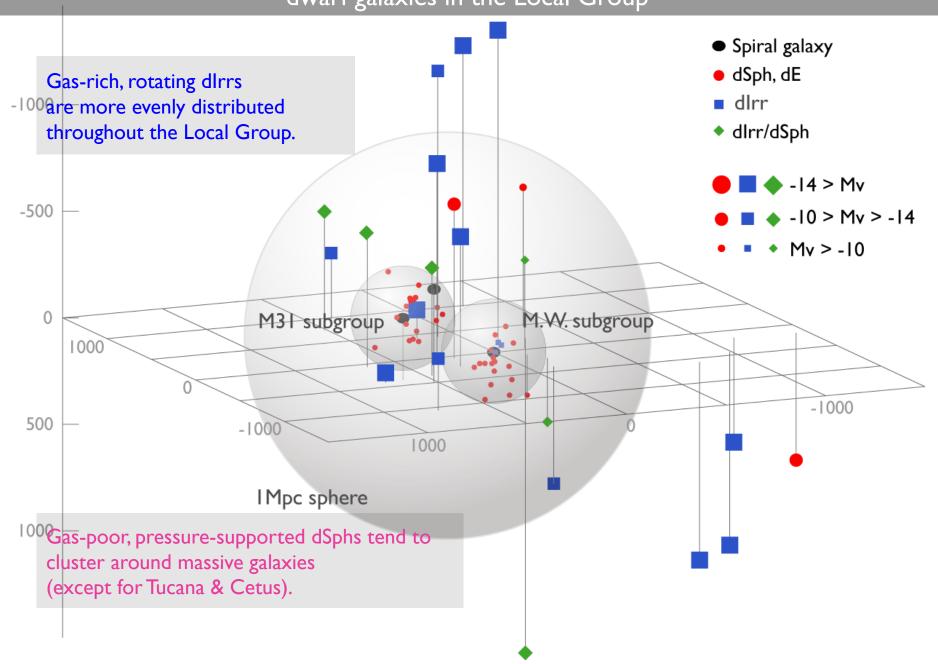
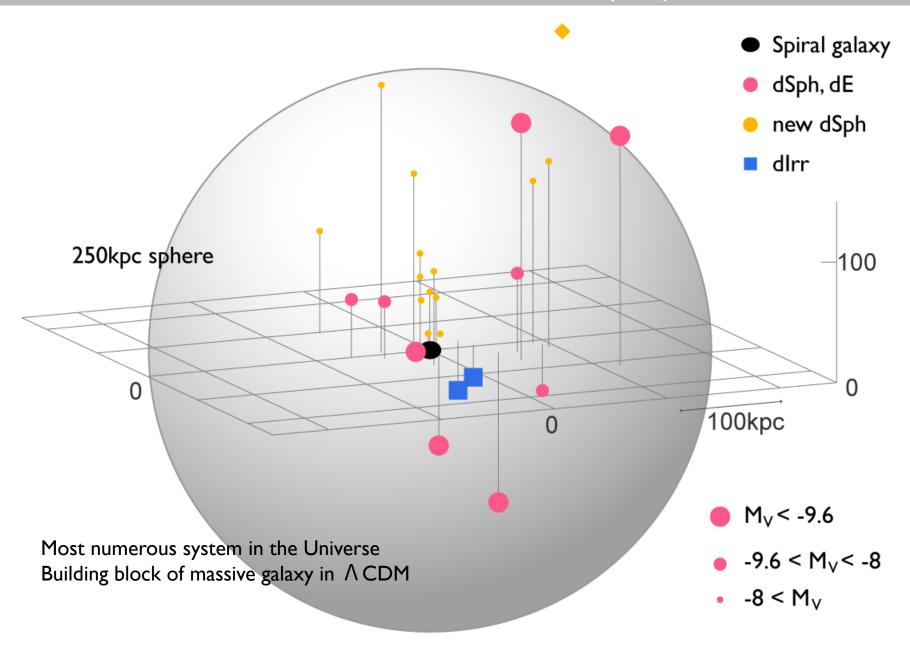
# Stellar populations of Galactic satellites and Near-field cosmology with HSC

Sakurako Okamoto Kavli Institute for Astronomy and Astrophysics, Peking University

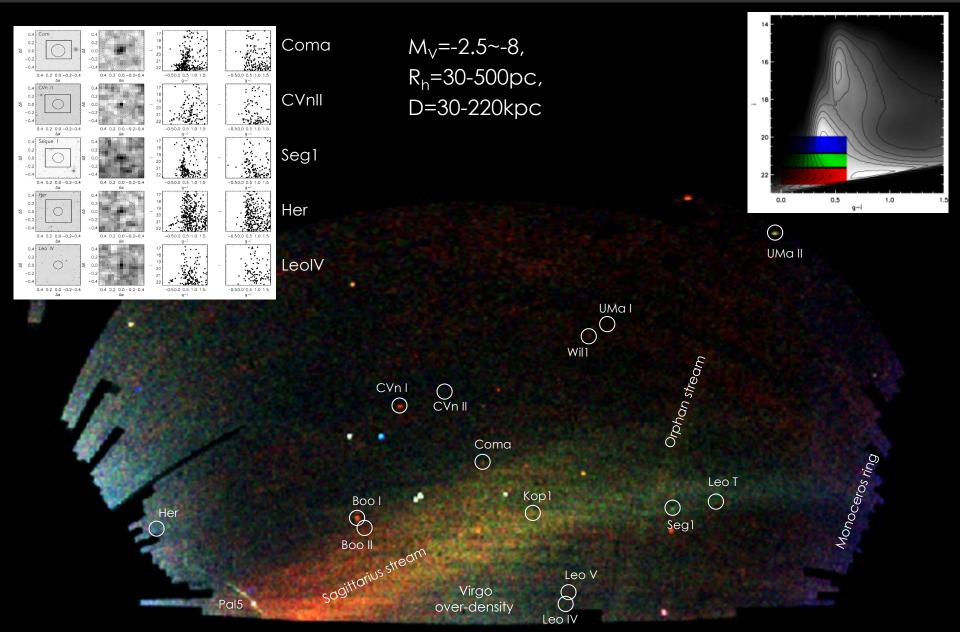
#### dwarf galaxies in the Local Group



#### dwarf satellites around the Milky Way



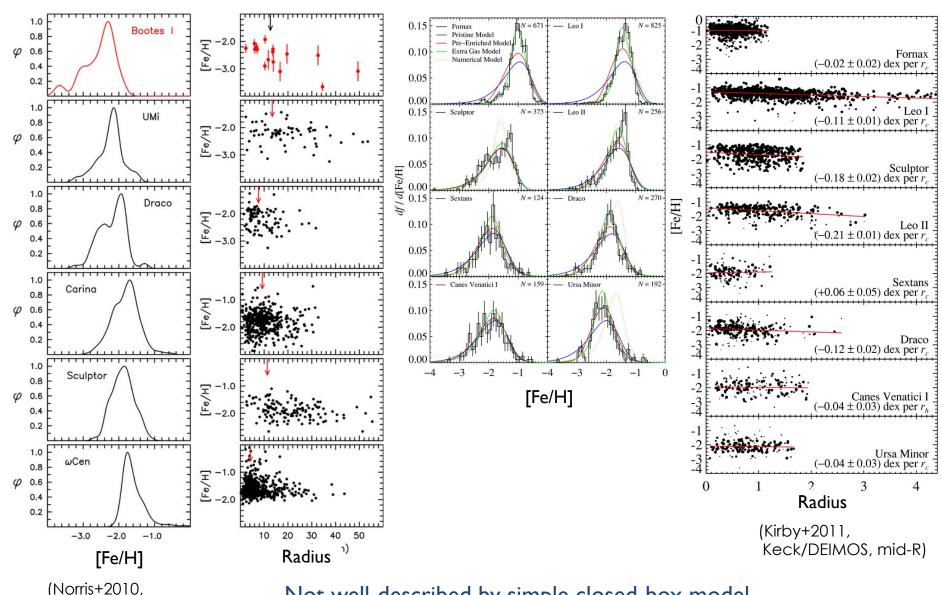
#### Discoveries of UFD galaxies and streams



# dSph satellites around the Milky Way

Name	Mv [mag]	D [kpc]	$\mu_0$ [mag/arcsec $^2$ ]	Population	SFH
Sgr / Fornax Leo I / Sculptor Leo II / Carina	-13.4 / -13.0 -11.9 / -10.7 -9.6 / -9.3	24 / 138 250 / 79 204 / 105	25.4 / 23.4 22.4 / 23.7 24.0 / 25.5	inter-age ~ old	Extended or Episodic SF
Sextans Draco Ursa Minor	-9.5 -9.1 -8.9	93 83 64	26.2 25.3 25.5	old?	simple?
CVn I	-7.8	220	27.5	old?	simple?
UMa I Her Boo I Leo IV CVn II	-6.8 -6.0 -6.0 -4.9 -4.9	97 140 66 160 150	29.5 (-) 27.8 29.5 28.2	old?	simple?
UMa II / Coma Boo II,,,	-3.8/-3.7 -2.3	30 /44 42	- / - 27.7	old?	simple?
LeoT	-7.0	420	27.7	young? old?	Extended?

