The Assembly of the Milky Way(s)

What we learnt from LAMOST and Gaia

&

What we will learn in near future

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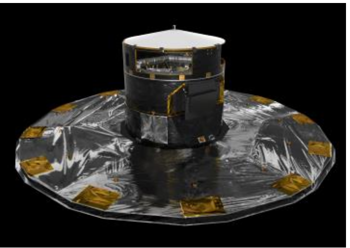
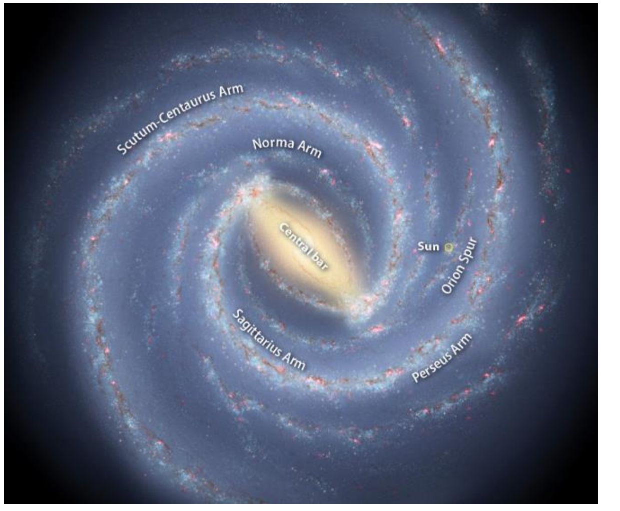


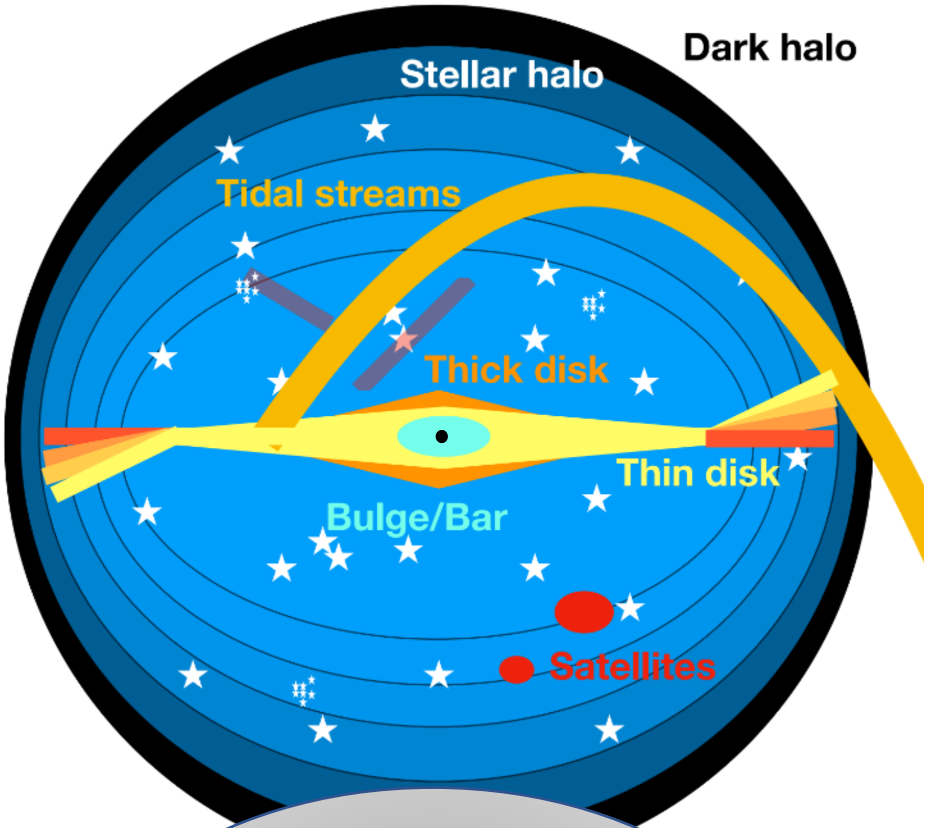
Outlines

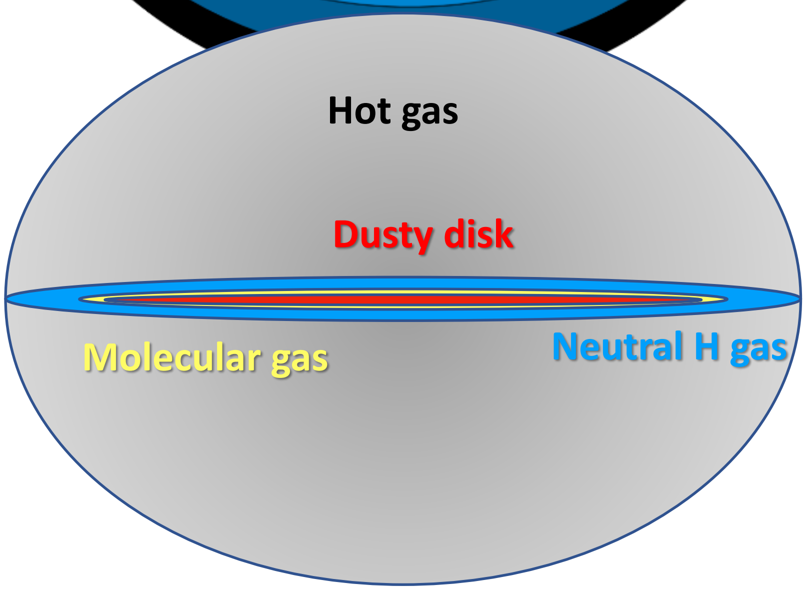
- 1. Overview of the Galaxy
- 2. Some fundamental parameters
- 3. The power of the Gaia + LAMOST
- 4. Updating Milky Way’s size and weight
- 5. Gaia-Sausage-Enceladus
- 6. A shaking disk
- 7. Future
- 8. Summary

