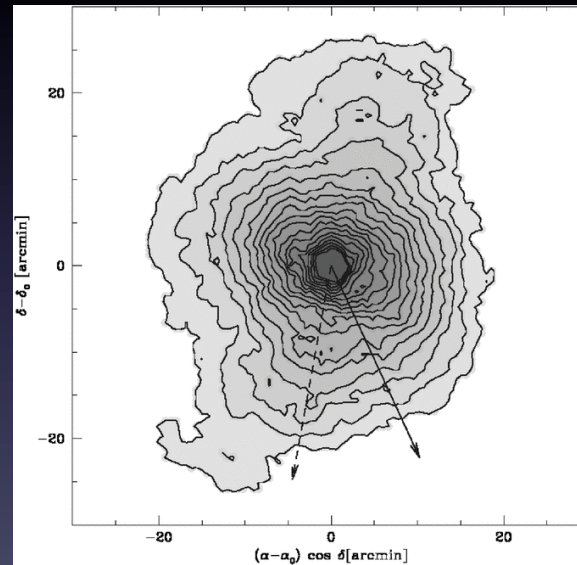


# Extra-tidal structure around the Milky Way's outer halo globular clusters

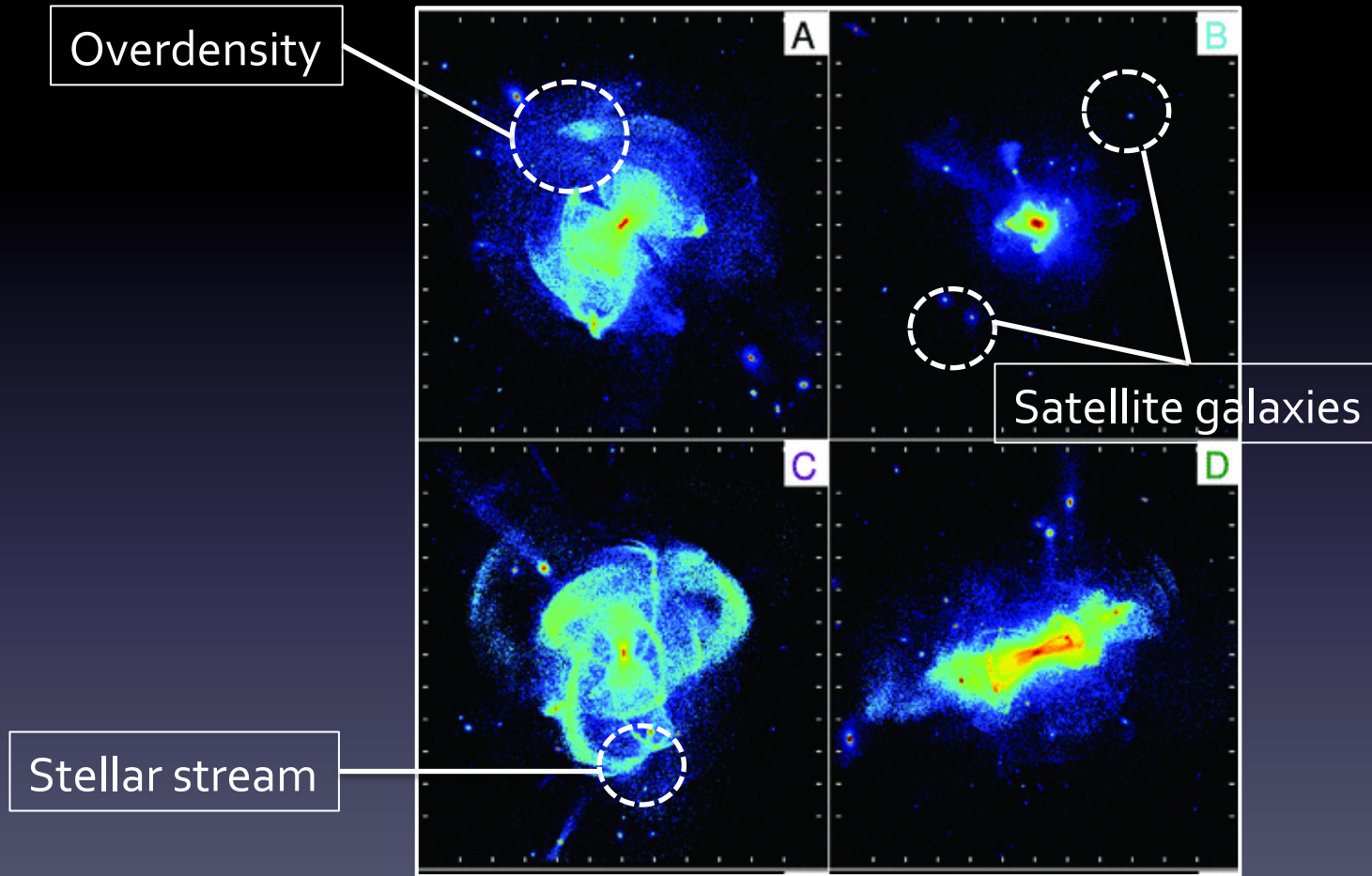
Sollima et al. 2011



Miho N. Ishigaki (東京大学/IPMU)

# Formation of the MW halo in $\lambda$ CDM

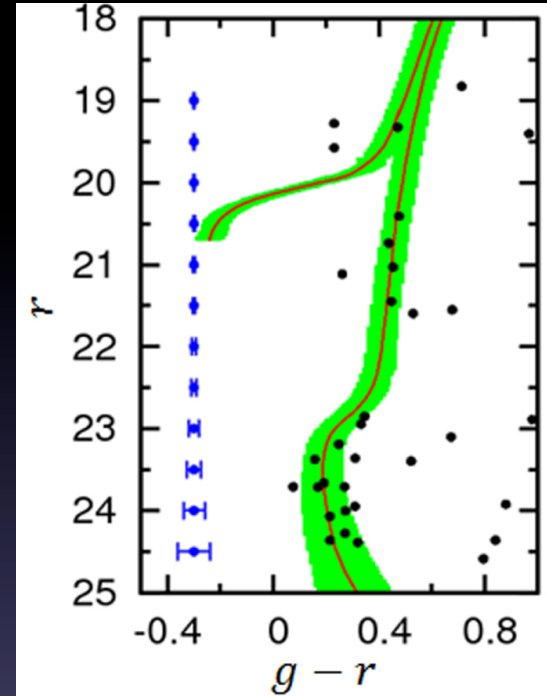
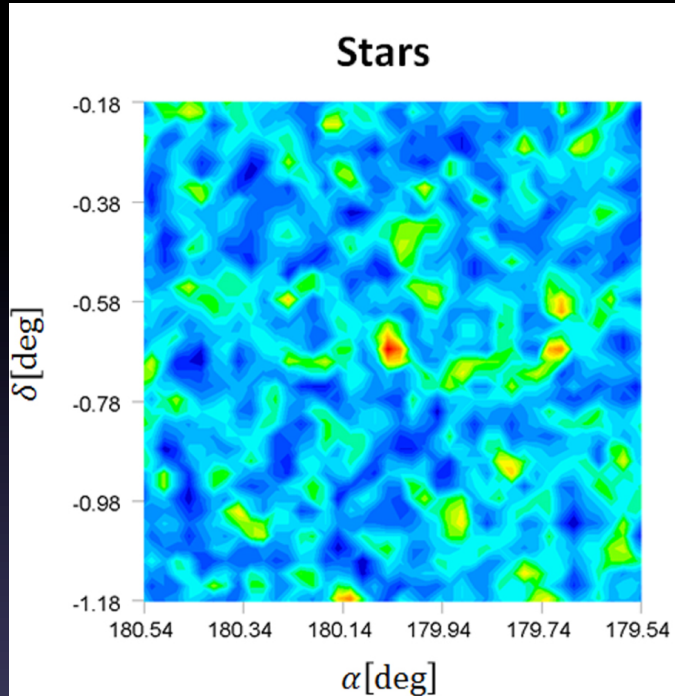
Surface brightness of stellar halos in cosmological simulations (Cooper et al. 2010)



*Main/sub-structures more frequent in the outer stellar halo  $\Rightarrow$   
Fossil records of the merging history of the Milky Way*

