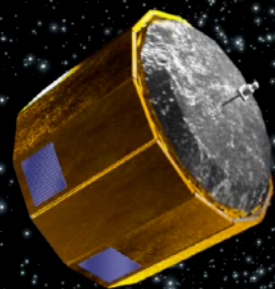


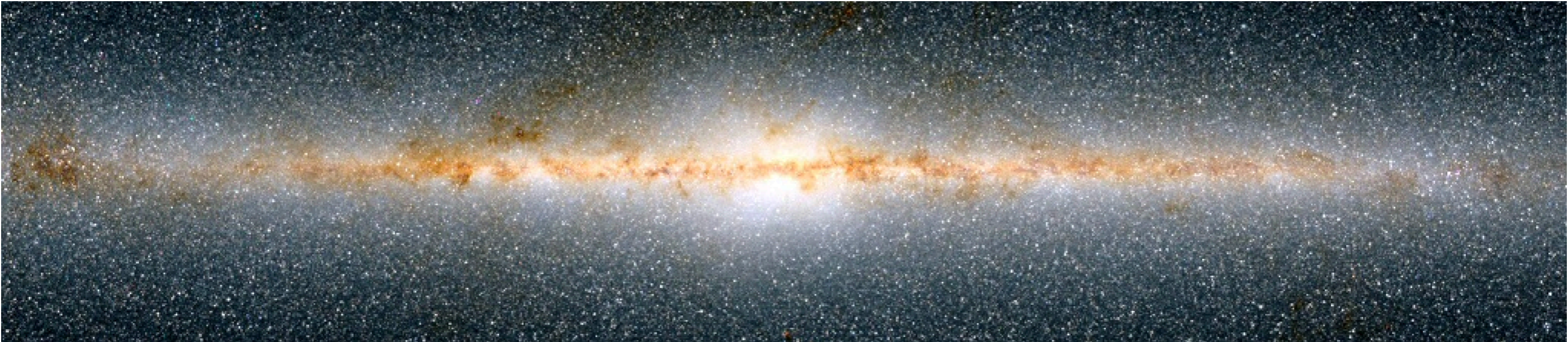
# Ripples, spirals, rings and flare:

Did they start from a bombardment of a dwarf?

Chao Liu, NAOC

collaborators: Yan Xu (NAOC), Haijun Tian (Three Gorges Univ.), Haifeng Wang (Yunnan Univ.), Xinlun Cheng (Tsinghua Univ.), Shude Mao (Tsinghua Univ./NAOC)



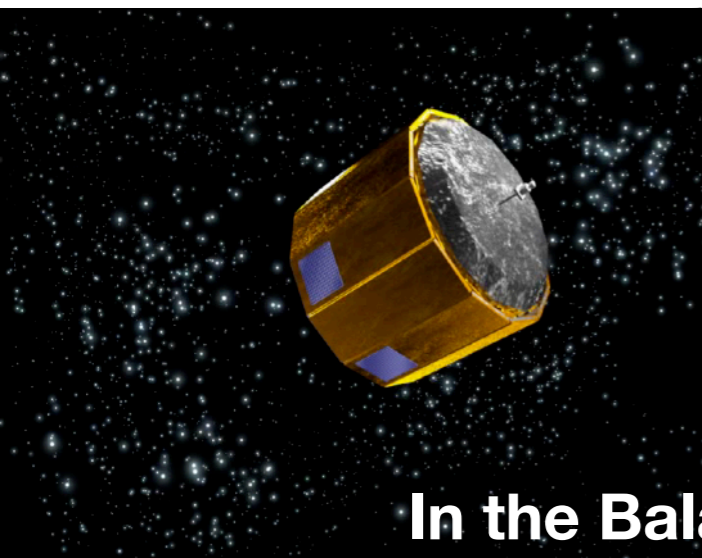


# Ripples, spirals, rings and flare:

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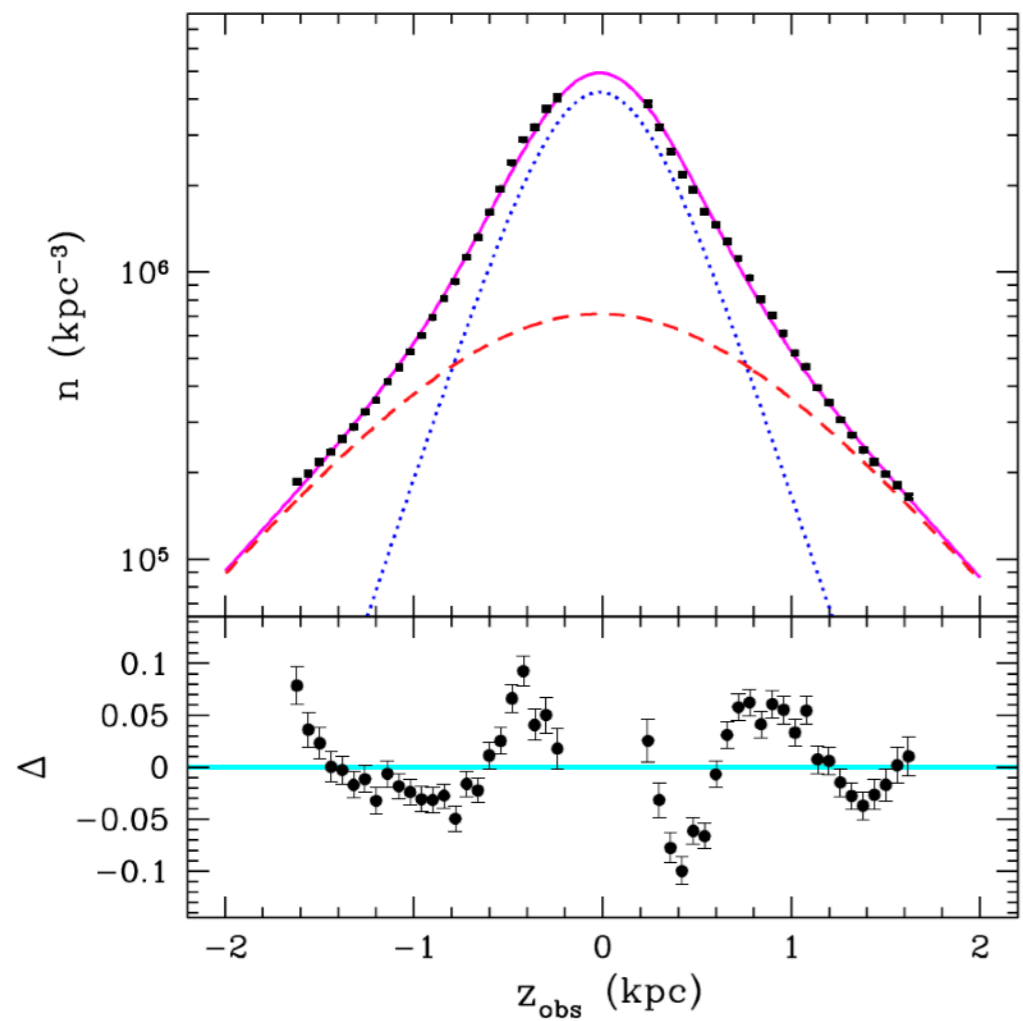
Chao Liu, NAOC

collaborators: Yan Xu (NAOC), Haijun Tian (Three Gorges Univ.), Haifeng Wang (Yunnan Univ.), Xinlun Cheng (Tsinghua Univ.), Shude Mao (Tsinghua Univ./NAOC)

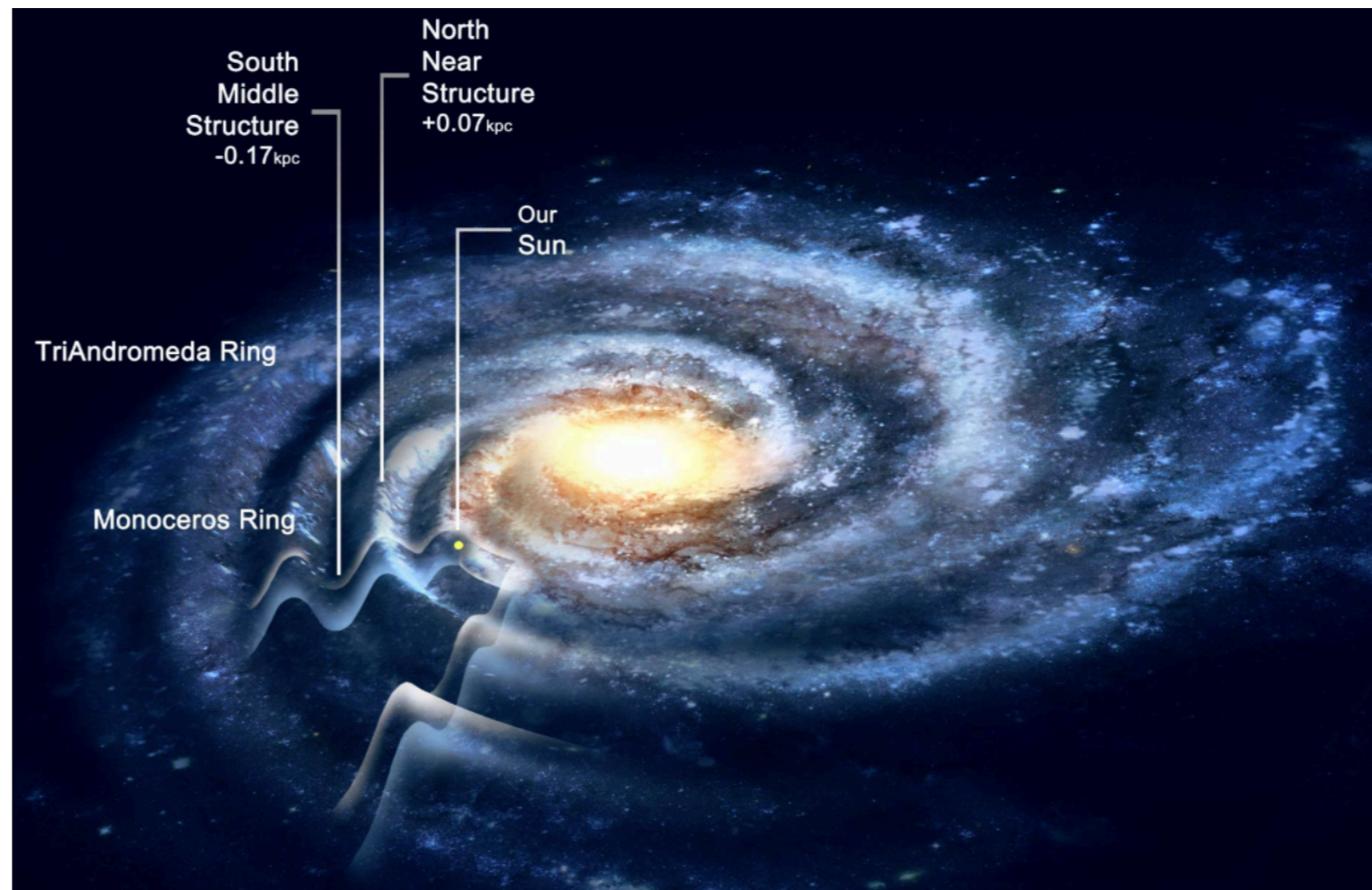


# All about disequilibrium

Xu+15



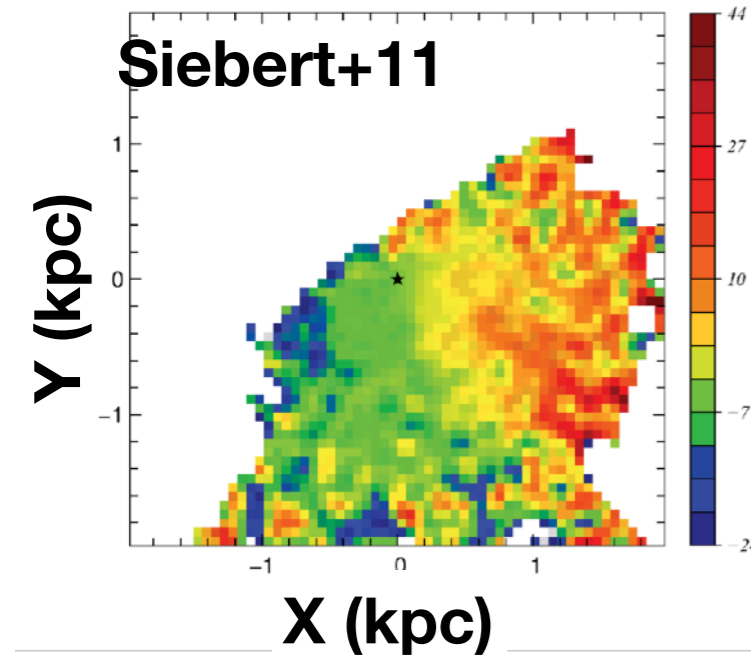
Widrow+12



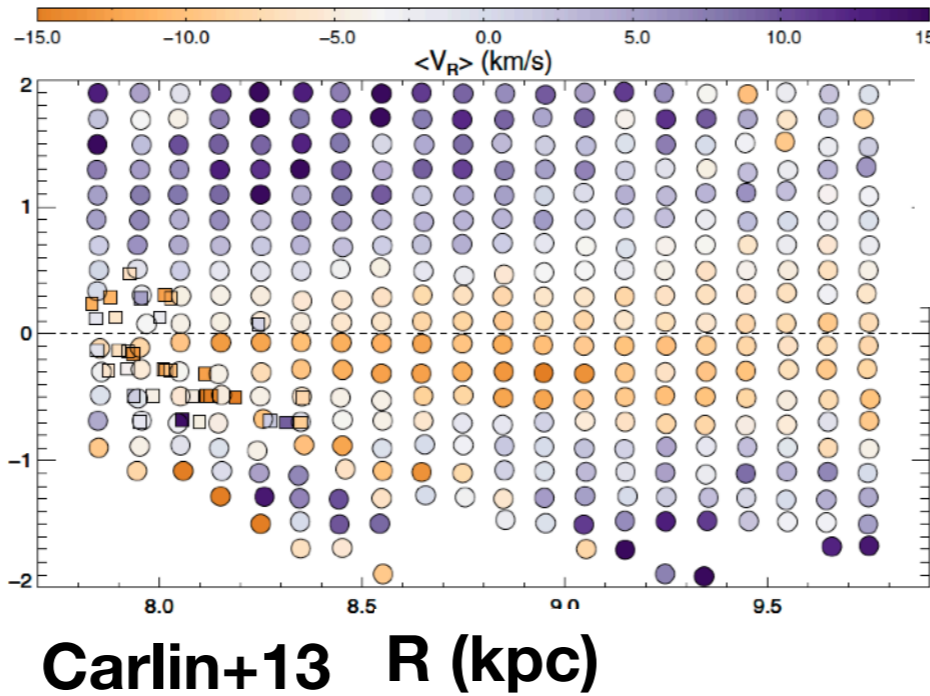
# Bulk motions

VR

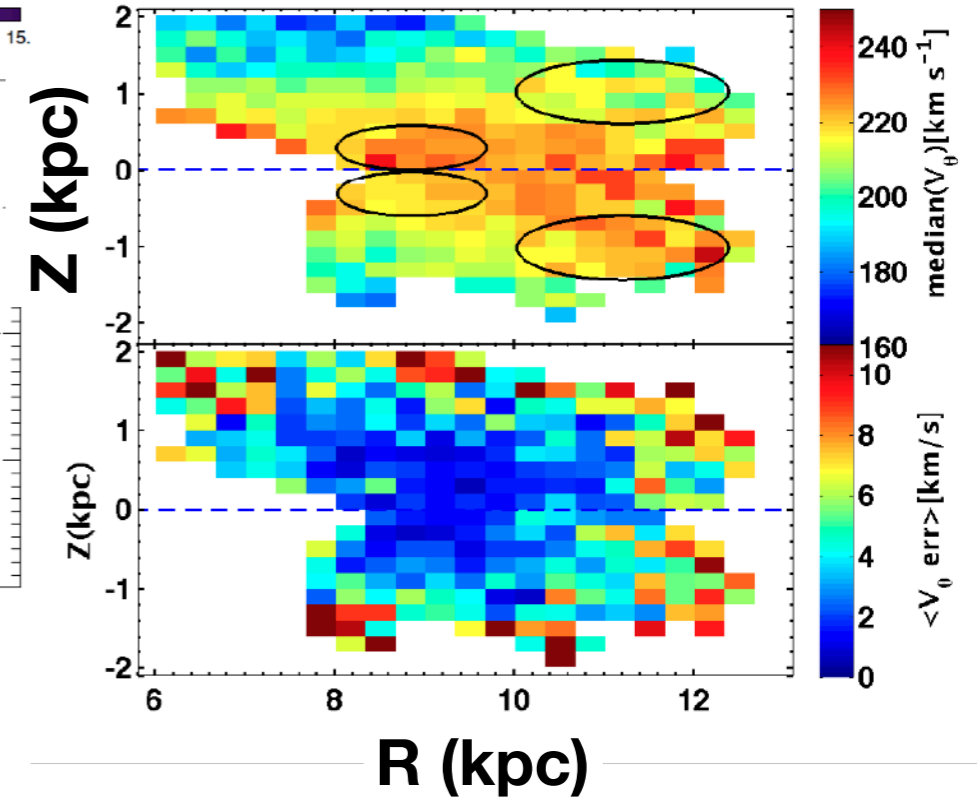
Siebert+11



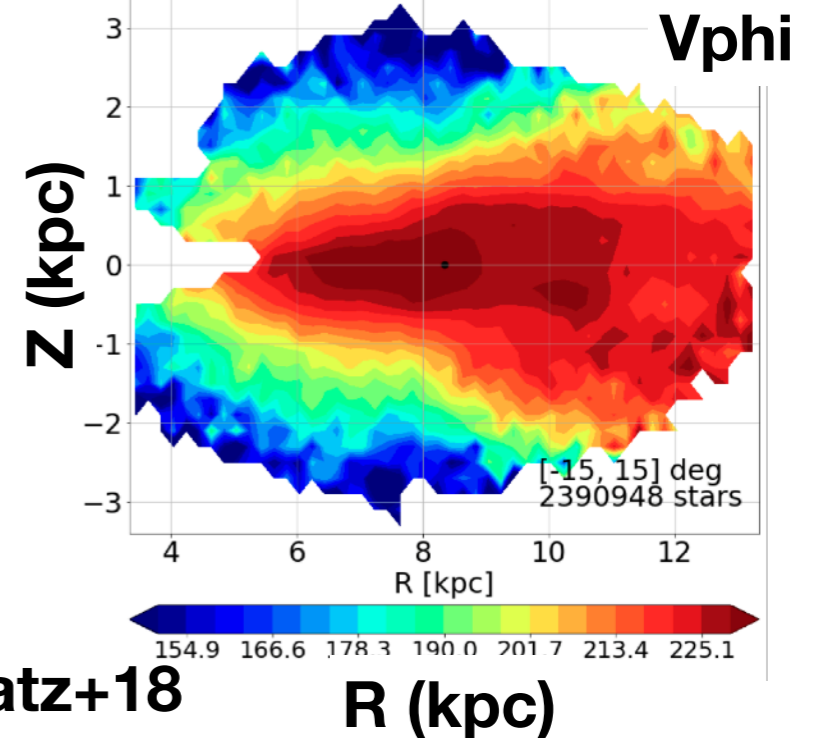
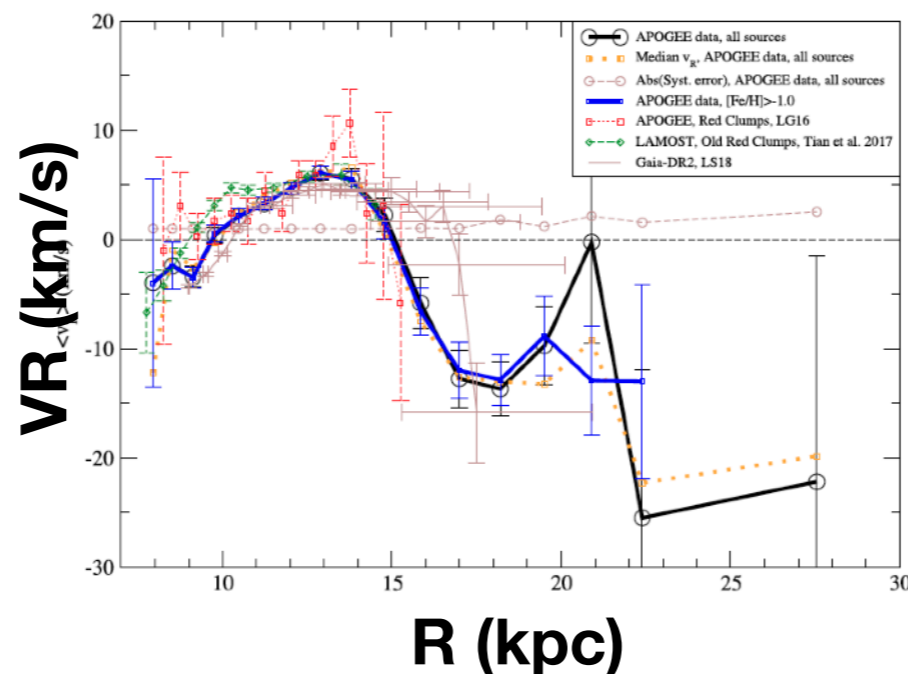
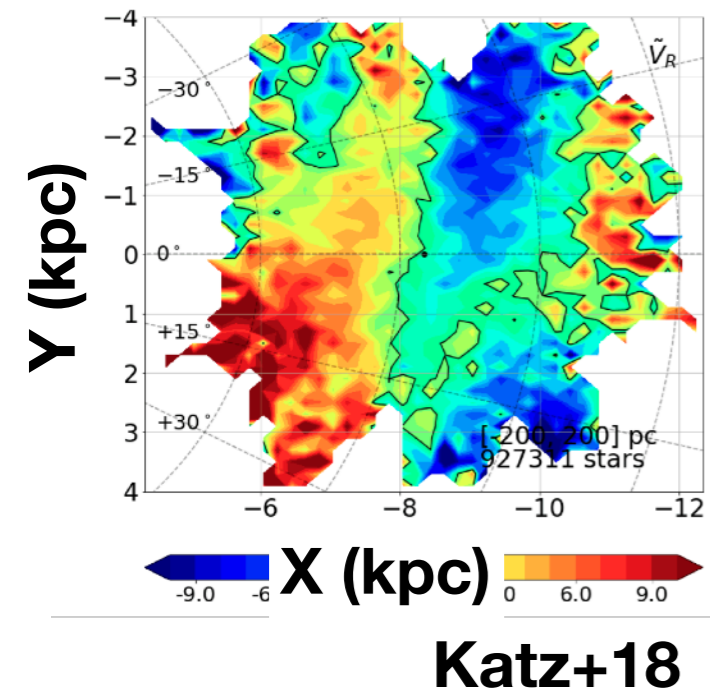
VR



Vphi H-F. Wang+18



VR



Lopez-Corredoira+19

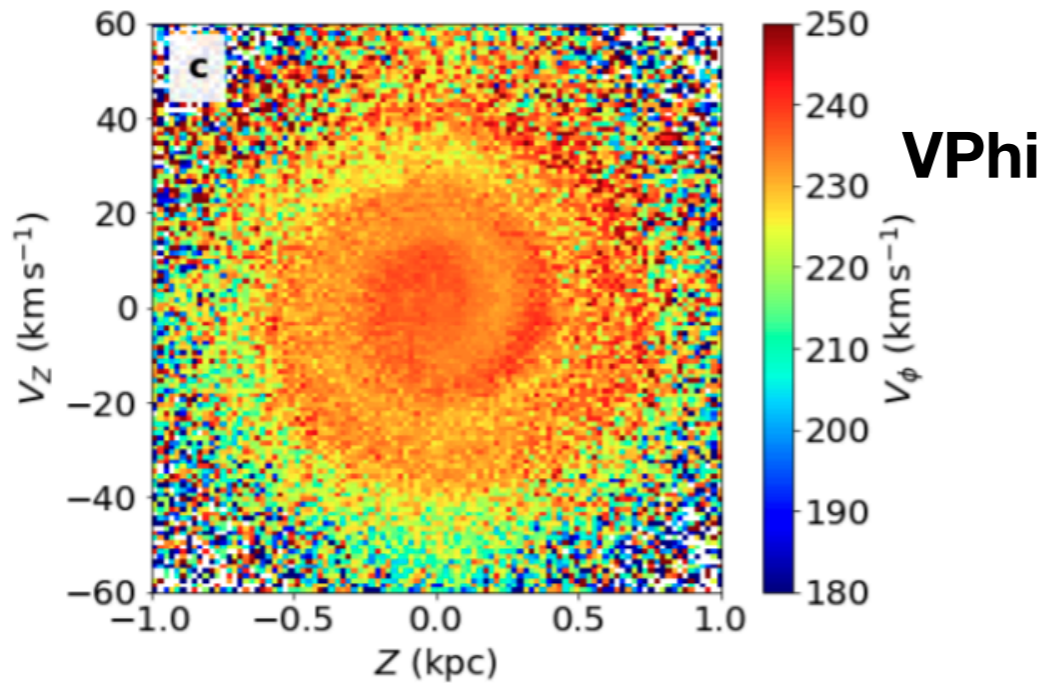
Katz+18

R (kpc)

# Phase-space features

Antoja+18

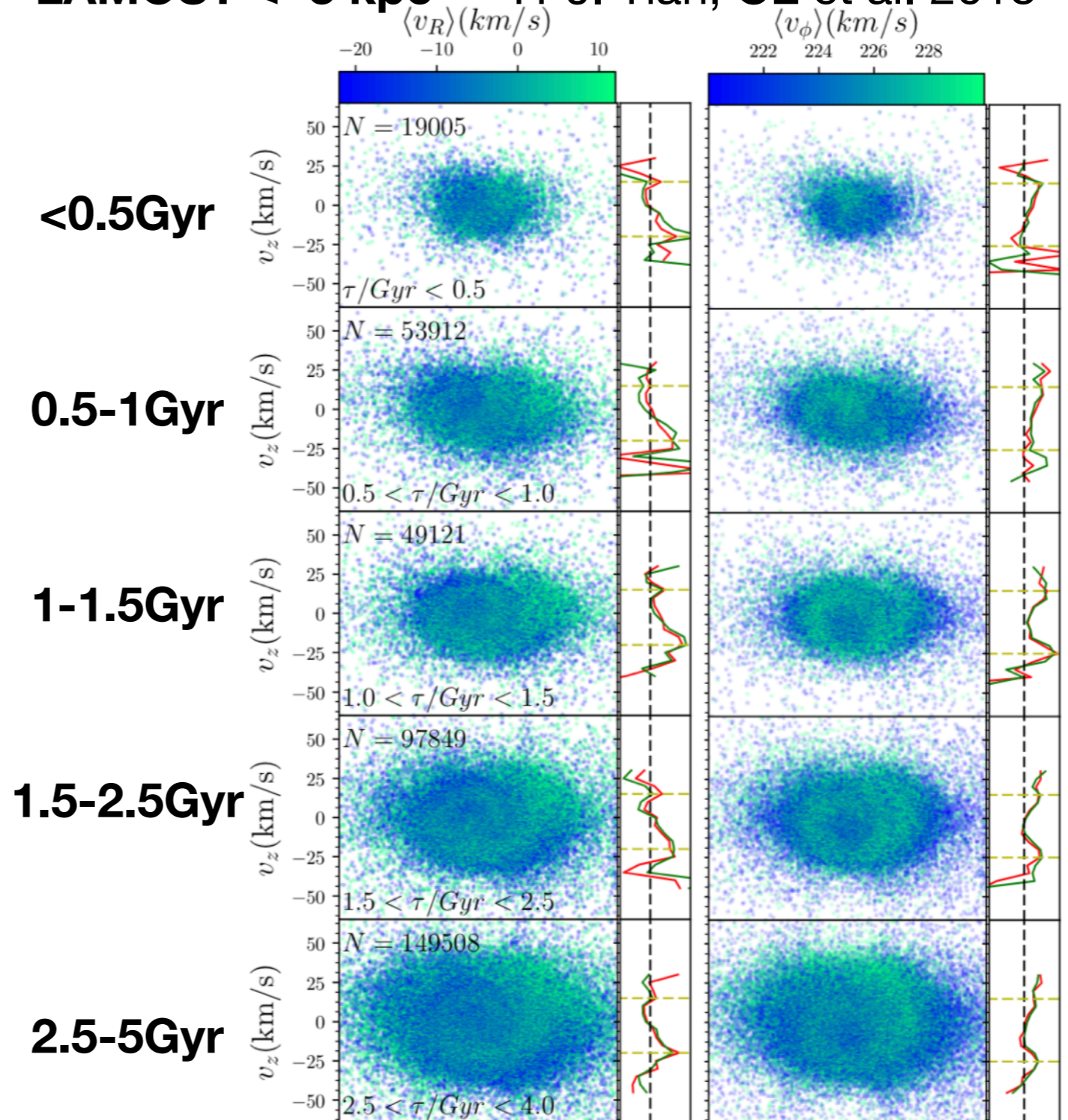
Gaia  $< \sim 3$  kpc



Also Binney & Schoerich 18,  
Bland-Hawthorn+18 etc.

Older populations do not show  
clear spirals because they are  
hot (also see Juntai Shen's talk)

LAMOST  $< \sim 3$  kpc H-J. Tian, CL et al. 2018



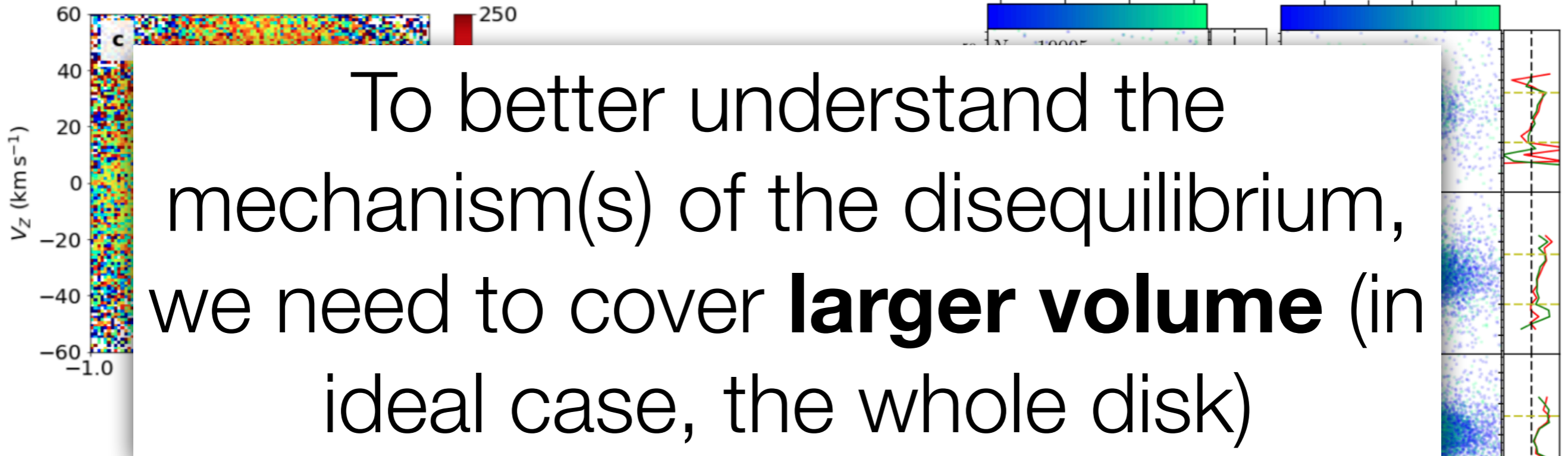
# Phase-space features

Antoja+18

Gaia  $< \sim 3$  kpc

LAMOST  $< \sim 3$  kpc

H-J. Tian, CL et al. 2018

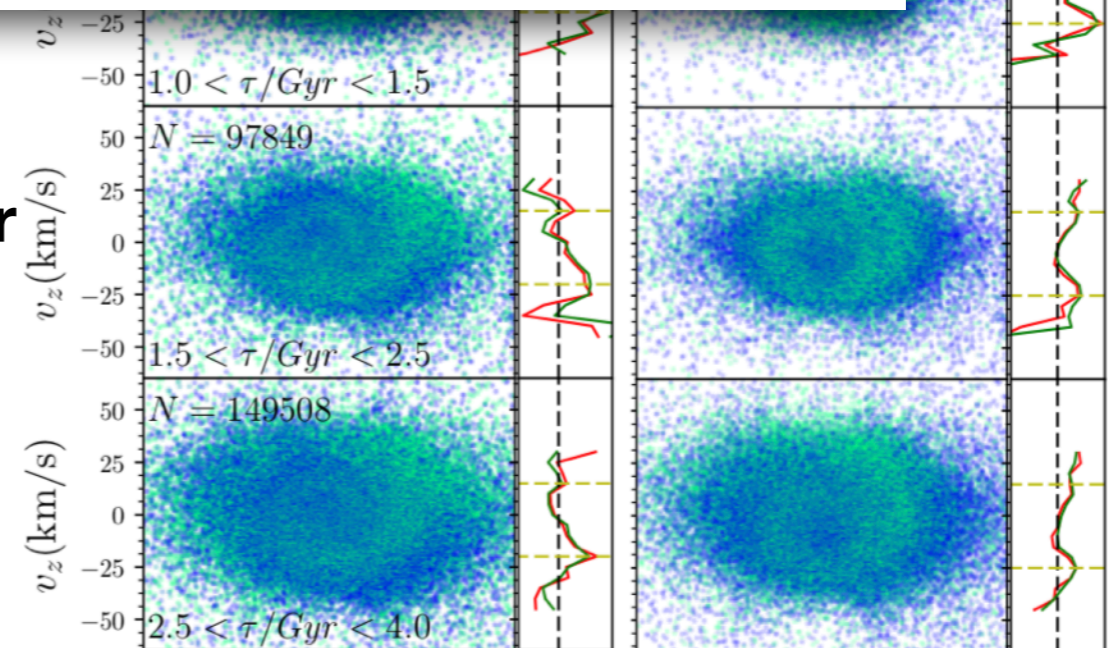


Also Binney & Schoerich 18,  
Bland-Hawthorn+18 etc.

