

Hierarchical galaxy formation in the Local Universe

David Martínez-Delgado (IAC)

N-body model “maker”:

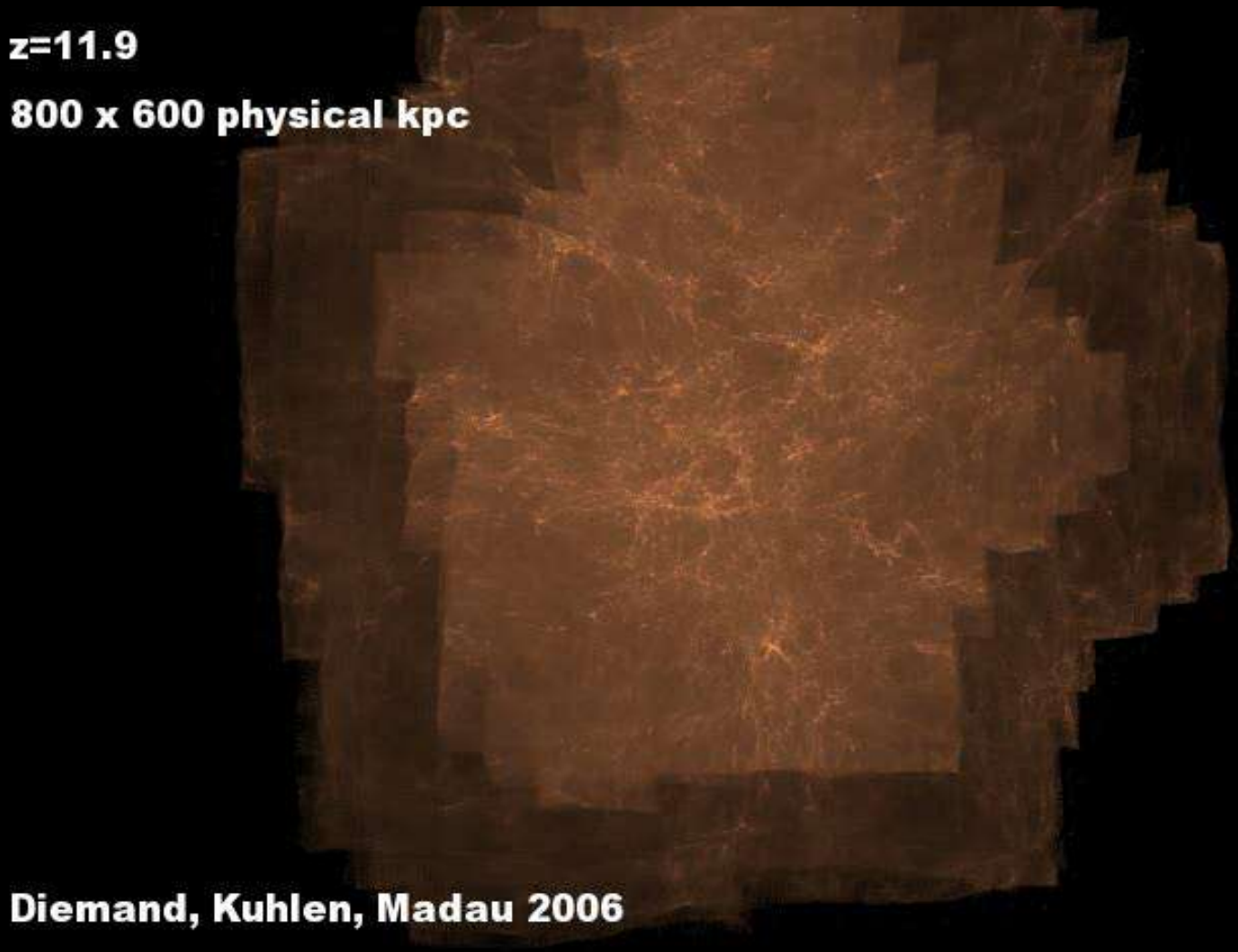
J. Peñarrubia (Univ. Victoria, Canada)

The SDSS collaboration for Galactic Structure:

Mario Juric (Princeton), Z. Ivezic (Princeton), H. W. Rix (MPIA), H. Newberg (RPI)

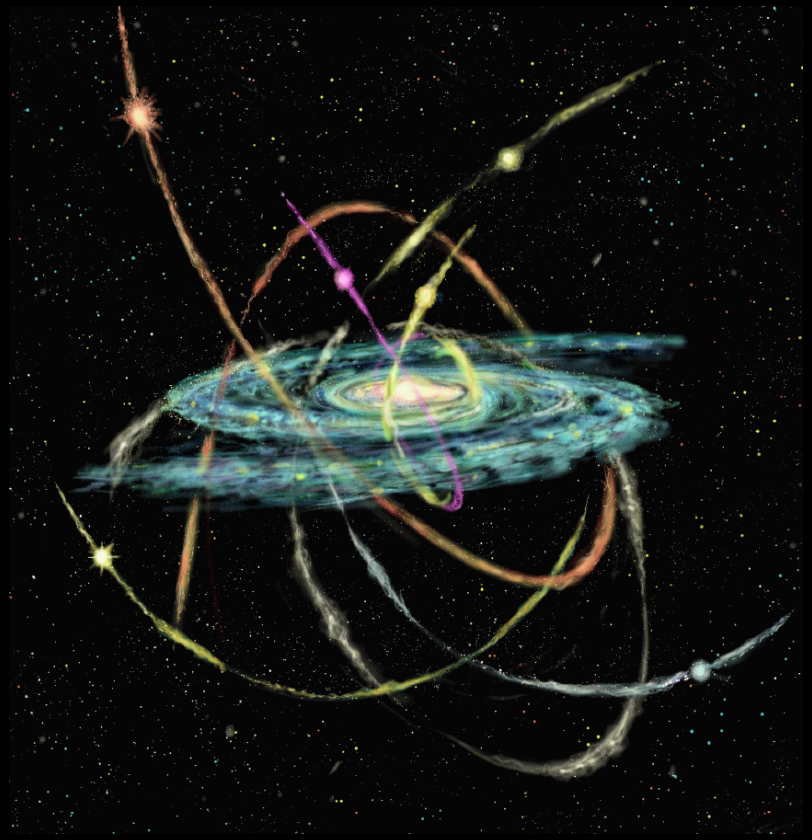
Also starring:

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

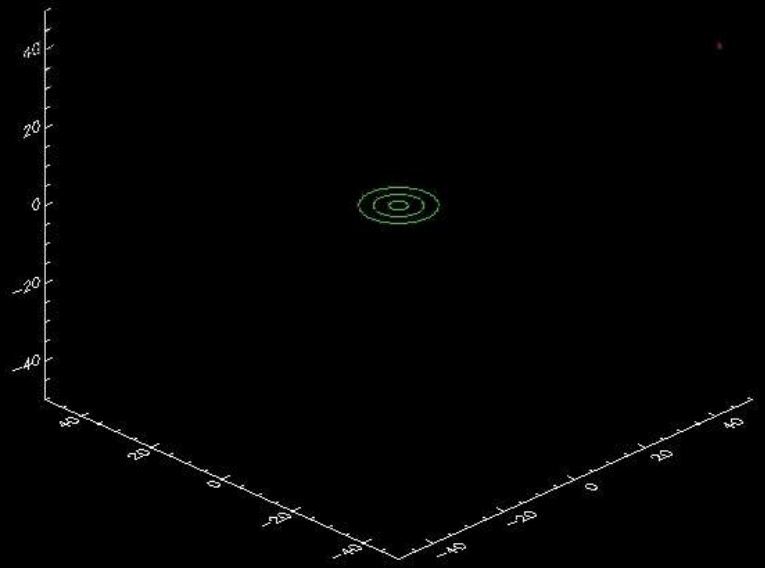


At high redshift, we can follow the evolution of the stellar population of galaxies, but not the process of assembly of the components (halo, disk) of individual systems.

THE FORMATION OF THE MILKY WAY

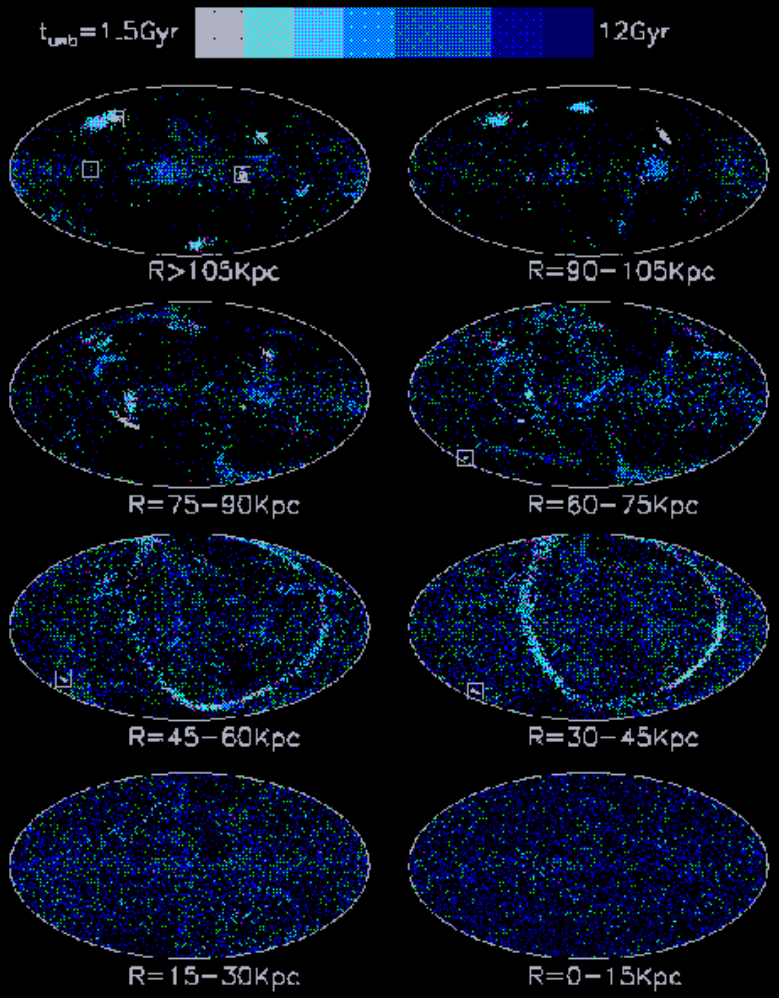


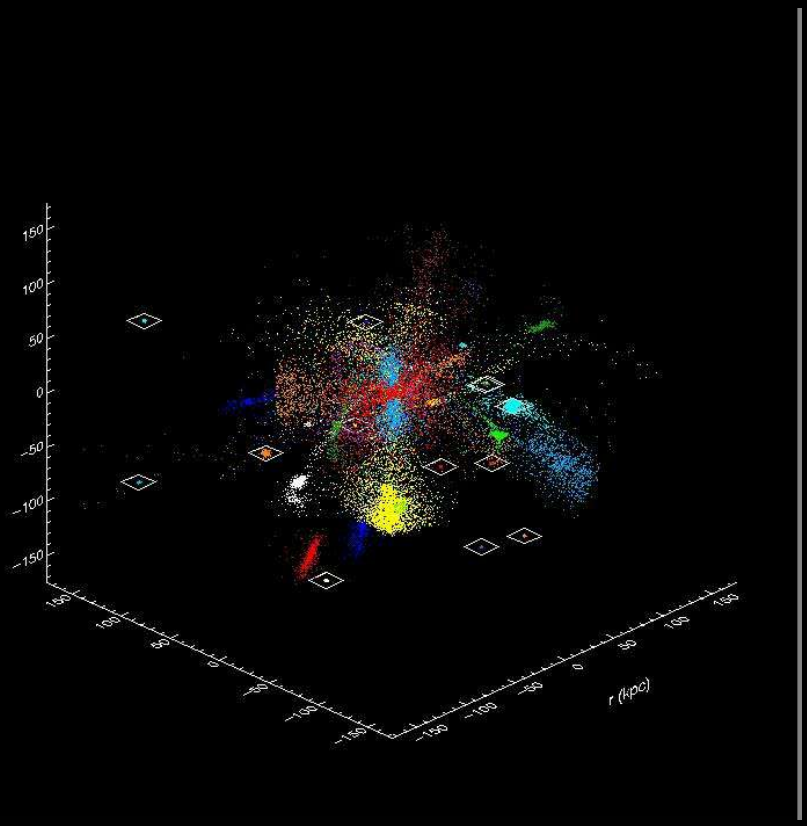
Searle & Zinn (1978)



