



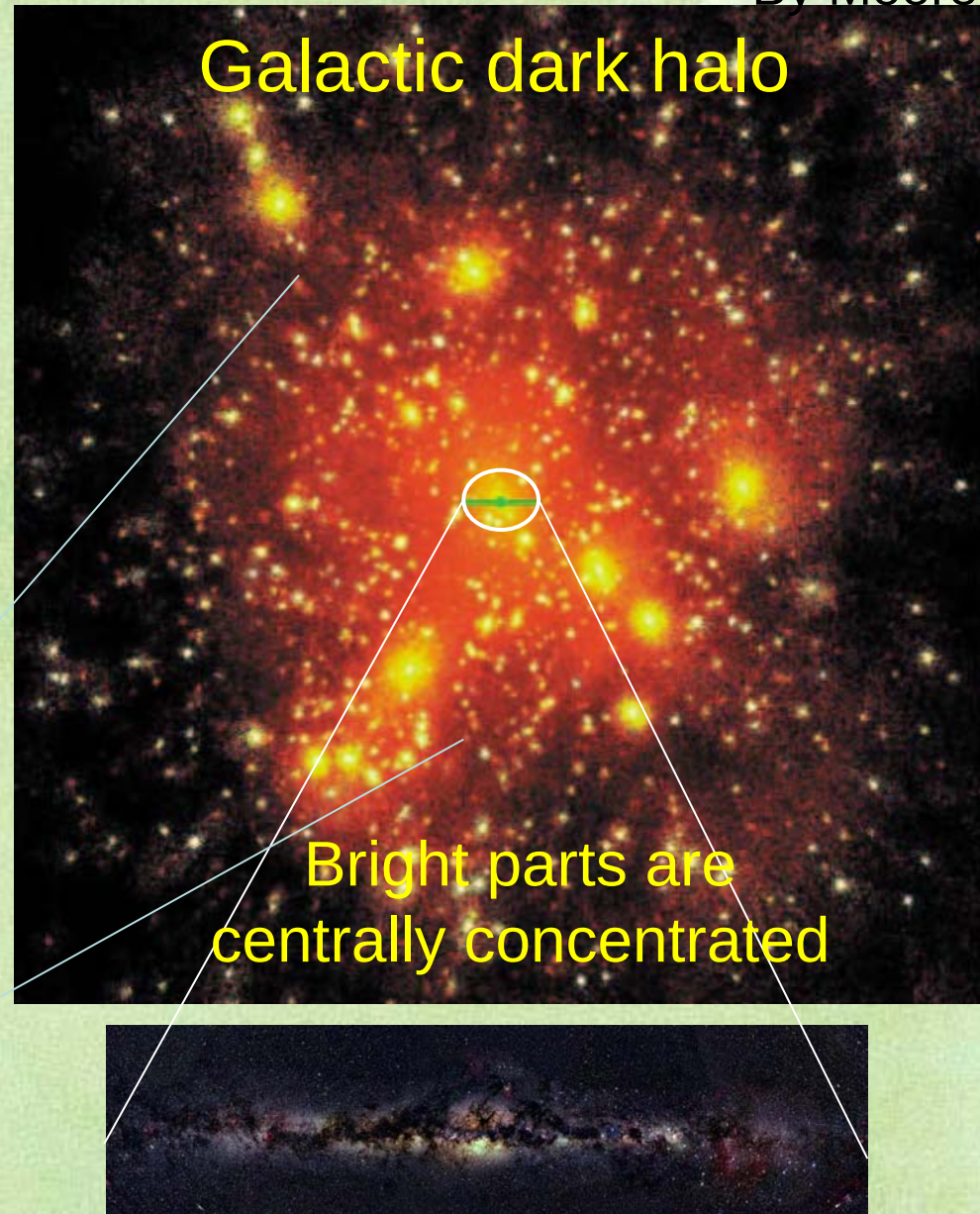
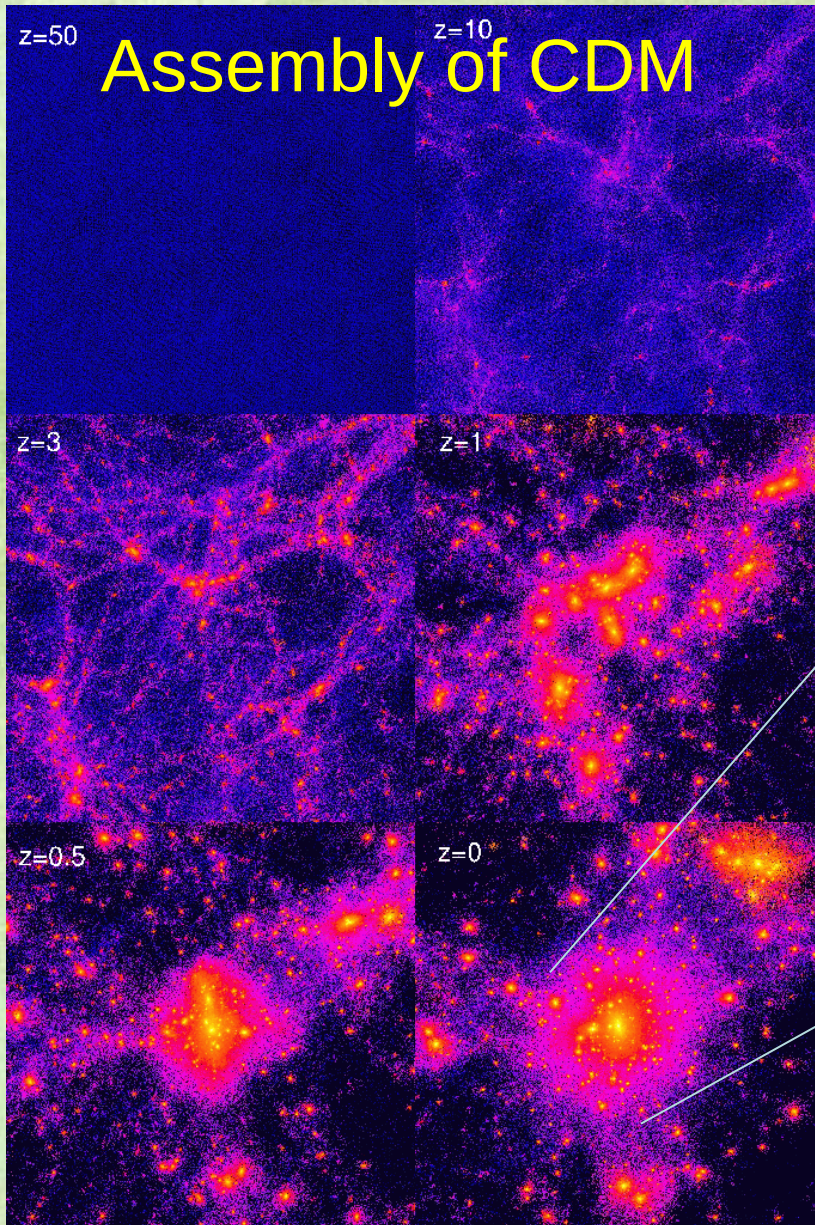
Galactic Archaeology with SuMIRe HSC/PFS

Masashi Chiba
(Tohoku University)

with W. Aoki, J. Cohen, M. Ishigaki
+ N. Hwang, D. Kawata , and more

Galaxy formation in CDM models

By Moore



Key science goals

1. Formation of Galactic structures

- ✓ Merging history of the Milky Way (MW)?
- ✓ Formation of old MW components (thick disk, halo)?
- ✓ Star-formation history of dwarf satellites?
- ✓ Formation of M31: is it different from the MW?

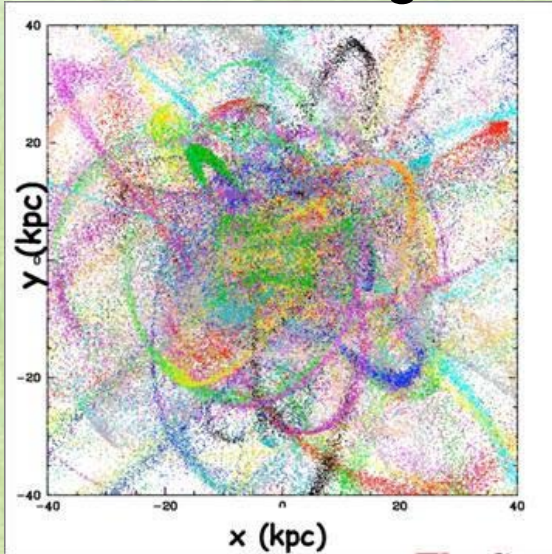
2. The nature of galactic dark matter

- ✓ How is dark matter distributed in the MW?
- ✓ Dark matter of dwarf satellites: is CDM correct?