Older populations do not show clear spirals because they are hot (also see Juntai Shen's talk)

1.5-2.5Gyr

2.5-5Gyr

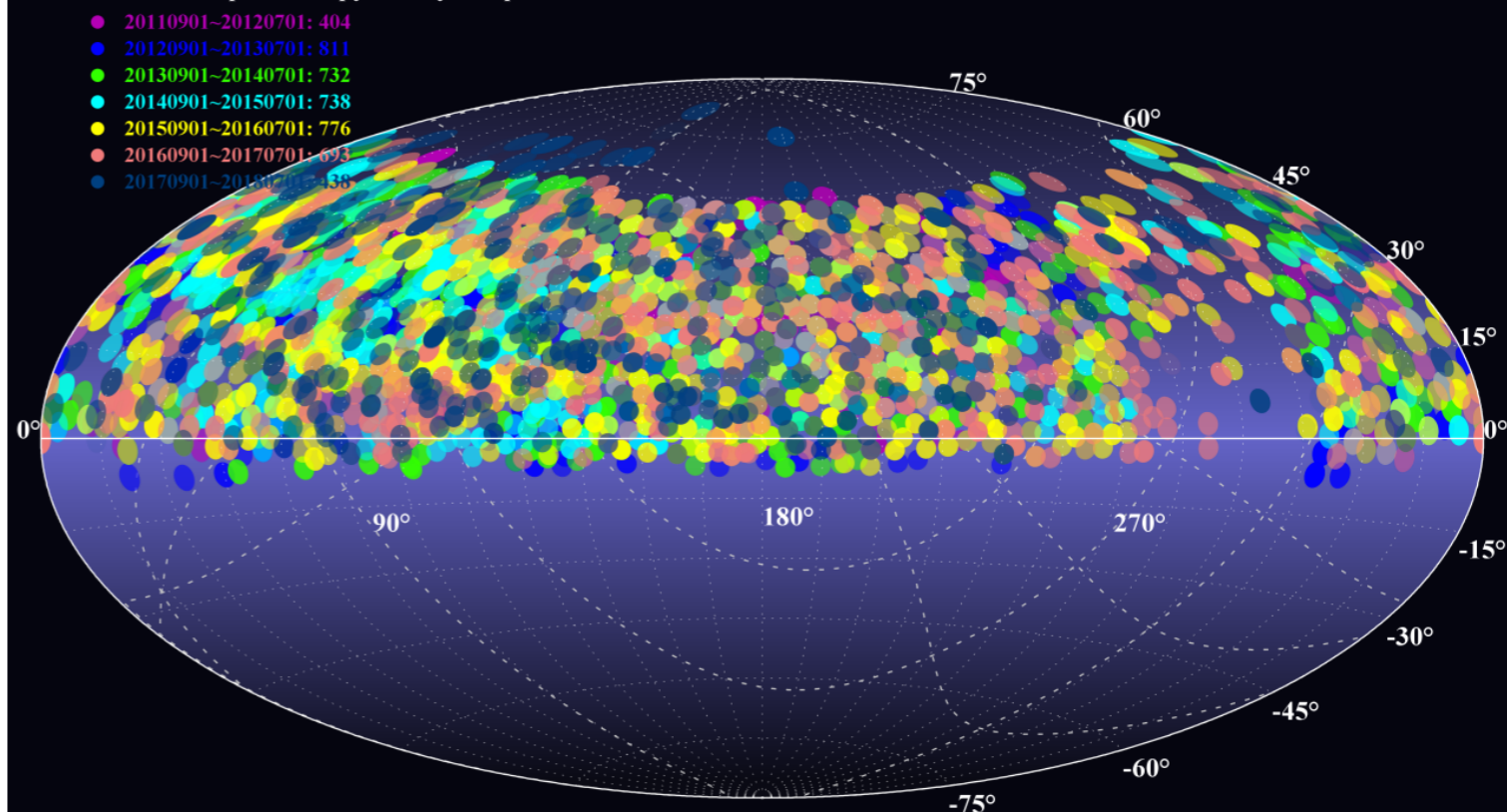


# LAMOST Telescope

- 4-meter reflective Schmidt telescope with segmental mirrors and active optics
- Quasi-meridian
- 4000 fibers on the 5 degree-FoV focal plane
- 16 spectrographs
- Low resolution spectra:  $R \sim 1800$ , wavelength: 370-900nm
- Over 10 million spectra have been collected



The LAMOST spectroscopy survey footprint

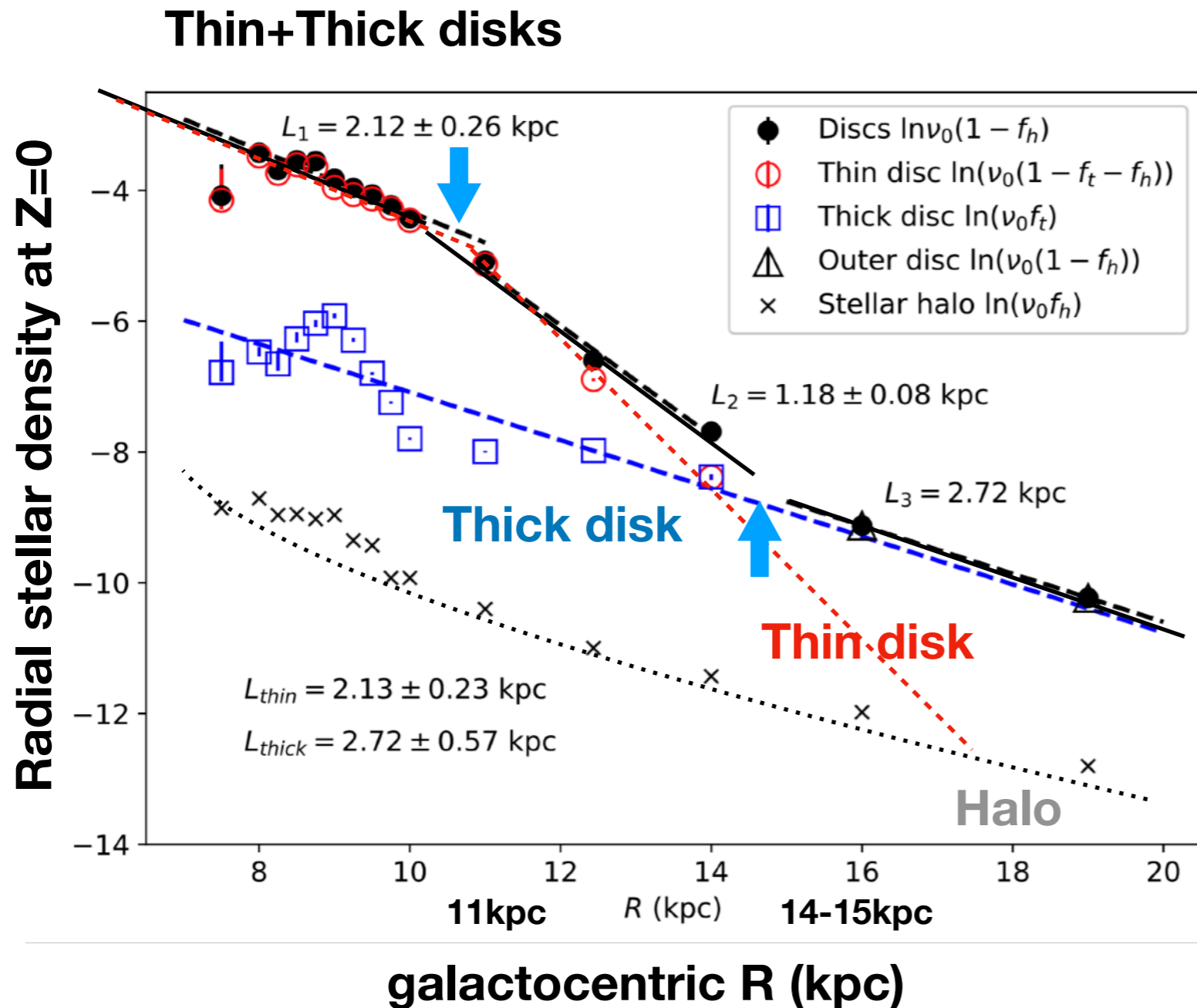


# §1 Ripples, waves, corrugations

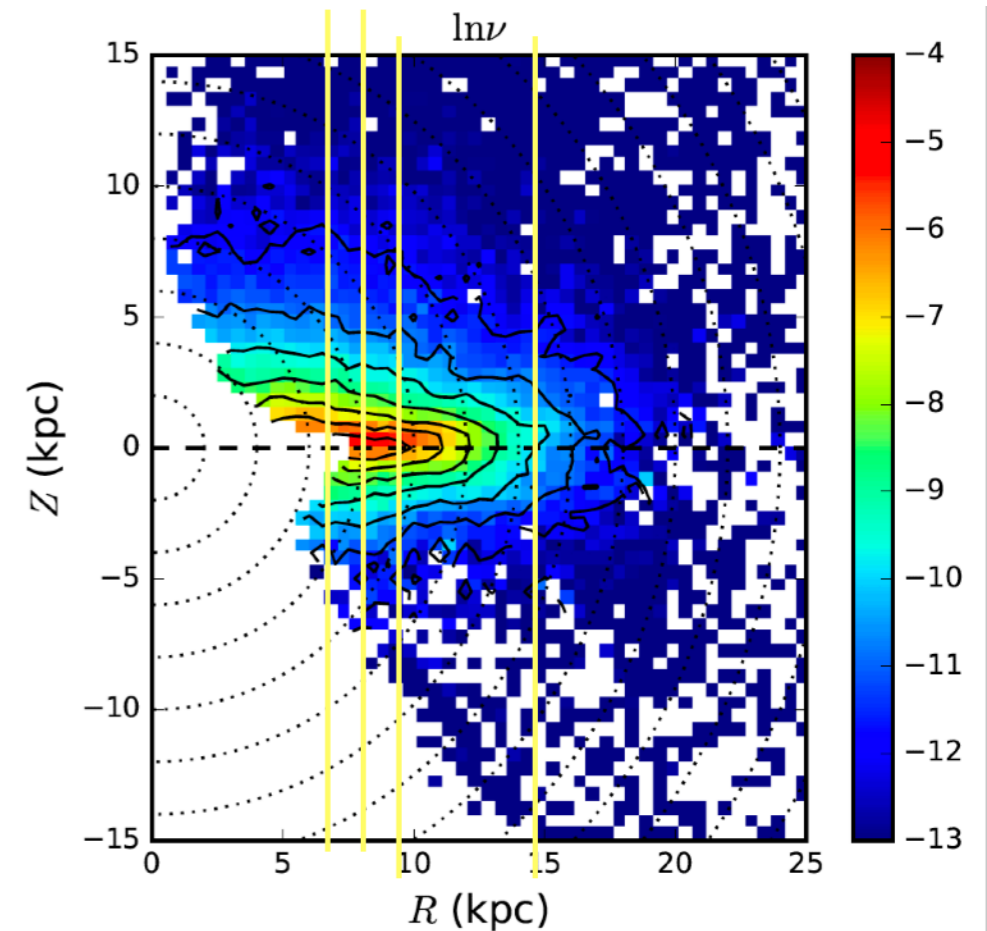
- In star counts
- In velocities



# 3D structure of the outer disk

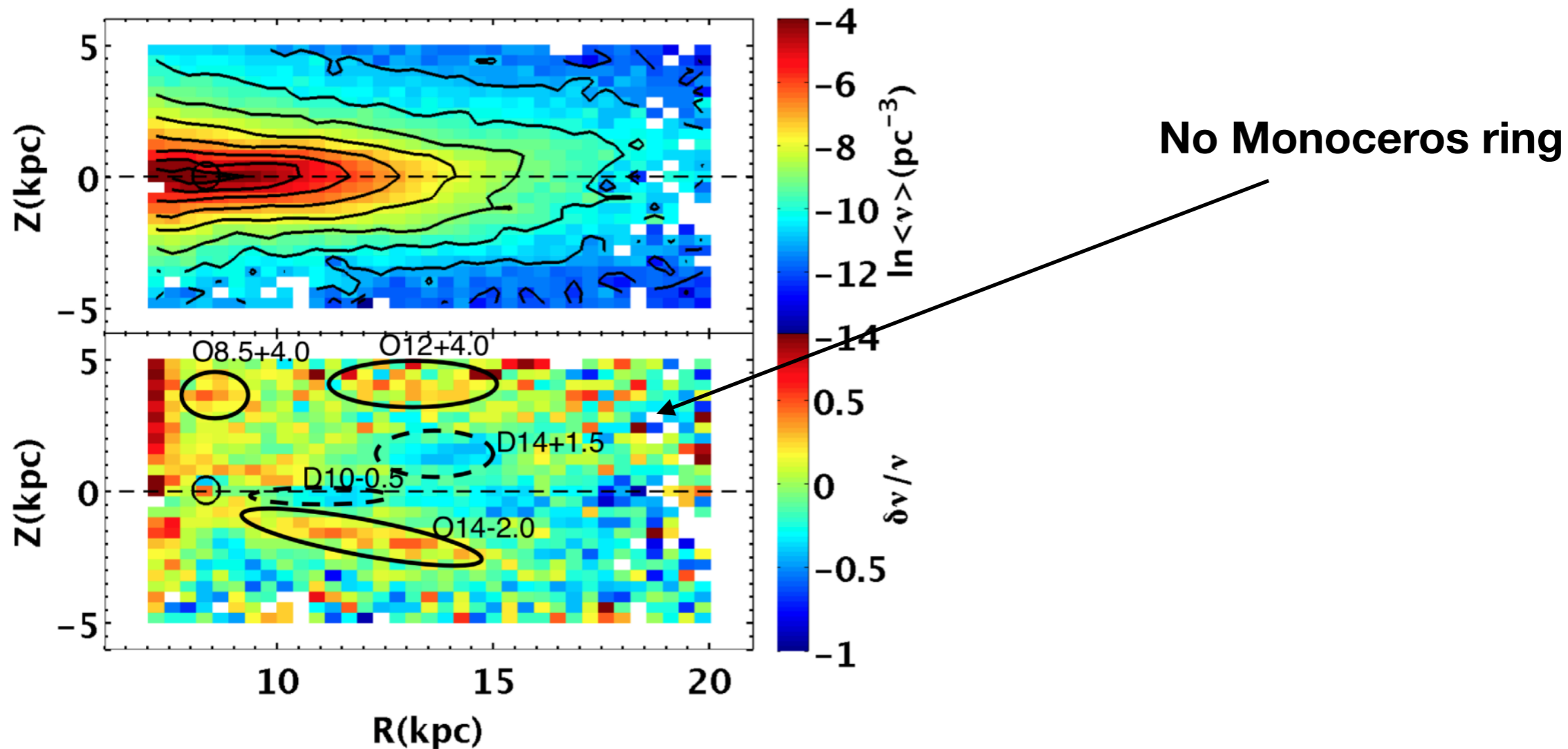


70000 LAMOST RGB stars  
 Flare is considered in the model



CL et al. 2017

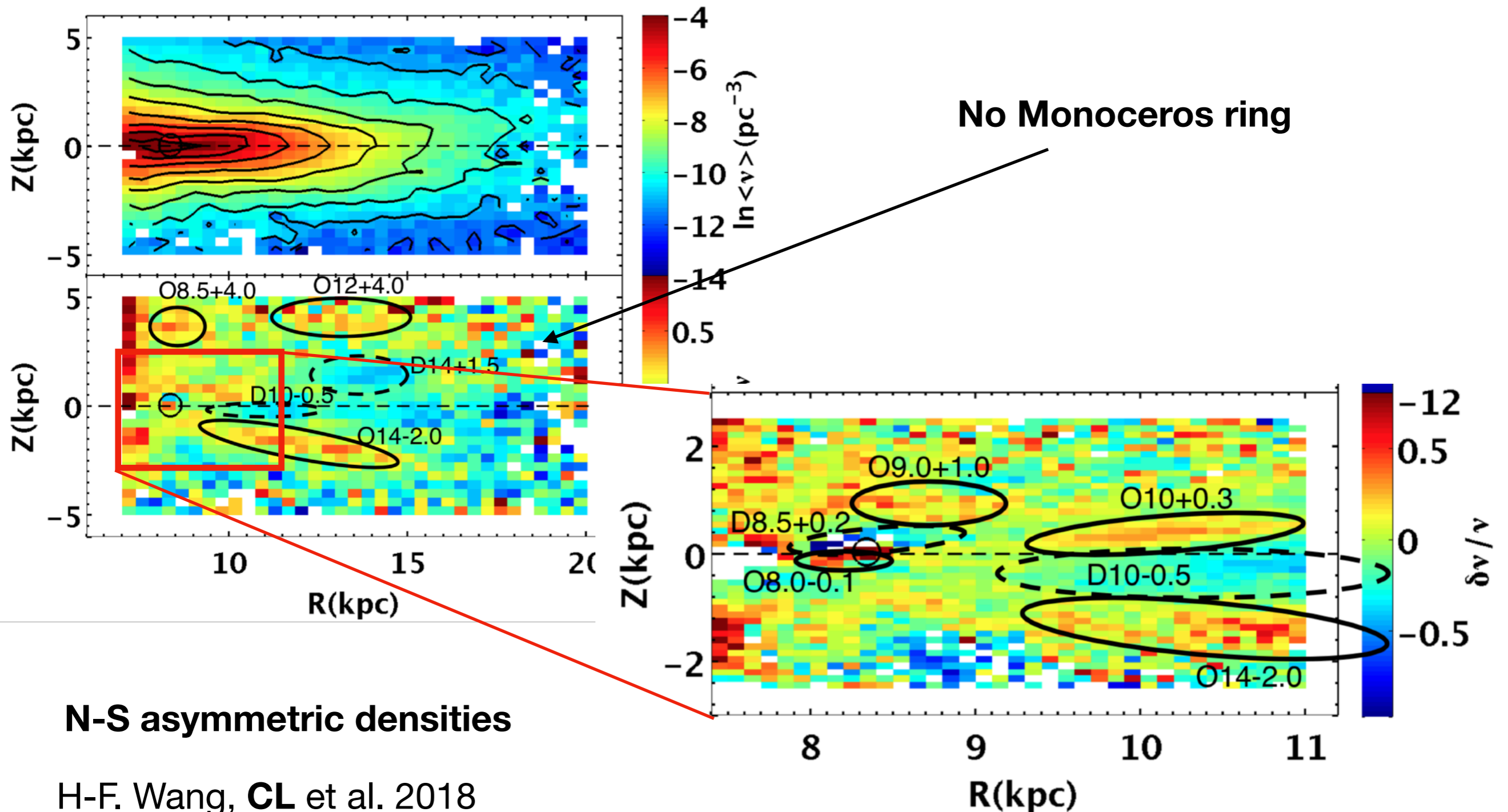
# Non-axisymmetric spatial substructures



**N-S asymmetric densities**

H-F. Wang, **CL** et al. 2018

# Non-axisymmetric spatial substructures

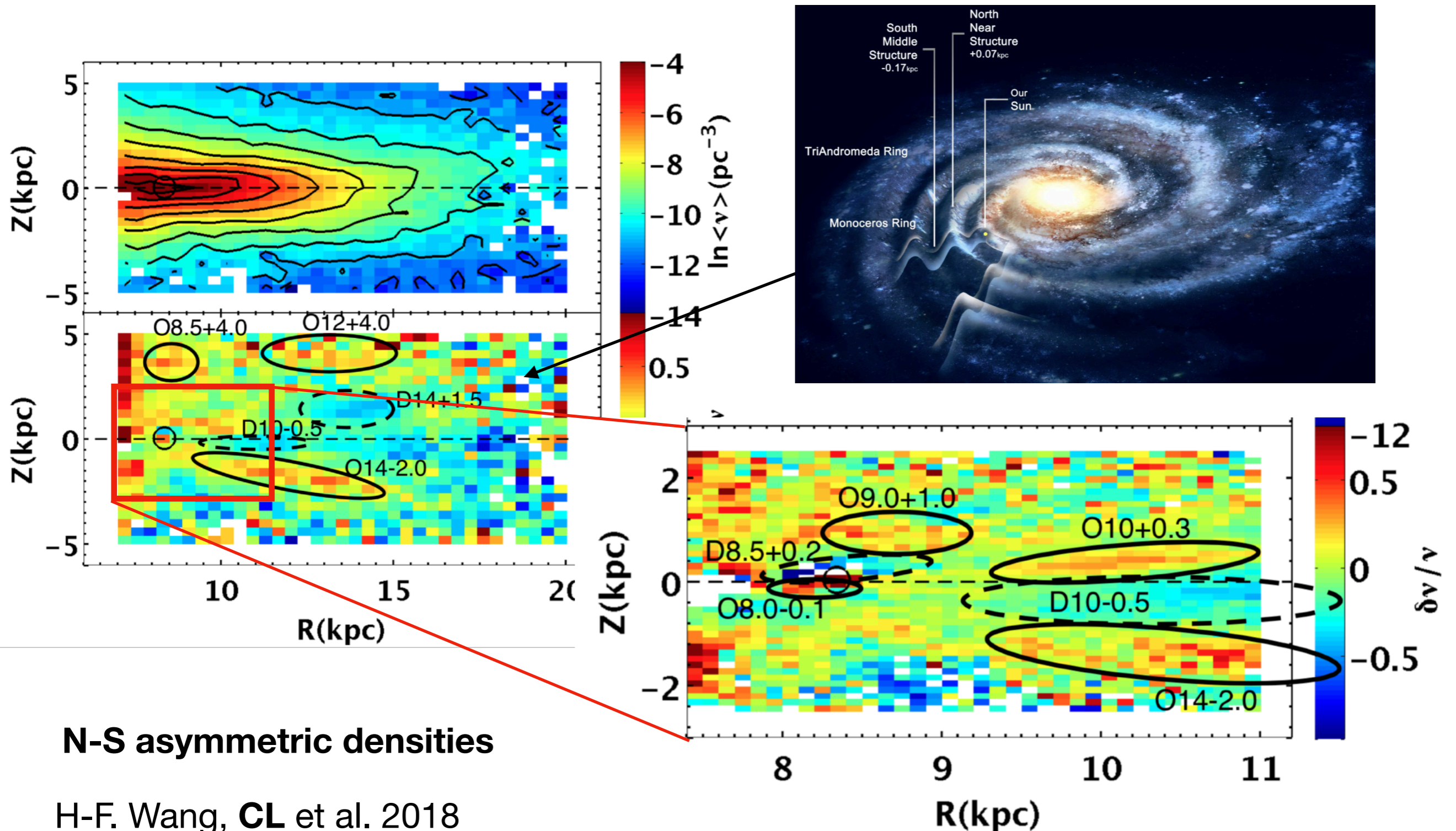


N-S asymmetric densities

H-F. Wang, CL et al. 2018

# Non-axisymmetric spatial substructures

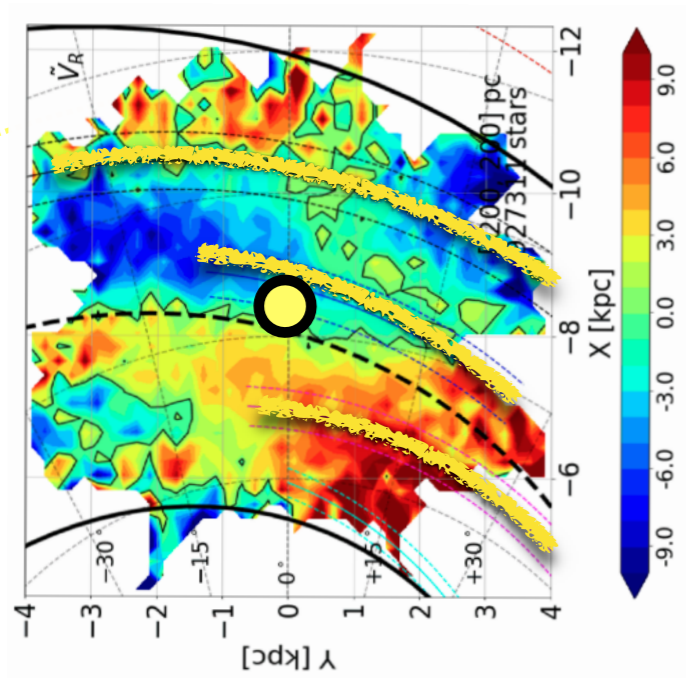
Y. Xu+15



N-S asymmetric densities

H-F. Wang, CL et al. 2018

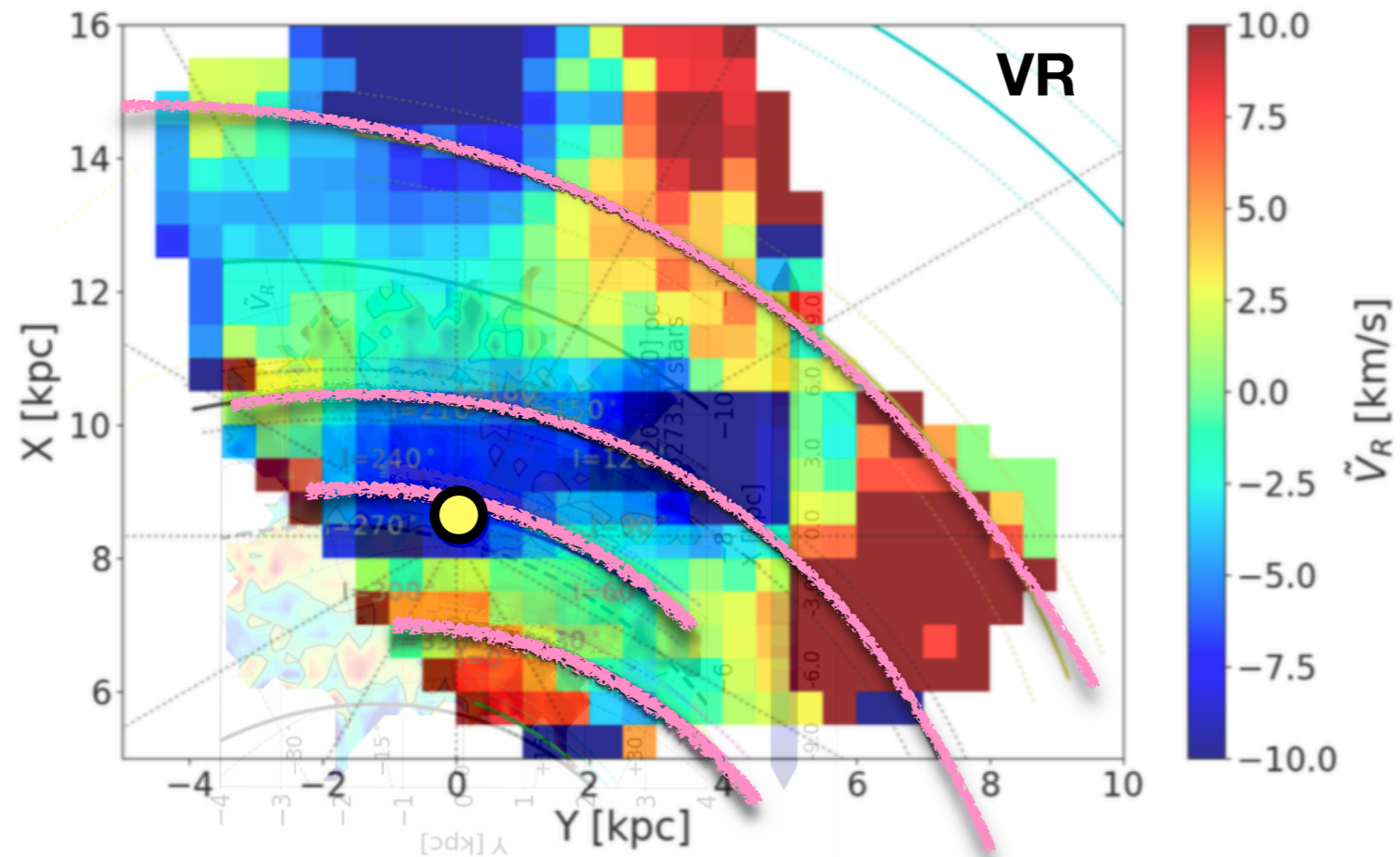
# Ripples in LAMOST OB stars



Katz et al. 2018 (Gaia DR2)

  
GC

# Ripples in LAMOST OB stars



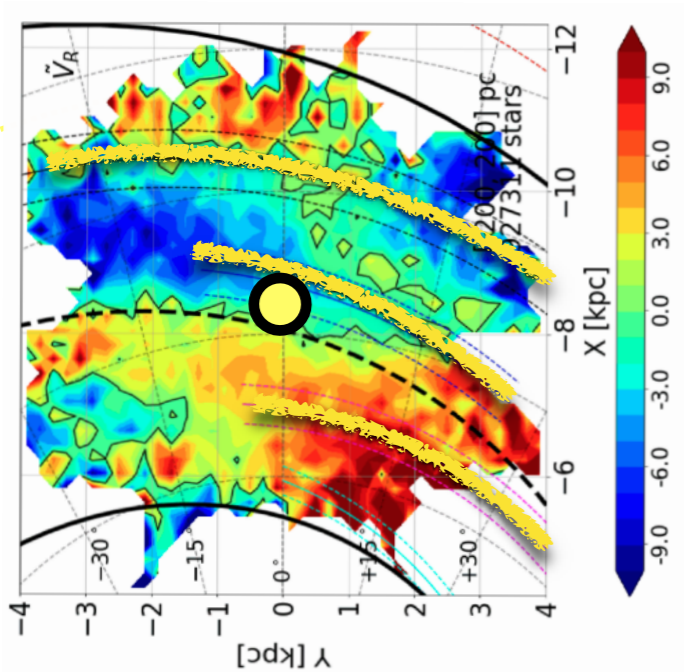
Katz et al. (2016) (Gal & DR2)  $\tilde{V}_R$

X-L. Cheng, **CL** et al. 2019



**GC**

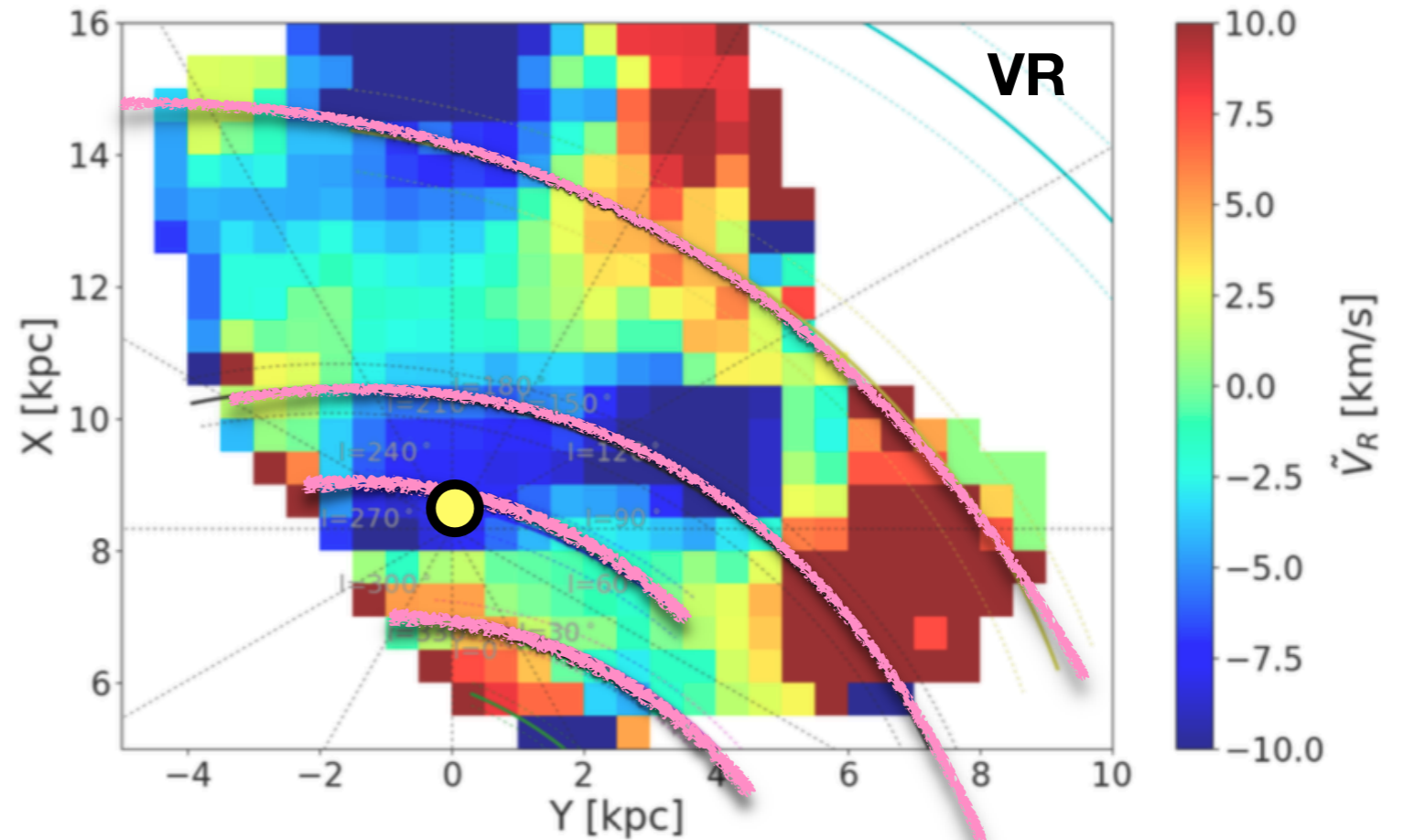
# Ripples in LAMOST OB stars



Katz et al. 2018 (Gaia DR2)



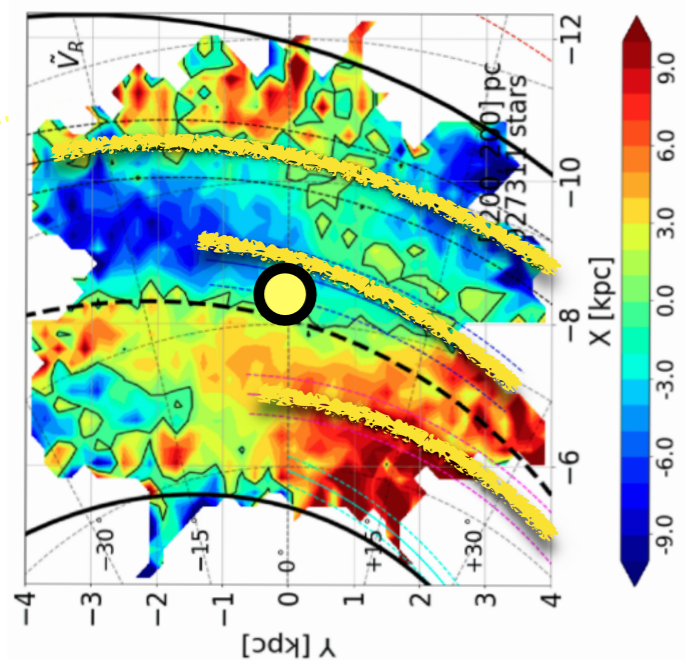
GC



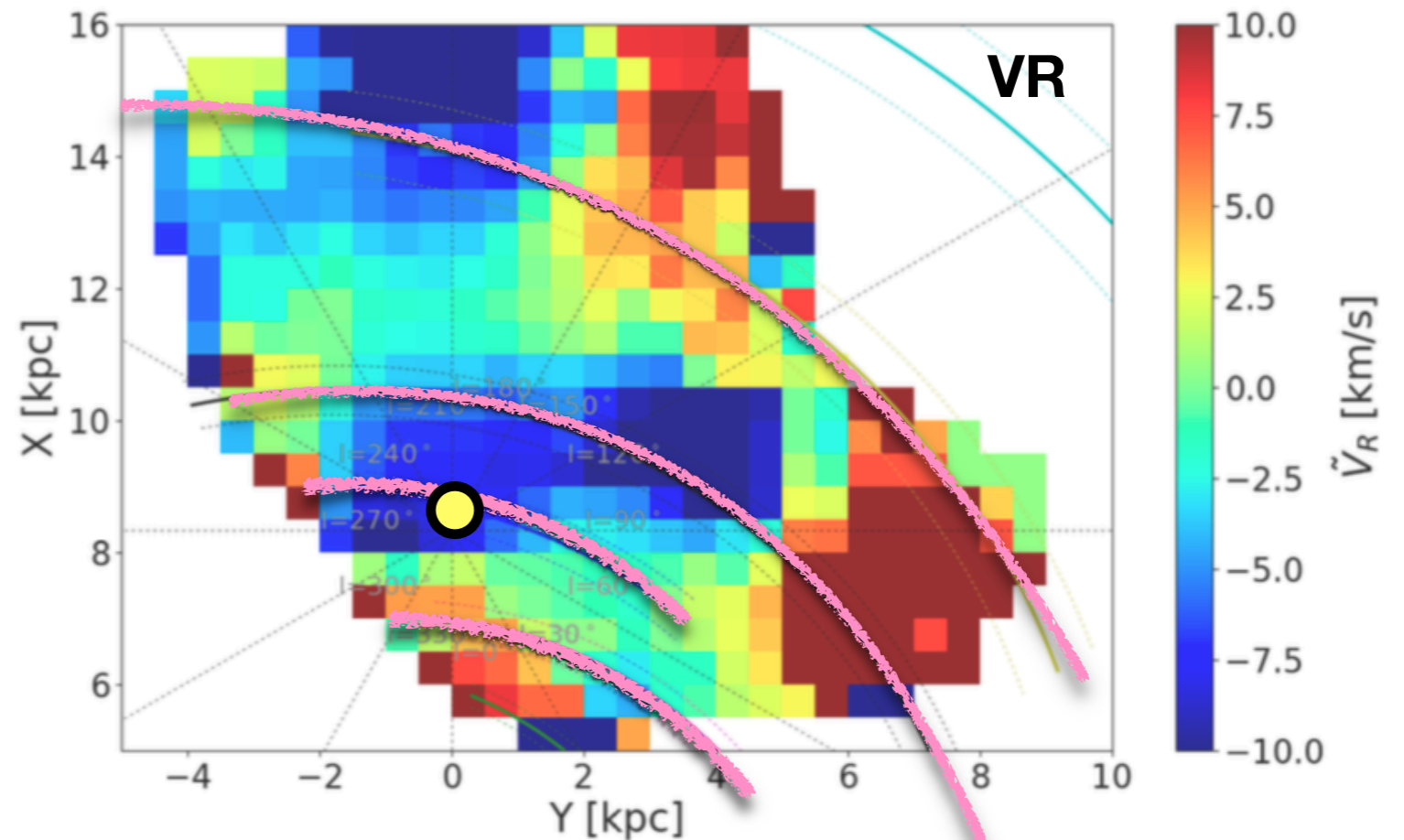
(a) Radial velocity  $\tilde{V}_R$

X-L. Cheng, **CL** et al. 2019

# Ripples in LAMOST OB stars



Katz et al. 2018 (Gaia DR2)



(a) Radial velocity  $\tilde{V}_R$

X-L. Cheng, **CL** et al. 2019

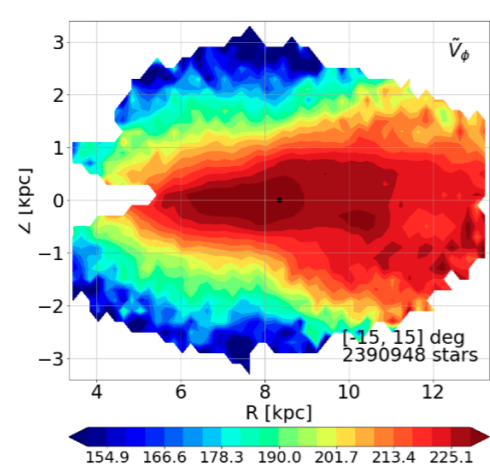


GC

The large scale of VR ripples do not align with the spiral arms.  
What is the reason that the young stars show large scale ripples?

