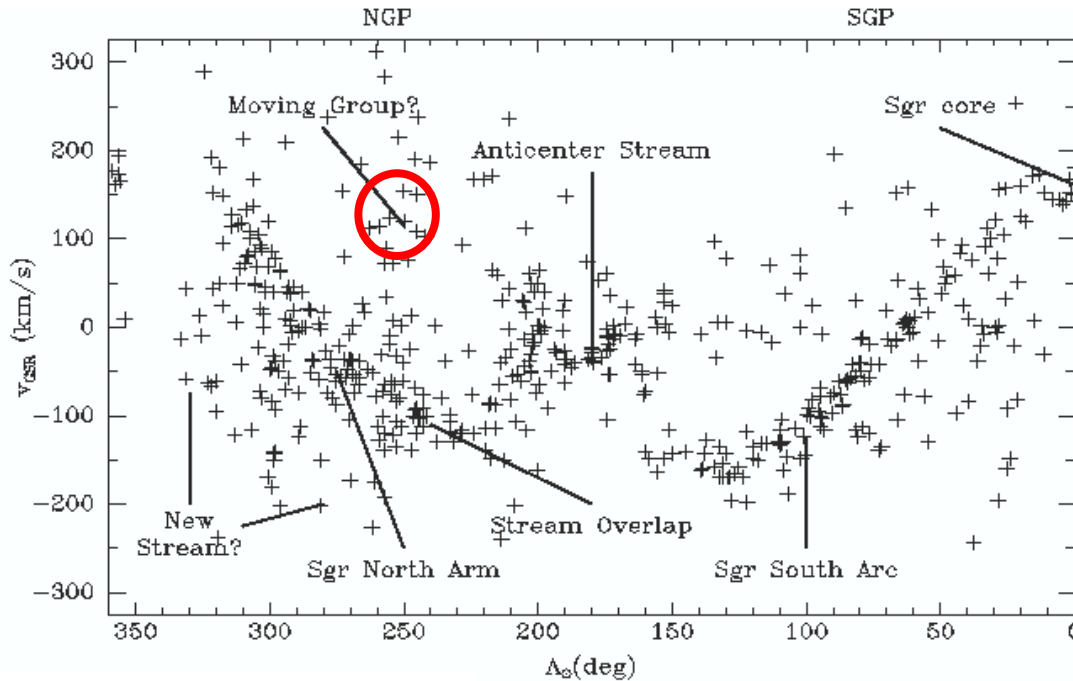
# Comparison with the 3D structure of Sgr tidal debris



$q_h = 0.8$  (oblate)

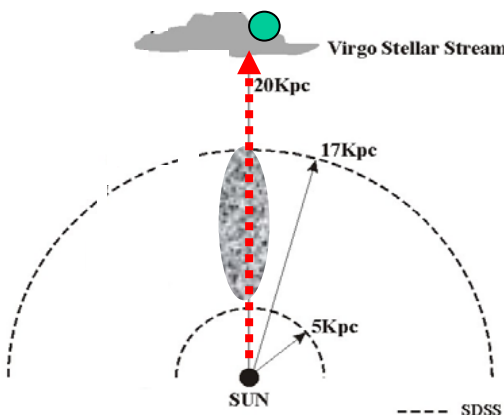
$q_h = 1.4$  (prolate)

