# The Local Group

*A detailed view of the closest galaxies*

*Examples of near-field cosmology*

References:

- Freeman & Bland-Hawthorn (2002, ARA&A 40, 487)
- Helmi et al. (2008, A&ARv 15, 145)
- Tolstoy, Hill & Tosi (2009, ARA&A 47, 371)

# The Milky Way and the Local Group

*Near-field cosmology*

- Are ***detailed observations of the Local Group*** compatible with the cosmology?
- Studying ***stars*** to understand galaxy formation
- The ***two*** big ***spirals***: The Milky Way & Andromeda
  - Structure (stellar halo, thick disk ⇔ history of formation)

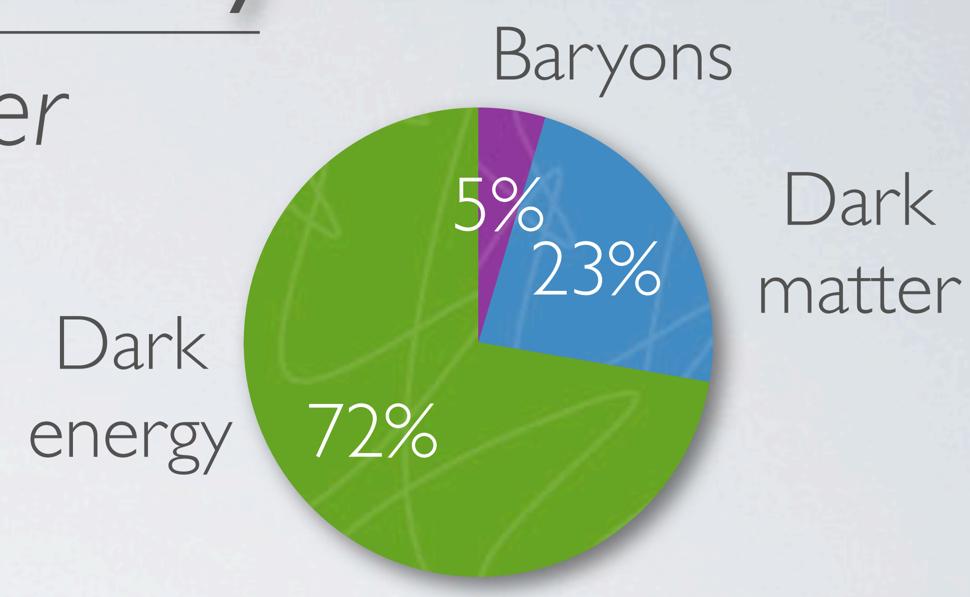
**[break]**

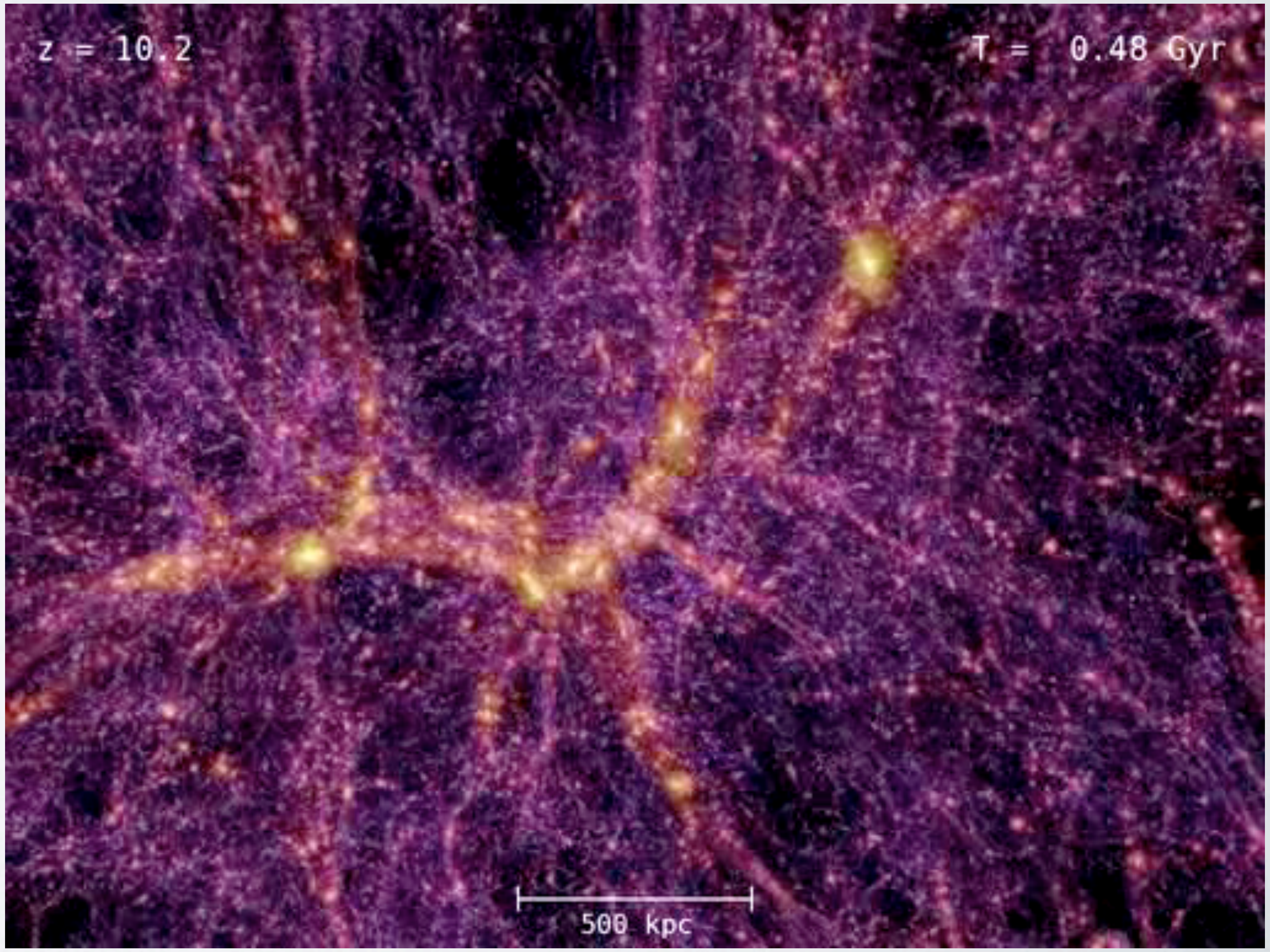
- The ***dwarf galaxies***
  - The faint end of galaxy formation
  - As a population: test of the cosmology

# Cosmology on galaxy scales

*the new frontier*

- Large scale cosmology is now largely understood
  - Λ Cold Dark Matter universe
- How do baryons condense at the center of dark matter halos?




Springel *et al.* (2009)

# Cosmology on galaxy scales

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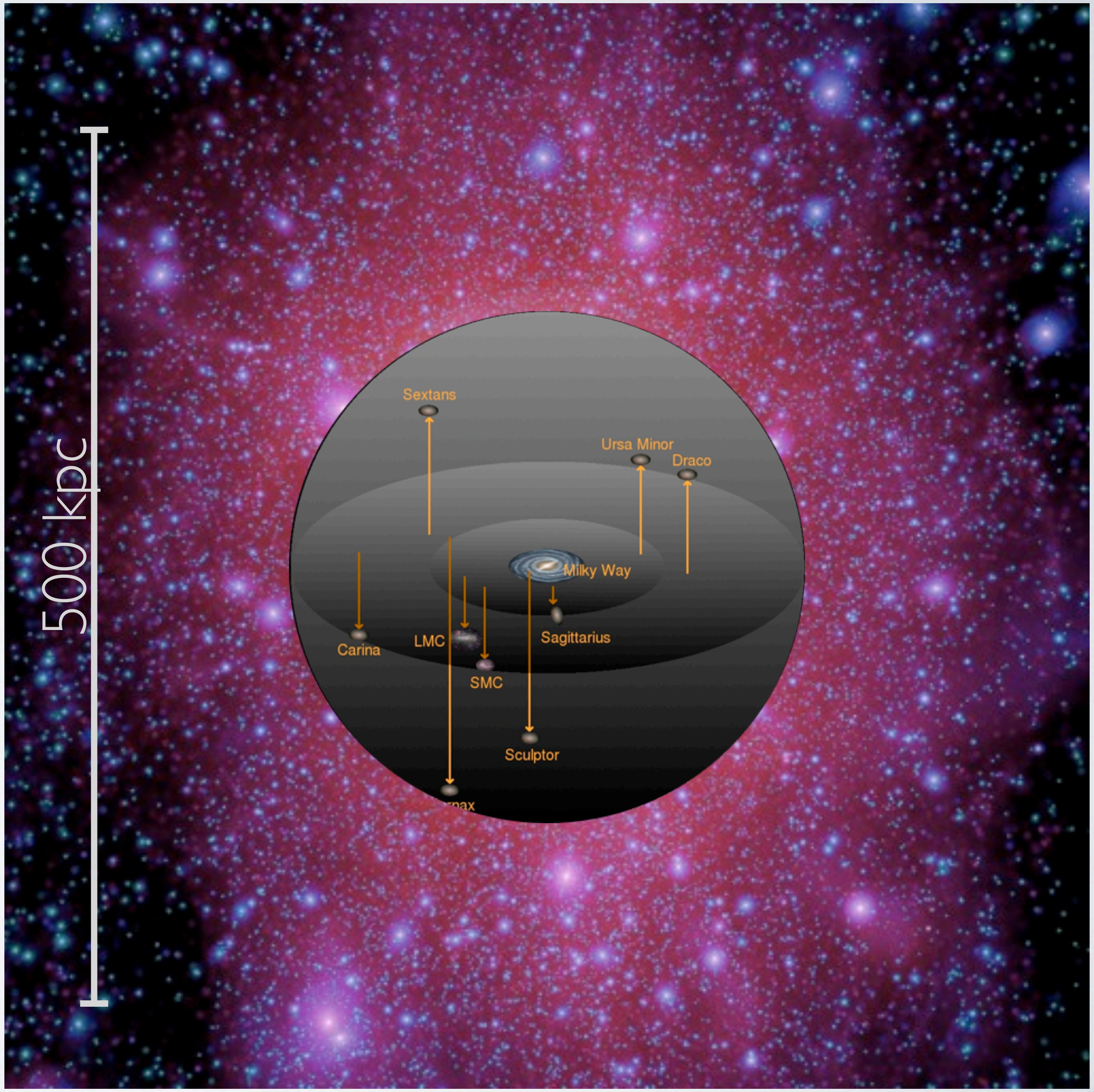
- Clear discrepancy between dark matter and stellar distributions
  - "missing satellite crisis"
  - hierarchical build-up?

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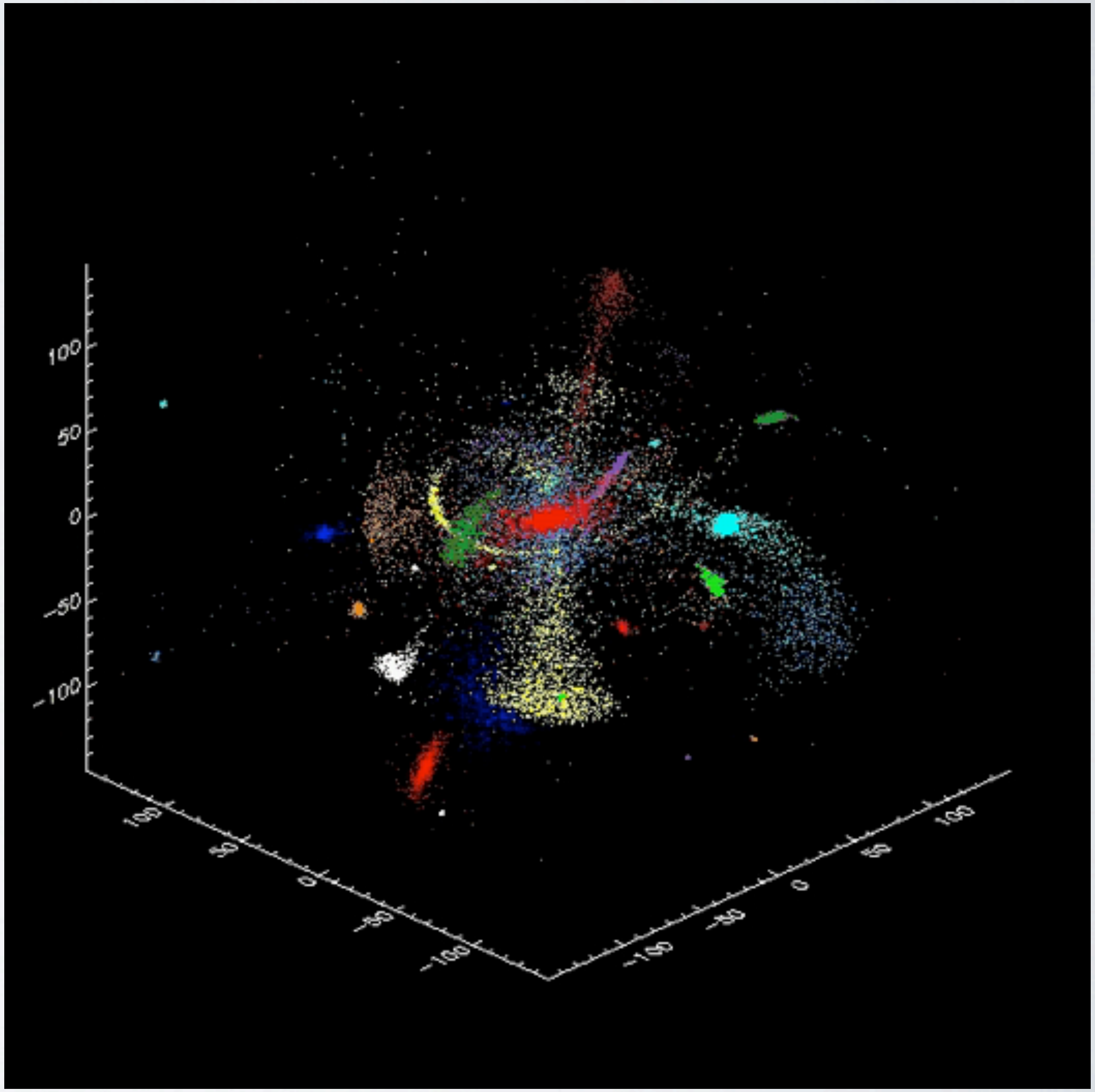

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  - $\Lambda$ Cold Dark Matter universe
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- Clear discrepancy between dark matter and stellar distributions
  - "missing satellite crisis"
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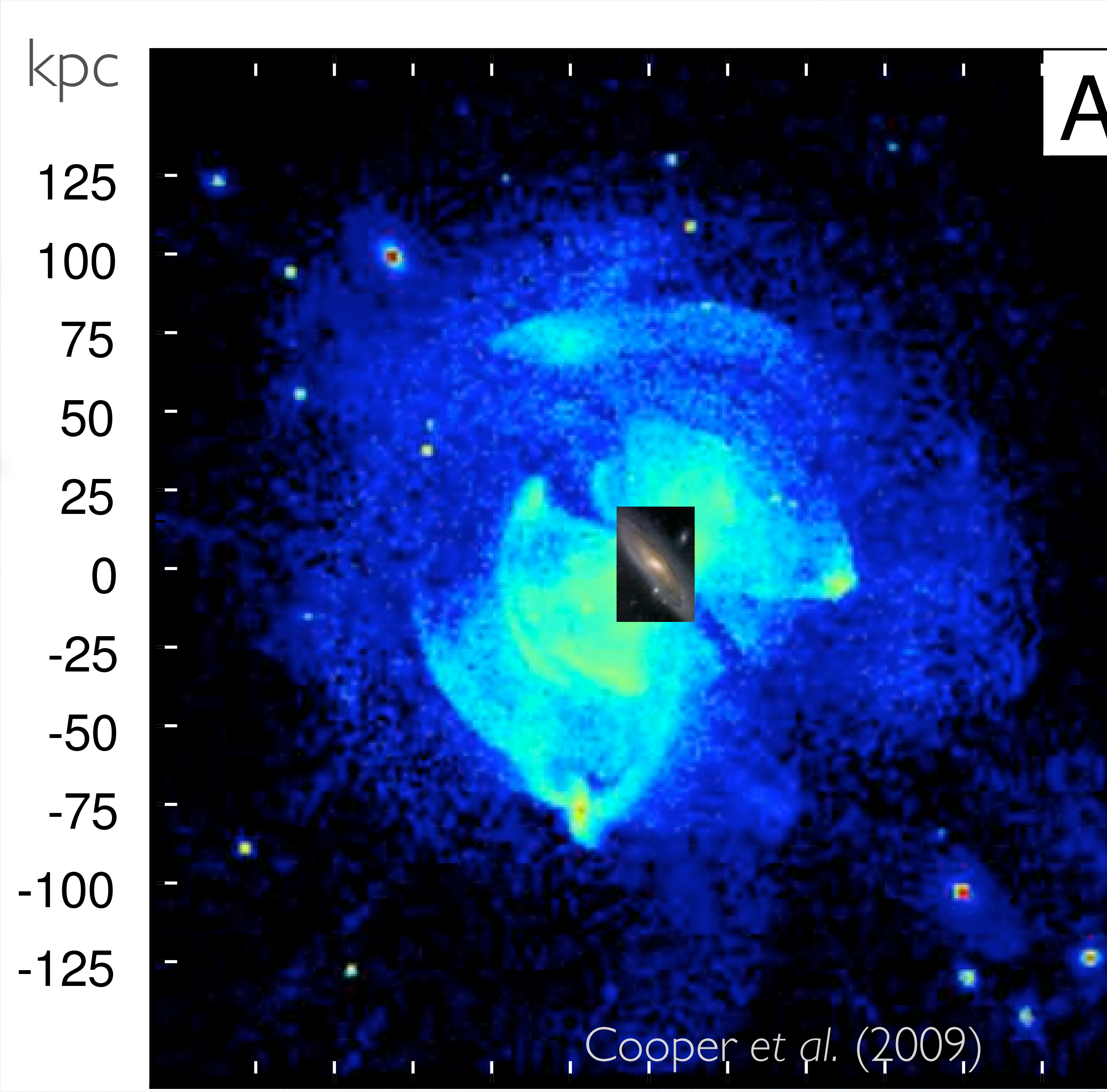
"observed" halo

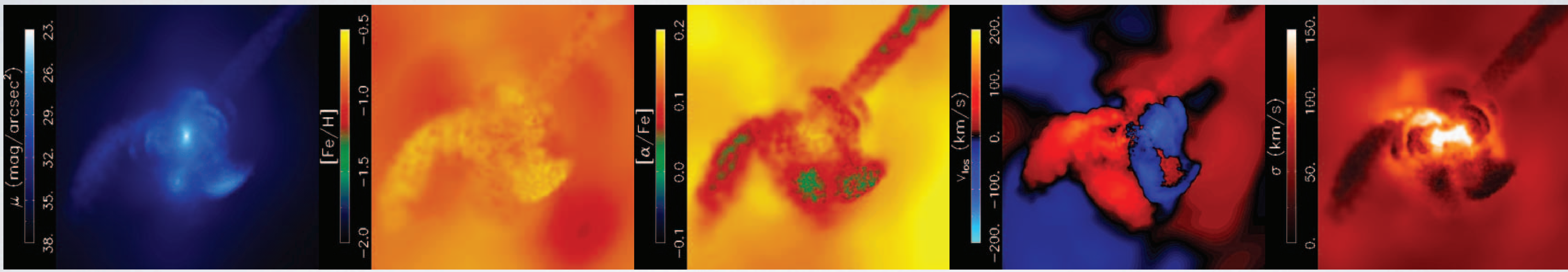


# Different causes produce different halos

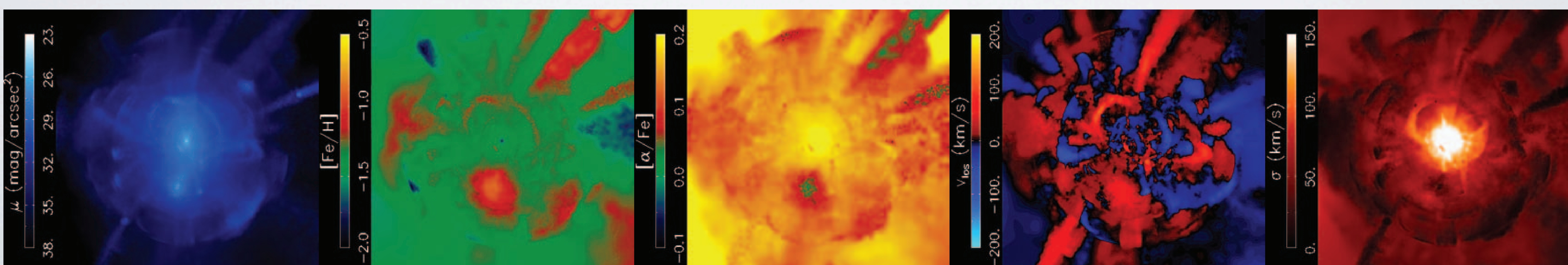
Johnston *et al.* (2008)

*Luminosity*

| $\mu$ (mag/arcsec$^2$) | [Fe/H] | [ $\alpha$ /Fe] | $v_r$ (km/s) | $\sigma$ (km/s) |
|---|---|---|---|---|
| 38 → 23 | –2.0 → –0.5 | –0.1 → +0.2 | –200 → +200 | 0 → +150 |