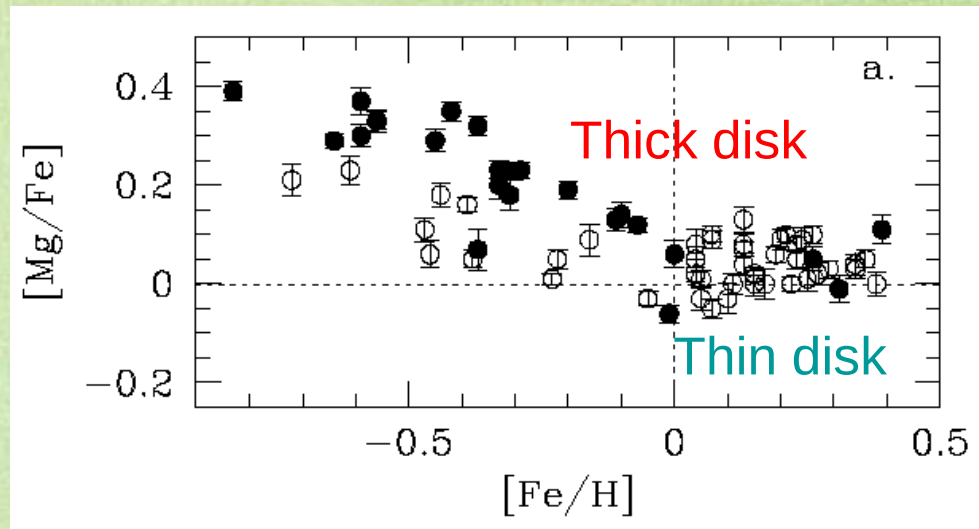
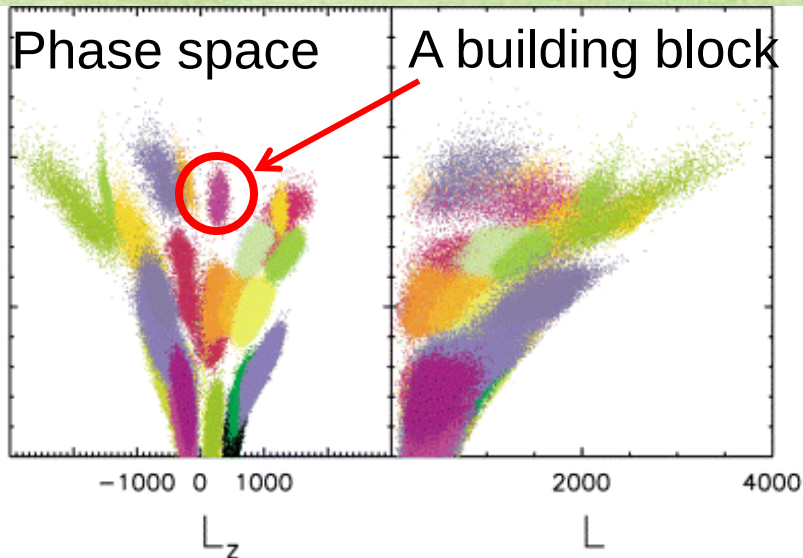
All are recorded in old stellar populations

Fossil records of galaxy formation

Debris of building blocks



1. Space and velocity distributions of ancient stars
 - ✓ Past collapse and merging events
 - ✓ Tracer of dark matter profiles
2. Chemical abundance of ancient stars
 - ✓ Star formation and chemical evolution



What data do we need?

■ Photometry :

HSC, SDSS, PanStar

- ✓ mag., color (→ color-mag. diagram)

■ Spectroscopy :

- ✓ metallicity , V_{rad} (kinematics)
- ✓ abundance pattern (→ SF & chemical evol.)

PFS

■ Astrometry :

- ✓ proper motion, distance (→ 6d phase space)

Gaia

Structure, dynamics, star formation
and chemical evolution

⇒ galaxy formation and evolution

Gaia

(2012~)

Cf. Hipparcos
 $V < 12$, 1mas



Astrometry:

$V=15$, 12~25 μas

$V=20$, ~300 μas

Photometry:

$V < 20$

RV measurement:

$V < 17$ (150M stars)

$R \sim 11,500$,

$\lambda = 8450\text{-}8750\text{\AA}$ (CaT)

$\Delta V_{\text{rad}} \sim 15 \text{ km/s}$

[Fe/H] measurement:

$V < 12$ (2M stars)

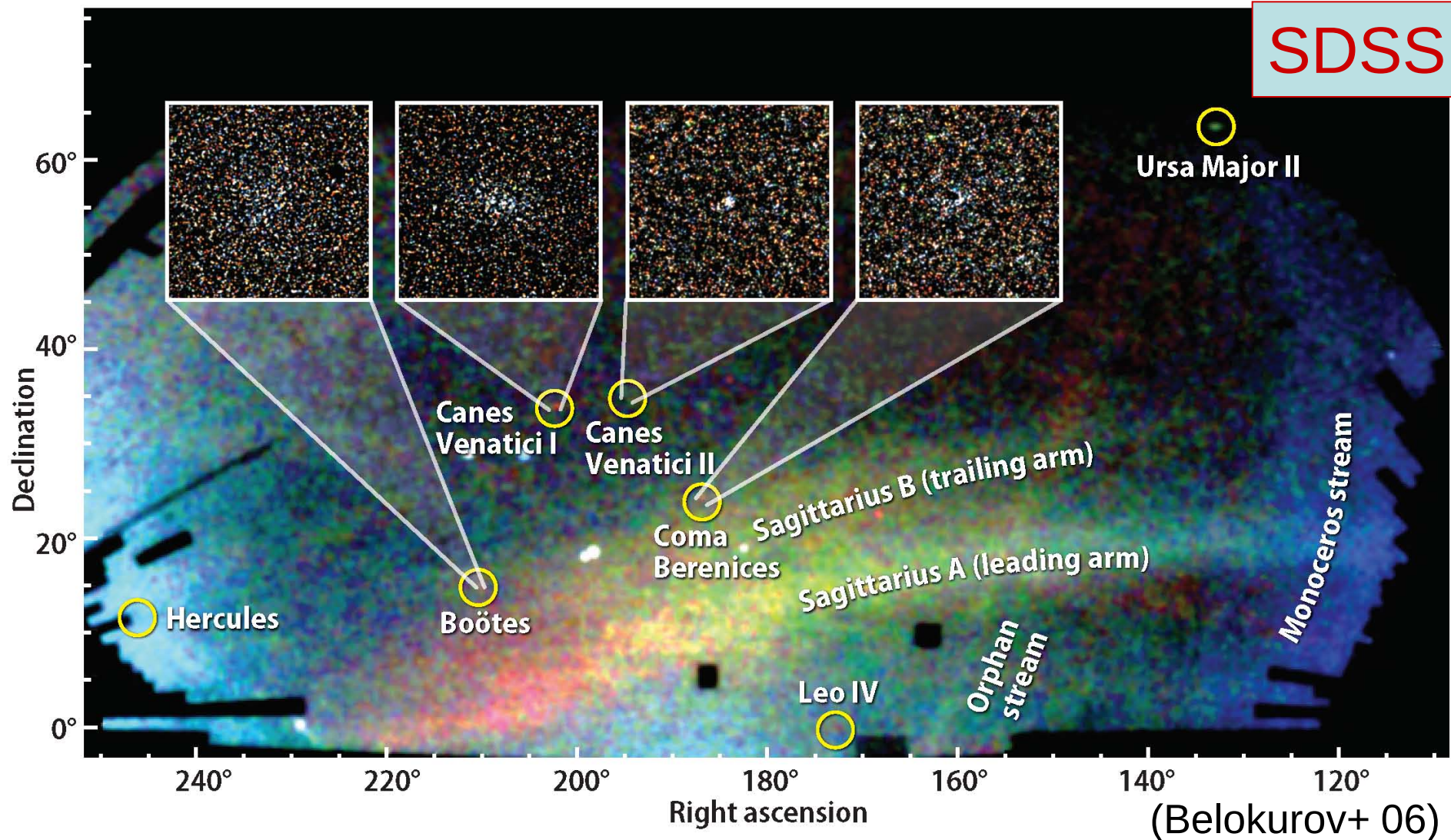
The background is a solid light green color. In the center, there are several concentric circles in a slightly lighter shade of green, creating a ripple effect. In the top-left and bottom-right corners, there are stylized floral motifs with multiple pointed petals, also in a light green color.

