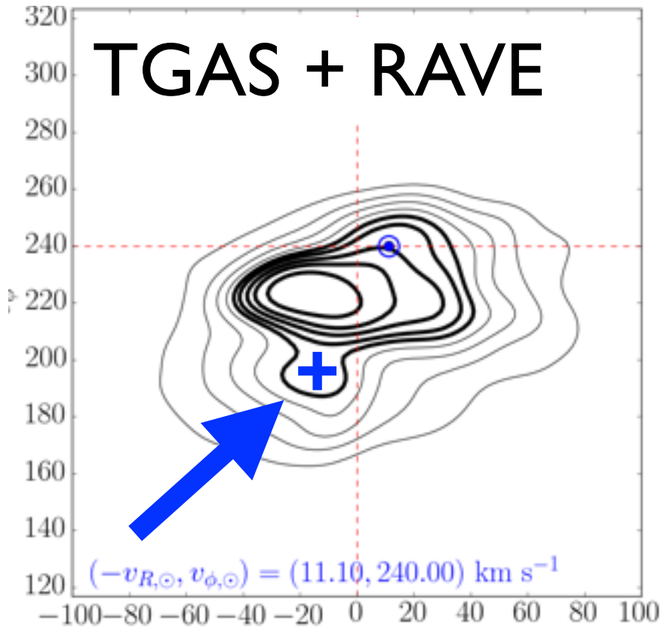
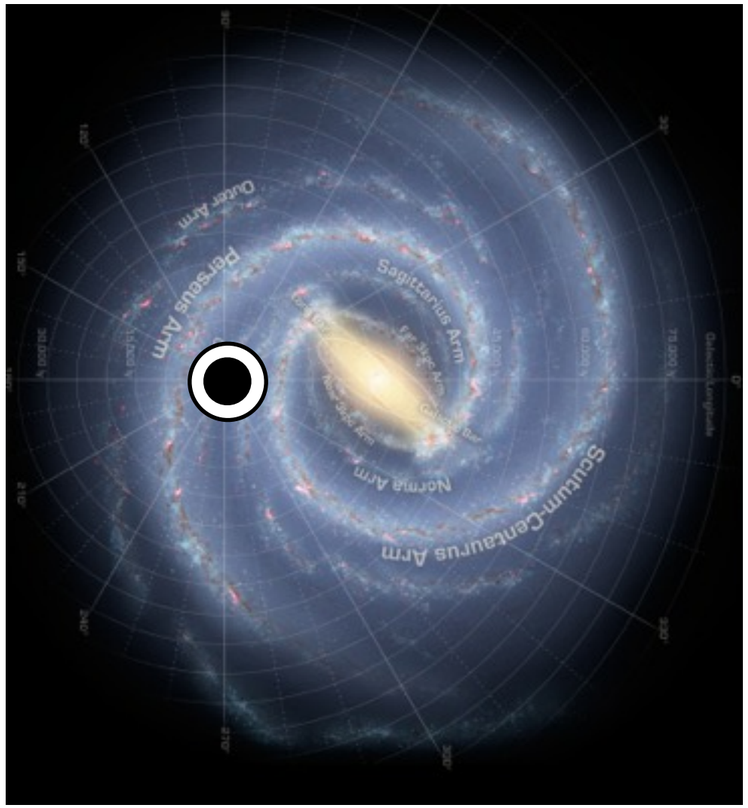
Dynamical effects of the spiral arms on the velocity distribution of disc stars

v_ϕ



$-v_R$



Kohei Hattori (Michigan)

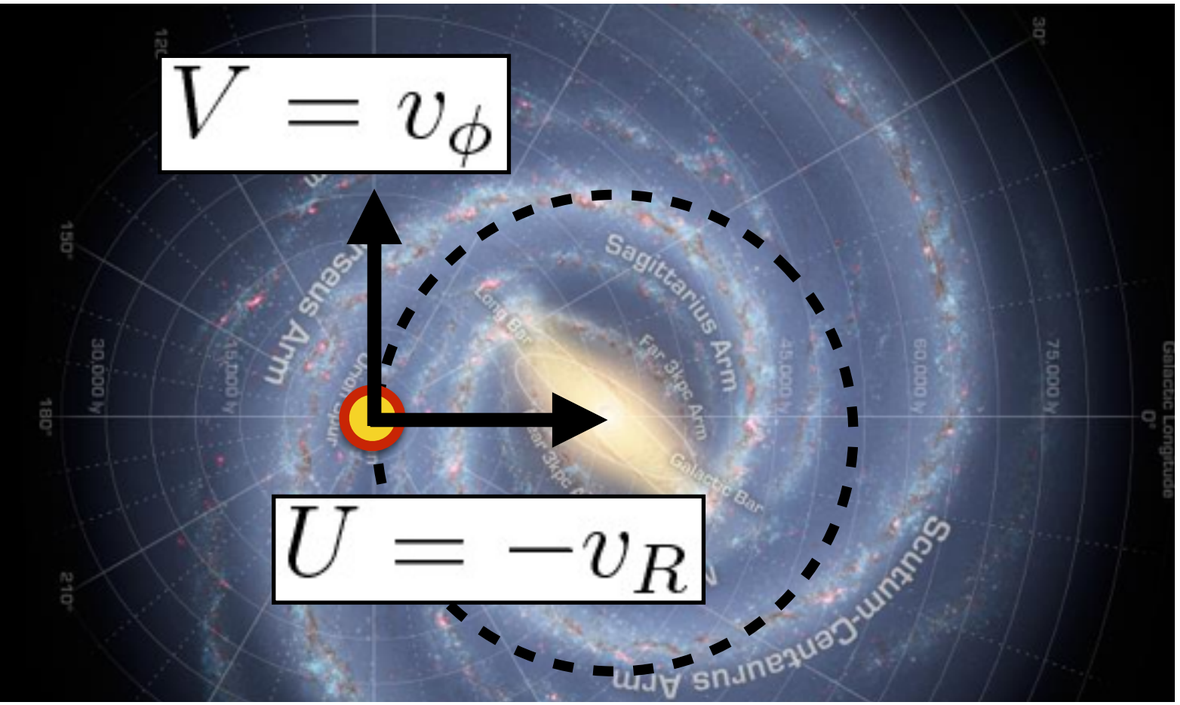
N. Gouda, T. Yano, N. Sakai, H. Tagawa (NAOJ)

Ω_{bar}

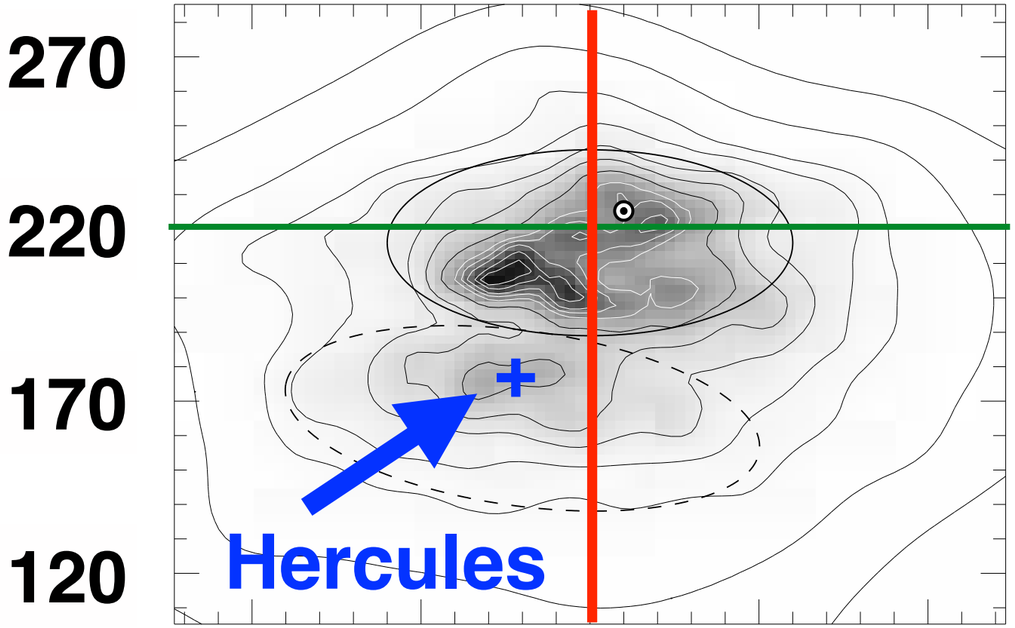

Outer Arm
Perseus Arm
Sagitt
s Arm
Long
r 3kpc Arm
Near 3kpc Arm
Galactic Bar
Orion Spur
Sun
Norma Arm
Scutum-Centaurus Arm
120°
150°
180°
210°
240°
30°
0°
330°
15,000 ly
30,000 ly
45,000 ly
60,000 ly
75,000 ly
Galactic Longitude

velocity substructure @ Sun

due to **bar ?**



$V = v_\phi$

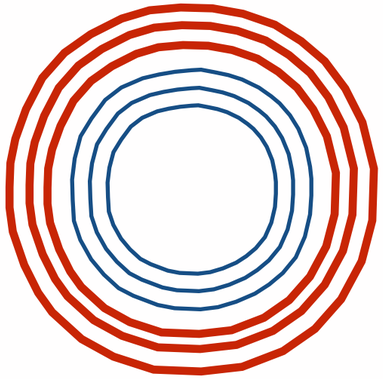


$U = -v_R$

Dehnen (2000)

axisymmetric

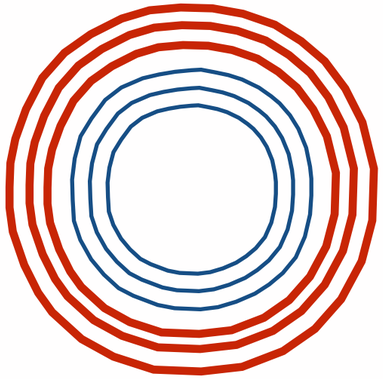
time



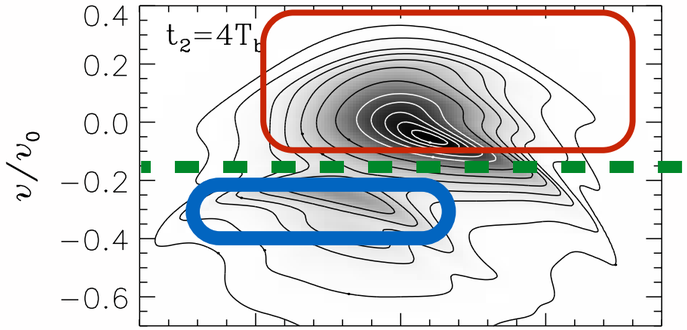
axisymmetric

time

bar formation

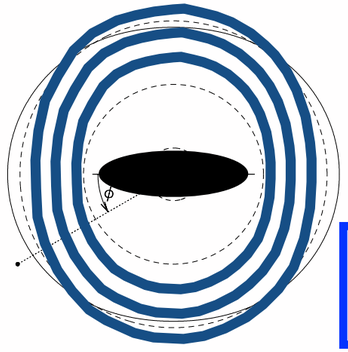


$$R > R(OLR)$$



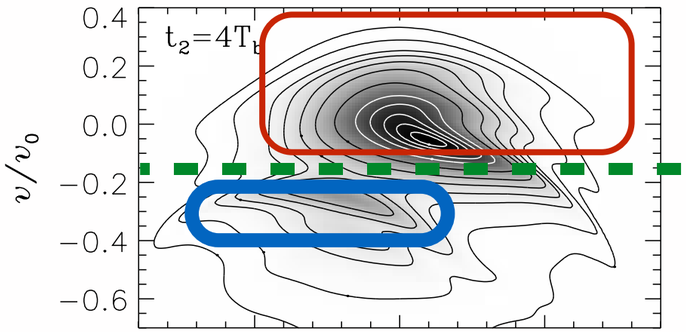
Outer Lindblad Resonance

$$R(OLR) = \left(1 + \frac{1}{\sqrt{2}}\right) \frac{v_0}{\Omega_{\rm bar}}$$



$$R < R(OLR)$$

Dehnen (1999) $\Omega_{\rm bar} = 53 \pm 3$ km/s/kpc



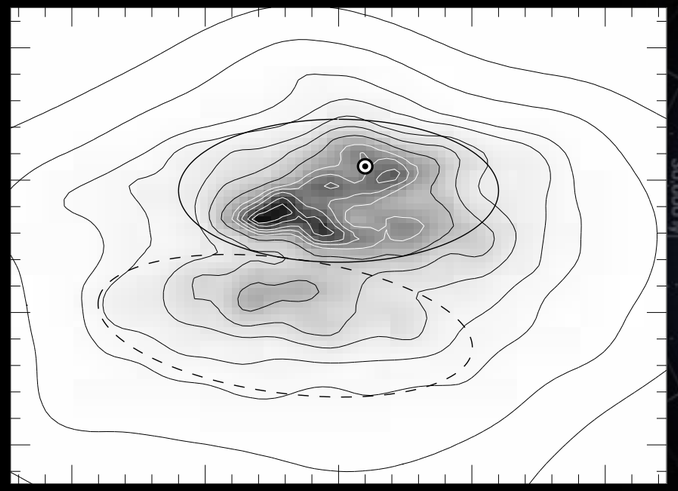
Outer Lindblad Resonance

$$R(OLR) = \left(1 + \frac{1}{\sqrt{2}}\right) \frac{v_0}{\Omega_{\rm bar}}$$

Fast bar?

