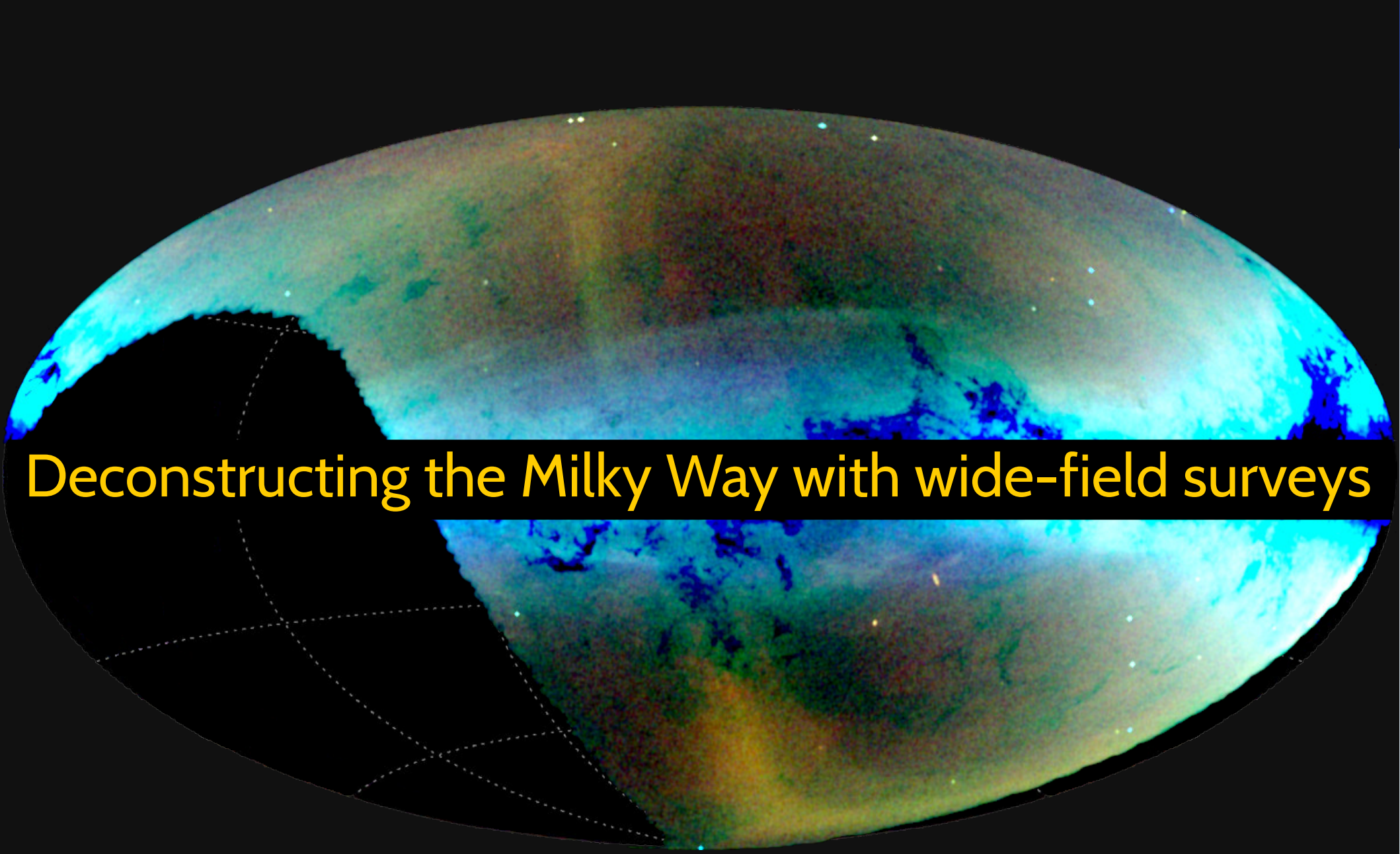


Deconstructing the Milky Way with wide-field surveys

Edouard Bernard
Observatoire de la Côte d'Azur

The formation of disc galaxies

- Disc galaxies made of thin and thick discs, bulge, halo

  → when did these structures form?

  → how do they relate to each other?

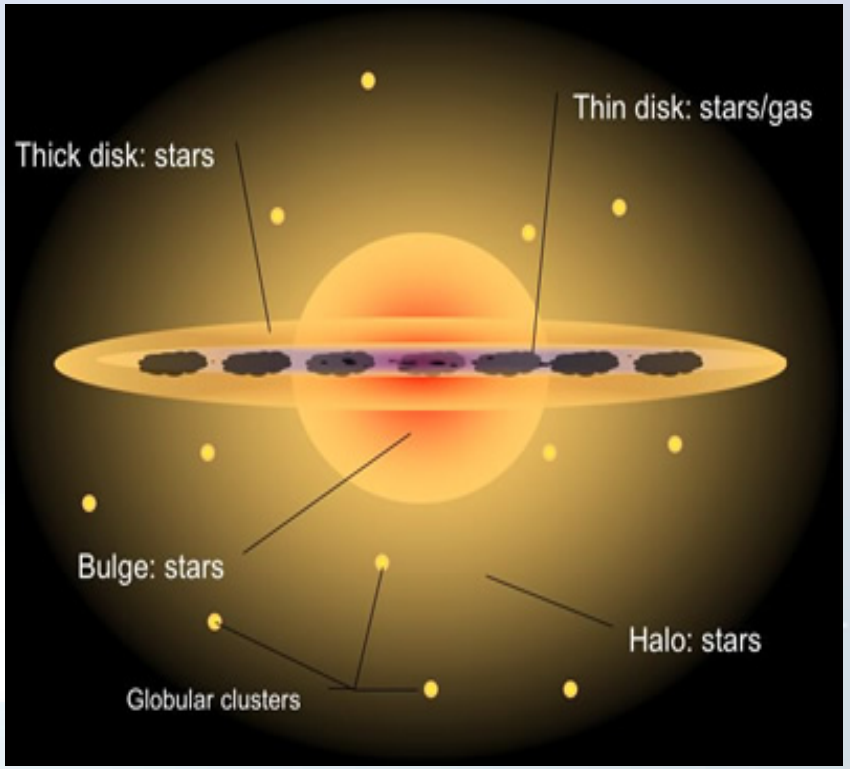
  → what mass fraction formed *in-situ*?

- Location inside the Milky Way:

  → properties of billions of stars

  → 3D positions/3D motions

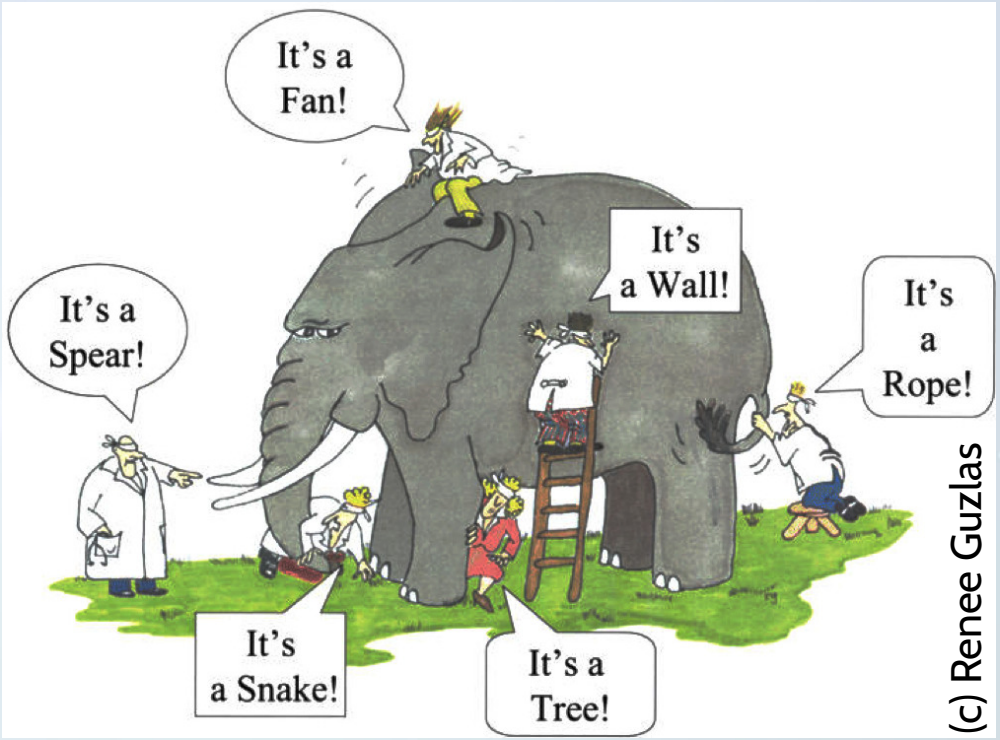
- But...



Credit: Swinburne University of Technology

The need for contiguous, wide-field coverage

You are here



John Godfrey Saxe "The Blind Men and the Elephant"

Outline

Part I

Milky Way halo substructures from deep, wide-field imaging

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RR Lyrae stars and the progenitors of the Milky Way halo

Part III

The outer disc and the anticenter “mess”

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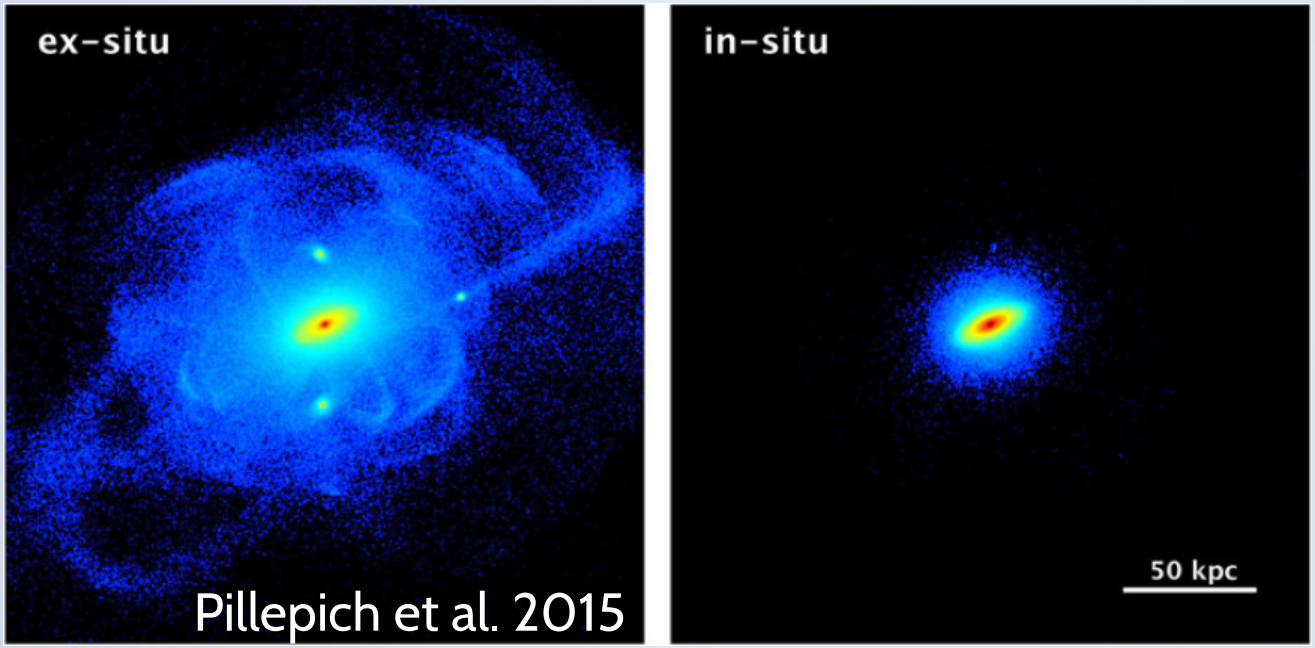
The formation of galactic haloes