Key science goals

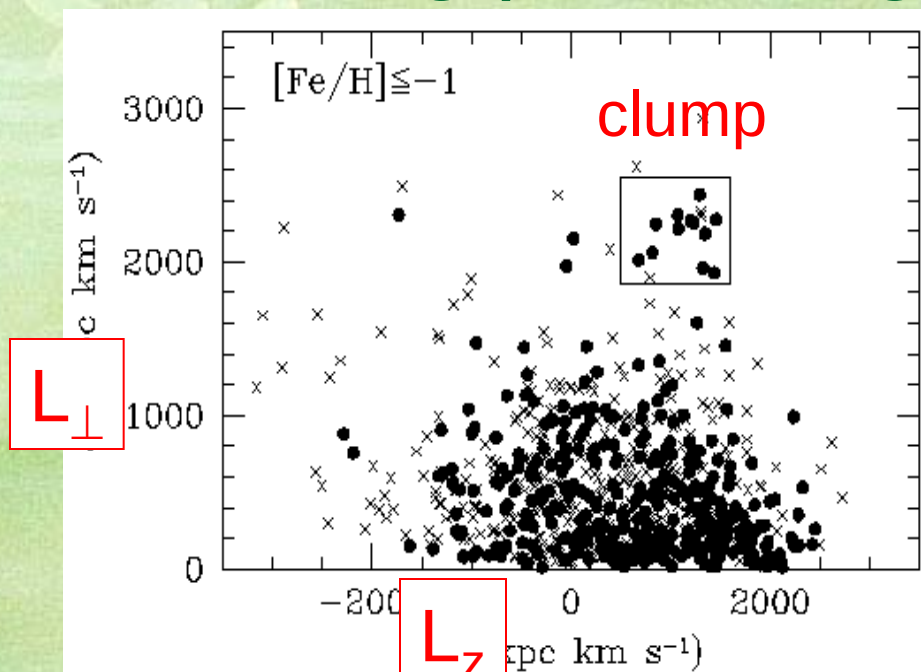
Extracting recent merging events in the MW

Spatial substructures in the halo

⇒ kinematics and metallicities



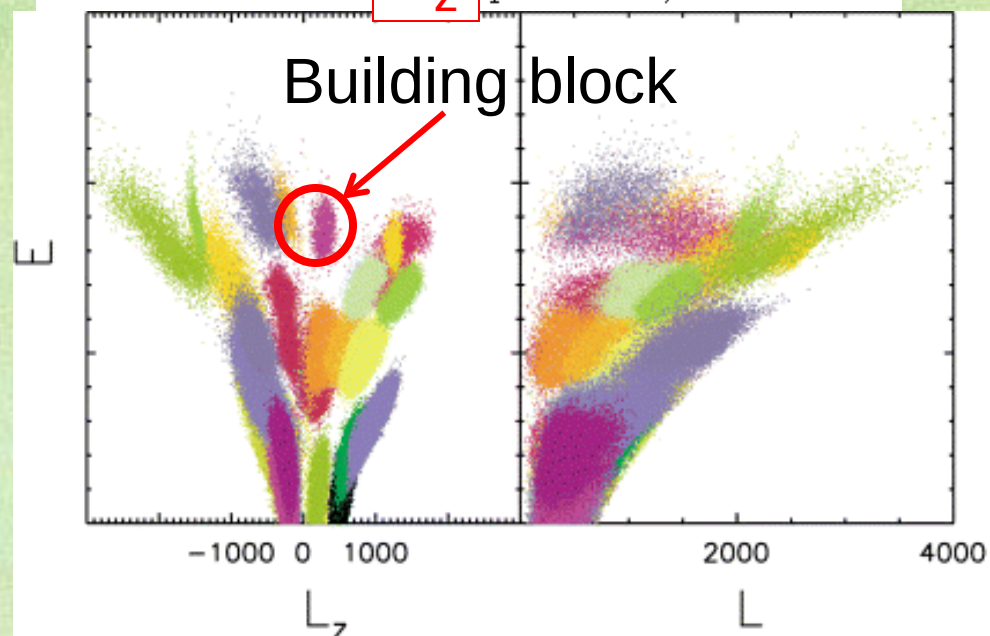
Extracting past merging history of the MW



Halo stars in phase space
(w. Hipparcos sample)

- measurement error of a few 100 (km s^{-1}) smears out substructures

MC & Beers 00



Astrometry with Gaia
(precise distances and proper motions)
+ V_{rad} & $[\text{Fe}/\text{H}]$ distrib.
with PFS

- resolves each of blocks and its chemical evolution

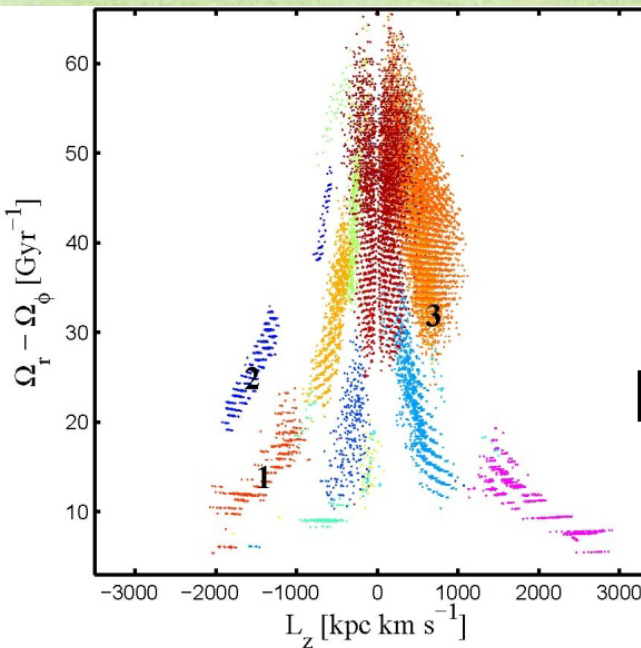
Helmi & de Zeeuw 00

Accretion time of a satellite can be deduced from phase-space distribution of stars (McMillan & Binney 2008, Gomez+ 2010)