# The Virgo Stellar Stream



**VSS detected as moving group in a M-giant radial velocity survey (Majewski 2002)**

**The "12.4h" RR Lyrae clump (see K. Vivas talk)**



**CMD MS turnoff and RR Lyrae yield the same distance:  $\sim 20$  kpc ( $\Delta \sim 1.5$  kpc)**

# The Virgo Stellar Stream (II)

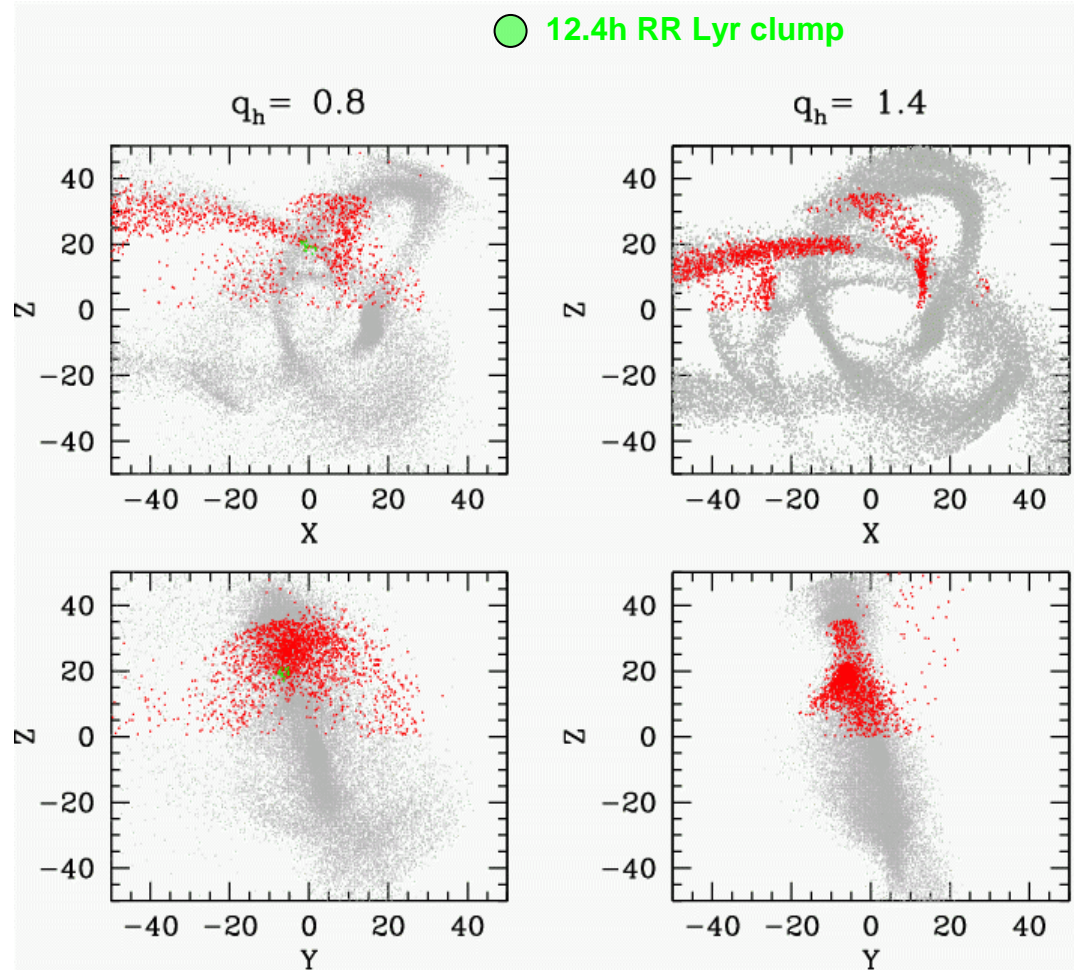
The positive radial velocity rejects its association with the Sgr leading arm: **something else is out there!!!**

