The Accretion History of the Milky Way

Julio F. Navarro
Julio F. Navarro

The Milky Way as seen by COBE

Collaborators

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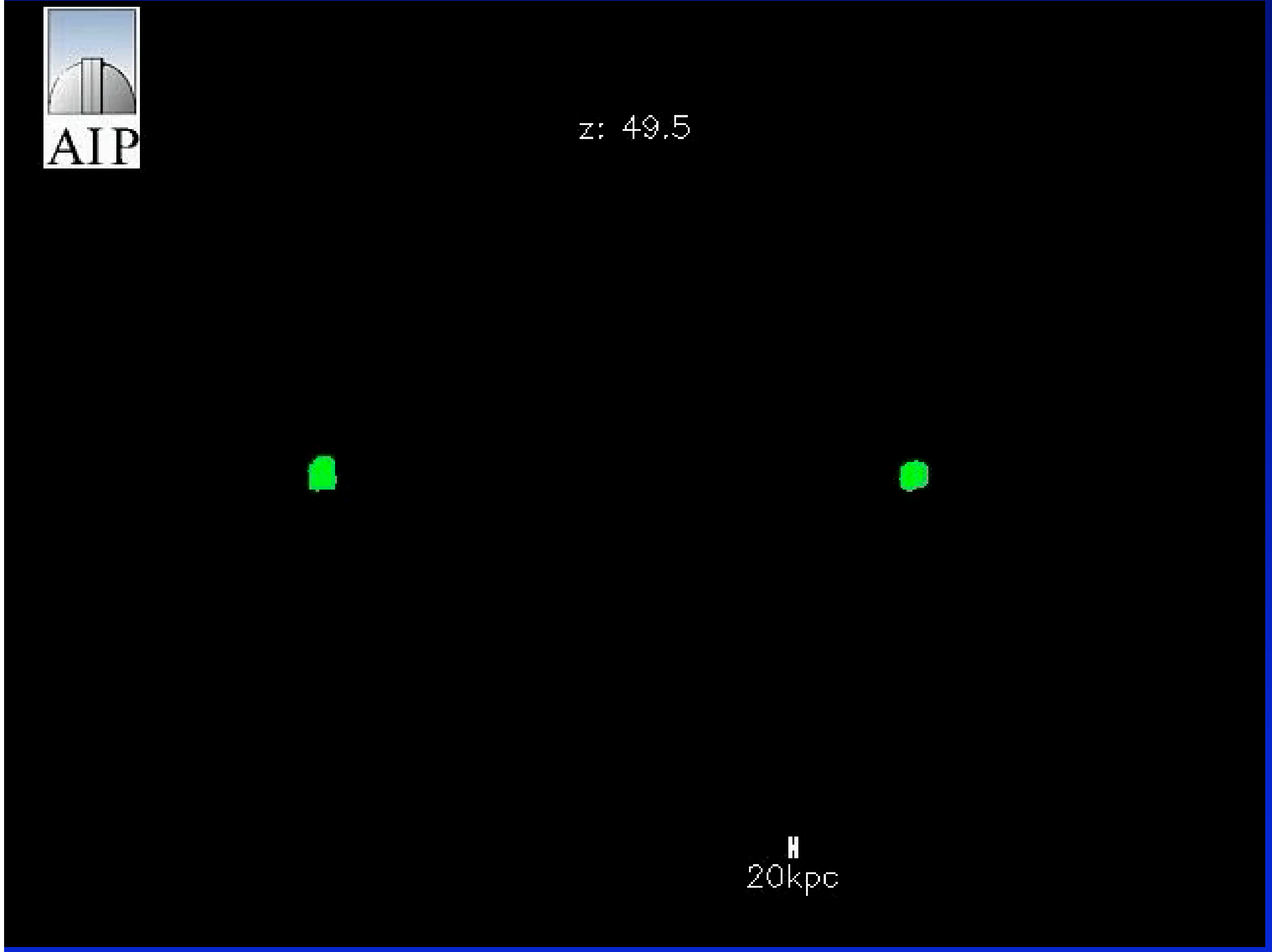
Andres Meza
Amina Helmi
Ken Freeman

The Hierarchical Formation of a Disk Galaxy



•Stellar disks form after the dissipative collapse of gas onto thin, centrifugally supported structures.

• Spheroids form subsequently as a consequence of mergers.

•Galaxy morphology is a transient, evolving feature in the lifetime of a galaxy.

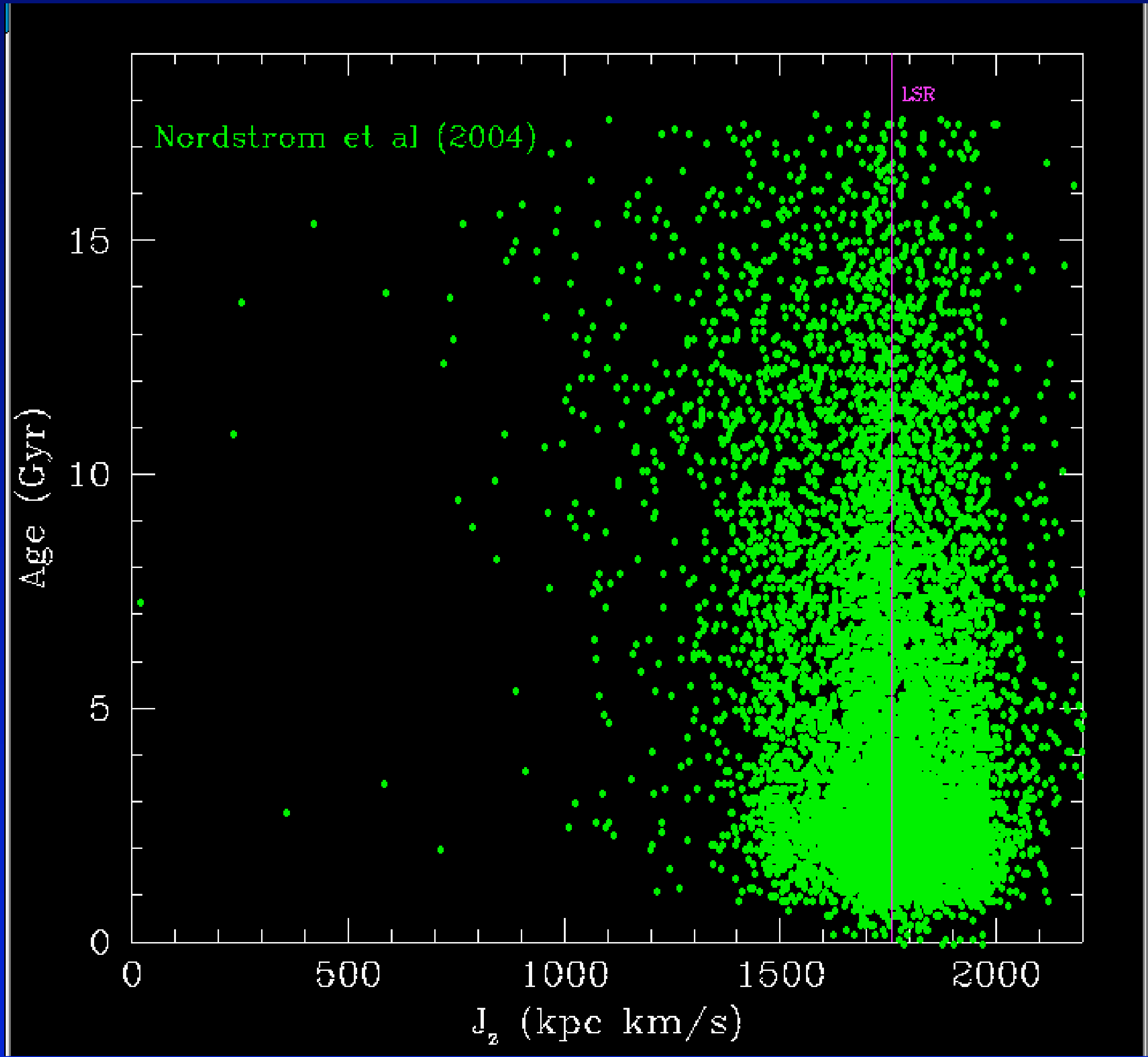
Steinmetz & Navarro 2000

The Hierarchical Formation of the Milky Way

- Galaxies are assembled hierarchically; i.e. most are likely to have experienced an early period of active merging activity
  - are there any relicts of this early merging history?
- In Milky Way-like galaxies this is followed by a relatively quiescent accretion epoch that led to the formation of the thin disk
  - but merging is still ongoing, as demonstrated by the Sagittarius dwarf
- Galactic disks date from the time of the last major merger and form from the inside out.
  - why are there thin disk stars in the solar neighborhood as old as the Galaxy?

Age-Angular Momentum Distribution in the Solar Neighbourhood

Age

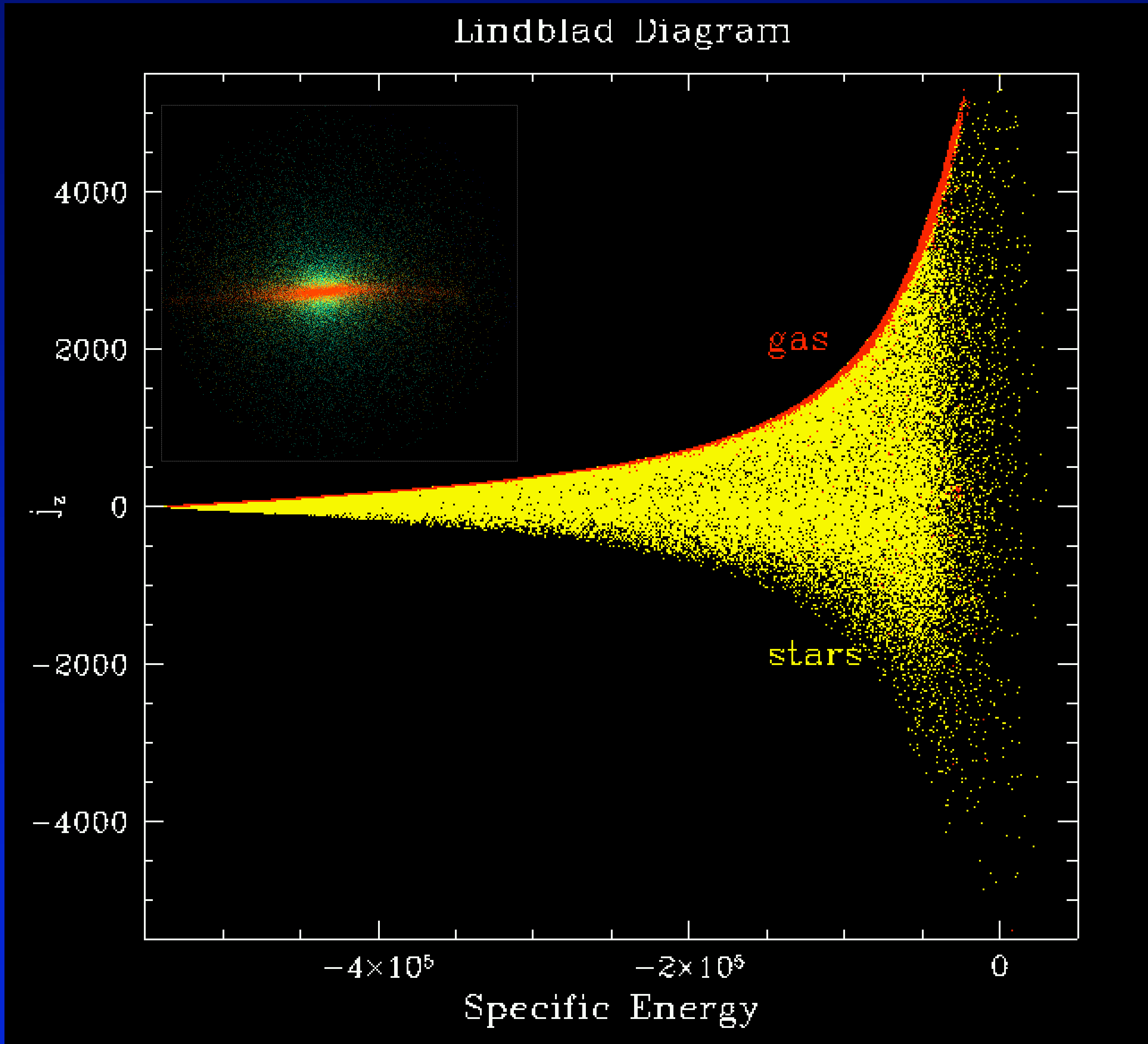


Specific Angular Momentum

From a catalogue of ~13,000 stars within ~100 pc of the Sun

Dynamical components of the simulated galaxy

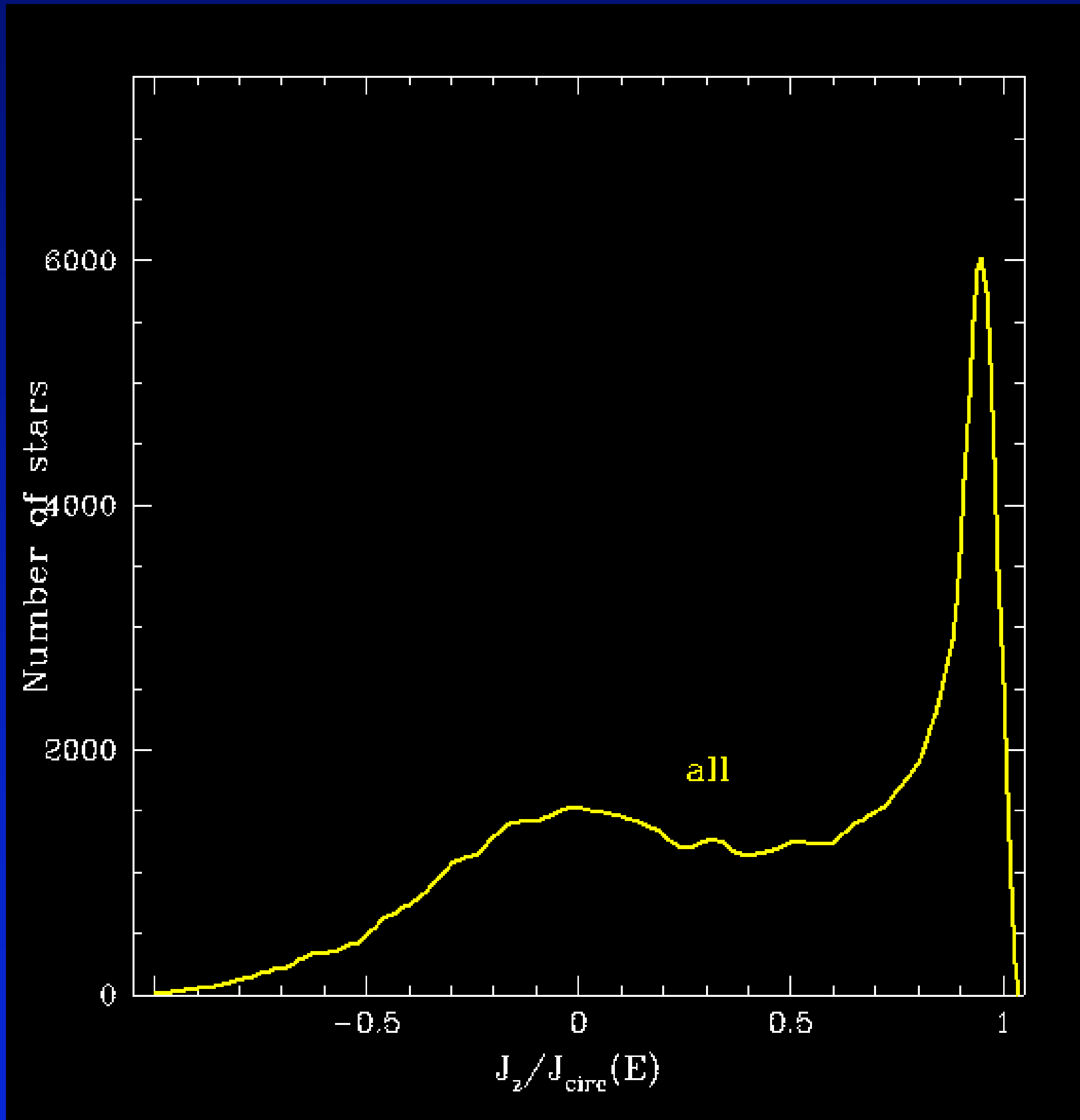
Specific Angular Momentum



Binding Energy

Abadi et al 2003

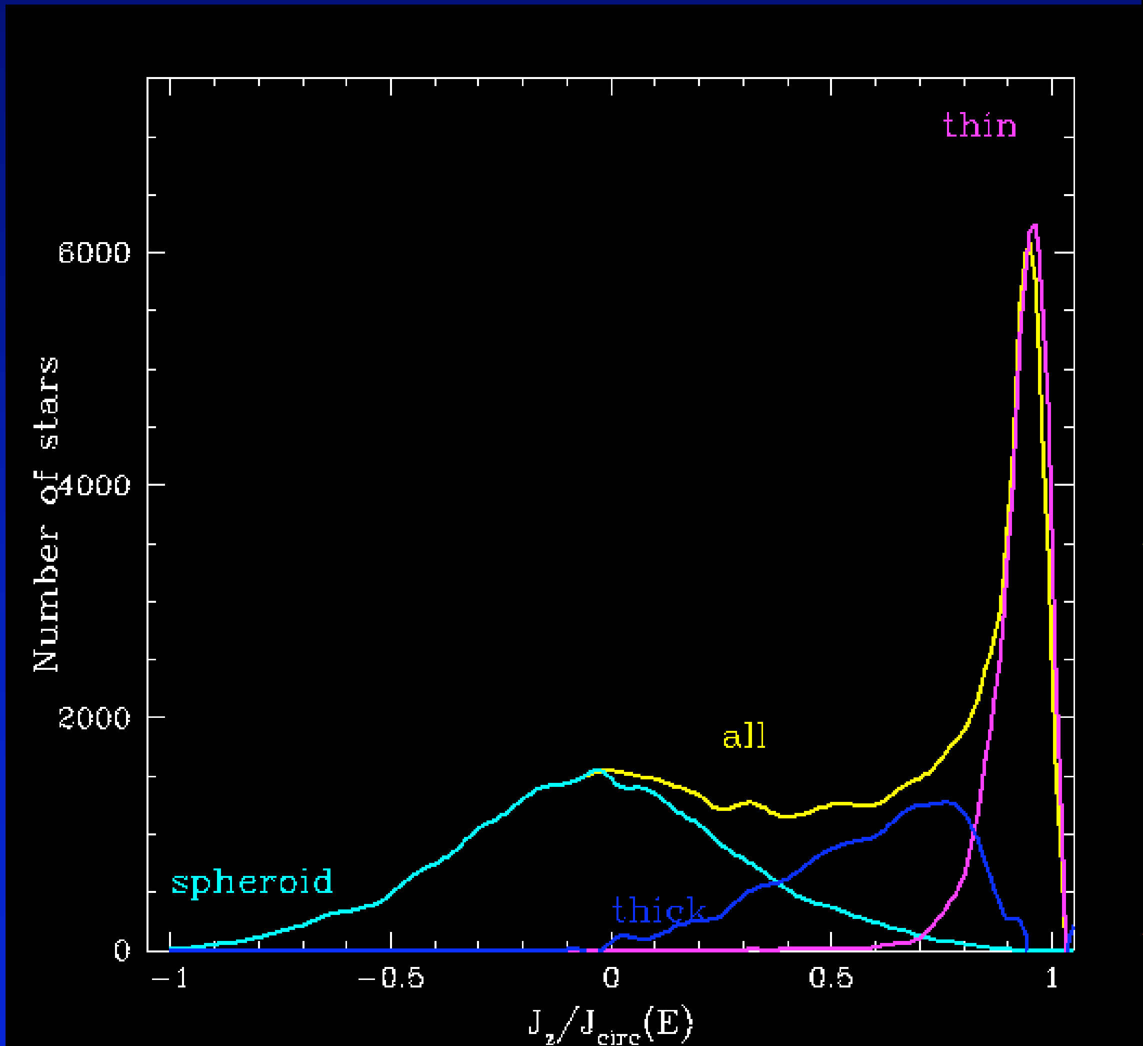
Dynamical components of a simulated galaxy