Hierarchical galaxy formation in CMD cosmology (present)

GALACTIC ARCHAEOLOGY

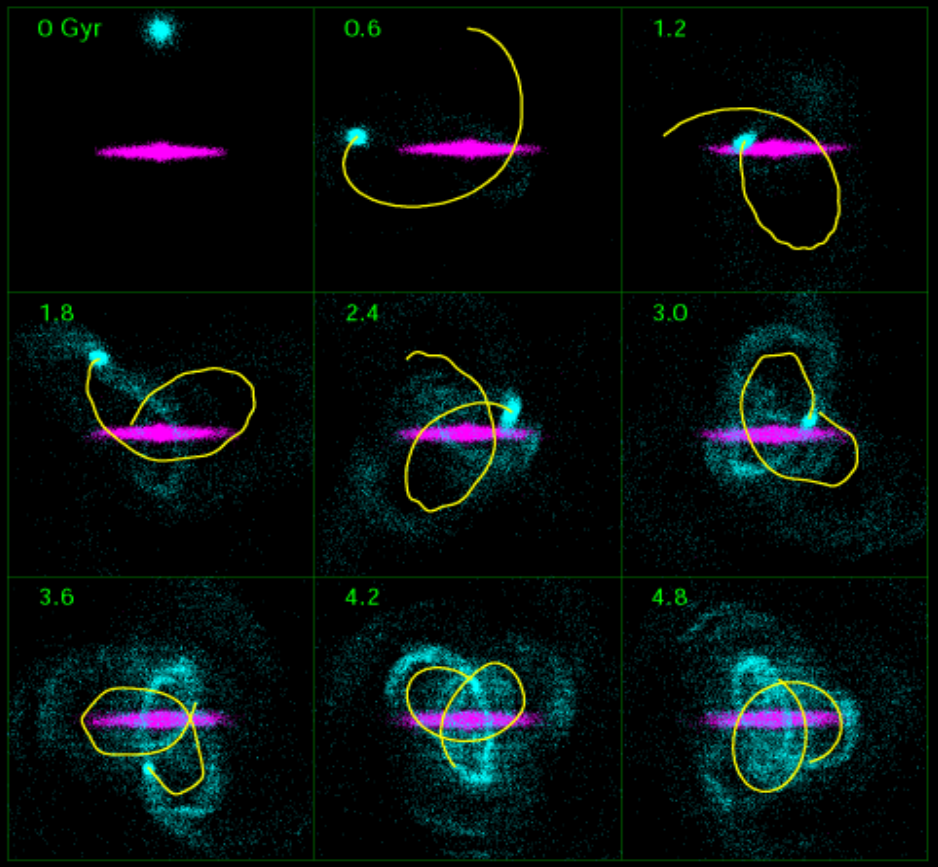


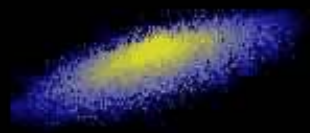


Outer regions of galaxies contains the fossils of the hierarchical galaxy formation

Bullock (2003)

The ghost of a dwarf galaxy: Stellar Tidal Streams



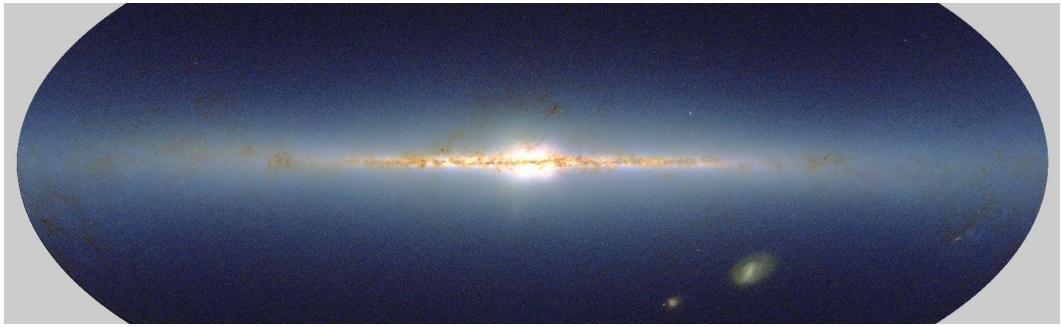




The Two Micron Sky Survey (2003)



Mt. Hopkins, 1.3m



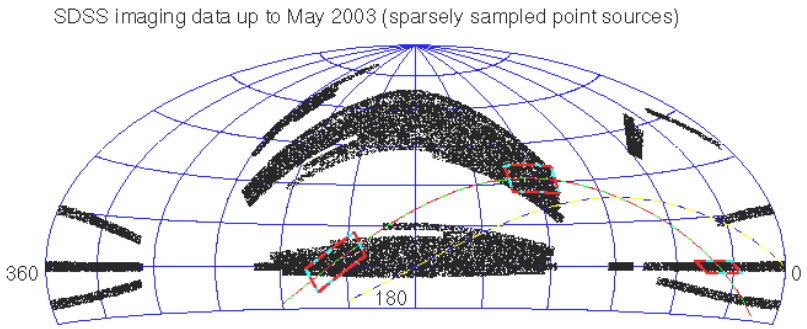
Uniform scan of the 70% of the sky
J,H,K filters, K~14.3

The Sloan Digital Sky Survey (2005)

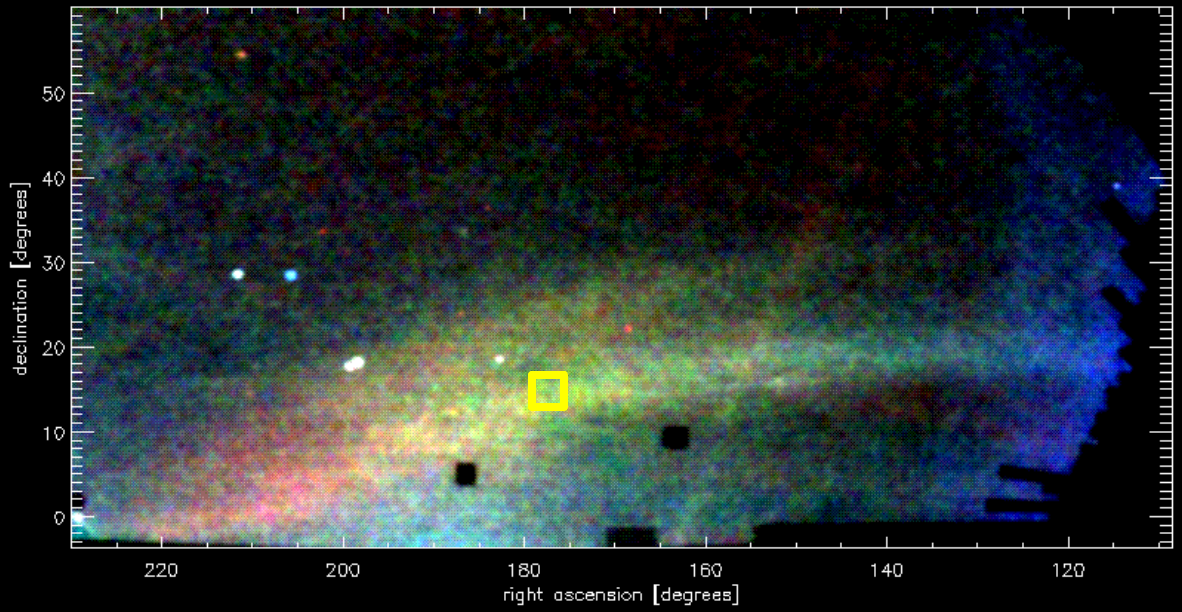
Imaging: 7500 deg^{2,} |b| > 30°
u'g'r'i'z' filters, r~22.5



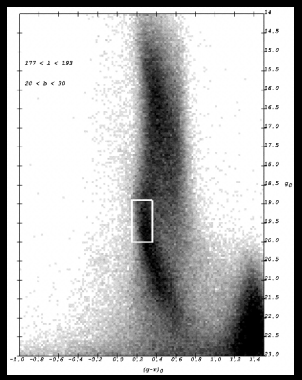
New Mexico, 2.2m

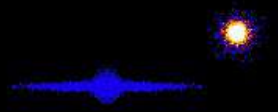


Galactic Tidal Streams









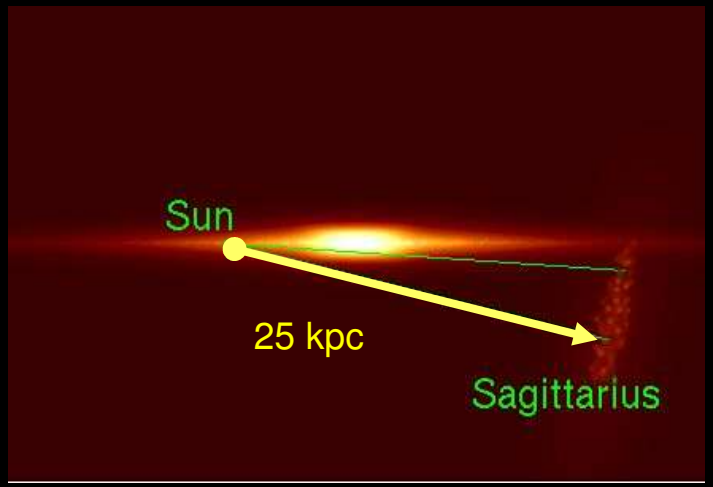
Streams resolved in stars. SB~30.5 mag/arcsec^2

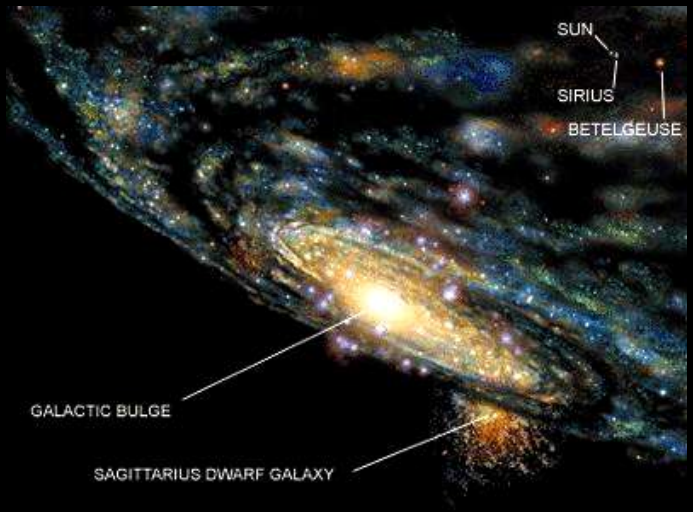
CMD provides positions, distances, targets for Vr