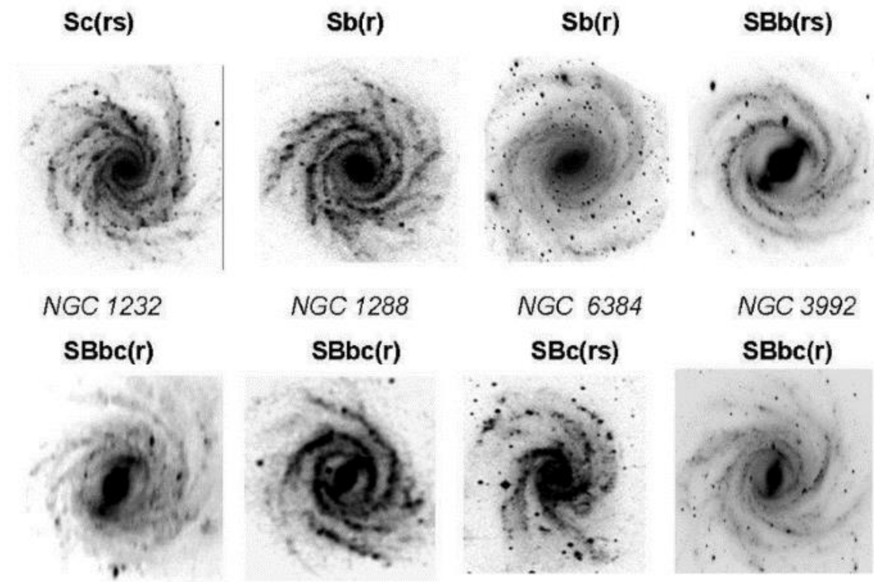


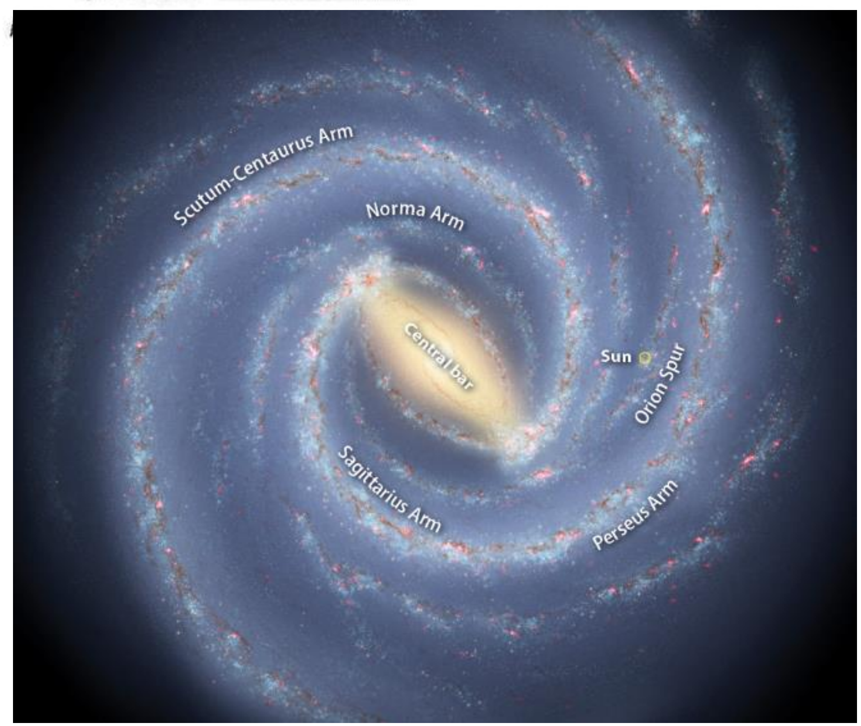
1. Overview of the Galaxy

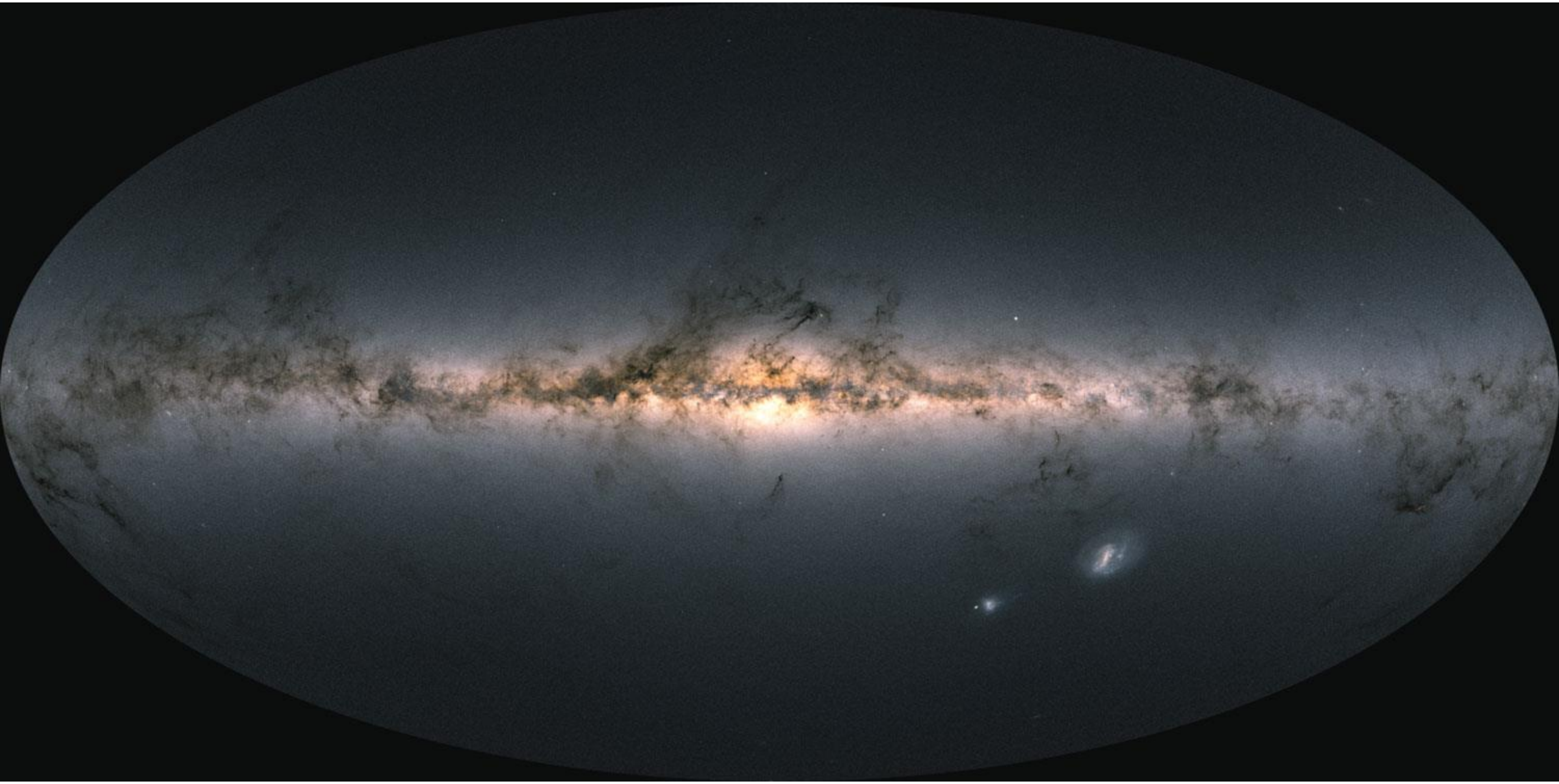

MICHAEL SHAINBLUM


Dark halo
Stellar halo
Tidal streams
Thick disk
Thin disk
Bulge/Bar
Satellites

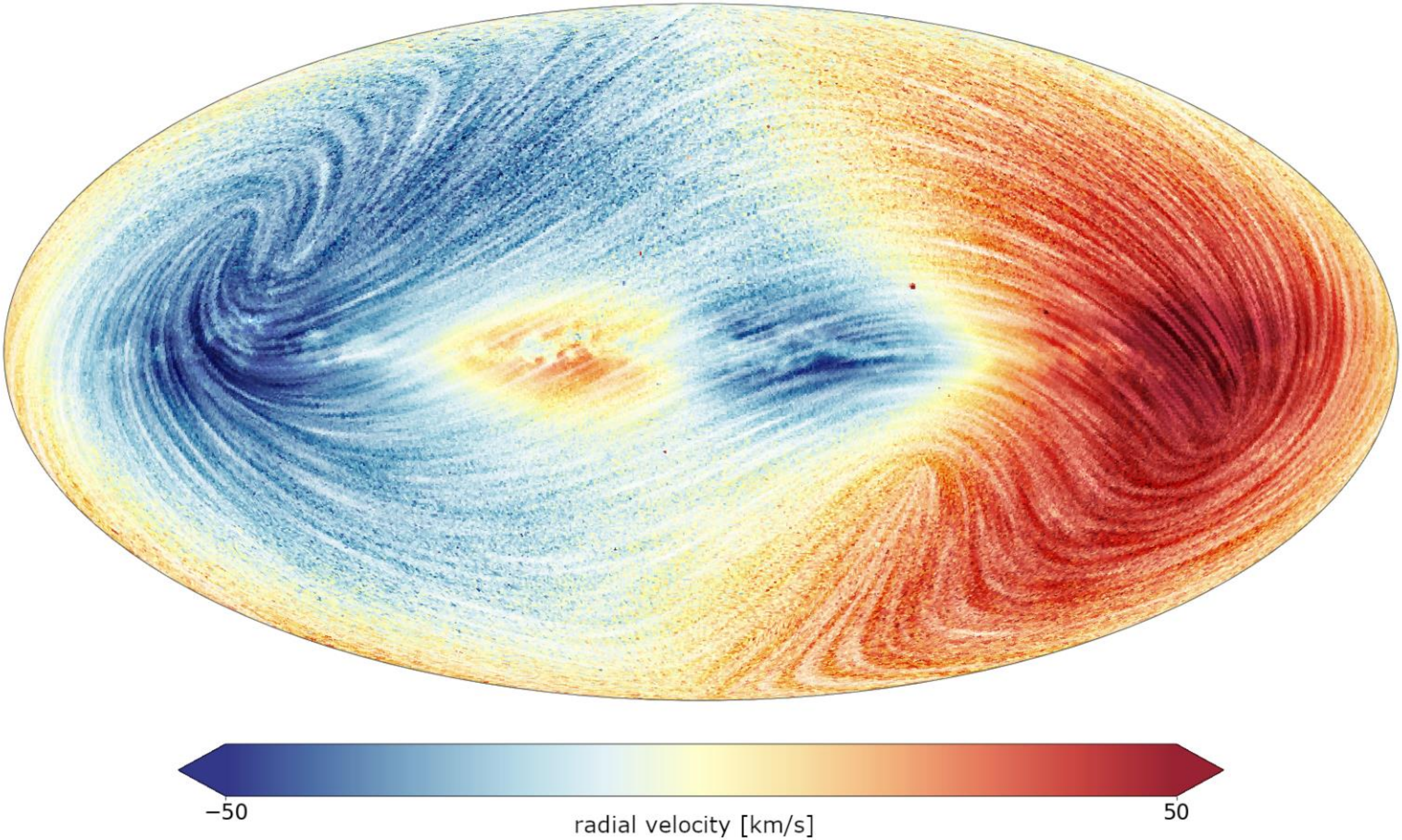

Hot gas
Dusty disk
Molecular gas
Neutral H gas


Sc(rs)
Sb(r)
Sb(r)
SBb(rs)
NGC 1232
NGC 1288
NGC 6384
NGC 3992
SBbc(r)
SBbc(r)
SBc(rs)
SBbc(r)

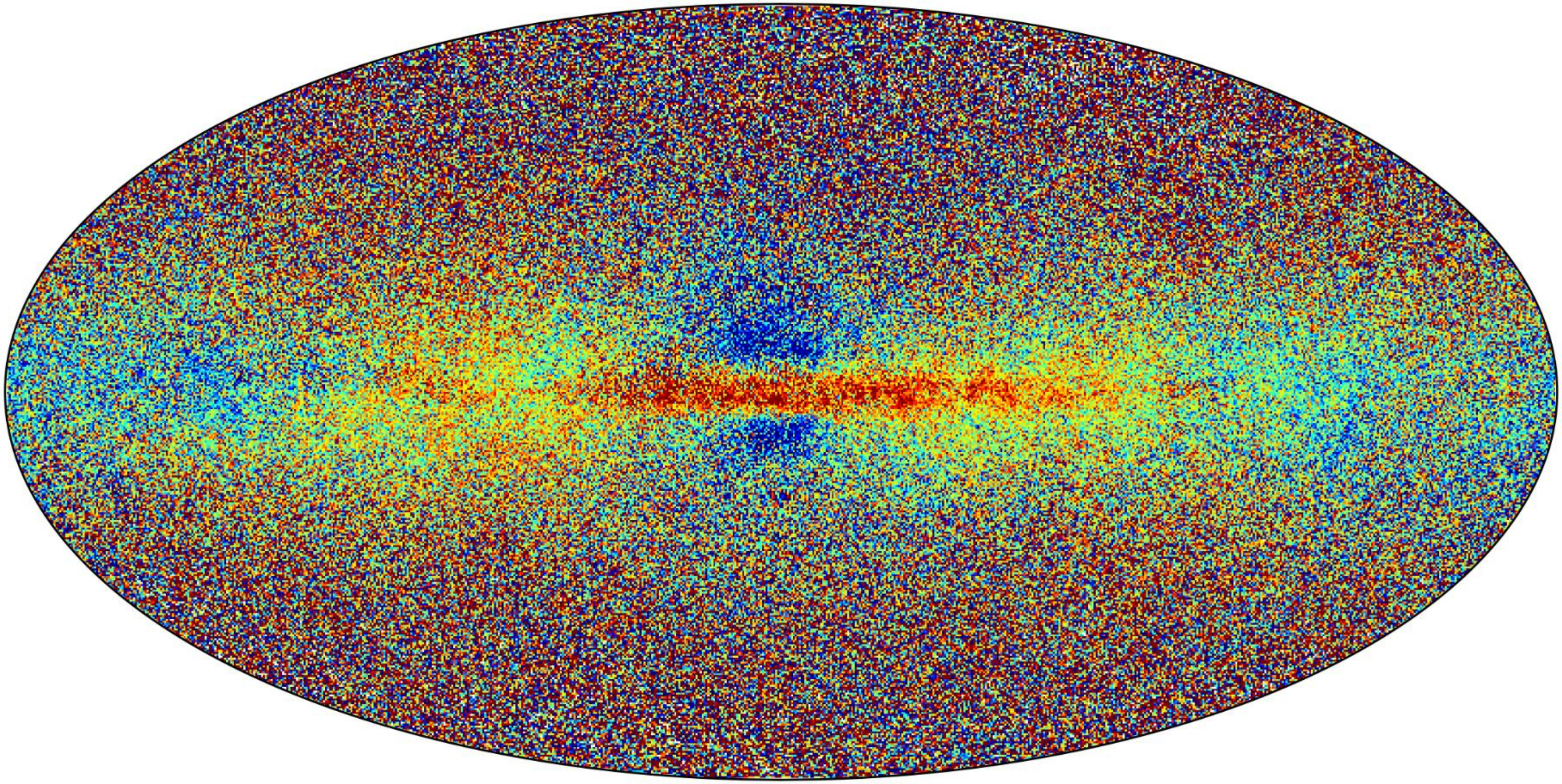

Scutum-Centaurus Arm
Norma Arm
Central bar
Sun
Orion Spur
Sagittarius Arm
Perseus Arm



Velocity map



Metallicity map



2. Some fundamental parameters

$M_\bullet$: $(4.2 \pm 0.2 \times 10^6)\ M_\odot$, mass of Galactic SMBH

$\rho_\bullet(< 125\,\mathrm{AU})$: $5 \times 10^{15}\ M_\odot\ \mathrm{pc}^{-3}$, mass density within pericenter of star S2

r_{infl}: $3.8\,\mathrm{pc}$, SMBH's dynamical influence radius

Halo mass:

M_{sub}: 2-3 $\times 10^8\ M_\odot$ Substructure mass

M_s: 4-7 $\times 10^8\ M_\odot$ Total stellar halo mass

$M_{\mathrm{b}}^{\mathrm{dyn}}$: $1.84 \pm 0.07 \times 10^{10}\ M_\odot$, dynamical mass in VVV bulge region

M_{b}^{*}: $(1.4\text{-}1.7) \times 10^{10}\ M_\odot$, stellar mass in VVV bulge region

M_{hot}: $2.5 \pm 1 \times 10^{10}\ M_\odot$; Galactic corona baryonic mass ($r \lesssim r_{\mathrm{vir}}$)

$M_{\mathrm{bary,tot}}$: $8.8 \pm 1.2 \times 10^{10}\ M_\odot$; Galactic total baryonic mass ($r \lesssim r_{\mathrm{vir}}$)

f_{bary}: $6 \pm 1\%$; Galactic baryonic mass fraction

z^{t}: 300±50 pc, thin disk vertical scalelength at R_0

z^{T}: 900±180 pc, thick disk vertical scalelength at R_0

f_ρ: 3.4%±2.5%, thick / thin disk local density ratio at R_0

f_Σ: 15%±6%, thick / thin disk surface density ratio at R_0

R^{t}: 2.6±0.5 kpc, thin disk radial scalelength

M^{t}: $4 \pm 1 \times 10^{10}\ M_\odot$, thin disk stellar mass

Σ_{tot}: 70±5 $\mathrm{M}_\odot\ \mathrm{pc}^{-2}$, local mass surface density $|z| \leq 1.1$ kpc at R_0

ρ_{tot}: 0.097±0.013 $\mathrm{M}_\odot\ \mathrm{pc}^{-3}$, local mass density at R_0

ϵ_{tot}: 0.49±0.13 GeV cm^{-3}, local dark matter energy density at R_0

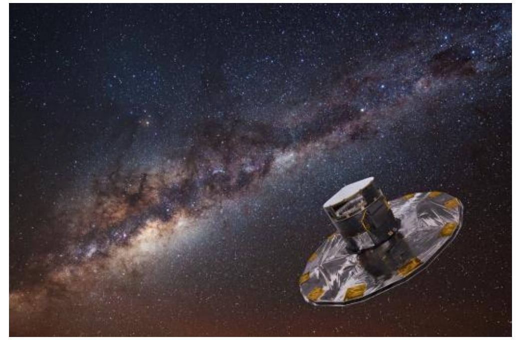
R^{T}: 2.0 ± 0.2 kpc, thick disk radial scalelength

M^{T}: $8 \pm 3 \times 10^9\ M_\odot$, thick disk stellar mass

Bland-Hawthorn & Gerhard 2016

Spectral types
Stellar parameters
Chemical abundances
Radial velocities
Time-domain spectra