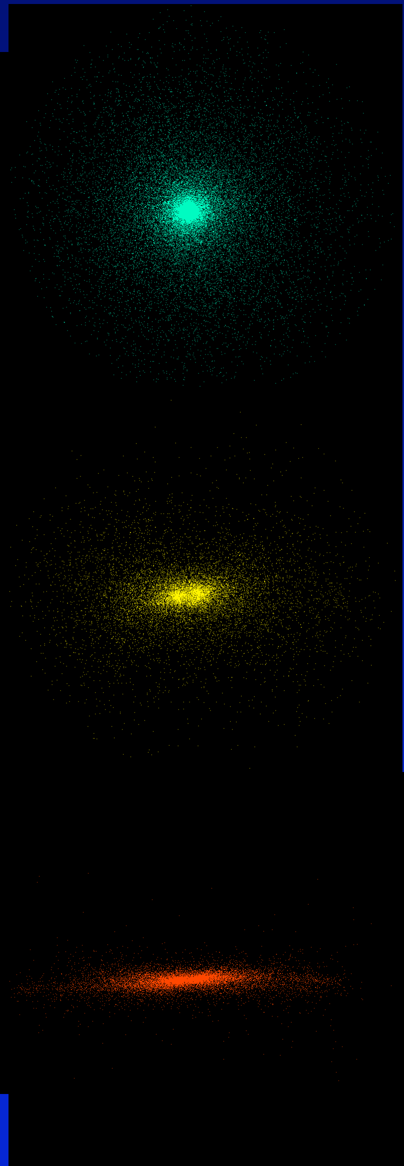
Orbital Circularity

Abadi et al 2003

Dynamical components of a simulated galaxy



Orbital Circularity



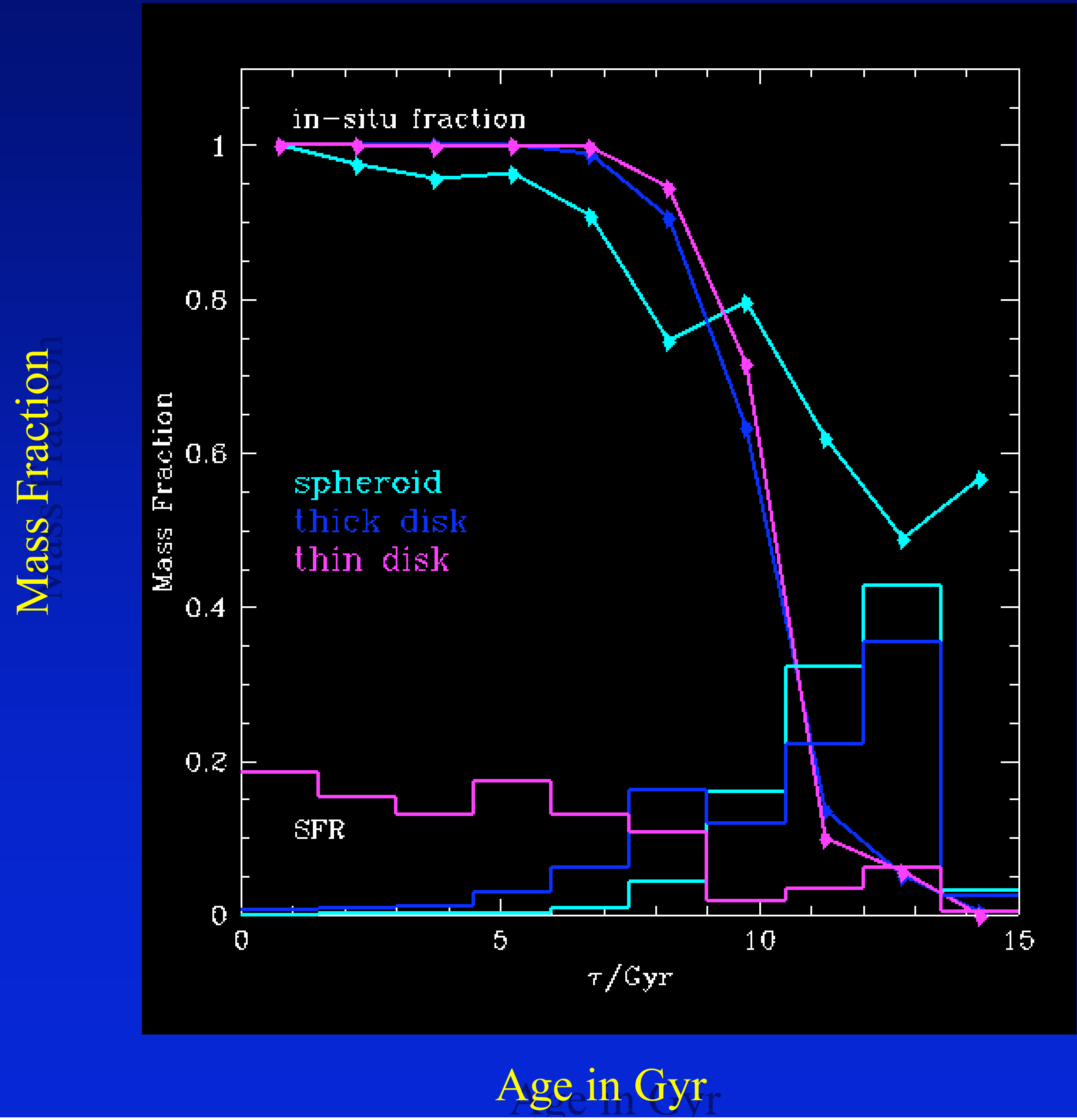
Non-rotating spheroid

thick disk

thin disk

Abadi et al 2003

The Star Formation History of the Simulated Galaxy

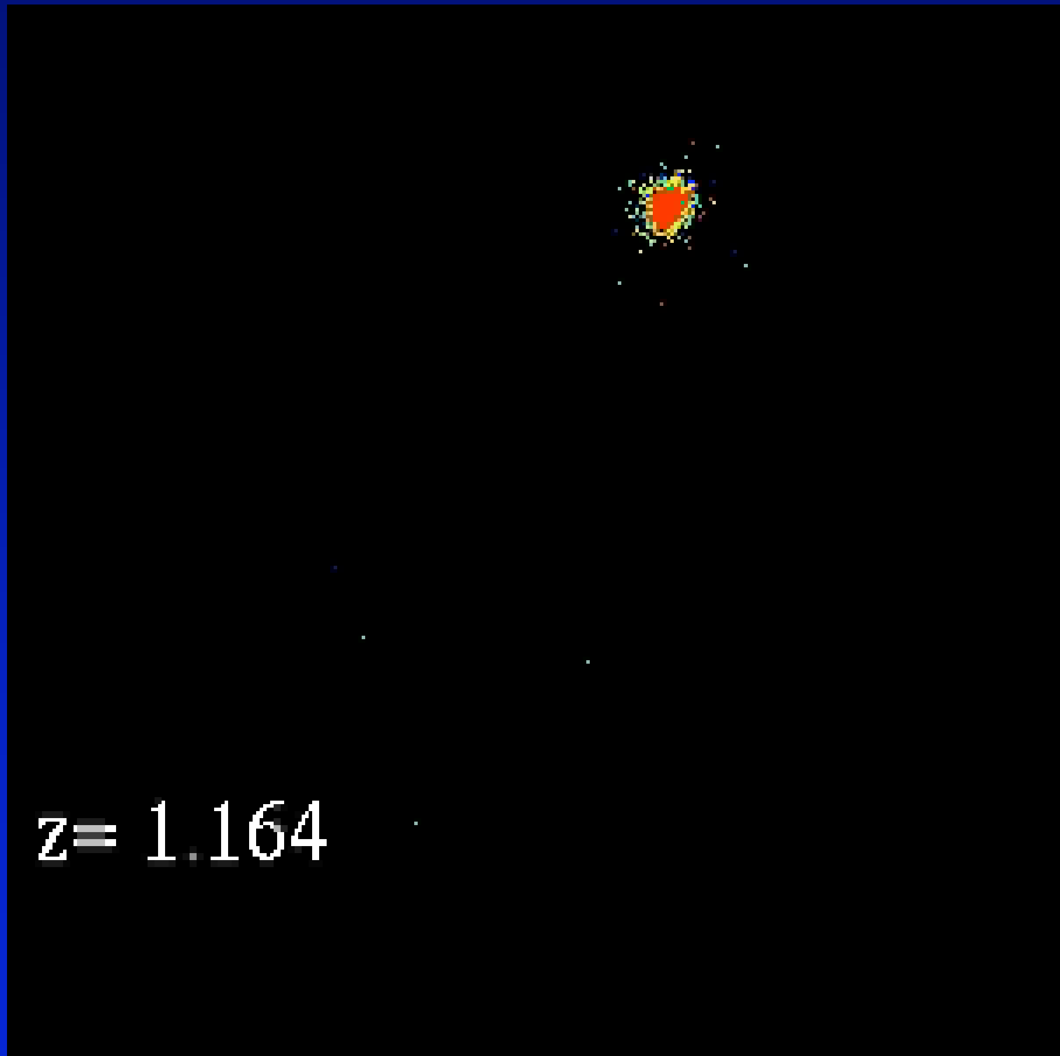


- The thin disk contains a significant number of old stars (15% are older than 10 Gyrs)
- >90% of old stars in the disk are the result of satellite accretion events
- The thick disk is ***not*** an early thin disk thickened by a minor merger but actually the accumulated debris from satellite accretion events

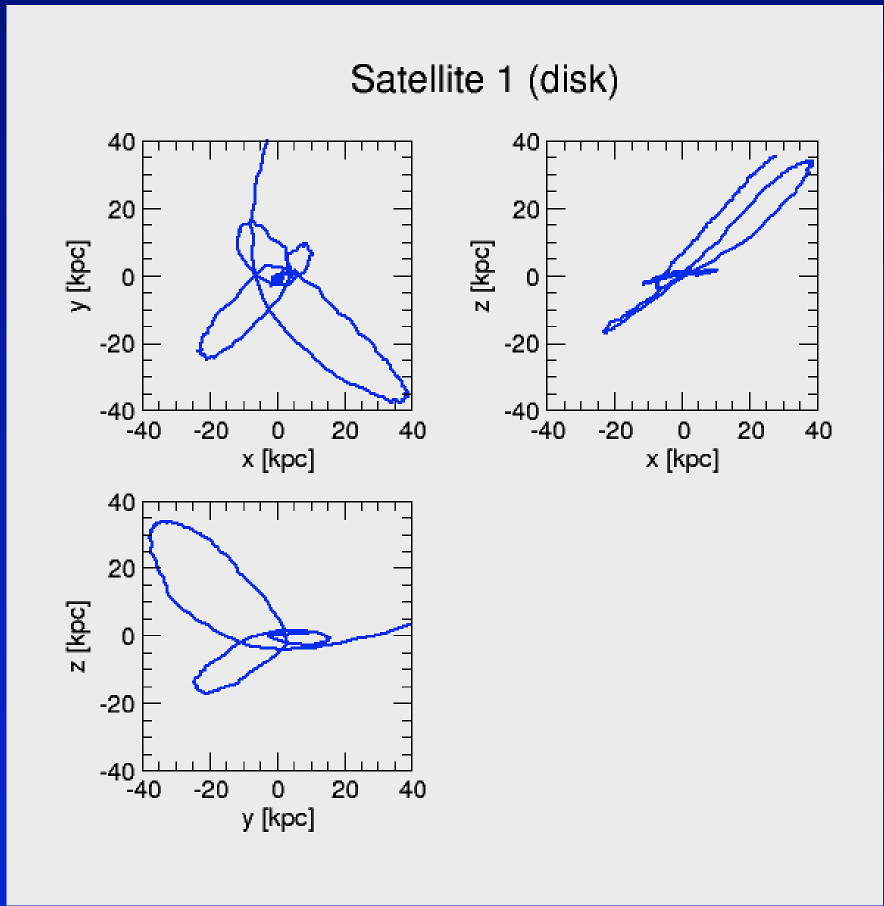
Abadi et al 2003

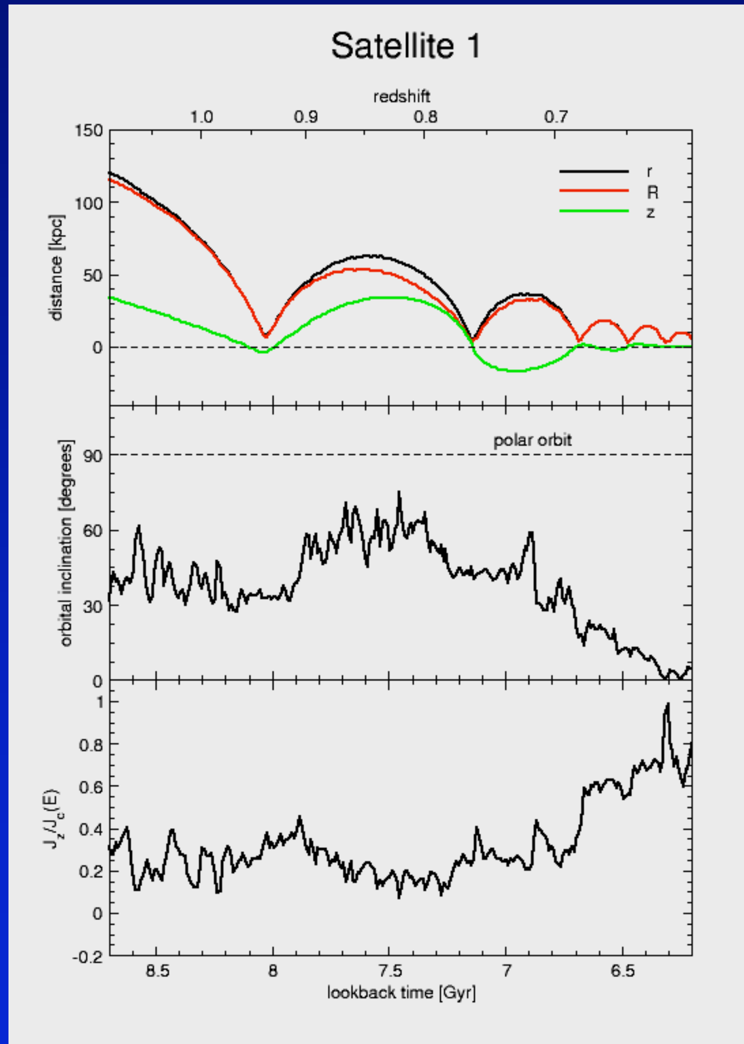
A disk made up of tidal debris: edge-on view

A disk made up of tidal debris: face-on view



Satellite orbit circularization





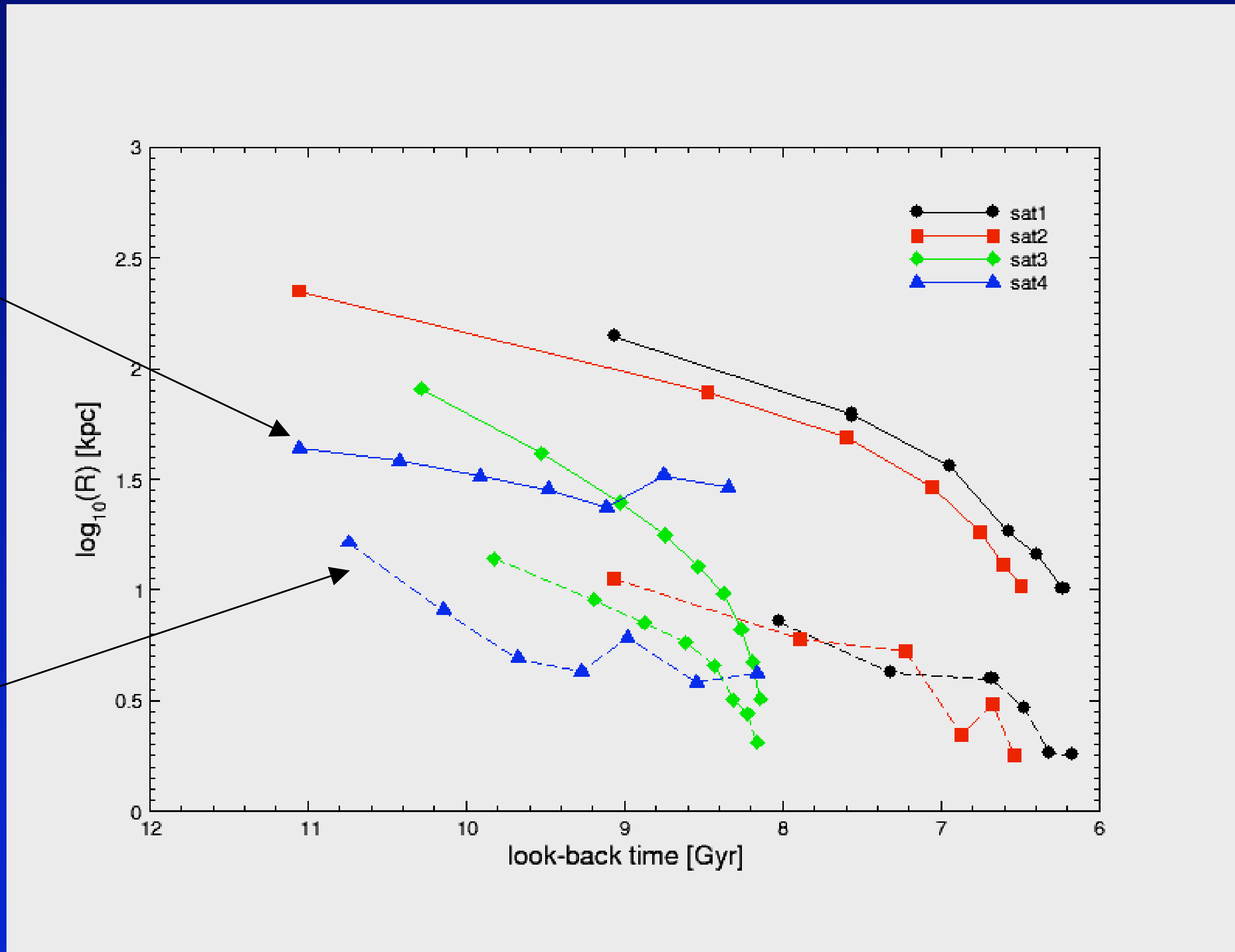
Satellites on roughly coplanar orbits are brought into the plane and circularized by dynamical friction

Meza, Navarro, Abadi, Steinmetz 2004

Satellite Orbit Circularization

$R_{apocenter}$

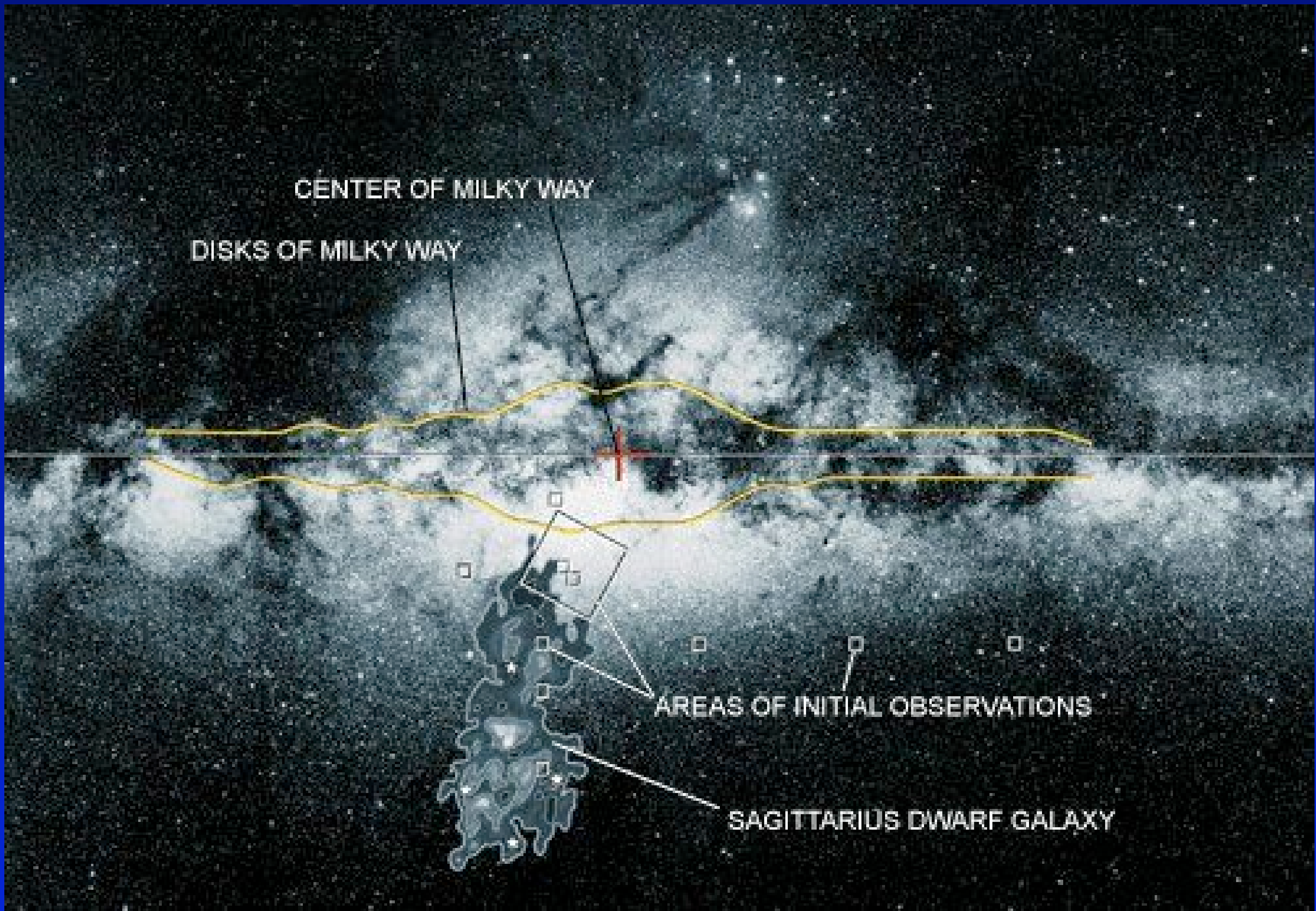
$R_{pericenter}$



Satellites orbits are generally circularized by dynamical friction

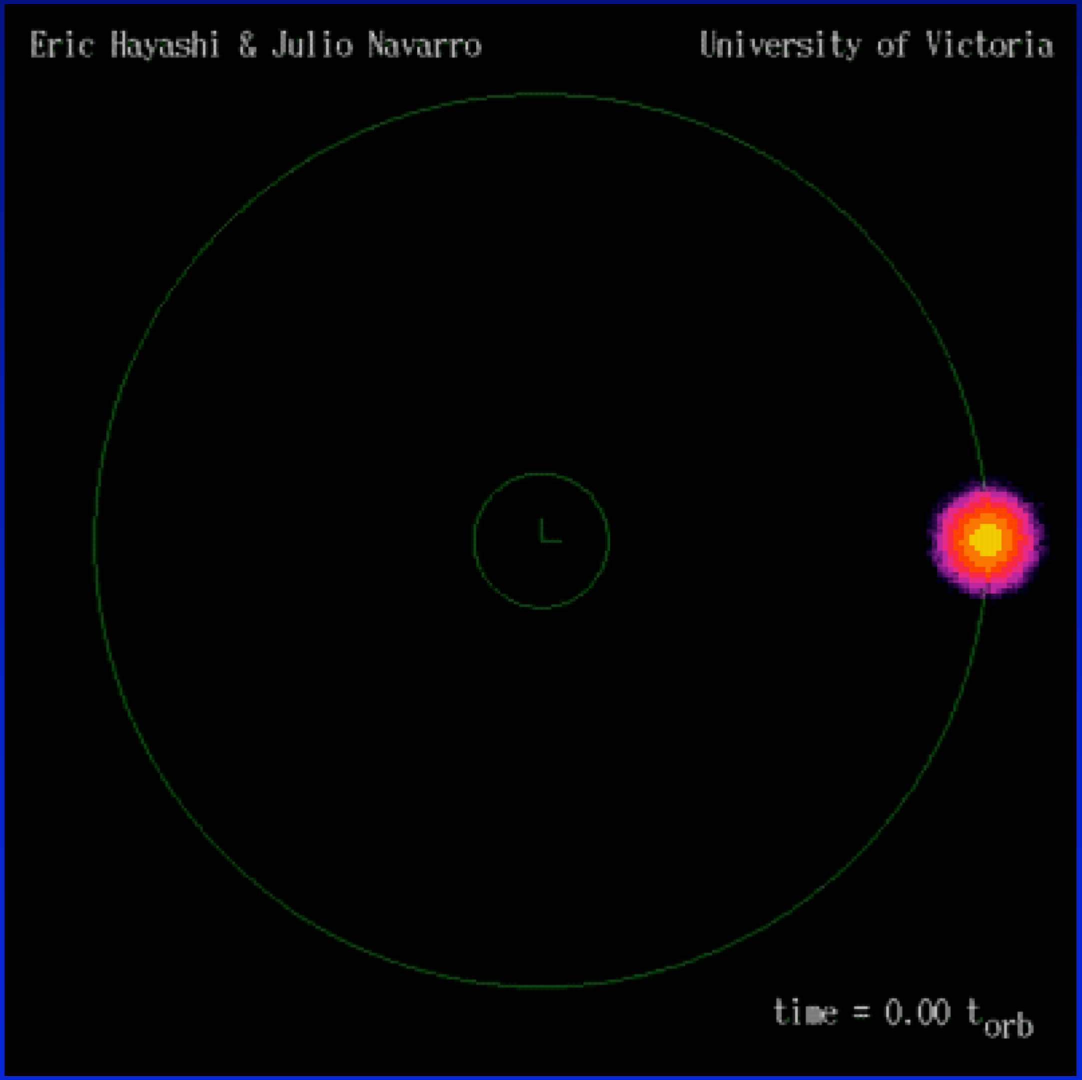
Meza, Navarro et al

Tidal Debris in the Milky Way Disk?