# Discovery of a new satellite in the outer halo by HSC

Virgo I @ distance=87 kpc; Homma et al. 2016

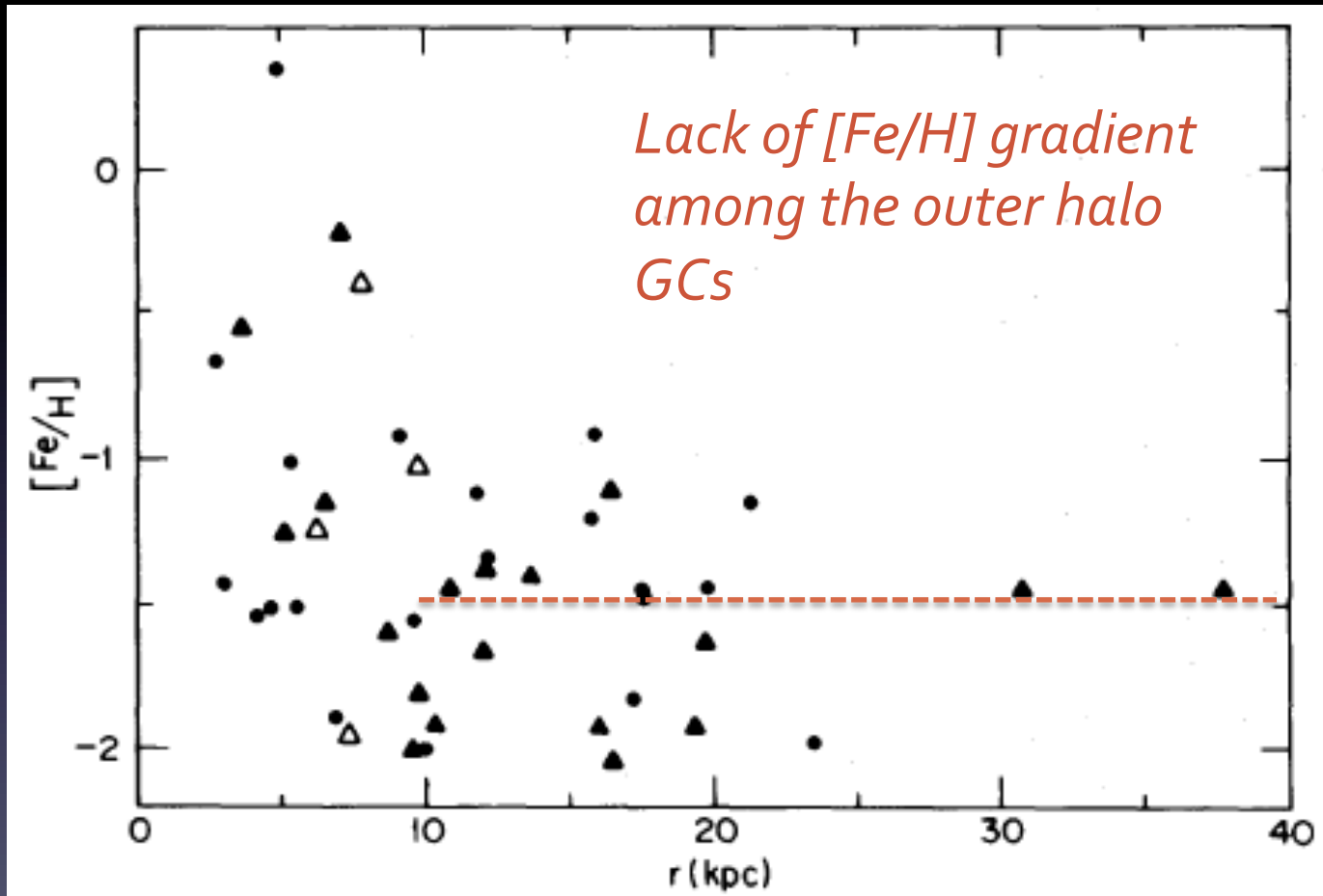


- What is the dark matter content?
- Formation mechanism of such a small galaxy?
- Where this satellite came from?
- What is the role of these faint satellites on the formation of the MW?
- Are the properties of this galaxy consistent with  $\Lambda$ CDM prediction in small scale?

➡ *Spectroscopic observation (e.g. Keck/DEIMOS) is essential*

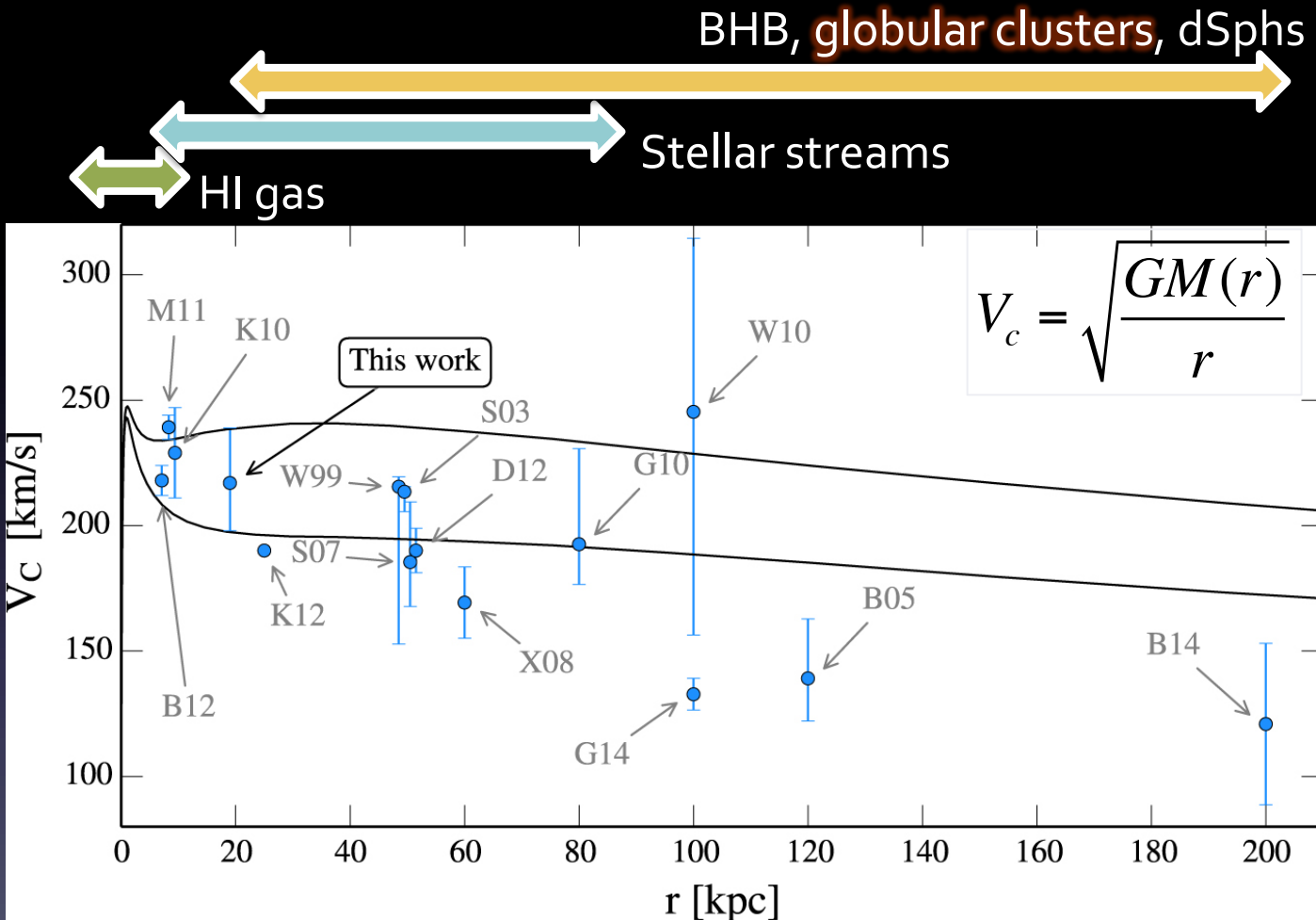
# Implication of GCs on the formation of the MW