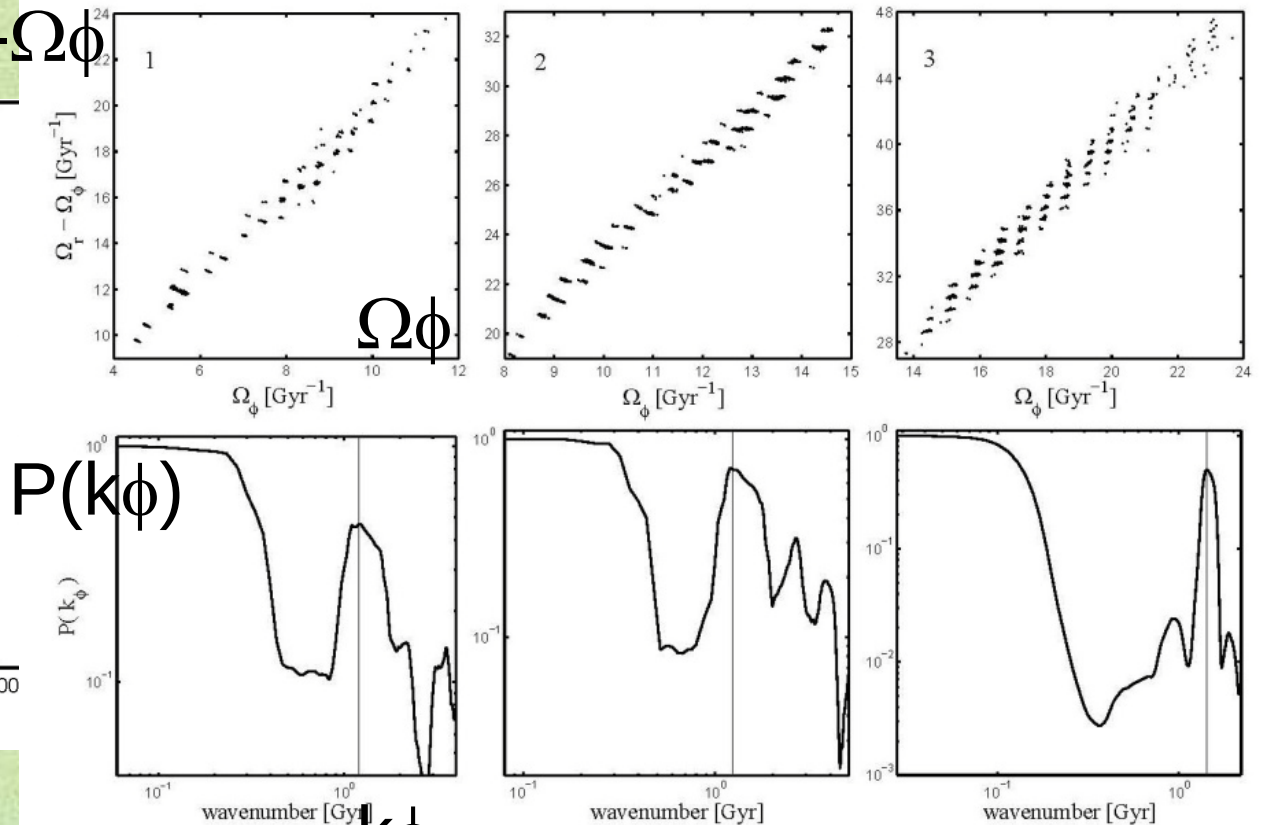
Orbital freq.

$\Omega_r - \Omega_\phi$

$\Omega_r - \Omega_\phi$



L_z

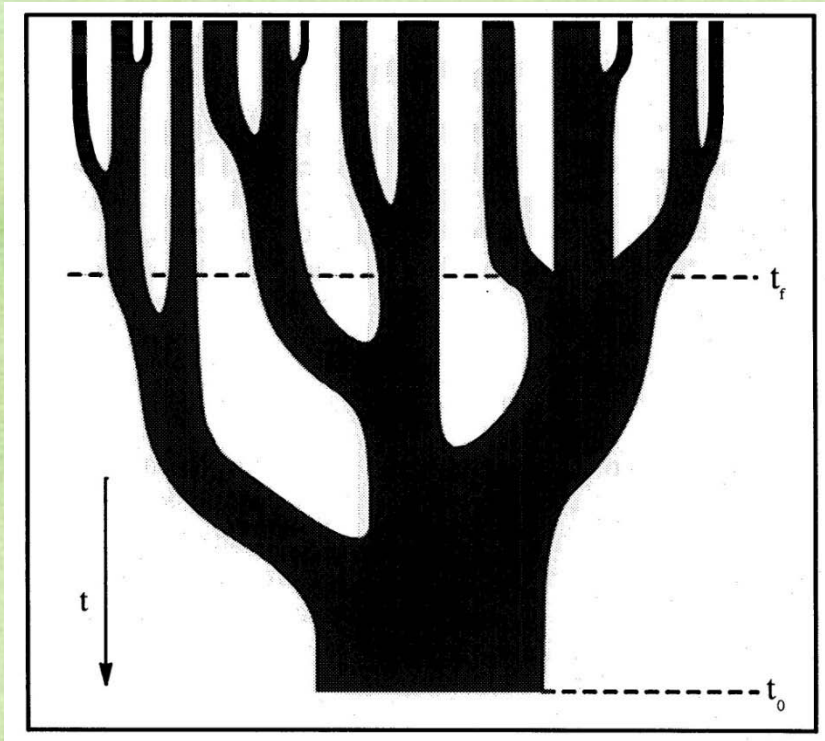


7.9 Gyr

8.9 Gyr

7.6 Gyr

How many stars are needed to trace the merging history?

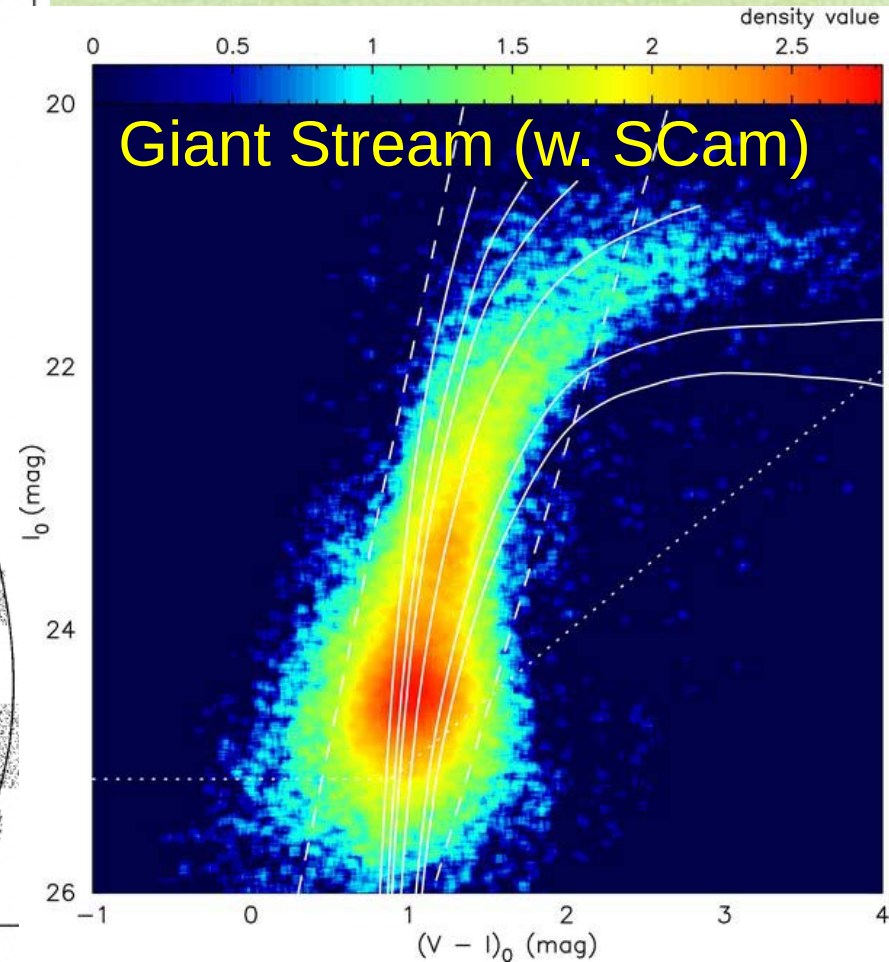
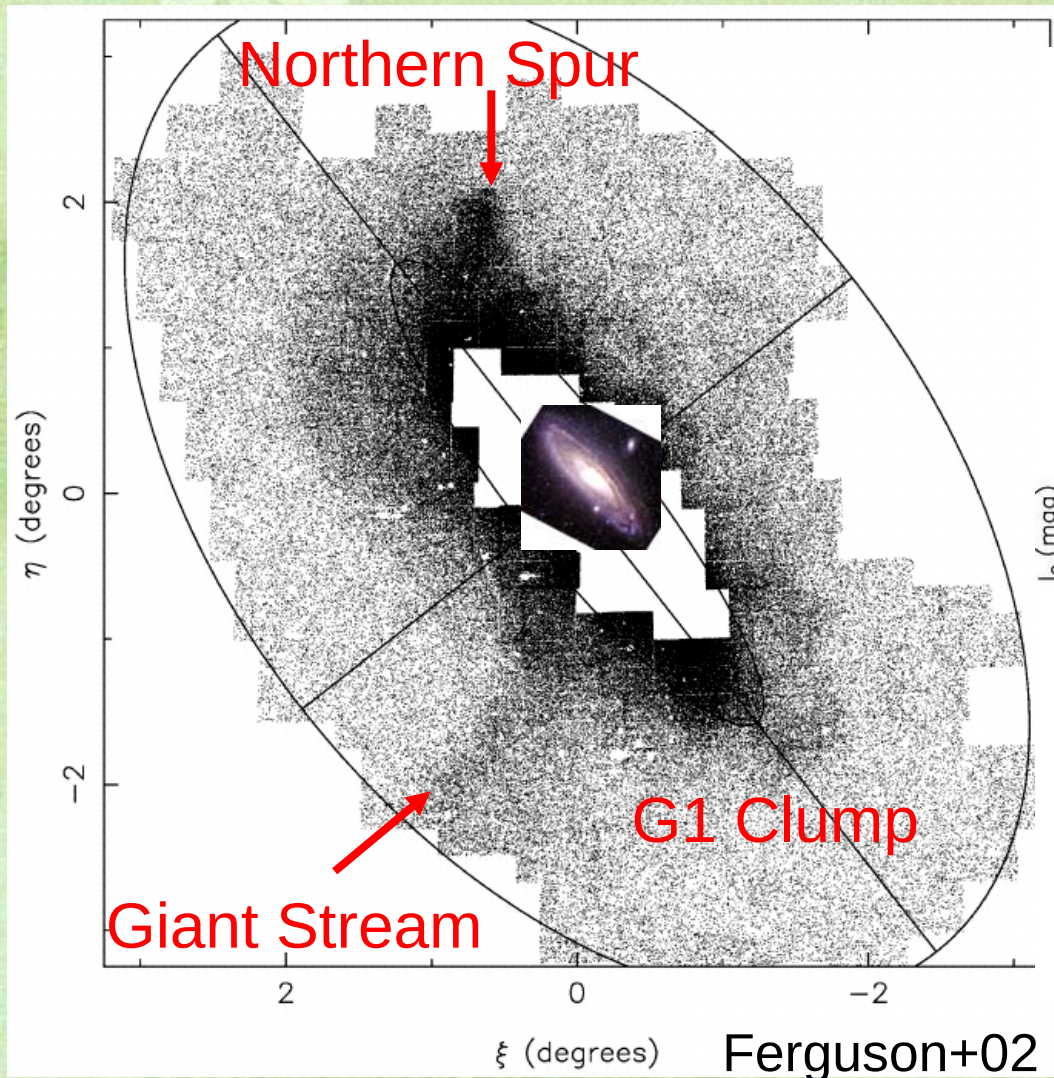