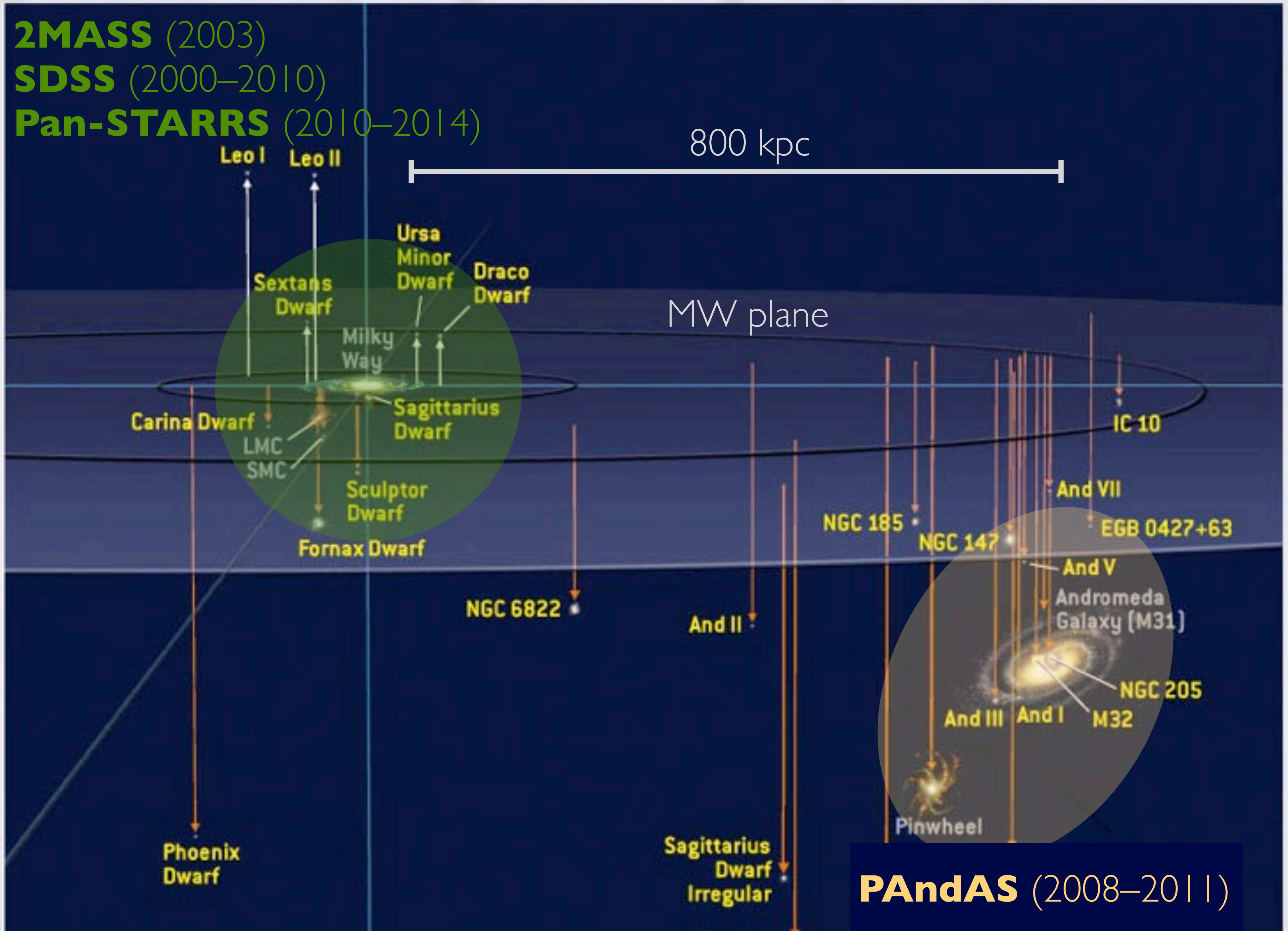

Highest luminosity accretion events




Lowest luminosity accretion events

# The Local Group as a cosmological laboratory

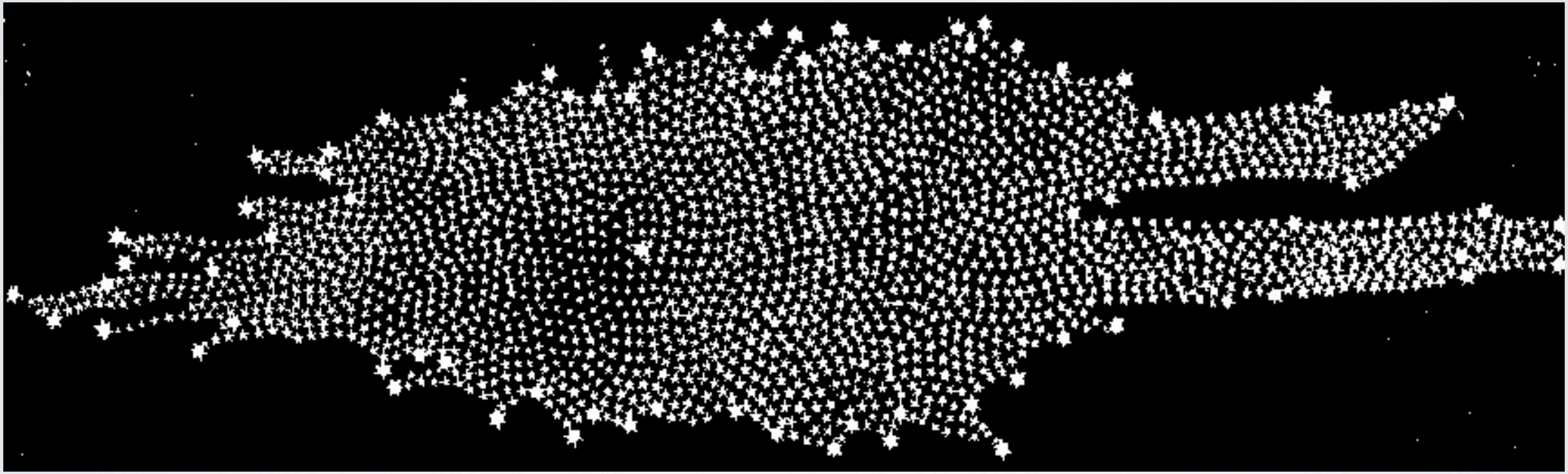
- Need to resolve stars → 100x fainter than with integrated light
  - Mainly in Local Group. Large use of large sky-surveys



# The Spiral galaxies

*The Milky Way & Andromeda*

*William Herschel's model of the Milky Way (18th century)*



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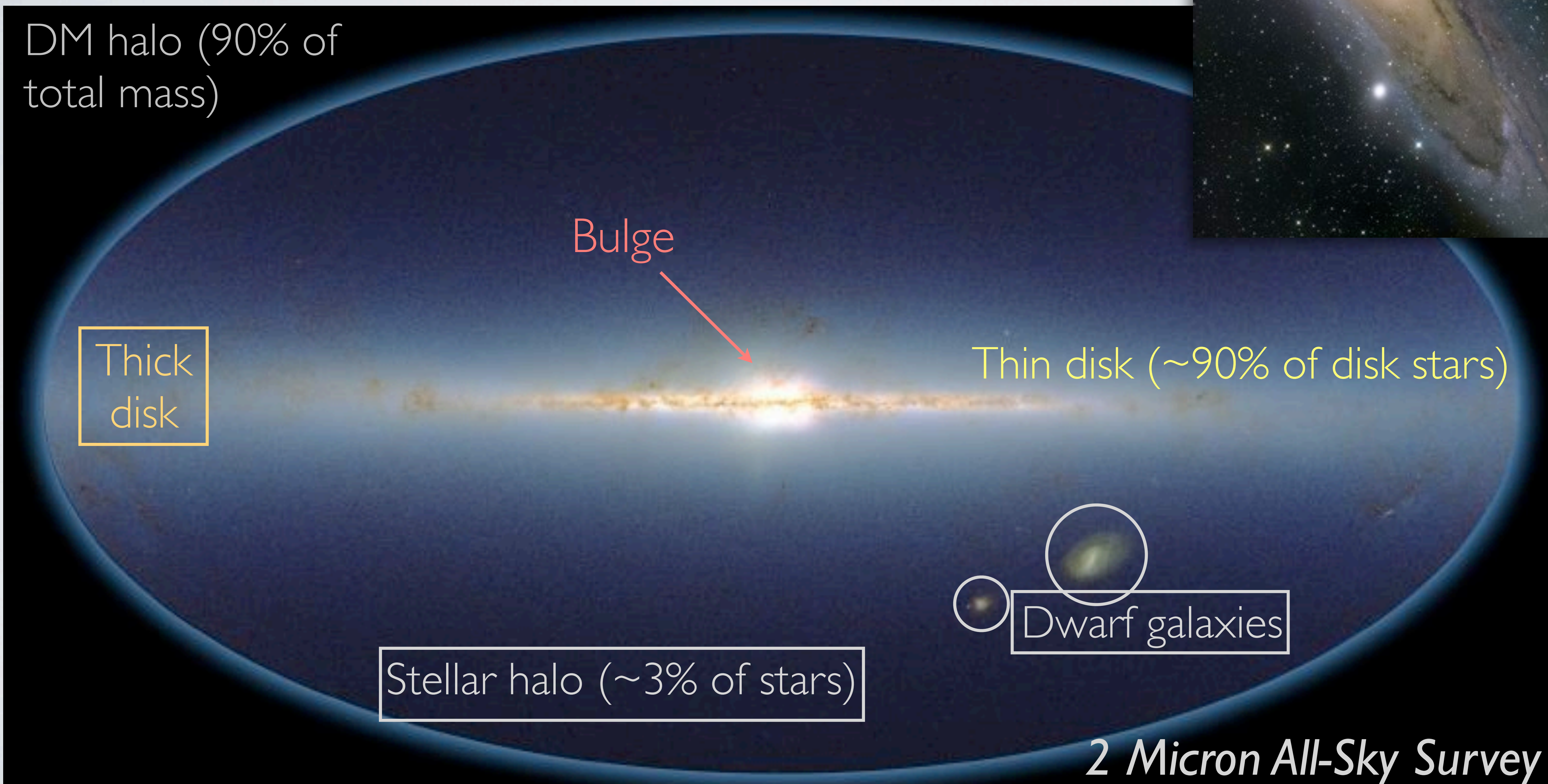
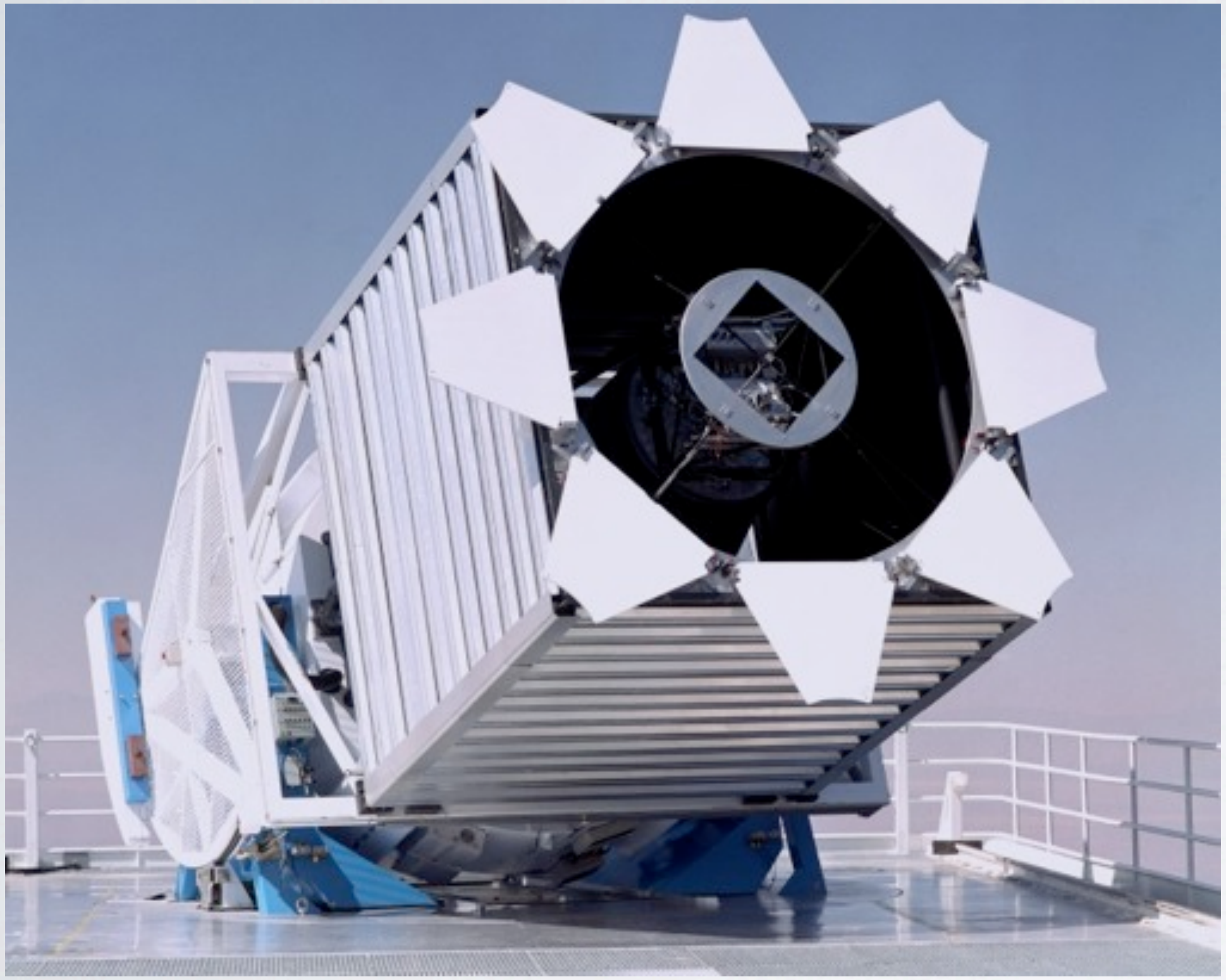



# The advent of large-sky surveys

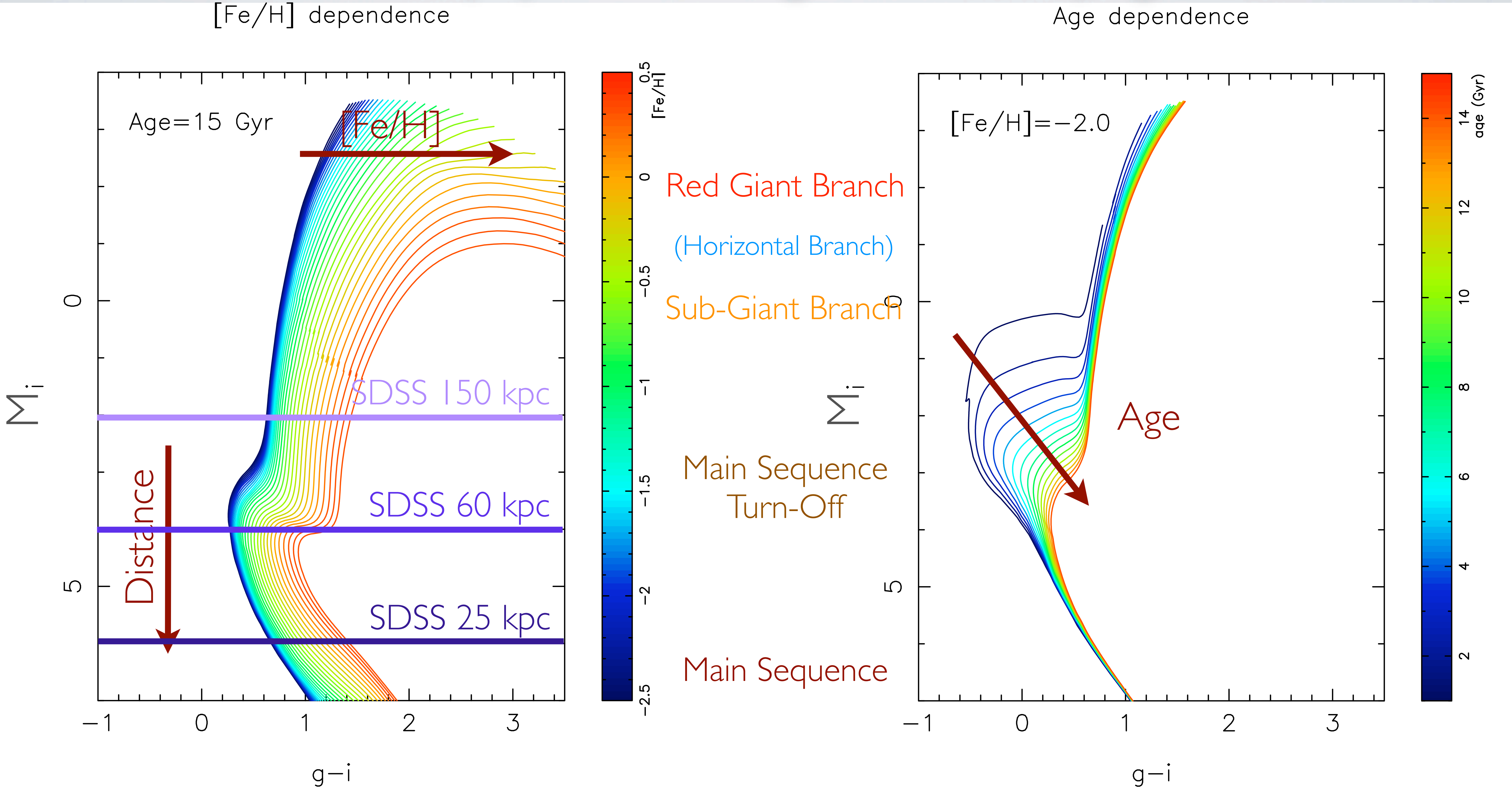
*Sloan Digital Sky Survey*



- Modest 2.5m-telescope
- Redshift spectroscopic survey
- ***But…***
  - also large photometric survey
  - quarter of the sky
  - systematic coverage
  - 5 filters from *u* (UV) to *z* (IR)

# A detour via Color-Magnitude Diagrams

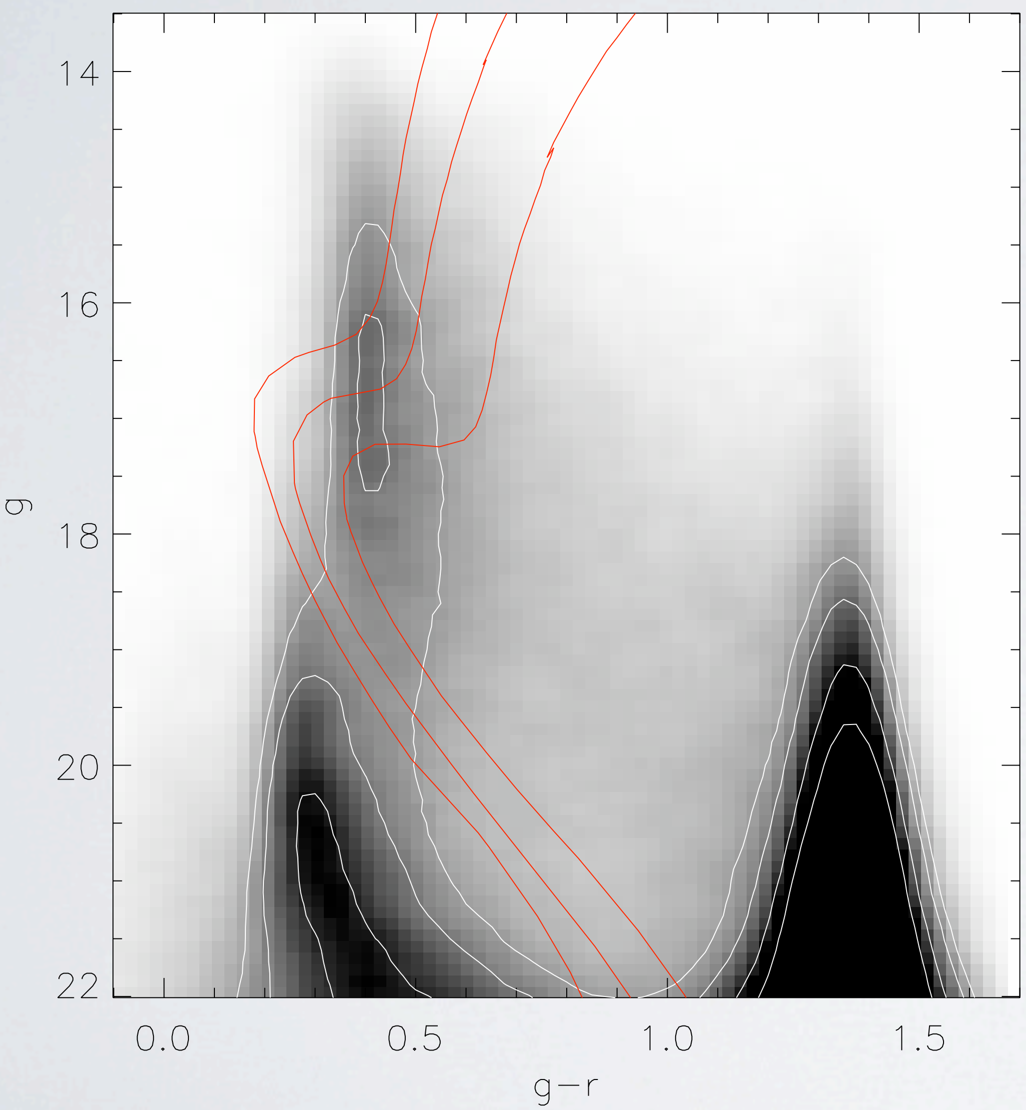
- Photometric surveys rely on CMD analyses to isolate tracers
  - isochrone: stellar population of a given metallicity, age, distance