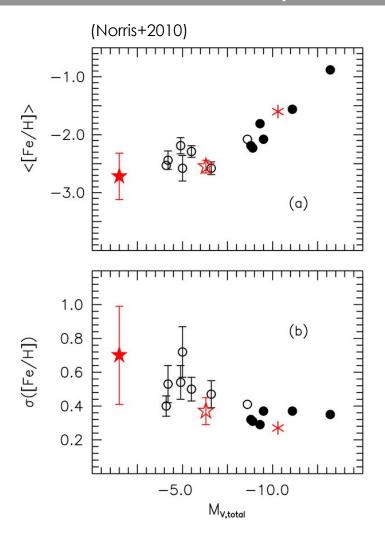
#### Metallicity gradients in MW satellites



Not well-described by simple closed-box model. Star formation more likely episodic.

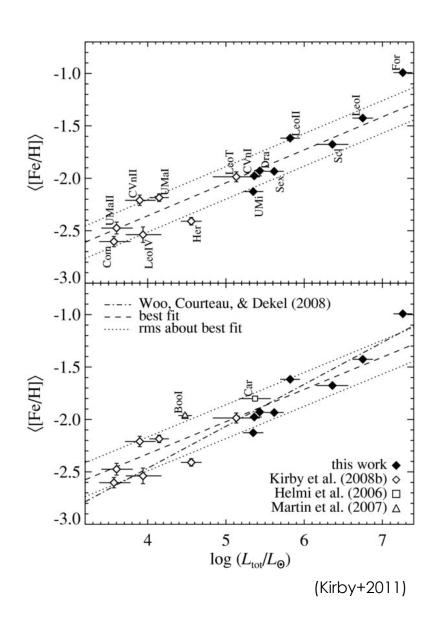
VLT, MMT, high-R)

#### Metallicity-Luminosity relation in MW satellites

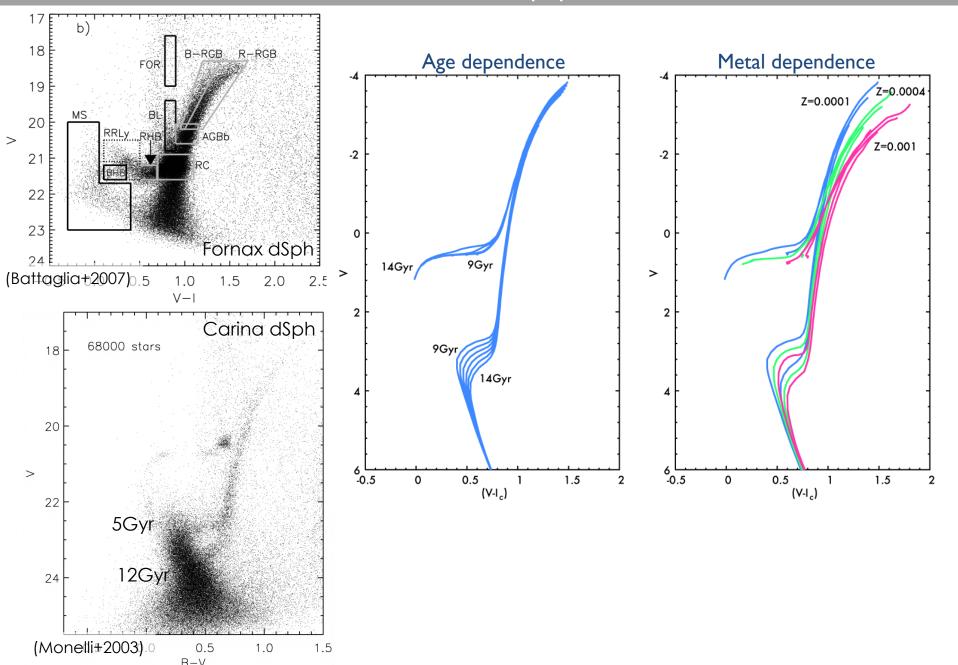


Metallicity dispersion increases as luminosity decreases

Inhomogeneous stochastic enrichment in low-mass halos?



#### Resolved old stellar population



#### Subaru/Suprime-Cam observation of UFDs & Draco, UMi, Sextans

Targets: Ursa Major I

Bootes I

Canes Venatici I

Canes Venatici II

Leo IV

Hercules

Leo T

+ each control fields

Draco 5 fields

Ursa Minor 2 fields

Sextans 26 fields (DART collaboration)

Band, exp-time:

V (10s / 600s~)

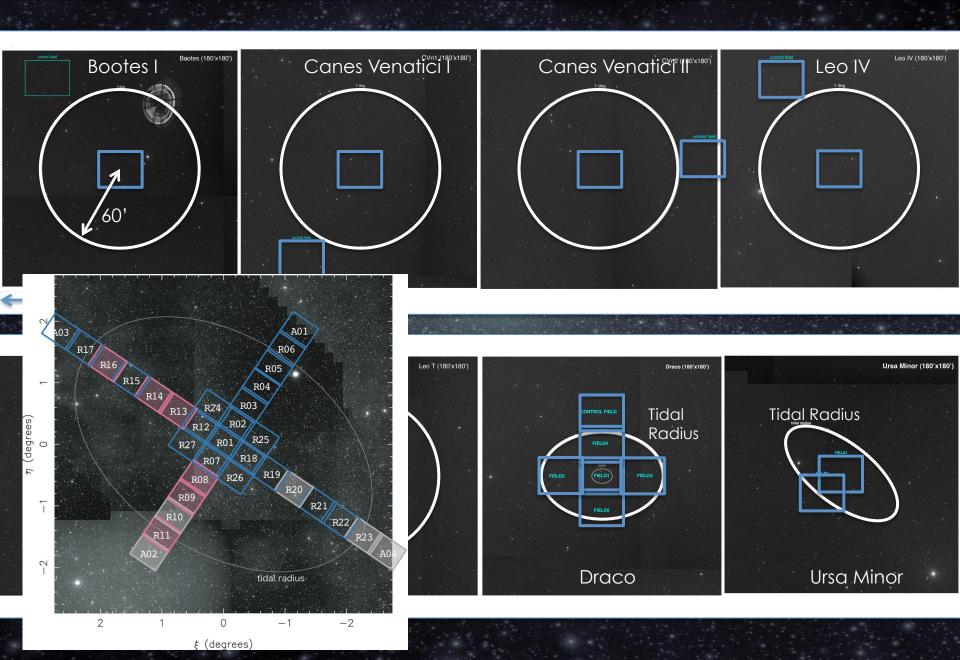
Ic (30s / 3000s~)

Seeing: 0.7~1.0"