Stellar halo component
with mass M_{tot}

- $M_{\text{tot}} \sim 10^9 M_{\text{sun}}$
- max. $\sim 10^4$ building blocks
(if $n(L)dL \sim L^{-1.5} dL$
for $L=10^3 \sim 10^7 L_{\text{sun}}$, $M/L \sim 1$)
- Total sample:
max. ~ 1 M stars
(if ~ 100 sample stars
for each building block)

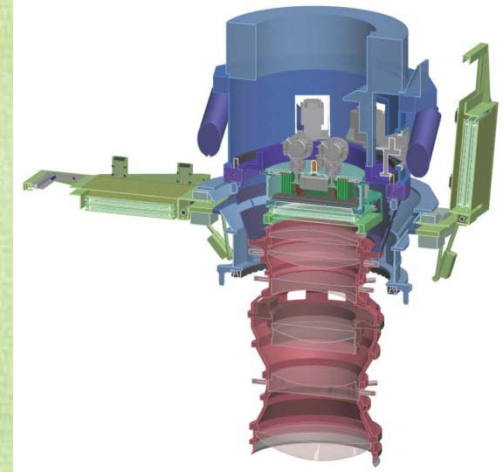
Formation of M31: Is it different from MW?

Halo substructures as merging remnants



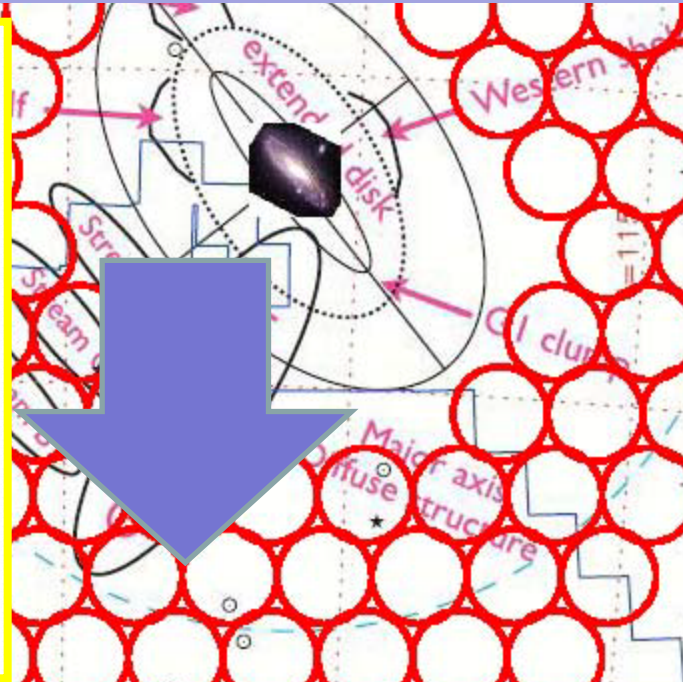
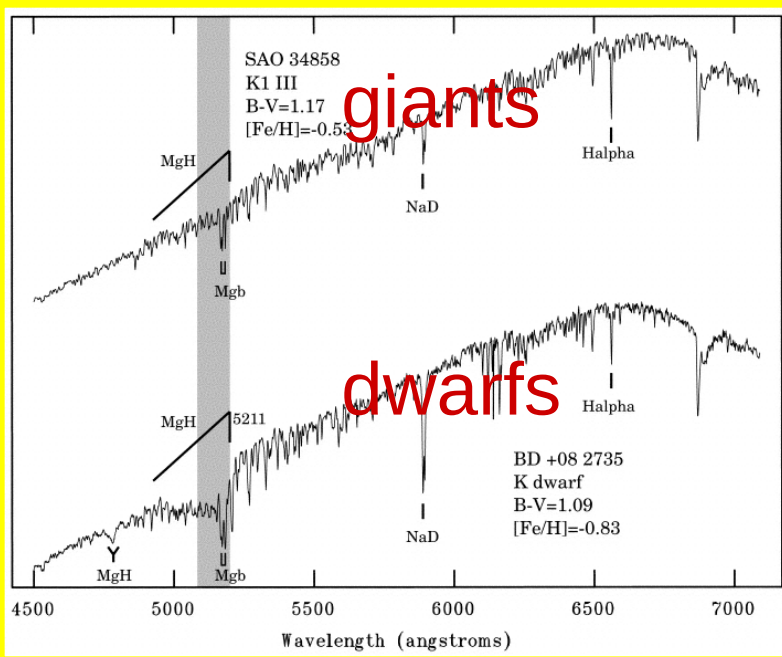
Tanaka+10

HSC



M31 covered with
180 CCDs

HSC survey of M31's halo with NB515
to select M31's RGB stars with $g < 22.5$



Metallicities and RVs of substructures
and satellites with PFS (+ star clusters)