$\Omega_{\rm bar} =$ 53 km/s/kpc

local data

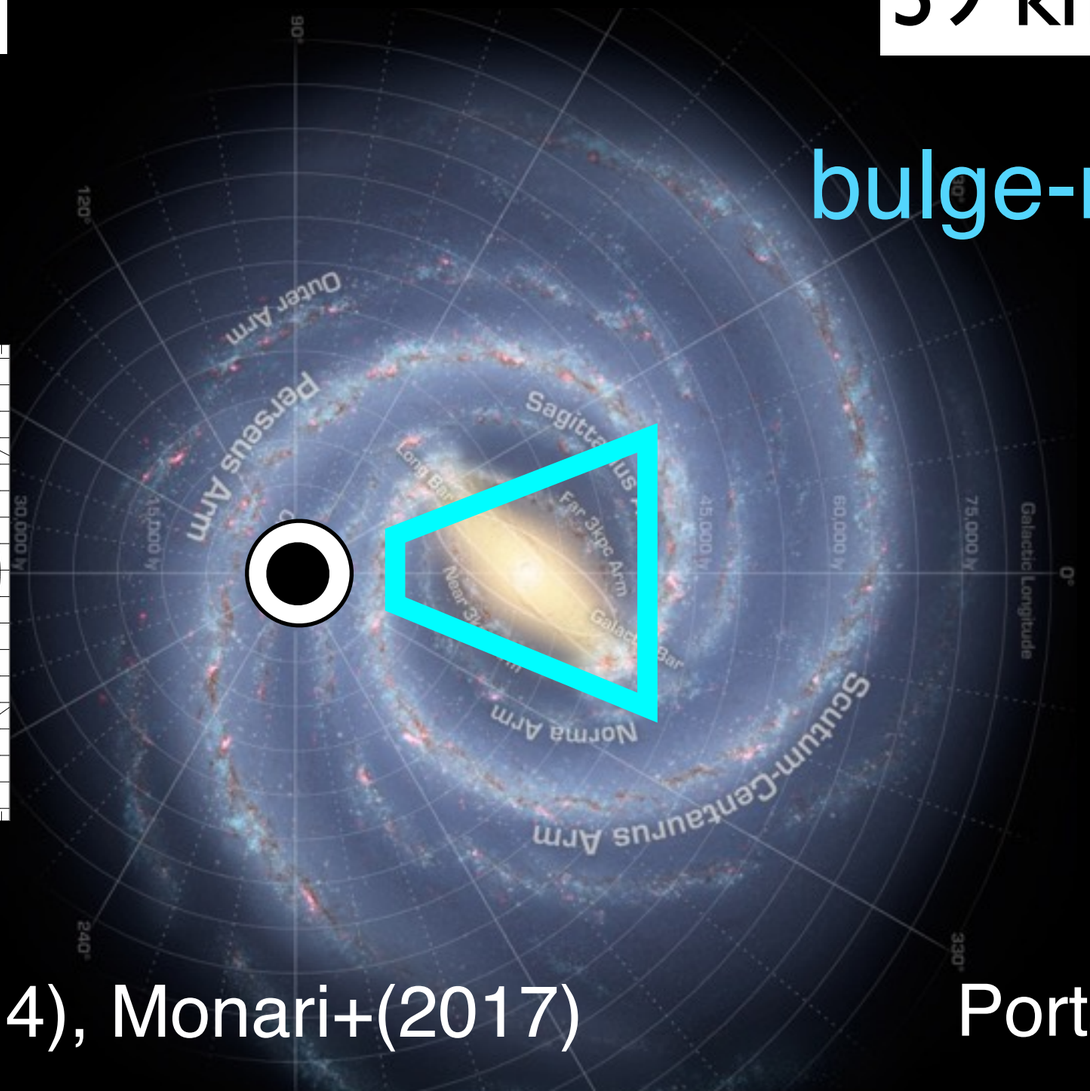


Dehnen (1999)
Minchev+(2009),Antoja+(2014), Monari+(2017)

Slow bar?

39 km/s/kpc

bulge-region data



Portail et al. (2017)

Fast bar?

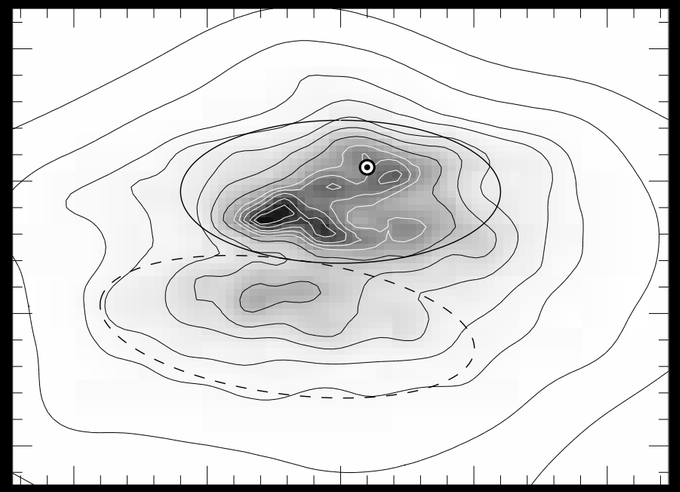
$\Omega_{\rm bar} =$ 53 km/s/kpc

local data

Slow bar?

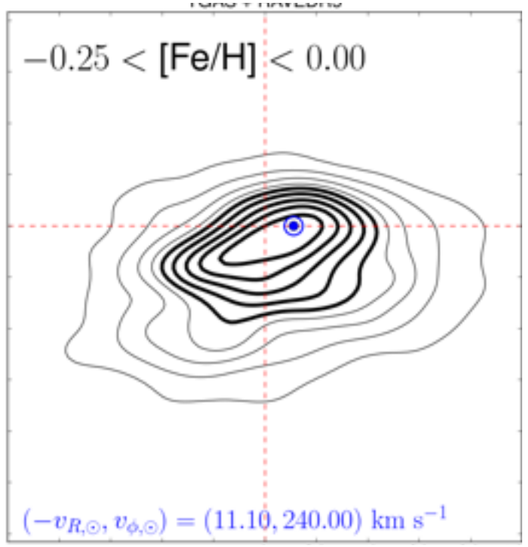
39 km/s/kpc

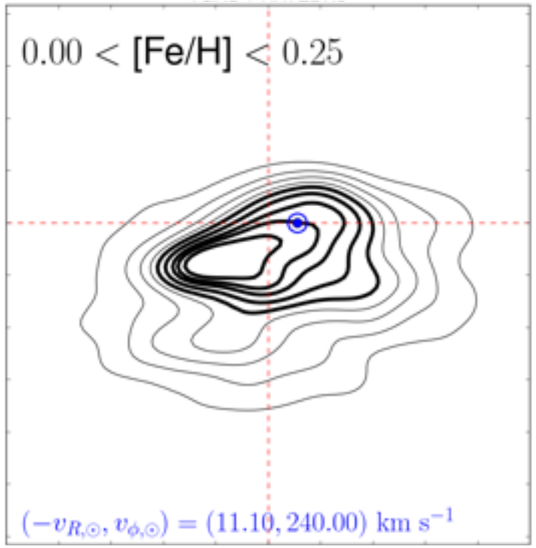
bulge-region data

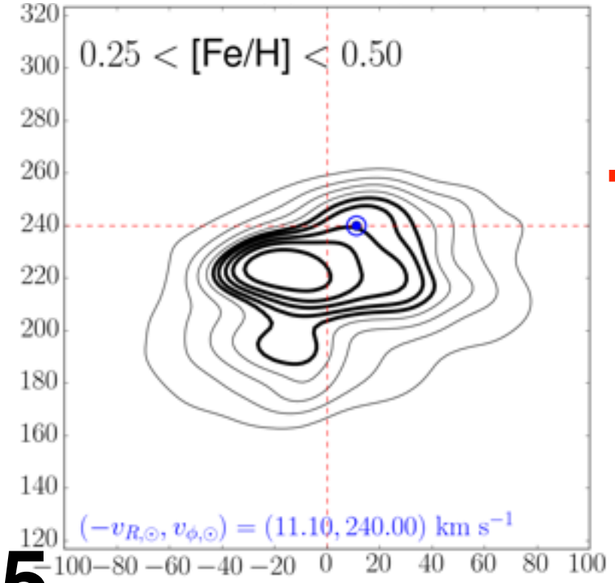


Hercules :
“slow bar + spirals” ?

Similar idea : Antoja+(2009,2011)