Searle & Zinn 1978



*Formation of the outer halo via accretion of smaller galaxies*

# Mass of the MW's dark matter halo

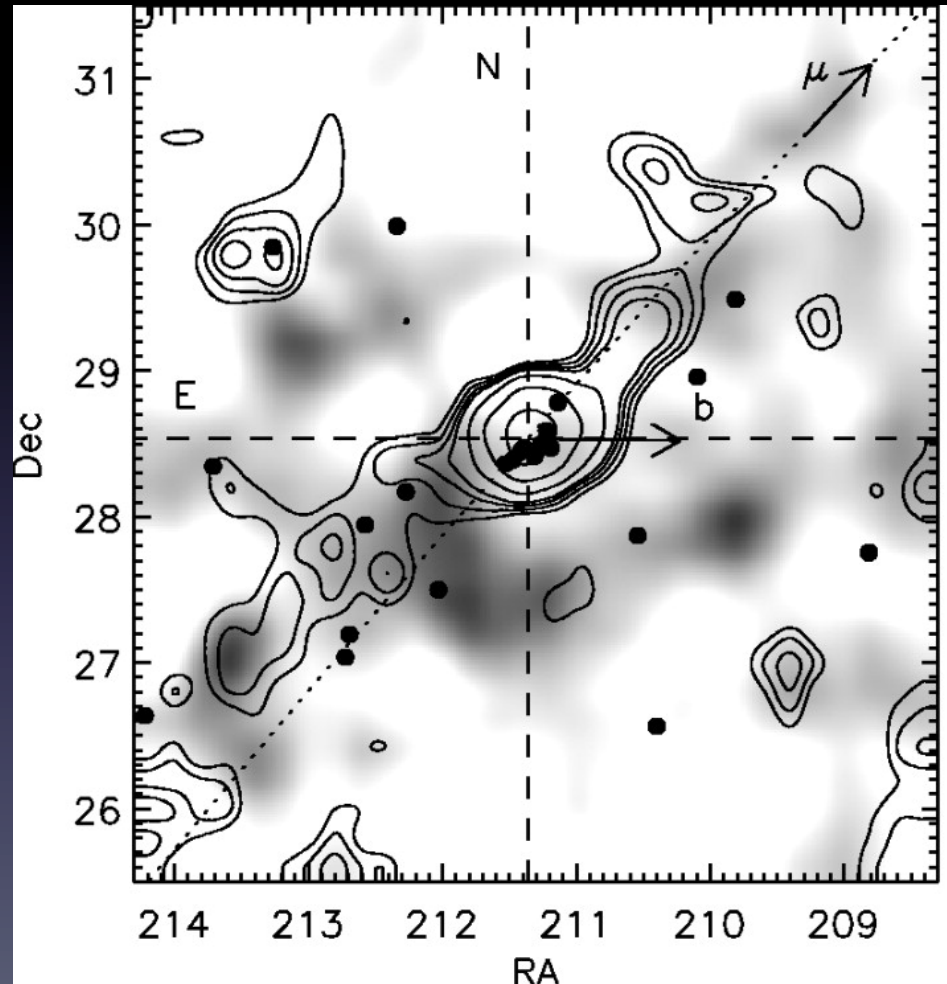


Kupper et al. 2015

*Globular clusters are important dynamical tracer in the outer halo:  
Total mass  $\sim 0.5 - 2.5 [10^{12} M_{sun}]$ : A factor of  $\gg 3$  uncertainty*