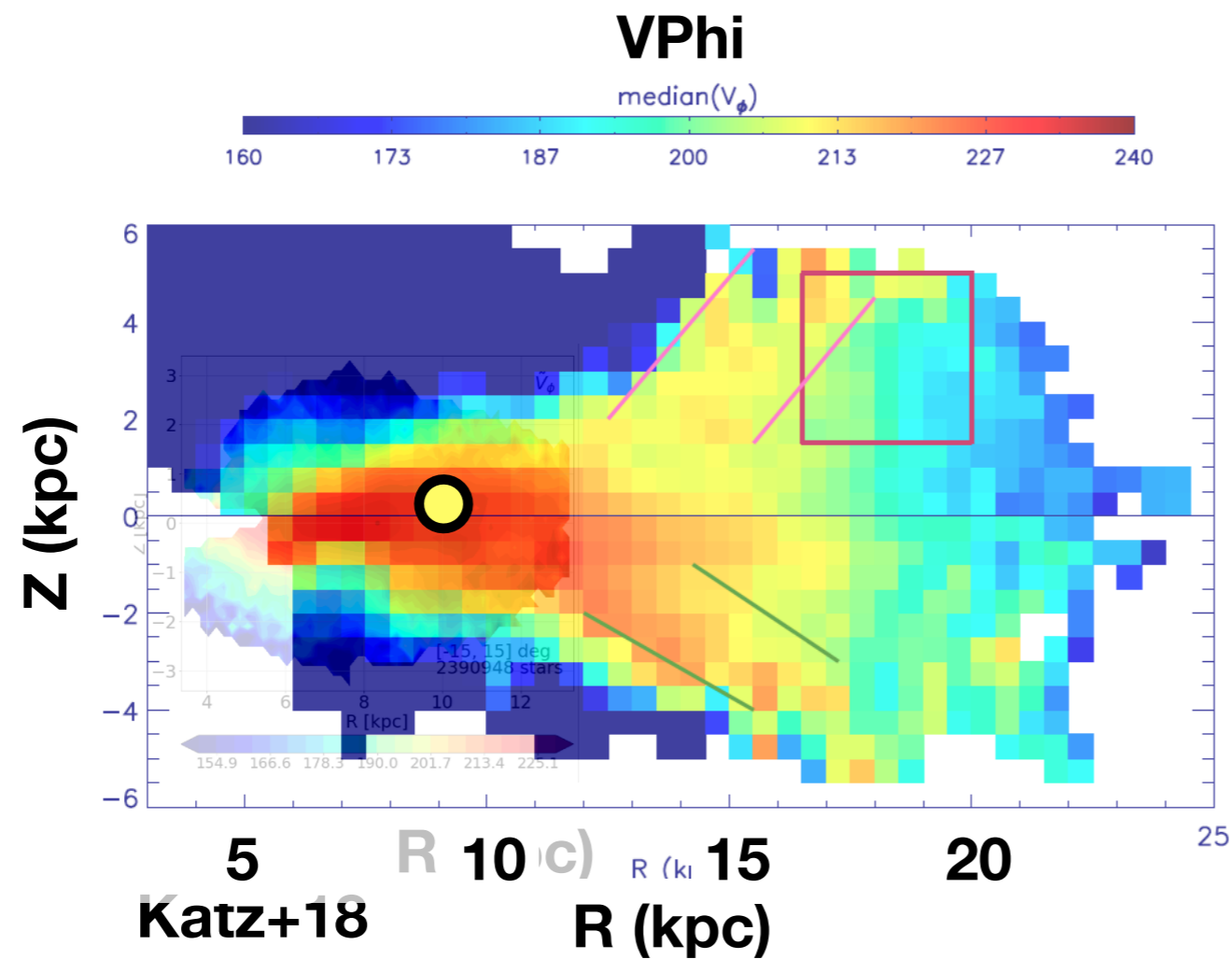


# Vphi in R-Z plane with RGBs

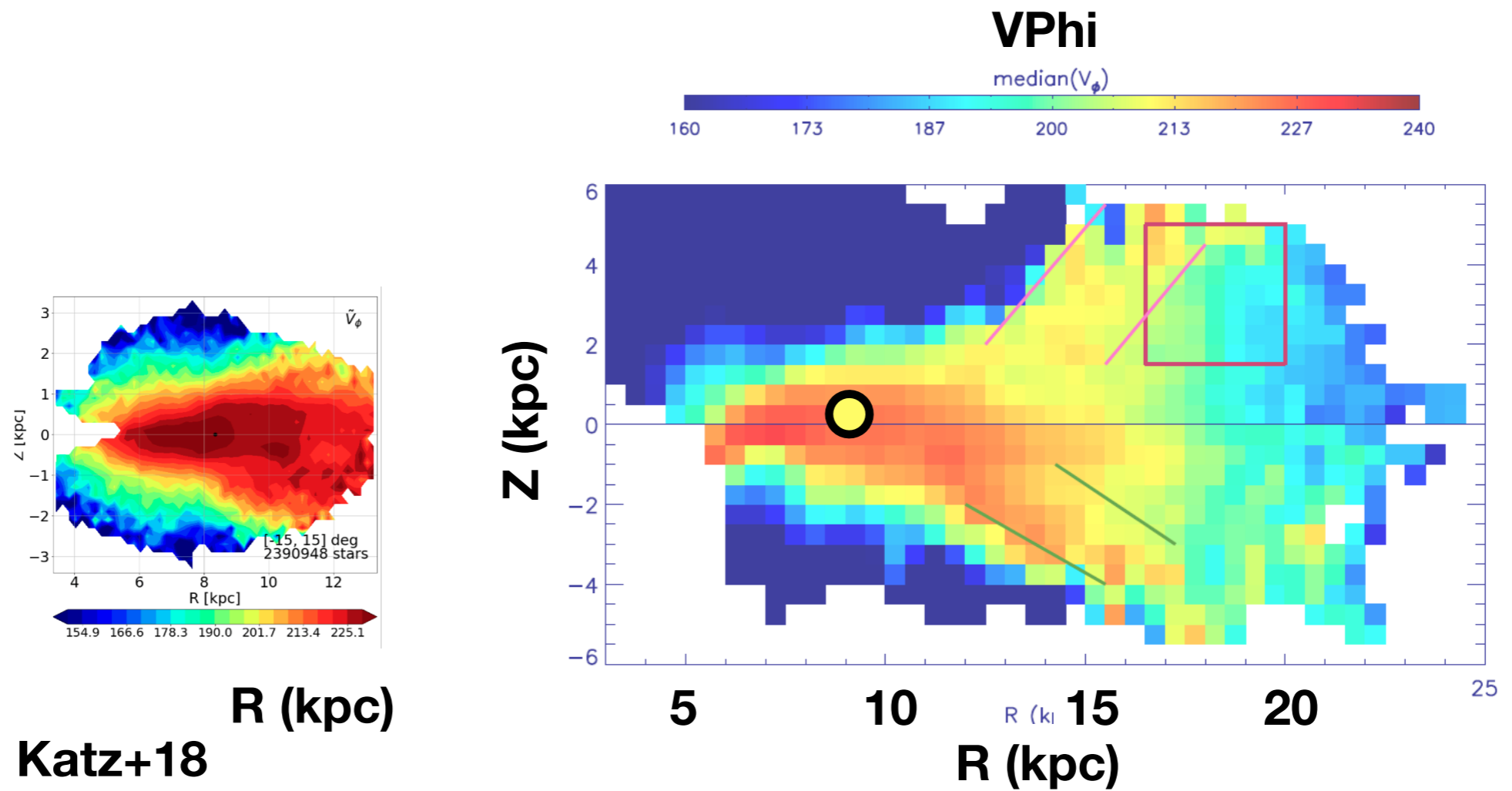


**R (kpc)**  
**Katz+18**

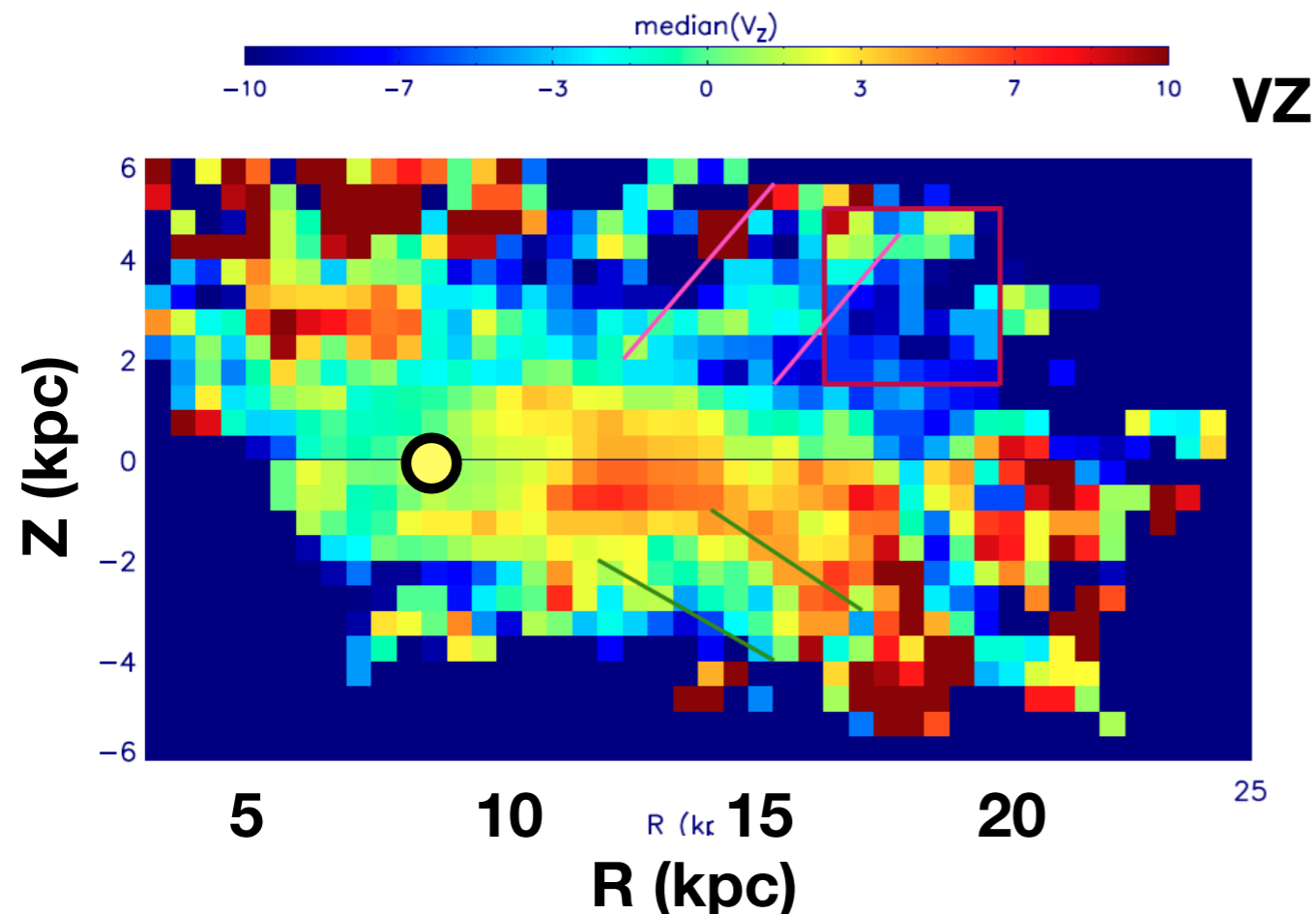
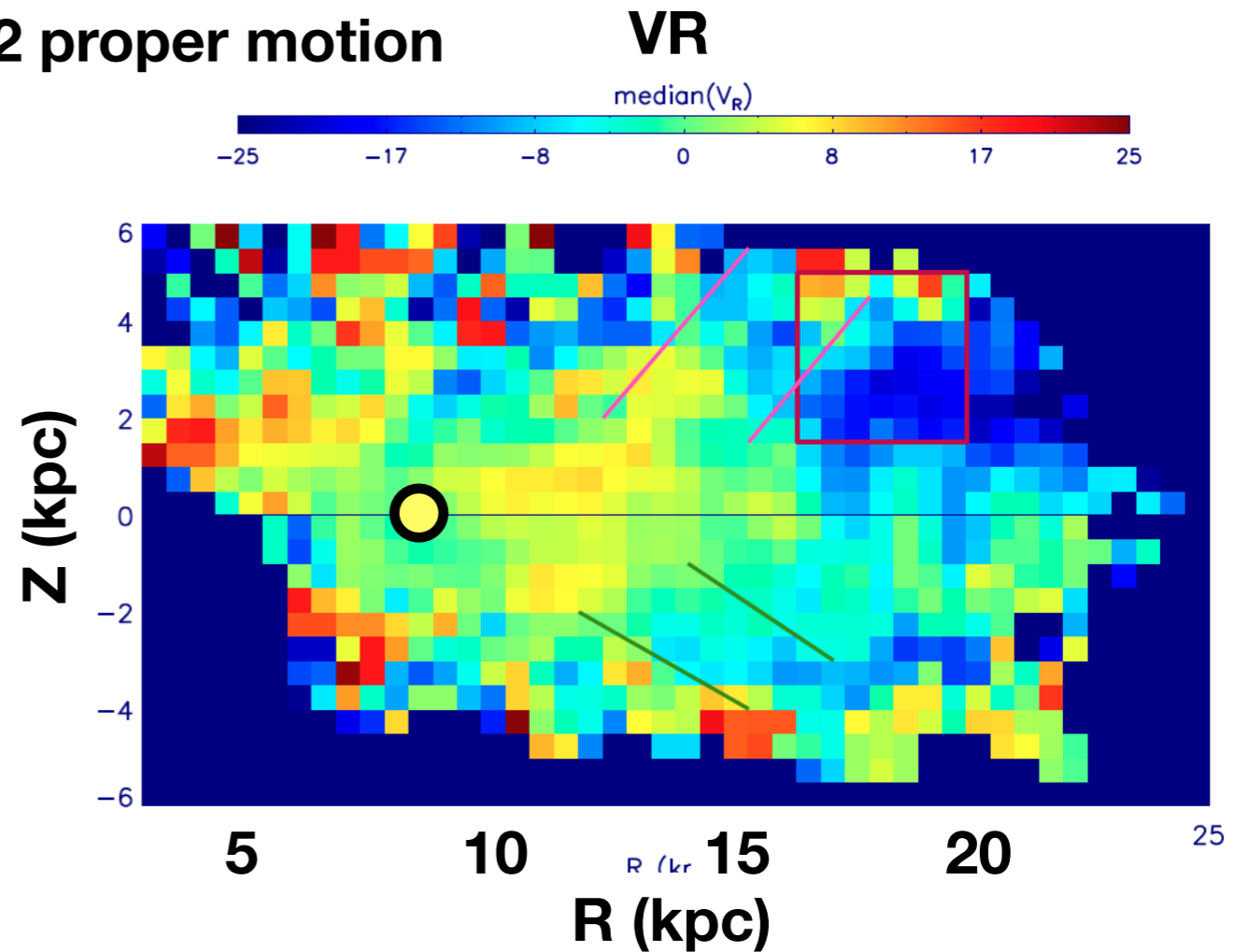
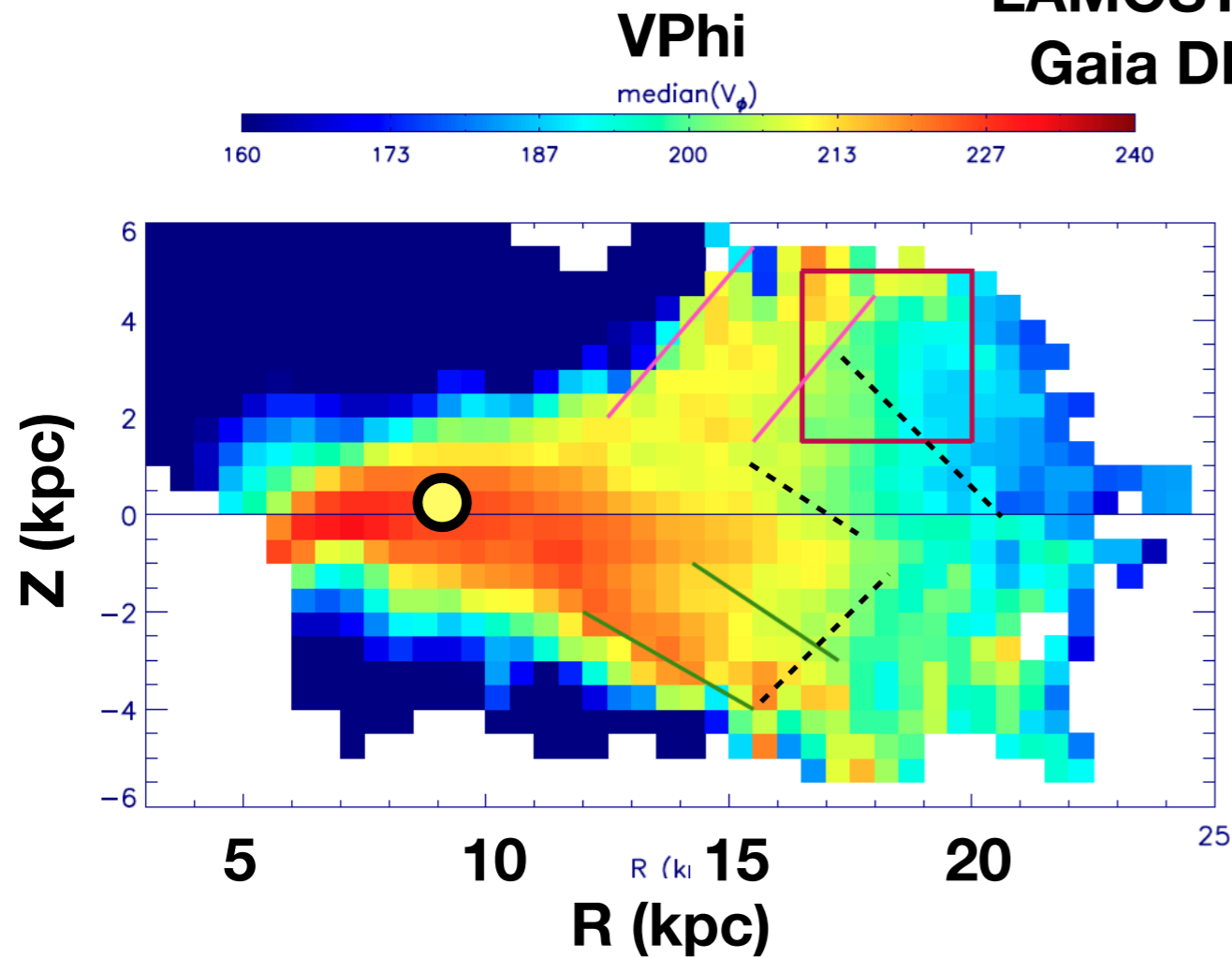
# Vphi in R-Z plane with RGBs



# Vphi in R-Z plane with RGBs

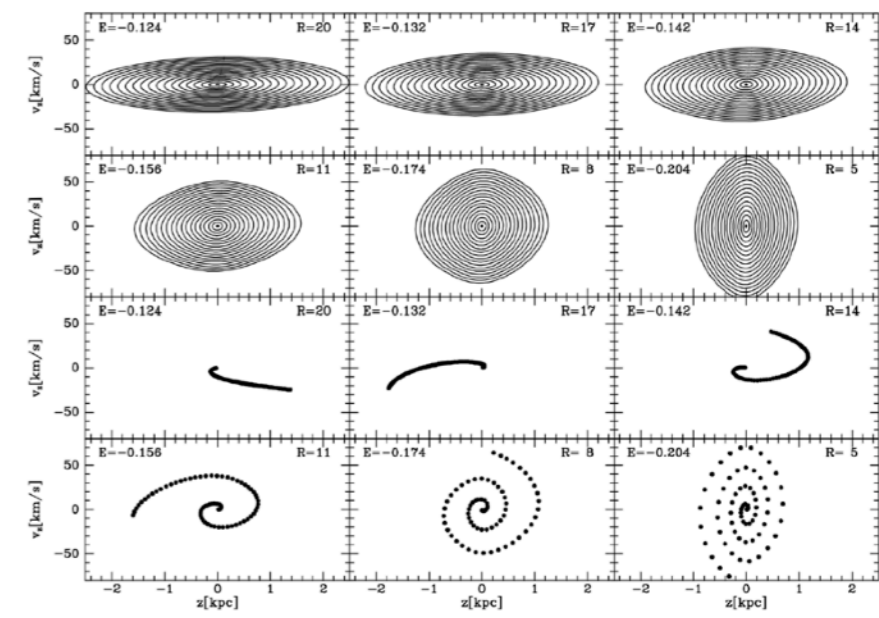


# LAMOST DR5 RGB stars + Gaia DR2 proper motion



- VPhi shows three branches and wedge-like features
- VR is full of fragmental structures
- VZ shows strong N-S asymmetry. Is it still the kinematic feature of warp?
- What happens out there making the velocities so chaotic?

# **§2 Phase spirals**



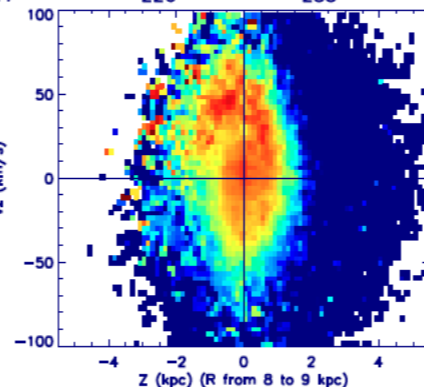
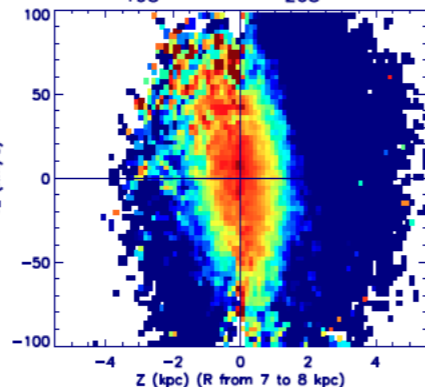
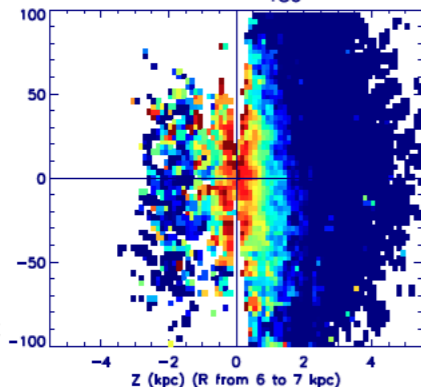
Bland-Hawthorn+18

# VPhi

median( $V_\phi$ )

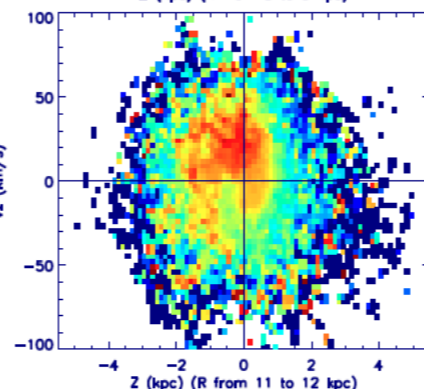
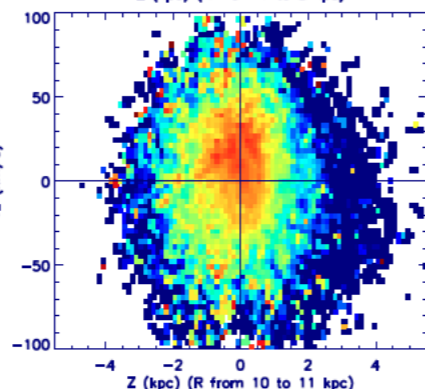
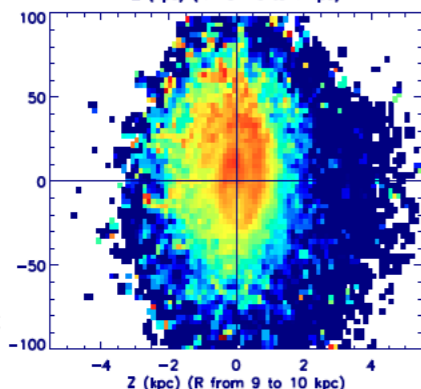


6kpc



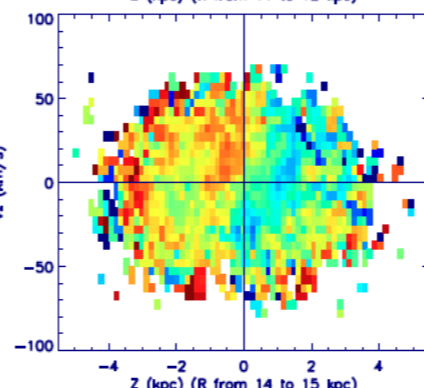
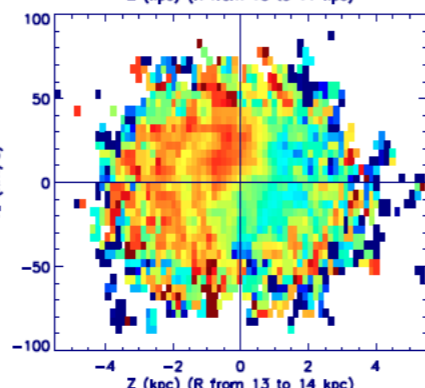
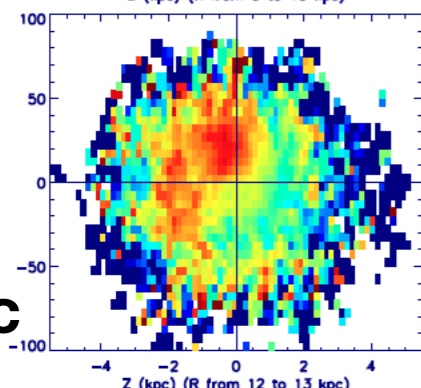
8kpc

9kpc



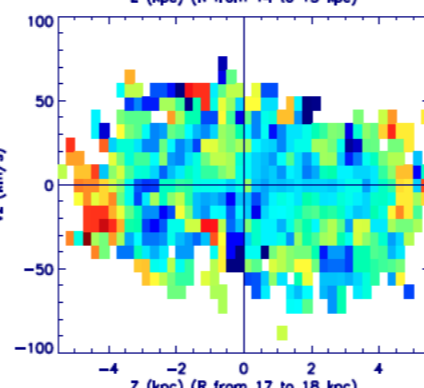
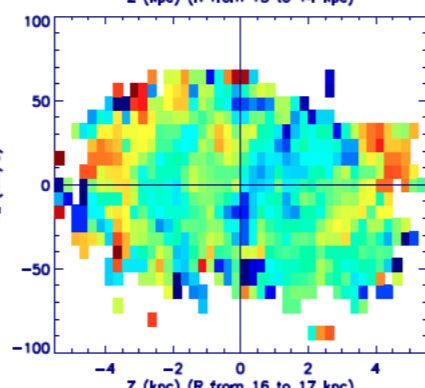
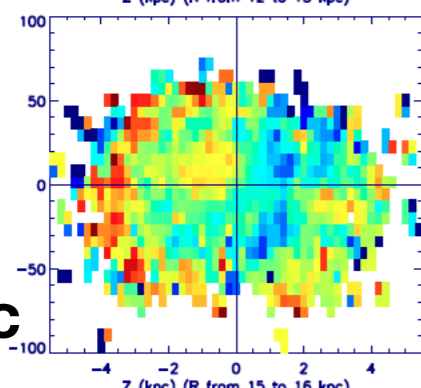
11kpc

12kpc



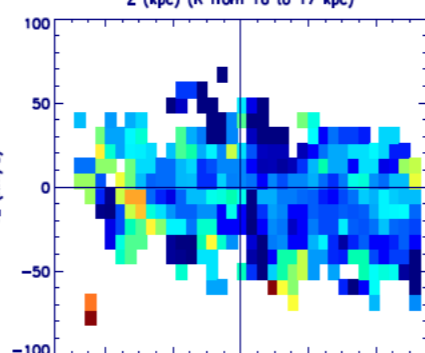
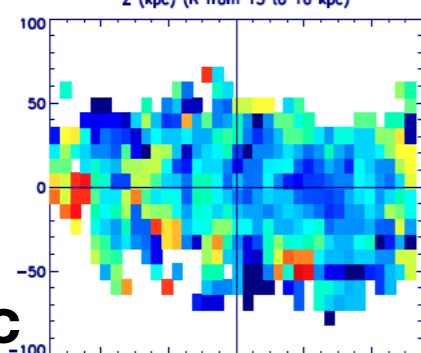
14kpc

15kpc

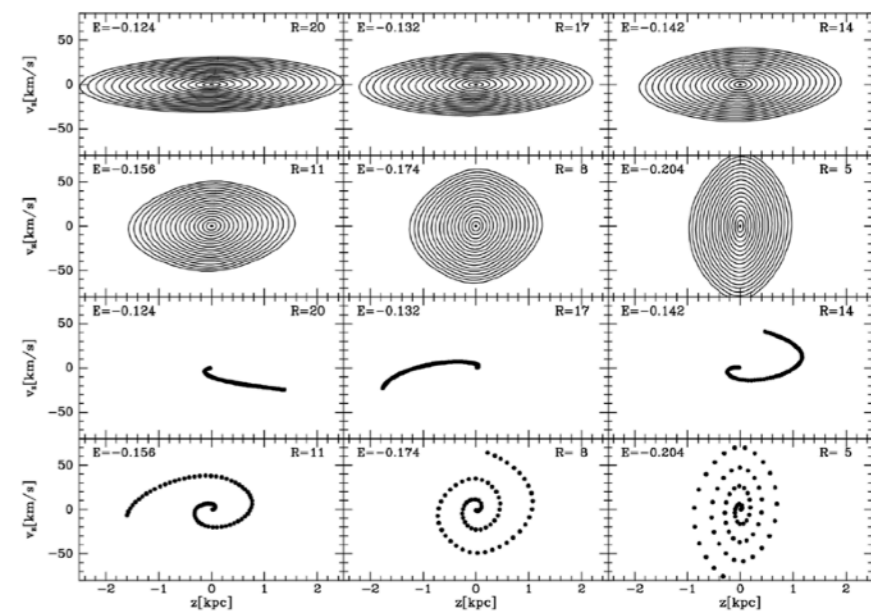


17kpc

18kpc



19kpc Y. Xu, CL et al. in prep



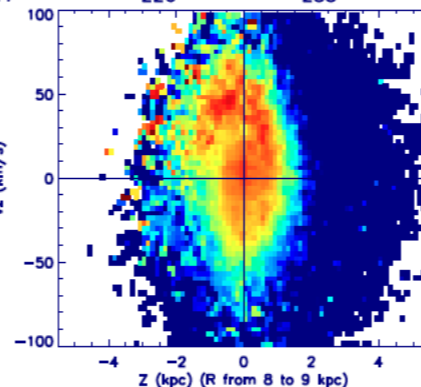
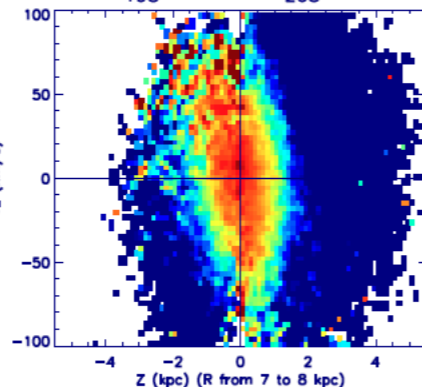
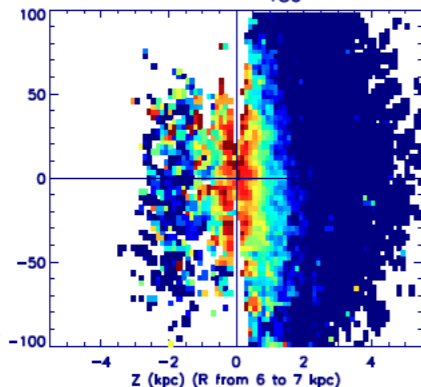
Bland-Hawthorn+18

# VPhi

median( $V_\phi$ )

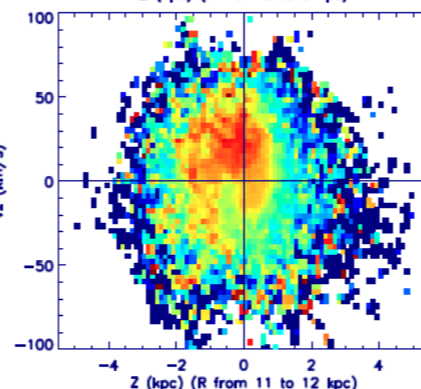
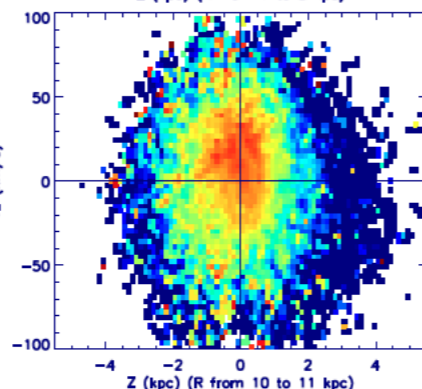
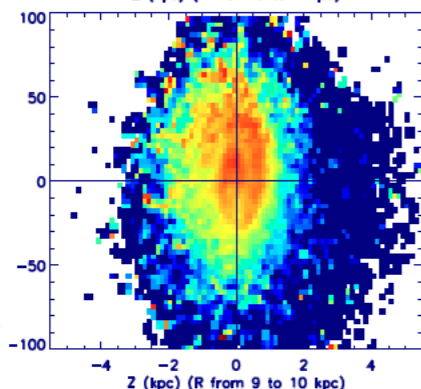


6kpc



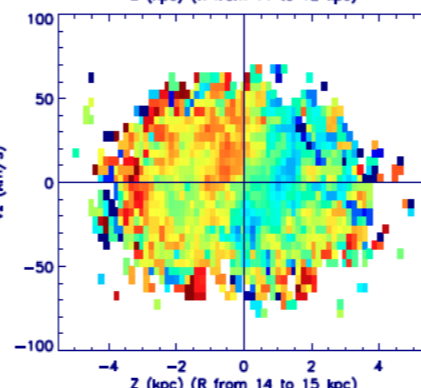
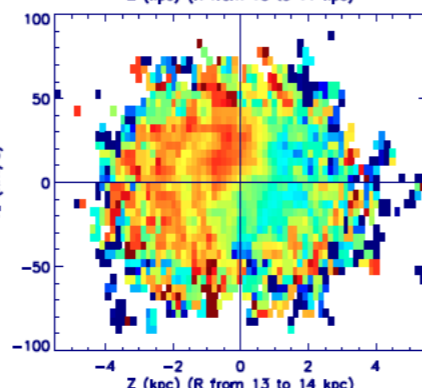
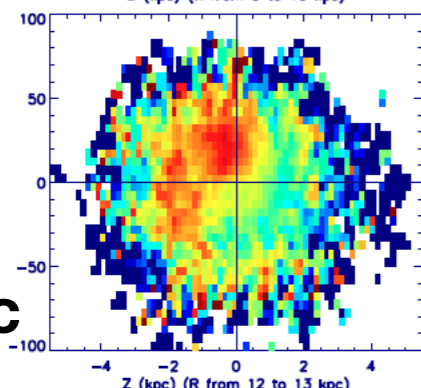
8kpc