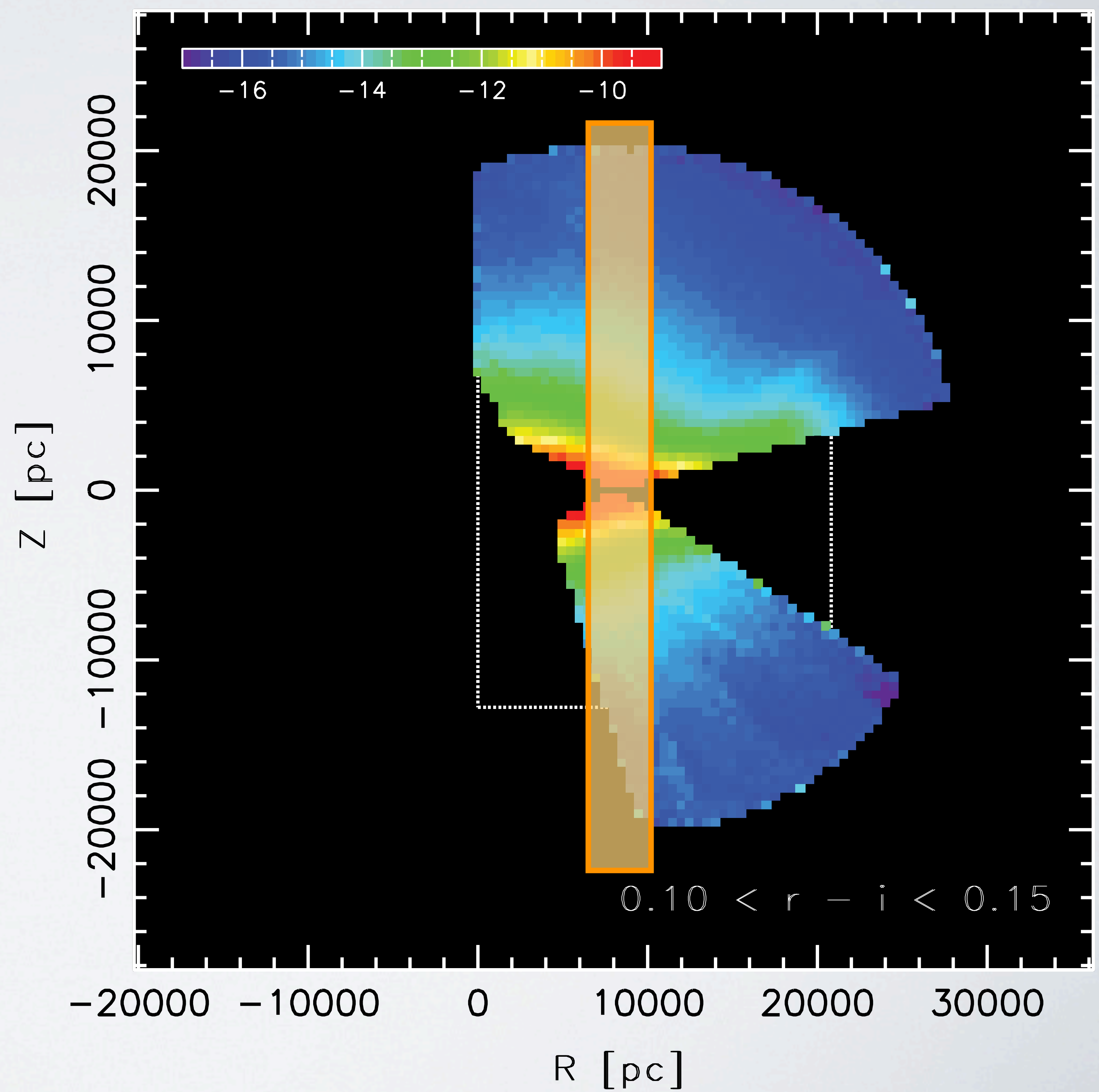


# A tomography of the Milky Way

*CMD → density maps*

Juric *et al.* (2008)



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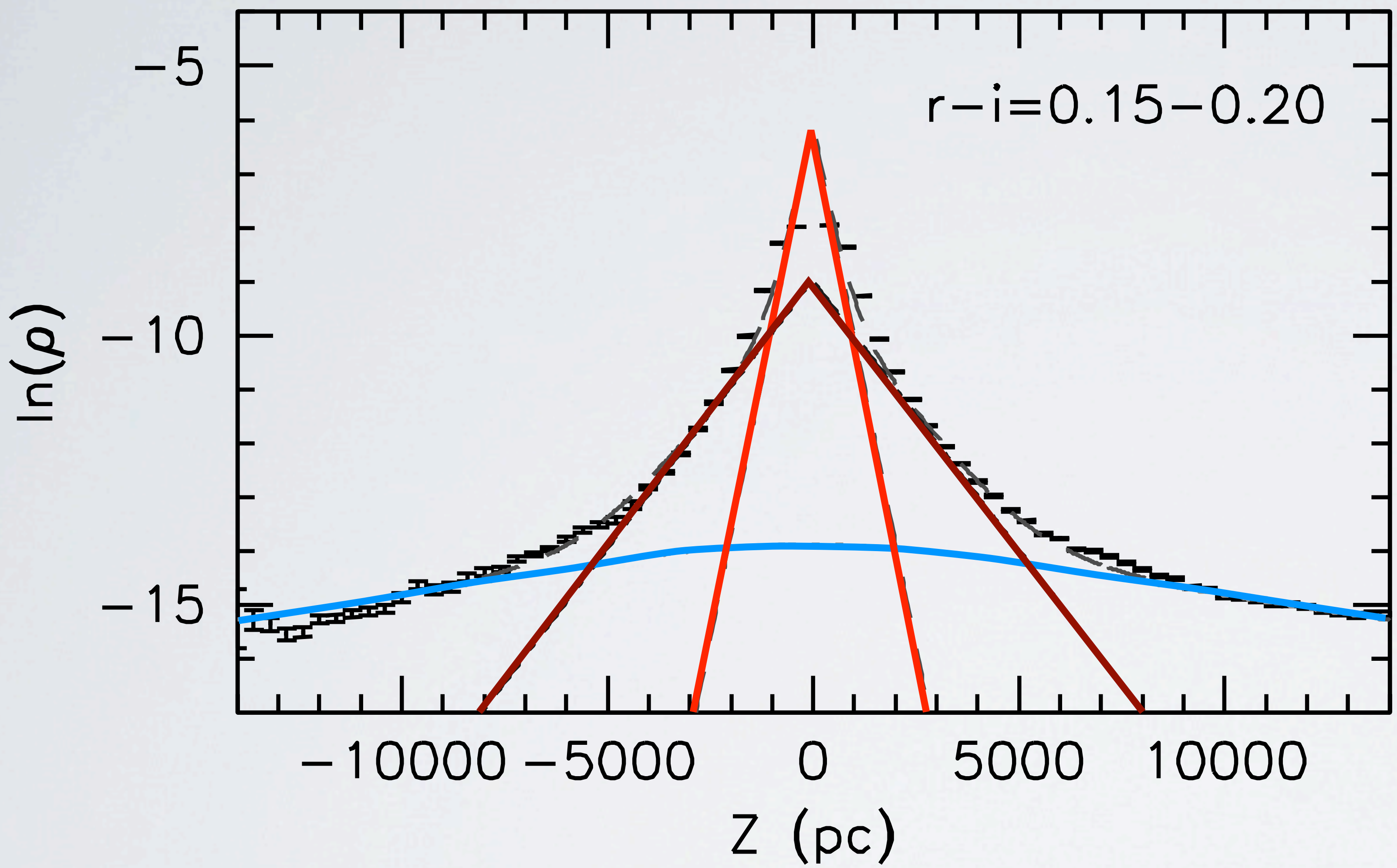
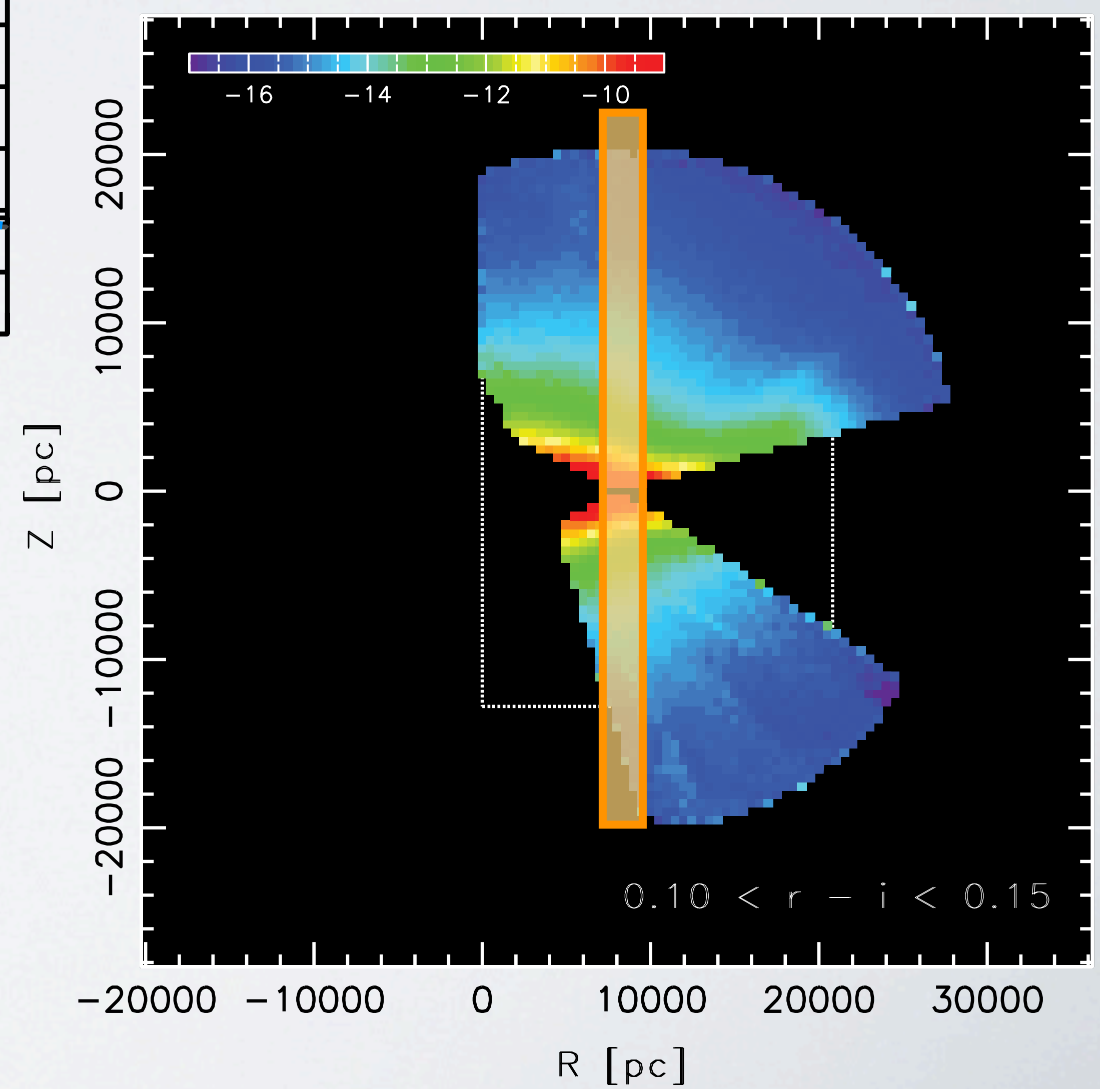



*Thin disk*

*Thick disk*

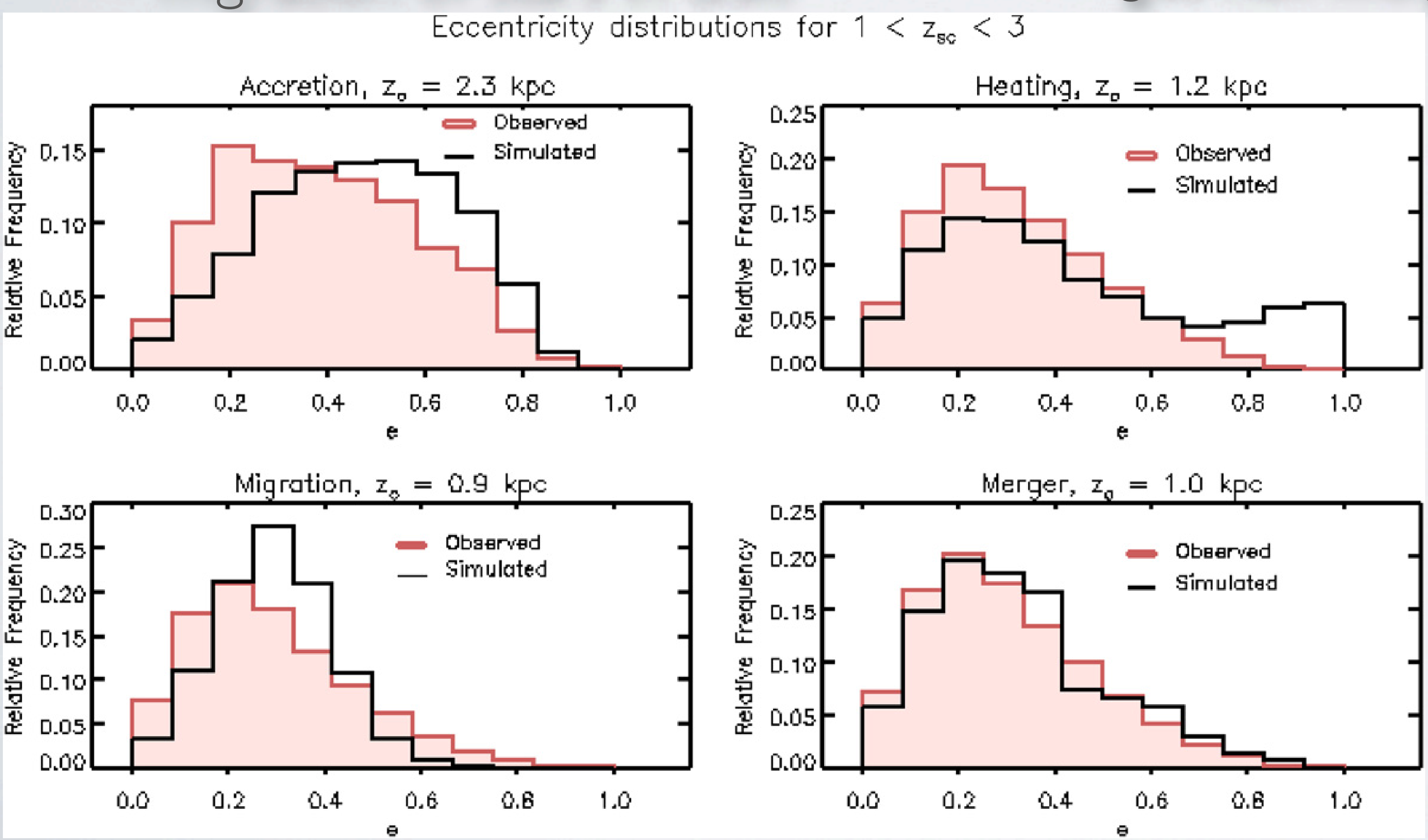
*Halo*



# The Thick disk

*Kinematics as a diagnostic of the MW past history*

- Origin?
  - accretion of dwarf galaxy?
  - migration of stars in disk?
  - heating from DM sub-halos
  - ***gas-rich merger?***




**Dierickx et al. (2010)**

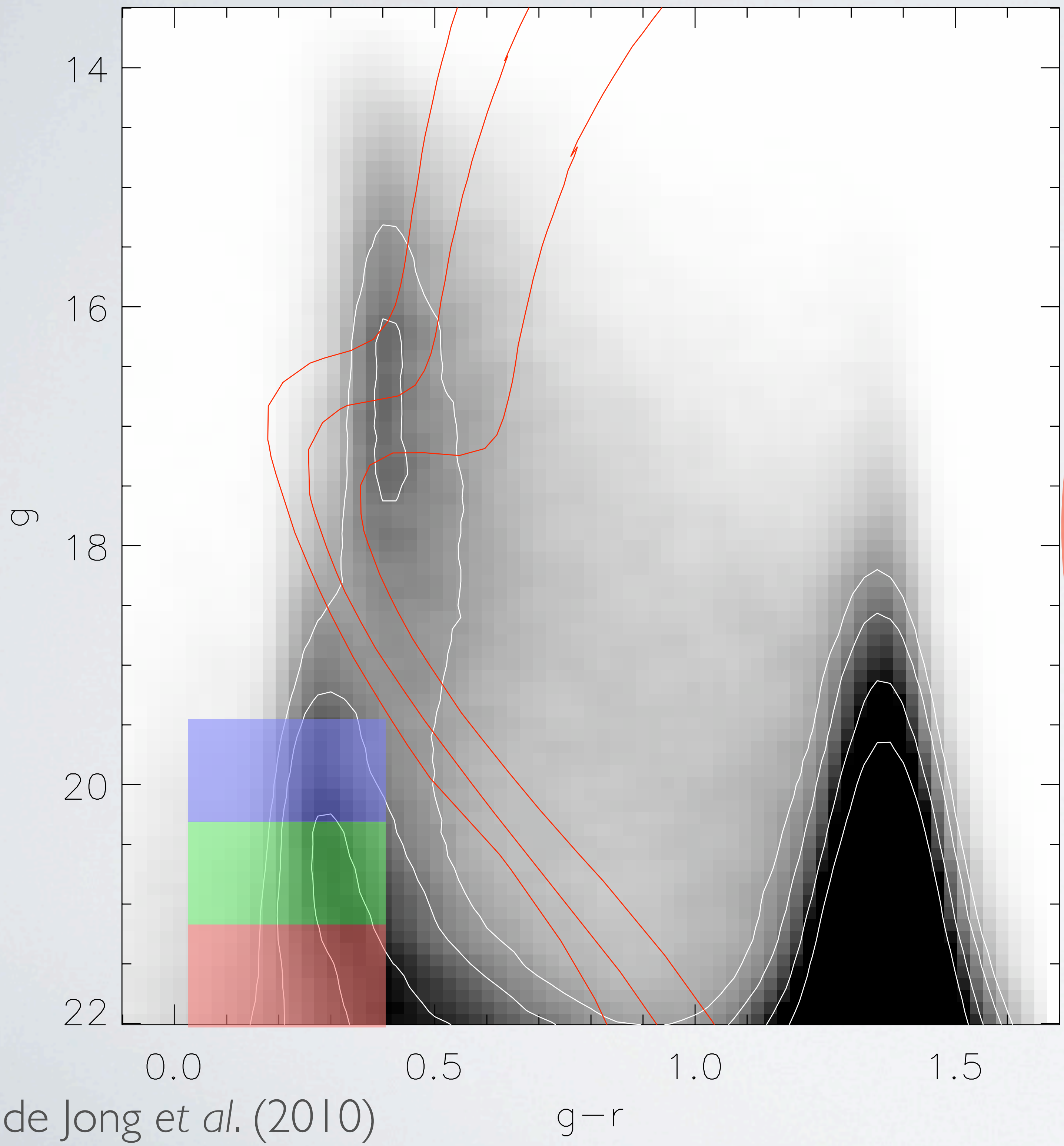
-31,535 SDSS spectra

-1 < |z| < 3 kpc

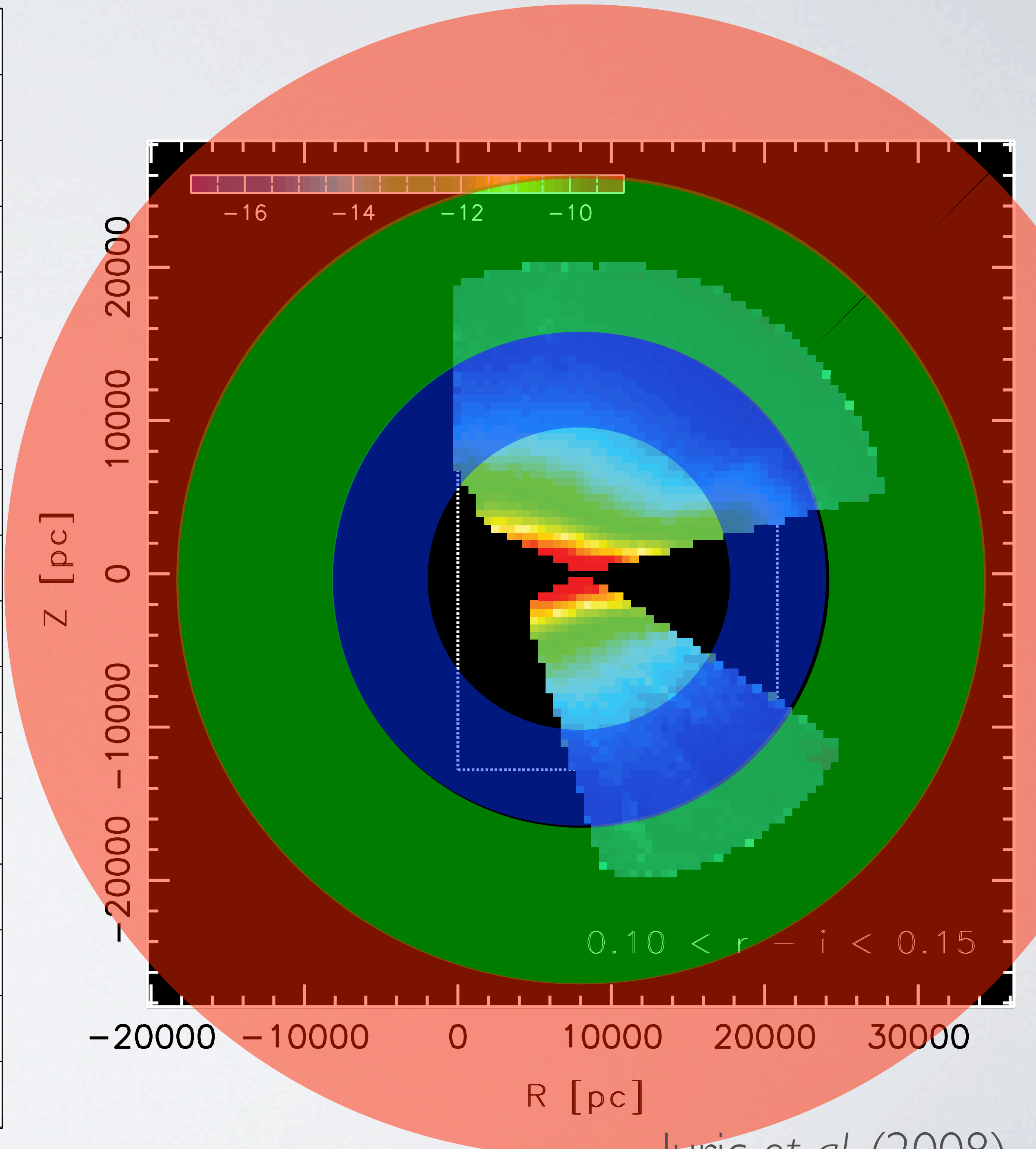
-6d information

- positions
- radial velocities
- proper motions

# The stellar halo



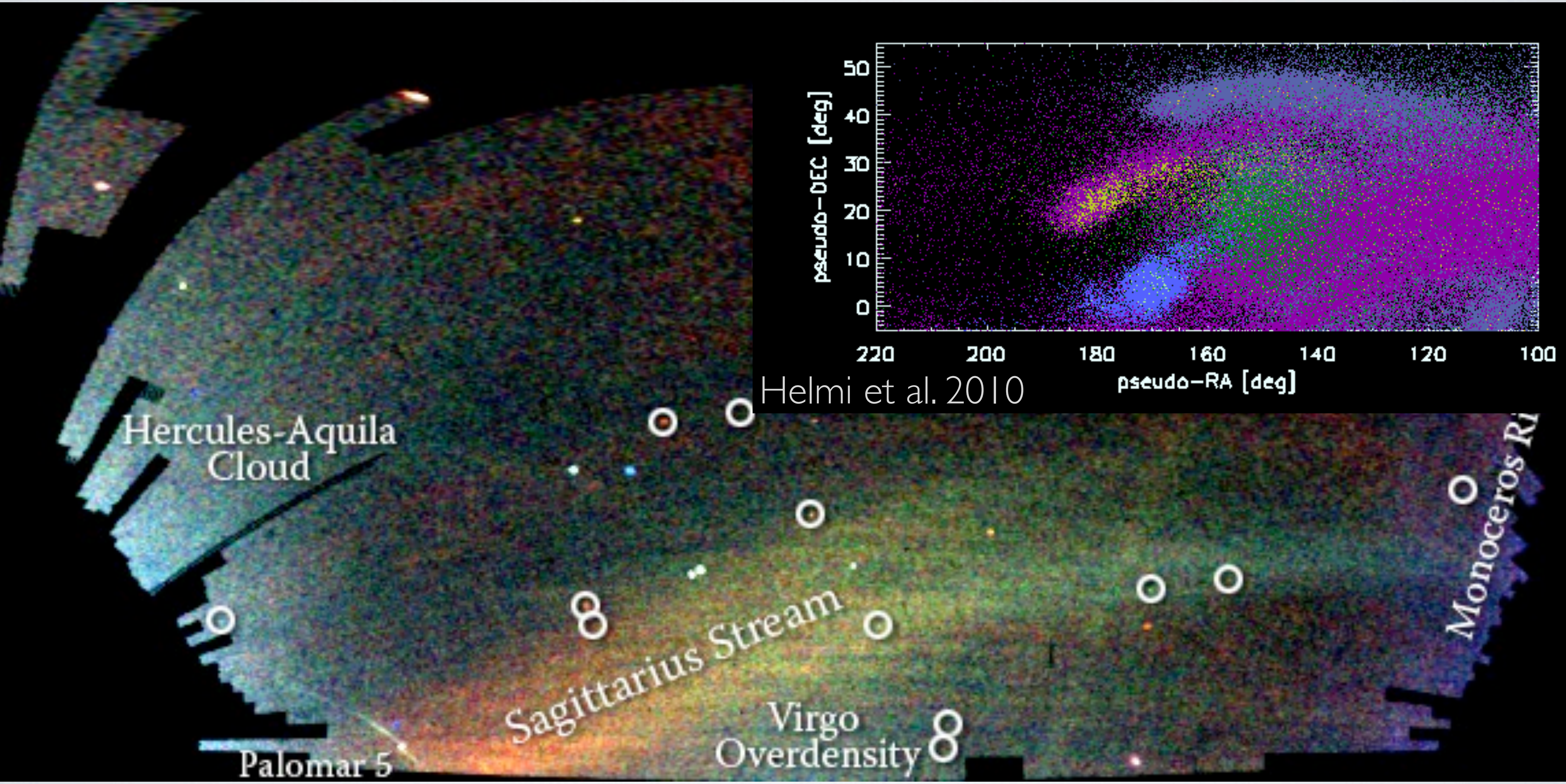

de Jong *et al.* (2010)