+

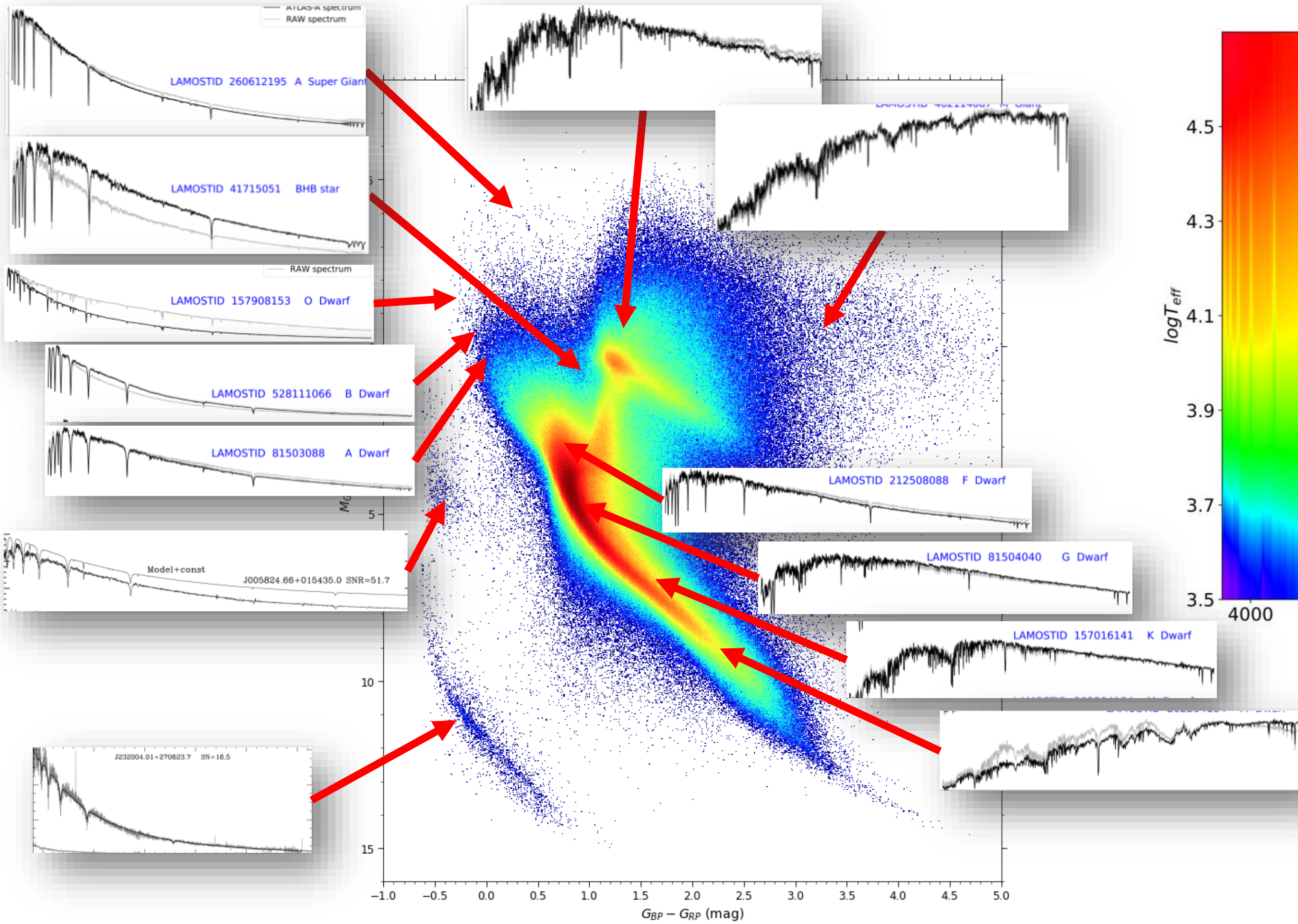


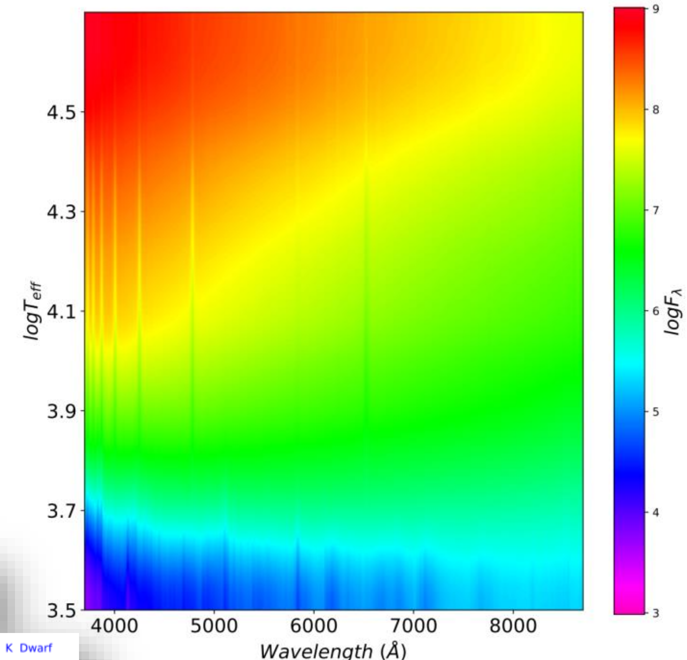
Parallaxes
Proper motions
(Time-domain) Photometries
Stellar parameters for bright star
Radial velocities for bright stars

=GaMOST

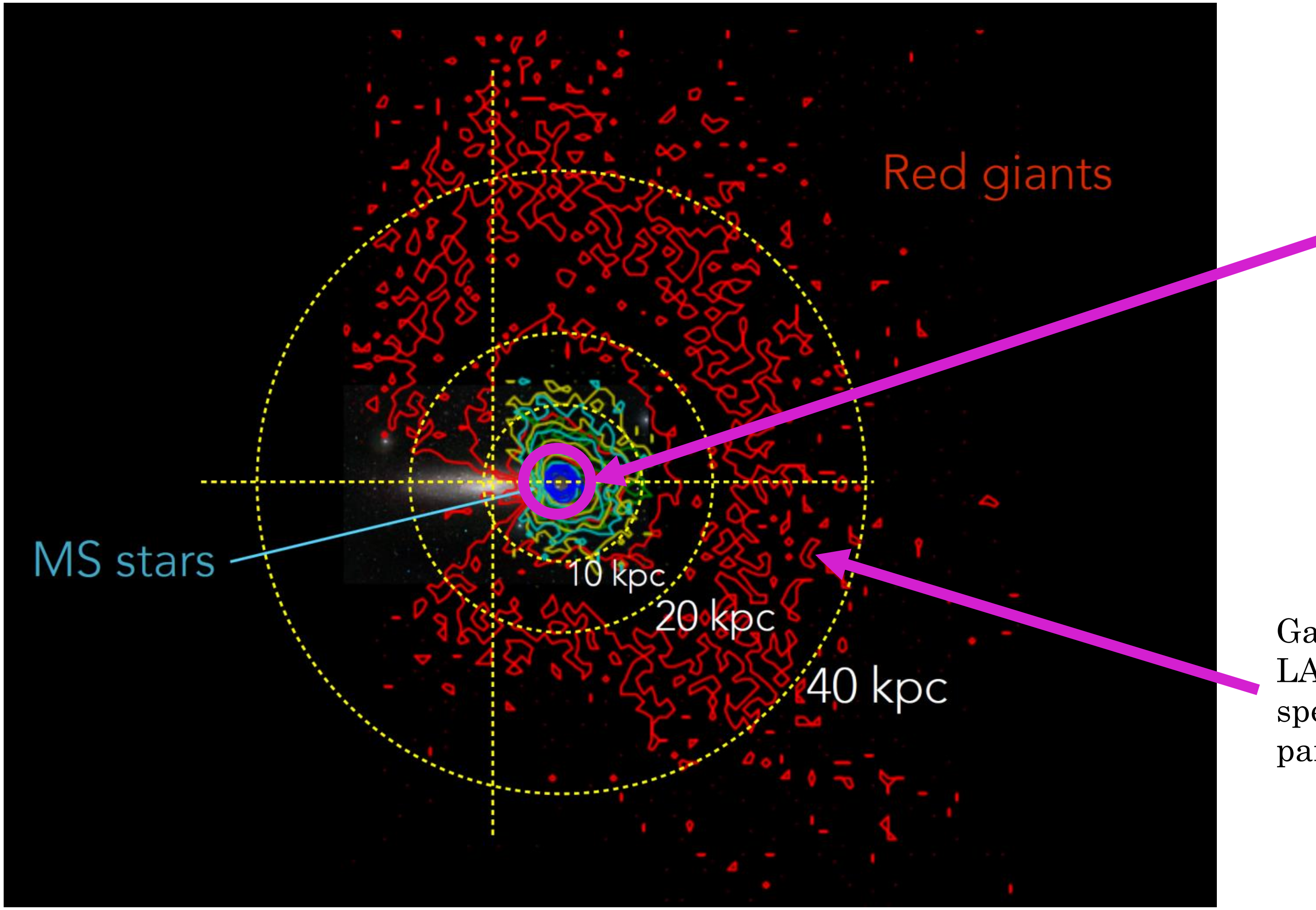
6D phase coordinates
Chemical abundances
Stellar ages
(Time-domain)

3. The power of Gaia+LAMOST





ainbow of stellar
fective temperatures

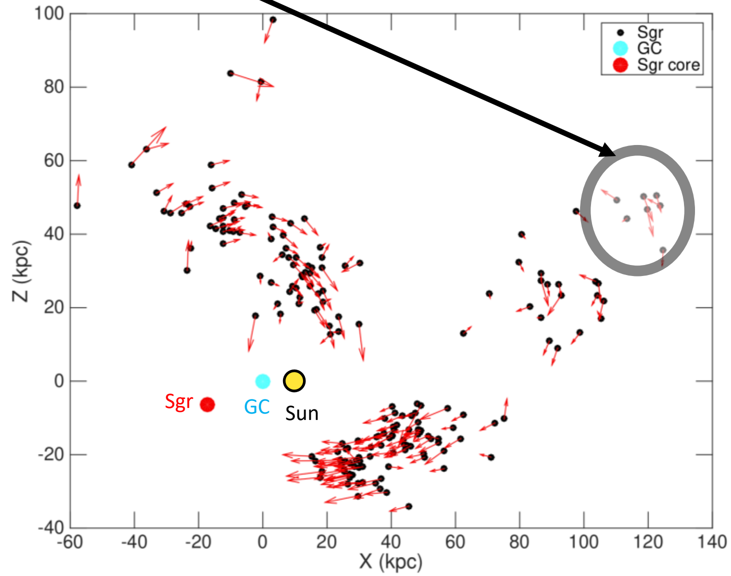


Gaia parallax/proper motion + LAMOST spectra

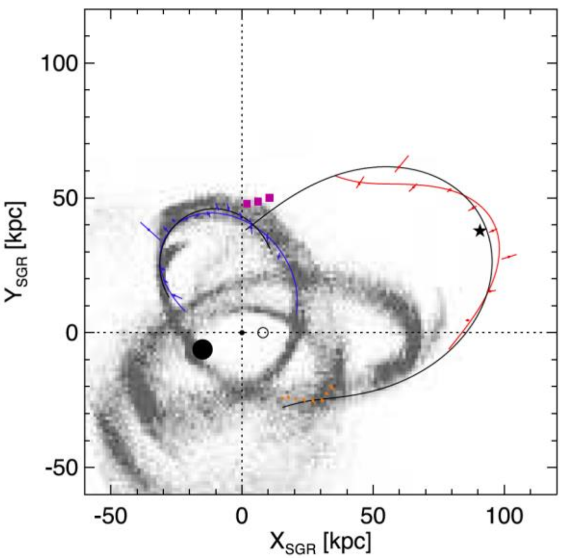
Gaia proper motion + LAMOST spectra/spectroscopic parallax

The far end of the Sgr stream

- LAMOST M-giants + Gaia proper motions
  - We identified the farthest members of Sgr streams beyond 100 kpc



Li, **LC** et al. 2019

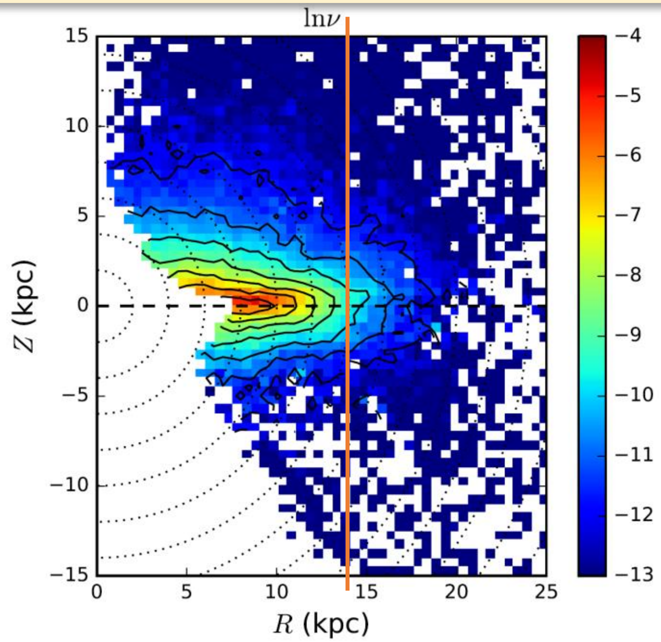


Belokurov+2014

4. Updating Milky Way’s size and weight

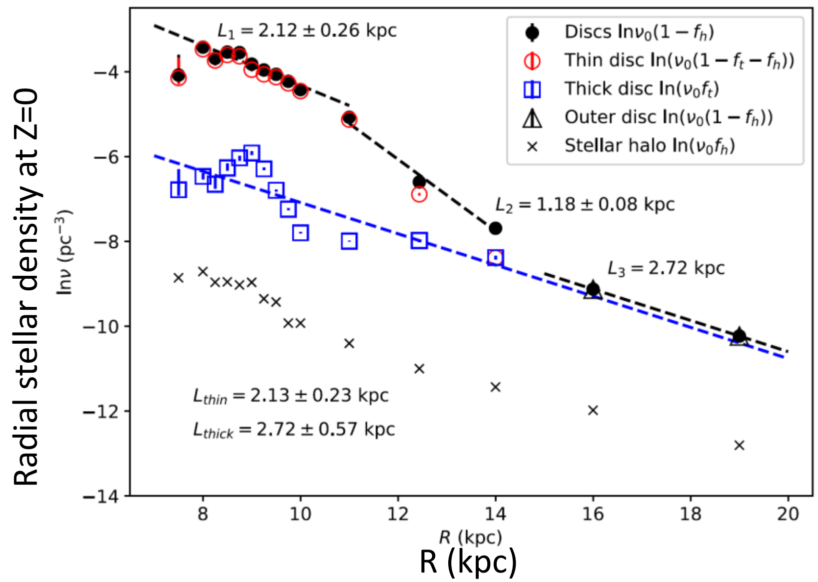
Frontiering the edge of the Galactic disk