# Extra-tidal structure around globular clusters

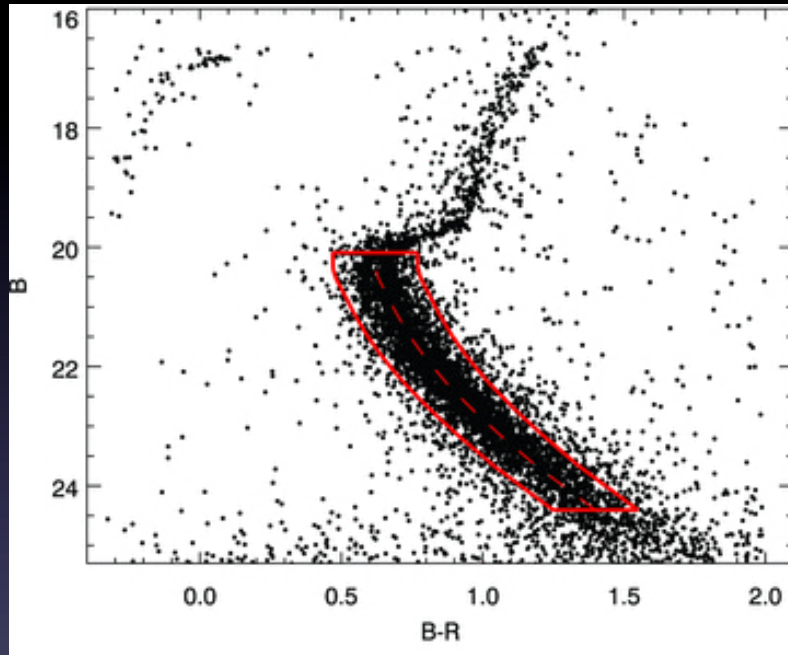
NGC 5466 @  $R_{GC} = 16\text{kpc}$



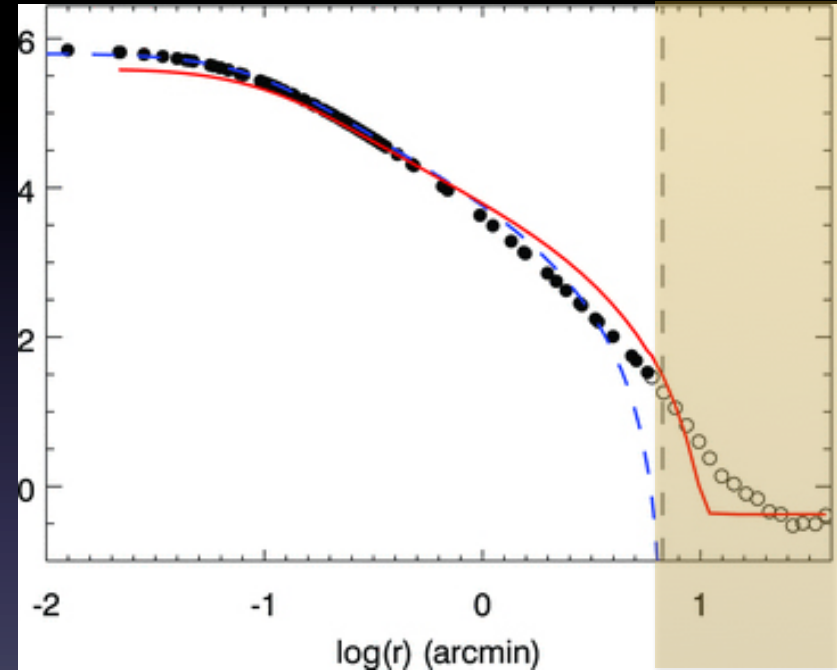
Belokurov et al. 2006

# Surface density profile

Carballo-Bello et al. 2012



Tidal radius ↓



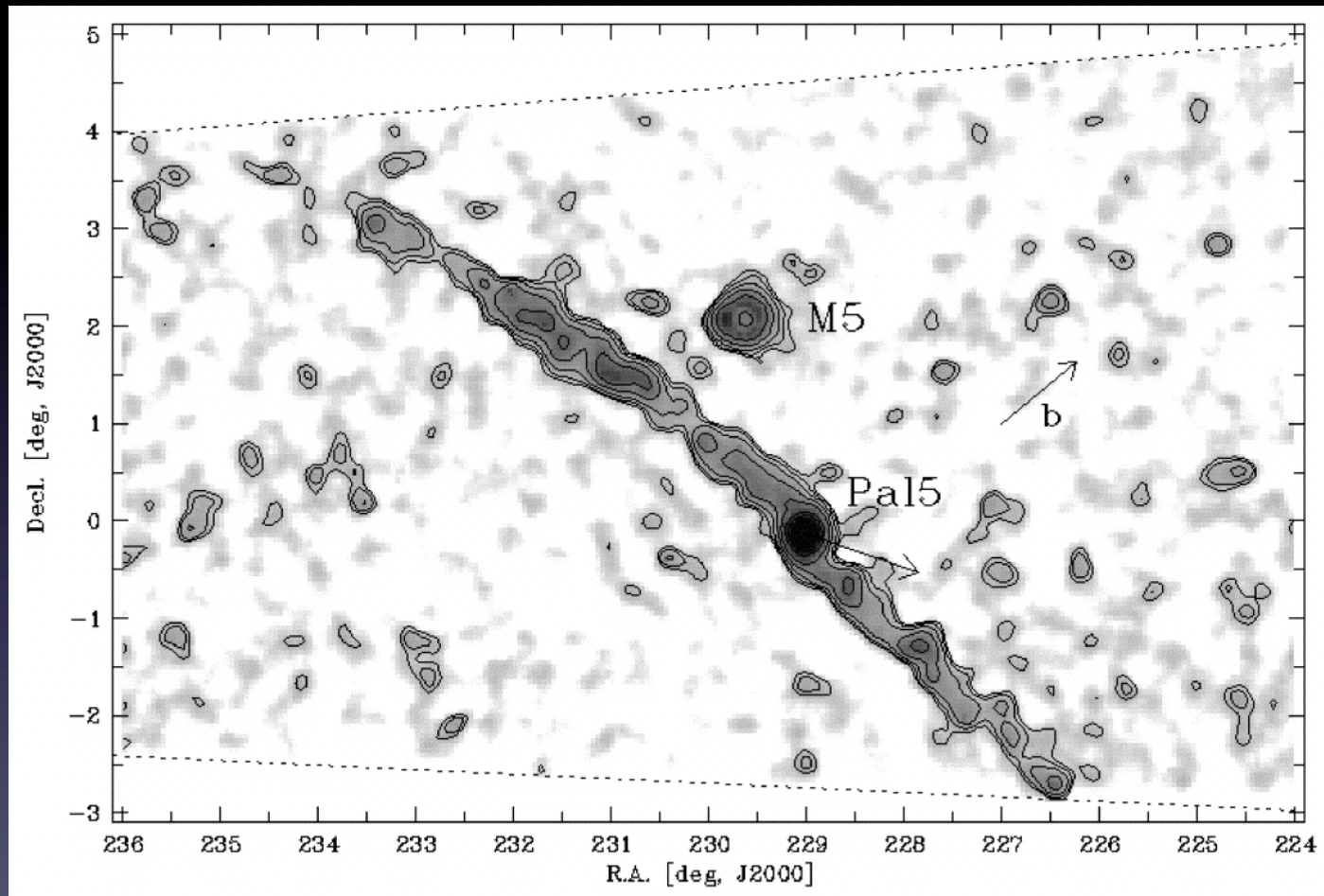
Deep and wide photometry



Detection of extra-tidal structure beyond ~ 20-30 arcmin

# The most prominent example of extratidal structure

Palomar 5 @  $R_{GC}=19$  kpc



Odenkirchen et al. 2003

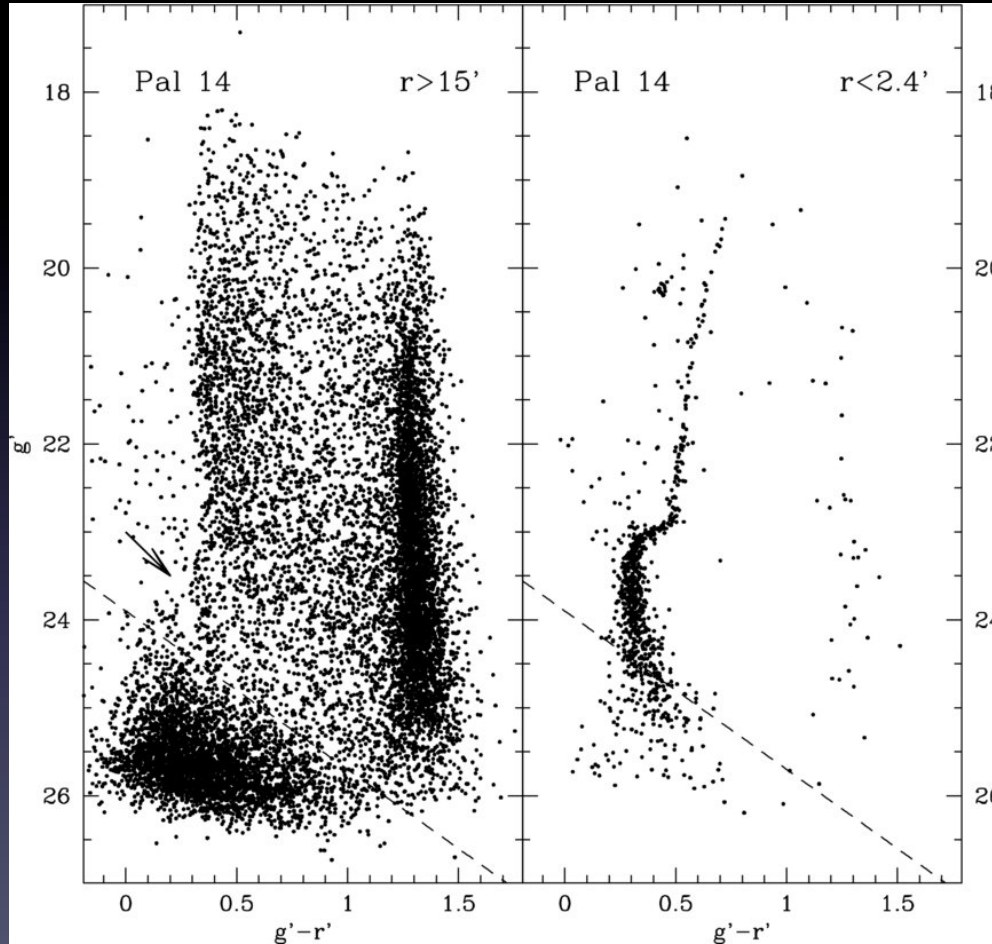
The only globular cluster known showing a very long and thin tidal tails.

# Extratidal structure of globular clusters: *Smoking-gun* of the MW formation

- Dynamical evolution of the GC partly driven by the tidal field of the host galaxy
  - Internal process: e.g. two-body relaxation
  - External process: e.g. tidal shock exerted by the Galactic disk/bulge
  - Whether a GC was formed within the MW or accreted through mergers of smaller galaxies
- Sufficiently long tidal tails (e.g. Palomar 5) tightly constrain the orbit of the GC around the MW
  - Present-day gravitational potential/total mass of the MW's dark matter halo

# Extra-tidal features around the outer halo GCs

CMD of Palomar 14 @  $R_{GC}=72\text{kpc}$  (CFHT/Mega-Cam)

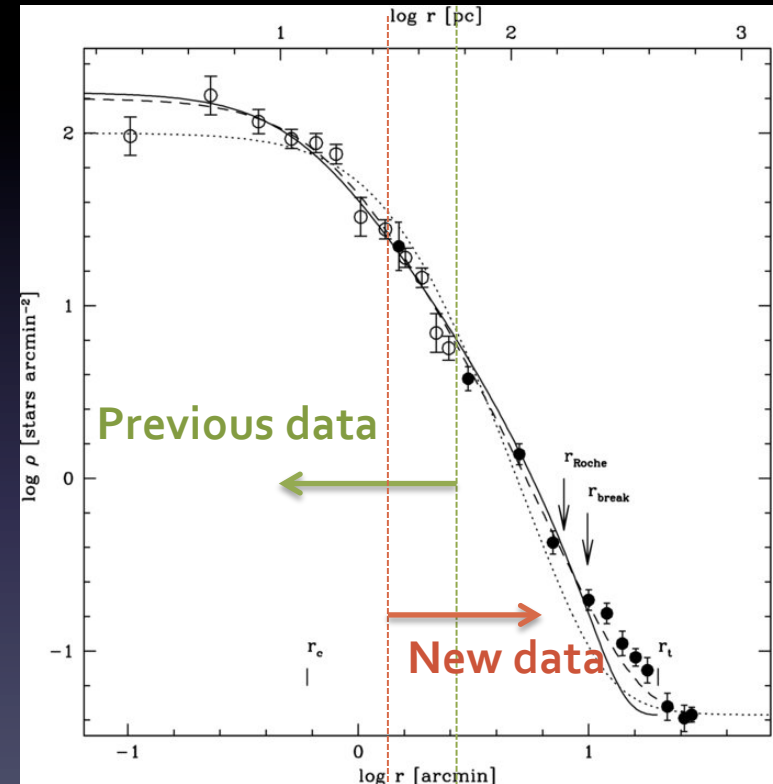
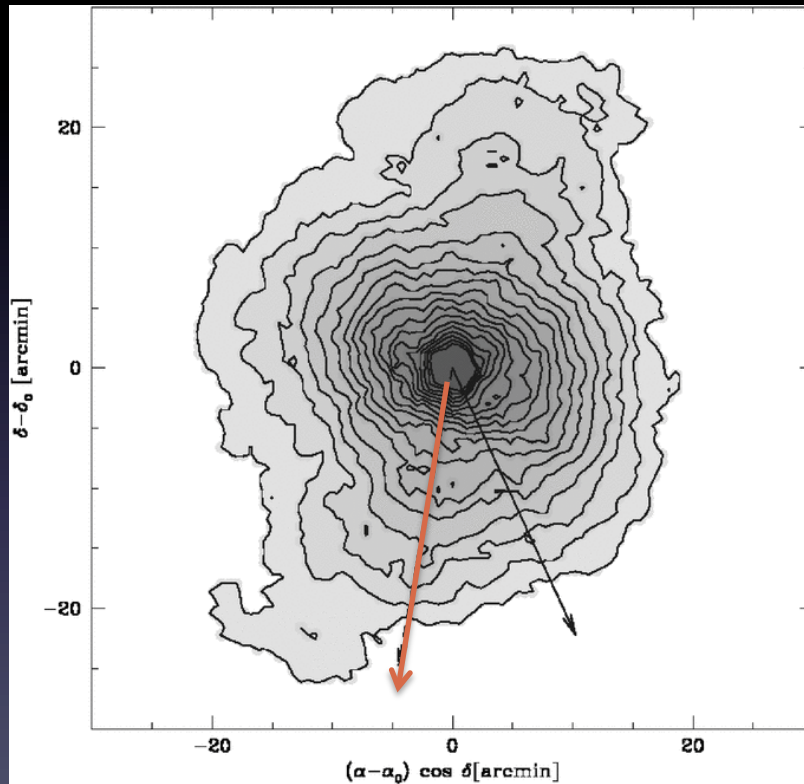