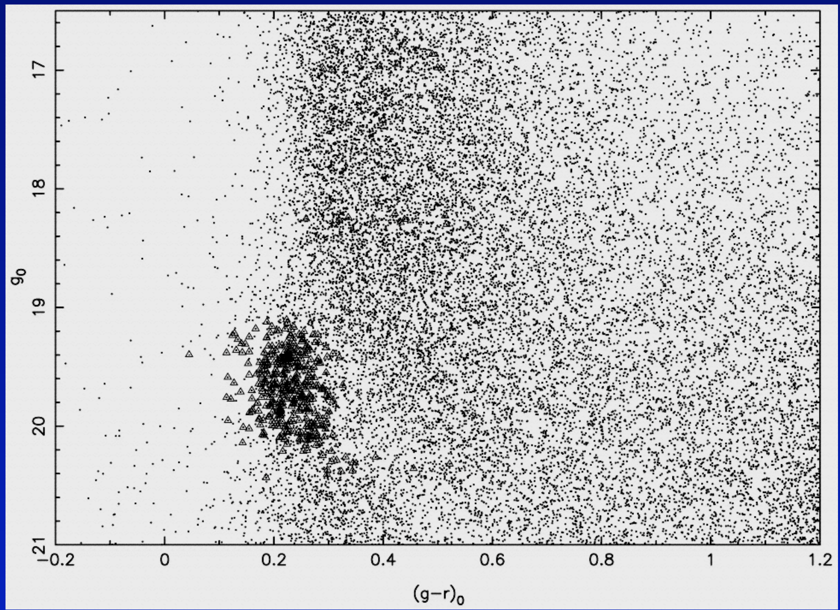


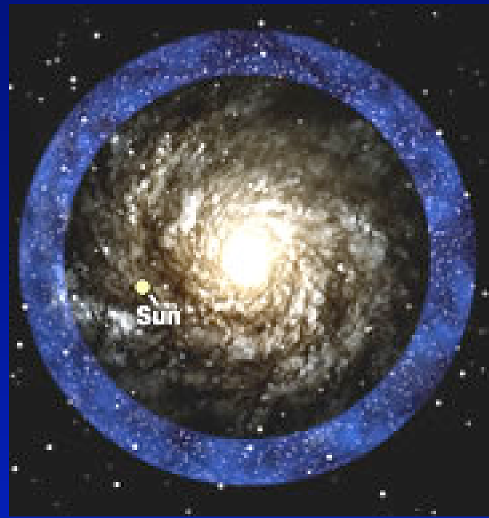
Tidal debris is usually assumed to contribute to the spheroidal component of the galaxy—like the Sagittarius stream—but it may also contribute to the Galactic disk(s)

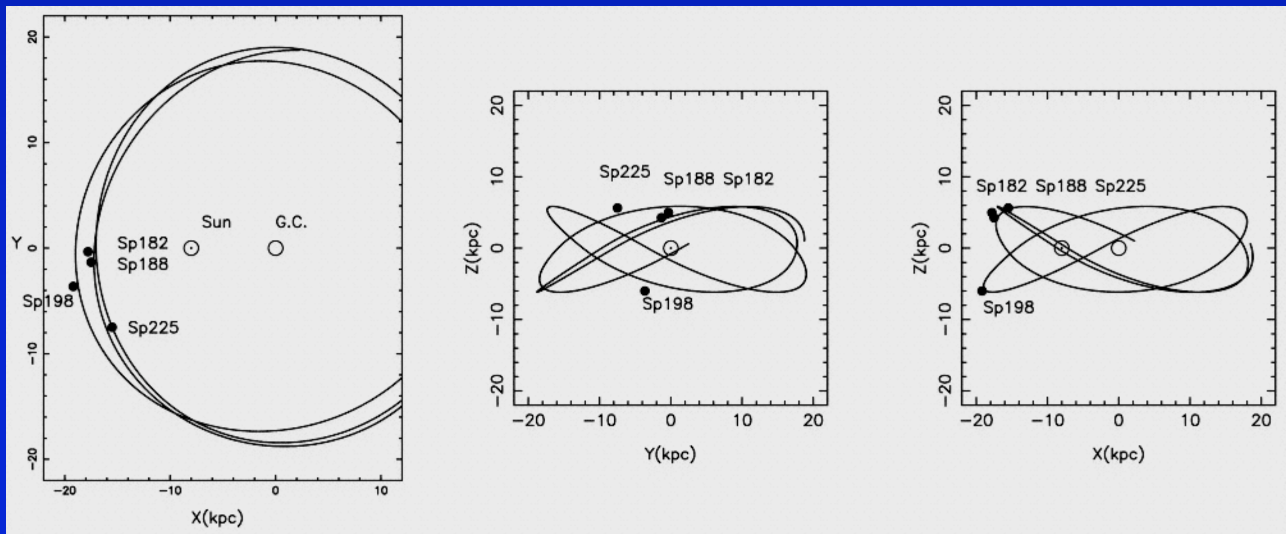
Signatures of ongoing disruption: "transient tidal arcs"



Ring around the Galaxy

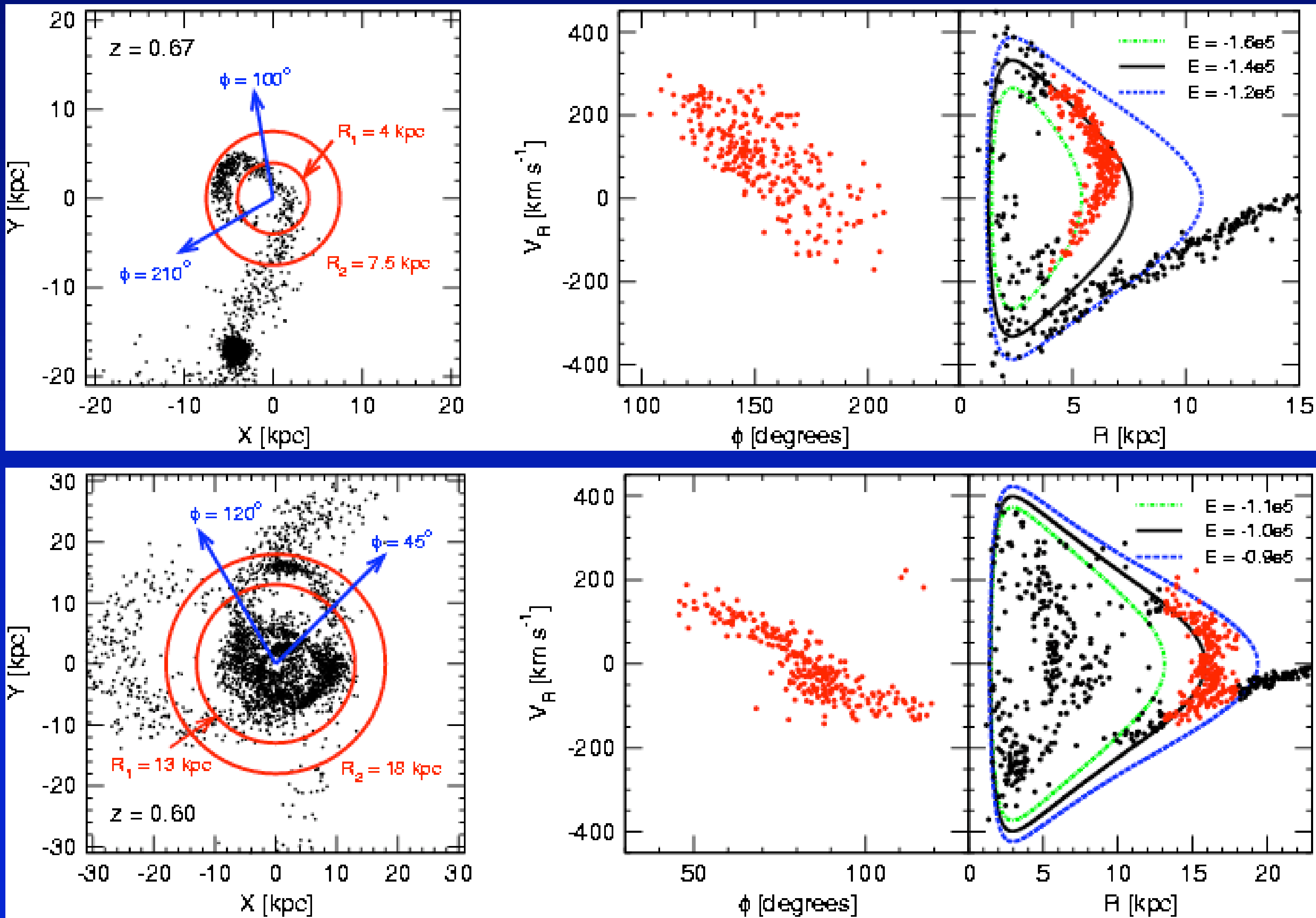






Yanny et al 2003
Newberg et al 2003

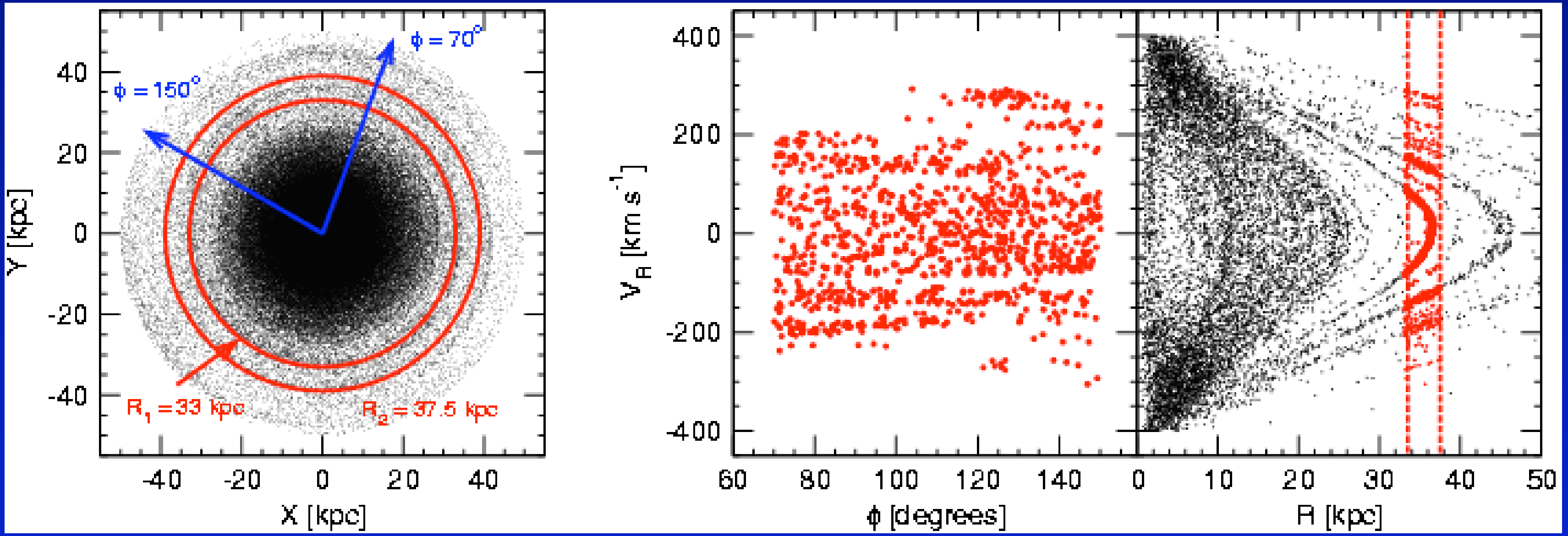
Ring around the Galaxy: a tidal arc?



Helmi, Meza, Navarro, Steinmetz, Eke 2003

Helmi, Meza, Navarro, Steinmetz, Eke 2003

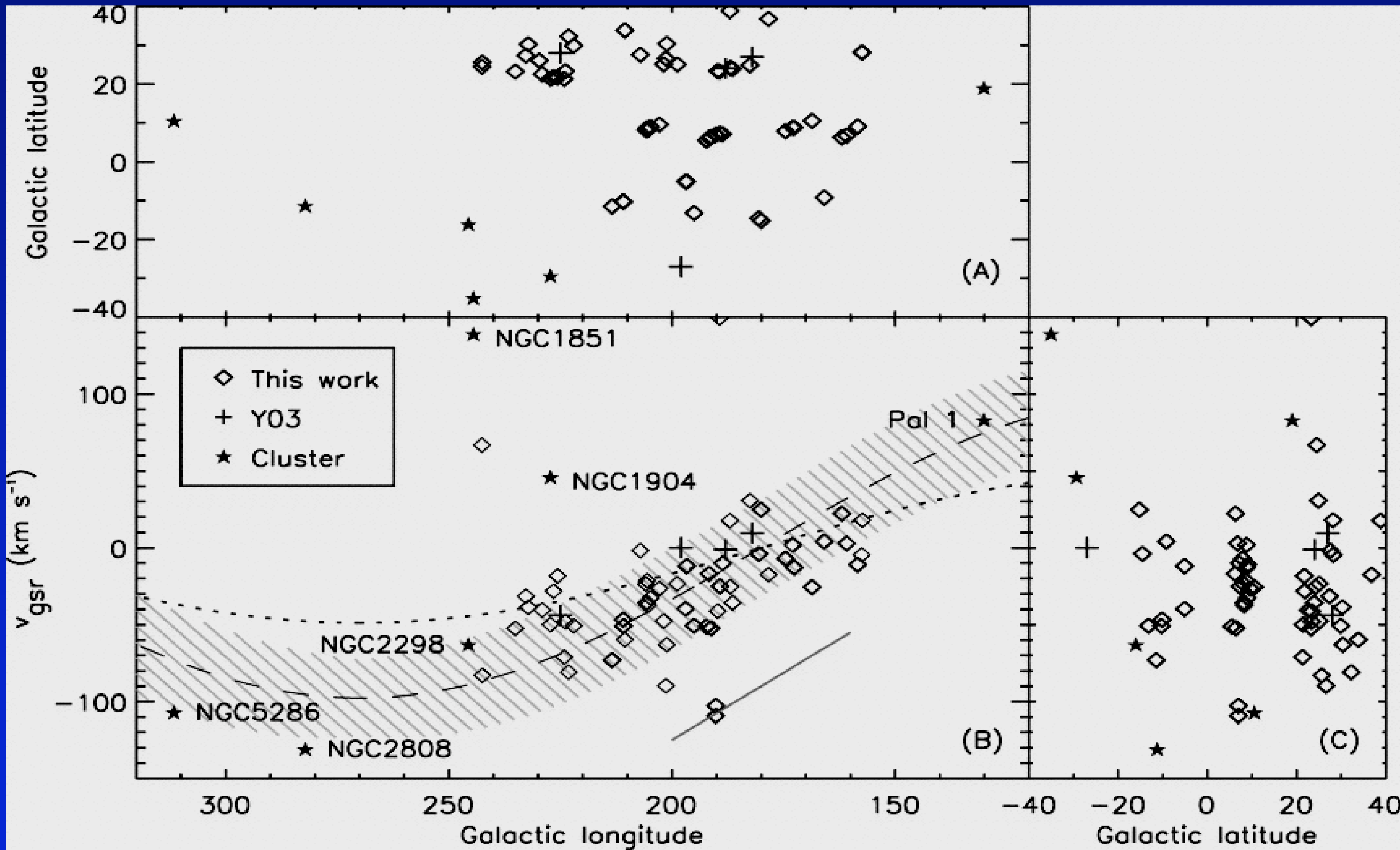
Ring around the Galaxy: a tidal shell?



Helmi, Meza, Navarro, Steinmetz, Eke 2003

Helmi, Meza, Navarro, Steinmetz, Eke 2003

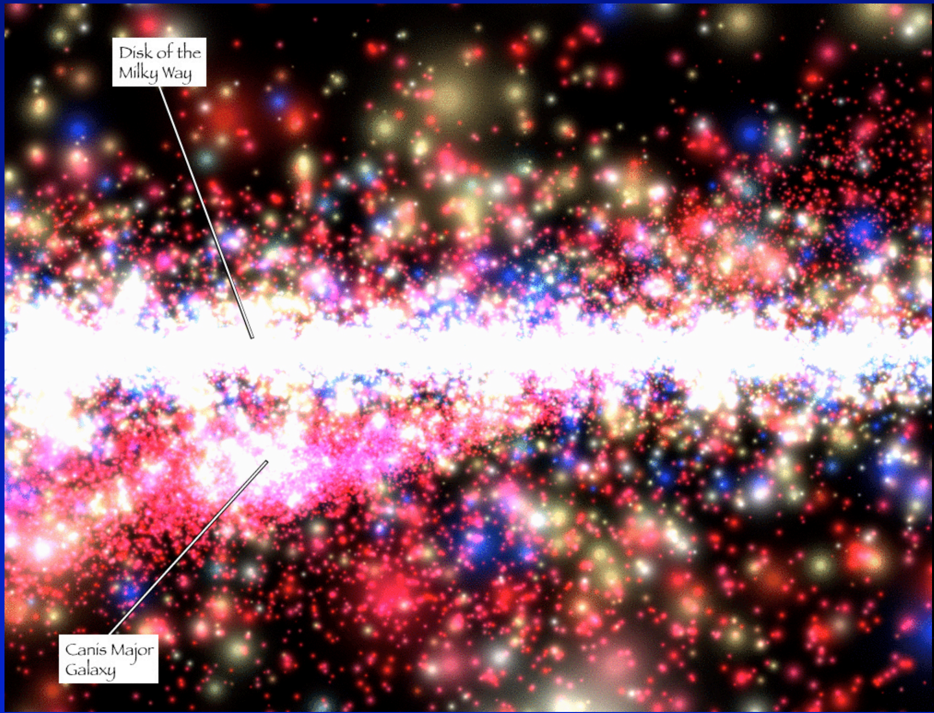
Ring around the Galaxy: a tidal arc?

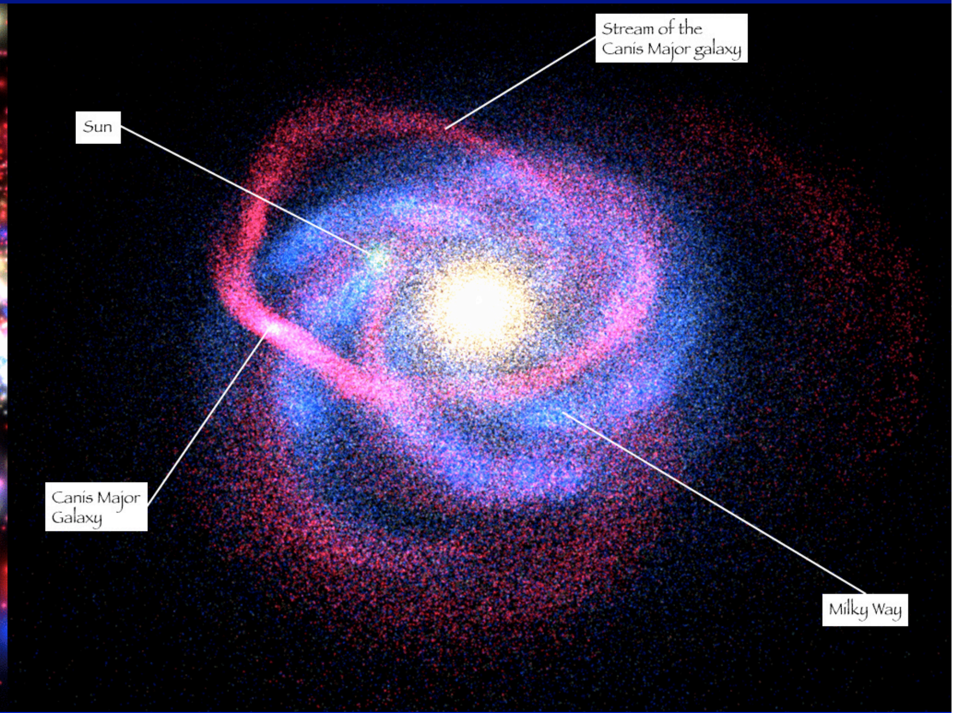


Crane et al 2003

Crane et al 2003

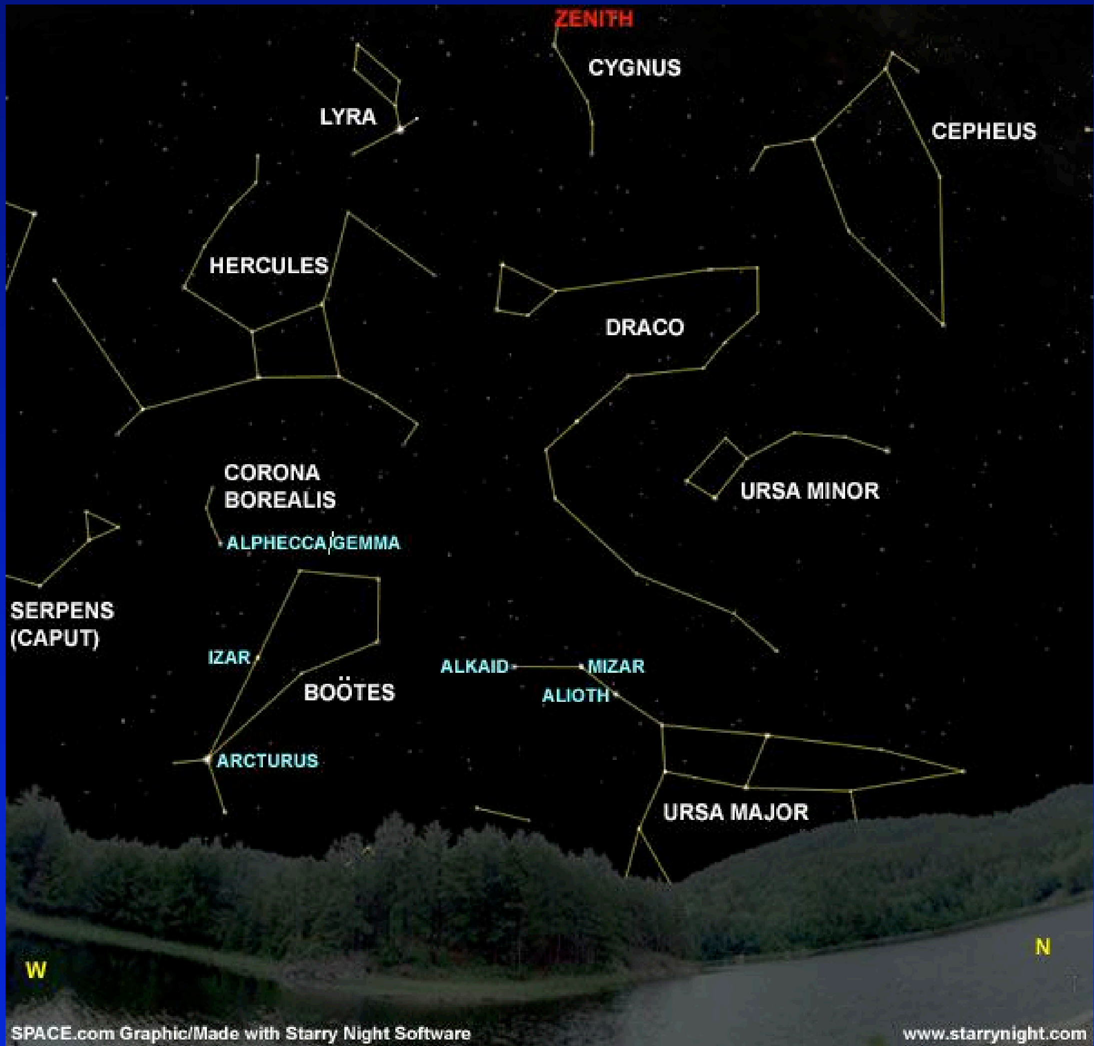
Ring around the Galaxy: its progenitor?





Ibata et al 2003
Ibata et al 2003

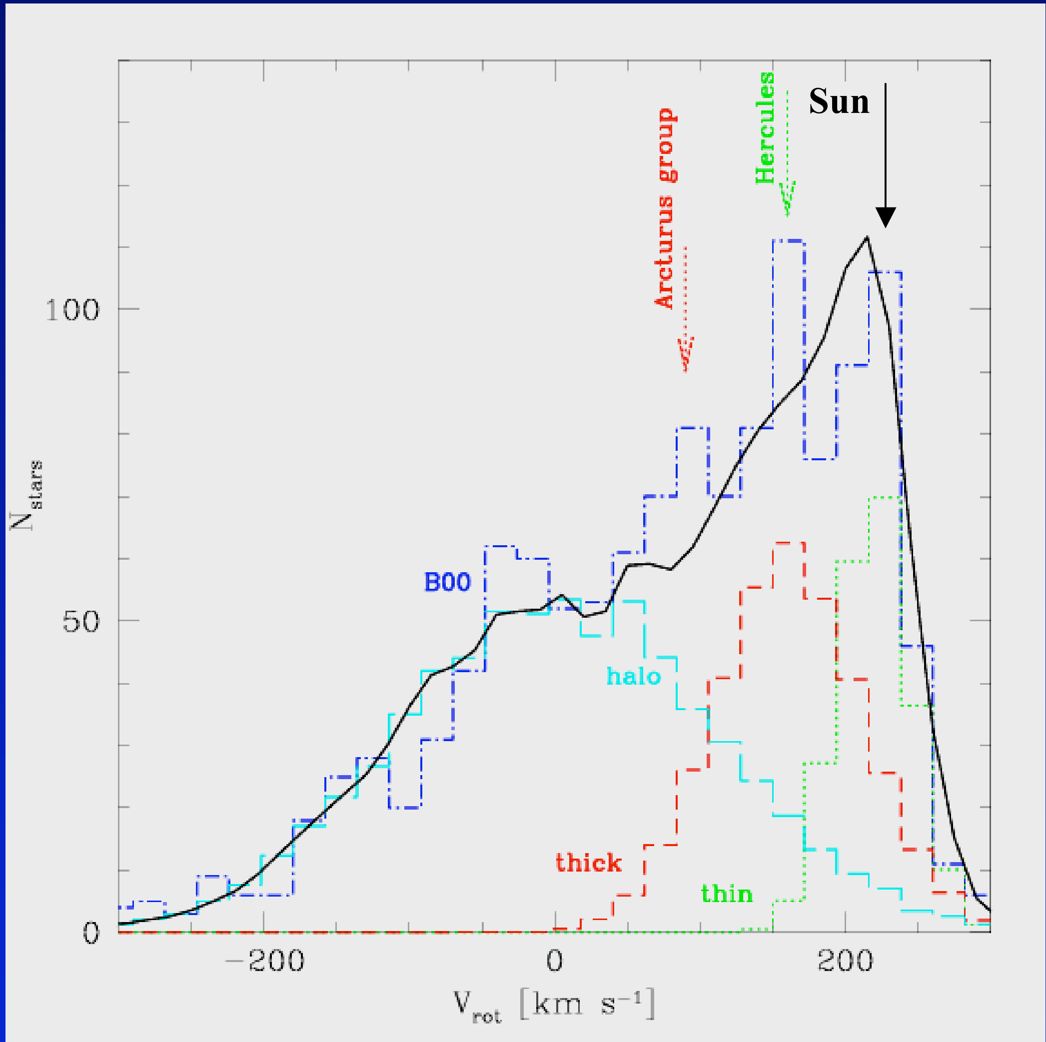
Are there further examples of accretion onto the Milky Way disk?



