Future Outlook

Galaxy Structure

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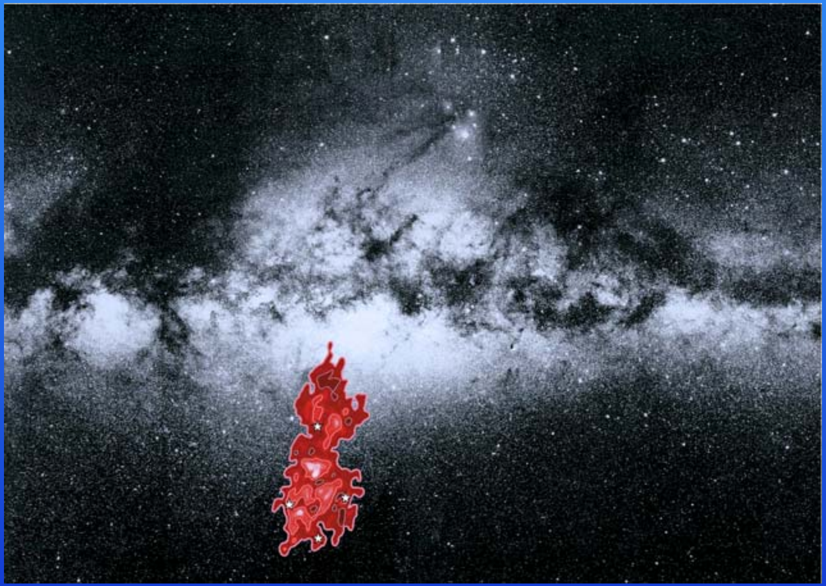
The Milky Way as a Template

- Recent developments, promise for the future
- Overall profile and shape
  - Stellar/baryonic
  - Mass
- Substructure
  - Stellar
  - Mass
- Distinct satellites
  - Mass profiles
  - Evolution



Sgr dSph as known in 1996 (RW, Gilmore & Franx 97; Ibata, RW et al 96; Ibata, Gilmore & Irwin 1994)

- Exciting times to be studying resolved stellar populations:
  - Large, high-resolution simulations of structure formation are allowing predictions of Galaxy formation in a cosmological context
  - Large observational surveys of stars in Local Group galaxies are now possible using wide-field imagers and multi-object spectroscopy, with new facilities promising much more
  - High-redshift surveys are now quantifying the stellar populations and morphologies of galaxies at high look-back times
  - Aided by gravitational lensing!

The Local Group

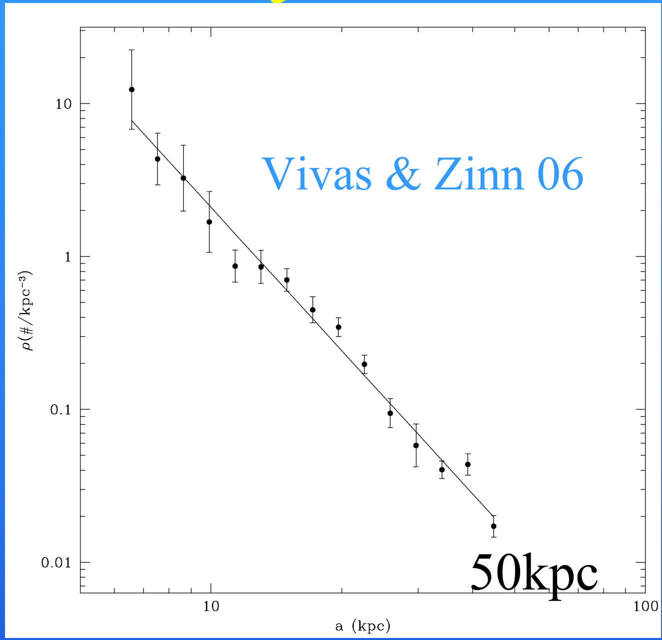
- Most low-redshift galaxies are in loose groups like the Local Group
- The colours, motions, spatial distributions, ages and chemical elemental compositions can be measured (with varying accuracies!) for individual stars in galaxies throughout the Local Group (plus gas, plus Pne etc)
- The Milky Way, M31, M33, gas-rich and gas-poor satellites
- Analyse to test models e.g. ΛCDM

Clues from Resolved Stellar Populations

- Star formation history
- Chemical evolution: flows
- Merging history: Match models? ΛCDM?
- Dissipative gas physics vs dissipationless
- Stellar Initial mass function – both now and a long time ago
- Potential well : dark matter
- Is the Milky Way typical?
- Is the Local Group typical?

The Galaxy: Overall Density Profile

- Stellar halo: RR Lyrae stars $\rho \propto a^{-3}$, oblate, variable flattening c/a ~ 0.6 locally, ~1 at R_{gal} ~20kpc
  - Triaxial? Hints from SDSS imaging (Newberg 06)



- Thick disk: exponential scale height ~ 1kpc, scale length ~3kpc; ~10% locally
- Thin disk: exponential scale height ~300pc, scale length ~3kpc
- Central triaxial bulge/bar, scaleheight ~300pc