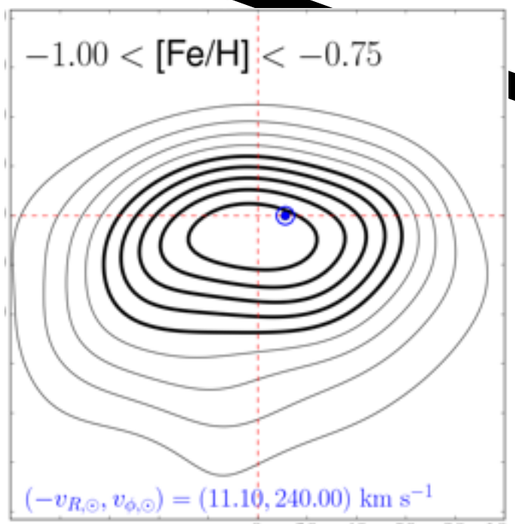


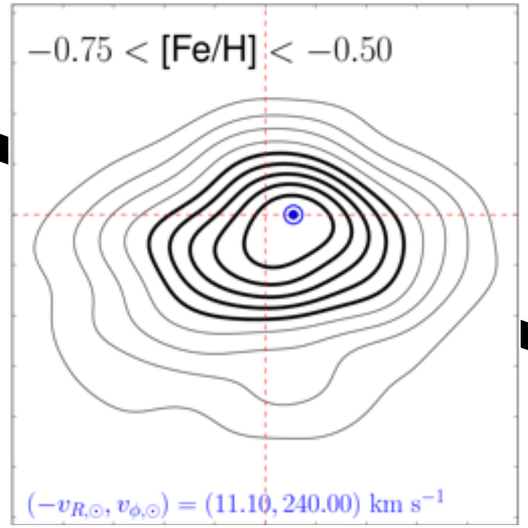


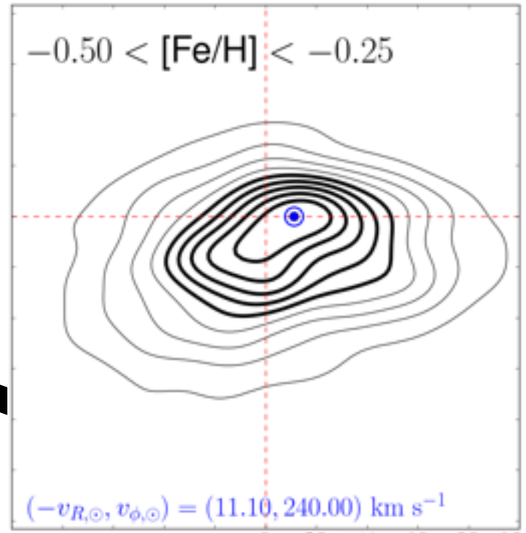


TGAS + RAVE

-0.25 **0** **0.25** **[Fe/H]**

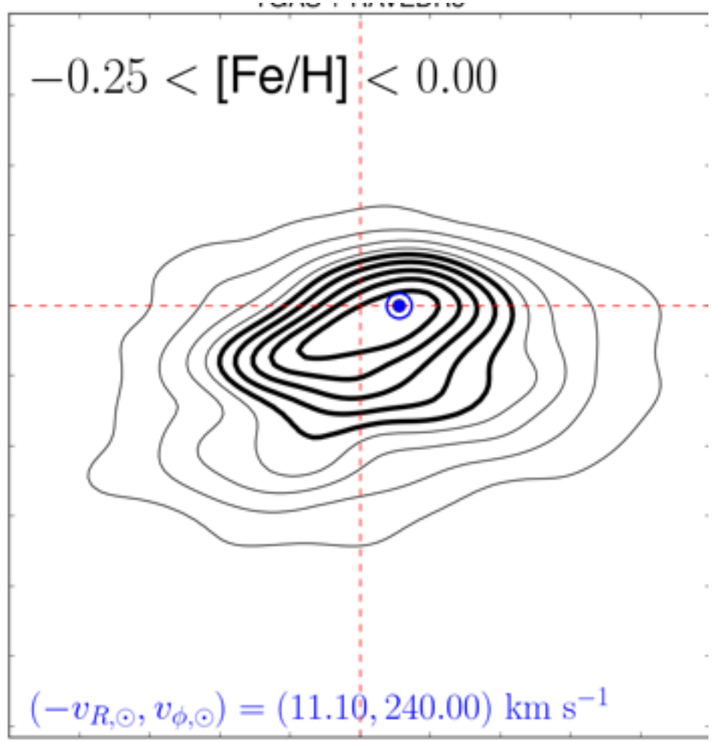


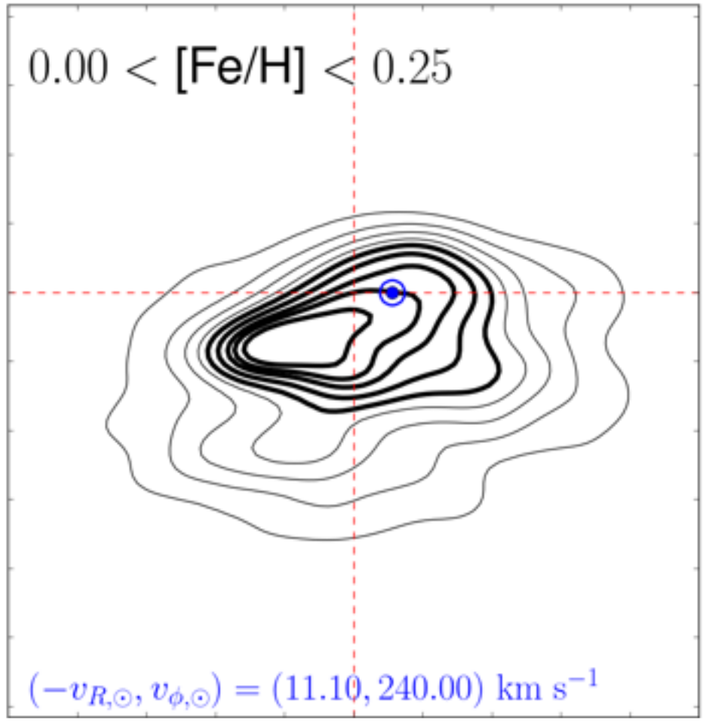


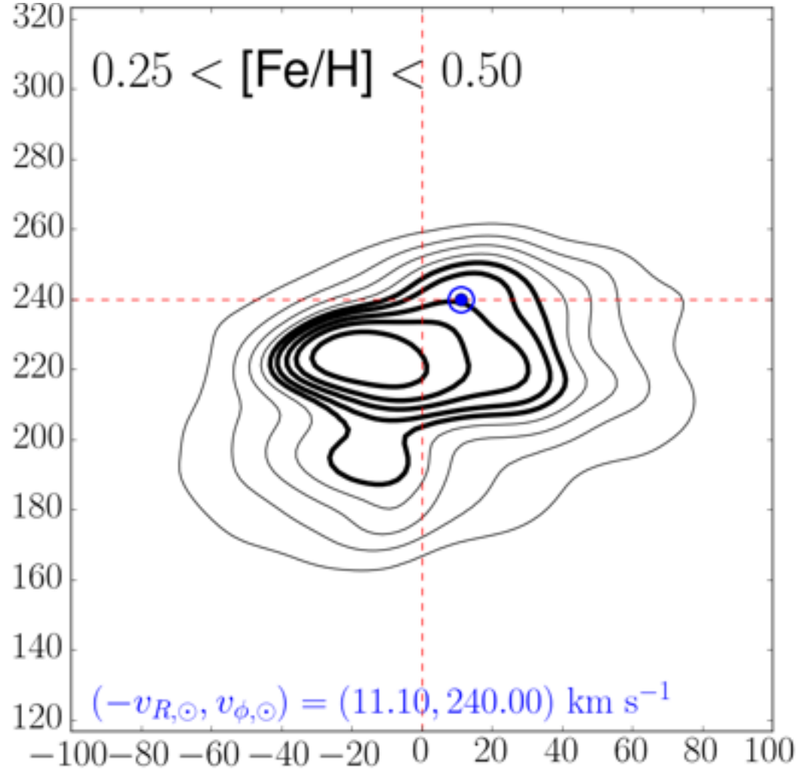


-1 **-0.75** **0.5** **-0.25**

Similar results : Pérez-Villegas +(2017)







-0.25 **0** **0.25** **[Fe/H]**

(1)bar-only models
(2)bar+spiral models

→ [Fe/H]-dependence

Conclusion first !

Bar only

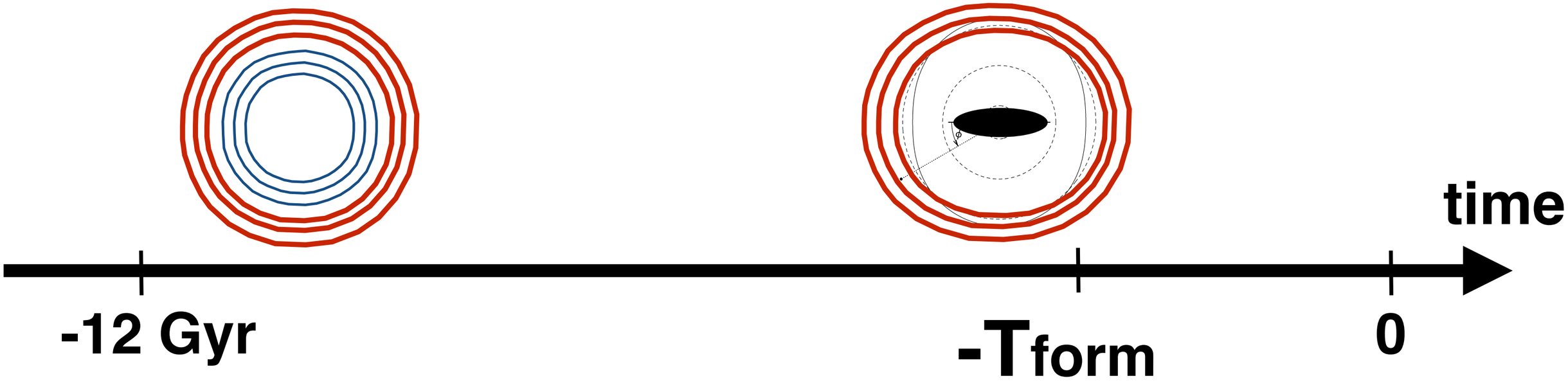
O : Fast bar

X : Slow bar

Slow bar + spiral

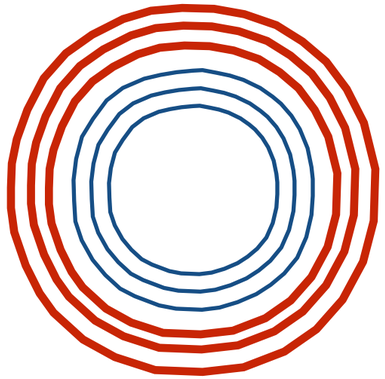
O : slow bar + 4-armed **steady** spiral

O : slow bar + 2-armed **transient** spiral



Method

axisymmetric



time

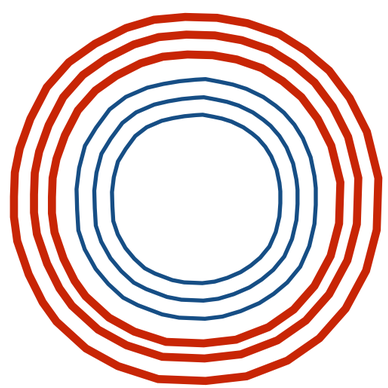
-12 Gyr

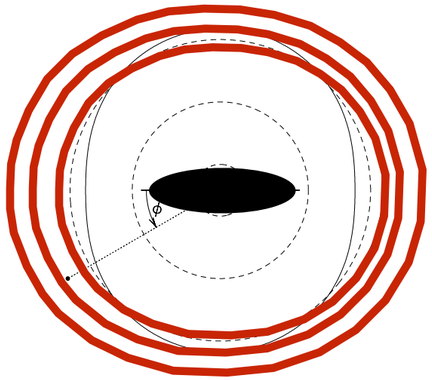
0

constant star formation

axisymmetric

bar formation





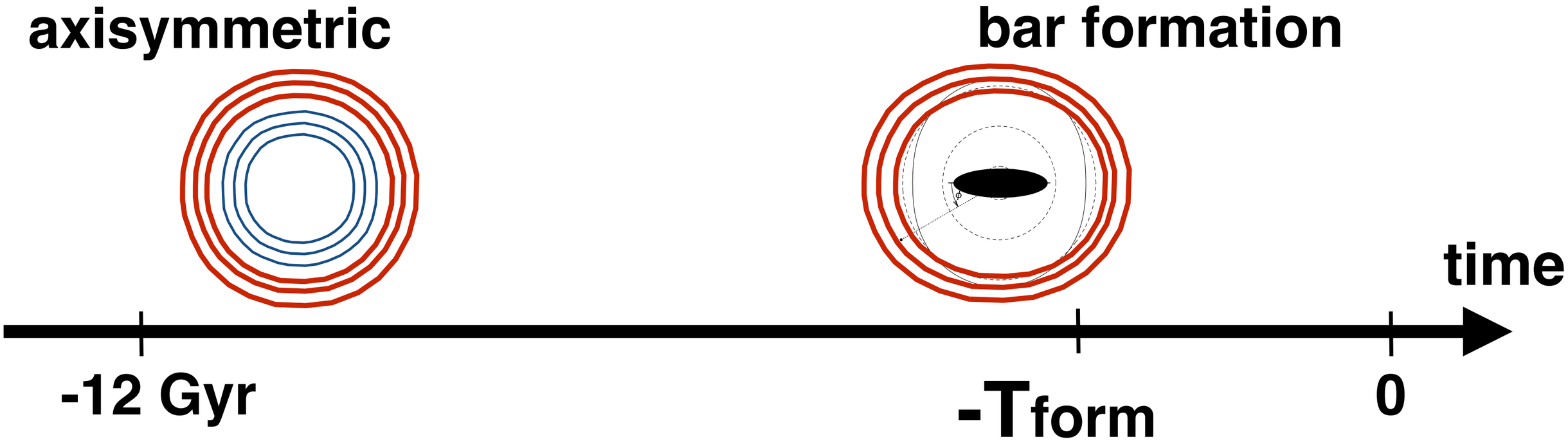
time

-12 Gyr

$-T_{form}$

0

constant star formation



constant star formation

internal heating

test particle simulation

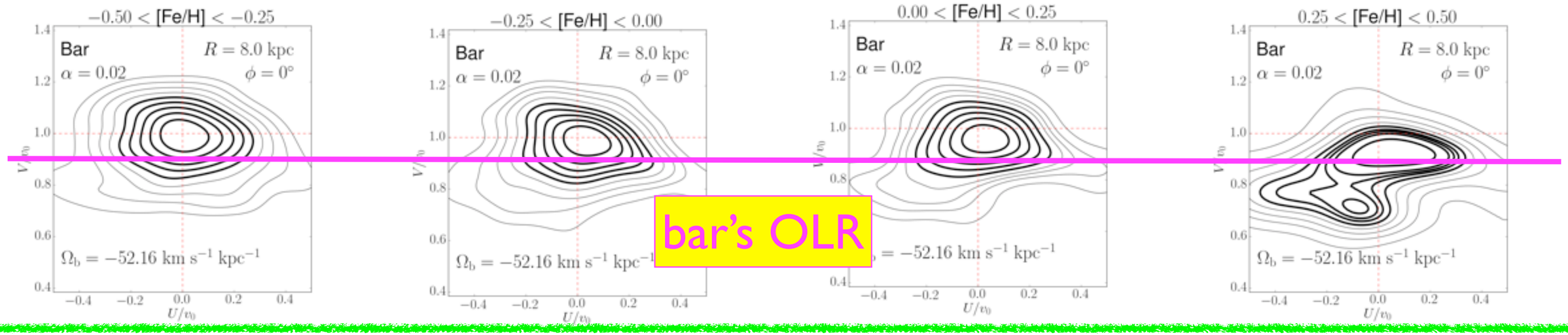
Result

	bar
shape	Dehnen (2000) bar
pattern speed	Ω_b 39, 52 km/s/kpc
T_{form}	0.5 - 10 Gyr

$$\Omega_{\rm bar} = 39 \pm 3.5 \ {\rm km/s/kpc}$$ (Portail+2017)