Tidal relicts are most easily identified in samples of stars that minimize the contribution of the young thin disk:

- metal poor stars
- stars above or below the Galactic plane
- stars at large Galactocentric distances

Metal-Poor Stars near the Sun



The rotation speed distribution of metal-poor stars and the three "canonical" components of the Milky Way
The rotation speed distribution of metal-poor stars and the three "canonical" components of the Milky Way

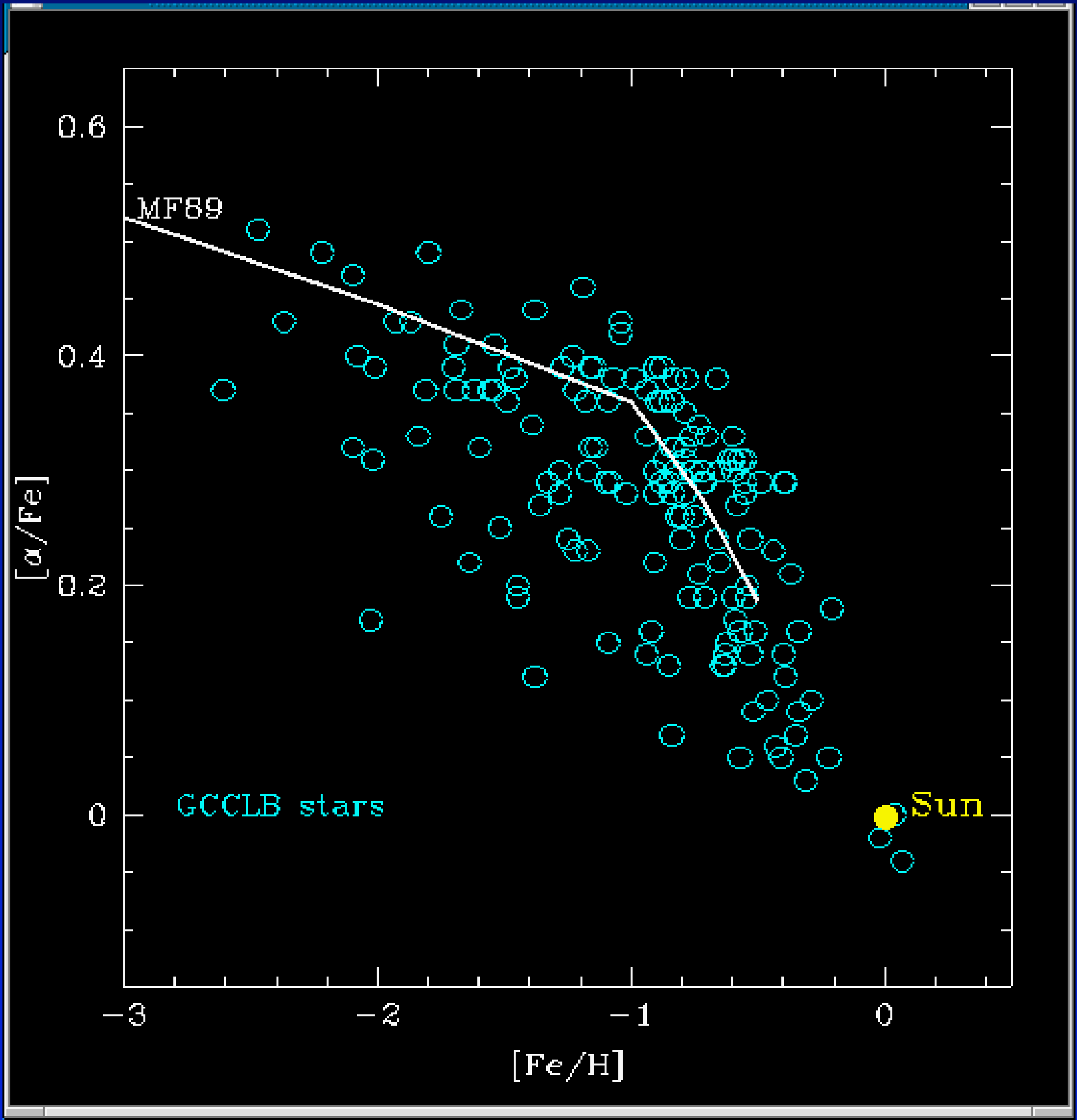
- They are less rotationally-supported than stars like the Sun

They are less rotationally-supported than stars like the Sun

Beers et al 2000
Beers et al 2000

Metal-Poor Stars near the Sun

Ratio of alpha elements/Fe relative to solar

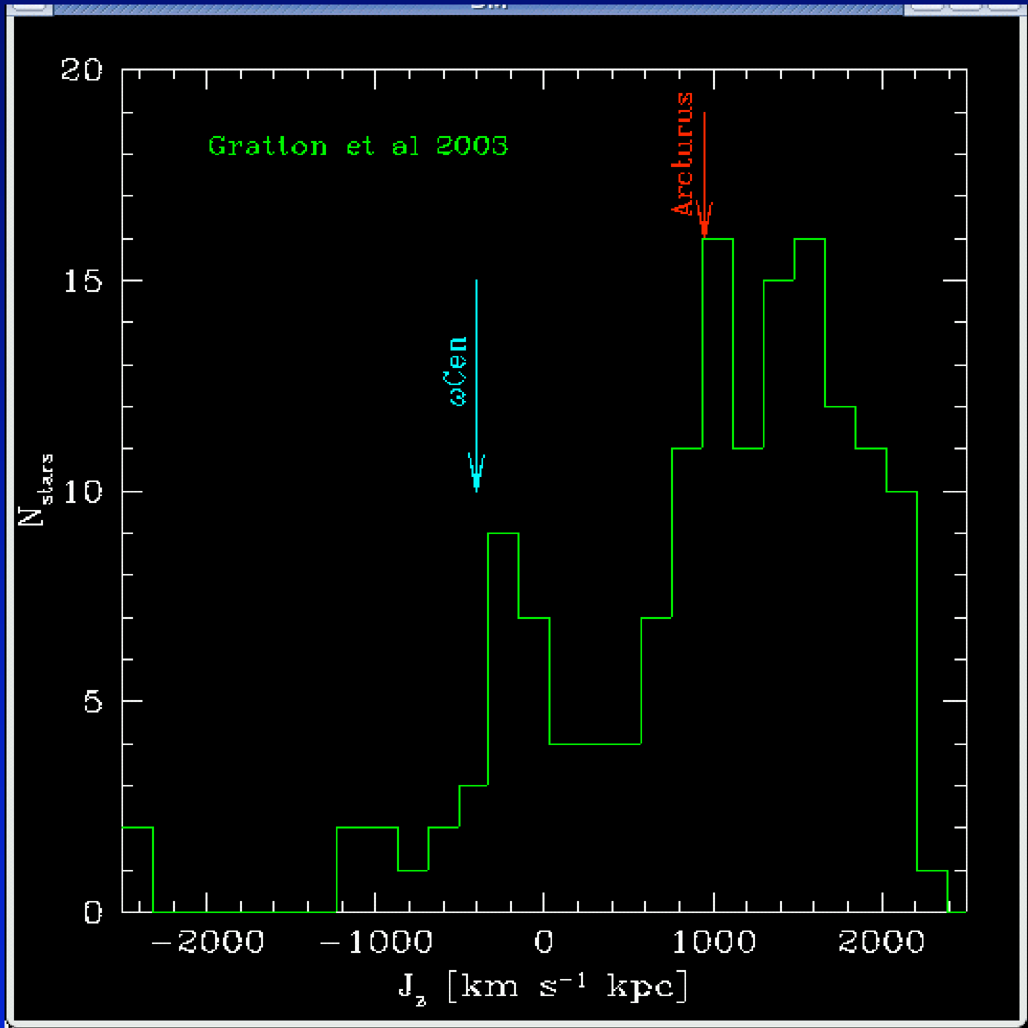


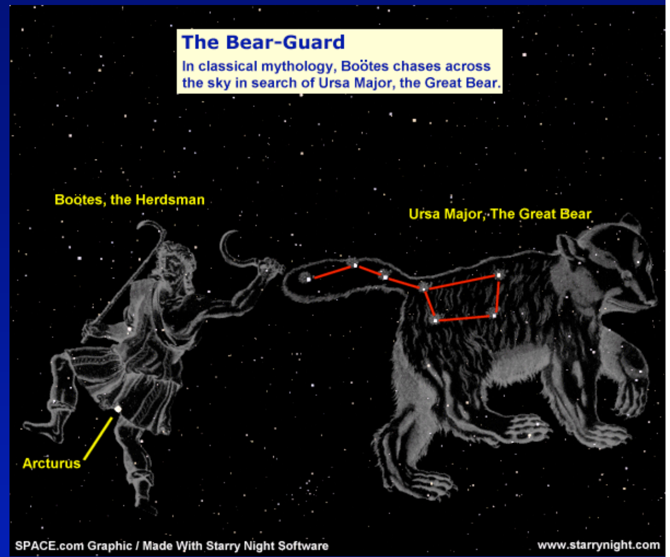
Iron abundance relative to solar

- Their chemical composition is enhanced in α-elements relative to the Sun.

Gratton et al 2003

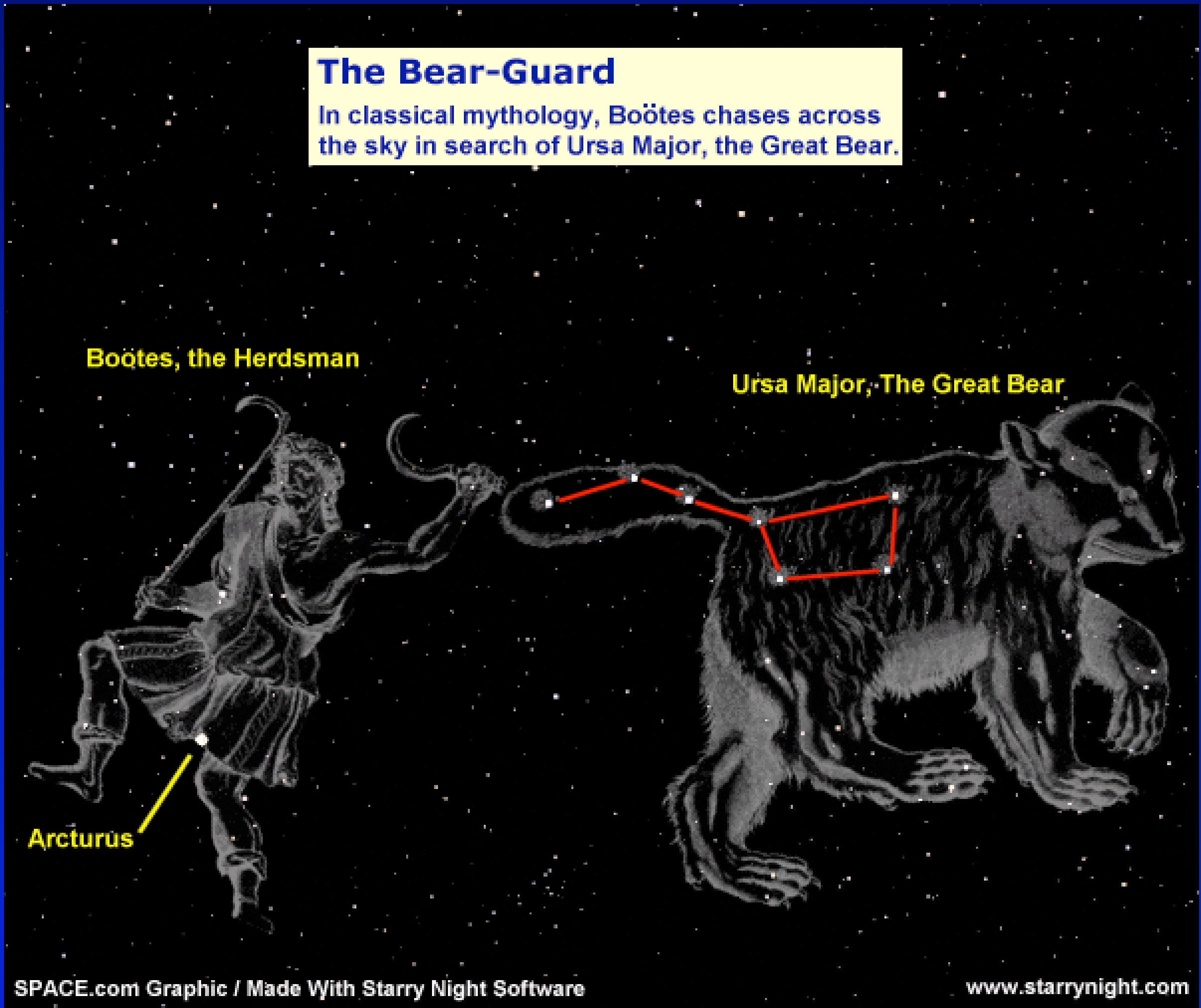
Tidal debris in the disk of the Milky Way





The J_z distribution of metal poor stars in the vicinity of the Sun suggests the presence of distinct kinematical groups

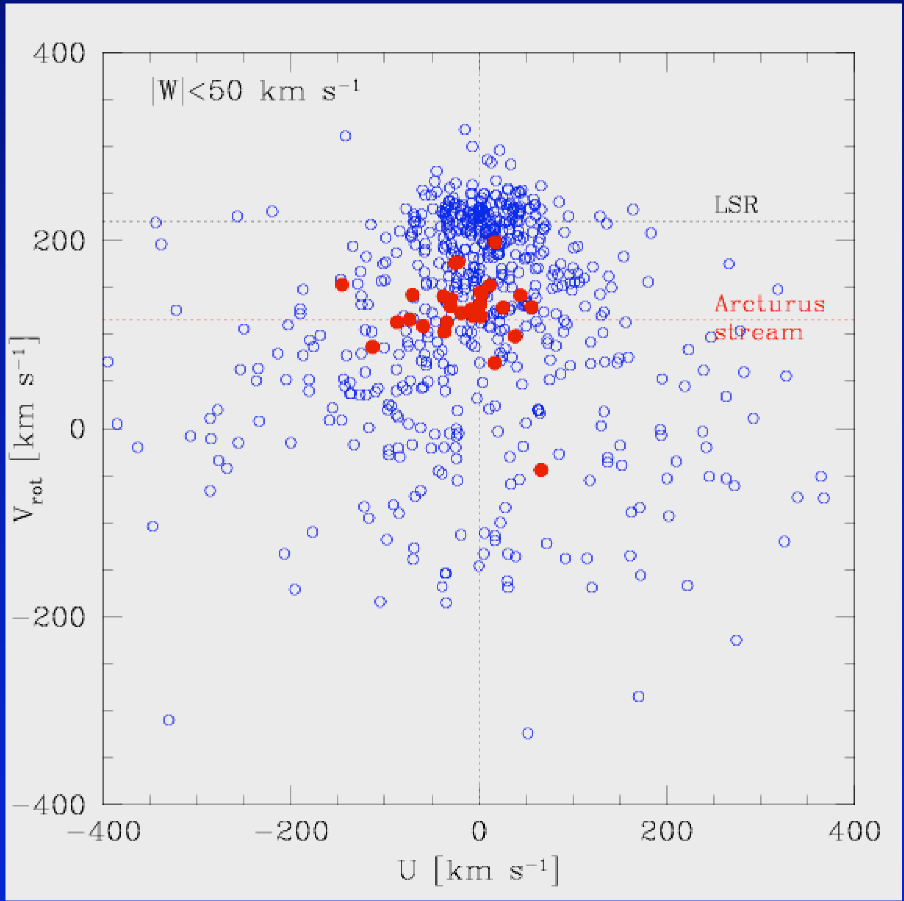
Arcturus: a night-sky witness of the merging history of the Milky Way?



In the early 70s, Eggen identified a number of bright stars with spatial motions similar to Arcturus.

The Arcturus group is one of the several "moving groups" (coherent dynamical structures in the solar neighbourhood) that Eggen identified and interpreted as the late stages in the disruption of old open clusters.

Dynamical Substructure in the Solar Neighbourhood



Open circles: metal-poor stars of Beers et al 2000
Filled circles: Eggen's Arcturus group candidates

Arcturus

• a metal-poor, [Fe/H]~-0.6, presumably old star

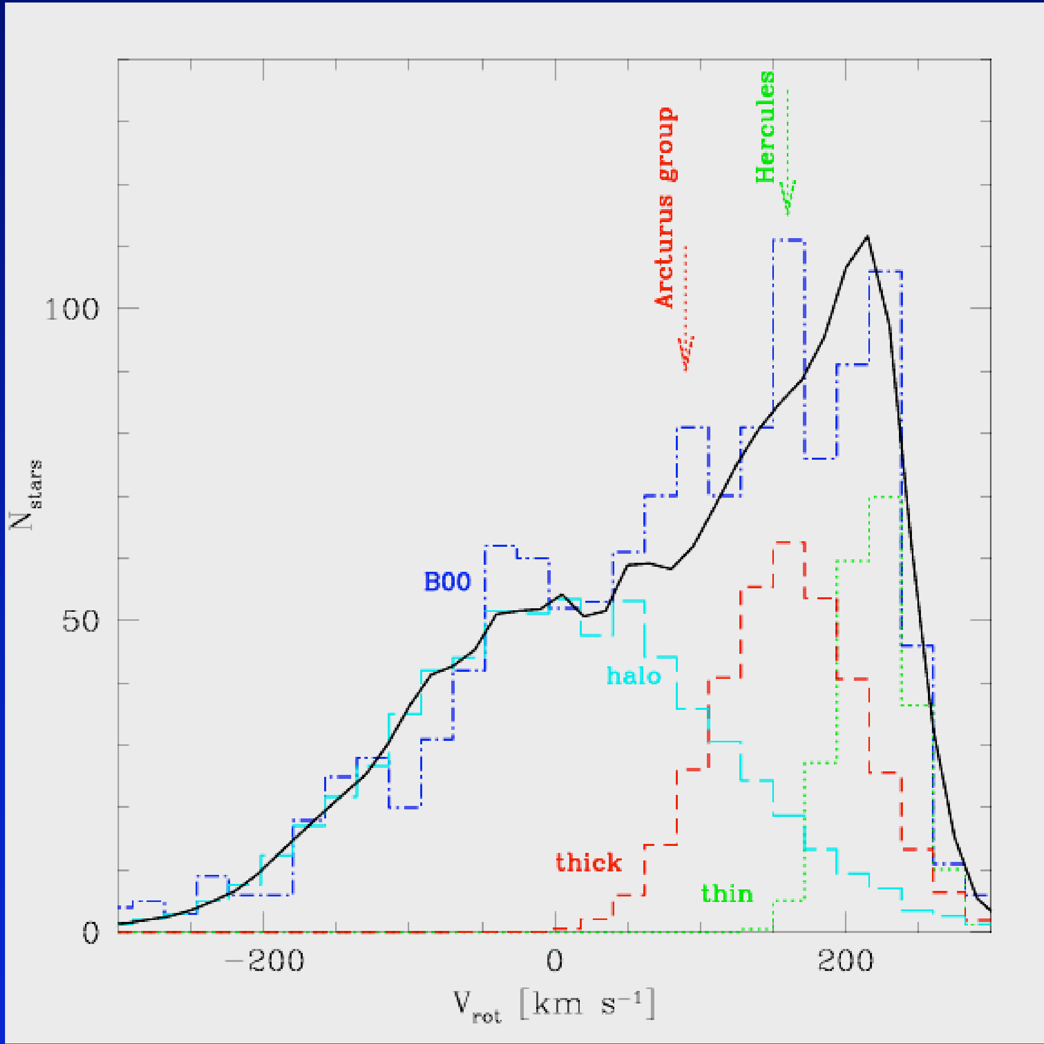
•on an disk-like orbit confined to within ~ 1 kpc of the Galactic plane

•with negligible radial velocity (near its apocenter)

•lagging the LSR rotation speed by ~110 km/s (more than twice as much as the canonical thick disk)

Navarro, Helmi & Freeman 2004

Dynamical Substructure in the solar neighbourhood



The rotation speed distribution of metal-poor stars decomposed in the three "canonical" components of the Milky Way

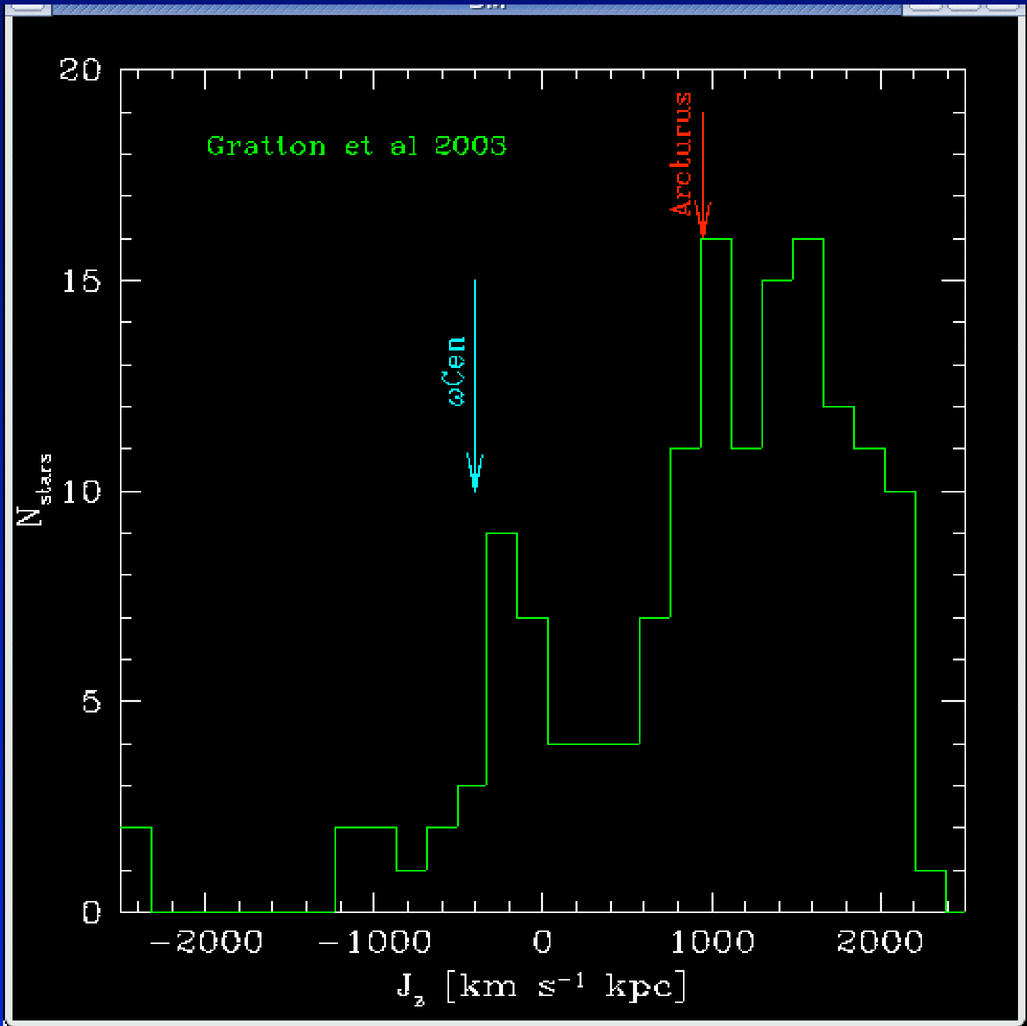
- Stellar groupings that lag the LSR by a few tens of km/s--such as the Hercules group--is an "excess" of stars probably caused by resonances induced by the Galactic bar (Dehnen 2000, Fux 2001)

- Such resonances, as well as perturbations by the spiral pattern may cause some moving groups, but it is unlikely their effect may lead to lags above ~50 km/s relative to the LSR.