*Deep photometry down to  $g \sim 24.5$  allow for detection of the member stars at larger distance than the previous estimate for the tidal radius*

# Extra-tidal features around the outer halo GCs

Surface density profile over the  $\sim 1 \text{ deg}^2$  FoV

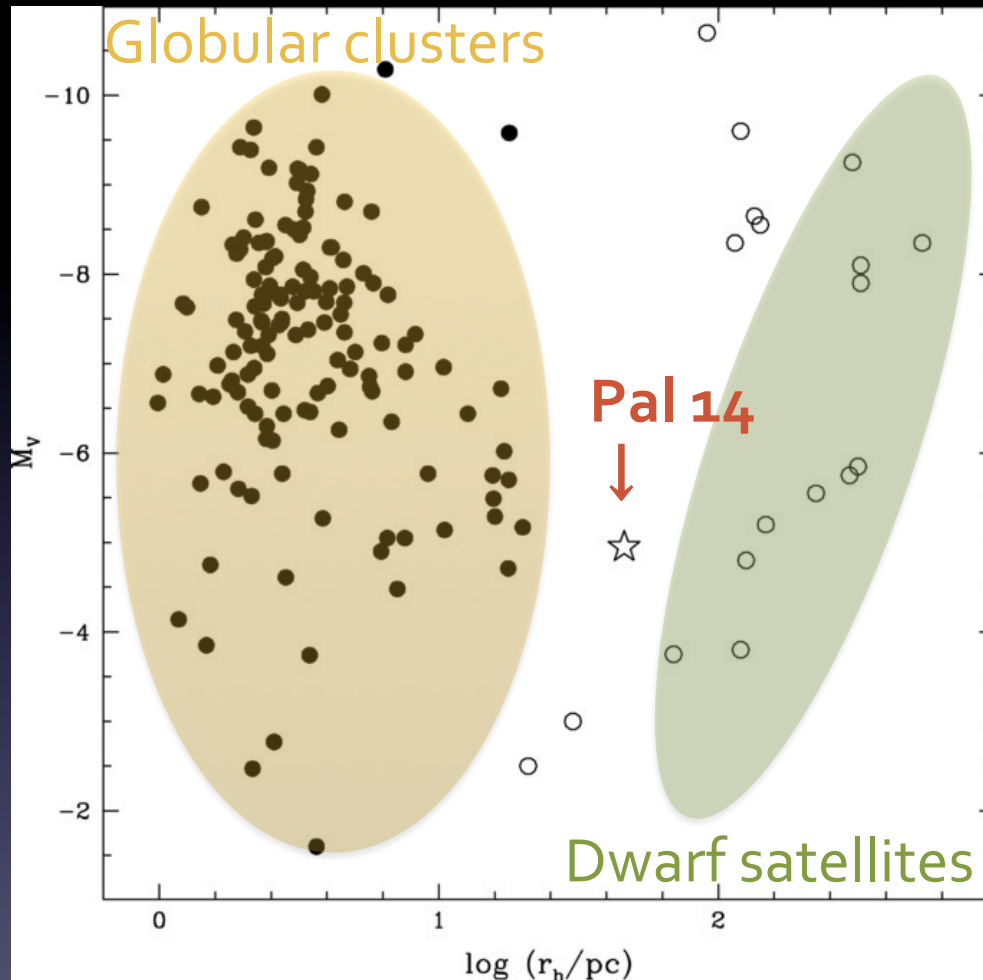
Sollima et al. 2011



- Elongated "S-shape" characteristic of the tidal tails
- The direction of the elongation is roughly coincide with the Fornax-Pal15 system

# External origin for Pal 14?

Sollima et al. 2011

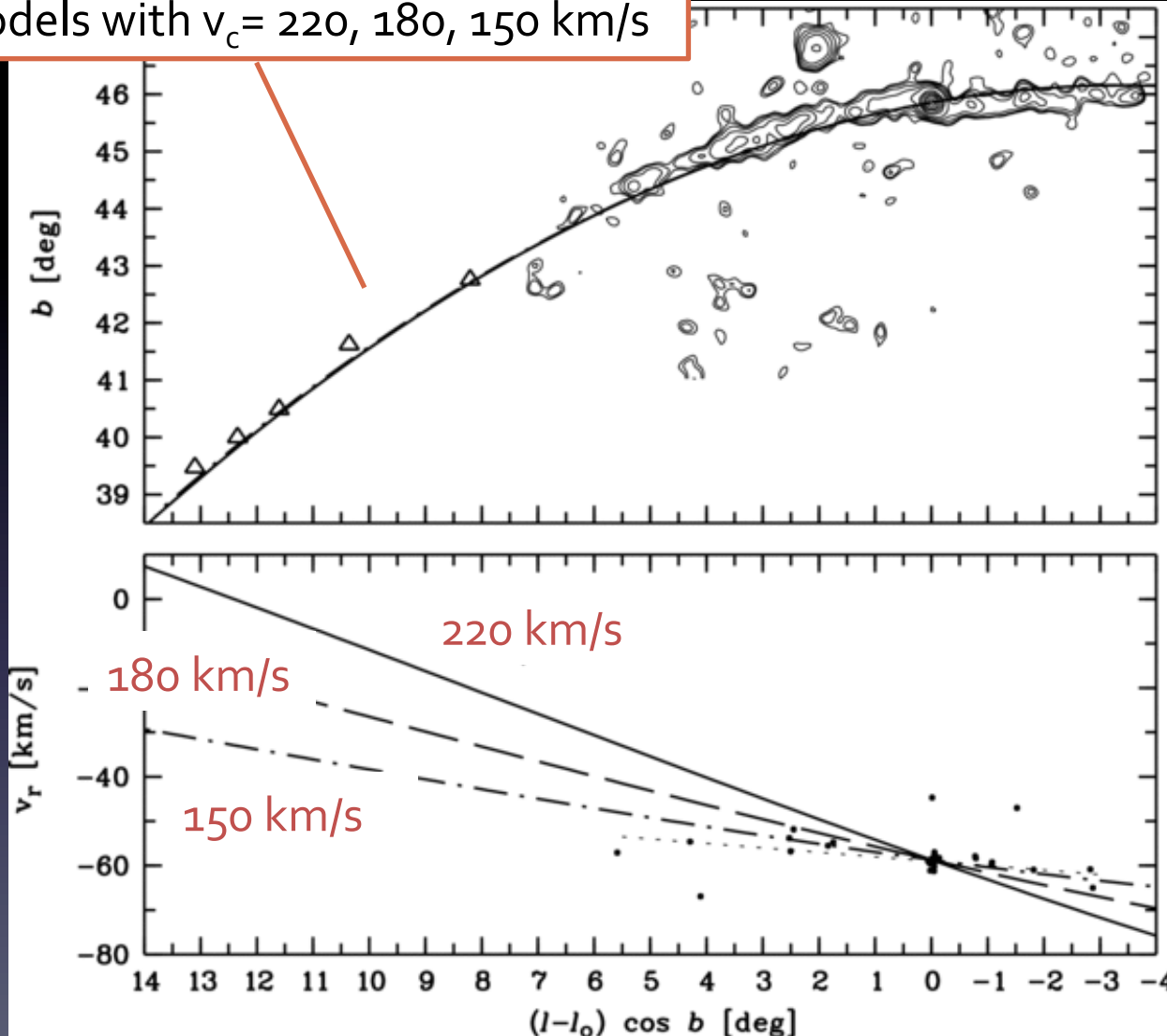


Pal 14 is unusually extended Compared to other GCs. It is difficult for such a low-density cluster to survive in the MW's potential