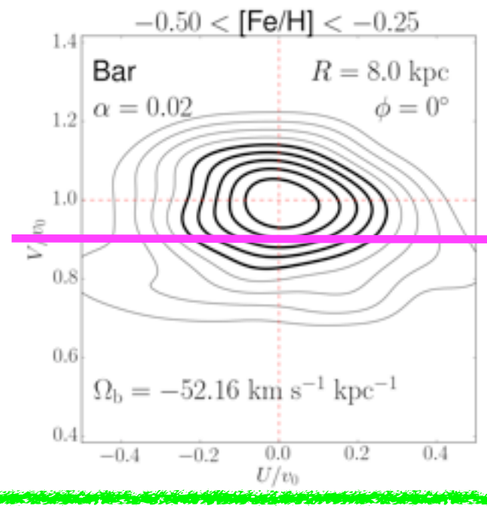
$$\Omega_{\rm bar} = 53 \pm 3 \ {\rm km/s/kpc}$$ (Dehnen 1999)

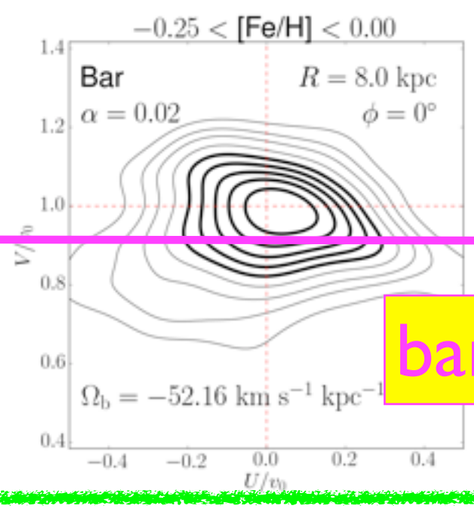
(1a) **fast** bar $\Omega_{\rm bar} = \mathbf{52}$, Tform = 5 Gyr

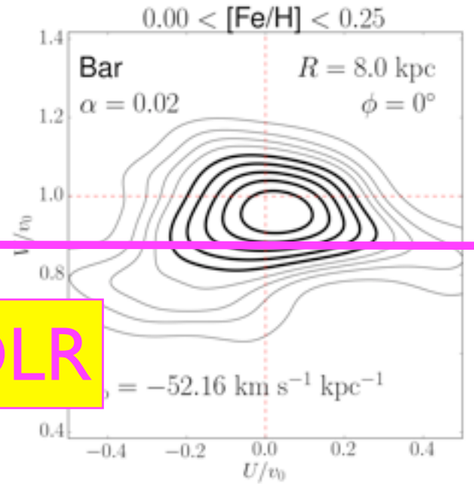


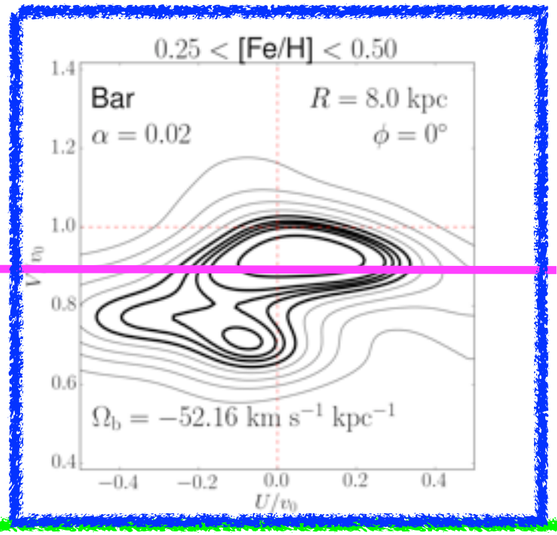
-0.5 -0.25 0 0.25 [Fe/H]

(1a) **fast** bar $\Omega_{\rm bar} = \mathbf{52}$, Tform = 5 Gyr





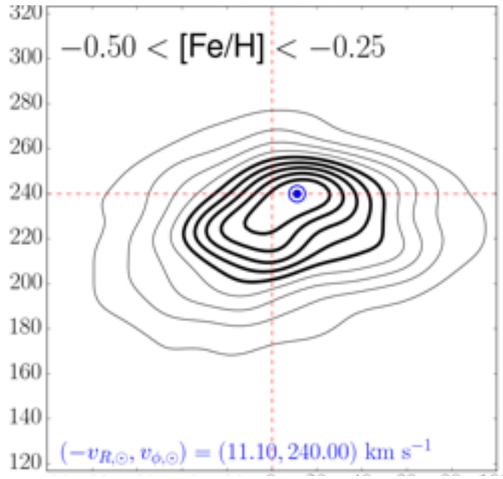


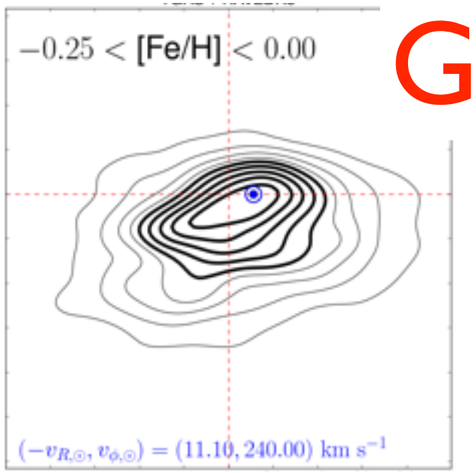


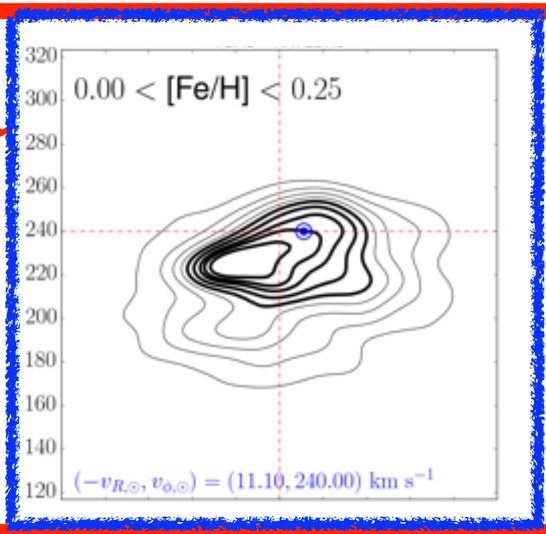
bar's OLR

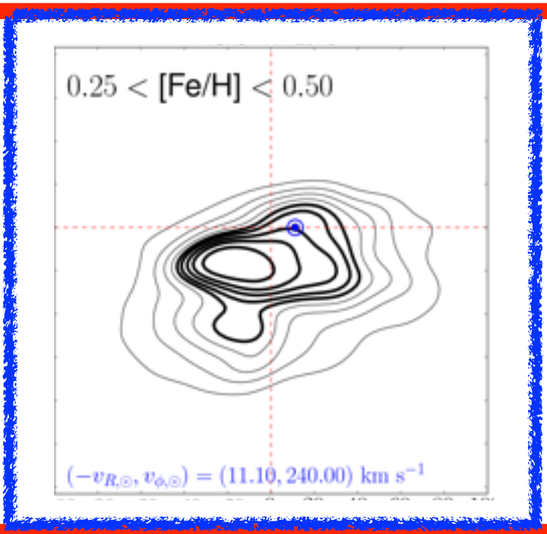
-0.5 -0.25 0 0.25 [Fe/H]

Gaia

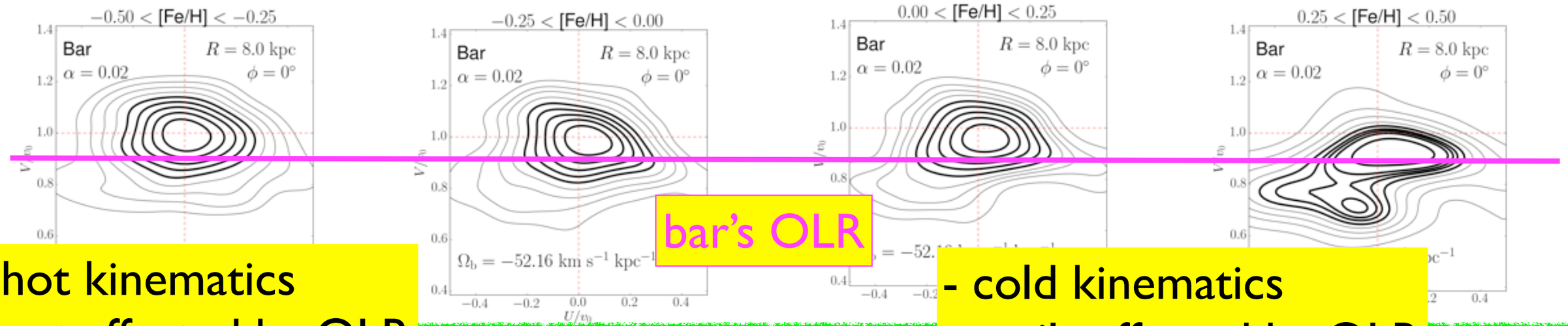








(1a) **fast** bar $\Omega_{\rm bar} = \mathbf{52}$, Tform = 5 Gyr



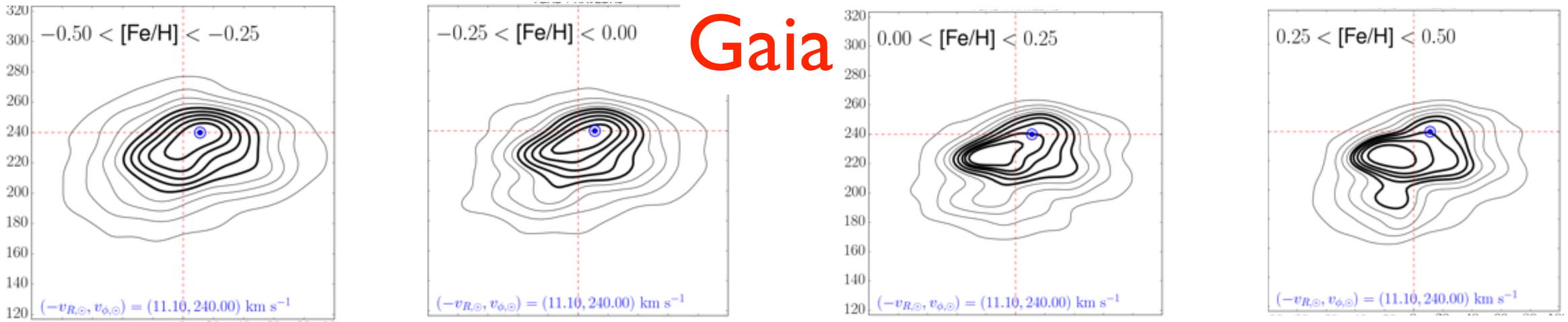
bar's OLR

- hot kinematics
- not affected by OLR

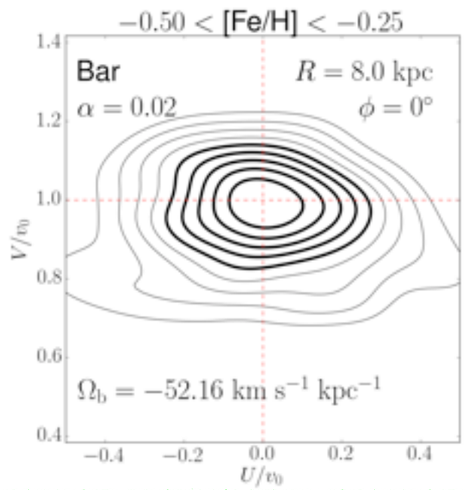
- cold kinematics
- easily affected by OLR

