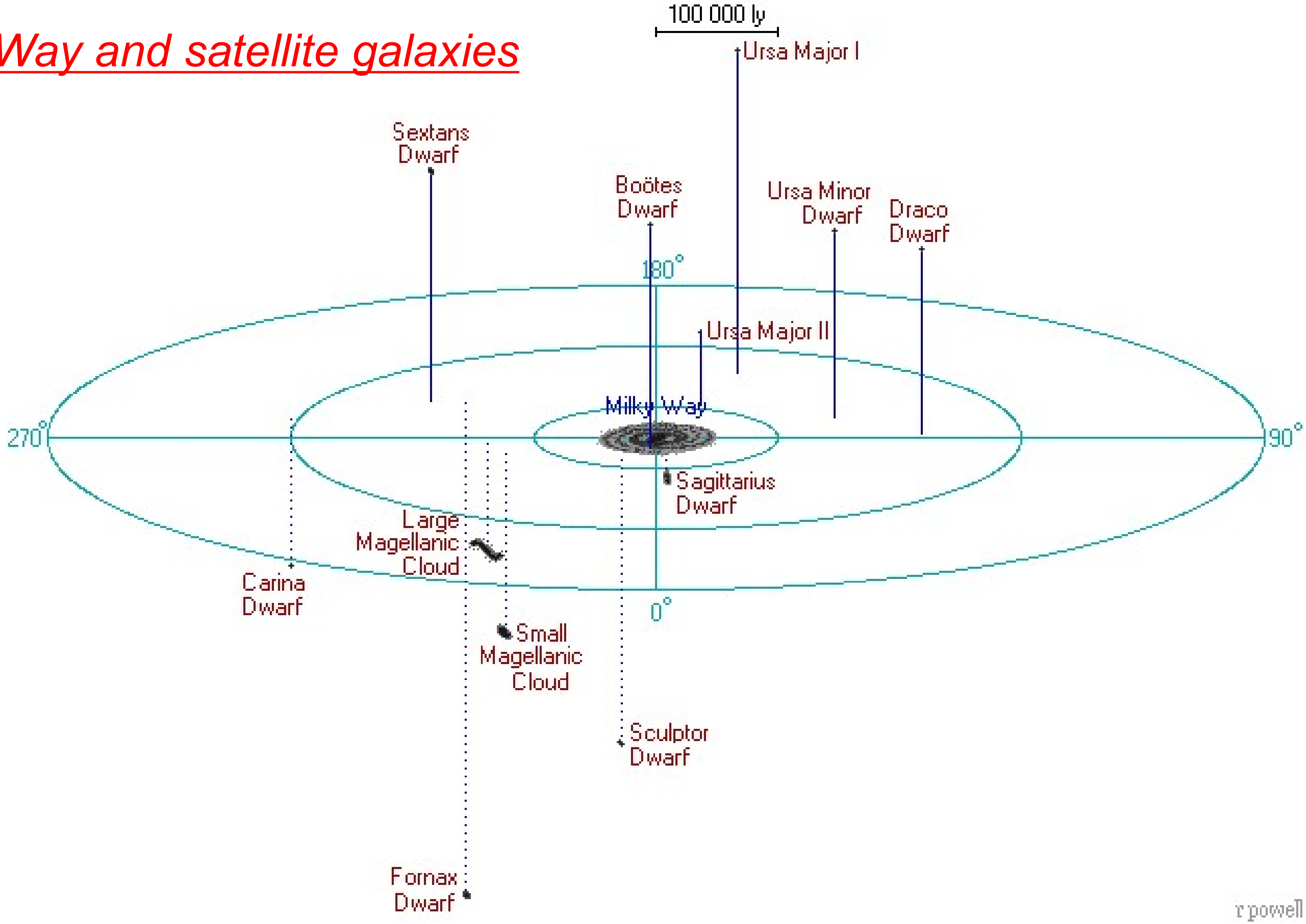
Chap.6 Formation and evolution of Local Group galaxies

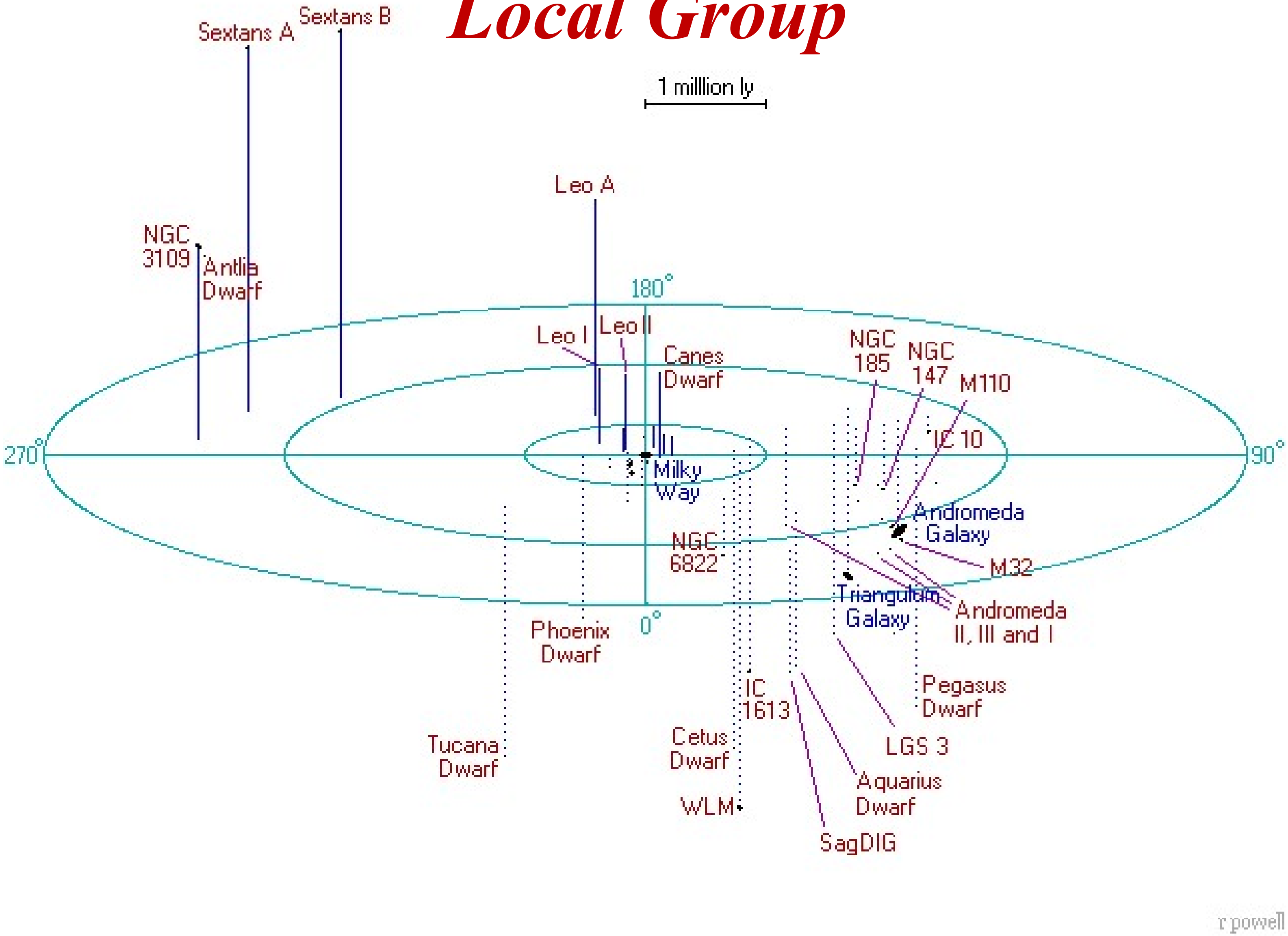
- Properties of Local Group galaxies
- New aspects of Magellanic Clouds
- Formation of satellite galaxies
- New insights into the missing satellites problem
- Formation of the Andromeda galaxy
- Future prospects

6.1 Properties of Local Group galaxies

Milky Way and satellite galaxies



Local Group

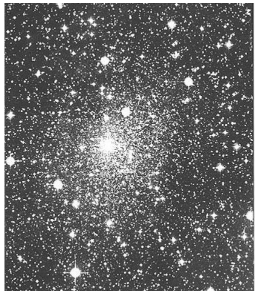

1 milllion ly
Sextans A
Sextans B
Leo A
NGC 3109
Antlia Dwarf
180°
270°
90°
0°
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
Milky Way
Andromeda Galaxy
M32
NGC 6822
Triangulum Galaxy
Andromeda II, III and I
Phoenix Dwarf
IC 1613
Pegasus Dwarf
LGS 3
Tucana Dwarf
Cetus Dwarf
Aquarius Dwarf
WLM
SagDIG
r powell

	Name	Type	l [deg]	b [deg]	$D_{\odot}$ [kpc]	$D_{\rm LG}$ [Mpc]	M_V [mag]	μ_V [mag/"^{2}]	$\langle$[Fe/H]$\rangle$ [dex]
MW	Galaxy	S(B)bcI-II	0.00	0.00	8	0.47	−20.9	—	—
	Sgr	dSph,N?	6.00	−15.00	28	0.47	−13.8	25.4	−1.0
	LMC	IrIII-IV	280.46	−32.89	50	0.49	−18.5	20.7	−0.7
	SMC	IrIV/IV-V	302.80	−44.30	63	0.49	−17.1	22.1	−1.0
	UMi	dSph	104.95	44.80	69	0.44	−8.9	25.5	−2.2
	Dra	dSph	86.37	34.72	79	0.44	−8.6	25.3	−2.1
	Sex	dSph	243.50	42.27	86	0.52	−9.5	26.2	−1.7
	Scl	dSph	287.54	−83.16	88	0.45	−9.8	23.7	−1.8
	Car	dSph	260.11	−22.22	94	0.52	−9.4	25.5	−2.0
	For	dSph	237.29	−65.65	138	0.46	−13.1	23.4	−1.3
	Leo II	dSph	220.17	67.23	205	0.57	−10.1	24.0	−1.9
	Leo I	dSph	225.98	49.11	270	0.63	−11.9	22.4	−1.5
	Phe	dIrr/dSph	272.49	−68.82	405	0.60	−9.8	—	−1.8
	NGC 6822	IrIV-V	25.34	−18.39	500	0.68	−16.0	21.4	−1.2
M31	M31	SbI-II	121.18	−21.57	770	0.31	−21.2	10.8	—
	M32	dE2,N	121.15	−21.98	770	0.31	−16.5	11.5	−1.1
	NGC 205	dE5p,N	120.72	−21.14	830	0.37	−16.4	20.4	−0.5
	And I	dSph	121.69	−24.85	790	0.33	−11.8	24.9	−1.5
	And III	dSph	119.31	−26.25	760	0.30	−10.2	25.3	−1.5
	NGC 147	dE5	119.82	−14.25	755	0.30	−15.1	21.6	−1.1
	And V	dSph	126.20	−15.10	810	0.36	−9.1	24.8	−1.9
	And II	dSph	128.87	−29.17	680	0.24	−11.8	24.8	−1.5
	NGC 185	dE3p	120.79	−14.48	620	0.17	−15.6	20.1	−0.8
	M33	ScII-III	133.61	−31.33	850	0.42	−18.9	10.7	—
	Cas dSph	dSph	109.46	−9.94	760	0.34	−12.0	23.5	−1.6
	IC 10	IrIV:	118.97	−3.34	660	0.26	−16.3	22.1	−1.3:
	And VI	dSph	106.01	−36.30	775	0.38	−11.3	24.3	−1.9
	LGS 3	dIrr/dSph	126.75	−40.90	810	0.41	−10.5	24.7	−2.2
	Peg	IrV	94.77	−43.55	760	0.44	−12.3	—	−1.3
	IC 1613	IrV	129.82	−60.54	715	0.47	−15.3	22.8	−1.4
isolated	Cet	dSph	101.50	−72.90	775	0.62	−10.1	25.1	−1.9
	Leo A	IrV	196.90	52.40	690	0.88	−11.5	—	−1.7
	WLM	IrIV-V	75.85	−73.63	945	0.80	−14.4	20.4	−1.4
	Tuc	dSph	322.91	−47.37	870	1.11	−9.6	25.1	−1.7
	DDO 210	IrV	34.05	−31.35	950	0.96	−10.9	23.0	−1.9

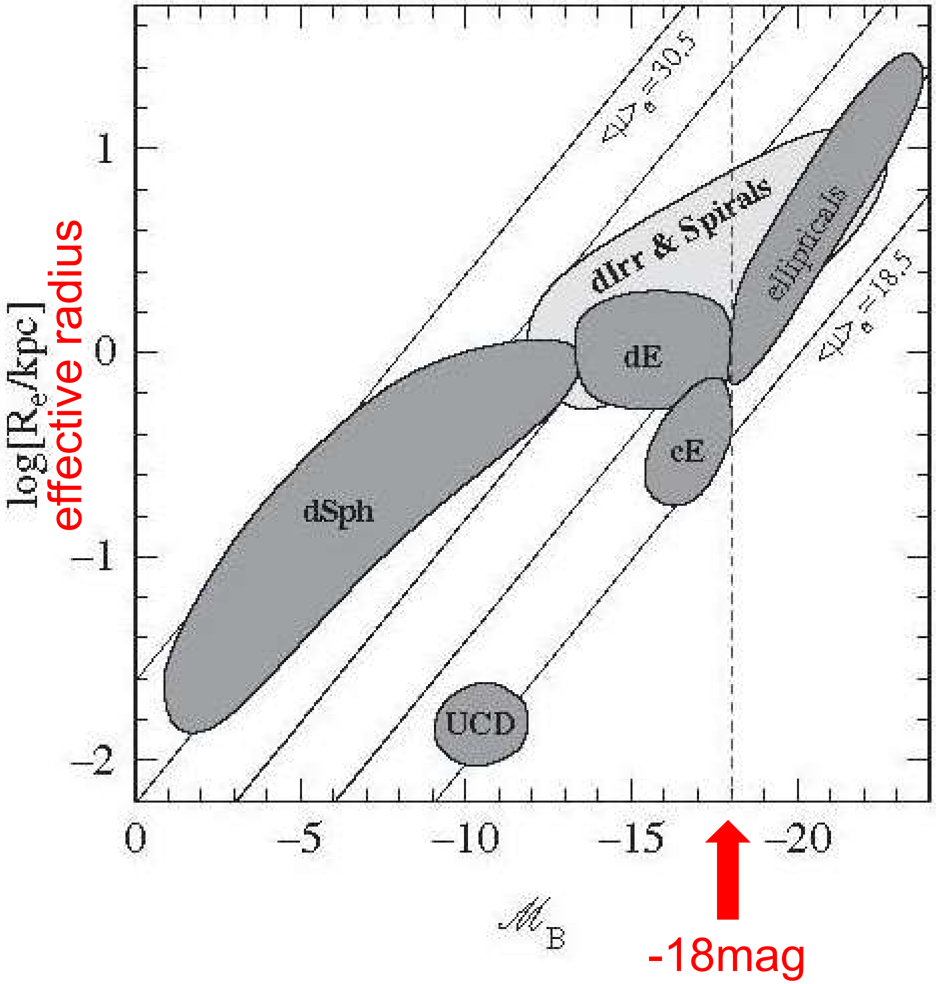
Dwarf galaxies

dwarf spheroidal galaxies
（dSphs 矮小楕円体銀河）

Leo I



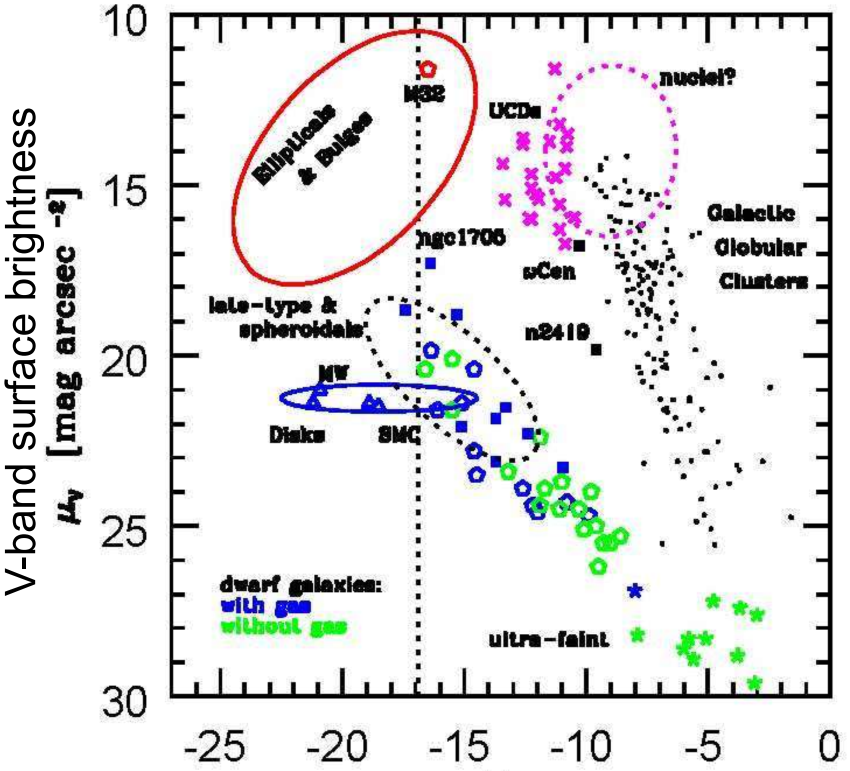
Carina

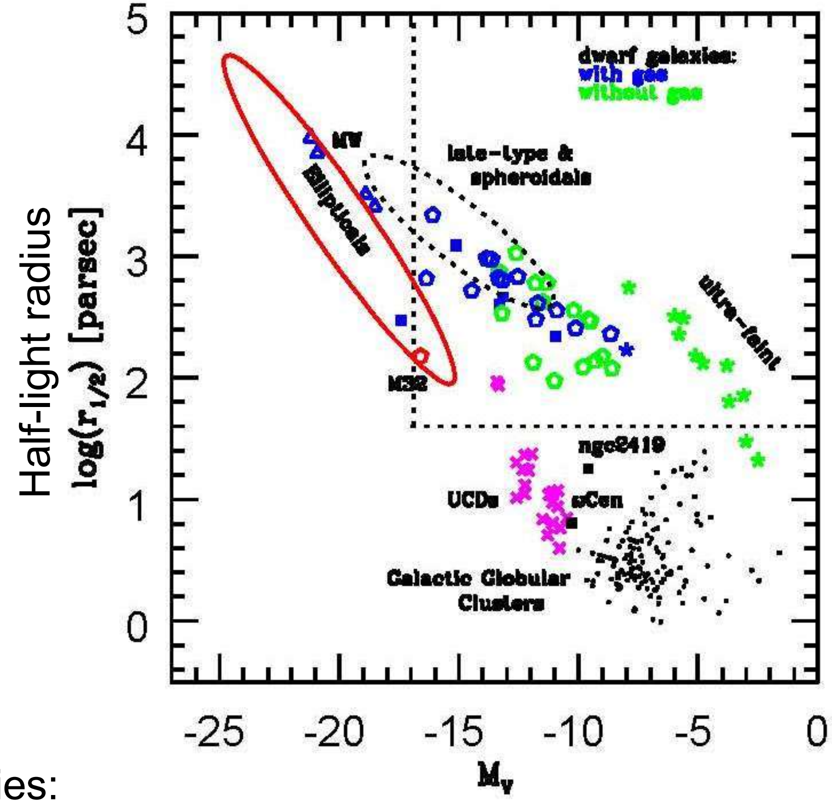


Structures of various types of galaxies

(Tolstoy+09, ARAA, 47, 371)

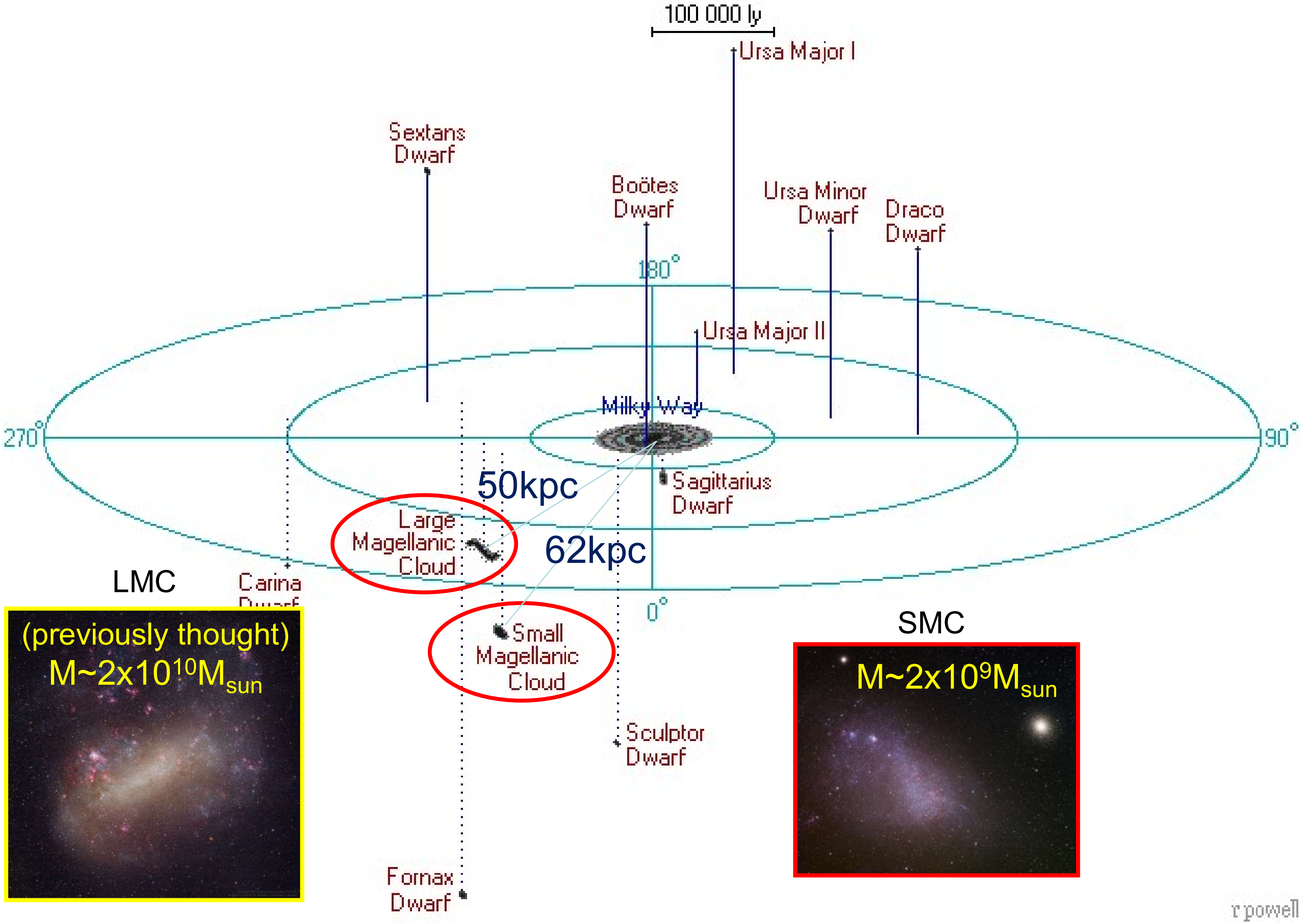
Classical dwarf satellites M_V < -8 mag
Ultra Faint Dwarfs (UFDs) M_V > -8 mag





dwarf galaxies:
Mv > -17 and more spatially extended than globular clusters
with gas: dIrr, without gas: dSph

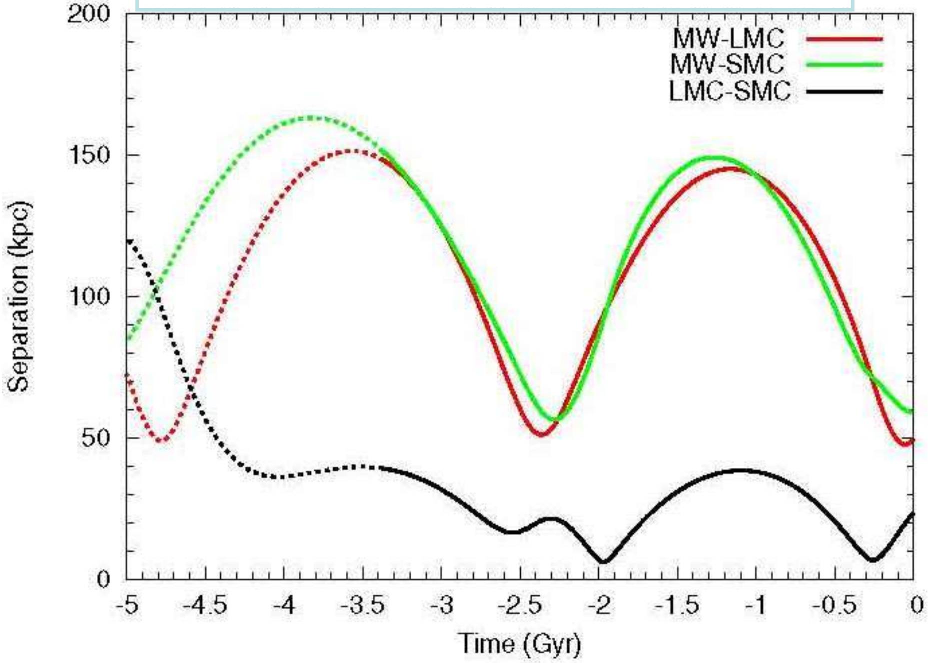
6.2 New aspects of Magellanic Clouds



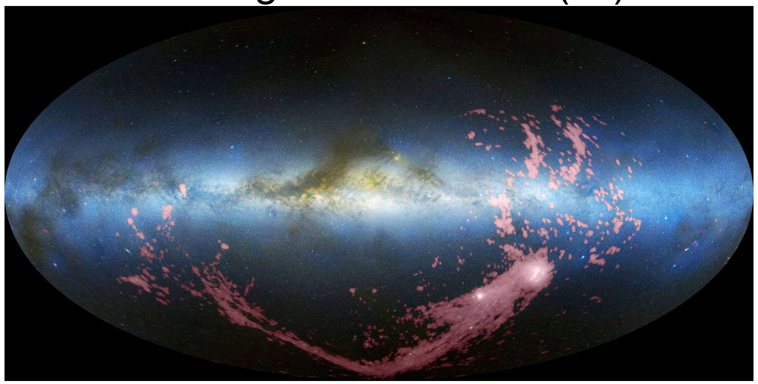
Most likely orbit of LMC/SMC to reproduce Magellanic Stream

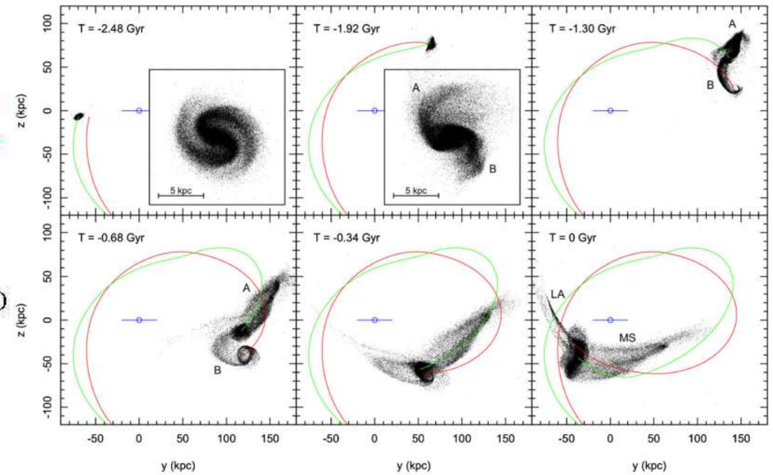
(Diaz & Bekki 2012)

At least 2 pericentric passages over the past 4Gyrs



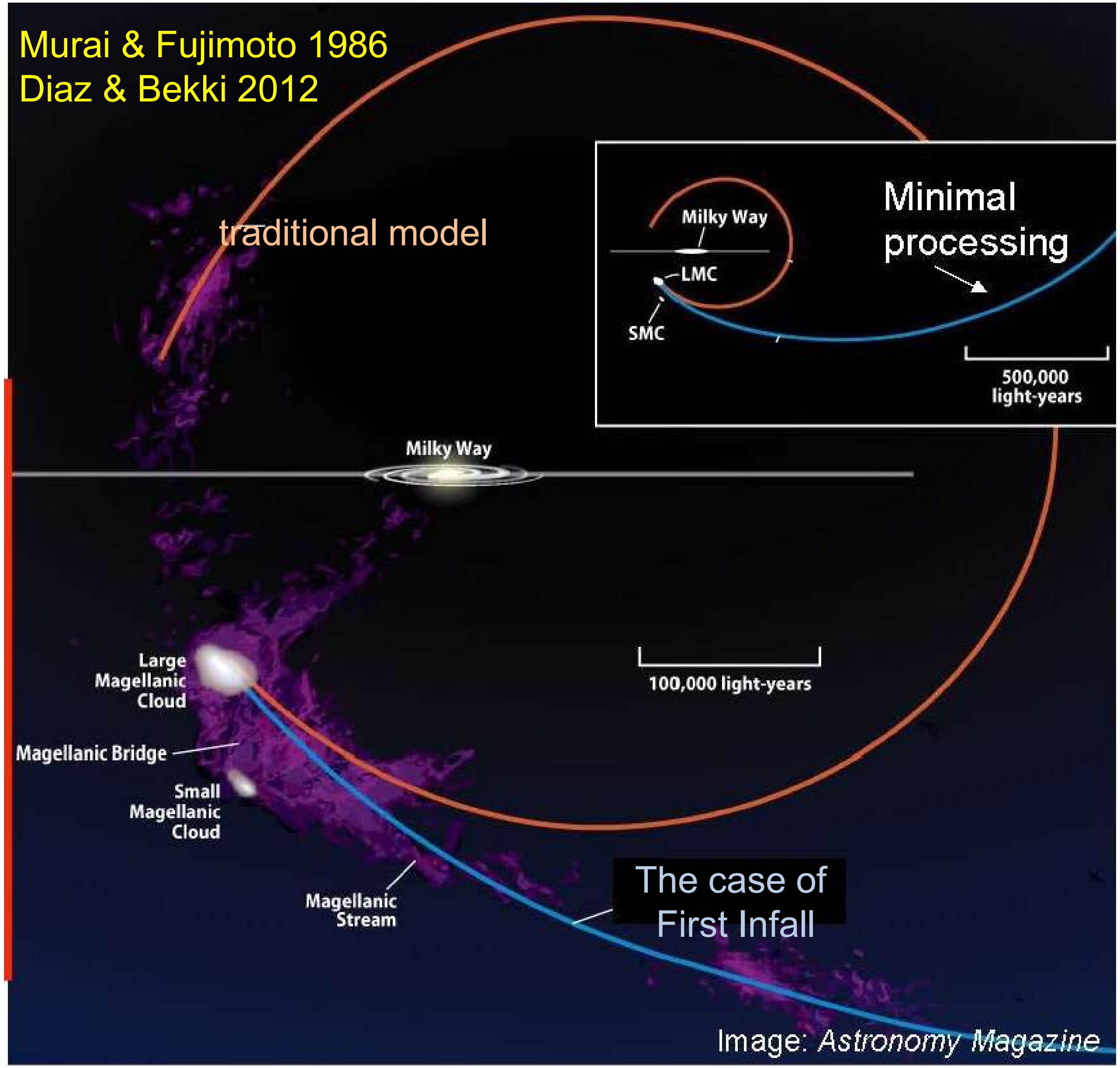
Magellanic Stream (HI)





LMC/SMC's orbit

Recent several works (large velocity using HST & Gaia) may suggest the first infall of LMC/SMC



Besla et al. 2010

Likely orbits of LMC/SMC + satellites using Gaia DR2: Patel et al. (2020)

