# Structures of the Milky Way stellar and dark halos revealed from the Subaru/Hyper Suprime-Cam survey

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With D. Homma, T. Fukushima, Y. Komiyama, Masayuki/Mikito Tanaka, and MW/HSC-SSP team

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## Thank you for supporting the following research works！

- Bootes IV: A New Milky Way Satellite Discovered in the Subaru/Hyper Suprime-Cam Survey and Implications for Dark Matter Models
  - Homma, Chiba, et al. 2019, PASJ, to be submitted very soon
- The stellar halo of the Milky Way traced by blue horizontal-branch stars in the Subaru Hyper Suprime-Cam Survey
  - Fukushima, Chiba, et al. 2019, PASJ, to be submitted very soon
- Metallicity Distribution of Disk Stars and the Formation History of the Milky Way
  - Toyouchi & Chiba 2018, ApJ, 855, 104
- The Missing Satellite Problem Outside of the Local Group. I. Pilot Observation
  - Tanaka, Chiba, et al. 2018, ApJ, 865, 125
- Structure of the Milky Way stellar halo out to its outer boundary with blue horizontal-branch stars
  - Fukushima, Chiba, et al. 2018, PASJ, 70, 69

# Milky Way halo as a probe of dark matter and galaxy formation

- Dark halo
  - reflects the nature of dark matter
    - Missing satellite problem in ΛCDM
    - Alternative DM models?
      Limitation in observations?

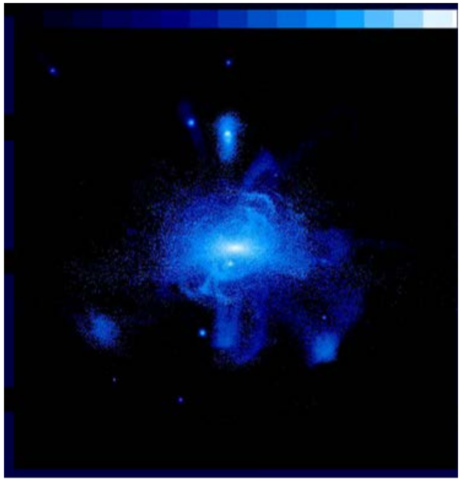
  ⇒Searching for new dwarf spheroidal satellites (dSphs)

- Stellar halo
  - contains the relics of galaxy formation
    - Global density structure, stellar streams
    - In situ. (inner) halo & accreted (outer) halo

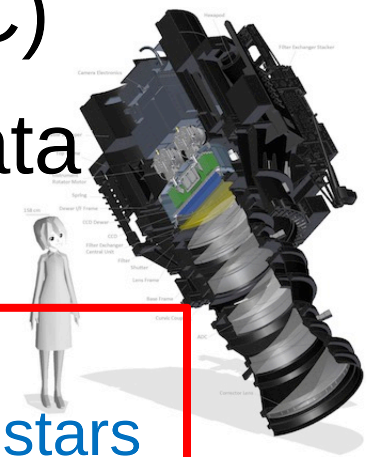
  ⇒Mapping with Blue Horizontal-Branch stars (BHBs)

ΛCDM simulation for a MW-sized halo
(Bullock & Boylan-Kolchin 2017)

Simulations for stellar halos
(Bullock & Johnston 2005)



# Subaru Strategic Program (SSP) with Hyper Suprime-Cam (HSC)



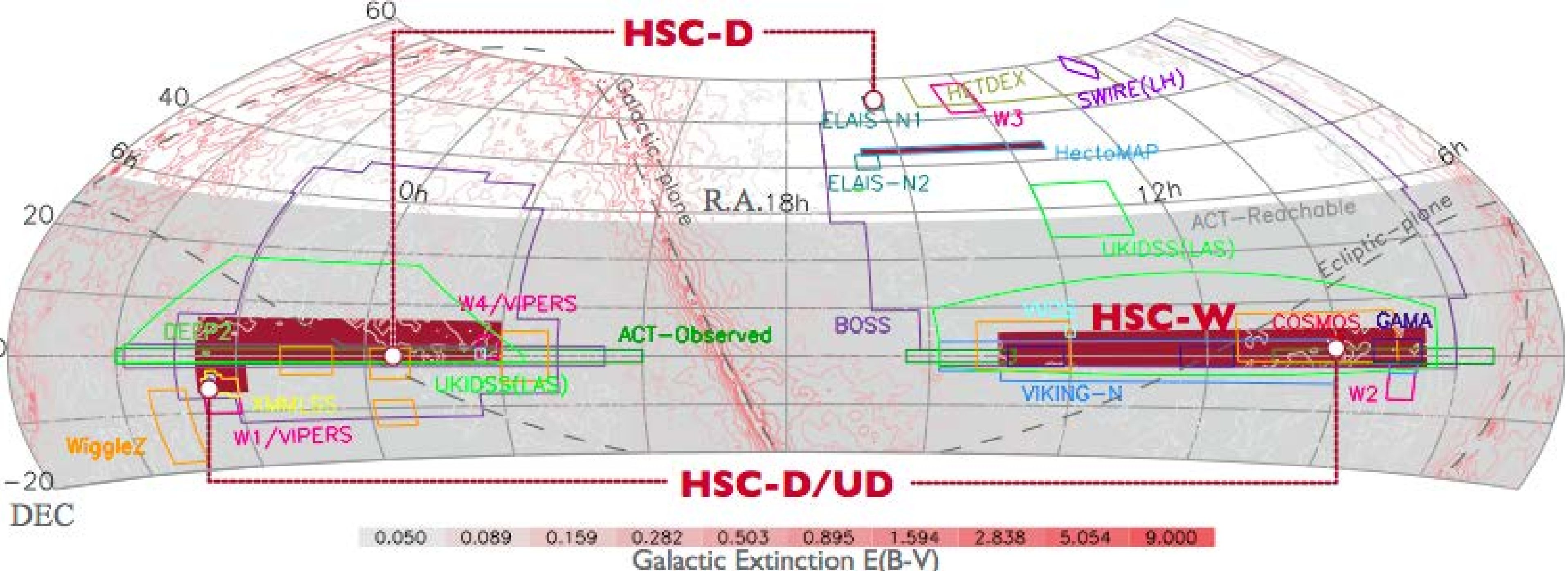
- MW science from the Wide-layer data

  S18A: ~ 860 deg$^2$ / 1,400 deg$^2$(goal)