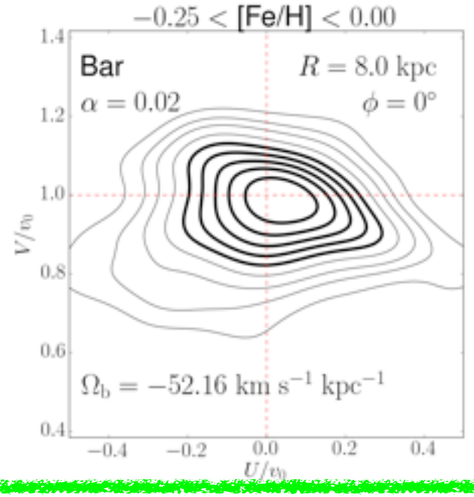
-0.5 -0.25 0 0.25 [Fe/H]

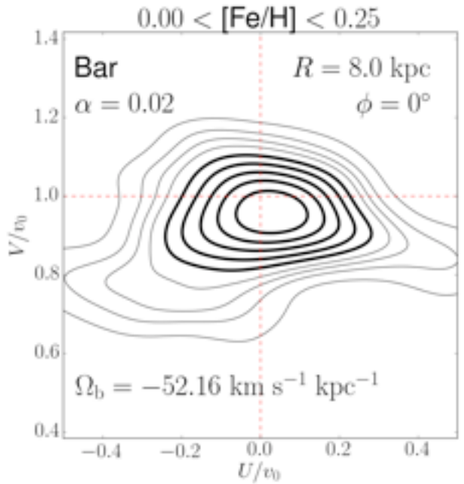
Gaia

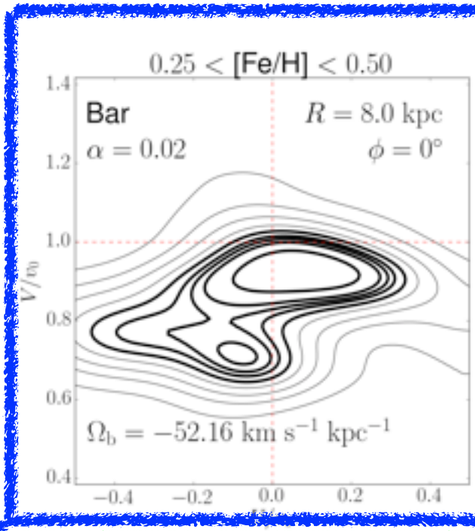


(1a) **fast** bar $\Omega_{\rm bar} = \mathbf{52}$, Tform = 5 Gyr



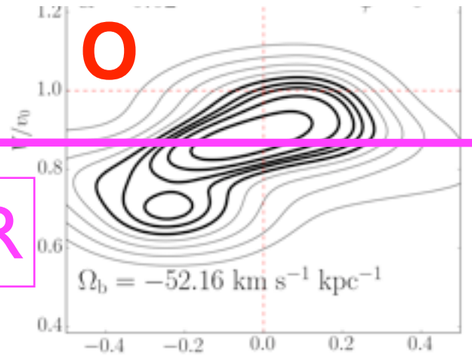




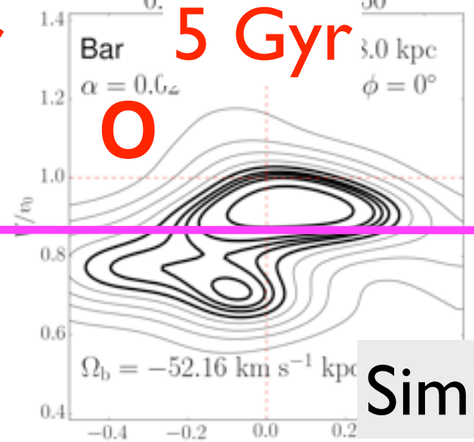


-0.5 -0.25 0 0.25 [Fe/H]

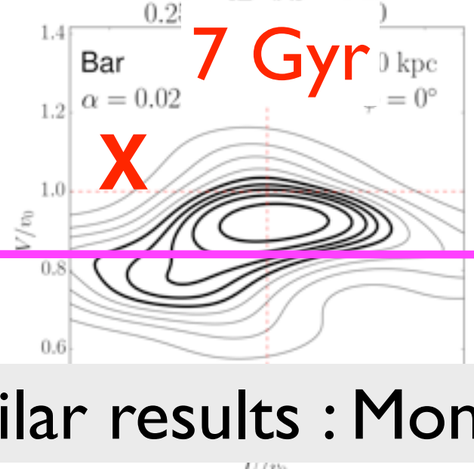
Tform = 2 Gyr o



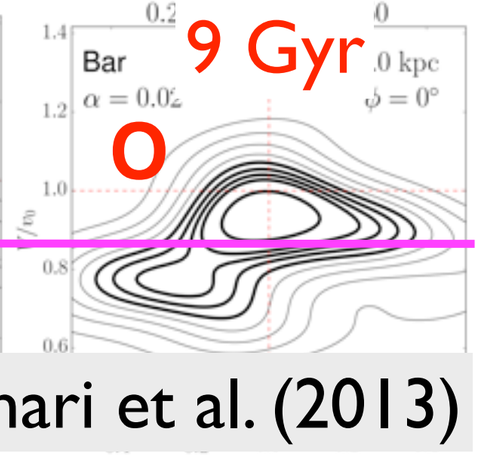
5 Gyr o



7 Gyr x



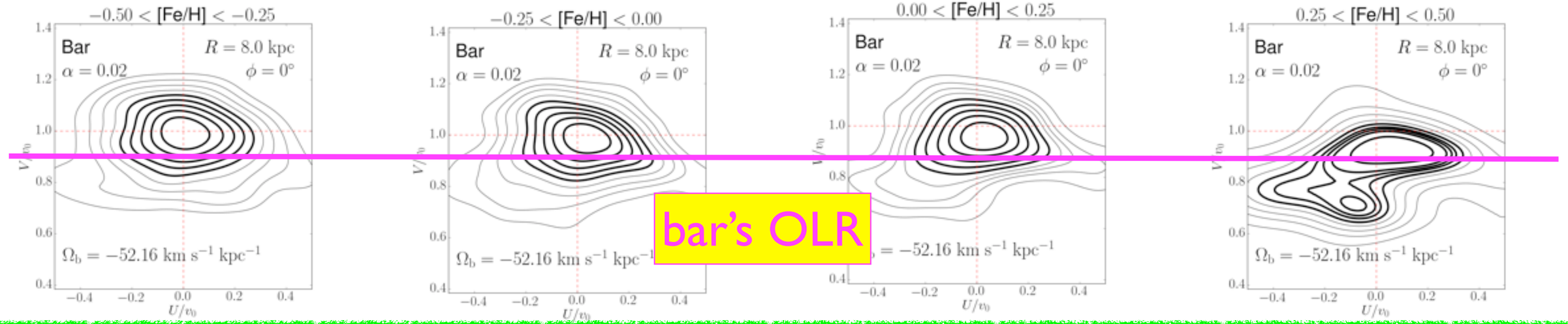
9 Gyr o



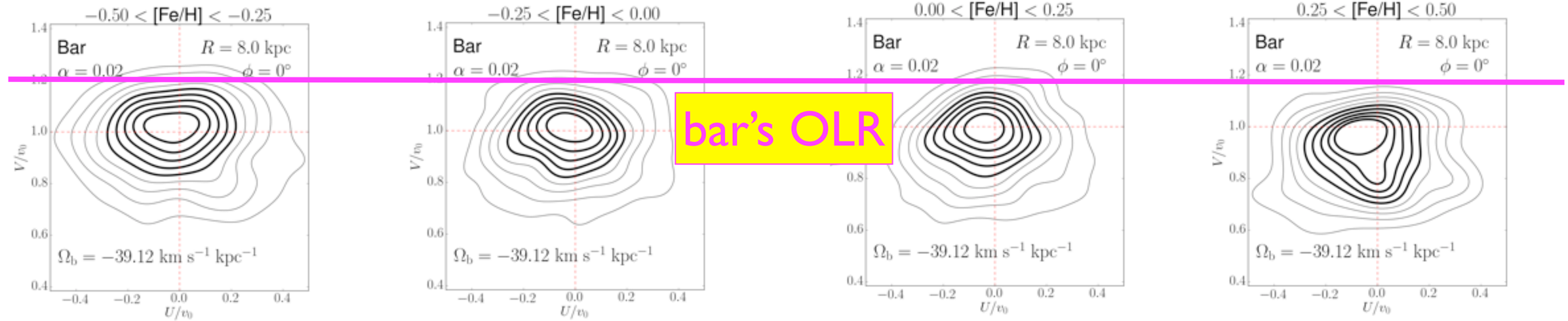
bar's OLR

Similar results : Monari et al. (2013)

(1a) **fast** bar $\Omega_{\rm bar} = \mathbf{52}$, Tform = 5 Gyr



(1b) **slow** bar $\Omega_{\rm bar} = \mathbf{39}$, Tform = 5 Gyr



-0.5 -0.25 0 0.25 [Fe/H]

Conclusion first !

Bar only

O : Fast bar
Naturally explains [Fe/H]-dependence of Hercules stream.

X : Slow bar
No Bimodal structure.

Slow bar + spiral

O : slow bar + 4-armed **steady** spiral

O : slow bar + 2-armed **transient** spiral

Conclusion first !

Bar only

O : Fast bar
Naturally explains [Fe/H]-dependence of Hercules stream.

X : Slow bar
No Bimodal structure.

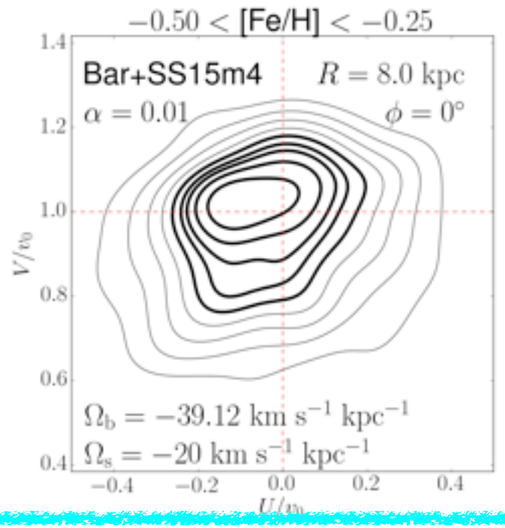
Slow bar + spiral

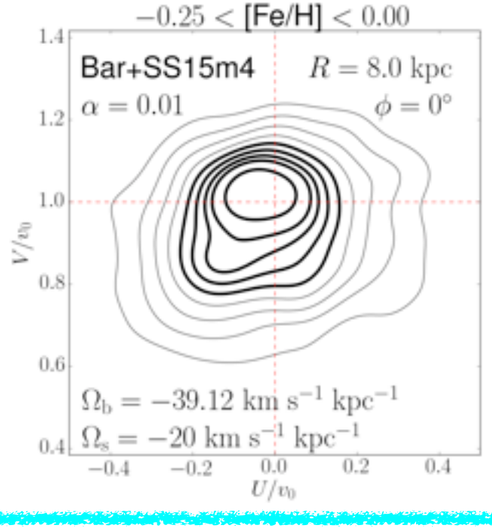
O : slow bar + 4-armed **steady** spiral

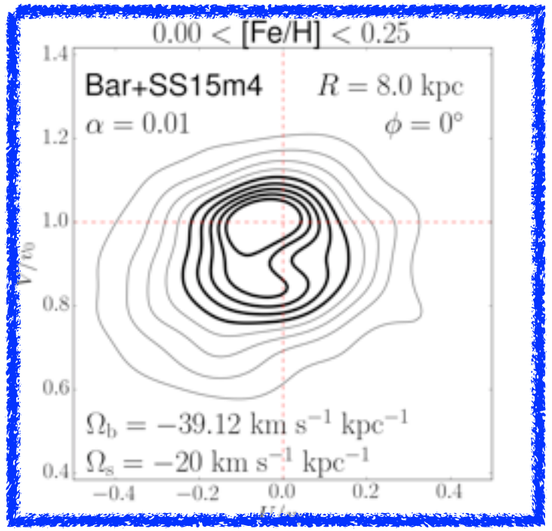
O : slow bar + 2-armed **transient** spiral