- The Galactic disk extends beyond 20 kpc from the GC



LC et al. 2017

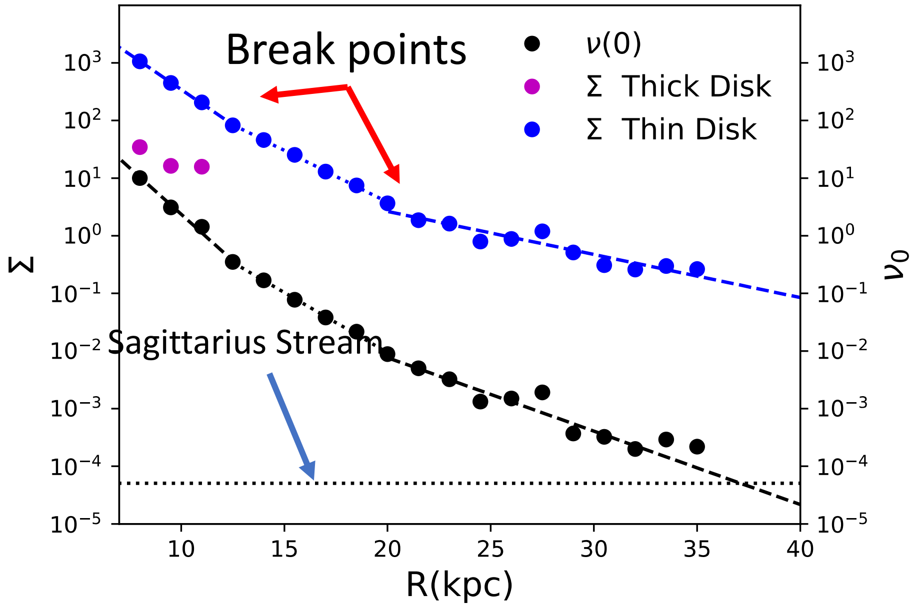
- ~70,000 disk-like RGB stars
- Type II+III radial density profile

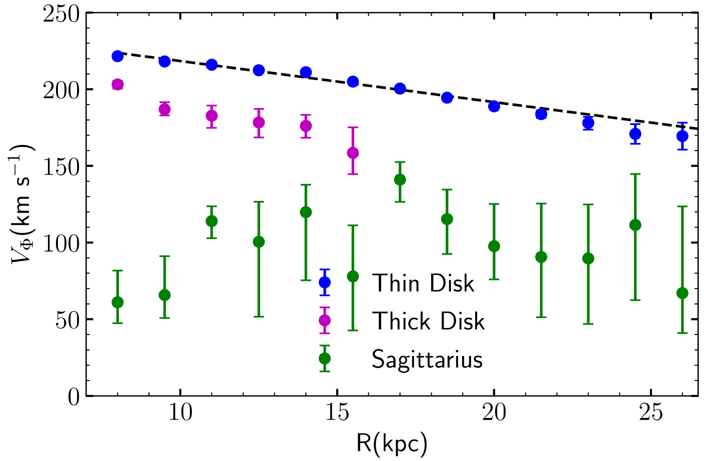


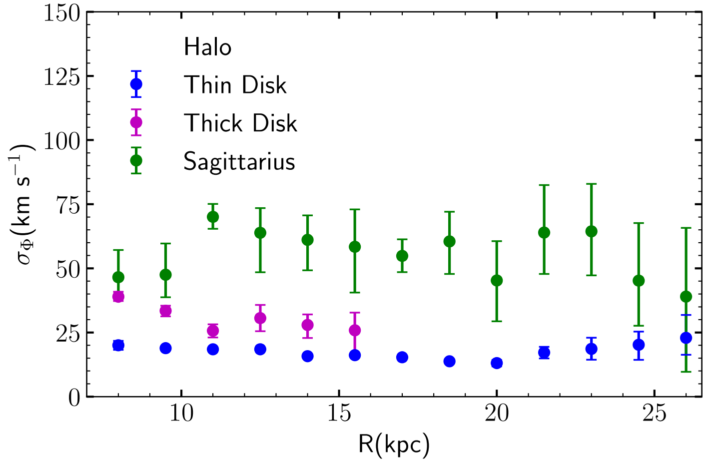
Wang, **LC** et al. 2018

Frontiering the edge of the Galactic disk

- The thin disk extends to around 35 kpc with M giant stars
- The thick disk ends around 15.5 kpc
- Two break points along the density profile







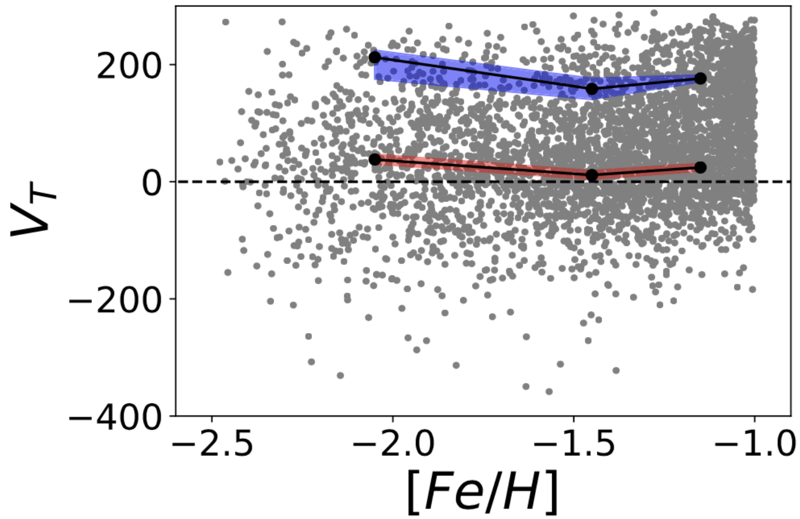
Tian, **LC** et al. submitted

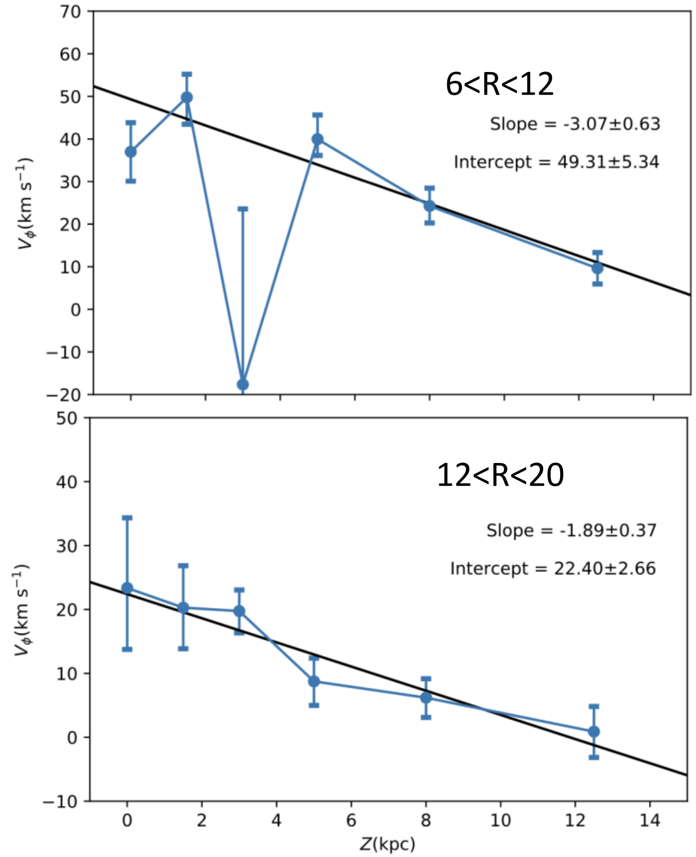
Rotation of the halo

- Differential rotation
  - K giant from LAMOST DR5+Gaia DR2
  - VT decreases with |Z| and R
  - Indicating an oblate halo profile

- Solar neighborhood
  - K giant from LAMOST DR5+Gaia DR2
  - $V_T = +27^{+4}_{-5}\ km/s$
  - Not correlated with [Fe/H]

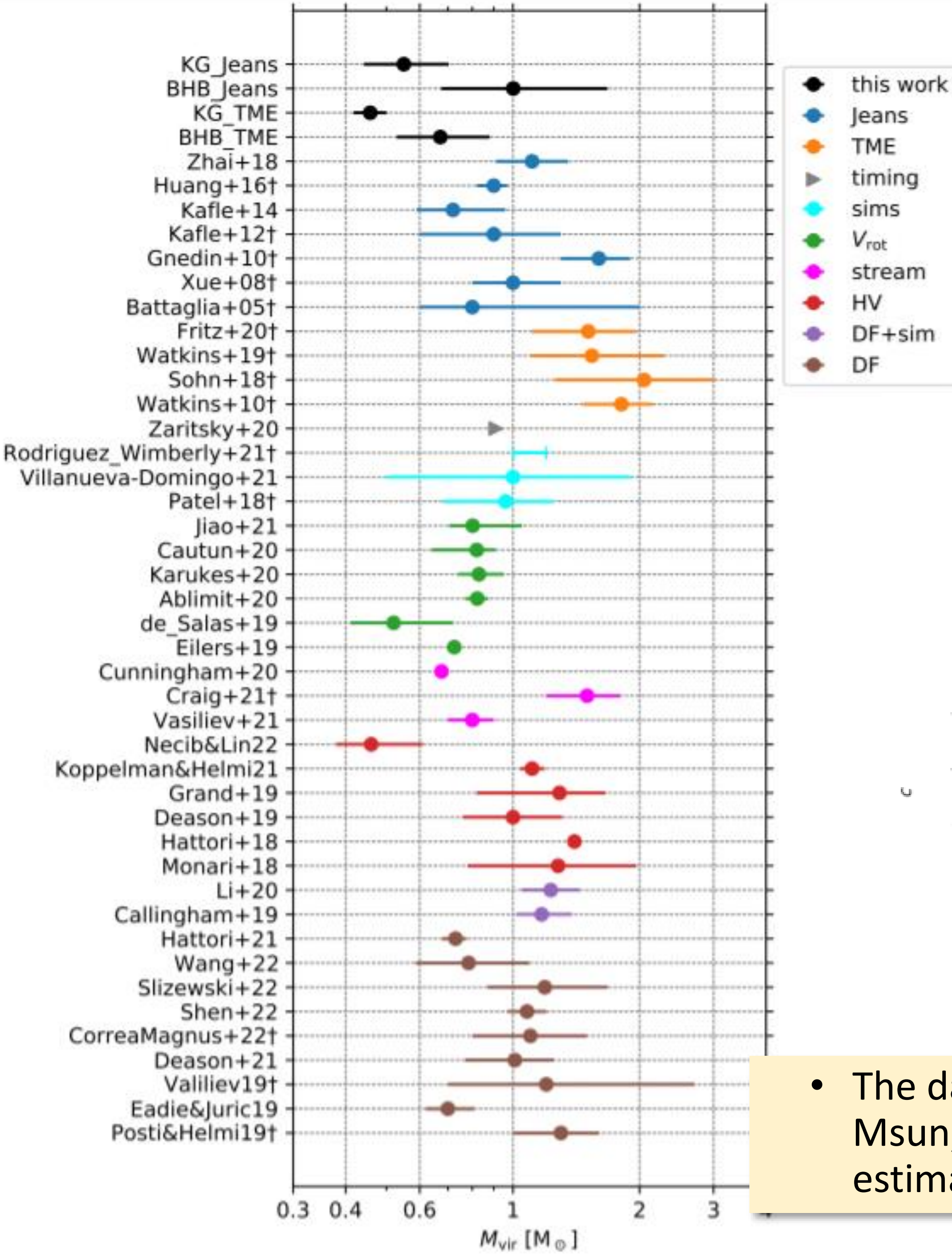
Tian, **LC** et al. 2019

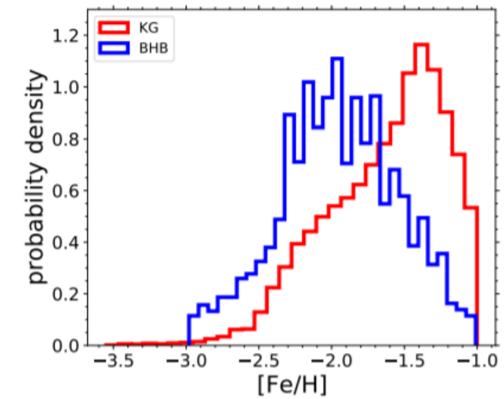


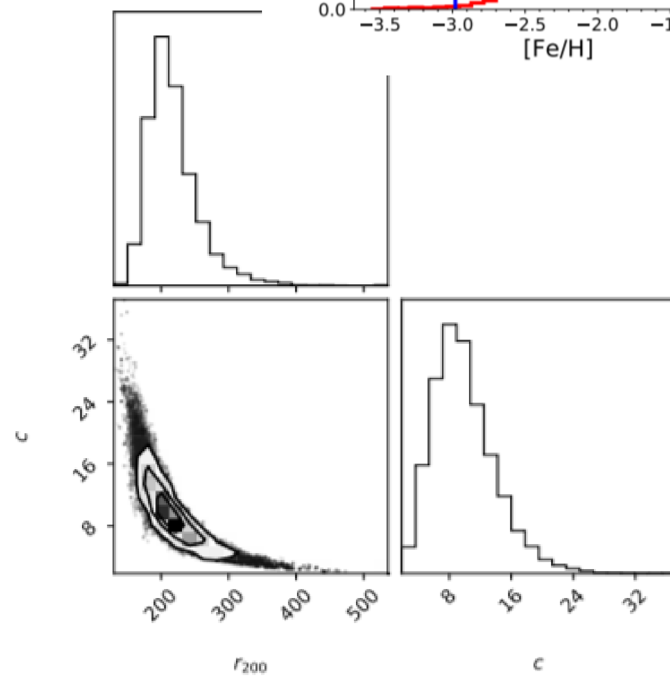


Tian, **LC** et al. 2020

Bird, Xue, **LC** et al. 2022





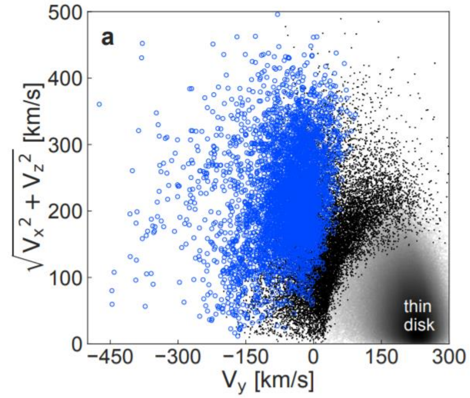


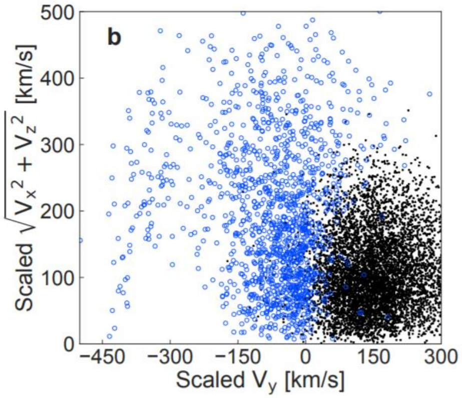
- The dark matter halo is around 5×10^{11} Msun, seems lighter than previous estimations