- The Arcturus group lags the LSR by 120-140 km/s

Navarro, Helmi & Freeman 2004

Dynamical Substructure in the Solar Neighbourhood

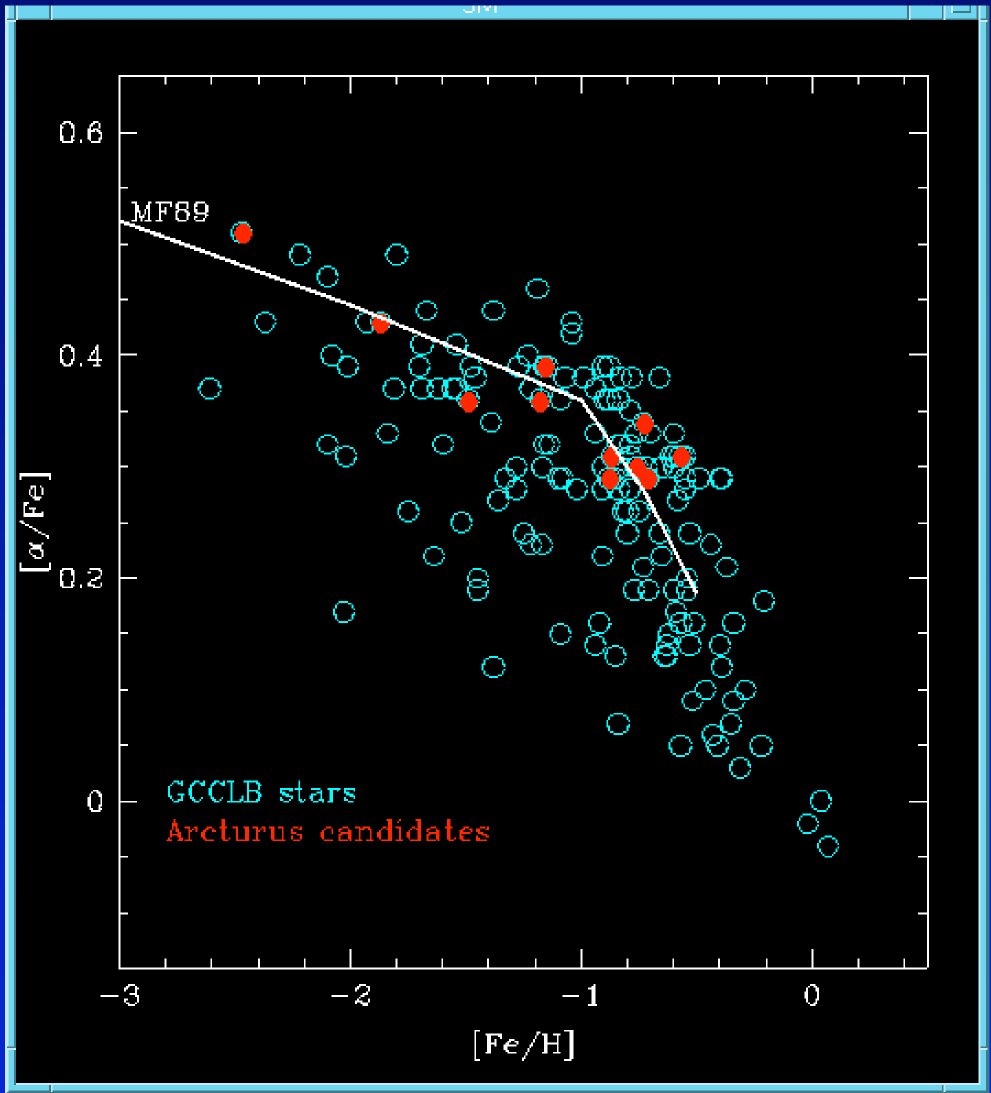


The J_z distribution of stars in various compilations.

- The **Arcturus group** appears as a recognizable "excess" of stars in various compilations of metal-poor stars, such as the samples of Beers et al (2000, B00) and Gratton et al (2003, GCCLB).

Navarro, Helmi & Freeman 2004

Chemical abundance of Arcturus group candidates



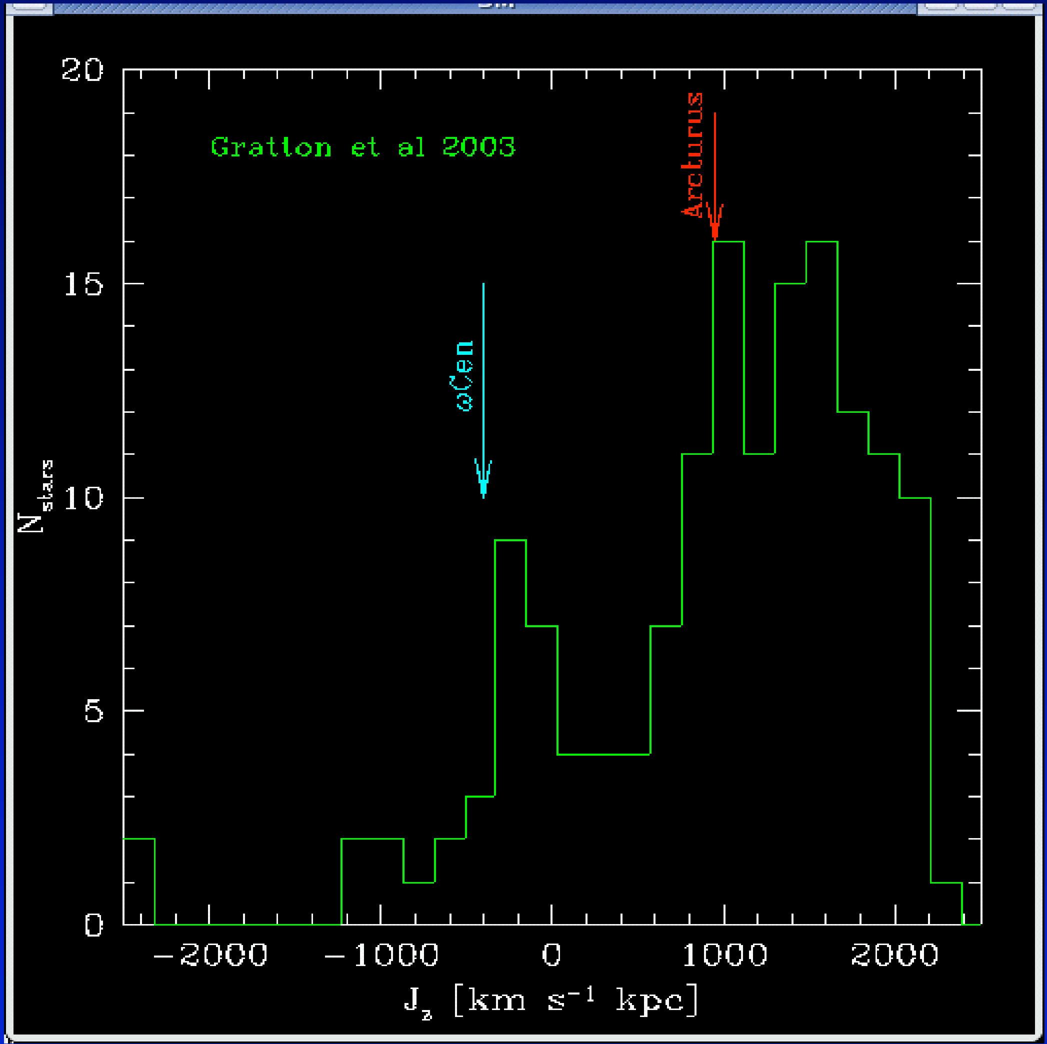
• Stars in the Arcturus group are fairly metal-poor, and trace a tight relation in the [α/Fe] vs [Fe/H] plane, as expected for a population of stars that self-enriched to a metallicity of about 1/3 solar.

Open circles: Gratton et al 2003 sample

Filled circles: stars with J_z comparable to Arcturus

Navarro, Helmi & Freeman 2004

More Substructures in the Solar Neighbourhood?



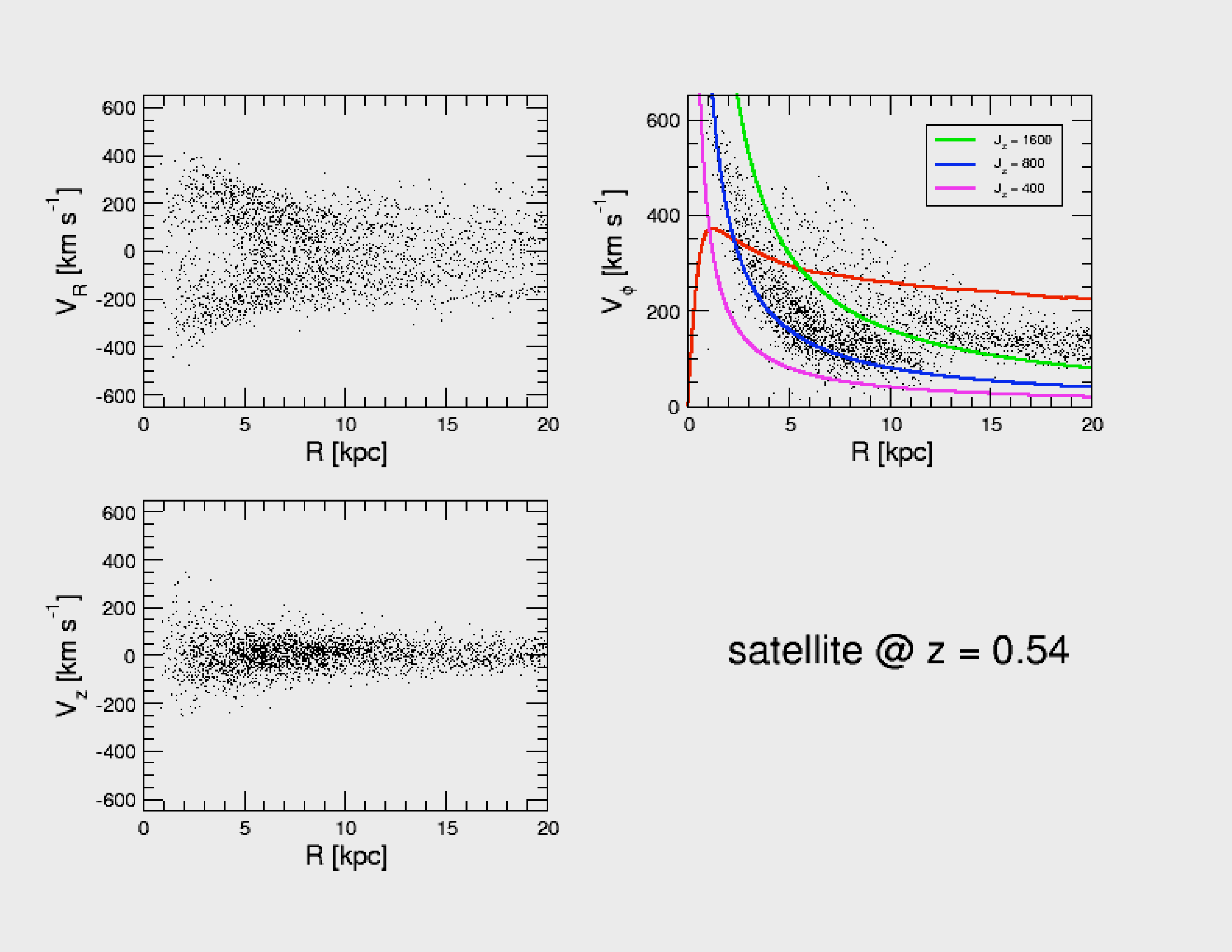
The rotation speed distribution of metal-poor stars decomposed in the three "canonical" components of the Milky Way

- The Beers et al catalog shows another possible "excess" of stars at slightly retrograde, very eccentric orbits.

- This peak has been associated with the unusual globular cluster ωCen, which might have been the nucleus of a disrupted dwarf galaxy.

Meza, Navarro et al 2004

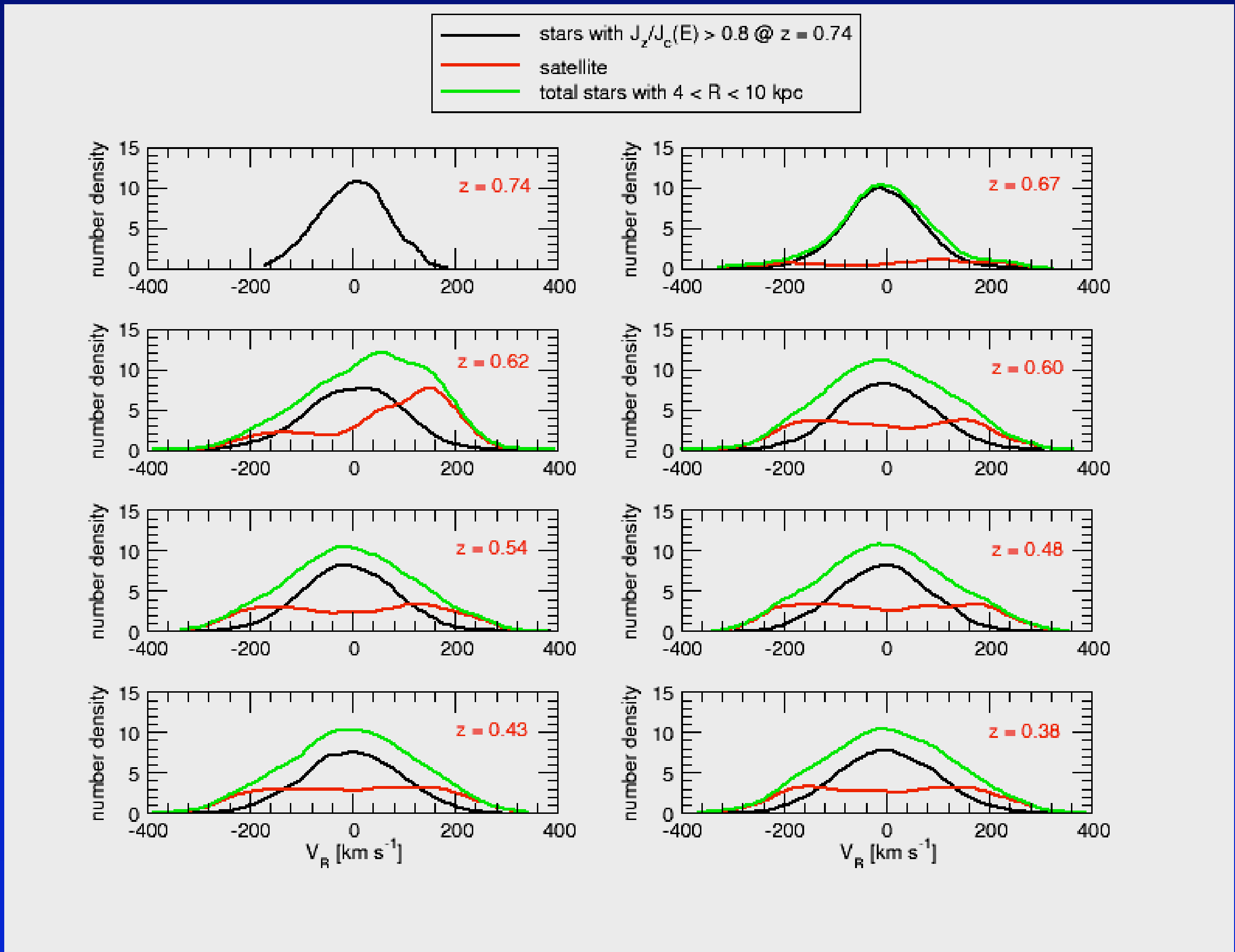
Dynamical properties of disk debris on eccentric orbits



- The satellite stars split into groups of similar angular momentum and binding energy at each pericentric passage.

Meza, Navarro et al 2004

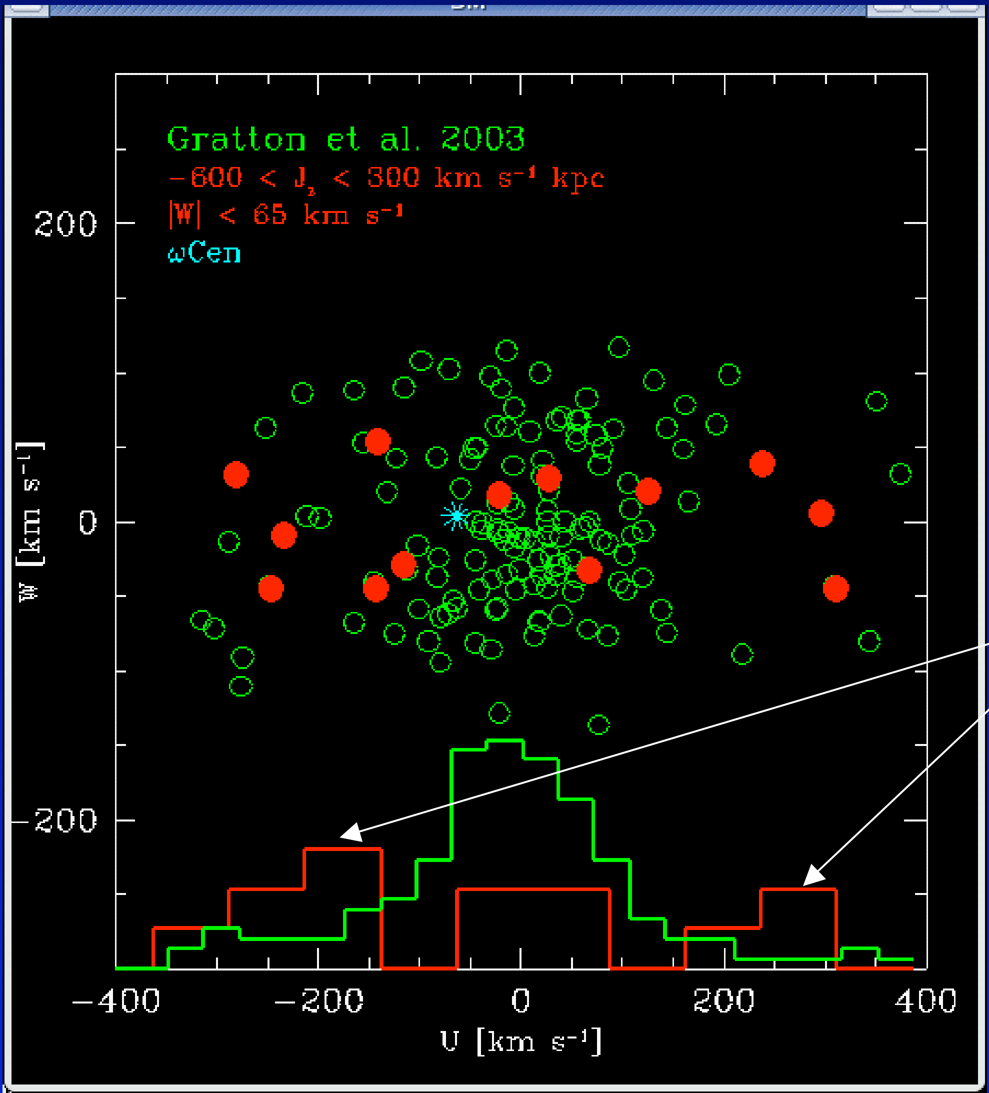
Dynamical properties of disk debris



- Debris stars are expected to show as a symmetric excess of stars with large galactocentric radial velocities, if observed from a radius between the apocenter and pericenter of their orbit.

Meza, Navarro et al 2004

Dynamical properties of ωCen group candidates



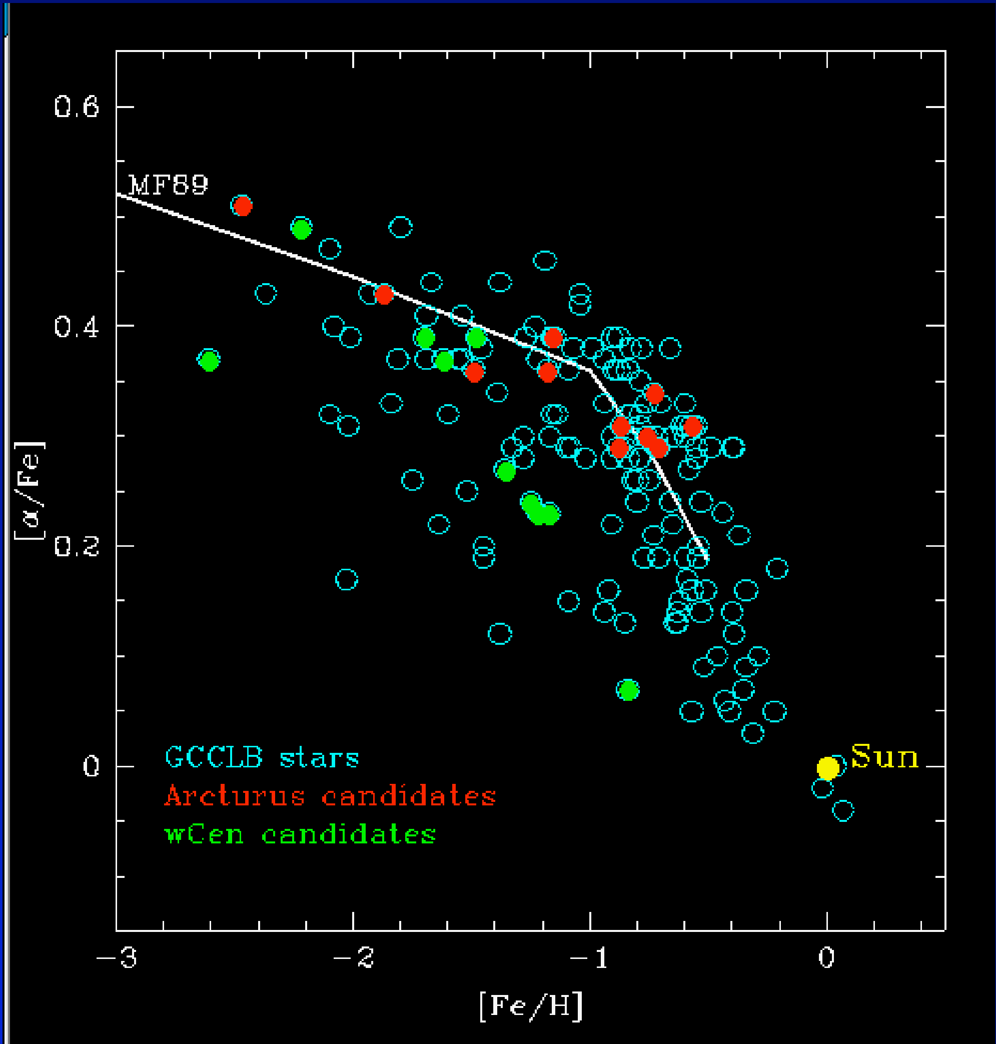
Vertical Velocity

Galactocentric Radial Velocity

- Stars confined to the disk and with similar angular momentum as **ωCen** appear to have an excess of large galactocentric radial velocities.

Meza, Navarro, et al 2004

Chemical abundance of ωCen group candidates



- Stars in the **ωCen** group are fairly metal-poor, and trace a tight relation in the [α/Fe] vs [Fe/H] plane, as expected for a population of stars that self-enriched to a metallicity of about 1/5 solar on a longer timescale than the Arcturus group.

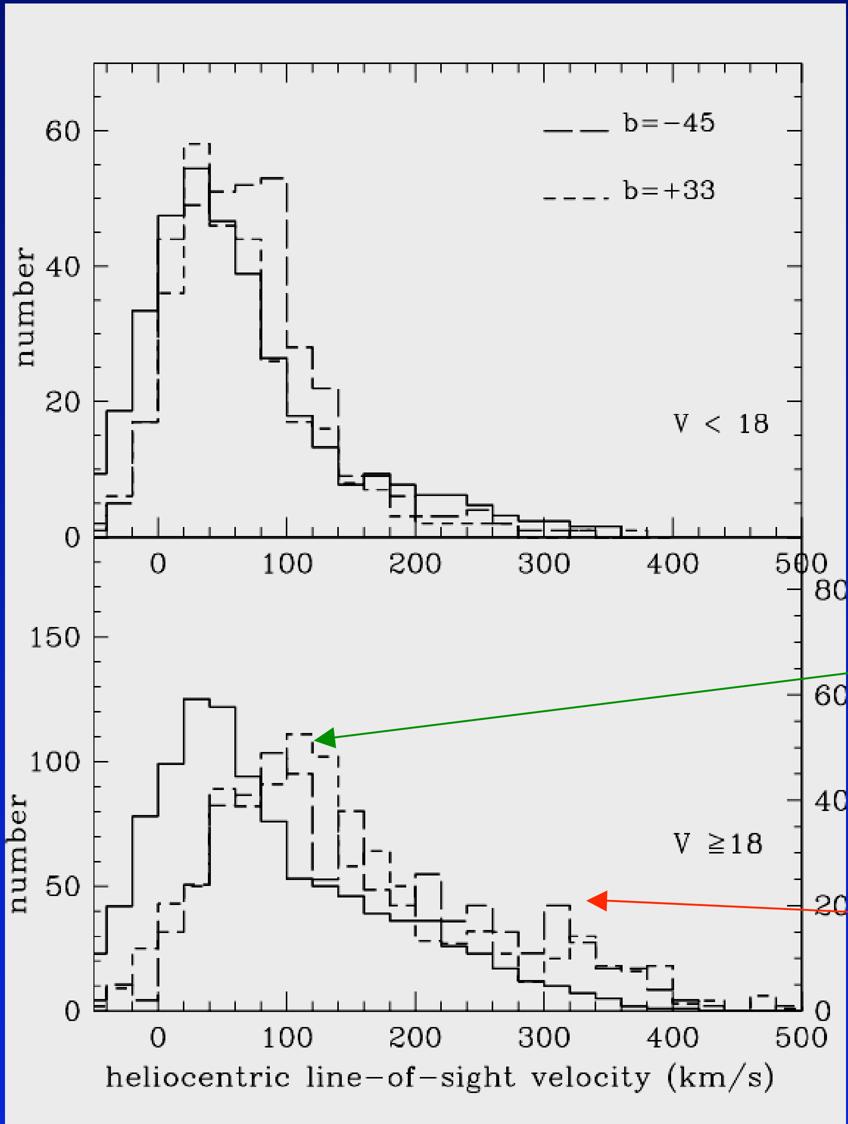
- It may be that *most* metal poor disk stars have been contributed by various accretion events!