  (1) Searches for new MW dSphs

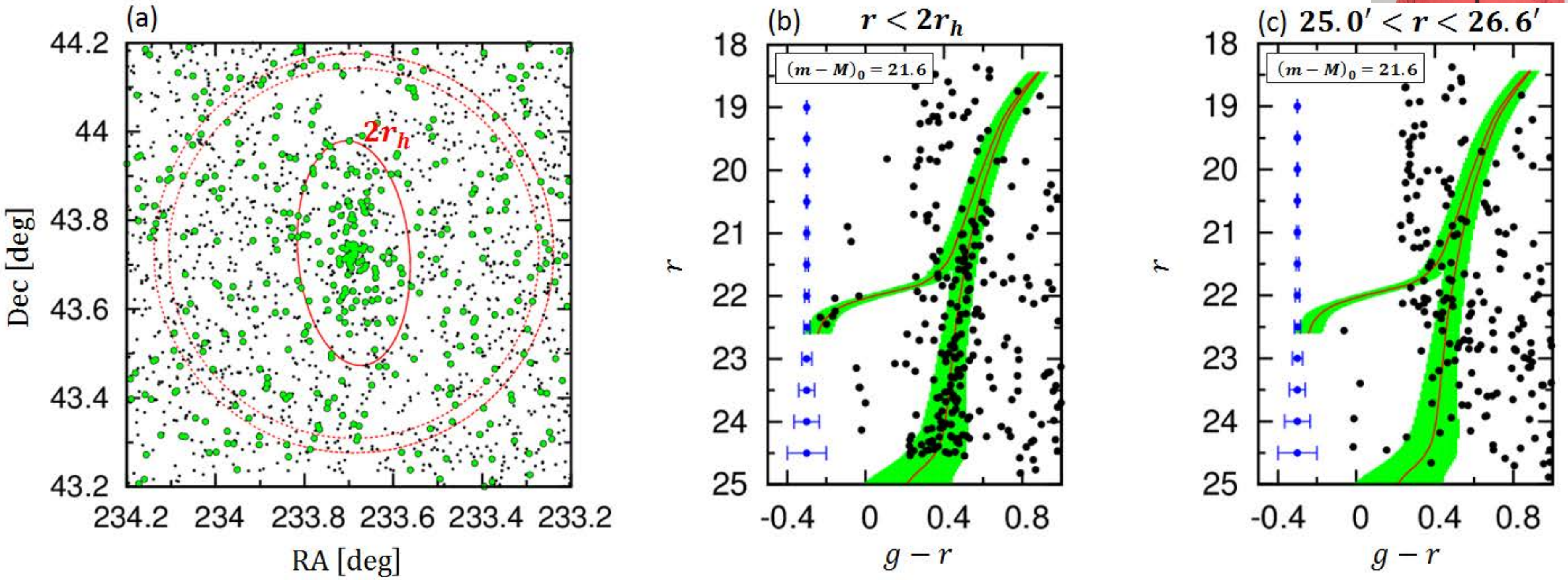
  (2) Halo mapping with Blue Horizontal-Branch stars

  (3) Searches for new stellar streams



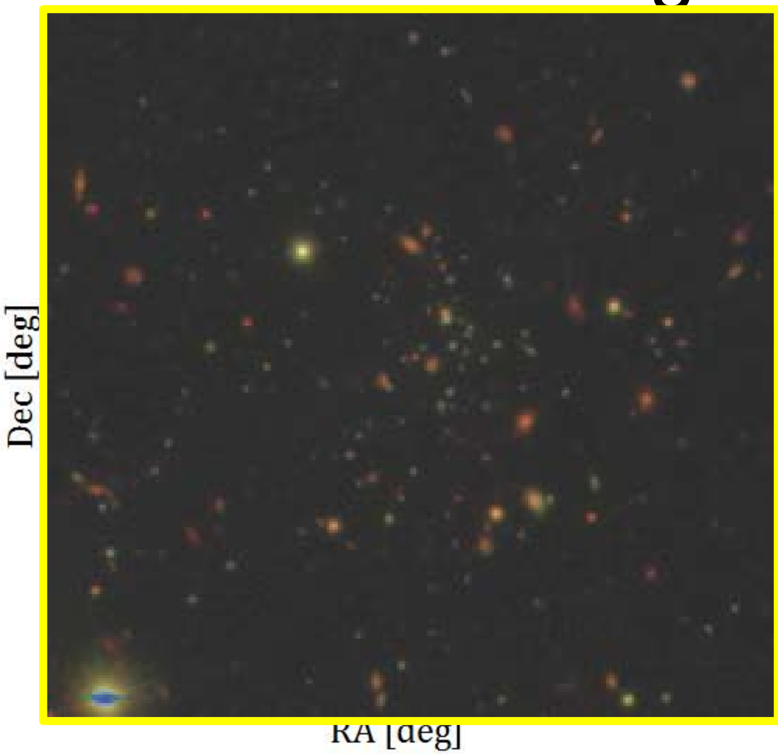
# (1) Searches for new MW dSphs with HSC

