Stellar Motion around co-rotating spiral arm: Gaia Mock Data

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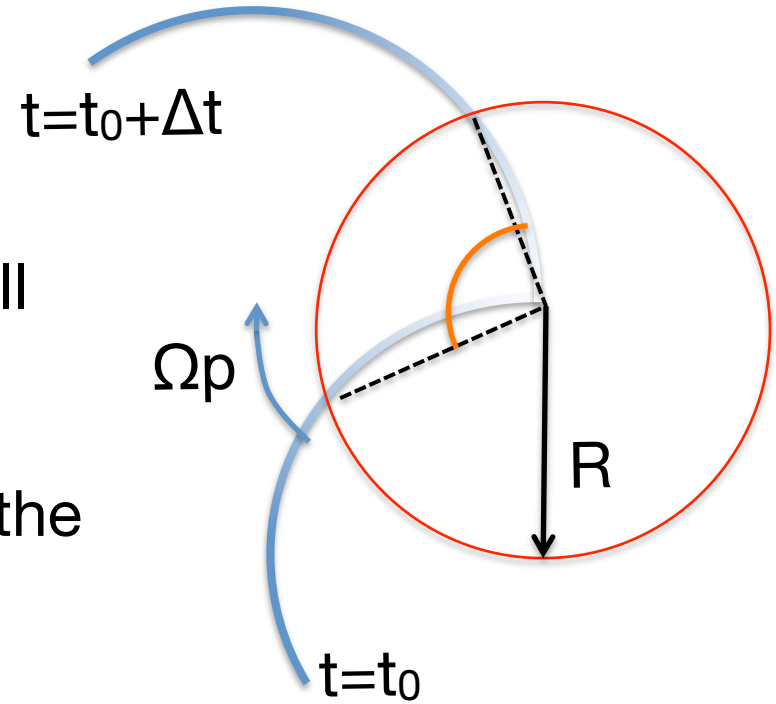
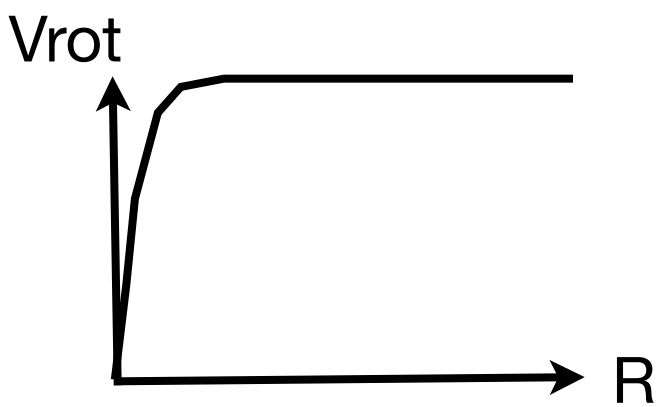
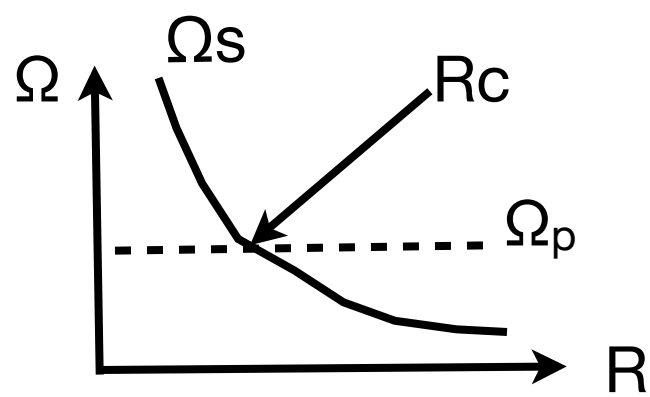
Lin-Shu-type classic density wave-scenario

- Spiral arms are a permanent feature.
- constant pattern speed, Ωp, at all radii
- star rotating faster (slower) than the pattern at R less (more) than co-rotation radius, Rc.

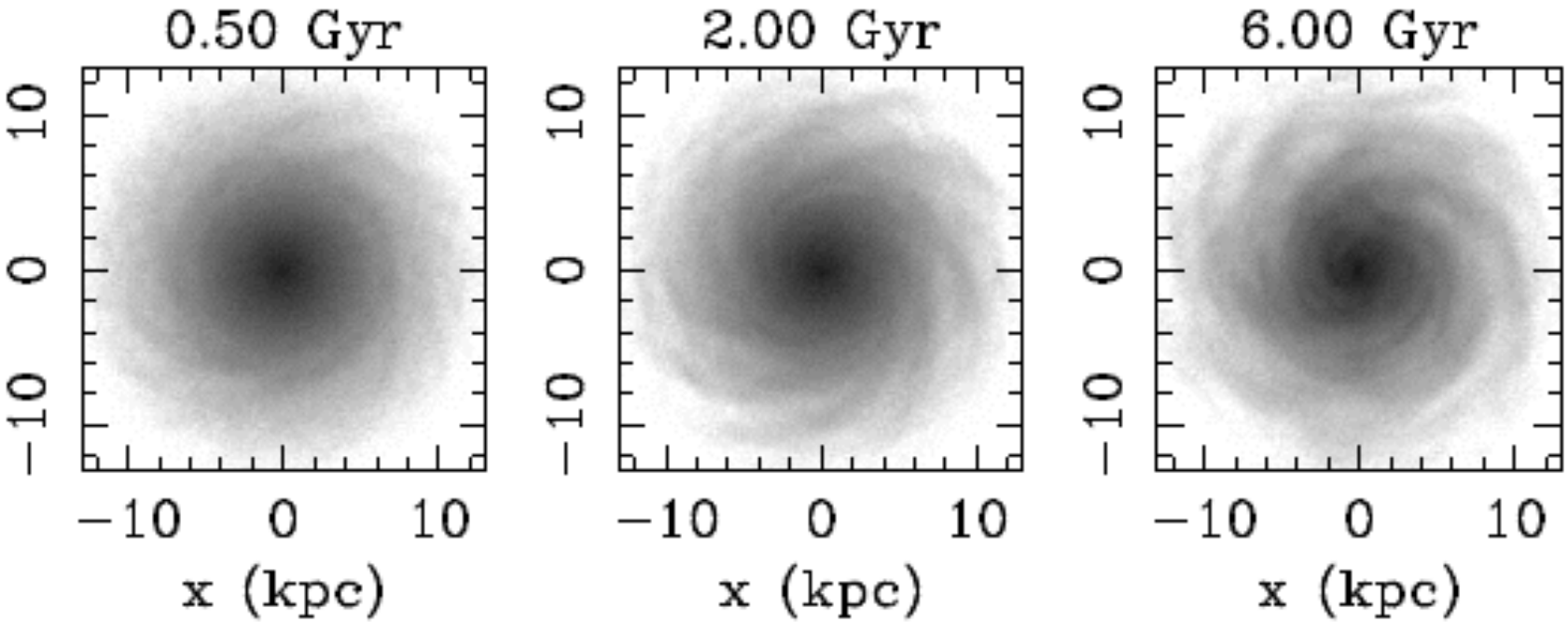






Tough to make long-lived spiral arm *features* in self-consistent numerical simulations with self-gravity...
Spirals are recurrent and transient.

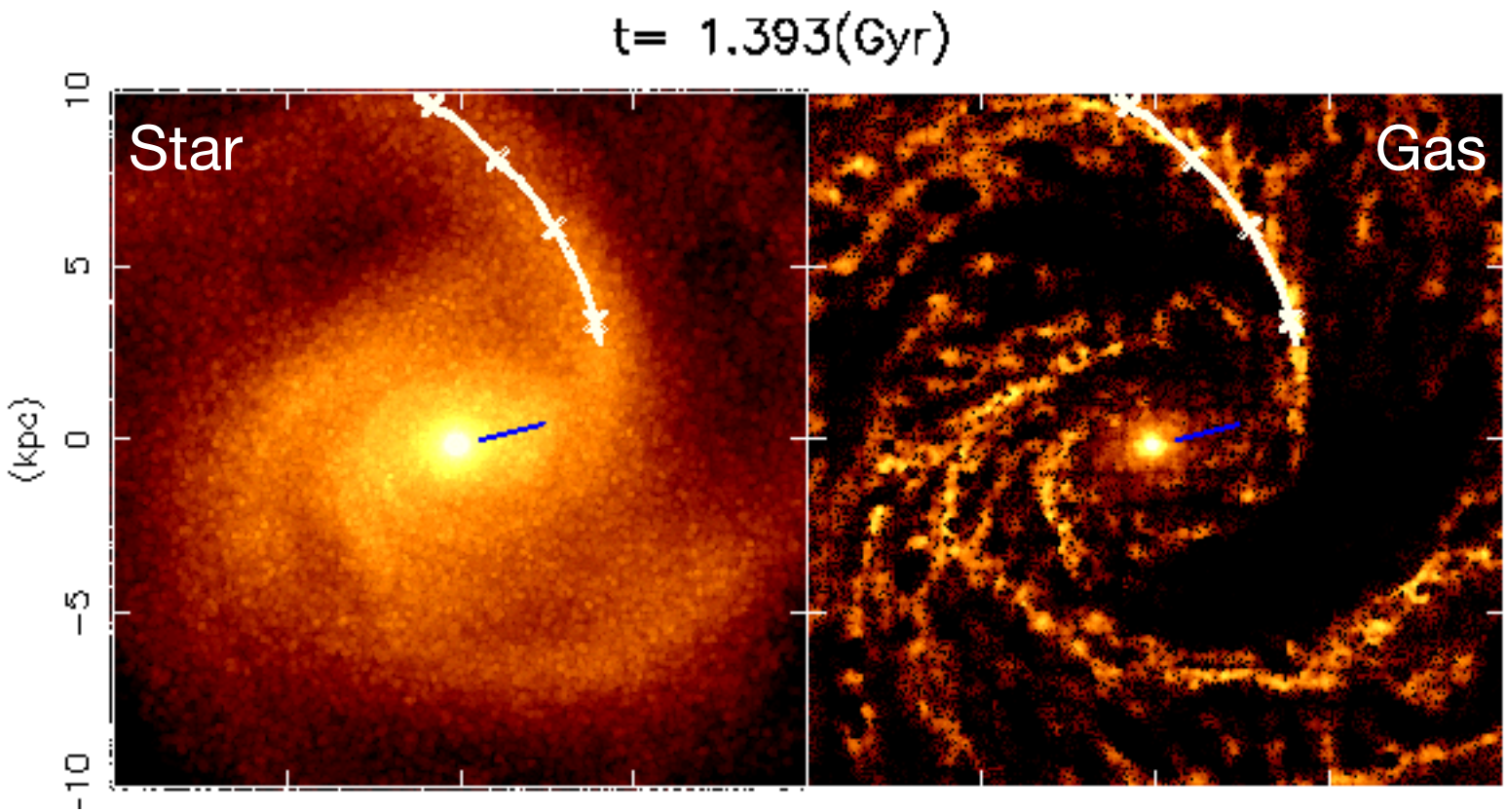
(e.g. Sellwood 2010, Fujii et al. 2010, Quillen et al. 2011, Wada et al. 2011, Grand, Kawata, Cropper 2012a,b, D'Onghia et al. 2013, Baba et al. 2013, Roca-Fàbrega et al. 2013)



9M N-body simulations (Fujii et al. 2010)