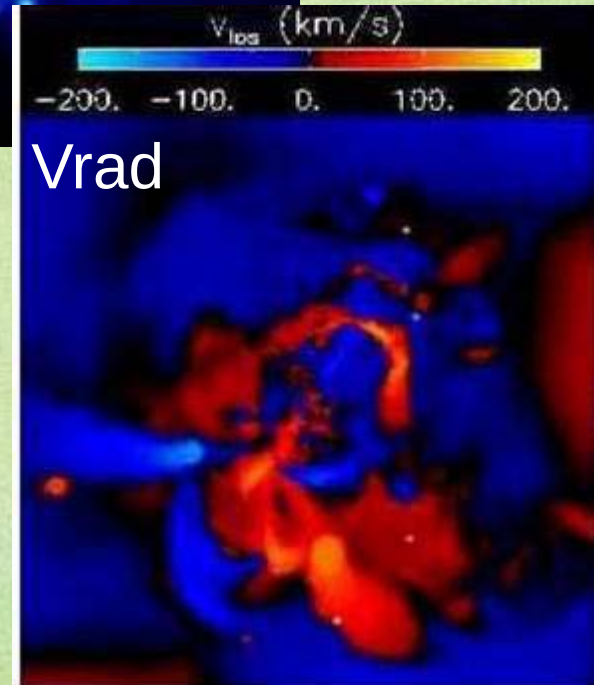
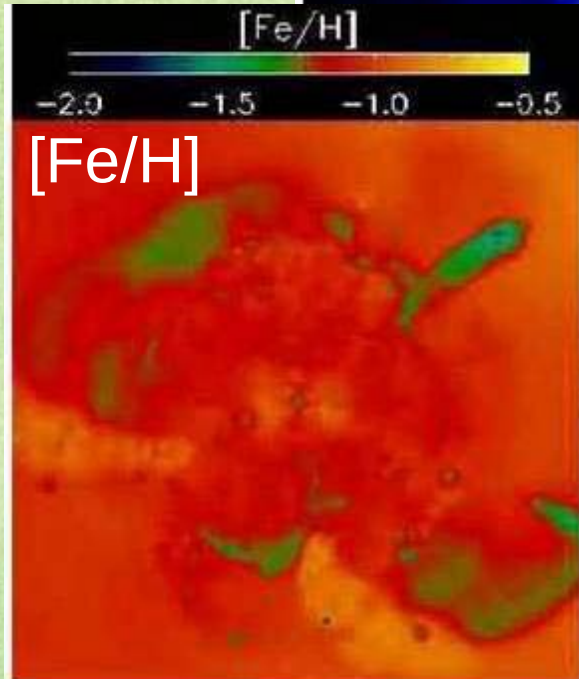
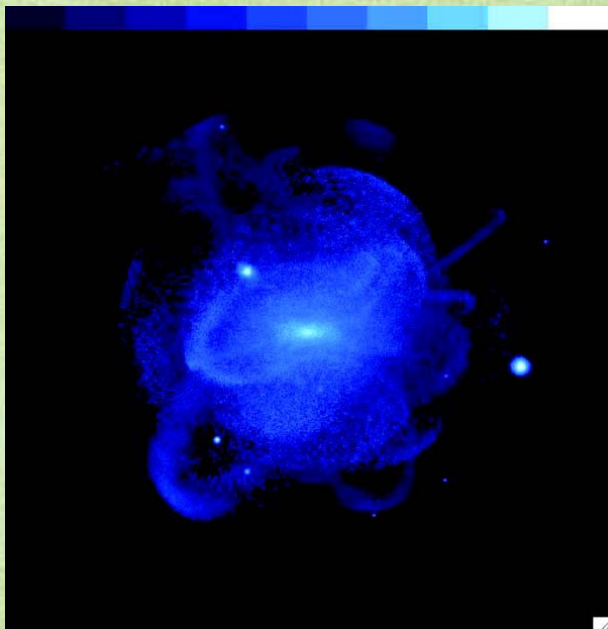
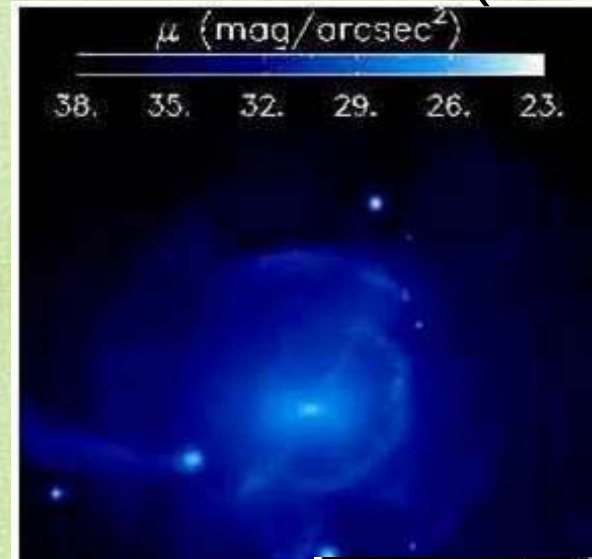
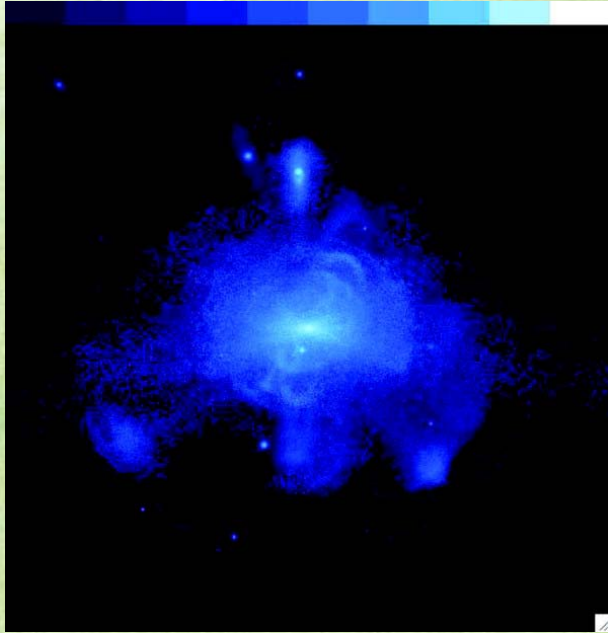
ξ (degrees)

130 pointings

$I_{\text{TRGB}}=20.5$

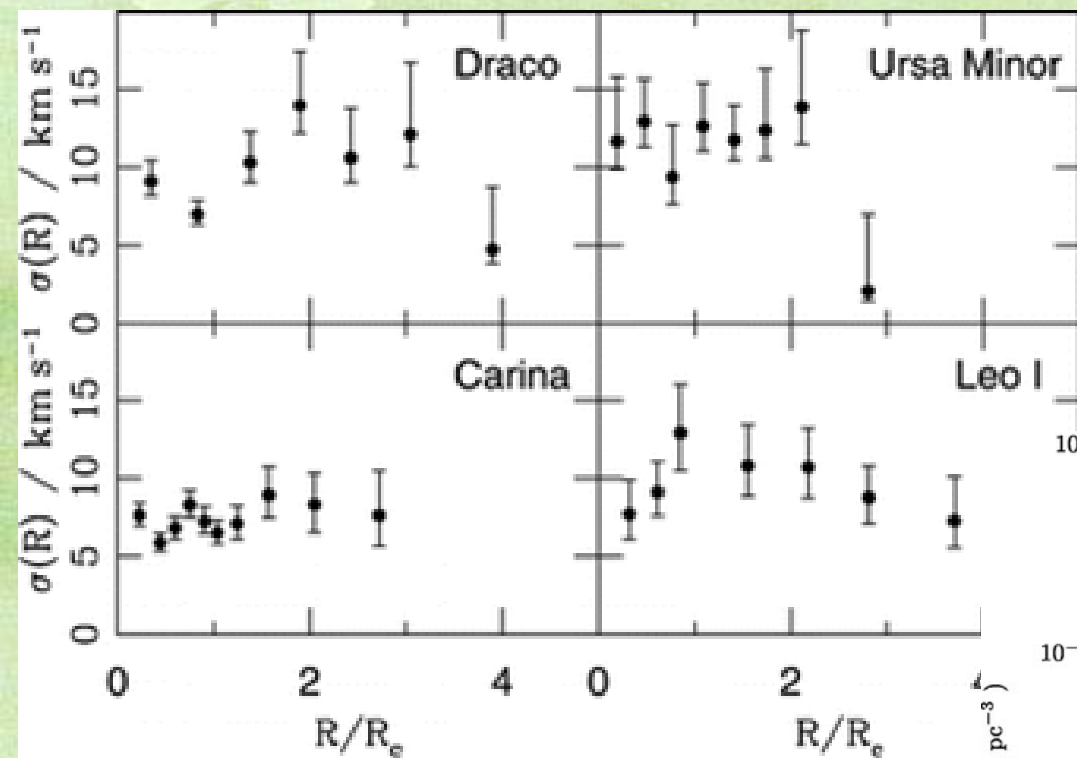
Several stellar halos from CDM models

(Johnston+08)