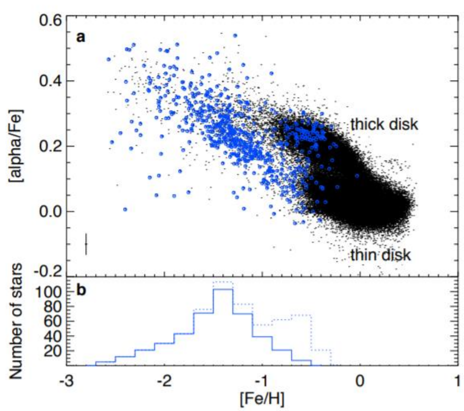
5. Gaia-Sausage-Enseladus

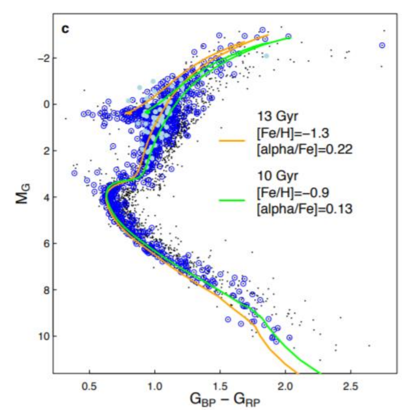
The cannibal Milky Way

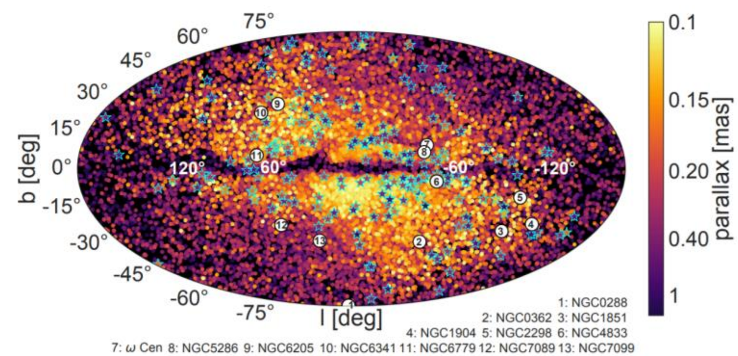
- Helmi et al. (2018) found a group of stars likely the debris of an accreted galaxy: Gaia-Enseladus



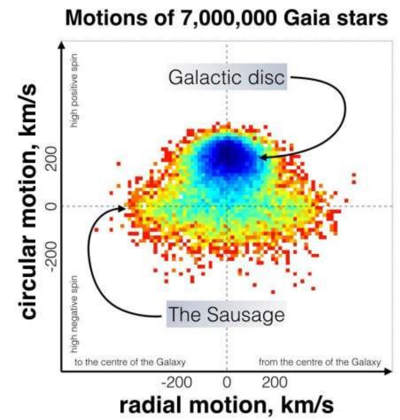




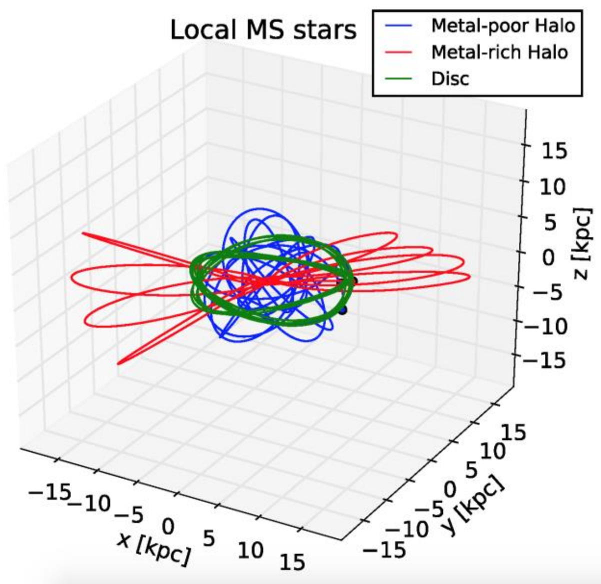


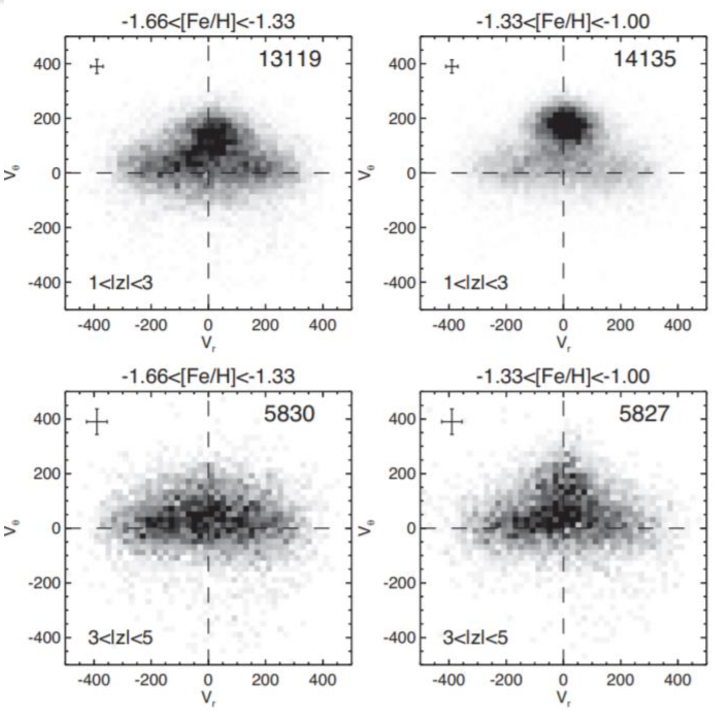


The cannibal Milky Way



- Gaia-Sausage is found in velocity space, showing a radially accreted debris of a probably heavy satellite

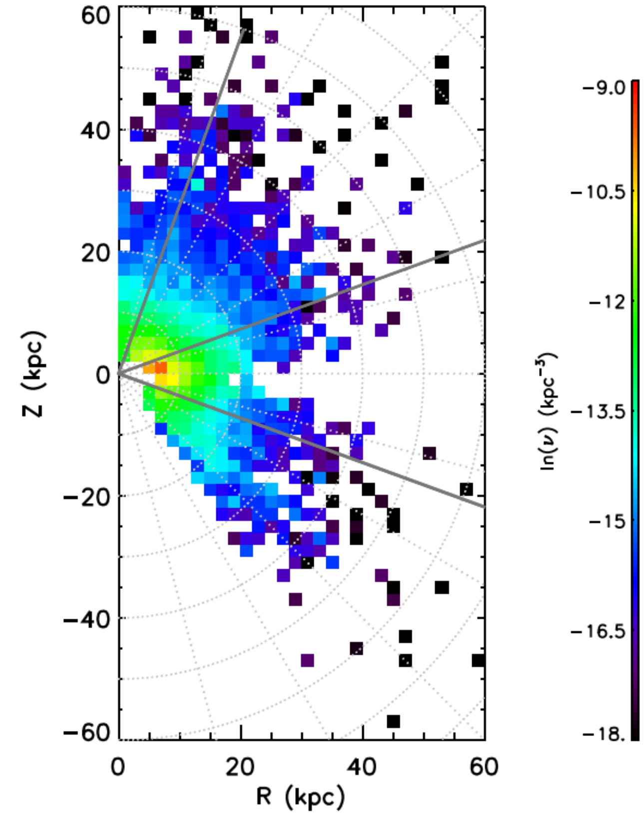


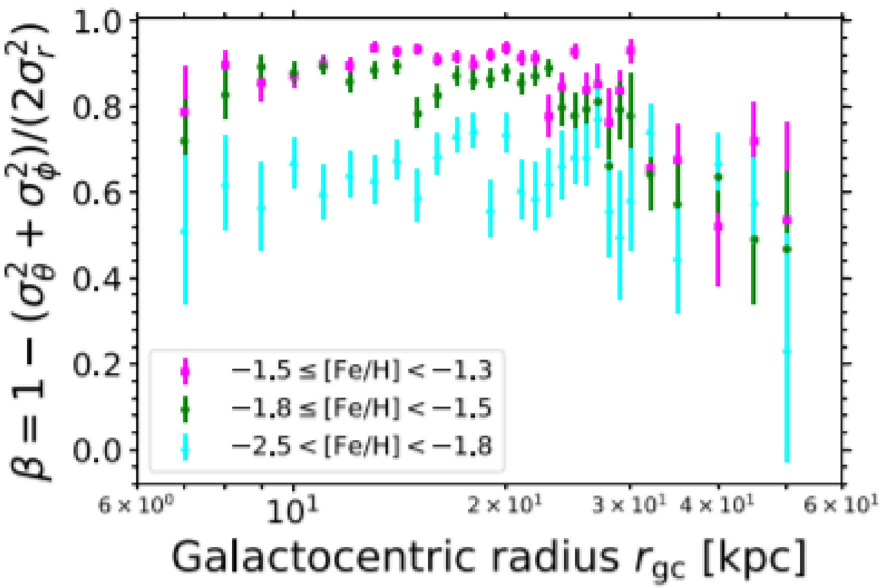


Belokurov et al. 2018

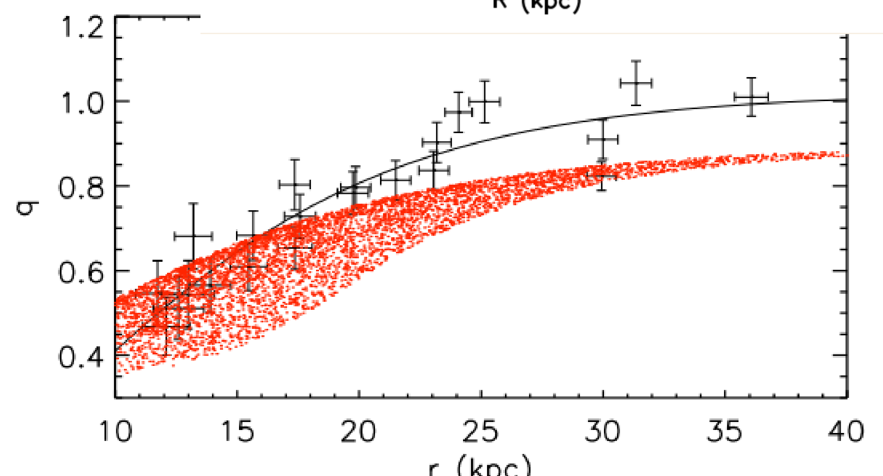
Is this a single merger or many merger events?

- The anisotropy is pretty large in a large volume in the halo
- Gaia Sausage ends at ~30 kpc?
- Is Gaia Sausage responsible for the oblate shape stellar halo within 30 kpc?