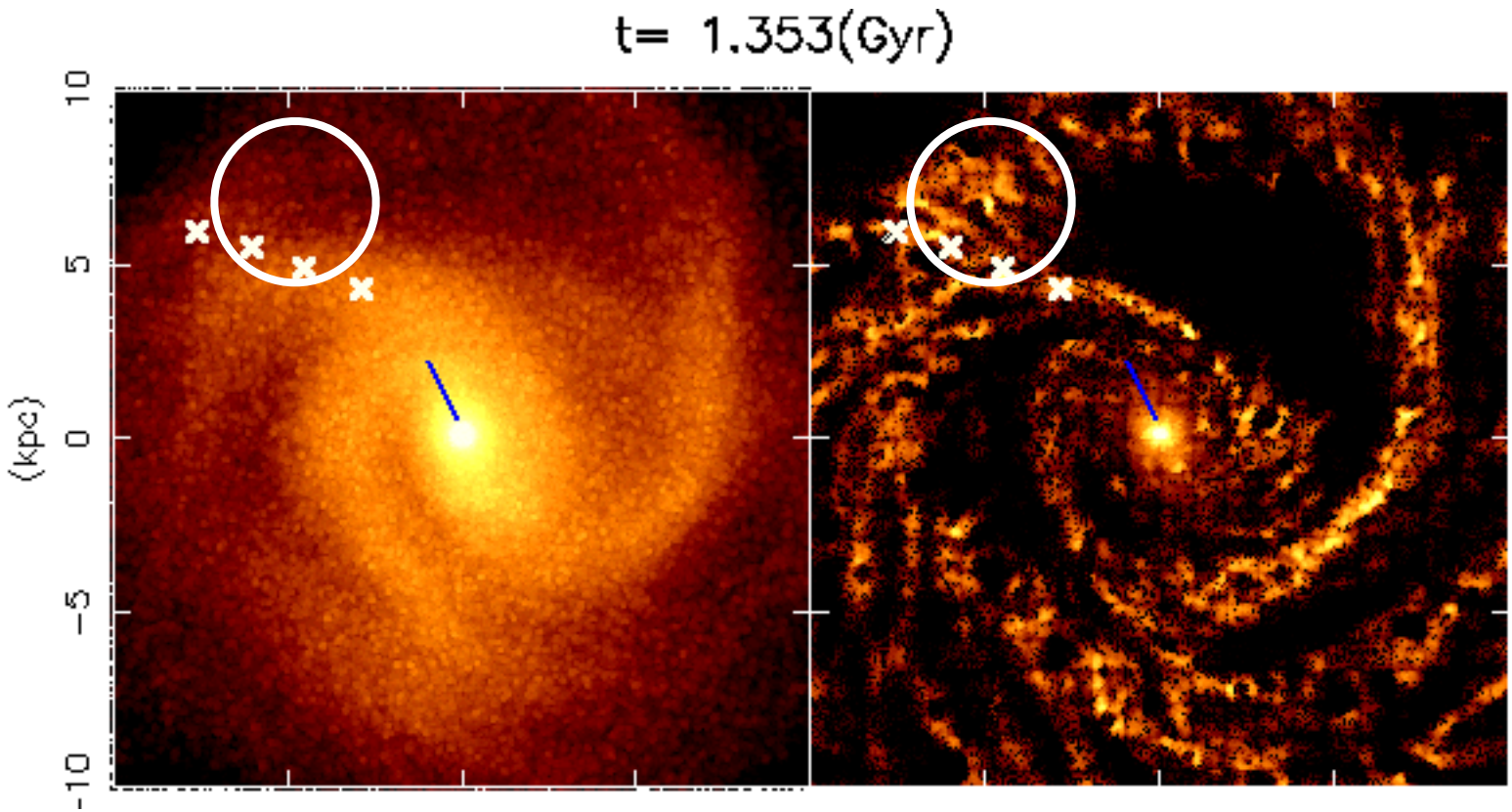
Milky Way sized disc simulation with original N-body/SPH code, GCD+ (since 1998, Kawata et al. 2013)

N~2.4x10^6 disk gas and star particles, m_p=2.5x10^4 M⊙ with a fixed NFW DM potential.



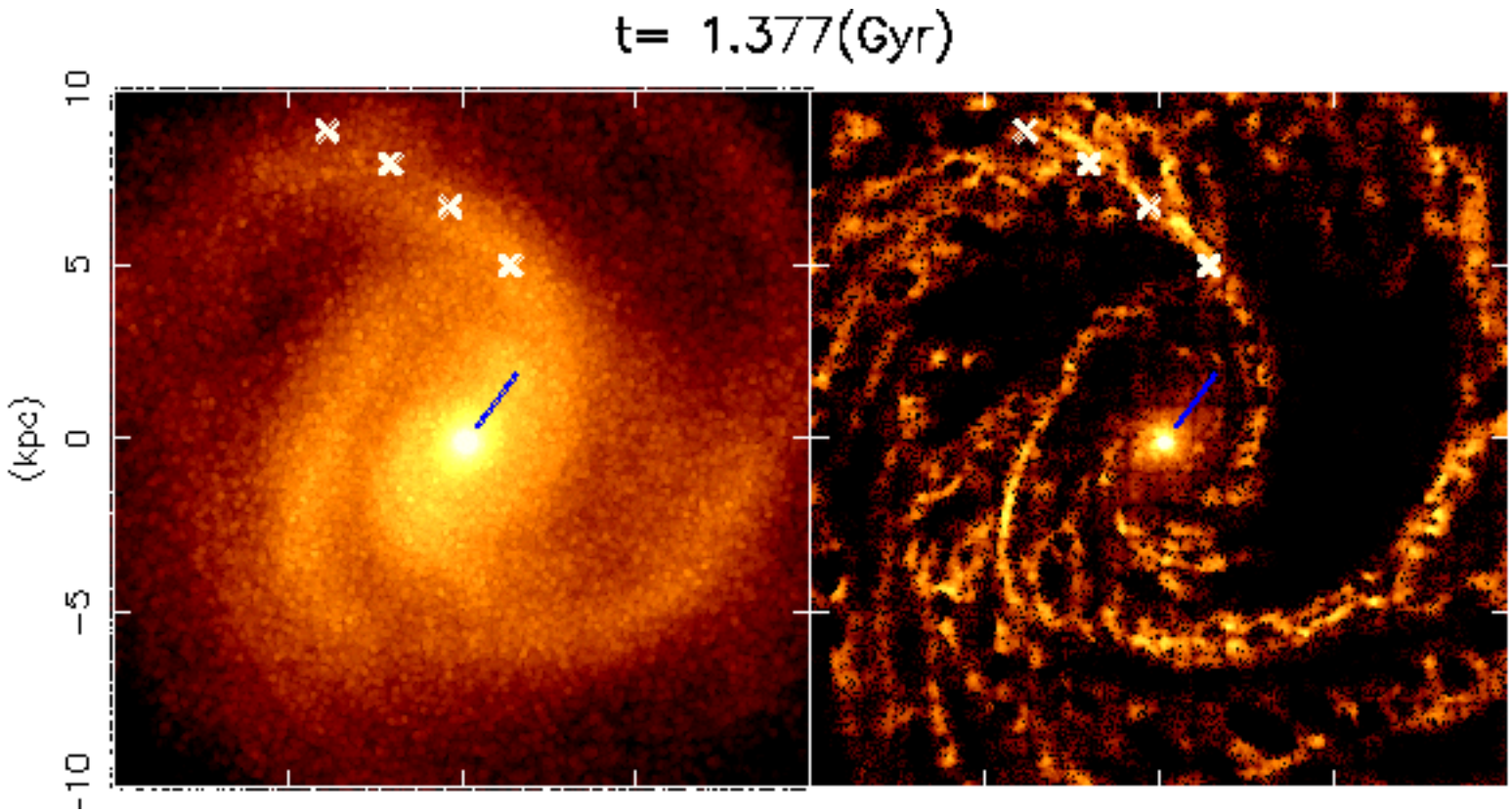
Life of a spiral arm

Grand, Kawata, Cropper (2012a,b)