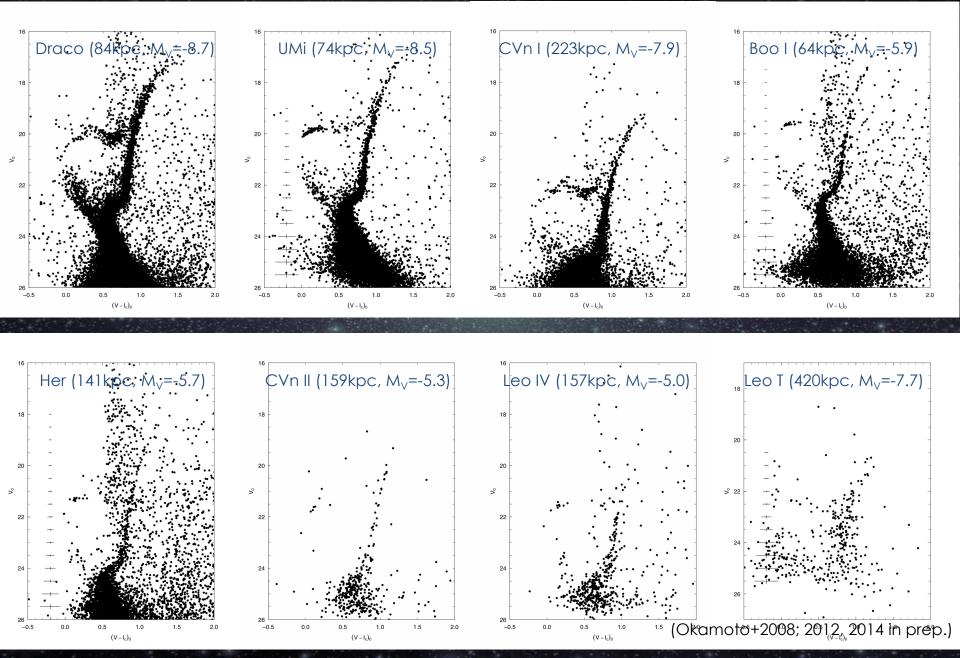


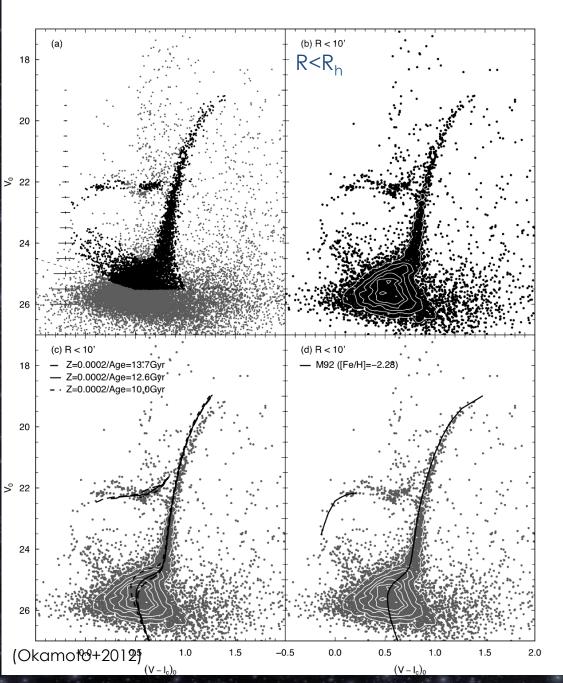
Suprime-Cam: FoV = 34' x 27' pixel scale = 0.202"

#### Subaru/Suprime-Cam, CFHT/MegaCam observation of UFDs & Draco, UMi



# CMDs within R<sub>h</sub>

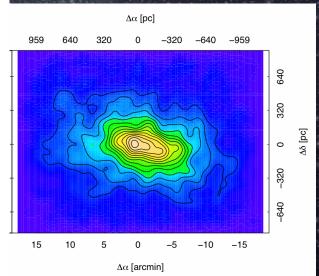


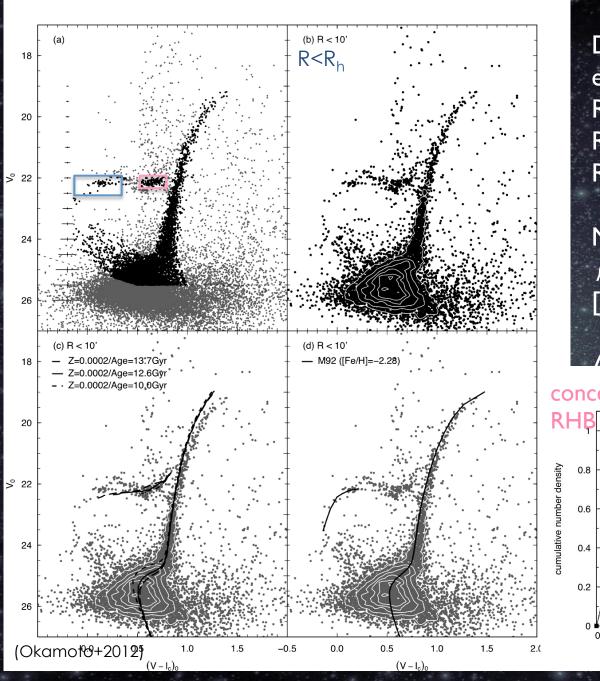


Distance = 223 ± 8 kpc ellipticity = 0.30  $R_C = 363 \pm 26 \text{ pc}$  $R_T = 3.5 \pm 0.8 \text{ kpc}$  $R_h = 596 \pm 25 \text{ pc}$ 

 $M_{V} = -7.93 \pm 0.2$   $\mu_{0} = 27.5 \pm 0.2$ [Fe/H] = -2.08 (by Kirby+2008)