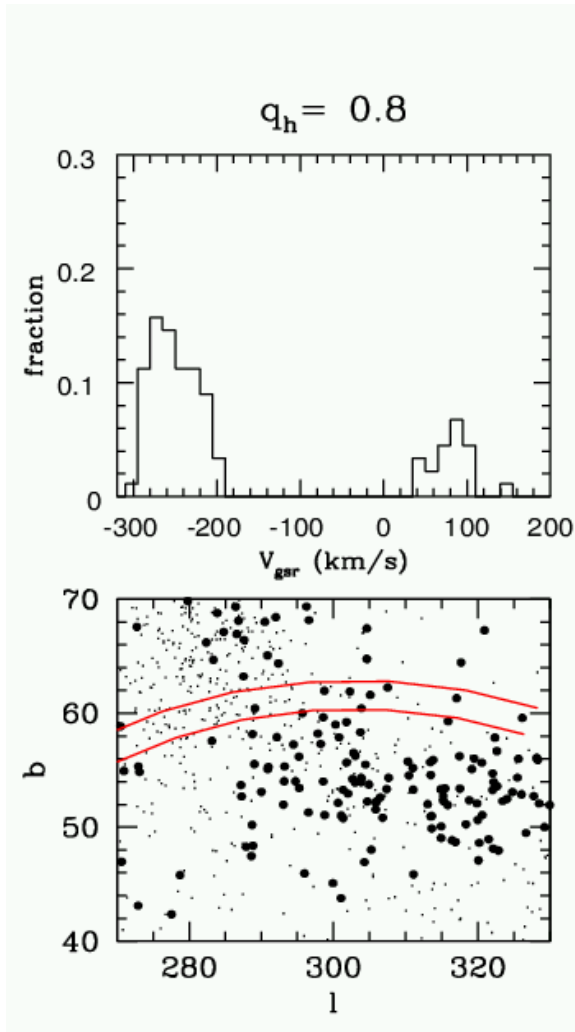
**Our best candidate is debris from a older wrap of the Sgr trailing tail**

RR Lyrae properties

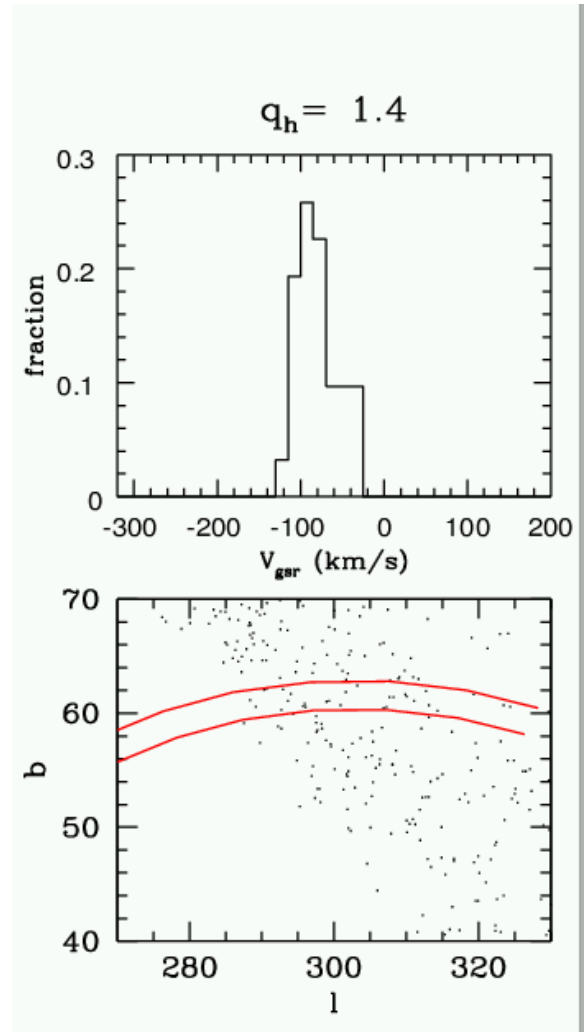
	[Fe/H]*	$\langle P_{ab} \rangle$
Sgr stream	-1.70	0.583±0.07
Virgo stream	-1.86	0.584±0.06