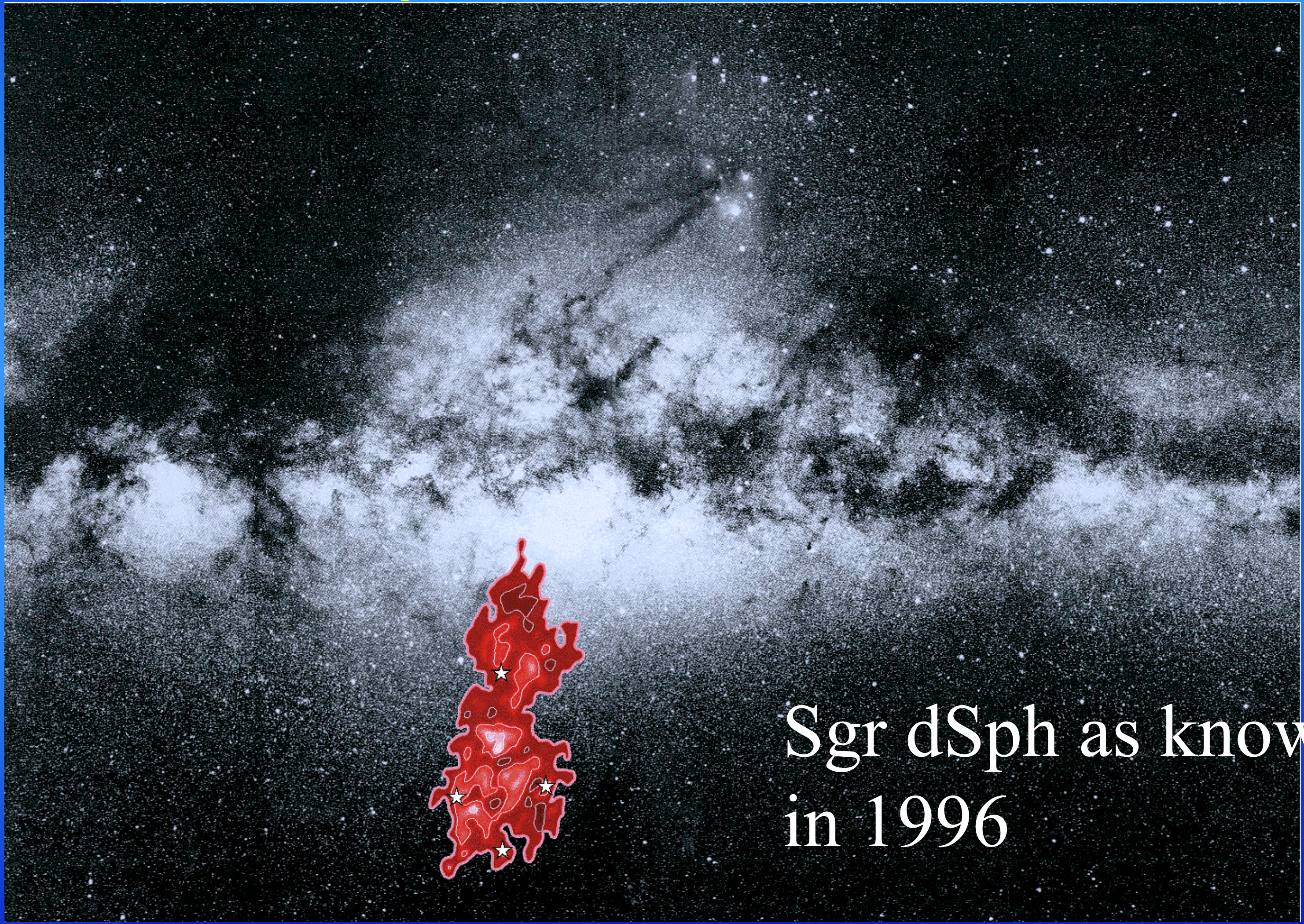
The Galaxy: Overall Density Profile

- Mass profile less well-determined
  - Baryon-dominated in inner Galaxy (microlensing, COBE bar + kinematics; Bissantz & Gerhard 2002)
  - Dark-matter-dominated in outer galaxy
  - Total mass ~ $10^{12}\ \mathcal{M}_\odot$ -- NFW profile?
  - Local escape velocity ~ 550^{-50}_{+100} km/s from high-velocity stars (e.g. Smith et al 06)
- Need larger samples of both distant and high velocity tracers

Substructure: Outer Stellar Halo:

- The outer halo, with dynamical timescales of > 1Gyr, is best place to find structure. Several streams found, in both coordinate space and kinematics
- Many due to the Sagittarius Dwarf e.g. Ibata et al 2001; Majewski et al 2003; Belokurov et al 2006
- Very fast-moving field! Several (~ 10) candidate new dSph, globulars and streams announced this year, in SDSS imaging data
- Mass function crucial, e.g. for 'satellite problem' : spectroscopic follow-up -underway

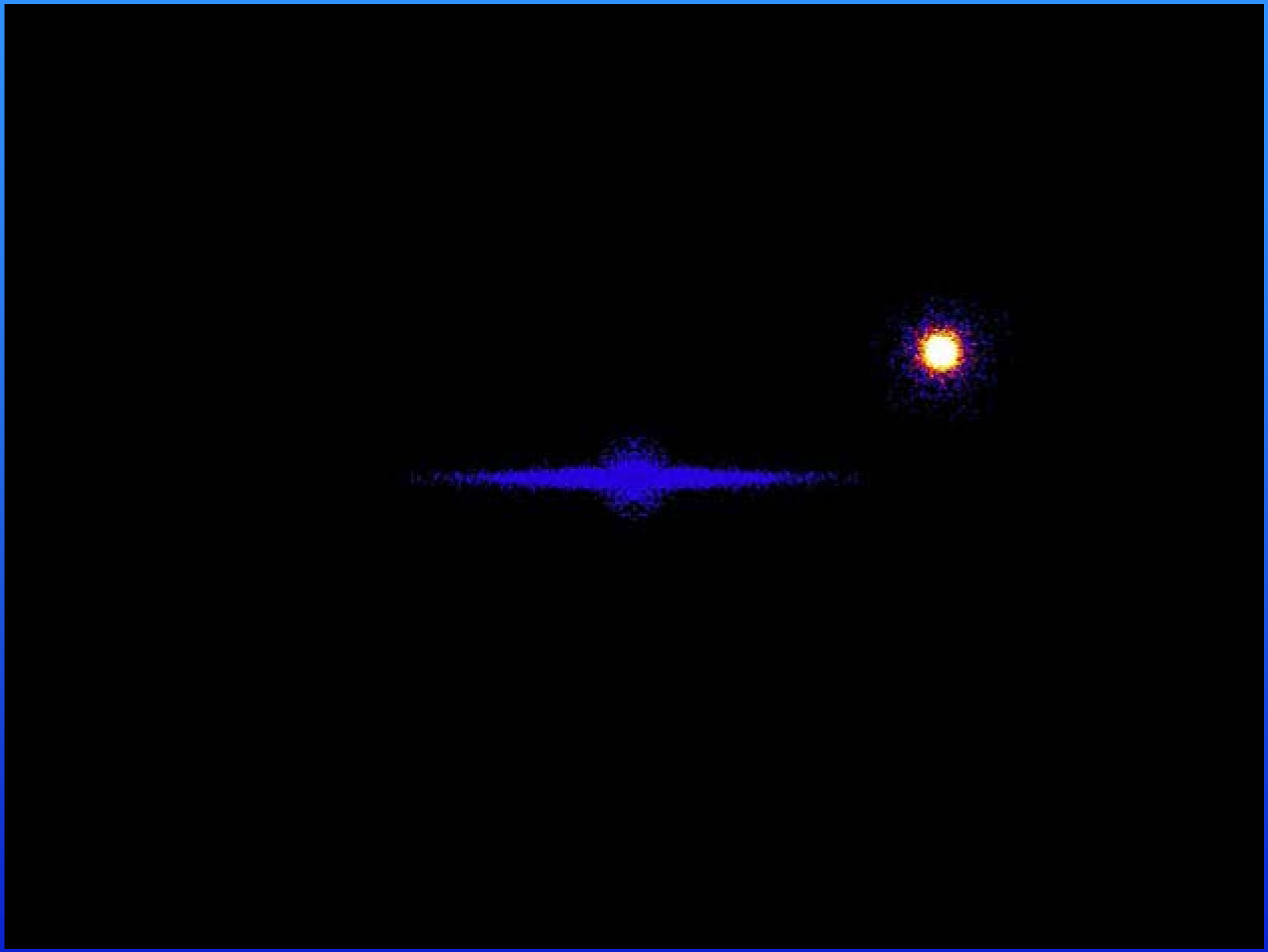
Substructure and accretion: outer Galaxy