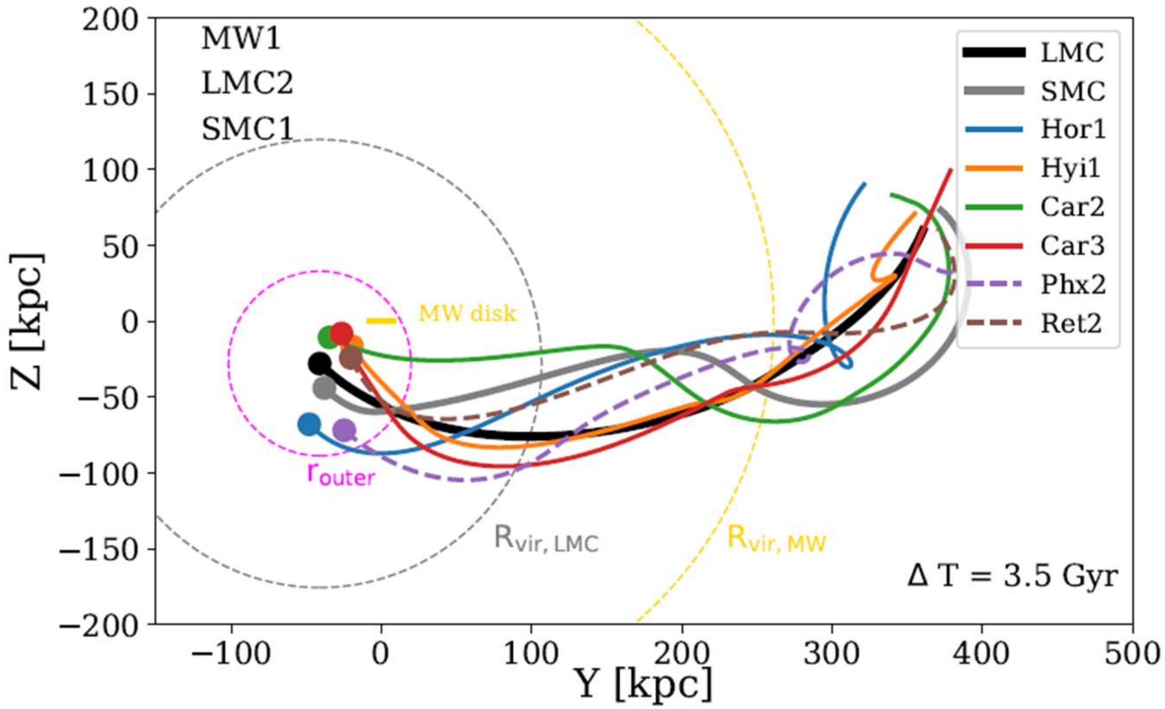
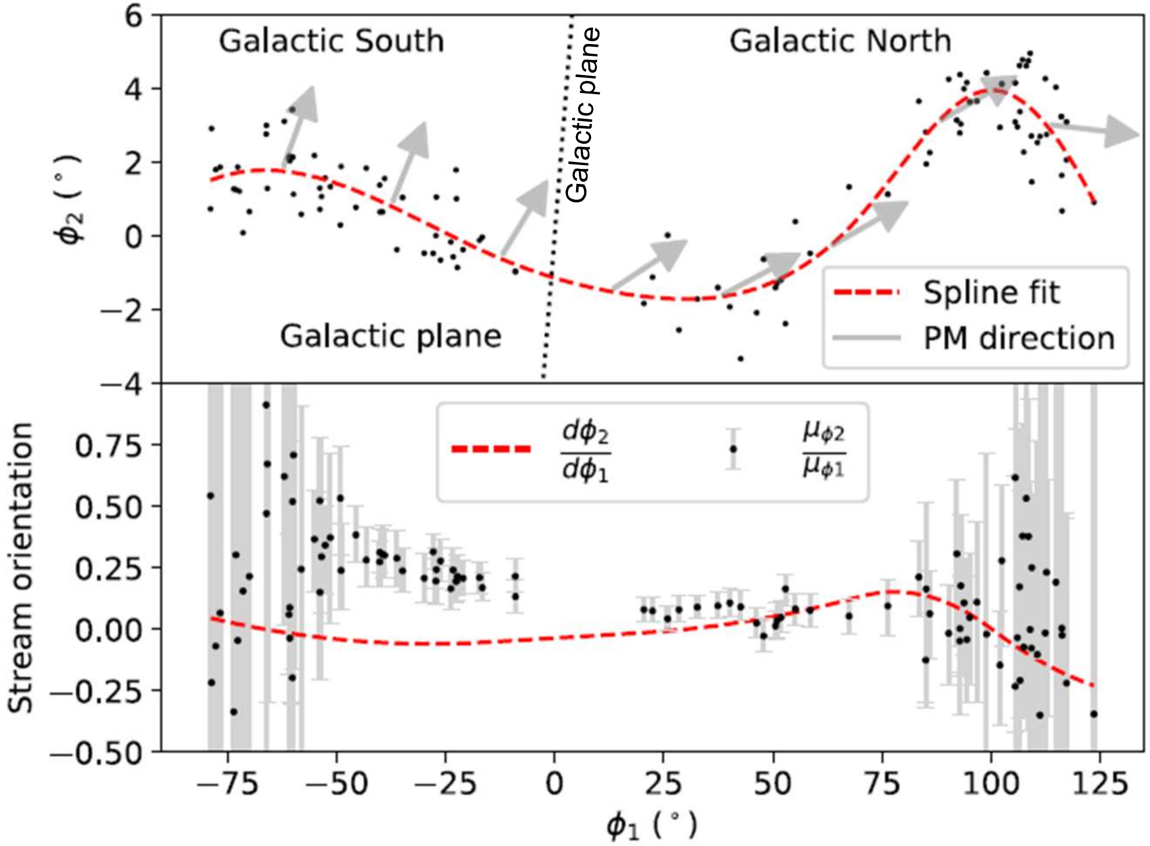


Figure 6. Direct orbits of all Magellanic satellites for the last 3.5 Gyr projected in the YZ-galactocentric plane. Recently captured Magellanic satellites (Ret2, Phx2) are illustrated with dashed lines and long-term Magellanic satellites (Car2, Car3, Hor1, Hyi1) are plotted with solid lines for MW1 using the fiducial LMC model. The disk of the MW lies along the z-axis. The orbit of the LMC (SMC) is illustrated in black (gray). The filled circles represent the positions of all satellites today. The magenta dashed circle indicates r_{outer} of the LMC and the gray dashed circle is the virial radius of the LMC. The gold dashed circle is the virial radius of the MW. The orbits of all Magellanic satellites follow the orbital path of the LMC.

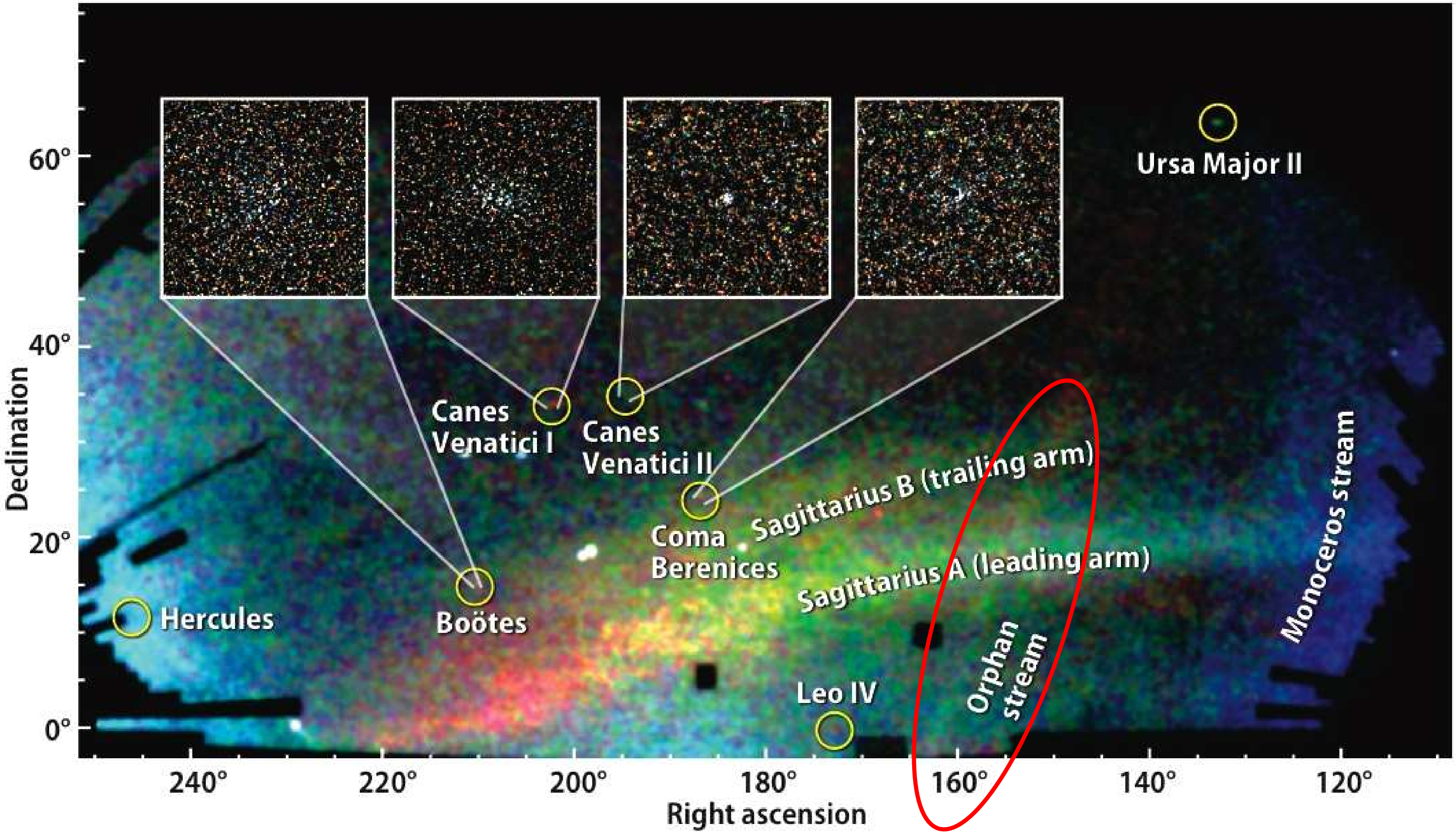
Misaligned Orphan Stream
~Effect of the very massive LMC?~

Erkal et al. 2019 (using Gaia DR2 PMs)



Points:
RR Lyrae
along OS

"Field of Streams" and new satellites in SDSS data (Belokurov et al. 2006)



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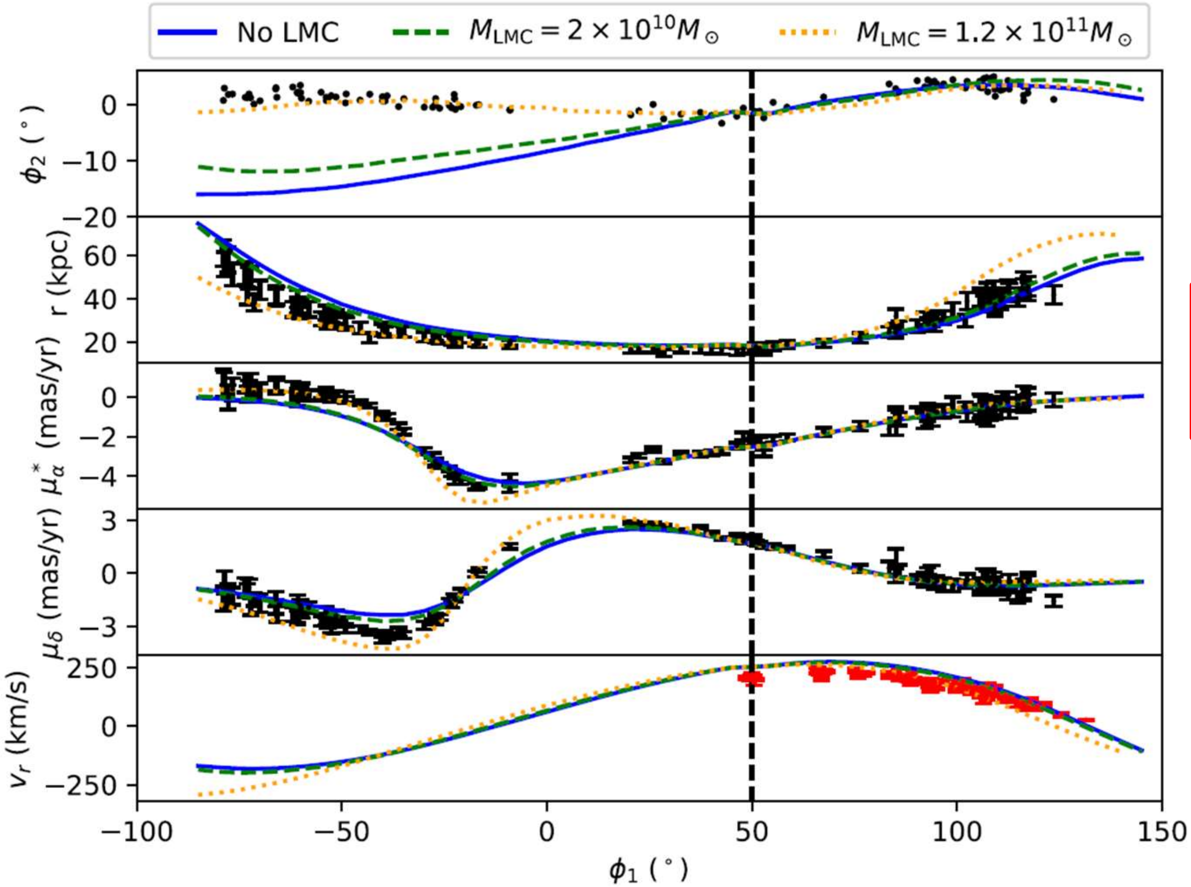
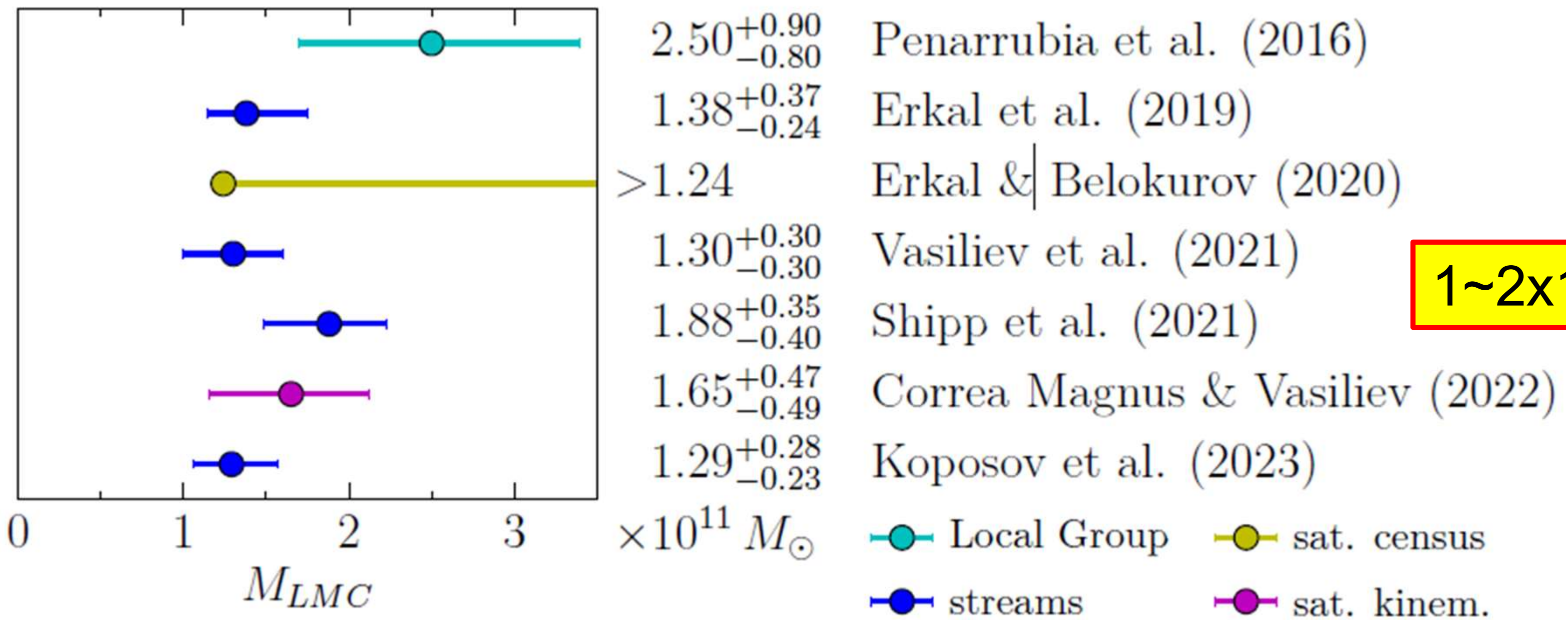


Best fit M_{LMC} ~ 1.38×10^{11} M_{sun}

An order of magnitude more massive than previously thought!

Recent determination of LMC's mass



$1 \sim 2 \times 10^{11}$ M_{sun}

Figure 1. LMC mass estimates from different methods: blue—perturbations inflicted on stellar streams; cyan—momentum balance in the Local Group; yellow—census of LMC satellites; magenta—kinematics of Milky Way satellites. From top to bottom: Peñarrubia et al. [32], Erkal et al. [33], Erkal and Belokurov [34], Vasiliev et al. [35], Shipp et al. [36], Correa Magnus and Vasiliev [37], Koposov et al. [38].

Vasiliev 2023

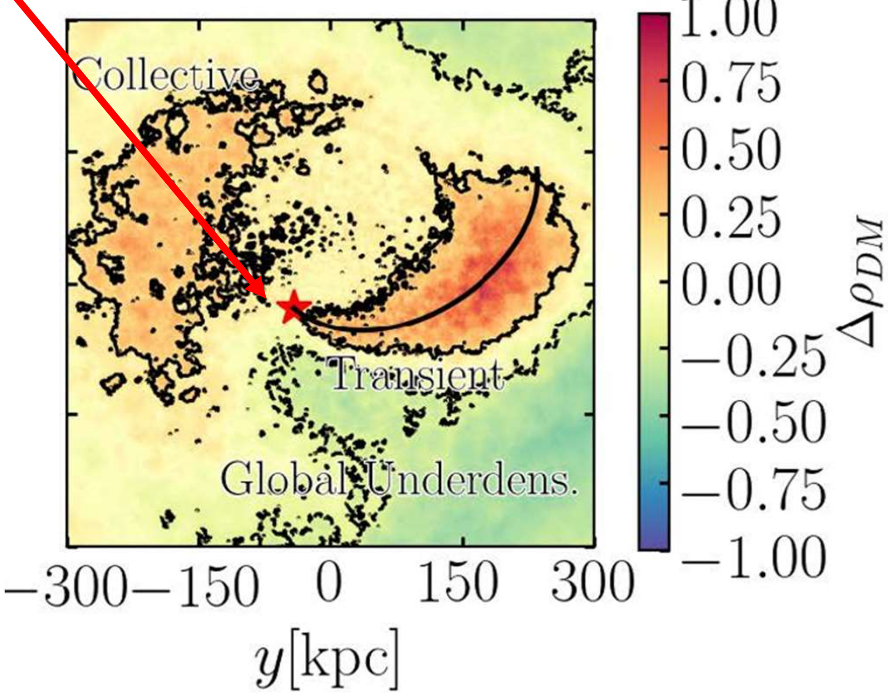
Wake effect of the massive LMC on MW's dark halo

If $M_{LMC} \sim 10^{11}\ M_{sun} \sim 1/10\ M_{MW}$

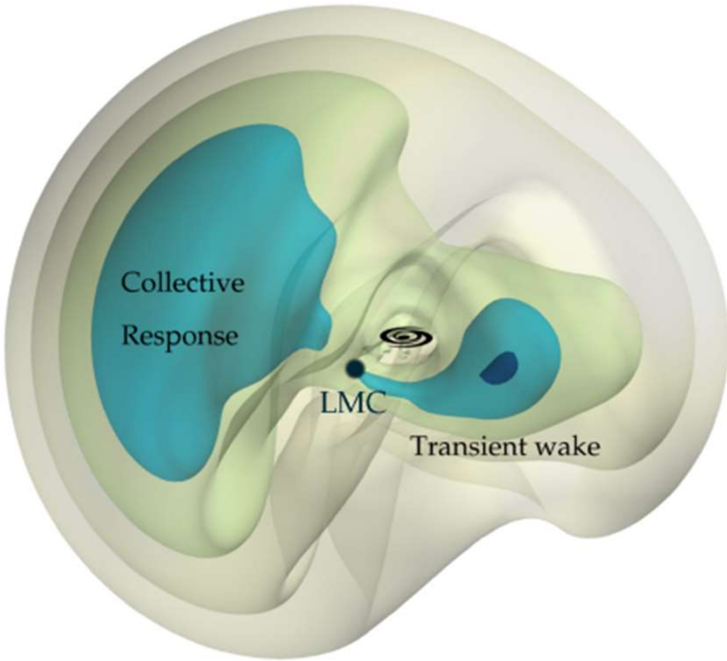
LMC

Effects on dark matter distribution in MW

Garavito-Camargo et al. 2019

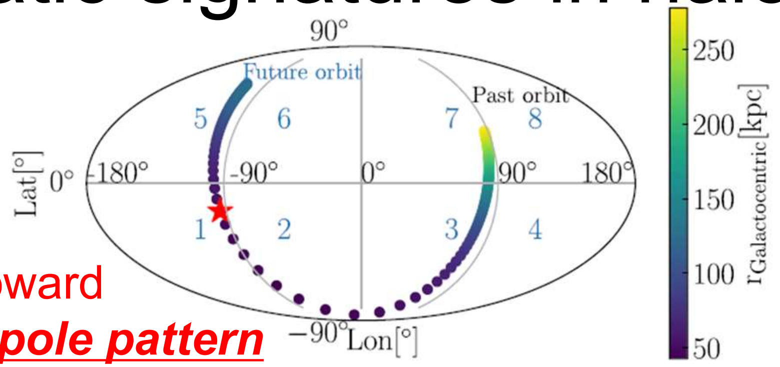


Garavito-Camargo et al. 2021

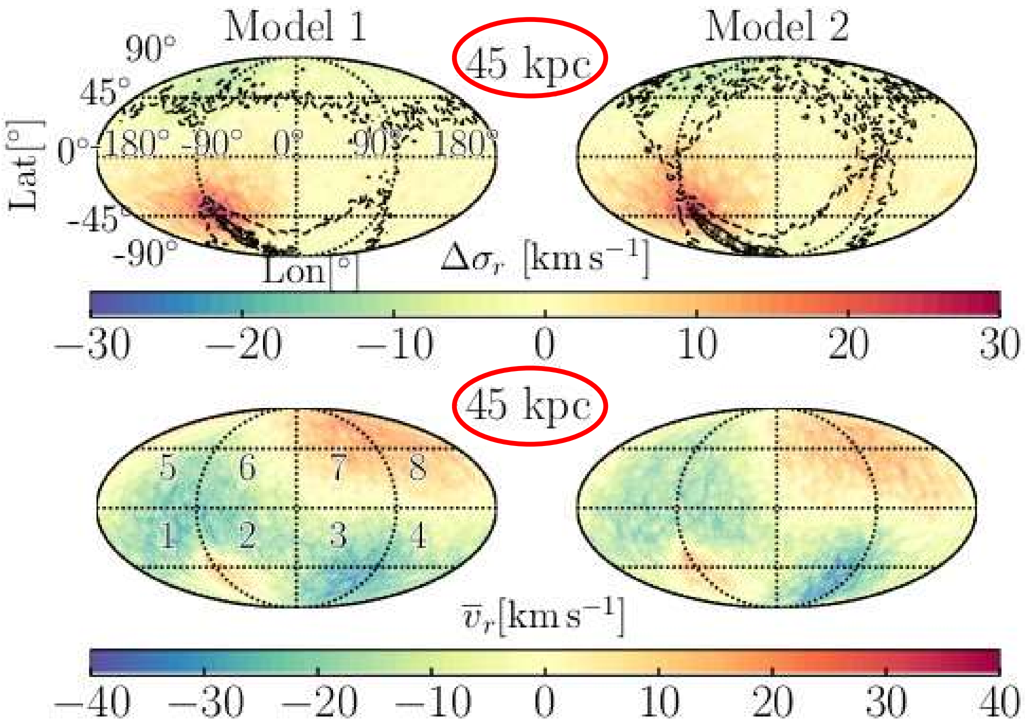


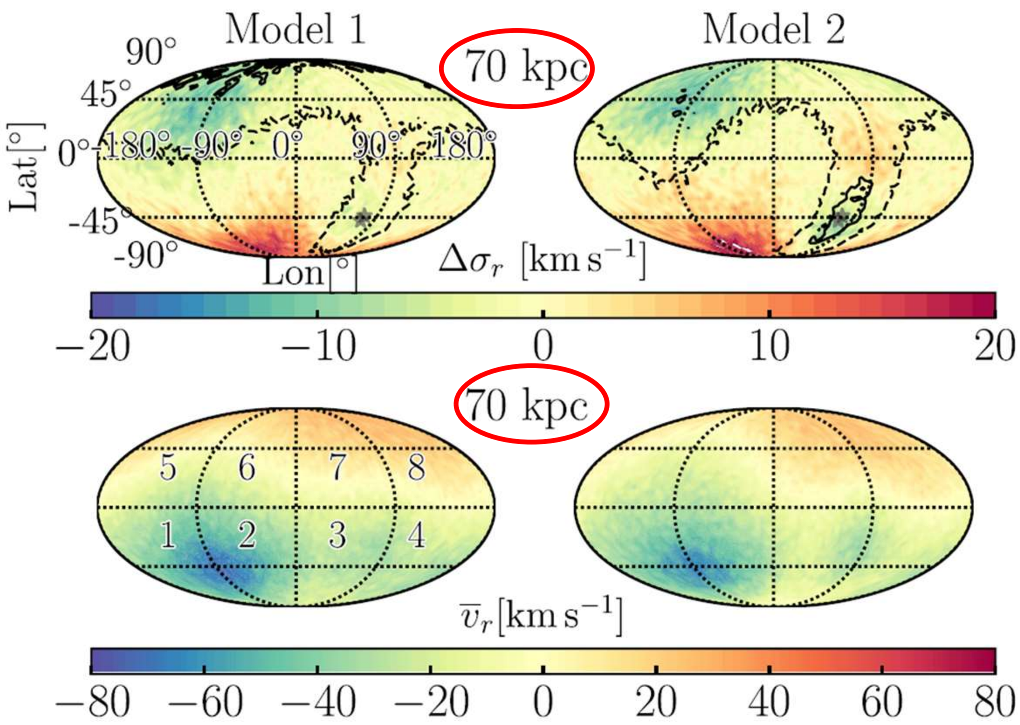
Kinematic signatures in halo stars

$\overline{v}_r$



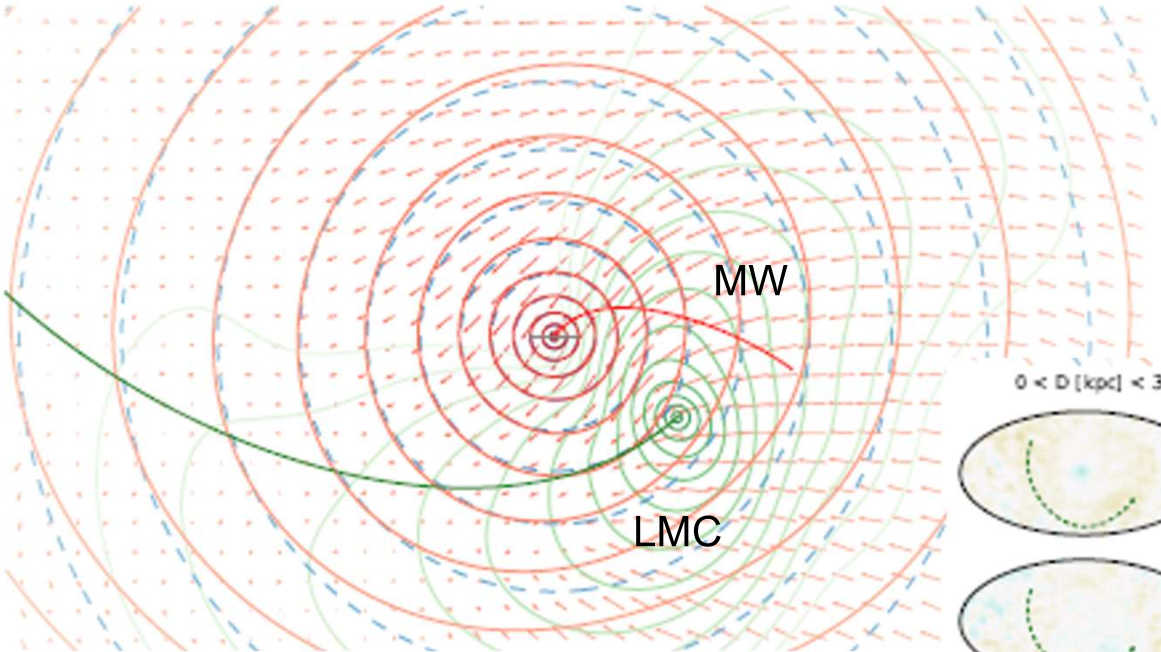
The reflex of the disk motion toward
the LMC at its pericenter -> ***dipole pattern***

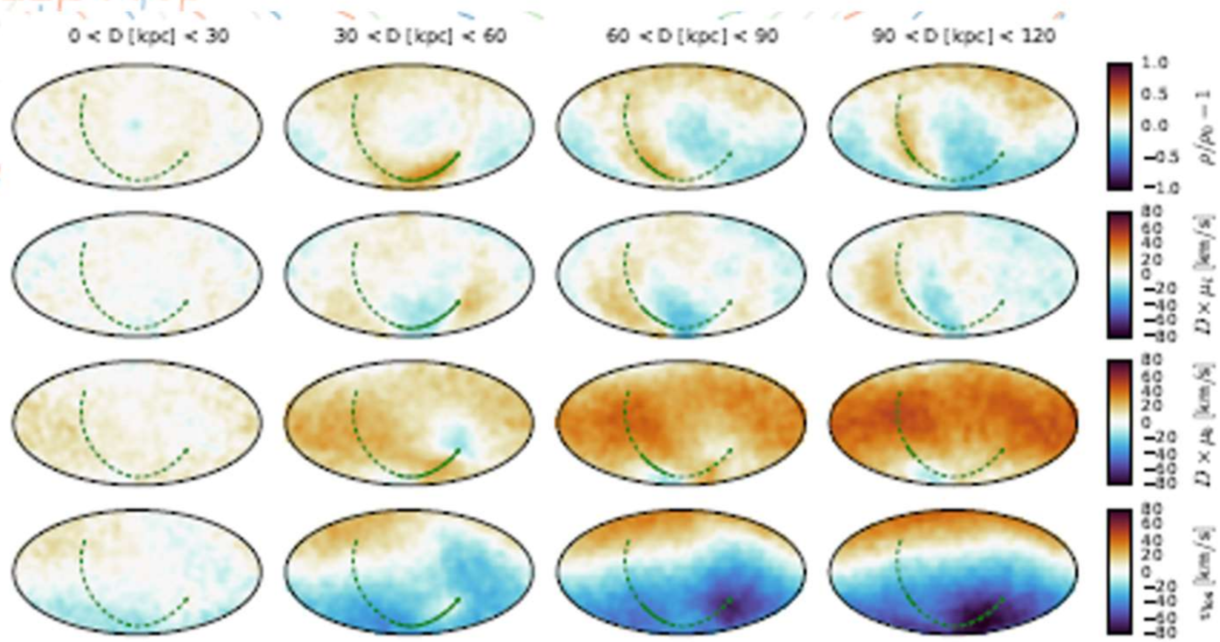




LMC effect on the MW

Vasiliev (2023)