Age~I2.6Gyr

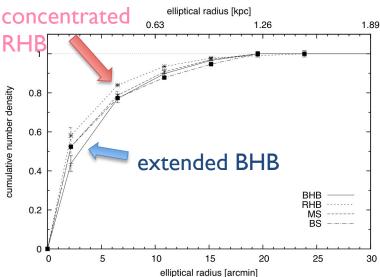


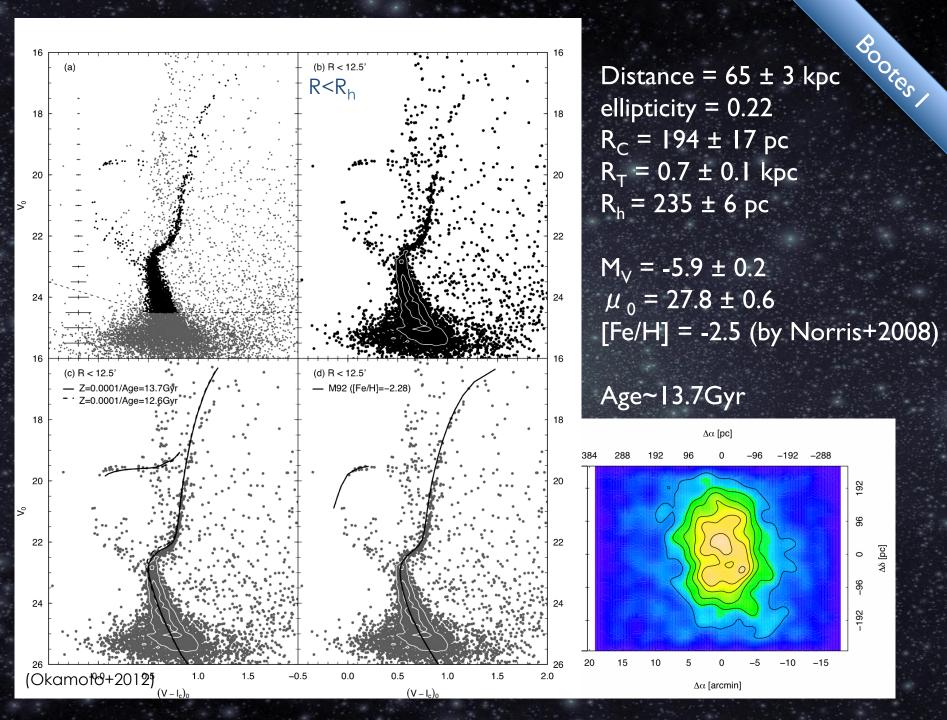


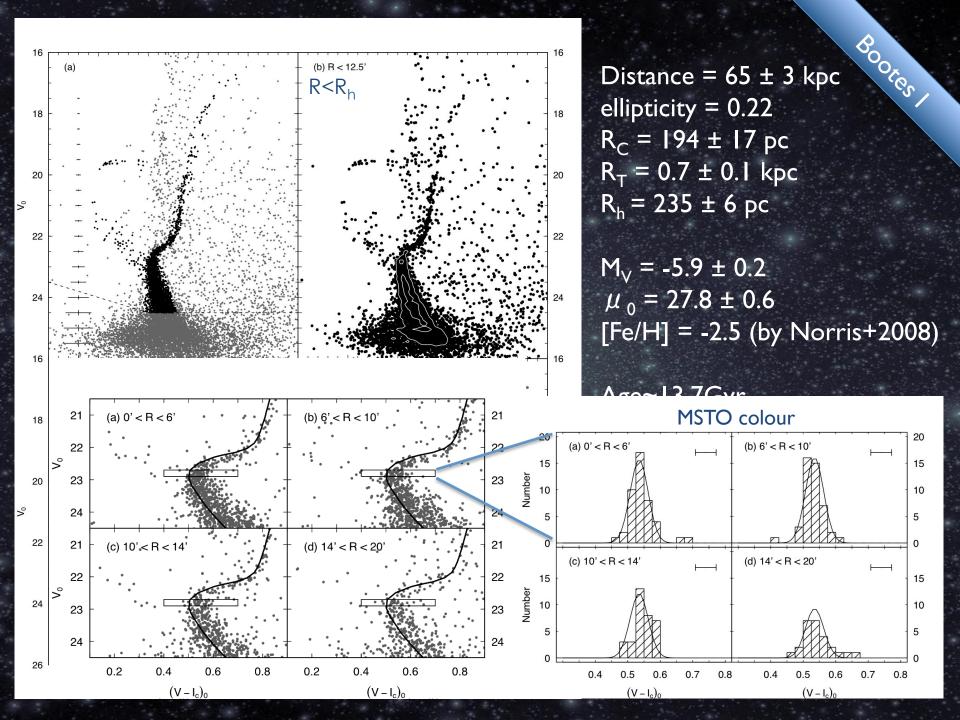
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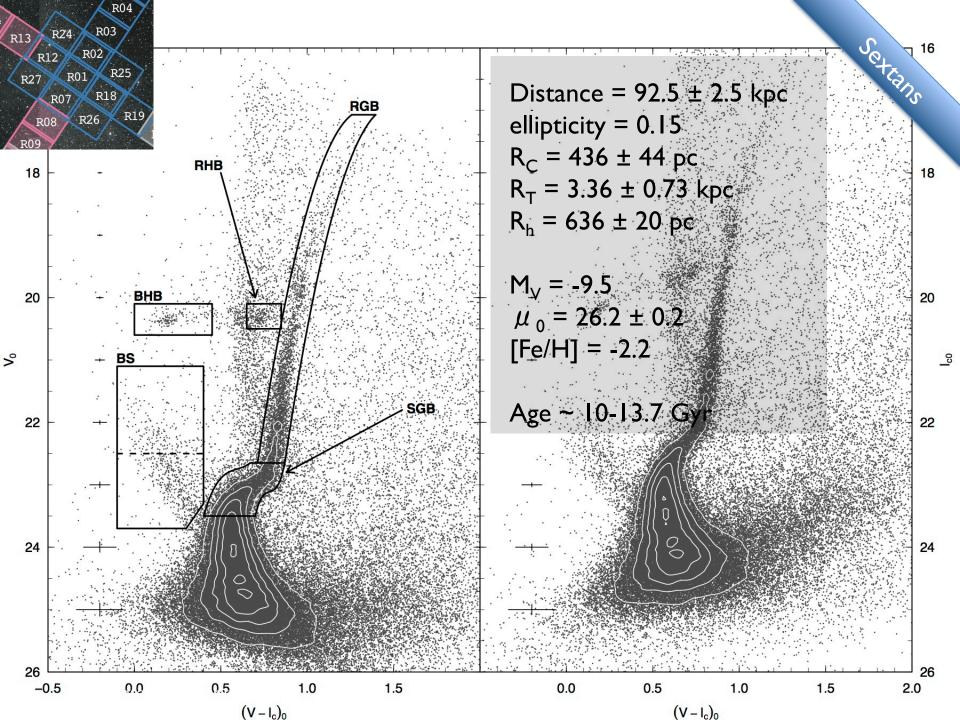
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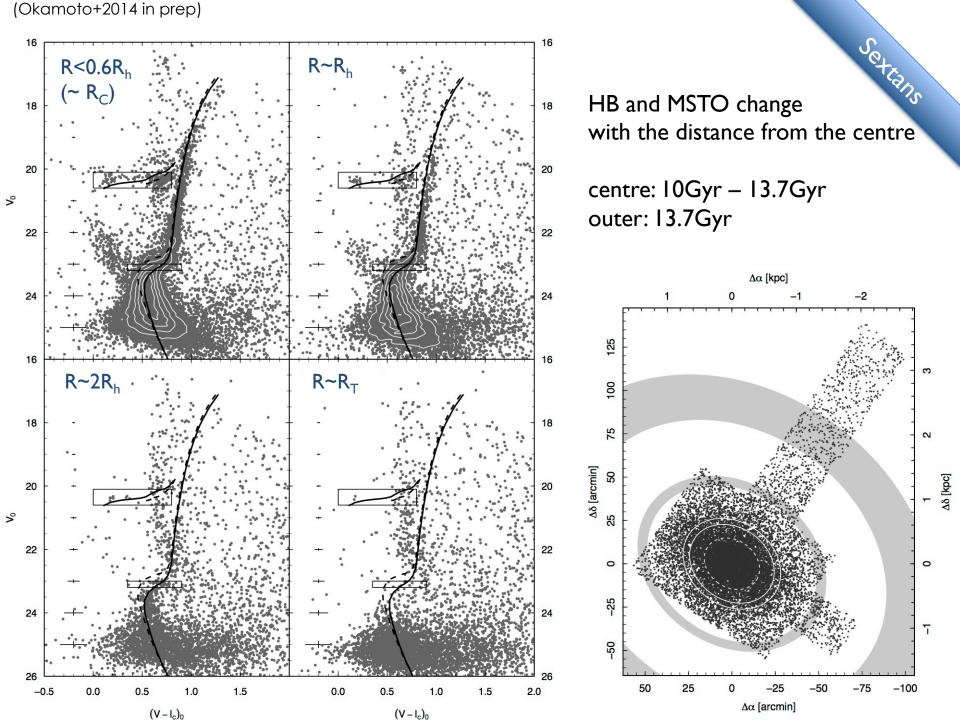


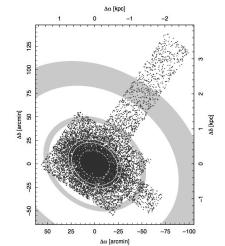












HB morphology: center (red) outer (blue)

young/metal-rich

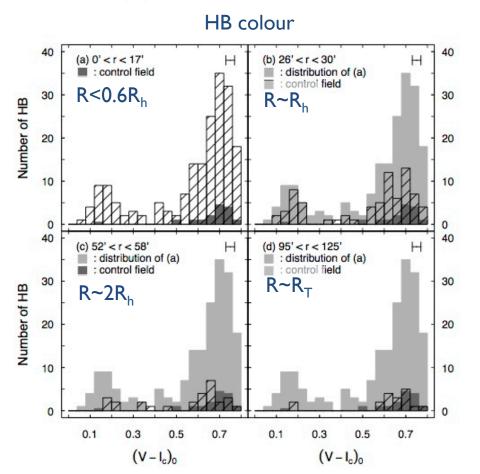
old/metal-poor

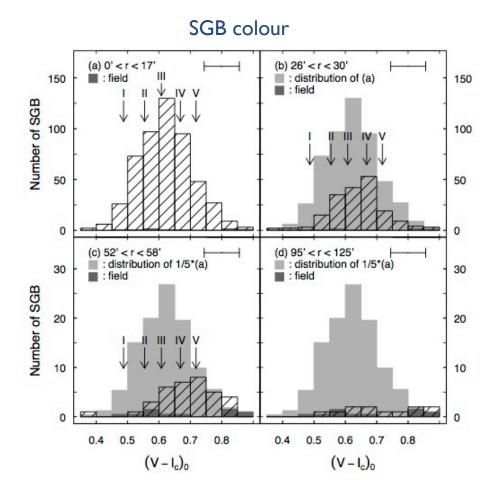
MS morphology: center (blue)