9kpc



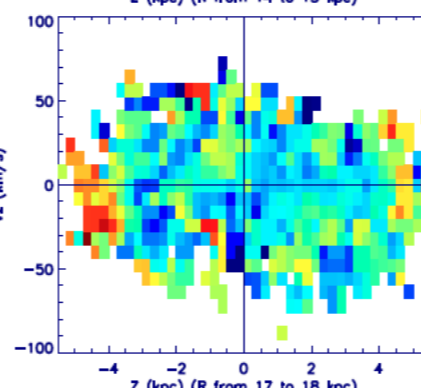
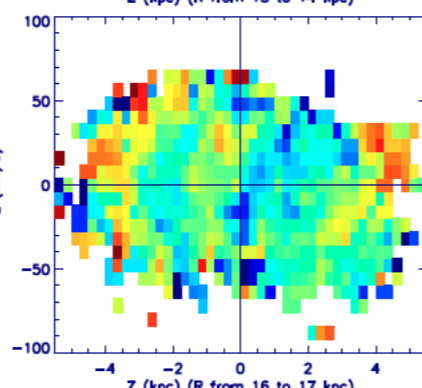
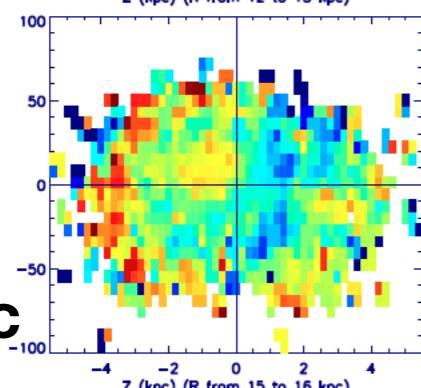
11kpc

12kpc



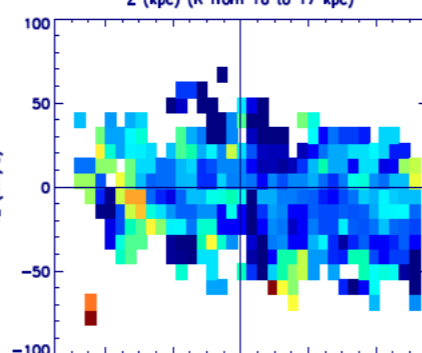
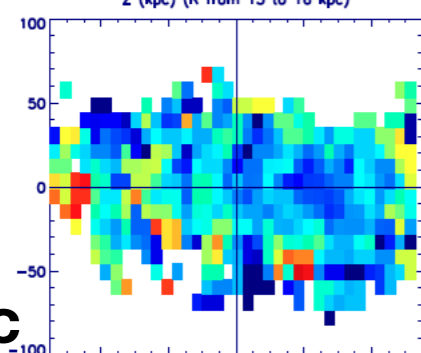
14kpc

15kpc



17kpc

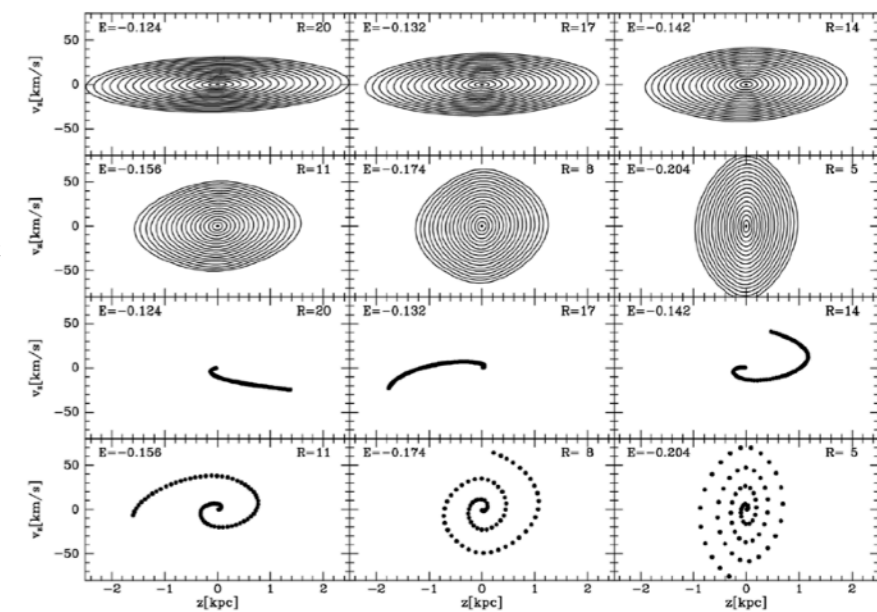
18kpc



19kpc

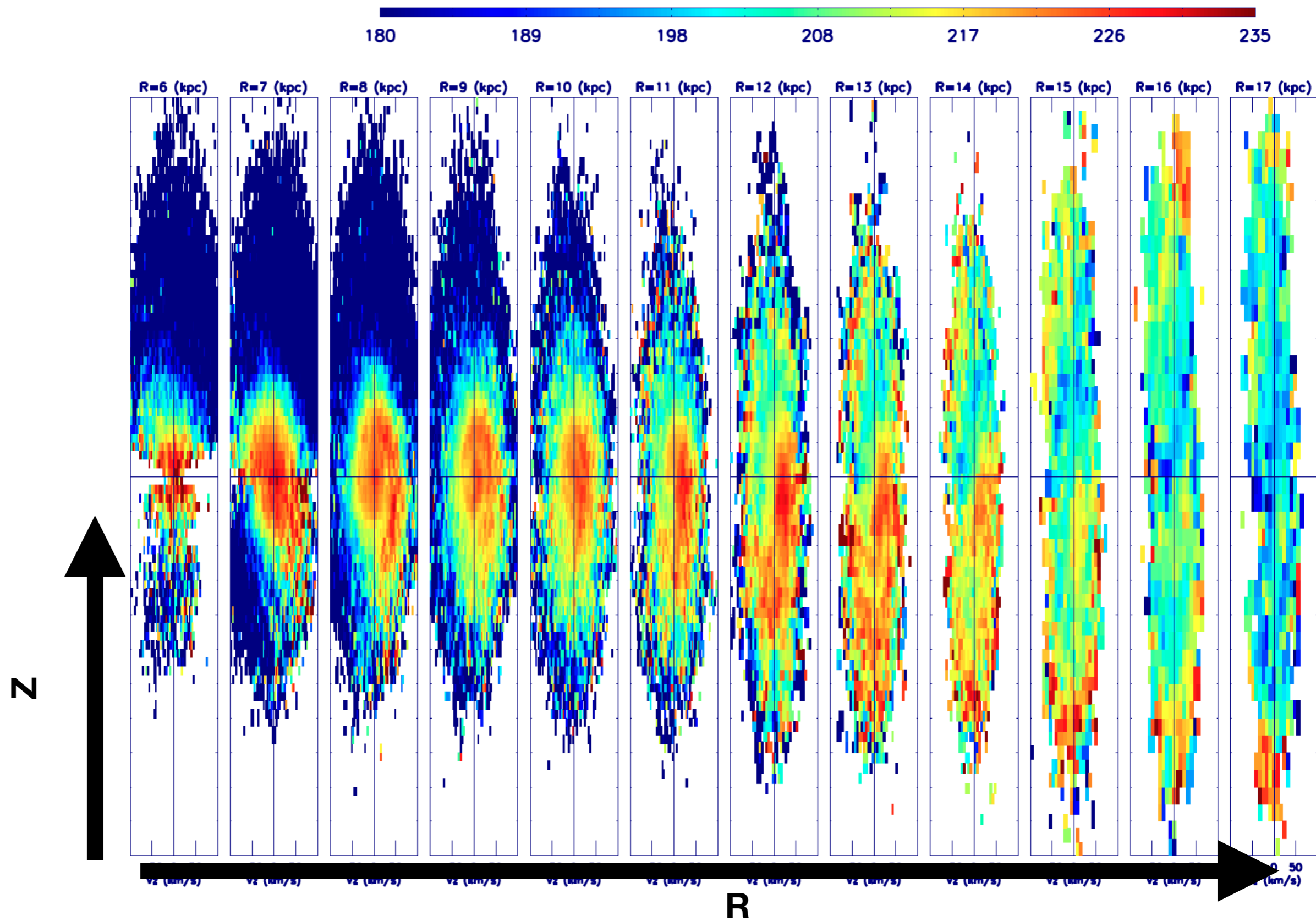
Y. Xu, CL et al. in prep

- Spiral patterns are seen at 7-15 kpc
- The spirals tightly wind at inner disk, but loosely wind at the outer disk
- Spiral disappears at  $R > 17$  kpc



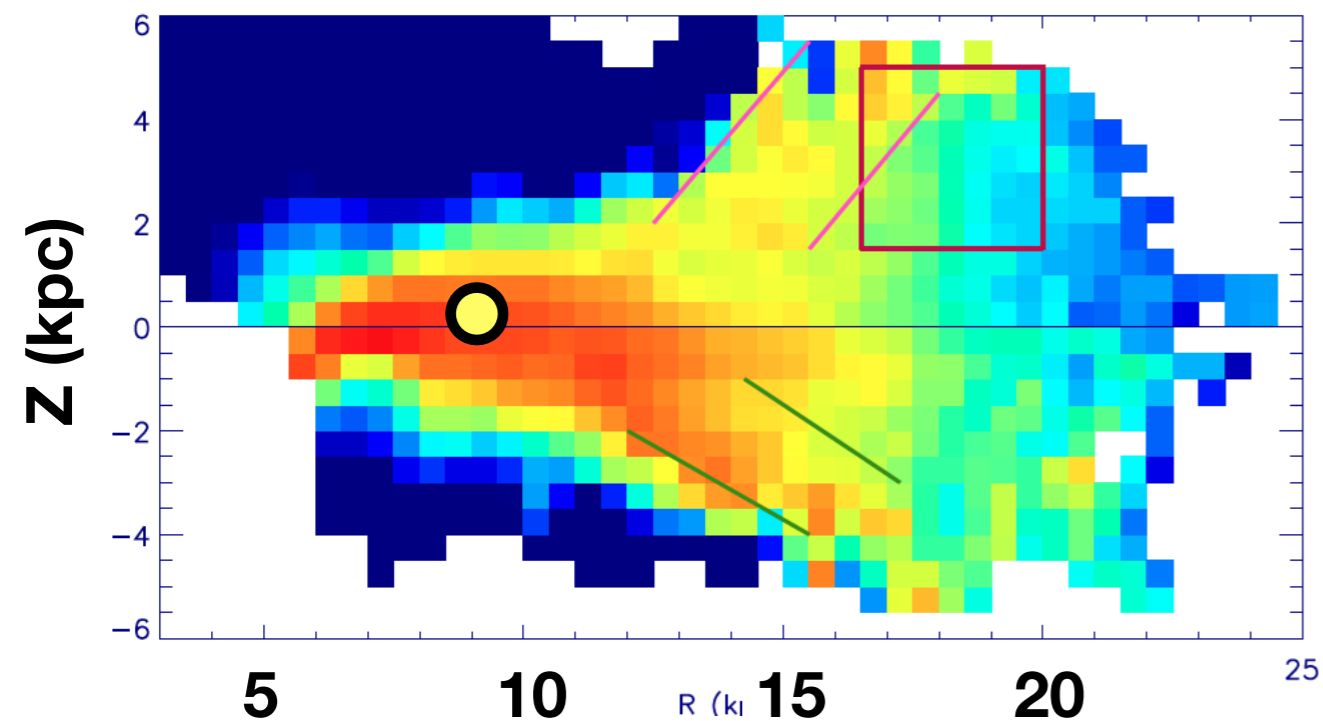
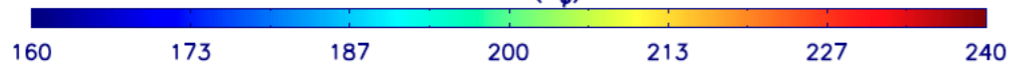
Bland-Hawthorn+18



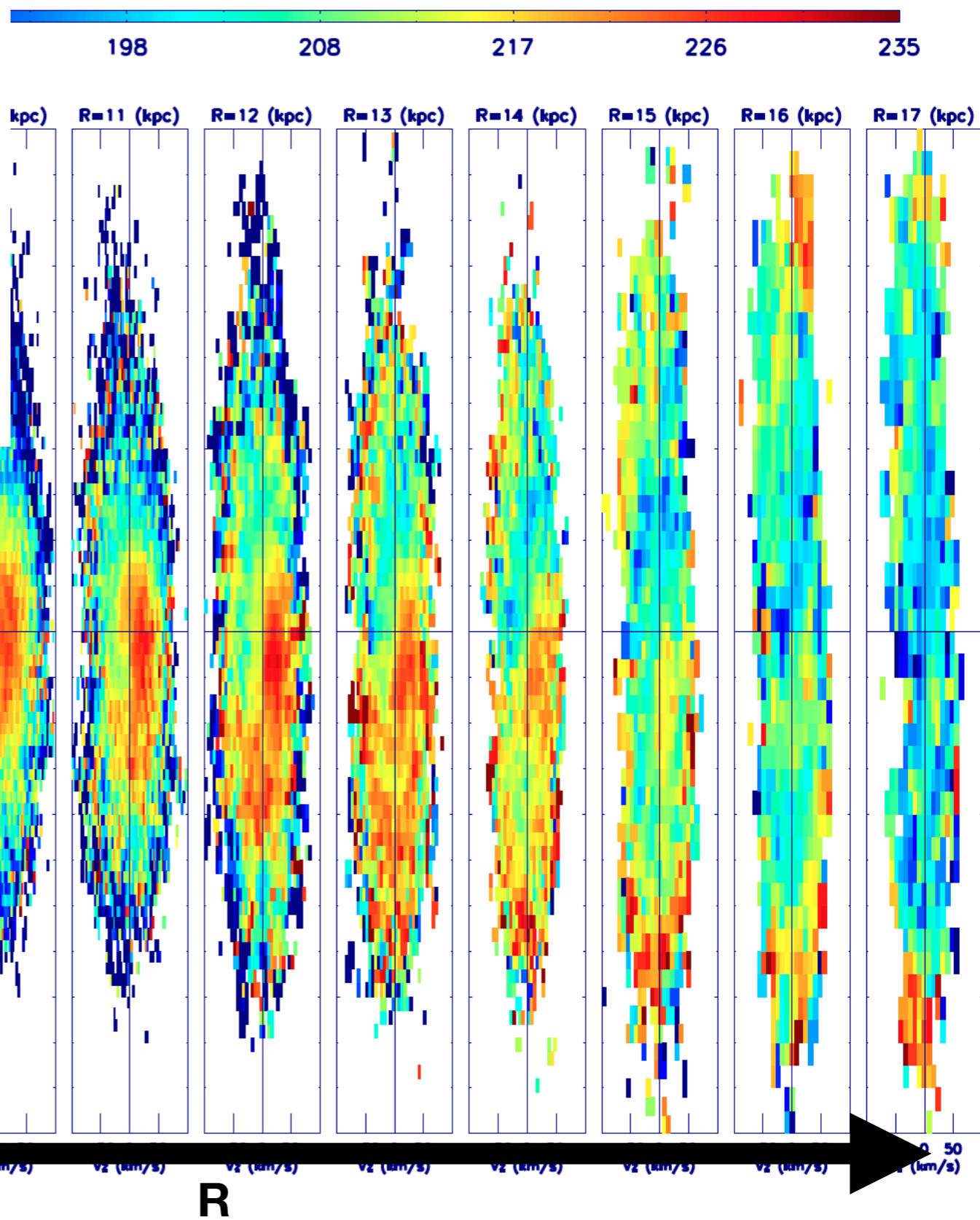


# VPhi

median( $V_{\phi}$ )

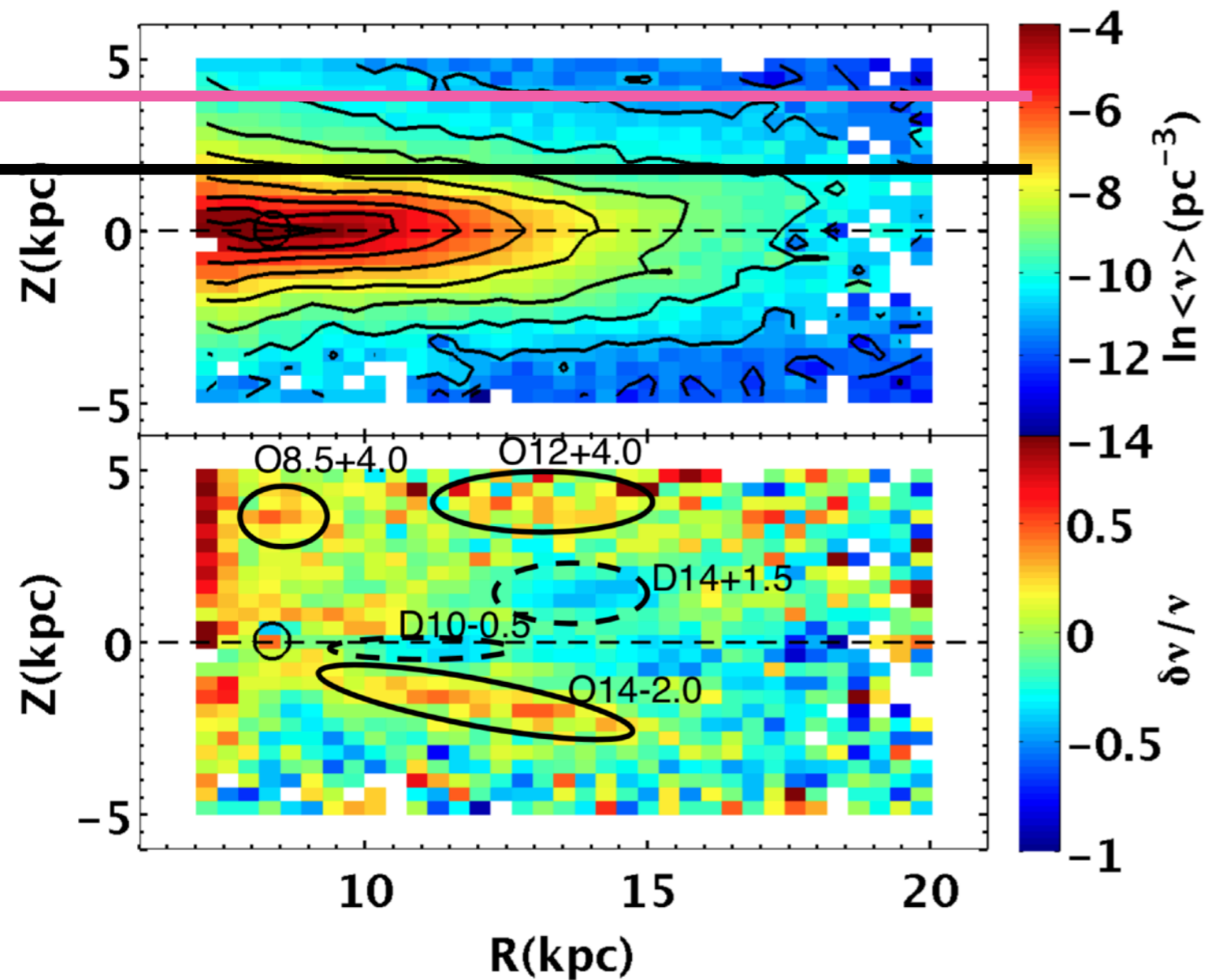


## The complicated asymmetric velocities are different projection of the phase spiral

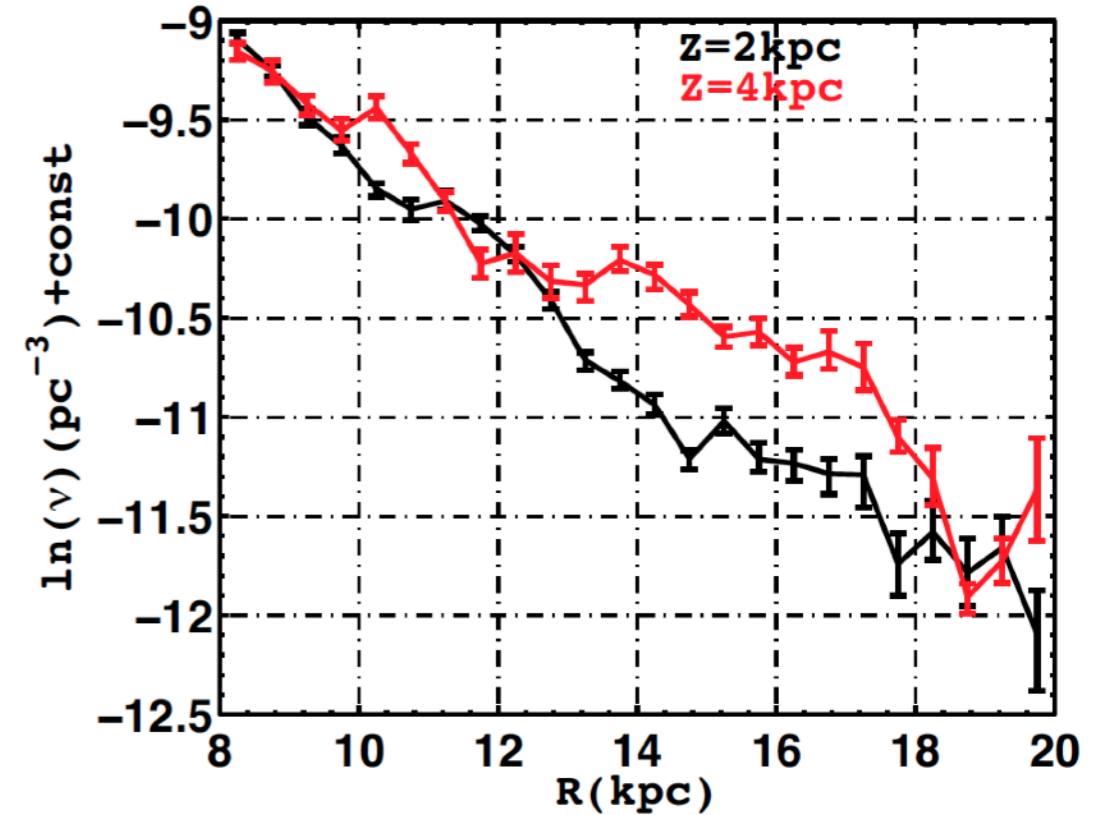
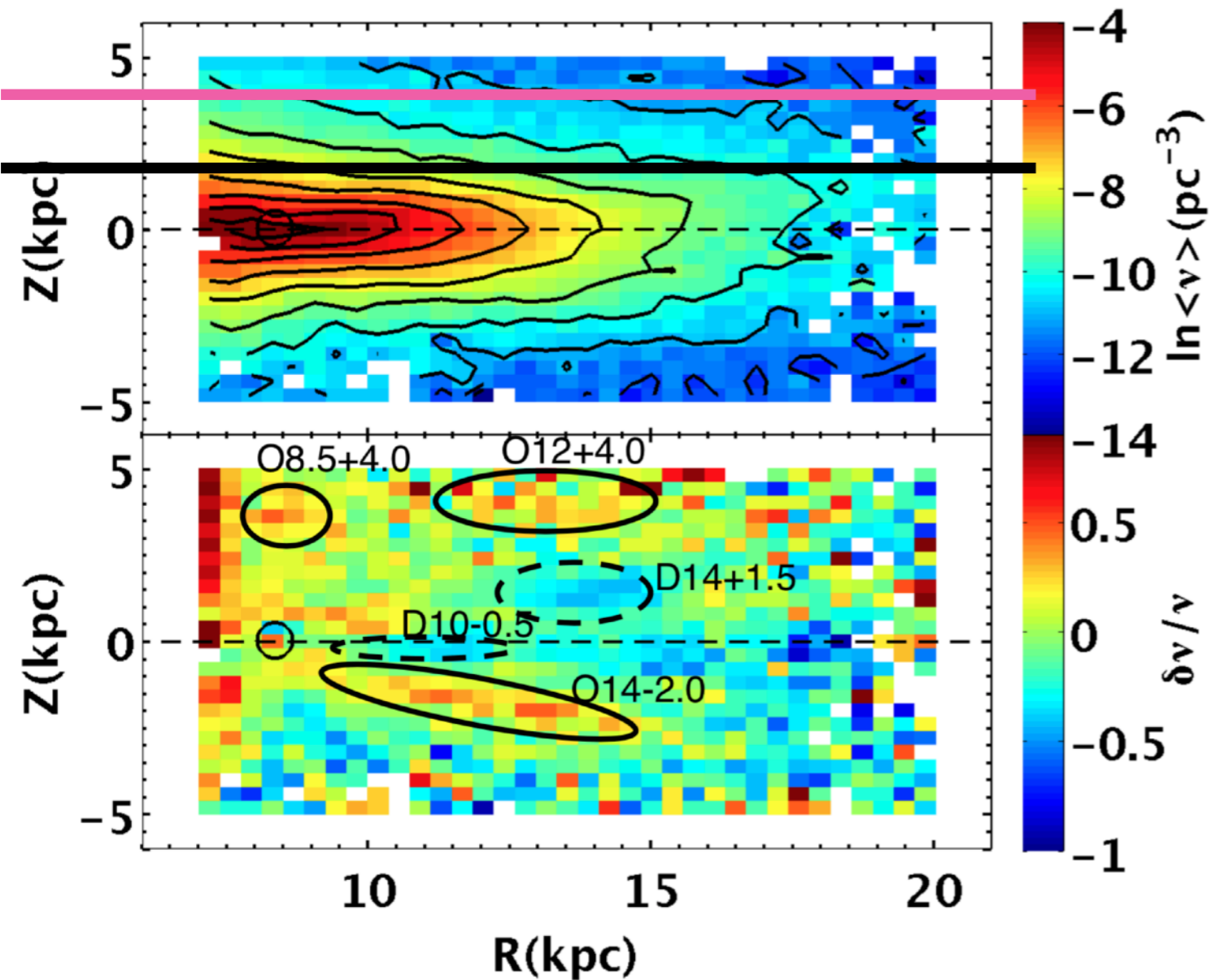


**§3 Monoceros ring**

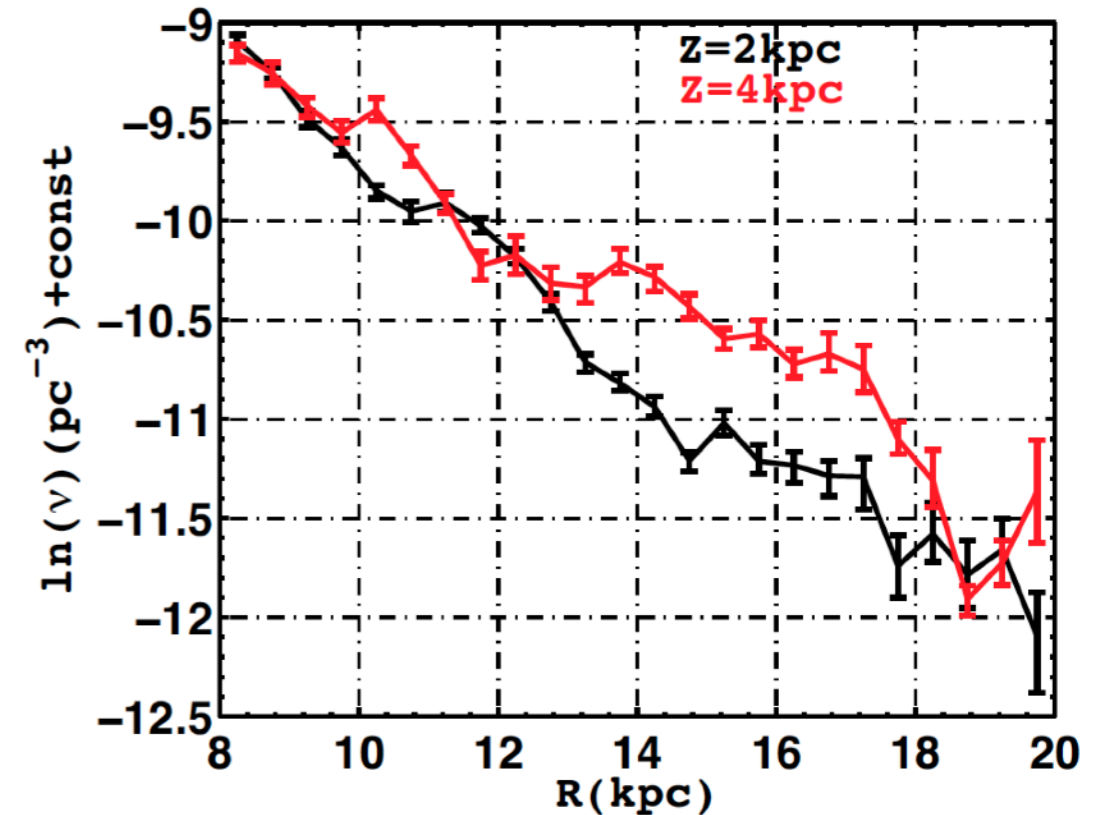
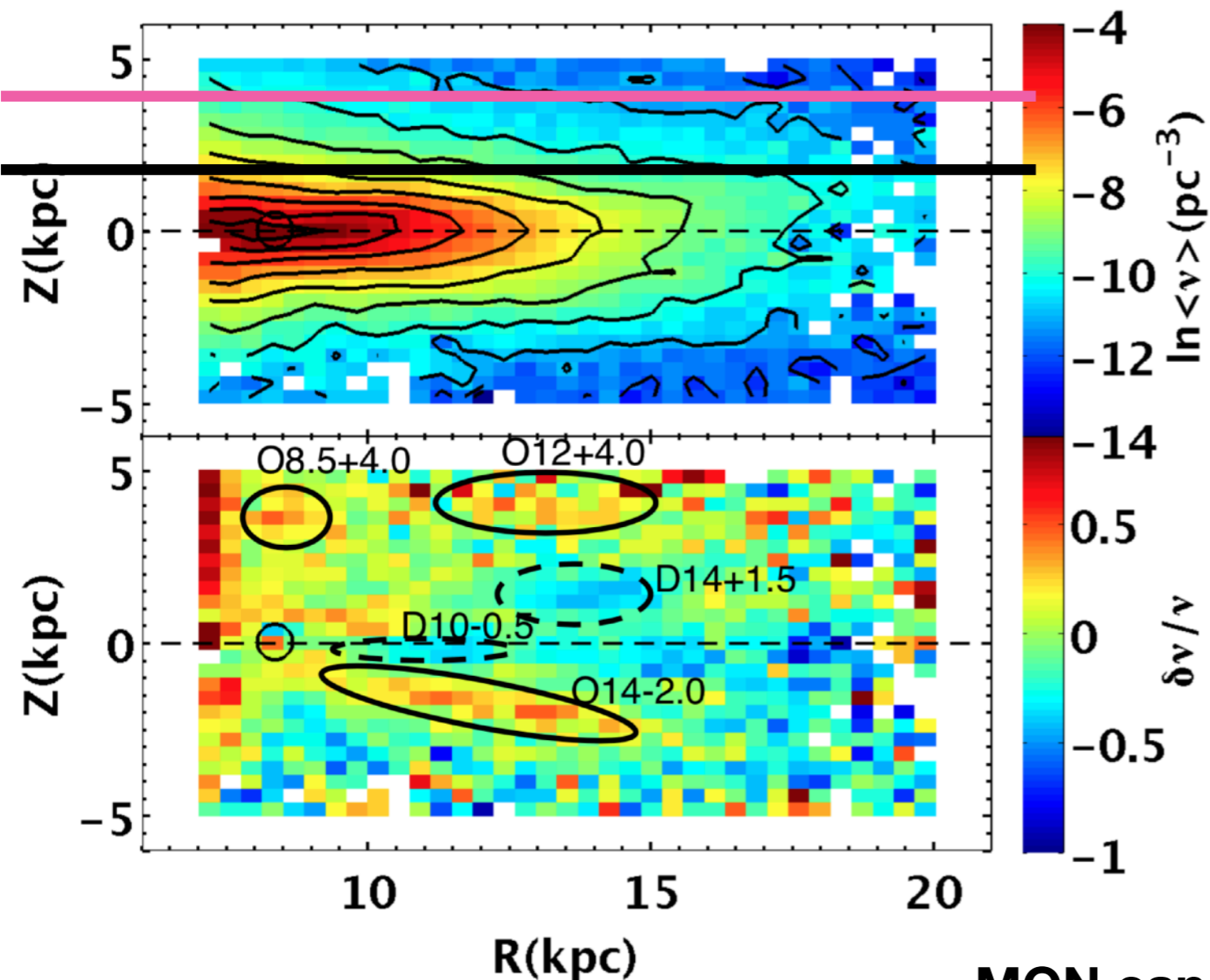
# No overdensity at MON