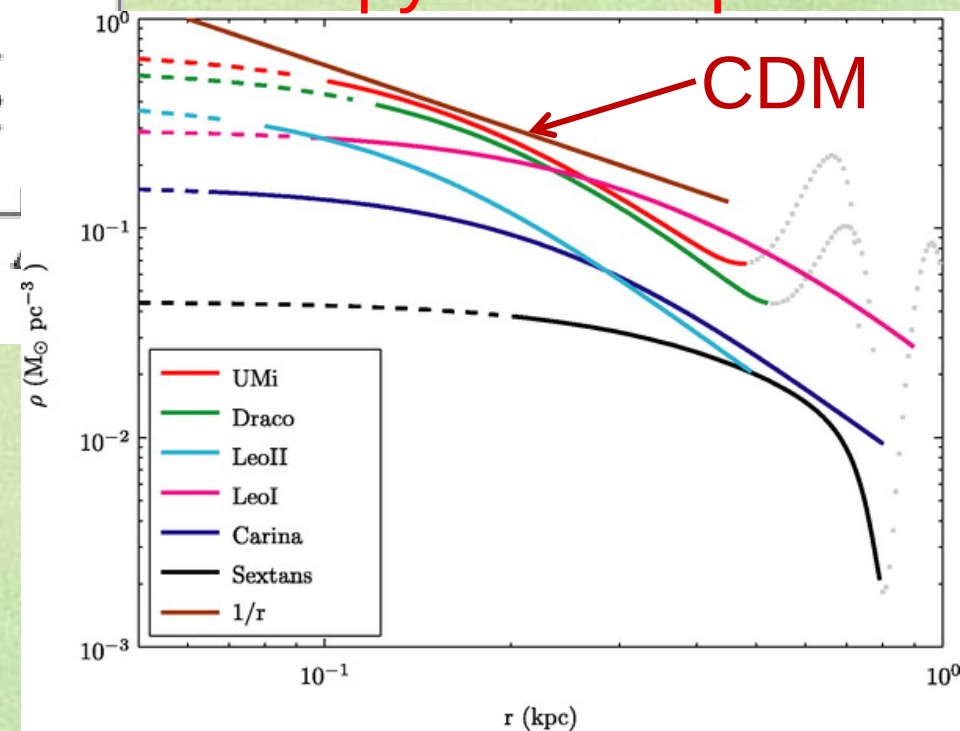
Dark matter of dwarf satellites: Is CDM correct?

Gilmore+07

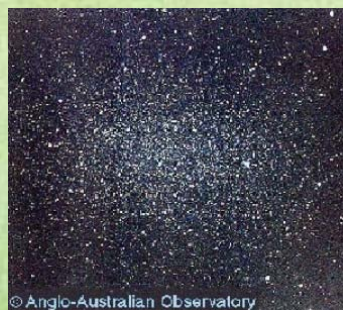


dSphs:

- DM dominated
($M/L = 10^2 \sim 10^3$)
- $\sigma \sim$ a few to 10 km/s
- **Cuspy or core profile?**



Car



Leo I

© Anglo-Australian Observatory

The background is a light green color with a subtle texture. In the center, there are several concentric circles in a slightly lighter shade of green. In the top-left and bottom-right corners, there are stylized floral motifs with multiple pointed petals.

Proposed survey and PFS requirements

Proposed survey with PFS

1. The Milky Way survey

- Sample: $\sim 10^6$ MW stars with $b > 20^\circ$, $18 < V < 21.5$ (Halo $\sim 55\%$, Thick disk $\sim 30\%$, Thin disk $\sim 5\%$), targets are taken from HSC, SDSS & PanStar
- Total area: ~ 1000 sq. deg (~ 560 pointings)
- Survey time: ~ 112 nights
- $\Delta[\text{Fe}/\text{H}] \sim 0.2$, $\Delta V_{\text{rad}} \sim \text{a few km/s}$

2. The M31 halo survey

- Sample: RGBs, $V < 21.5$, from HSC
- Total area: ~ 230 sq. deg (~ 130 pointings)
- Survey time: ~ 30 nights (can be PI-led programs)

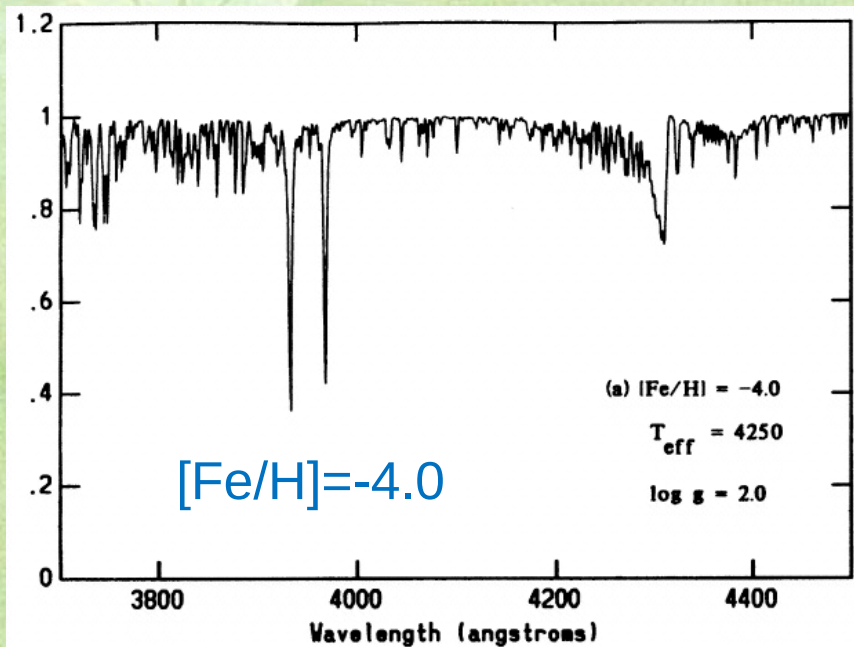
3. Dwarf galaxy survey

- Sample: RGBs, $V < 21.5$, from SCam & HSC
- Survey time: ~ 30 nights (can be PI-led programs)

Requested performance of PFS

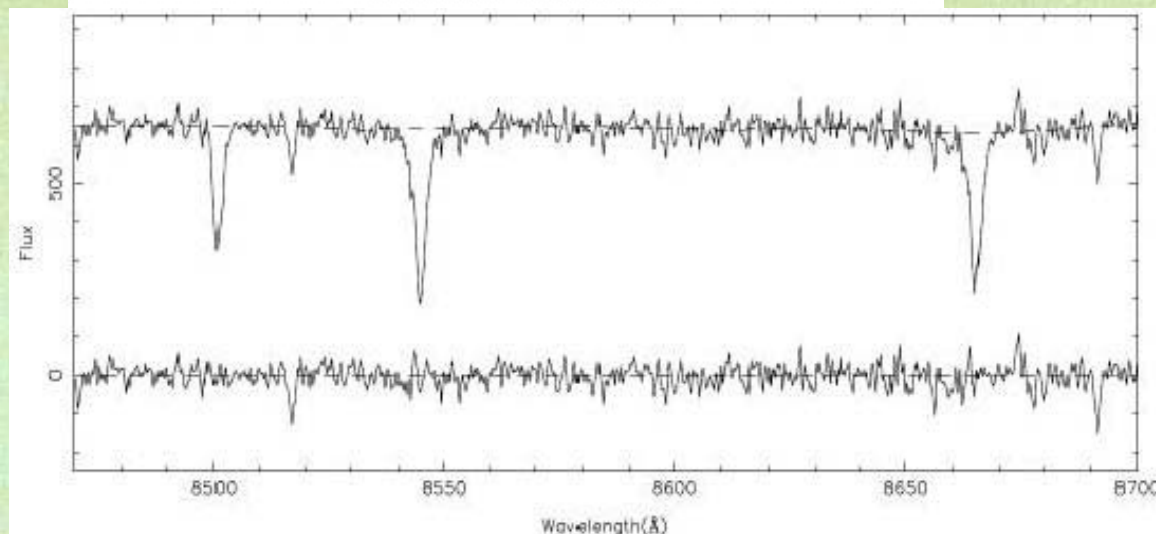
- Synergy with Gaia for Galactic stars
 - $V > 12$ mag for RVs
 - $V > 17$ mag for $[\text{Fe}/\text{H}]$
 - Early data release in 2015
- Enable to determine metallicity and velocity distributions of stars
 - $\Delta[\text{Fe}/\text{H}] \sim 0.2$, $\Delta V_{\text{rad}} \sim$ a few km/s
- Enable to observe M31 and satellite stars
 - $I_{\text{TRGB}} = 20.5$ mag, i.e., $V_{\text{lim}} \sim 21.5$ mag