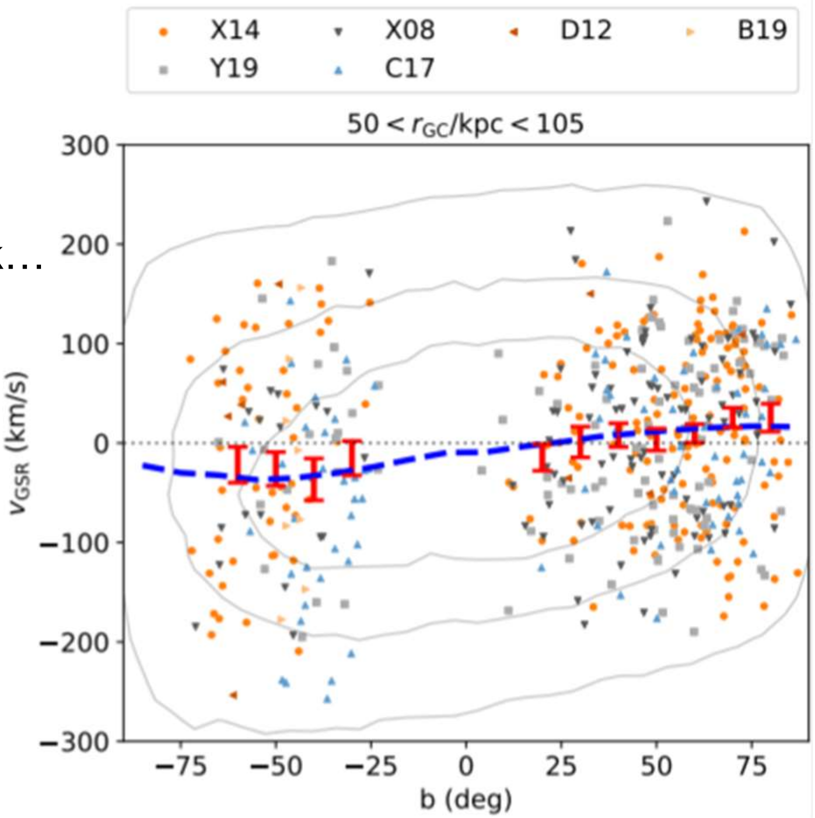
Dipole pattern in Vr

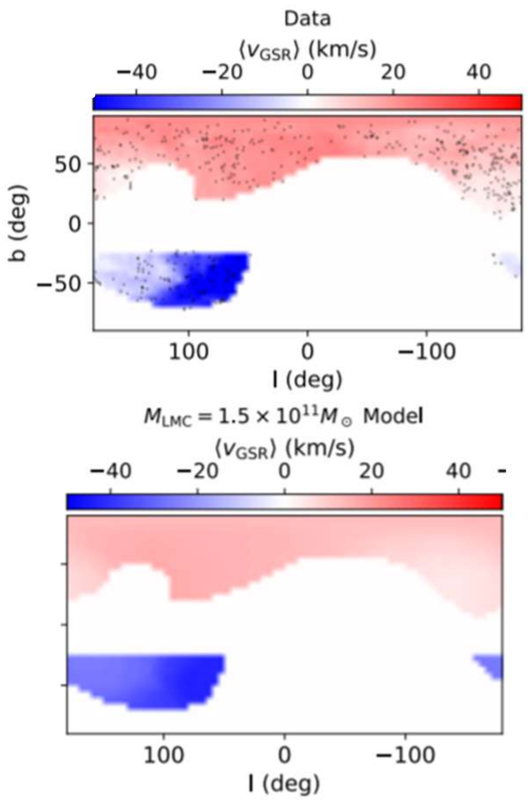
Detection of the LMC-induced sloshing of the Galactic halo Erkal et al. 2021

Table 1

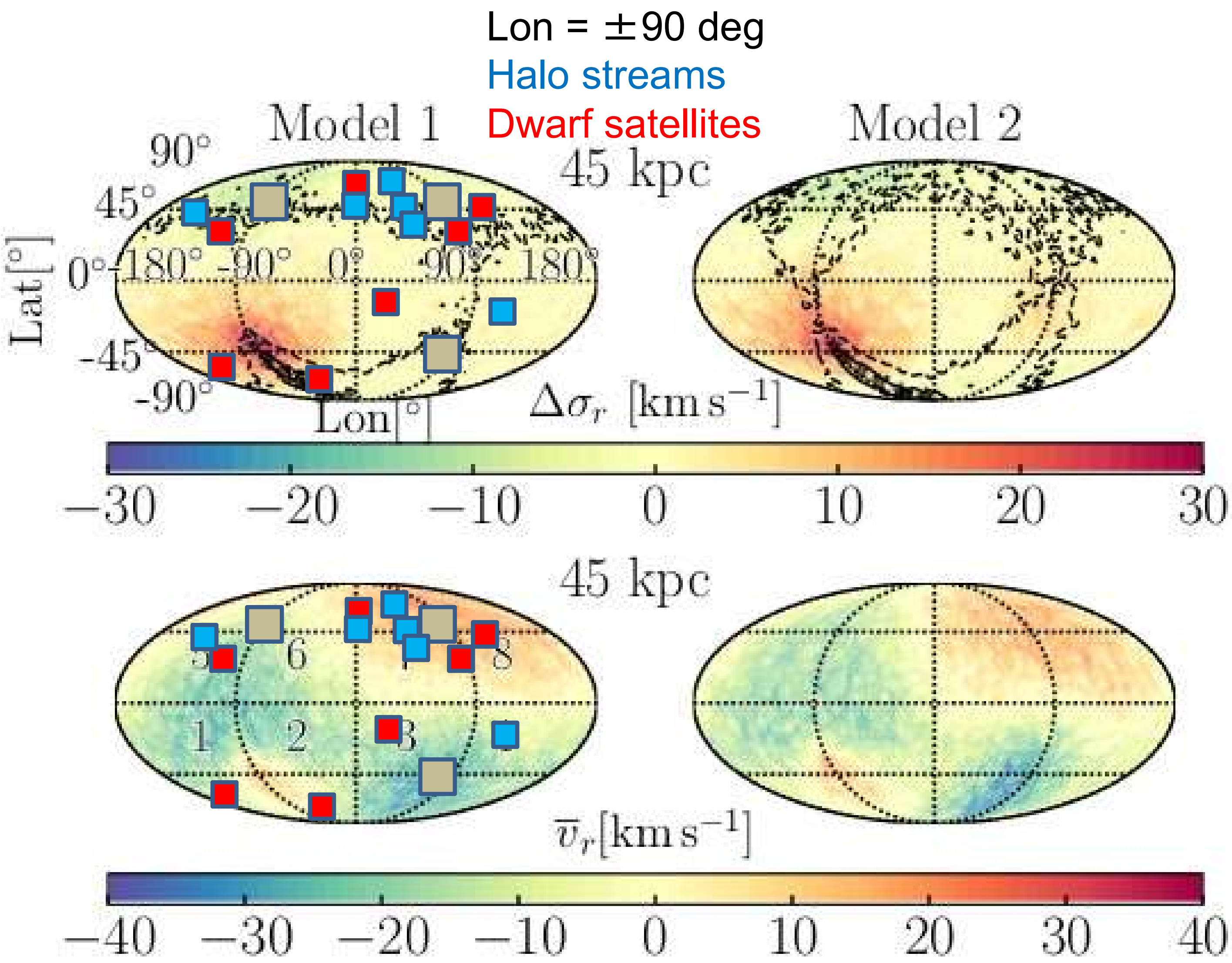
Sample	Star type	$50 < r_{GC}/(\mathrm{kpc}) < 105$	Astrometric cuts	Sgr cuts	$\langle v_{GSR} \rangle_{b<0°}$ (km/s)	$\langle v_{GSR} \rangle_{b>0°}$ (km/s)
Xue et al. (2014)	K-giants	280	275	189	-9.4 ± 15.1	16.1 ± 7.1
Yang et al. (2019)	K-giants	301	171	101	-6.3 ± 21.8	4.1 ± 9.9
Xue et al. (2008)	BHB/BS	123	113	99	-30.8 ± 21.3	11.3 ± 9.8
Cohen et al. (2017)	RR Lyrae	111	88	86	-66.7 ± 16.8	2.9 ± 10.5
Deason et al. (2012b)	BHB/BS	23	22	9	–	–
Belokurov et al. (2019)	BHB	8	8	8	–	–

Signal is yet weak…





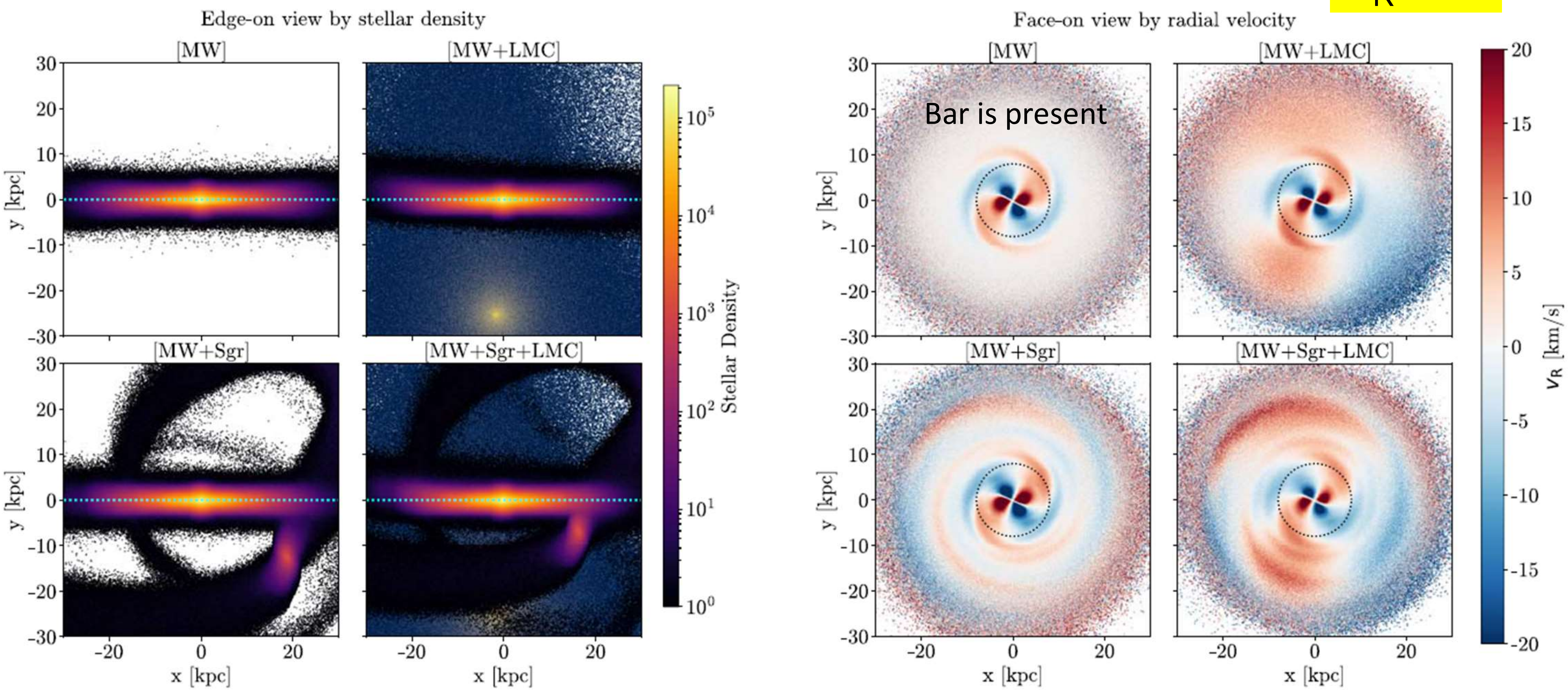
PFS survey for the wake in halo stars



Impact of LMC & Sgr on the disk

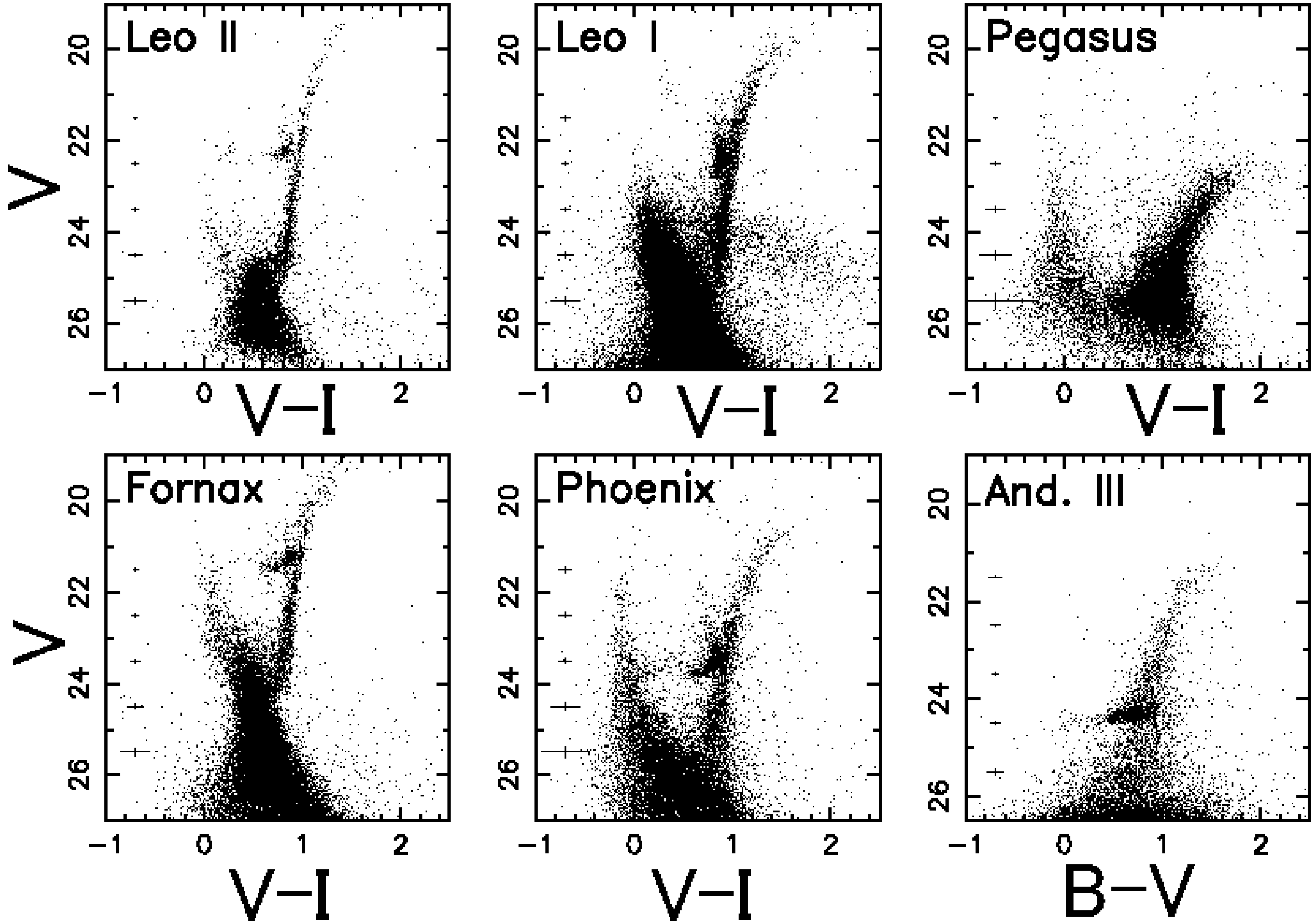
Stelea, Hunt & Johnston 2024

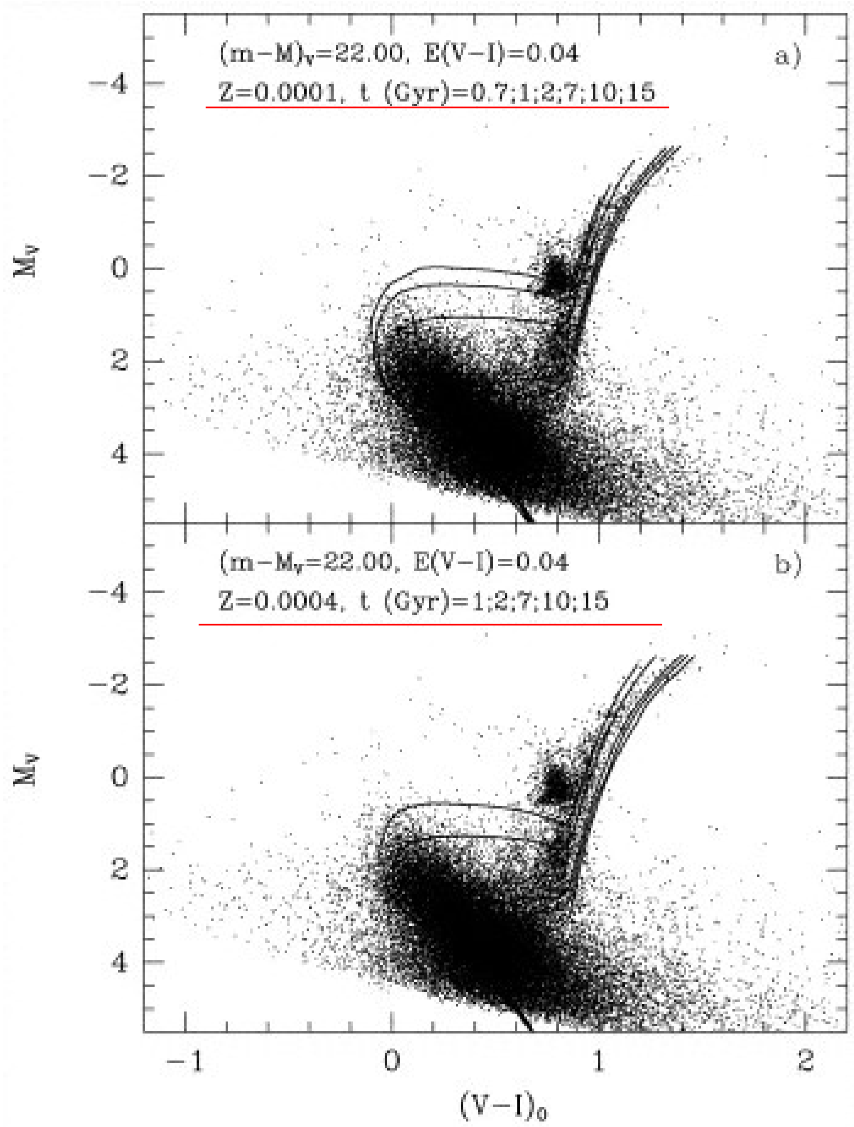
V_R field



6.3 Formation of satellite galaxies

HST photometry of satellite galaxies





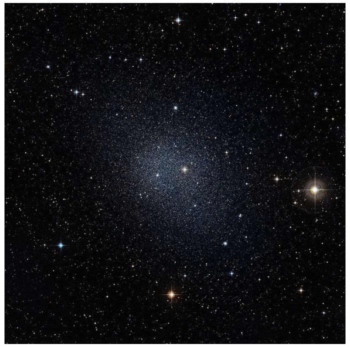
Leo I @ D=260kpc

Low SFR
lasting over ~10Gyr

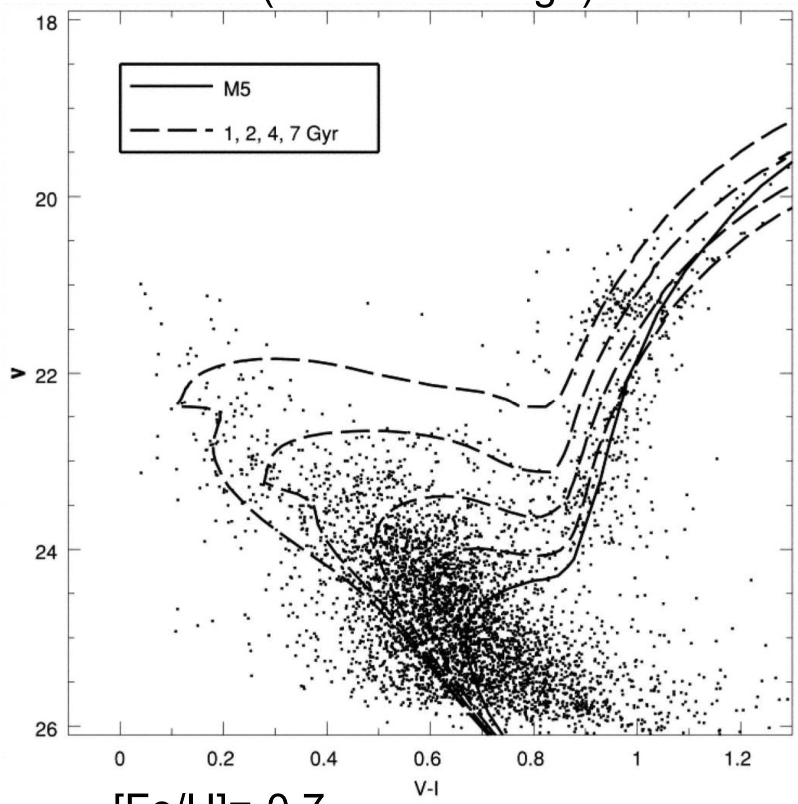
Metallicity & Age
are degenerated

Spectroscopy

Fornax @ D=138 kpc

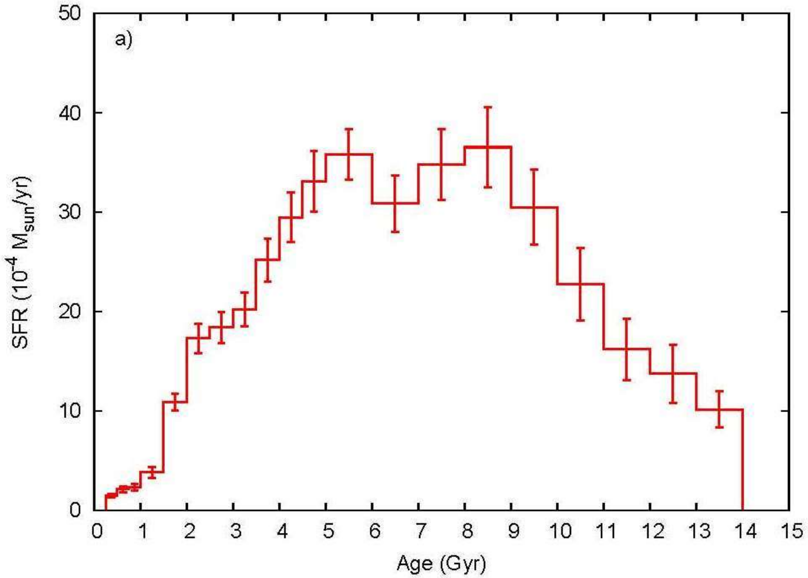


Buonanno+ 1999
(from HST image)



[Fe/H]=-0.7

de Boer+2012
(from CTIO image)



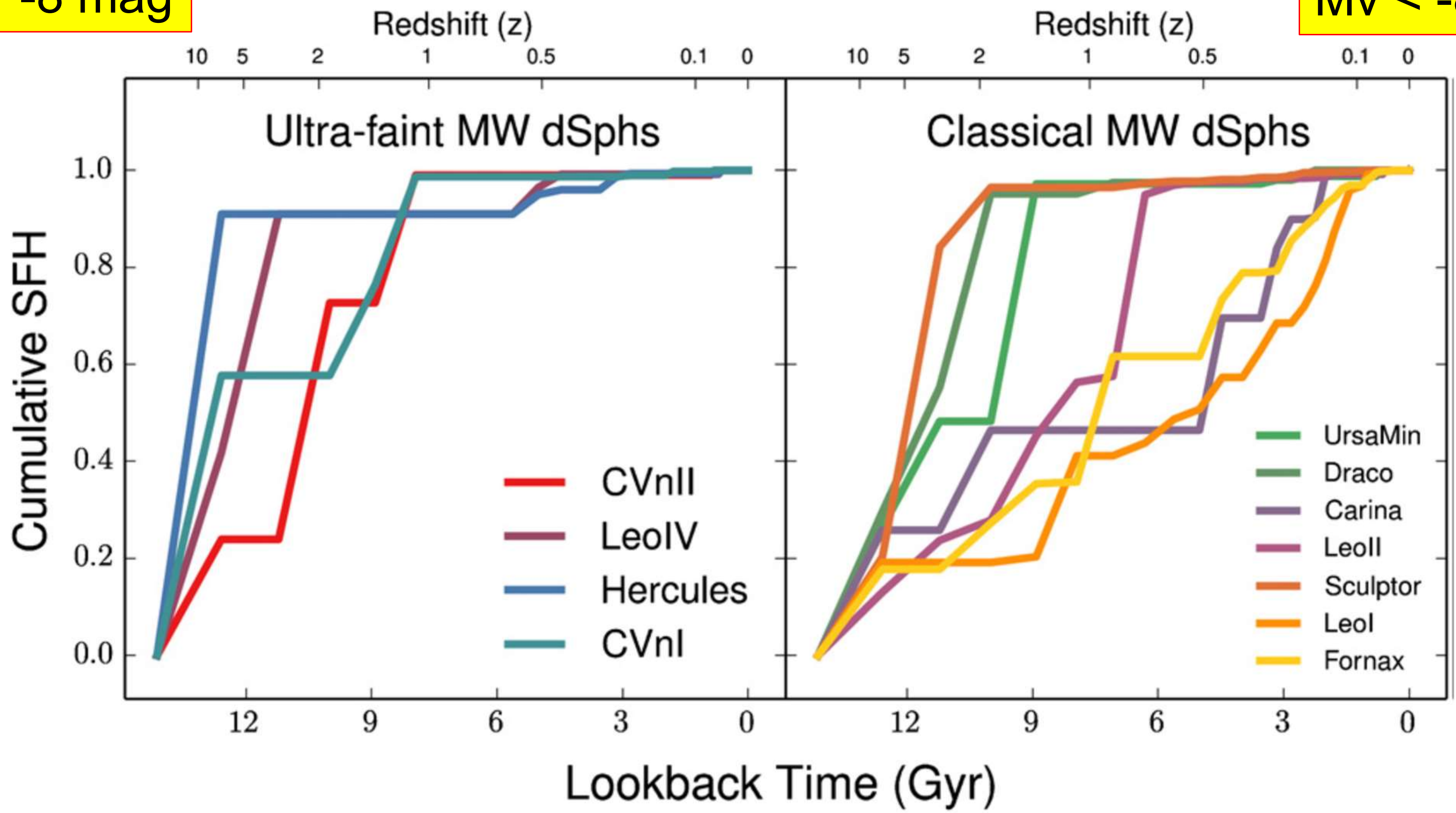
HST/WFPC2 results

(Weisz et al. 2014)

Varieties in SF histories

Mv > -8 mag

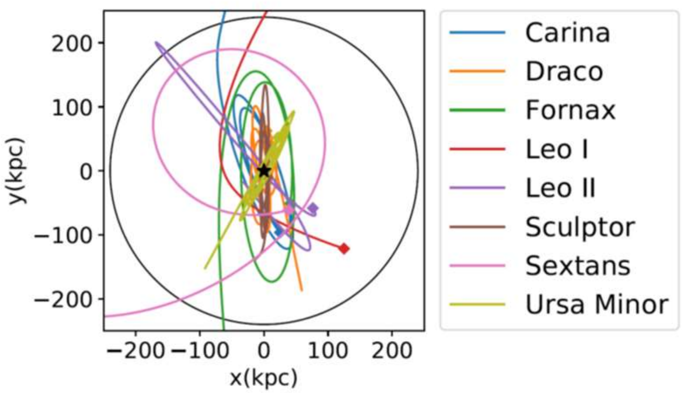
Mv < -8 mag



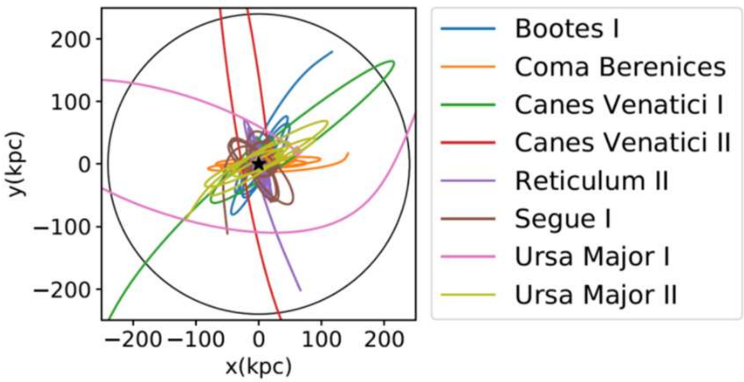
Long-term orbital motions of Galactic satellites in the growing mass of the Galactic halo
(Miyoshi & Chiba 2020)

Orbits using Gaia DR2

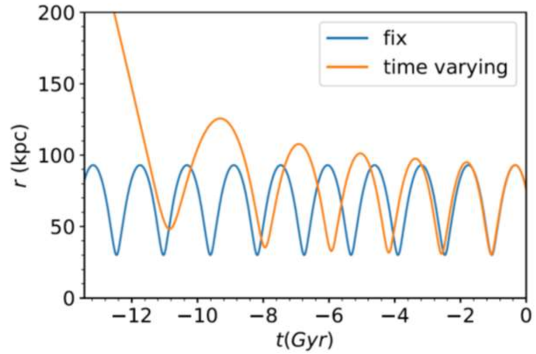
Classical dSphs (M_V < -8)



UFDs (M_V > -8)

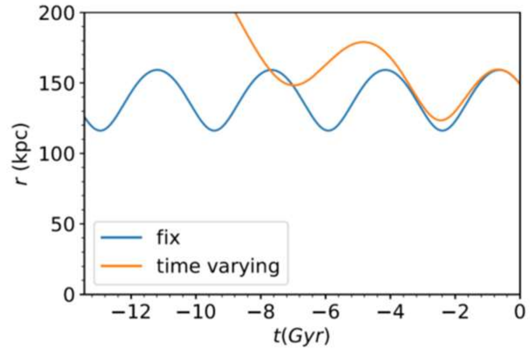


Draco



Look back time

Fornax



Look back time

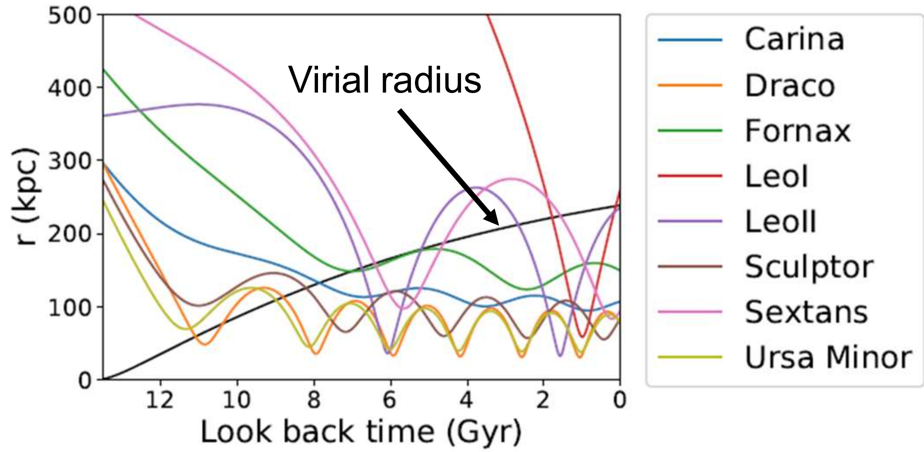
Comparison between a fixed and evolving MW potential

(different at t > 4 Gyr)