N-body simulations build the dynamical history of the stream

The tidal stream of the Sagittarius dwarf galaxy



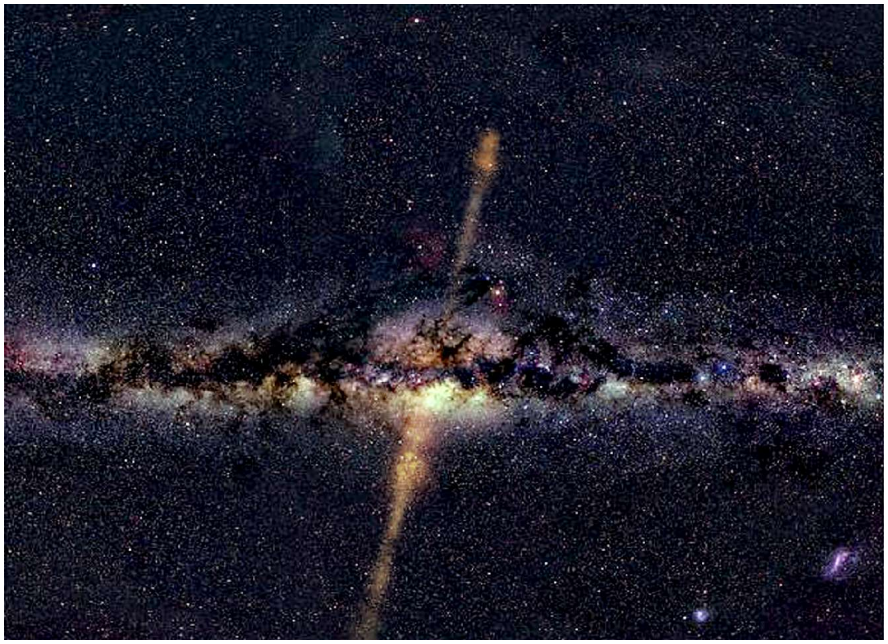


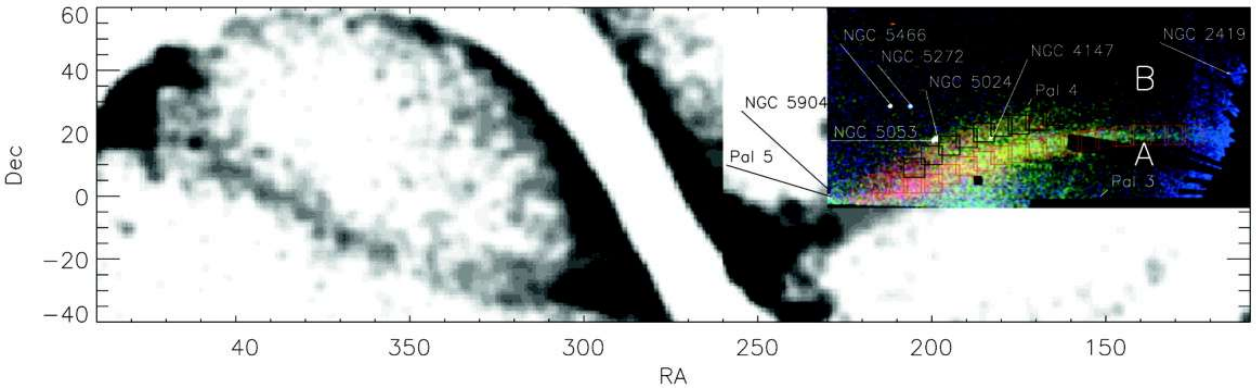


Discovered by Ibata et al (1994) at 16 kpc from the center of the Milky Way

THE SAGITTARIUS TIDAL STREAM







Martinez-Delgado et al. 2001

AN ALL SKY VIEW OF THE SGR STREAM!!

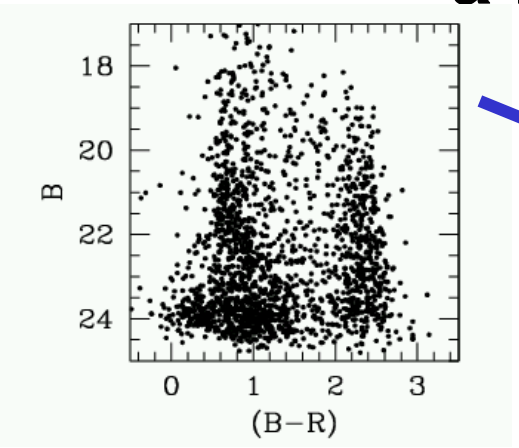
Majewski et al. 2003

Belokurov et al. 2006

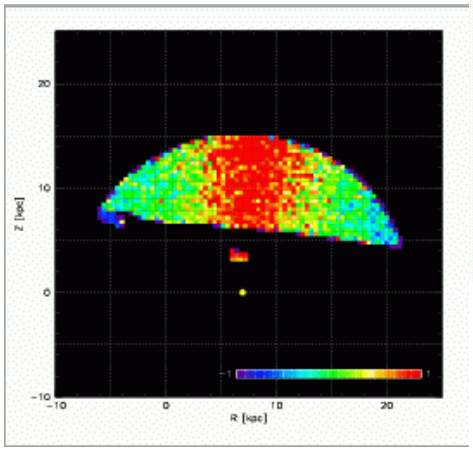
Mv=-13.3; M/L~25

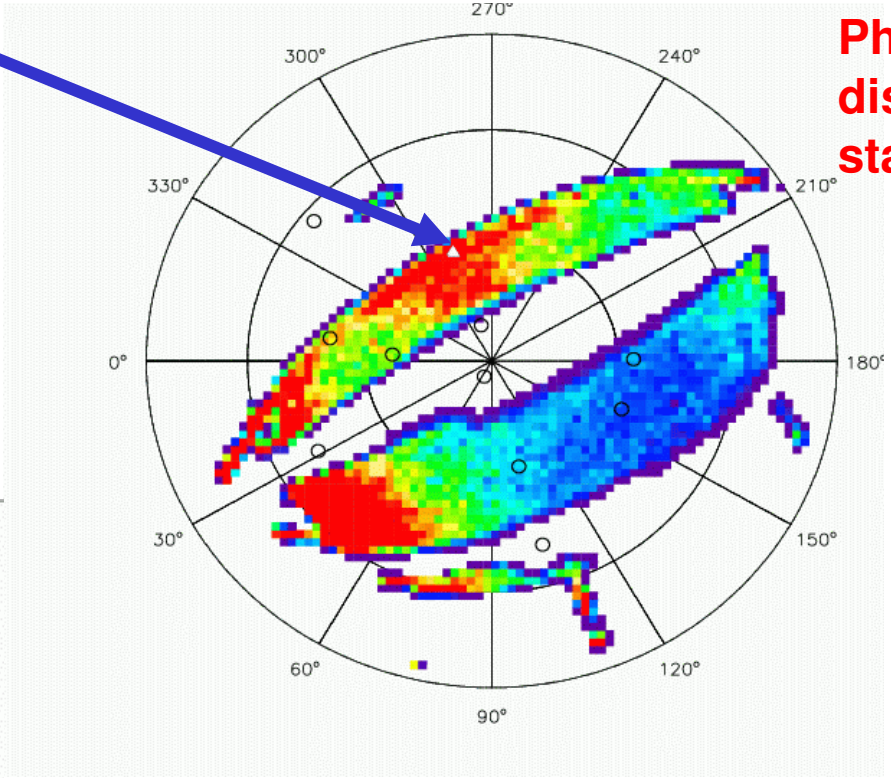
15% mass in tidal stream !

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



Martinez-Delgado et al. 2006





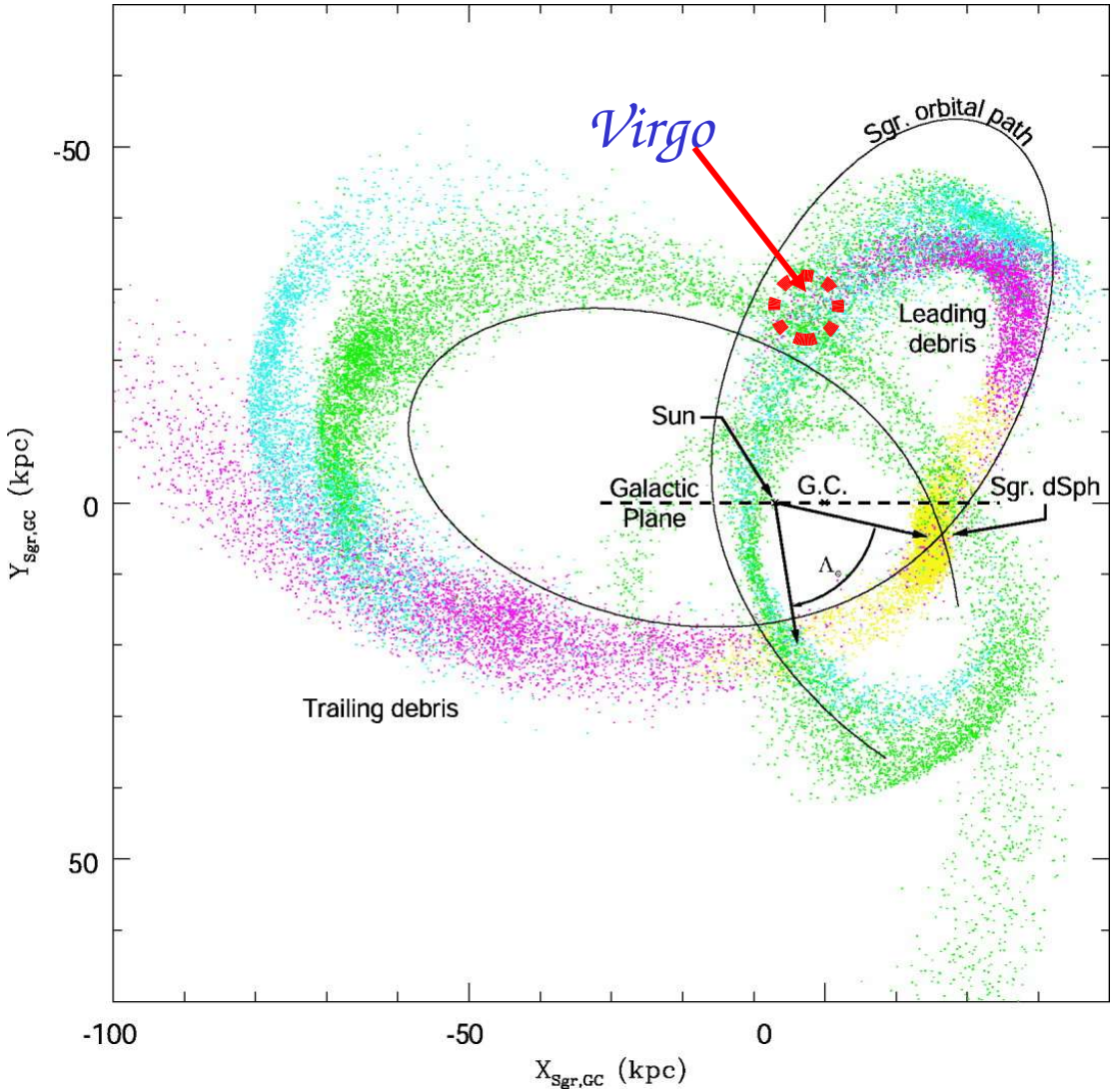
Photometric parallax distances of 48 million stars (Juric et al. 2006)