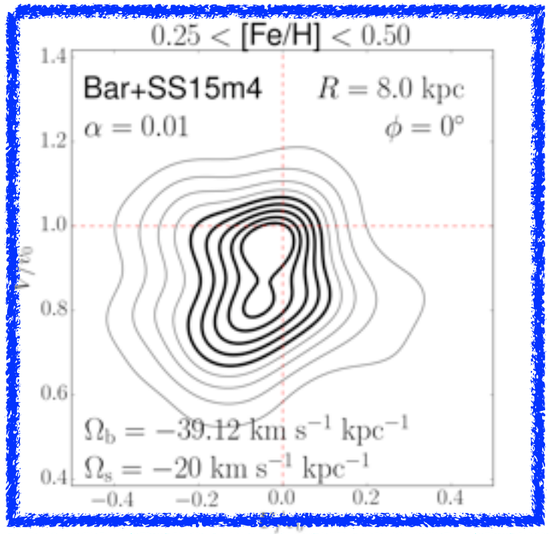
(2) **slow bar + steady spiral (m=4)**

$\Omega_{\rm bar} = 39$, $\Omega_s = 20$, Tform = 8 Gyr



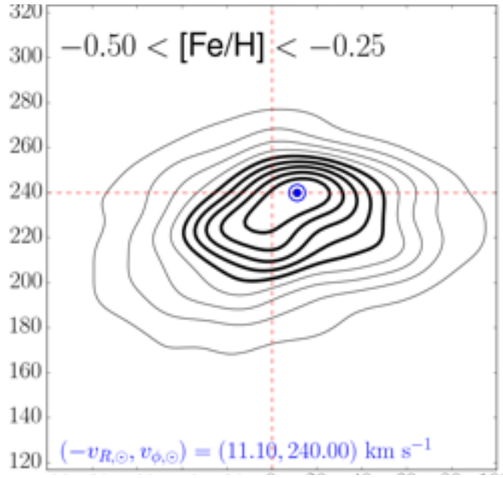


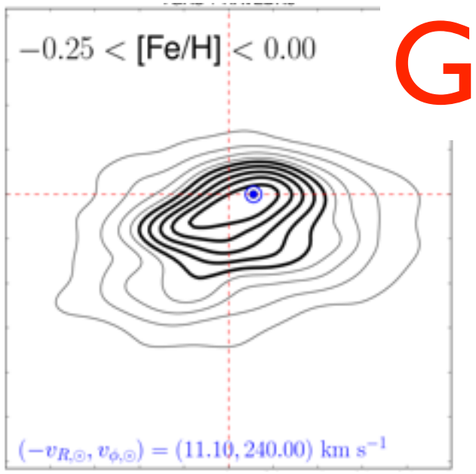


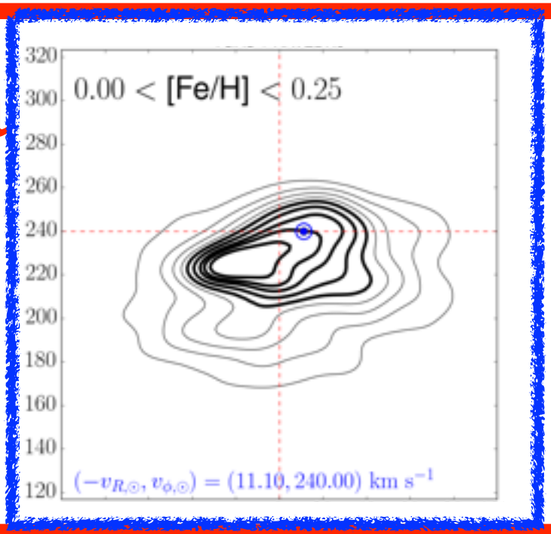


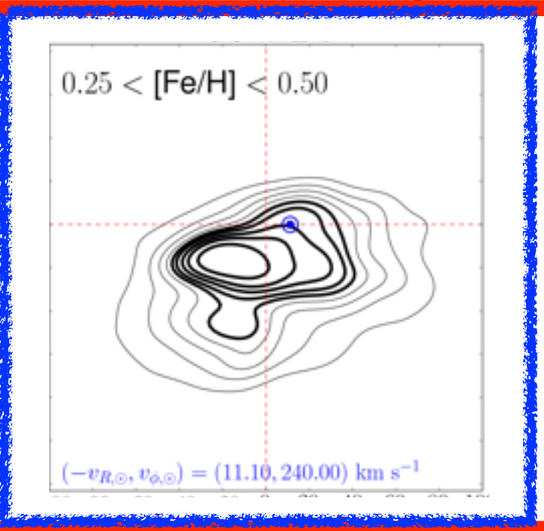
-0.5 -0.25 0 0.25 [Fe/H]

Gaia



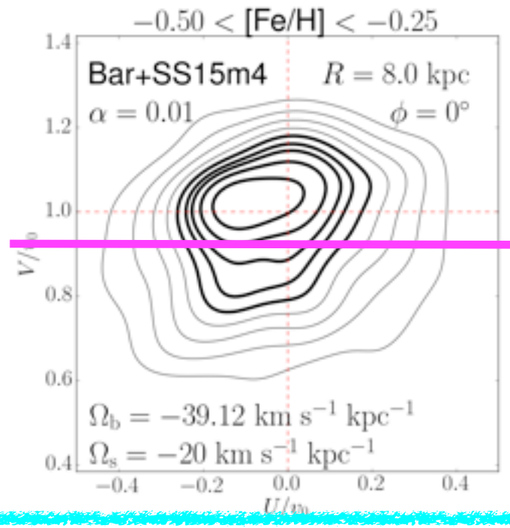


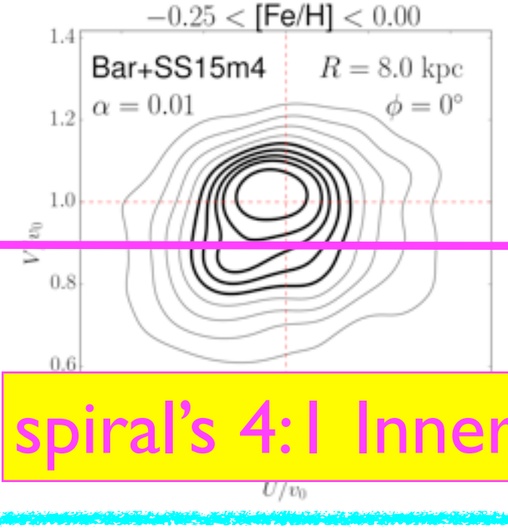


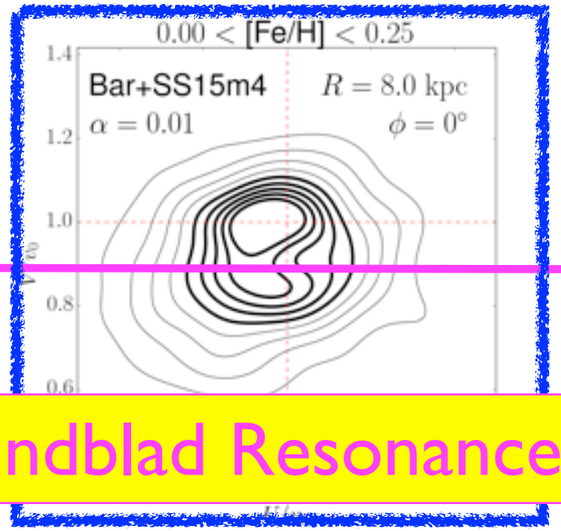


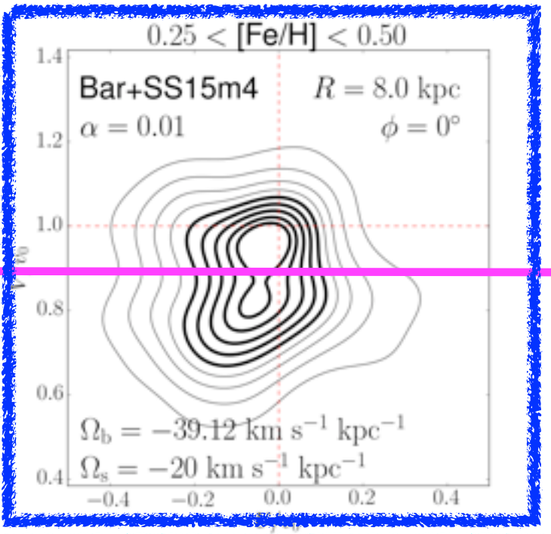
(2) **slow bar + steady spiral (m=4)**

$\Omega_{\rm bar} = 39$, $\Omega_s = 20$, Tform = 8 Gyr







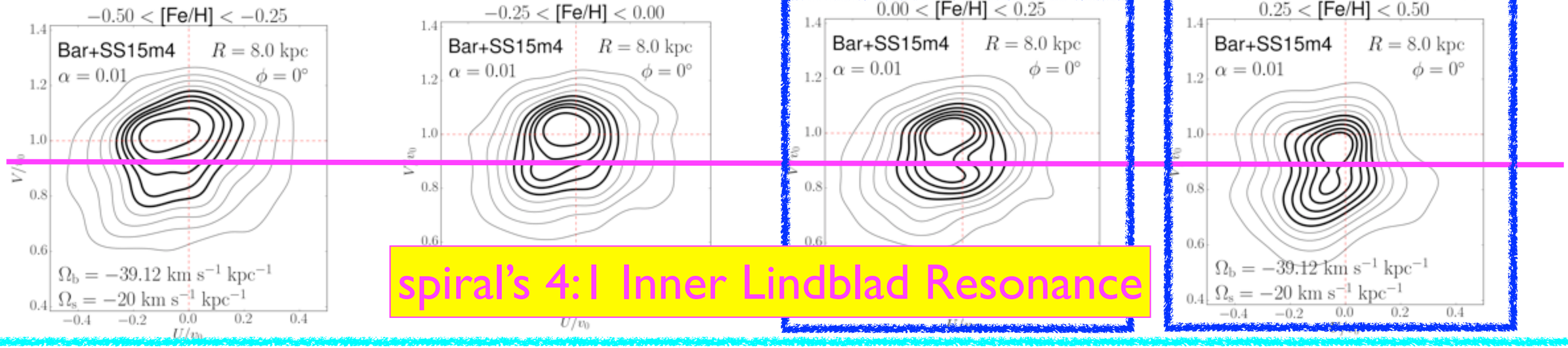


spiral's 4:1 Inner Lindblad Resonance

-0.5 -0.25 0 0.25 [Fe/H]

(2) **slow bar + steady spiral (m=4)**

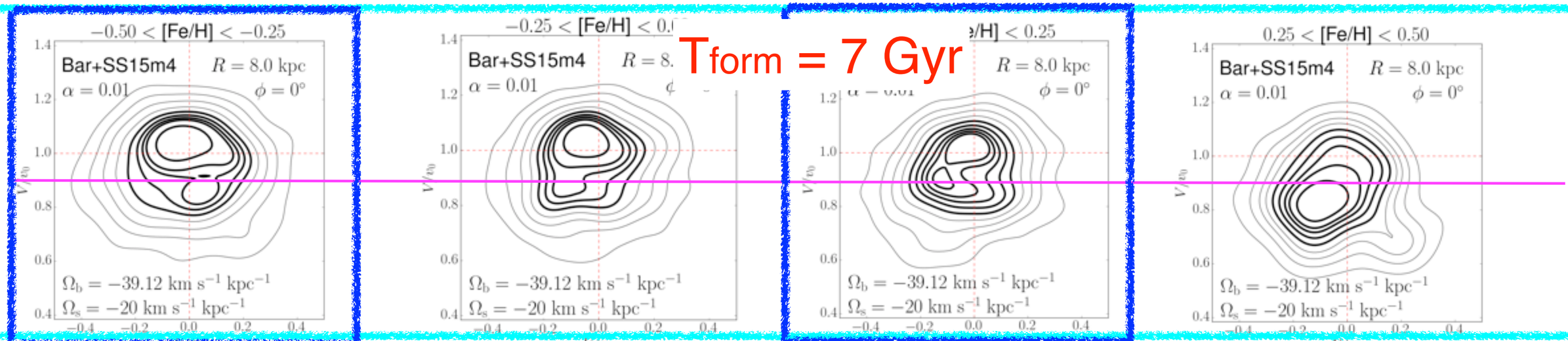
$\Omega_{\rm bar} = 39$, $\Omega_s = 20$, Tform = 8 Gyr



spiral's 4:1 Inner Lindblad Resonance

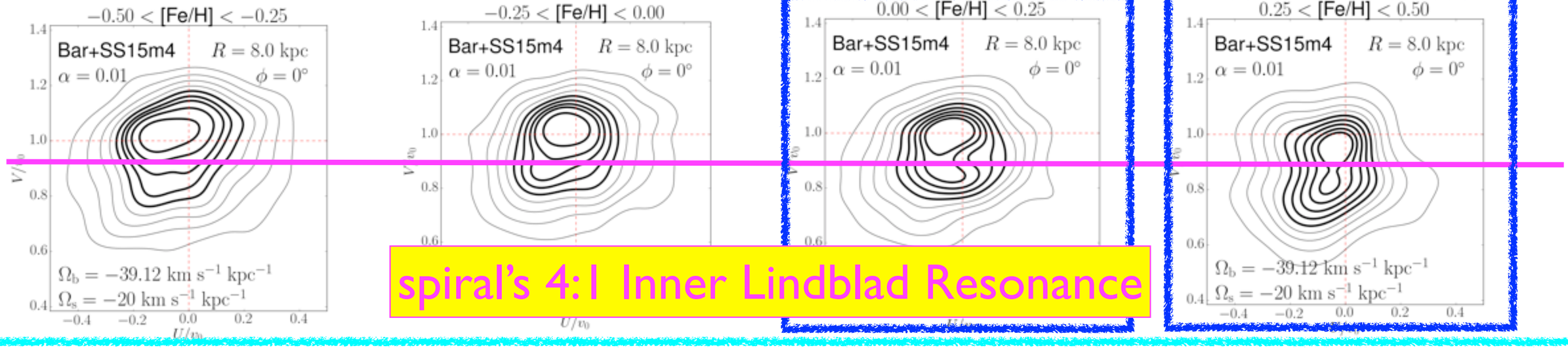
-0.5 -0.25 0 0.25 [Fe/H]