Sgr dSph as known in 1996

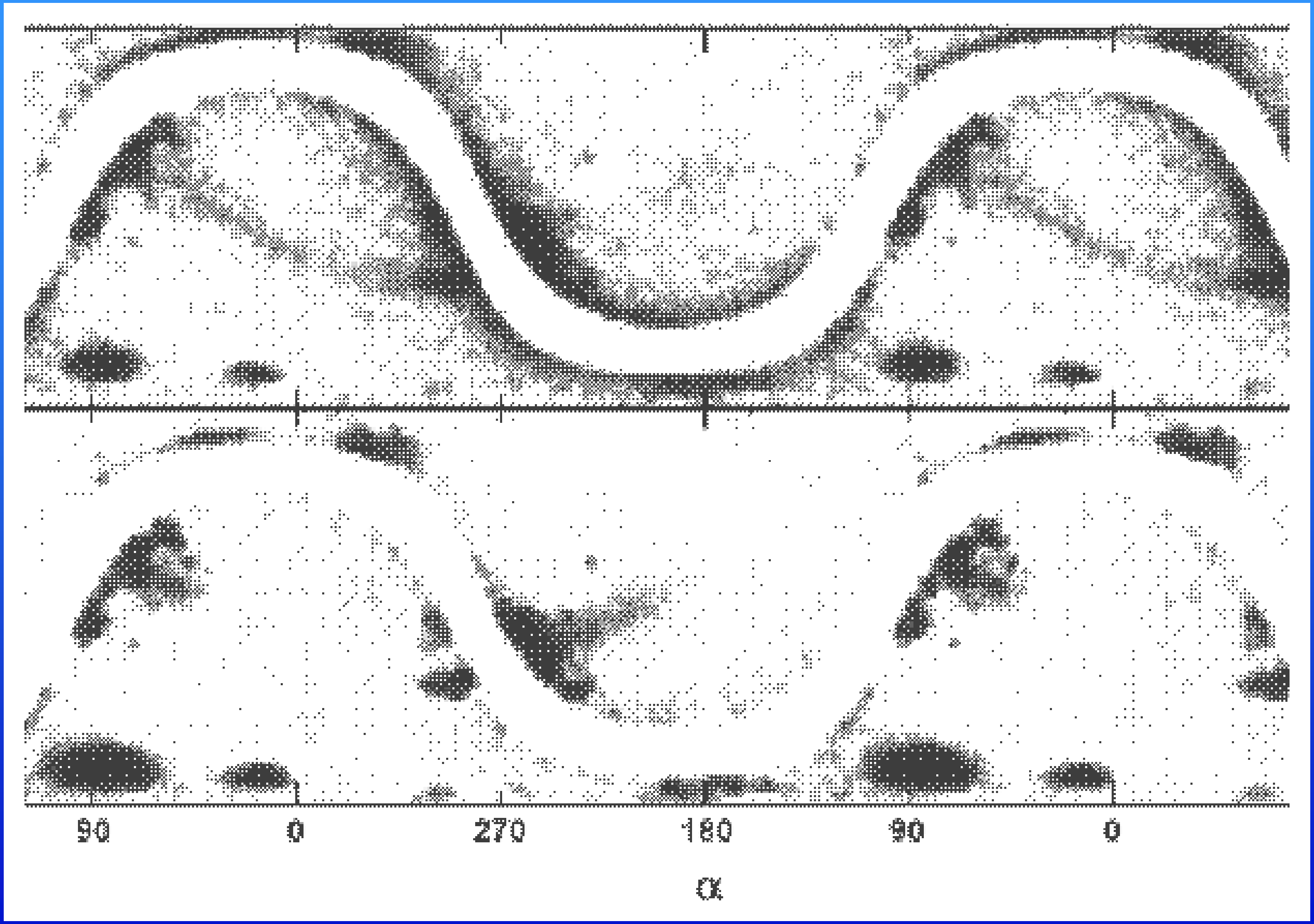
Wyse, Gilmore & Franx 1997; Ibata et al 1994; 1996