Open circles: Gratton et al 2003 sample

Filled circles: stars with J_z comparable to ωCen

Meza, Navarro et al 2004

Further evidence above and below the plane?



Gilmore, Wyse & Norris 2002

- Gilmore, Wyse and Norris (2002) report the presence of a substantial population of stars lagging the LSR rotation by about 100 km/s at ~3 kpc above and below the Galactic plane.

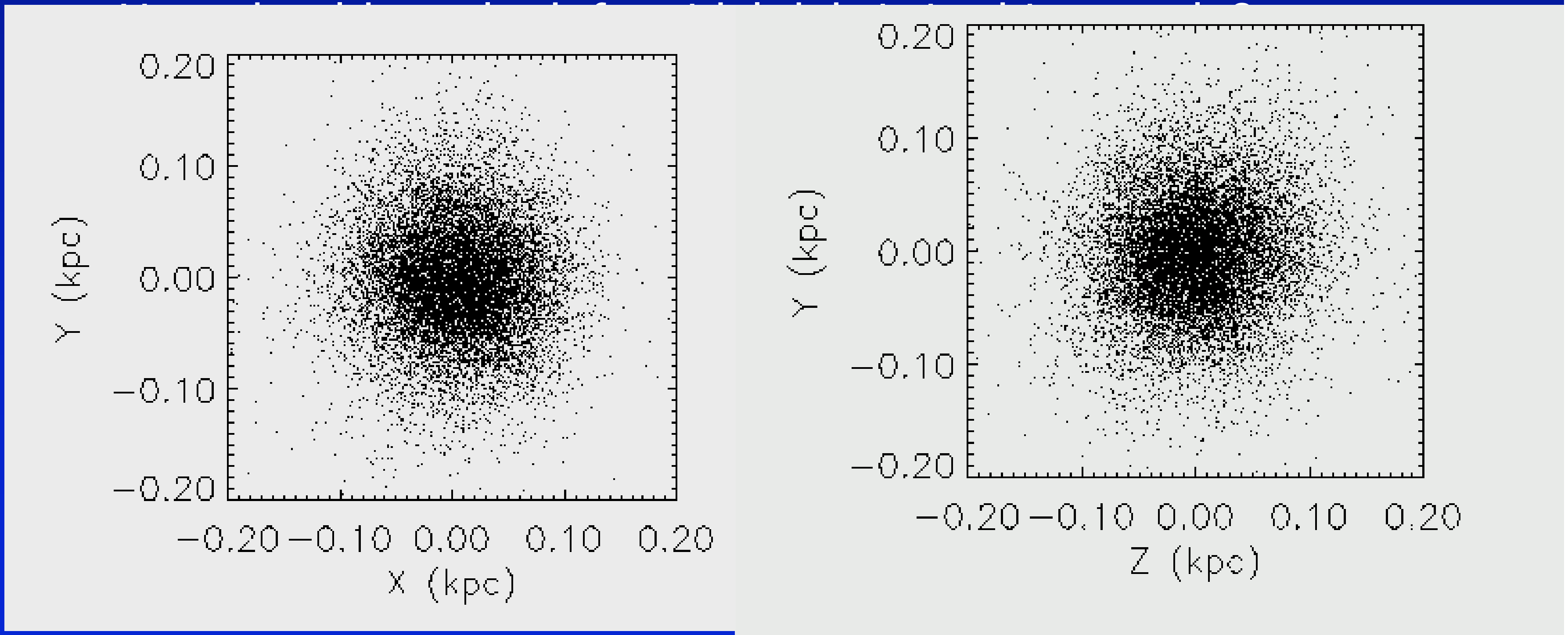
- Arcturus is in all likelihood the solar neighbourhood extension of such population.

- Could this secondary peak be an extension of **ωCen** group?

Navarro, Helmi & Freeman 2004

Substructure in the Solar Neighborhood

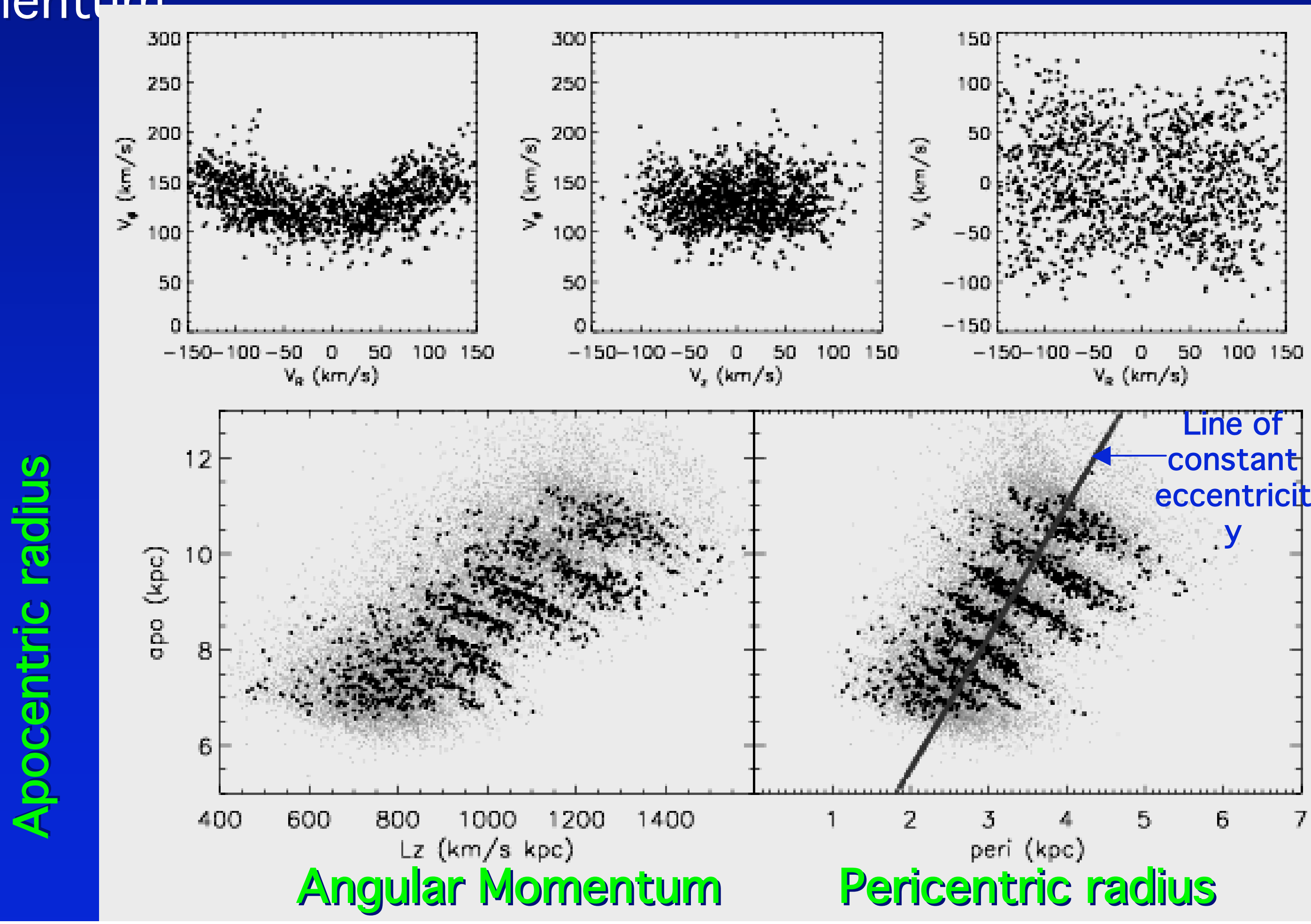
- Nordstrom et al (2004) recently published the results of a survey of ~16,000 nearby (~100 pc) F-G stars with accurate distance and kinematics, as well as estimates of metallicity and ages.
- Their sample is dominated by stars in the Galactic disk.



Helmi et al (2005)

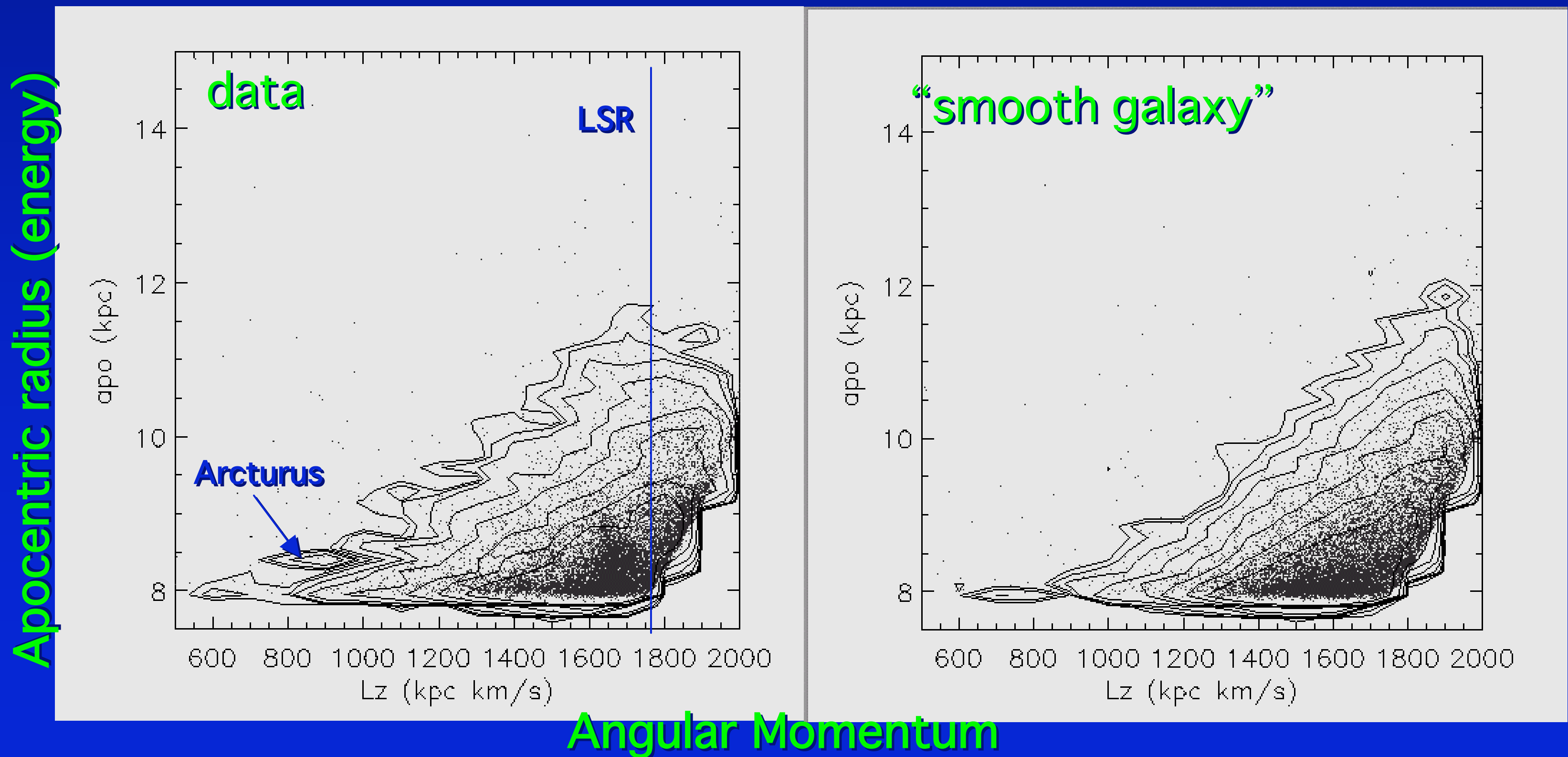
Substructure in the Solar Neighbourhood: the example of Arcturus

Simulations show stars that belonged to Arcturus' progenitor scatter across phase space, albeit preserving tight correlations between nearly conserved quantities, such as apocenter and angular momentum



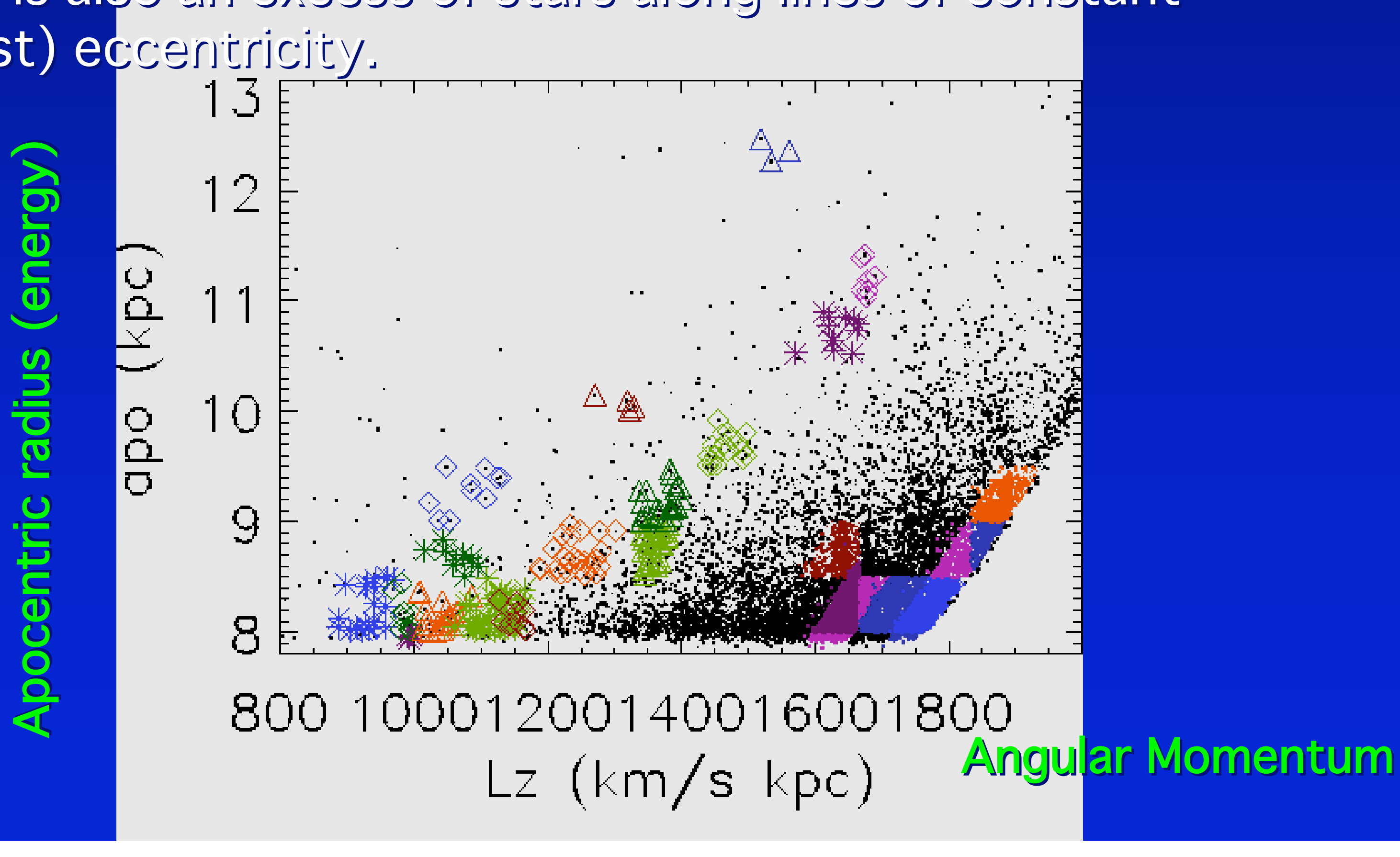
Substructure in the Solar Neighbourhood

The Nordstrom et al (2004) sample, although it is dominated by stars in the Galactic disk, shows clear evidence for the presence of dynamical substructure. Much of this substructure affects stars on nearly-circular orbits.

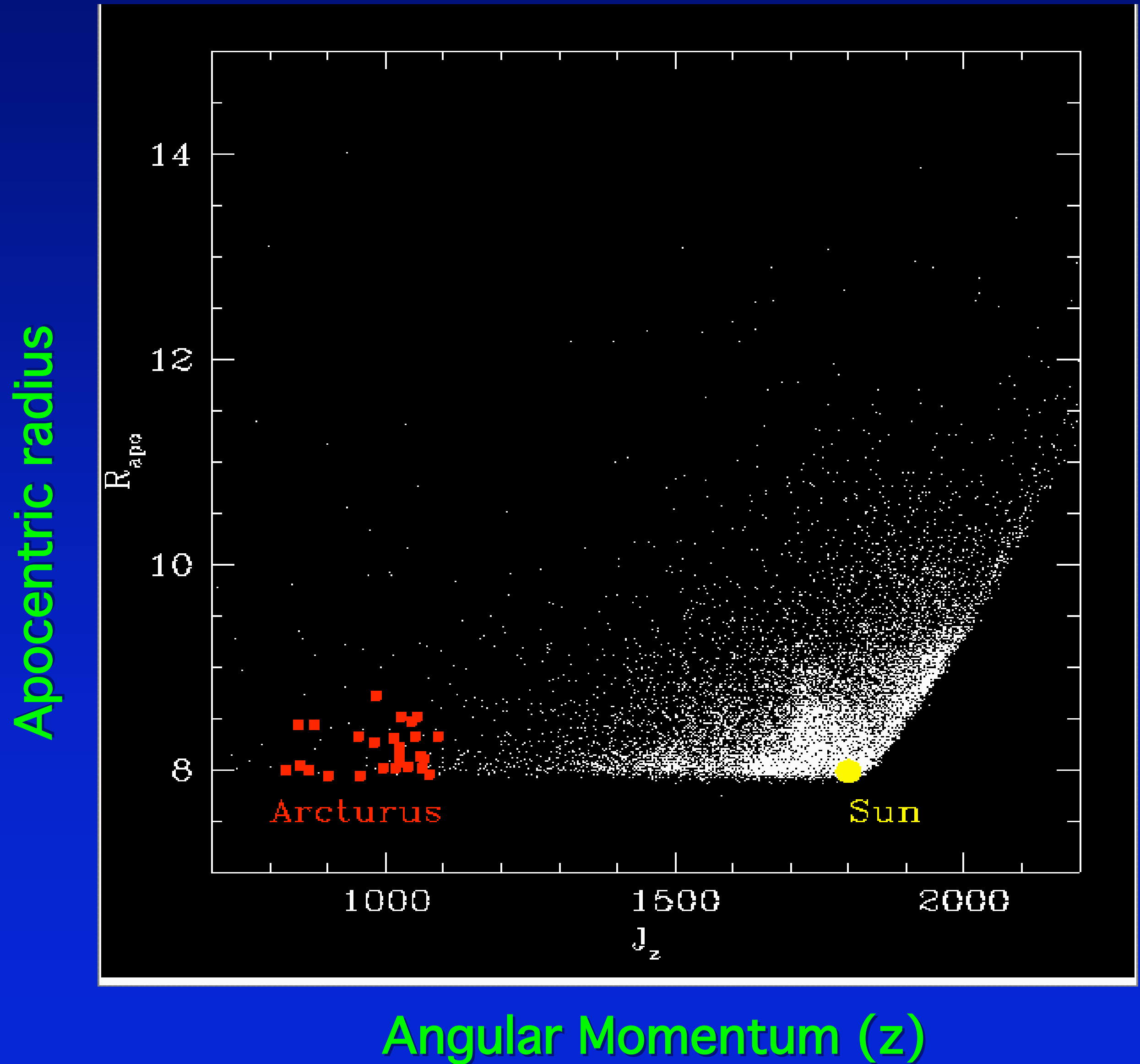


Substructure in the Solar Neighbourhood

- The Nordstrom et al (2004) sample shows clear evidence for the presence of dynamical substructure.
- Much of this substructure affects stars on nearly-circular orbits.
- There is also an excess of stars along lines of constant (modest) eccentricity.

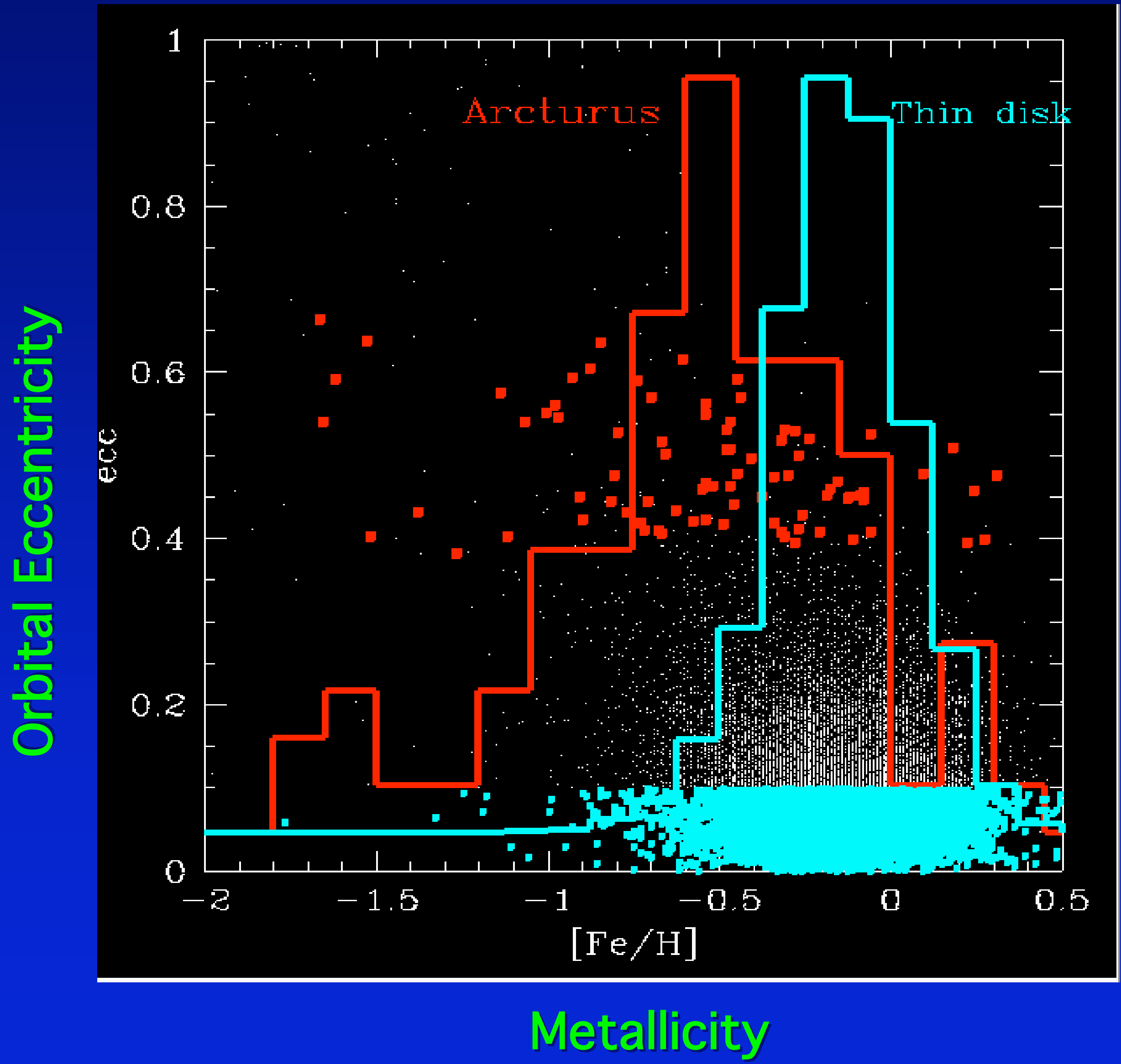


Arcturus' stars in the Solar Neighbourhood



- Stars on orbits similar to Arcturus' have eccentricities in the range 0.4-0.6 and a distinct metallicity distribution which peaks at about ~1/3 solar.