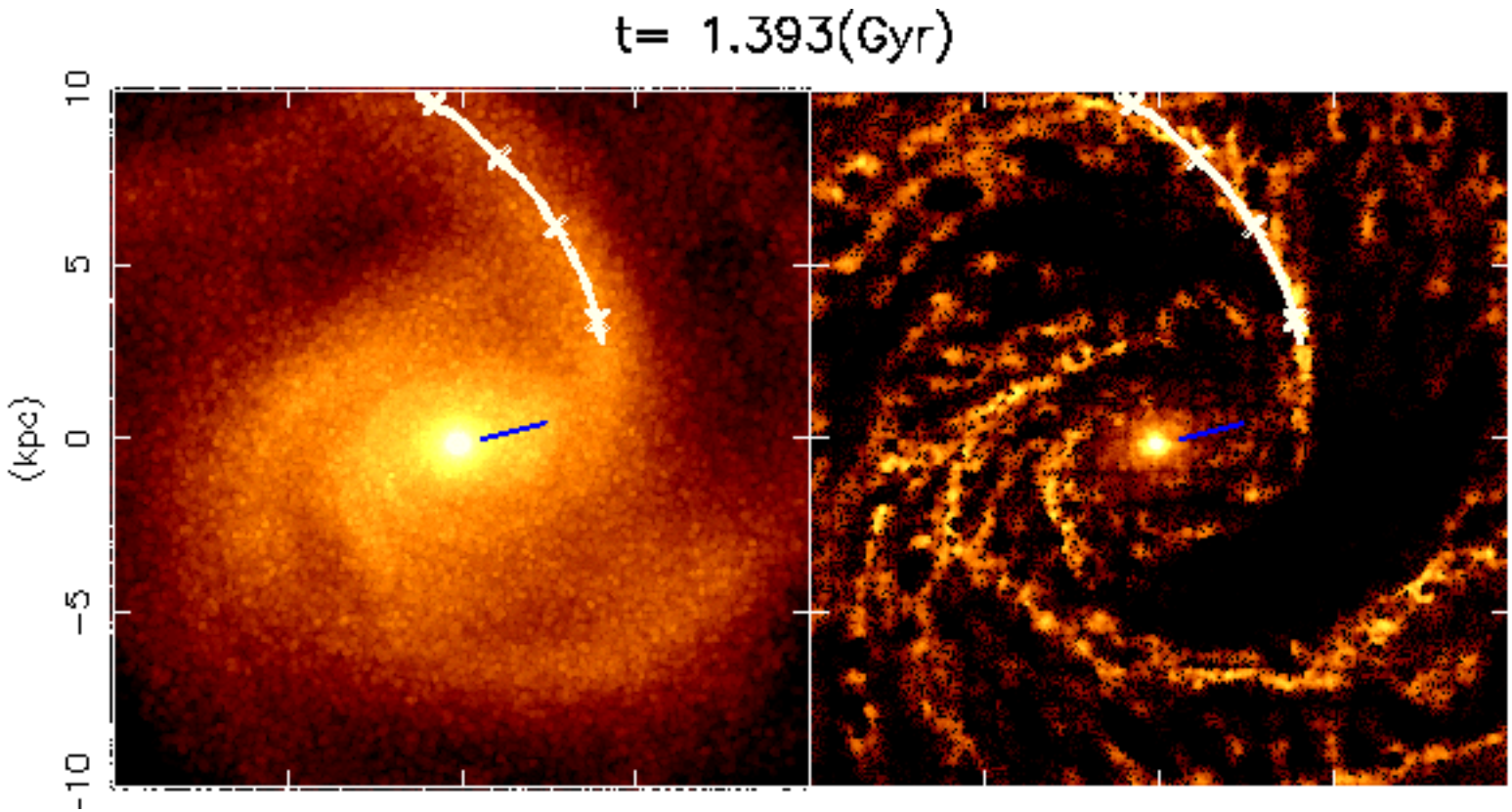


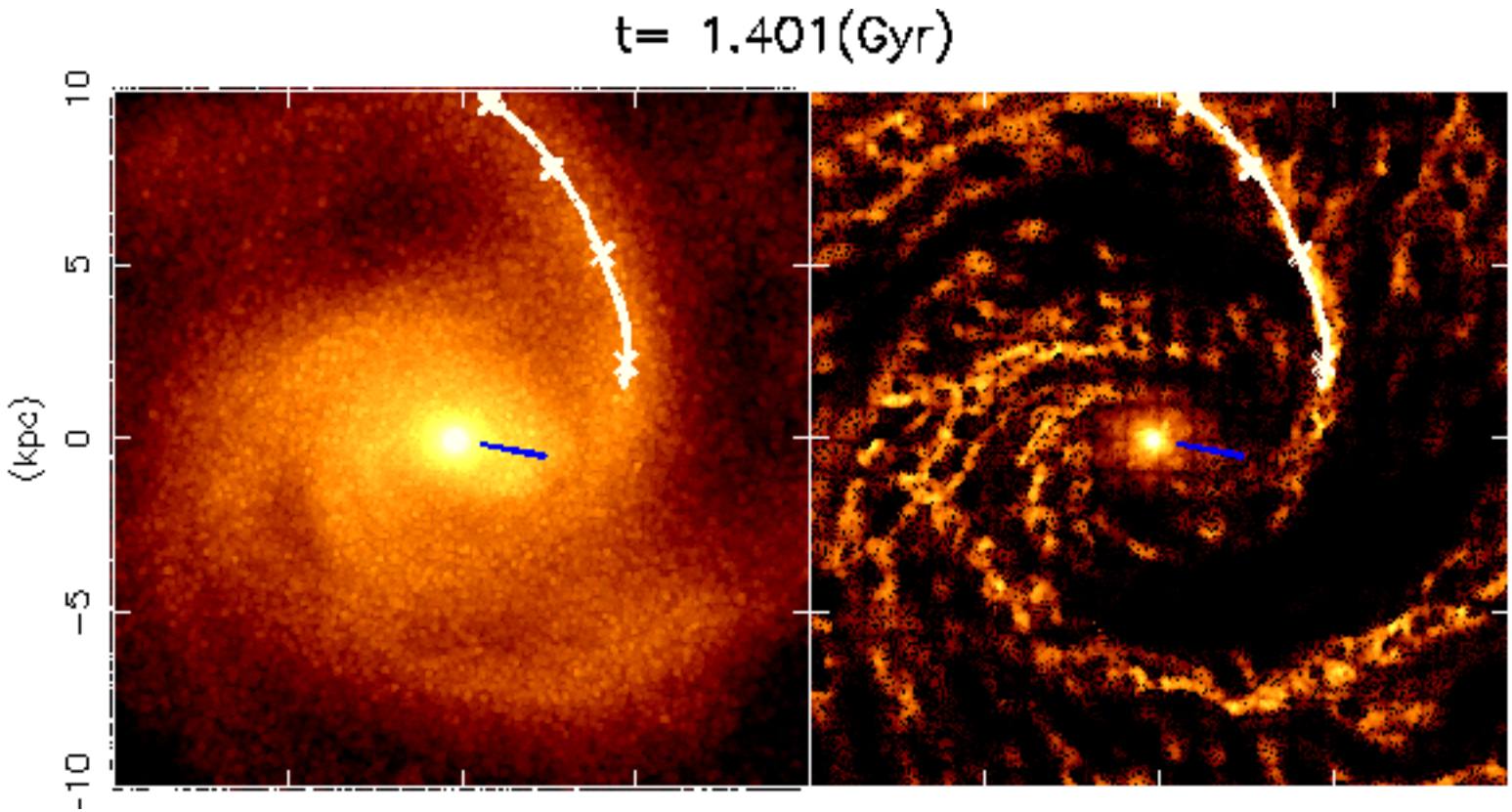
40 Myr ago

Arm starts forming due to collision of two winded arms?



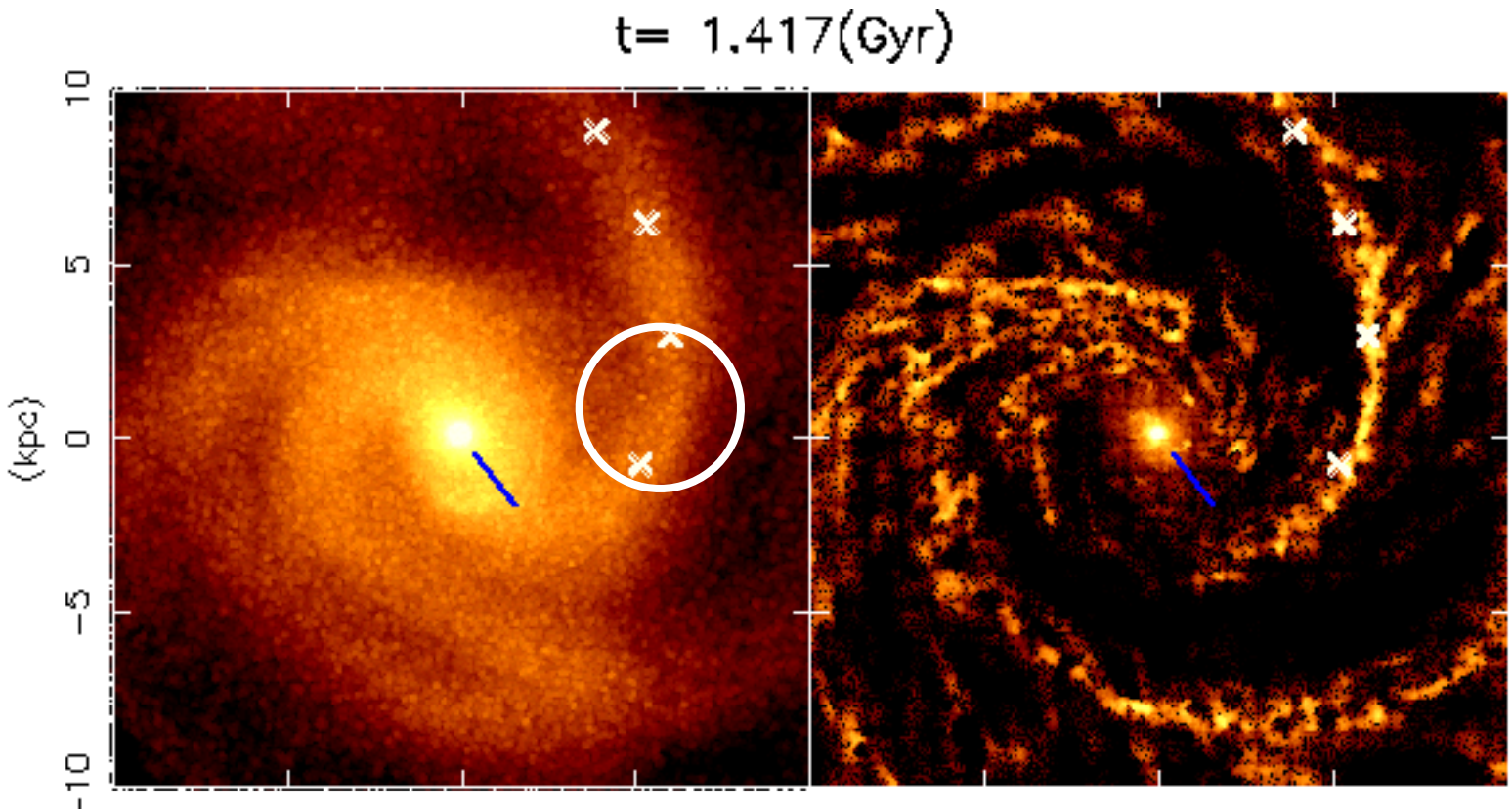
20 Myr ago


t= 1.393(Gyr)
10
5
0
−5
−10
(kpc)

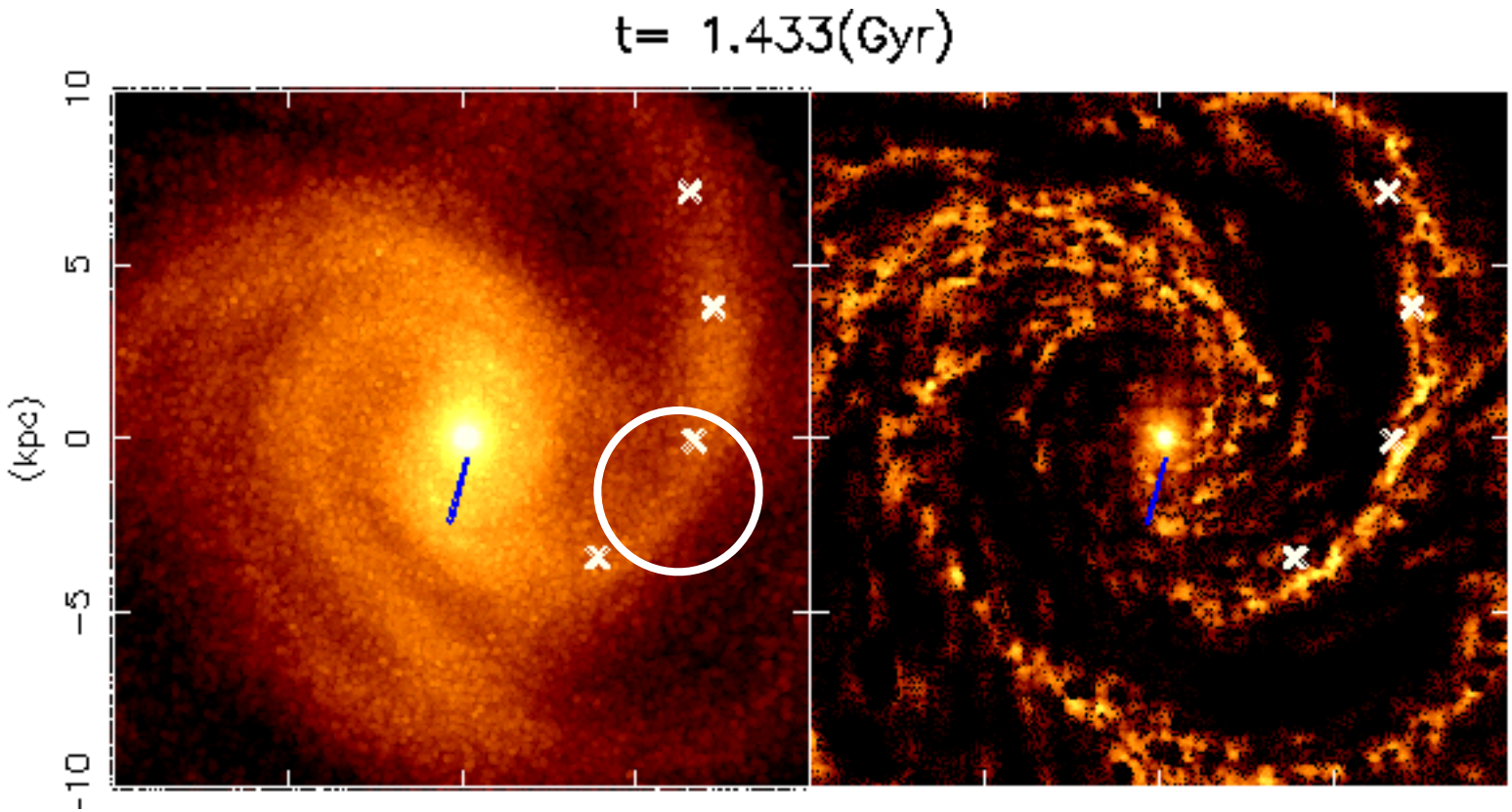


8 Myr after

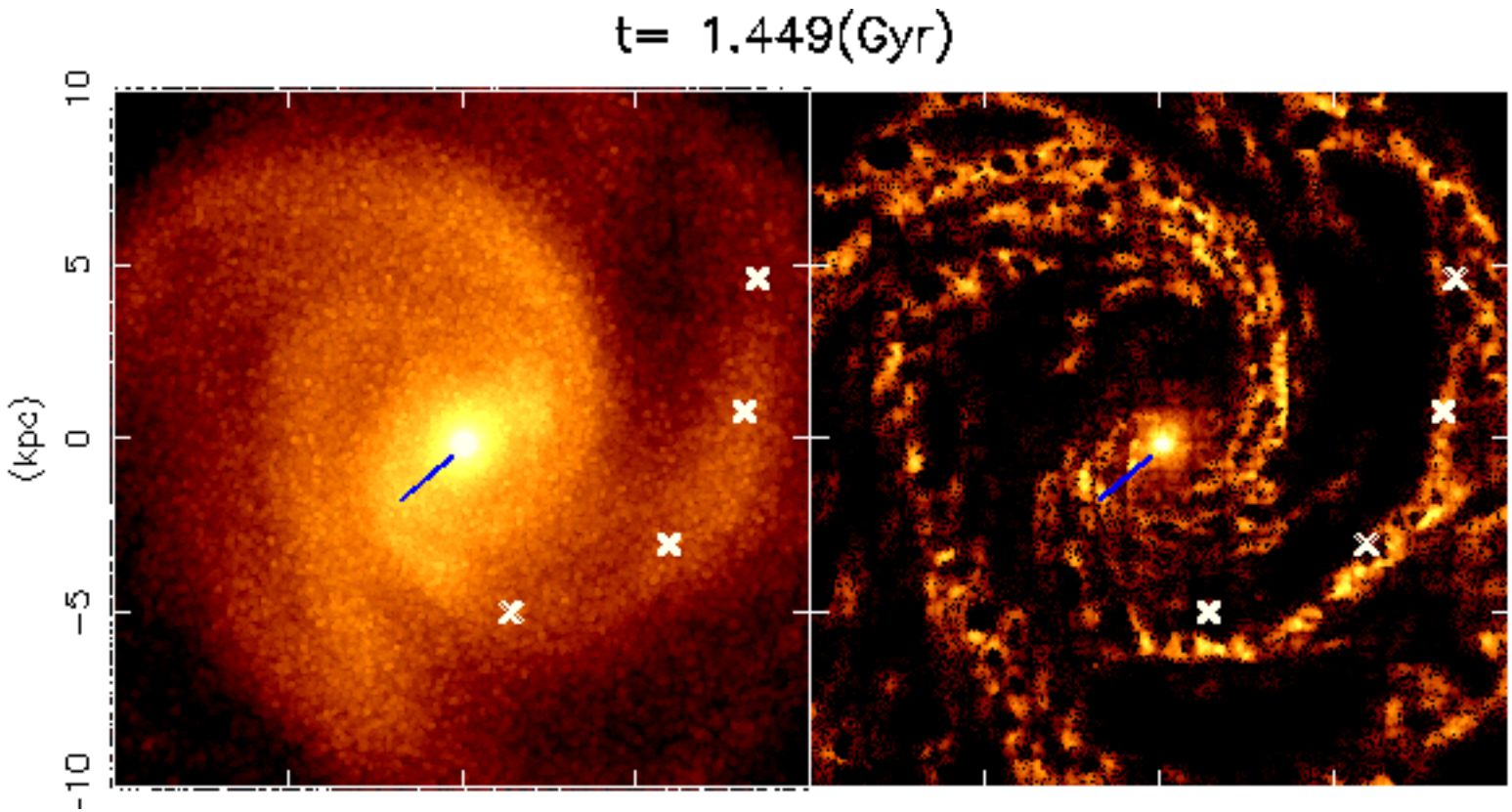
Rotating with similar speed to the circular speed of the stars and winding