Ca II lines as [Fe/H] indicator



Blue:
Ca II K (3933A) & (B-V)
For both dwarfs and giants
with $-4.0 < [Fe/H] < 0.5$

Beerrs+99



Red:
Ca II triplet
(8400-8700A)
& ($V_{HB} - V$)
For RGBs with
 $-3 < [Fe/H] < -0.5$

Starkenbourg+10

PFS requirements

1. Spectral resolution, λ coverage, and SNR

Call lines at blue and red regions for [Fe/H],
 $\lambda 5150\text{\AA}$ (Mgb) for logg, SNR ~ 30 , $V < 21.5$

- R=3,000, $\lambda = 3,900\text{--}6,700\text{\AA}$
targets: metal-poor stars in the MW
(If R=5,000 in blue, then many lines incl. Ba, Mg, etc.
would be resolved. Wavelength coverage being fixed.)
- R=3,000, $\lambda = 6,500\text{--}9,900\text{\AA}$
targets: (bright) RGBs in the MW and M31
- IR range: will be very useful for studying disk stars

2. Fibers

MW: $\sim 1,400$ stars/PFS field at $V=17$, $b=|45|$

M31: $\sim 5,000$ stars/sq.deg at $V=22.5$, $R=30\text{kpc}$

- 2,000-3,000 fibers with size $1.2''$ are sufficient

Necessity of HR spectroscopy

Chemical tagging of each building block
⇒ detailed chemical evolution history

1. Spectral resolution, λ coverage, and SNR

- $R = 35,000$, $SNR \sim 100$, $V < 17$ mag
- Any of $\lambda = 4112\text{-}4322\text{\AA}$, $5015\text{-}5268\text{\AA}$, $6280\text{-}6593\text{\AA}$, $6456\text{-}6779\text{\AA}$, $8380\text{-}8804\text{\AA}$

2. Fibers

- ~ 200 fibers are sufficient for follow-up studies

Other major facilities and projects

- AAO/RAVE

- 1.2m UKST, $R=8,500$, 150fibers, $9 < I < 12$

- AAT/HERMES

- 3.9m, $R=28,000$, 392fibers, $\lambda 4708-4893\text{\AA}$, $5649-5873\text{\AA}$, $6481-6739\text{\AA}$, $7590-7890\text{\AA}$, $10 < V < 14$

- LAMOST

- 4m, $R=1,800$, 4,000fibers, $\lambda 3700-5900\text{\AA}$, $5700-9000\text{\AA}$

- VLT/FLAMES

- 8.2m, $R \sim 5,000$, 20,000, 130fibers, $V < 16$ for $[\text{Fe}/\text{H}]$, $V < 19$ for RVs, 10^5 stars

- CFHT/GYES

- 4m, $R=20,000$, 500fibers, $\lambda 3900-4500\text{\AA}$, $5880-6700\text{\AA}$, $V < 16 \sim 18$

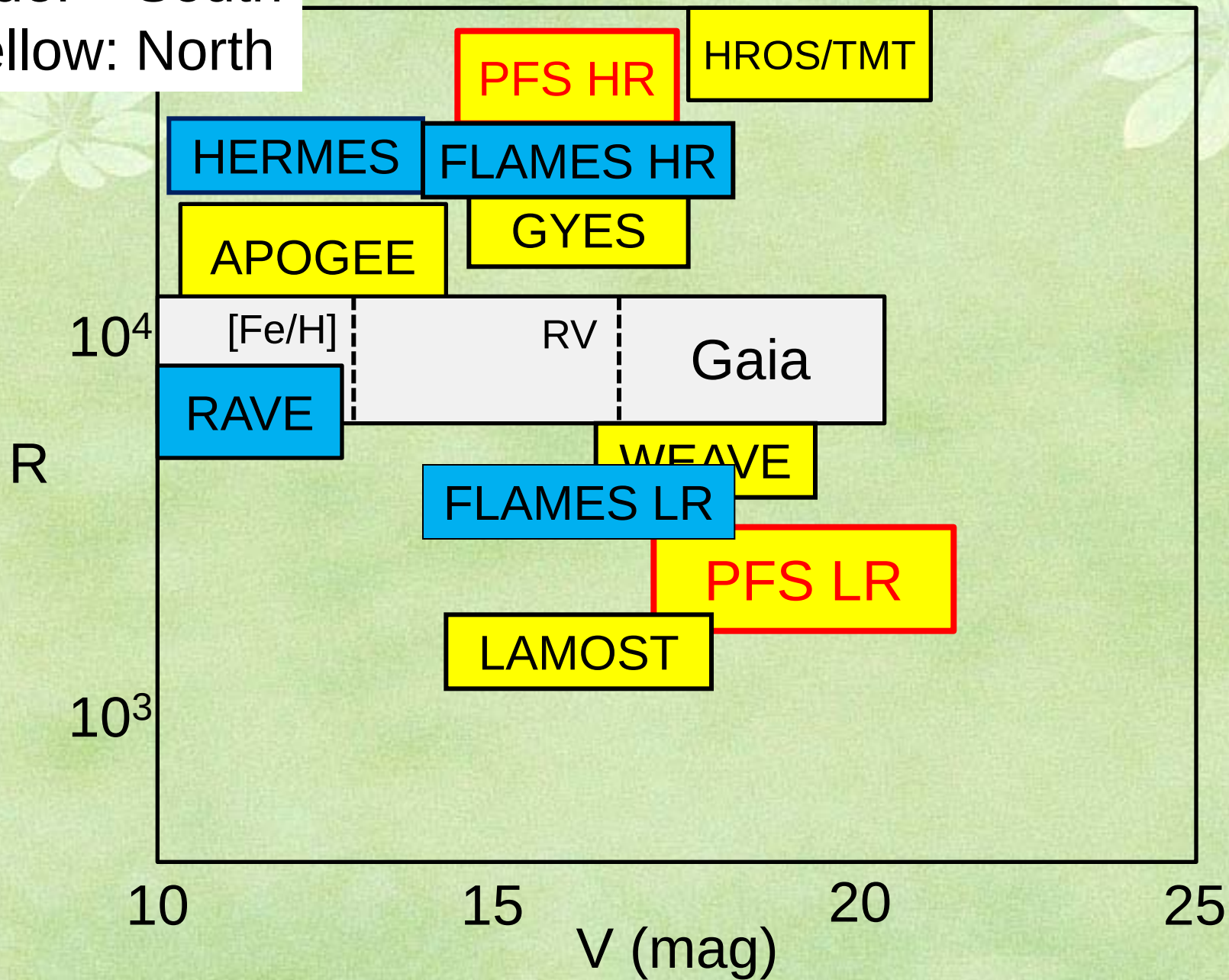
- WHT/WEAVE

- 4.2m, $R=5,000 + 20,000$, 800fibers, $\lambda 4000-9500\text{\AA}$, 2sq.deg, $V < 20?$

- VISTA

- 4m, $R=3-5,000$ & $20,000$, 1500fibers, 2sq.deg, $V?$

Blue: South
Yellow: North



Summary: GA with PFS

■ PFS LR in synergy with Gaia

- $R=3,000$, $\sim 3,000$ fibers,
 $\lambda=3900-9000\text{\AA}+\text{IR}$ mode, $18 < V < 21.5$
- Discover many substructures and
identify merger history

■ Hope: PFS HR for follow-up studies

- $R=35,000$, ~ 200 fibers, $V < 17$,
Any of $\lambda=4112-4322\text{\AA}$, $5015-5268\text{\AA}$,
 $6280-6593\text{\AA}$, $6456-6779\text{\AA}$, $8380-8804\text{\AA}$
- Chemical history of each building block



End