~1000 square degress (Juric et al. 2006)

PRESS RELEASE January 9th, 2006:

"The SDSS reveals a new Milky Way neighbor"

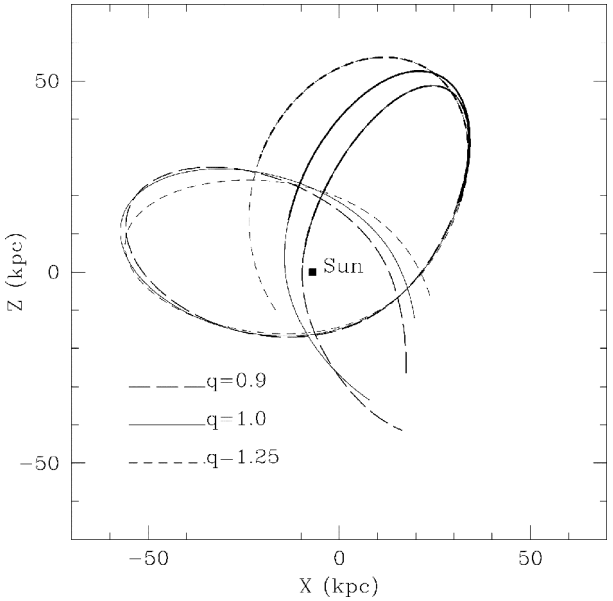
Tidal debris from Sagittarius dwarf?



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…

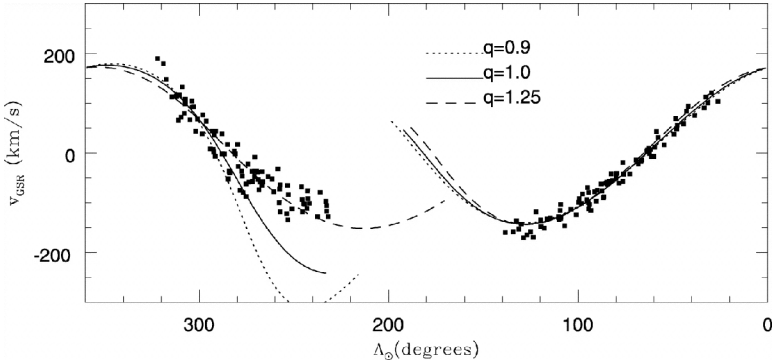
but never observed…



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!:

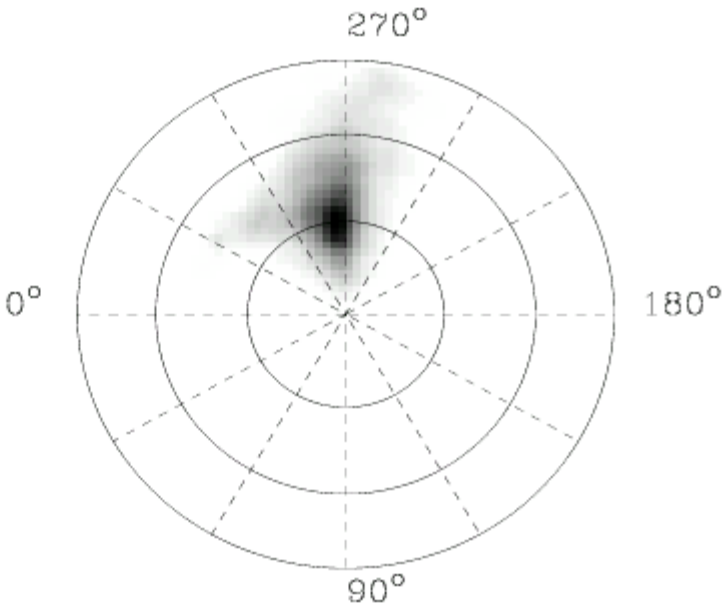


Radial velocities of the Sgr leading arm can only fitted with a prolate halo model (Helmi 2004)

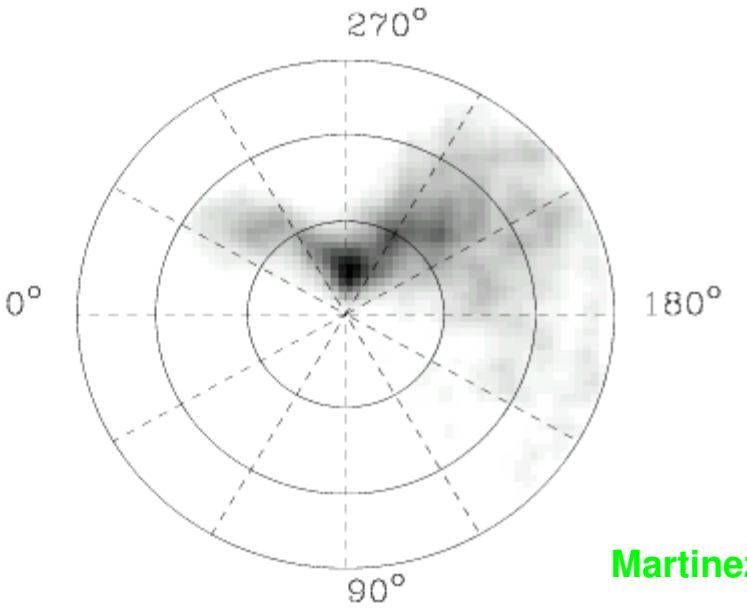
Johnston et al. (2005) find prolate halos cannot reproduce the precession rate in the youngest pieces of the Sgr stream (excluding models with q>1)

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

q_h=0.8



q_h=1.4



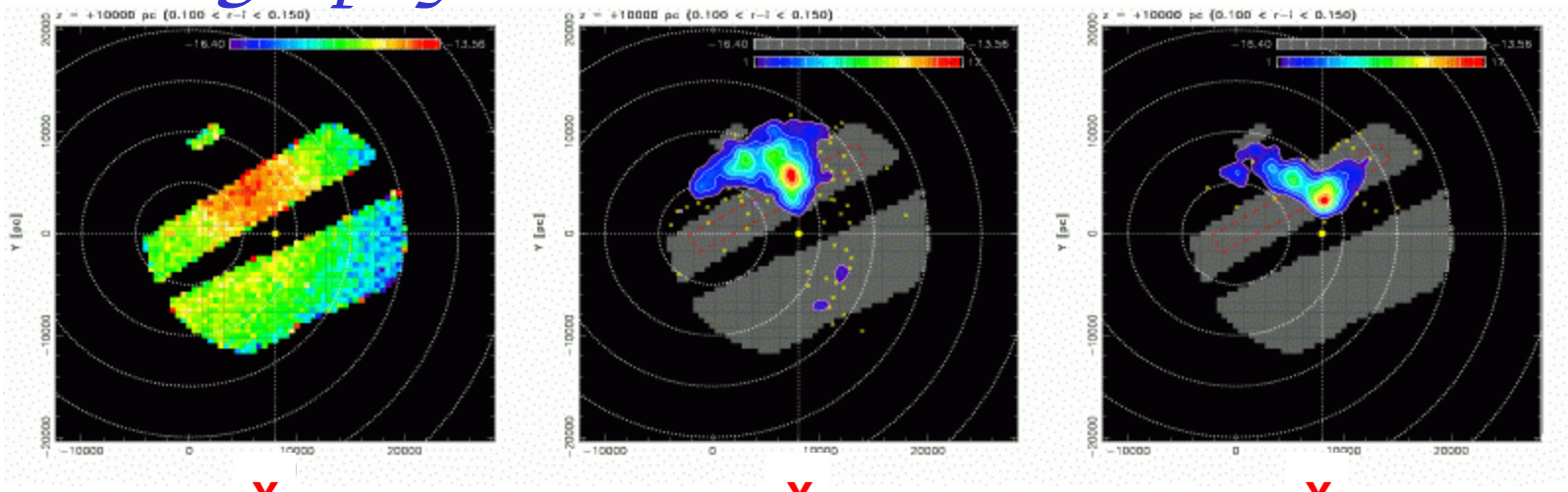
Martinez-Delgado et al. 2006

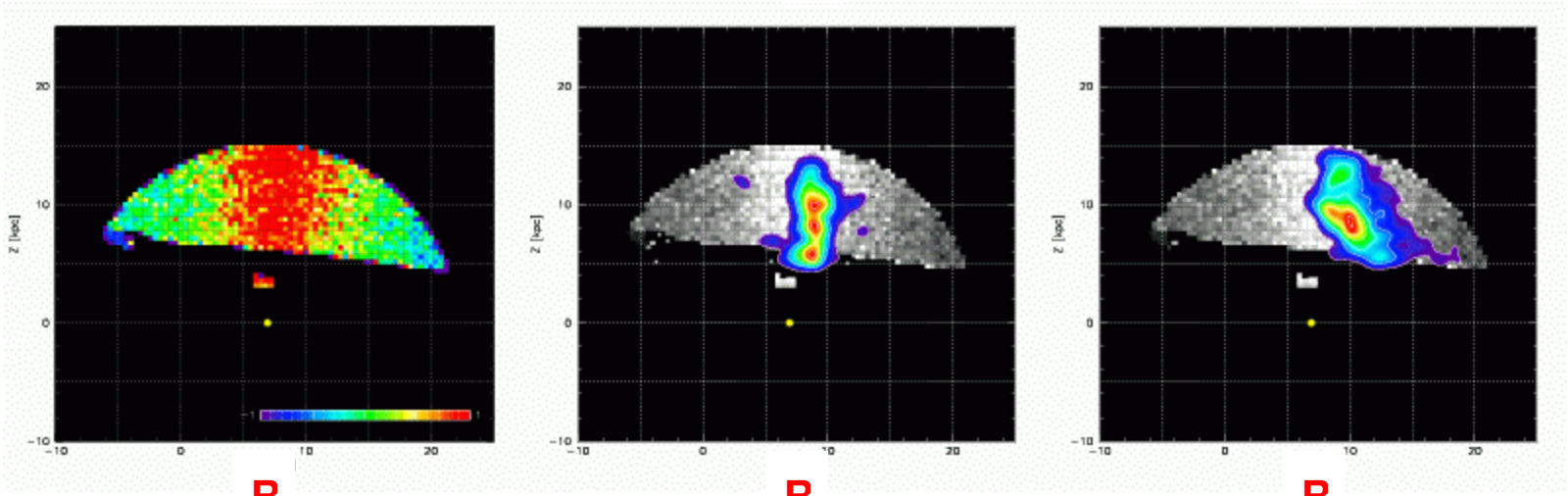
$(l,b)_{obs}$~(290,65)