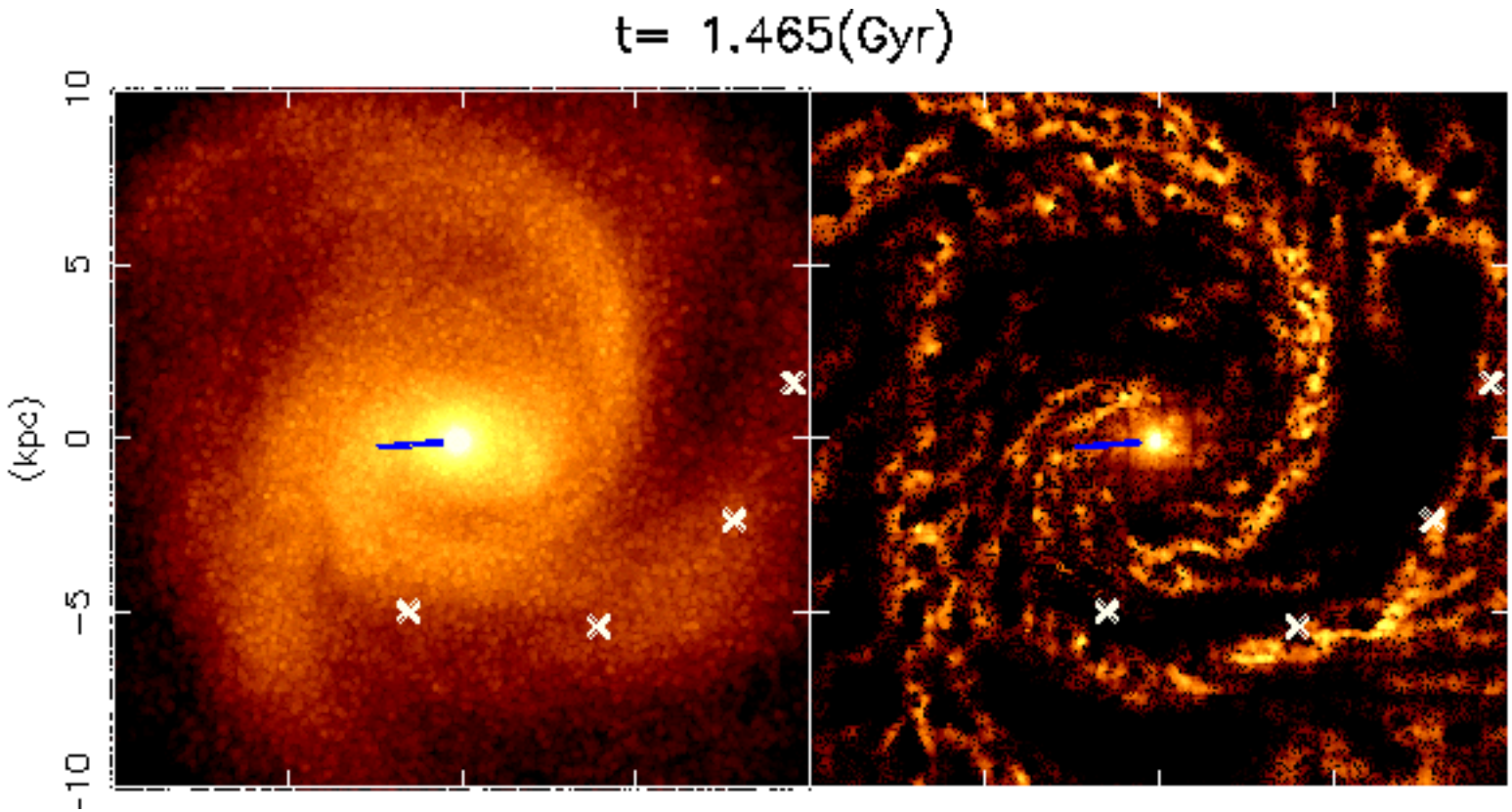
24 Myr after
Arm starts breaking



40 Myr after



56 Myr after

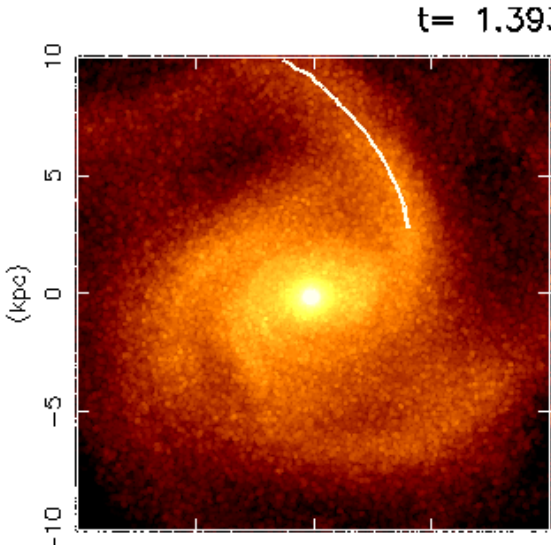


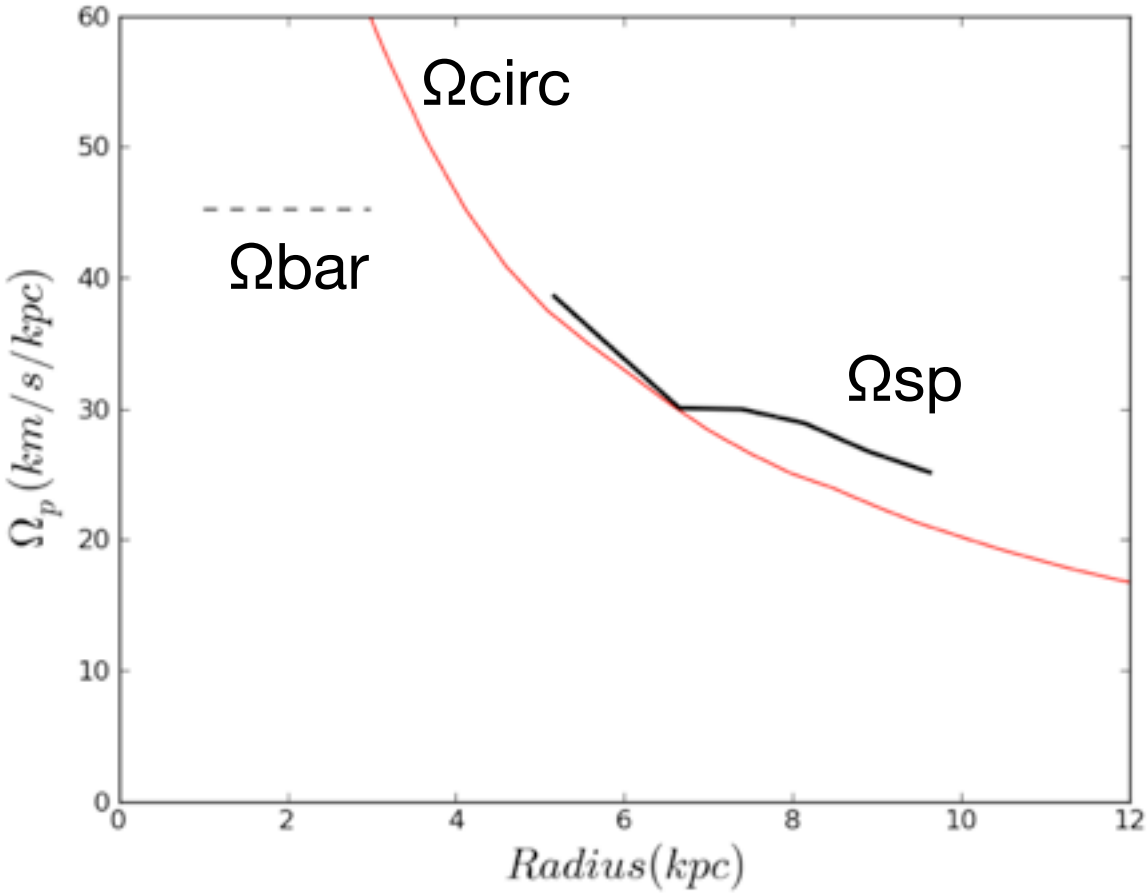
72 Myr after
arm winding and disrupted
~110 Myr lifetime

Pattern speed of the spiral arms

decreasing with radius and similar to the circular speed.