Tides: Satellite Snacks

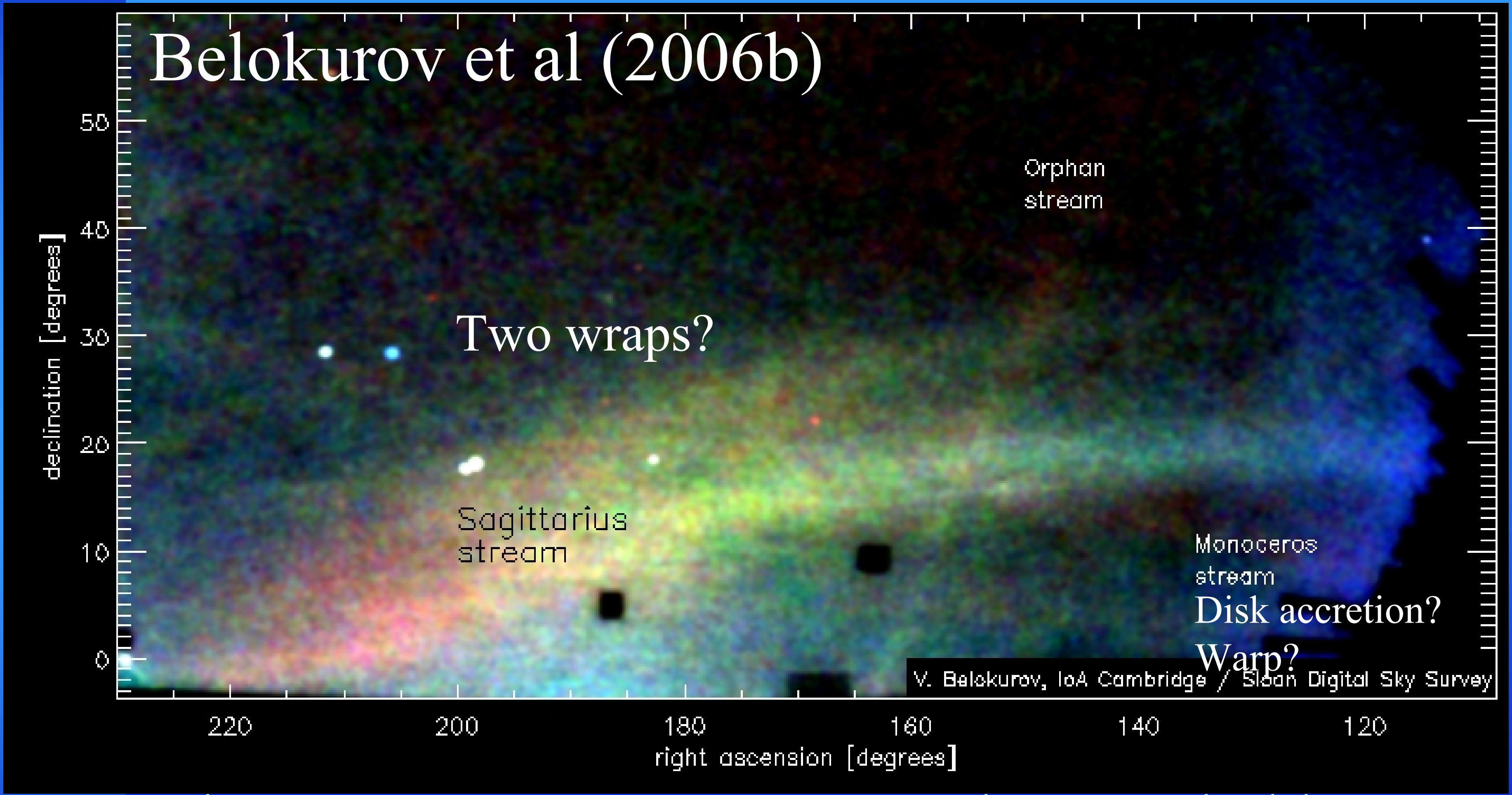


K.V. Johnston

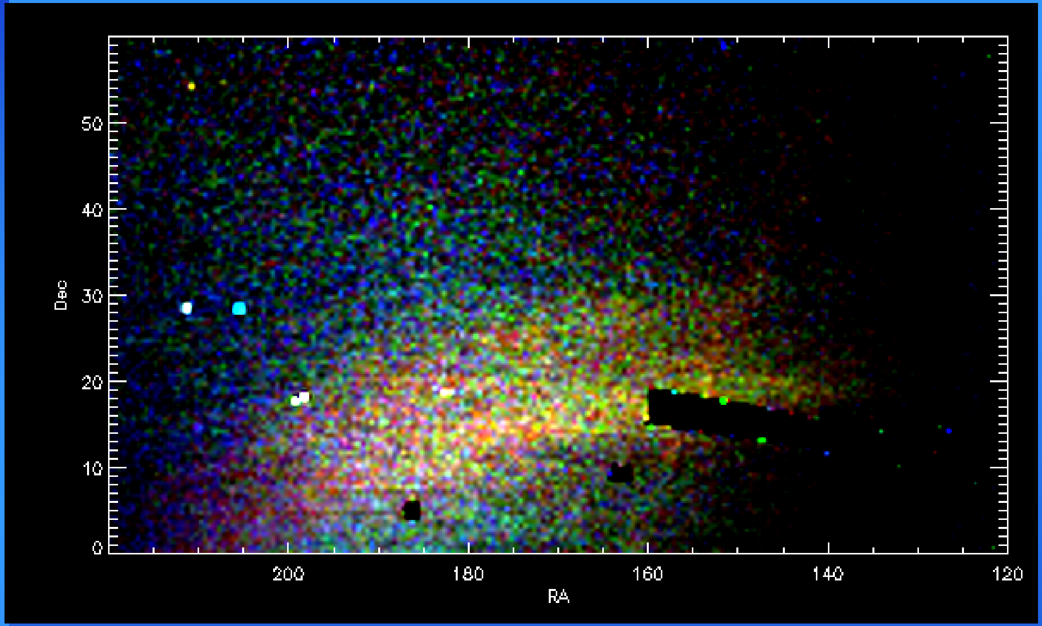
2Mass revealed streams from Sagittarius dwarf around the sky (Majewski et al 2003)



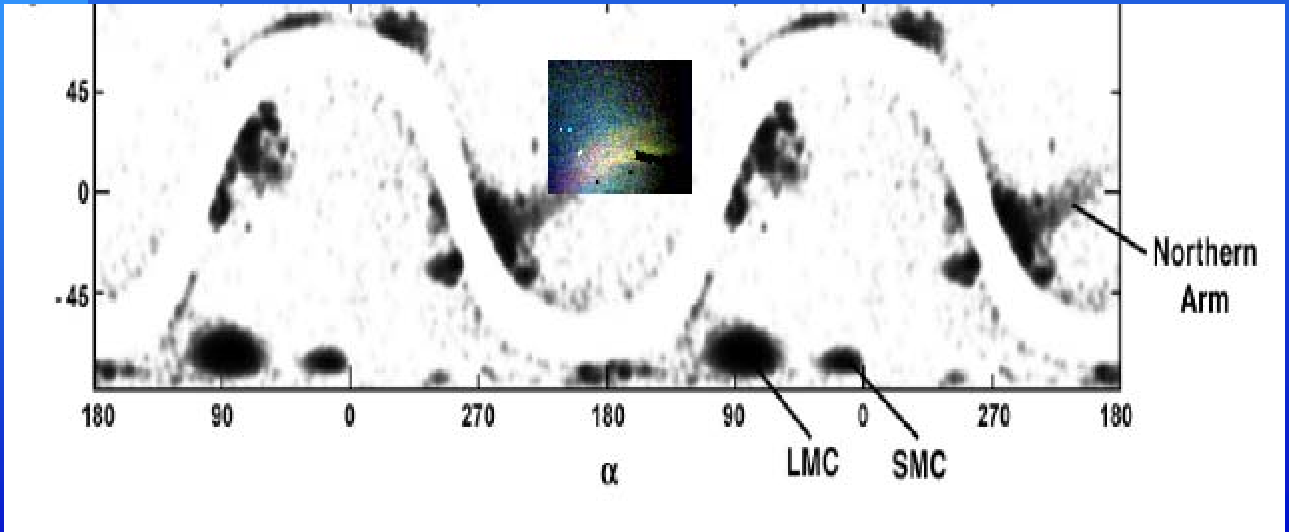
Field of Streams



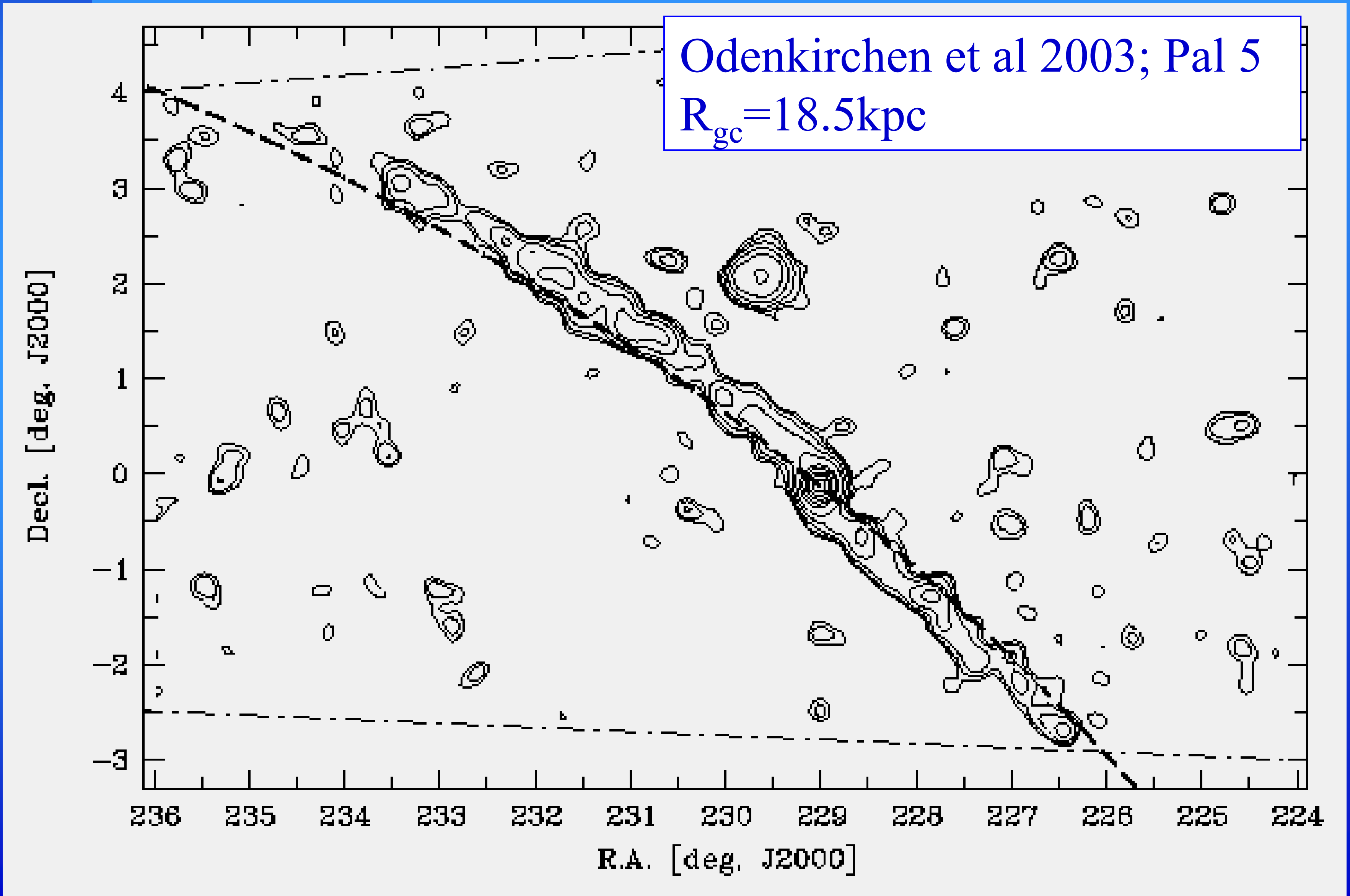
SDSS data, 19< r< 22, g-r < 0.4 colour-coded by mag (distance), blue (~10kpc), green, red (~30kpc)