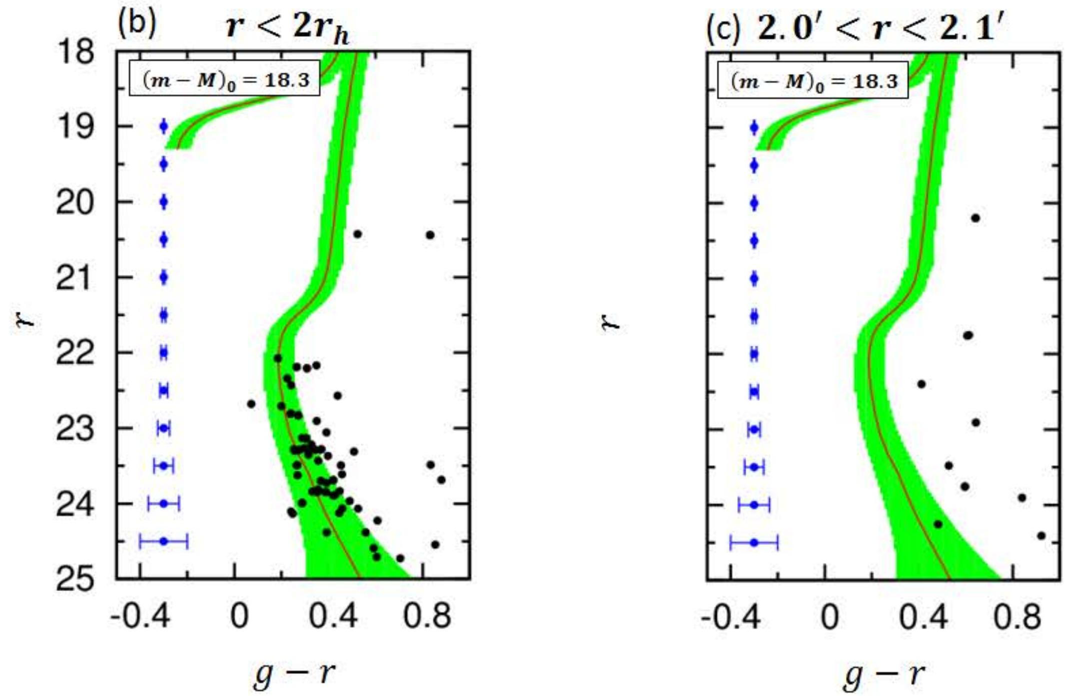
## 3rd new dwarf galaxy, Bootes IV

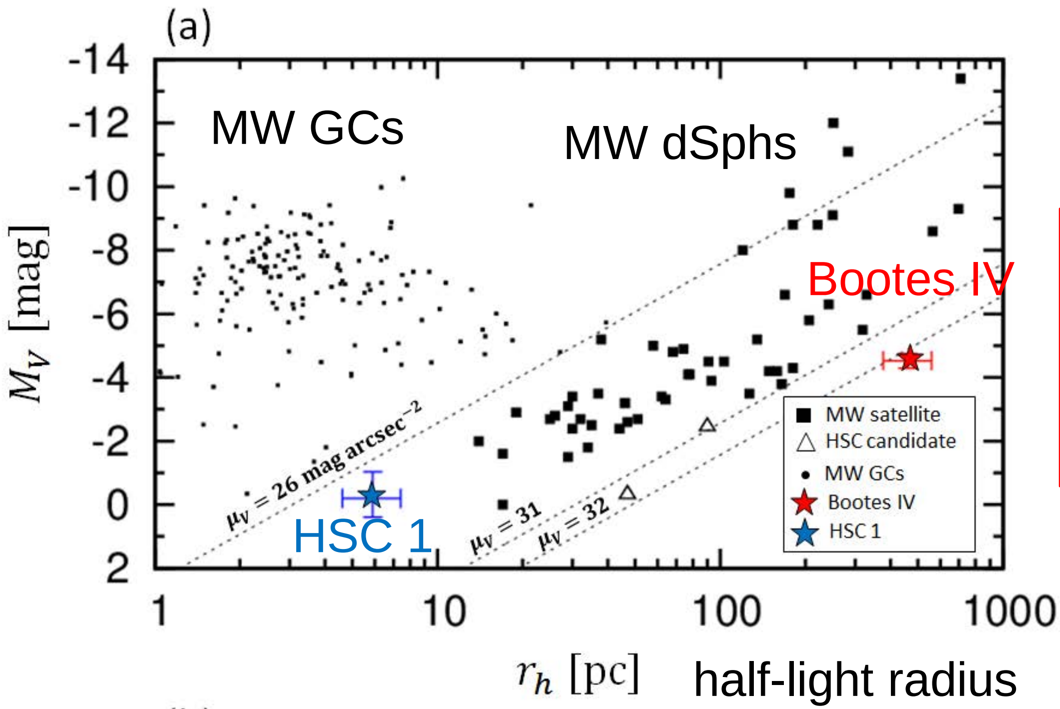

| Parameter | Value |
|---|---|
| Coordinates(J2000) | $(233°.69, 43°.73)$ |
| Ellipticity | $0.64^{+0.05}_{-0.05}$ |
| Heriocentric distance, $D_\odot$ | $209^{+20}_{-18}$ kpc |
| Half light radius, $r_\mathrm{h}$ | $7'.6^{+0'.8}_{-0'.8}$ *or* $462^{+98}_{-84}$ pc |
| $M_\mathrm{tot,V}$ | $-4.53^{+0.23}_{-0.21}$ mag |