SDSS tomography

q_h=0.8

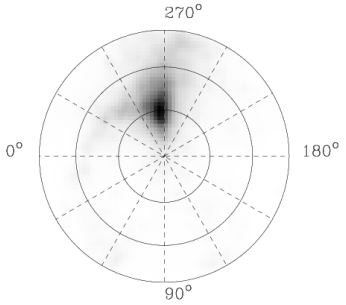
q_h=1.4

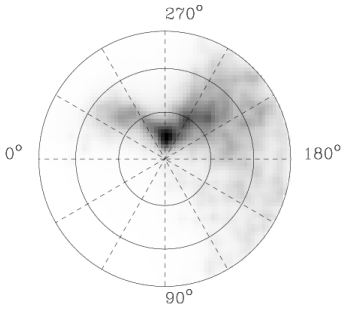


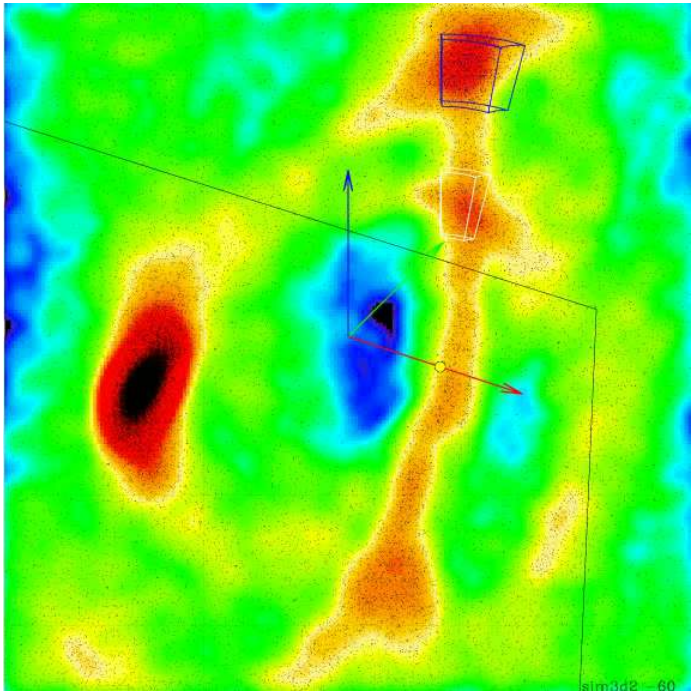


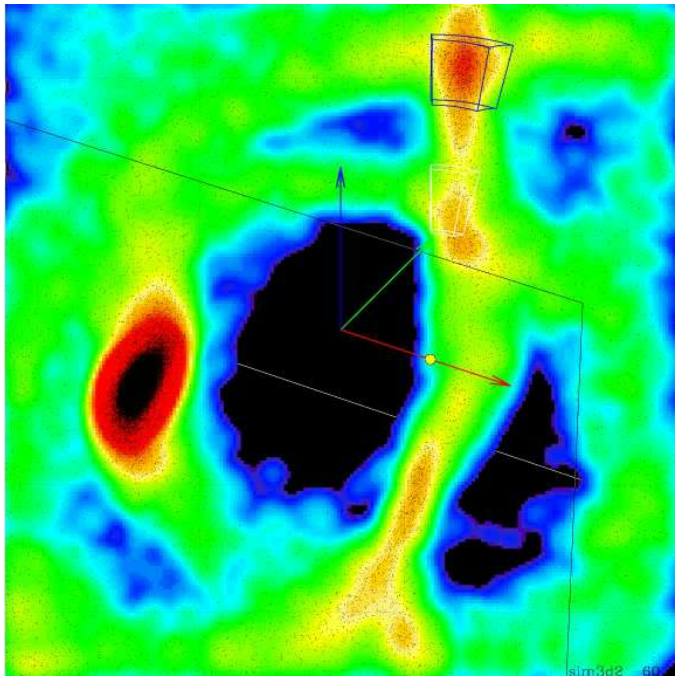
Martinez-Delgado et al. 2006

Comparison with the 3D structure of Sgr tidal debris



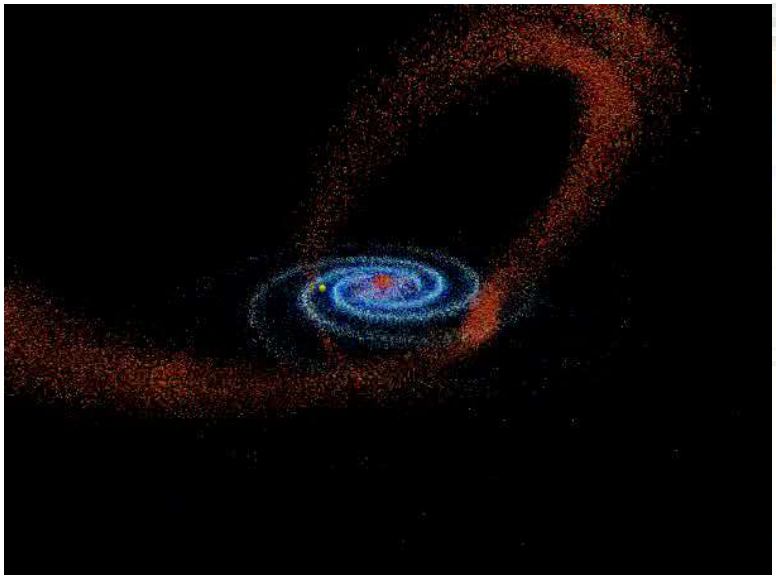


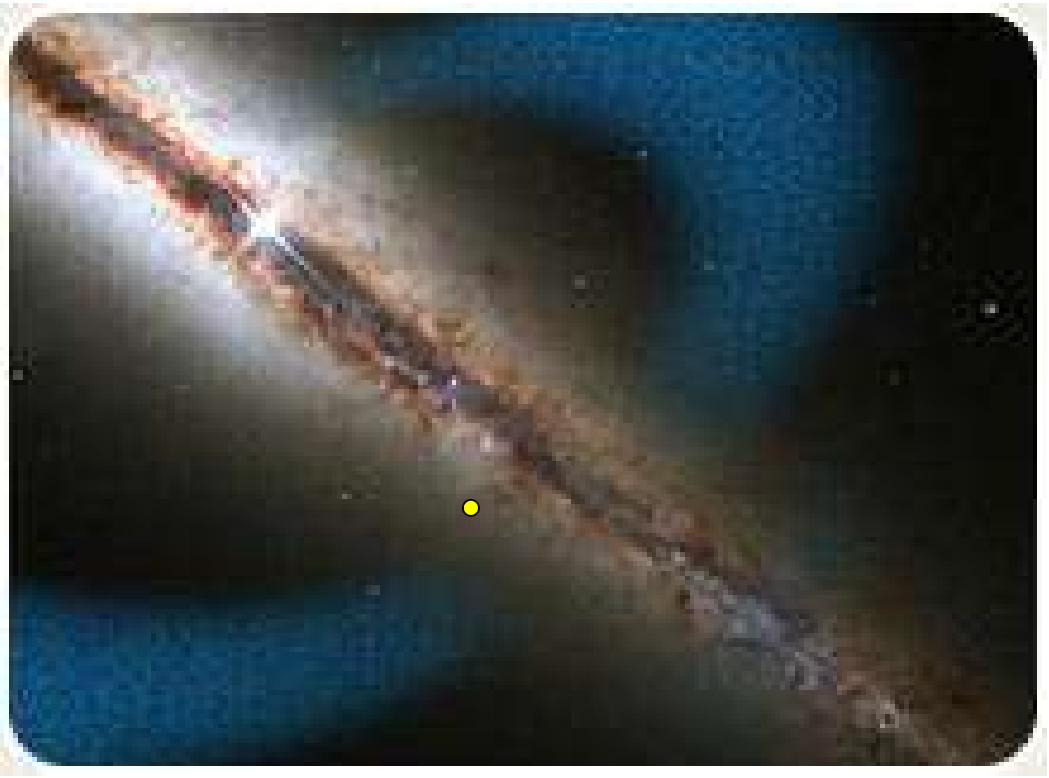




q_h=0.8 (oblate)

q_h=1.4(prolate)





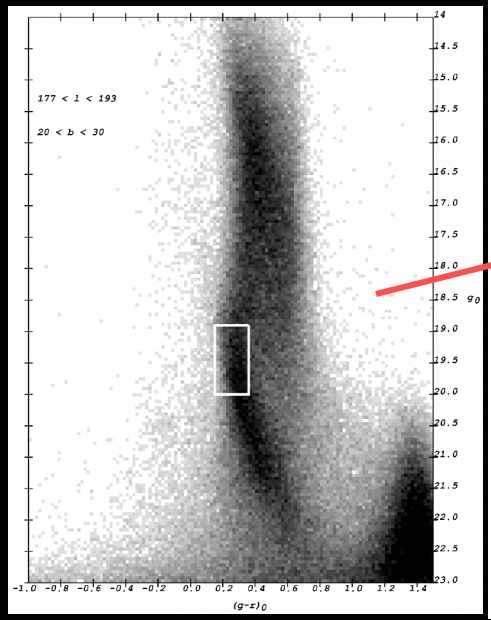
A highway of dark matter crossing the solar vecinity: a wonderful target for dark matter detection experiments (DAMA)

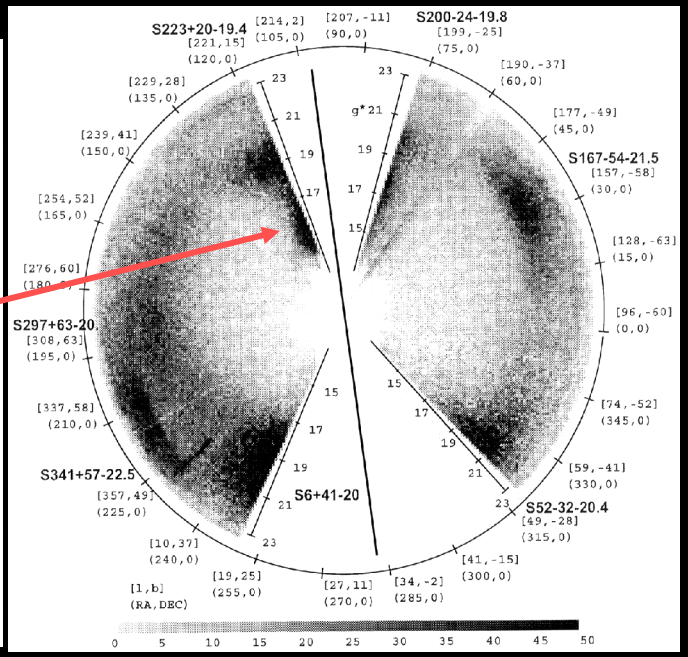
The Monoceros tidal stream

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

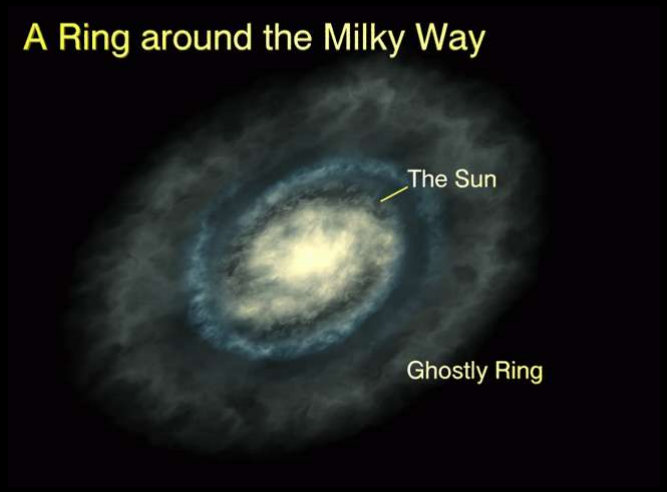
Only visible at low galactic latitude (|b|<25)

Tidal stream detected before the discovery of its parent galaxy.