Juric *et al.* (2008)

# The stellar halo

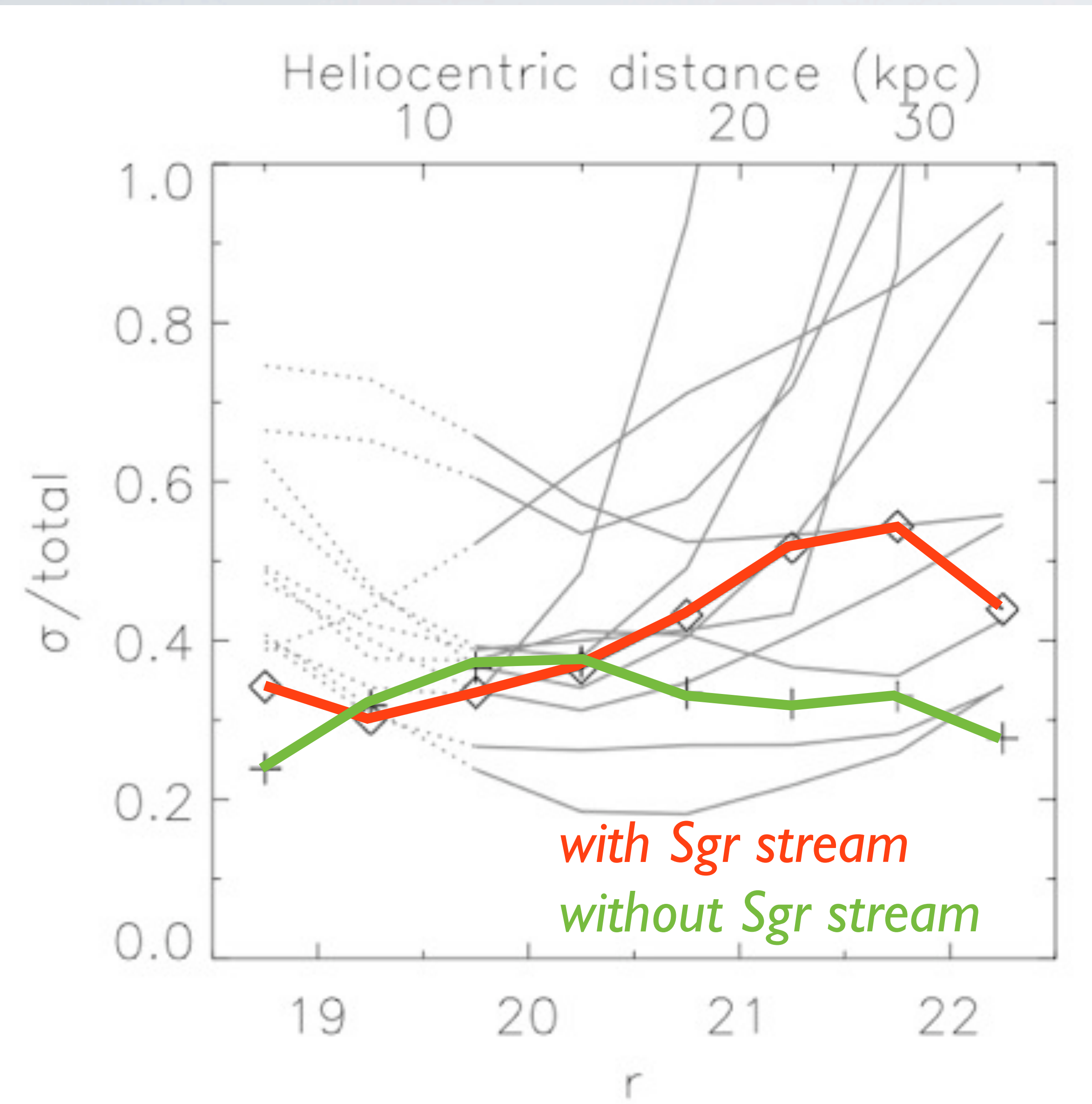
*A view from inside*

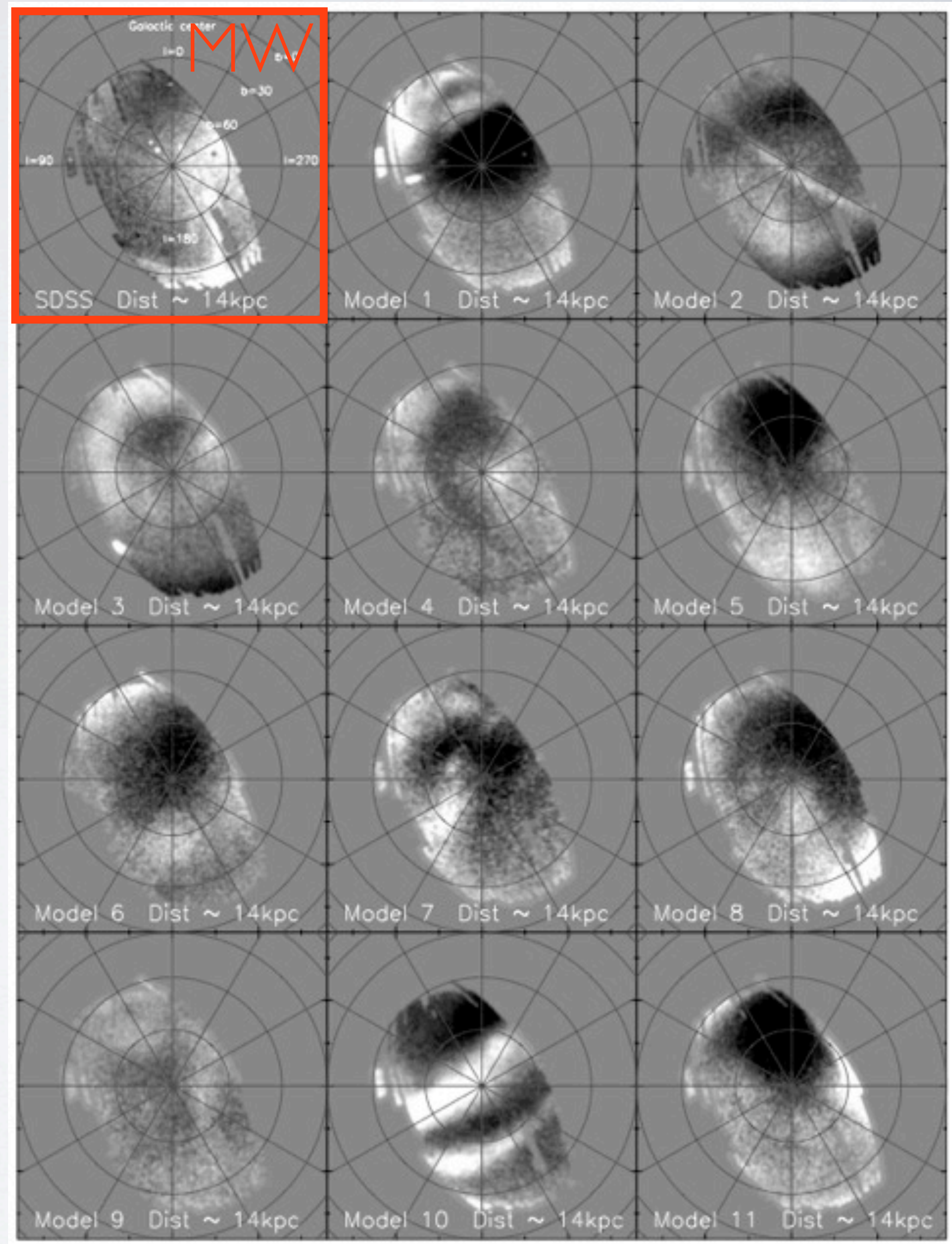



Belokurov *et al*. (2006)

# Are structures consistent with ΛCDM?

Bell *et al.* (2008)

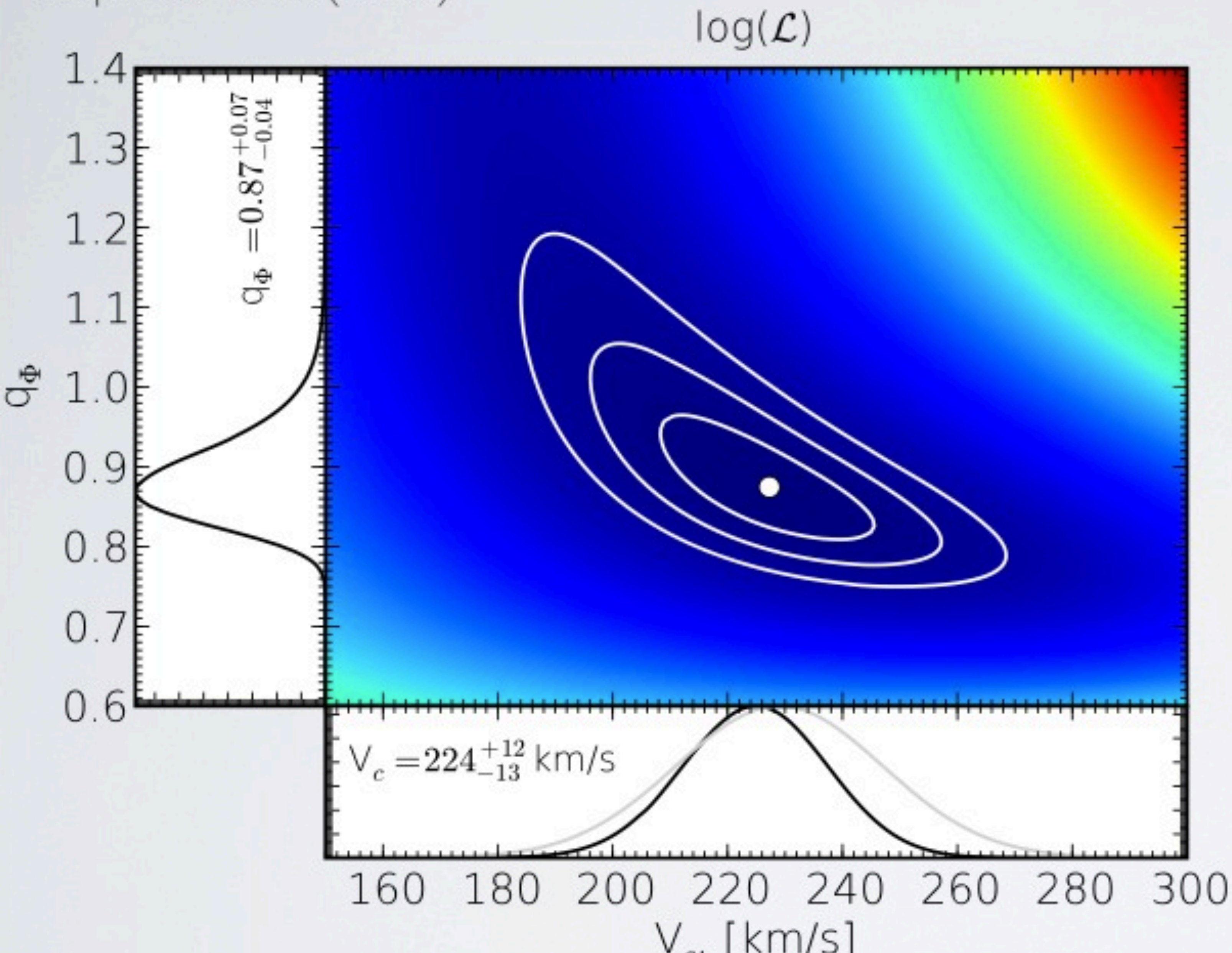


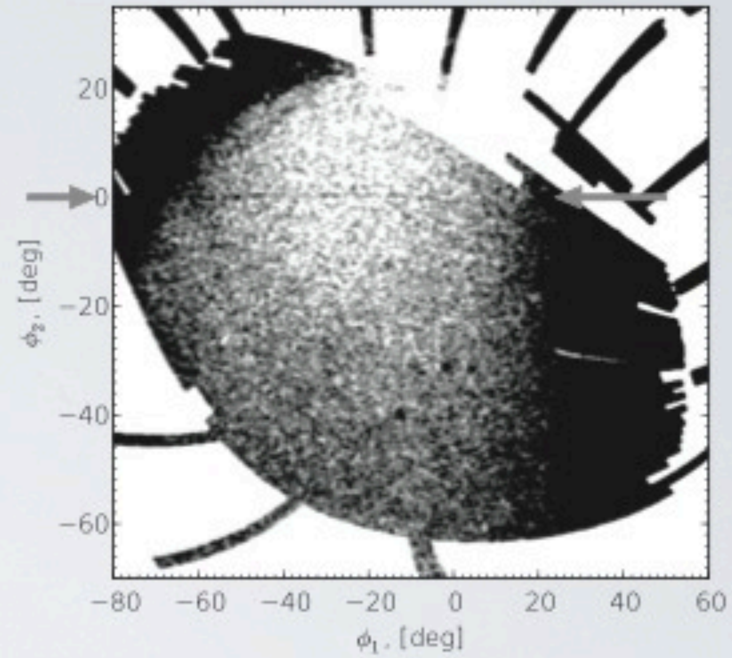



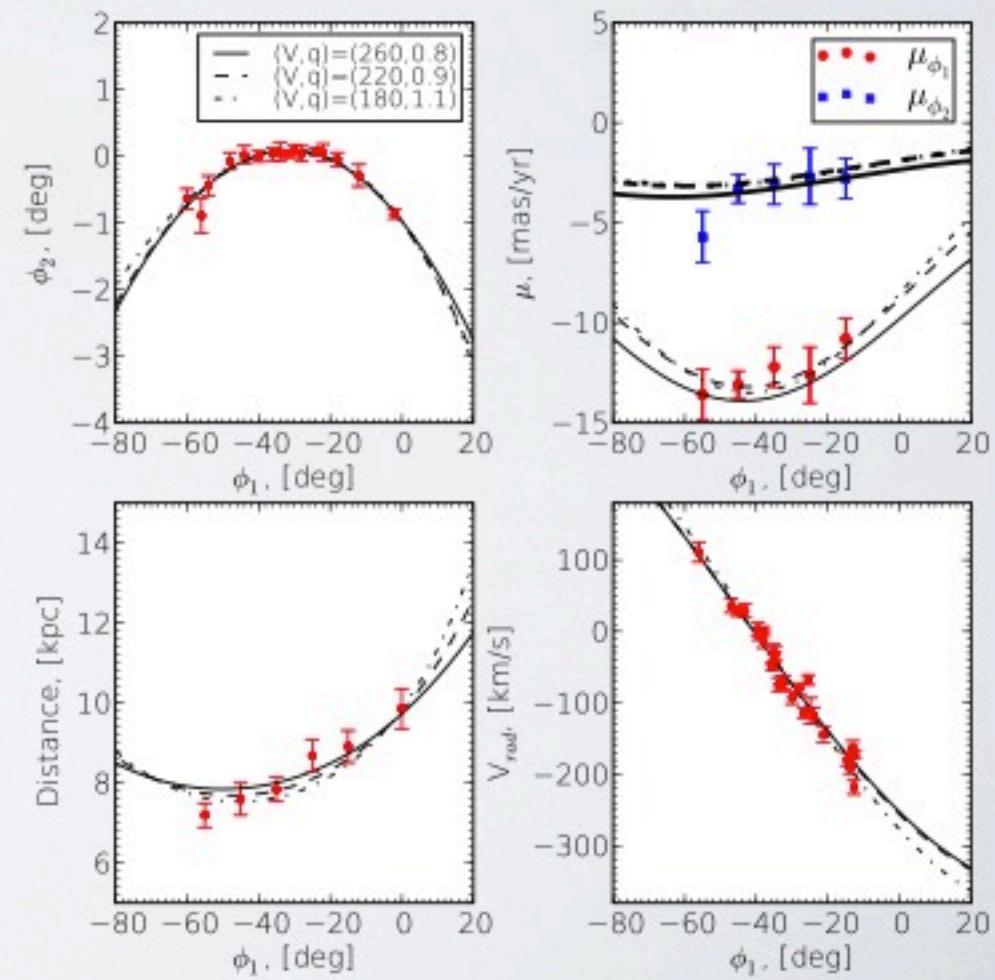

Sub-structure is important and far from being produced only by the Sgr stream.