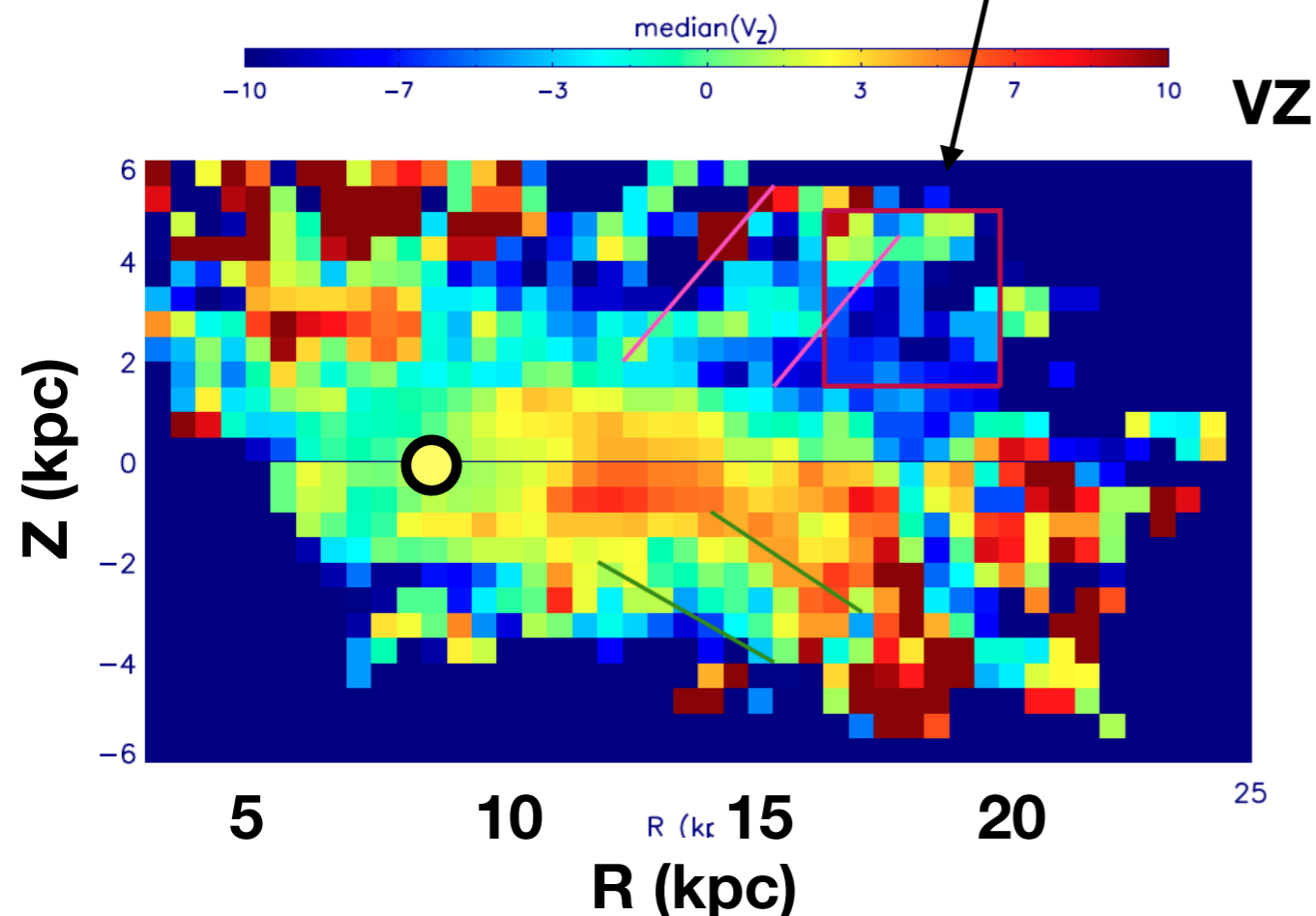
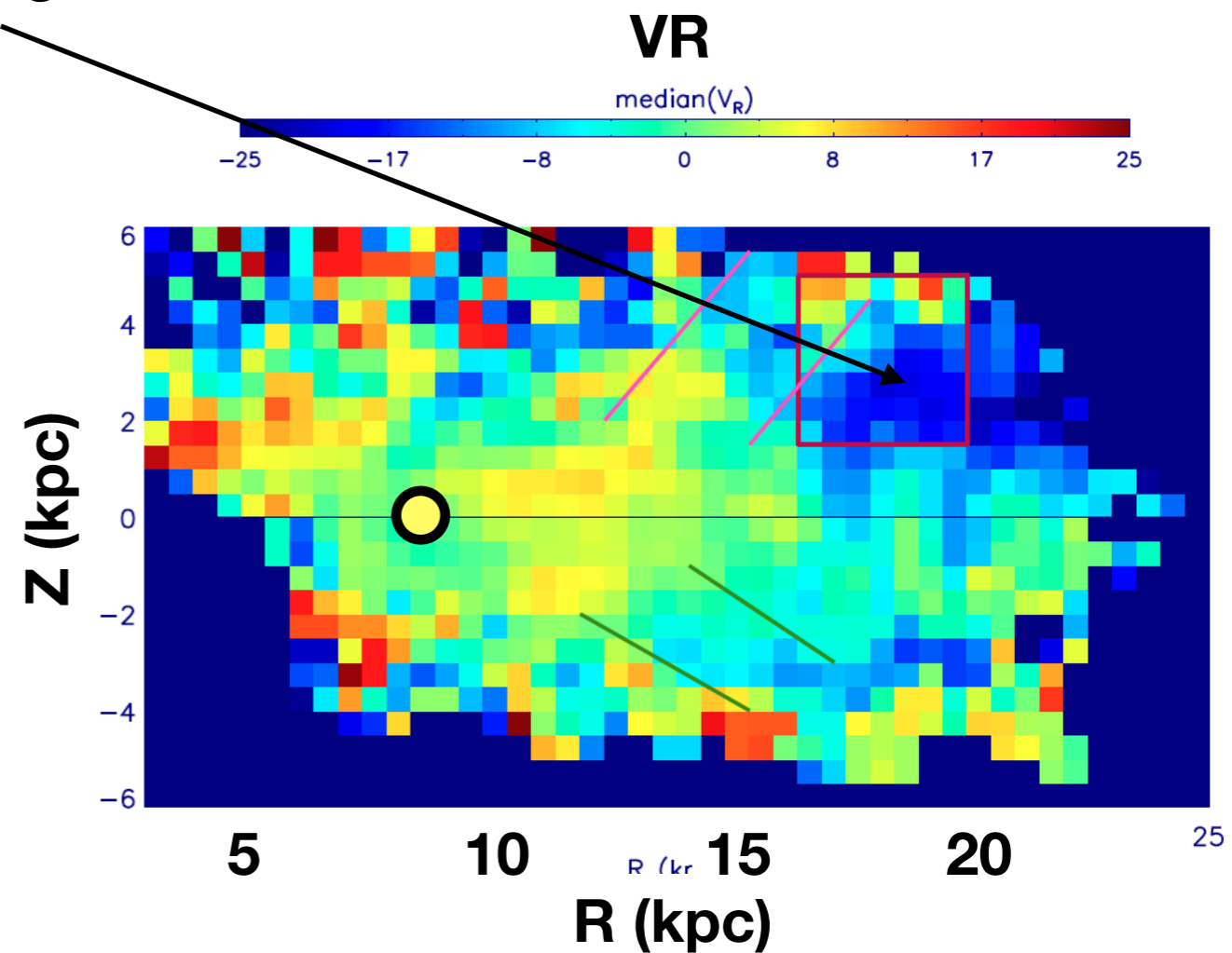
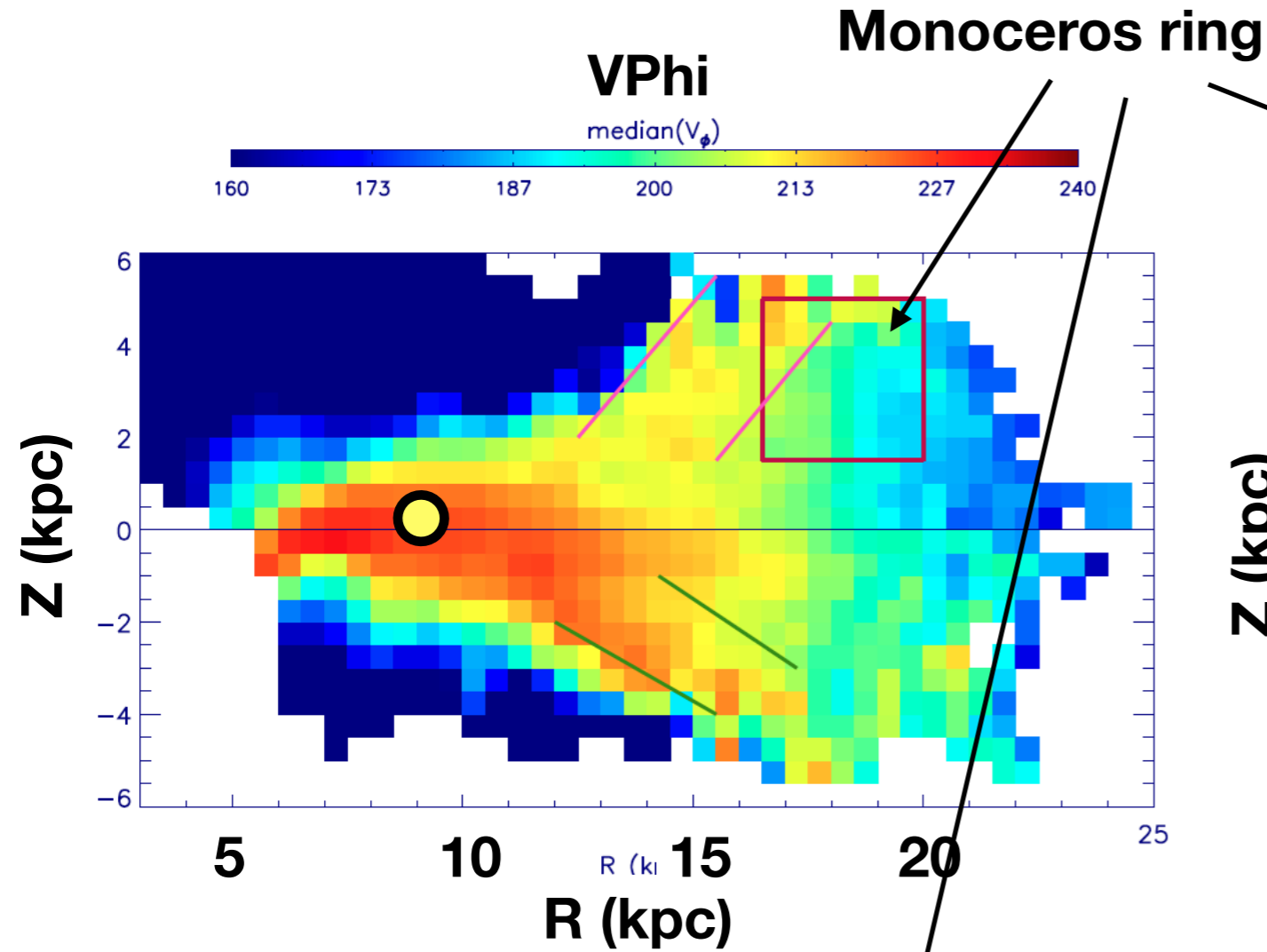
# No overdensity at MON



# No overdensity at MON



MON can be explained with a flared disk model



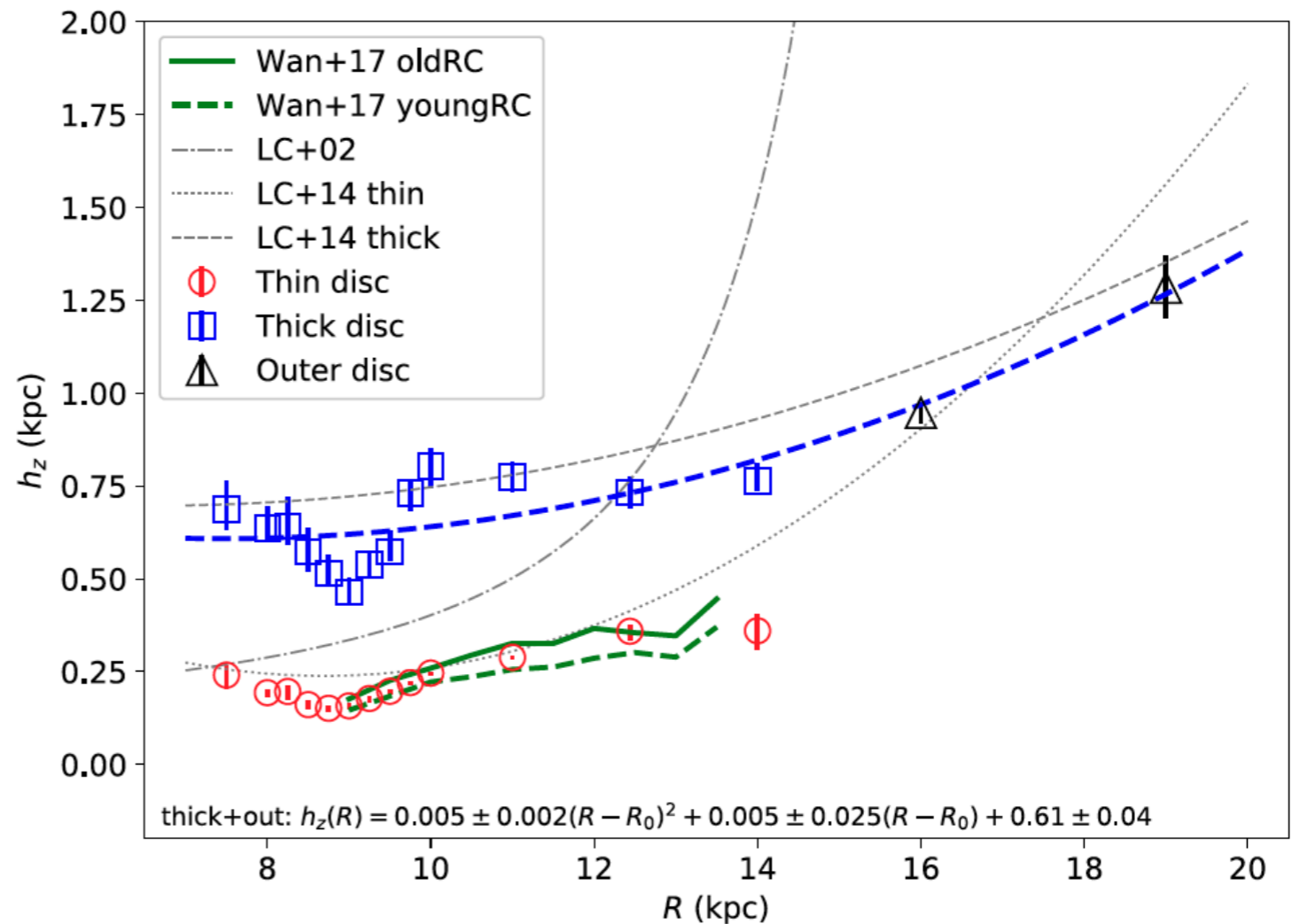
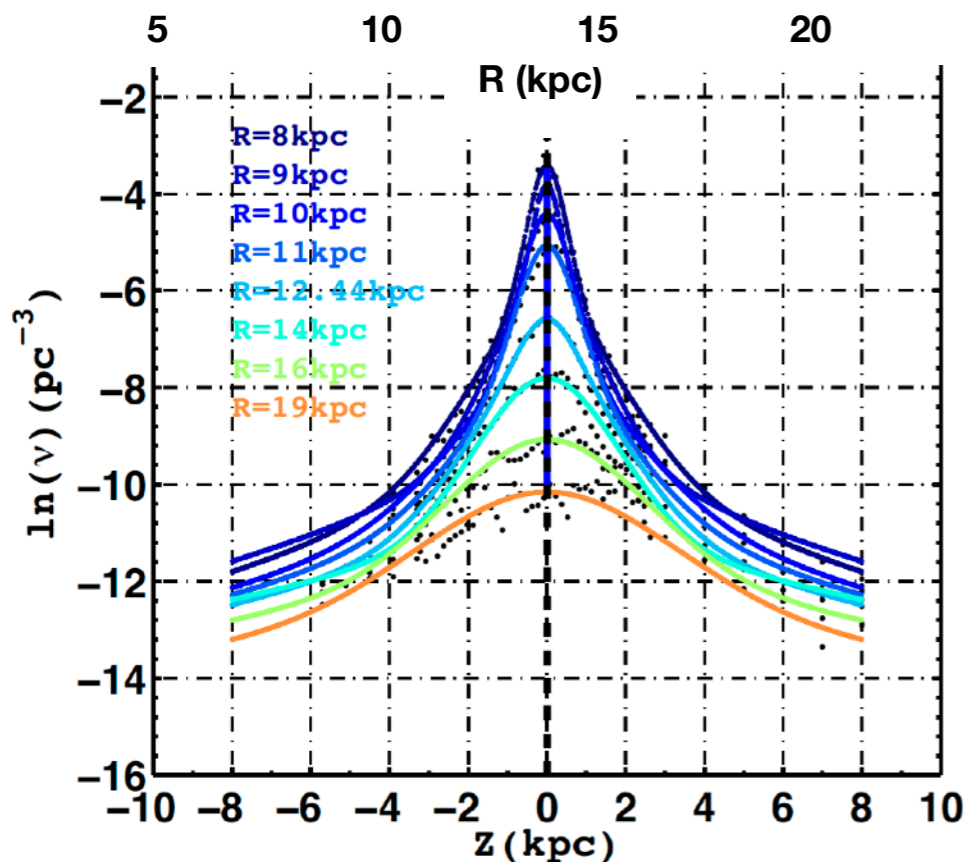
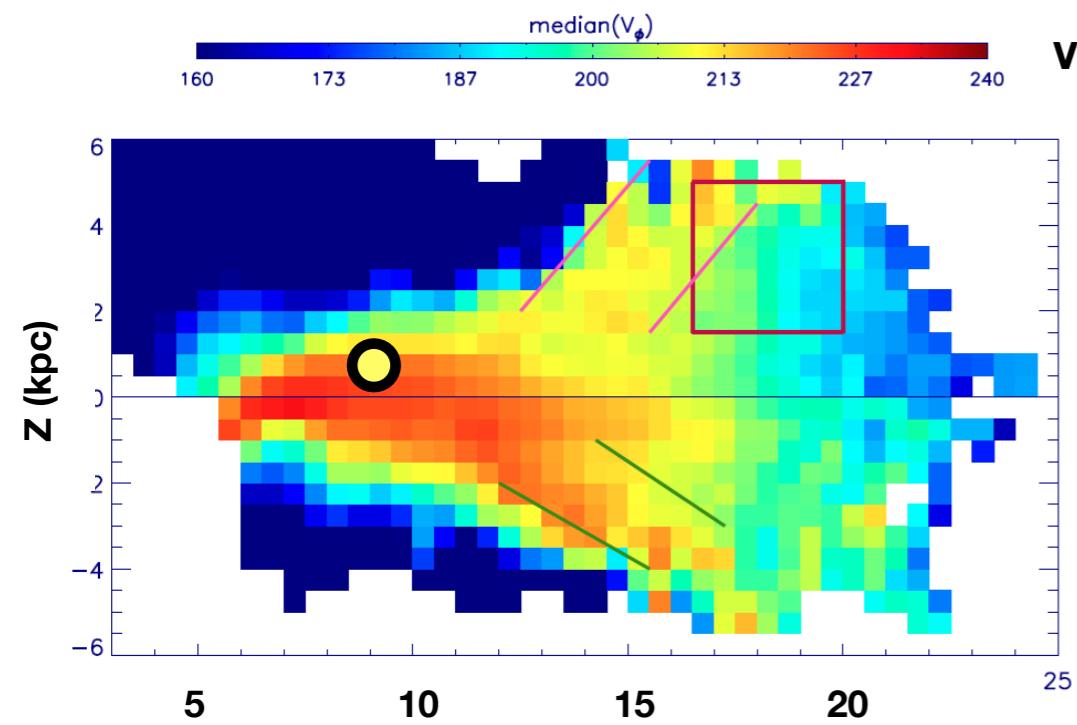
**LAMOST DR5 RGB stars +  
Gaia DR2 proper motion**

**$V_\phi \sim 190$  km/s,  
 $V_R \sim -15$  km/s,  
 $V_z \sim -10$  km/s**

# **§4 Flared disk**

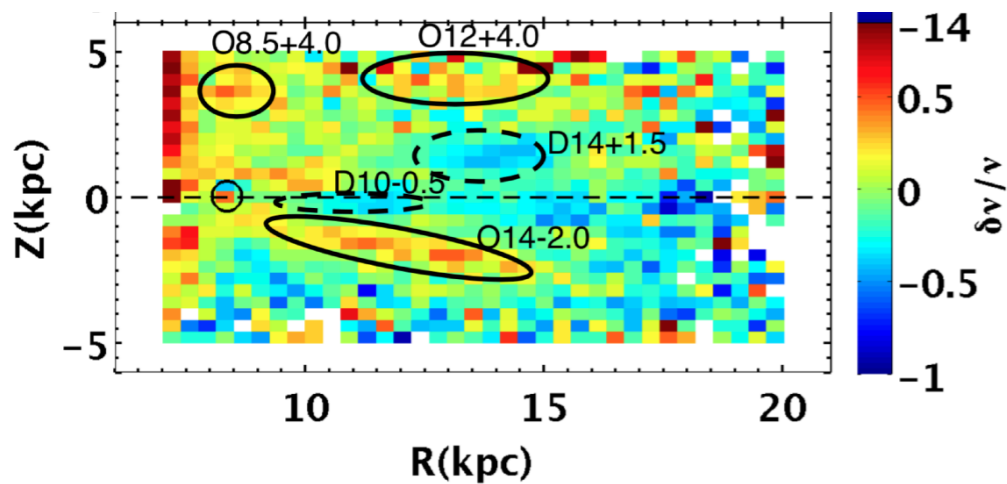


# Disk substantially flared beyond R=12 kpc

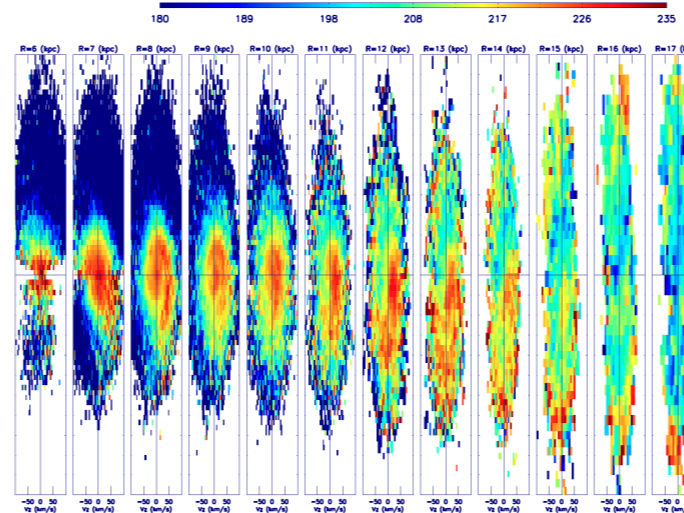


# §5 Understand the complicated non-axisymmetric features with simulations

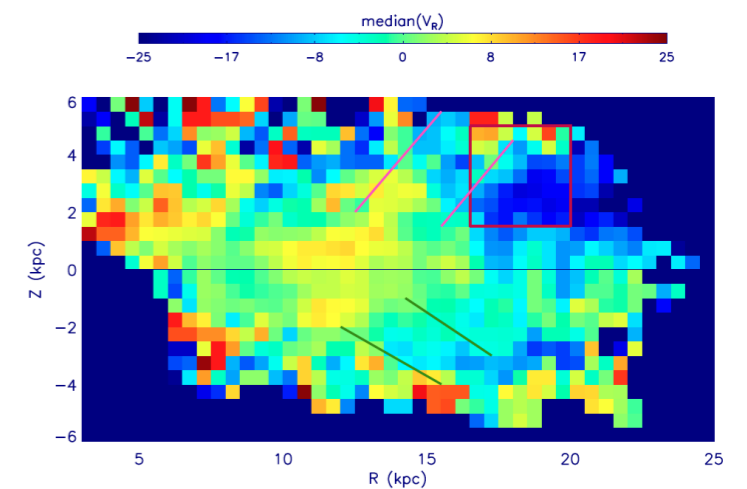
## Ripples



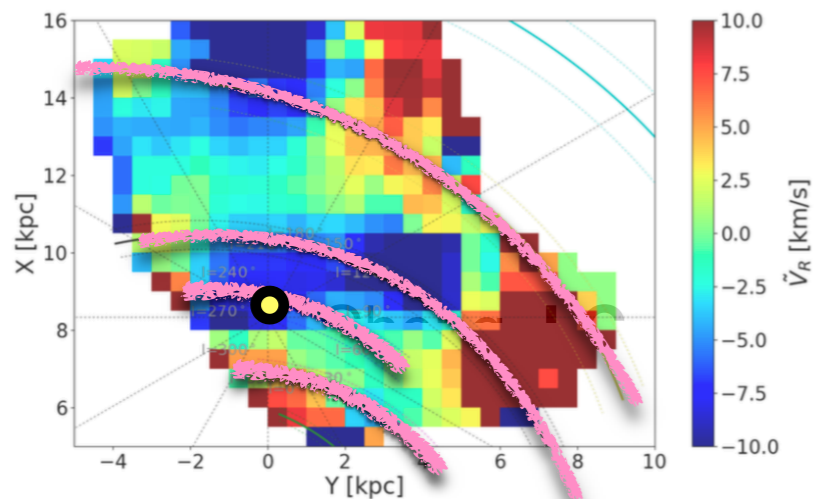
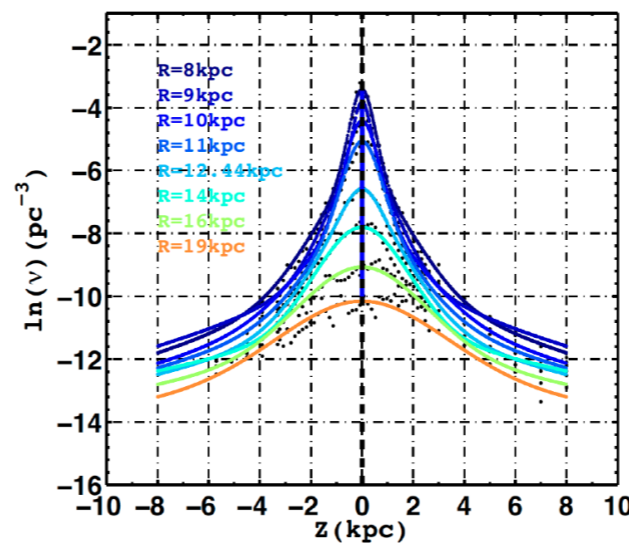
## Spirals



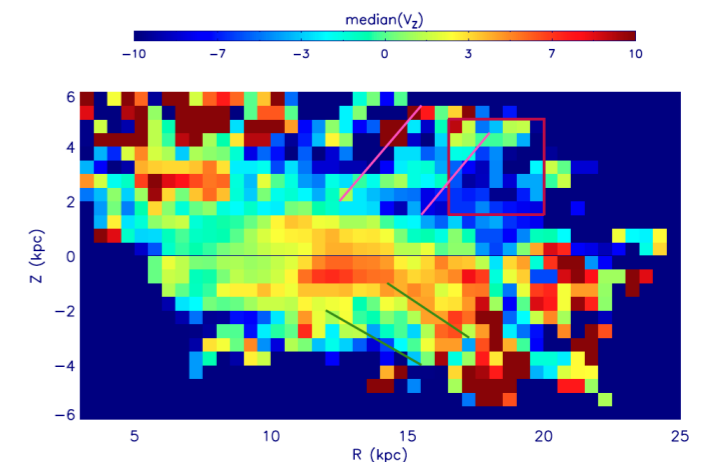
## Ring (streaming velocities)

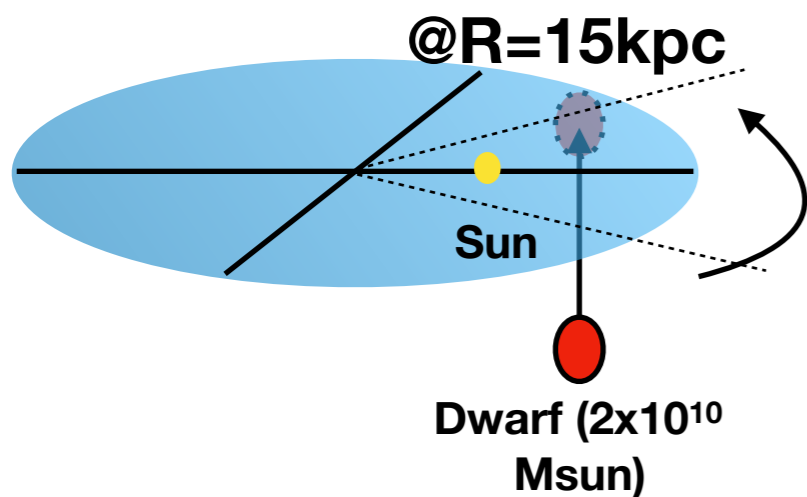
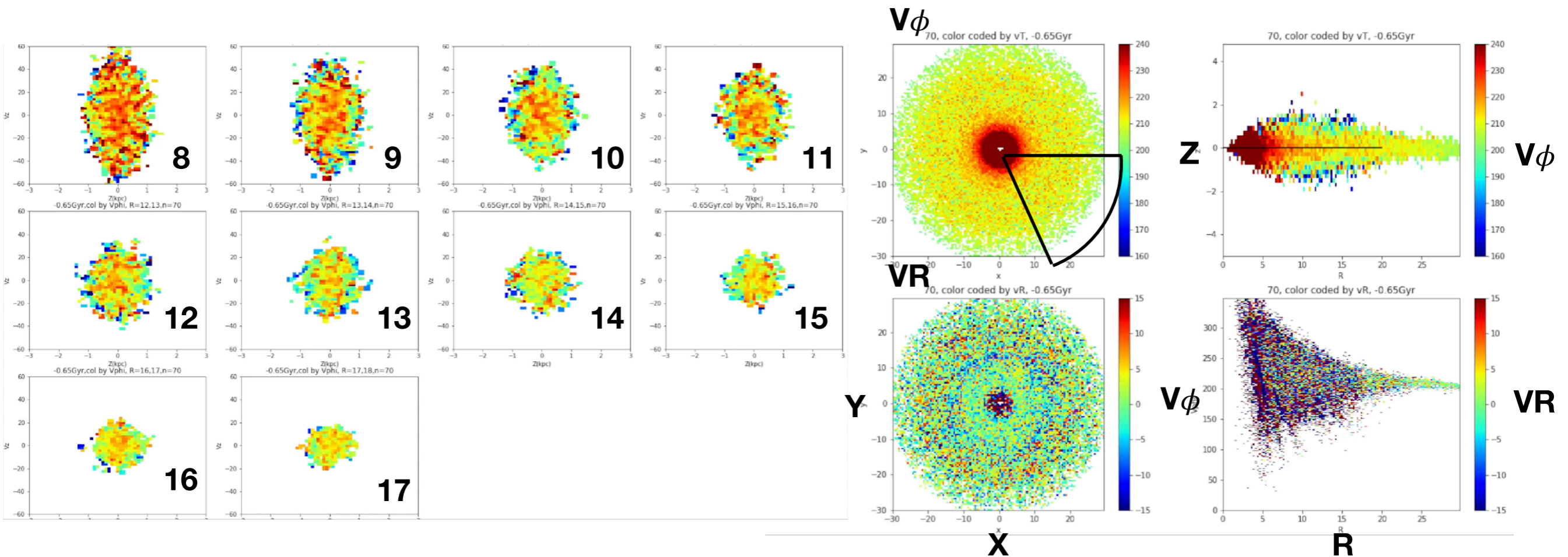


## Flare

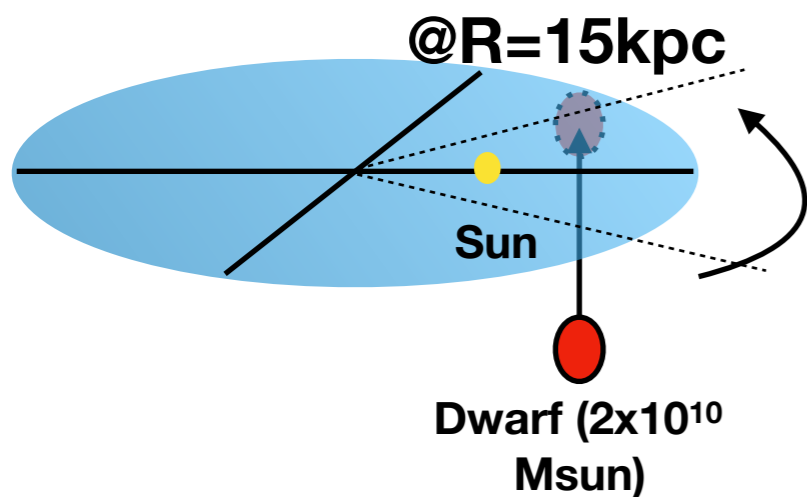
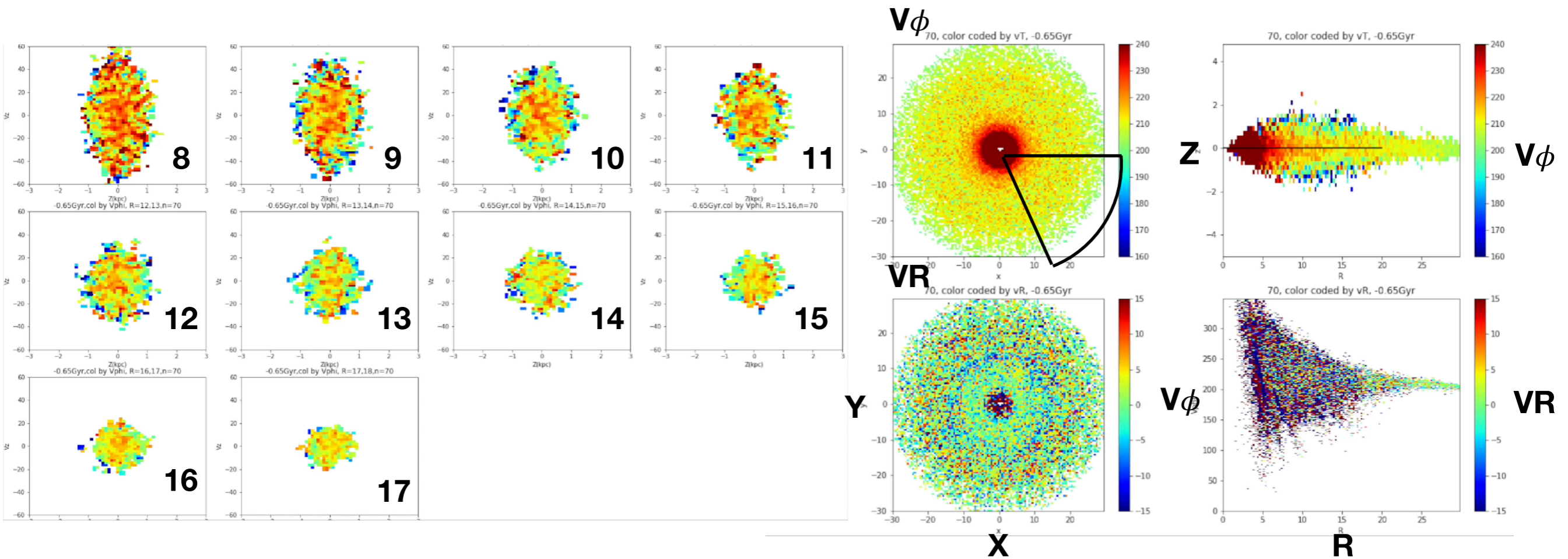


(a) Radial velocity  $\tilde{V}_R$



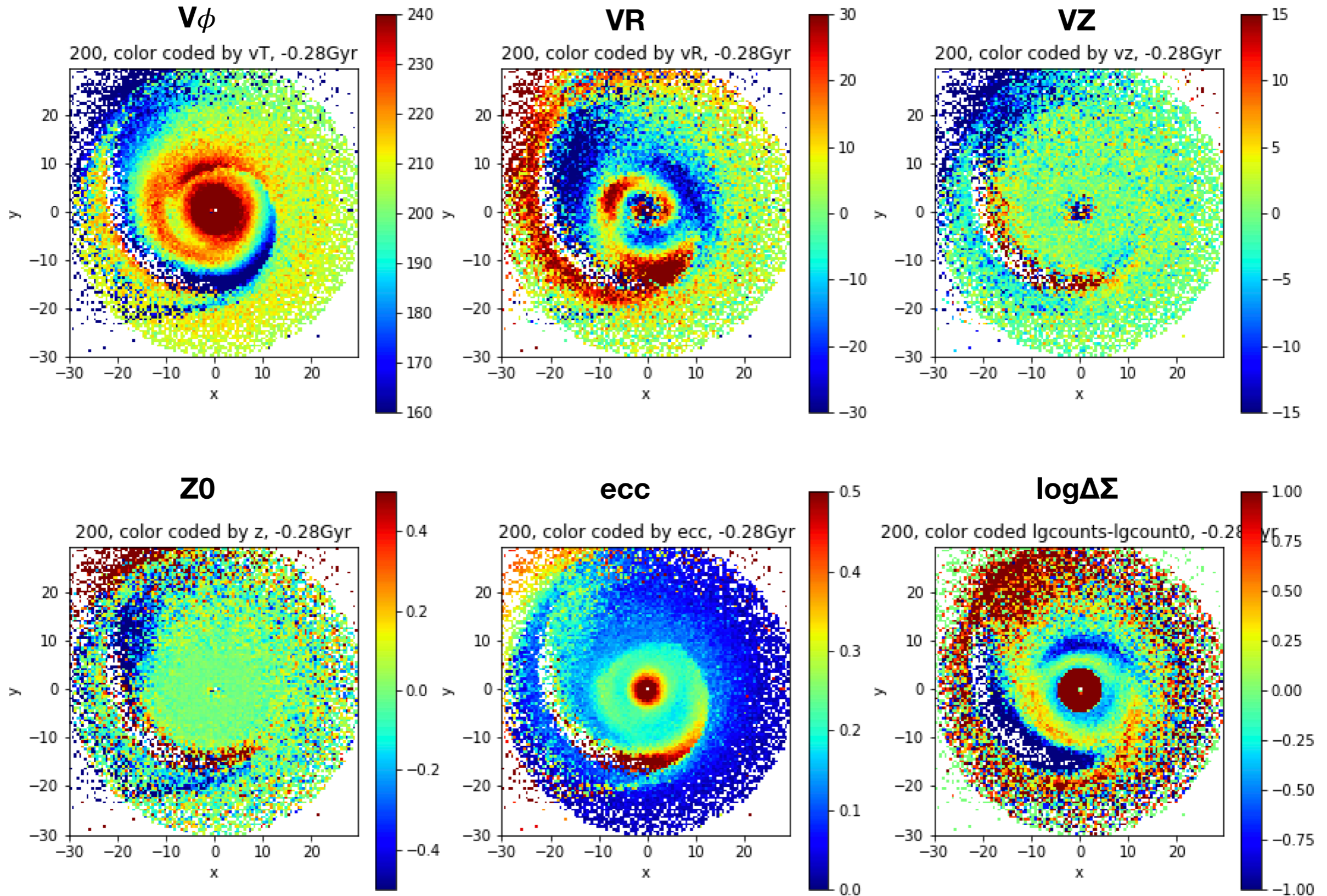


- **Smaller R shows spiral first, then, gradually push to larger R, because that azimuthal frequency decreases with R**
- **Spirals wind up quickly after a few orbital periods**
- **Substructures in X-Y and R-Z plane is the same feature as spirals but projected to other space**