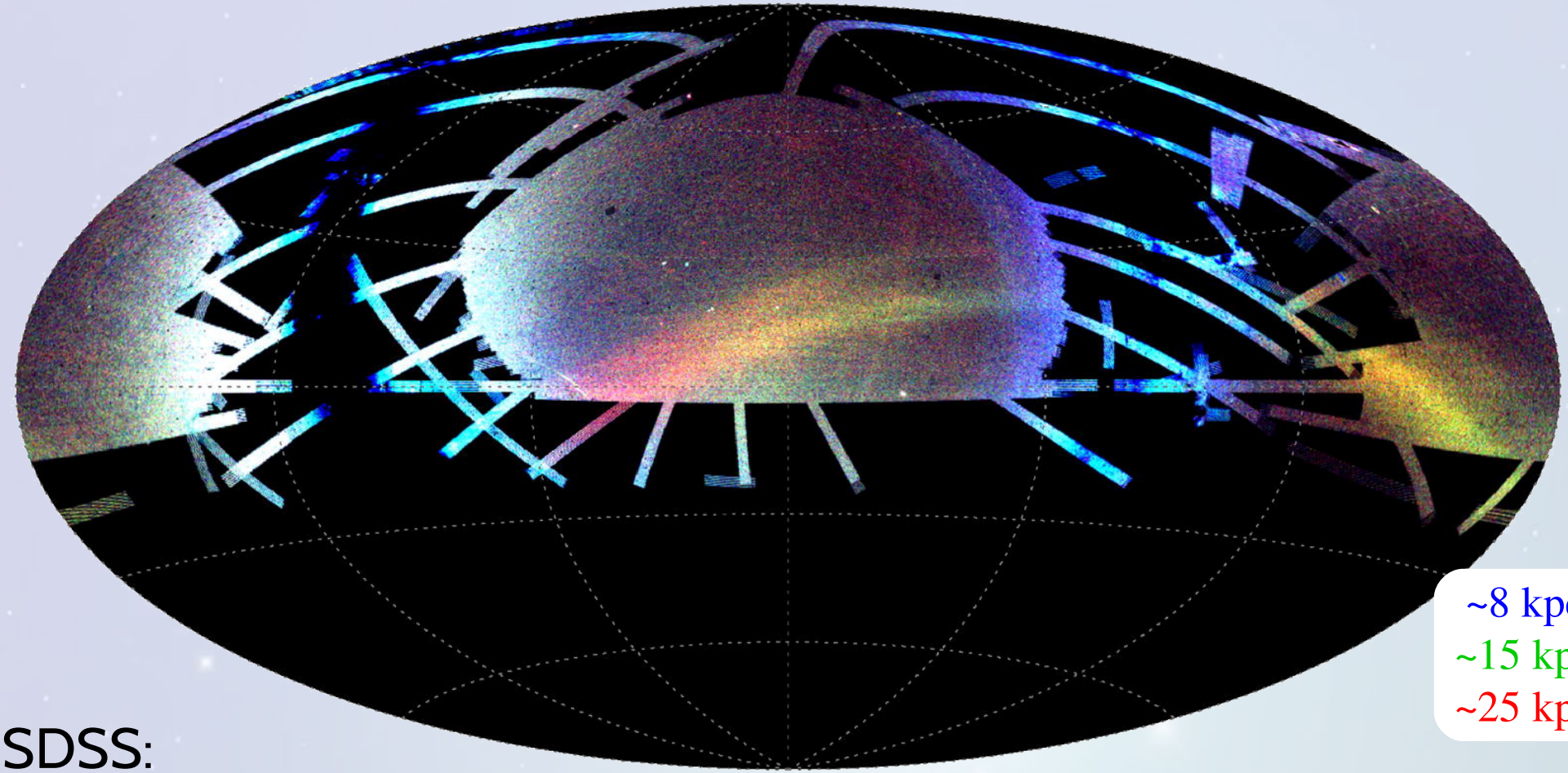
- Searle-Zinn 1978: hierarchical process

  → many substructures... most fainter than 30 mag arcsec^{-2}

  → better seen in star count maps



The SDSS "field of streams"

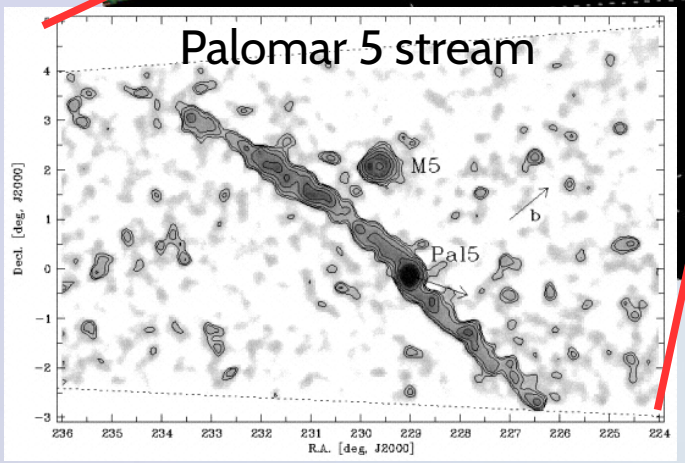


Belokurov et al. 2006, 2013

SDSS:

- 14,055 deg^2
- r ~ 22

The SDSS "field of streams"

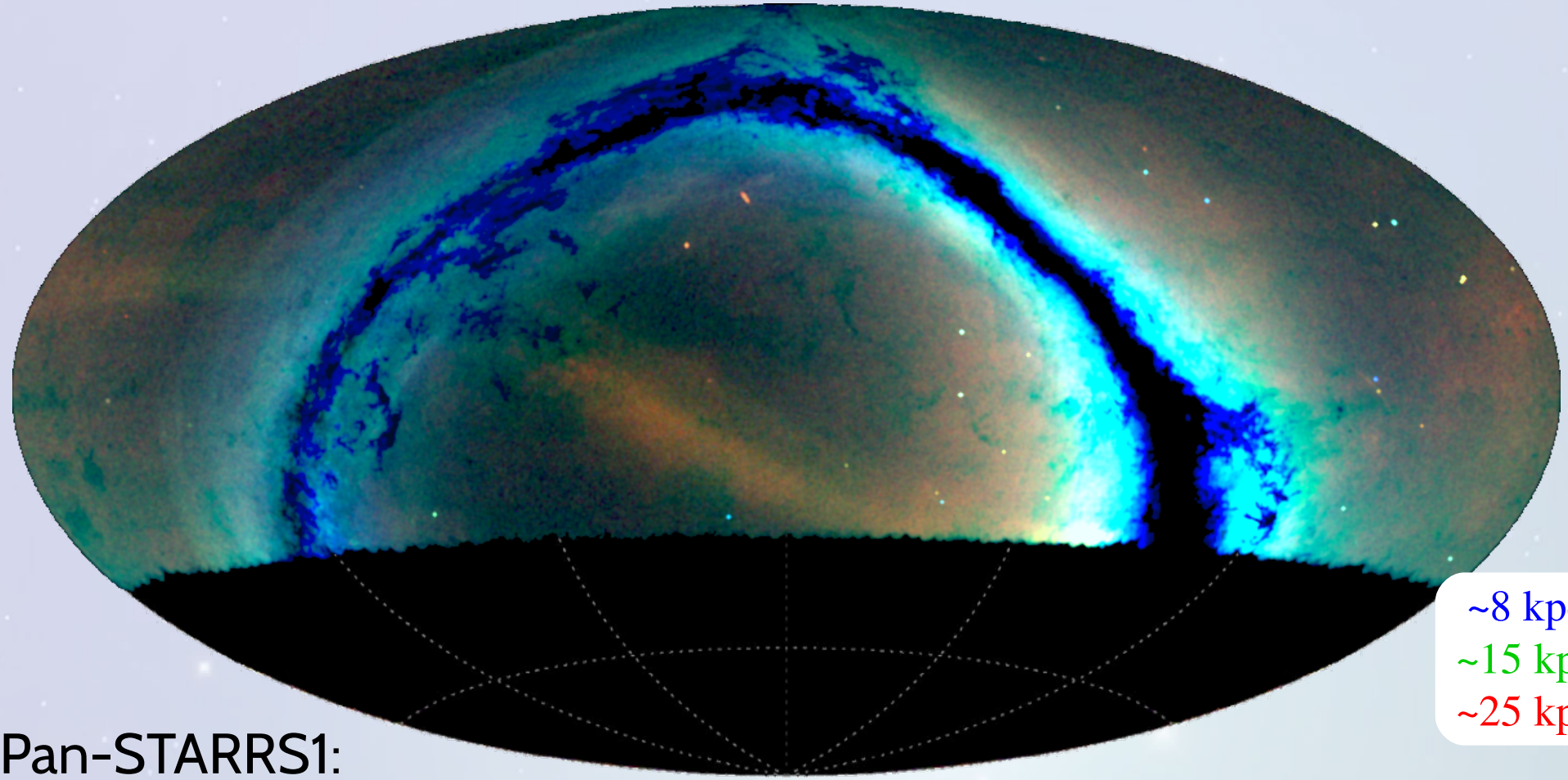


Odenkirchen et al. 2003

→ 15 new satellites
→ 12 new stellar streams
→ 2 "over-densities"

~8 kpc
~15 kpc
~25 kpc

The Pan-STARRS 3π Survey

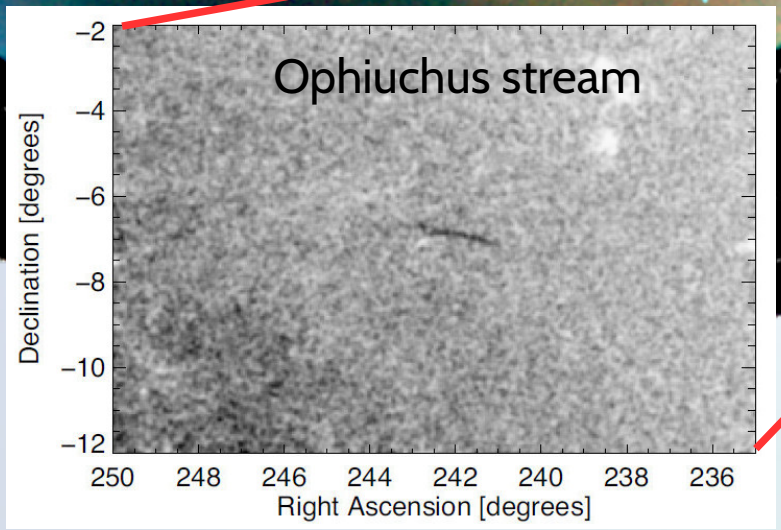


Bernard et al. 2016

Pan-STARRS1:

- 30,000 deg^2
- r ~ 22

The Pan-STARRS 3π Survey

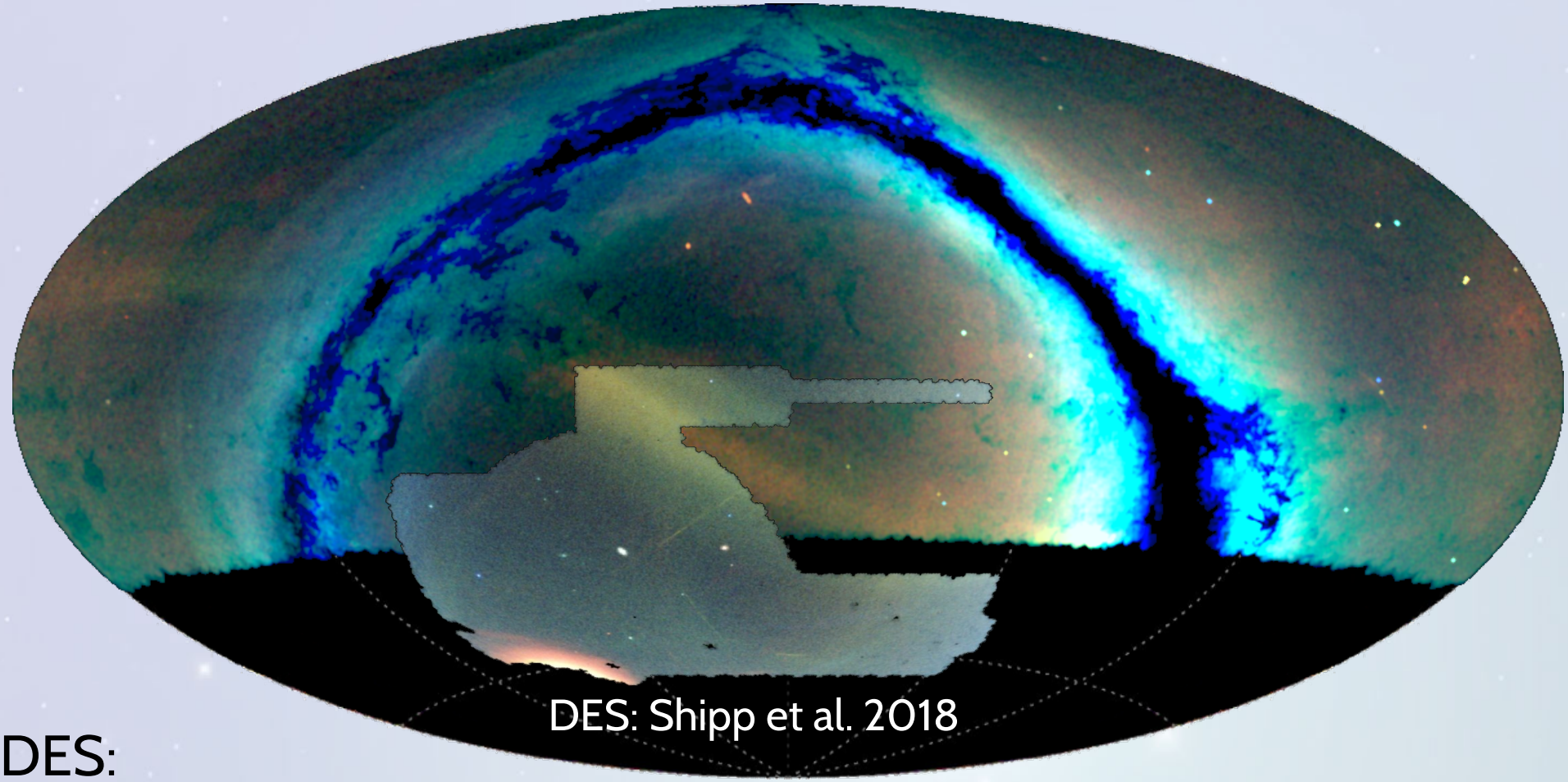


Bernard et al. 2014

~8 kpc
~15 kpc
~25 kpc

→ 5 new satellites
→ 12 new stellar streams

The Dark Energy Survey



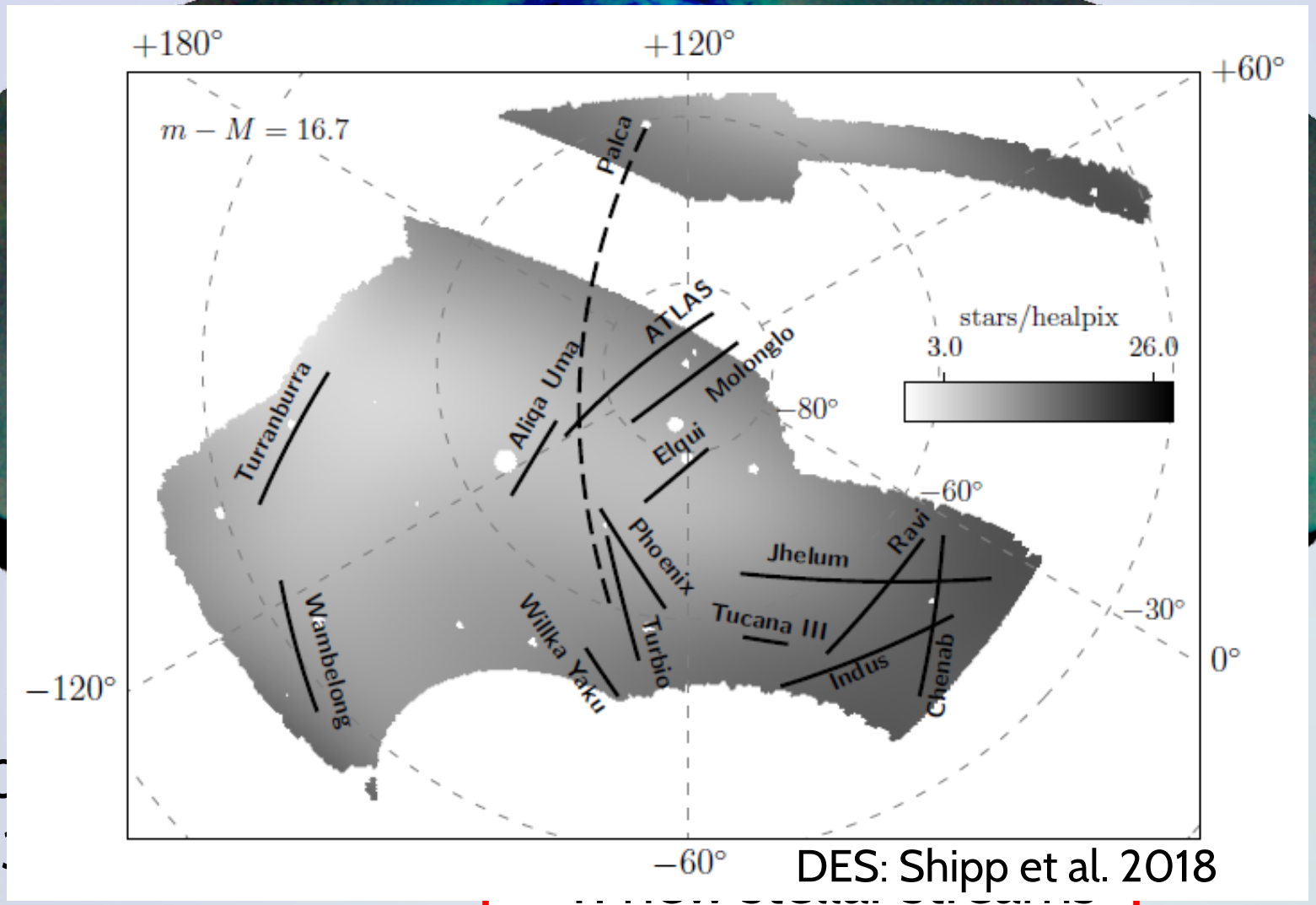
DES: Shipp et al. 2018

DES:

- 5,000 deg^2
- r ~ 23

→ 9 new satellites
→ 11 new stellar streams

The Dark Energy Survey



DES: Shipp et al. 2018

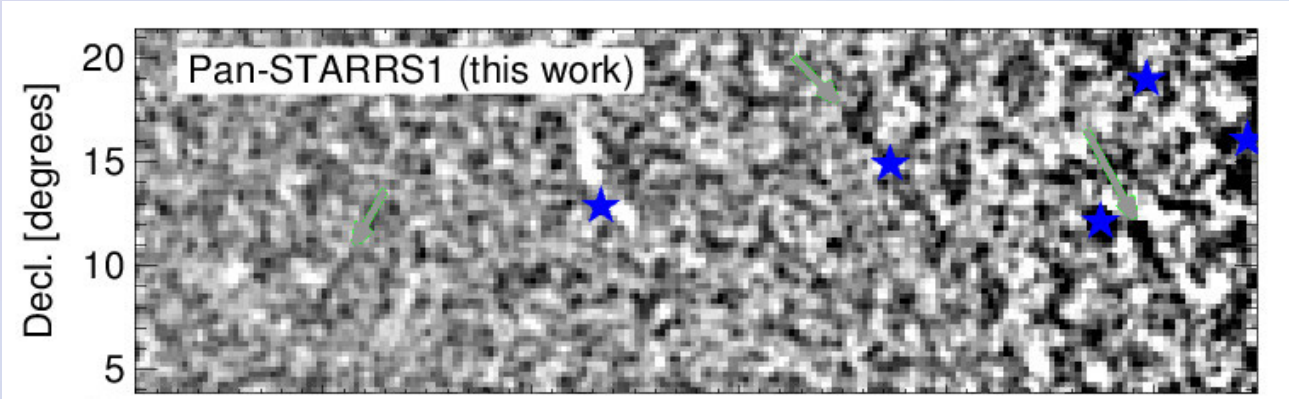
DES:

- 5,0
- r ~ 2

How smooth is the “smooth halo”?

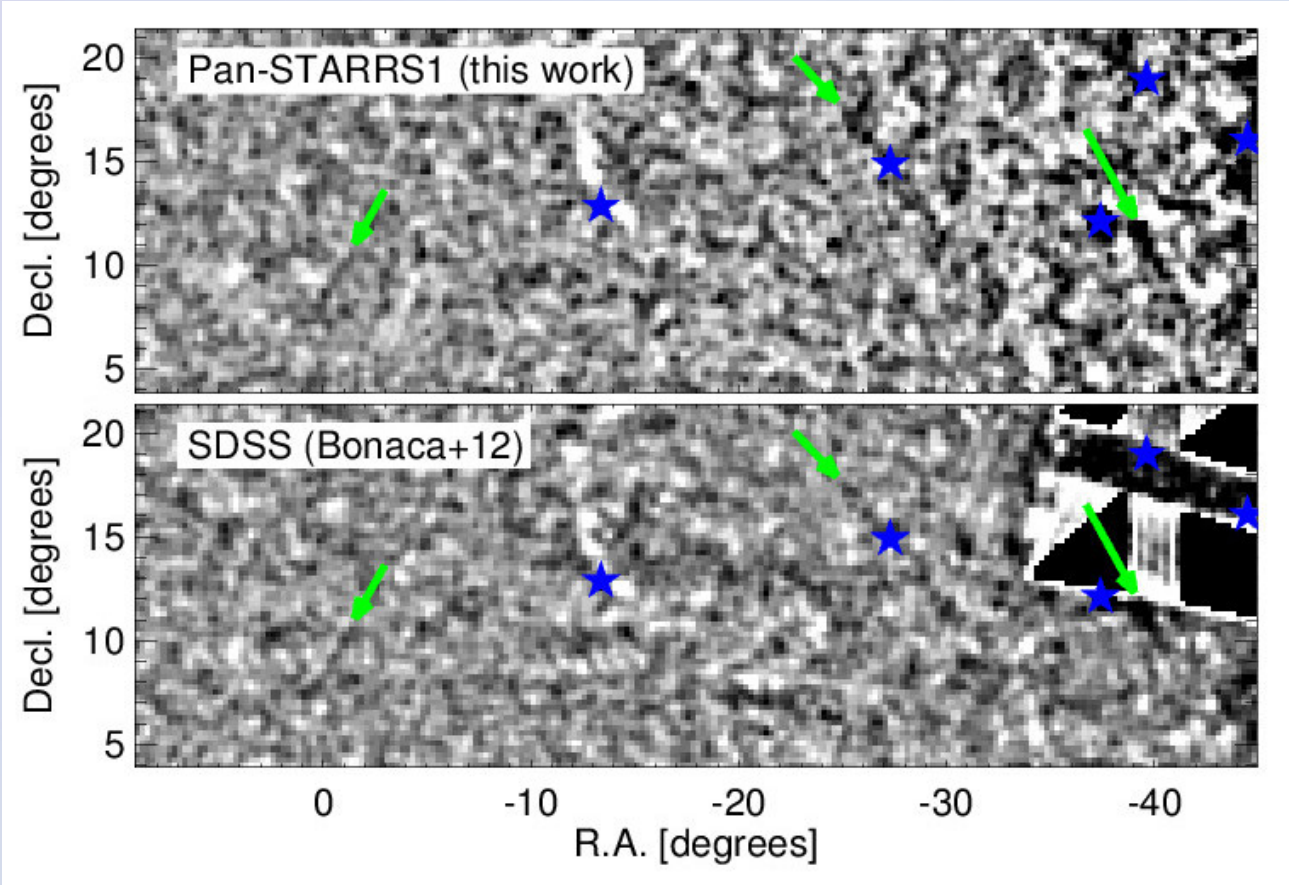
Stellar density at ~15 kpc

Bernard et al. 2016



How smooth is the "smooth halo"?

Stellar density at ~15 kpc Bernard et al. 2016



→ many stream-like features at the photometric detection limit
→ need LSST depth to answer that question

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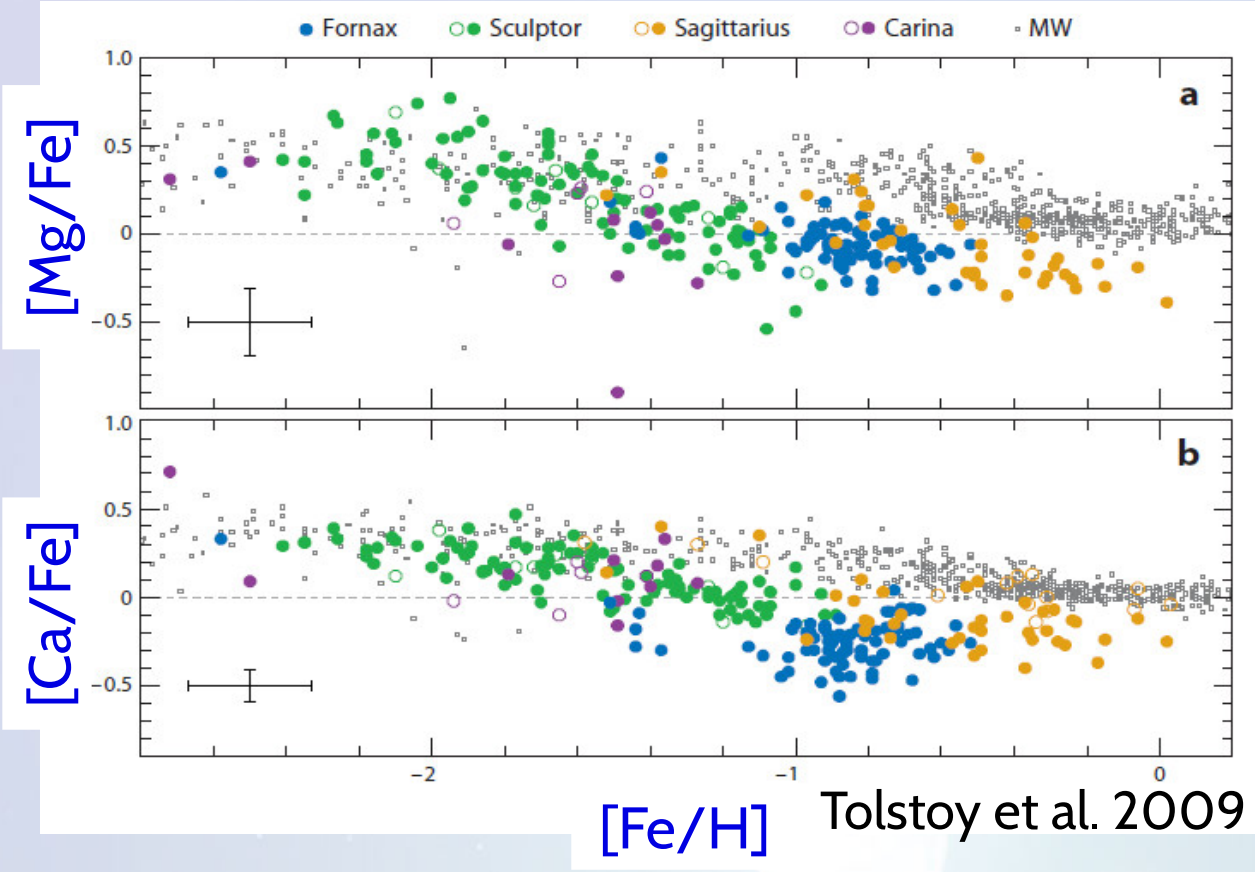
Milky Way halo vs. present day dwarf spheroidals