\* Spectroscopy abundances



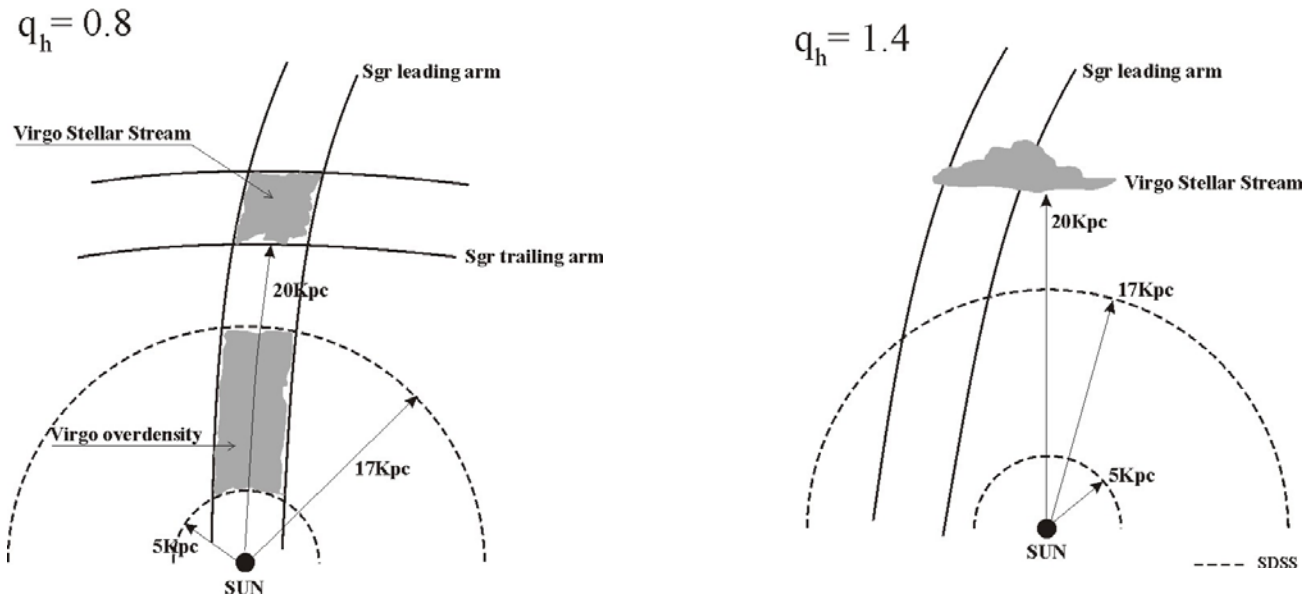


Velocity peak explained by the presence of a older wrap of the Sgr stream



Tidal debris of an unknown stellar system: **a new merger in the halo!!!**

# Some possible scenarios:

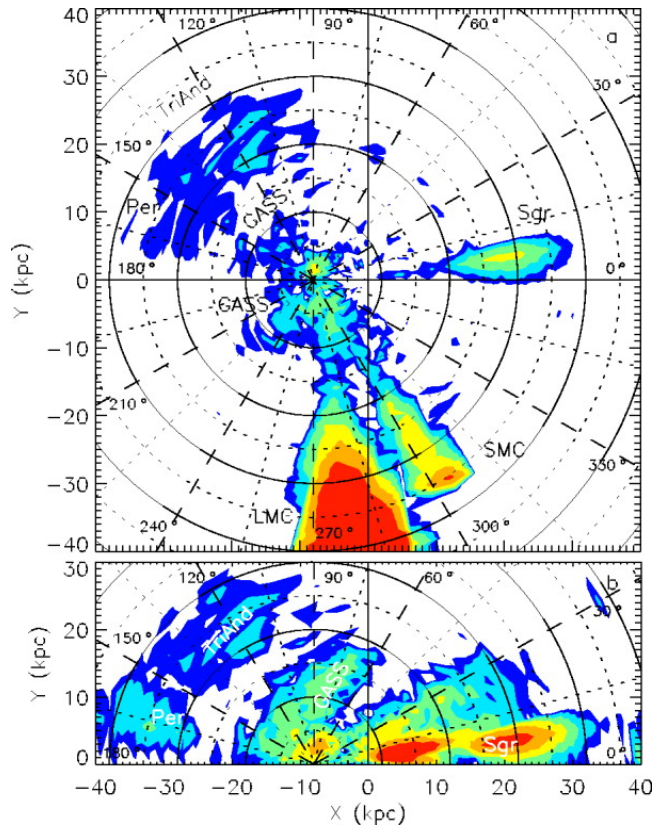


- A.** A mix of stellar debris from two different Sgr tidal tails
- B.** The relics of an unknown stellar system + Sgr debris contamination
- C.** Debris of an unknown dwarf galaxy (see Newberg talk)