Bird, Xue, **LC** et al. 2019



Xu, **LC** et al. 2018

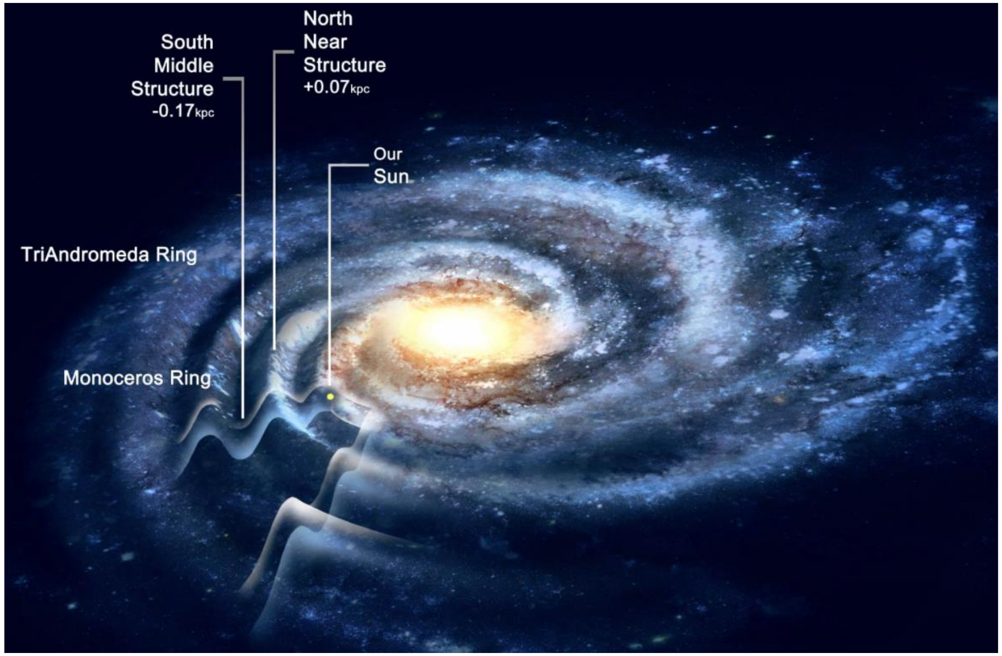
6. A Shaking disk

The MW is in disequilibrium

Carlin...**LC** et al. 2013

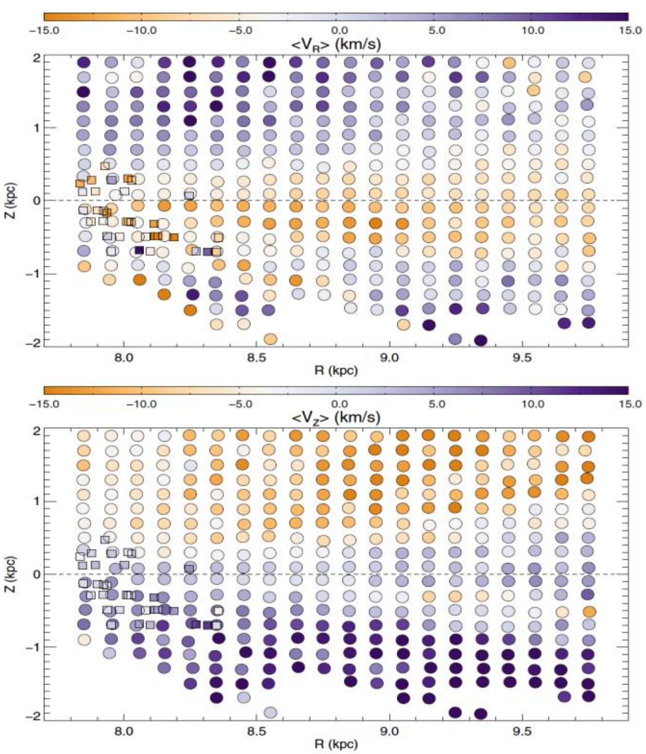
- Corrugation in outer disk
- Disk is larger than 20 kpc

Xu...**LC** et al. 2015



Z

Z



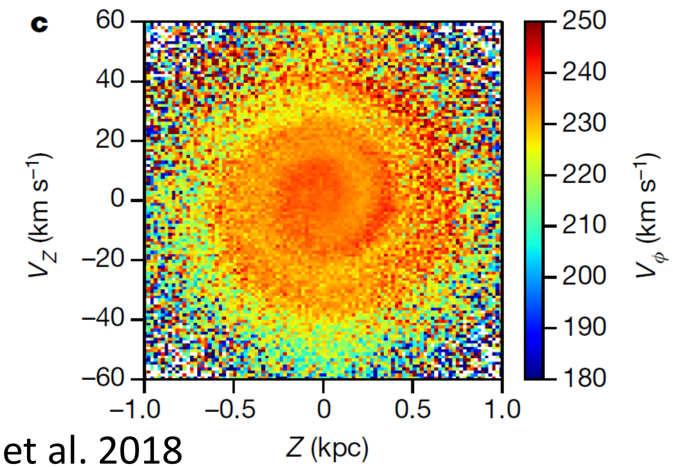
VR

VZ

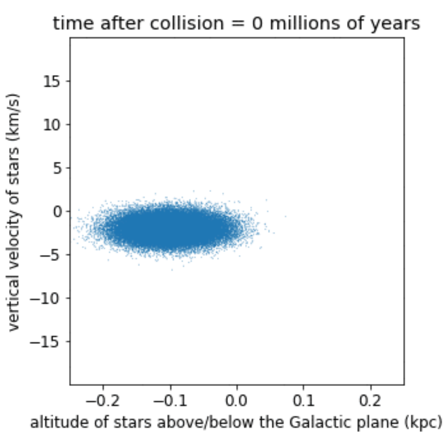
R

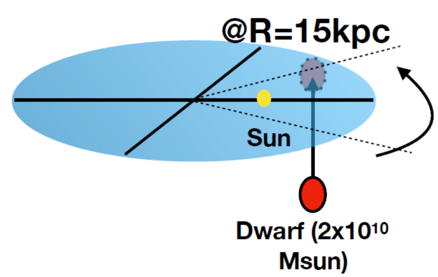
The MW is in disequilibrium

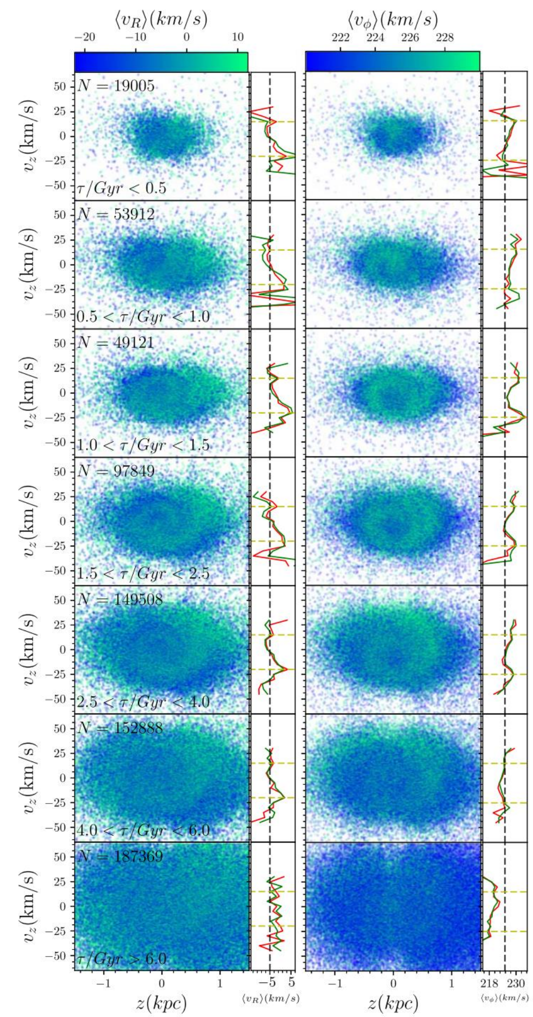
- Phase spiral (snail)



Antoja et al. 2018



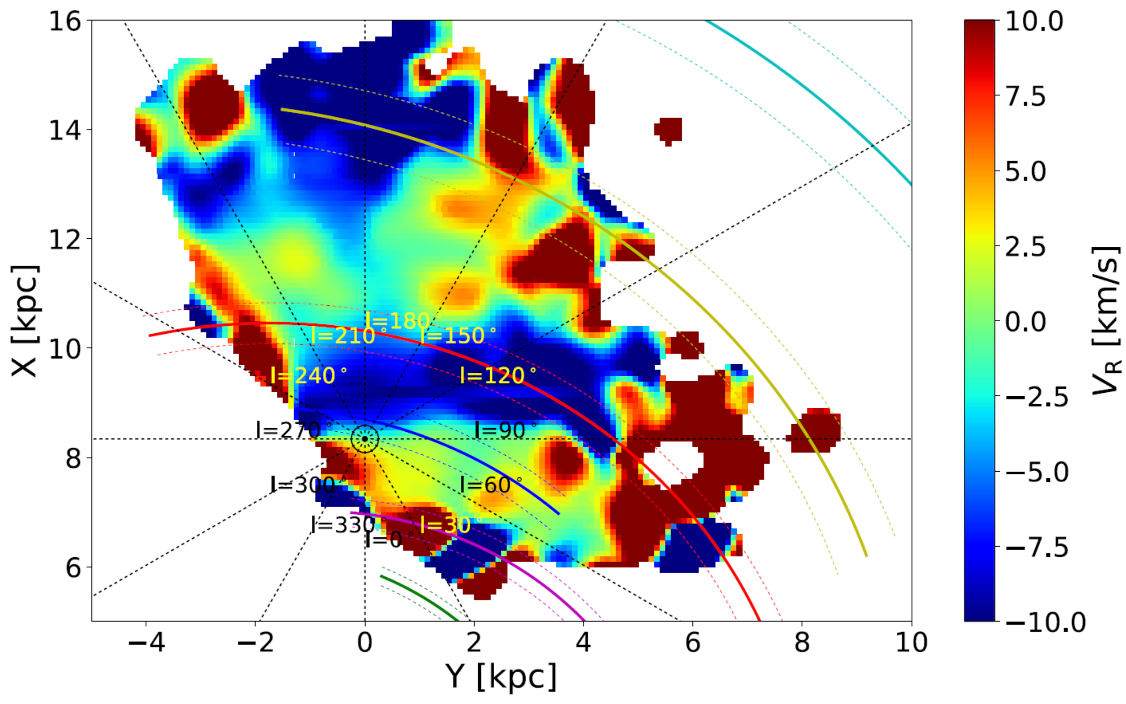




Tian, **LC** et al. 2018

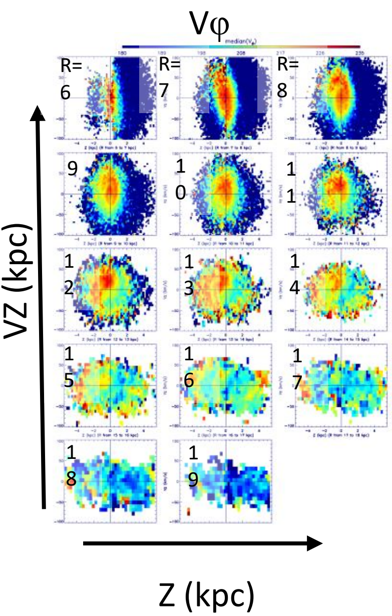
The asymmetric motion in the outer disk

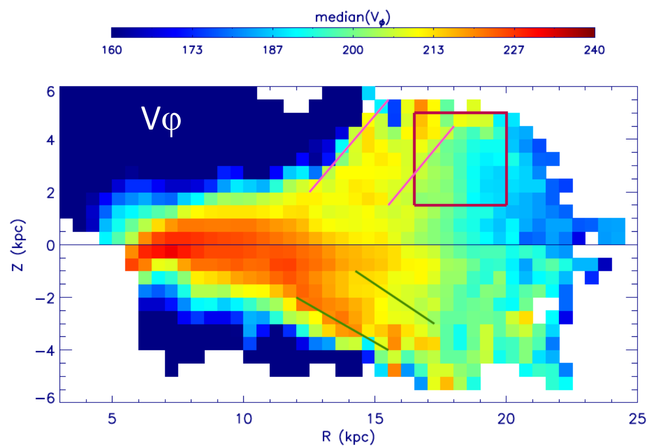
- The young OB stars show ripple-like radial velocity in the global disk
- It obviously not correlated with the spiral arms, but may be the perturbation inherited from the gaseous disk