# $1^{st}$ new globular cluster, HSC 1

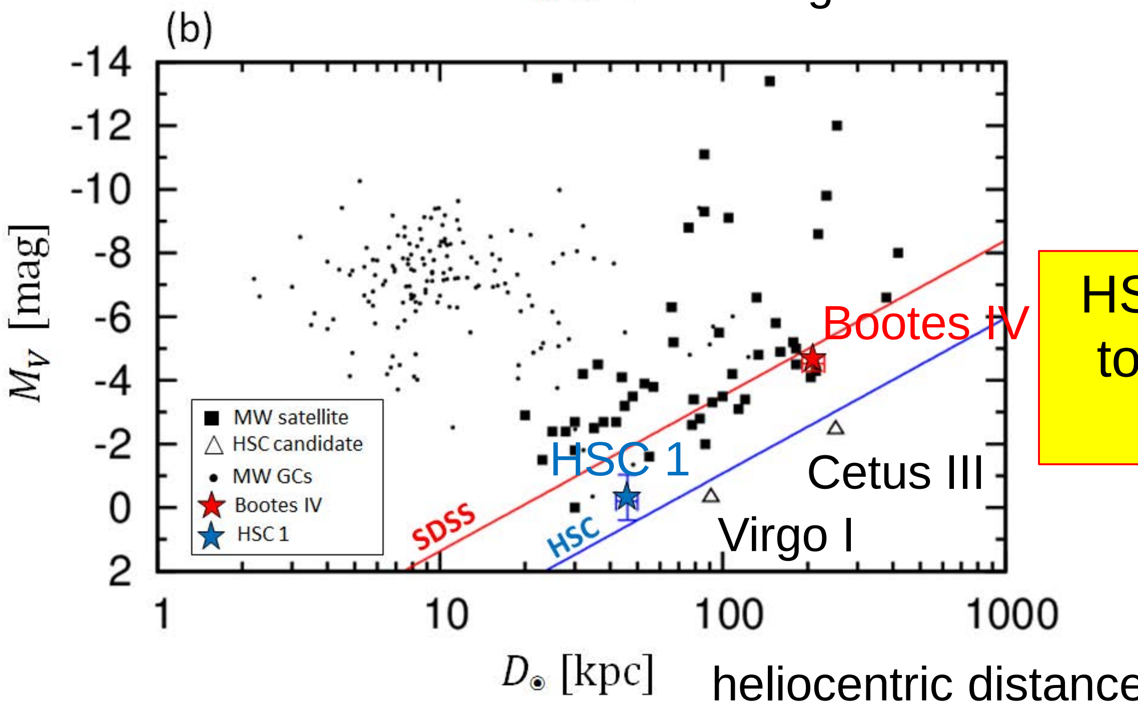



| Parameter | Value |
|---|---|
| Coordinates(J2000) | $(334°.31, 3°.48)$ |
| Ellipticity | $0.46^{+0.08}_{-0.10}$ |
| Heriocentric distance, $D_{\odot}$ | $46^{+4}_{-4}$ kpc |
| Half light radius, $r_\mathrm{h}$ | $0'.44^{+0'.07}_{-0'.06}$ *or* $5.9^{+1.5}_{-1.3}$ pc |
| $M_{\mathrm{tot,V}}$ | $-0.20^{+0.59}_{-0.83}$ mag |

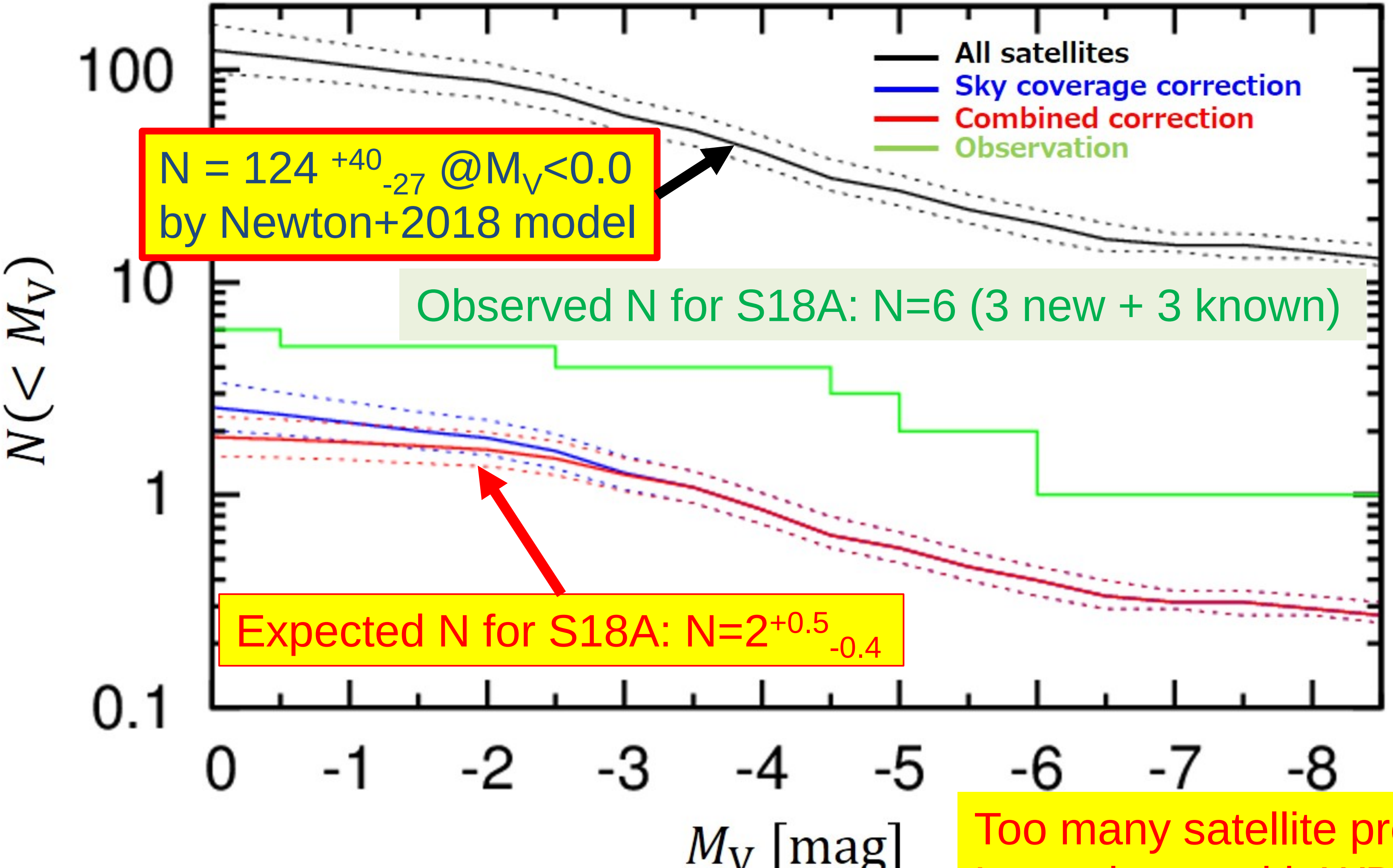



Bootes IV has a very large size compared to globular clusters.