The best candidate is a overdensity of red giant stars discovered in the Canis Major constelation with the 2MASS (Martin et al. 2004)





versus



Galactic cannibalism

Galactic perturbation

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

Low inclination, circular satellite orbits are very unlikely in theoretical models based on the CDM theory.

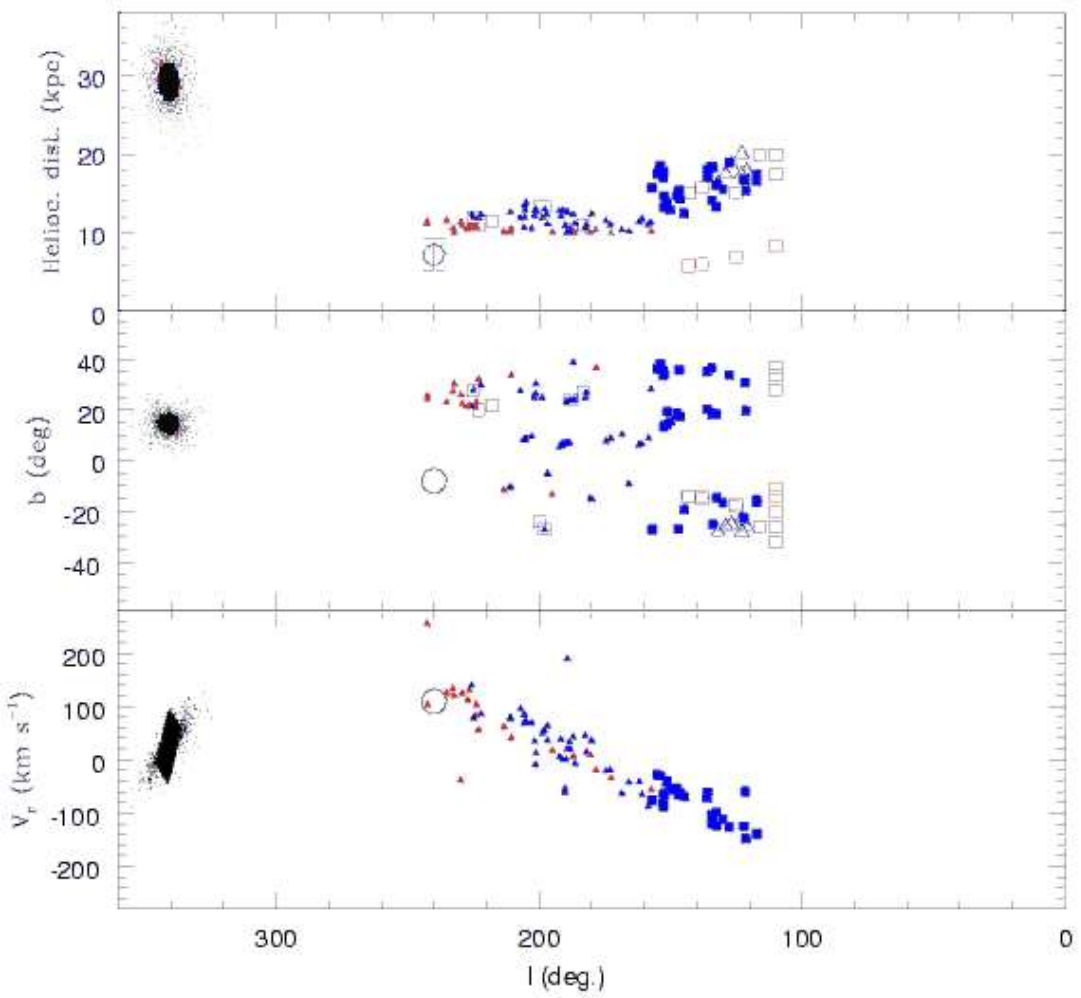
Is the Monoceros ring the signature of the Galactic flare or the outer region of the MW warped disk? (Momany et al. 2006)?

A comprehensive model of the Monoceros Stream

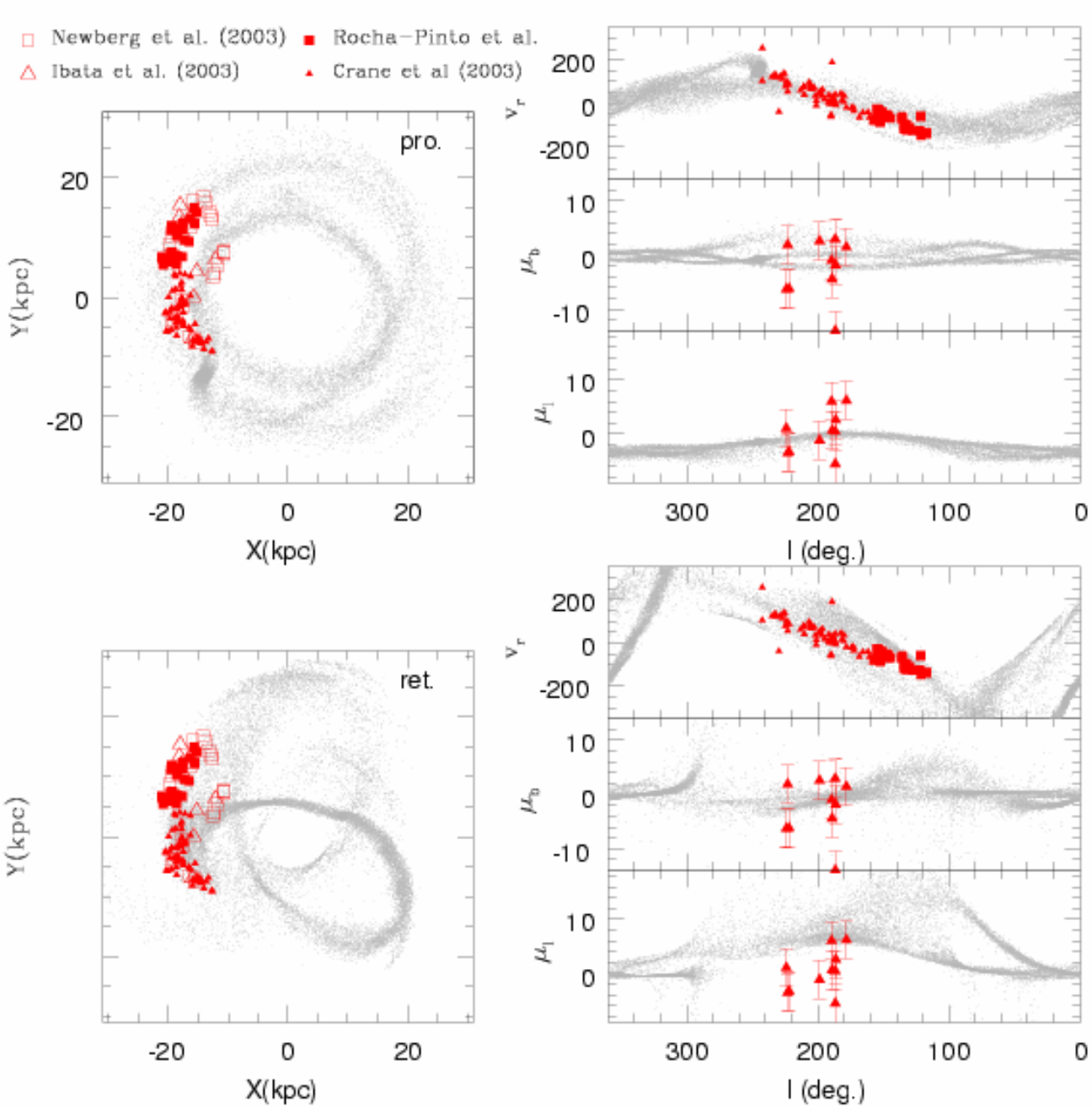
An extraordinary observational effort in the last year for different groups to trace this stream.

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

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



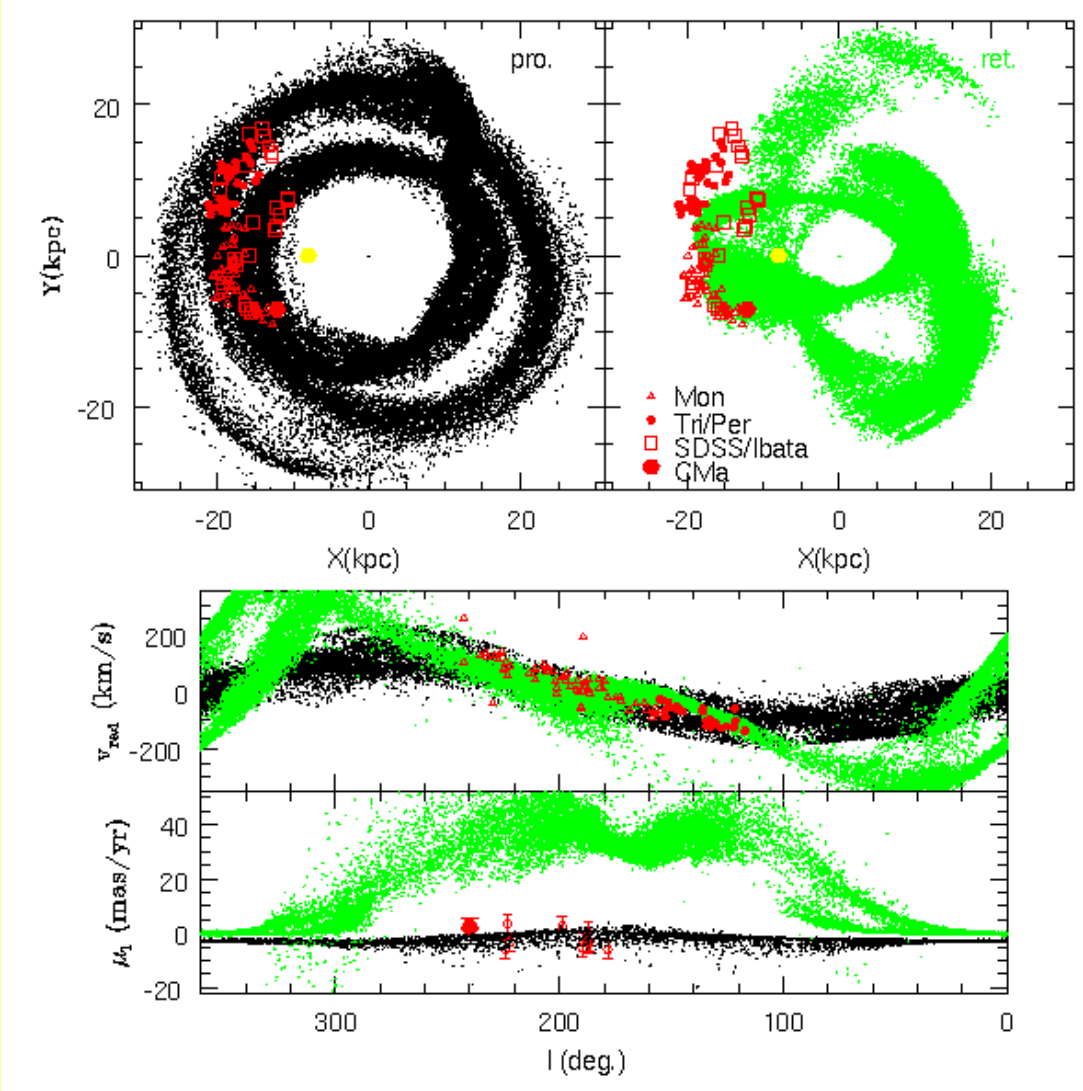
Observational data consistents with a huge tidal stream disrupted in the last 2.5 Gyr


Newberg et al. (2003)
Rocha−Pinto et al.
Ibata et al. (2003)
Crane et al (2003)
pro.
ret.
Y(kpc)
X(kpc)
v_r
μ_b
μ_l
l (deg.)