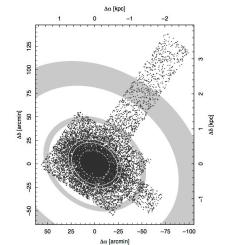
outer (red)

young/metal-poor

old/metal-rich







HB morphology: center (red) outer (blue)

young/metal-rich

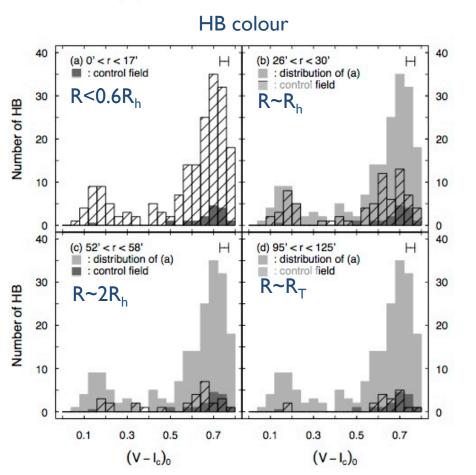
old/metal-poor

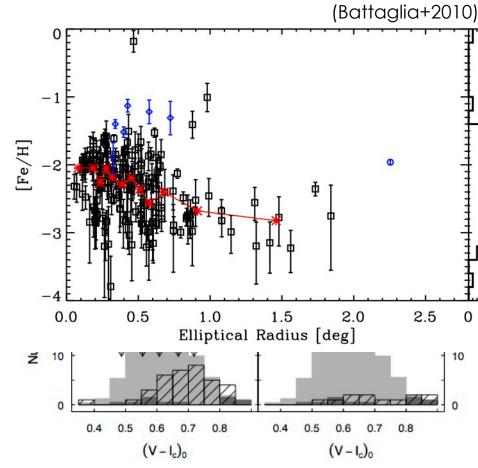
MS morphology: center (blue)

outer (red)

young/metal-poor

old/metal-rich





#### Spatial distributions of each age population

Δδ [arcmin]

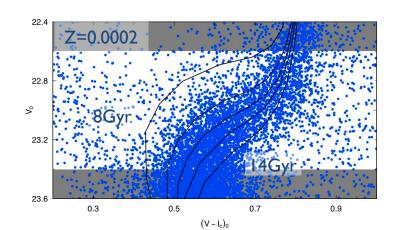
SF continued a few Gyr in the innermost region.

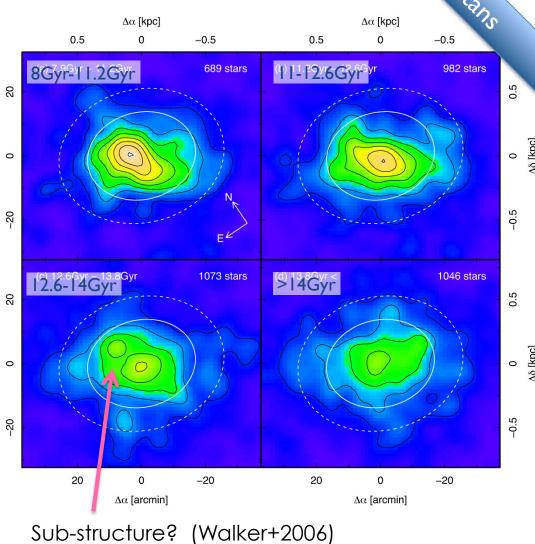
SF region becomes more and more centrally concentrated as the galaxy evolved.

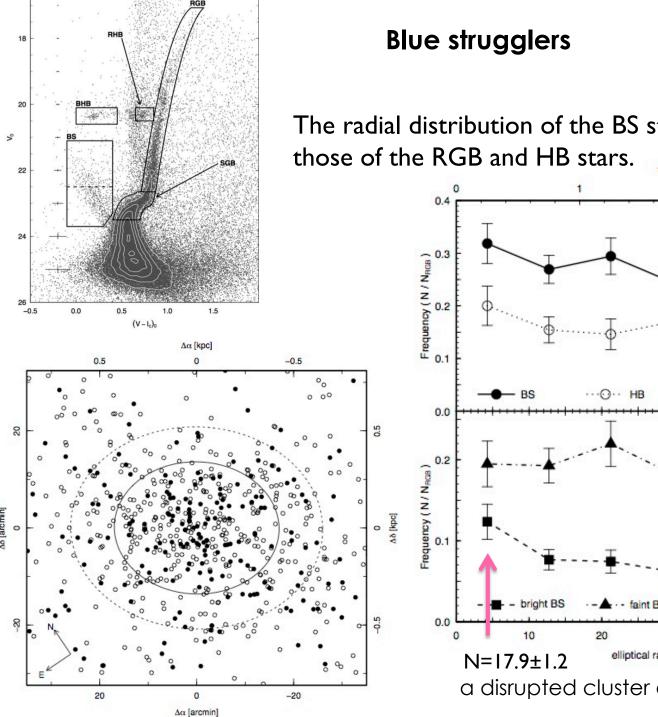
Accreted between 7 and 9 Gyr ago?

(Rocha, Peter, & Bullock 2012)

SF was finally stopped when it fell into the Milky Way.

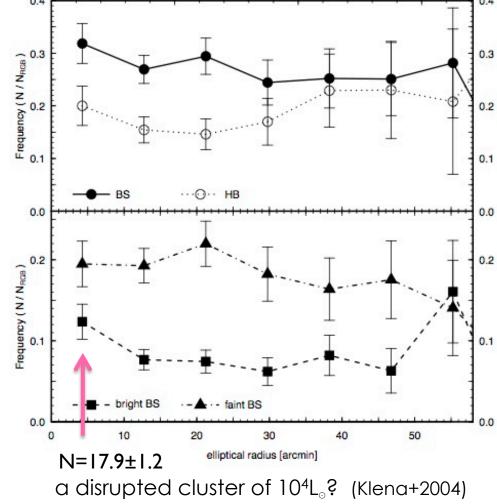






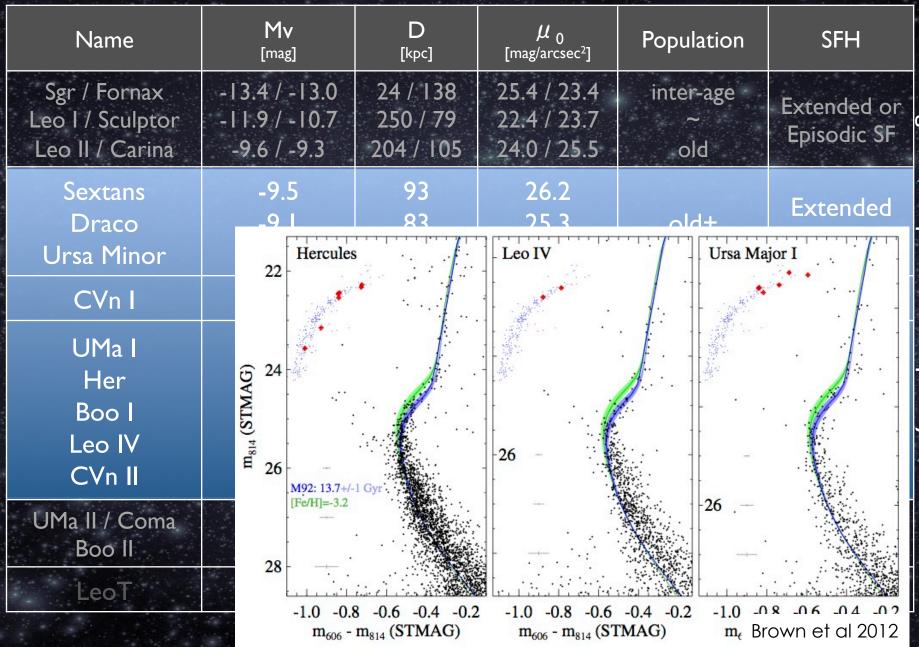
Setans

The radial distribution of the BS stars is similar to



# <u></u>

#### dSph satellites around the Milky Way



#### Star Formation in dSphs

All UFDs (except for CVn I) are purely old & metal-poor, and brighter dSphs (Draco, Sextans, CVn I) have complex pops.

fainter UFDs had stopped SF earlier than brighter dSphs.



Gas was removed more efficiently in the progenitor of UFDs

- external effect on gas removal from UFD
  - √ re-ionization Shallower potential?
- internal effect on UFD
  - ✓ SNe feedback Shallower potential?
- external effect on regulating SF in brighter dSph
  - ✓ tidal effect and ram pressure of Milky Way (Galactic dSphs are not likely be TDG!)