~ co-rotating at ever radii

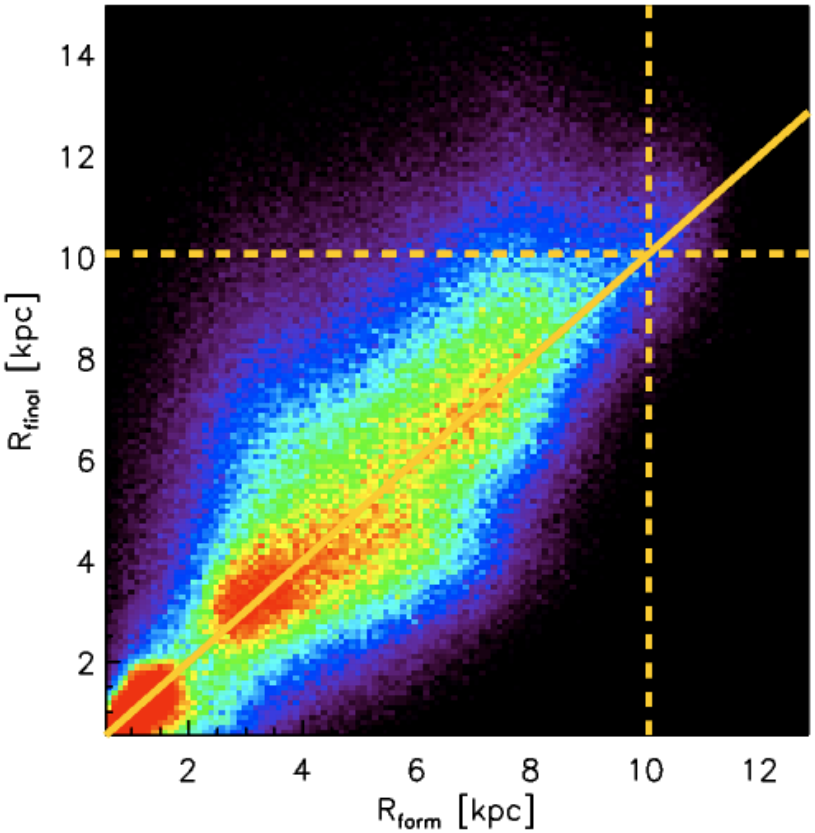




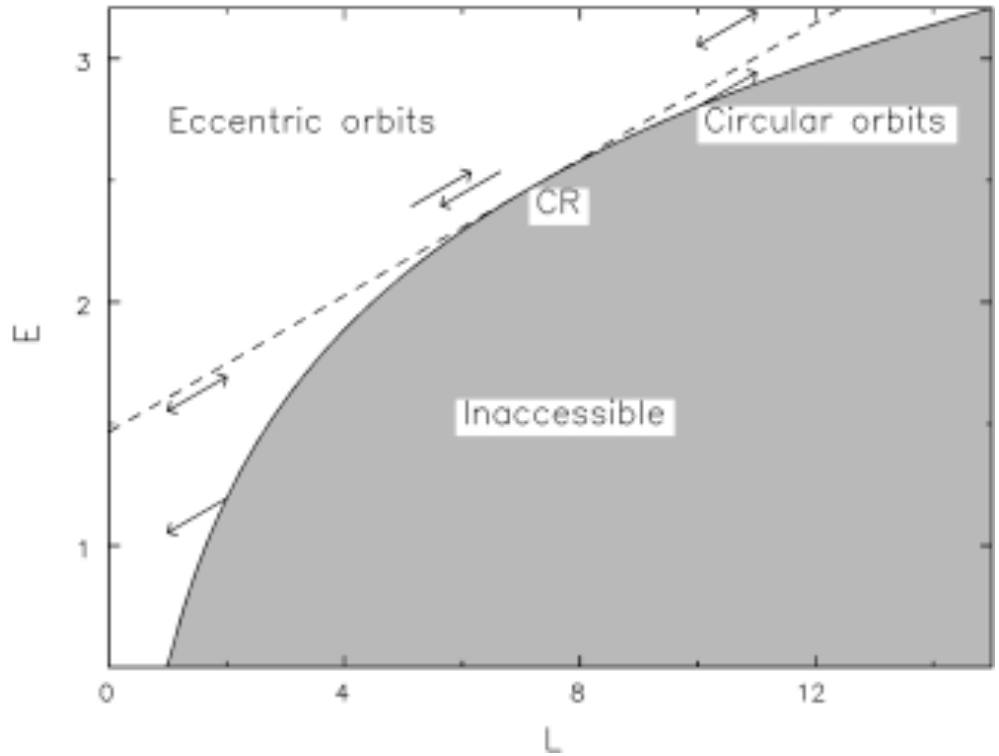
Grand, Kawata, Cropper (2012b)

Radial migration (churning) due to transient spiral arms

(e.g. Sellwood & Binney 2002; Roškar et al. 2008a,b; Sánchez-Blázquez et al. 2009; Minchev et al. 2010, Brunetti et al. 2011; Kubryk et al. 2013)



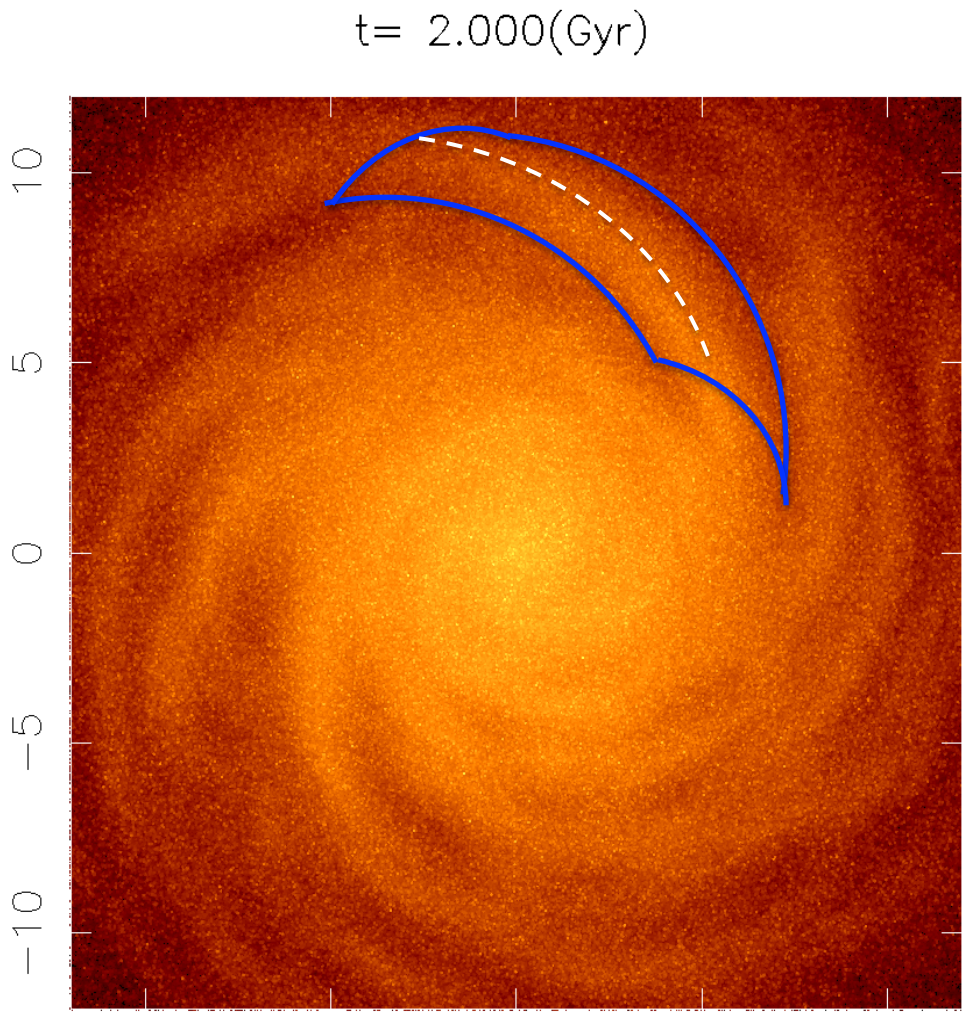
Rošker et al. (2008a,b)



Sellwood & Binney (2002)

Impact on star particle motion

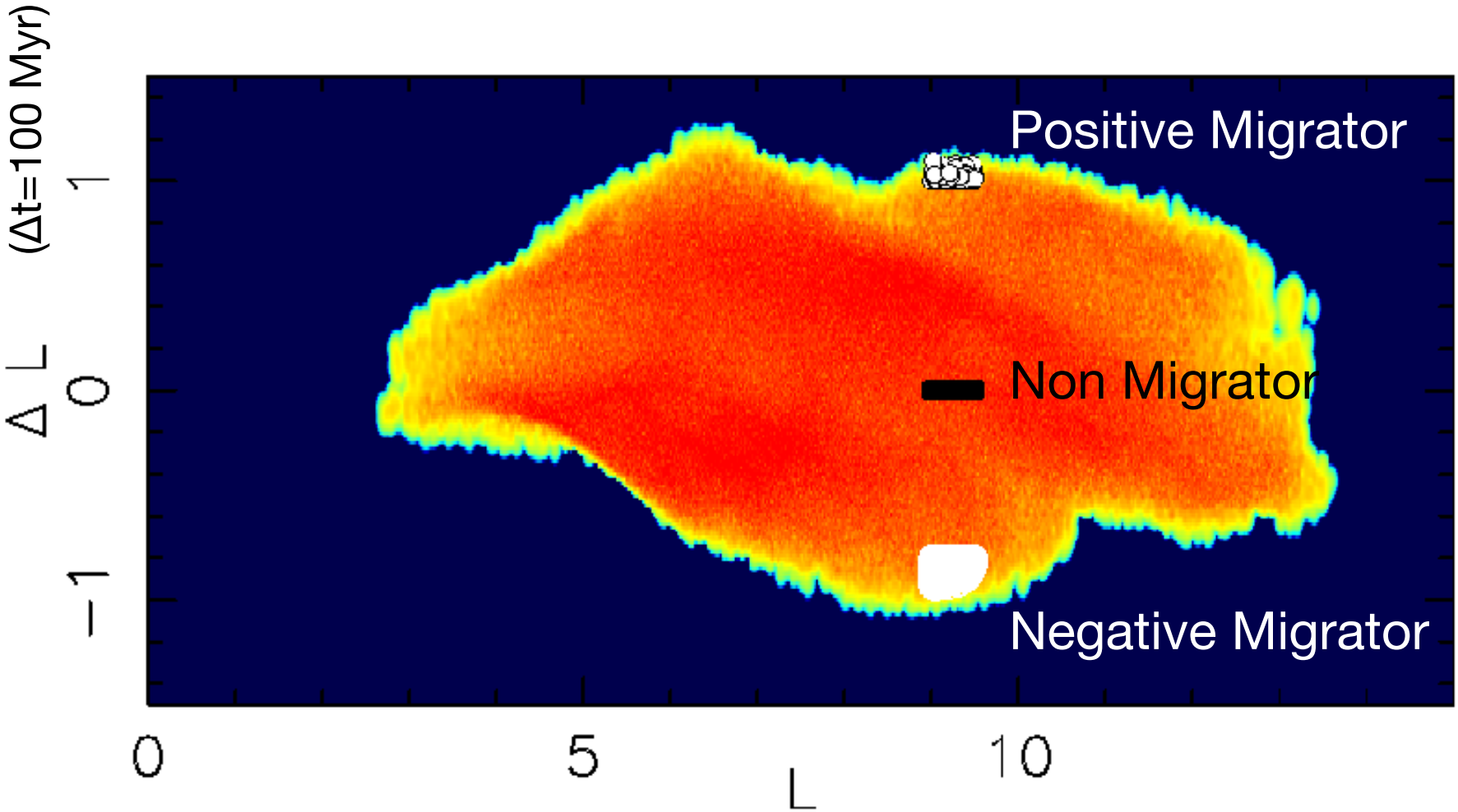
(Grand, Kawata, Cropper 2012a,b, **2014**)