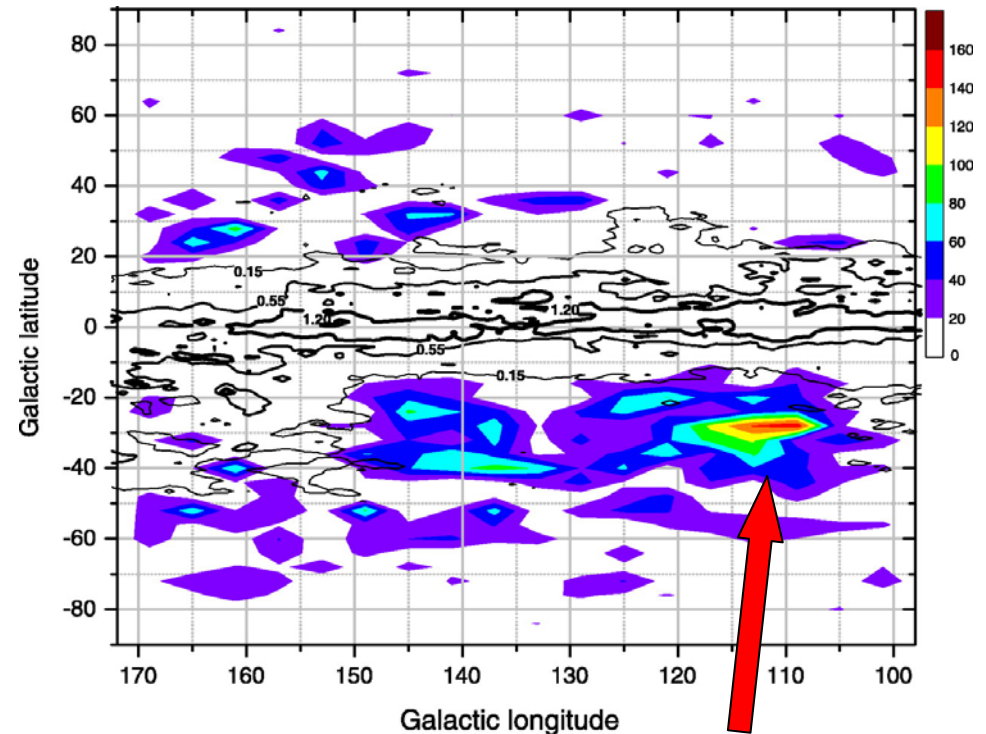
**PROPER MOTION OF VOD STARS WOULD BE A STRONG TEST**



# The origin of the Tri/And tidal stream



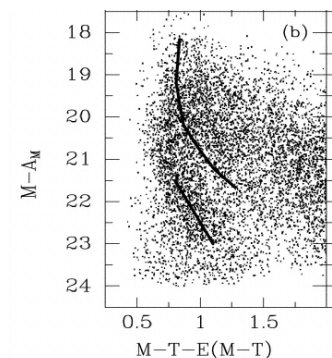
Two tidal streams in the same field:  
Monoceros stream  
in the same field at  
8 kpc.