# Constraints on dark matter halo potential

Odenkirchen et al. 2009

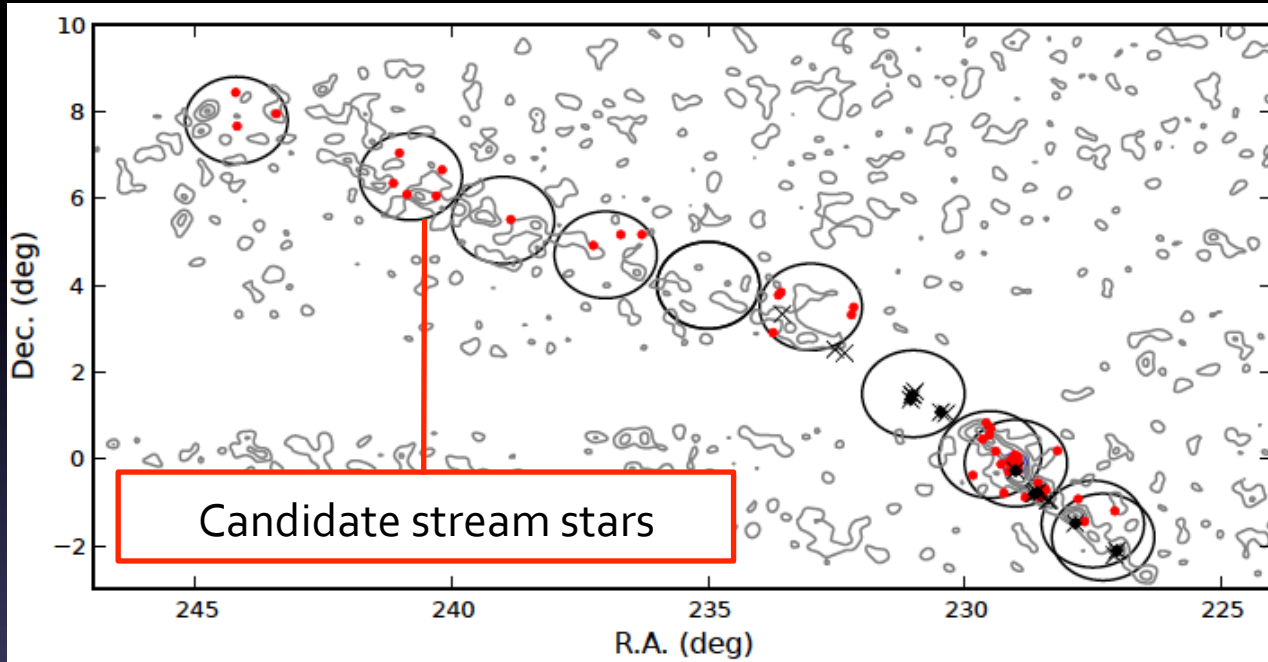
The models with  $v_c = 220, 180, 150$  km/s



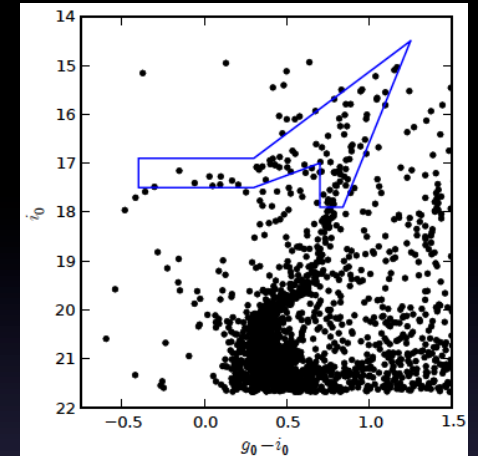
*Line-of-sight velocity measurements at the outer part of the stream is important*