# Streams as gravitational probes

Koposov *et al.* (2010)



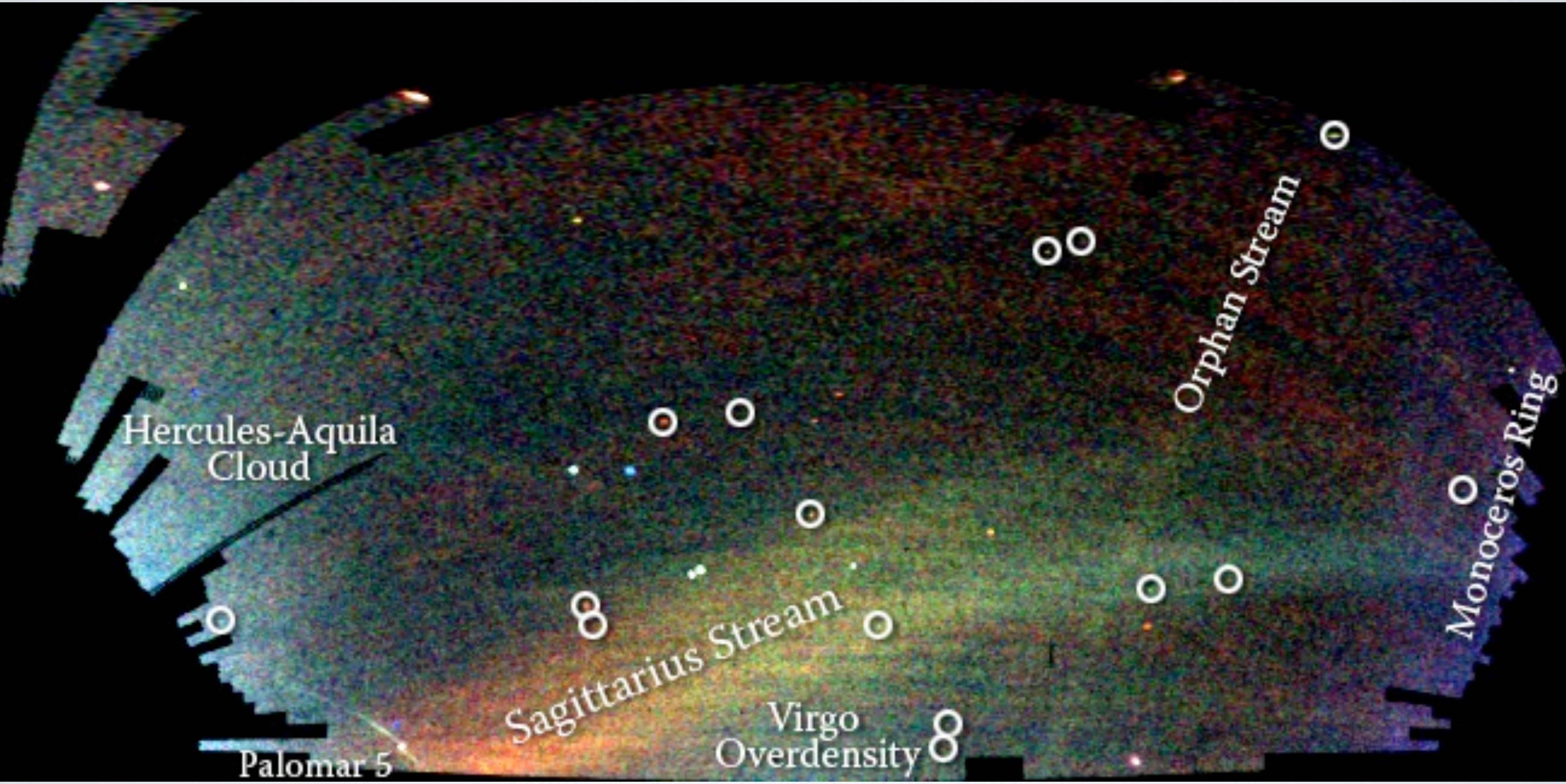



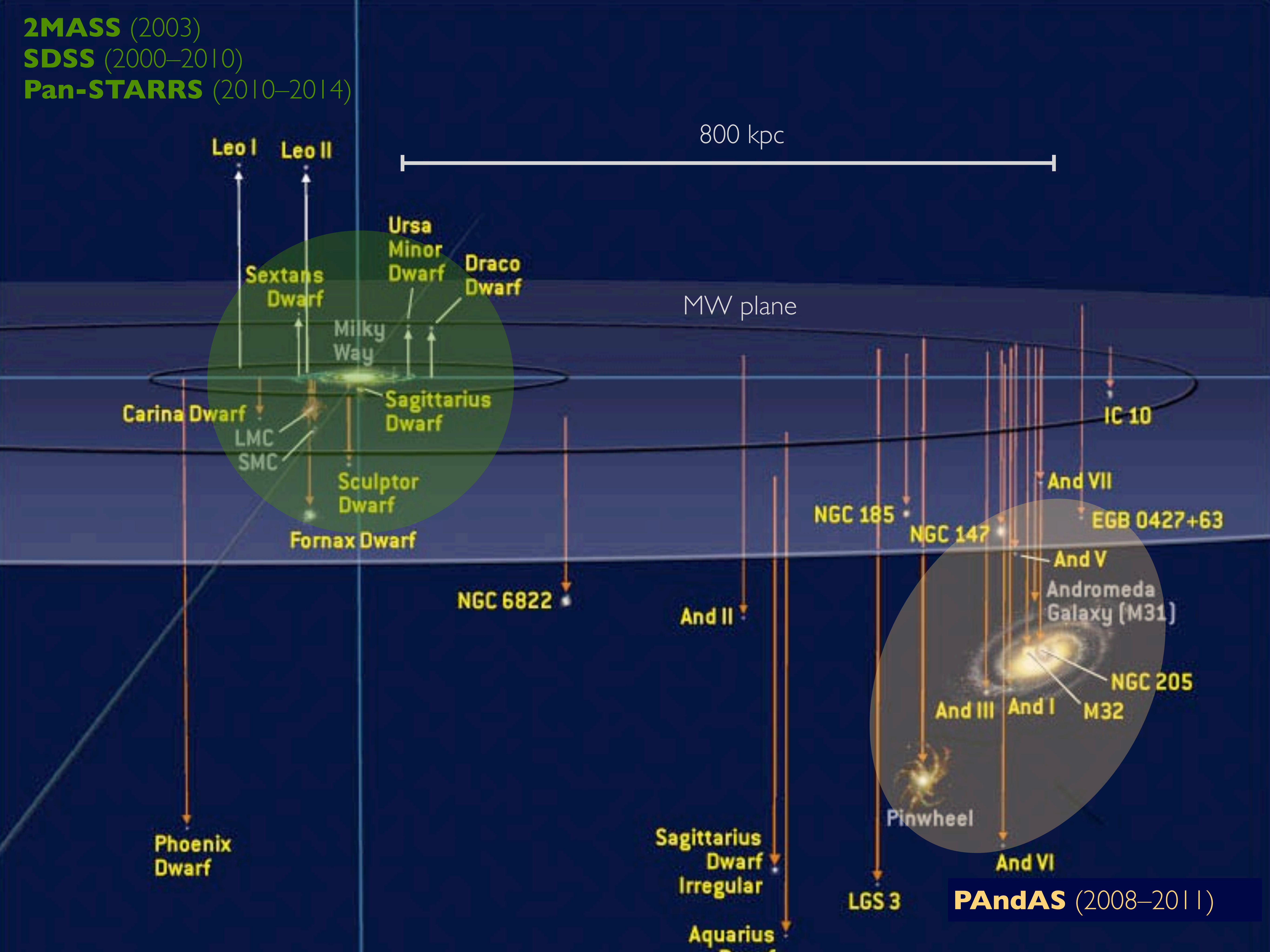

- Halo stracers can also be used in a similar way (BHB stars, Xue et al. 2008)

# The stellar halo

*A view from inside*




Belokurov *et al*. (2006)

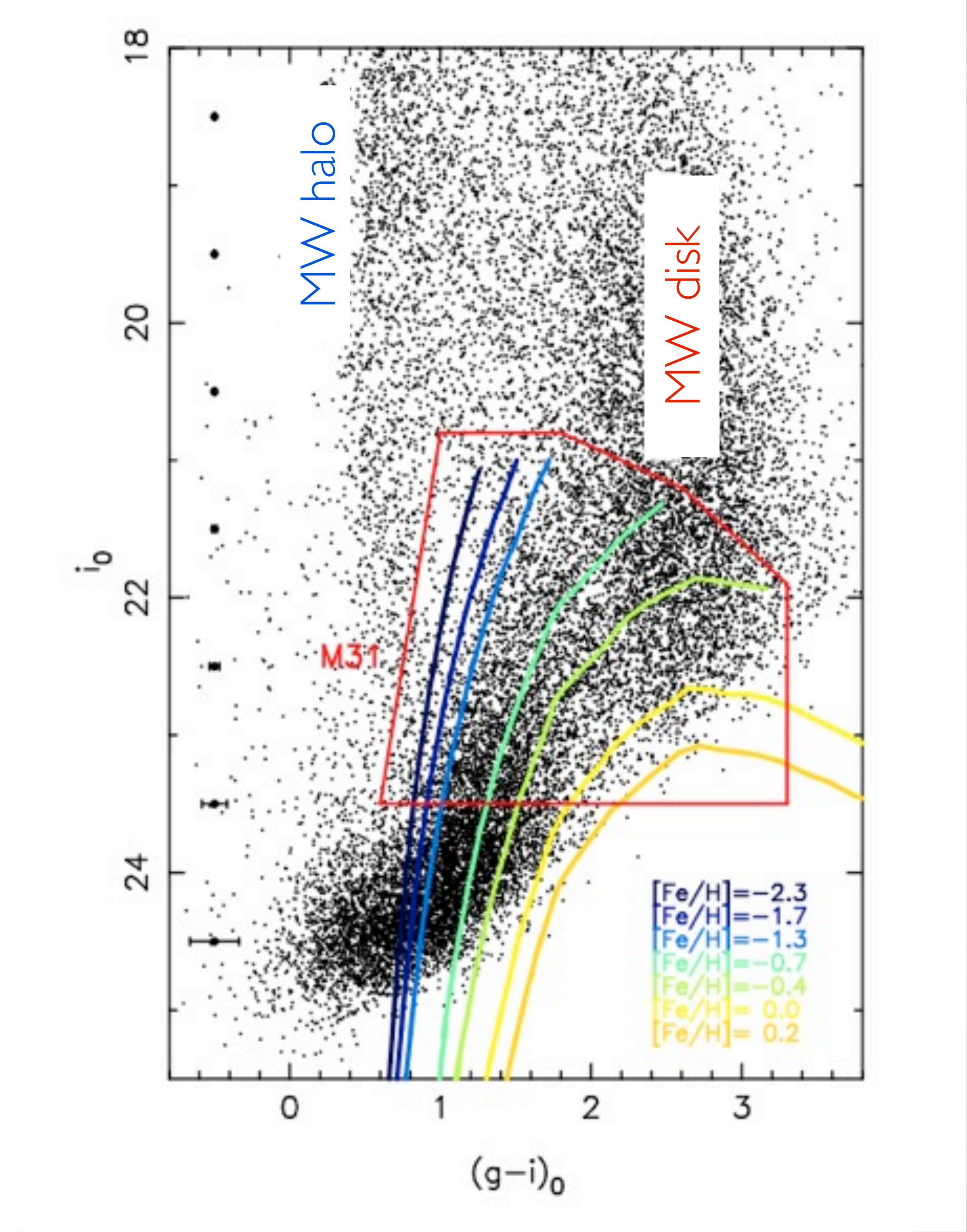


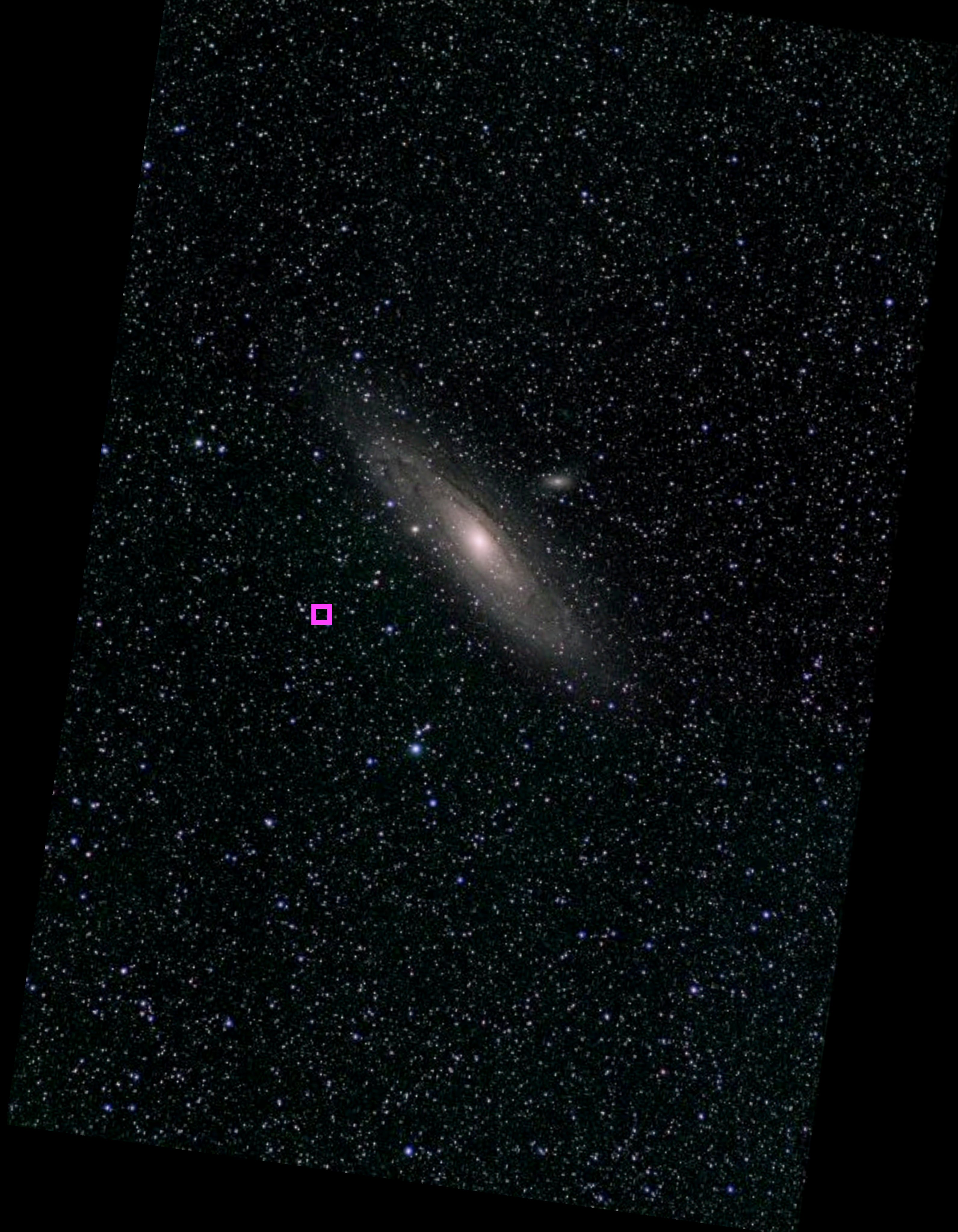
**2MASS** (2003)
**SDSS** (2000–2010)
**Pan-STARRS** (2010–2014)
800 kpc
MW plane
Leo I
Leo II
Ursa Minor Dwarf
Draco Dwarf
Sextans Dwarf
Milky Way
Carina Dwarf
LMC
SMC
Sagittarius Dwarf
Sculptor Dwarf
Fornax Dwarf
Phoenix Dwarf
NGC 6822
And II
Sagittarius Dwarf Irregular
Aquarius
LGS 3
NGC 185
NGC 147
And VII
EGB 0427+63
IC 10
And V
Andromeda Galaxy (M31)
NGC 205
M32
And III
And I
Pinwheel
And VI
**PAndAS** (2008–2011)

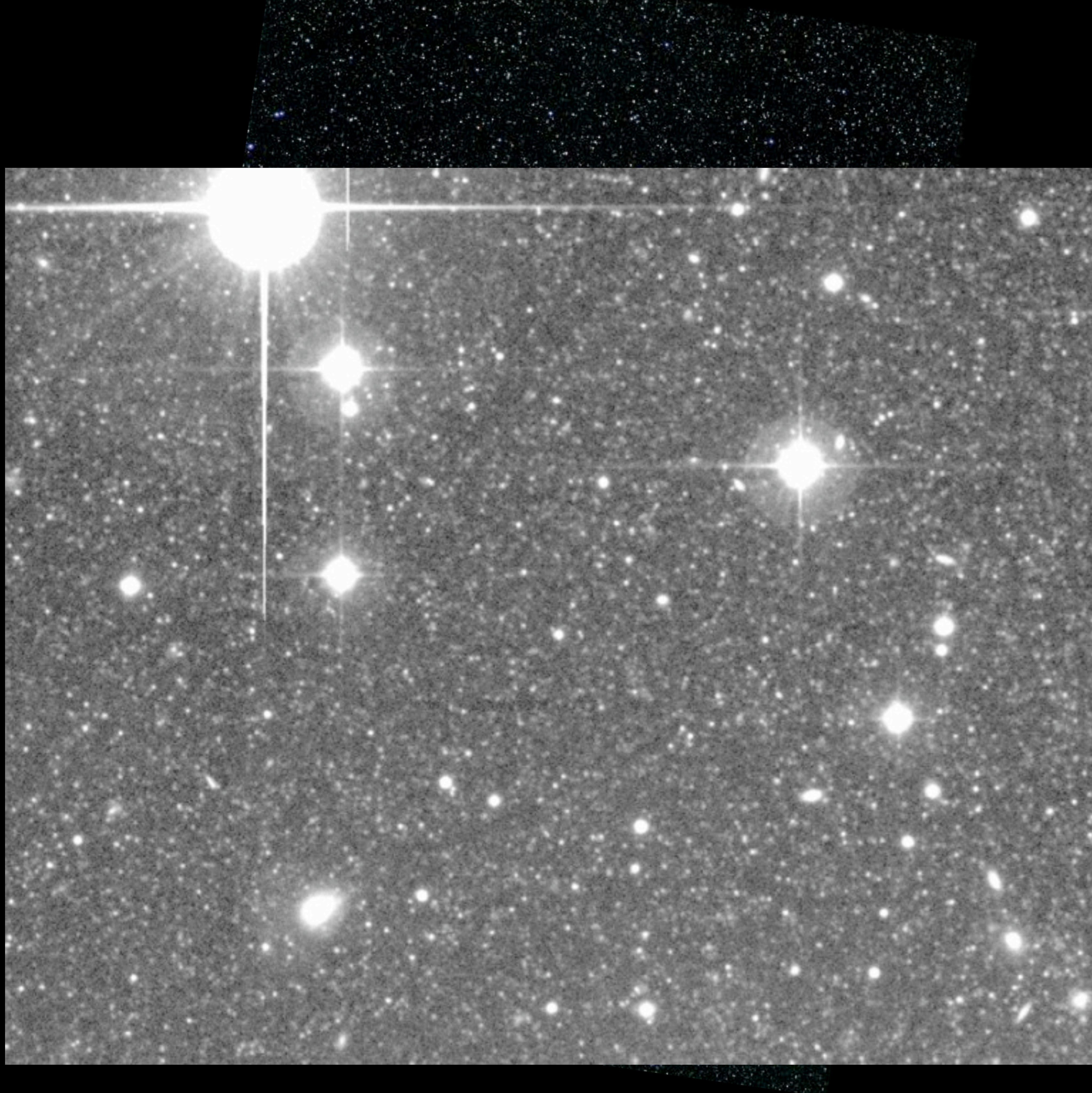
# Andromeda

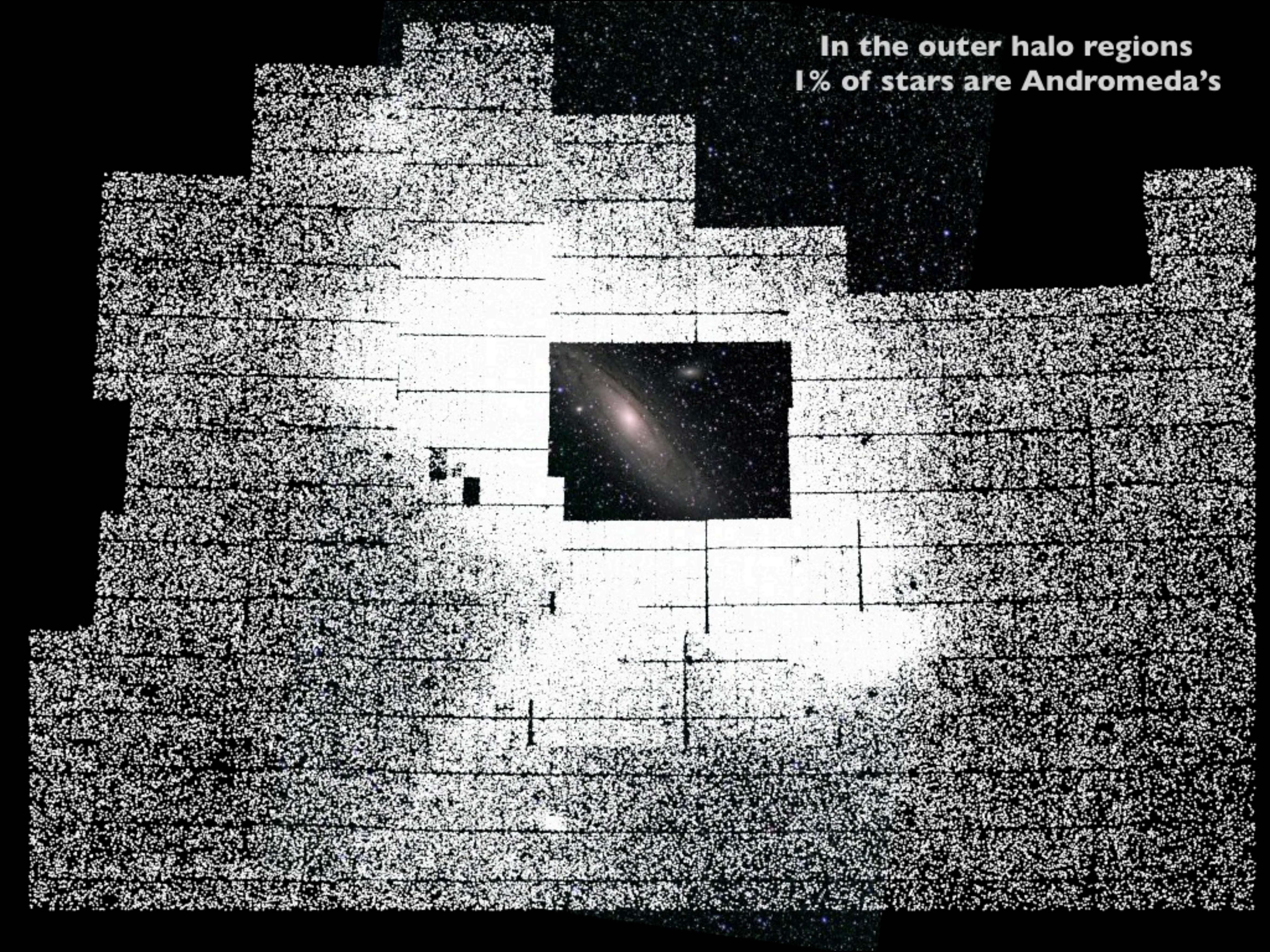
*The **P**anoramic **And**romeda **A**rchaeological **S**urvey*