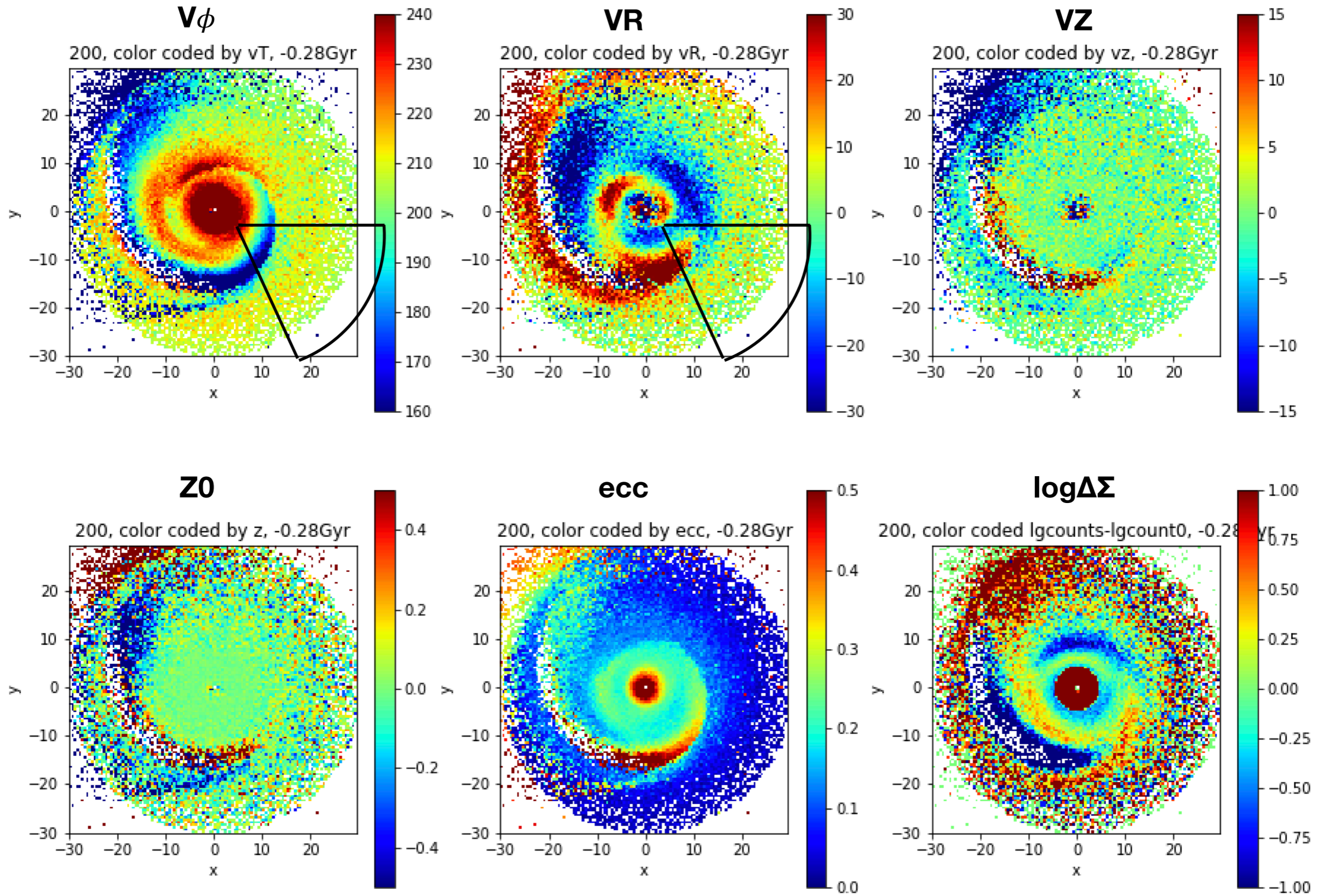


- **Smaller  $R$  shows spiral first, then, gradually push to larger  $R$ , because that azimuthal frequency decreases with  $R$**
- **Spirals wind up quickly after a few orbital periods**
- **Substructures in  $X$ - $Y$  and  $R$ - $Z$  plane is the same feature as spirals but projected to other space**

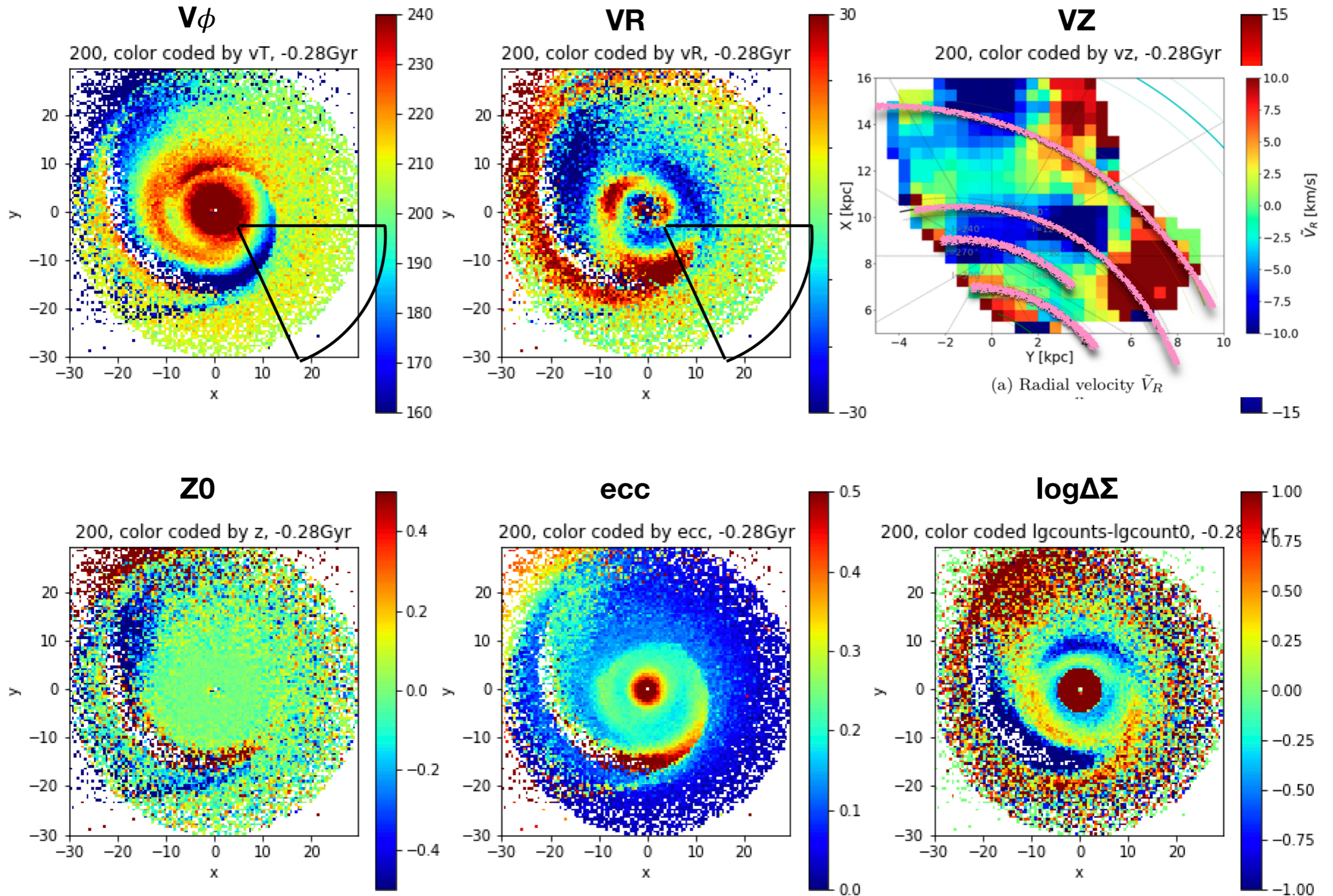
**Model:  $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$**



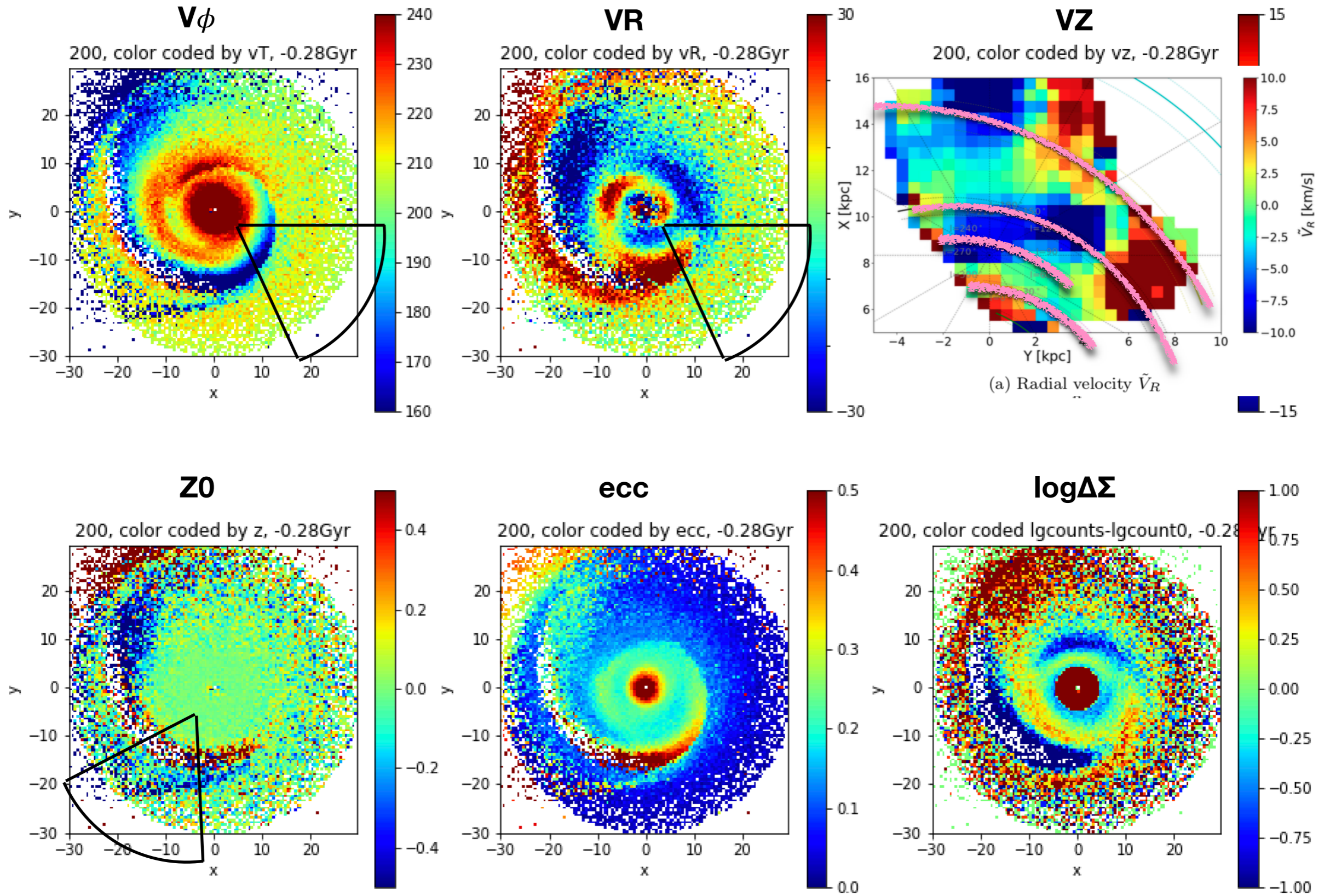
**Model:  $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$**



# Model: $M_{\text{dwarf}}=2 \times 10^{10} \text{ M}_{\text{sun}}$ , $R_{\text{hit}}=15 \text{ kpc}$ , $t=0.3 \text{ Gyr}$

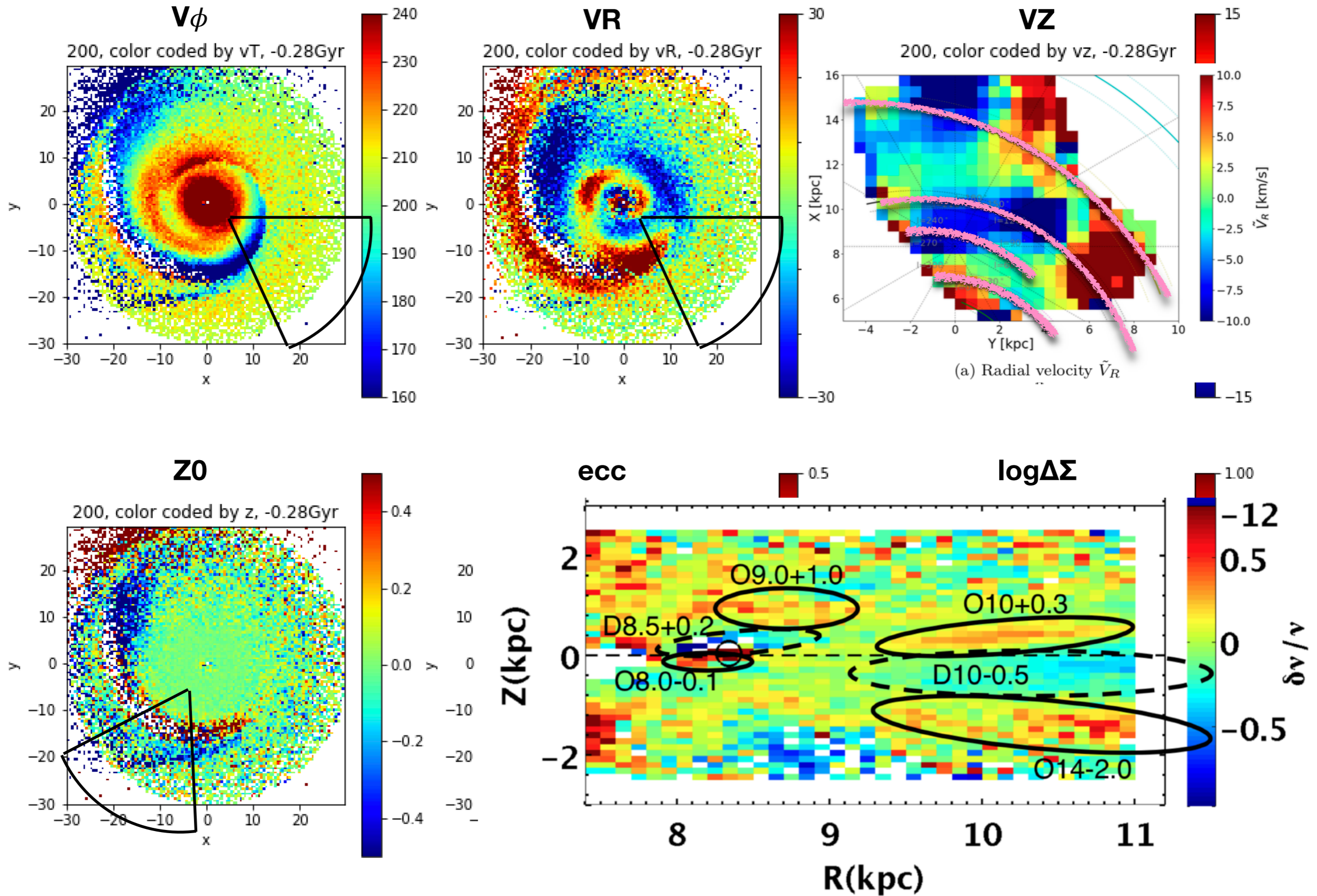


**Model:  $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$**

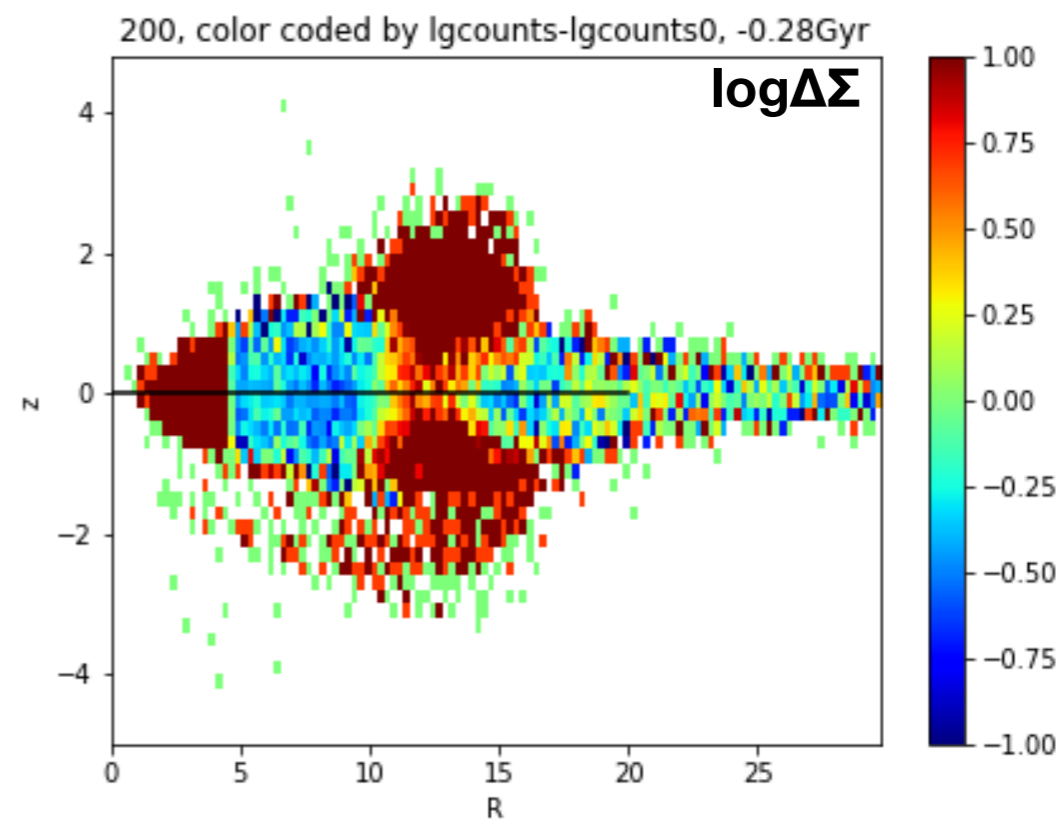
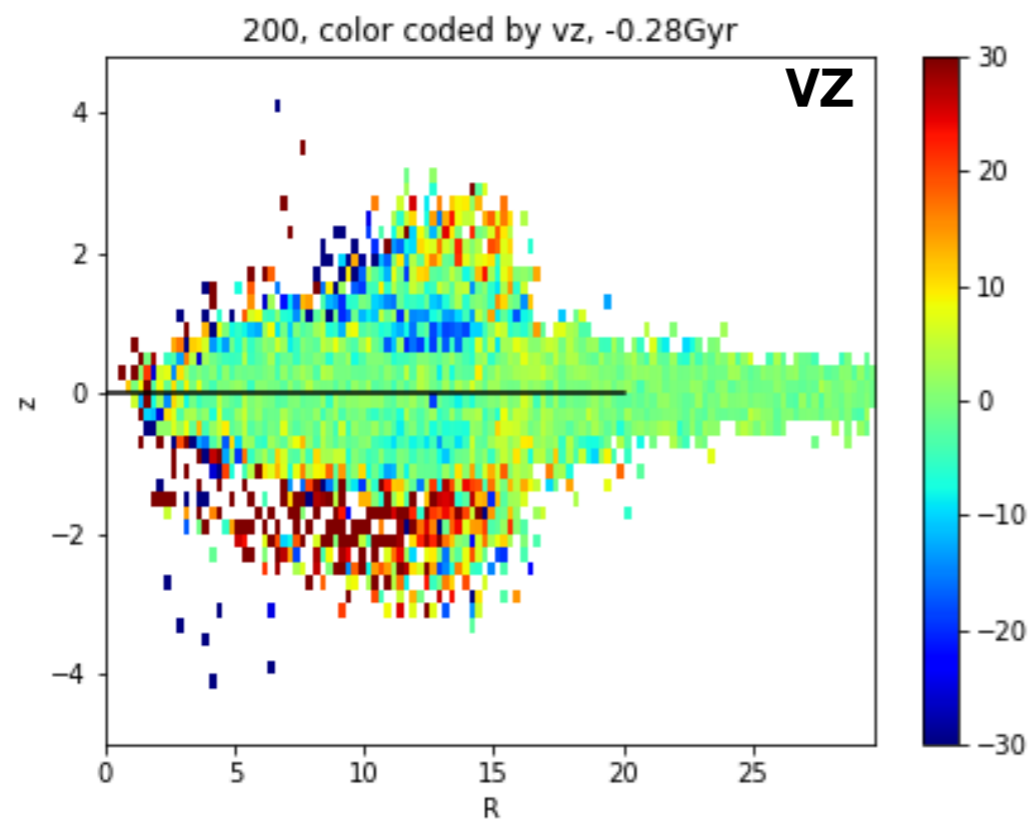
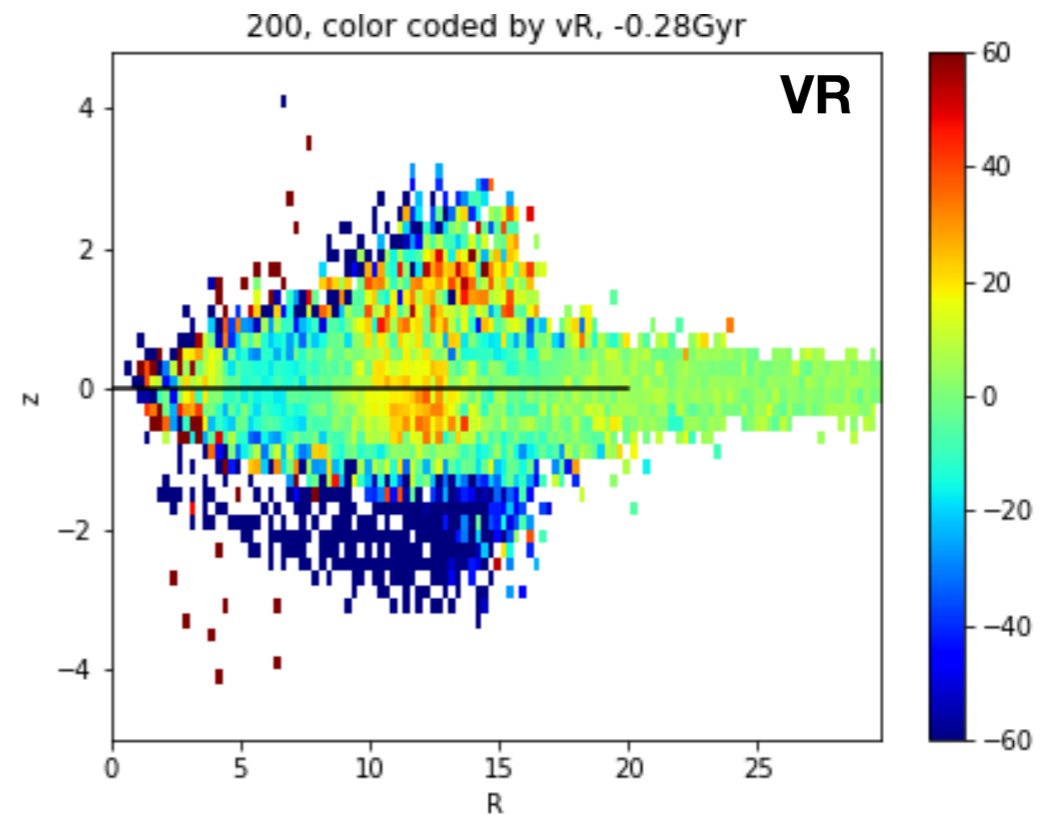
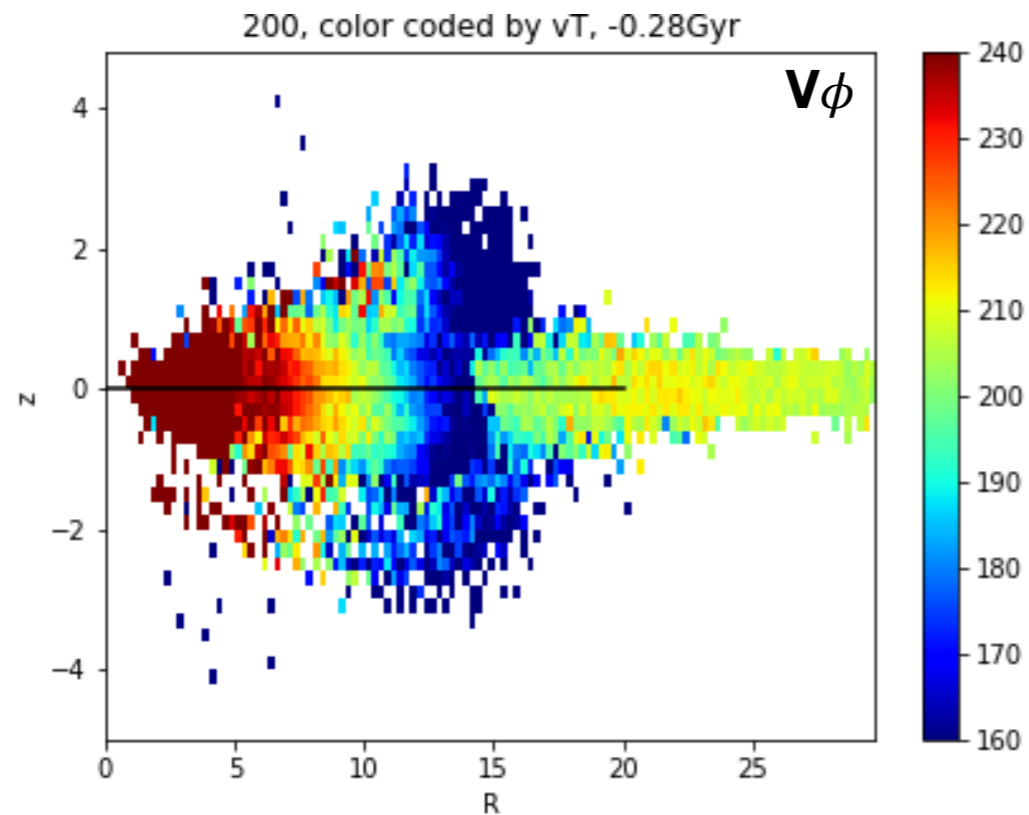




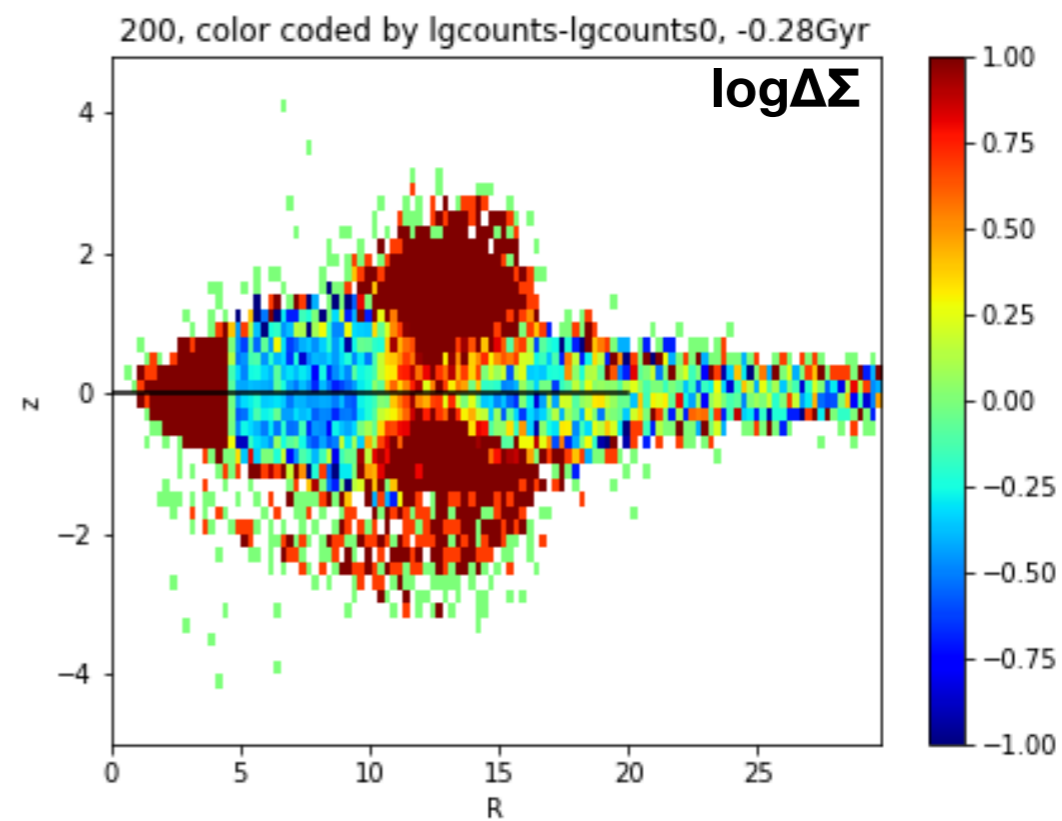
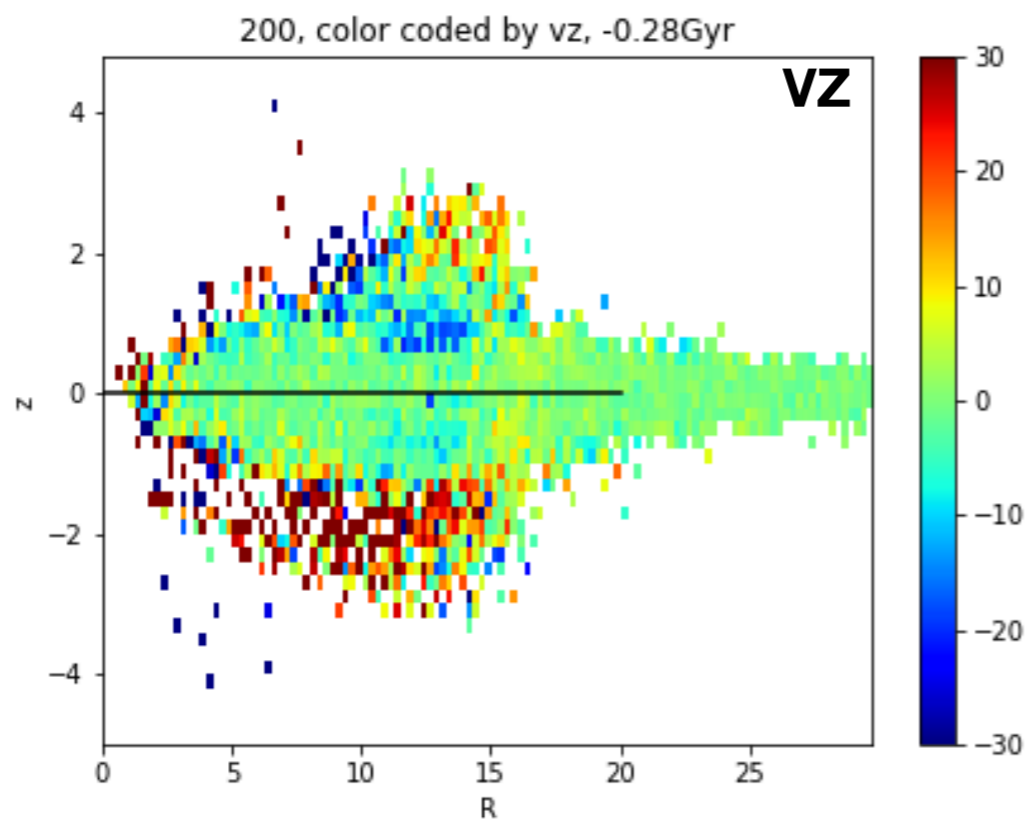
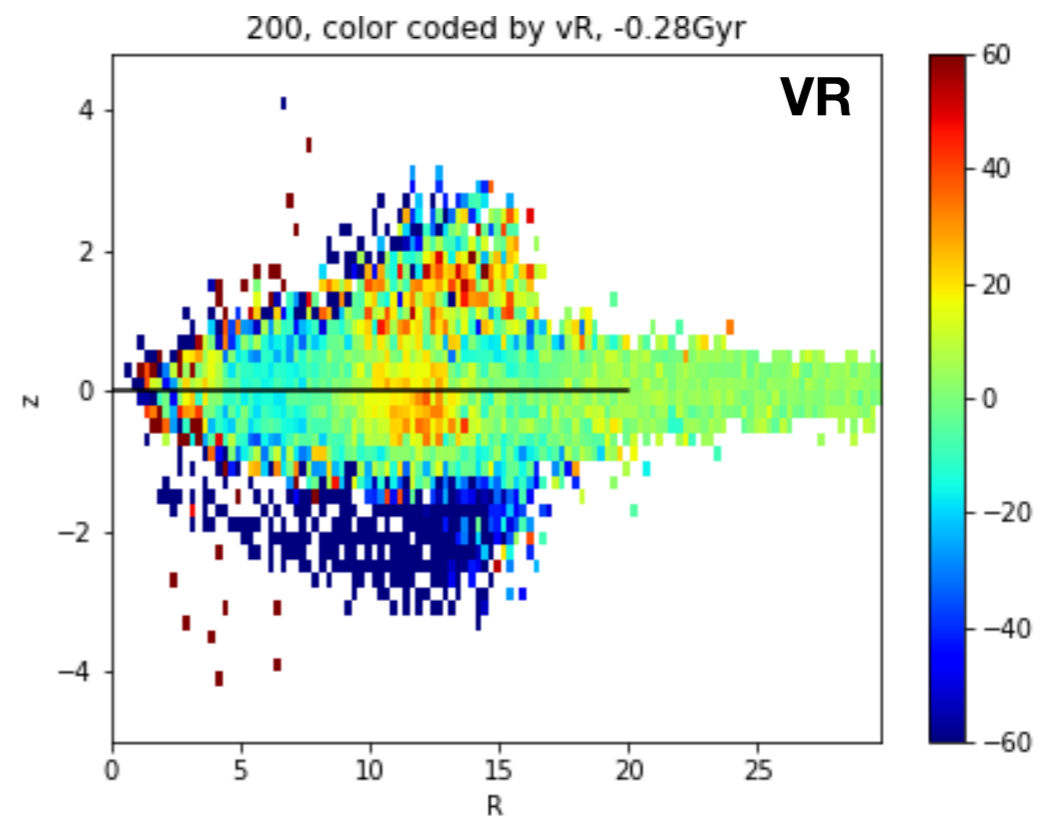
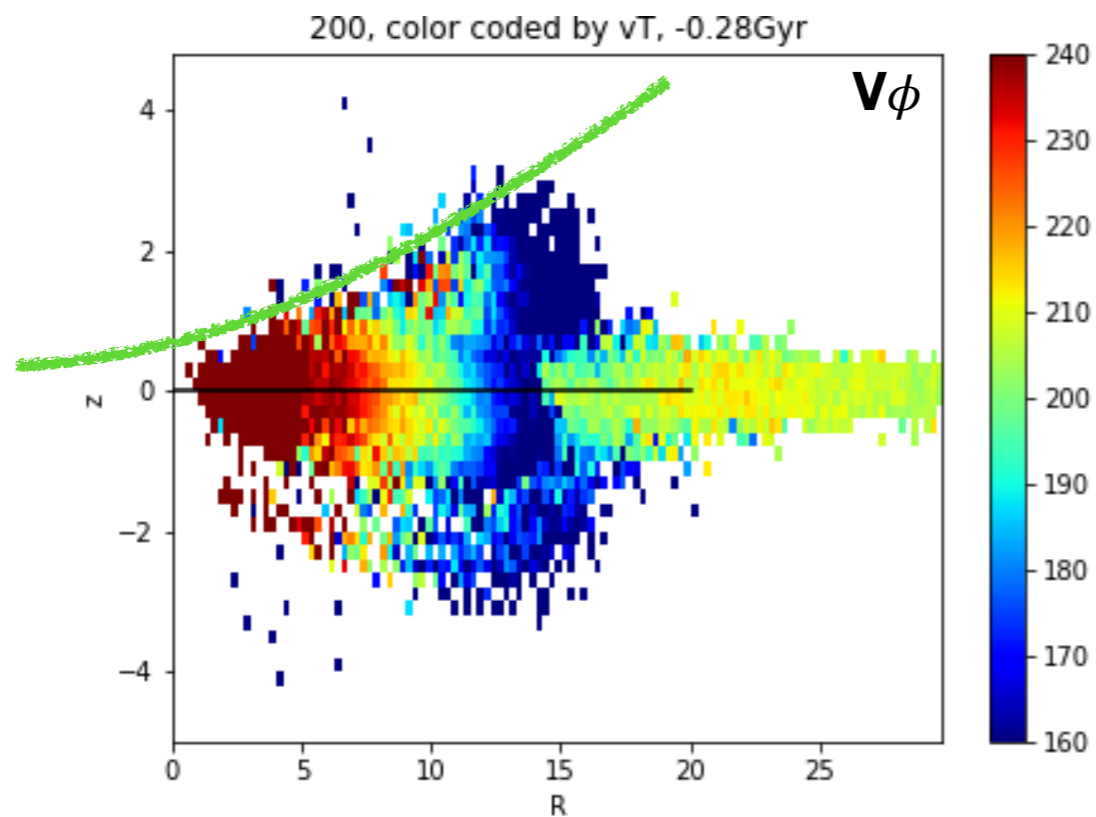
**Model:  $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$**