# Identifying the member stars by multi-object spectroscopy

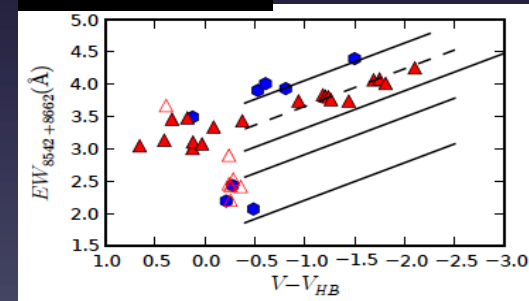
Kuzma et al. 2015



(1) Color-magnitude



(2) CaT EW

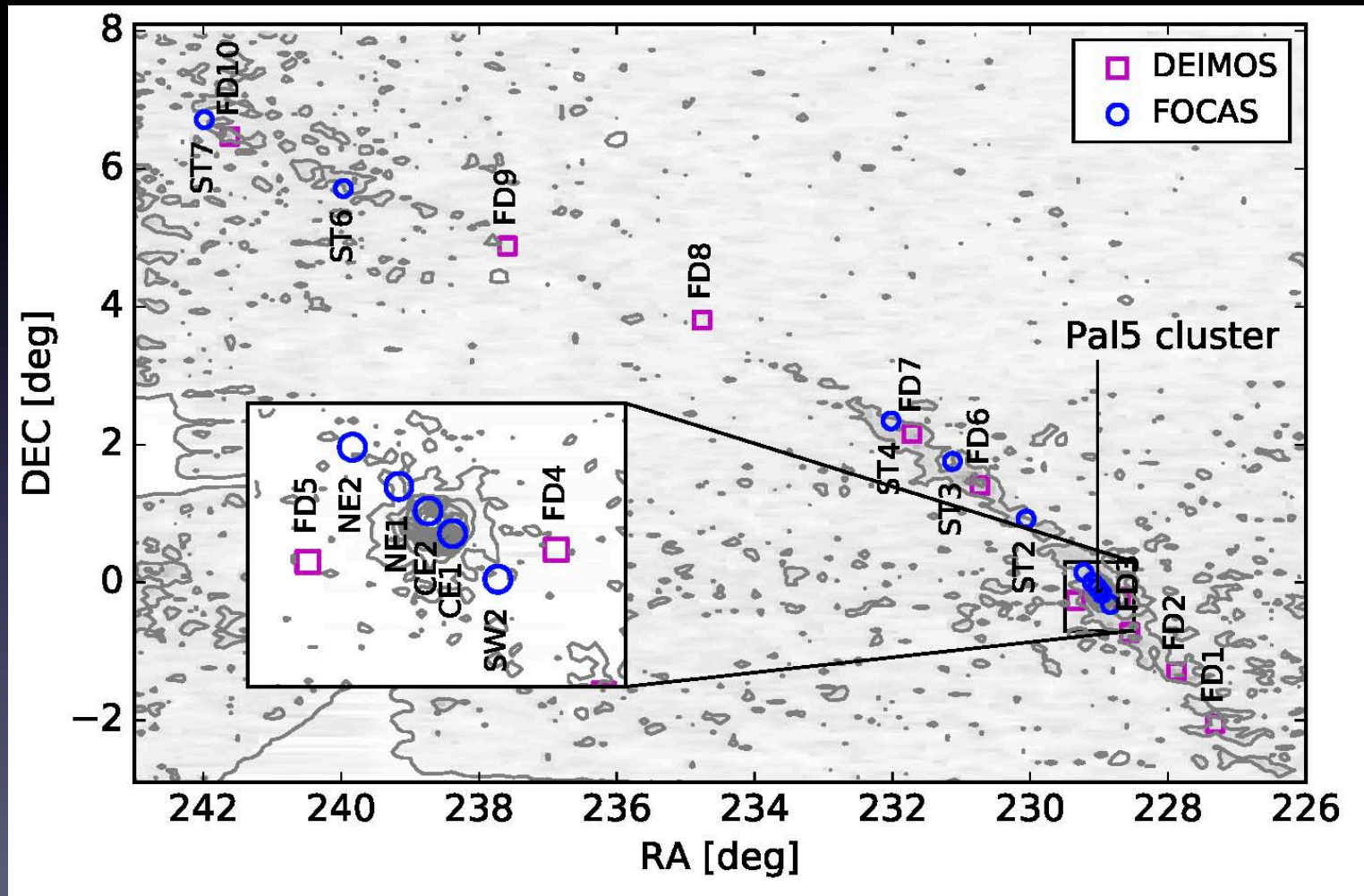


(3) Line-of-sight velocity:  $-70 < V_{\text{los}} < -30$  km/s

- Spectroscopy up to fainter magnitude  $\rightarrow$  8-10m-class telescope
- Chemical composition measurements (e.g.  $[\text{Fe}/\text{H}]$ ,  $[\alpha/\text{Fe}]$ )  $\rightarrow$  spectral resolution at least  $R \sim 5000$

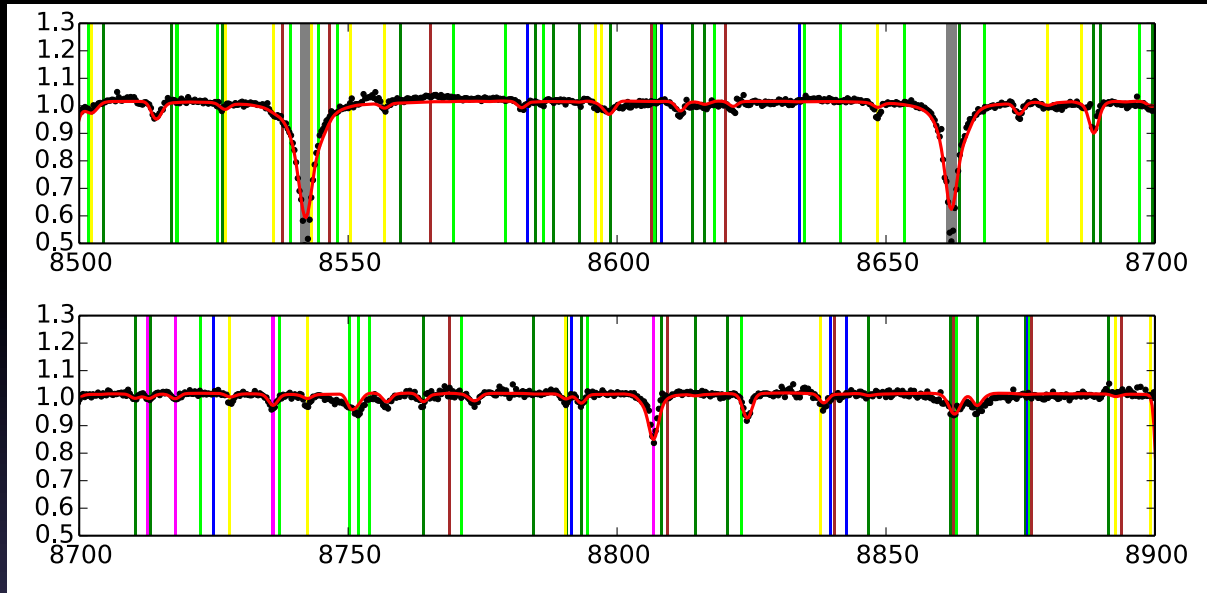
# Medium resolution spectroscopy along the Pal 5

Stellar density map for the color-magnitude selected stars based on SDSS DR12

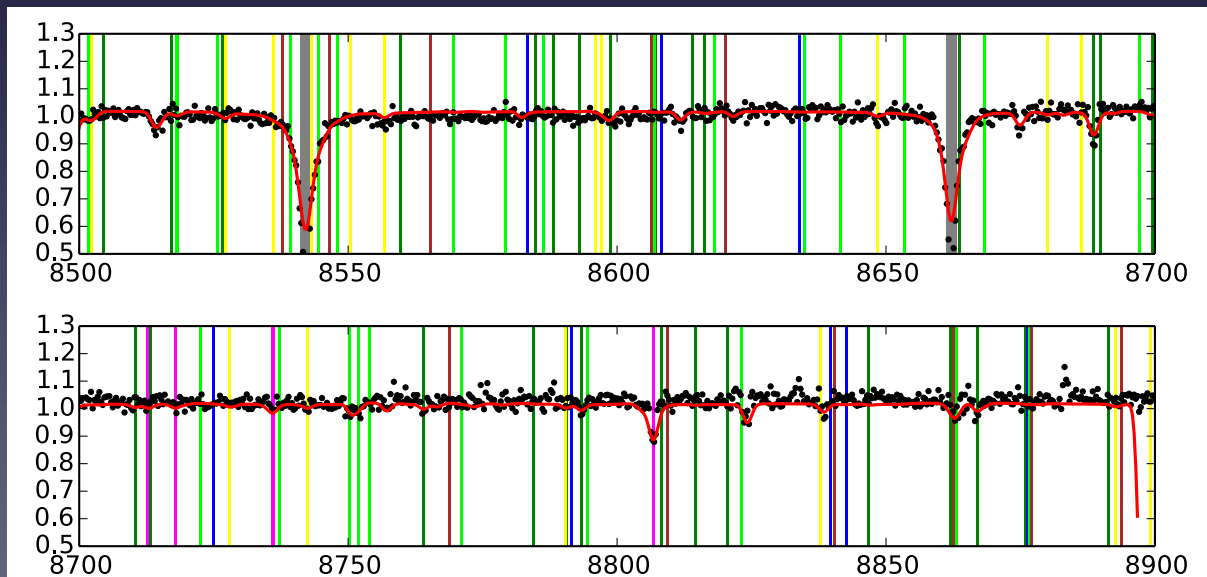


# Stellar [Fe/H] measurements

Keck/DEIMOS spectra (R~6500) of stars in the Pal 5 stream fields



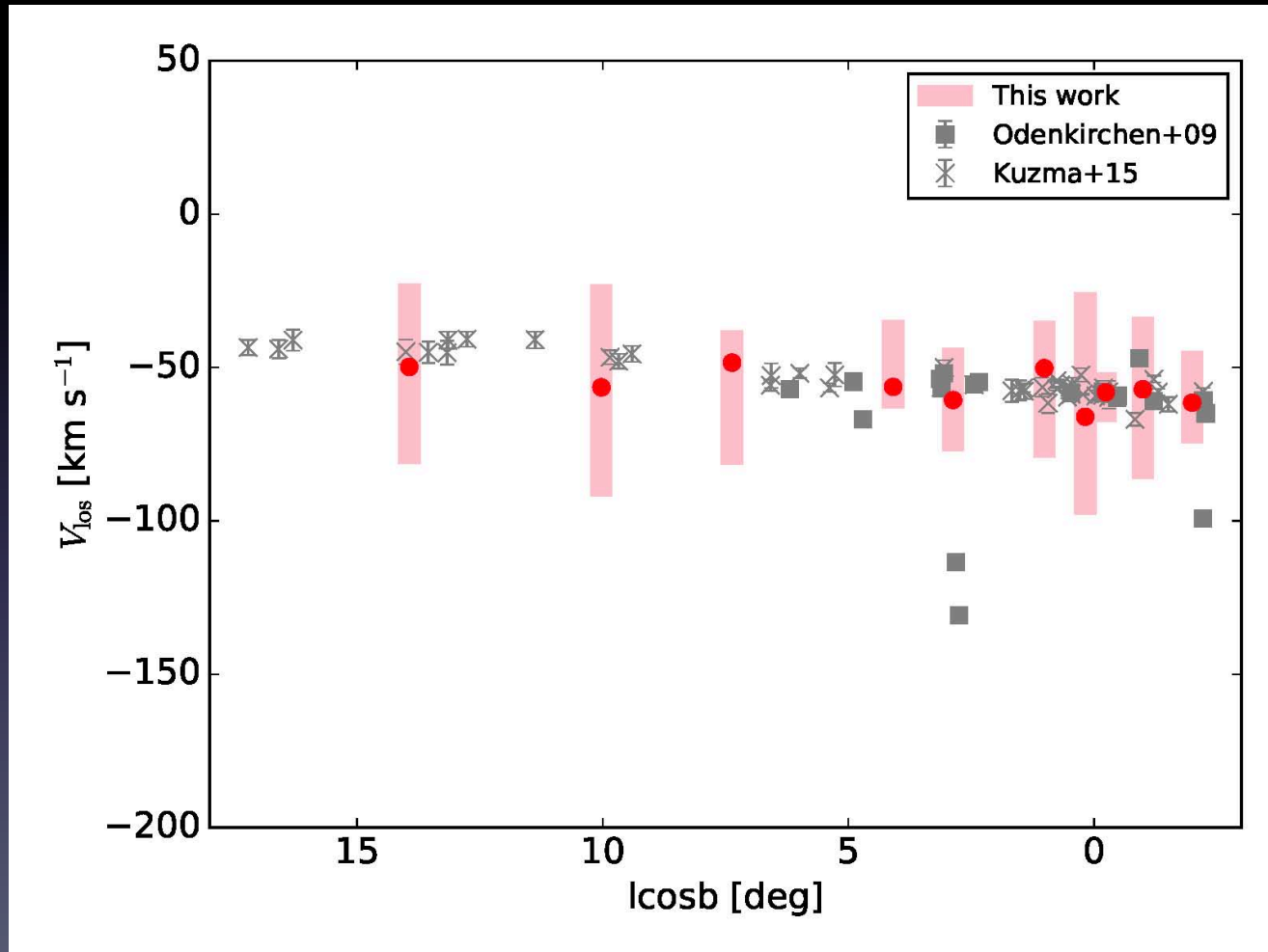
$T_{\text{eff}} = 5508\text{K}$   
 $\log g = 4.6$   
 $[\text{Fe}/\text{H}] = -0.94$