HSC-SSP is powerful to identify very faint stellar systems.

# Expected number of dSphs in HSC-SSP based on Newton et al. (2018) (ΛCDM model combined with SDSS+DES results)




Too many satellite problem?
Inconsistent with WDM

# Why too many satellites?

- Newton et al (2018) model
  - The ΛCDM prediction for the number of satellites is normalized to the observed value by SDSS+DES

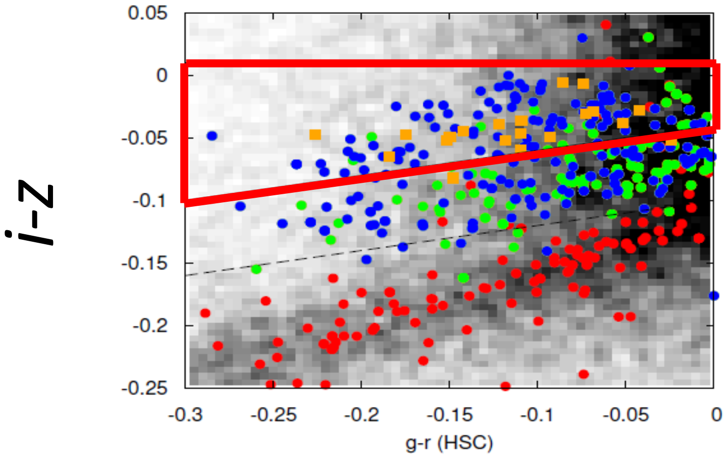
  ⇒ less sensitive to satellites at outer halo regions
  - Statistics of subhalos is based on only 6 MW-sized simulated halos

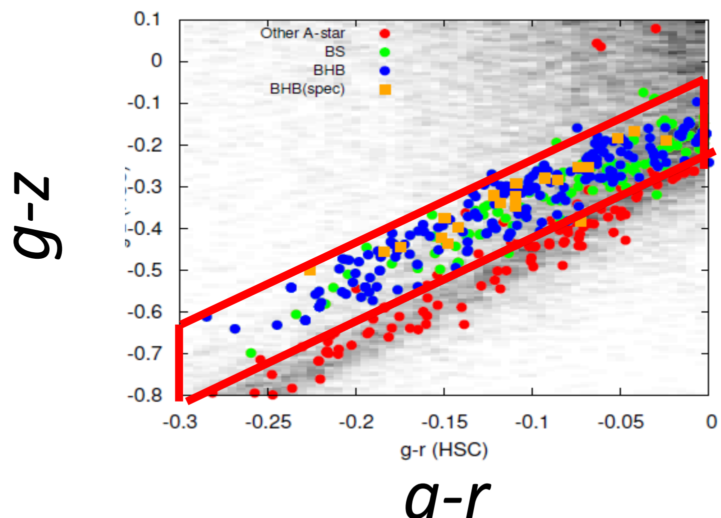
  ⇒ diversity is presnt in actual halos (Cf. Tanaka+ 2018)
- Dooley et al (2017) model
  - Based on abundance matching in ΛCDM
  - The predicted number = 6, i.e. consistent with this work!

More work is needed for the theoretical prediction with ΛCDM

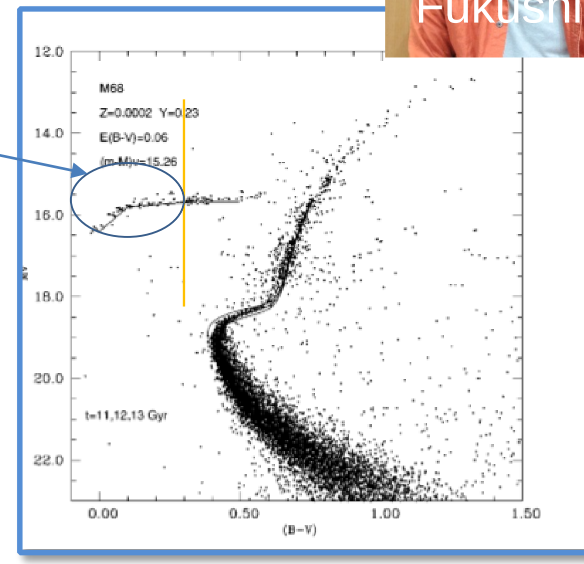
# (2) Halo mapping with BHBs


## BHBs are good stellar halo tracers




BHBs




- Bright
- Same luminosity

orange points : BHB (spectroscopy)
blue : BHB (photometric : *g-r* vs. *u-g*)
green points : blue straggler
red points : white dwarf