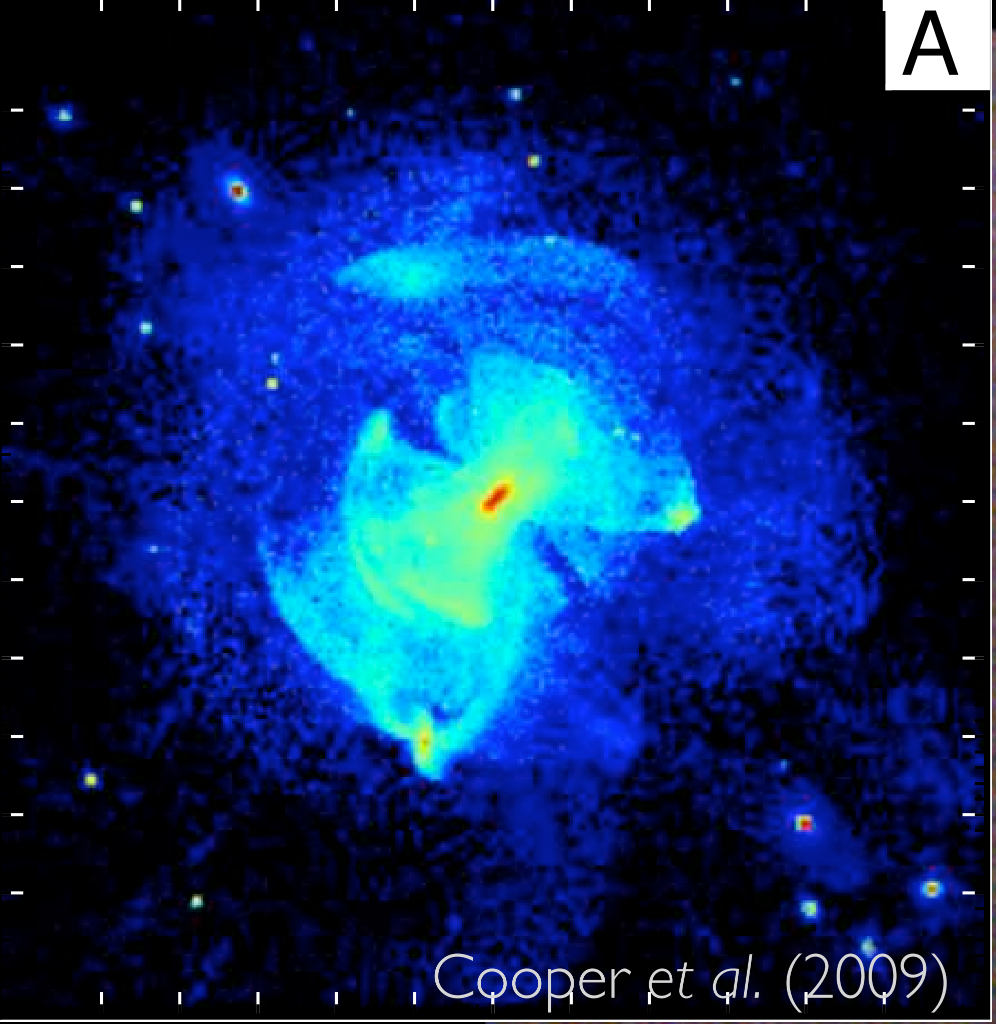
- M31 @ ~800 kpc
  - Reachable
  - Not as detailed as MW
  - ***But*** a panoramic view
- PAndAS
  - 45-minute observations/deg$^2$
  - 4m telescope (CFHT)
  - 2 bands (g and *i*)



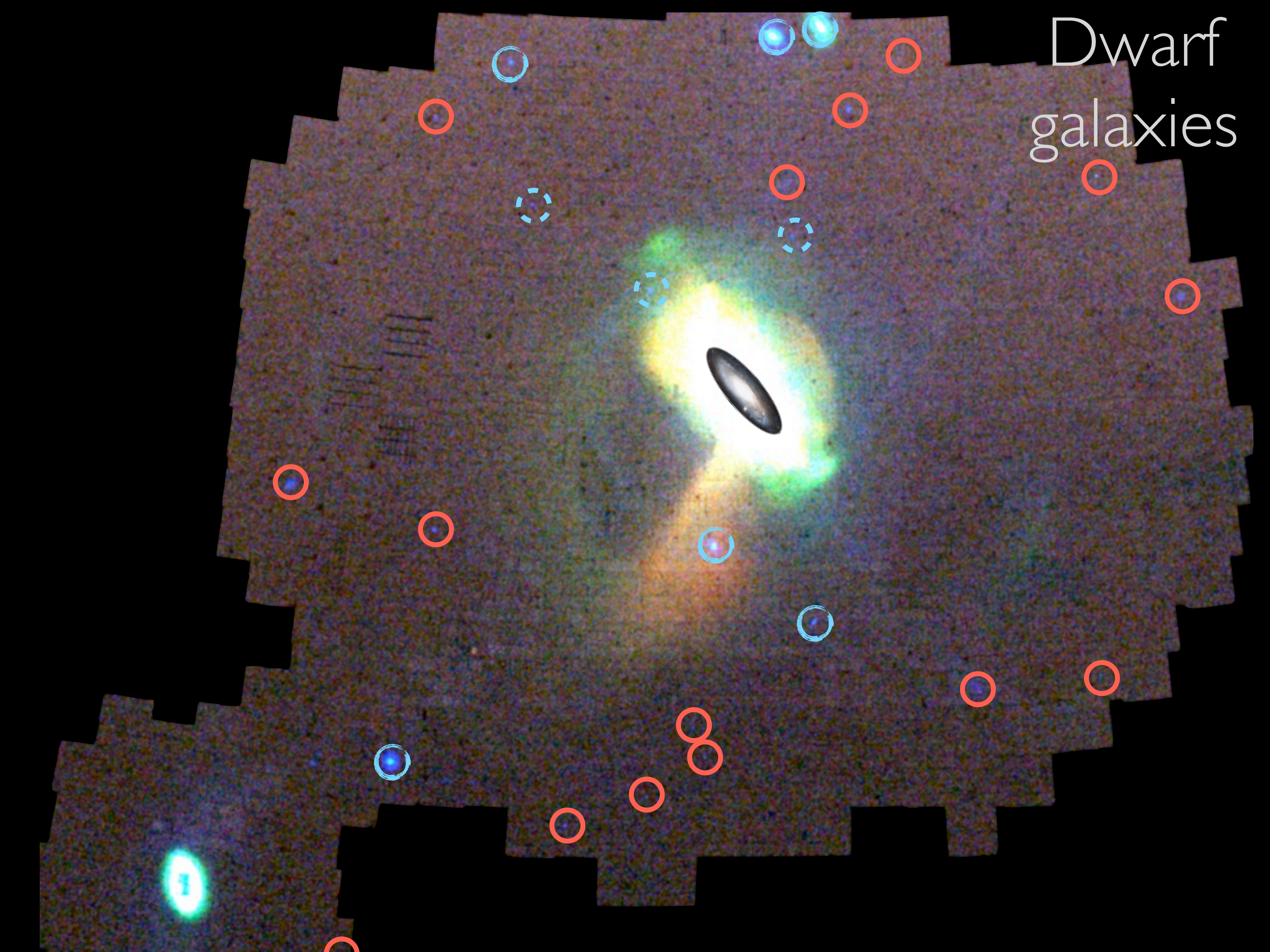





In the outer halo regions
1% of stars are Andromeda's



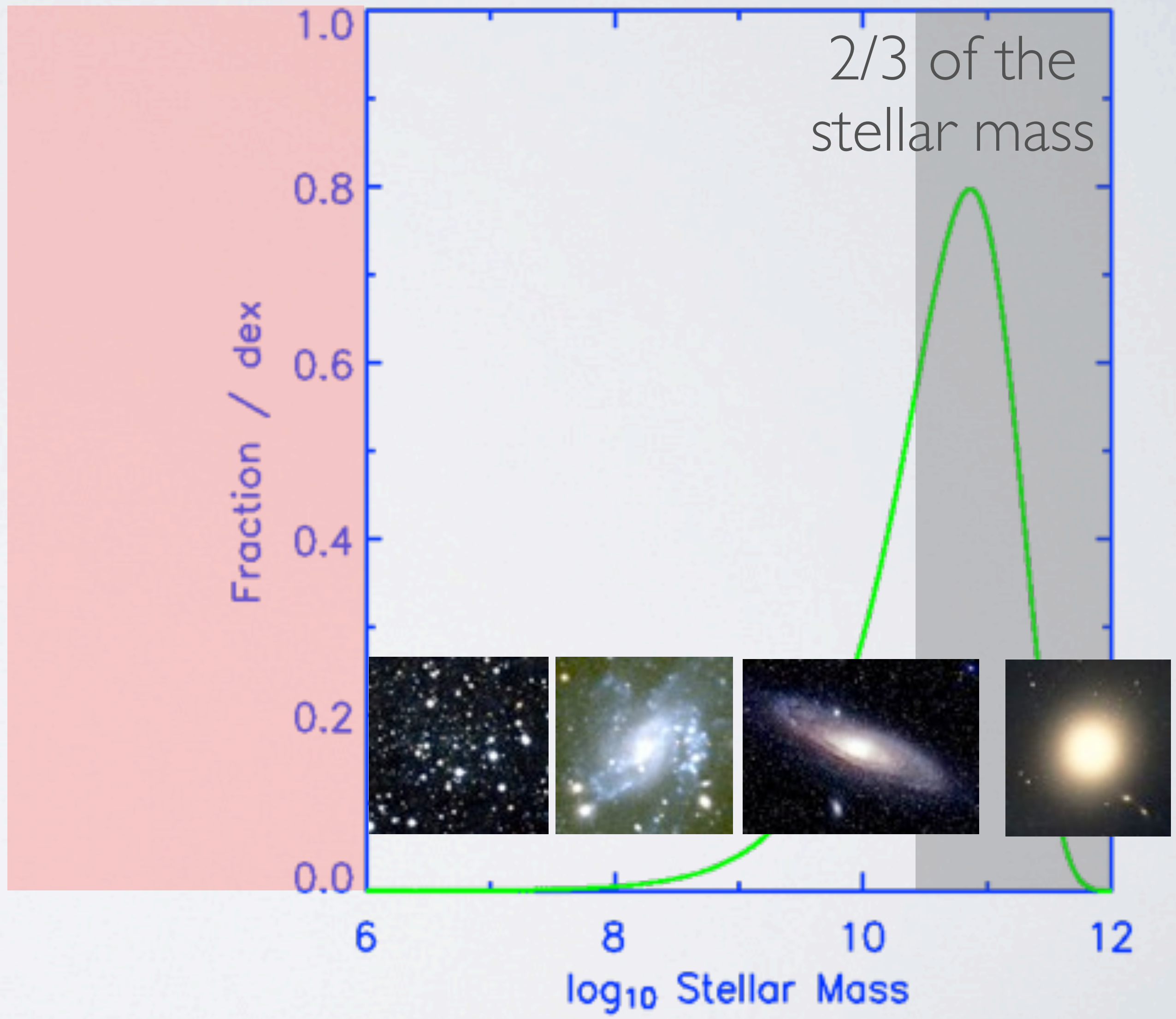

- *Using detailed obs of galaxy structure to test cosmology/galaxy formation*
  - *amount of structure in qualitative agreement with simulations*
- *Panoramic view from large surveys (2MASS, SDSS, Pan-STARRS, PAndAS…)*
  - *using CMD tracers (MSTO stars, BHB stars, RGB stars)*
  - *accurate mapping of disk, halo,…*


Dwarf
galaxies

# Why study the faintest galaxies?

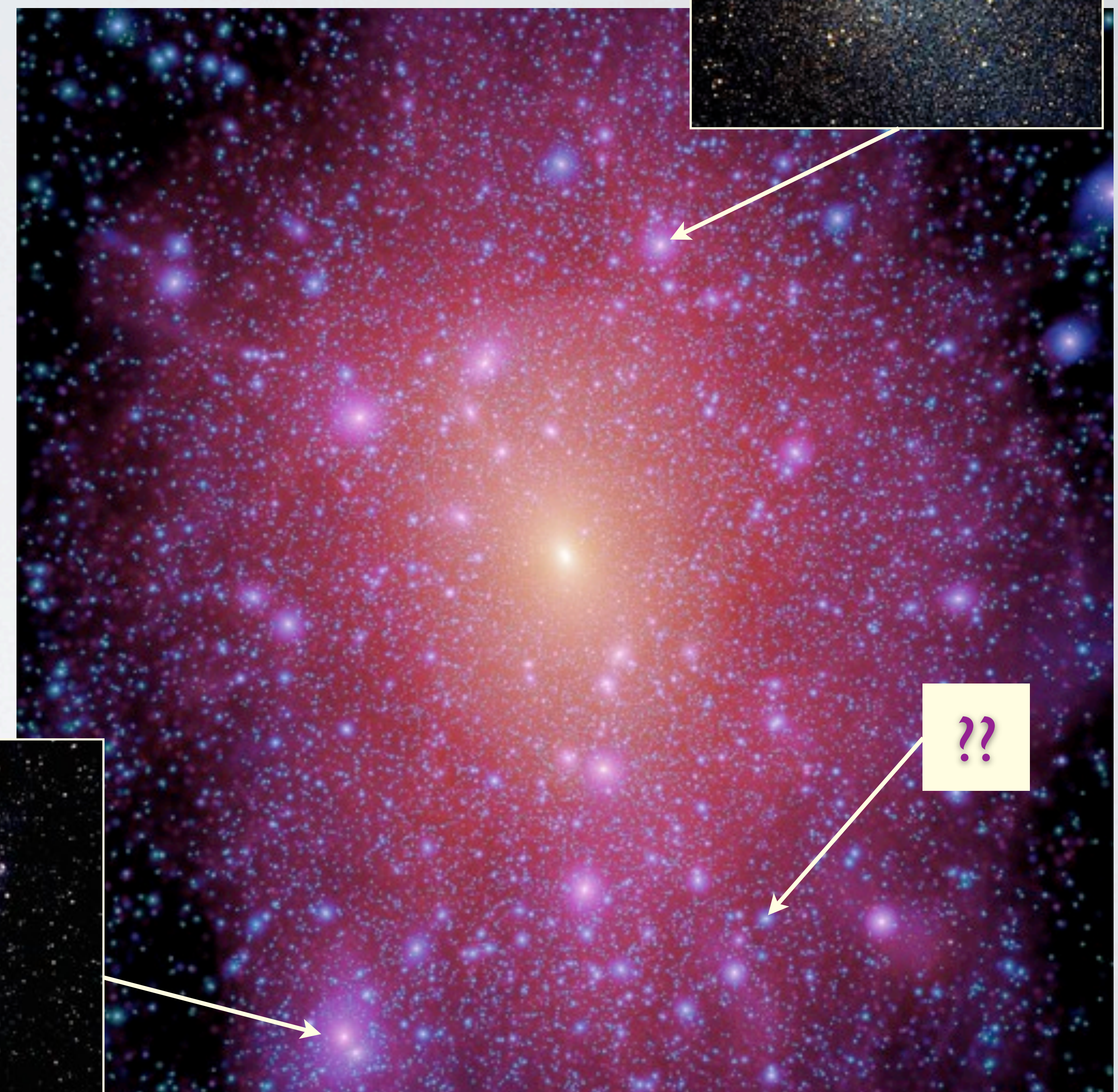
- Massive galaxies contain the majority of the universe's stellar mass
- Is there a faint end to galaxy formation?
  - sensitive to star formation suppression mechanisms
  - "missing satellite crisis"?
- Which dark matter halos contain stars?
  - What sets their numbers? their properties (luminosity, size, shape)?

*Contribution of galaxies of mass M to the universe's stellar content*



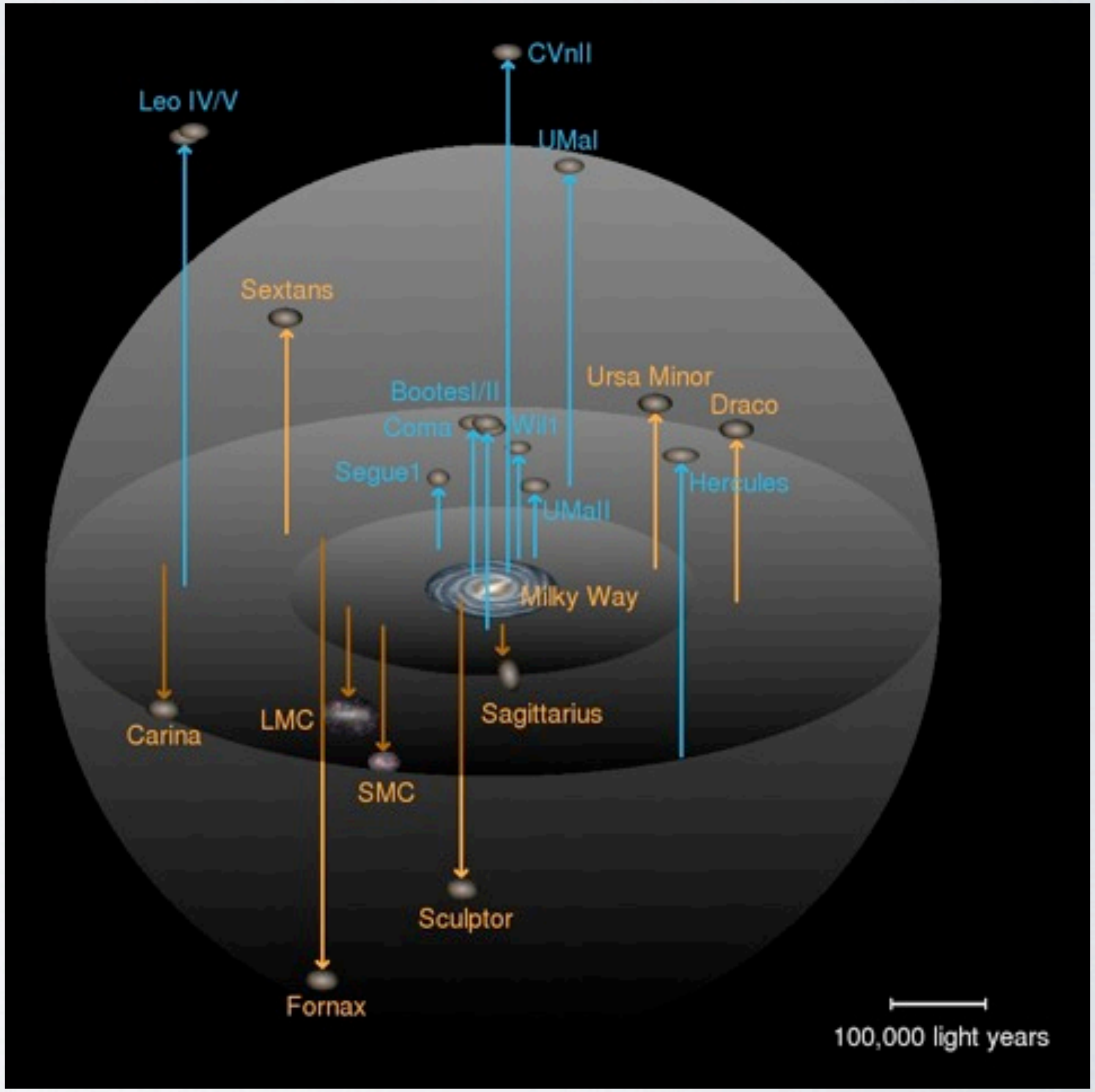
# Dwarf galaxies

- ***Interesting in their own right***
  - Is there a faint limit to galaxy formation?
- ***Interesting as a population***
  - Do they follow cosmology predictions?

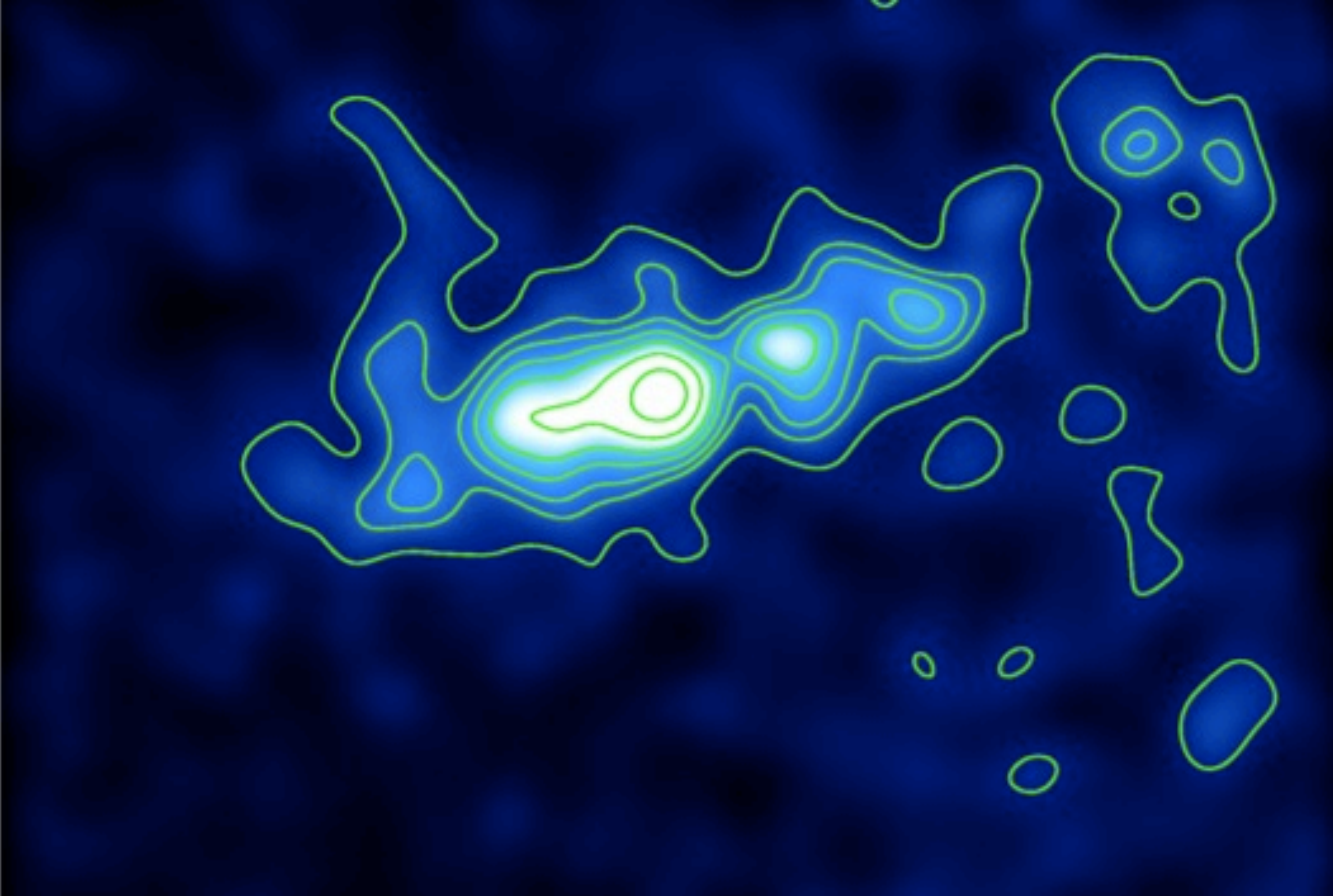



# Where the Local Group comes into play

- ~20 dwarf galaxies known until 2003
- Many new discoveries
  - 12–15 around the MW (SDSS)
  - ~20 around M31 (mainly PAndAS)