Searching distant UFDs, faint streams, by HSC, SSP

# Near field cosmology with Hyper Suprime-Cam

## Galactic Archeology:

reconstruct the disrupted stellar substructures of the proto-galaxy, thereby obtaining a detailed physical picture of the formation and evolution of the Milky Way.

#### Formation history of Galactic structures

- Merging history of the Milky Way?
- Formation of old Galactic components? Accretion vs In-situ
- Star formation history of dwarf satellites?
- How are galaxies in general build up? M31? etc.?

#### The nature of Galactic dark matter

- How is dark matter distributed in the Milky Way?
- ♦ Dark matter of dwarf satellites; is LCDM correct?

# All are recorded in old stellar populations

## Galactic Archeology:

reconstruct the disrupted stellar substructures of the proto-galaxy, thereby obtaining a detailed physical picture of the formation and evolution of the Milky Way.

- Detection, Stellar population, spatial distribution
   Wide-field photometry SDSS, HSC, LSST
- Metallicity, V<sub>rad</sub> (kinematics)
   LR/MR spectroscopy
   LAMOST, PFS, ngCFHT
- Abundance patterns, chemical tagging
   HR spectroscopy
   TMT, E-ELT, GMT, ngCFHT
- Proper motions, distances, OrbitsAstrometryGAIA

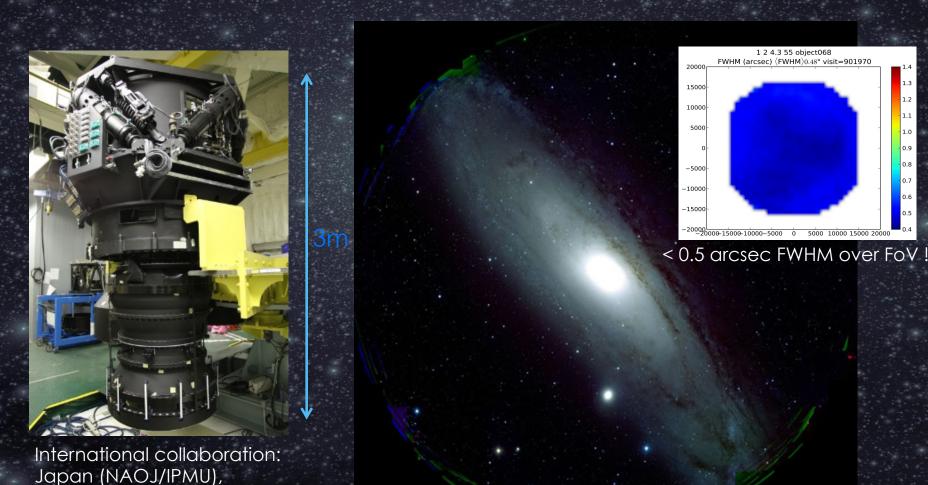
Wide-Field, Multi-objects

# Hyper Suprime-Cam/Subaru

Princeton, Taiwan

FoV=1.77deg<sup>2</sup>, Pixel=0.17"/pix, CCD=116 x 2k\*4k, FL=Feb, 2013, Filters=grizy + several NB,

HSC SSP wide survey: 1,400 deg<sup>2</sup>, grizy ~ 26mag, 2014A~ (5years)



# **Hyper Suprime-Cam SSP:**

wide:  $1,400 \text{ deg}^2$ , grizy  $\sim 26 \text{ mag}$ , i $\sim 26$ 

Fall/Spring equatorial regions

deep:  $28 \text{ deg}^2$ , girzy+3NBs, i~27

U deep: 3.5 deg<sup>2</sup>, grizy+6NBs, i~28

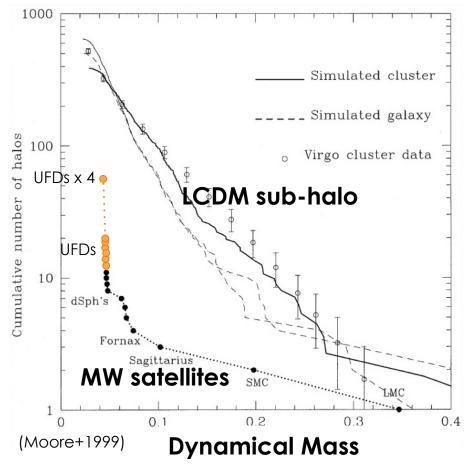
# Galactic Archeology with HSC SSP:

- Search missing Galactic faint satellites
- Search missing streams at the outer halo (>30kpc)
- Search missing distant faint galaxies in the LG
- Study the properties of known streams, dSphs and dIrrs
- Probe 3D structure of Galactic outer halo
- Search extremely LSB galaxies and their tidal features

Resolved stars



#### Missing satellite problem in CDM framework

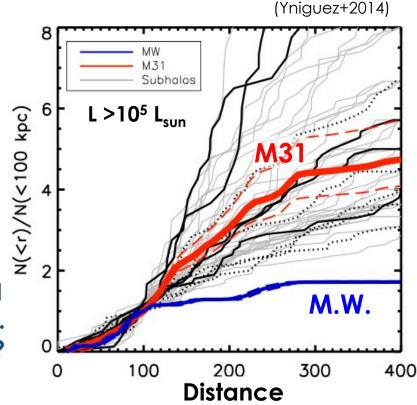


#### SF was suppressed in low-mass halos?

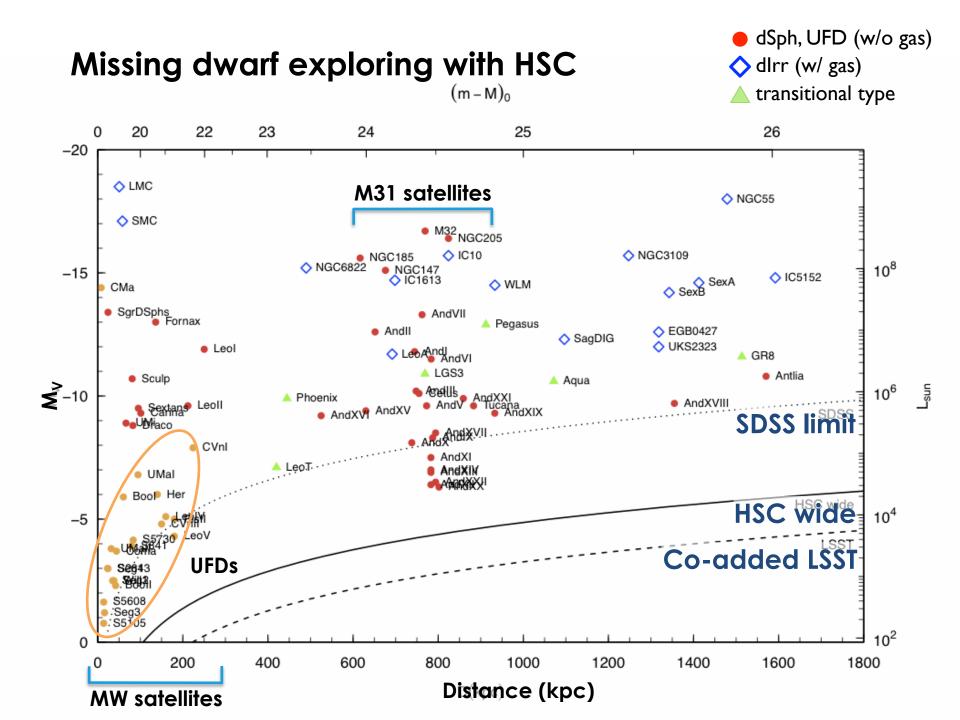
Reionization (e.g. Gnedin+2000) SNe feedback and tidal effects (e.g. Larson+1974)

#### Fewer low-mass halos?

WDM etc. (e.g. Zentner+2003) Cusp/Core (e.g. Penarrubia+2010)