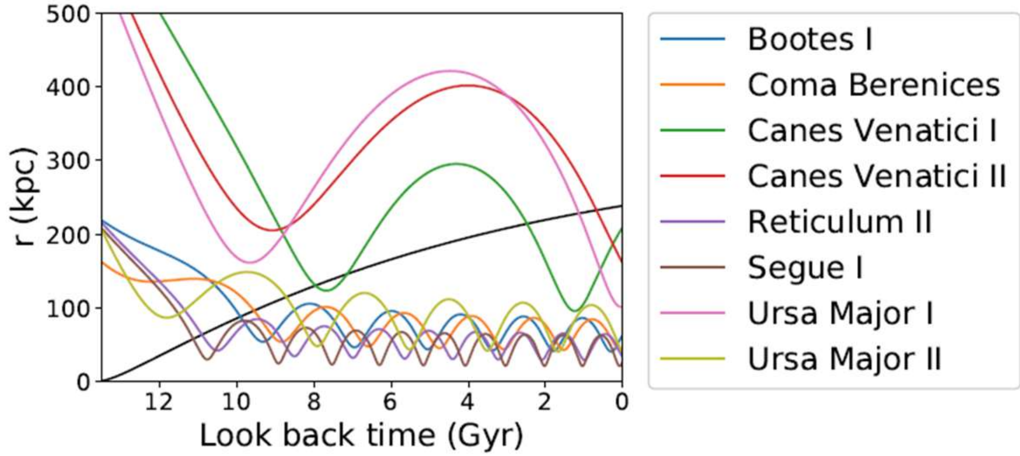
Long-term orbital motions of Galactic satellites in the growing mass of the Galactic halo

(Miyoshi & Chiba 2020)

Classical dwarfs
($M_V < -8$)



Ultra-faint dwarfs
(UFDs)
($M_V > -8$)



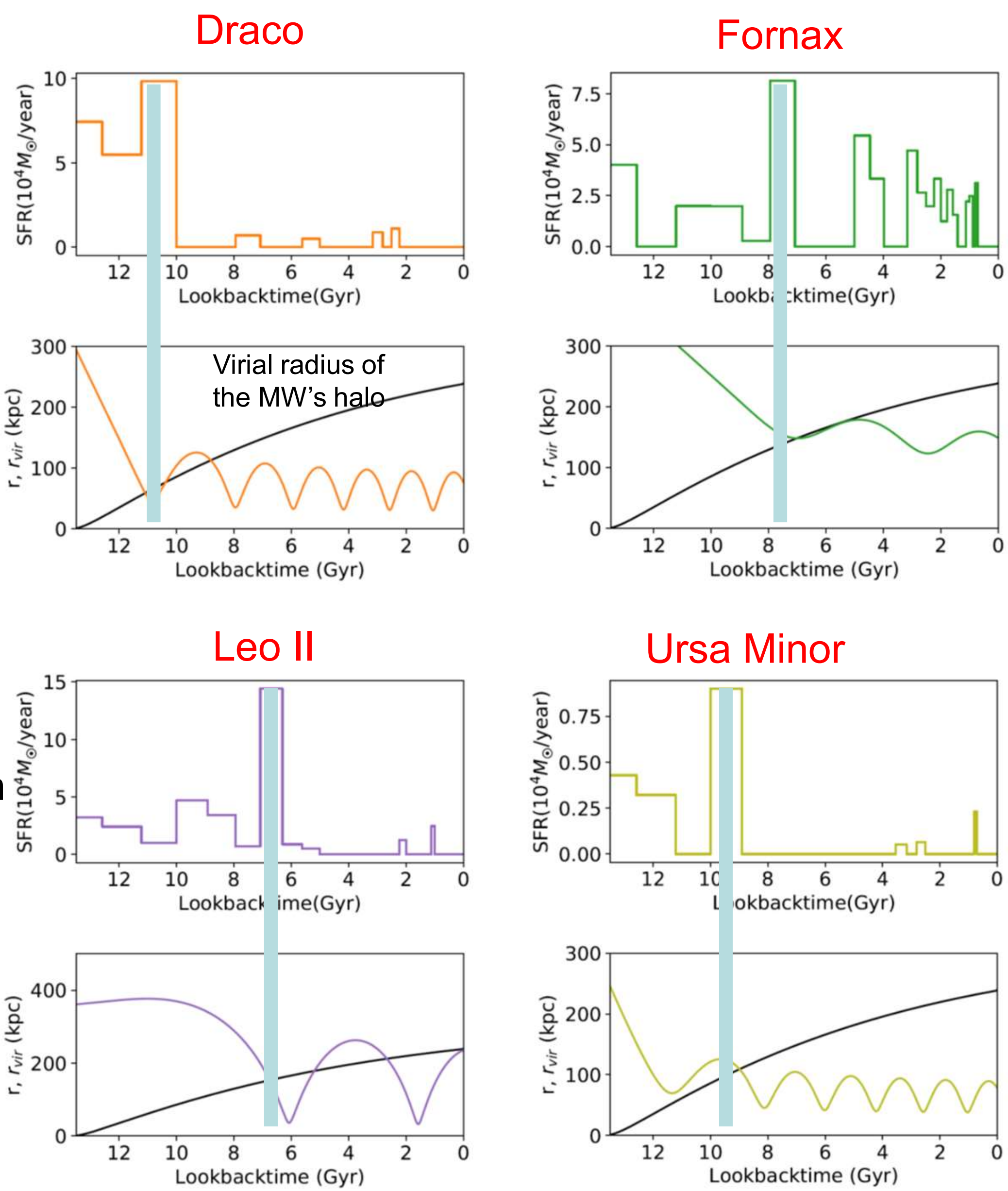
Miyoshi & Chiba 2020

Star formation history

Orbital evolution

Star formation history

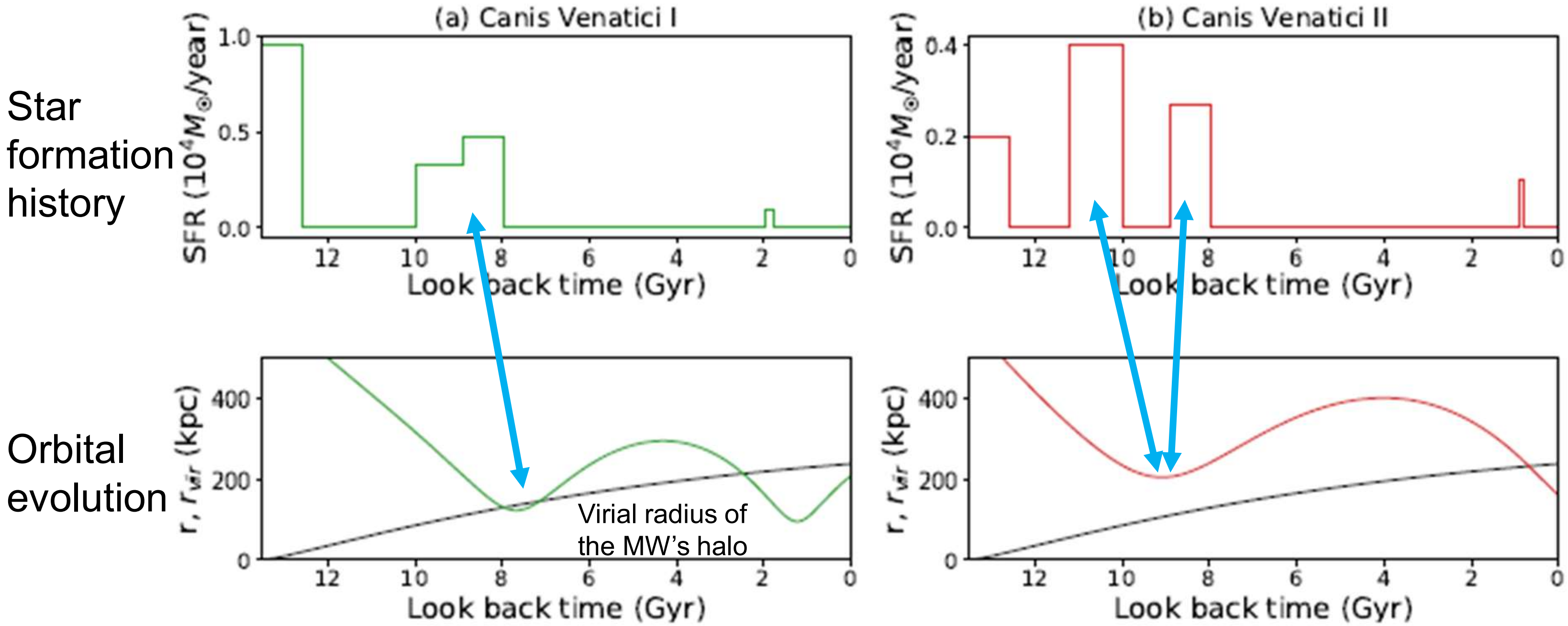
Orbital evolution



First infall time crossing virial radius = time of SF peak
(Star formation trigged by tidal effect + ram-pressure)

UFDs

Miyoshi & Chiba 2020



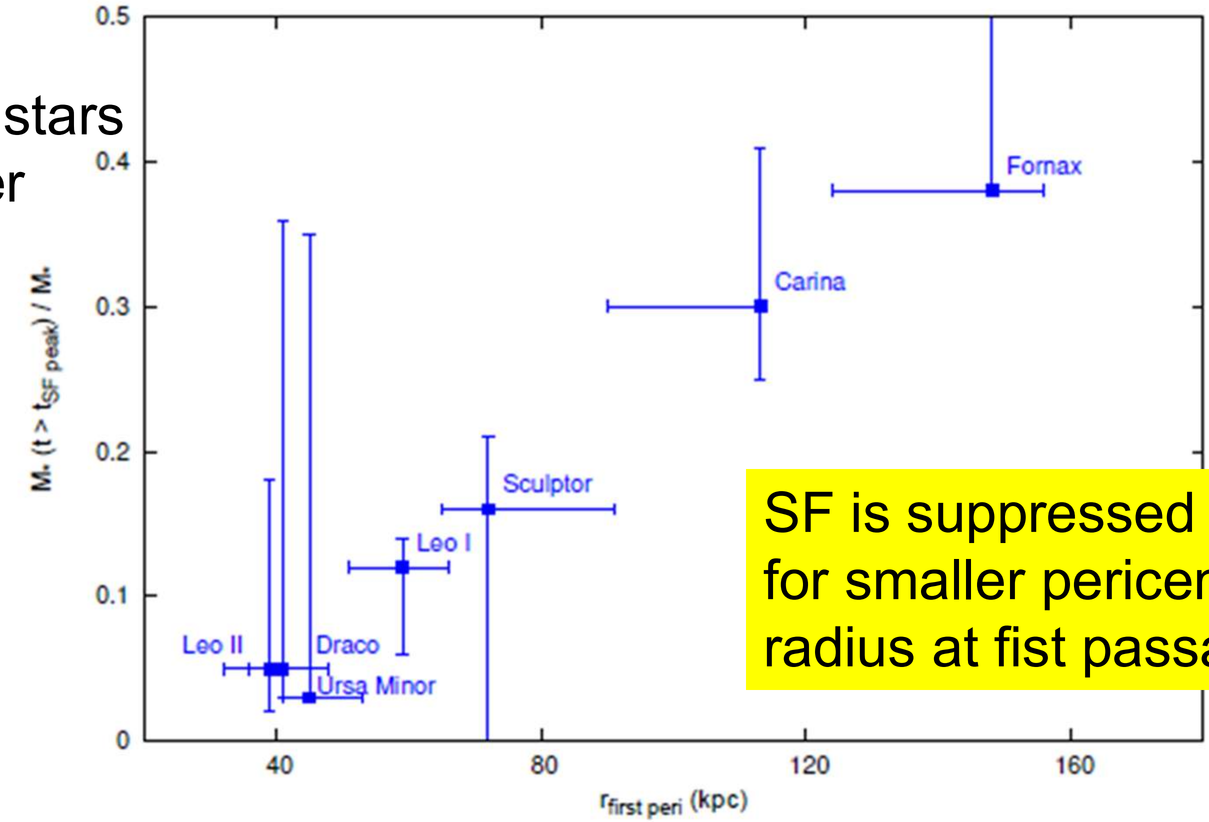
- 1st SF ended before the 1st infall and 2nd/3rd SF can be related to the infall
- What is the relation with r-process element production?

Satellites’ orbits vs. SF histories

~ evidence for environmental effects ~

Miyoshi & Chiba 2020

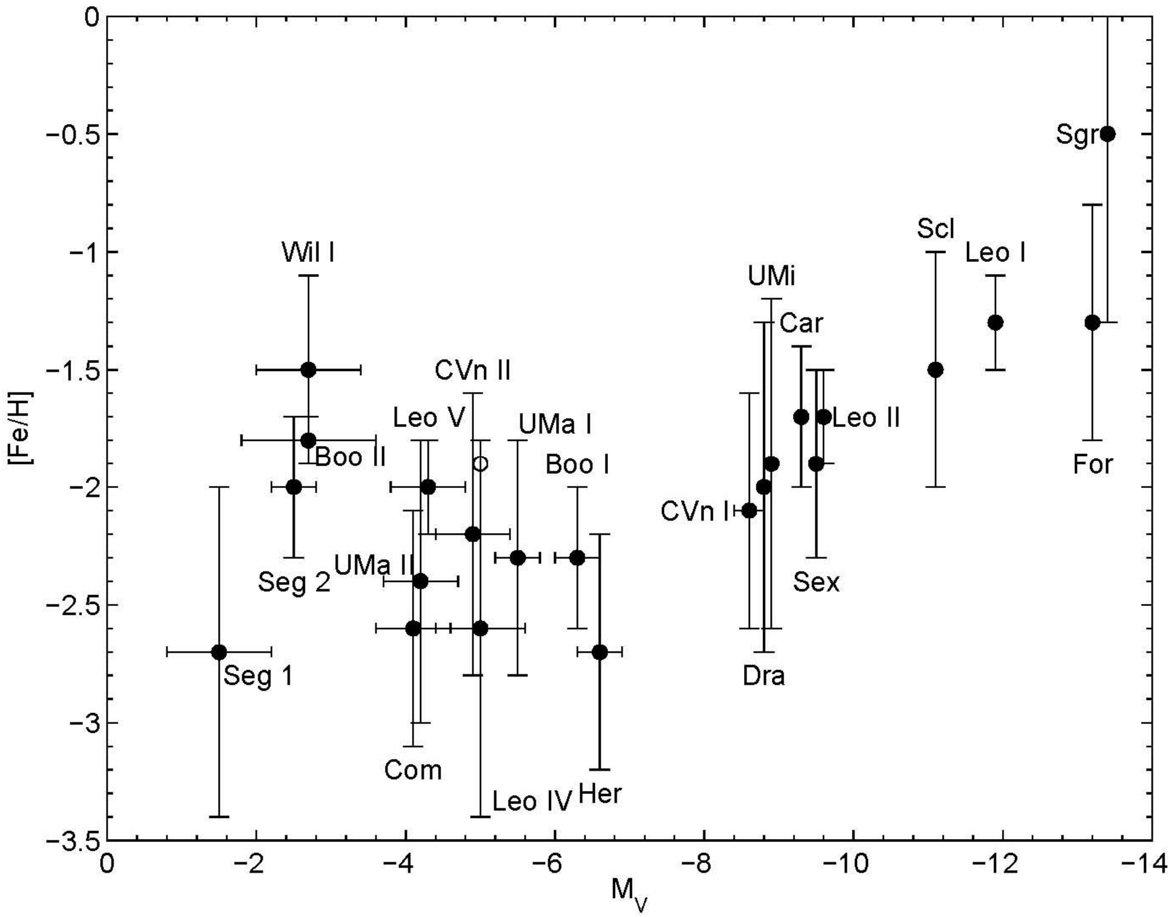
Fraction of stars formed after SF peak



SF is suppressed more for smaller pericentric radius at fist passage

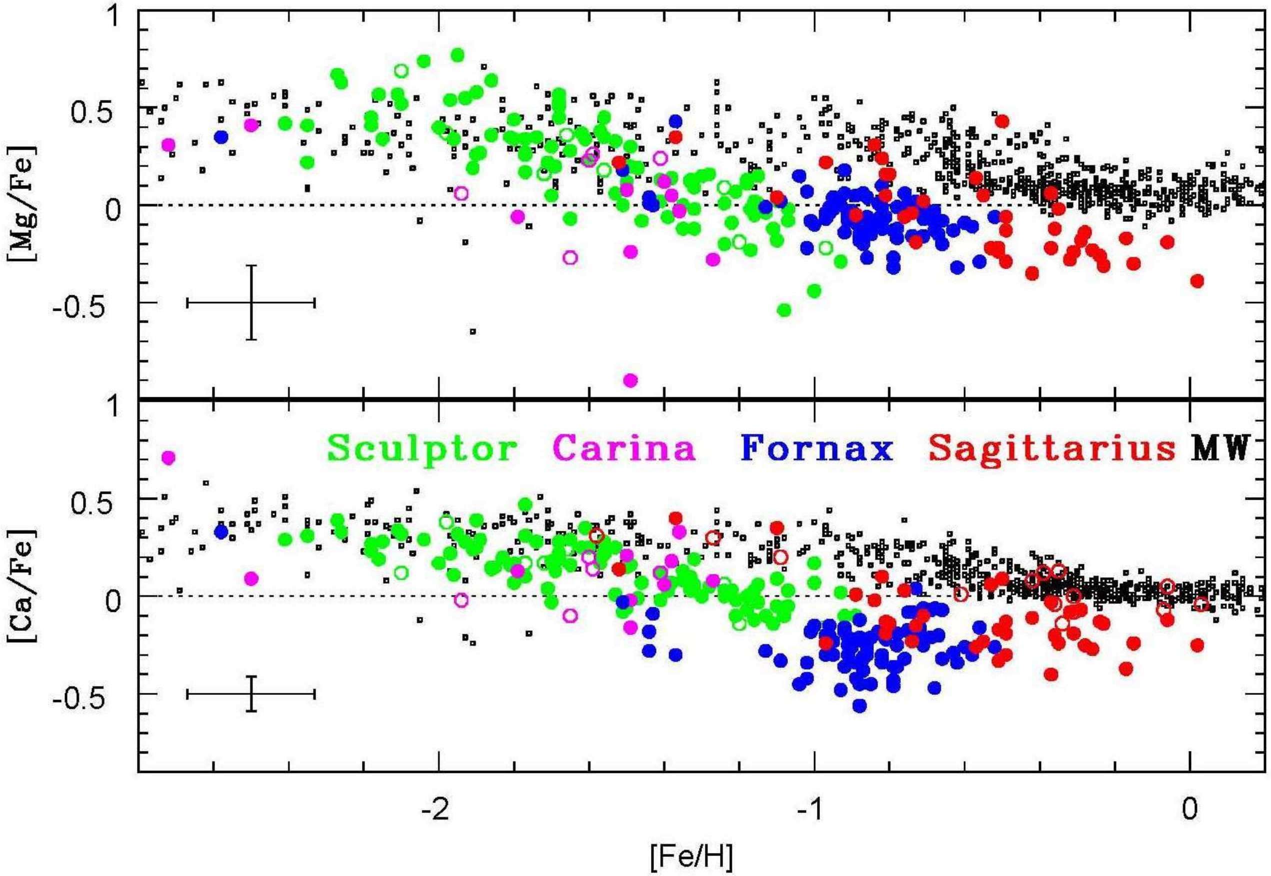
Pericenter at first passage (kpc)

Metallicity vs. luminosity relation



UFDs appear to show different metallicities

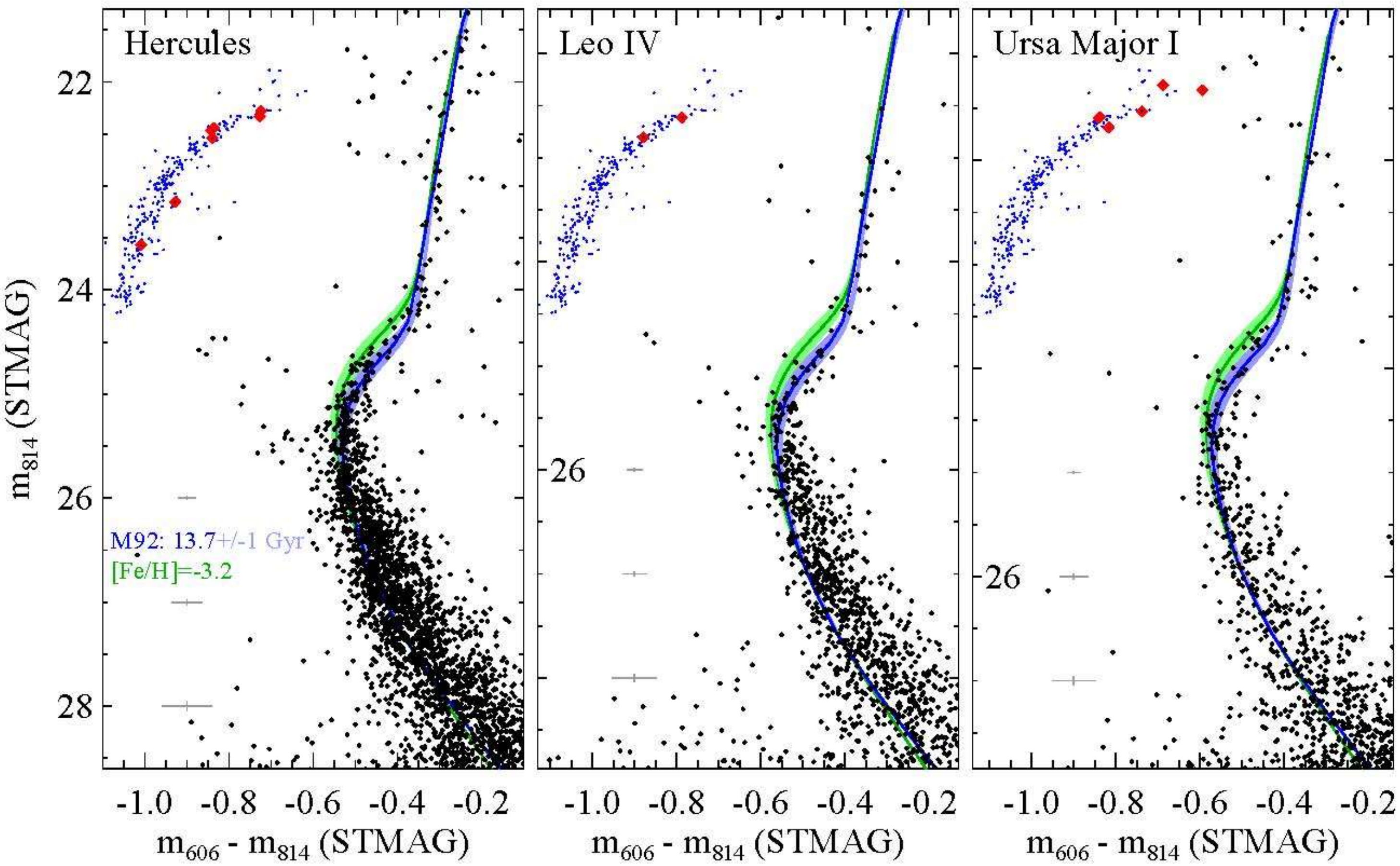
[α/Fe] ratios in several classical dSphs (Tolstoy+ 2009)



List of known UFD galaxies

名前	M_V [mag]	$D_\odot$ [kpc]	r_h [pc]	L_V [$L_\odot$]	$\langle[\mathrm{Fe/H}]\rangle$ [dex]
CVn I	−8.6	218	564	2.3×10^5	−2.08
Her	−6.6	132	330	3.6×10^4	−2.58
Boo I	−6.3	66	242	3.0×10^4	−2.55
UMa I	−5.5	97	318	1.4×10^4	−2.29
Leo IV	−5.0	160	116	8.7×10^3	−2.58
CVn II	−4.9	160	74	7.9×10^3	−2.19
UMa II	−4.2	30	140	4.0×10^3	−2.44
Com	−4.1	44	77	3.7×10^3	−2.53
Boo II	−2.7	42	51	1.0×10^3	−1.79
Wil 1	−2.7	38	25	1.0×10^3	−2.19
Seg 2	−2.5	35	34	900	−2.26
Seg 1	−1.5	23	29	335	−2.72

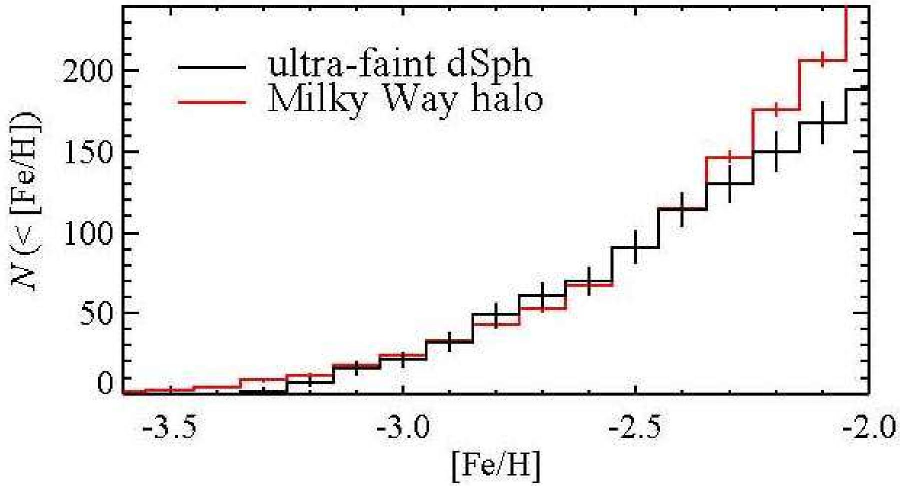
HST results by Brown+2012
UFDs are very old systems (as old as M92)



Synchronization of SF truncation within ~1 Gyr ?

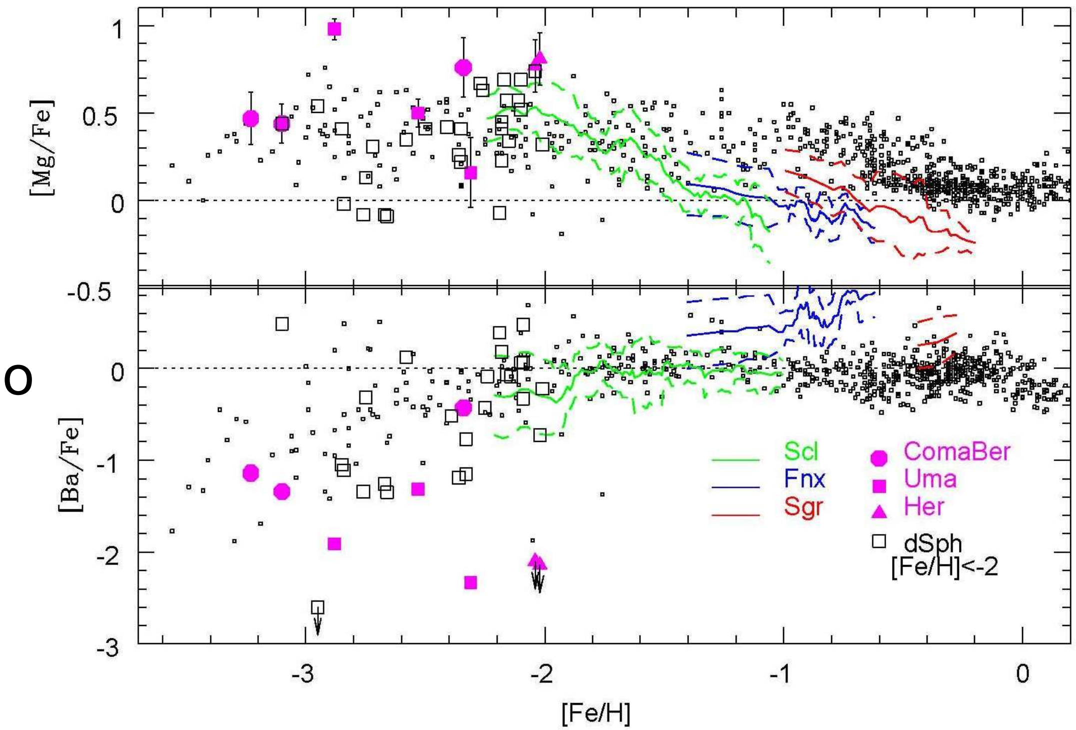
Kirby+ 08

Assembly of the stars in ultra-faint dwarf galaxies reproduces the MW halo



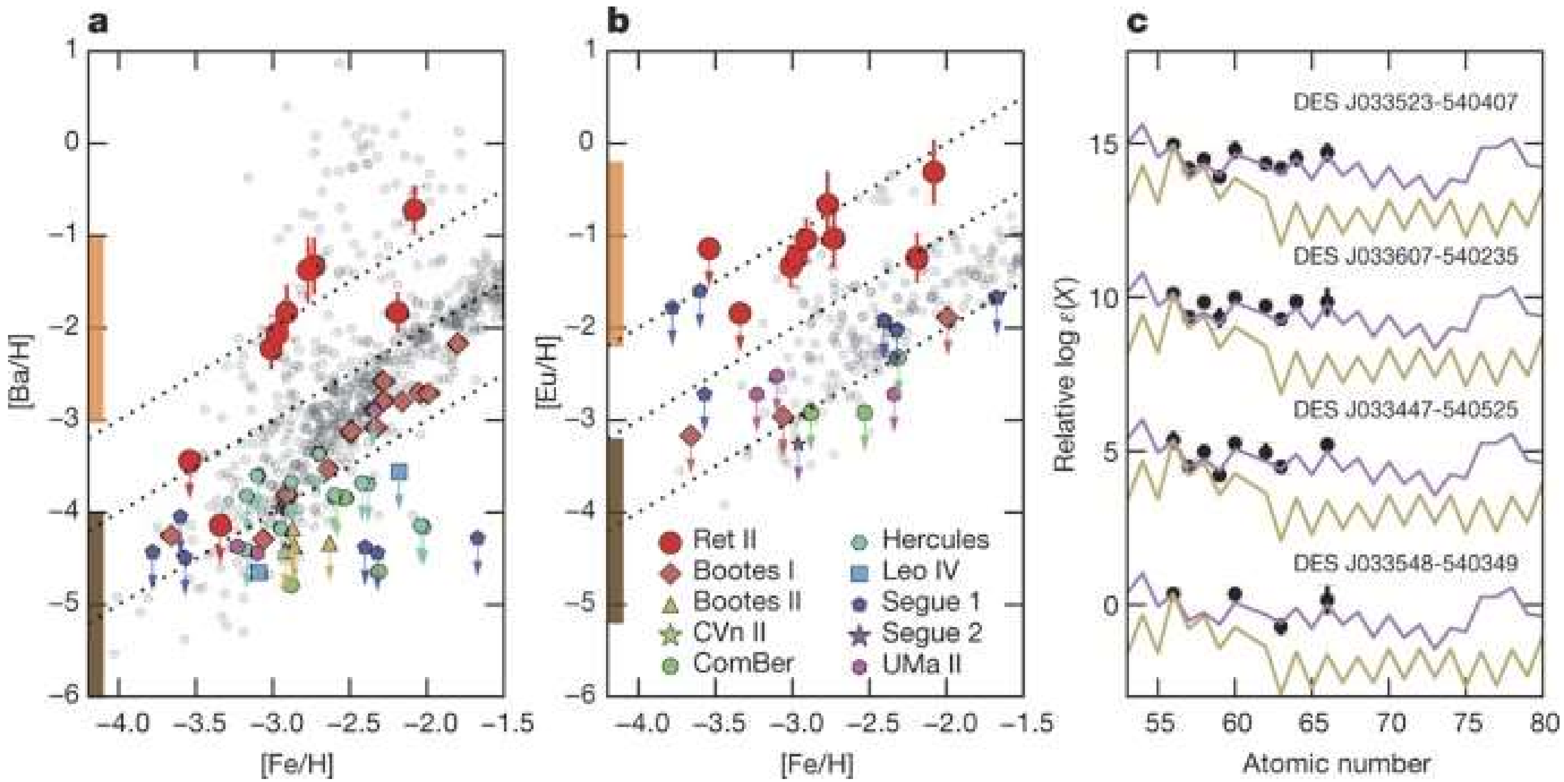
Tolstoy +08

UFDs show similar abundance pattern to the metal-poor MW halo



R-process enrichment in UFDs

Reticulum II: Ji et al. (2016)



Solar r-process
Solar s-process

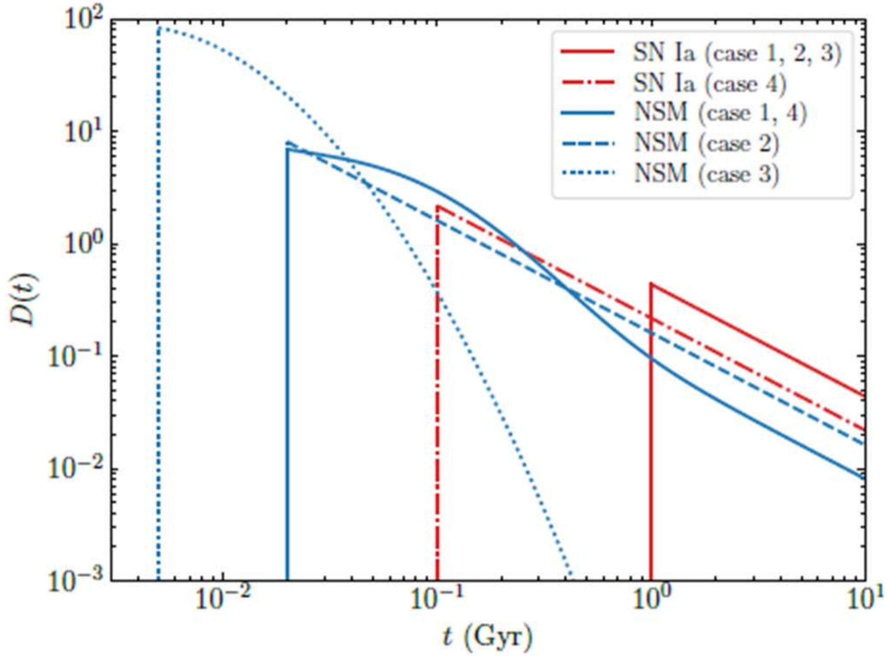
An event of NS mergers is suggested.