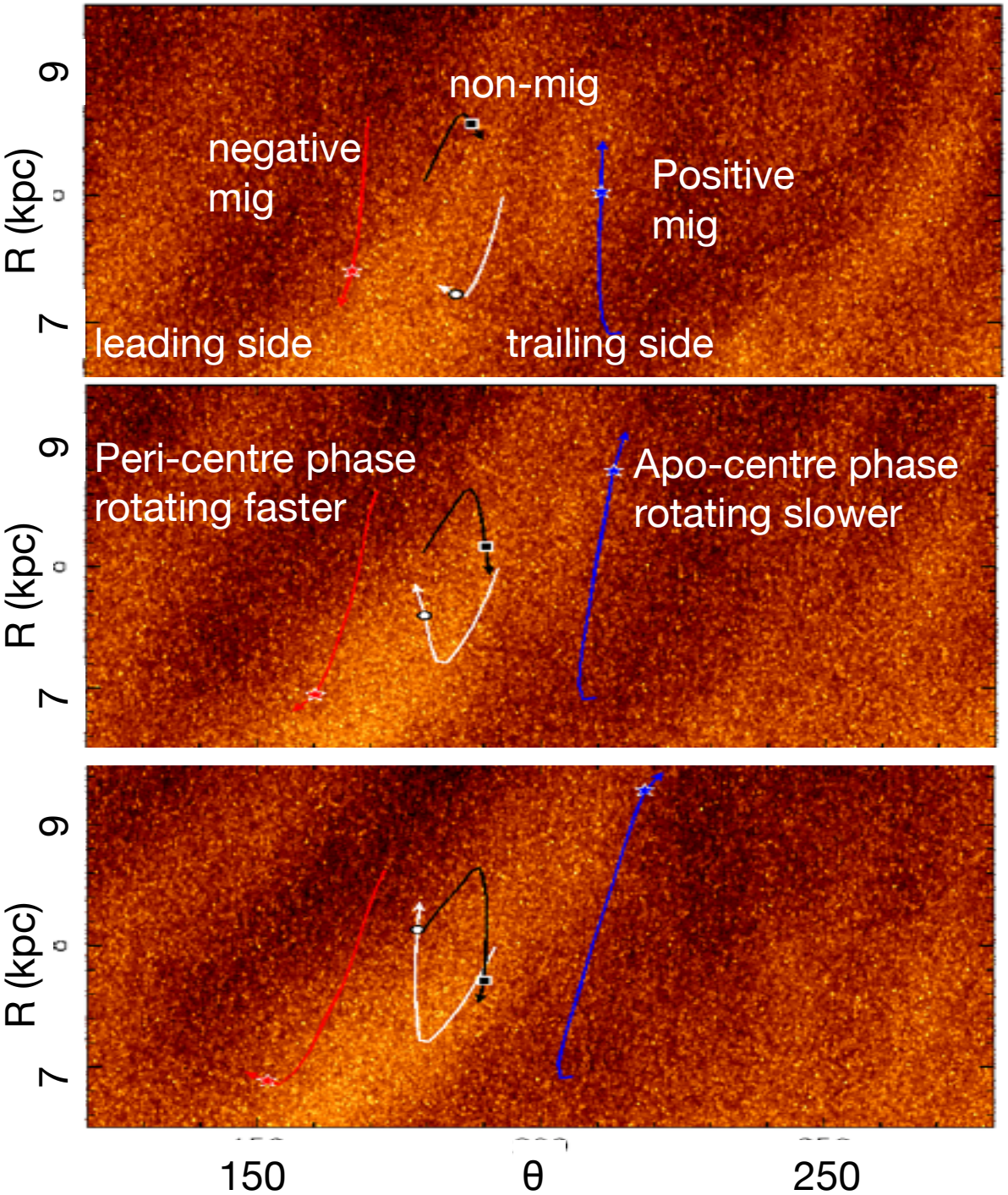


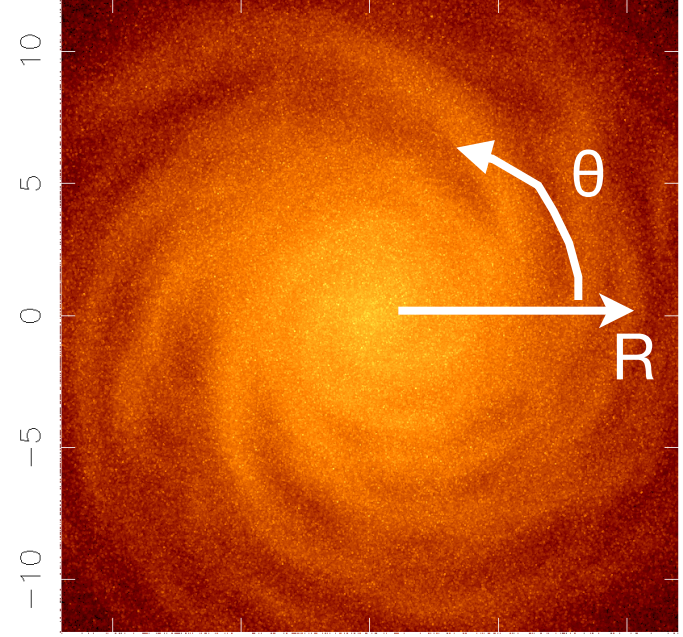
$N=10^7$
pure N-body
disk particles

Co-rotating and winding, and the lifetime of ~100 Myr

Radial Migration occurs at every L, i.e. R even within 100 Myr



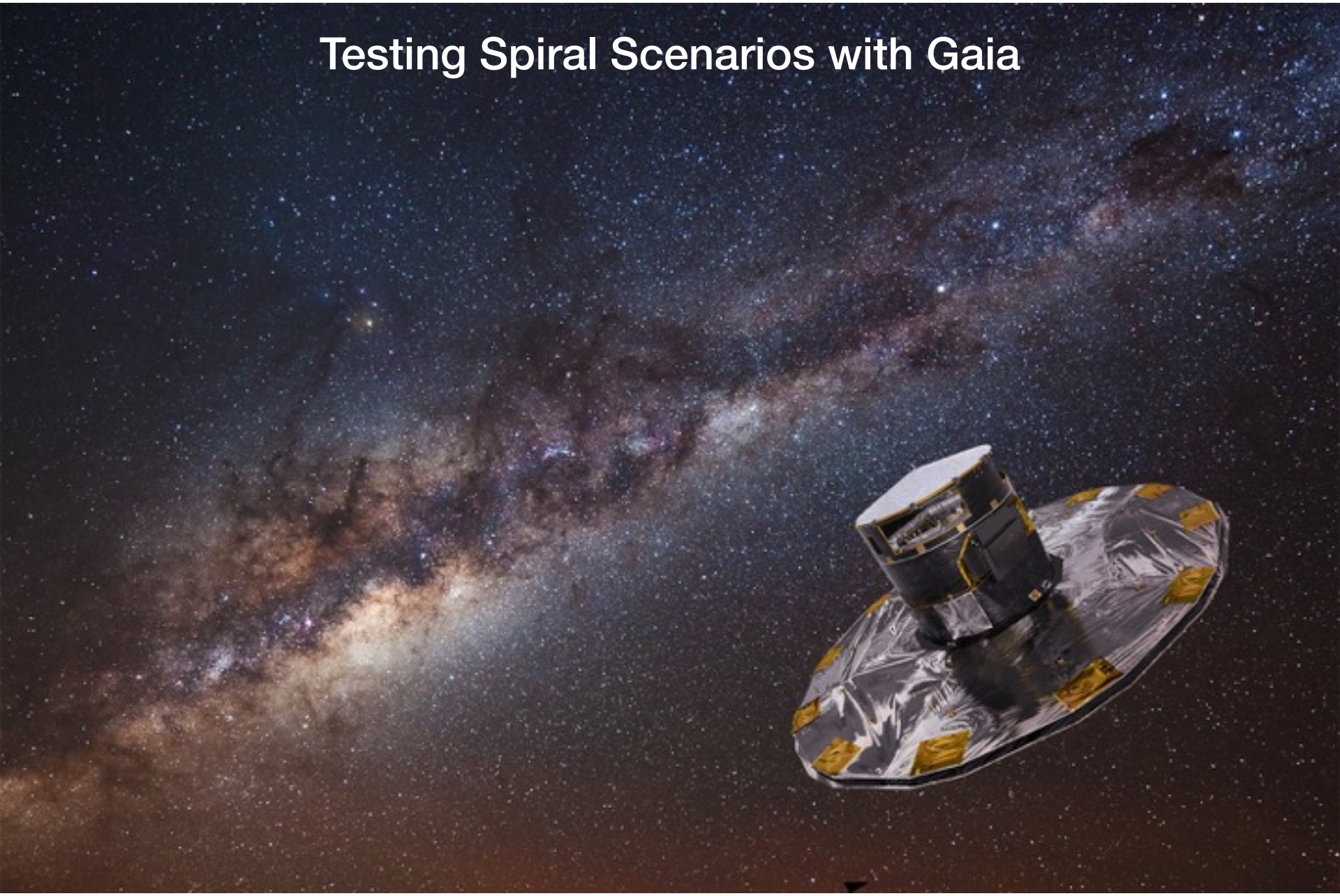




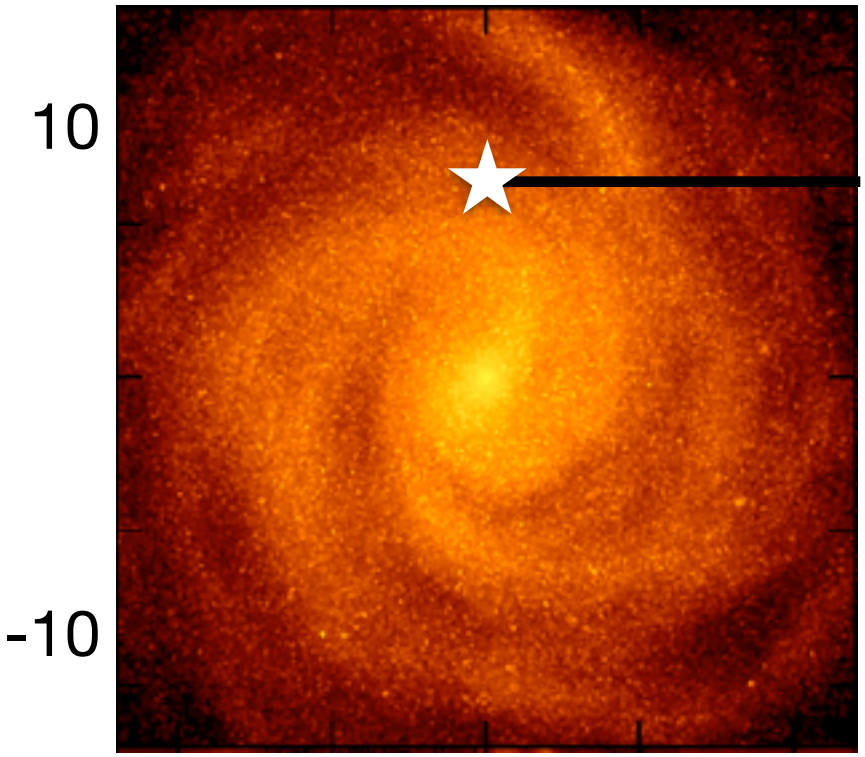
Positive (negative) migrators have Vrot < Vcirc (Vrot>Vcirc), stay behind (on the front of) the spiral arm, and keep gaining (losing) Ang.Mom. till the arm disappears.

Non-migrators orbit the spiral arm, continuously moving from one side to the other, and no net-Ang.Mom. change.

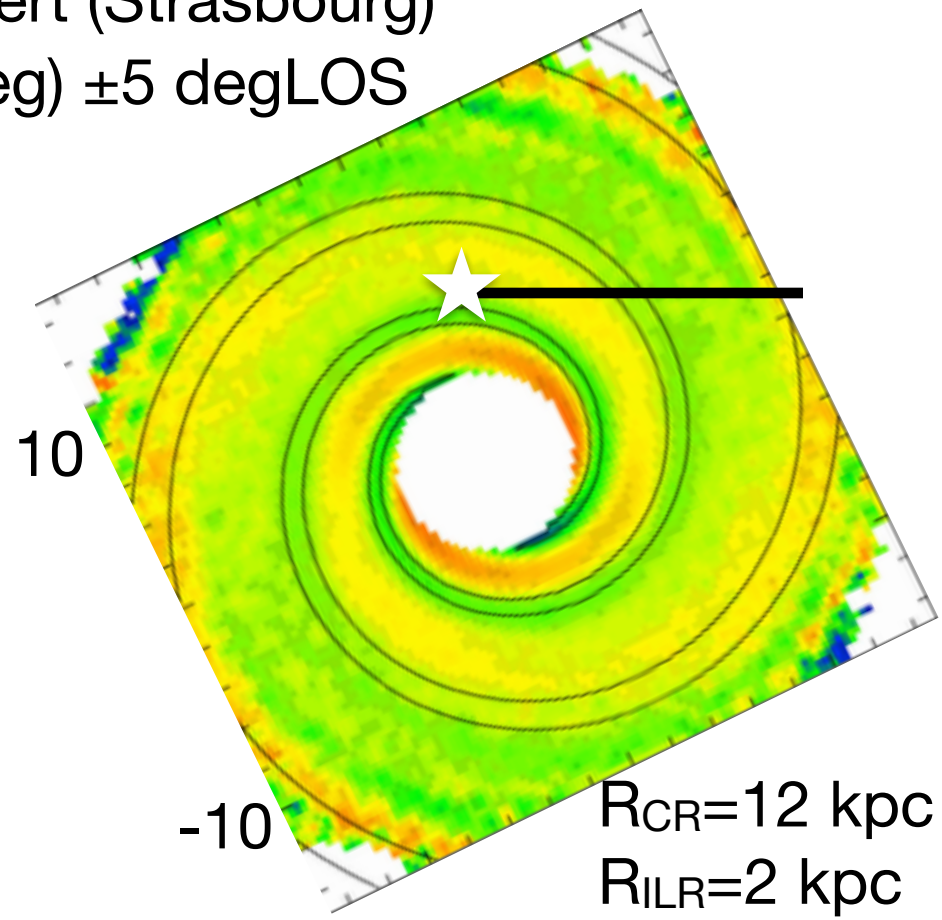
Testing Spiral Scenarios with Gaia



Stellar motion around the spiral arm
co-rotating vs. density-wave like spiral arm
w/Arnaud Siebert (Strasbourg)
(l,b)=(90,0 deg) ±5 degLOS