Tform = 7 Gyr



(2) **slow bar + steady spiral (m=4)**

$\Omega_{\rm bar} = 39$, $\Omega_s = 20$, Tform = 8 Gyr



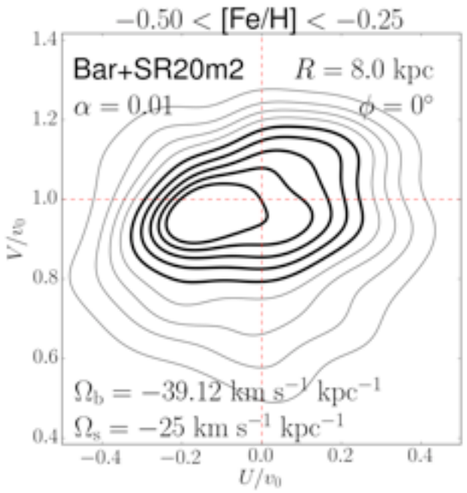
spiral's 4:1 Inner Lindblad Resonance

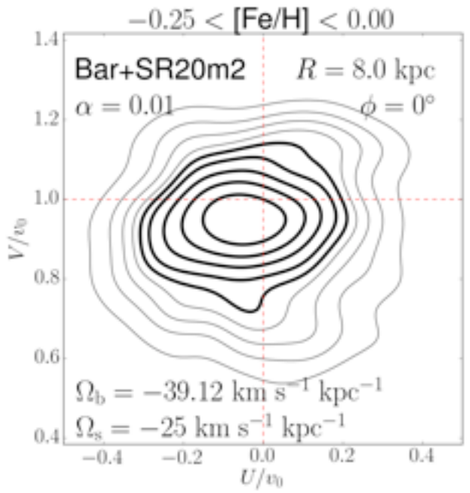
-0.5 -0.25 0 0.25 [Fe/H]

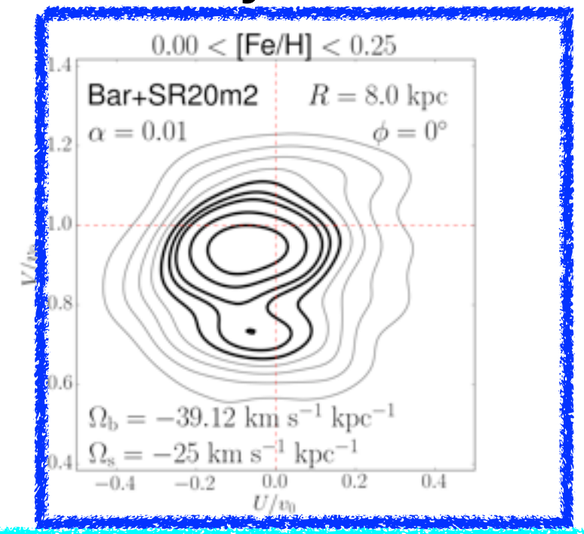
- Bimodality is due to spiral.
- [Fe/H]-dependence is sensitive to **Tform** (due to chaotic orbits)
  → **Observed [Fe/H]-dependence is not informative.**

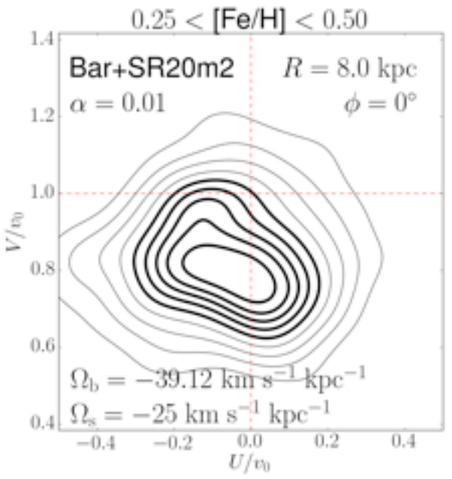
(3) bar + transient spiral (m=2, lifetime = 100Myr)

$\Omega_{\rm bar} = 39$, $\Omega_s = 25$, Tform = 8 Gyr



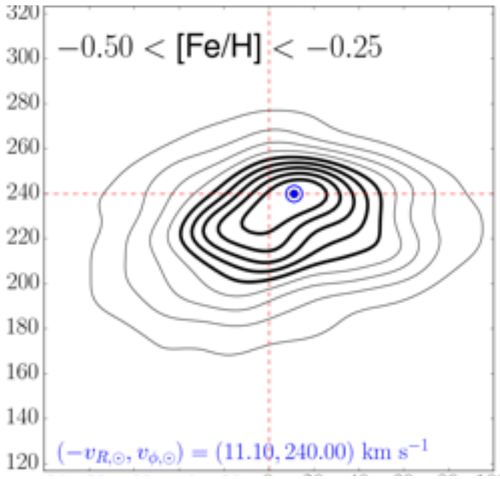


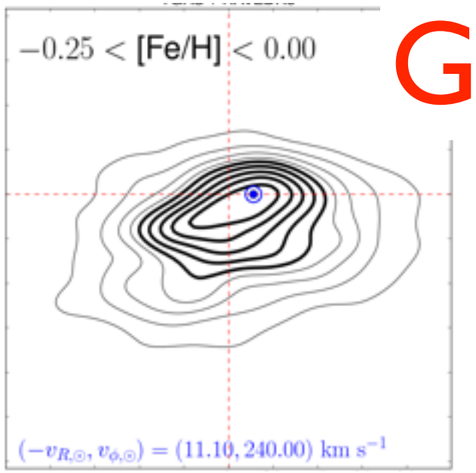


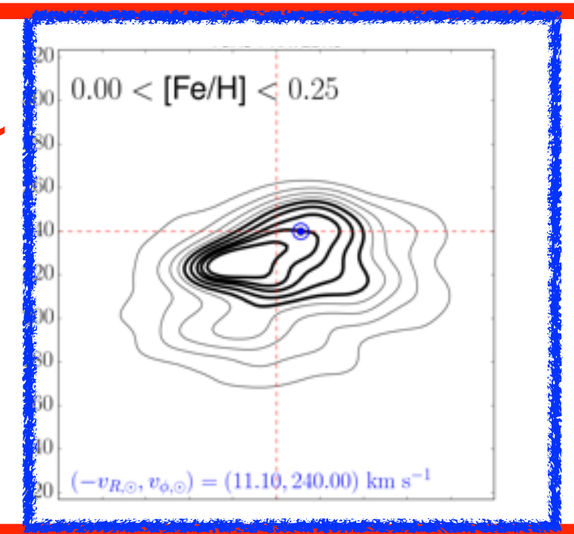


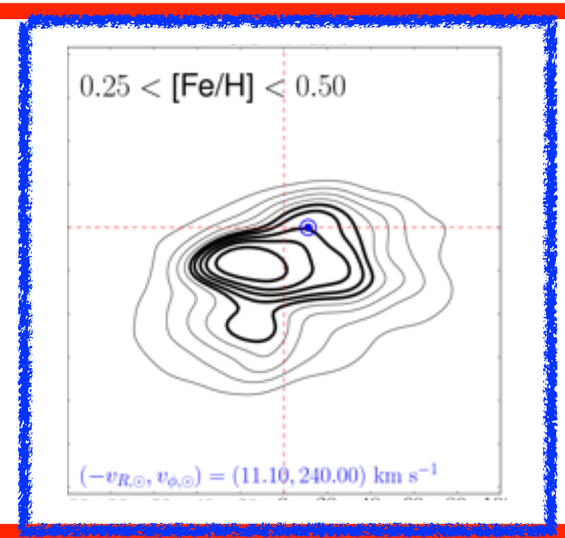
-0.5 -0.25 0 0.25 [Fe/H]

Gaia



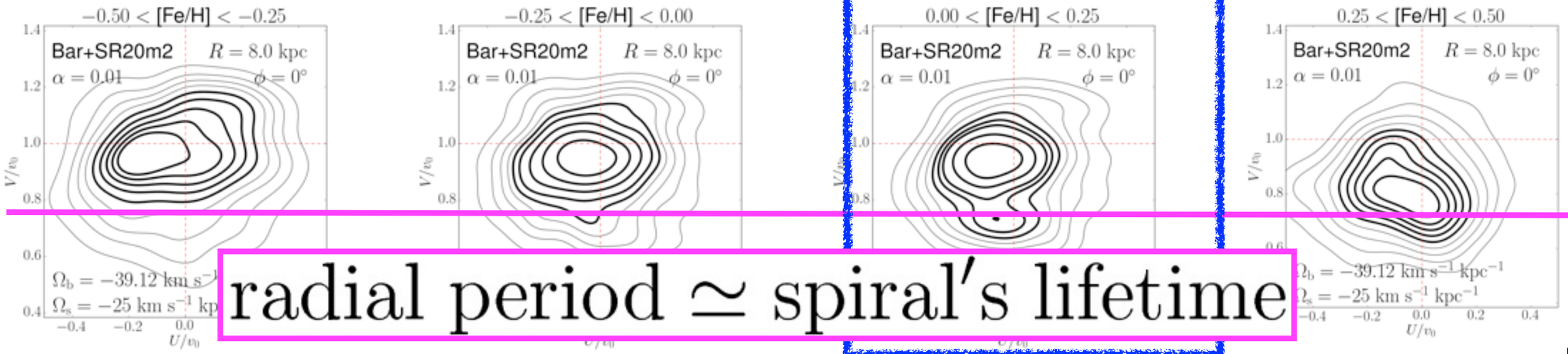






(3) bar + transient spiral (m=2, lifetime = 100Myr)