Arcturus' stars in the Solar Neighbourhood



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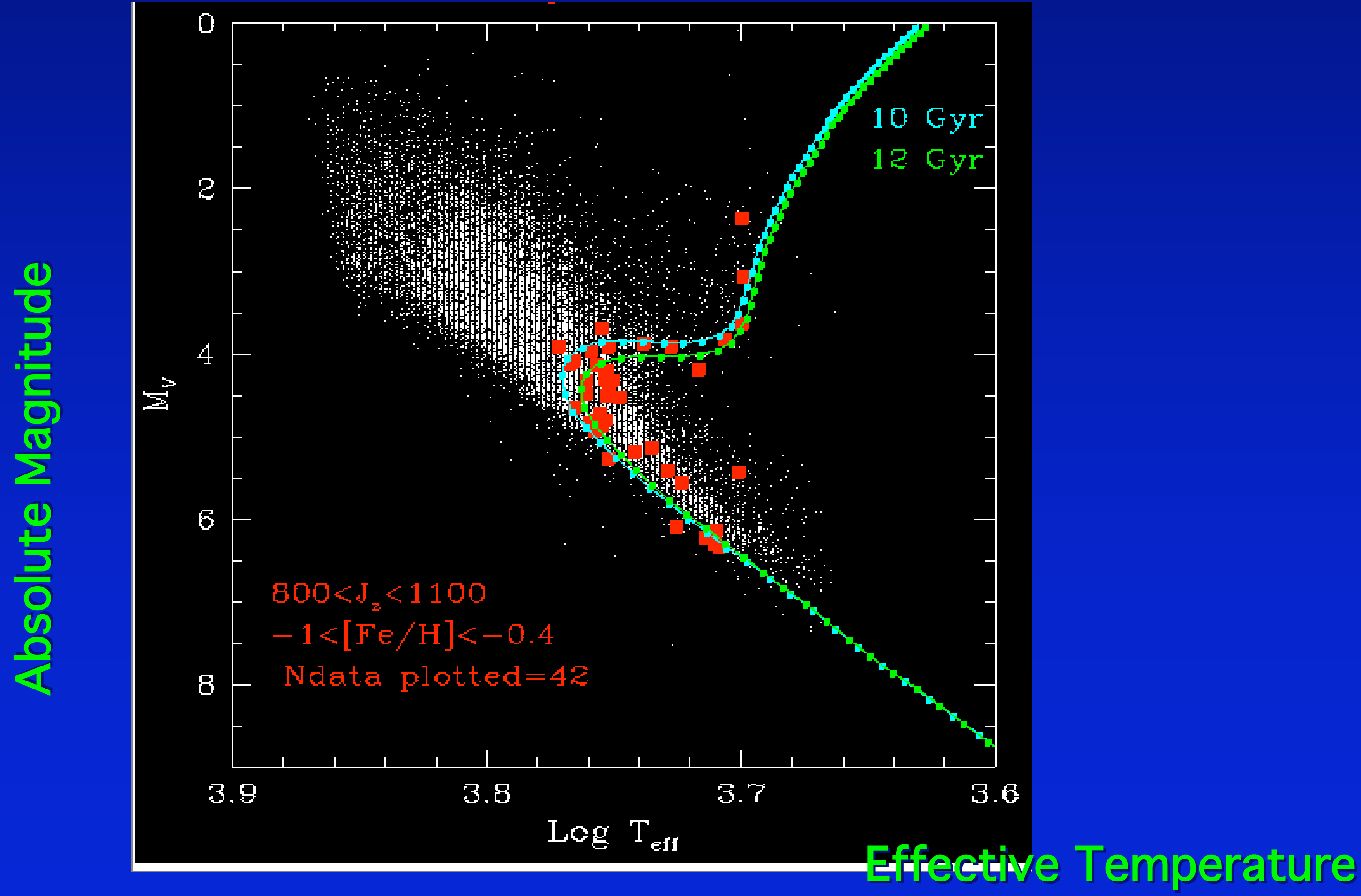
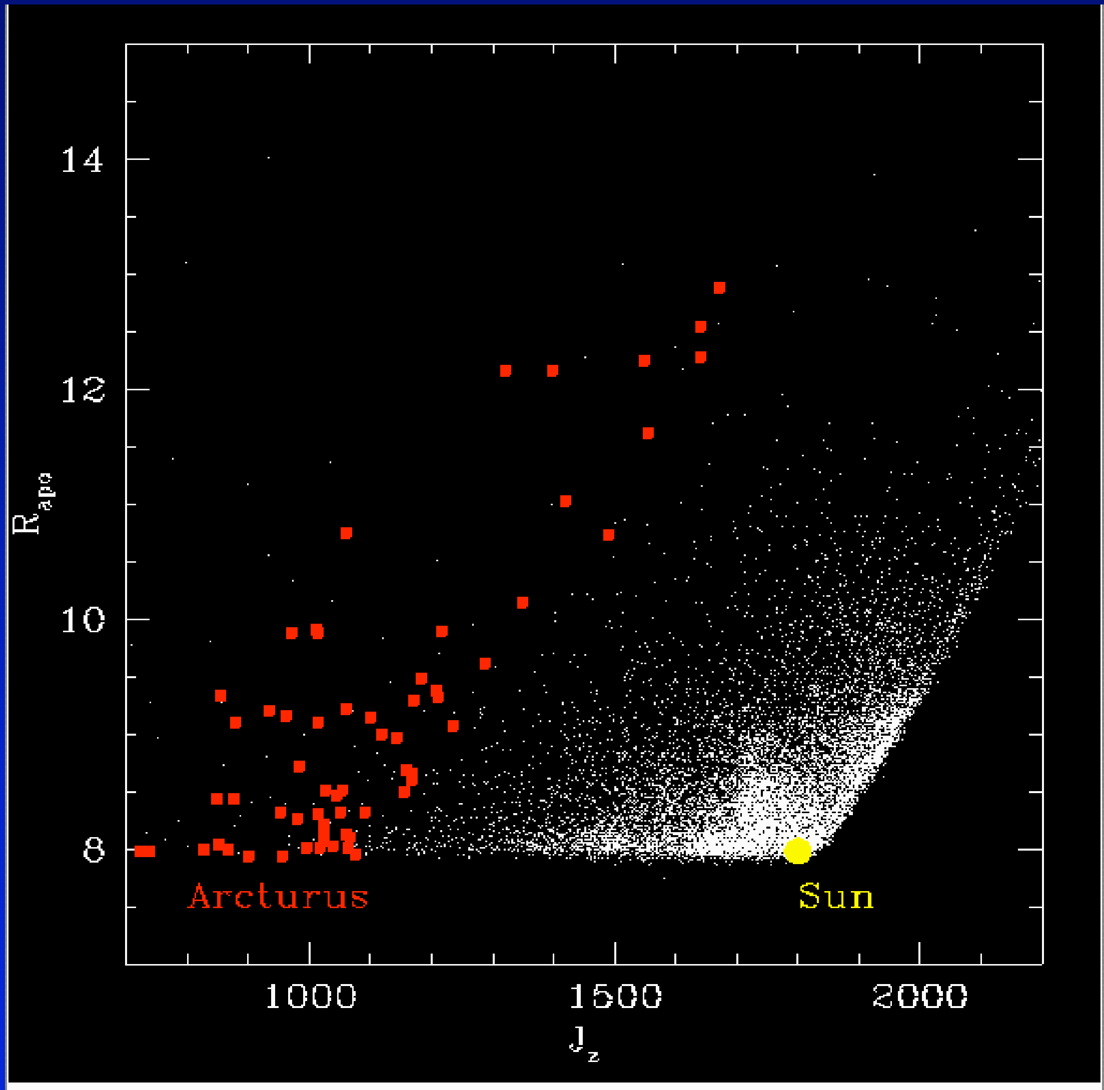
Arcturus' stars in the Solar Neighbourhood

Stars similar in metallicity and orbital parameters to Arcturus form a coherent group in a colour-magnitude diagram suggestive of a narrow range of ages and a common origin.



Arcturus' stars in the Solar Neighbourhood

Apocentric radius



Angular Momentum (z)

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Arcturus' stars in the Solar Neighbourhood

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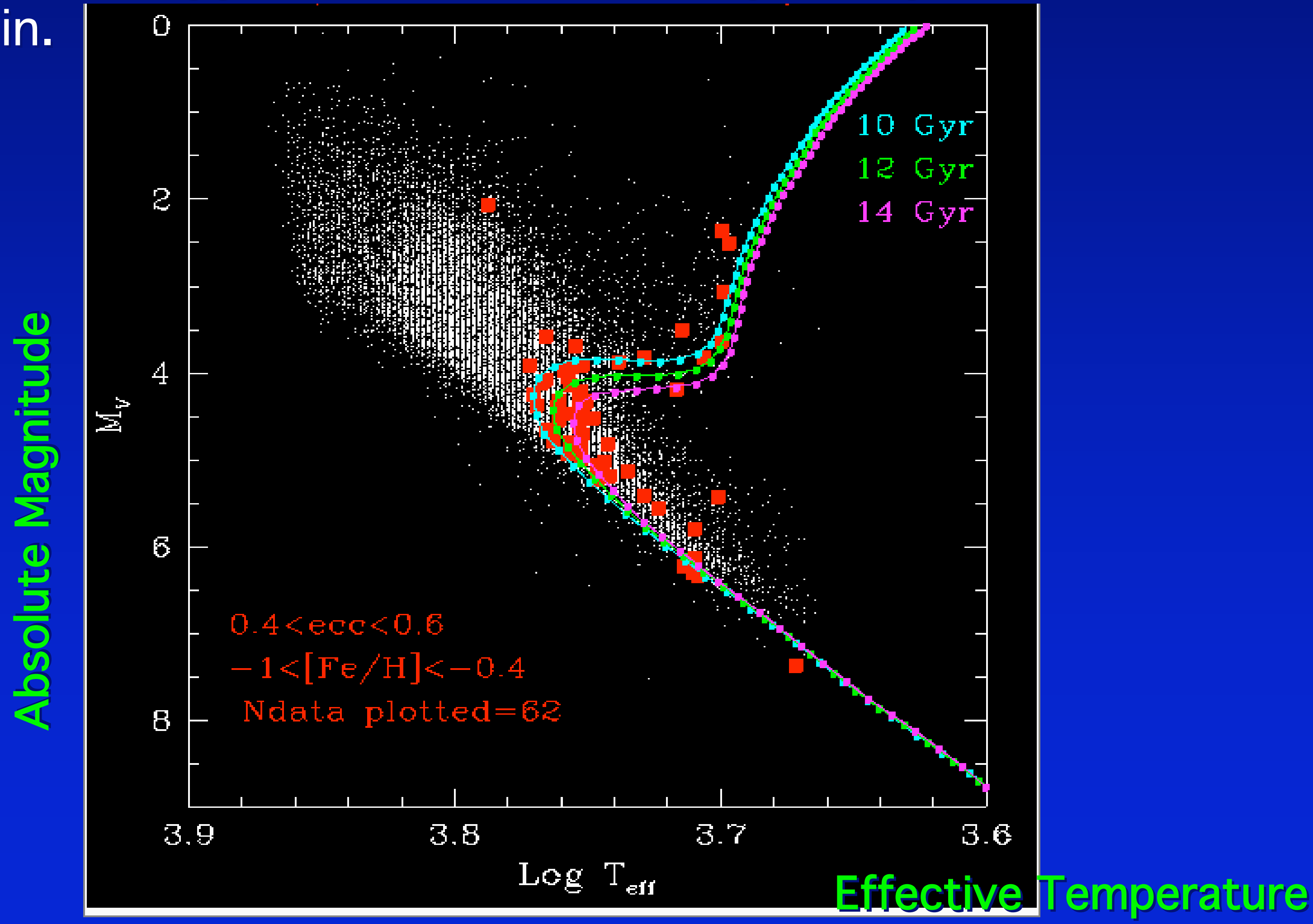
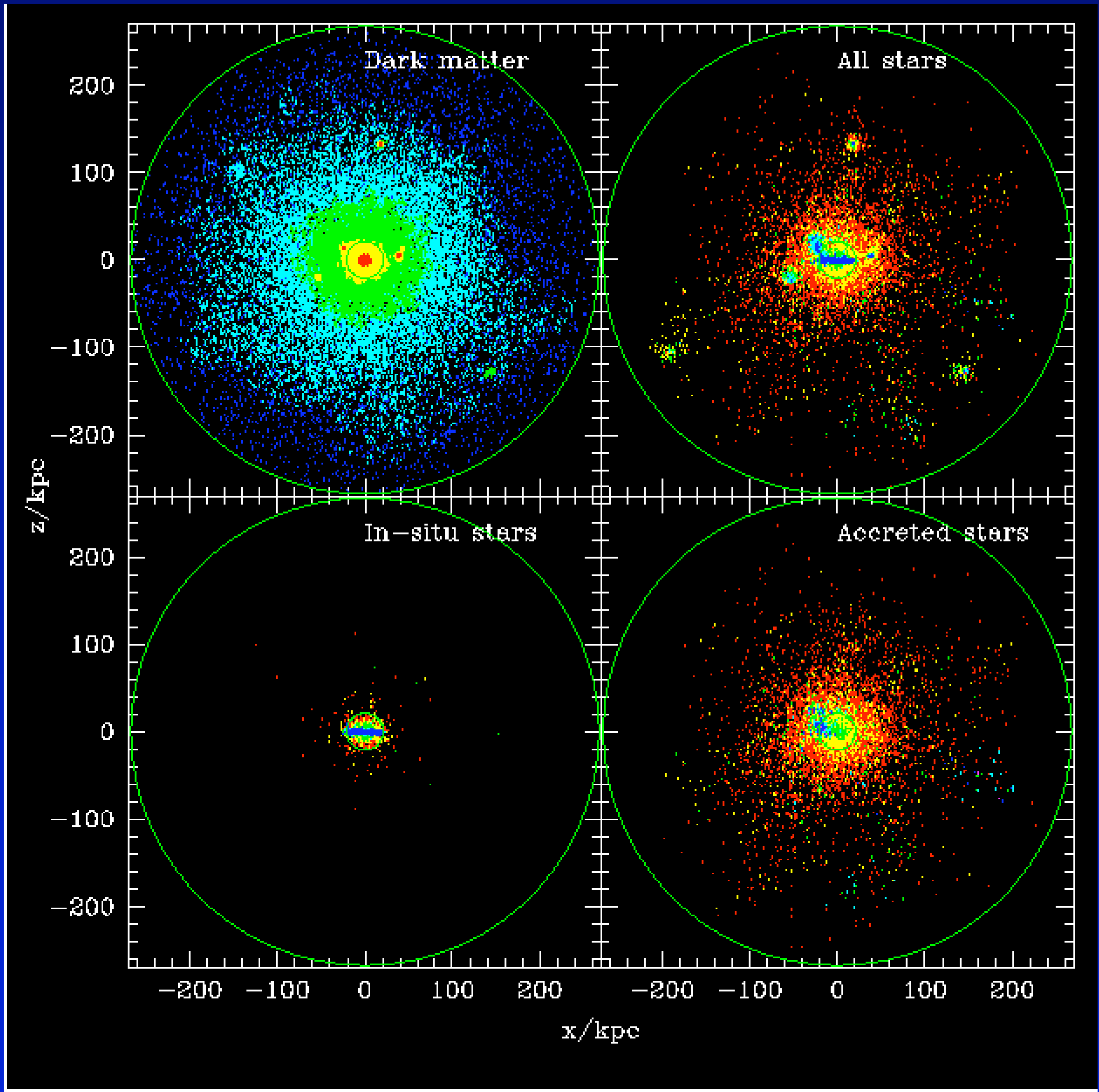


Stars Beyond Galaxies: Luminous Halos Around Galaxies

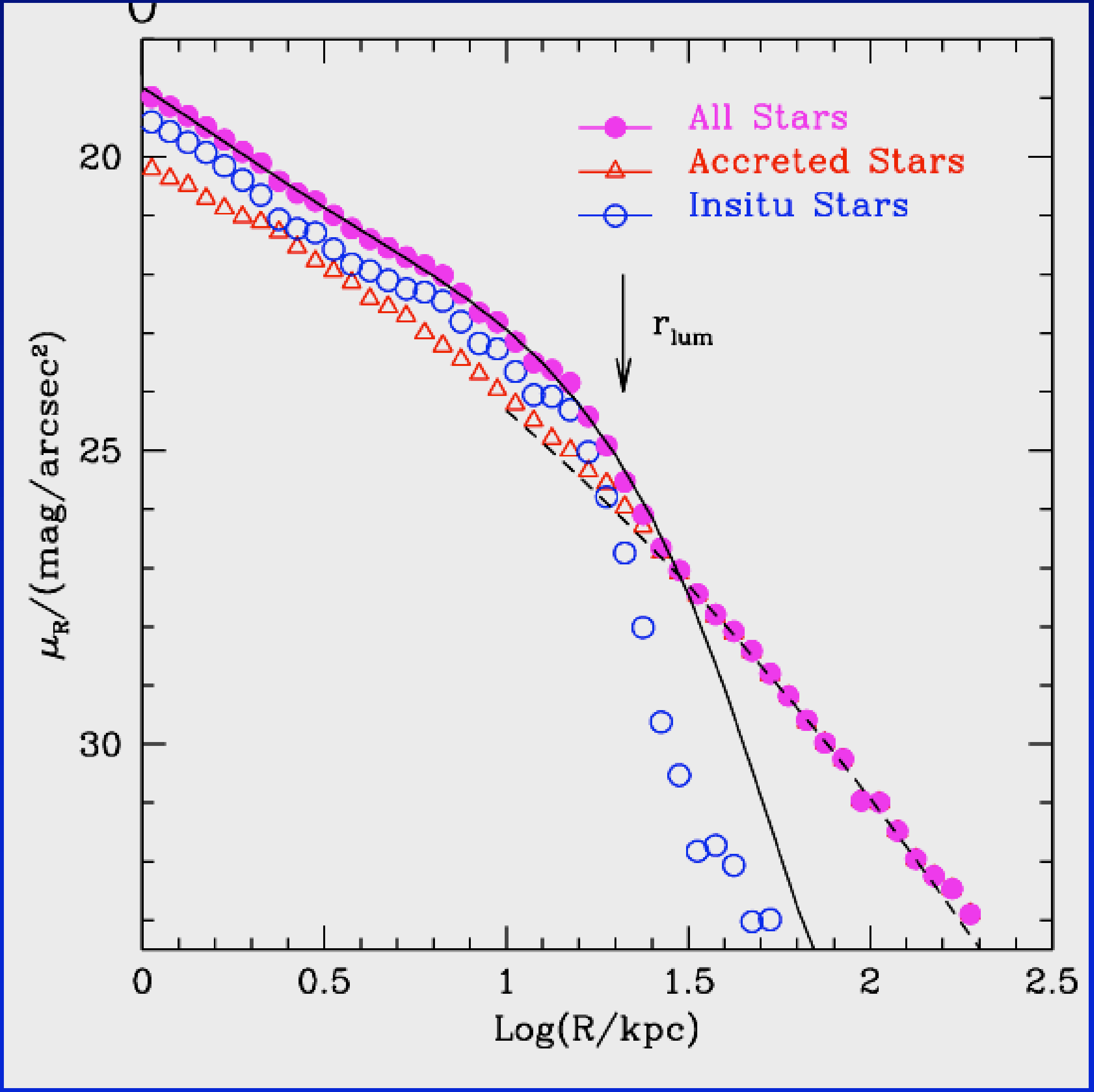


Essentially all stars beyond the traditional luminous radius of a galaxy (and not in satellites) originate in past accretion events

The outer luminous halo of a galaxy holds important clues to the merging history of a galaxy

Abadi, Navarro & Steinmetz 2005

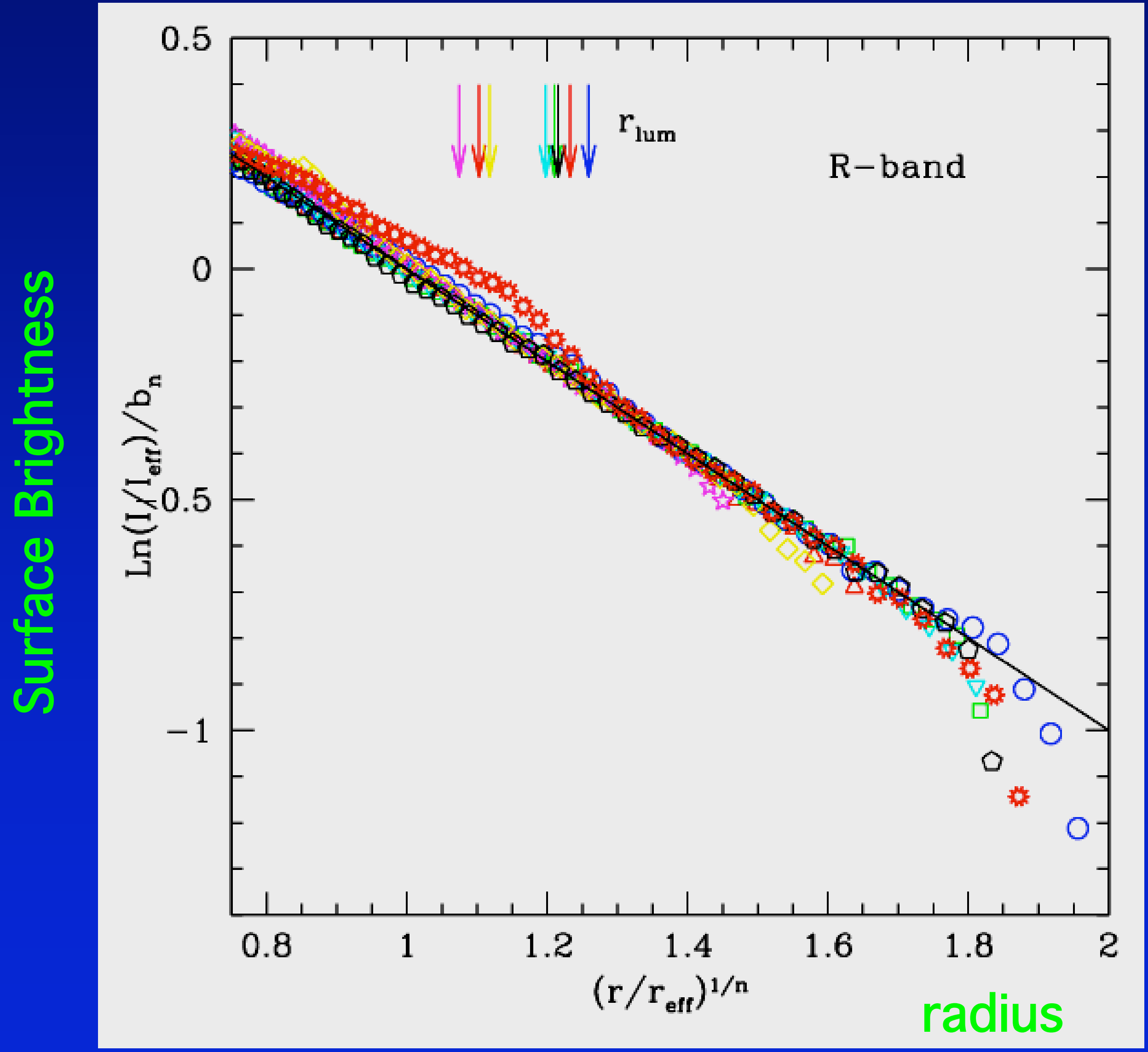
The Outer Surface Brightness Profile of Galaxies



- Outer halos appear as an "excess" of light over extrapolations of the inner surface brightness profile of a galaxy.
- The outer halo is well approximated by a Sersic law
- The same law describes very well the profile of all accreted stars