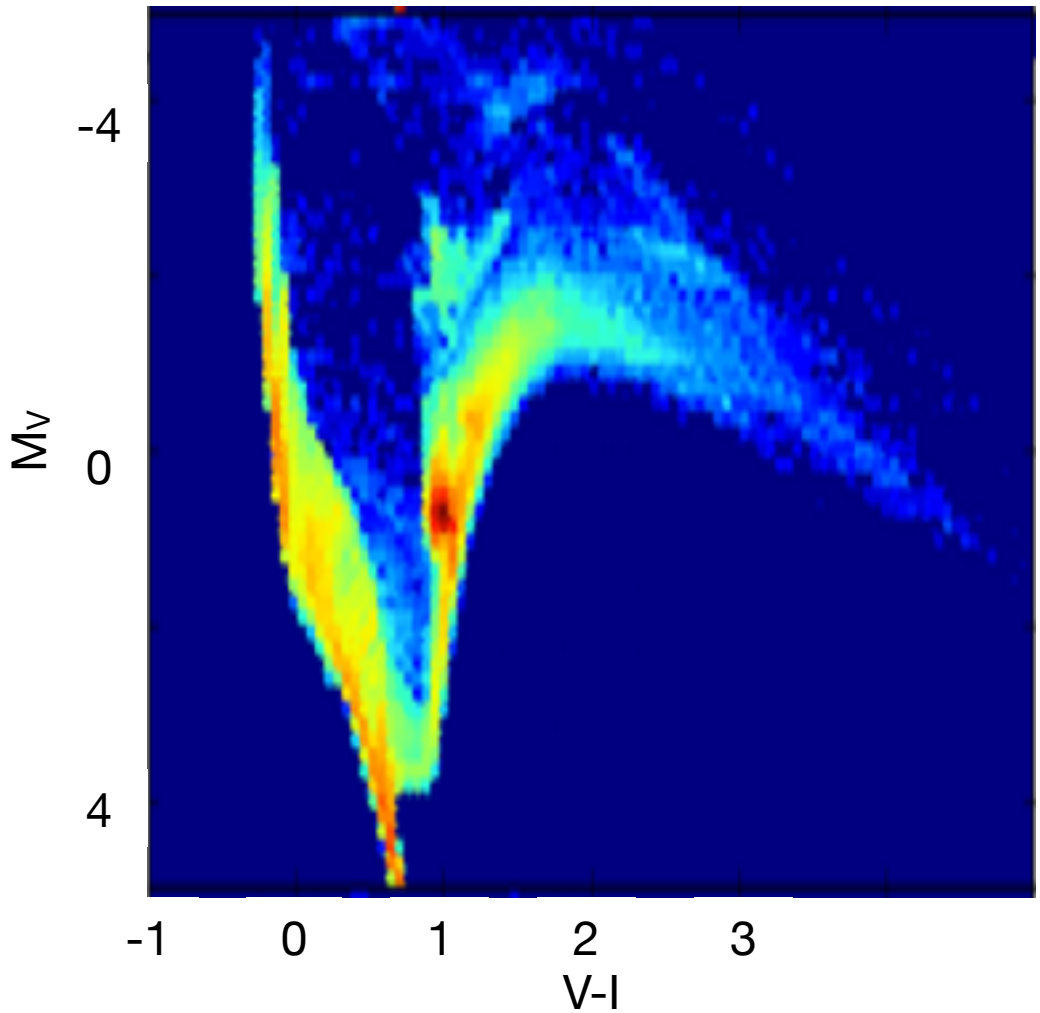


co-rotating spirals
in N-body simulation
(Kawata et al. 2014)



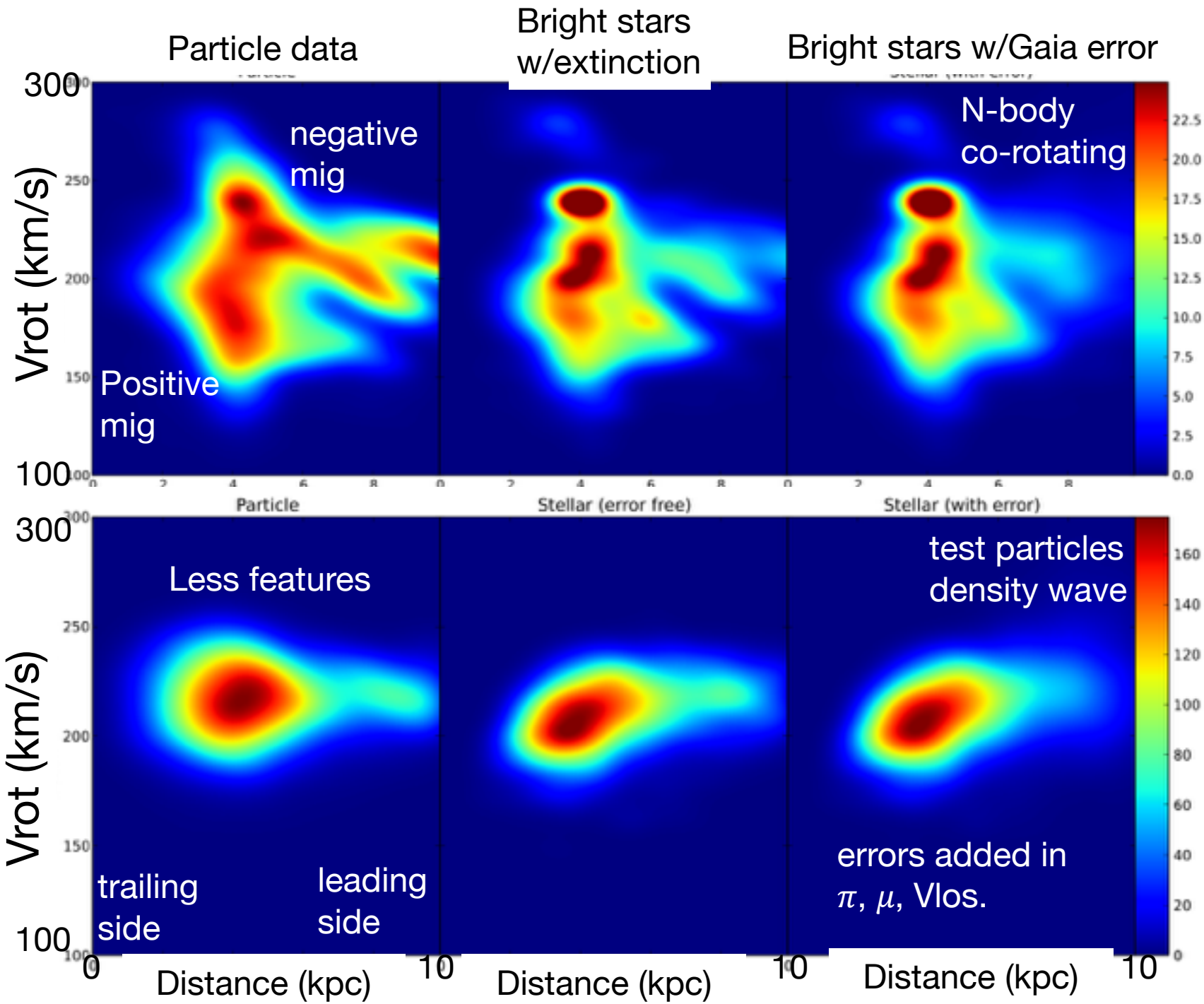
3D test particle simulations with
rigidly rotating spiral potentials
(Faure, Siebert, Famaey 2014)

SNAPDORAGONS (**Jason Hunt**):
Generating “stars” from star particles + 3D extinction
(borrowing the data from Galaxia, Sharma et al. 2011)
add Gaia post-launch errors (Romero-Gómez et al.)→ mock Gaia data.

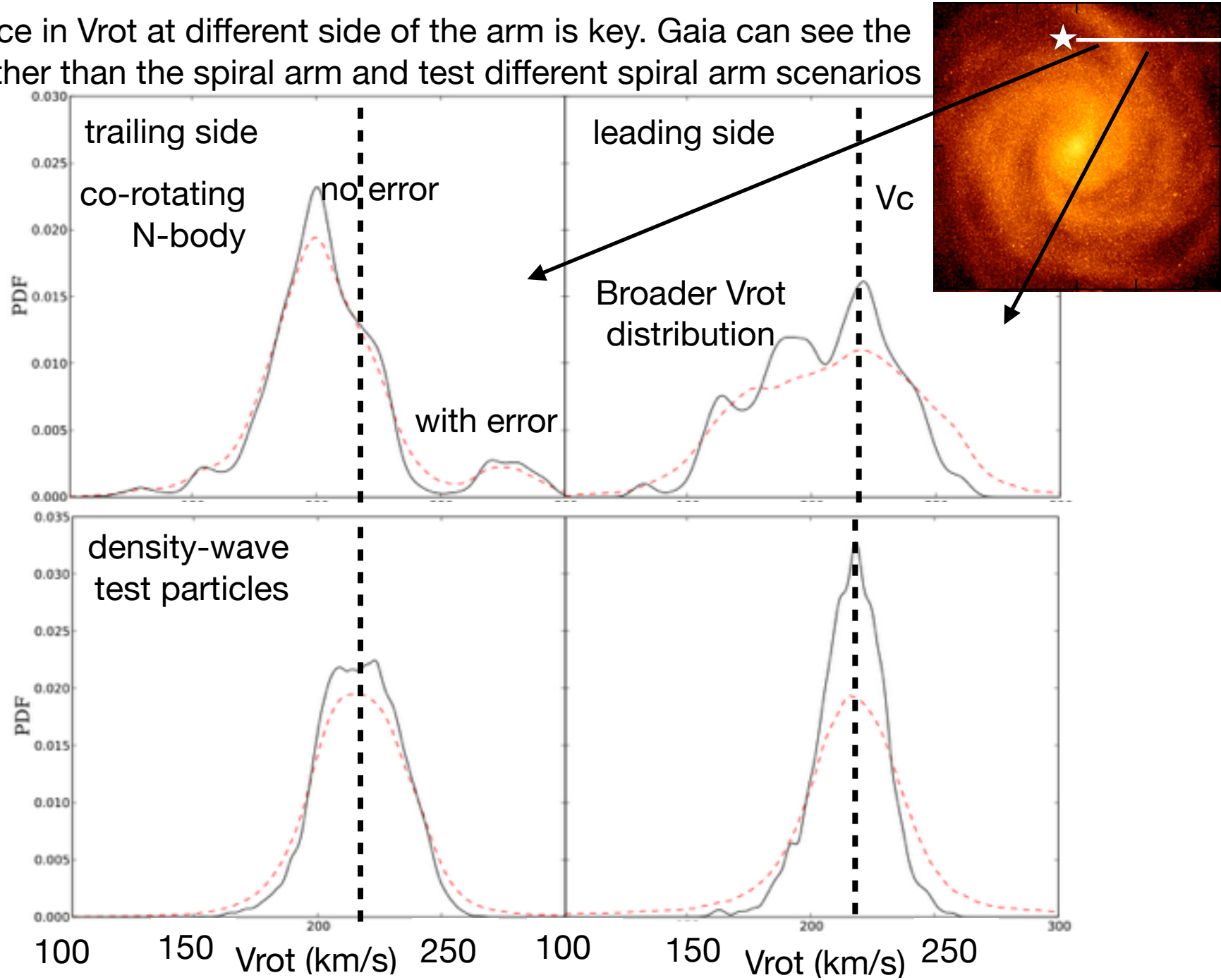


(l,b)=(90,0) deg sample

No smoothing is applied: clear connection particle ↔ stars.