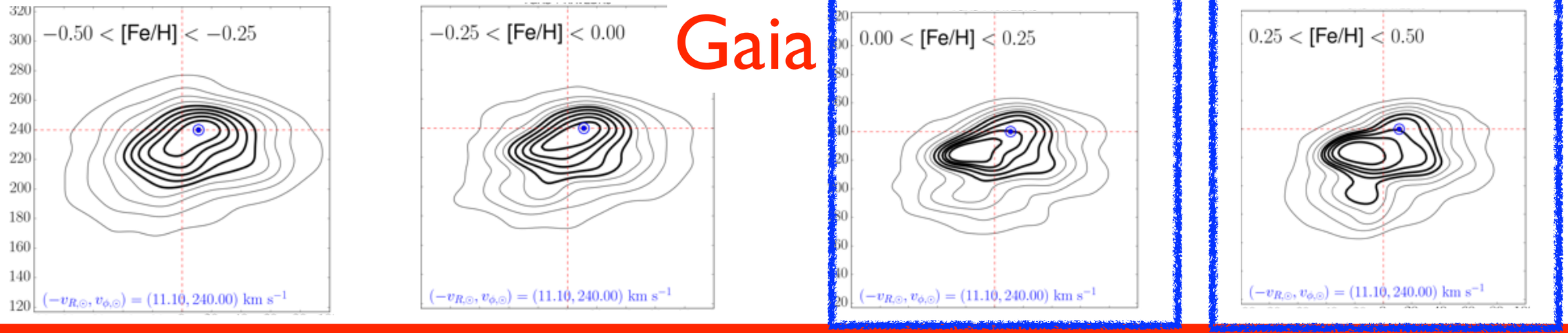
$\Omega_{\rm bar} = 39$, $\Omega_s = 25$, Tform = 8 Gyr



radial period ≃ spiral's lifetime

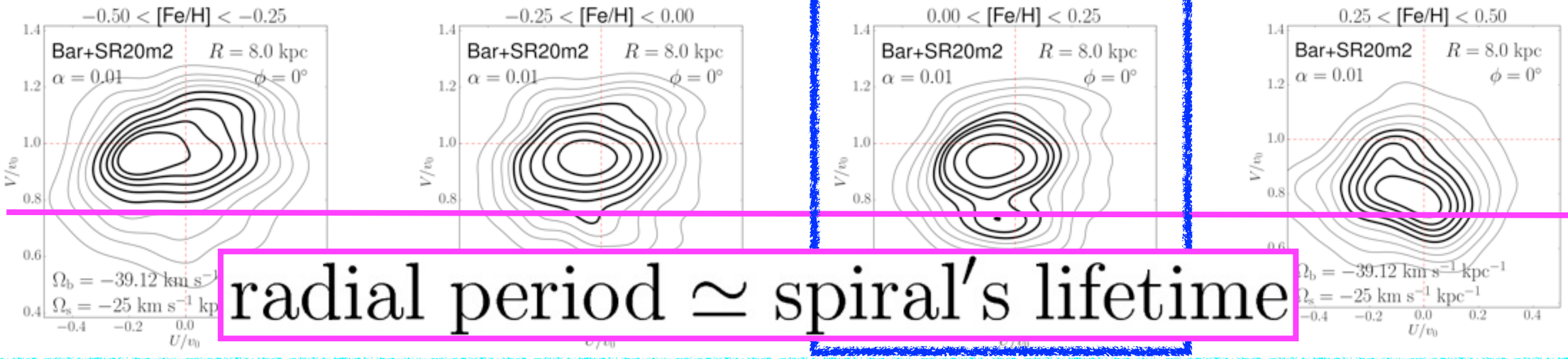
-0.5 -0.25 0 0.25 [Fe/H]

Gaia



(3) bar + transient spiral (m=2, lifetime = 100Myr)

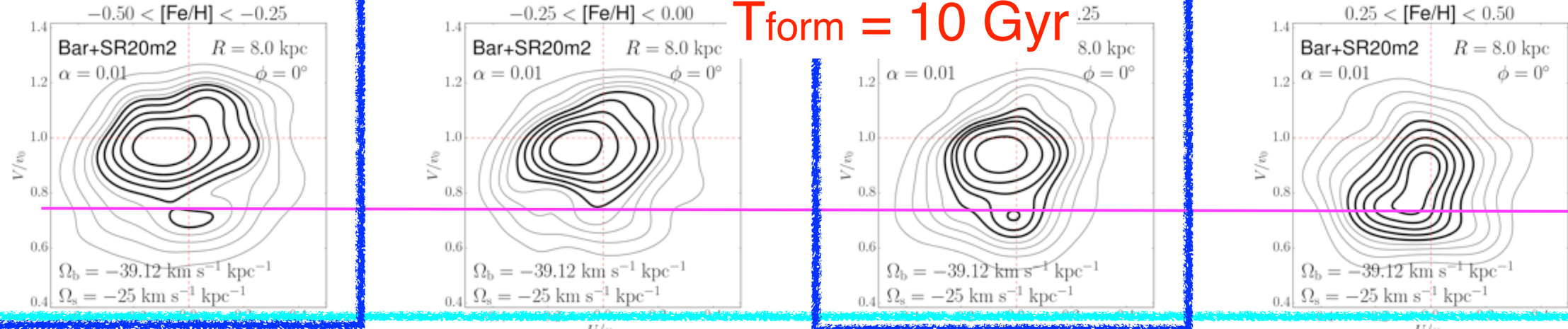
$\Omega_{\rm bar} = 39$, $\Omega_s = 25$, Tform = 8 Gyr



radial period ≃ spiral's lifetime

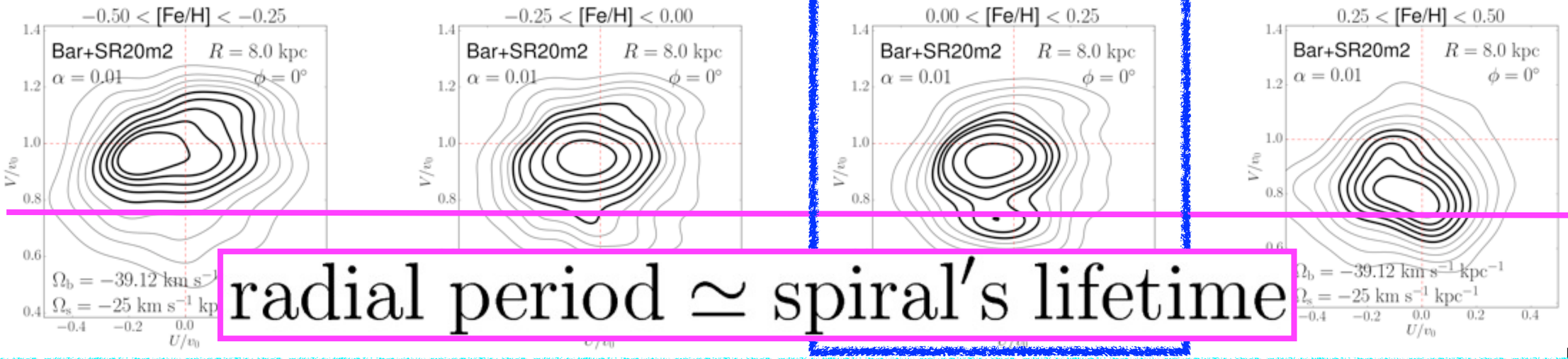
-0.5 -0.25 0 0.25 [Fe/H]

Tform = 10 Gyr



(3) bar + transient spiral (m=2, lifetime = 100Myr)

$\Omega_{\rm bar} = 39$, $\Omega_s = 25$, Tform = 8 Gyr



radial period ≃ spiral's lifetime

-0.5 -0.25 0 0.25 [Fe/H]

- Bimodality is due to spiral's lifetime.
- [Fe/H]-dependence is sensitive to **Tform** (due to chaotic orbits)
  → **Observed [Fe/H]-dependence is not informative.**

TGAS+RAVE : [Fe/H]-dependence of Hercules

Conclusion

Bar only

O : Fast bar
Naturally explains [Fe/H]-dependence of Hercules.

X : Slow bar
No Bimodal structure.

Slow bar + spiral

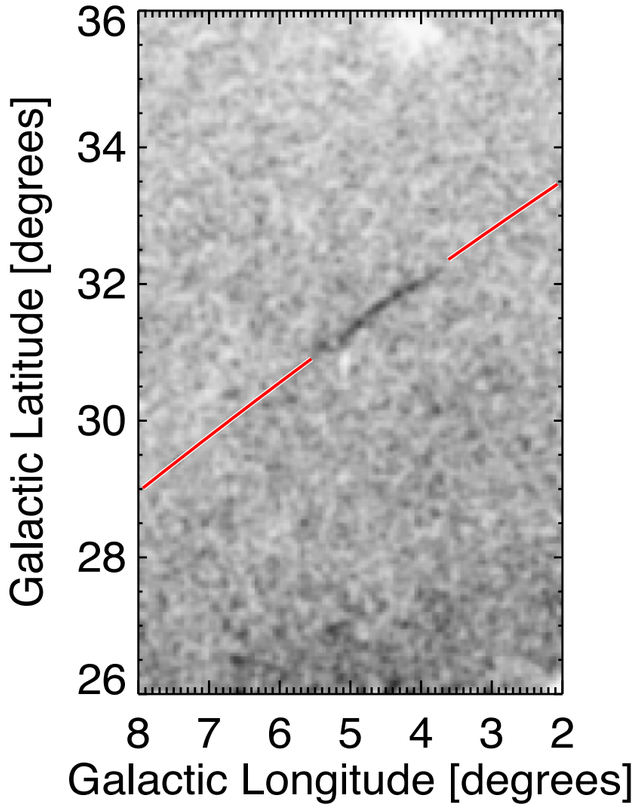
O : slow bar + **steady** spiral
Bimodality : spiral's inner Lindblad resonance.

O : slow bar + **transient** spiral
Bimodality : due to spiral's lifetime.

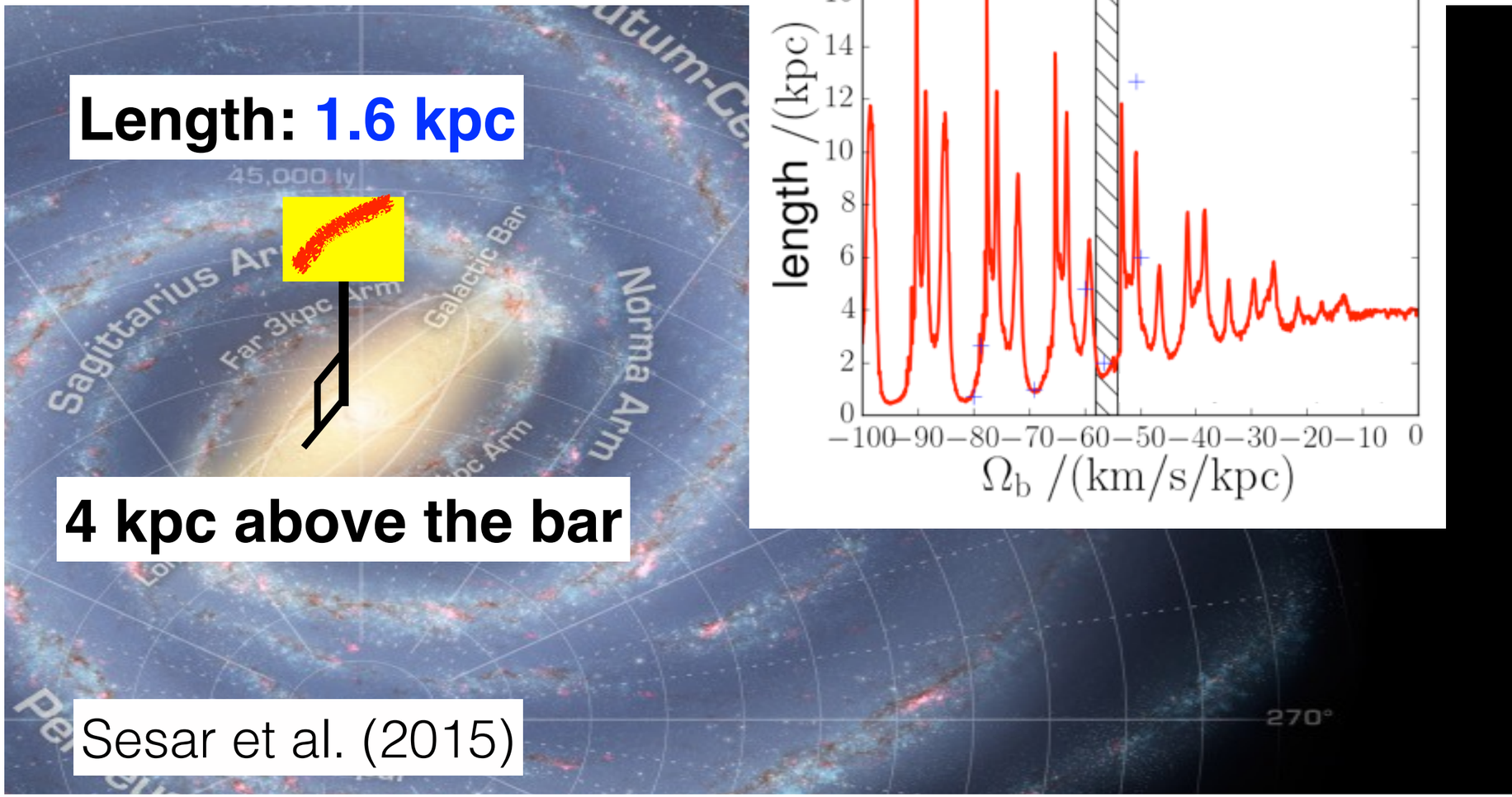
} [Fe/H]-dependence is NOT informative (**chaotic orbits**).

Independent measurement for $\Omega_{\rm bar}$

Ophiuchus stream



Bernard et al. (2014)



Sesar et al. (2015)

Hattori, Erkal, Sanders (2016)