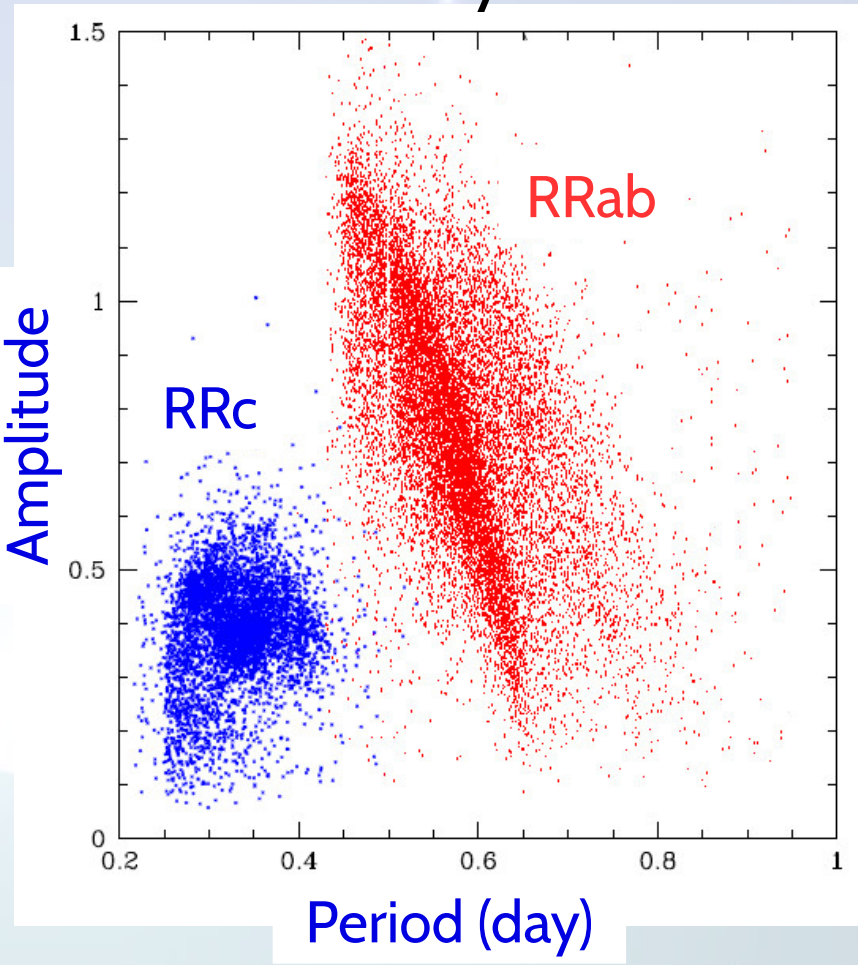
Tolstoy et al. 2009

- Halo and *present day* dSph have different abundance patterns
- But RGB stars in spectroscopic sample have a wide range of ages
- Purely old stellar tracers needed!

RR Lyrae stars

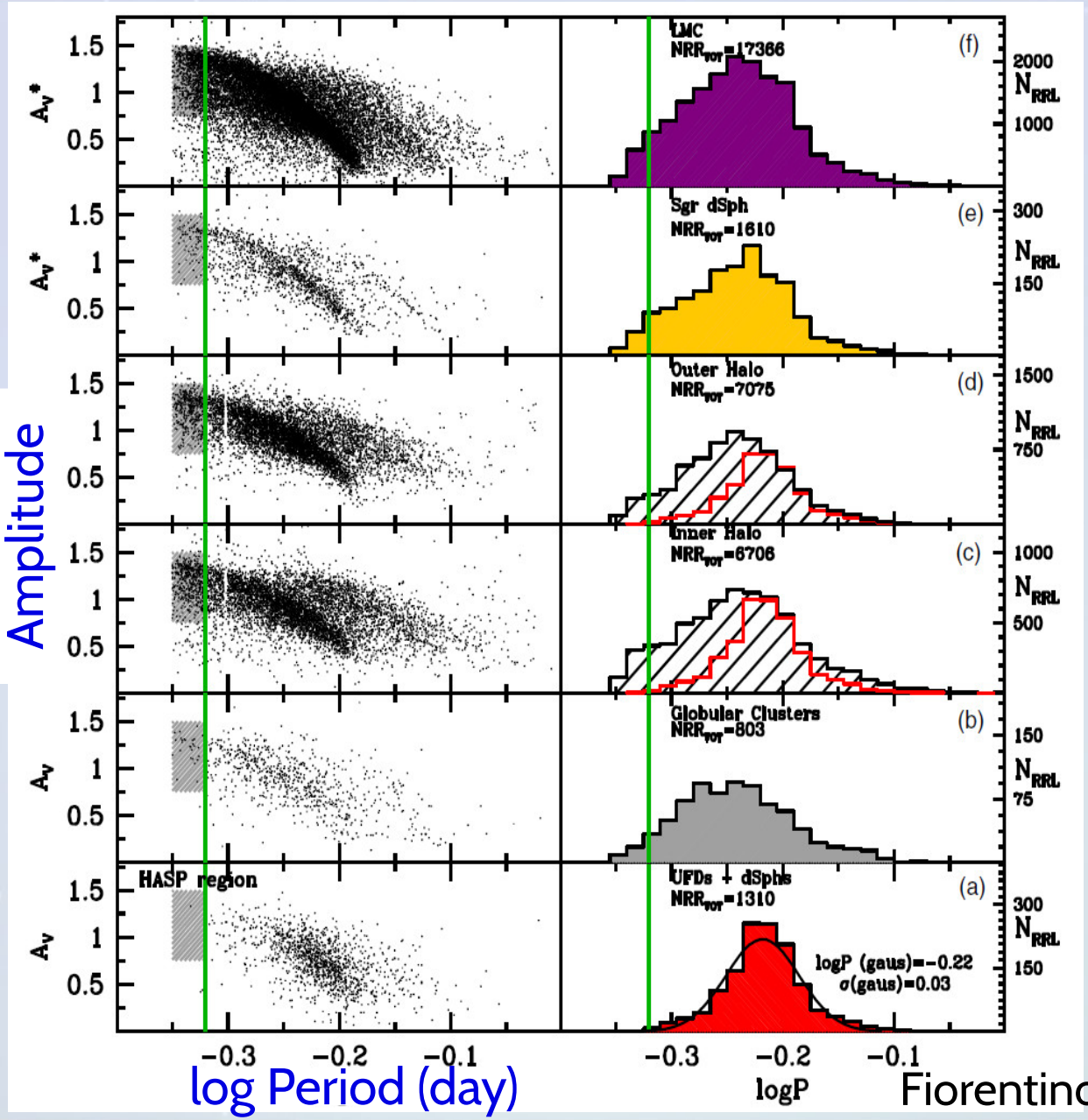
- Pulsating stars on horizontal-branch
- > 10 Gyr old
- Standard candles → accurate distances
- Distance- & reddening-free parameters: period & amplitude
- Present in most environments

LMC RR Lyrae stars



Soszyński et al. 2009

RR Lyrae properties in various environments



LMC

Sagittarius

Outer halo

Inner halo

Globulars

dSph

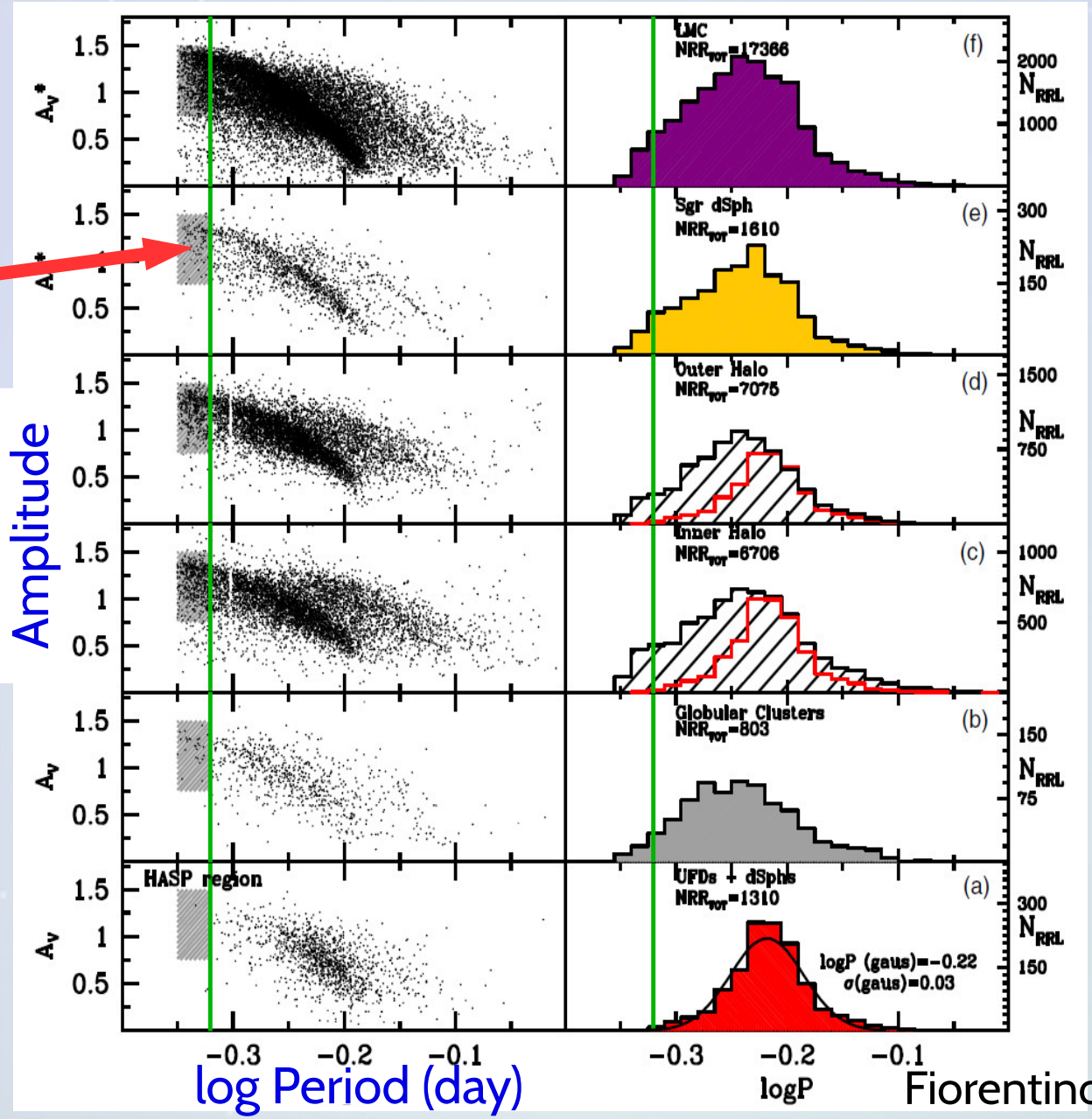
Draco, Carina, Sculptor,
Leo I, Cetus, Tucana
+ 11 ultra-faint dwarfs