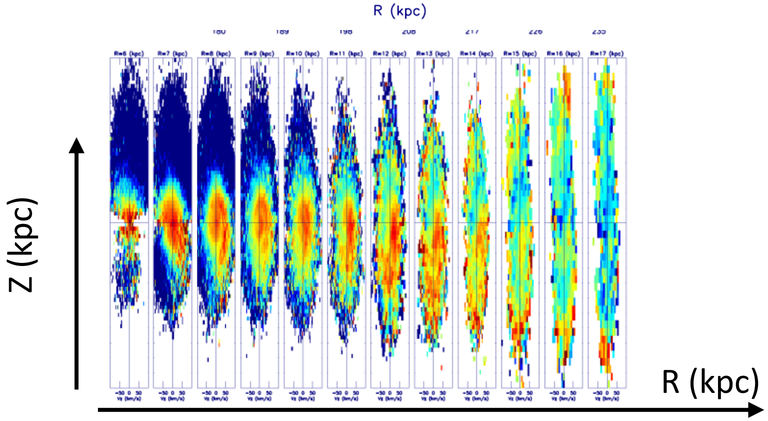


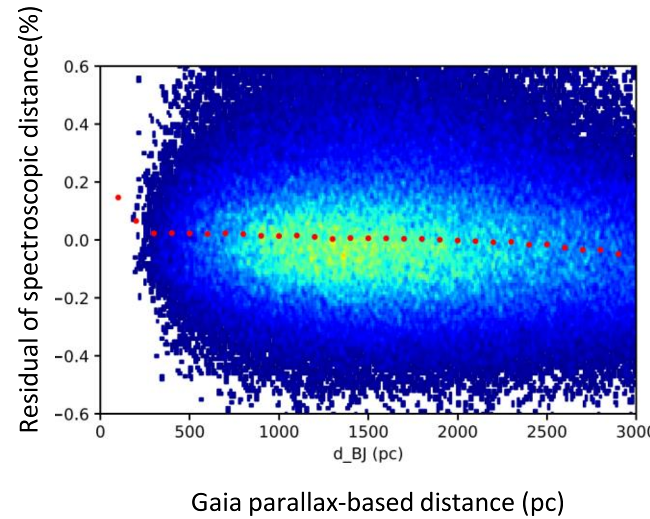
Cheng, **LC** et al. 2019

The asymmetric motion in the outer disk



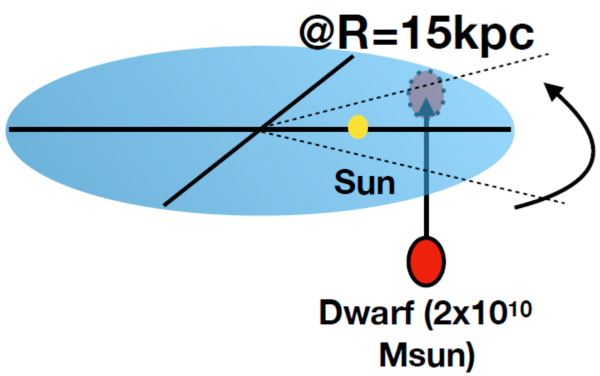


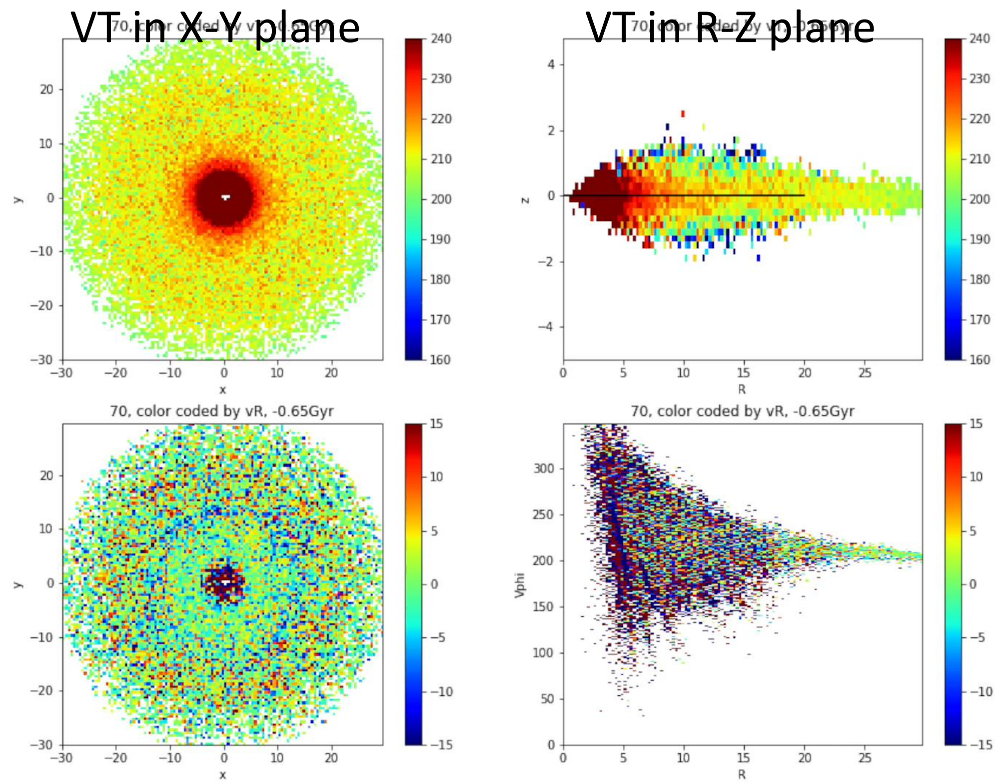




Xu, **LC** et al. 2020

The asymmetric motion in the outer disk



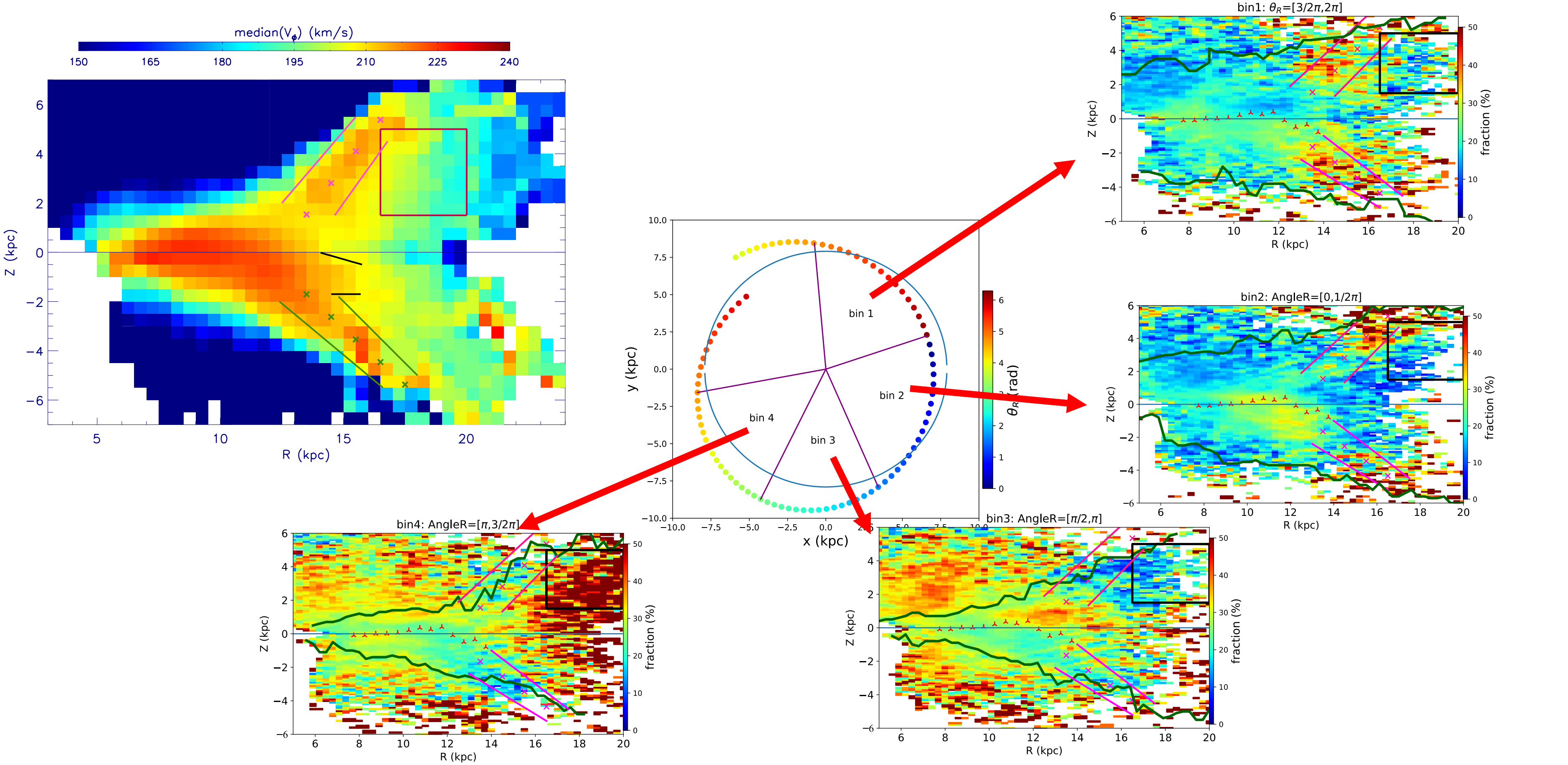


VR in X-Y plane

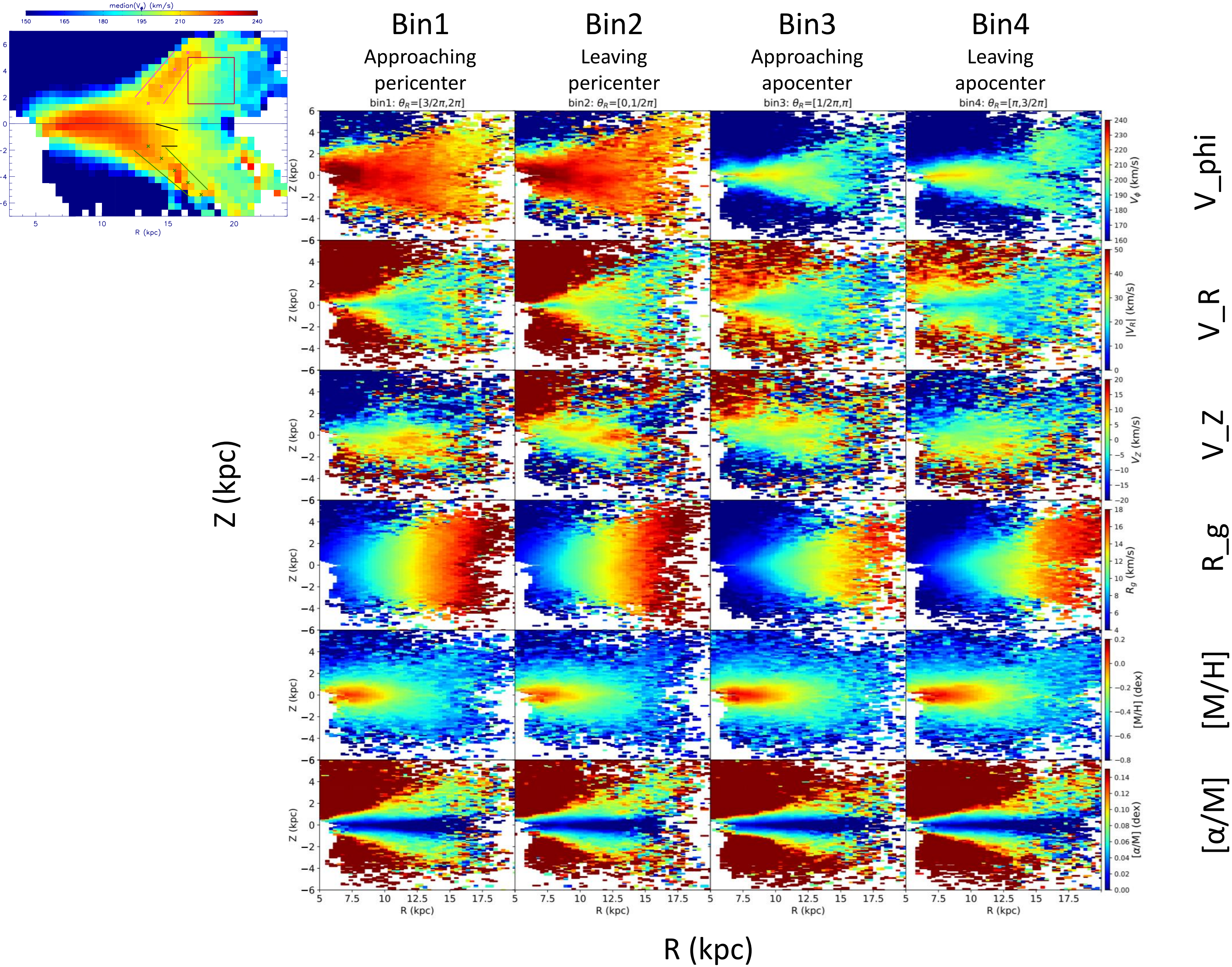
VR in R-VT plane

- Spec. parallax is calibrated by Gaia's
- Phase spirals are extended from 7 to 15 kpc
- Spirals are projected to Vphi map in R-Z plane to explain the complicated asymmetric motion
- It is evident that a heavy dwarf has been bombarded the disk a few hundred million years ago

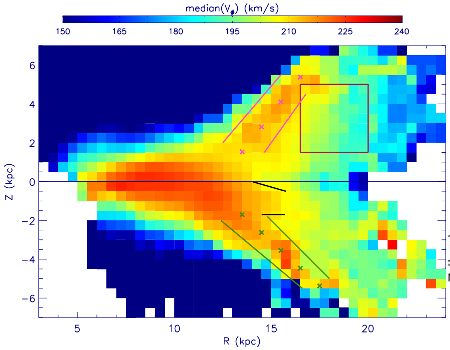
Asymmetric substructures based on the conjugate angle of the radial action