Belokurov et al 06



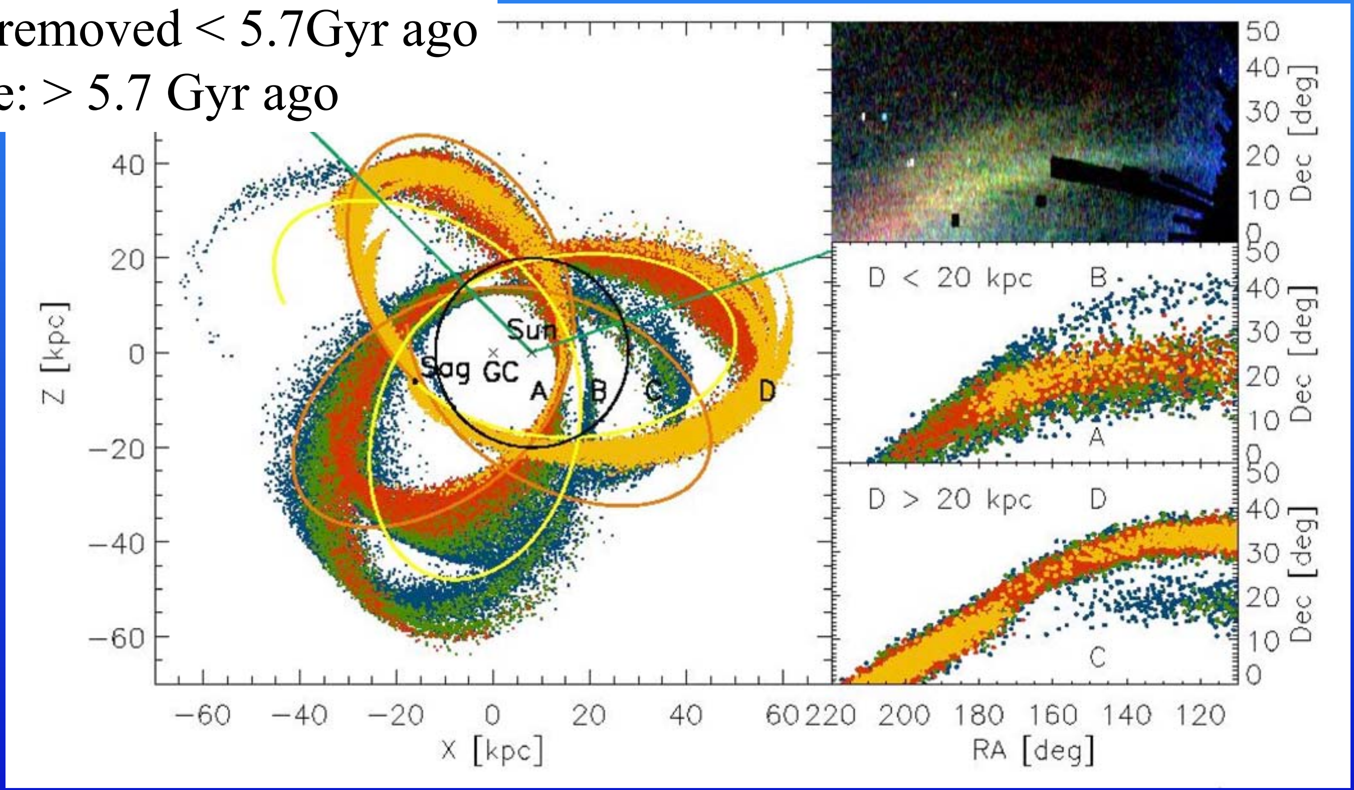
Globular clusters also can give rise to streams; streams not necessarily a signature of accretion



Halo potential nearly spherical:

Narrow bifurcation of the two Sgr arms (young leading and old trailing) implies little precession