Fiorentino et al. 2015

RR Lyrae properties in various environments

HASP:
High-amplitude
Short-period

P < 0.48 day
f ~ 6-8 %



LMC

Sagittarius

Outer halo

Inner halo

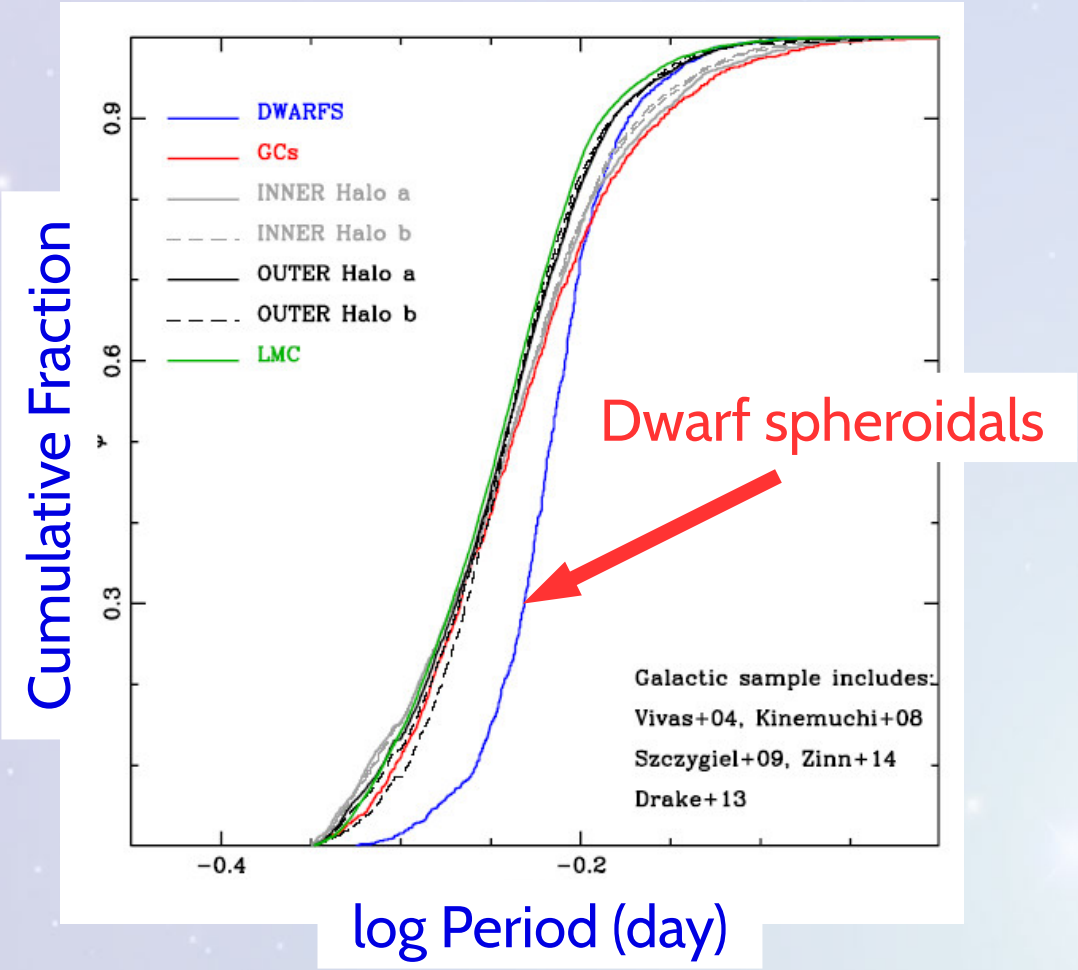
Globulars

dSph

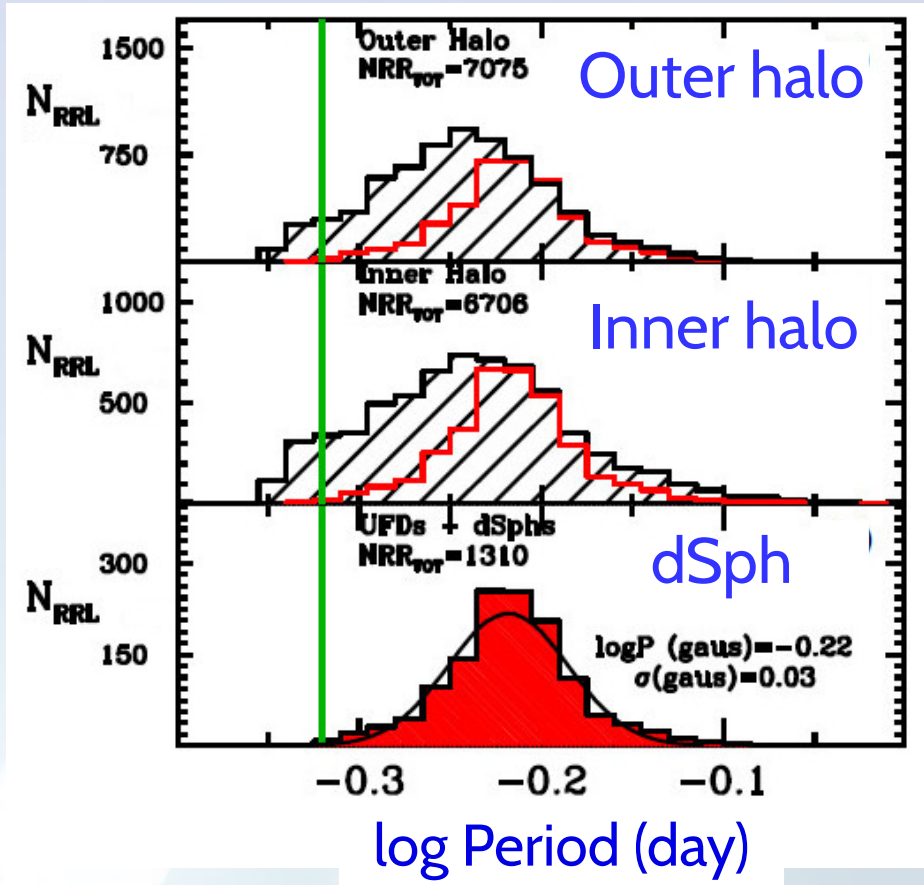
Draco, Carina, Sculptor,
Leo I, Cetus, Tucana
+ 11 ultra-faint dwarfs

Fiorentino et al. 2015

Lack of HASPs in dSph is very significant



Stetson et al. 2014



Fiorentino et al. 2015

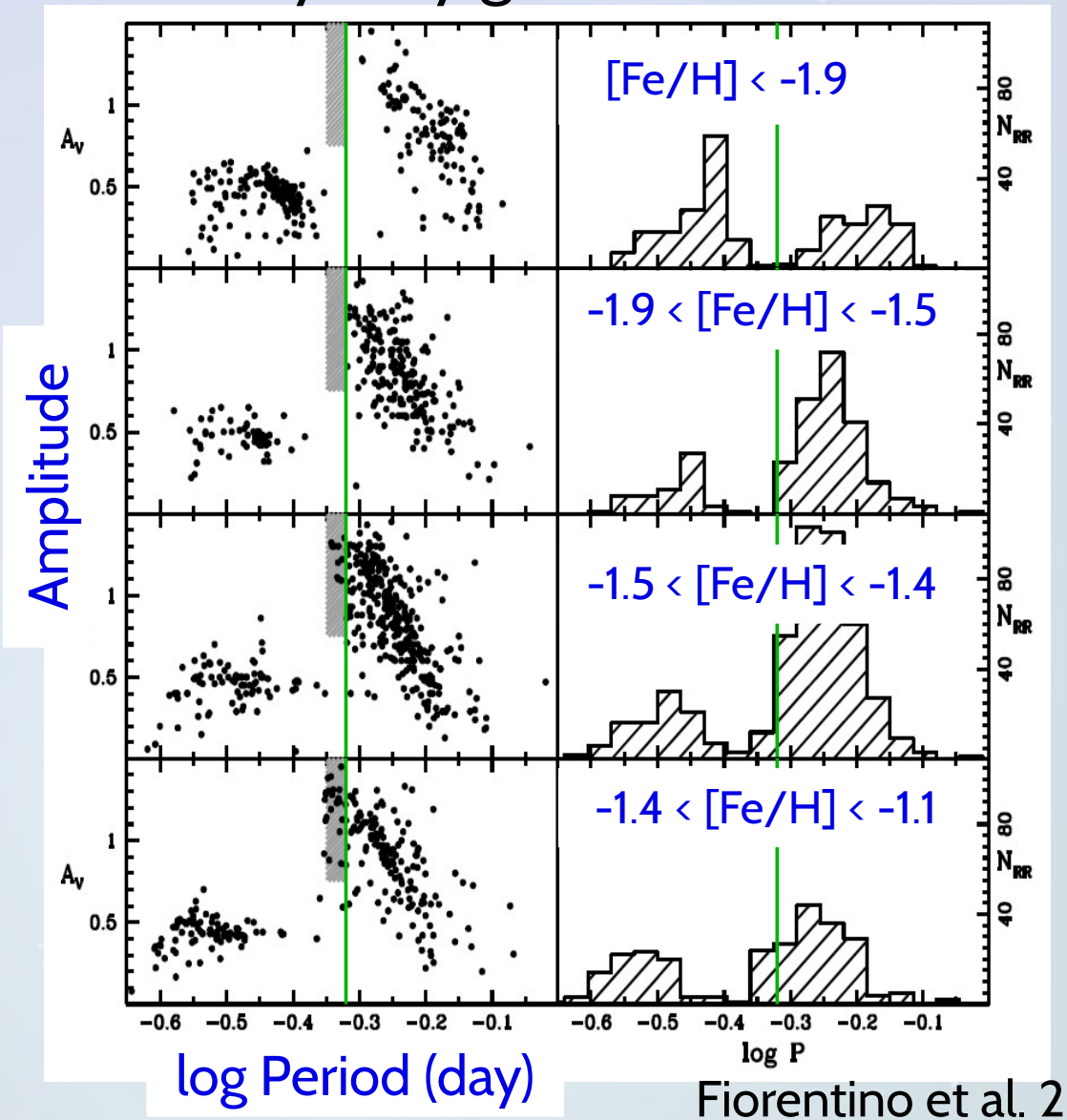
Galaxies similar to present-day dSph have only contributed ~10-20% of the halo stellar mass

Origin of the HASP?

- Shorter period with increasing metallicity

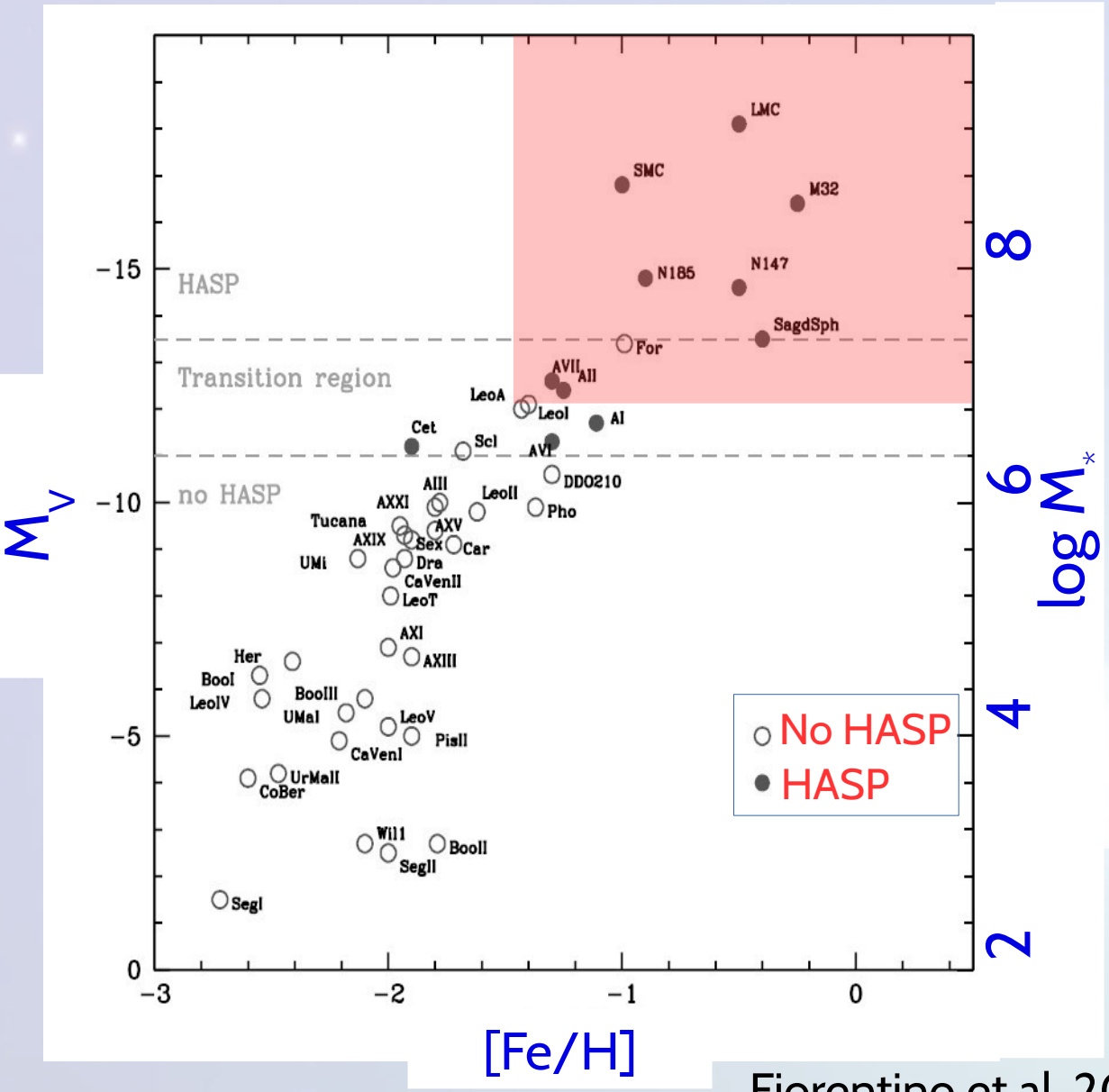
HASPs come from progenitors sufficiently massive to enrich to [Fe/H] > -1.5 by redshift = 2