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

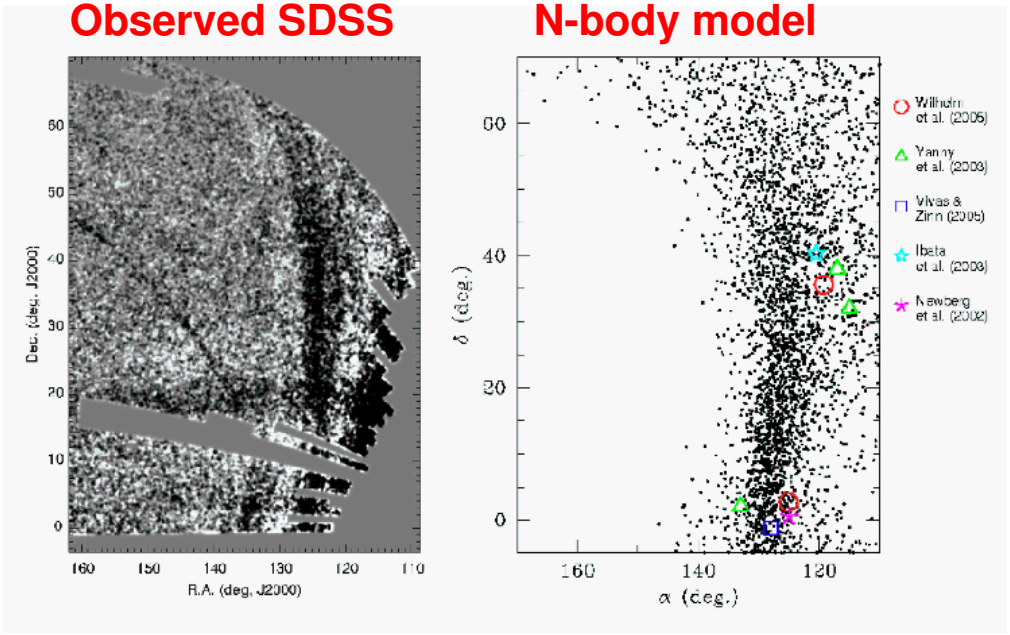
A low inclinated (i= 20 ±5º), almost circular (e=0.10±0.05), PROGRADE orbit

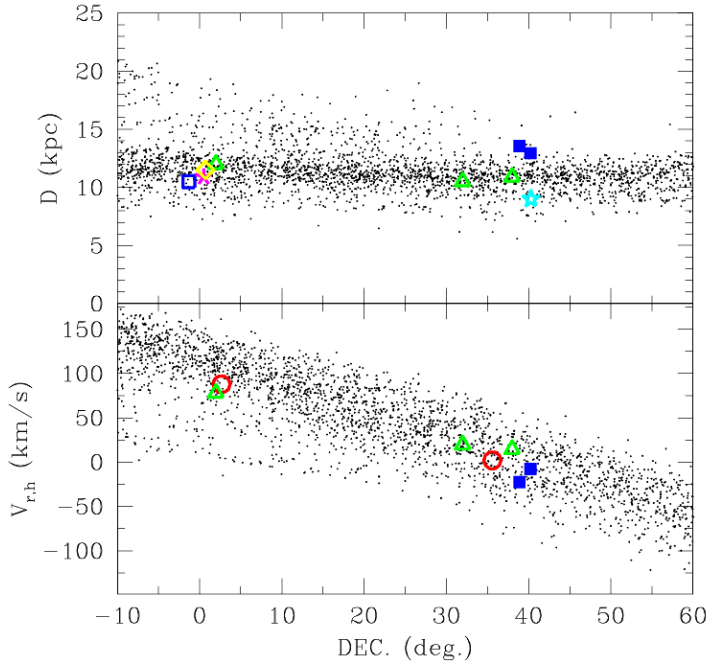
Distance and kinematical data are not enough to constrain the position of the main body of the parent galaxy: progenitor can be in **100 >l >200**



Peñarrubia, Martínez-Delgado, Rix et al. 2005, ApJ, 629,85

The Galactic Anticenter Stream?



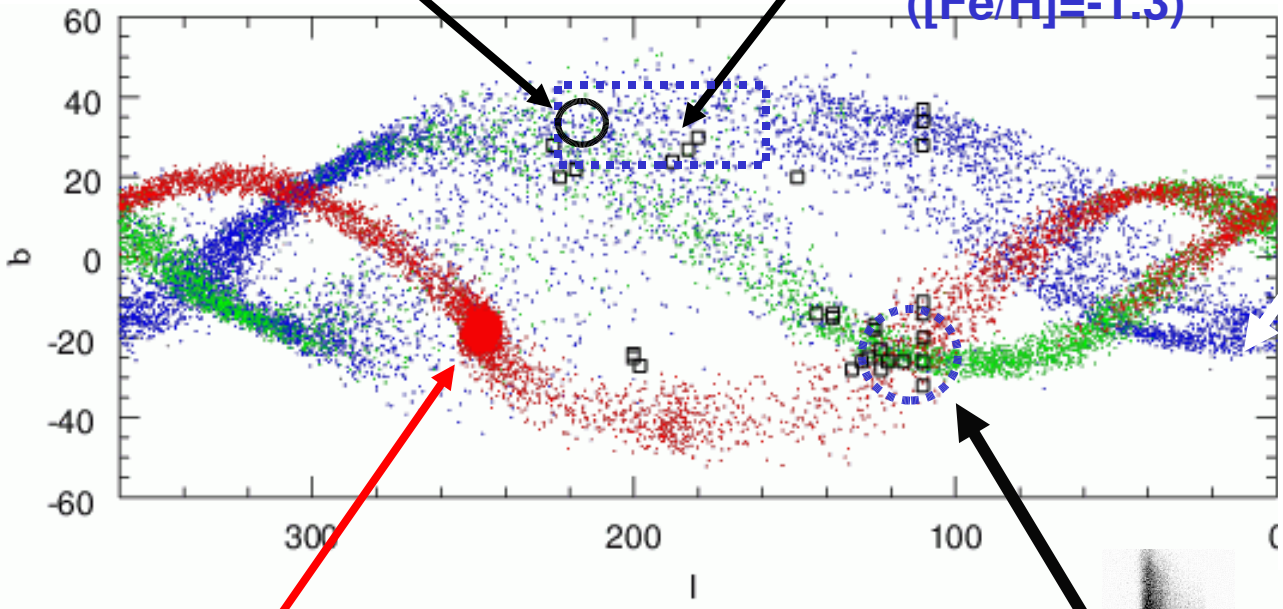


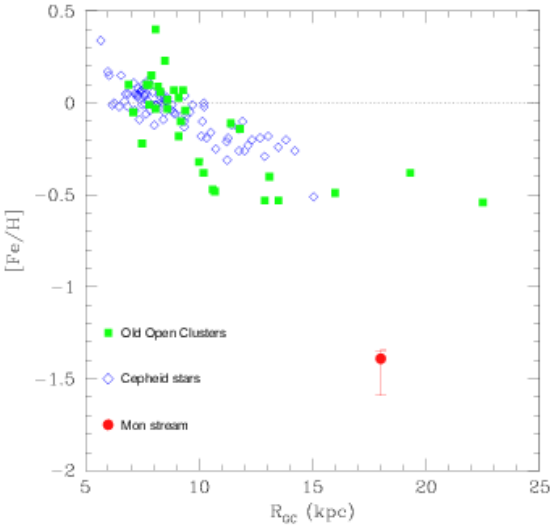
Grillmair (2006) reports the discovery of a coherent 60º-long unknown tidal stream in the Galactic Anticenter.

However, we find a excellent agreement with the Monoceros tidal stream N-body model: the first panoramic view of this outer stellar ring.

RR Lyr clump

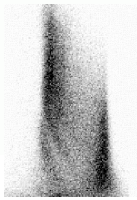
Anticenter stream
([Fe/H]=-1.3)





Progenitor position:
CMa dwarf [Fe/H]=-0.4

A cross of 2 different tails



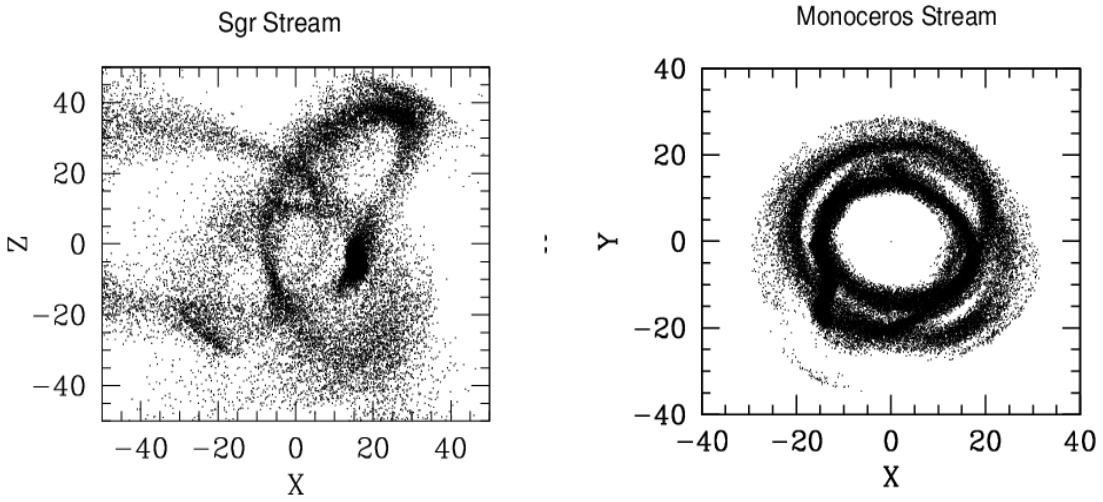
THE MONOCEROS STELLAR RING IS THE TIDAL STREAM OF A SATELLITE IN A PROGRADE CIRCULAR ORBIT. ITS ORIGINAL STELLAR POPULATION IS METAL-POOR AND OLDER THAN THE MW DISK.
(Peñarrubia, Martínez-Delgado, Rix 2007)

No metallicity gradient outside R_{gc}=10 kpc: merger are playing an important role in the outer disk formation of the Milky Way. A survival "building-block"?

Hierarchical galaxy formation in the Local Universe: A GTC project

- Stellar Tidal Stream: (edge-on galaxies)
  - What is the role of these processes in the formation of the halos and their globular cluster systems?
  - Is observed halo sub-structure degree consistent with the CMD theory simulations? Where are the “missing satellites”?
  - Can tidal debris explain the metal-rich halos? Can we trace the dark matter around neaby spirals with tidal streams?
- Extended outer disks: (face-on galaxies)
  - Are extended disk of spirals formed via satellite acretion?
  - What are the mechanisms of star formation in these very low density galactic regions? Are they older than the normal disks?