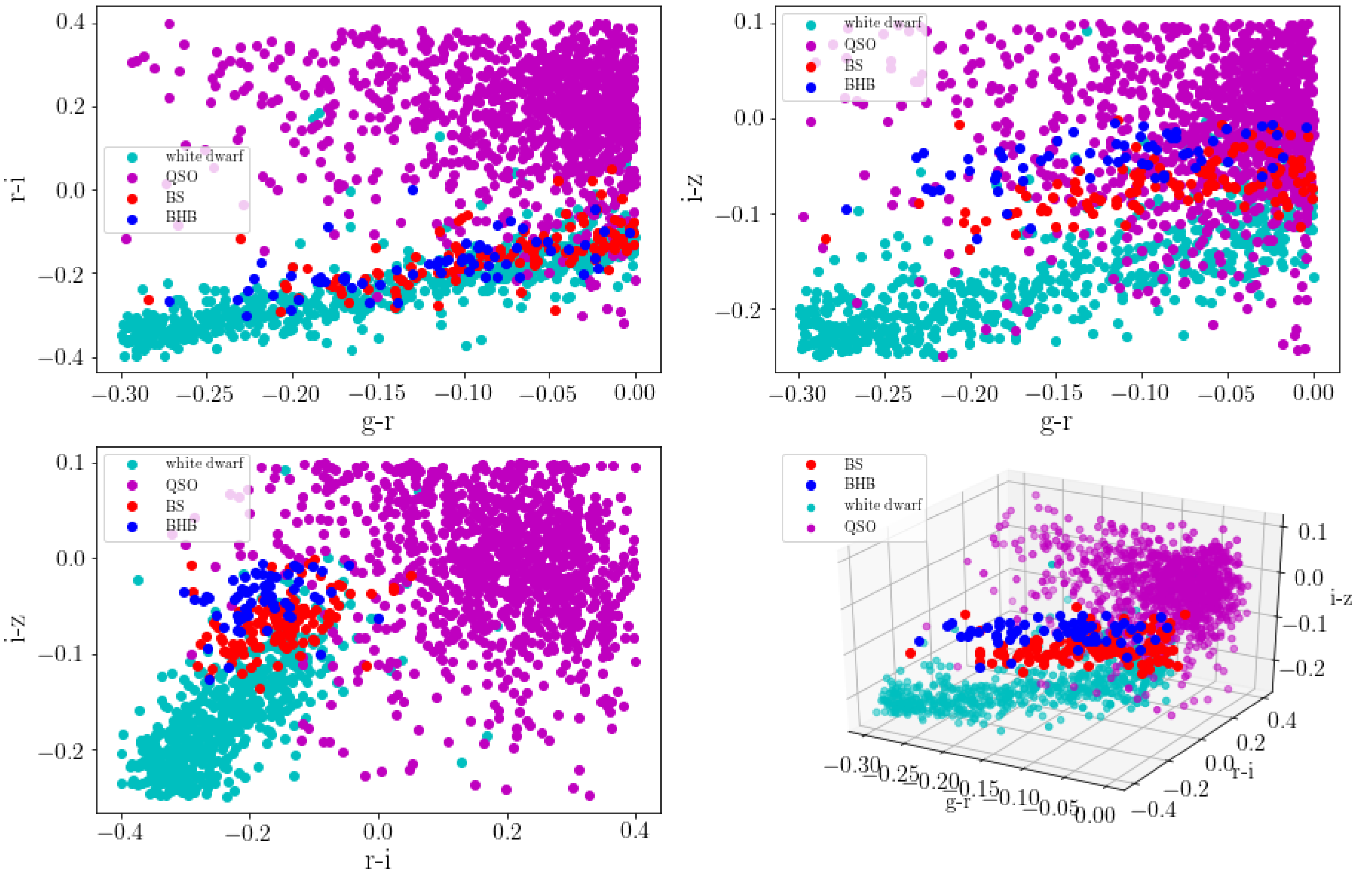
But BHBs are largely contaminated from Blue Stragglers, QSO, White dwarfs and galaxies

- BHBs are selected with color cuts in *g-r* vs. *i-z* and *g-r* vs.*g-z* space.
- Selection accuracy (using Sextans)
  - completeness∼67%, purity∼62%

Fukushima, Chiba et al. 2018, PASJ, 70, 69

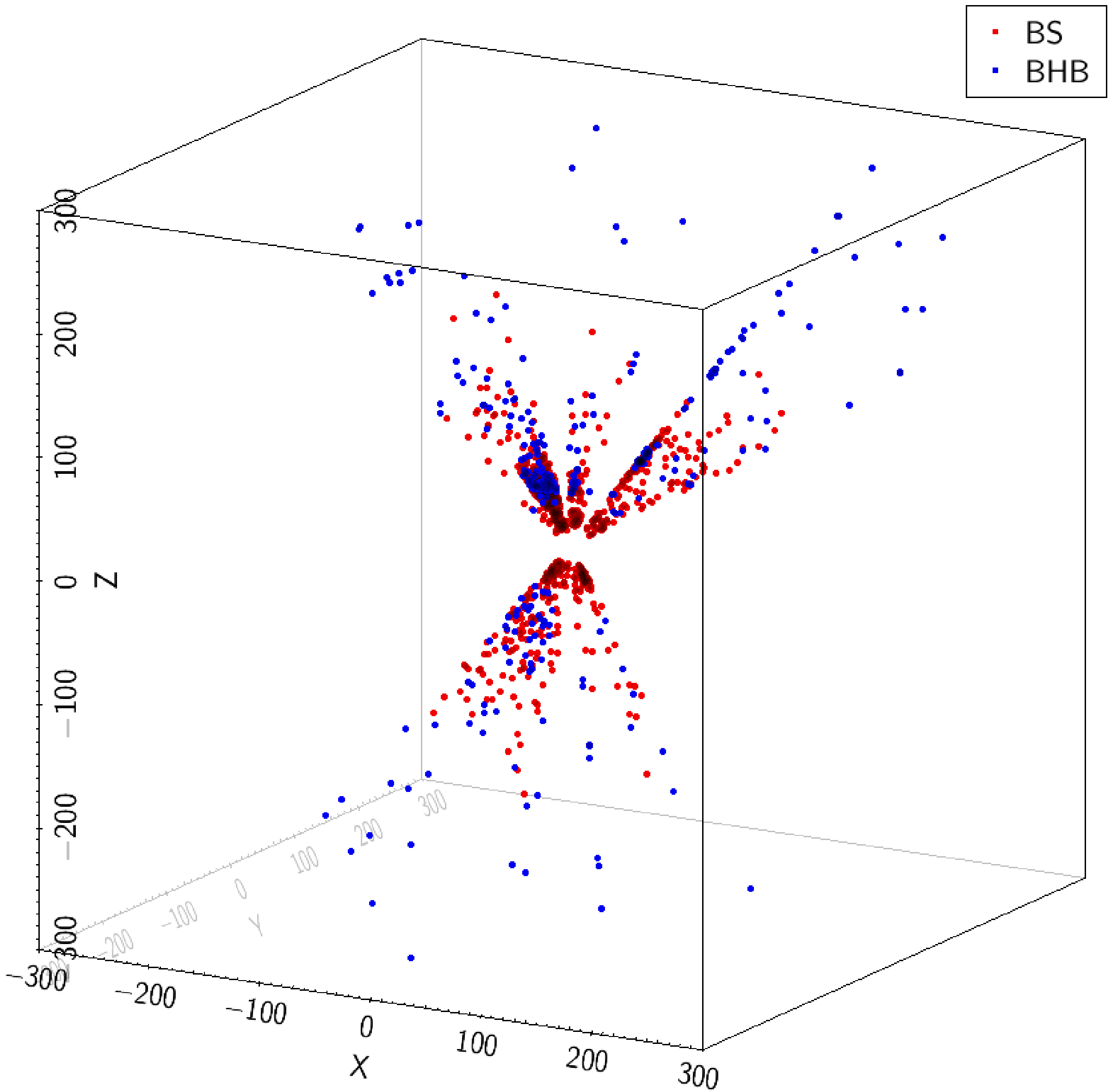
# New Bayesian method for the selection of BHBs in griz color space