Milky Way globular clusters



Fiorentino et al. 2015

The halo was built from few massive progenitors

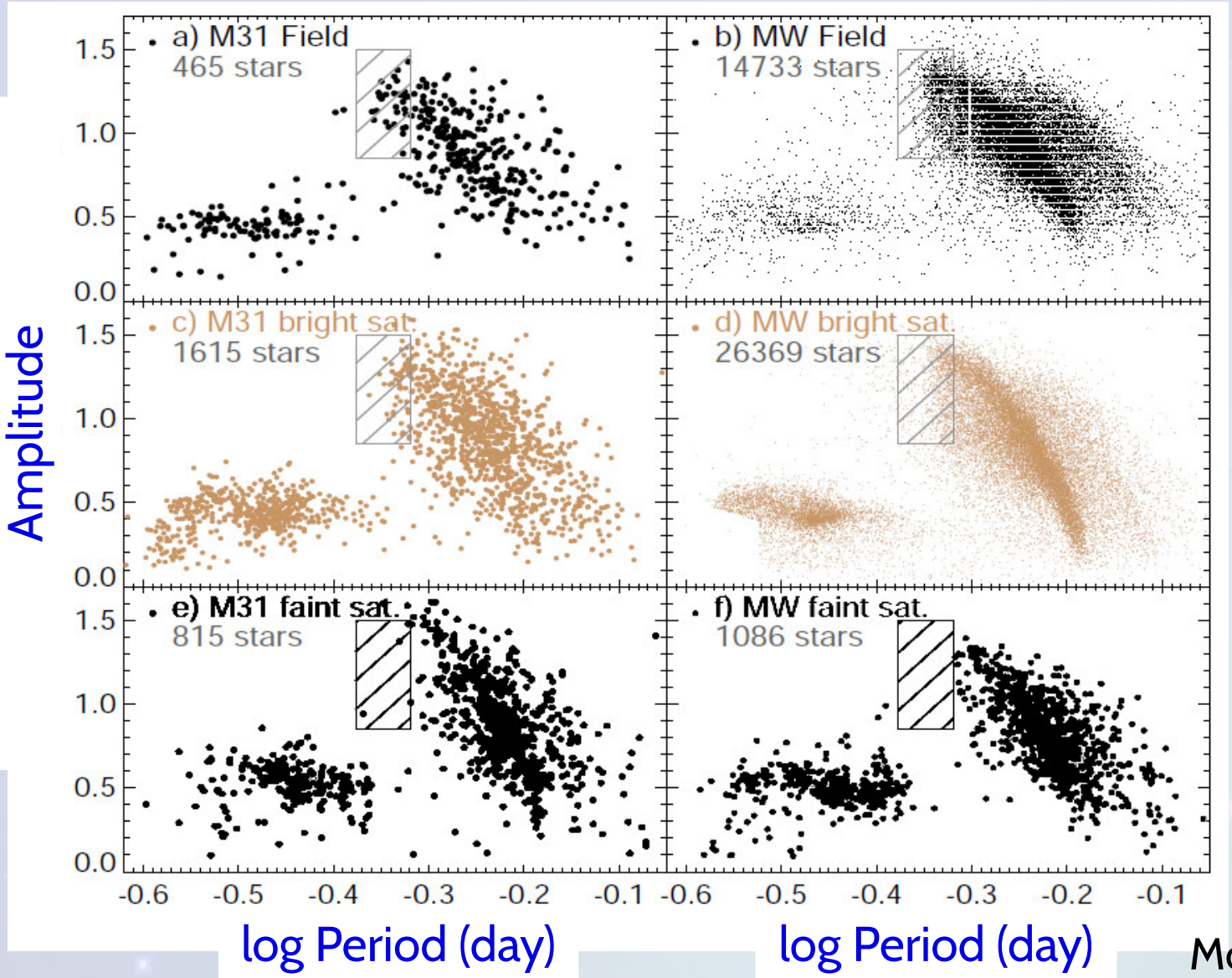


- galaxies similar to present day dSph did not have a dominant role building the halo (<20%)
- halo mainly built from few massive progenitors (M_V < -12)
- see also:
  Bullock & Johnston 2005: N-body
  Kirby et al. 2015: [C/Fe]
  Deason et al. 2015: BSS/BHB ratio

Fiorentino et al. 2017

Comparison between Andromeda and the Milky Way

M31 and satellites | Milky Way and satellites



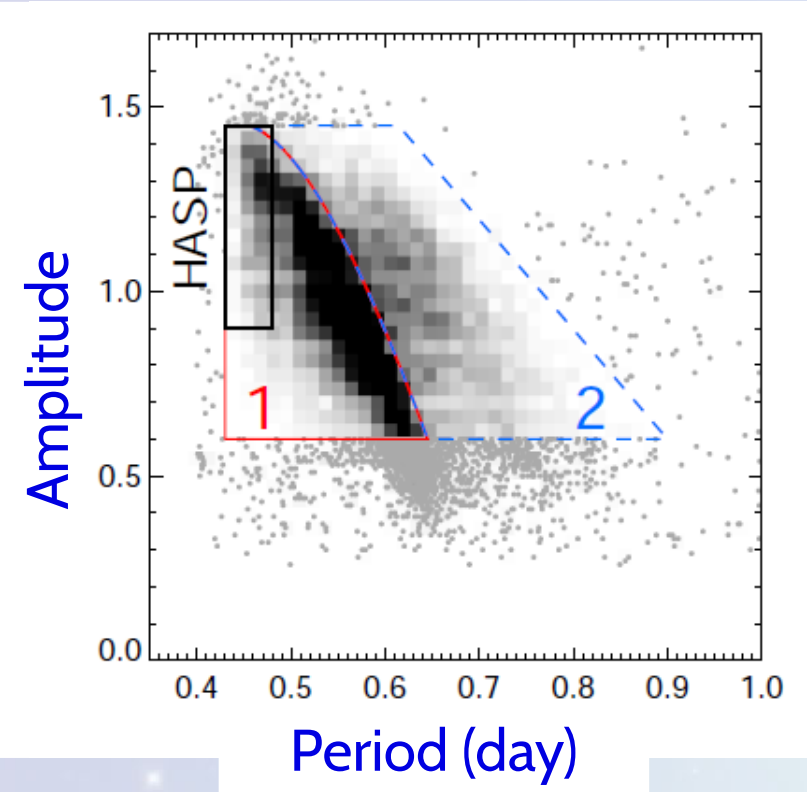
Field

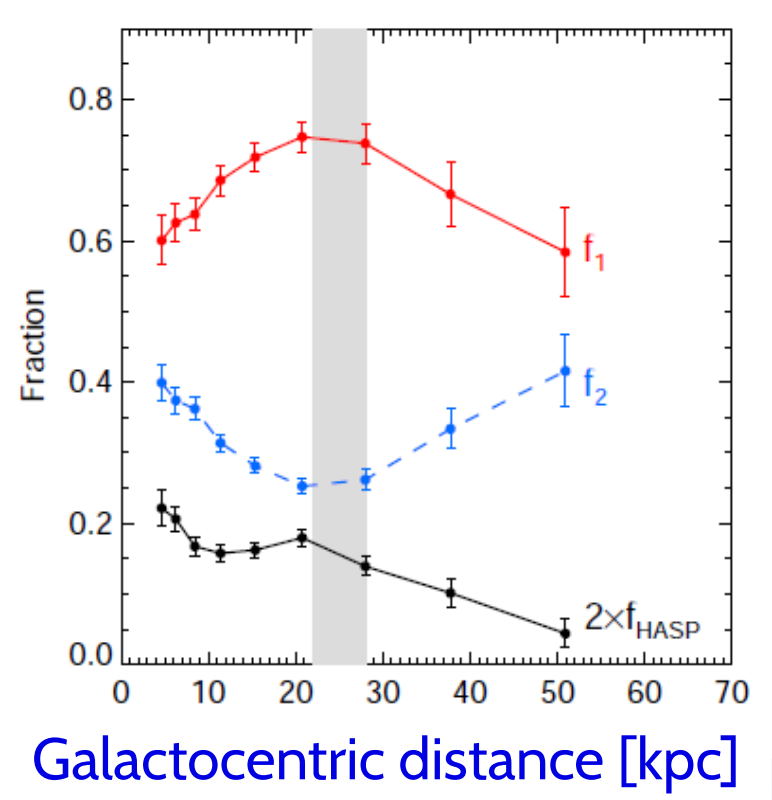
Bright satellites

Faint satellites

Monelli et al. 2017

Different progenitor masses at different radii



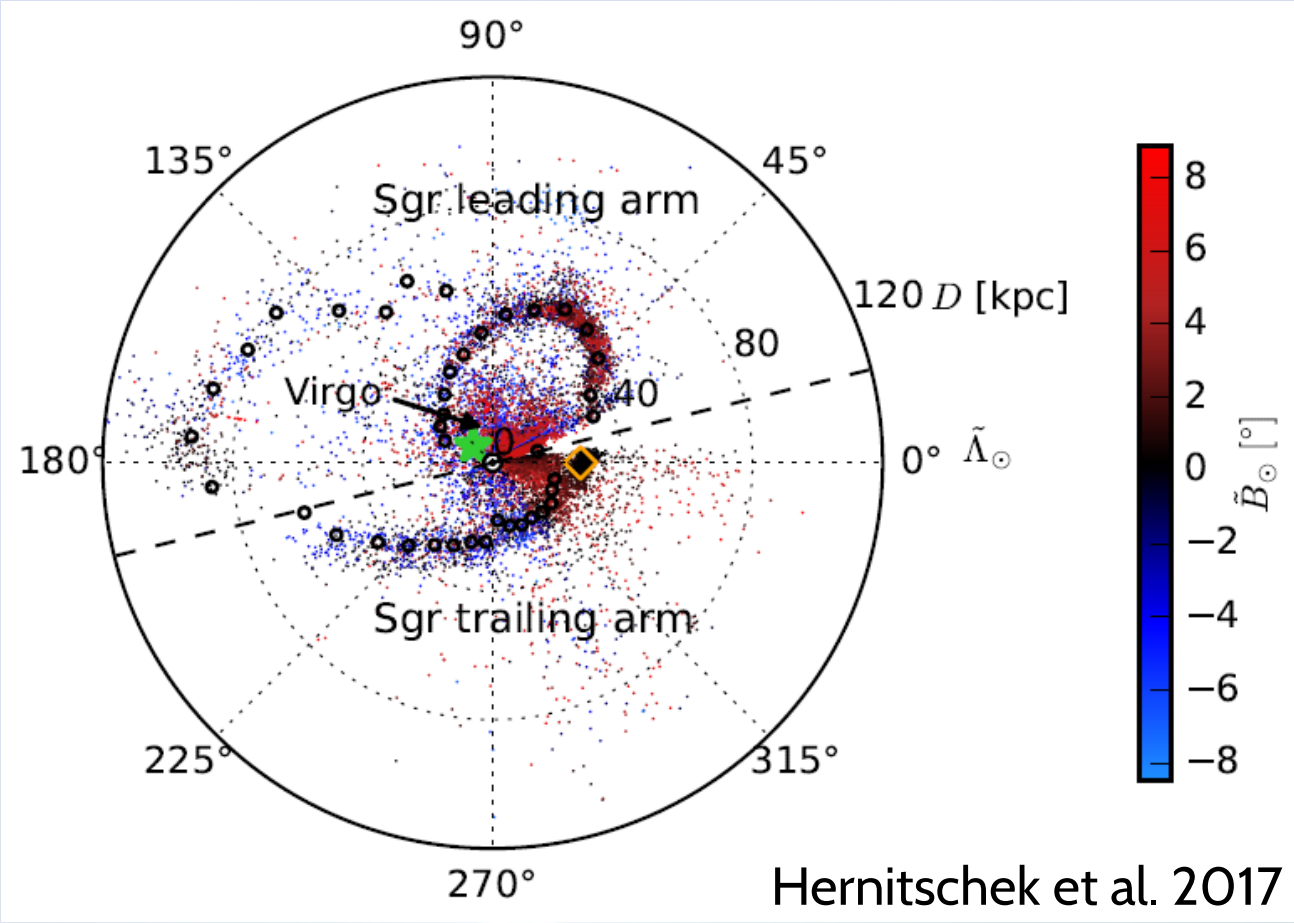


- Variations in the fractional contribution of the halo progenitors of different masses