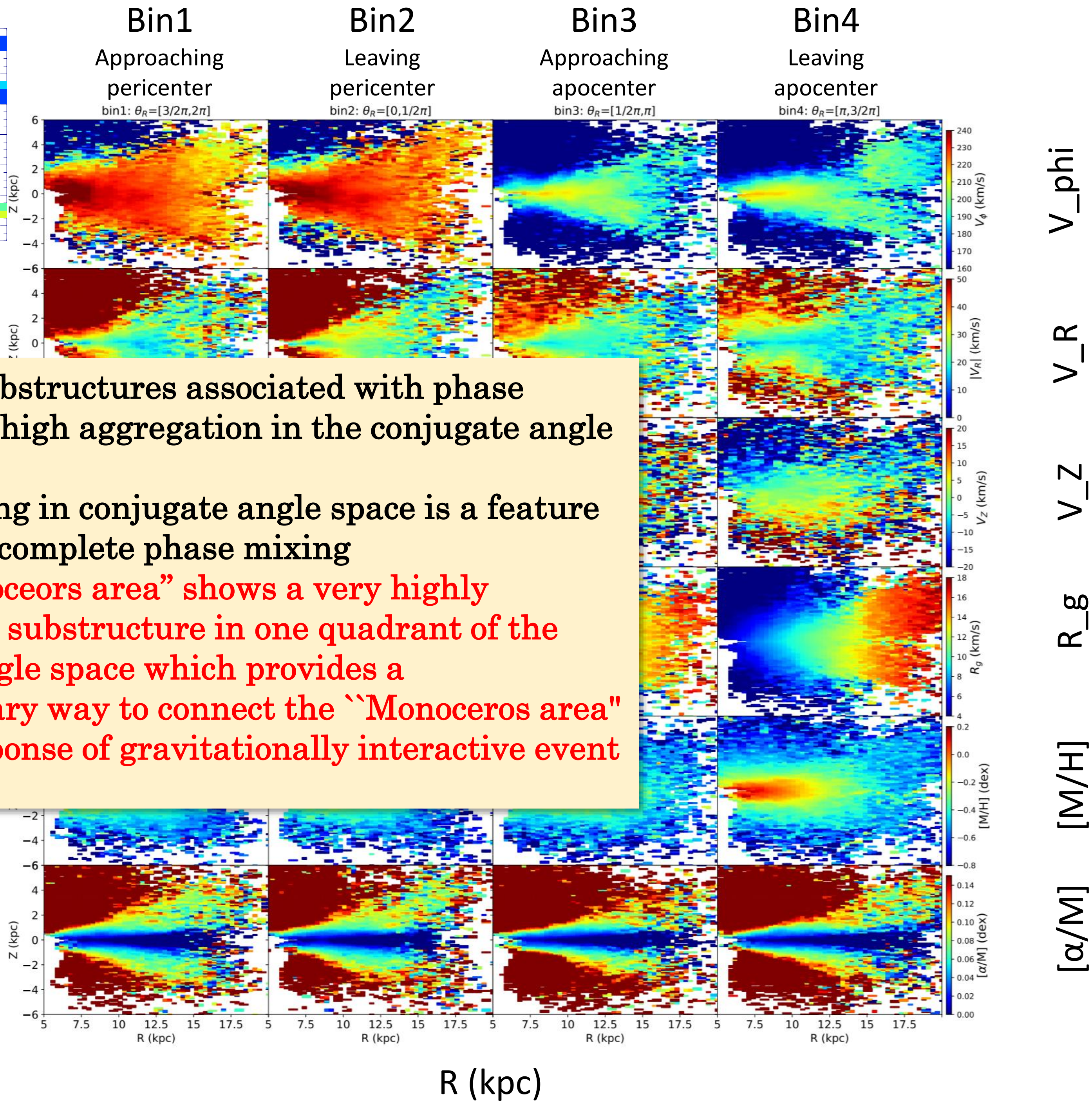


Xu, **LC** et al. submitted



median(V_φ) (km/s)
Z (kpc)
R (kpc)
Bin1
Approaching pericenter
Bin2
Leaving pericenter
Bin3
Approaching apocenter
Bin4
Leaving apocenter
bin1: θ_R=[3/2π,2π]
bin2: θ_R=[0,1/2π]
bin3: θ_R=[1/2π,π]
bin4: θ_R=[π,3/2π]
V_φ (km/s)
|V_R| (km/s)
V_Z (km/s)
R_g (km/s)
[M/H] (dex)
[α/M] (dex)
V_phi
V_R
V_Z
R_g
[M/H]
[α/M]
Z (kpc)
R (kpc)





- all of the substructures associated with phase spirals show high aggregation in the conjugate angle space
- The clumping in conjugate angle space is a feature of ongoing incomplete phase mixing
- The ``Monoceors area” shows a very highly concentrated substructure in one quadrant of the conjugate angle space which provides a complementary way to connect the ``Monoceros area" with the response of gravitationally interactive event

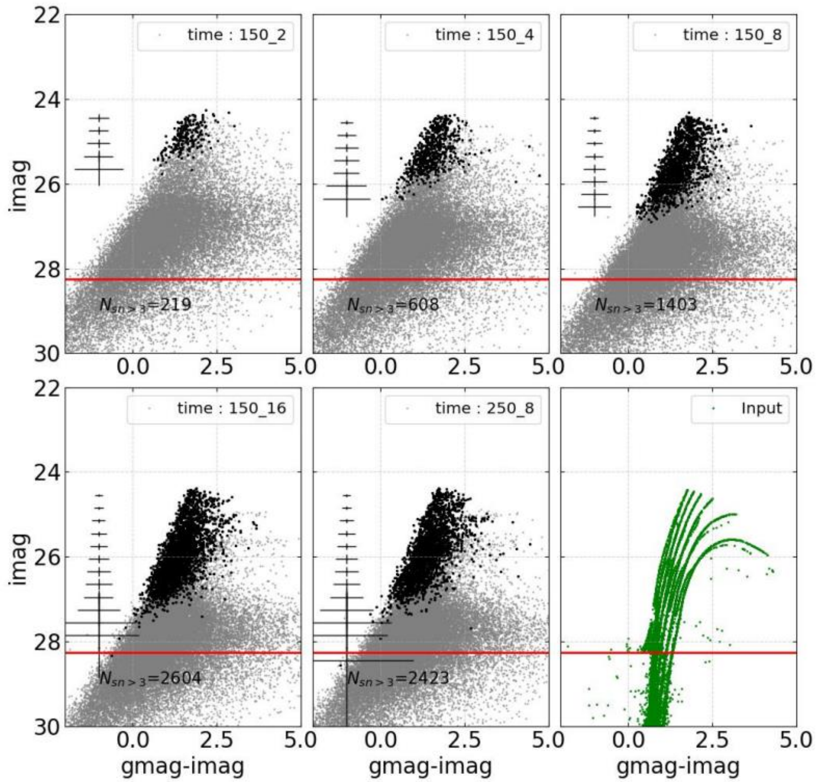
7. Future

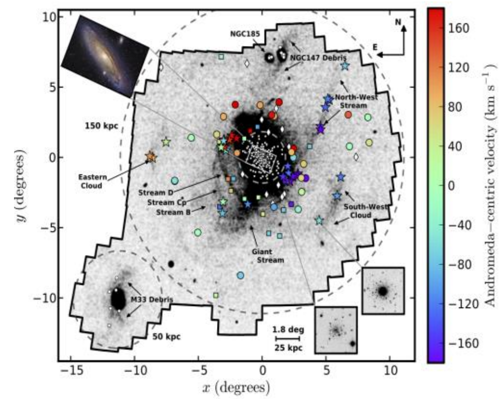
CSST is able to do a SURVEY within a few Mpc

- Where individual stars (mainly giants & supergiants) can be resolved and can be studies as what we have done in the Milky Way
- Therefore, we may obtain information of around one hundred galaxies, big or small, blue or red, young or old, spiral or irregular, …
- These sample can provide unique statistics to show whether our Milky Way is spectral or common

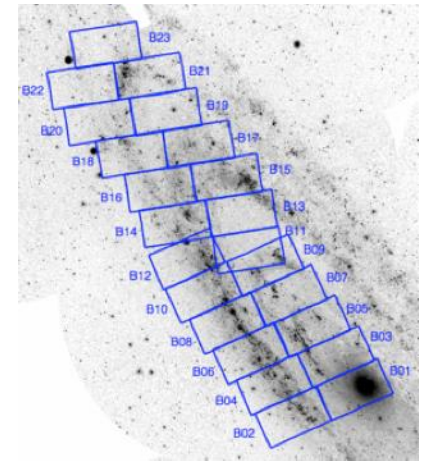
Distance : 4.0 Mpc, i vs (g-i)

Yang et al.



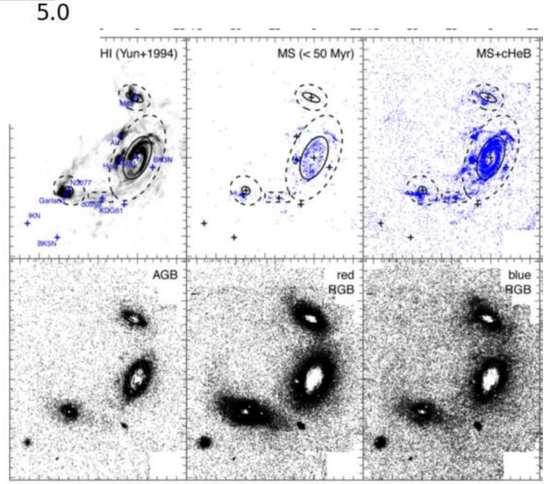


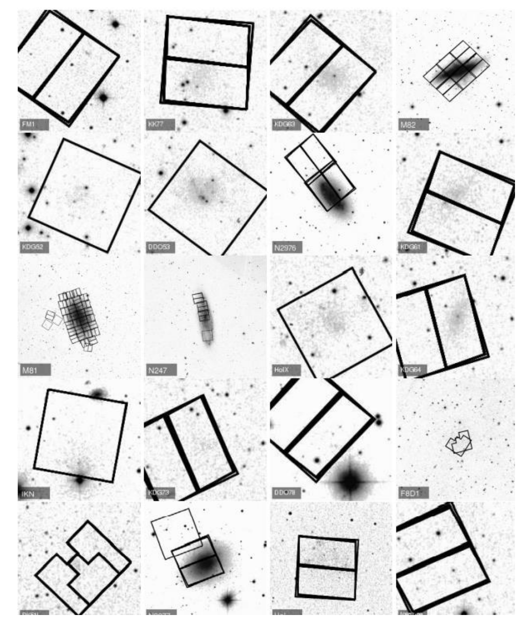
CFHT



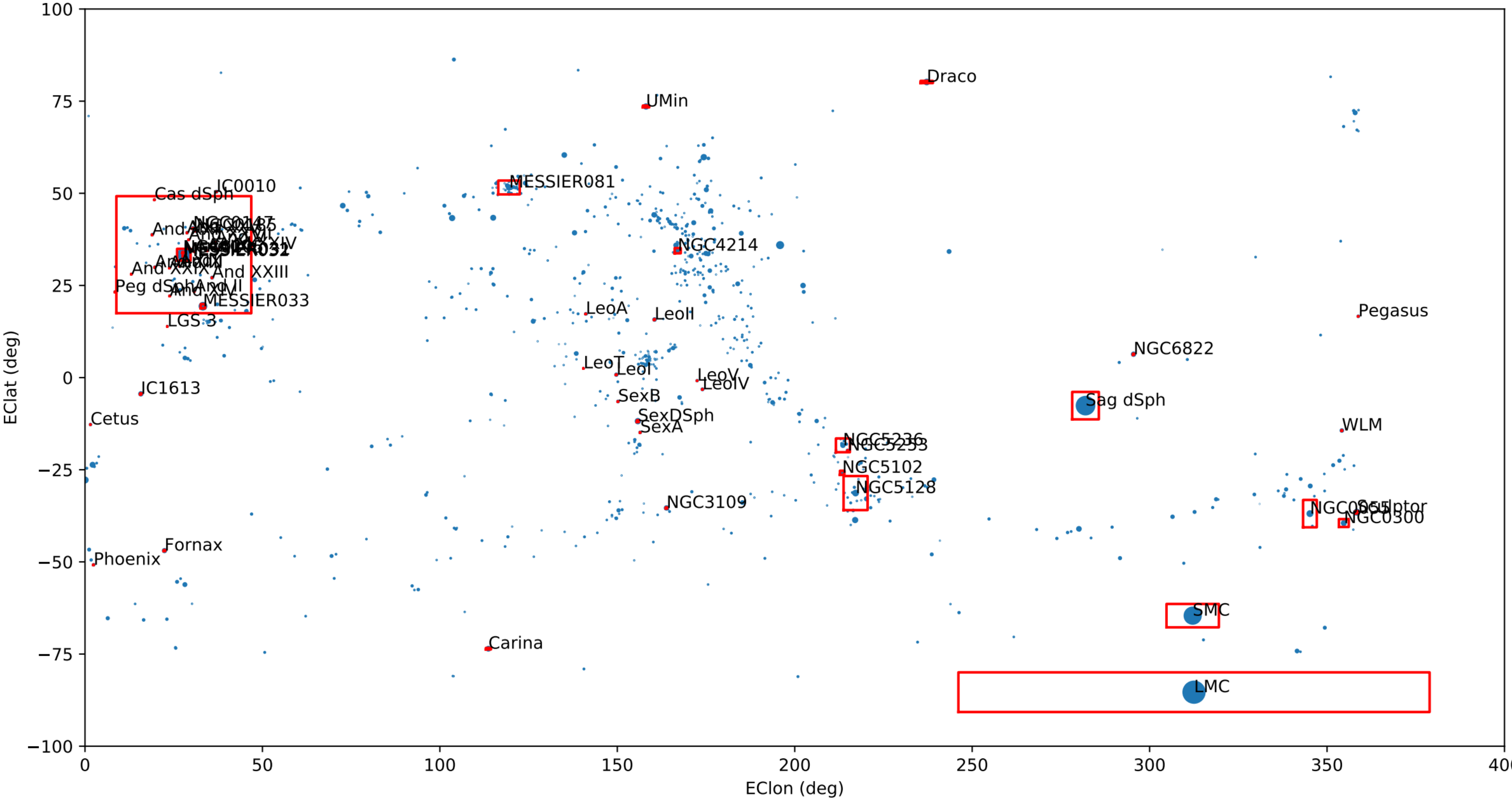
HST

M81 group





With 8x150sec exposure, CSST is able to detect to about 2mag deeper than the tip-RGB of a galaxy located at 4 Mpc



EClat (deg)
EClon (deg)
100
75
50
25
0
−25
−50
−75
−100
0
50
100
150
200
250
300
350
400
Draco
UMin
MESSIER081
IC0010
Cas dSph
NGC4214
And XXIII
Peg dSph
MESSIER033
LGS 3
LeoA
LeoII
Pegasus
NGC6822
LeoT
LeoI
LeoV
LeoIV
IC1613
SexB
Sag dSph
SexDSph
SexA
Cetus
WLM
NGC5236
NGC5253
NGC5102
NGC5128
NGC3109
NGC0300
Fornax
Phoenix
SMC
Carina
LMC

7. Summary

- The Galactic disk is at least larger than 35 kpc
- The MW may contain a lighter dark halo (~0.5×10^{12}Msun), a factor of two smaller than usual values
- People believe that the MW has experienced a major merger, which present-day debris is known as Gaia-Sausage-Enceladus, many Gyrs ago.
  - But anisotropy is worthy to be investigated in more details
- Not far ago, about a few hundred million years ago, the MW has been bombing by a large satellite. As a consequence, The whole disk is in trembling (disequilibrium)
- In near future, CSST will observe ~100 resolved galaxies, and make detailed statistics using individual stars of these galaxies to answer the question that if our galaxy is common or special.