# $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ , $R_{\text{hit}}=15 \text{ kpc}$ , $t=0.3 \text{ Gyr}$

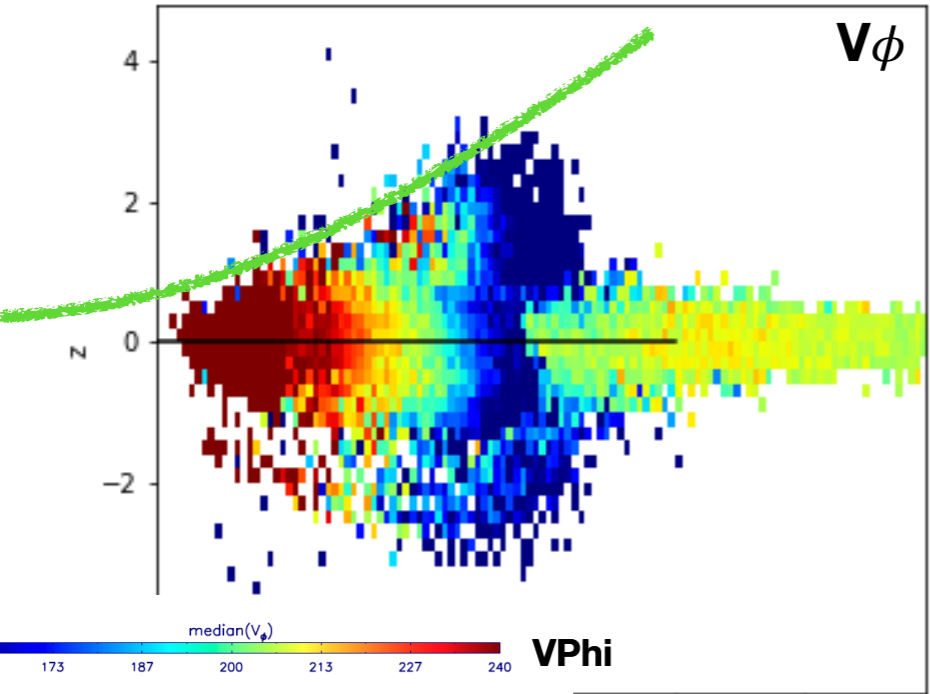


$M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$

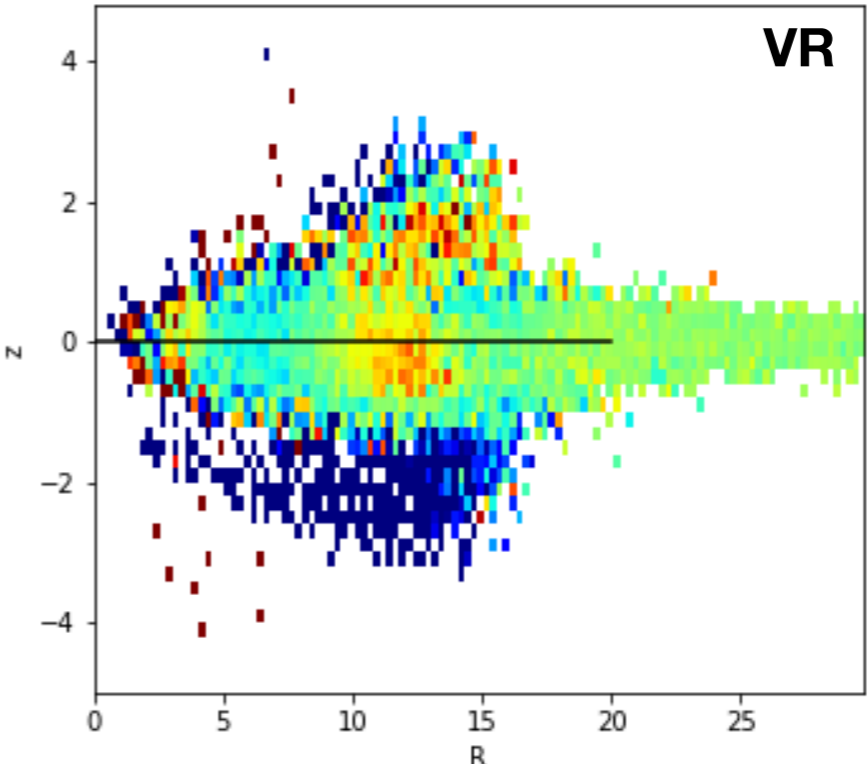


M\_dwarf=2x10^10 Msun, R\_hit=15kpc, t=0.3Gyr

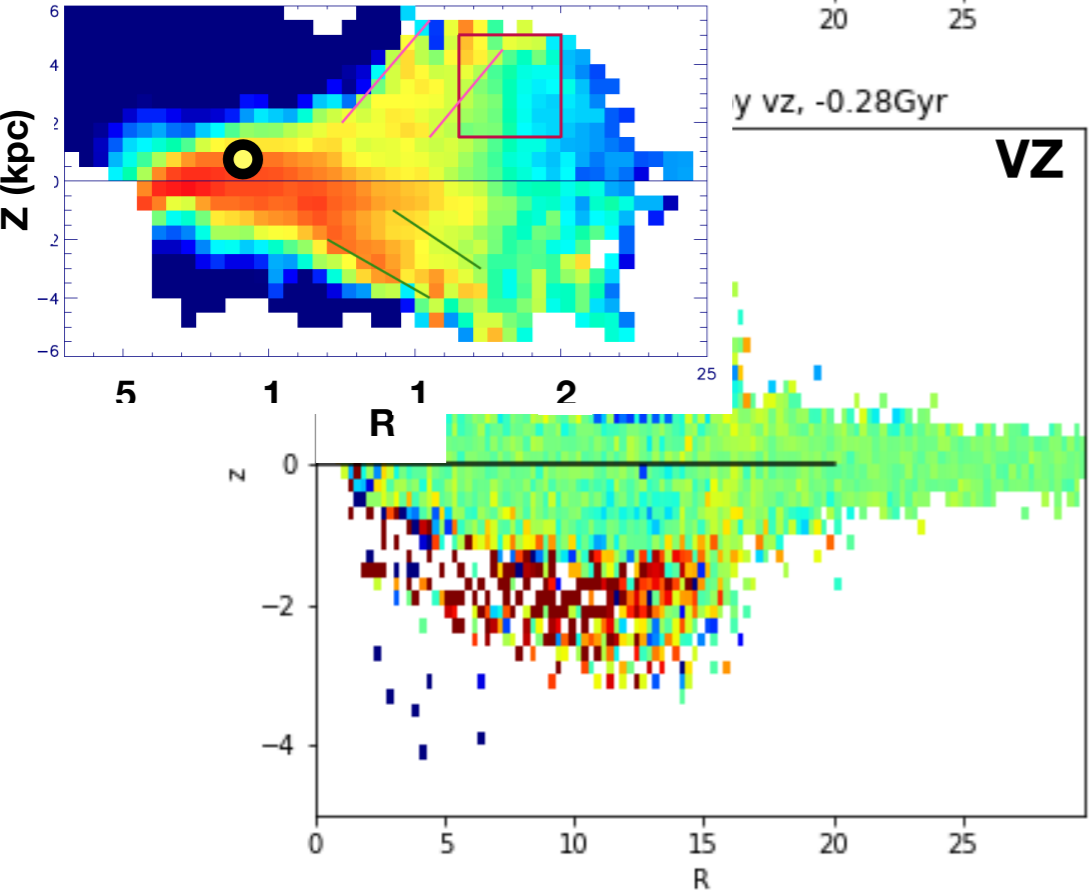
200, color coded by vT, -0.28Gyr



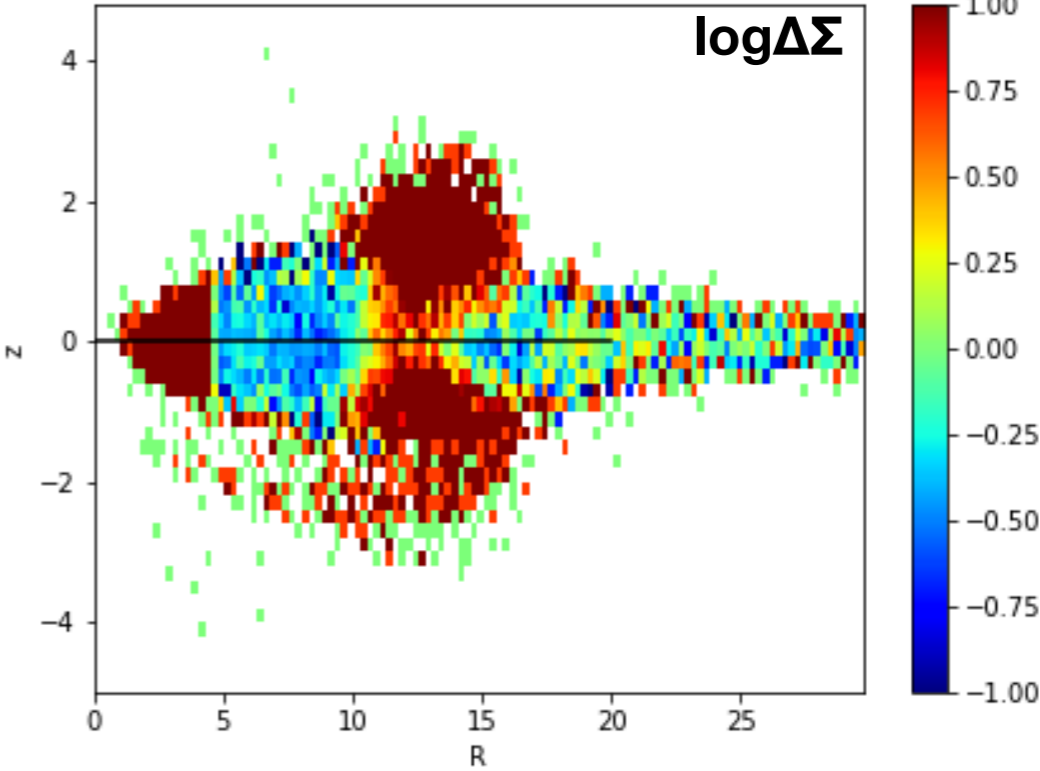
200, color coded by vR, -0.28Gyr



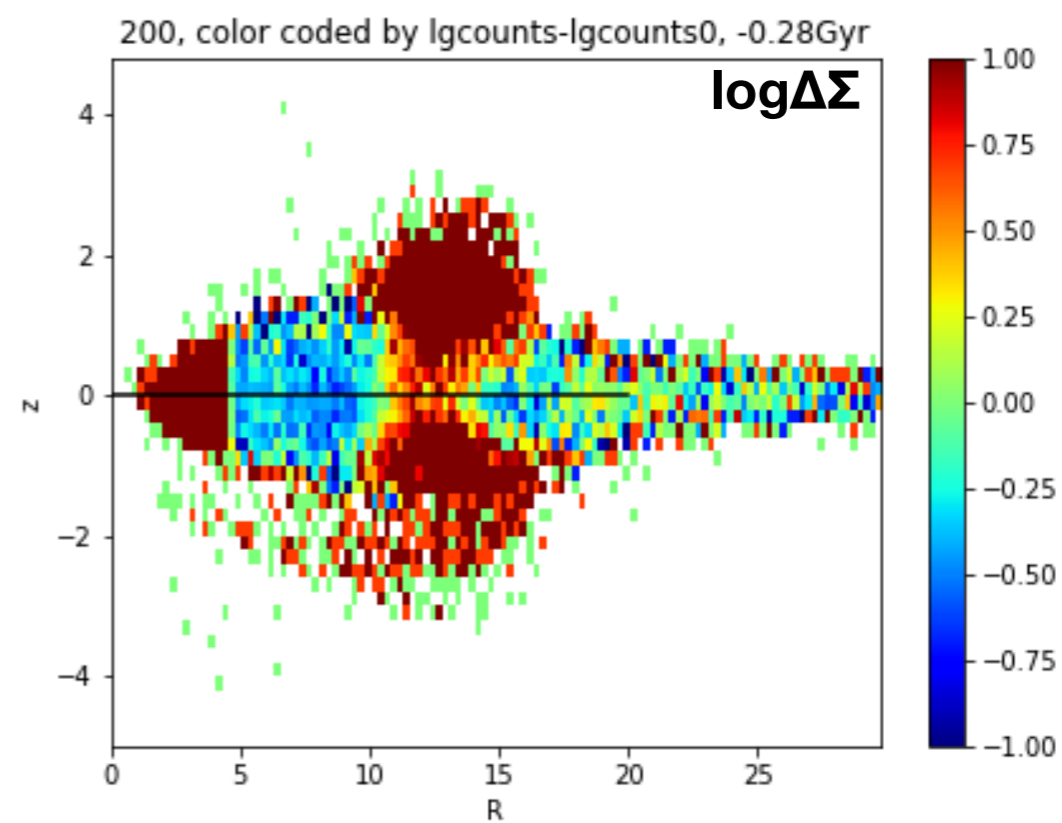
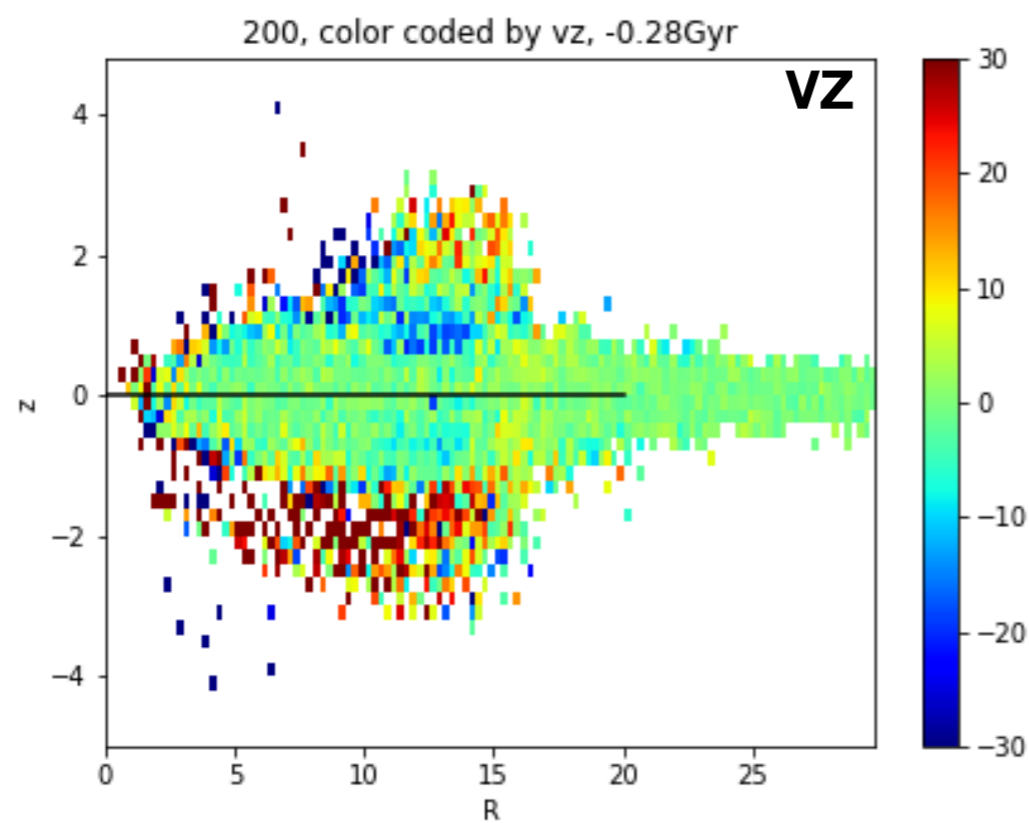
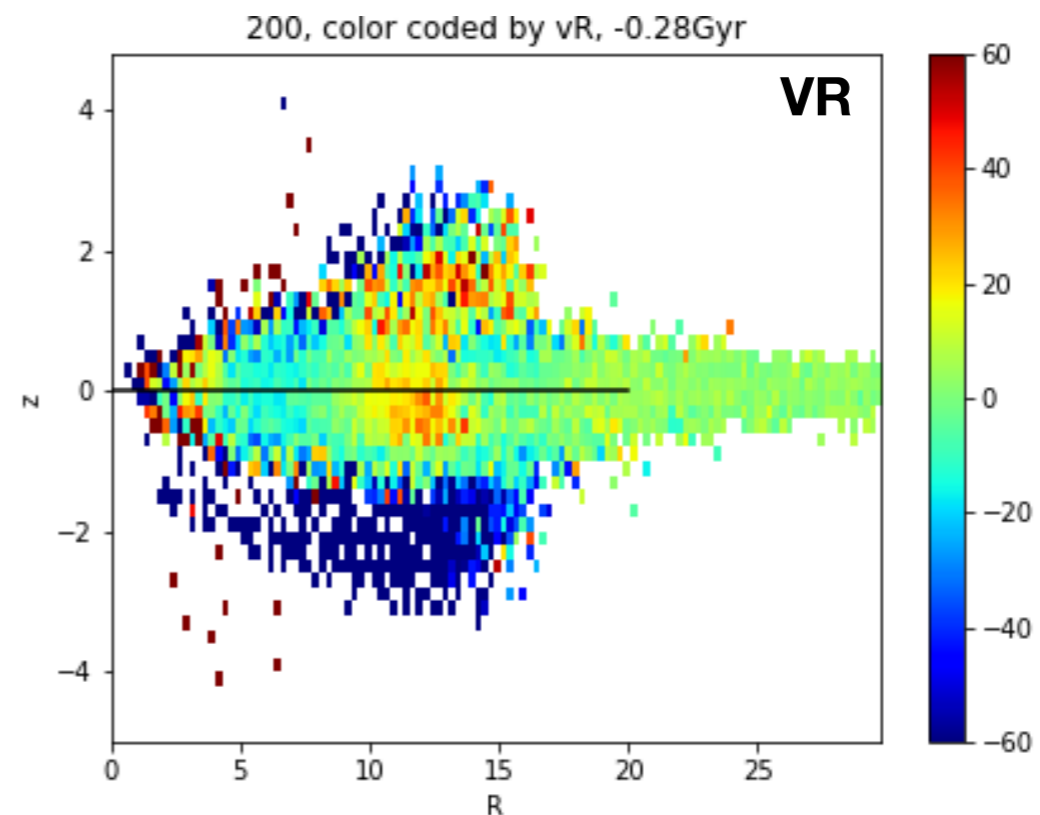
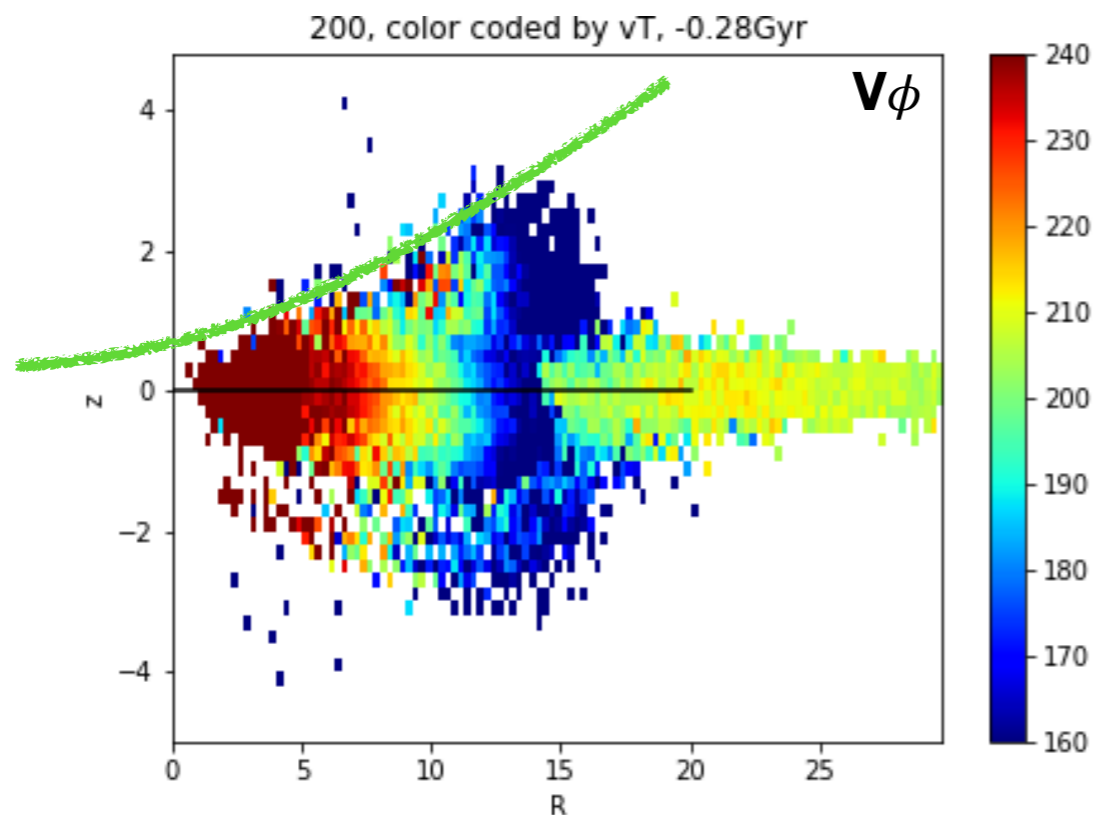
y vz, -0.28Gyr



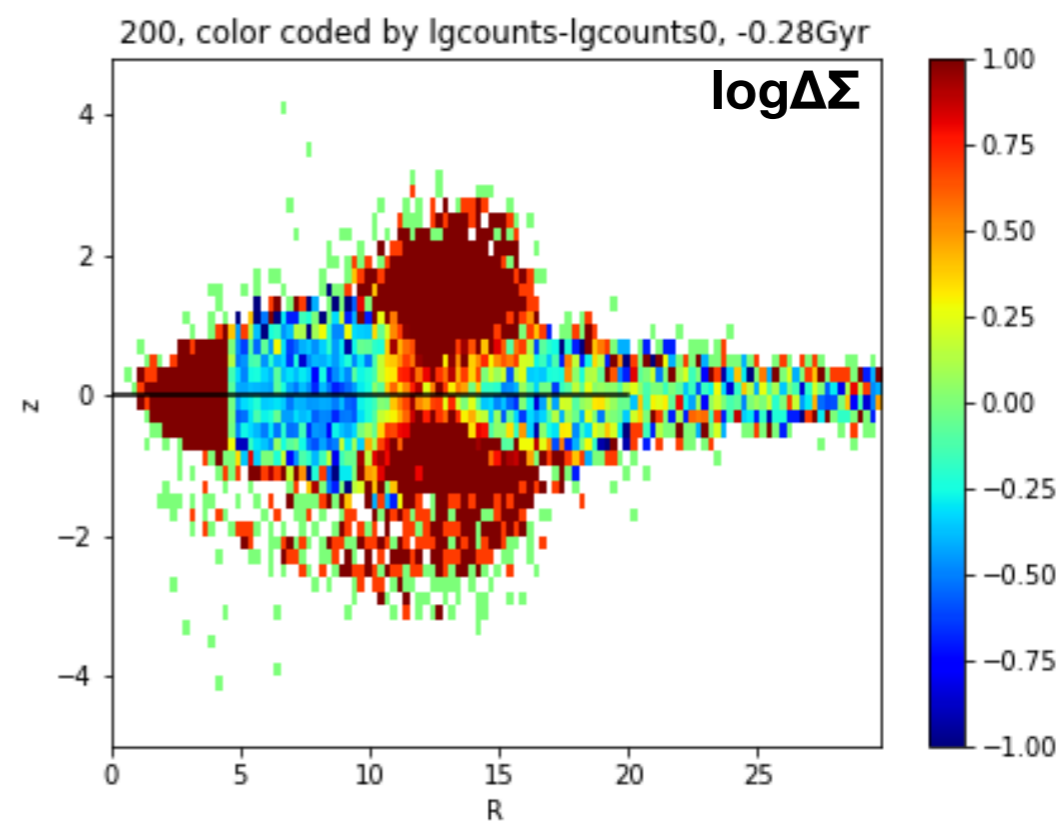
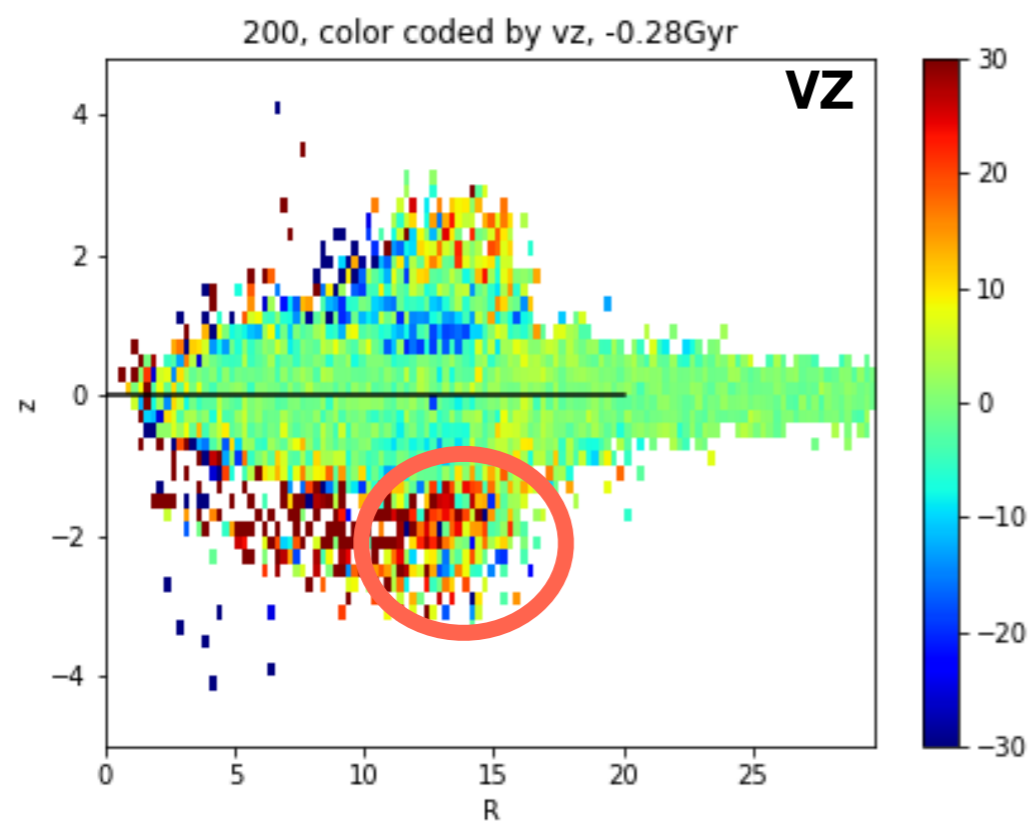
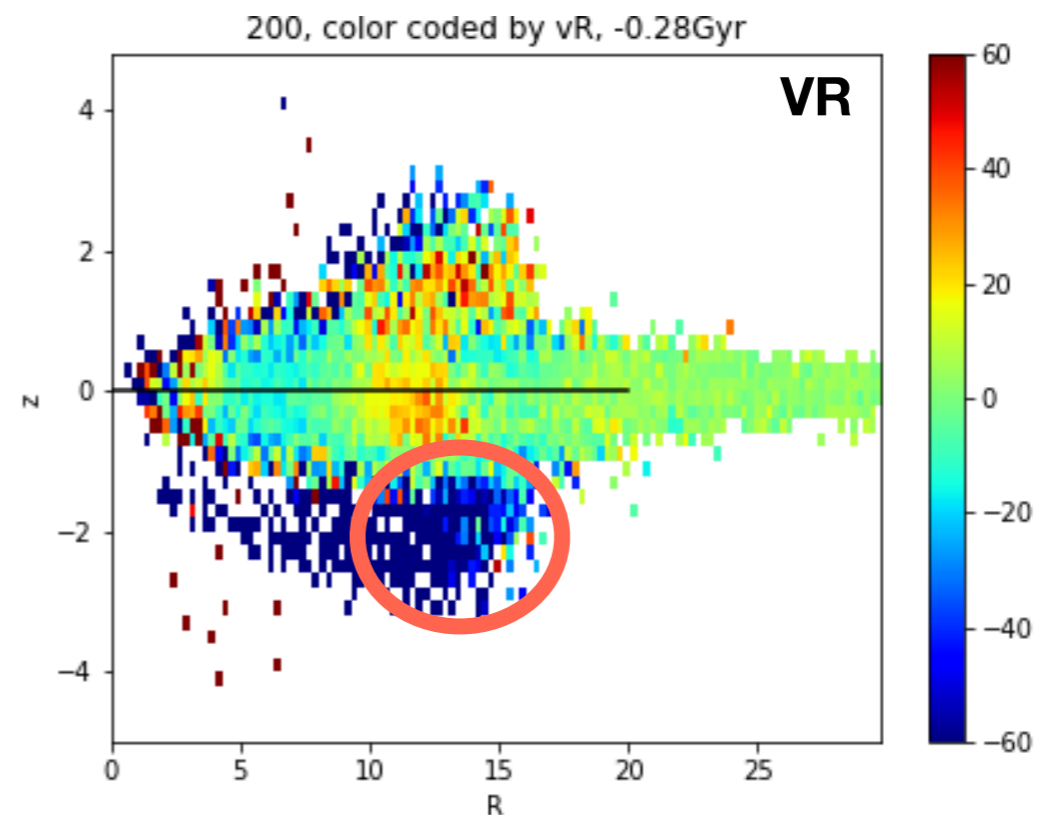
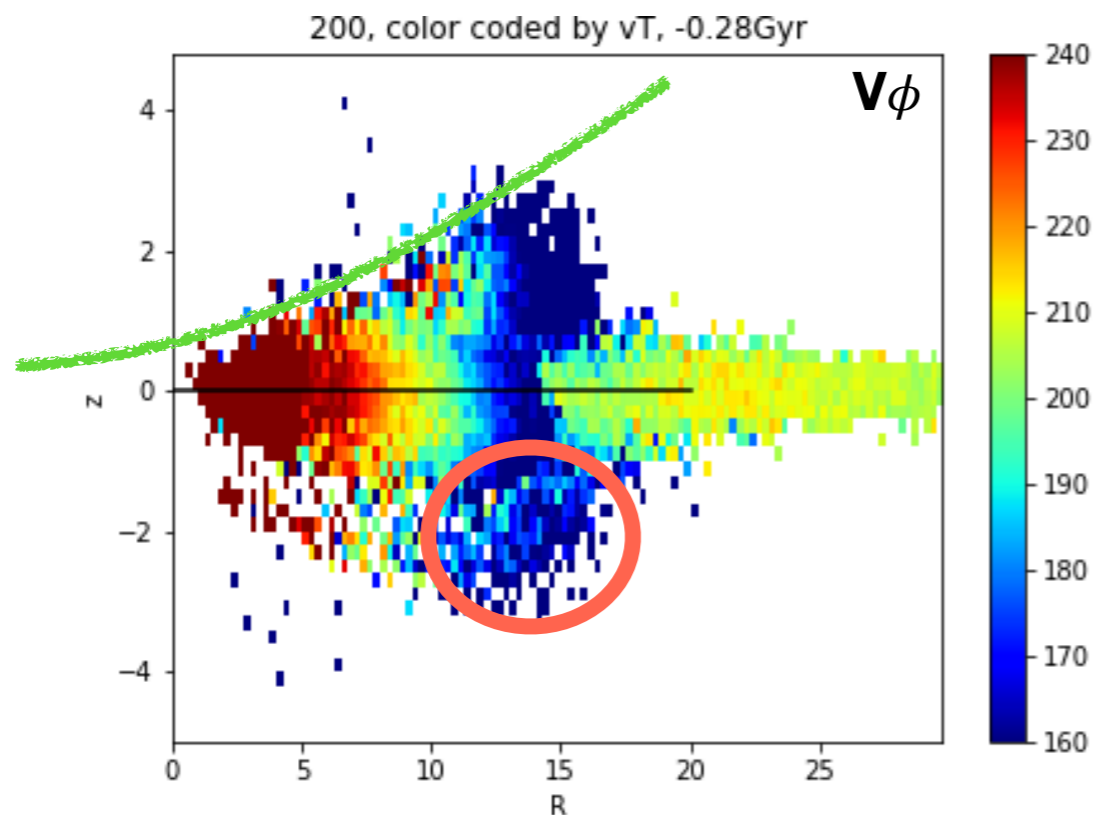
200, color coded by lgcounts-lgcounts0, -0.28Gyr