Gold, red: removed < 5.7Gyr ago
Green, blue: > 5.7 Gyr ago



Fellhauer et al 06 – but see Helmi 2004, strongly prolate

Five new ‘substructure’ systems

dSph, d=45kpc

dSph, d=150kpc

Glob, d=25kpc

dSph, d=140kpc

dSph, d=160kpc

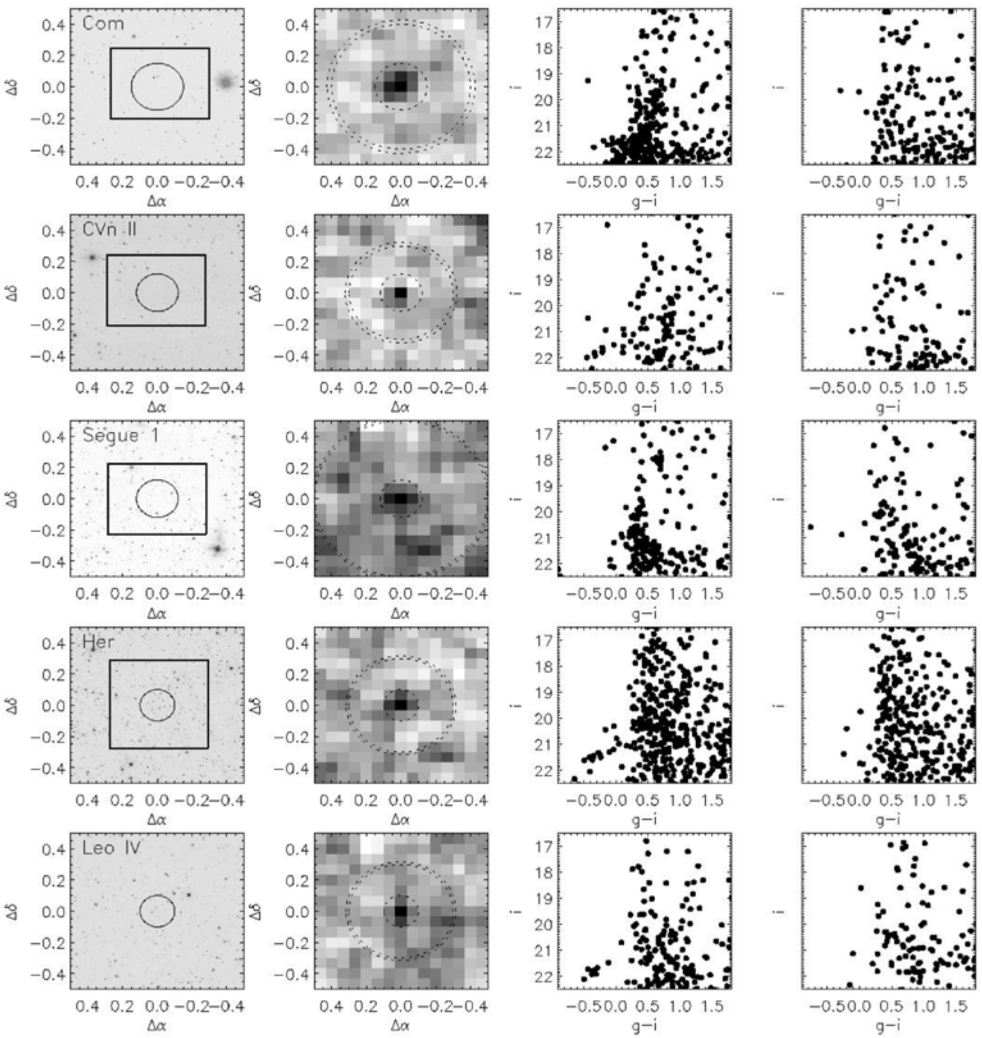
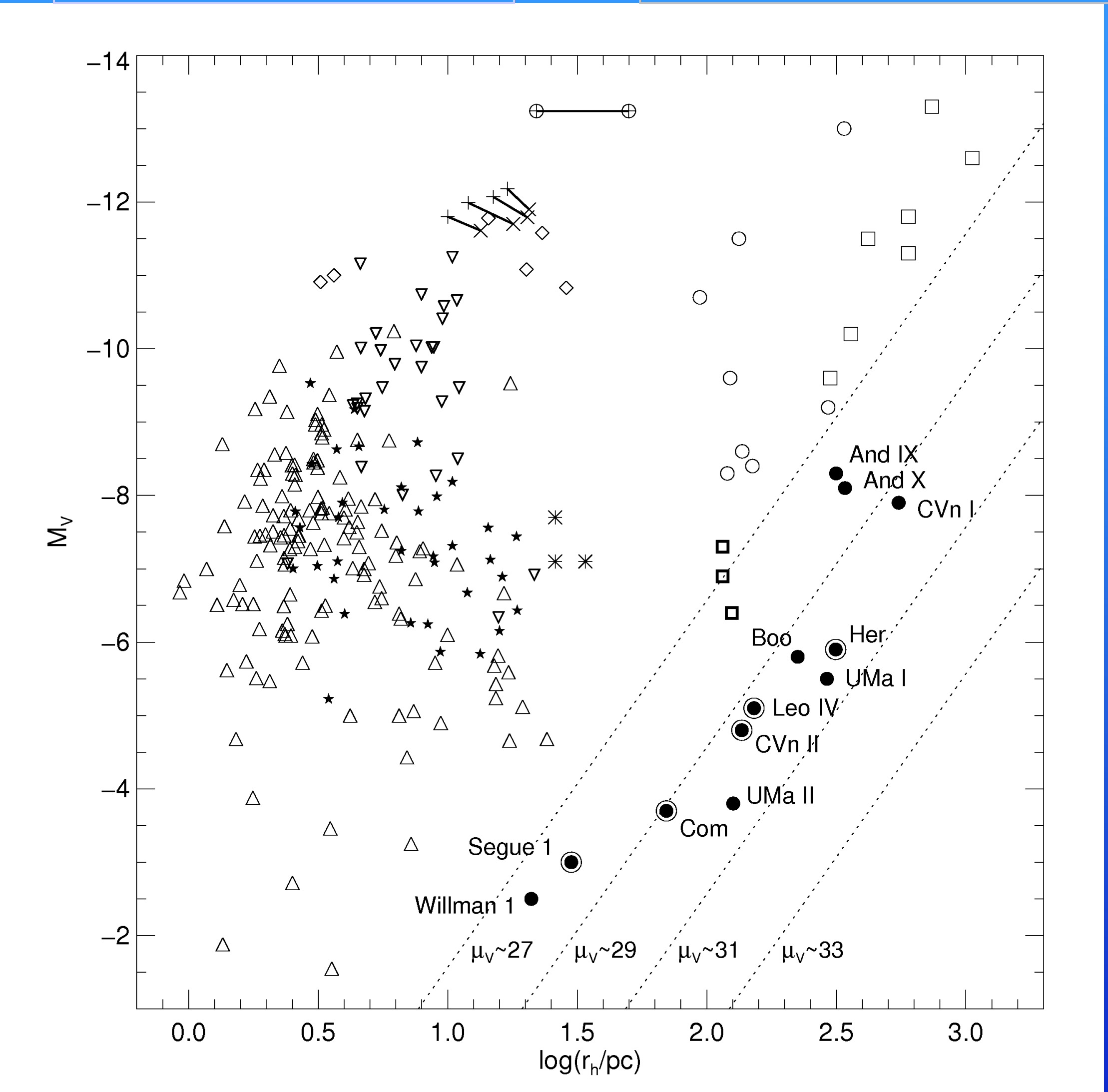


FIG. 1.— Discovery panels for the 5 new satellites. The first column is a cut-out of the SDSS, with a box showing the location of the Subaru field ($34' \times 27'$) or INT field ($34' \times 34'$) and a circle marking the central part of the object. The second column shows the pixellated stellar density. The pixels are $4'$ on each side. For each object, 3 circles are shown of radii r_1, r_2 and r_3. The CMD of stars lying within a circle of radius r_1 is given in the third column. The CMD of stars lying in the annulus defined by the outer radii (r_2 and r_3) is given in the fourth column. [r_1, r_2, r_3 for Coma are $0.15°, 0.4°, 0.43°$, for CVn II ($0.12°, 0.3°, 0.32°$), for Segue 1 ($0.12°, 0.5°, 0.51°$), for Her ($0.1°, 0.3°, 0.32°$) and for Leo IV ($0.1°, 0.3°, 0.32°$].

Belukurov et al 06c

Star clusters

Dwarf galaxies



No dark matter

Dark matter dominated

Belokurov et al 06c

- SDSS discovery

SDSS to date

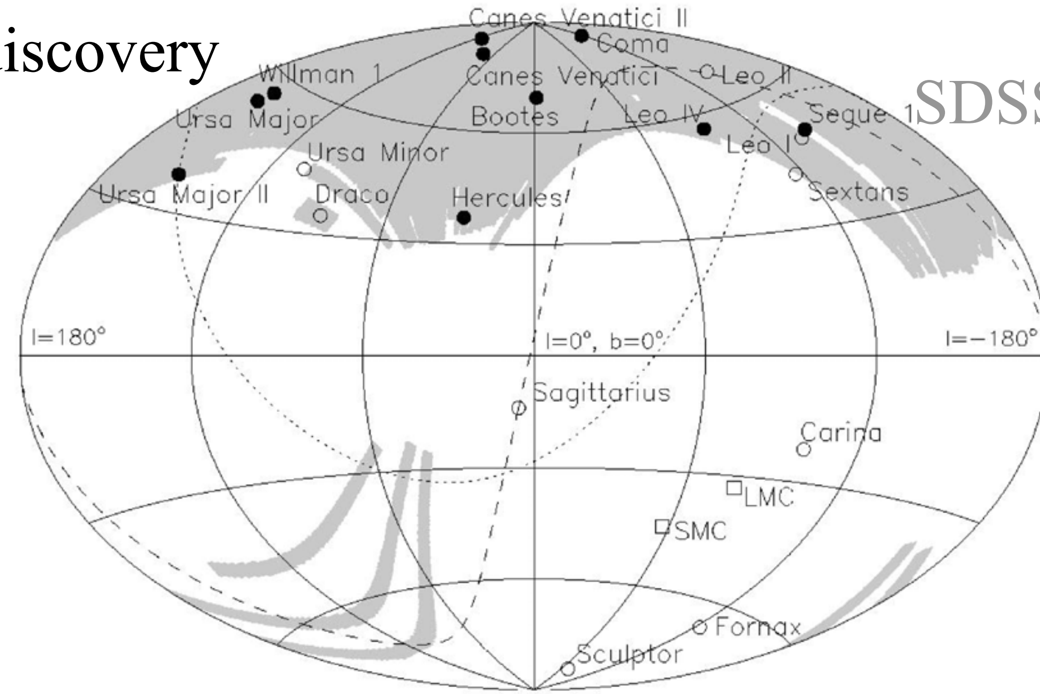


FIG. 7.— The locations of Milky Way satellites in Galactic coordinates. Filled circles are satellites discovered by SDSS, unfilled circles are previously known Milky Way dSphs. The light grey shows the area of sky covered by the Sloan survey and its extensions to date. The dashed and dotted lines show the orbital planes of the Sagittarius and Orphan Streams, respectively, taken from Fellhauer et al. (2006a) and Fellhauer et al. (2006b).