Milky Way



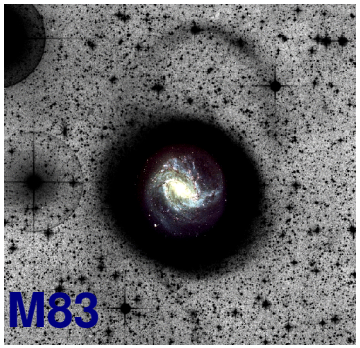
Local Universe

(dist< 15 Mpc)

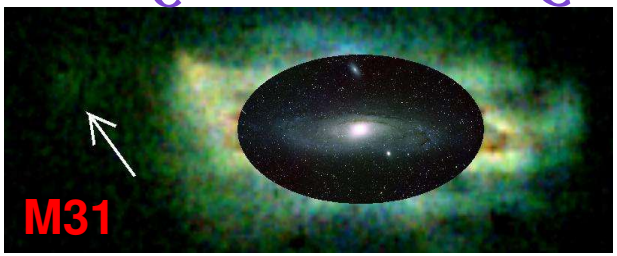
Nearby massive spiral galaxies provide an external view of these merger events observed in the Milky Way

Tidal streams



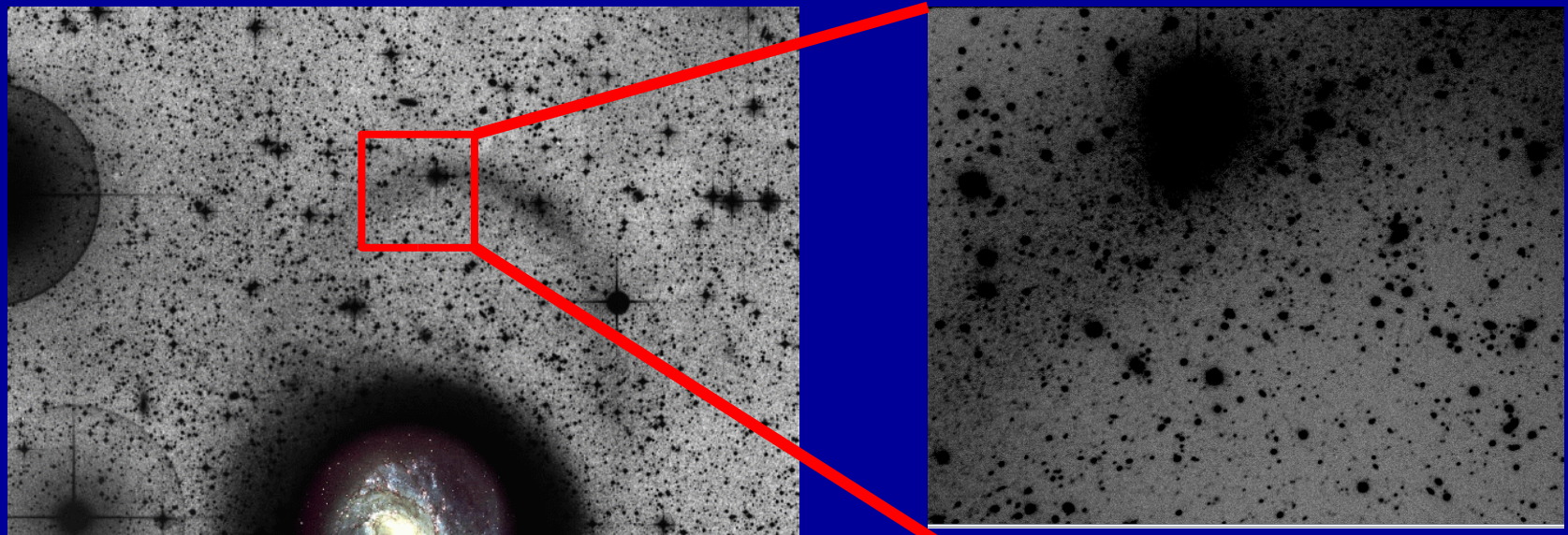


"Extended disks"





A river of stars in the M83 halo



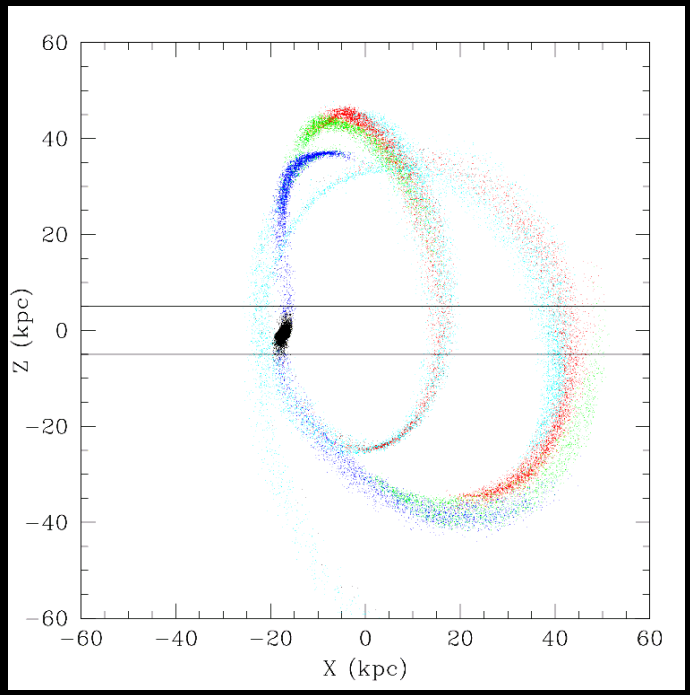
VIMOS VLT PI. Martínez-Delgado

Sub-arcsecond imaging provided by 8 meter-class telescope allows to resolve stellar streams and extended disks in spiral galaxies within 5 Mpc (HST-ACS 11 Mpc)

Deep Diving in the halo of NGC 5907



Martínez-Delgado et al. 2007



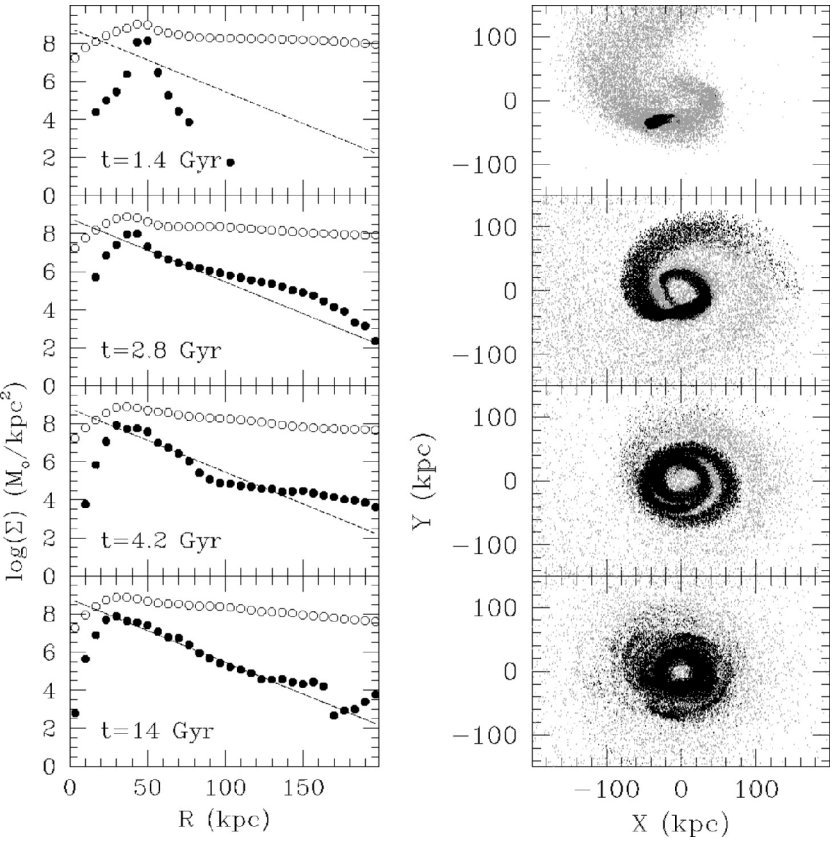
Complex structure explained by one merger 4.5 Gyr ago: an unprecedent view of a multi-warp old tidal stream

Progenitor survived! Possible hidden behind the disk.

Sacket (1995) reported a metal-rich halo, but fields are contaminated by tidal debris.

THE FORMATION OF THE OUTER EXTENDED DISKS

Theoretical model shows that extended disk around spiral galaxies could be formed by accretion of a dwarf satellite



Peñarrubia et al. 2006



Martínez-Delgado et al. 2007

CONCLUSIONS

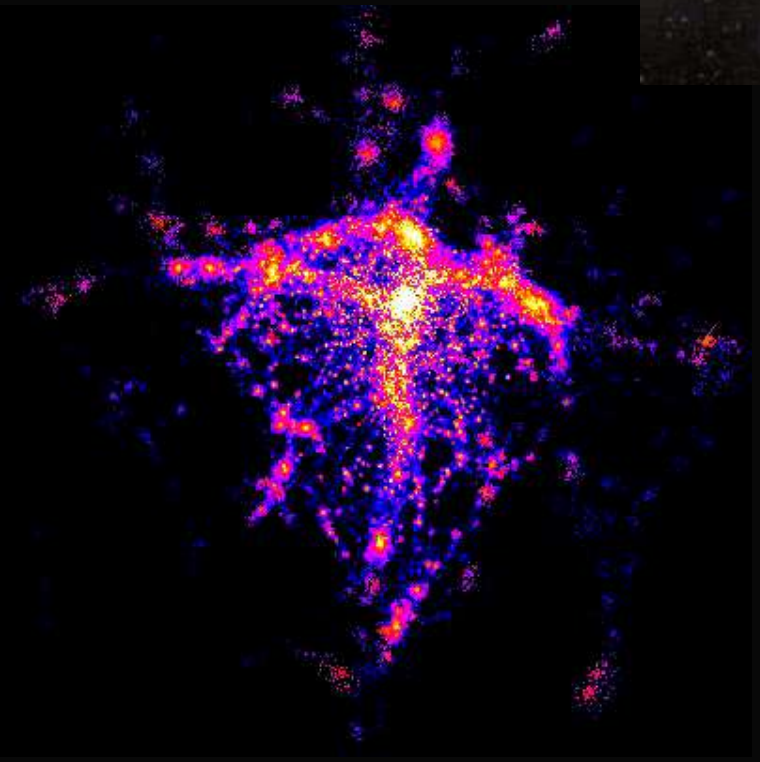
I. *There is an excellent agreement between the observations of the Monoceros stellar ring and N-body simulations of tidal disruption of a dwarf satellite in a low inclinated, almost circular prograde orbit. The stellar population of this stream support the extra-Galactic origin of this structure, rejecting that it is a Galactic feature.*

II. *We provide evidence on the presence of infall of the Sgr leading tail onto the Galactic disk. This would explain the giant over-density discovered in Virgo.*

III. *The study of tidal streams and extended disks in spiral galaxies in the Local Universe will allow to extend this research on the formation of the components of spiral galaxies.*

Halo formation z~15

Disk formation z~2





At high redshift, we can follow the evolution of the population, but not the evolution of individual systems

The “missing satellite” crisis of the Cold Dark Matter Cosmology