NS mergers and chemical evolution

Wanajo, Hirai, Prantzos (2021)
Chemical evolution of halo building blocks

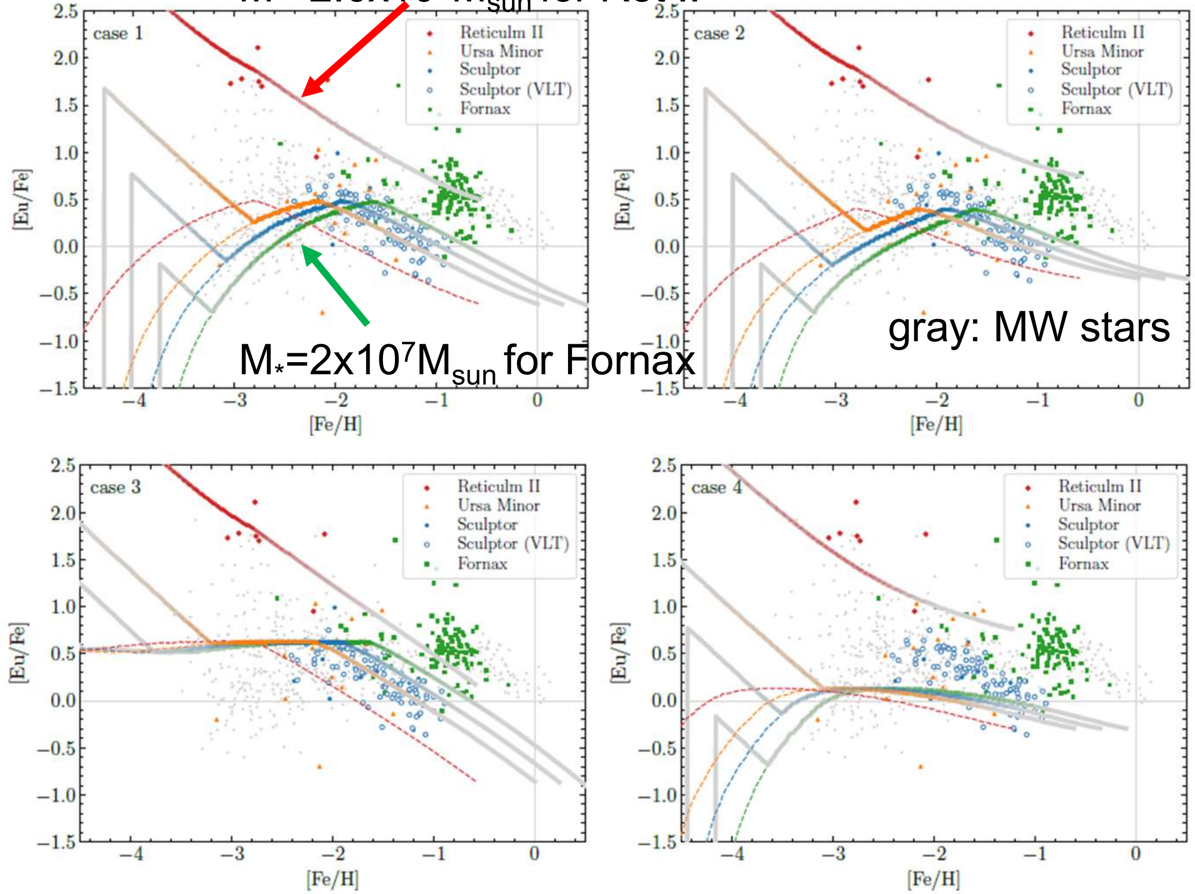
[Eu/Fe]>1 stars originate from building blocks with $M_* < 10^5 M_{sun}$

Delay time distribution



NSMs with delay time of 0.1 Gyr for
> 50 % can reproduce the observation

$M_* = 2.6 \times 10^3 M_{sun}$ for Ret II



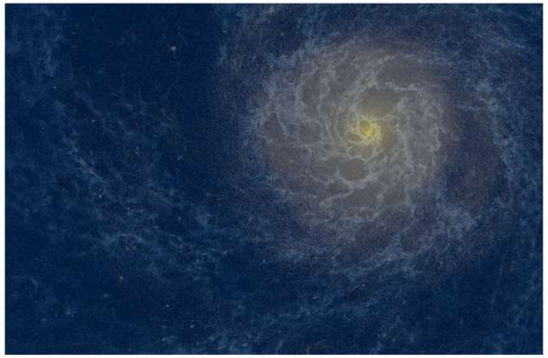
$M_* = 2 \times 10^7 M_{sun}$ for Fornax

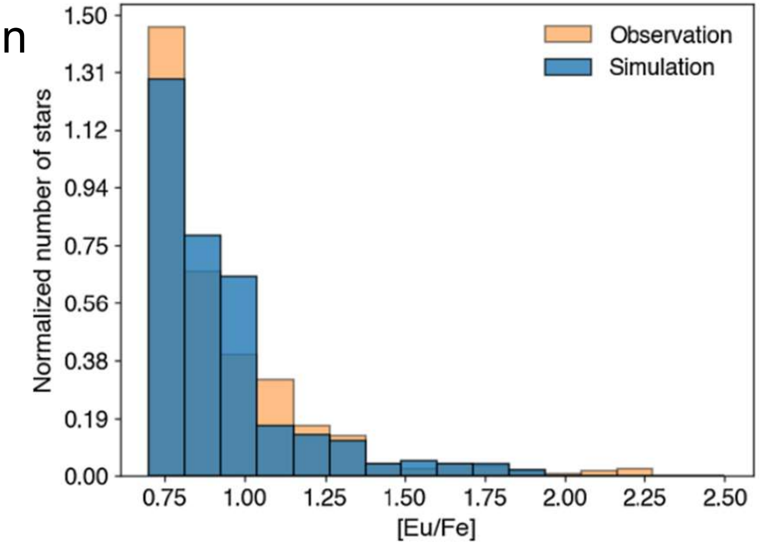
gray: MW stars

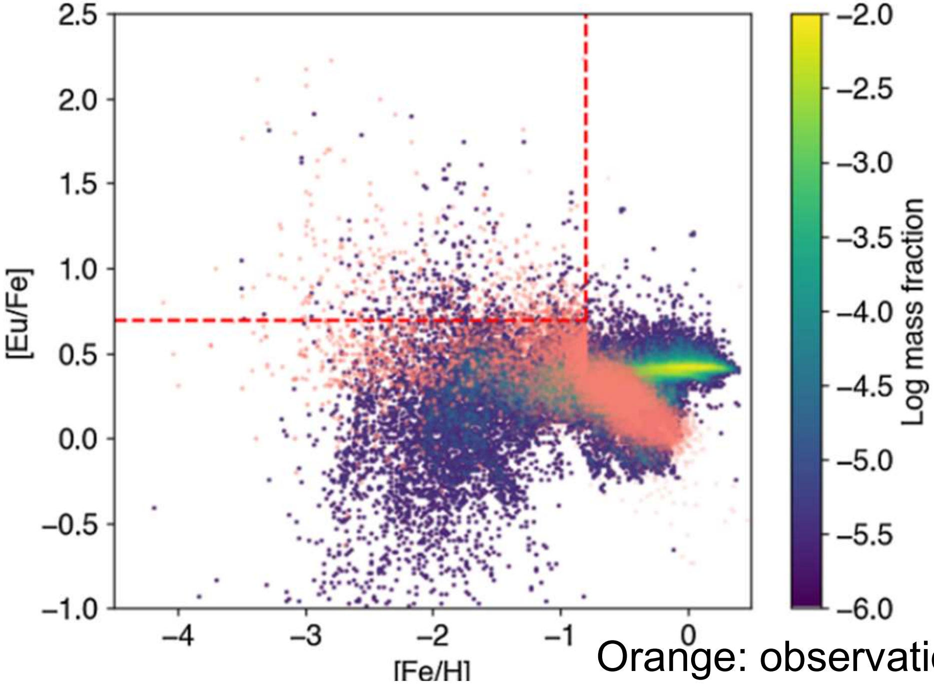
Cosmological zoom-in simulation for galaxy formation and origin of r-process enhanced stars

Hirai, Beers, Chiba, et al. (2022)

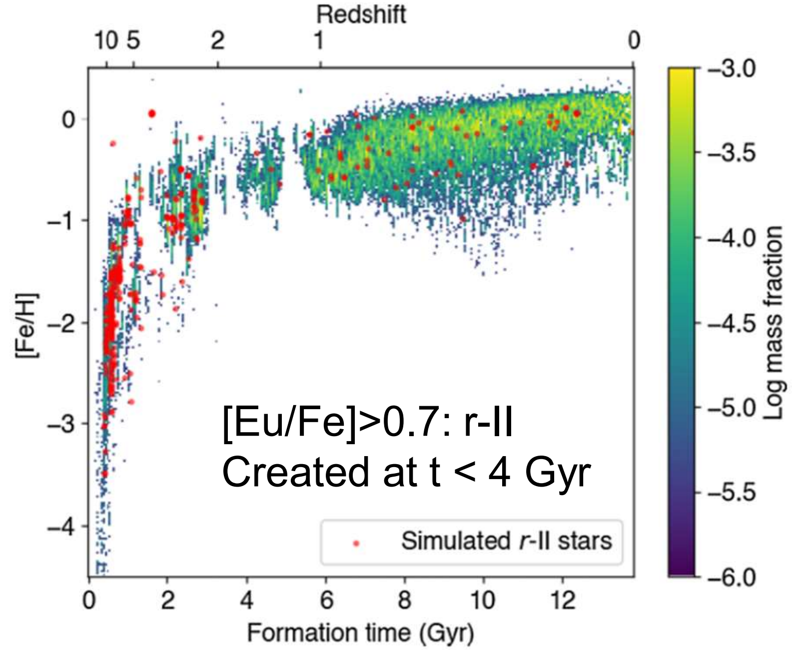
UFD galaxy as a site of r-process enrichment







Orange: observation

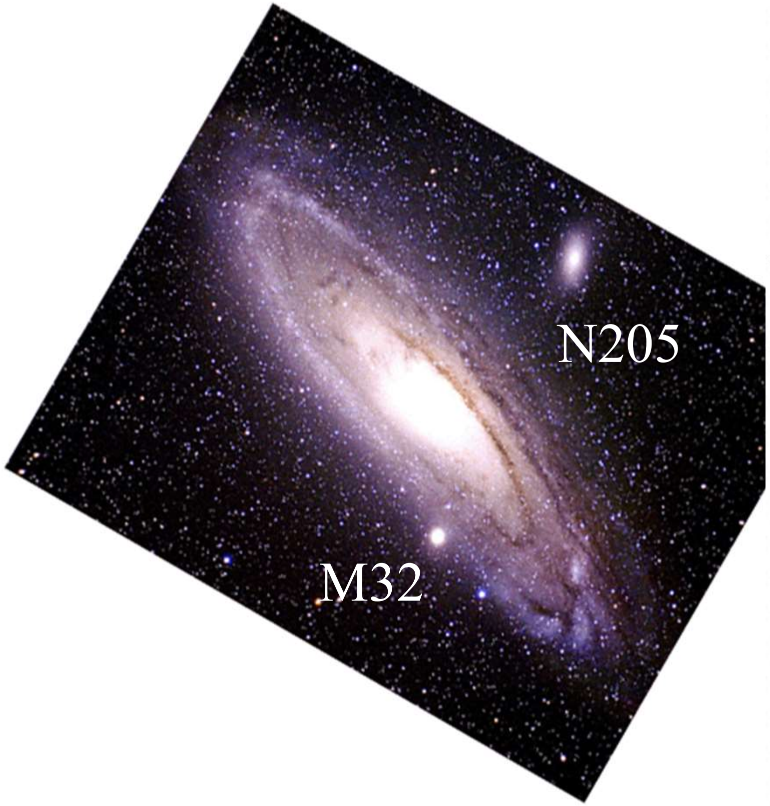


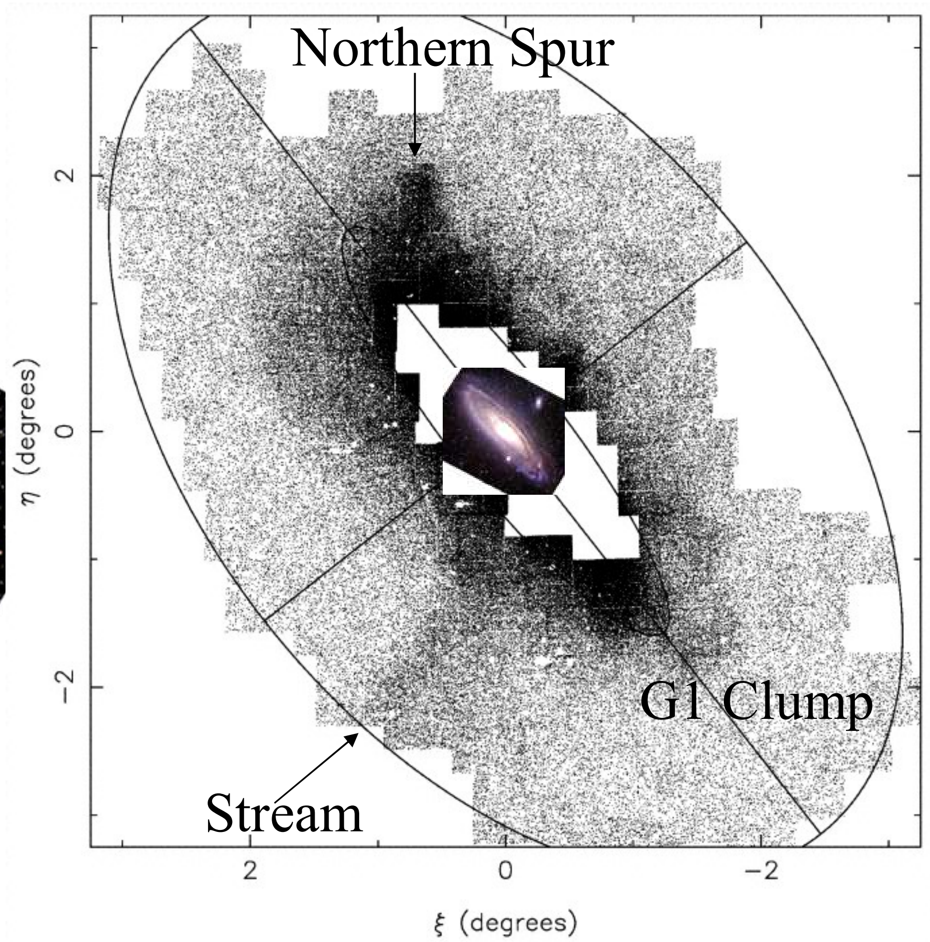
[Eu/Fe]>0.7: r-II

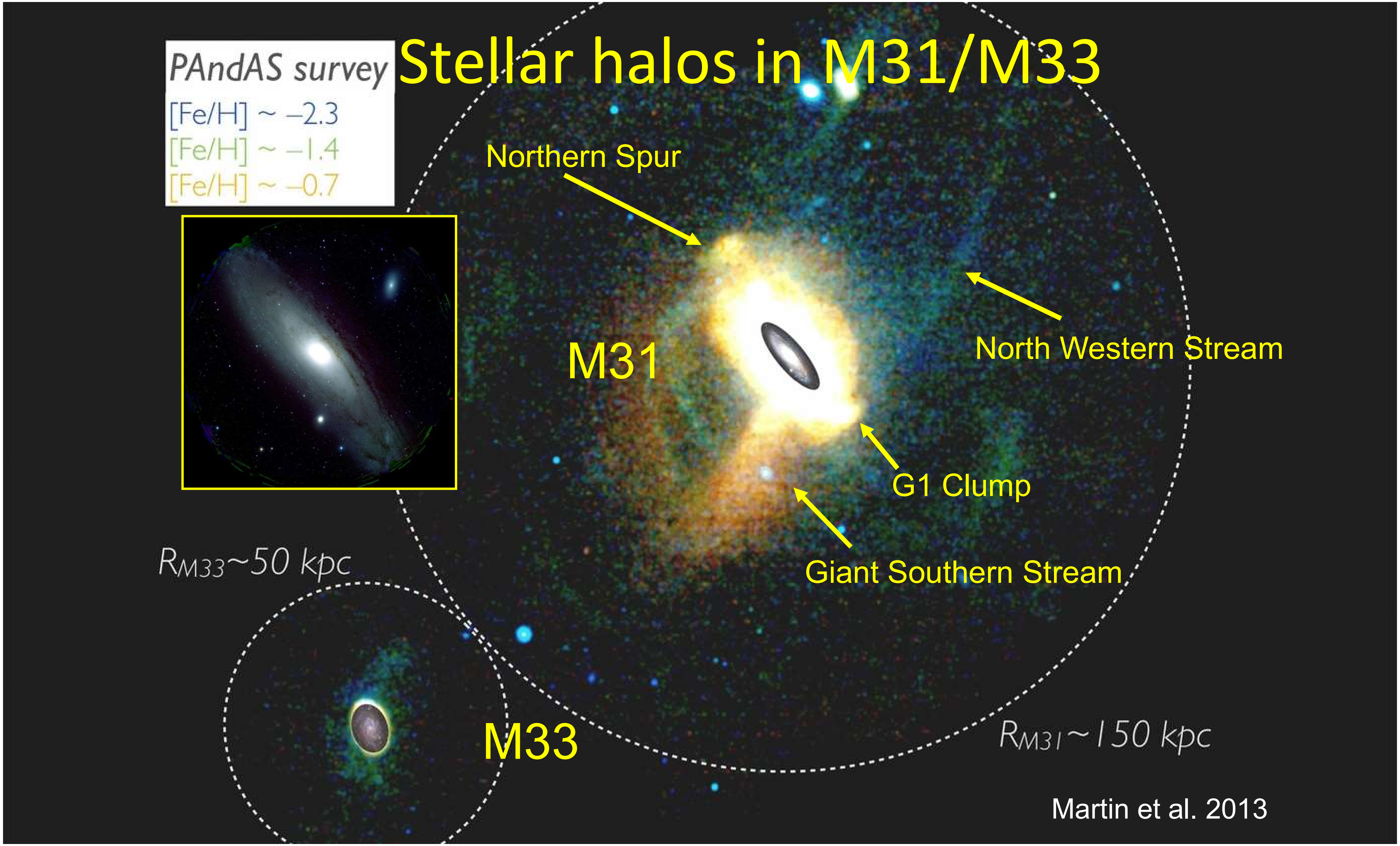
Created at t < 4 Gyr

Andromeda Halo

(Ferguson et al. 2002)



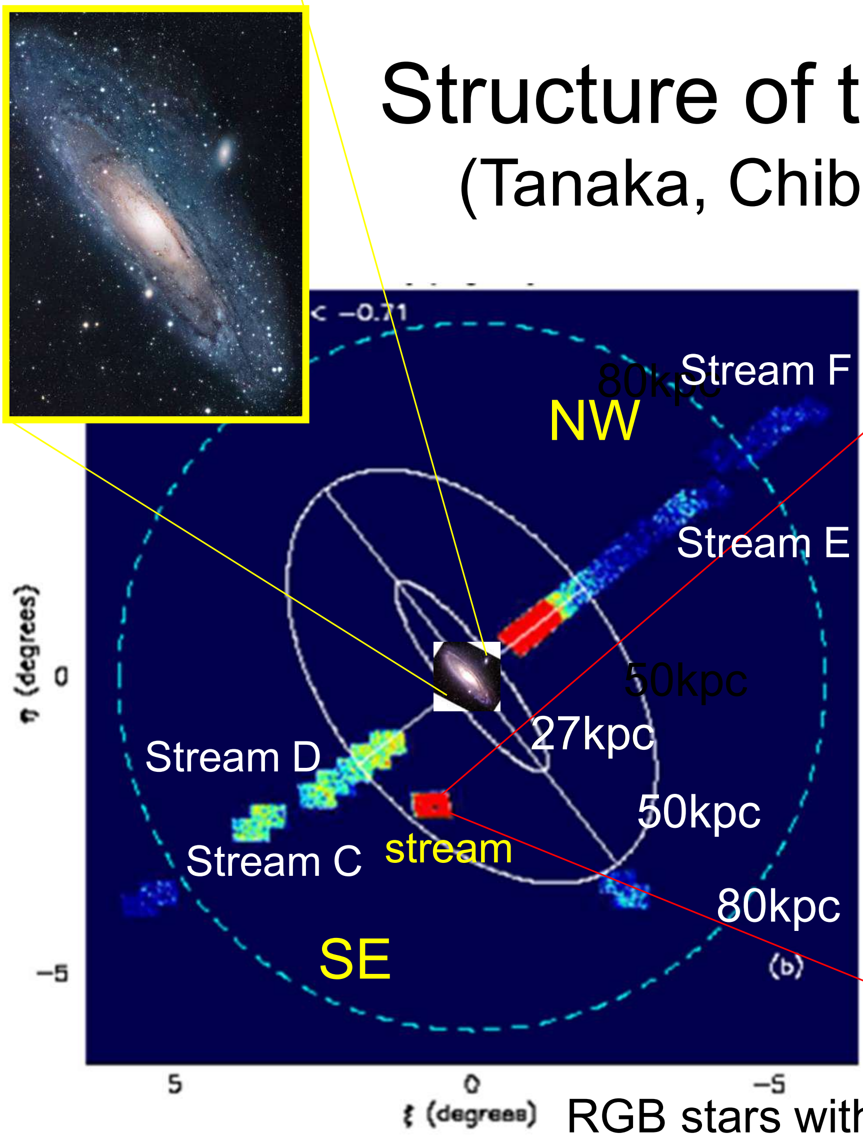




Stellar halos in M31/M33
PAndAS survey
[Fe/H] ~ –2.3
[Fe/H] ~ –1.4
[Fe/H] ~ –0.7
Northern Spur
M31
North Western Stream
G1 Clump
Giant Southern Stream
R_{M33}~50 kpc
M33
R_{M31}~150 kpc
Martin et al. 2013

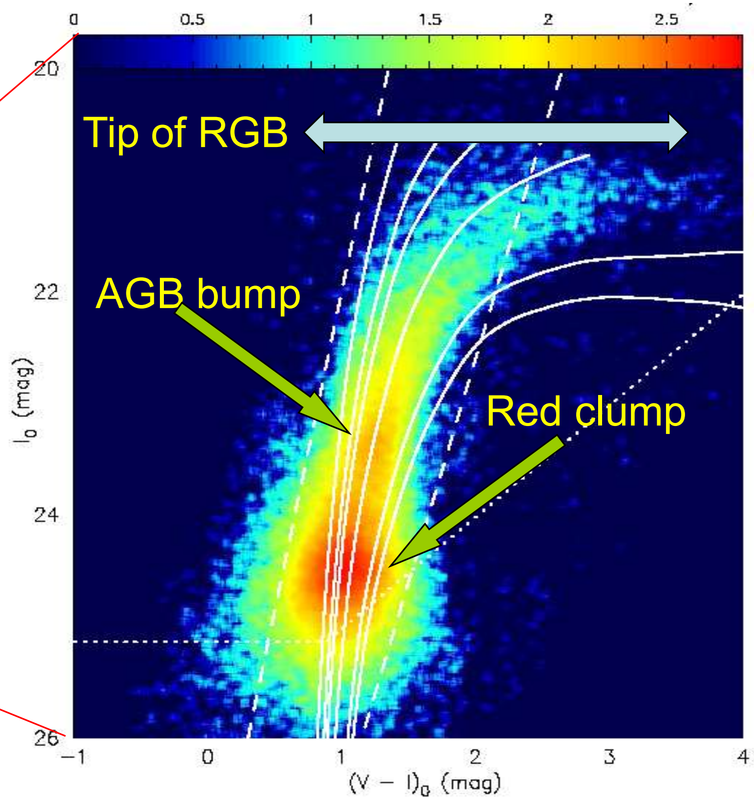
Structure of the M31 halo

(Tanaka, Chiba et al. 2010)

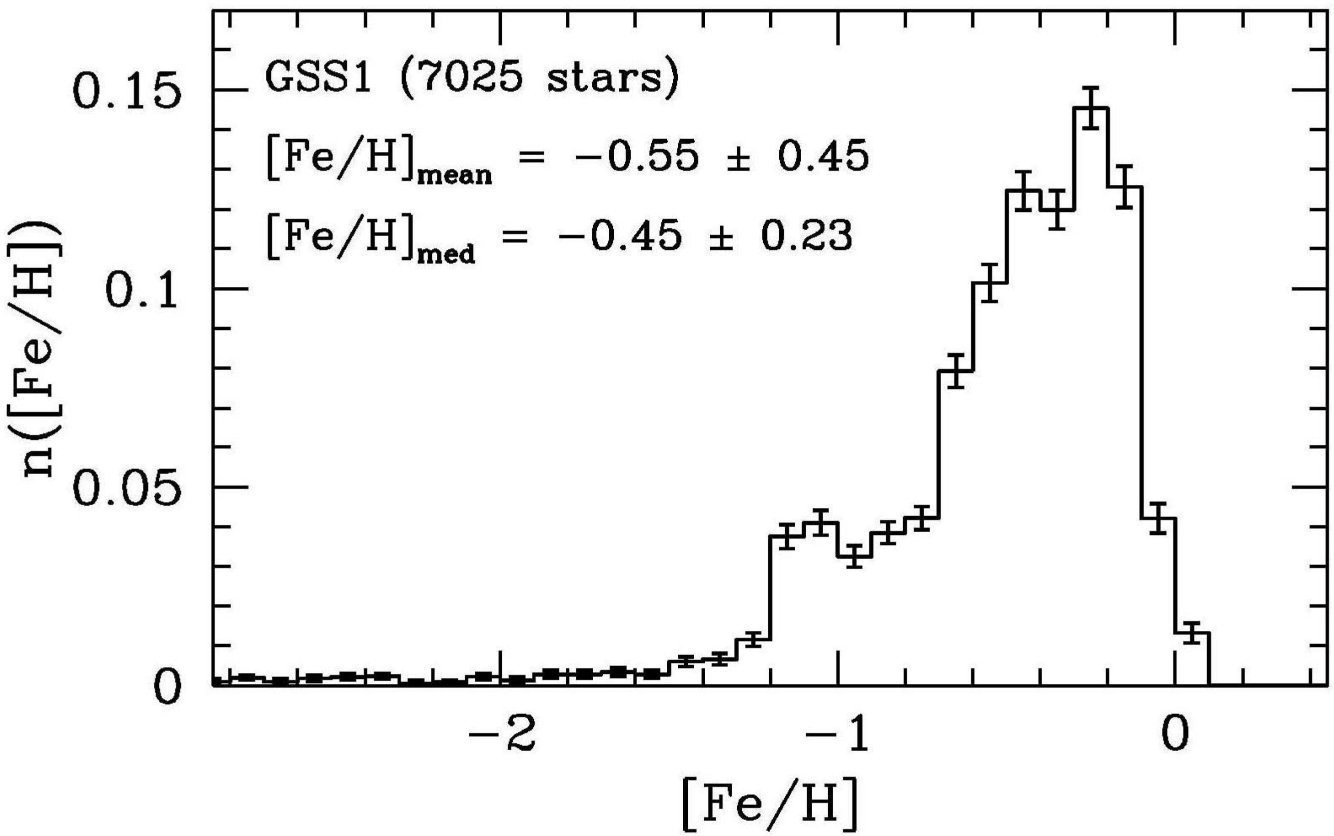


RGB stars with
I_0<24, V_0<24.8
-1.71<[Fe/H]<-0.71

Stream field



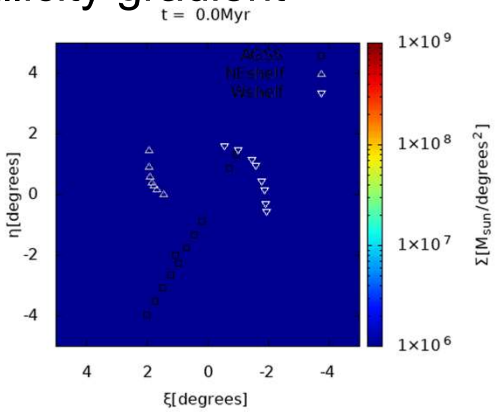
(Photometric) metallicity distribution of Giant Southern Stream