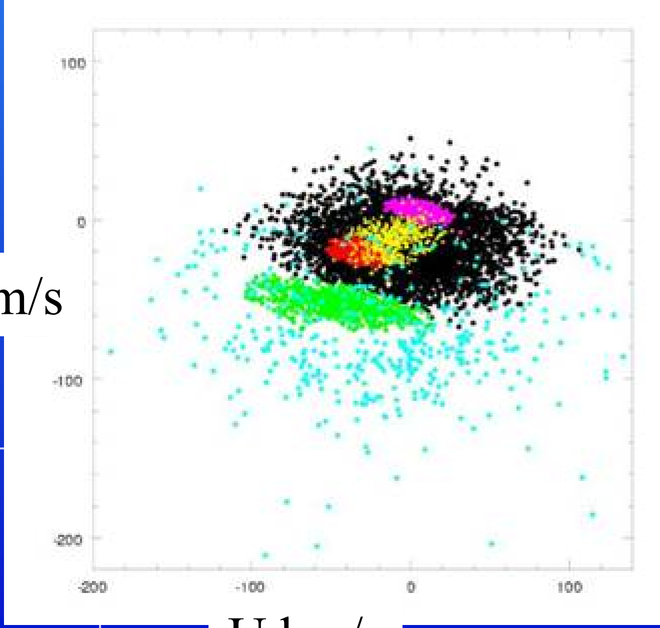
Belokurov et al 06c

Dark Substructure:

- Constrain through dynamical effects
  - Disk heating: few young stars in thick disk implies little ongoing or recent heating
    - even minor mergers ruled out back to > 10Gyr ago for Milky Way
  - Disruption of streams: smooth streams argue against dark blobs (Zhao et al 99)
  - Disruption of wide binaries: no MACHOs $> 40\mathcal{M}_\odot$ (Yoo et al 2004)

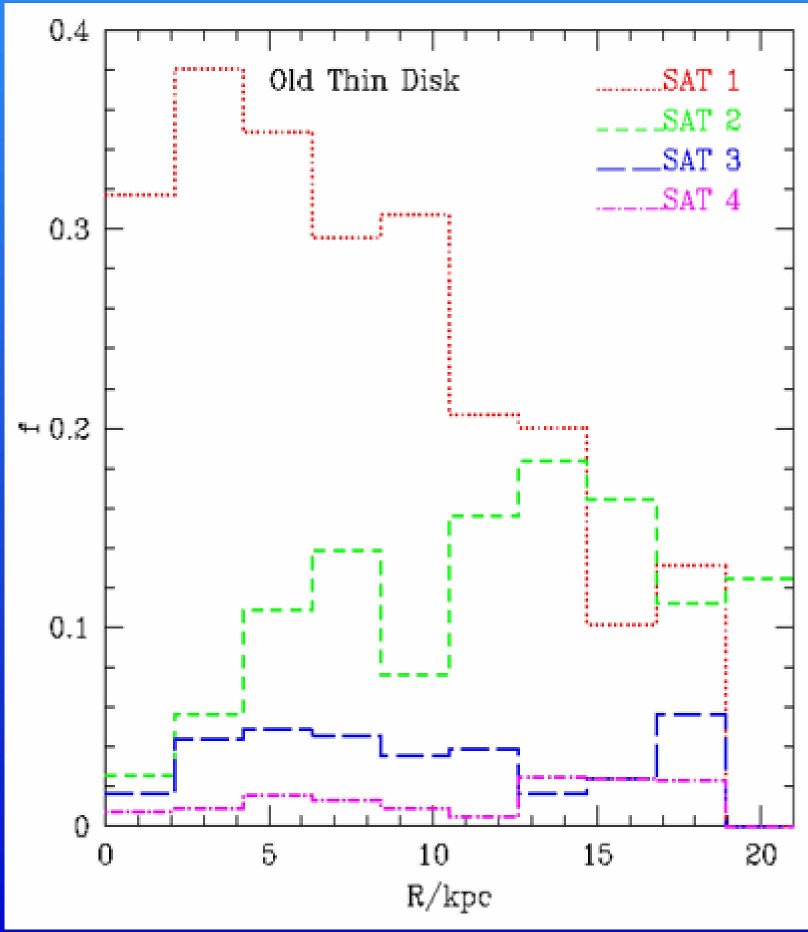
Thin disk substructure

- Spiral arms can cause significant disturbances that persist in stellar kinematics after arm perturbation has gone (e.g. de Simone et al 2004)
- The source of 'moving groups' and 'streams' with large range of stellar ages and metallicities, rather than accretion from a dwarf galaxy?
  → Need careful analysis of complete dataset…