Abadi, Navarro & Steinmetz 2005

The Surface Brightness Profile of Accreted Stars



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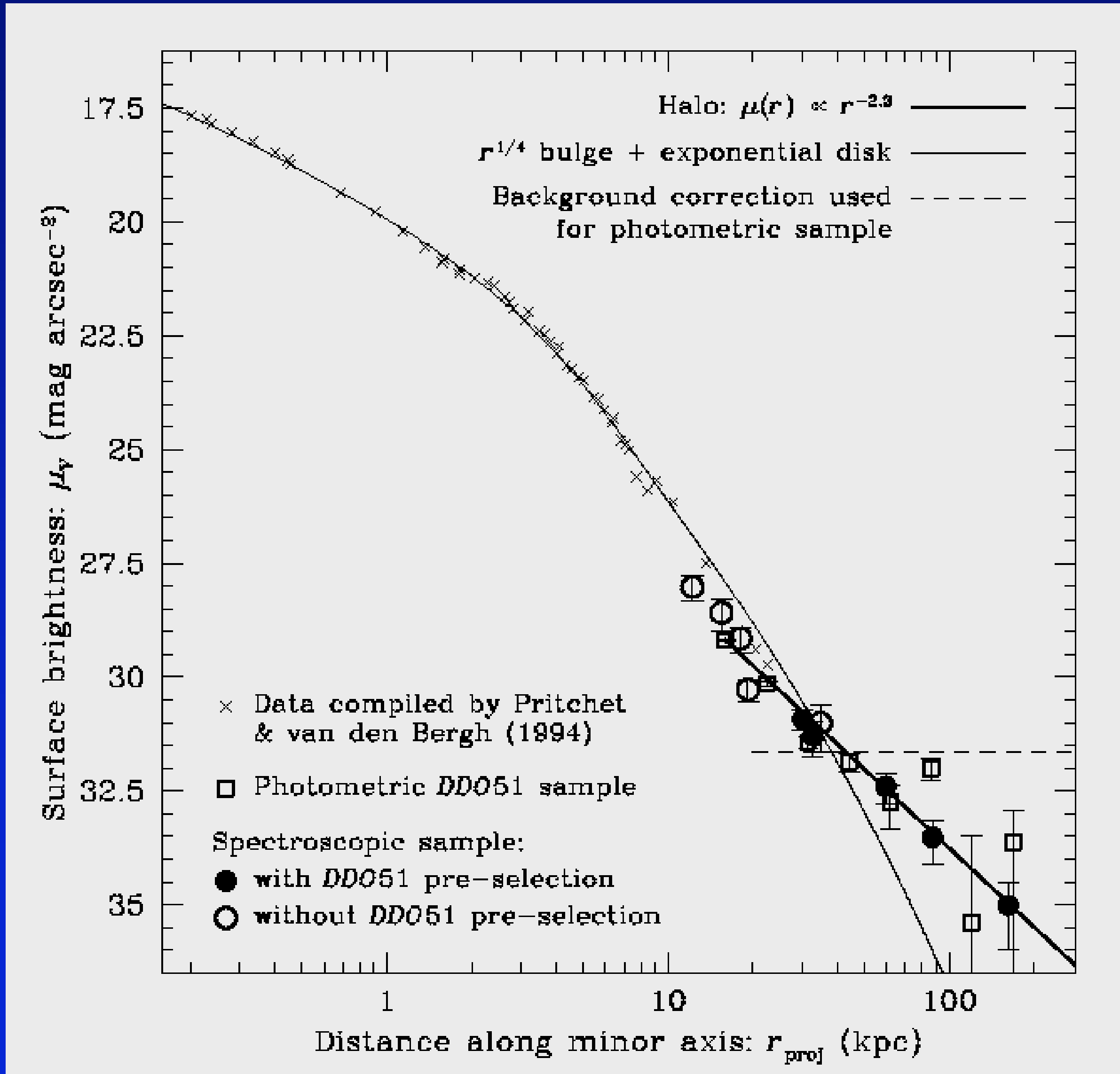
Abadi, Navarro & Steinmetz 2005

The Outer Surface Brightness Profile of M31

Surface Brightness

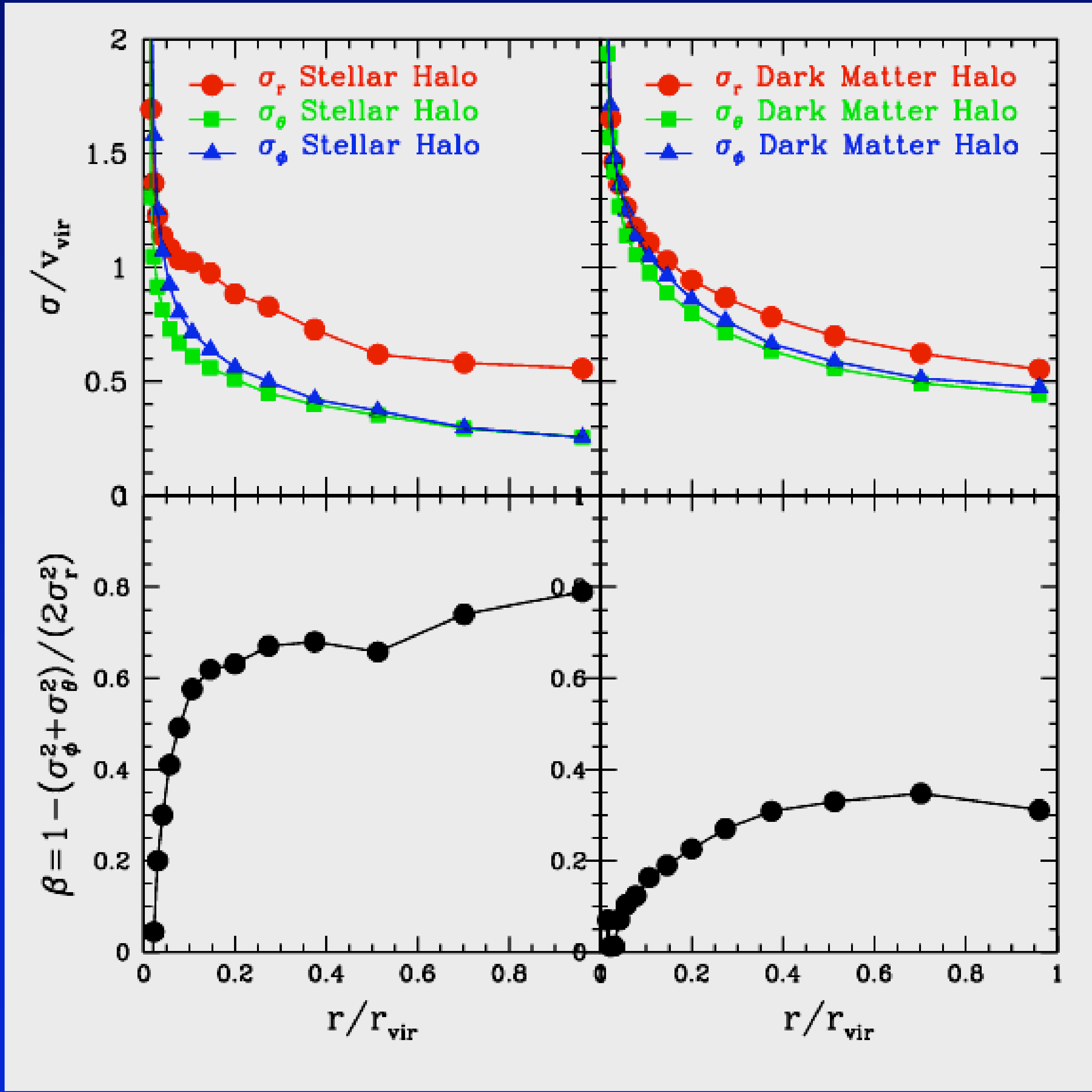


Such outer halos have been detected around isolated spirals (edge-on, see Zibetti et al 2004) and M31 (see also Irwin et al 2005)

•The outer spheroid may be used to estimate the total number of accreted stars in a galaxy!

Guhatakurta et al 2005

The Dynamics of Luminous Halos



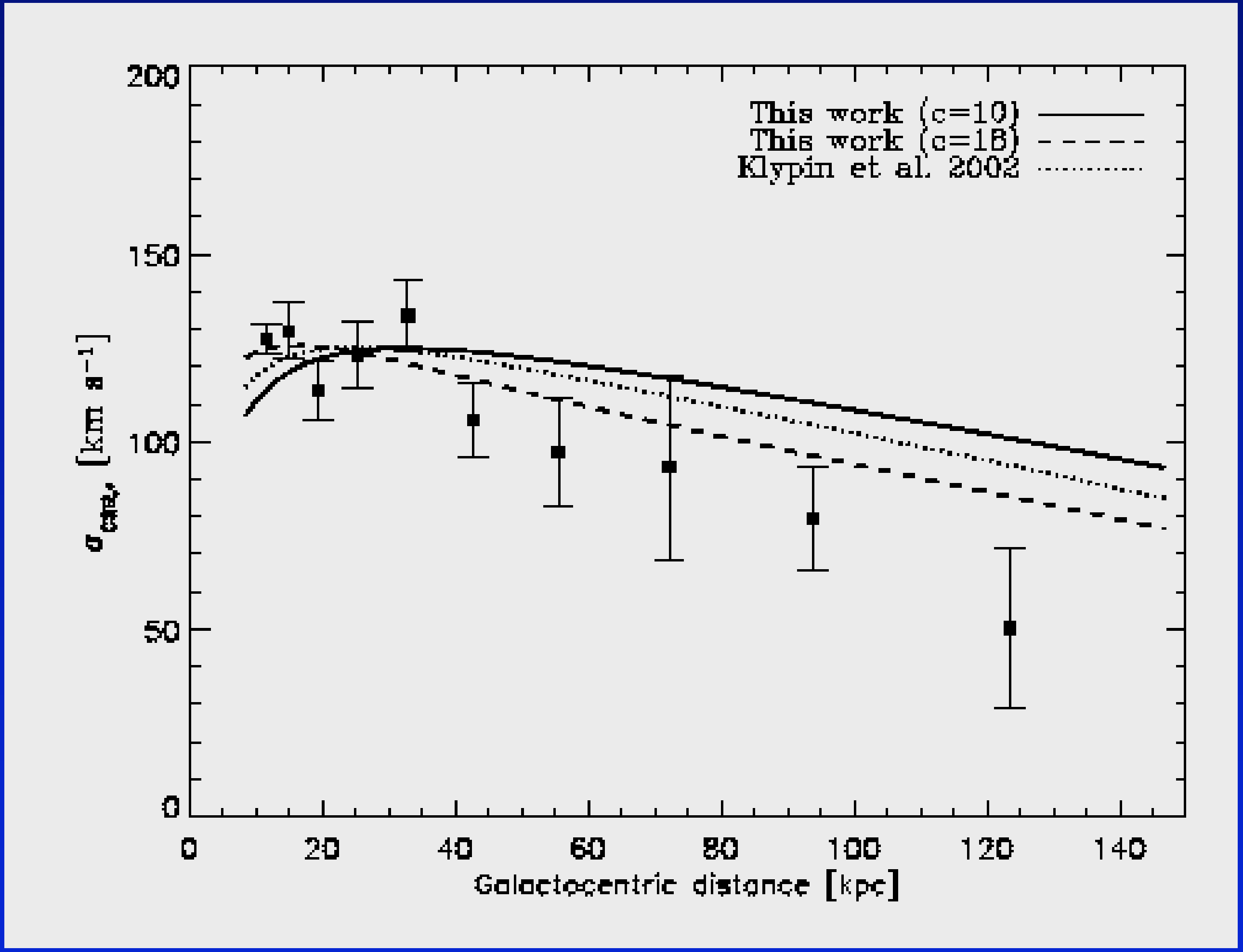
•The velocity dispersion tensor of stars in the outer halo is remarkably anisotropic:

$\sigma_r^2 \sim 4\, \sigma_t^2$

•This, combined with the progressive steepening of the outer density profile, explains why traditional modeling of the outer halo of the Milky Way favors truncated dark matter halos (see Battaglia et al 2005)

Abadi, Navarro & Steinmetz 2005

The Dynamics of the Milky Way's Luminous Halo



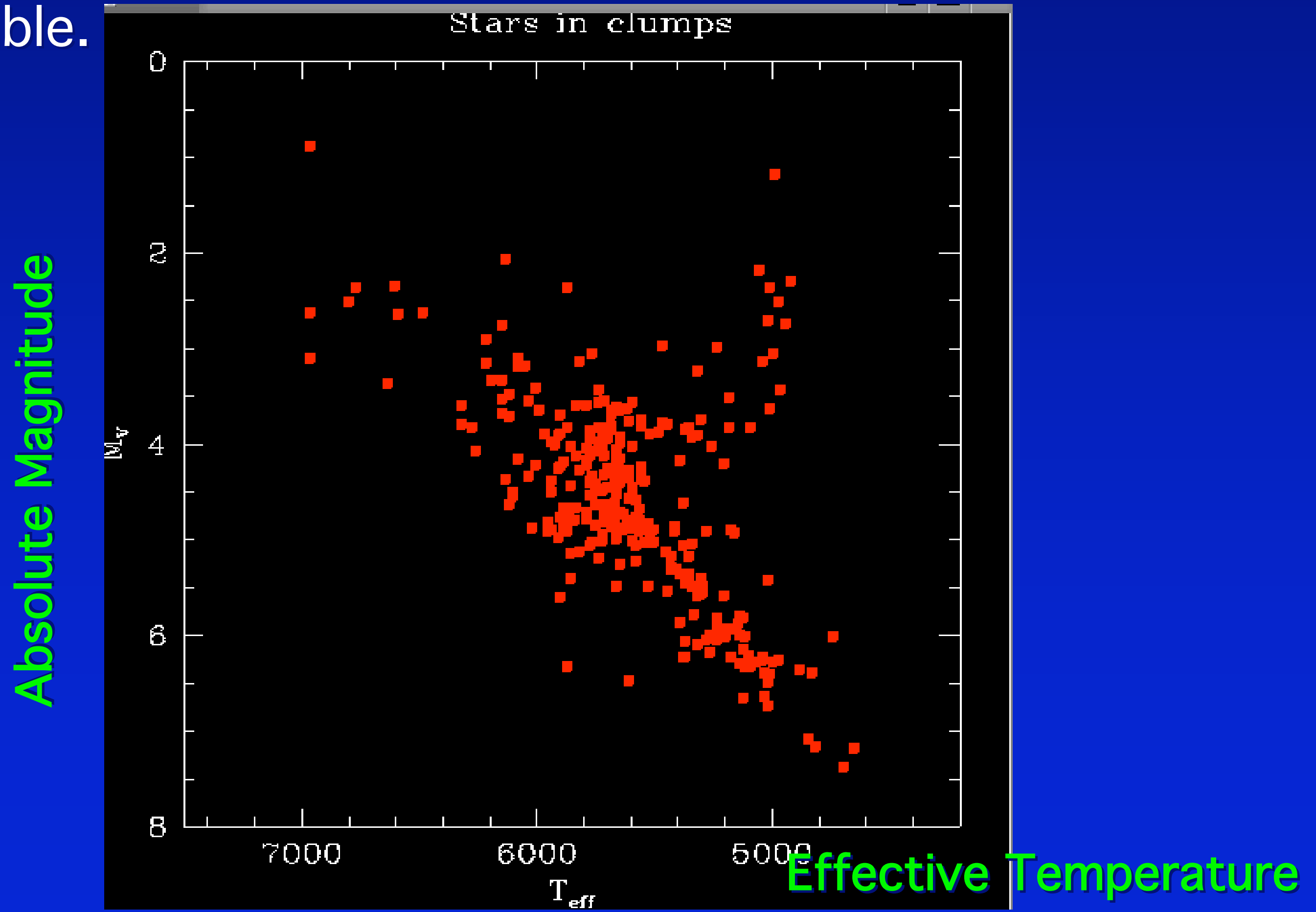
The velocity anisotropy, combined with the progressive steepening of the outer density profile explains why traditional modeling of the outer halo of the Milky Way favors truncated dark matter halos

Battaglia et al 2005

Substructure in the Solar Neighbourhood

Indeed, stars in these clumps split naturally into groups of stars of distinct age and metallicity.

The Arcturus group ([Fe/H]~-0.5) has an age of ~8-10 Gyr, but several others (of various age and metallicity) are clearly discernible.

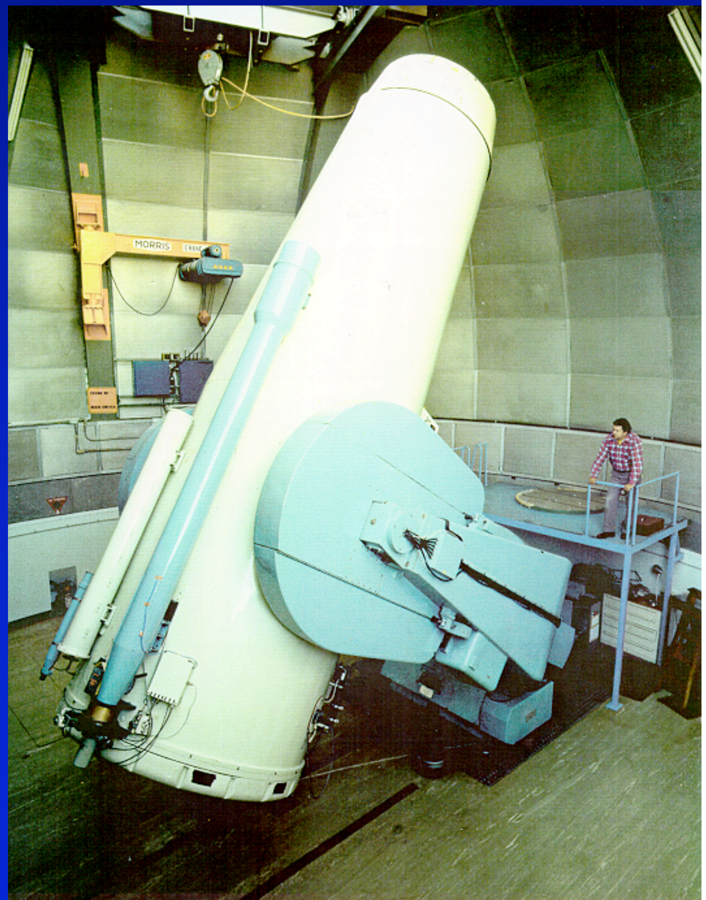


A RAVE to Unravel the Formation of the Milky Way

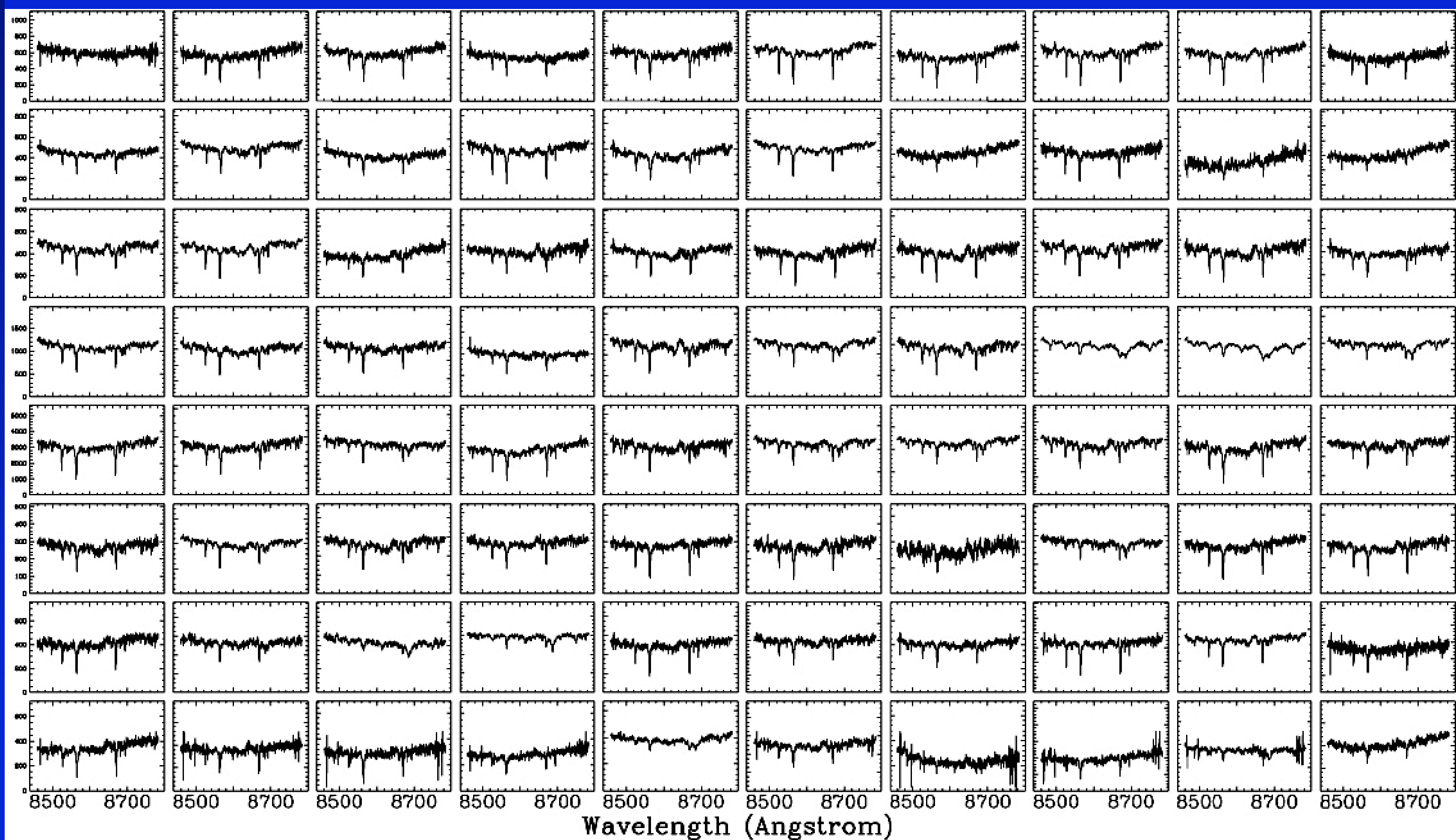
RAVE
RADIAL VELOCITY EXPERIMENT

Pilot Project

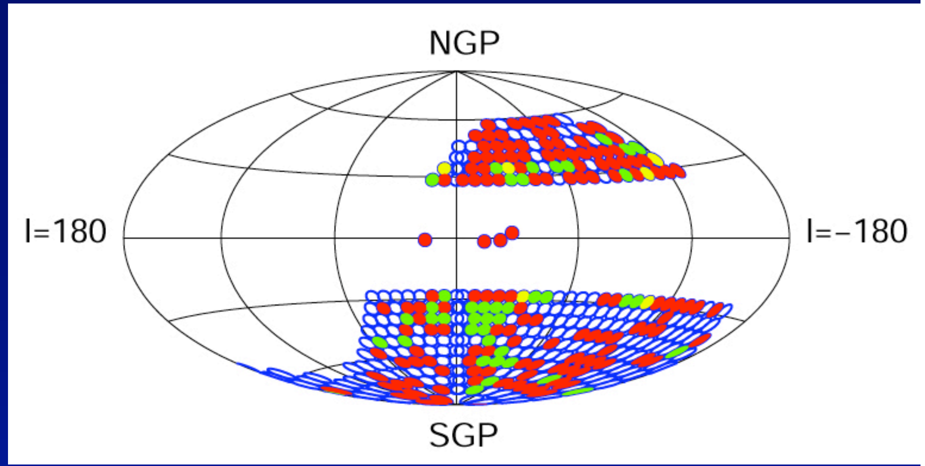
- up to 279 nights of unscheduled bright-time at the 6dF (UK Schmidt) in 2003-2005
- 100 000 targeted stars $9<I<12$, on the southern hemisphere
- no color selection
- ~120 fibres per field, 7” diameter
- Ca-triplet at 8400-8750Å at R=7000
- RVs to 2 km/s



Typical Spectra



Current Status



- Phase I started on April 11th 2003 @ 7 nights/lunation
  - >50000 spectra collected (as of March 05)
  - expected: 70000 spectra by mid 2005
- Data analysis
  - RV pipeline finished
  - metallicity pipeline in progress
  - data verification in progress
- Data distribution
  - data base, VO interfaces in progress
  - internal data release v0.3 out
  - first public data release envisioned for mid 2005
  - critical path: sky subtraction/wavelength calibration

The End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"Great PowerPoint, Kevin, but the answer is no."