Belokurov et al. 2018

RR Lyraes in LSST: 3D map of halo & substructures

R = 400 kpc



Hernitschek et al. 2017

- Pan-STARRS1: RR Lyrae completeness drops beyond 80 kpc
- LSST: RR Lyraes out to ~400 kpc

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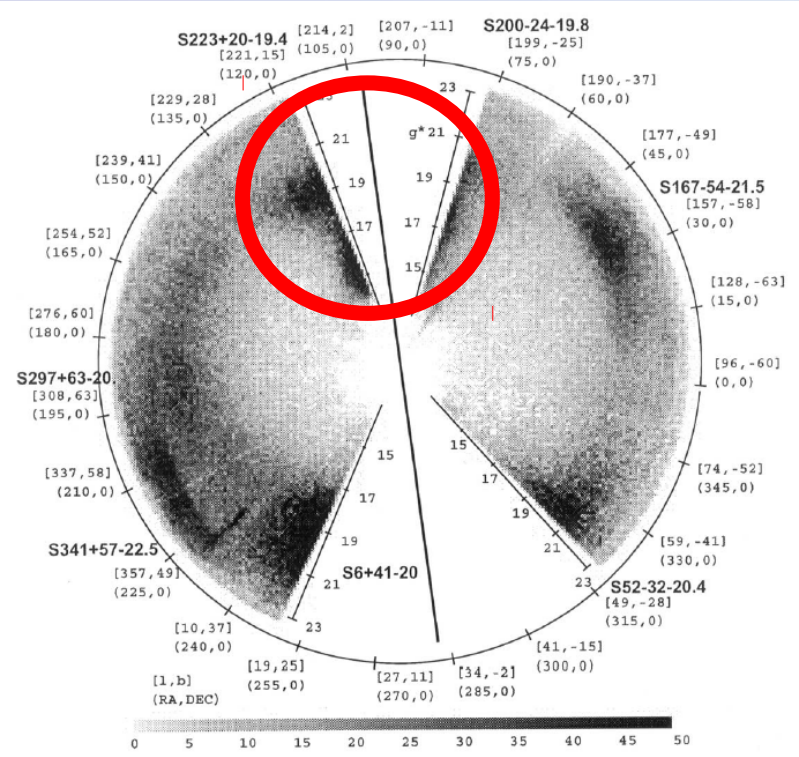
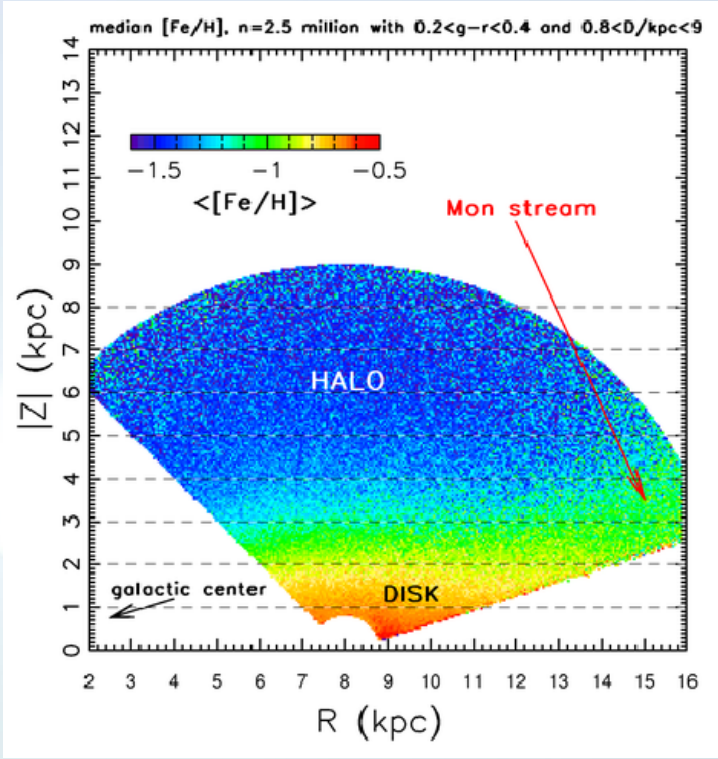
The anticenter "mess"

- Monoceros ring, galactic anticenter stellar stream (GASS), Canis Major overdensity, Triangulum-Andromeda overdensity,...

  → many names, different structures, same origin?

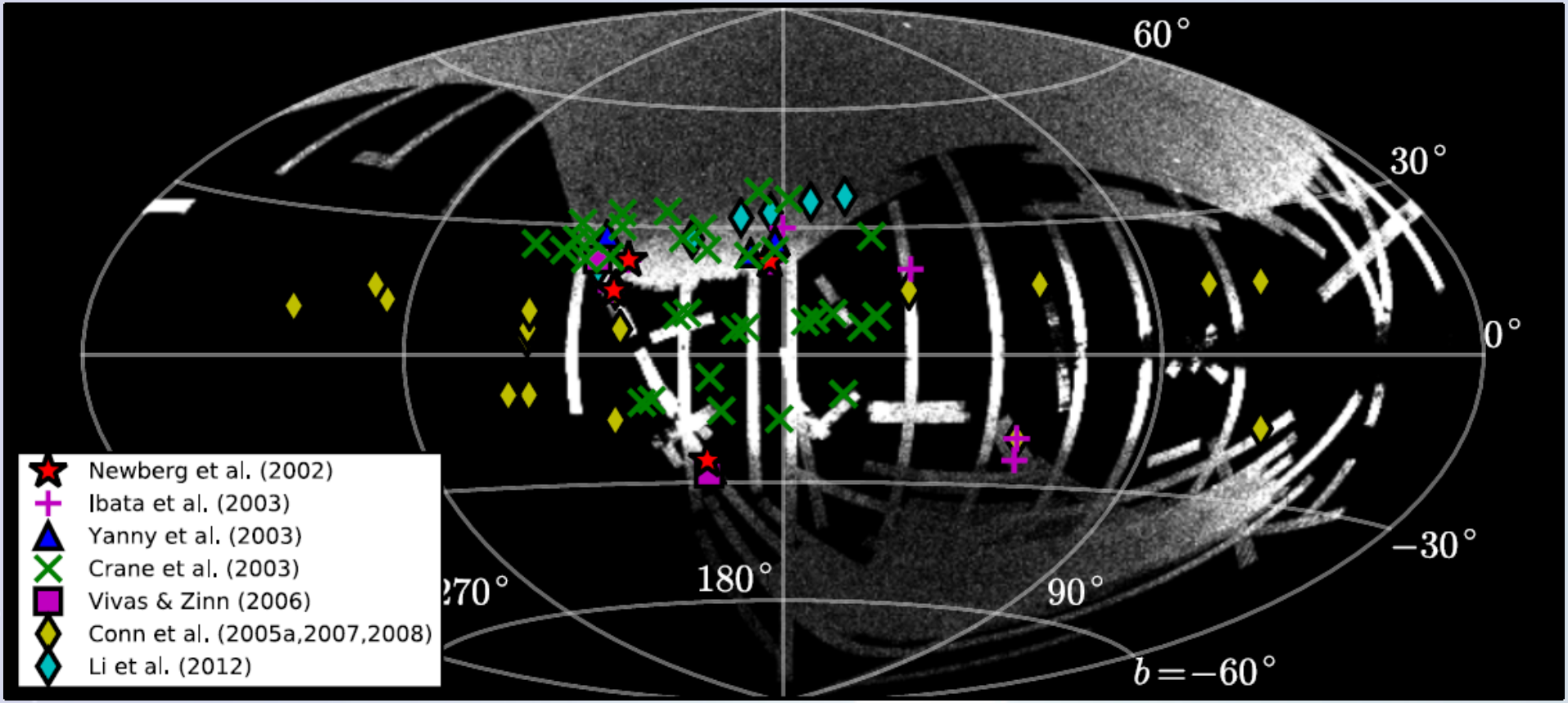


Newberg et al. 2002



Ivezić et al. 2008

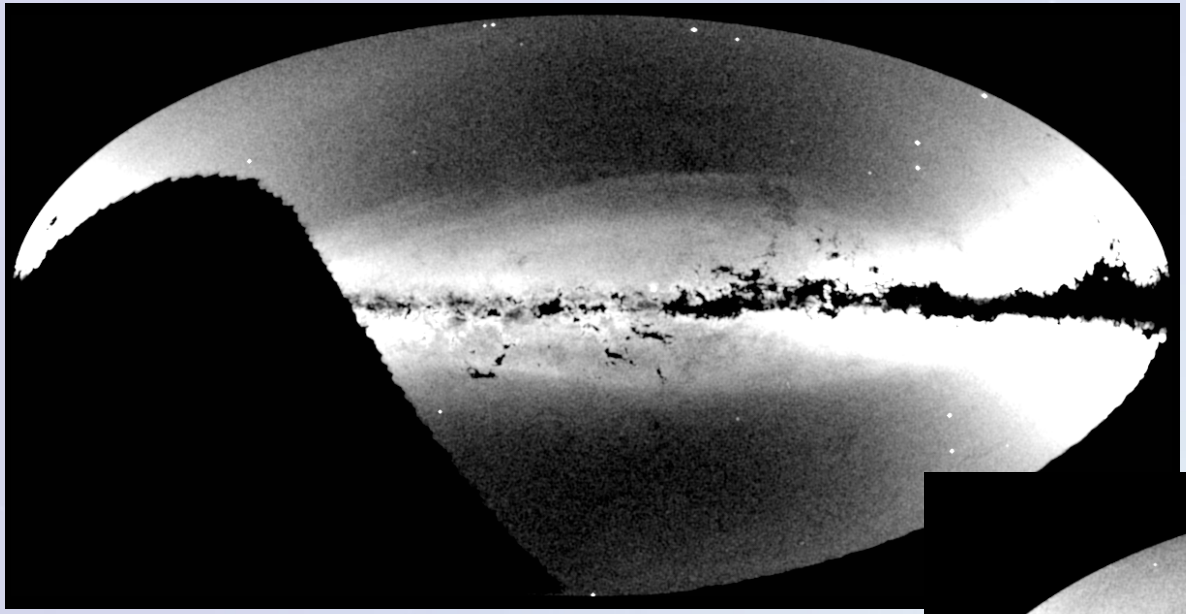
The anticenter in SDSS



Slater et al. 2014

- Remnant of an accreted dwarf galaxy orbiting in the plane?
- Warp/flare of the outer disc due to perturbations?