Fukushima, Chiba, et al. 2019




BHBs
BSs
QSOs
WDs

Setting multiple probability distributions
⇒ more statistically significant sampling of BHBs


BS
BHB
Z
X
Y
300
200
100
0
−100
−200
−300
−300
−200
−100
0
100
200
300

# Maximum Likelihood results

Halo structure over 36~360 kpc

- single power-law

  $\alpha \sim 3.7, q \sim 1.8$ (prolate)

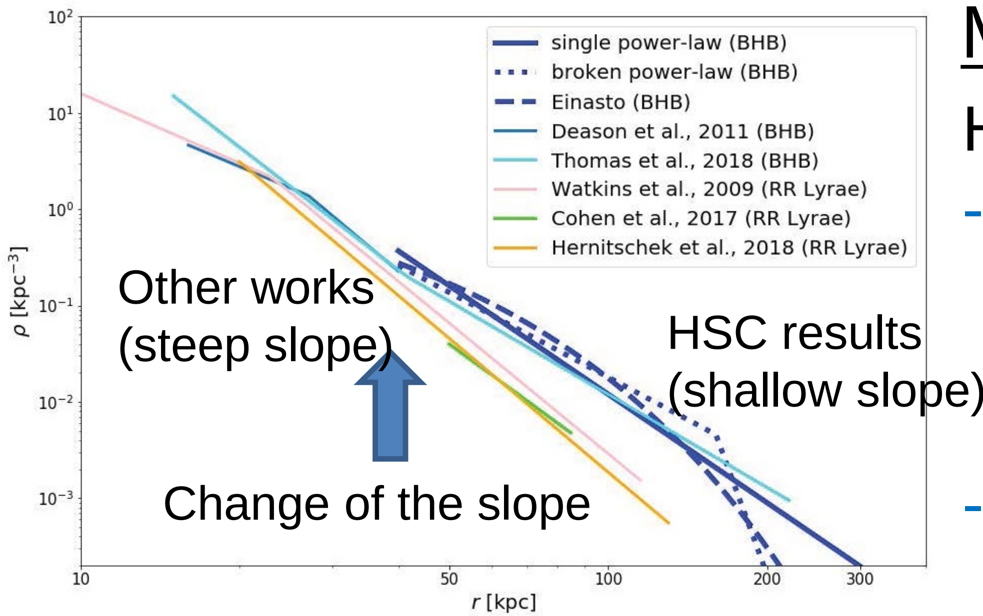
  $\alpha$ : power-law index

  $q$ : axial ratio

- broken power-law (better fitted)

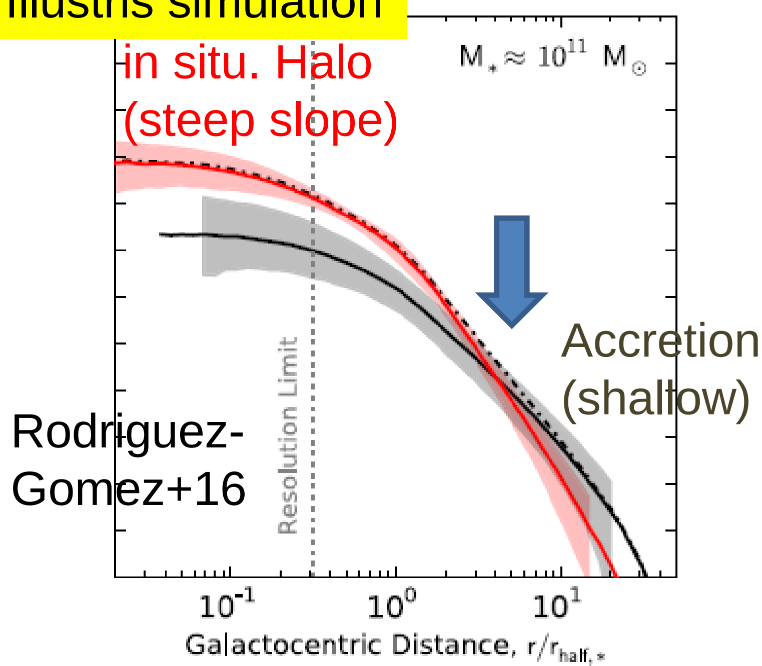
  power-law indices change steep at break radius r~160 kpc