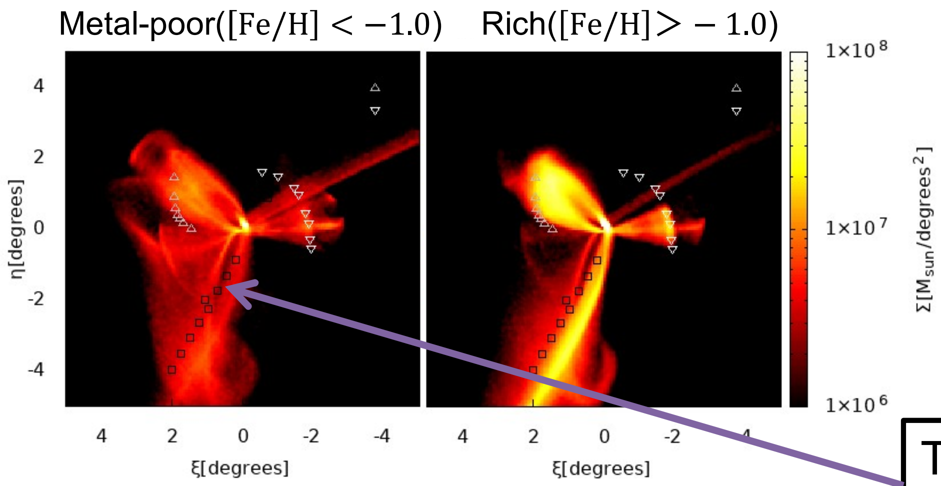


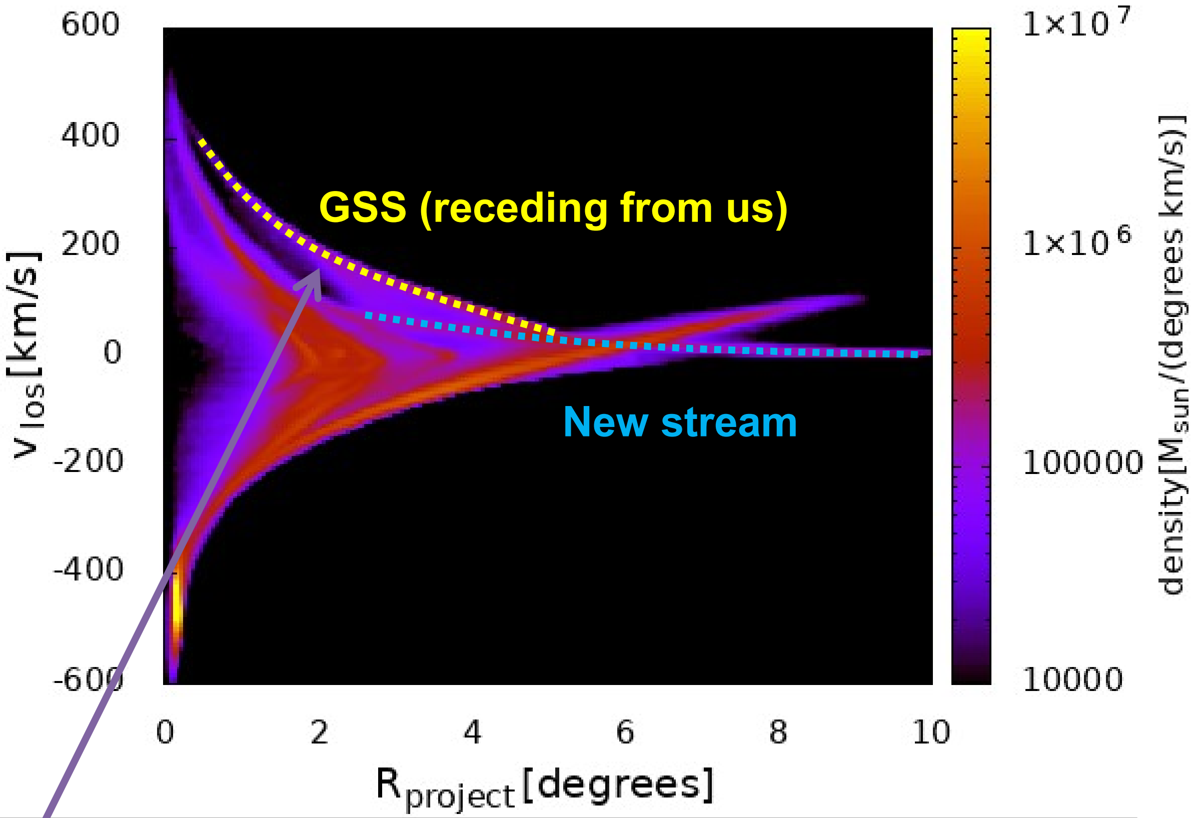
Numerical simulation of GSS

Progenitor: disk galaxy
with metallicity gradient

Yamaguchi, Mori, Kirihara+ 2025

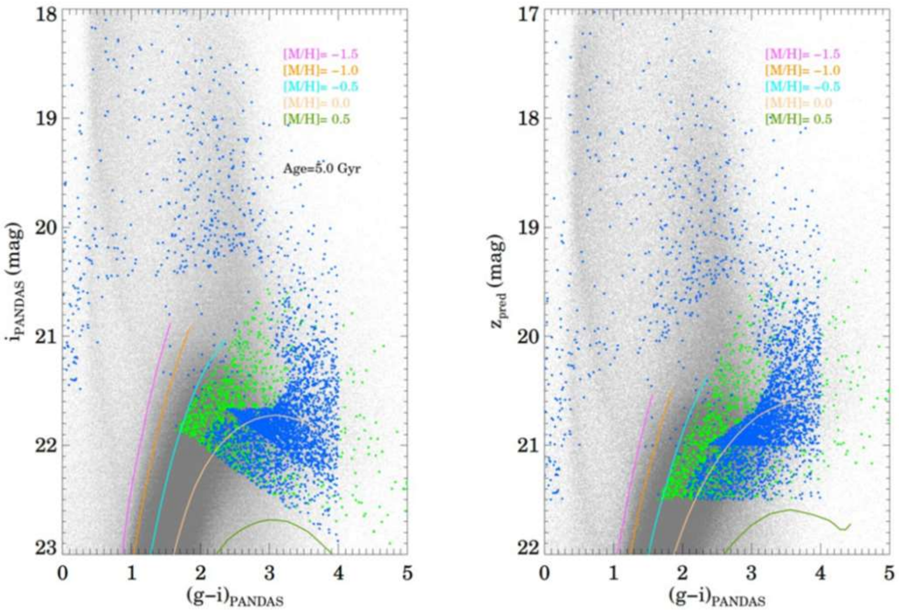




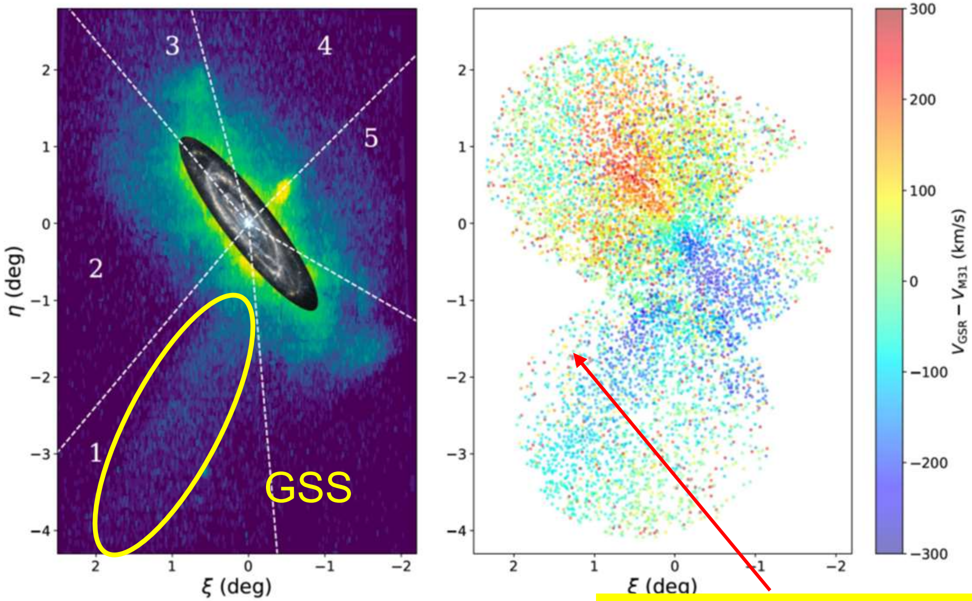


This **metal poor, faint, and positive velocity stream** at the eastern side of GSS is **missing in DESI map**.

Dey et al. (2023) with DESI
Machine-learning selection of very red, metal-rich, bright RGBs
2 < (g-i) < 4, z < 21.5 mag



Complicated selection function
Biased for very metal-rich stars
(-0.5 < [Fe/H] < +0.5)

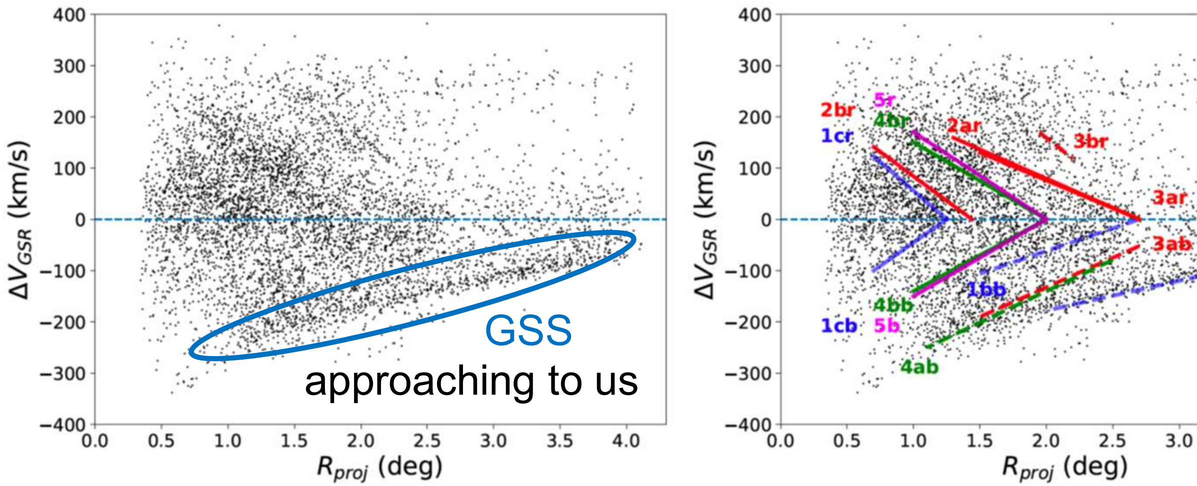


Los velocities (wrt. M31)

Metal-poor substructures are entirely disappeared!

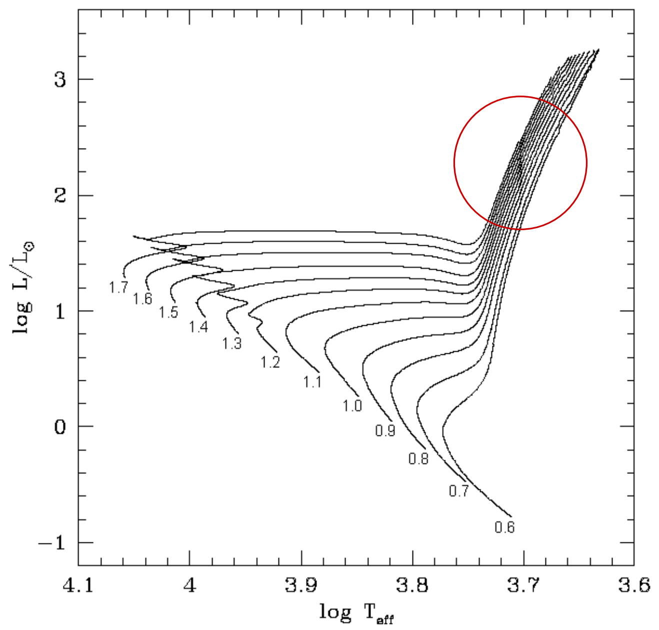
Phase-space diagram

Los velocities (wrt. M31)



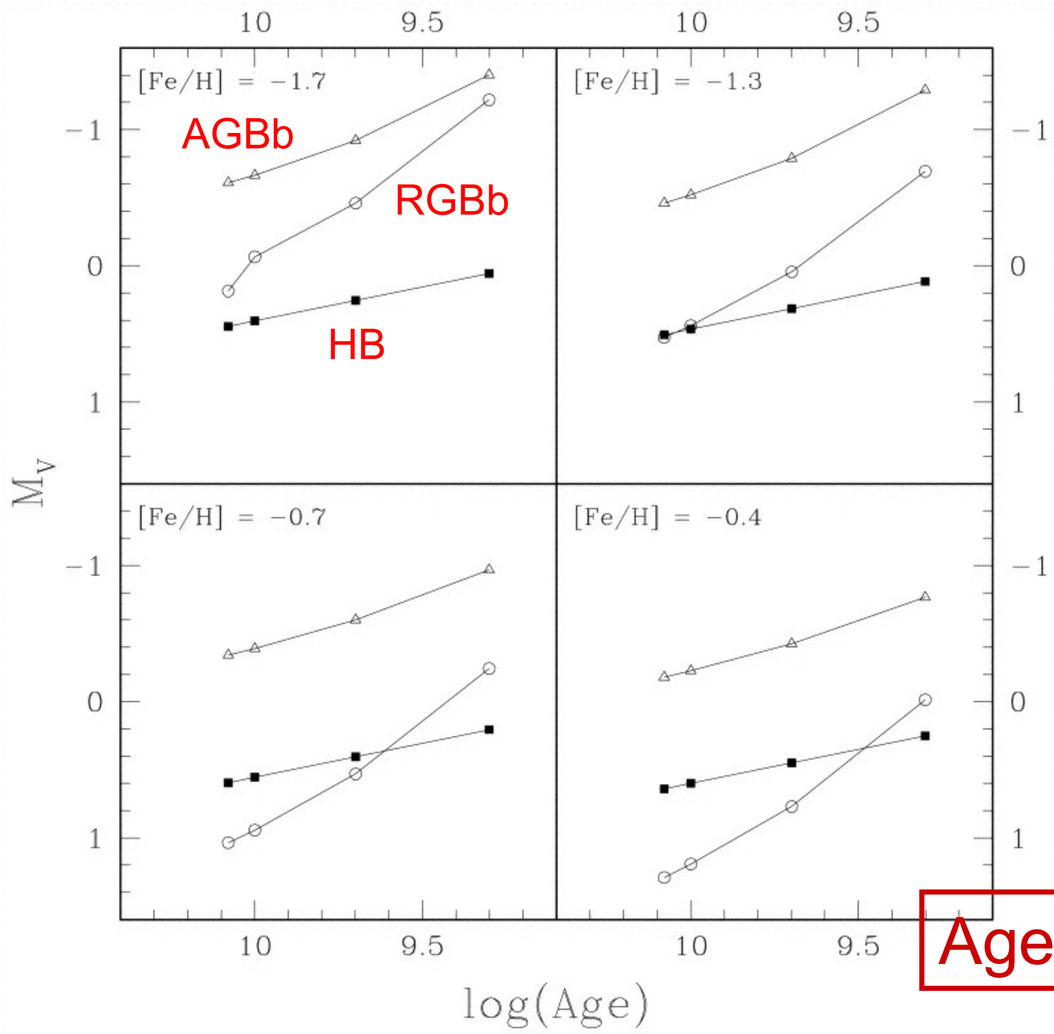
Important features in CM diagram

- RGB bump (RGBb)
  - Evolutionary pause when the H-burning shell crosses a discontinuity left by the convective envelope
- Tip of RGB (TRGB)
  - He-burning ignition through the He flash
  - Nearly constant I-band mag ⇒ standard candle
  - 843±48kpc, 855±48kpc > D=770kpc
- Red Clump (RC)
  - Clustered feature of red HB (He core-burning) stars being metal-rich / young age
- AGB bump (AGBb)
  - Clustered feature of AGB stars at the beginning of He shell-burning evolution



Luminosities of RGBb, RC, & AGBb depend on age.
⇒ age distribution

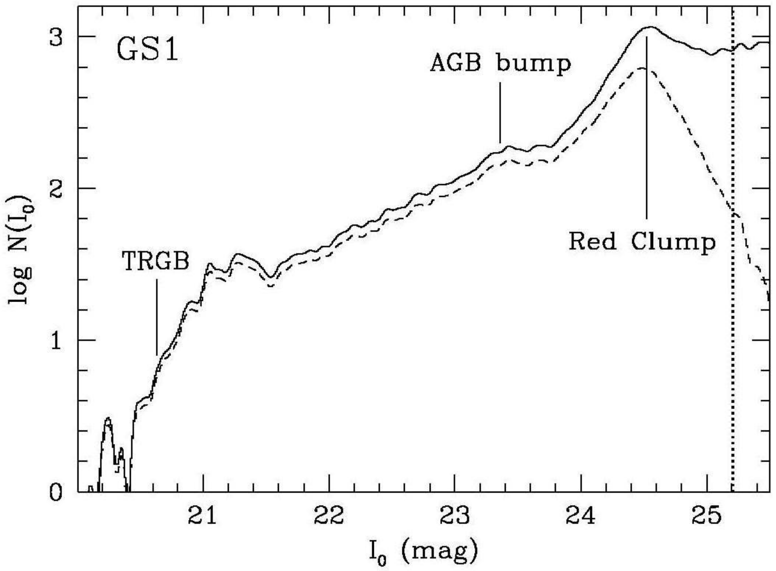
Alves & Sarajedini 1999

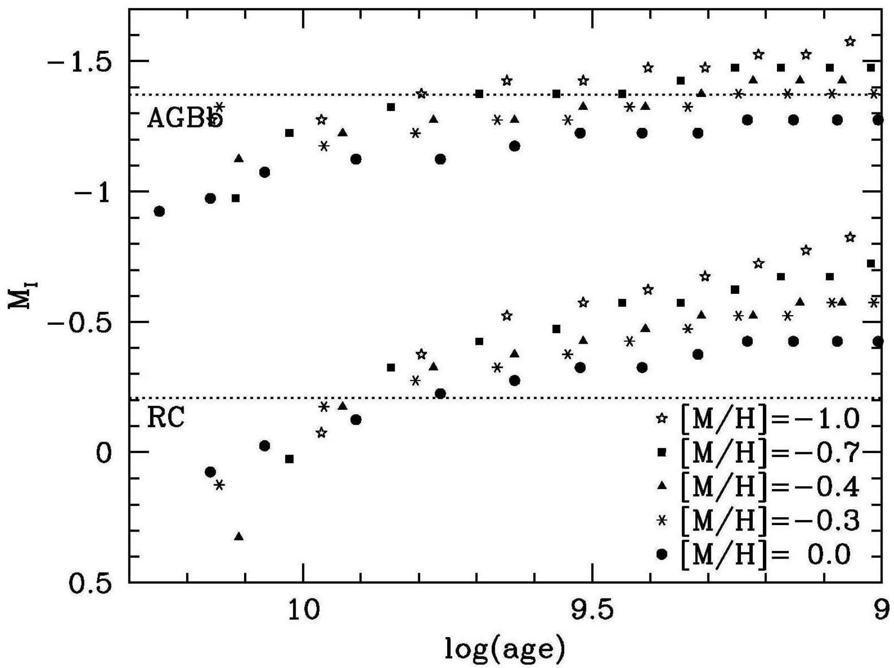


Fainter for Z↑M↓

Age indicator

Age calibration for giant stream





Mean Age ~ 7.1 Gyr

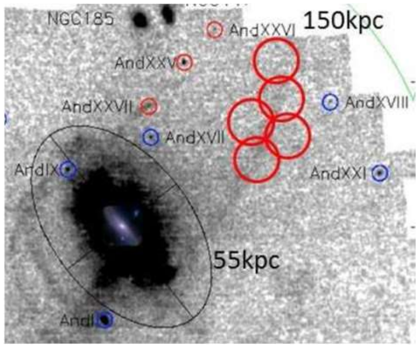
Tanaka+2010

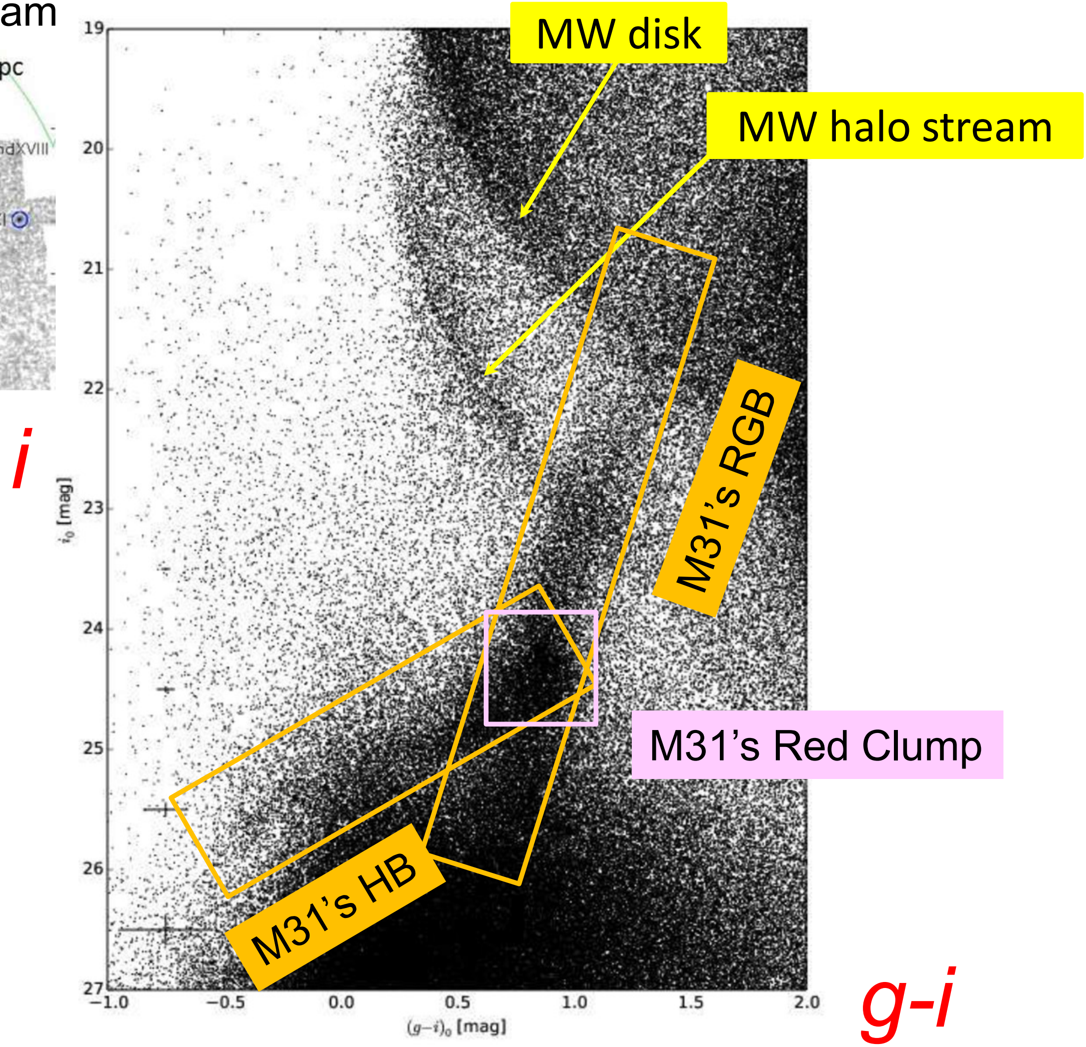
North Western Stream

Subaru/HSC data

Komiyama, Chiba et al.2018

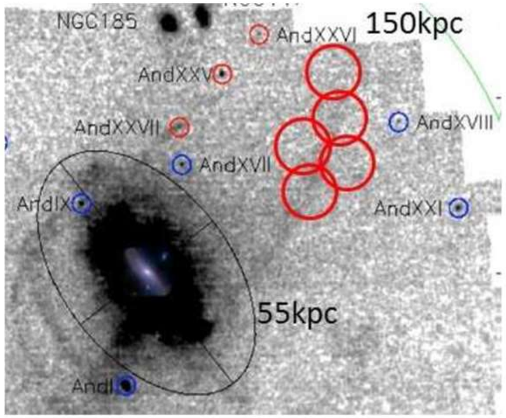
North Western Stream

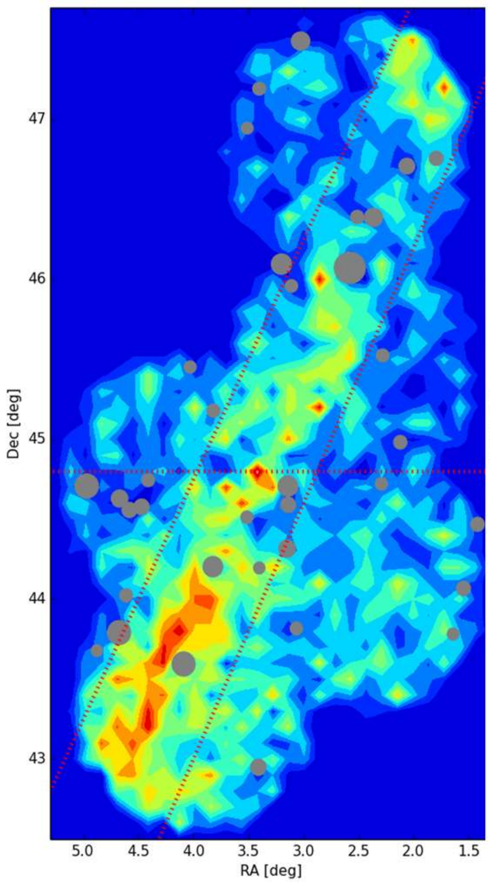


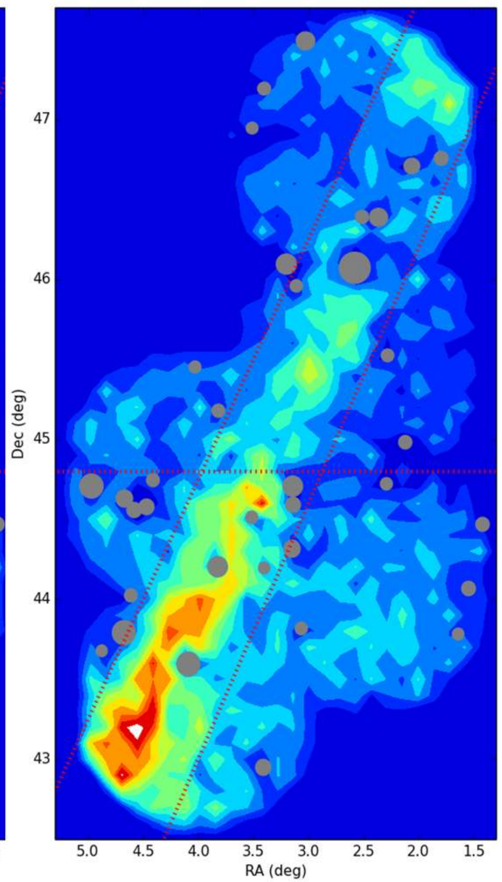


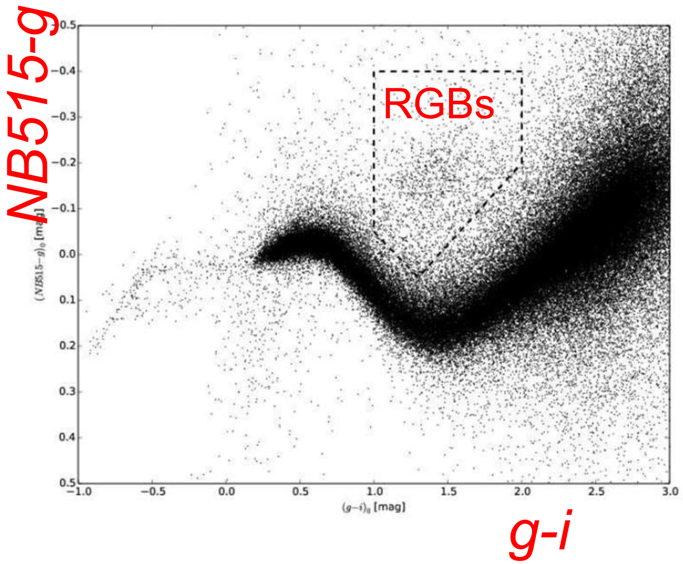
Komiyama et sl.2018

North Western Stream





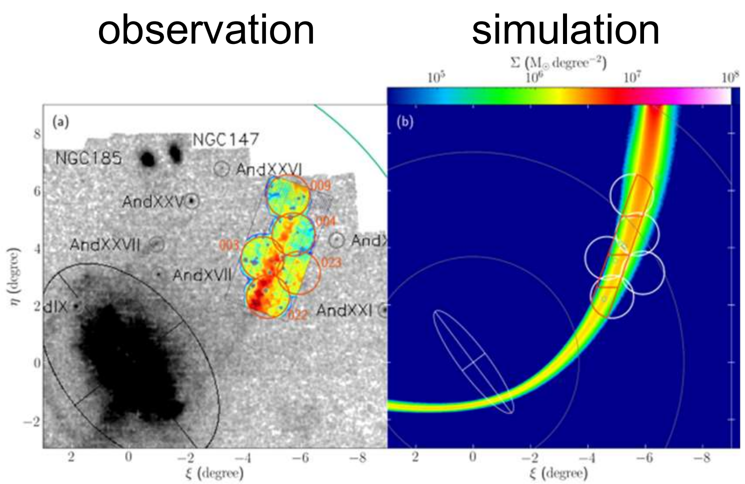


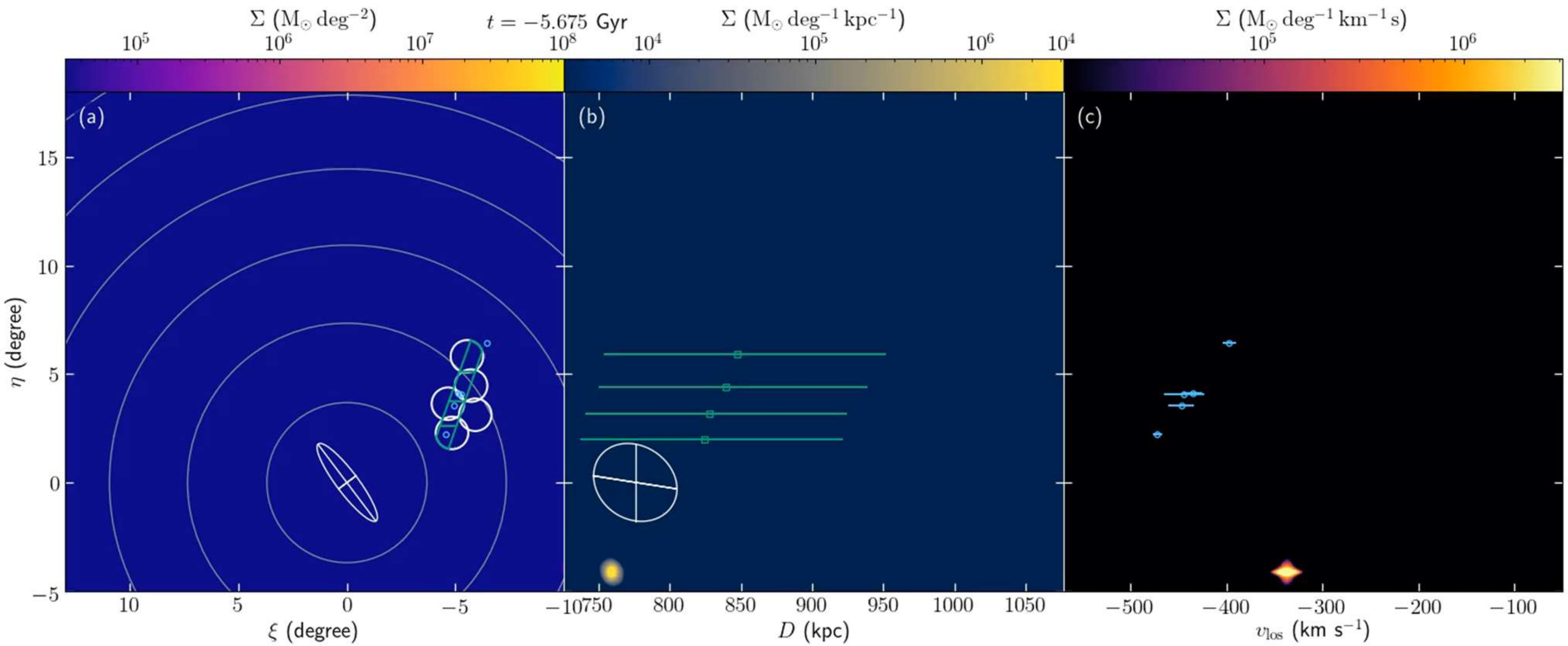


Formation of the North Western stream

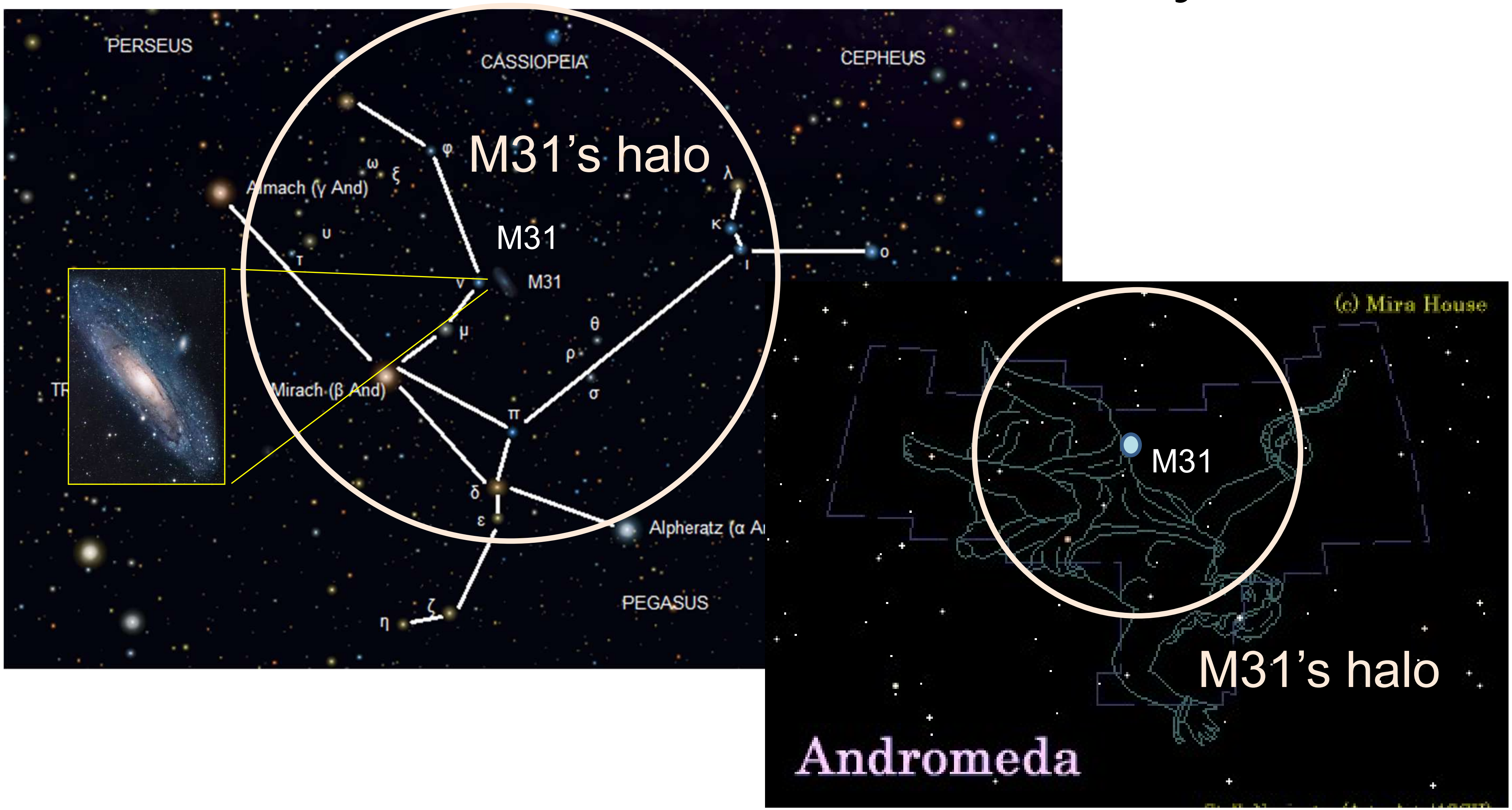
By Y. Miki

Merging of the satellite with $M = 5 \times 10^7 M_\odot$



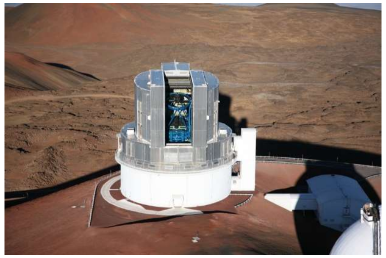


True size of Andromeda Galaxy



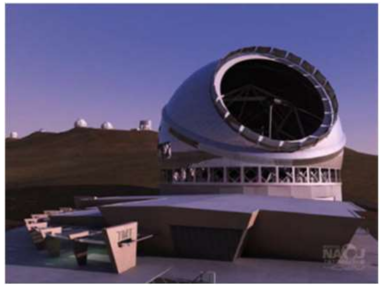
Future Prospects

Major telescopes/instruments

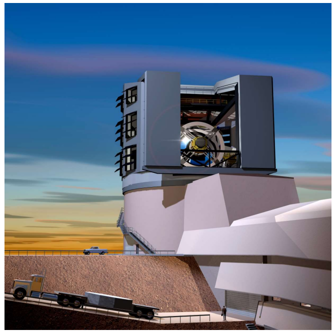


Subaru
HSC
PFS : 2025-
Ultimate:

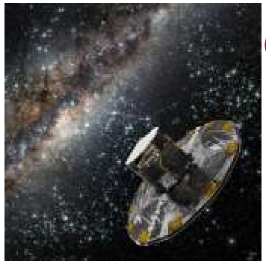
ALMA



TMT
WFOS
HROS
NIRES
2032?