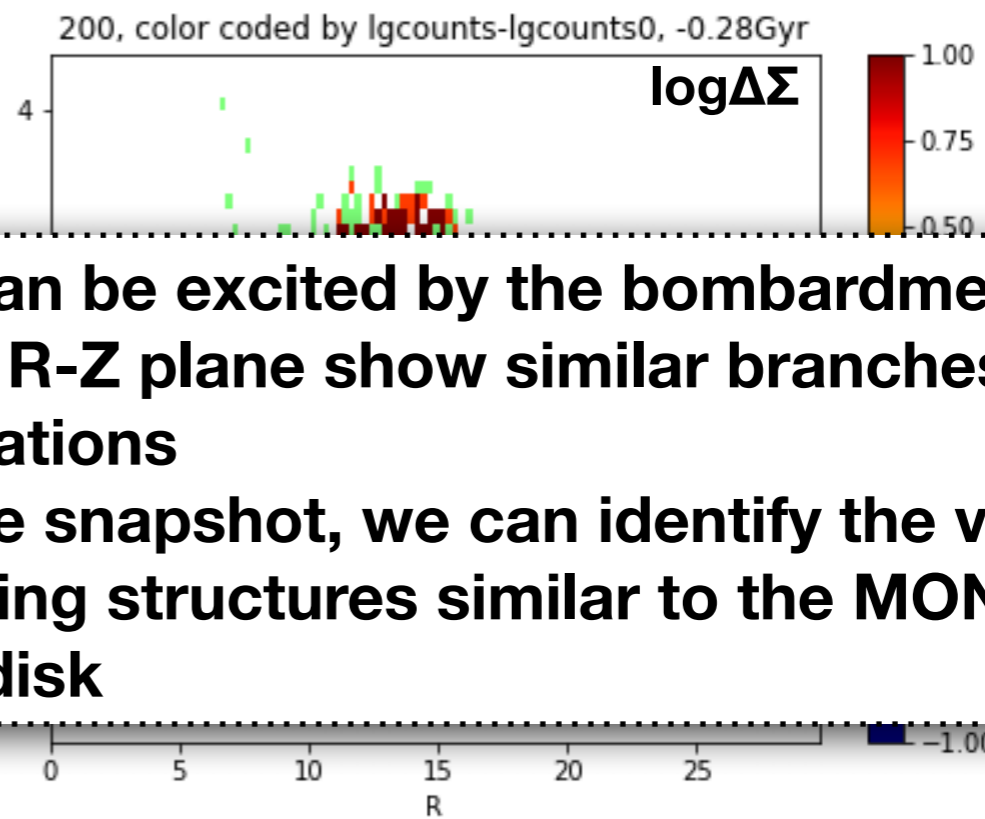
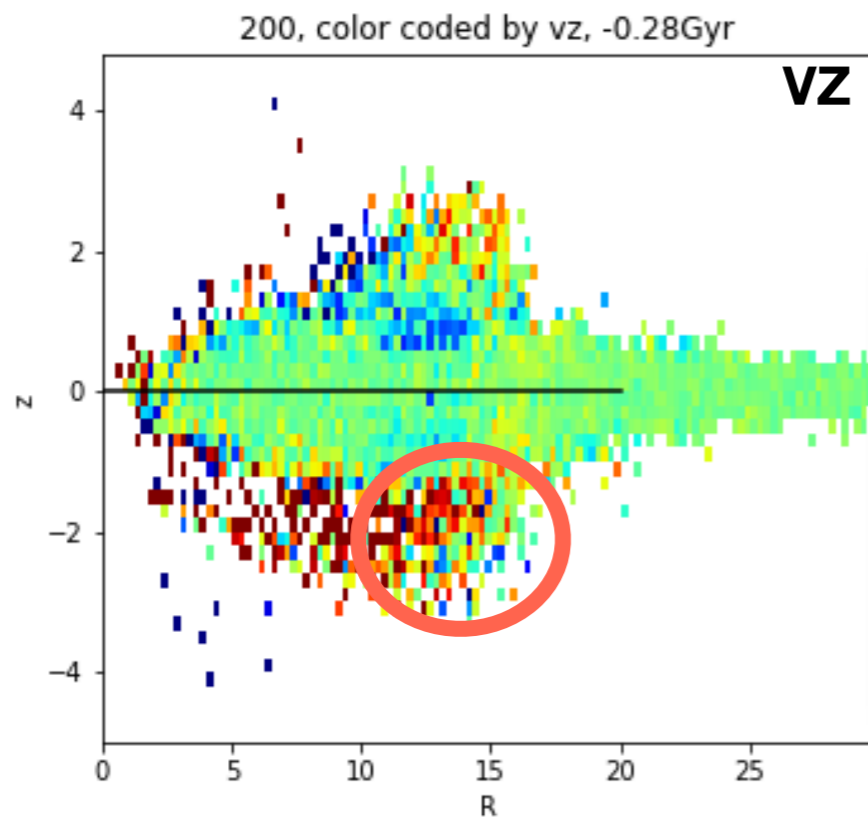
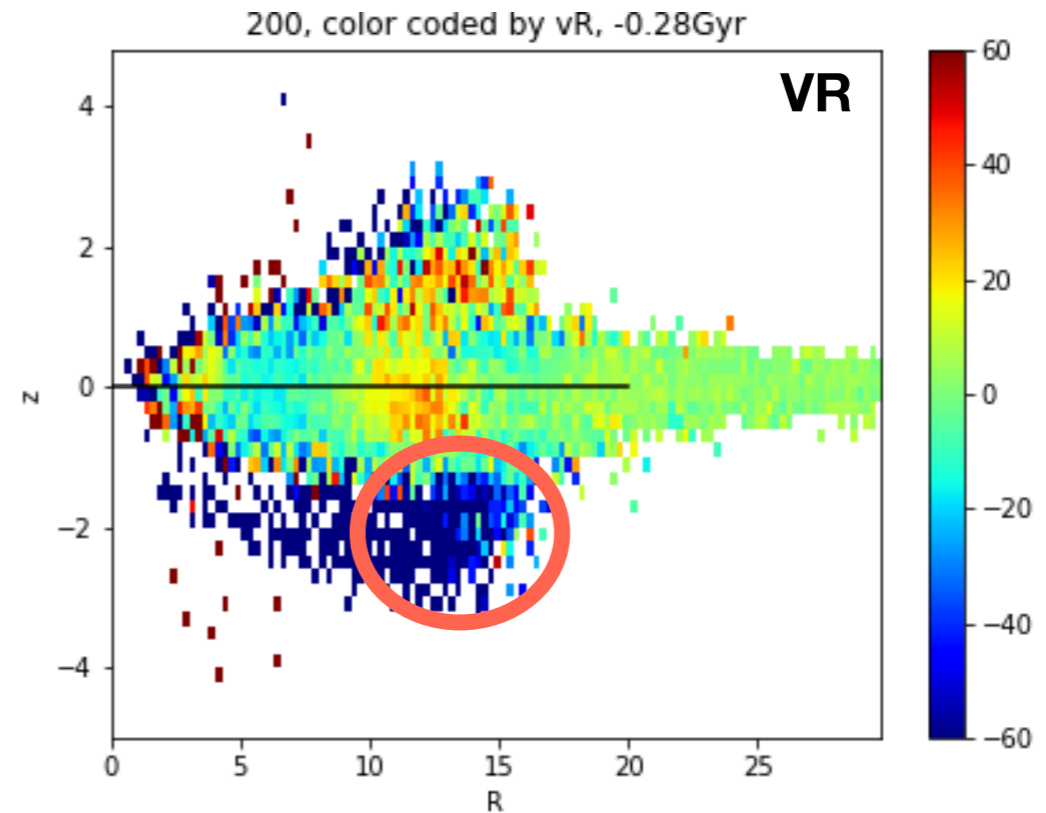
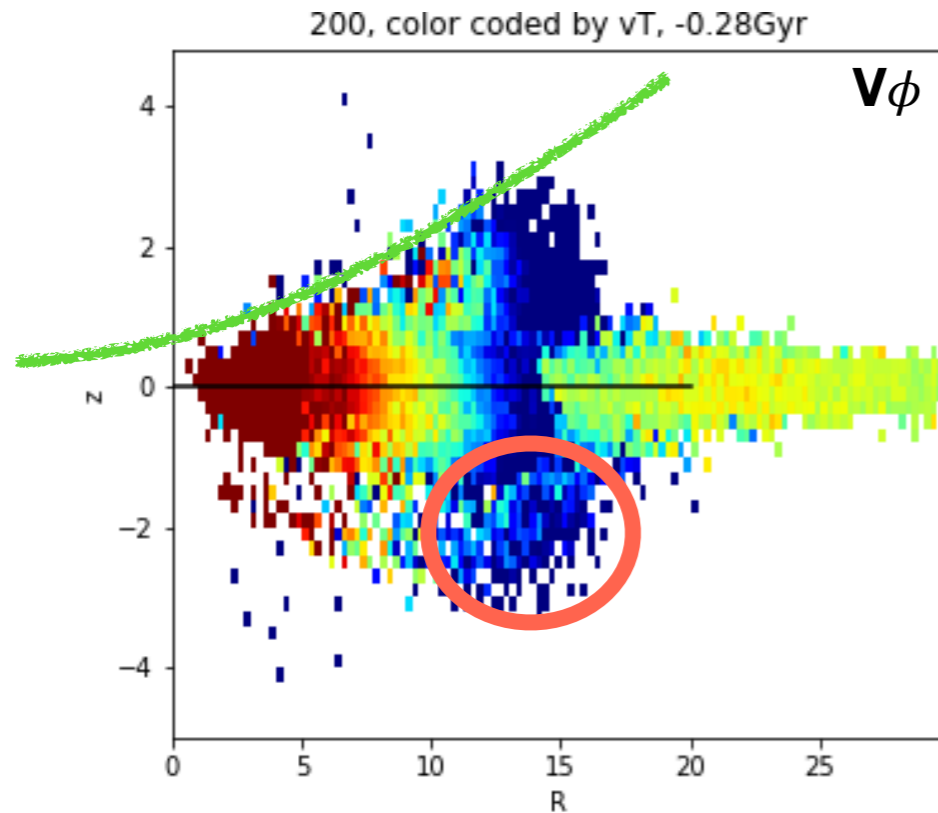
# $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ , $R_{\text{hit}}=15 \text{ kpc}$ , $t=0.3 \text{ Gyr}$



# $M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ , $R_{\text{hit}}=15 \text{ kpc}$ , $t=0.3 \text{ Gyr}$



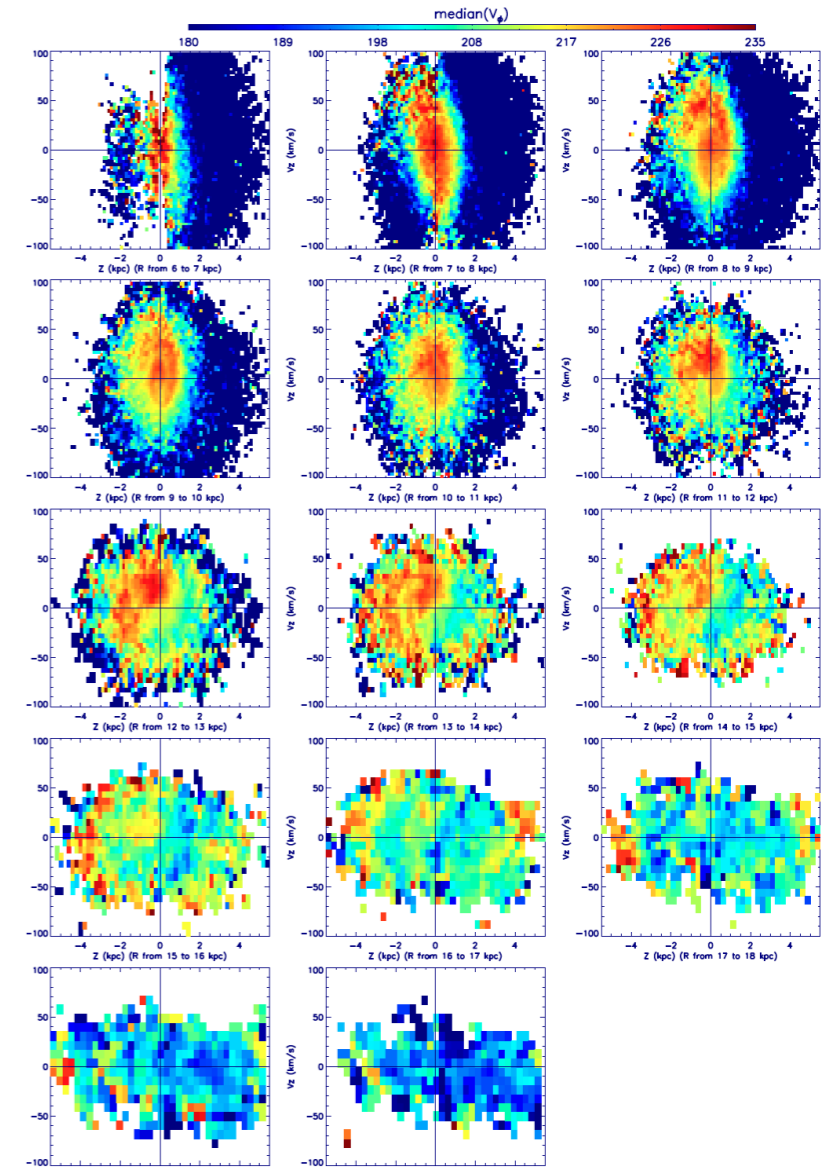
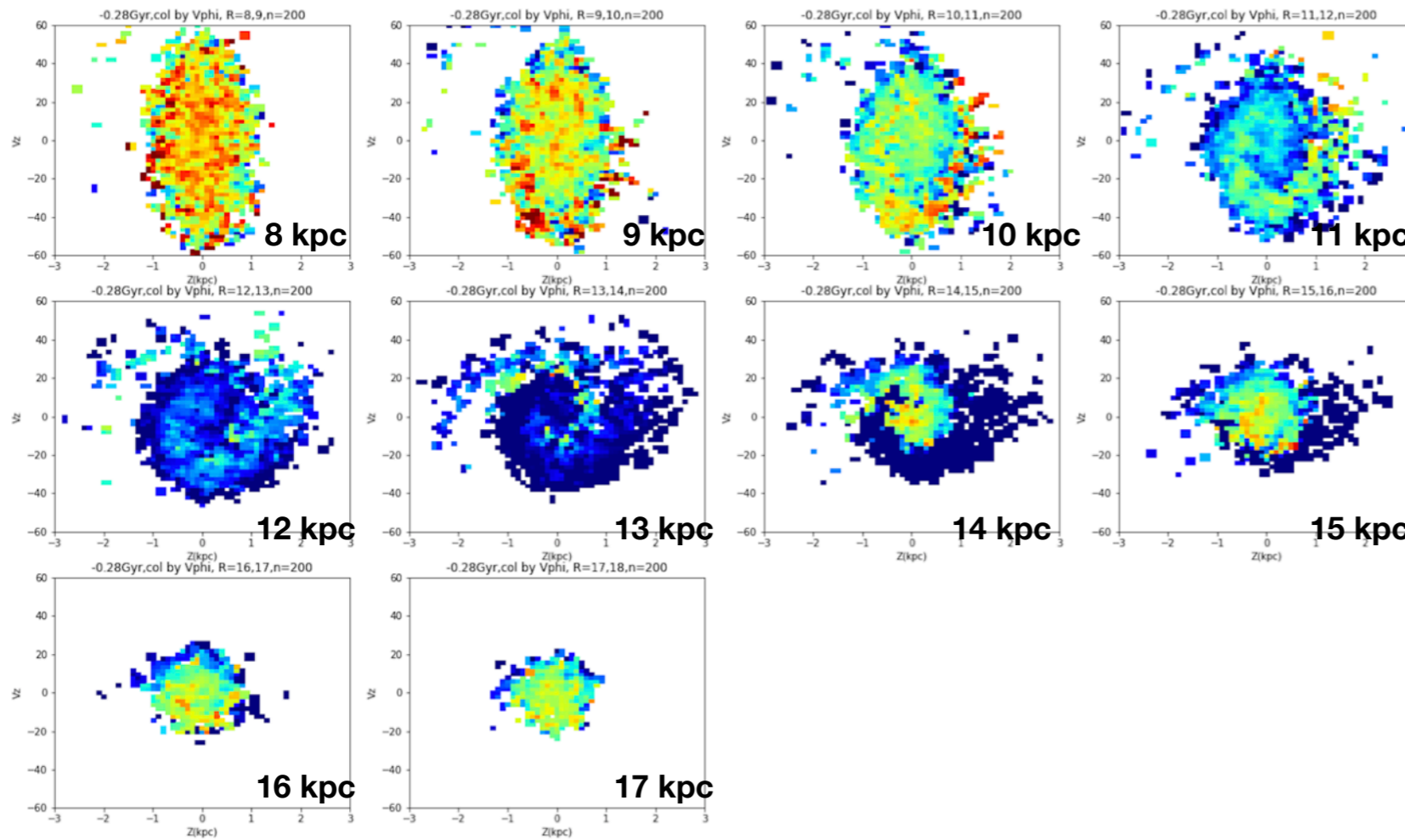
$M_{\text{dwarf}}=2 \times 10^{10} \text{ Msun}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$



- Flare can be excited by the bombardment
- $v_\phi$  in R-Z plane show similar branches as observations
- In some snapshot, we can identify the velocity streaming structures similar to the MON in the flared disk

**Model:  $M_{\text{dwarf}}=2 \times 10^{10} M_{\text{sun}}$ ,  $R_{\text{hit}}=15 \text{ kpc}$ ,  $t=0.3 \text{ Gyr}$**

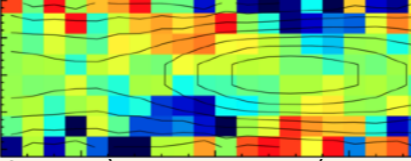
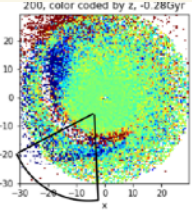
**Obs. data**

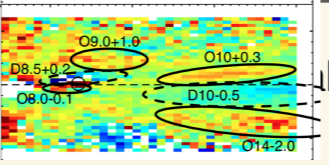
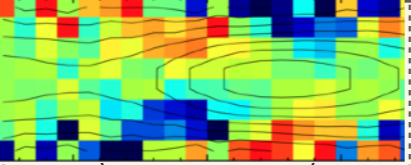
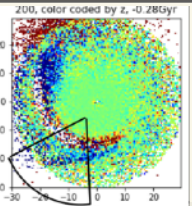
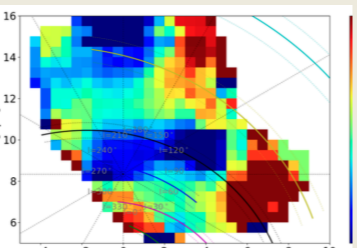
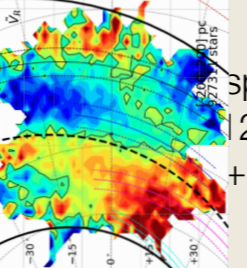
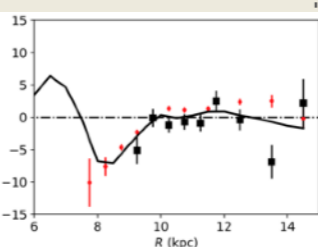
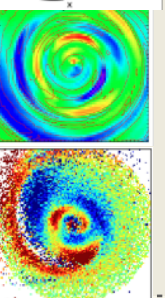


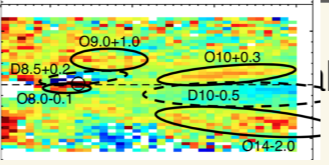
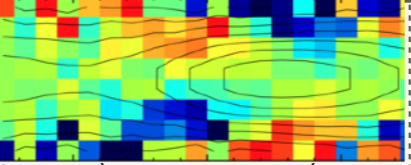
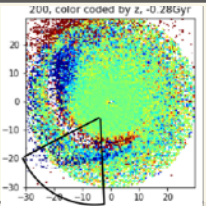
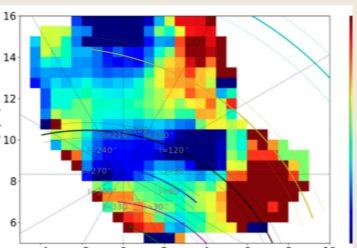
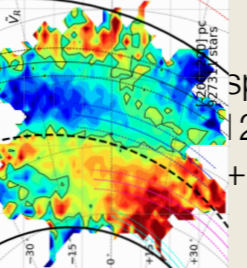
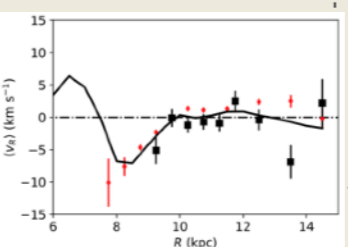
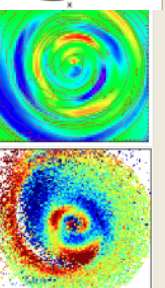
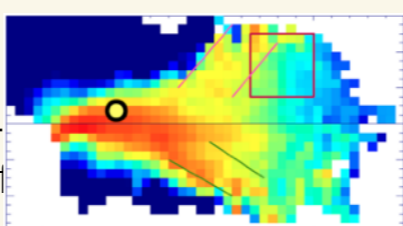
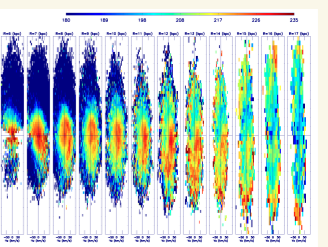
**The covering range of R may give a constraint of the time of bombardment 200-500 Myr simply from orbital periods**

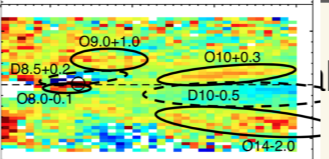
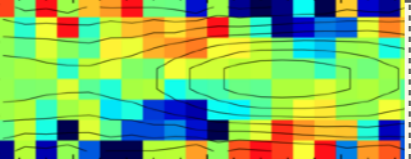
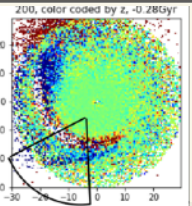
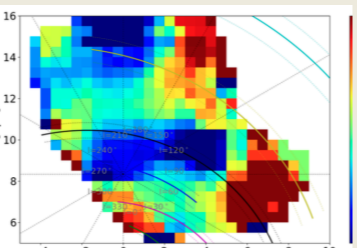
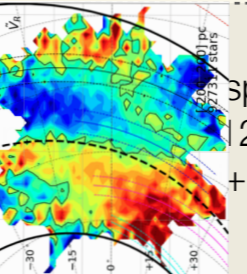
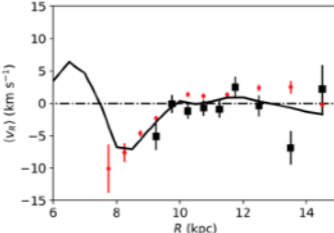
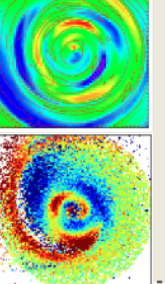
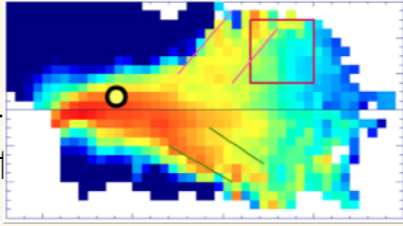
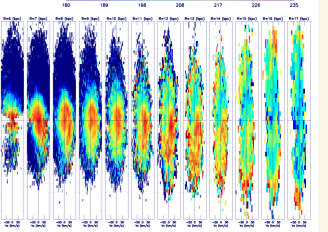
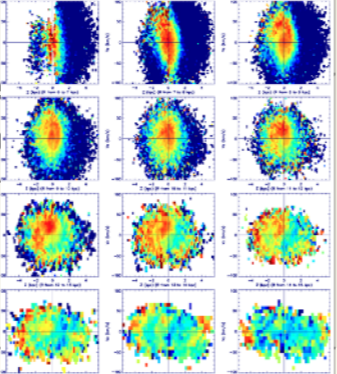
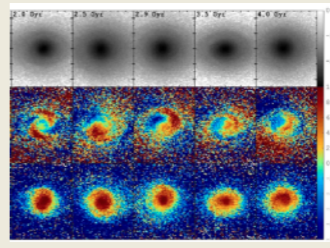
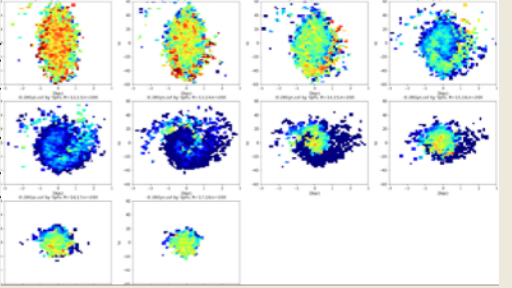


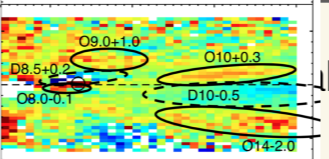
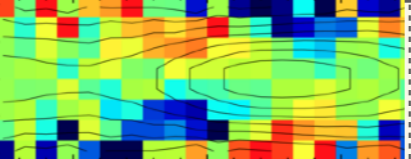
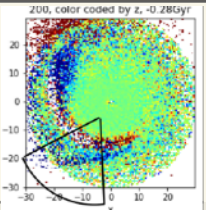
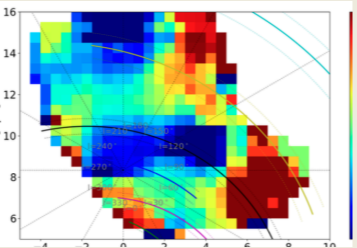
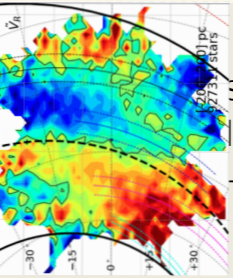
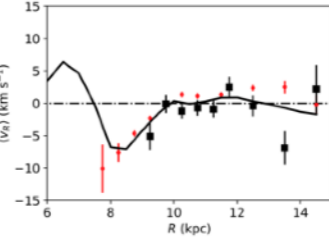
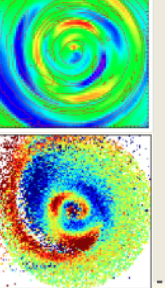
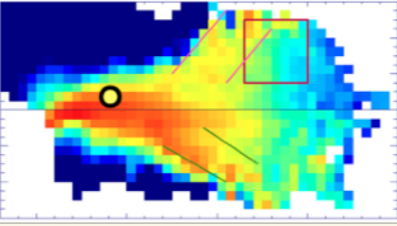
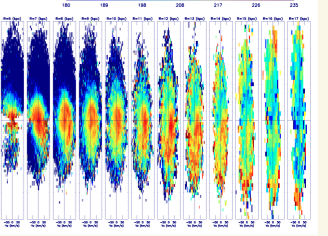
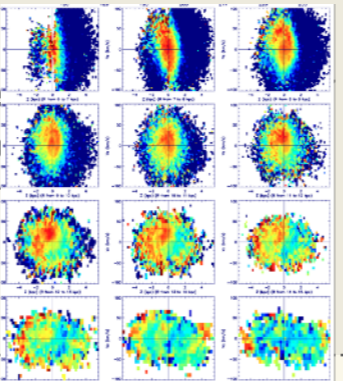
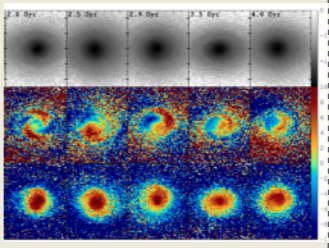
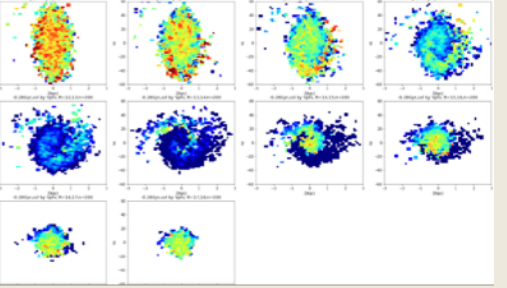
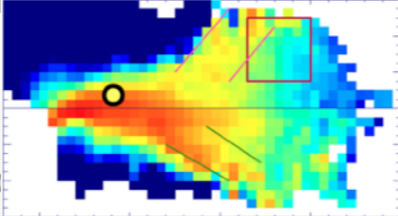
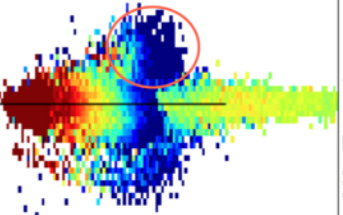
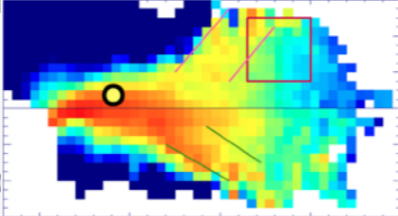
SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	Rich substructures shows the disk has vertical and radial <b>waves</b>	Possibly raised with heavy spiral arms (Debattista14)	?	Gomez+13, D'Onghia+16, Laporte+19, this work
	VR, VPhi show clear <b>ripples</b> , which is not aligned with spiral arms, in large area of X-Y plane	should follow the spiral arms (Siebert+12; Faure+14; Monari+16; Katz+18)	need large bar pattern speed (Liu17)	D'Onghia+16, Laporte+19, this work
	VPhi is <b>branched</b> in R-Z plane and show <b>wedge</b> -like feature;	?	?	<b>Another aspect of the phase spiral; Wedge like feature is due to the rotating non-axisymmetric disk plane (this work)</b>
Spiral patterns in Z-VZ plane	<b>Spiral</b> patterns in Z-VZ plane <b>extend</b> from R=7 to 15 kpc and <b>disappear</b> beyond R=17 kpc; Spirals are more <b>tightly</b> winding at smaller R but <b>loosely</b> winding at larger R	?	Buckling of the bar (Khopersky+19)	phase spiral consistent with models (Binney+18, Bland-Hawthorn+18, Laporte+19); 0.2-0.5 Gyr (this work)
MON ring	No over-density in the flared disk model; velocity <b>streaming</b> feature	?	?	<b>A snapshot of stars in disequilibrium (this work)</b>
Flared disk	<b>Flare</b> is substantial; Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood	?	?	<b>z-amplitude increase with R (Bland-Hawthorn+18) Seen in test-particle sim. (this work)</b>

SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	Rich substructures shows the... and radial wa... 		?	Gomez+13, D'Onghia+16, Laporte+19, this work 
	VR, VPhi show clear <b>ripples</b> , which is not aligned with spiral arms, in large area of X-Y plane	should follow the spiral arms (Siebert+12; Faure+14; Monari+16; Katz+18)	need large bar pattern speed (Liu17)	D'Onghia+16, Laporte+19, this work
	VPhi is <b>branched</b> in R-Z plane and show <b>wedge</b> -like feature;	?	?	<b>Another aspect of the phase spiral; Wedge like feature is due to the rotating non-axisymmetric disk plane (this work)</b>
Spiral patterns in Z-VZ plane	<b>Spiral</b> patterns in Z-VZ plane <b>extend</b> from R=7 to 15 kpc and <b>disappear</b> beyond R=17 kpc; Spirals are more <b>tightly</b> winding at smaller R but <b>loosely</b> winding at larger R	?	Buckling of the bar (Khopersky+19)	phase spiral consistent with models (Binney+18, Bland-Hawthorn+18, Laporte+19); 0.2-0.5 Gyr (this work)
MON ring	No over-density in the flared disk model; velocity <b>streaming</b> feature	?	?	<b>A snapshot of stars in disequilibrium (this work)</b>
Flared disk	<b>Flare</b> is substantial; Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood	?	?	<b>z-amplitude increase with R (Bland-Hawthorn+18) Seen in test-particle sim. (this work)</b>

SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	Rich substructures shows the <b>bar</b> and radial <b>waves</b> 		?	Gomez+13, D'Onghia+16, Laporte+19, this work 
	VR, VPhi show clear <b>ripples</b> aligned with spiral arms, in the <b>vertical</b> plane 	show <b>phase spiral</b> features; see also Faloutsos+16; 		D'Onghia+16, Laporte+19, this work 
	VPhi is <b>branched</b> in R-Z plane and show <b>wedge</b> -like feature;	?	?	<b>Another aspect of the phase spiral; Wedge like feature is due to the rotating non-axisymmetric disk plane (this work)</b>
Spiral patterns in Z-VZ plane	<b>Spiral</b> patterns in Z-VZ plane <b>extend</b> from R=7 to 15 kpc and <b>disappear</b> beyond R=17 kpc; Spirals are more <b>tightly</b> winding at smaller R but <b>loosely</b> winding at larger R	?	Buckling of the bar (Khopersky+19)	phase spiral consistent with models (Binney+18, Bland-Hawthorn+18, Laporte+19); 0.2-0.5 Gyr (this work)
MON ring	No over-density in the flared disk model; velocity <b>streaming</b> feature	?	?	<b>A snapshot of stars in disequilibrium (this work)</b>
Flared disk	<b>Flare</b> is substantial; Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood	?	?	<b>z-amplitude increase with R (Bland-Hawthorn+18) Seen in test-particle sim. (this work)</b>

SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	<p>Rich substructures shows the <b>bar</b> and radial <b>waves</b></p> 		<p>?</p>	<p>Gomez+13, D'Onghia+16, Laporte+19, this work</p> 
	<p>VR, VPhi show clear <b>ripples</b> aligned with spiral arms, in the <b>plane</b></p> 	<p>show <b>ripples</b> in the <b>plane</b> of the <b>bar</b> and <b>spiral arms</b>; (Laporte+16; Laporte+19; this work)</p>  	<p>D'Onghia+16, Laporte+19, this work</p> 	
	<p>VPhi is <b>branched</b> in R-phi plane, <b>wedge-like</b> structure</p> 	<p>?</p>	<p>?</p>	<p><b>Another asymmetric spiral; Wedge-like structure due to the axisymmetric bar (this work)</b></p> 
<p><b>Spiral patterns in Z-VZ plane</b></p>	<p><b>Spiral</b> patterns in Z-VZ plane <b>extend</b> from R=7 to 15 kpc and <b>disappear</b> beyond R=17 kpc; Spirals are more <b>tightly</b> winding at smaller R but <b>loosely</b> winding at larger R</p>	<p>?</p>	<p>Buckling of the bar (Khopersky+19)</p>	<p>phase spiral consistent with models (Binney+18, Bland-Hawthorn+18, Laporte+19); 0.2-0.5 Gyr (this work)</p>
<p><b>MON ring</b></p>	<p>No over-density in the flared disk model; velocity <b>streaming</b> feature</p>	<p>?</p>	<p>?</p>	<p><b>A snapshot of stars in disequilibrium (this work)</b></p>
<p><b>Flared disk</b></p>	<p><b>Flare</b> is substantial; Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood</p>	<p>?</p>	<p>?</p>	<p><b>z-amplitude increase with R (Bland-Hawthorn+18) Seen in test-particle sim. (this work)</b></p>

SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	<p>Rich substructures shows the <b>bar</b> and radial <b>waves</b></p> 		<p>?</p>	<p>Gomez+13, D'Onghia+16, Laporte+19, this work</p> 
	<p>VR, VPhi show clear <b>ripples</b> aligned with spiral arms, in the <b>plane</b></p> 	<p>show <b>ripples</b> in the <b>plane</b> and <b>Far</b> spiral arms; D'Onghia+16;</p> 		<p>D'Onghia+16, Laporte+19, this work</p> 
	<p>VPhi is <b>branched</b> in R-phi plane, <b>wedge-like</b></p> 	<p>?</p>	<p>?</p>	<p><b>Another asymmetric spiral; We conclude due to the axisymmetric (this work)</b></p> 
<p>Spiral patterns in Z-VZ plane</p>	<p><b>Spiral</b> patterns in Z-VZ plane to 15 kpc and <b>disappear</b> beyond 15 kpc. Spirals are more <b>tightly</b> winding in the inner disk but <b>loosely</b> winding in the outer disk.</p> 	<p>?</p>		
<p>MON ring</p>	<p>No over-density in the flared disk model; velocity <b>streaming</b> feature</p>	<p>?</p>	<p>?</p>	<p><b>A snapshot of stars in disequilibrium (this work)</b></p>
<p>Flared disk</p>	<p><b>Flare</b> is substantial; Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood</p>	<p>?</p>	<p>?</p>	<p><b>z-amplitude increase with R (Bland-Hawthorn+18) Seen in test-particle sim. (this work)</b></p>

SUMMARY	Observed evidence	Internal (spiral arms)	Bar	dwarf galaxy
Ripples, corrugations, waves	<p>Rich substructures shows the ... and radial wa</p> 		<p>?</p>	<p>Gomez+13, D'Onghia+16, Laporte+19, this work</p> 
	<p>VR, VPhi show clear <b>ripples</b> aligned with spiral arms, in the plane</p> 	<p>show ... spiral ... +16;</p> 		<p>D'Onghia+16, Laporte+19, this work</p> 
	<p>VPhi is <b>branched</b> in R-phi plane</p> 	<p>?</p>	<p>?</p>	<p>Another as ... due to the axisymme ... (this work)</p> 
<p>Spiral patterns in Z-VZ plane</p>	<p><b>Spiral</b> patterns in Z-VZ plane to 15 kpc and <b>disappear</b> beyond. Spirals are more <b>tightly</b> winding but <b>loosely</b> winding</p> 	<p>?</p>		
<p>MON ring</p>	<p>No over-density in the flared disk model; velocity <b>streaming</b> feature</p> 	<p>?</p>	<p>?</p>	<p>A snapshot of stars in disequilibrium (this work)</p> 
<p>Flared disk</p>	<p>Flare is sub ... Flare in outer disk is even <b>thicker</b> than the thick disk in the solar neighborhood</p> 	<p>?</p>	<p>?</p>	<p>... e with R ... seen in test-particle sim. (this work)</p> 