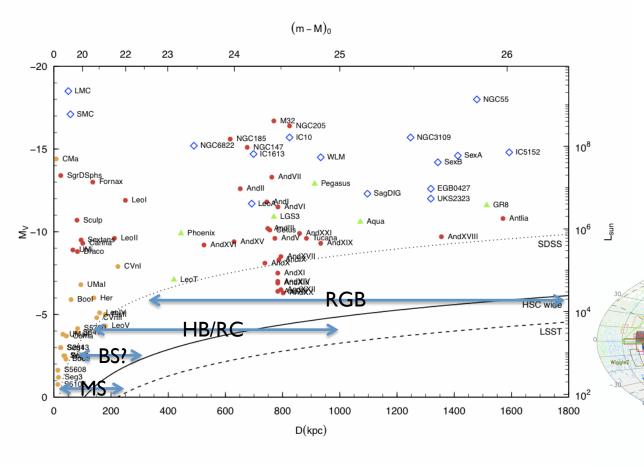


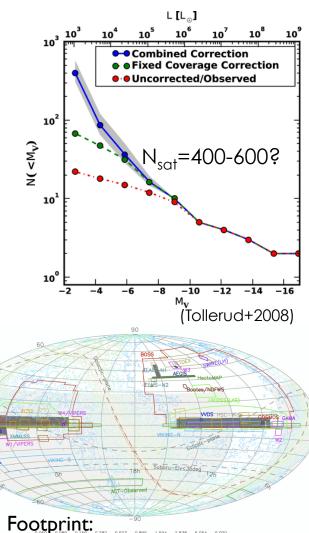
Centrally concentrated than M31 and any of LCDM simulations. Incomplete sample beyond ~100kpc?



# **HSC** wide survey may find:

~20 new faint satellites, diffuse over-densities, stellar streams at 30-250kpc dwarf (isolated) galaxies at >250kpc,  $M_V$ < -7



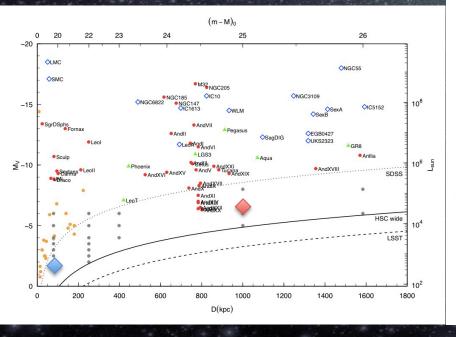


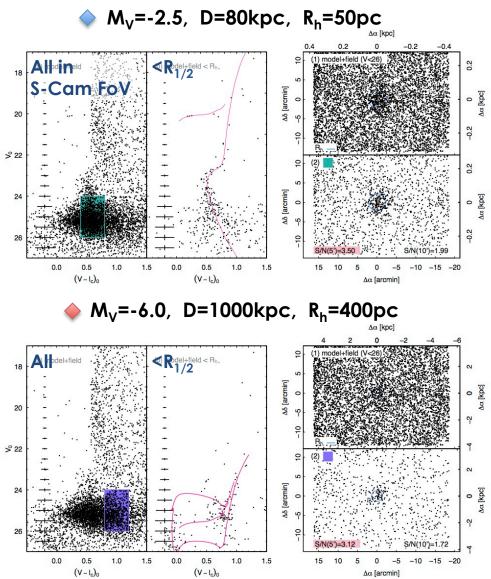
Fall/Spring equatorial regions

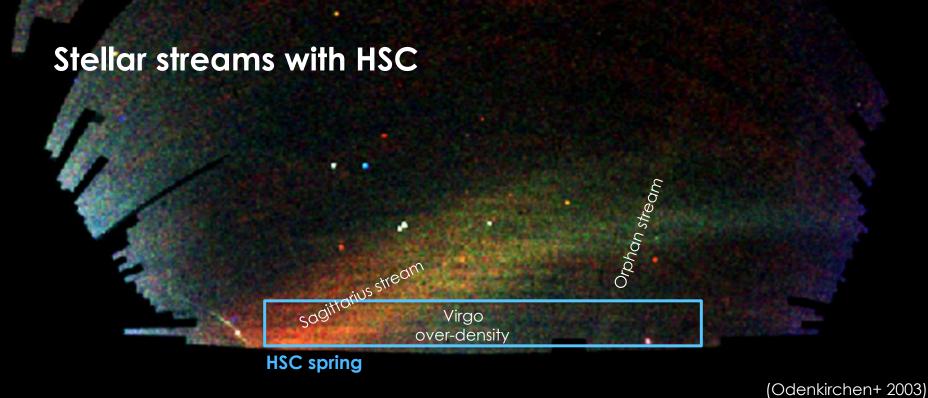
# HSC wide survey may find:

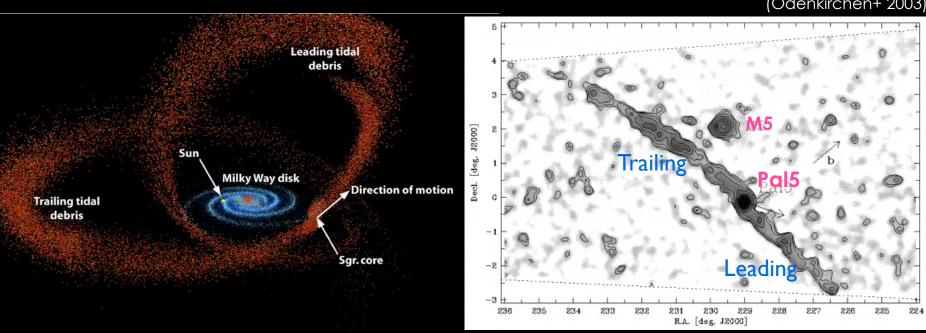
~20 new faint satellites and distant dwarf galaxies

True luminosity / radial distribution of satellites and their populations will be the strong constraints for the SF in low-mass halos

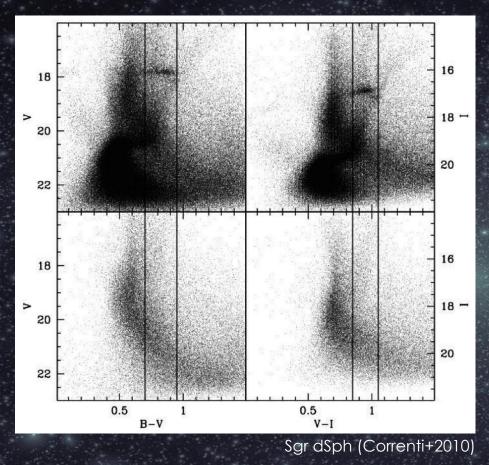




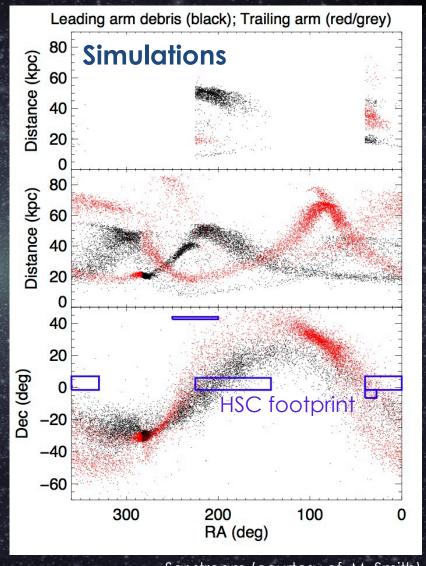




#### Stellar streams with HSC



- Complex populations
- Distance determination required <= BHB, PFS,</p>
- Heavy contaminants for the detection of unknown objects

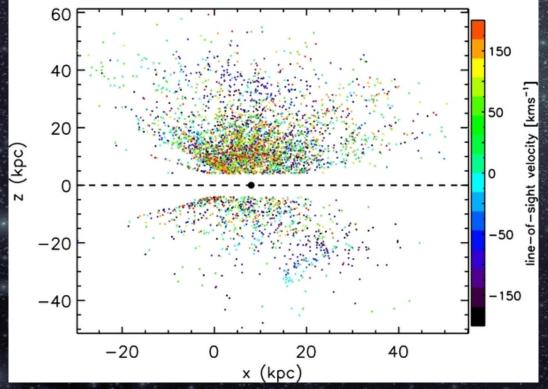


Sgr stream (courtesy of M. Smith)