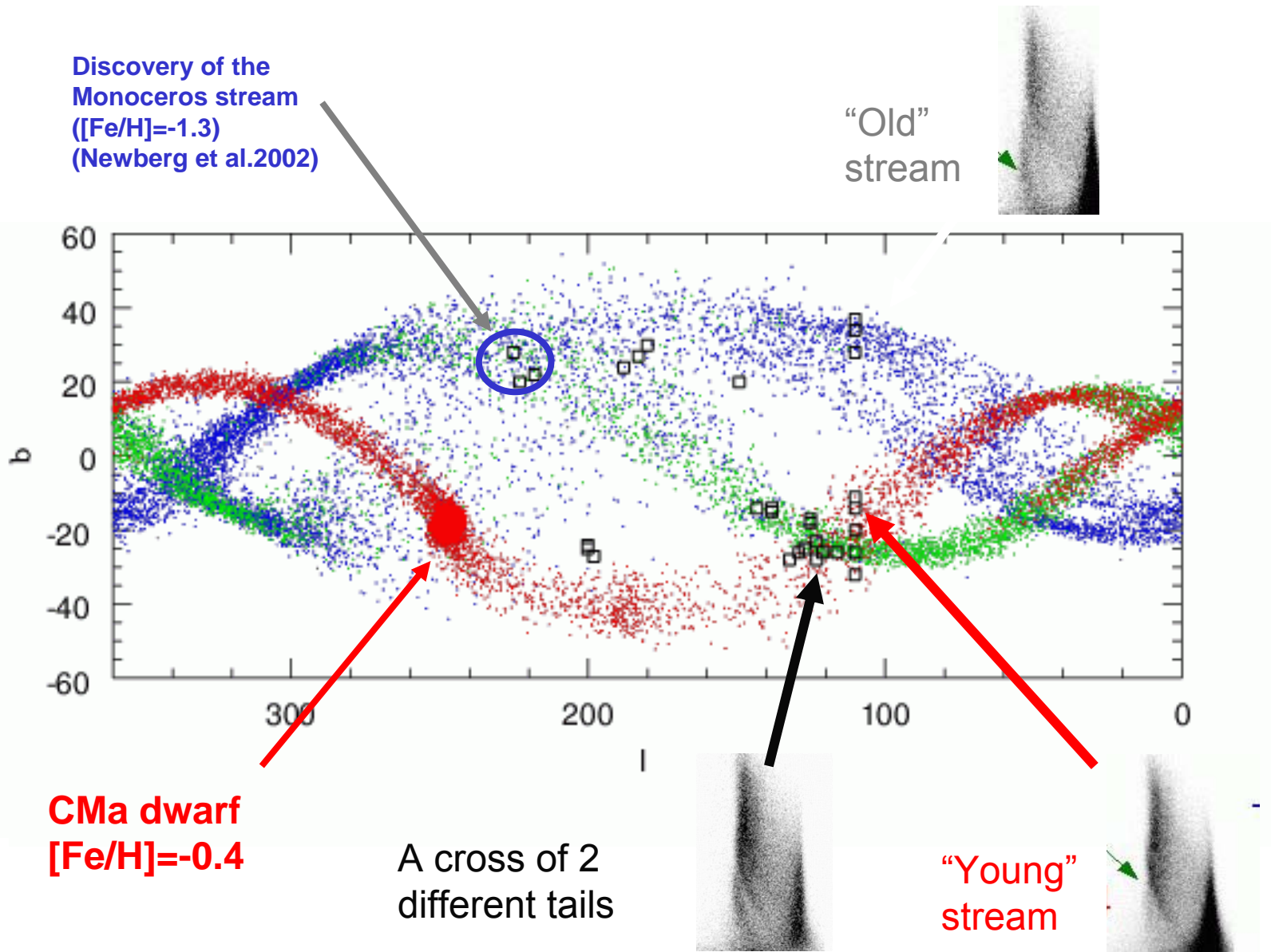
$d \sim 17-20$  kpc

$[\text{Fe}/\text{H}] \sim -1.0$

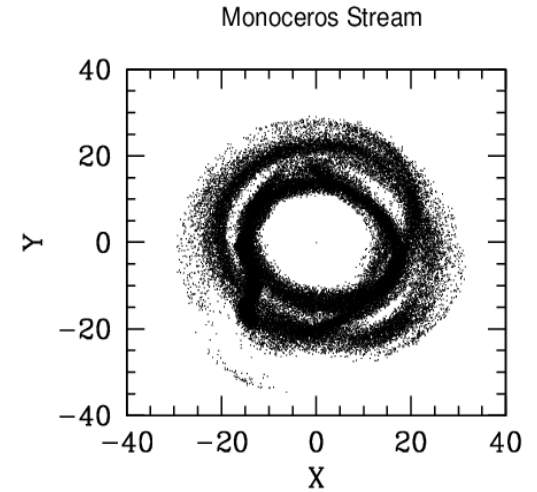
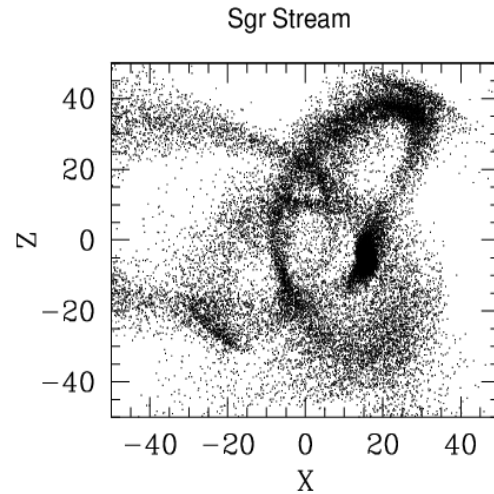
Majewski et al 2004;  
Martin et al. 2007



Differences in metallicity across the stream are consistent with the time when the tidal debris was unbound



# Milky Way

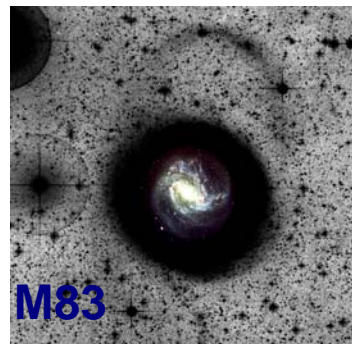


## Local Universe (dist < 15 Mpc)

Nearby massive spiral galaxies provide an external view of these merger events observed in the Milky Way

*Tidal streams*

*“Extended disks”*



# CONCLUSIONS

I. The position and structure of the Virgo over-density is consistent with expected for the Sgr leading tail falling down on the Galactic disk in a position close to the Sun.

II. The positive velocity peak from the Virgo Stellar Stream is predicted by some Sgr models only if the MW dark matter halo is oblate. The best candidate is then an "old" debris of the Sgr trailing arm. **If the MW DM halo is prolate, Virgo stream would be the remnant of a tidal disrupted unknown satellite.**

III. The Tri/And tidal stream could be explained as a more distant wrap of the Monoceros tidal stream.

IV. The study of tidal stream in spiral galaxies in the Local Universe will allow to extend this research on the formation of the components of spiral galaxies.

# REFERENCES

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**Forbes et al. 2003, Science,**

**Grillmair 2006, ApJ, 651, L29**

**Helmi 2004, ApJ, 610, L97**

**Johnston et al. 2005, ApJ, 619, 800**

**Juric et al. 2007, ApJ, submitted**

**(astro-ph/0510520)**

**Law et al. 2005, ApJ, 619, 807**

**Newberg et al. 2002, ApJ, 569, 242**

**Majewski et al. 2003, ApJ, 599, 1082**

**Majewski et al. 2004, ApJ, 615, 738**

**Martínez-Delgado et al. 2004, ApJ,  
601,242**

**Martínez-Delgado et al. 2007, ApJ, 660,  
1264**

**Peñarrubia et al. 2005, ApJ, 629, 85**

**Peñarrubia, Martínez-Delgado & Rix  
2007, ApJ, submitted (astro-ph/  
0703601)**

**Vivas et al. 2005, ApJ, 129, 189**

**Searle & Zinn 1978, ApJ, 225, 357**