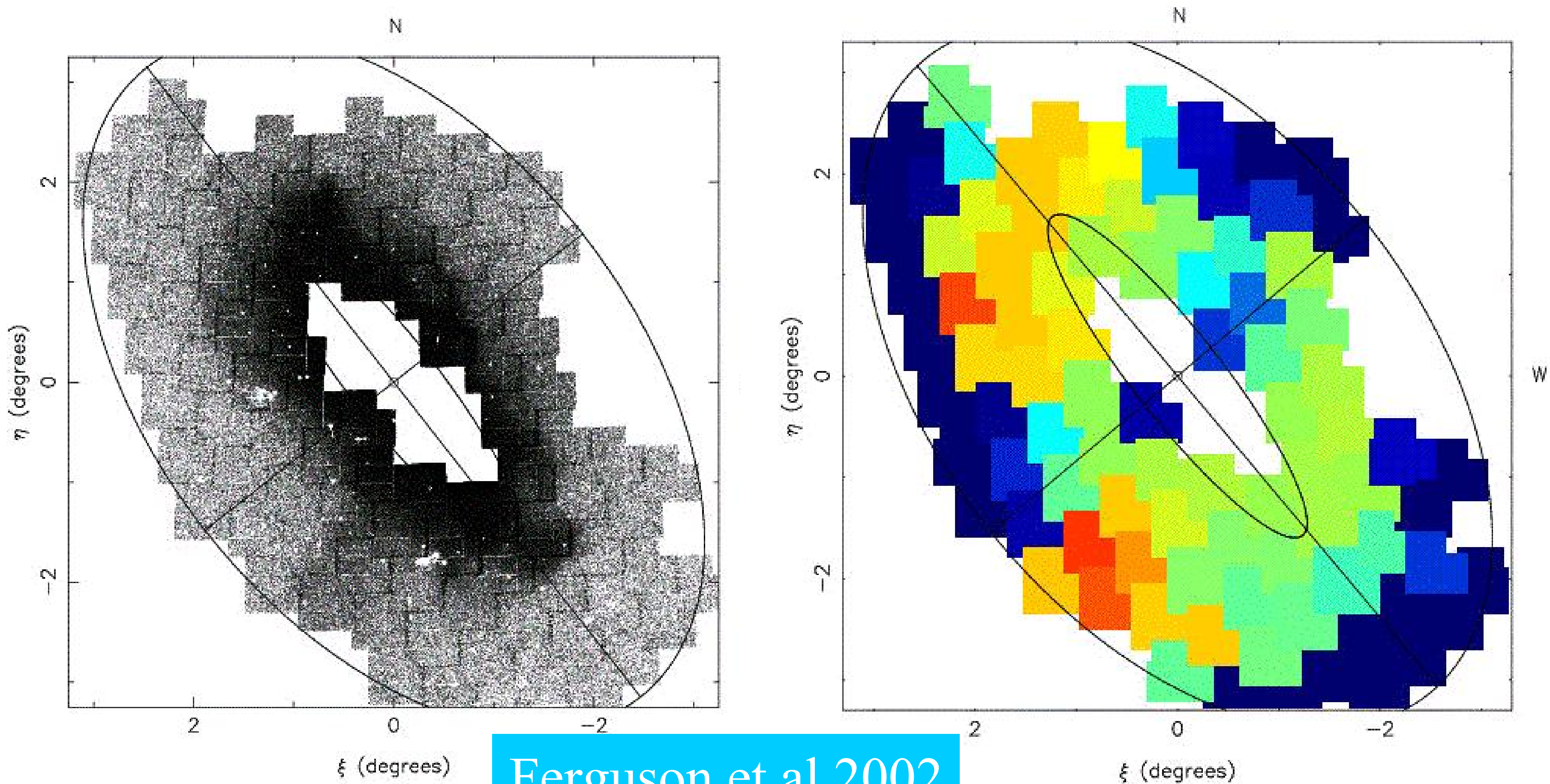


Famaey et al, local K/M giants with 3D data (2005)

- Or is the old thin disk stellar debris from accreted satellites? cf. Abadi et al 2003
- Ongoing (e.g. RAVE; SDSS2/SEGUE) and future spectroscopic surveys will detect substructure in the thin disk, and constrain the merger history
- WFMOS for elemental abundances and 'chemical tagging'



M31 substructure: map fully with WFMOS



Ferguson et al 2002

Inhomogeneities in stellar spatial distributions and colors, metallicity – also age ranges and kinematics; Guhathakurta

- Future: Compare and contrast Milky Way, M31 and M33…

Future Survey Requirements:

- Large surveys needed to quantify both small-scale and large-scale structures, tracers for potential/mass
- Need input catalogue with excellent photometry and positions and proper motions
  - Analyse spatial structure, in colour space
  - Spectroscopic targets: understand selection function
- Medium resolution spectroscopy (few Å) for hundreds of stars each line-of-sight: kinematics plus metallicity
  - Sampling strategy plus selection tuned to science
  - IR for bulge plus lowest-latitude disk?
- High resolution spectra for elemental abundances for brighter subset, again MOS best, plus trace cold systems

- All-sky surveys with multi-bandpass CCD data to faint magnitudes, probe turn-off stars in outer Galaxy: SDSS/SEGUE, VST, PANSTARRS, LSST
- Spectroscopic survey for radial velocities and metallicities (distances, plus stellar population assignment): RAVE RADIAL VELOCITY EXPERIMENT 6dF/UKSchmidt; SDSS/SEGUE; AAOmega/AAT; FLAMES/VLT; WFMOS/Gemini-Subaru
- Elemental abundances plus exquisite radial velocities for cold systems : WFMOS
- Astrometric surveys, culminating in GAIA (SIM?)

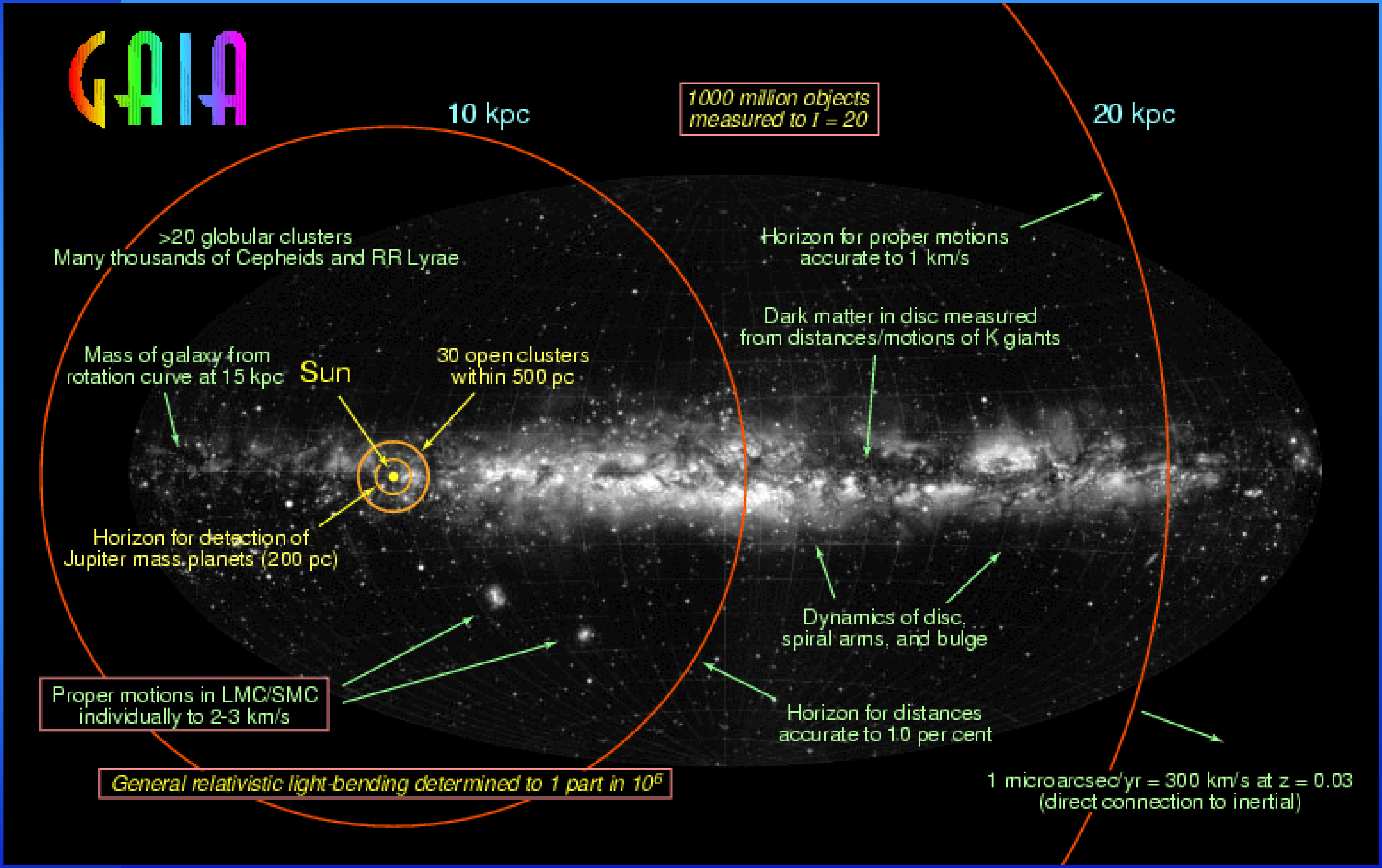
GAIA

Composition, Formation and Evolution of our Galaxy

ESA Cornerstone mission on schedule for launch 12/2011
6 years operation at L2
Complete photometric census to V=20
Imaging at ~0.2arcsec resolution
Spectrophotometry with 14 bands 400nm – 1000nm
Spectra/radial velocities (Ca II) for all stars V~17 (15 km/s)
Astrometry for 1 billion sources
Parallax to 7μas (V<10), 300μas (V=20)

Final instrument optimisation underway, maintaining performance

Gaia: mapping Dark Matter, forming a Galaxy



10 μas = 10% distances at 10 kpc

10 μas/yr = 1 km/sec at 20 kpc

Concluding Remarks

- Many open issues, both observational and theoretical
- Exciting times! Confluence of techniques promises much activity and advances
- 30m and larger: beyond the Local Group