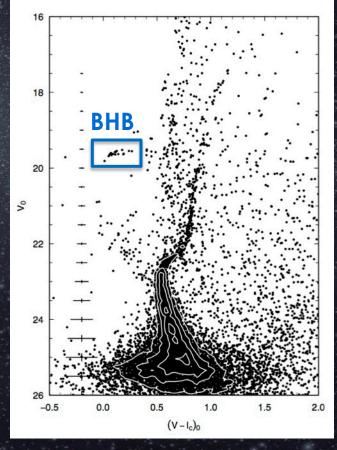
# 3D Halo structure by BHB stars

# Blue Horizontal Branch star (core He-burning star)

- ♦ Comparatively bright: M<sub>g,BHB</sub>~0.6mag,
- Accurate distance



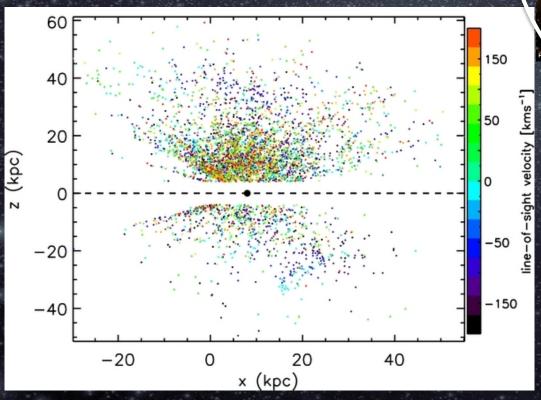
(Okamoto+2012, Bootes dSph)



# Halo 3D structure by BHB stars

#### **Blue Horizontal Branch star**

- ♦ Comparatively bright: M<sub>g,BHB</sub>~0.6mag,
- Accurate distance

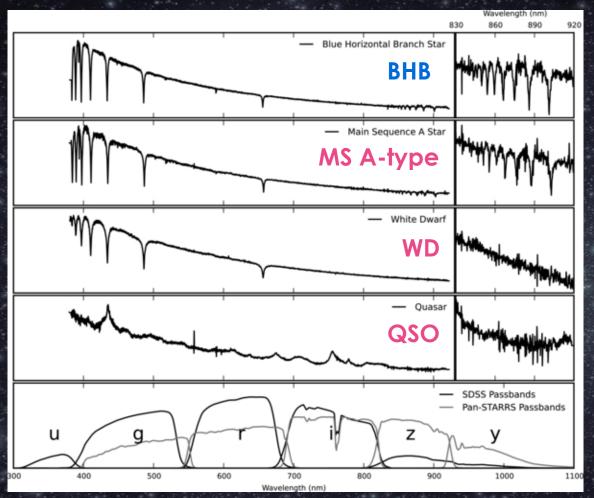


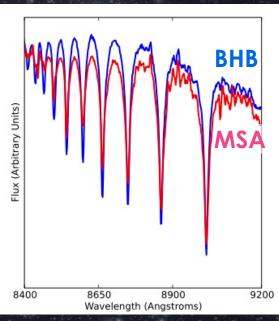


HSC D<400kpc

(Xue+2011, SDSS, spec)

# BHB stars can be identified by z-filter

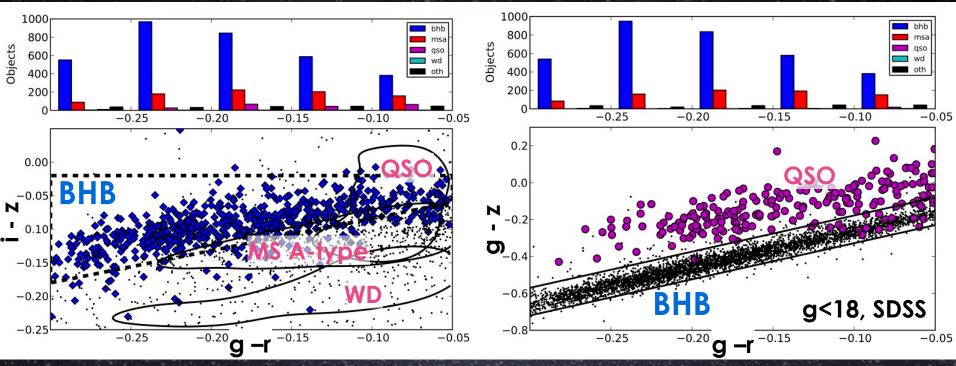




- Paschen features will be measured by z-filter to extract BHB stars from WD, MS-A stars
- the g-z colour will be used to separate blue stars from distant QSO

Paschen absorption in z-band

# z-filter based photometric BHB sample

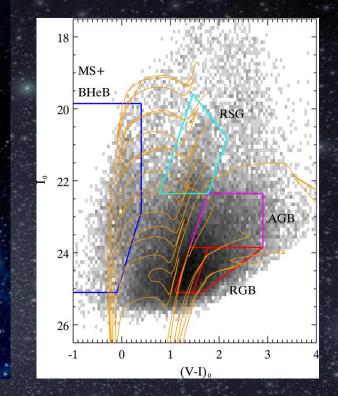


(Vickers+2012, SDSS)

- Paschen features will be measured by the i-z colour to extract BHB stars from WD, MS-A stars
- the g-z colour will be used to separate blue stars from distant QSO

77% pure, 51% complete !! (c.f. u-based : 74% pure, 57% complete)

# Near field cosmology beyond the LG with HSC

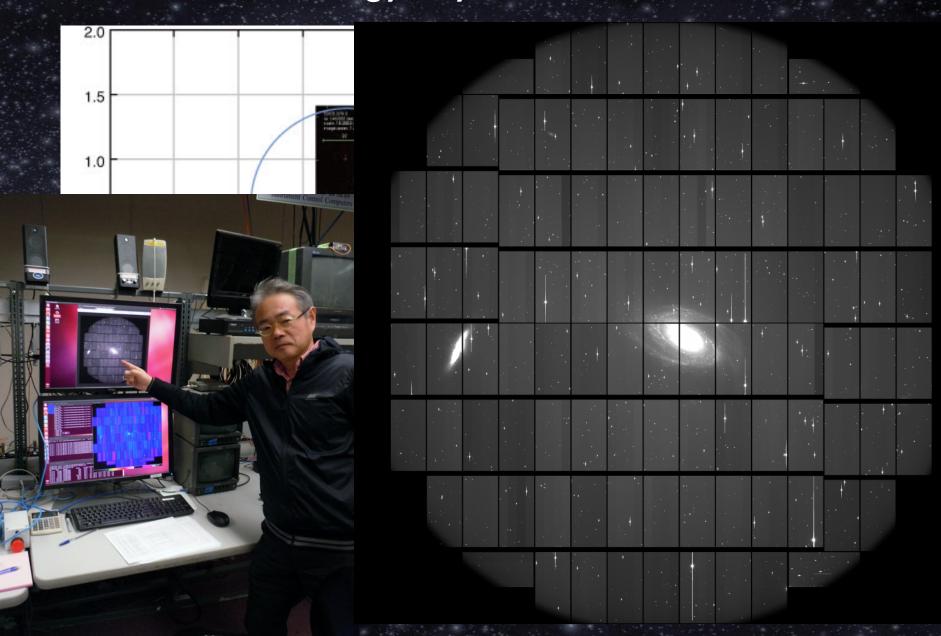


#### M81, MW analogue which lies at 3.6Mpc

- True Nature of stellar contents in the large scale structures
- Age and Metallicity constraints for the extended component
- New stellar debris, satellites, streams, arcs in the entire region
- → Globular clusters in the M81 group

S-Cam (VI) (Barker+2

# Near field cosmology beyond the LG with HSC



#### Conclusions

# The UFDs do not have the same stellar pop as bright dSph, but have older population.

- ✓ The fainter UFDs (M<sub>V</sub>>-7; Boo, UMaI, Her, LeoIV, CVnII) show a purely old and metal-poor population.
- ✓ The brighter UFDs ( $M_V$ =-7.8; CVn I) dSph shows the different spatial distribution of each evolutionally phases (BHB, RHB, RGB,,,).
- ✓ The stellar population of the brighter classical dSphs (Sextans, Draco, UMi) have the spatial gradient.

#### Near field cosmology with HSC:

- Search missing streams, debris, faint satellites of MW
- Search missing distant faint galaxies in the LG
- Study the properties of known streams, dSphs and dIrrs
- Probe 3D structure of Galactic outer halo
- Search extremely LSB galaxies and their tidal features
- ♦ M81 archeology

Resolved stars

Diffuse liahts