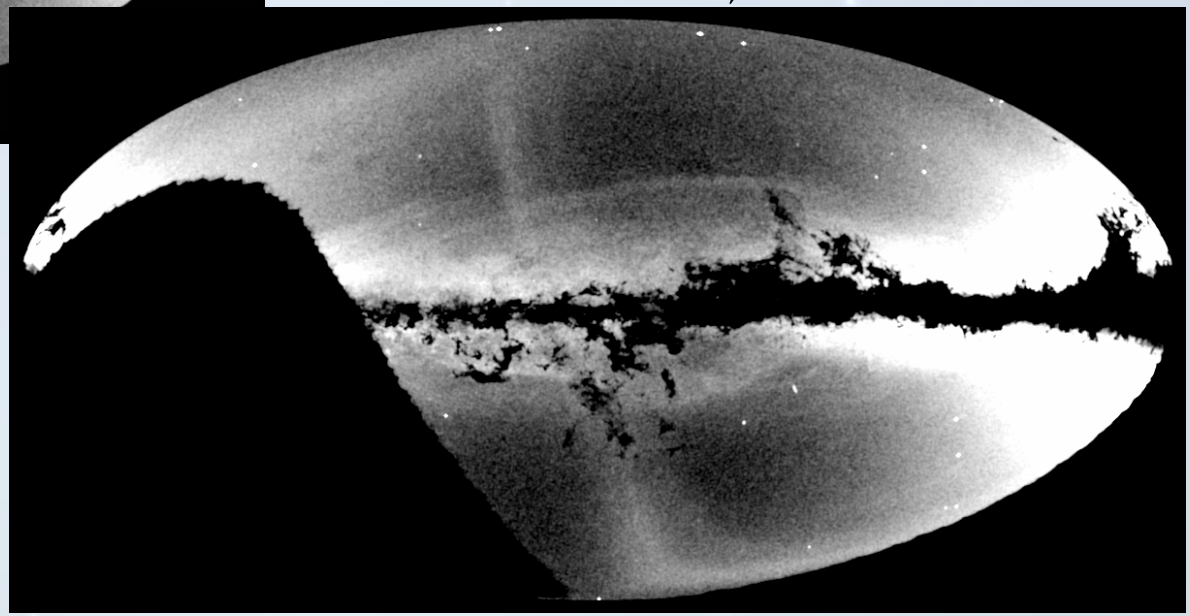
The anticenter in Pan-STARRS1



8 kpc

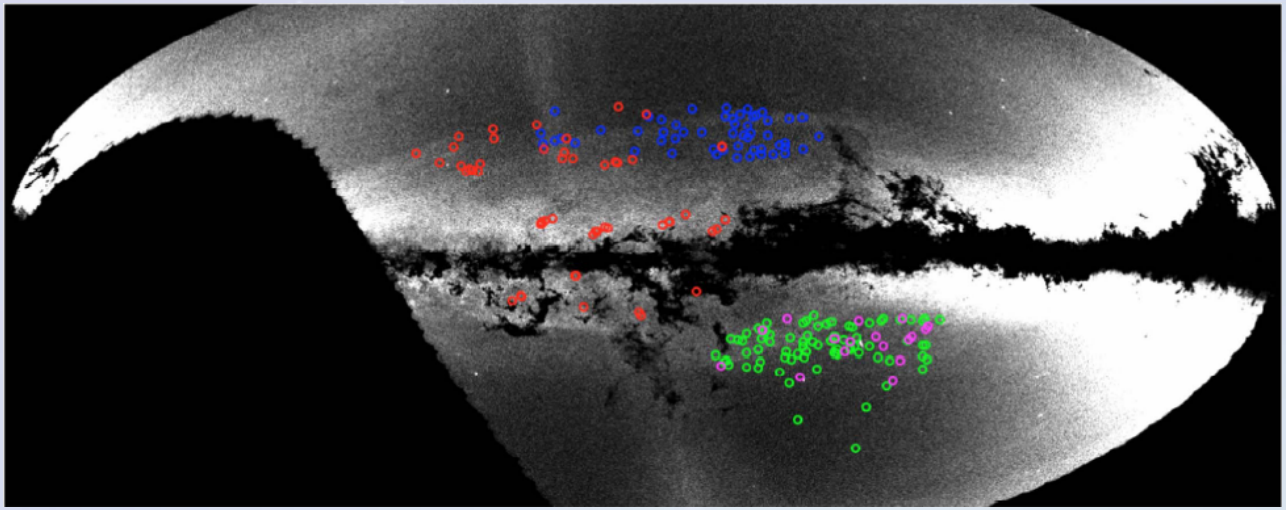
Slater et al. 2014, Bernard et al. 2016

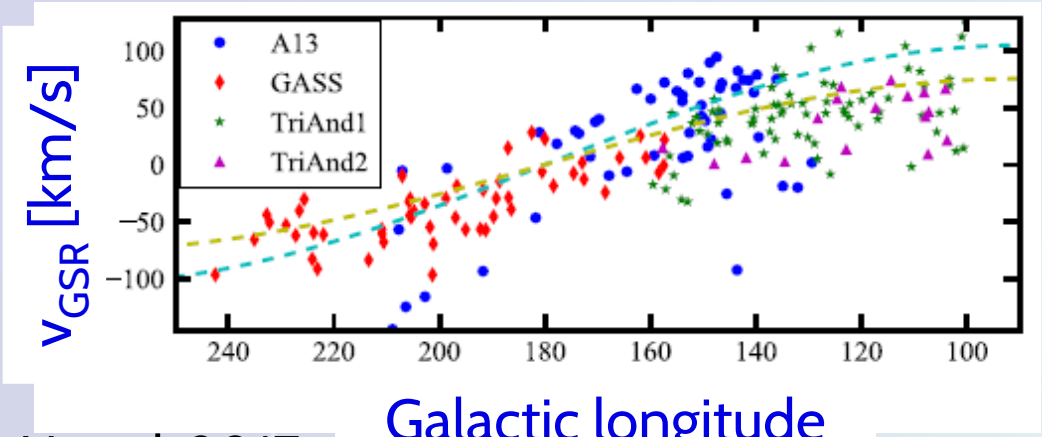
15 kpc



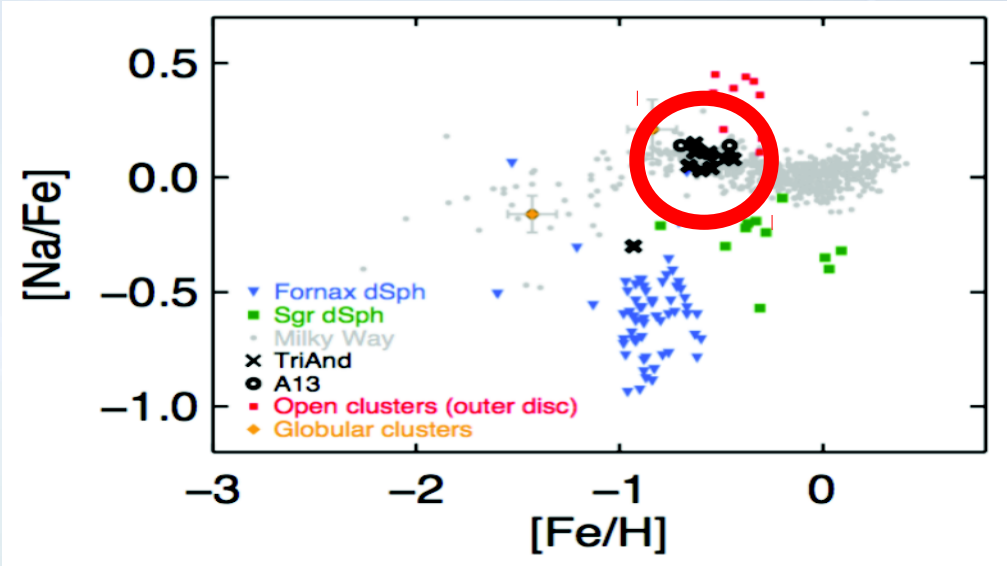
Panoramic view favors the disc perturbation hypothesis

Spectroscopic follow-up of M-giants





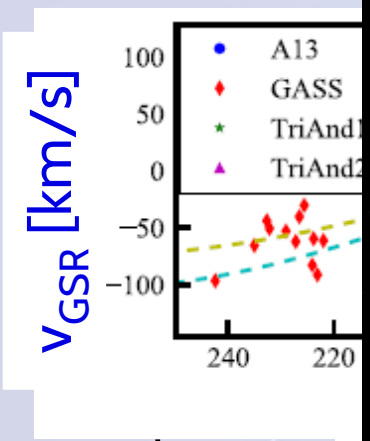
Li et al. 2017



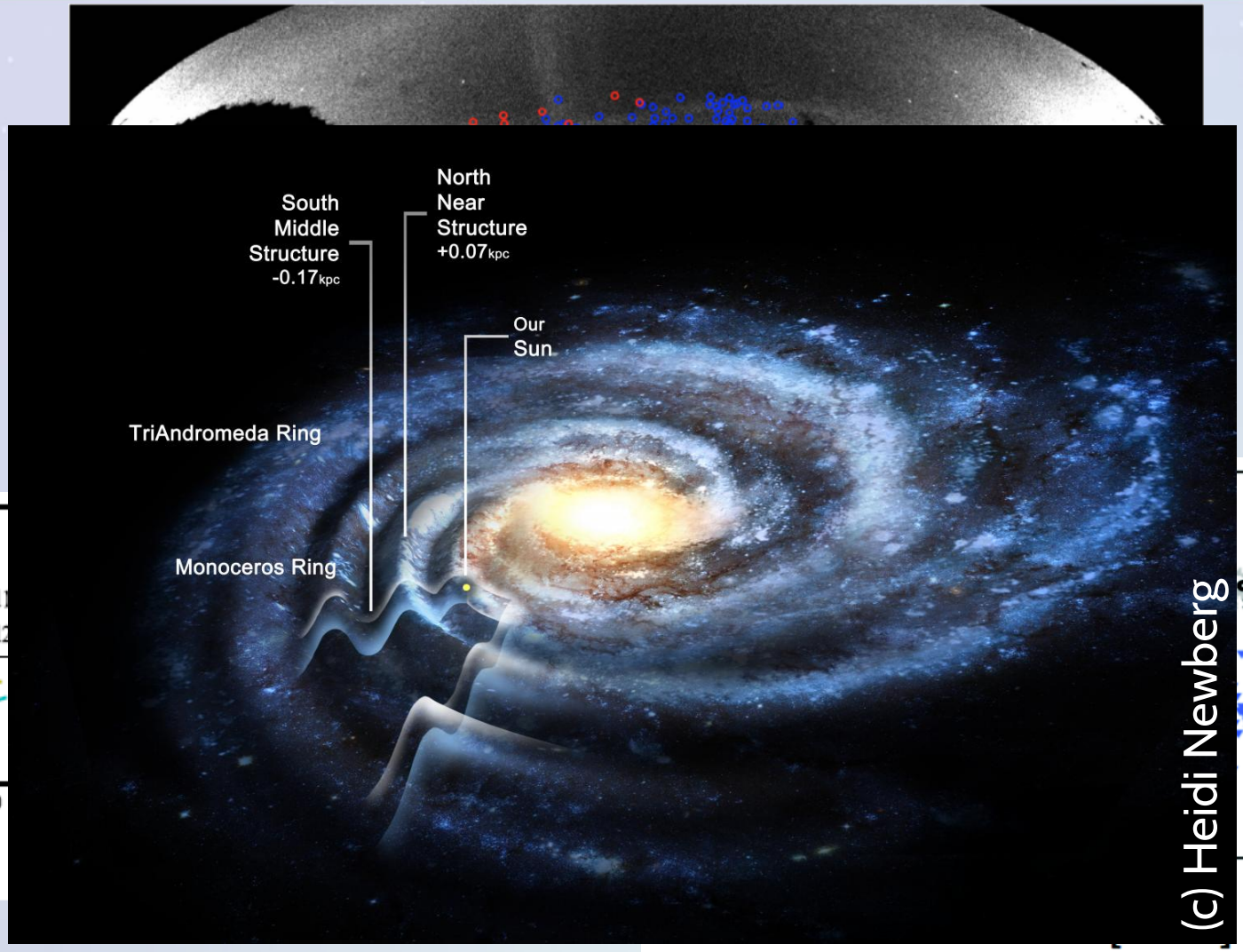
Bergemann et al. 2018, Hayes et al. 2018

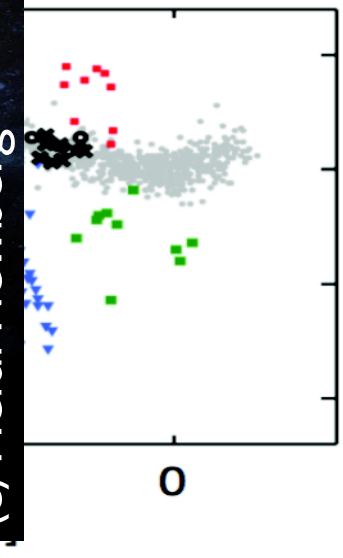
Targeted structures have disc-like rotation and abundances

Spectroscopic follow-up of M-giants



Li et al. 2017





Bergemann et al. 2018, Hayes et al. 2018

Targeted structures have disc-like rotation and abundances

Summary

- Some results from wide-field photometric surveys:
  - halo is highly substructured (>50 satellites, >50 streams)
  - main contributors to halo mass were massive satellites (M_V < -12)
  - the outer disc is corrugated from satellite interactions

- Bright future thanks to synergy with large spectroscopic surveys:
  - WEAVE (5Million stars), 4MOST (15M), GALAH (2M), DESI (10M)
  - Gaia (150 million stars) + parallaxes, proper motions