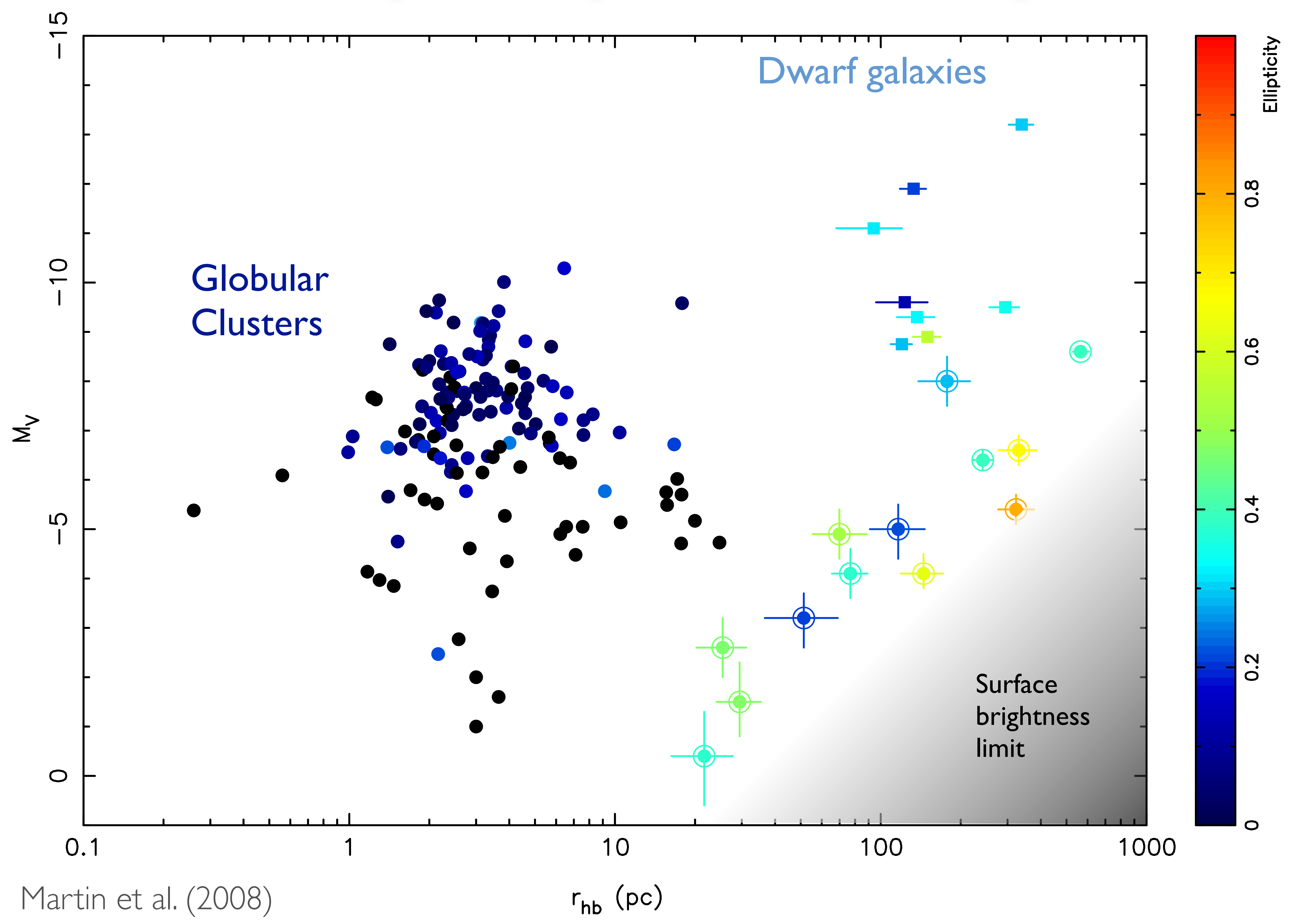


*The Hercules dwarf galaxy view by the LBT (Coleman et al. 2007)*



*The Hercules dwarf galaxy view by the LBT (Coleman et al. 2007)*

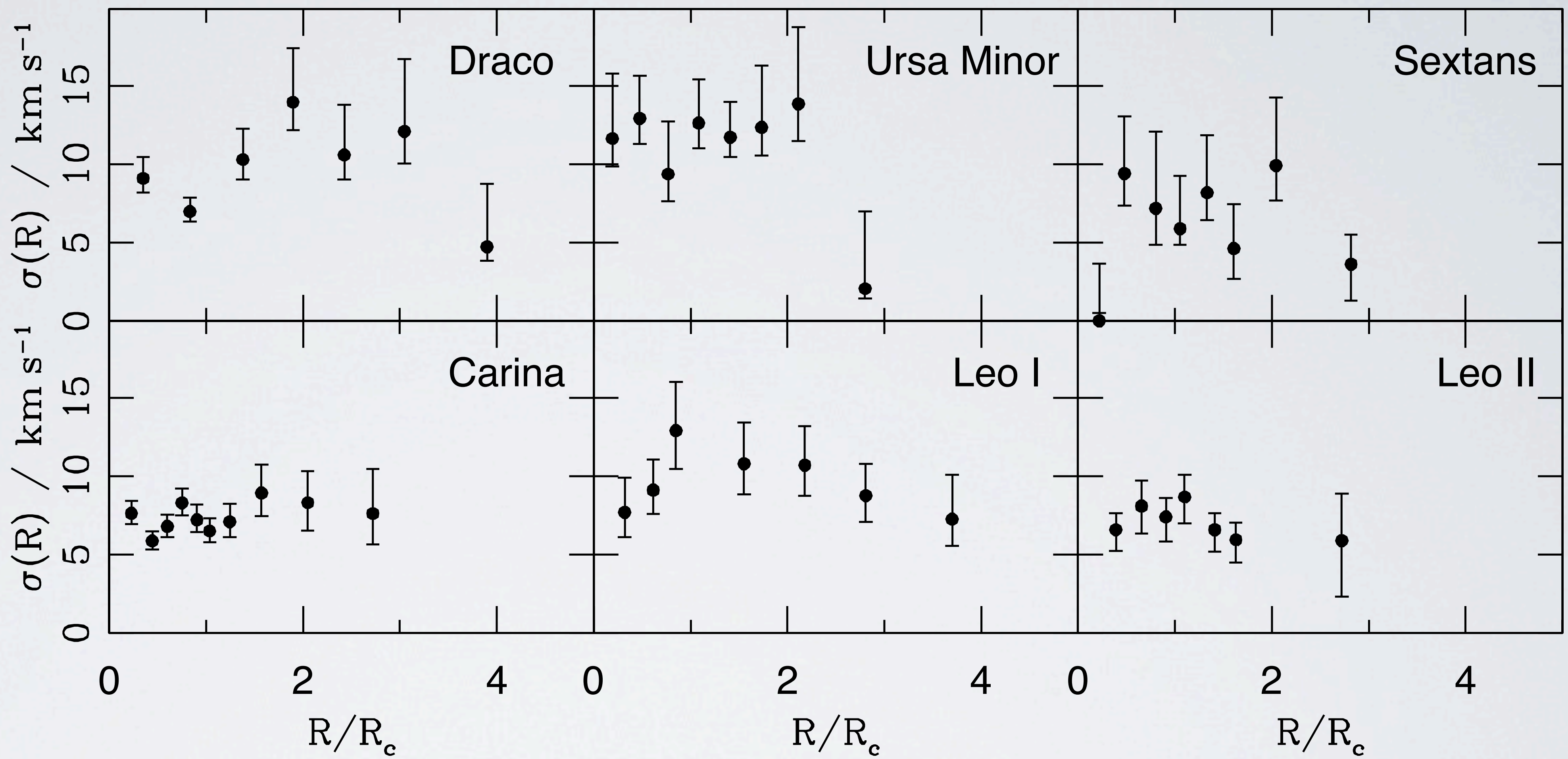
# The Milky Way satellite system



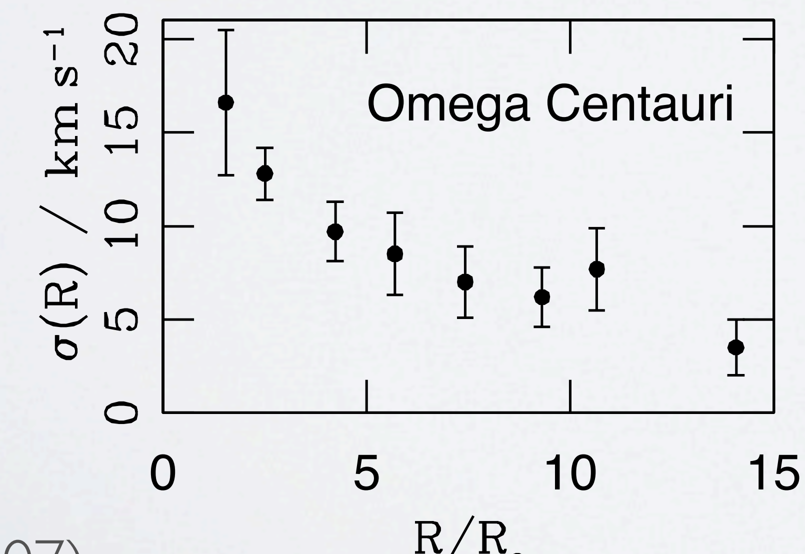

Martin et al. (2008)

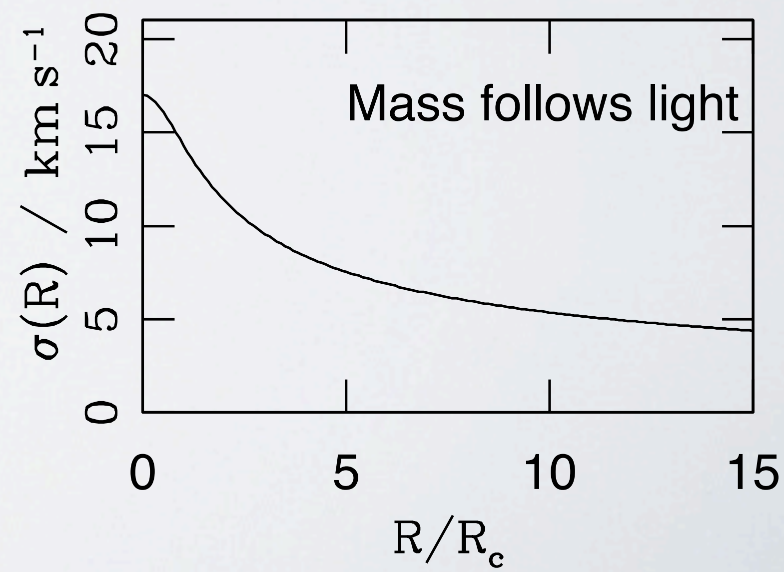
# Dwarf galaxies vs. Globular Clusters

***Dwarf galaxies:***
extended dark matter halos



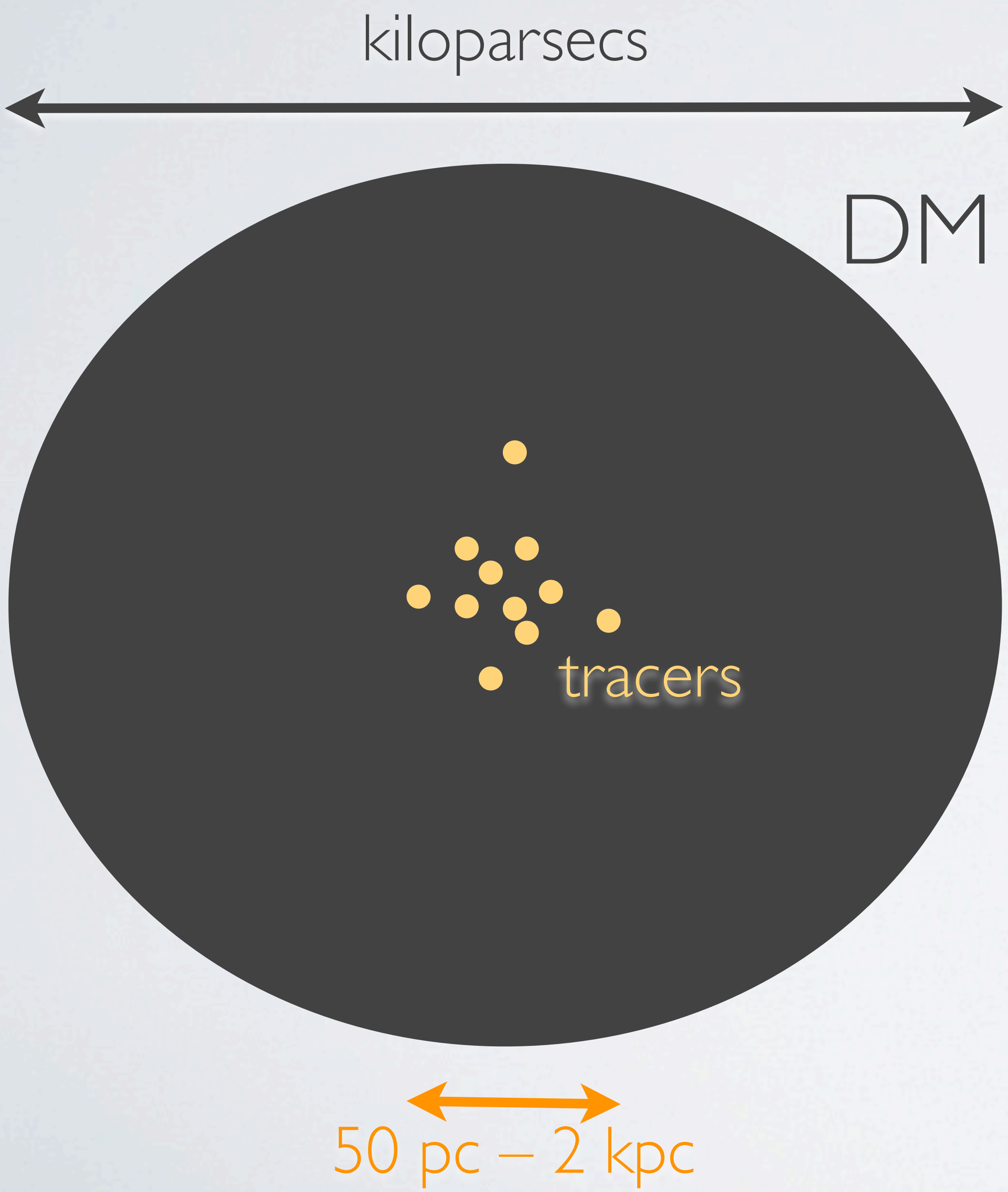

***Globular Cluster:***
no dark matter




Gilmore et al. (2007)

# Estimating masses




- Velocity dispersion → instantaneous mass estimate of the system
  - Jeans equation – for a collisionless, spherical system, in equilibrium

vel. disp.

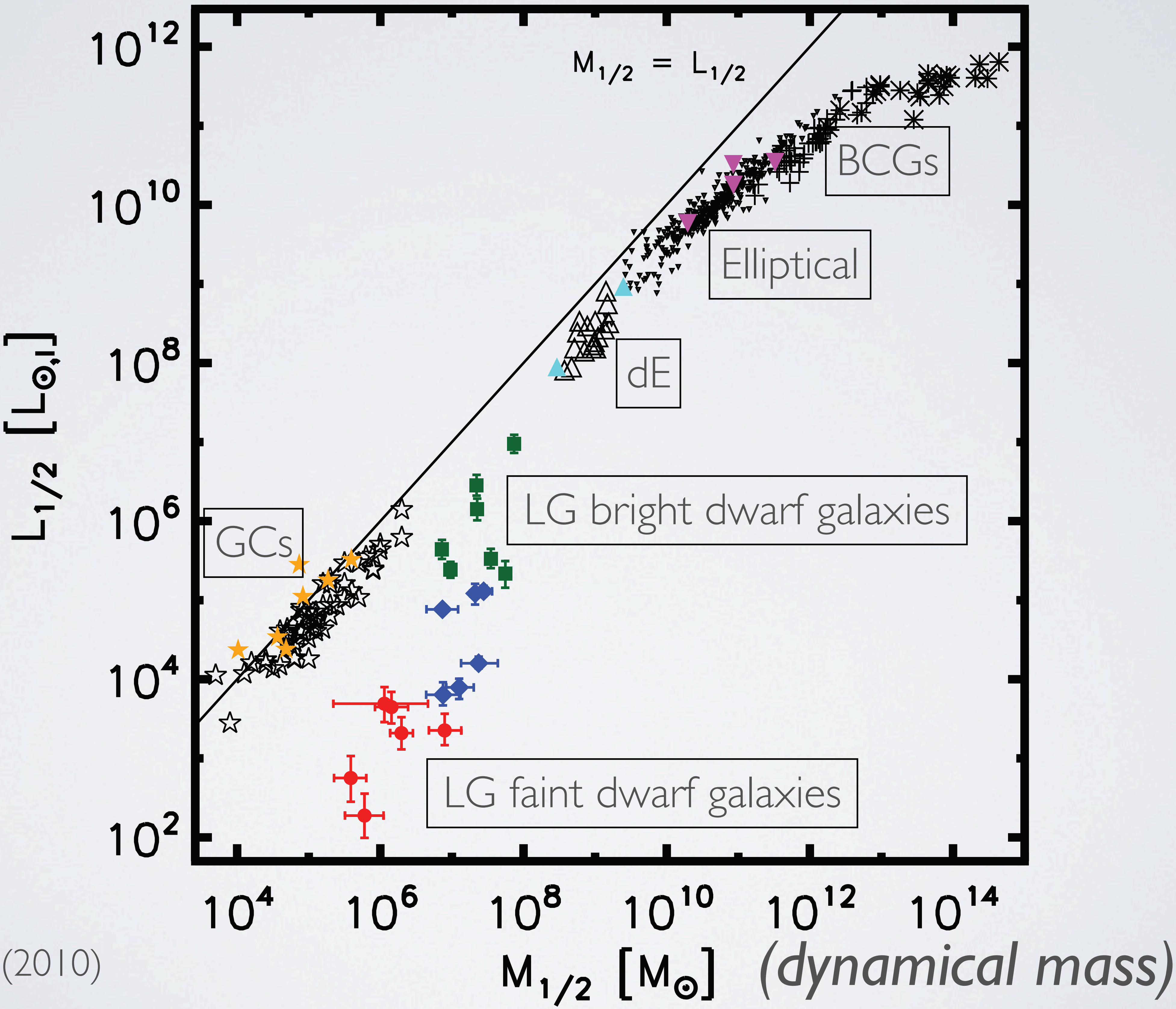
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{d\nu\sigma_r^2}{dr} + 2\frac{\beta\sigma_r^2}{r}\right),$$

stellar density distribution

orbit anisotropy

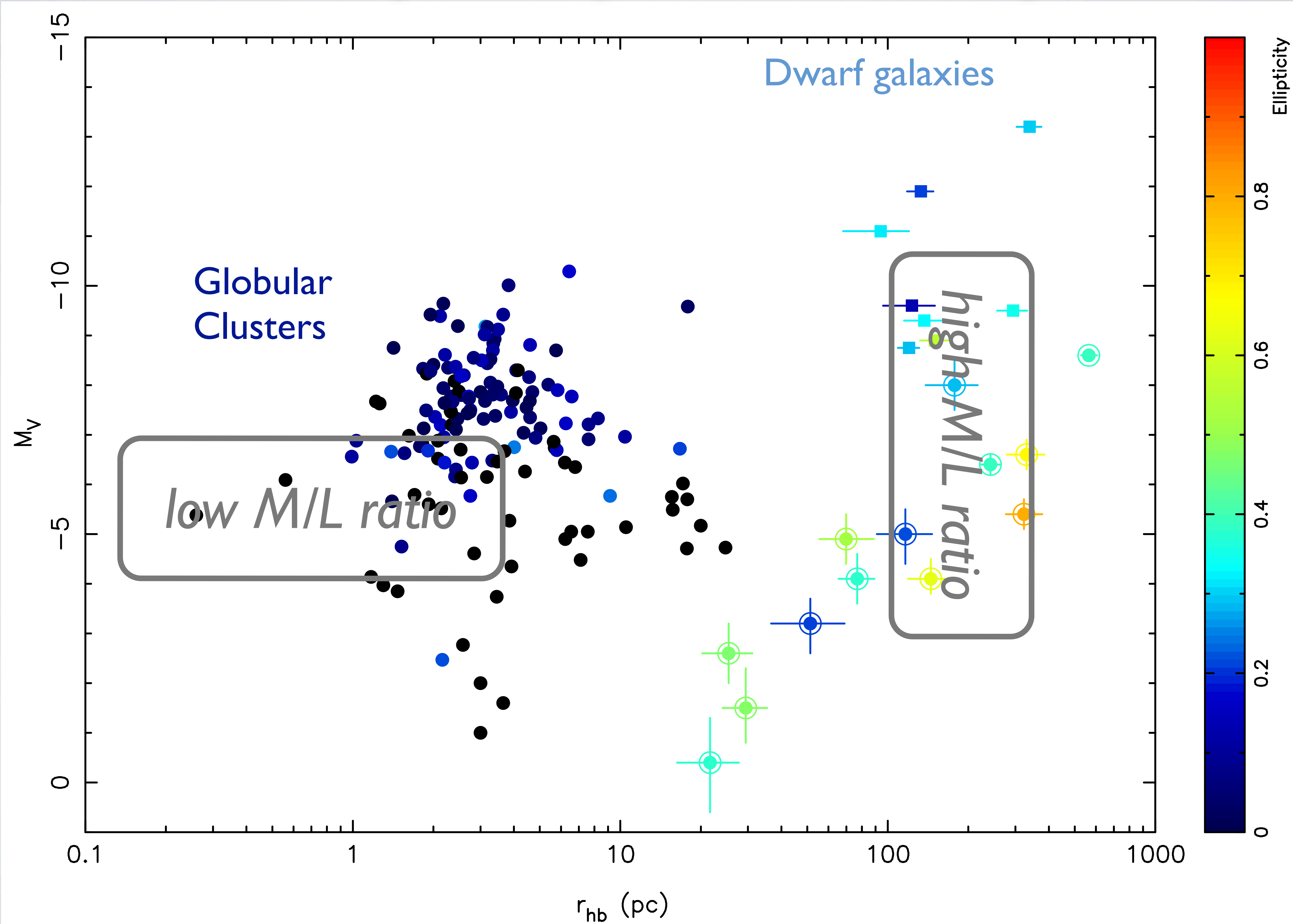
$$\beta = 1 - \frac{\langle v_t^2 \rangle}{\langle v_r^2 \rangle}$$

# The mass of spheroidal systems




Wolf et al. (2010)