  ($\alpha_{in}$ = 2.9 to $\alpha_{out}$ = 15)

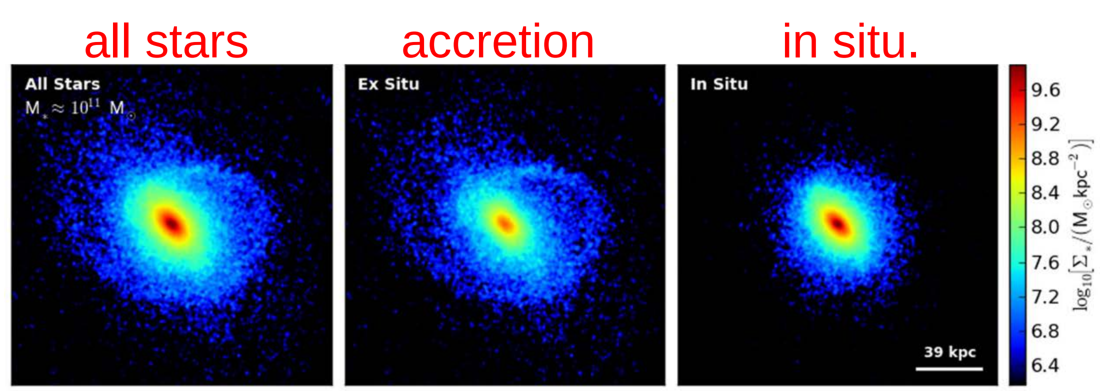



Distance from the Galactic Center r (kpc)

Illustris simulation



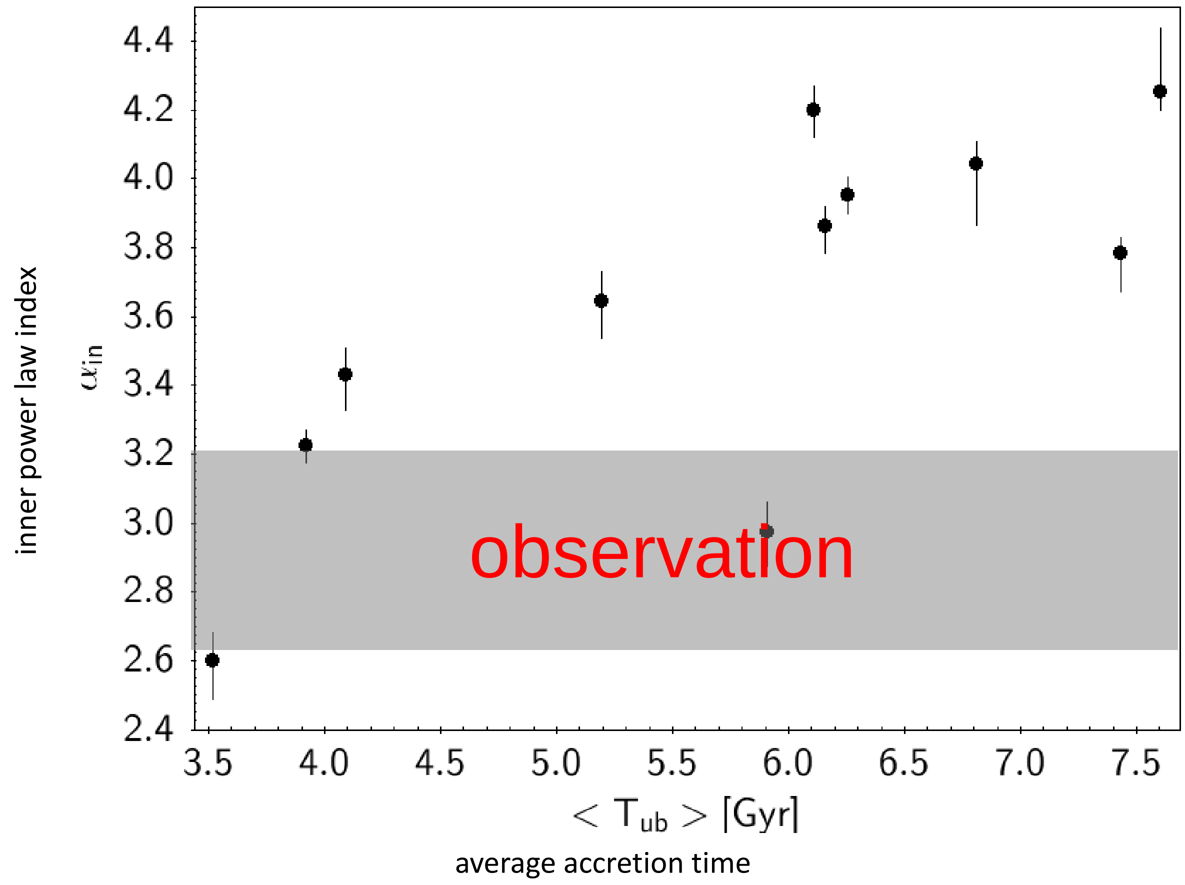

A signature of the boundary between in situ. vs. accretion halo?



# Constraint on accretion history

MW outer halo is mainly made from recent accretion (<~ 4Gyr)

Density slope vs. average accretion time from Bullock & Johnston (2005) simulation



# Summary

- Another new MW satellite is discovered
  - This discovery rate so far would rule out WDM.
  - Further search for new satellites will increase this statistical significance.
  - Spectroscopic follow-ups are ongoing to tighten membership and derive chemo-dynamics.
- MW halo mapping with BHBs is made
  - Identify the boundary between in situ. vs. accretion halos
  - Average accretion time <~ 4 Gyr