$T_{\text{eff}} = 4898\text{K}$   
 $\log g = 2.7$   
 $[\text{Fe}/\text{H}] = -1.45$

# The robust constraints on the $V_{\text{los}}$ ranges for the stream

Modeling  $V_{\text{los}}$  distribution of Pal 5 stream + foreground MW stars



Ishigaki et al. 2016

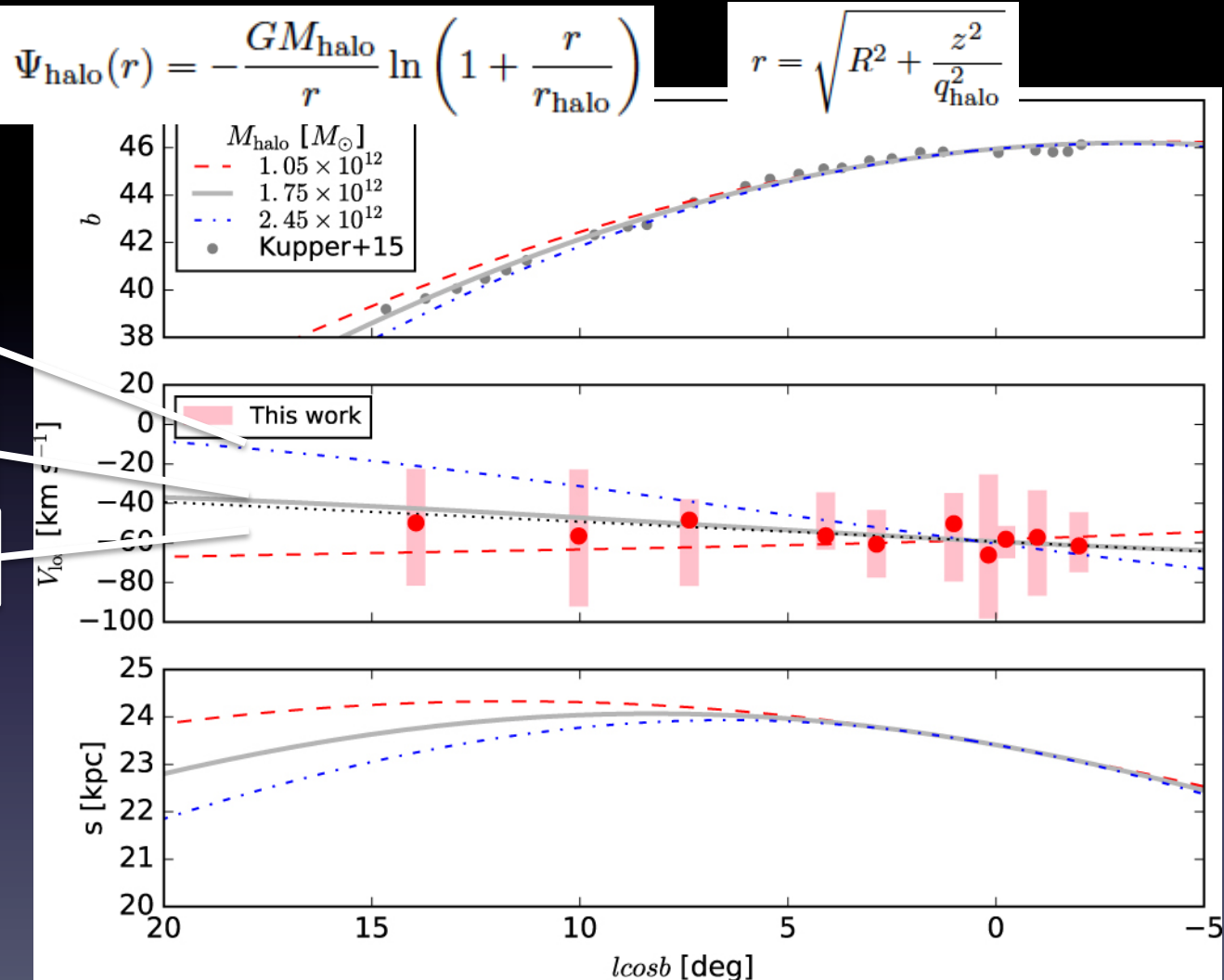
# Comparison with models for the dark matter halo

$V_c(R_\odot)$  of the models

242km/s

231km/s

218km/s



Ishigaki et al. 2016

*For a given assumption about bulge/disk potentials, the model for a relatively massive dark halo model is ruled out*

# Other outer halo GCs beyond $R_{GC} > 30$ kpc

- 14 clusters from Harris et al. (2003) catalog beyond  $R_{GC} > 30$  kpc
  - Photometric data with sufficient depth and FoV are available only for Pal 14
- Turn-off magnitudes  $g \sim 23-24$  : In order to reach main-sequence, photometry down to  $g \sim 24-25$  is needed
- Extra-tidal structure @  $r > 20'$  or more
- Whether they show significant extra-tidal structure?
  - If yes...
    - What is the spatial distribution of the structure?
    - Does it show “s-shape”, characteristic of the tidal tail
    - Does it show spatial variation in  $V_{los}$ ?
  - If no...
    - Internal dynamical evolution of the cluster
    - Constraints on the interaction with MW

# Systematic survey of the extra-tidal structure in the outer halo GC with Subaru/HSC + Keck/DEIMOS

- **Subaru/HSC**: Deep+Wide imaging down to main-sequence magnitudes:
  - High contrast of member stars vs foreground stars allow for detecting faint extra-tidal structure
  - Identifying bright spectroscopic targets in the outer part of the GCs
- **Keck/DEIMOS**: Spectroscopy to measure line-of-sight velocity and metallicity of the candidate members
  - Separation of stars belonging to the GCs from foreground stars
  - Line-of-sight velocity gradient along the extra-tidal structure as a constraint on its Galactic orbit
- Subaru/PFS: larger-scale structure of the tidal streams

# Summary

- Extratidal structures in globular clusters in the Milky Way outer halo are unique tracers of the dynamical structure and the assembly history of our Galaxy
- Deep ( $g \sim 24$ ) and wide ( $\sim$  a few  $\text{deg}^2$ ) photometry is essential to securely detect faint extra-tidal features over the field stars: **Subaru/HSC**
- Deep ( $g \sim 21$ ) spectroscopy provides kinematics of the extra-tidal structure that can tightly constrain dynamical evolution of the cluster and the potential of the Milky Way outer halo: **Keck/DEIMOS**