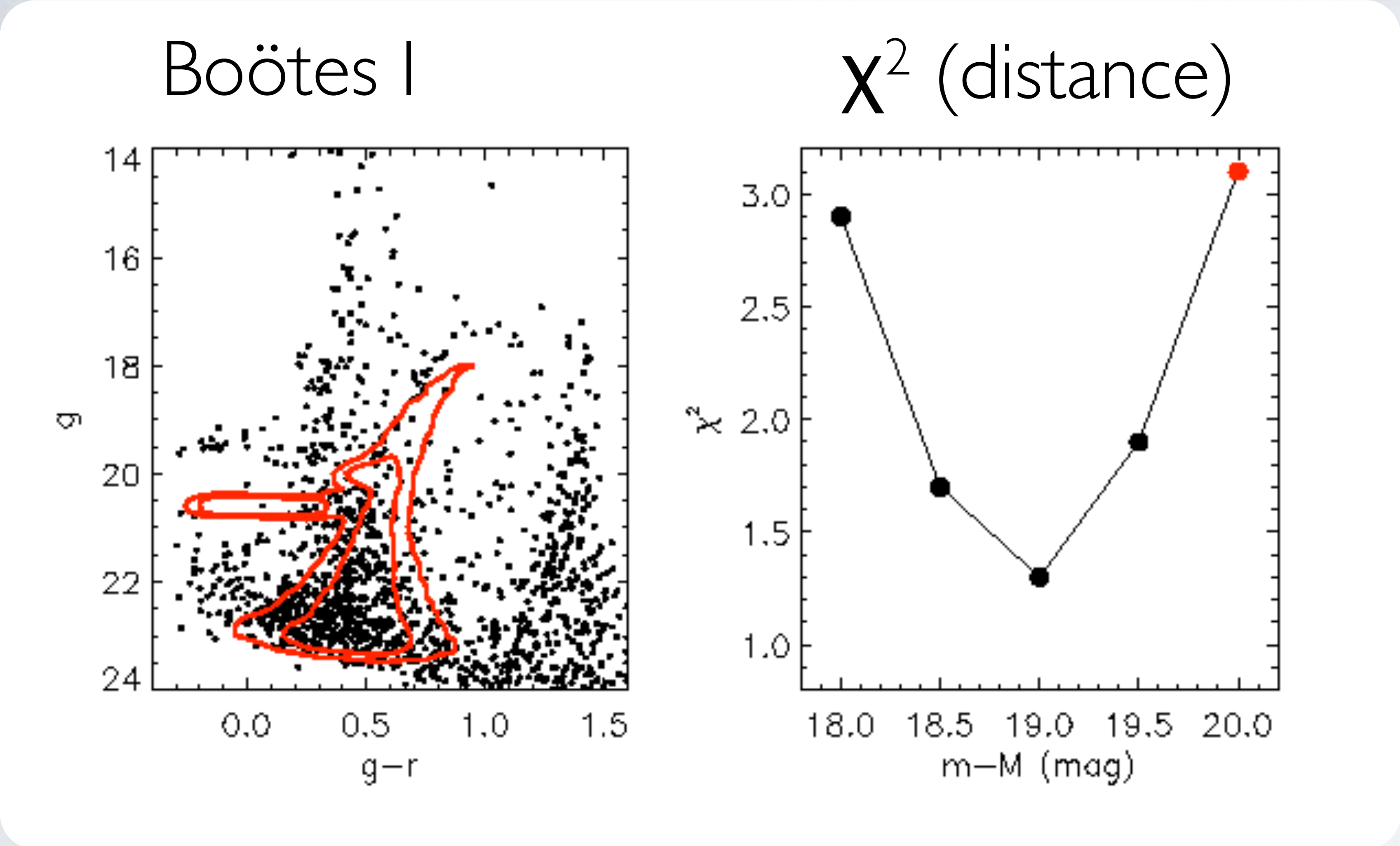
# The Milky Way satellite system



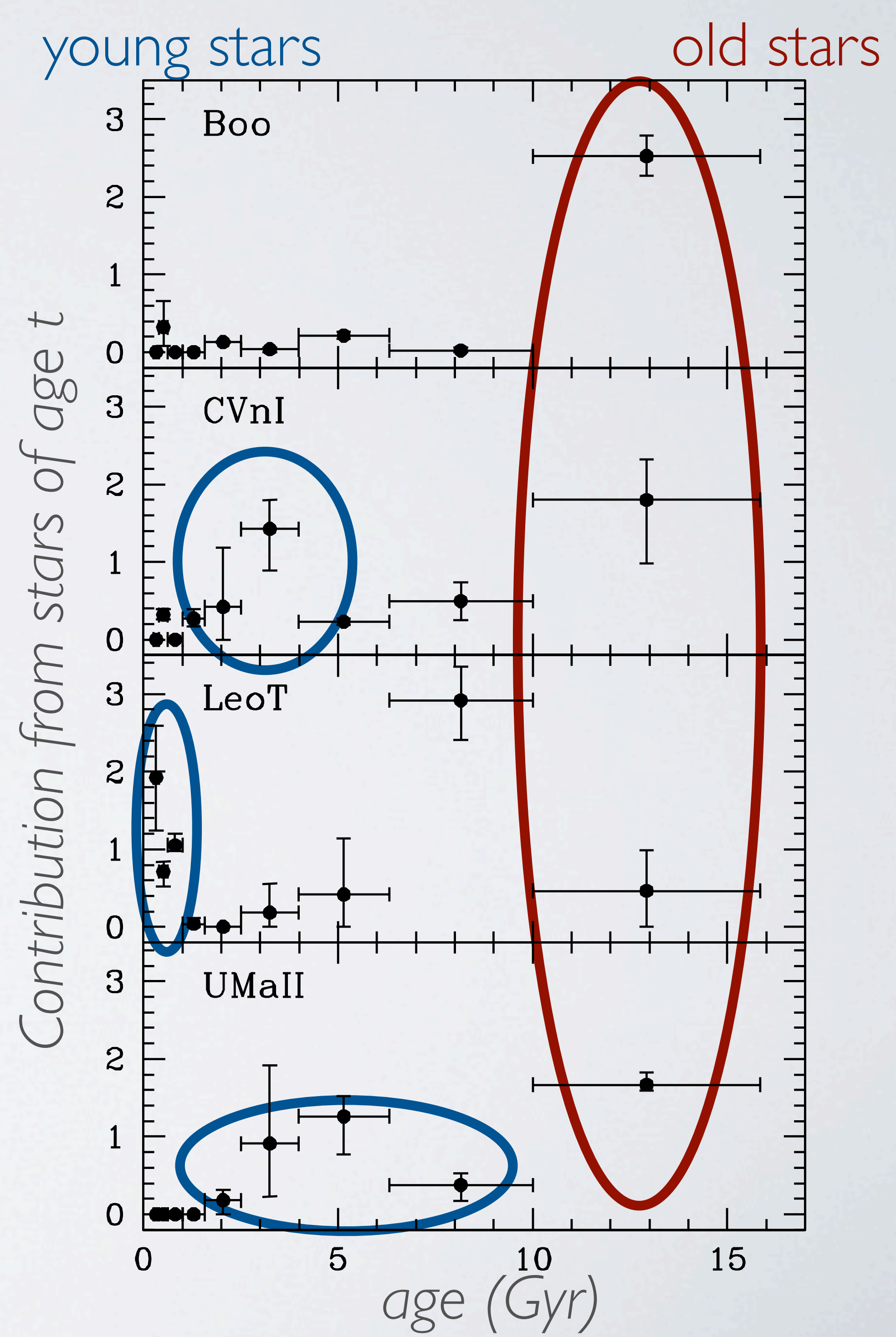
# They have complex stellar populations

de Jong et al. (2008)

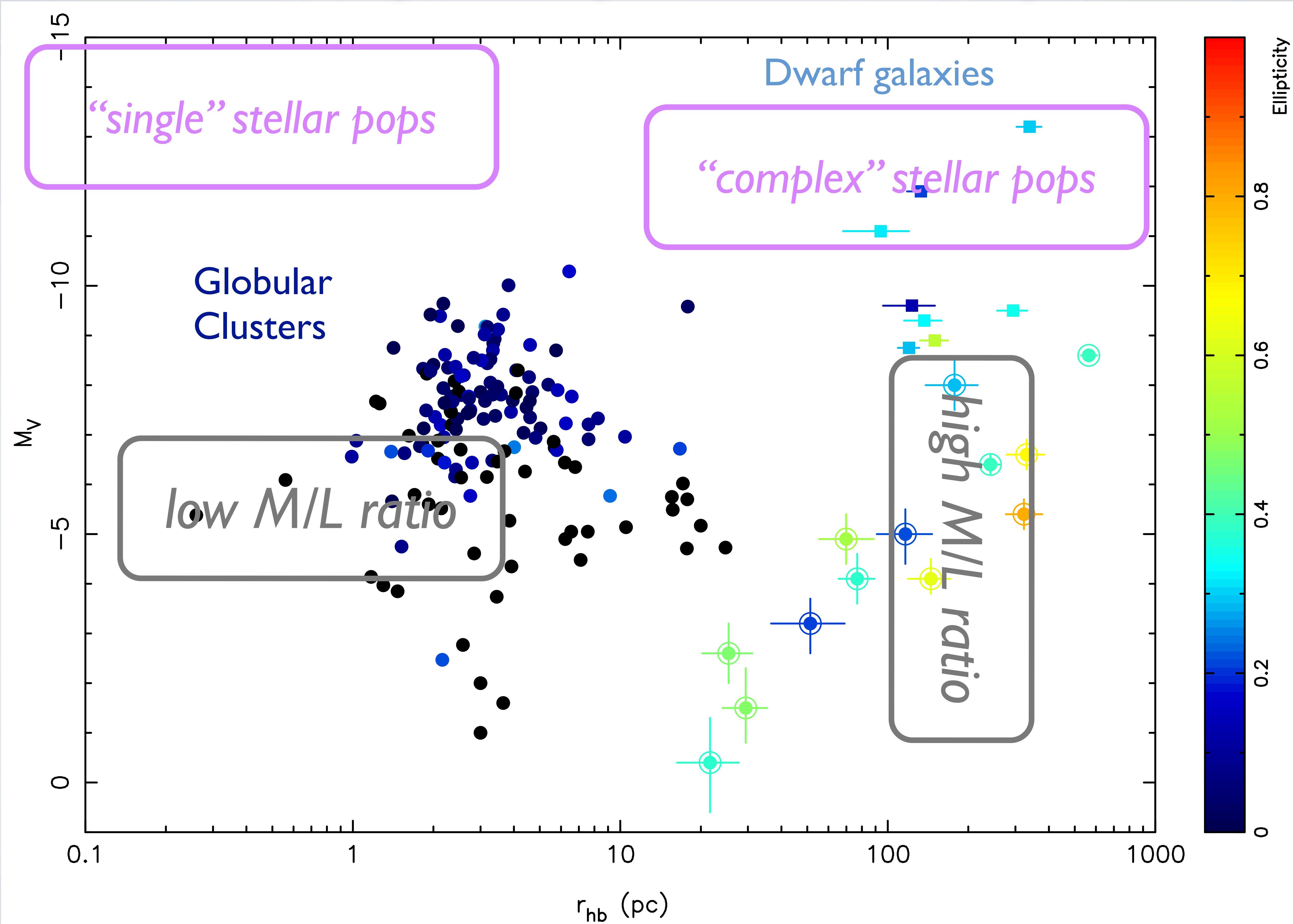
- Automatically fitting distance, metallicity, age from the CMD




- Complex SFH
  - fundamentally different from star clusters
  - Spread in [Fe/H]

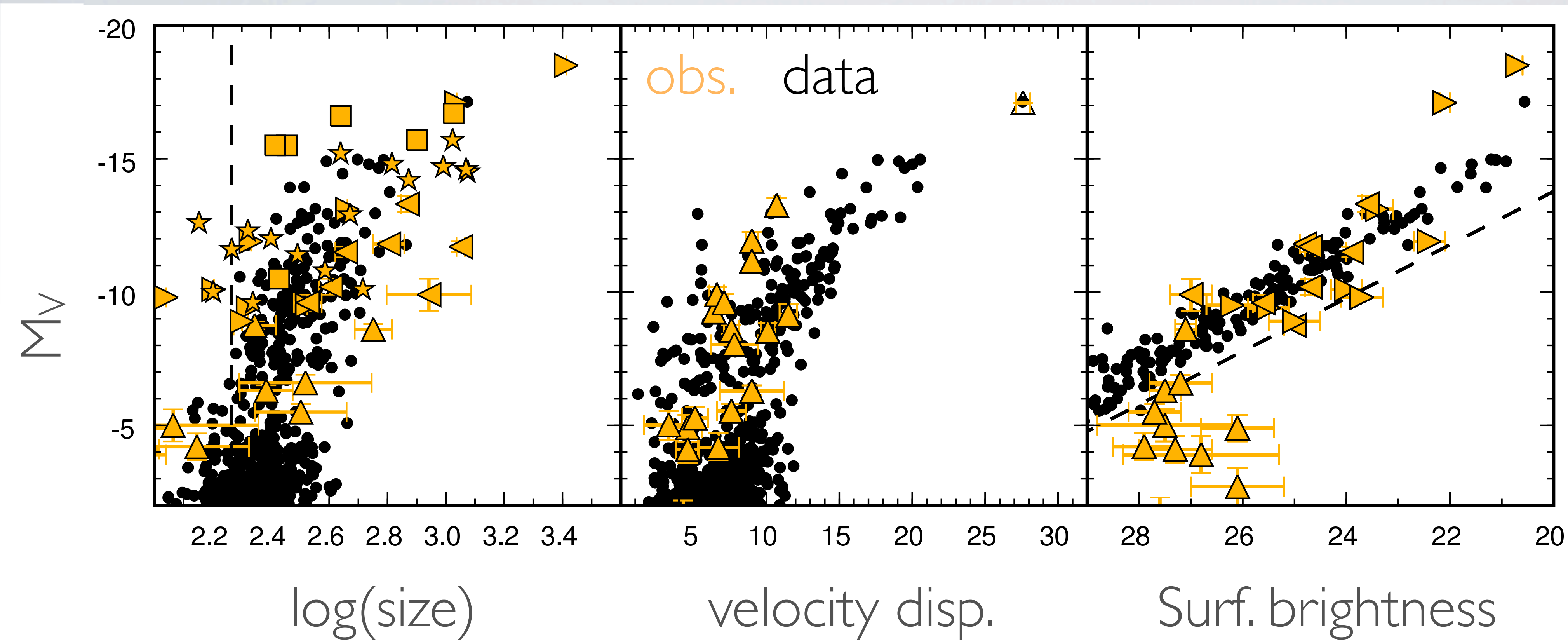


# The Milky Way satellite system

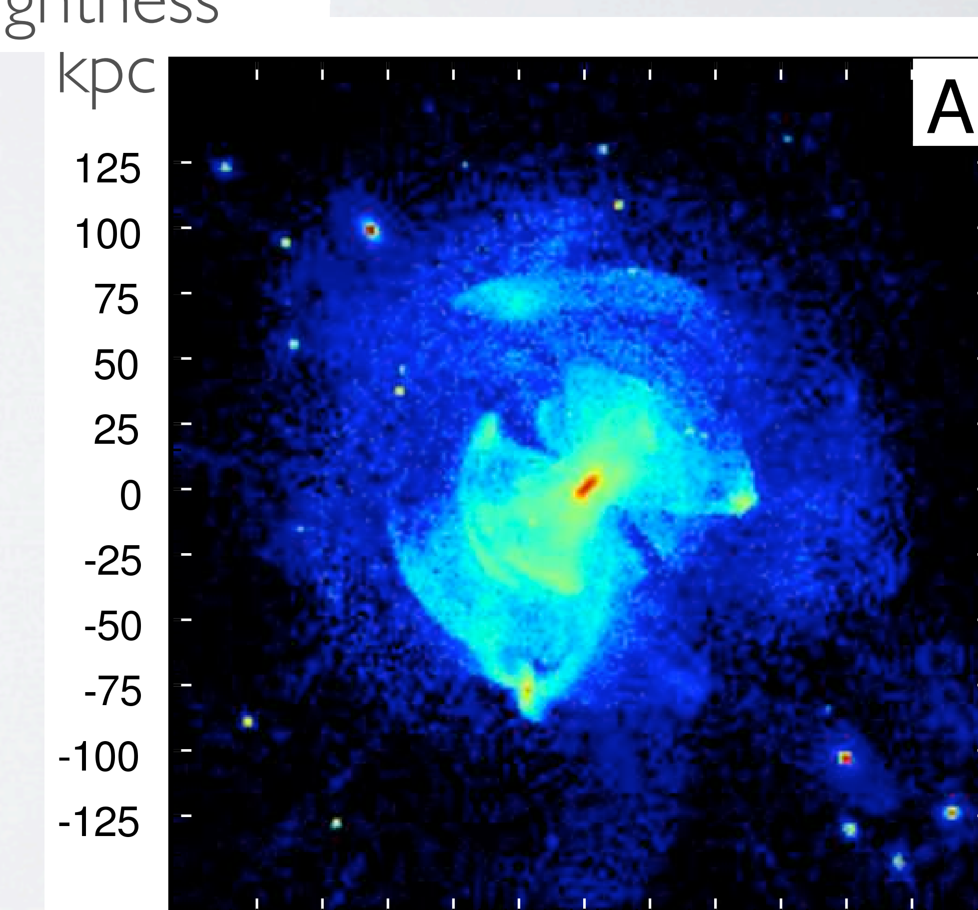


# Testing the cosmology with dwarf galaxies

Koposov *et al.* (2009)
Macciò *et al.* (2009)
*Cooper et al. (2010)*
……



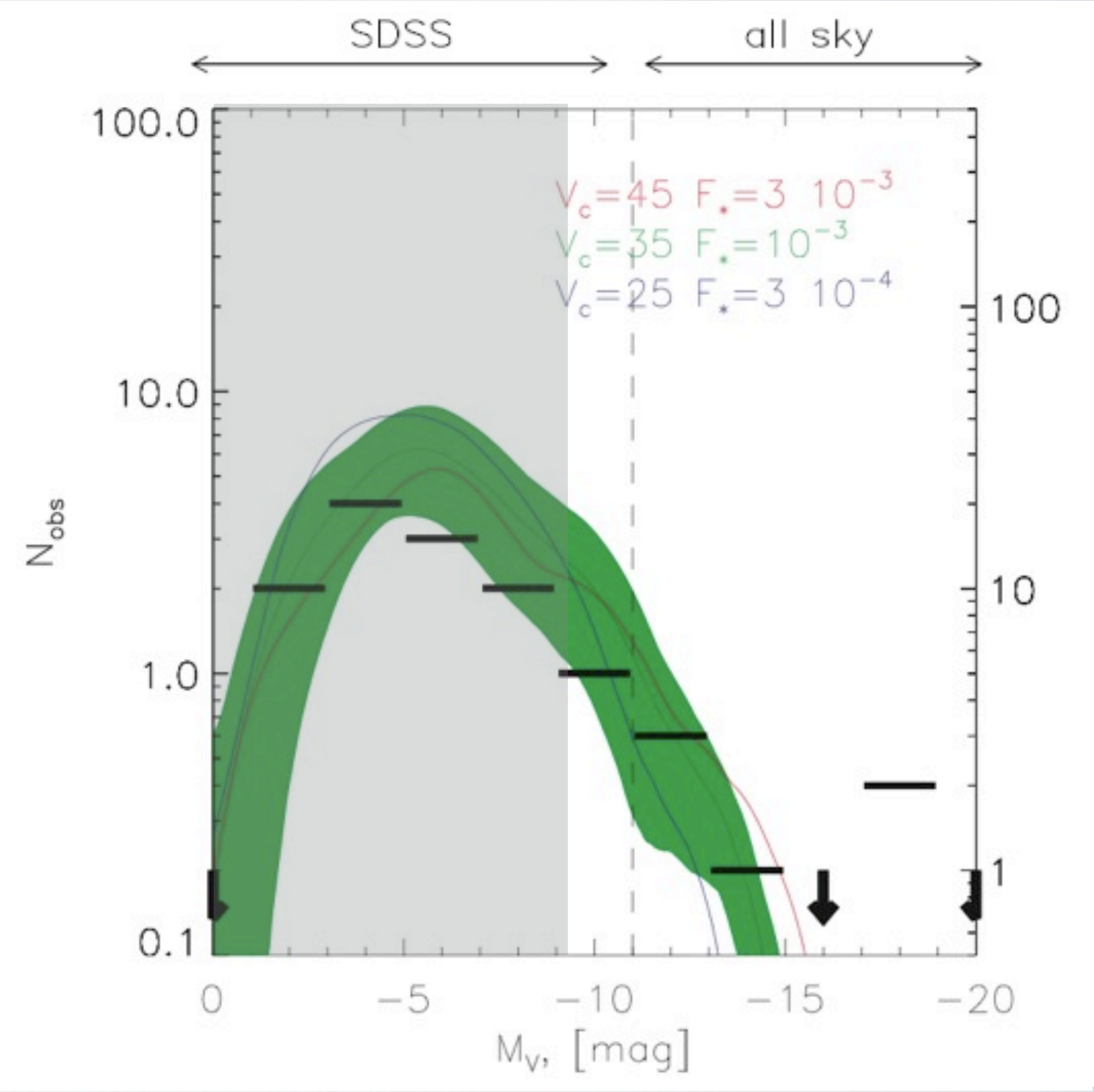

- Observed galaxies are broadly reproduced
  - galaxies with a few 100s of stars are expected
  - Will we be able to find them?



# A solution to the "missing satellite crisis"

Koposov *et al.* (2009)

- "Semi-Analytic Models"
- Based on dark matter sub-halos as predicted
- Postulated star formation suppression:
  - if $v_{circ}$<10 km/s ($H_2$ cooling limit)
  - if $v_{circ}$<35 km/s after $z_{rei}$ (photo-heating)
  - after system becomes a satellite
- Adding selection effects



# What are the faintest galaxies?

- The ‘realm of galaxies’ has expanded by ~100 since 2003
  - A few 100 stars at the bottom of dark matter potential wells
- Census still incomplete, even around the Milky Way
  - Current searches find objects at the surface brightness limit
- ‘Galaxy formation’ becomes extremely inefficient in low-mass dark matter halos
  - It is plausible that many low-mass DM sub-halos are ‘empty’

# Summary

- Looking at ***stars*** to understand galaxy formation
- Large surveys have revolutionized the field
  - ***structured*** stellar ***halos*** resulting from history of formation
  - dwarf galaxies can be ***very faint***
- Limits of star-formation in galaxies?
  - presence of "galaxies" without stars is likely!