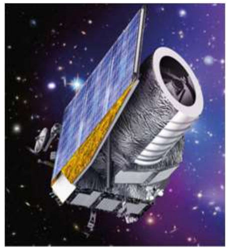


Vera C. Rubin (LSST)
2025-

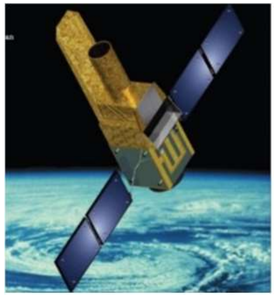


Gaia

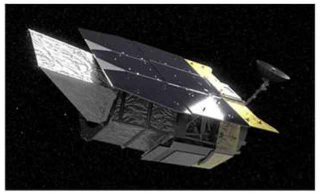
JWST
NIRCam
NIRSpec
MIRI
2022-



Euclid
YJH
2023-



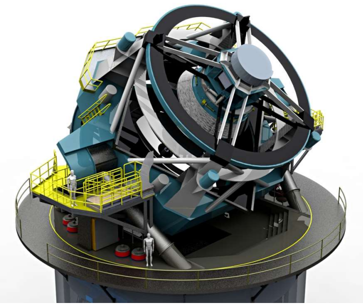
JASMINE
NIR astrometry
Late 2031



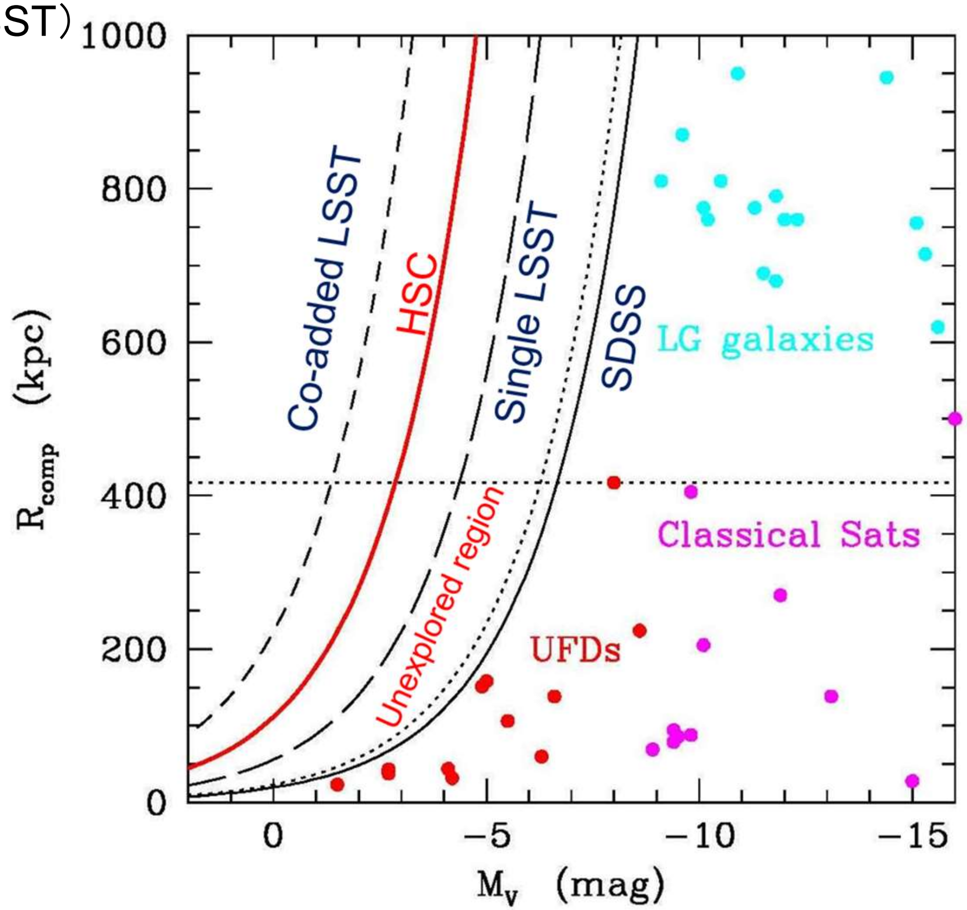
Nancy Grace Roman Space Telescope (WFIRST)
2026-

LSST at Vera C. Rubin Observatory

Large Synoptic Survey Telescope（LSST）




- 8.4-meter, in Chile
- 3.2 Gpix camera
- Operation: 2025~
- ~10 years operation



Single LSST:
r_{lim} = 24.5
Co-added LSST:
r_{lim} =27.5
Subaru/HSC
(wide field layer):
r_{lim}~26

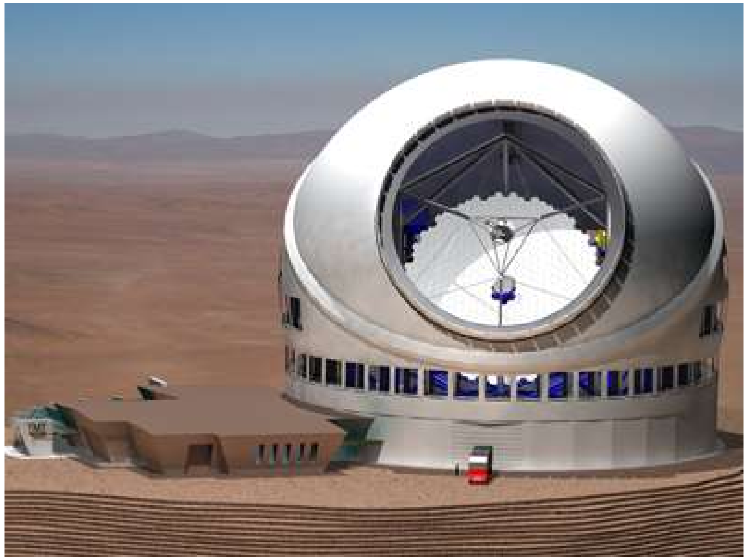
Tollerud+2008

Deeper and wider survey for satellites in the outer parts of the halo

Vera Rubin Observatory のfirst image

June, 2025 (https:/skyviewer.app)

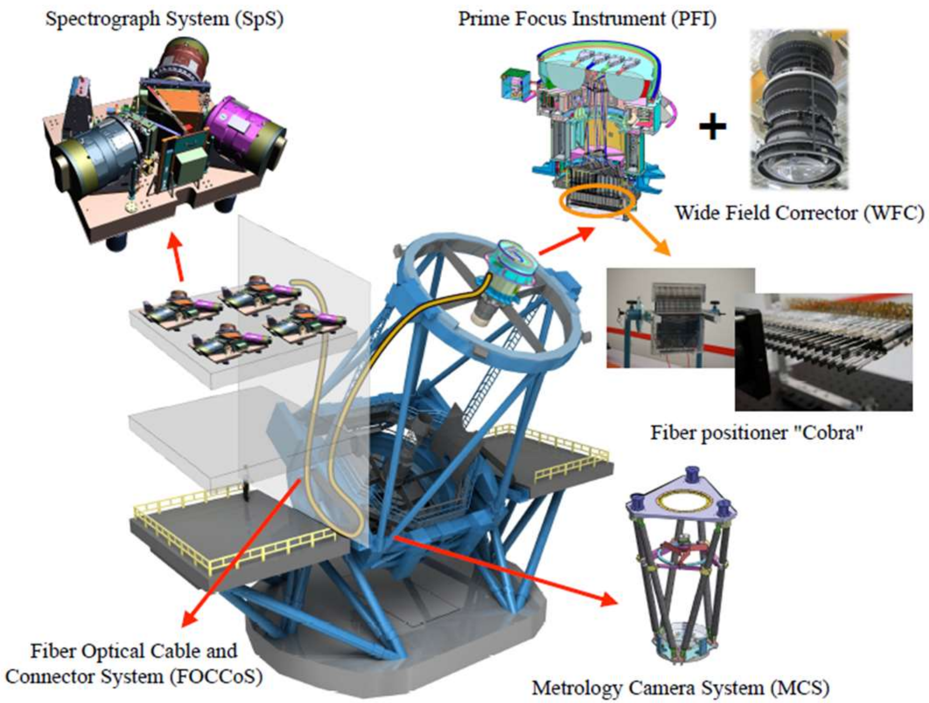
TMT
(Thirty Meter Telescope)



WFOS, IRIS, IRMS, HROS, NIRES etc.
R~5,000 for m_V<26 mag
R~50,000 for m_V<21 mag
First light: 2032~

Goal: ultimate understanding of galaxy formation based on resolved stars in the local universe

Subaru/PFS (Prime Focus Spectrograph)

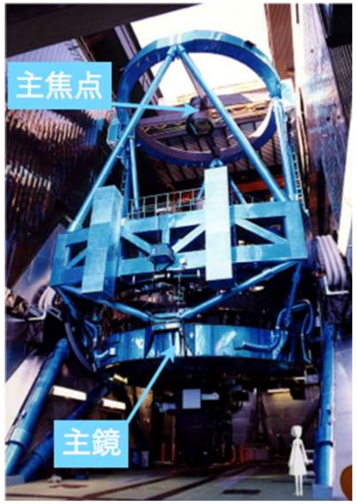


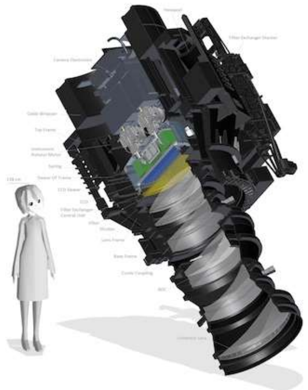
FOV: 1.3 deg in diameter
2400 fiber positioners
λ: 380~1,300 nm
(3 channels: Blue, Red, IR)
R: ~3,000 (LR), 5,000 (MR)
Scientific run: 2025 ~

International collaboration:
IPMU (U. of Tokyo) & NAOJ/Subaru
+ Caltech/JPL, Princeton, JHU, LAM,
Taiwan, UK, Brazil, China

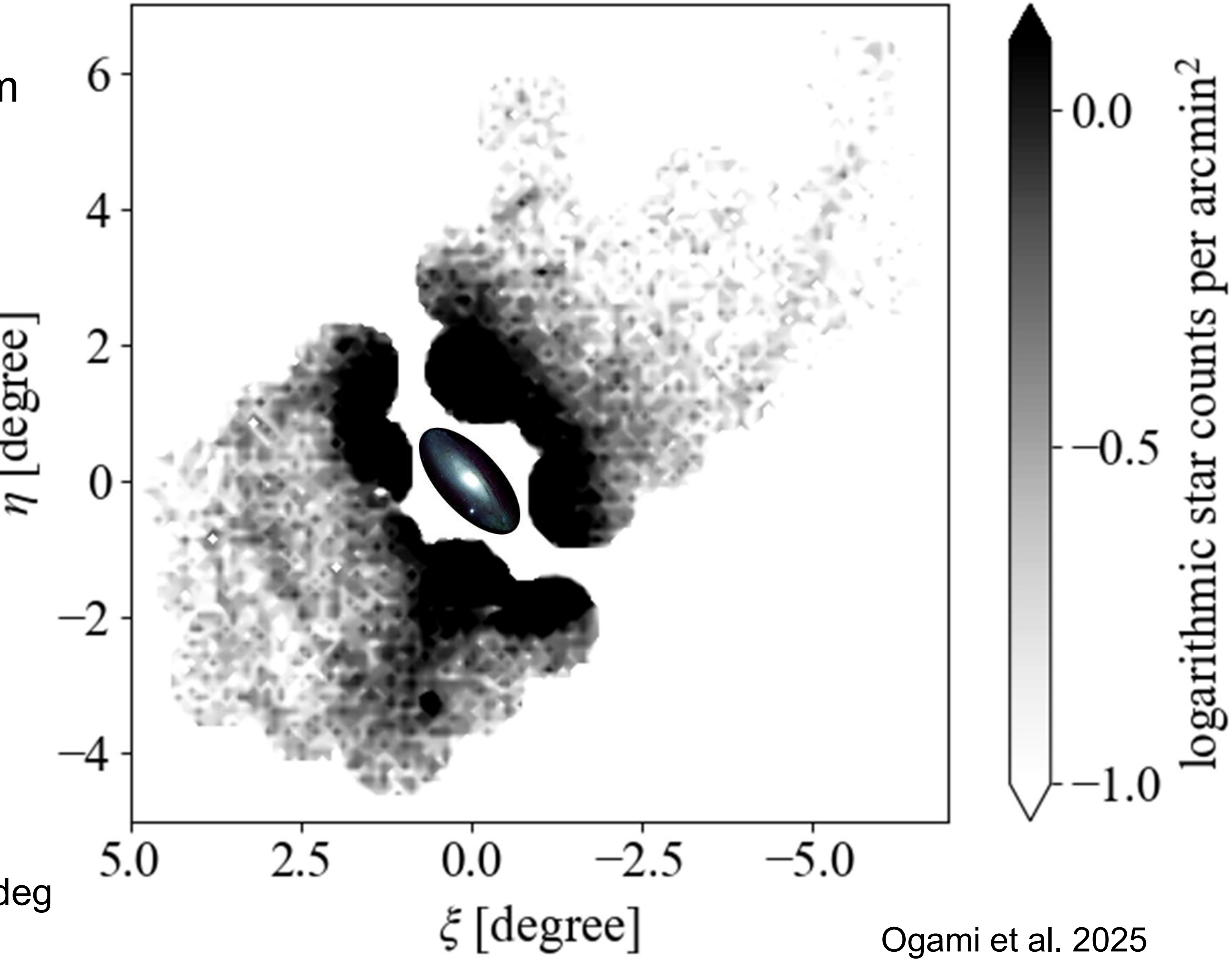
Subaru Strategic Program (SSP: 360 nights over 6 years)
1. Cosmology, 2.Distant Galaxies,
3. Galactic Archaeology (MW dSphs, M31, MW disk/halo)

Subaru
Hyper Suprime-Cam





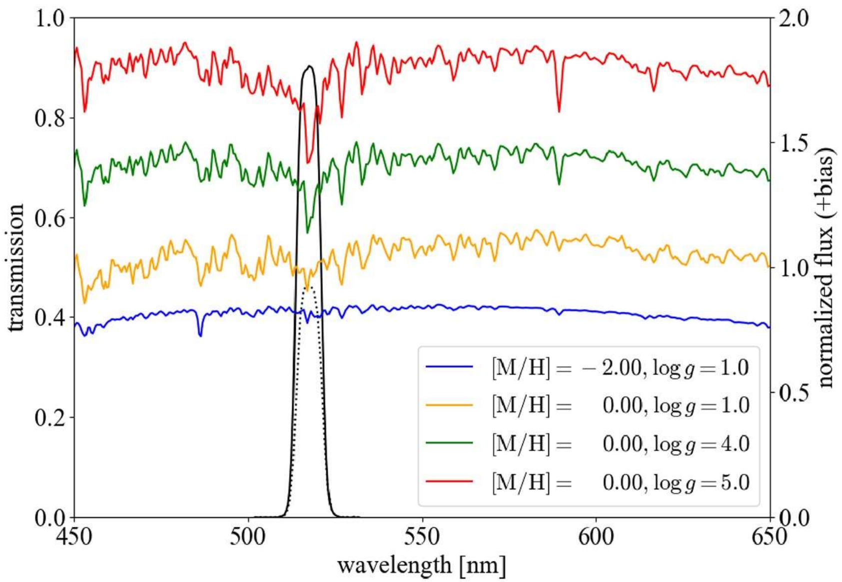
Field of View: 1.77 sq deg
(1.5 deg diameter)

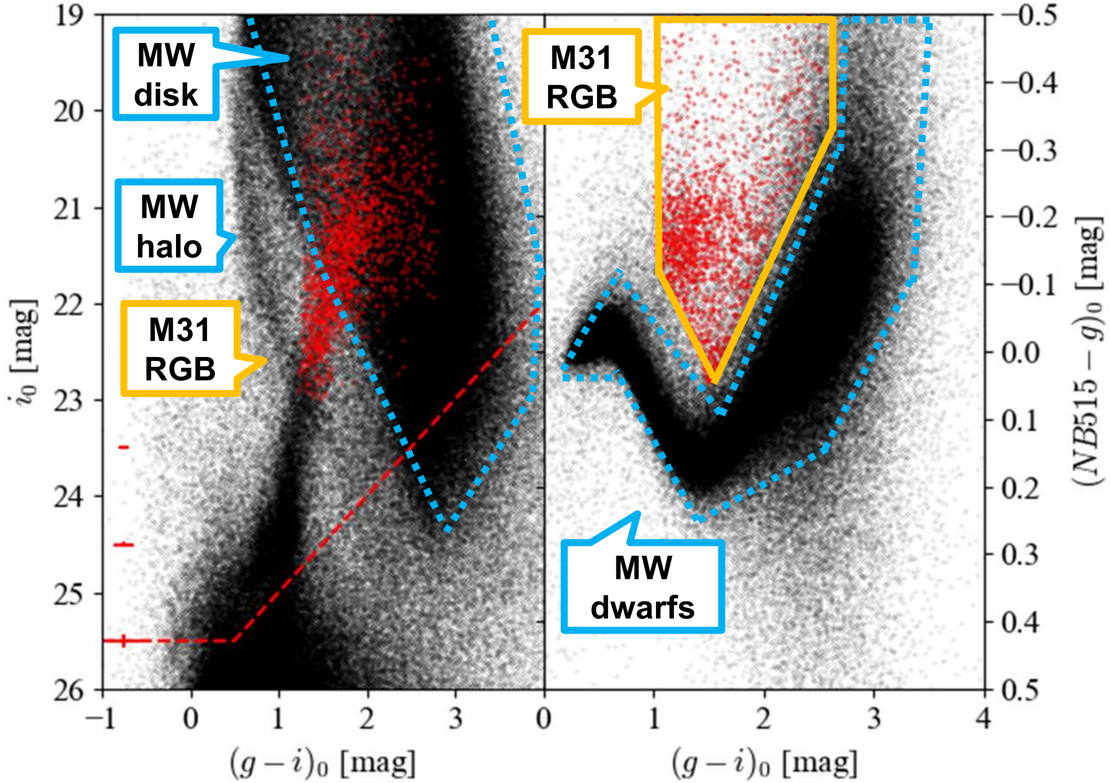


Ogami et al. 2025

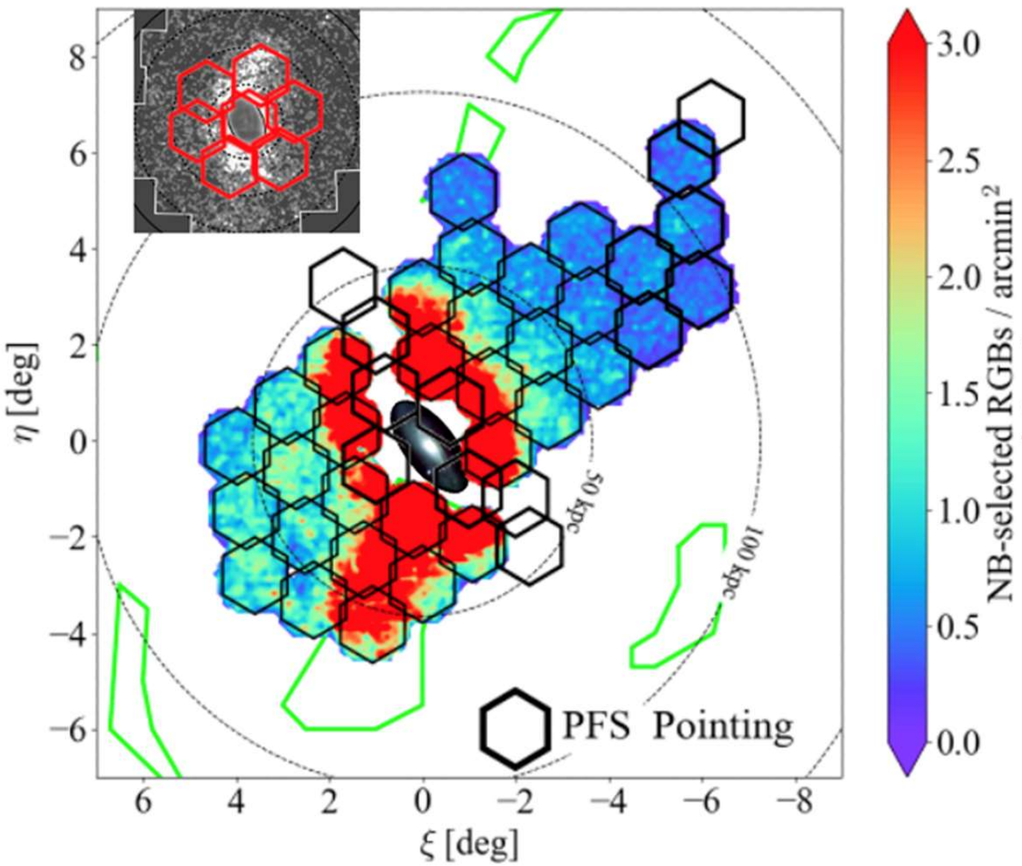
Selection of M31's RGBs against MW's dwarfs

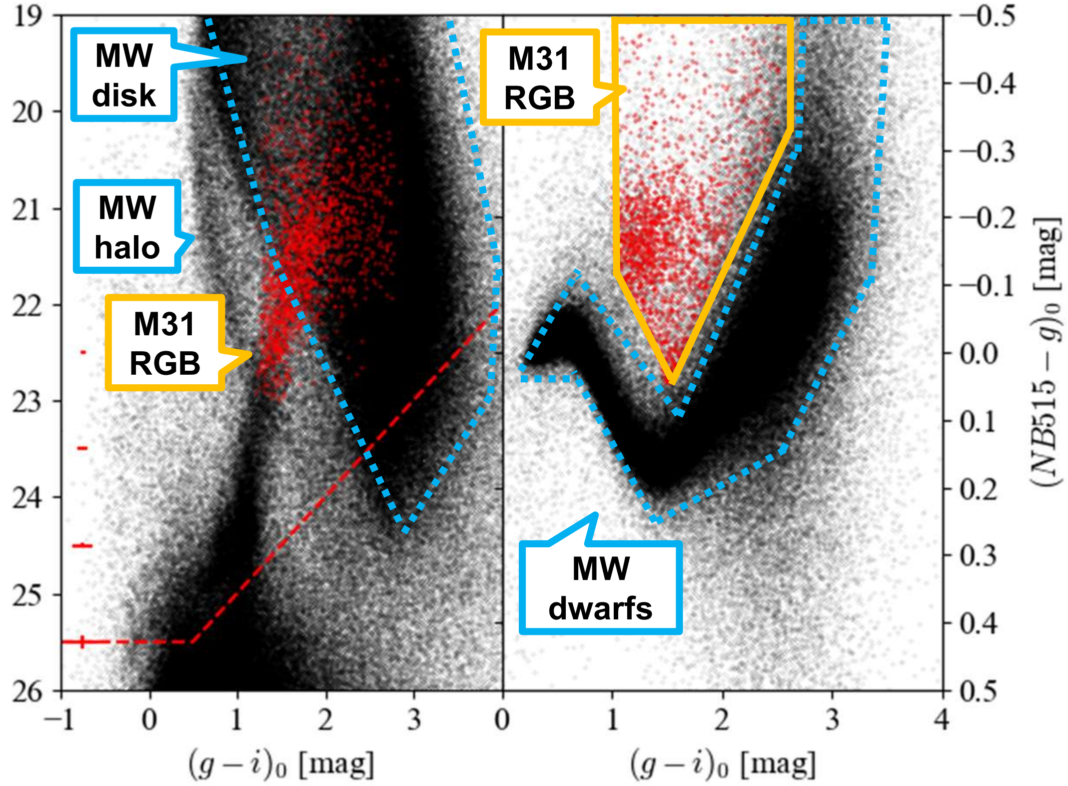
NB515 narrow-band filter
(MgH+Mgb absorption at λ~515nm)
Sensitive to the star's surface gravity (log g)
-> separate between RGB and dwarf





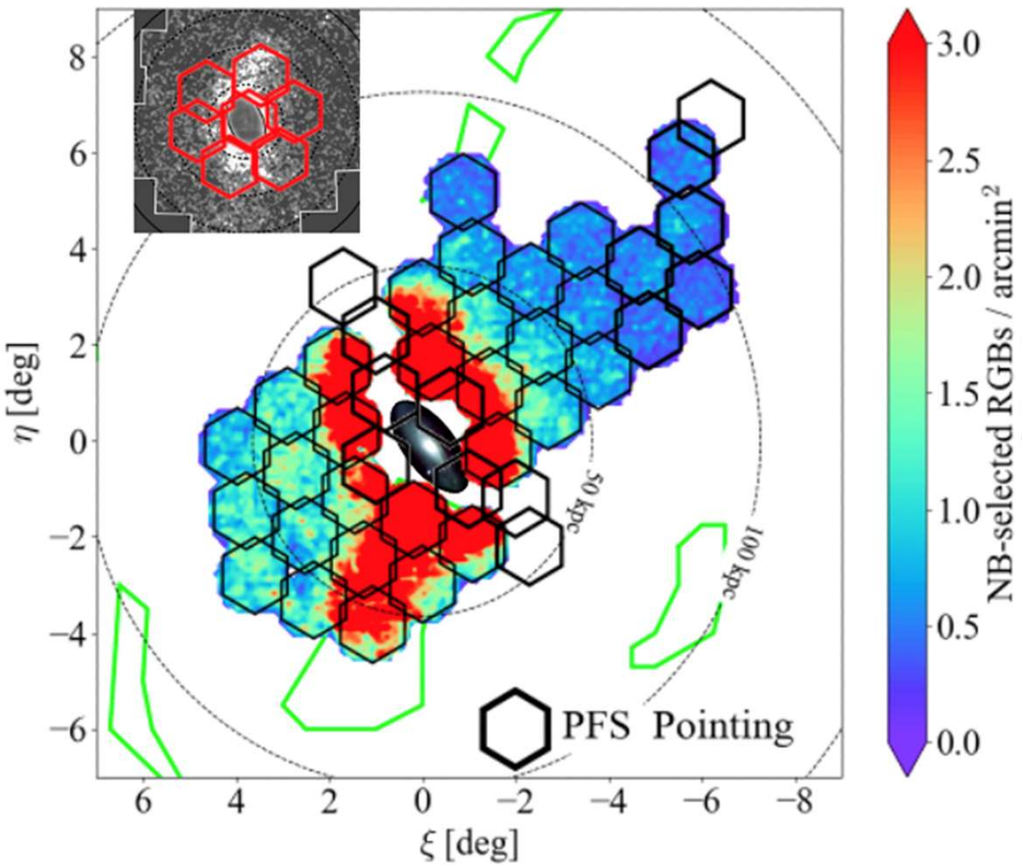
M31/M33's halo survey with PFS

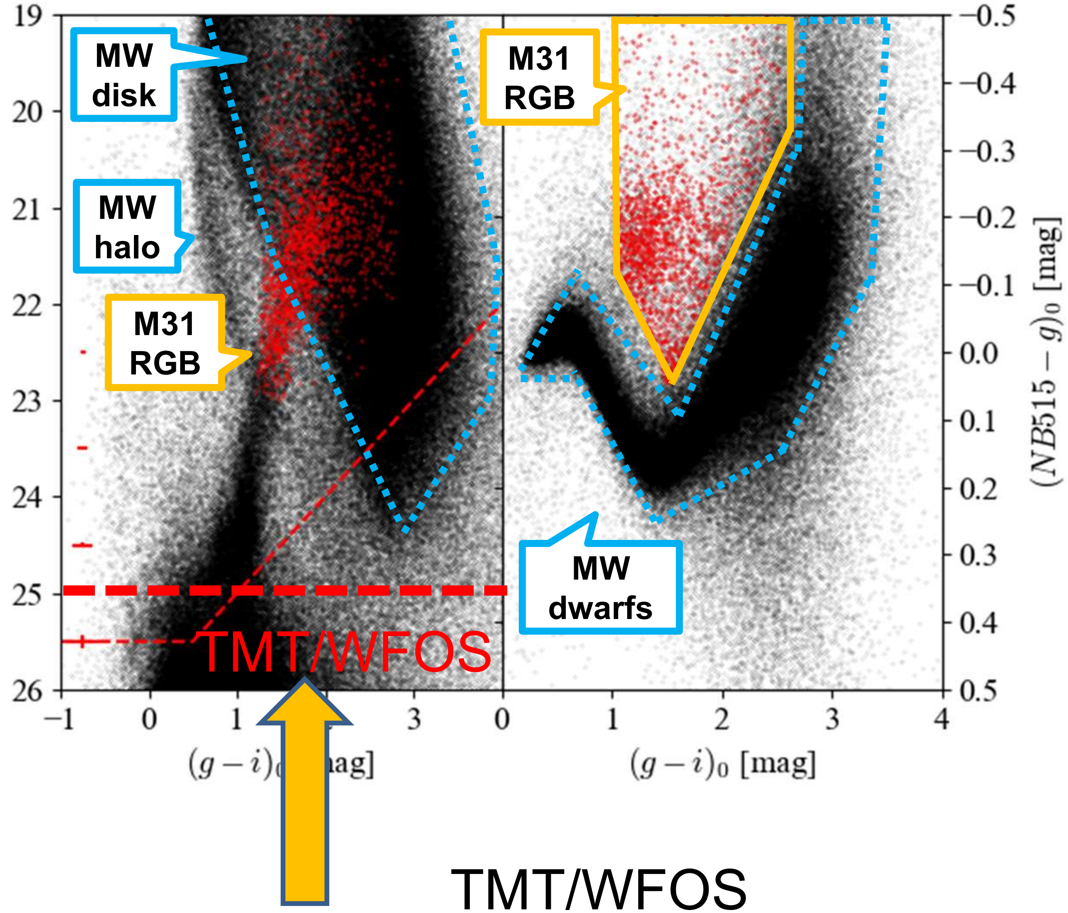




200〜400 RGBs/field with PFS

M31/M33's halo survey with PFS





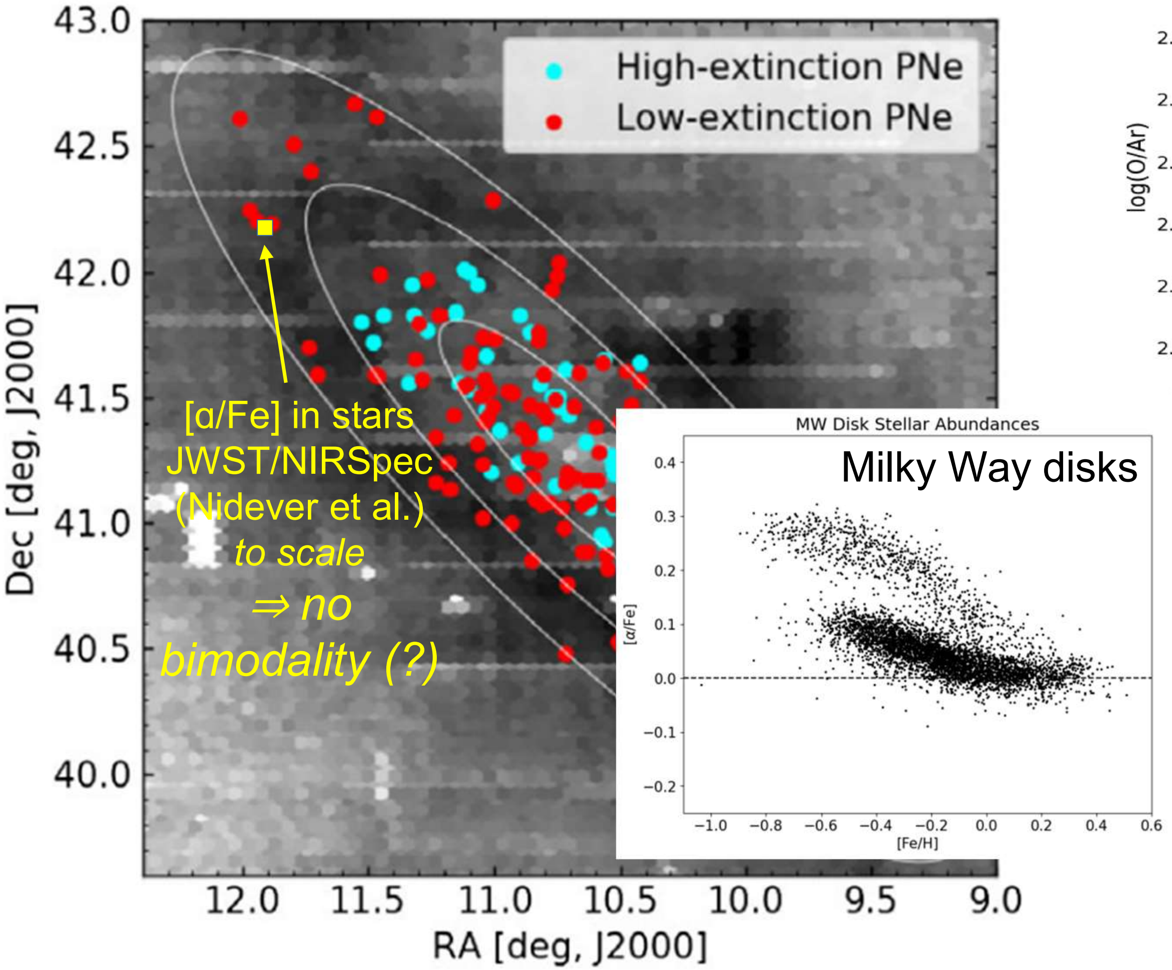
200～400 RGBs/field with PFS

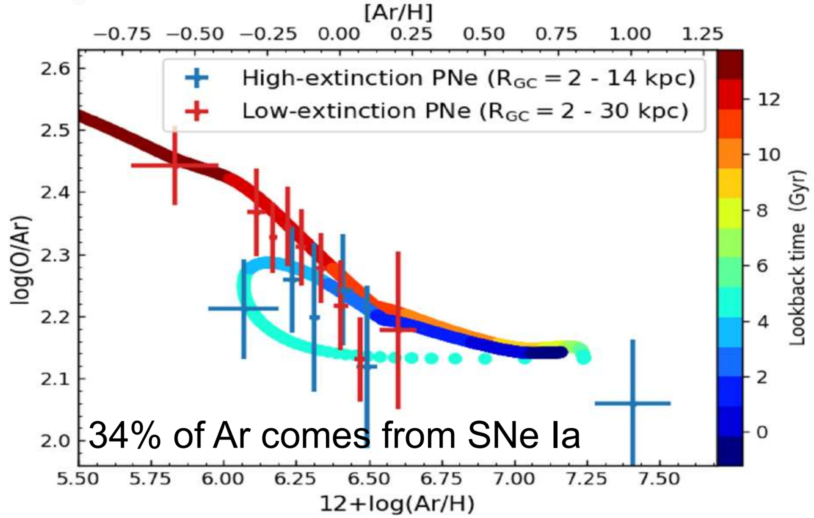
TMT/WFOS

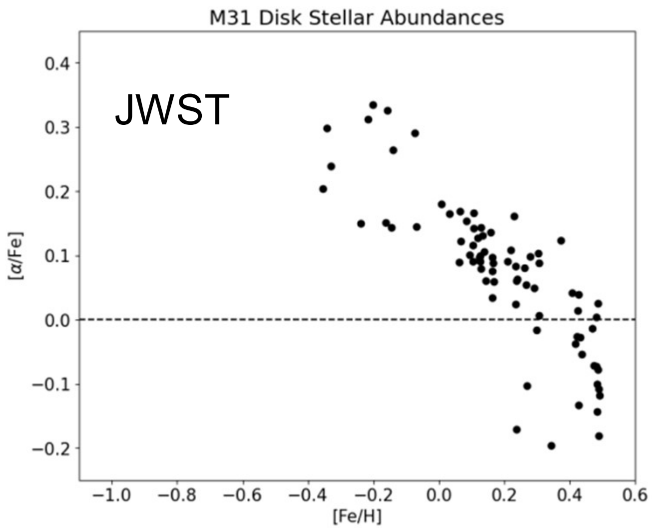
Planetary Nebulae (PNe)

M31'disk has the [α/Fe] bimodality?

PNe: O/Ar ratio measurements (Arnaboldi et al. 2022)



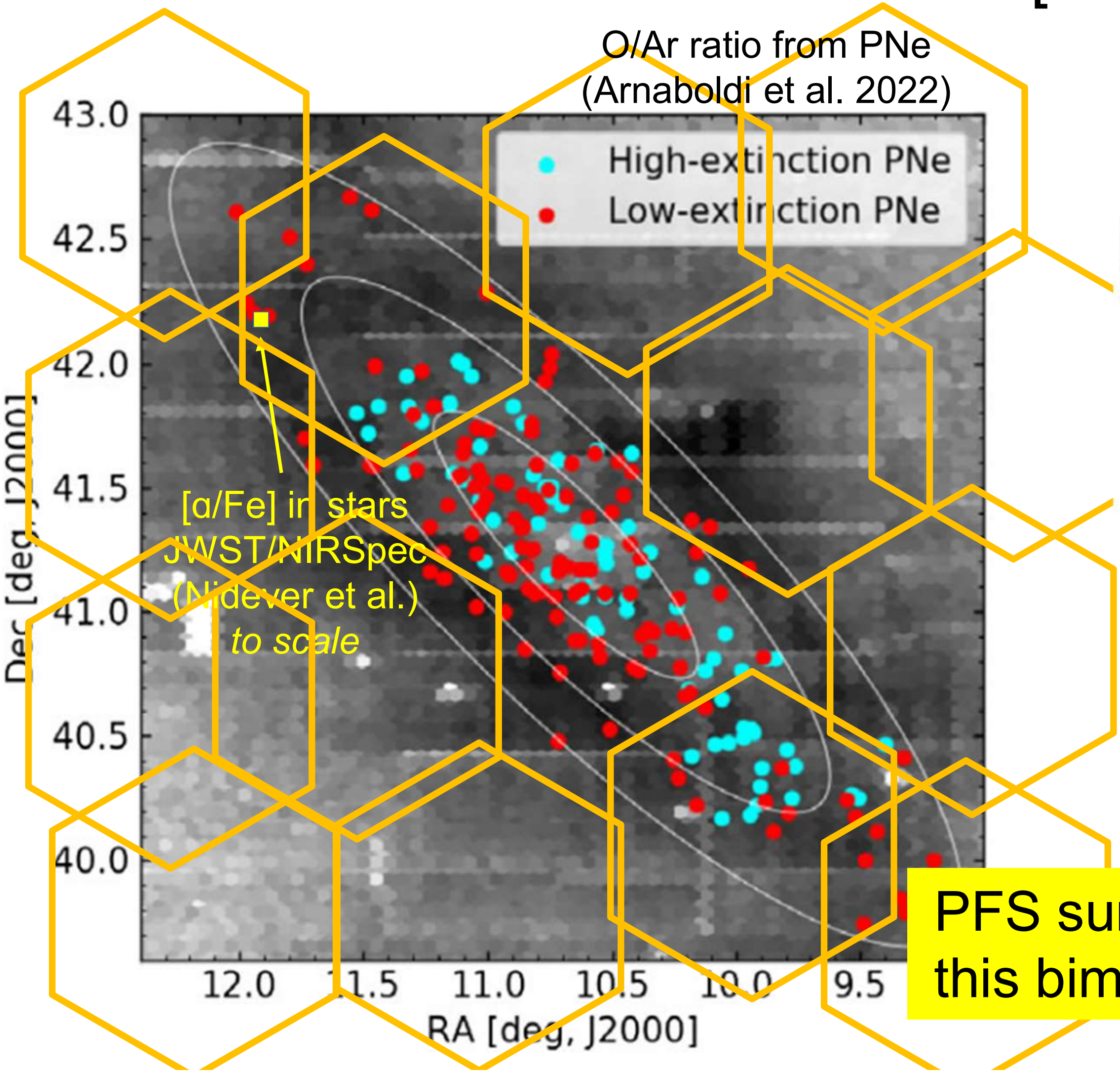


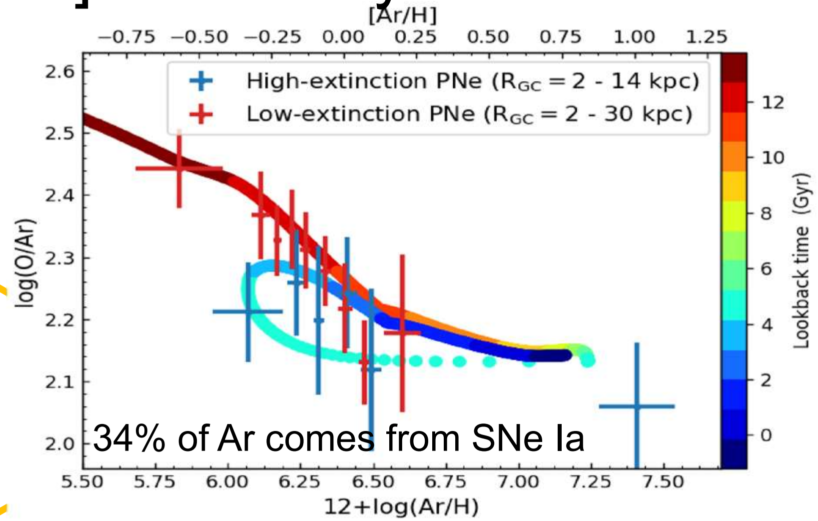


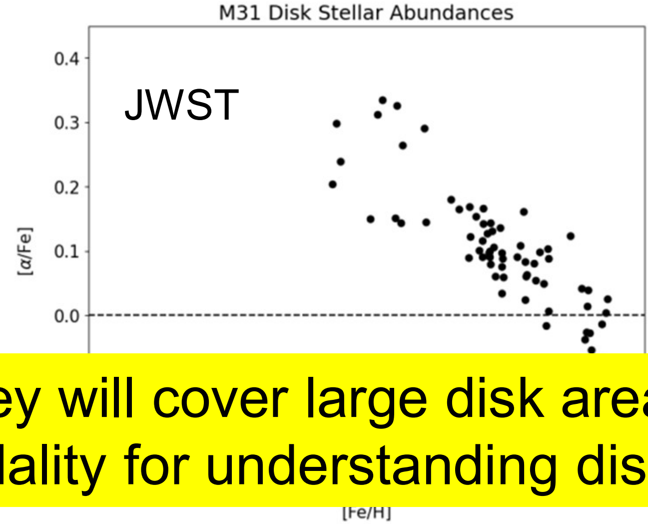
Planetary Nebulae (PNe)

M31'disk has the [α/Fe] bimodality?

O/Ar ratio from PNe
(Arnaboldi et al. 2022)



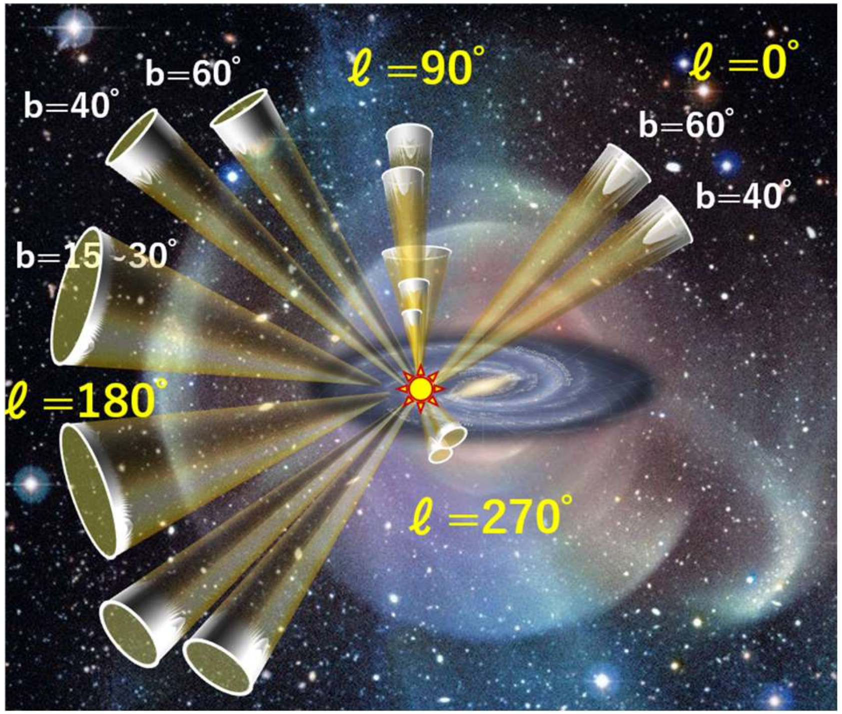




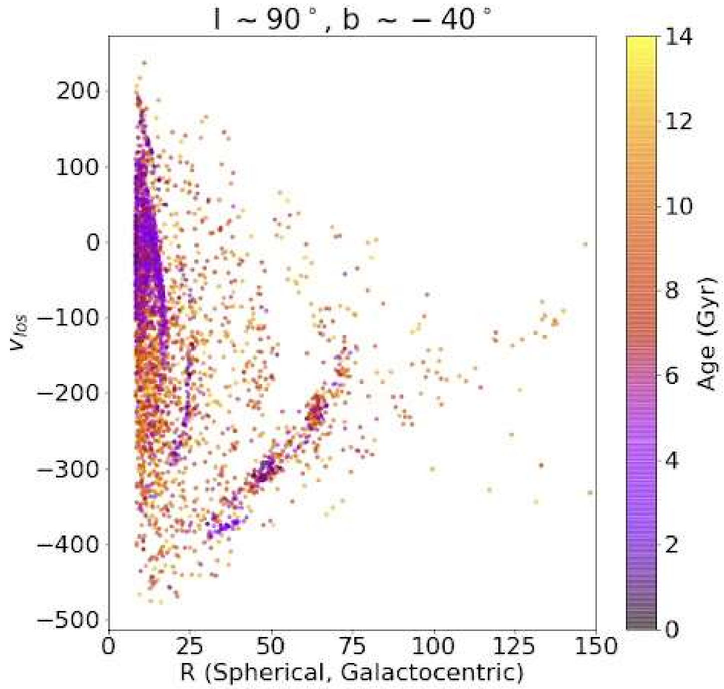
PFS survey will cover large disk areas to clarify this bimodality for understanding disk formation

MW outer disk/halo with PFS

- Investigation of the physical mechanisms that determine the ongoing build-up of the outer disk/halo regions of the Milky Way
  - Galactico-seismology for outer disks from velocities and distances, Age-metallicity relations (MSTOs) in the outer disk, Phase-space distribution of halo stars

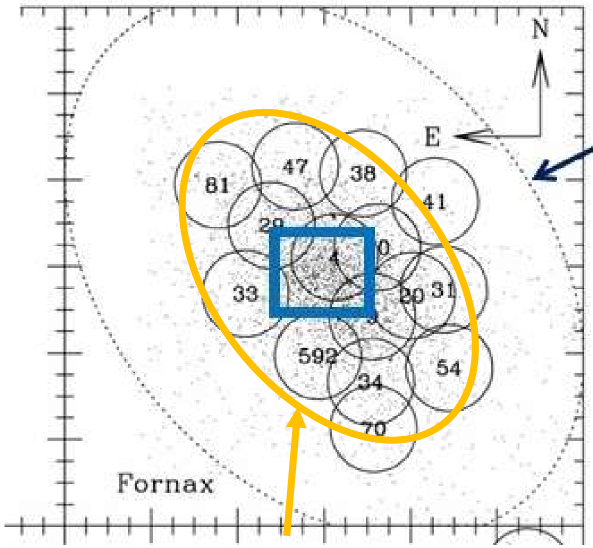


Expected (r, V_{los}) phase space for halo stars



DM of MW dwarf satellites with Subaru/PFS

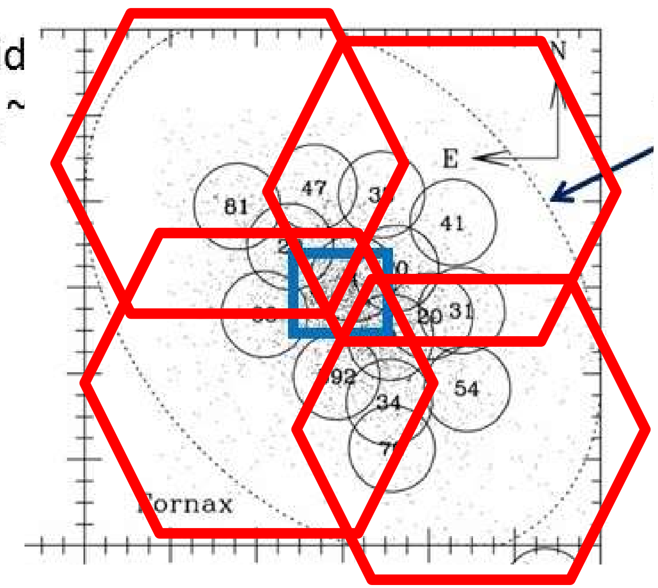
Fornax dSph



previous range for measuring dark halo profiles

Walker et al. 2009

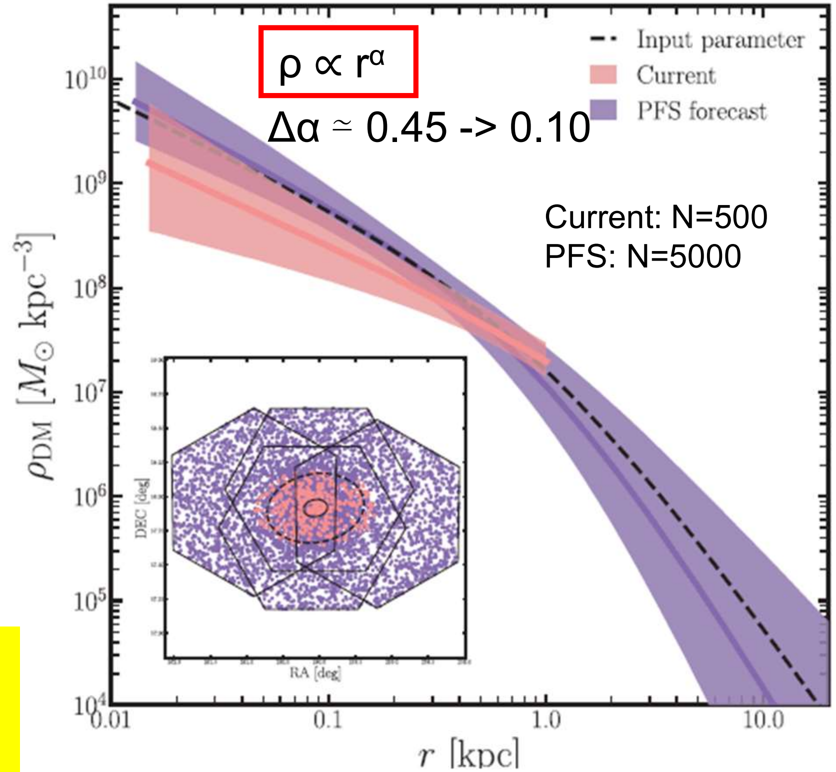
PFS pointings



Mapping dark matter
⇒ Nature of dark matter

Test for Draco Mock

Precise DM density profile with PFS



Selection of the 7 MW dwarf satellites

(~ 1 deg extent, varieties in several aspects)

Fornax

(long SF time scale)

Sculptor

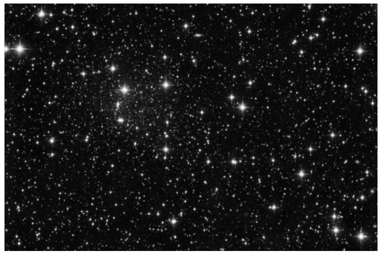
Ursa Minor

(same M_v but different SF time scale)

Sextans

(large r_half~700pc)

Draco



(nearly circular orbit)

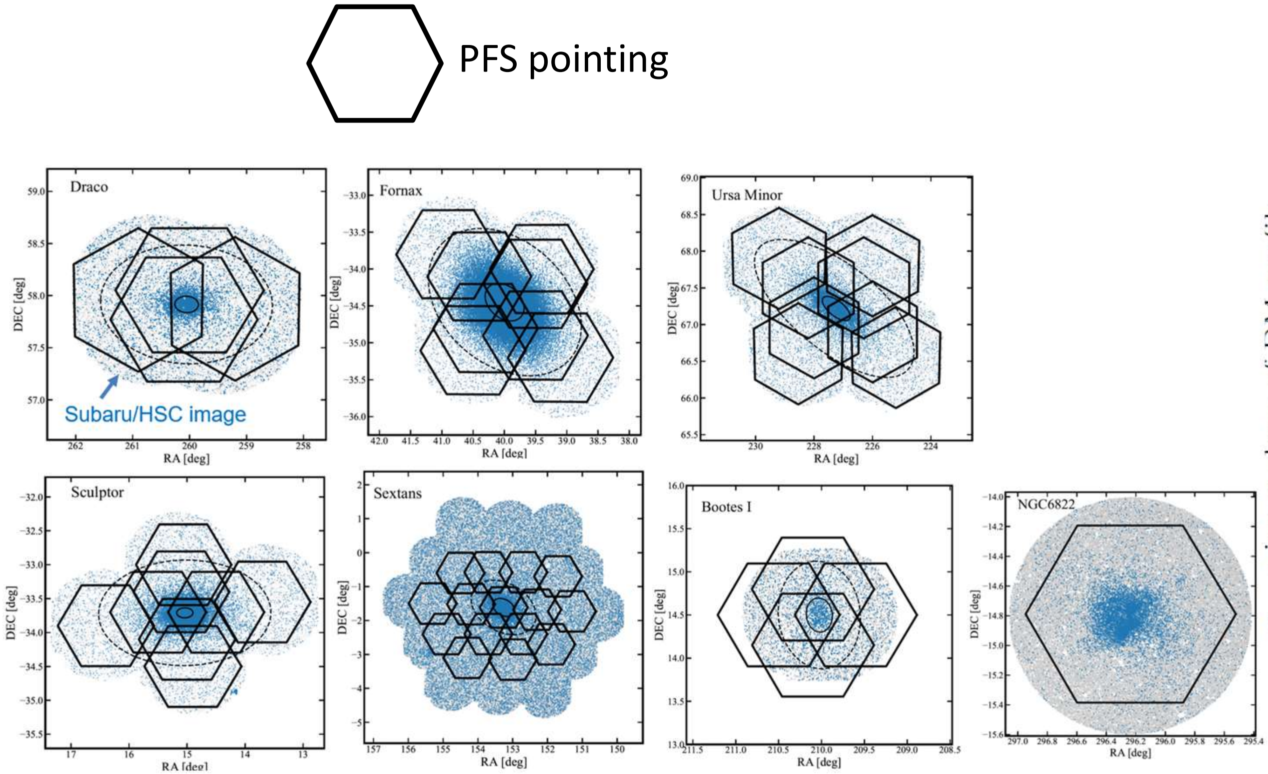
Bootes I

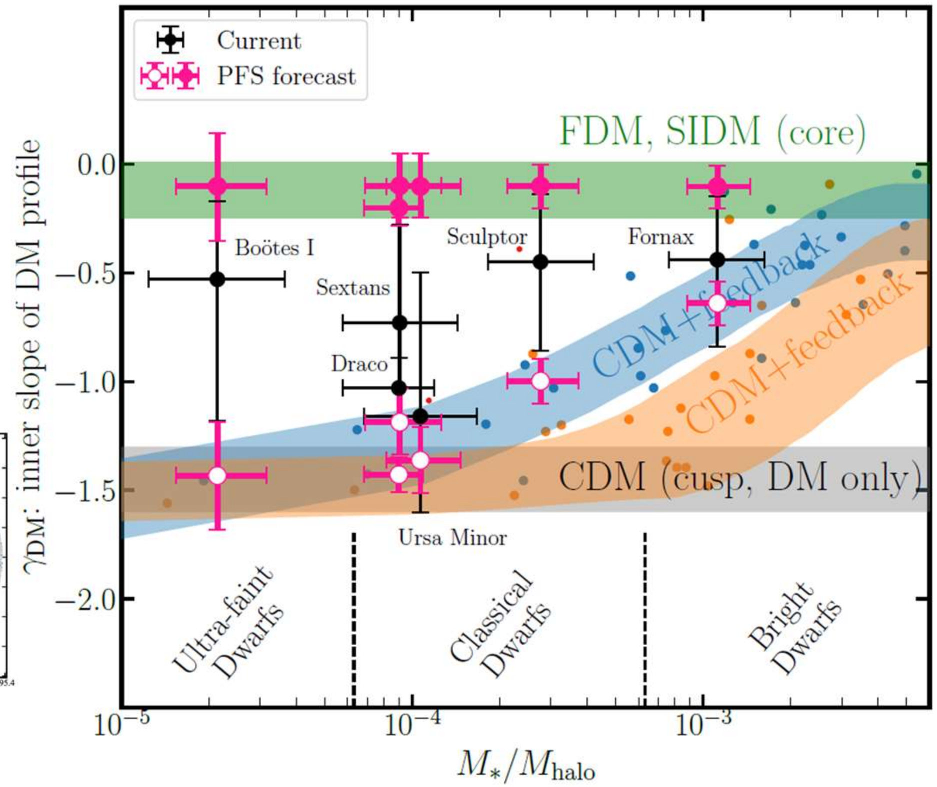
(UFD: M_v=-6.3)

NGC6822

(dIrr, D=460kpc)

Subaru/PFS observation of 7 MW satellites

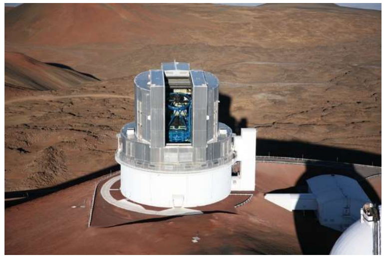




⇒ DM density profiles (CDM? SIDM? FDM?)

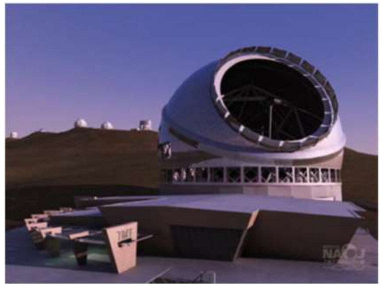
Constraints on the nature of dark matter

Conclusions

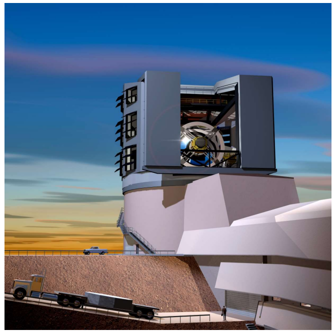


Subaru
HSC
PFS : 2025-
Ultimate:

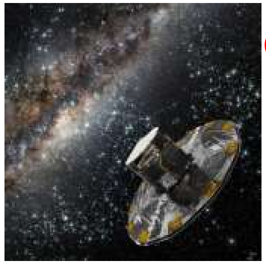
ALMA



TMT
WFOS
HROS
NIRES
2032?

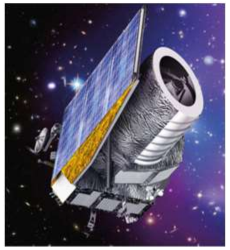


Vera C. Rubin (LSST)
2025-



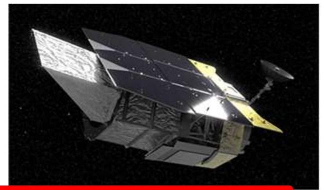
Gaia

JWST
NIRCam
NIRSpec
MIRI
2023-



Euclid
YJH
2023-

JASMINE
NIR astrometry
Late 2031



Nancy Grace Roman Space Telescope (WFIRST)
2026-

Very promising future prospects!