Particle data
Bright stars w/extinction
Bright stars w/Gaia error
negative mig
Positive mig
N-body co-rotating
Vrot (km/s)
300
250
200
150
100
Particle
Stellar (error free)
Stellar (with error)
Less features
test particles density wave
trailing side
leading side
errors added in π, μ, Vlos.
Distance (kpc)
0
10

Difference in Vrot at different side of the arm is key. Gaia can see the stars further than the spiral arm and test different spiral arm scenarios

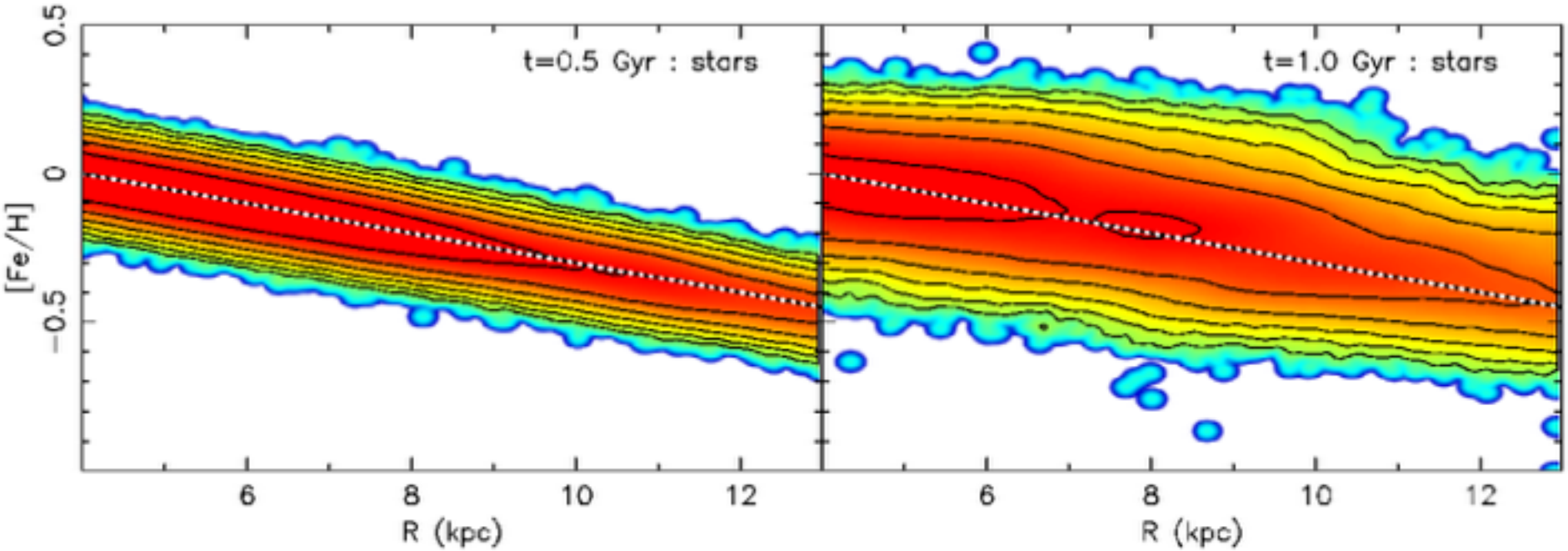


see also Roca-Fàbrega et al. (2014) : using vertex deviation

Summary

- Transient (~100 Myr) and recurrent spiral arms are ubiquitous in N-body simulations.
- The pattern speed is decreasing with radius. Similar to co-rotation.
- Radial migration can work at every radii in a short time scale, ~100 Myr due to the co-rotating spiral arms. Migrating particles stay on one side of spiral arm.
- Gaia can test the different spiral arm scenarios by measuring the motion around the spiral arms.
  → more prediction from different models with pattern speeds and pitch angles and etc..

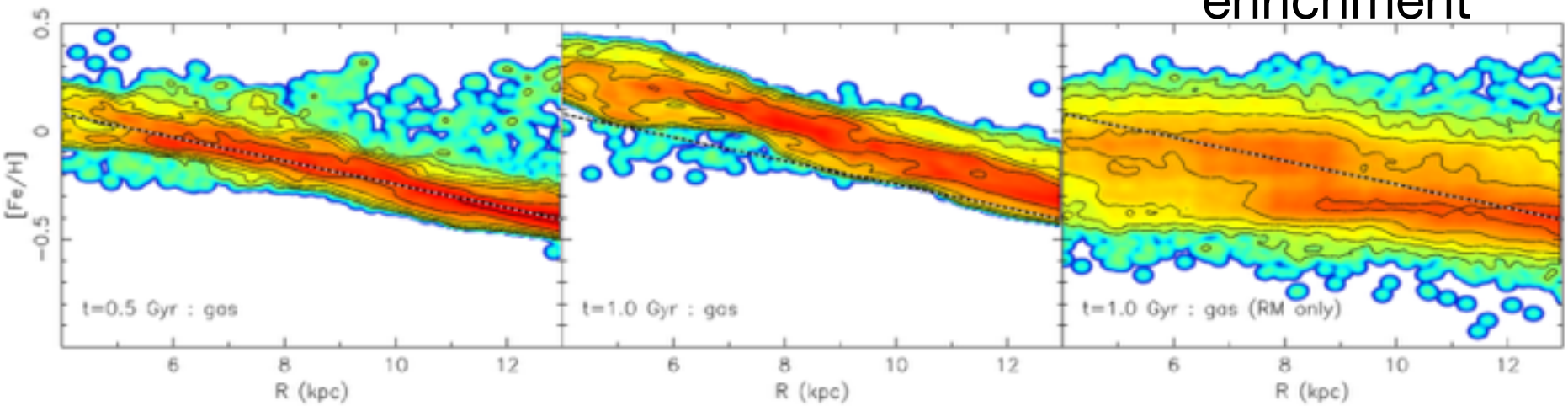
stellar metallicity gradient evolution



Grand, Kawata, Cropper (2014)

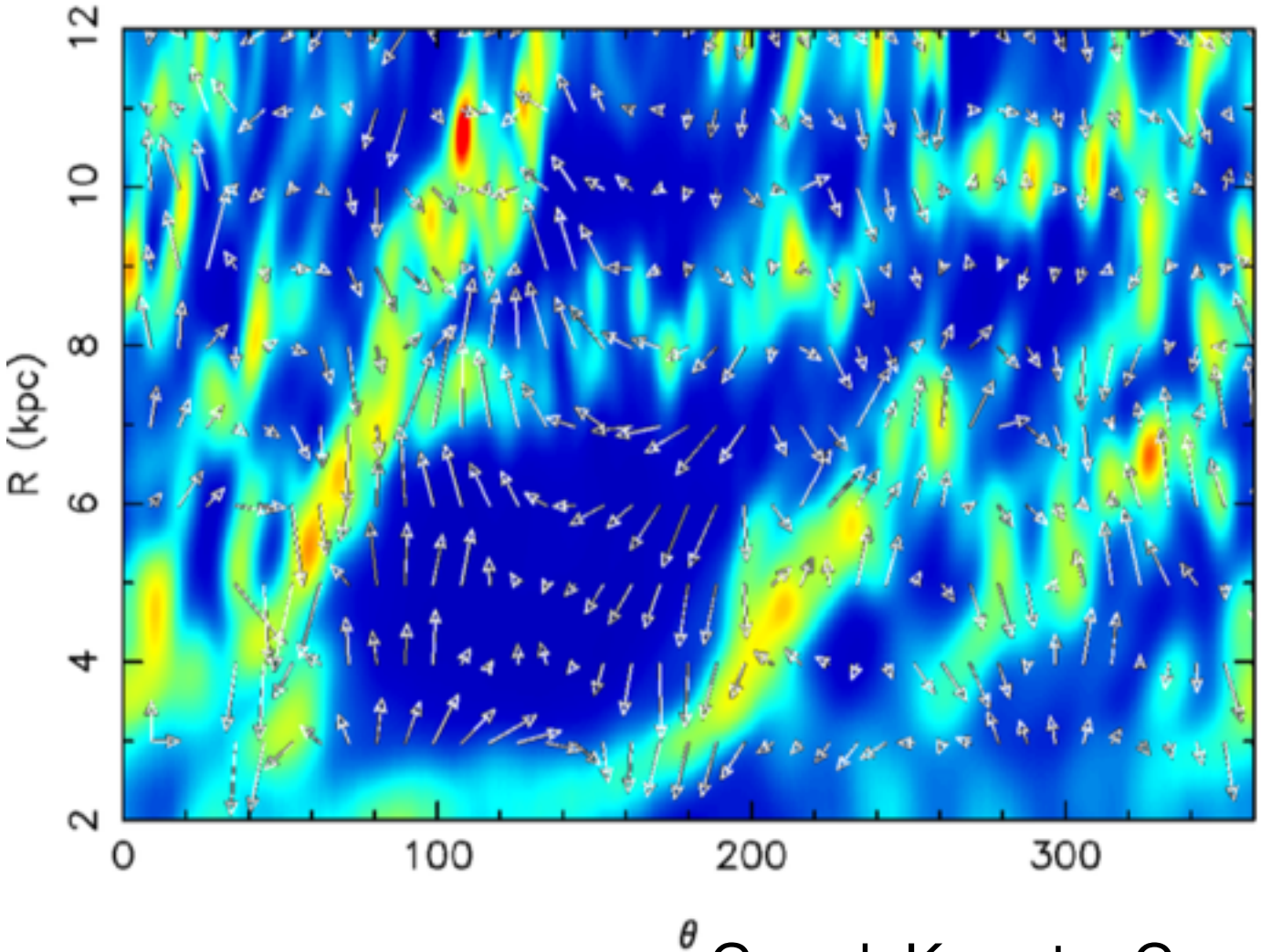
gas metallicity gradient evolution

Ignore
metal mixing
enrichment



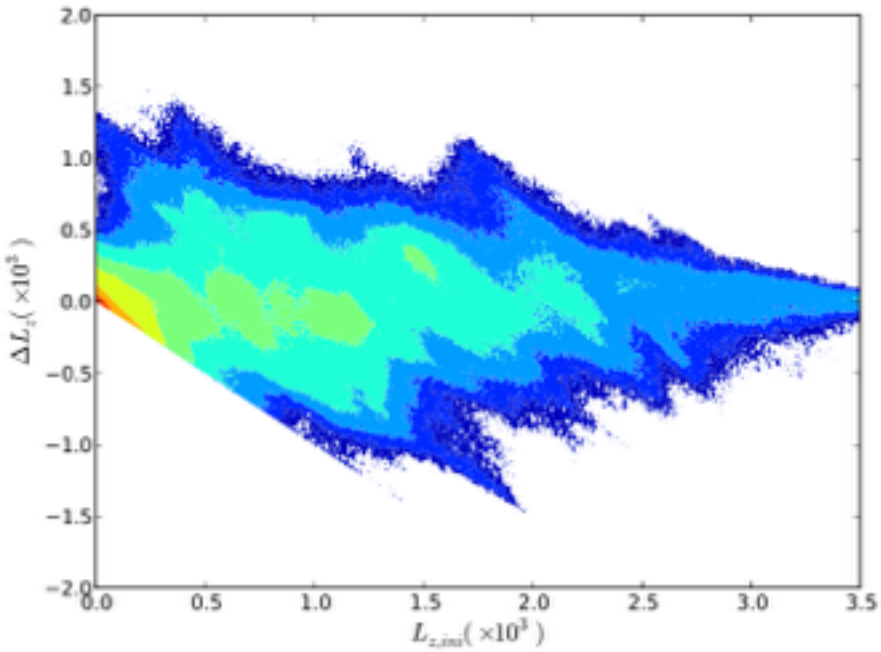
Grand, Kawata, Cropper (2014)

Gas motion

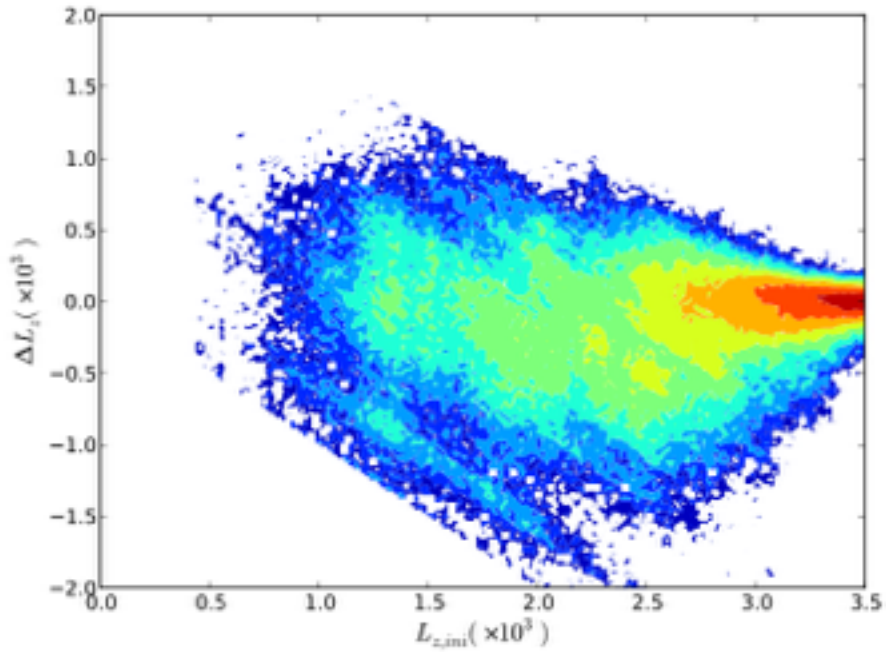


Grand, Kawata, Cropper (2014)

Stars

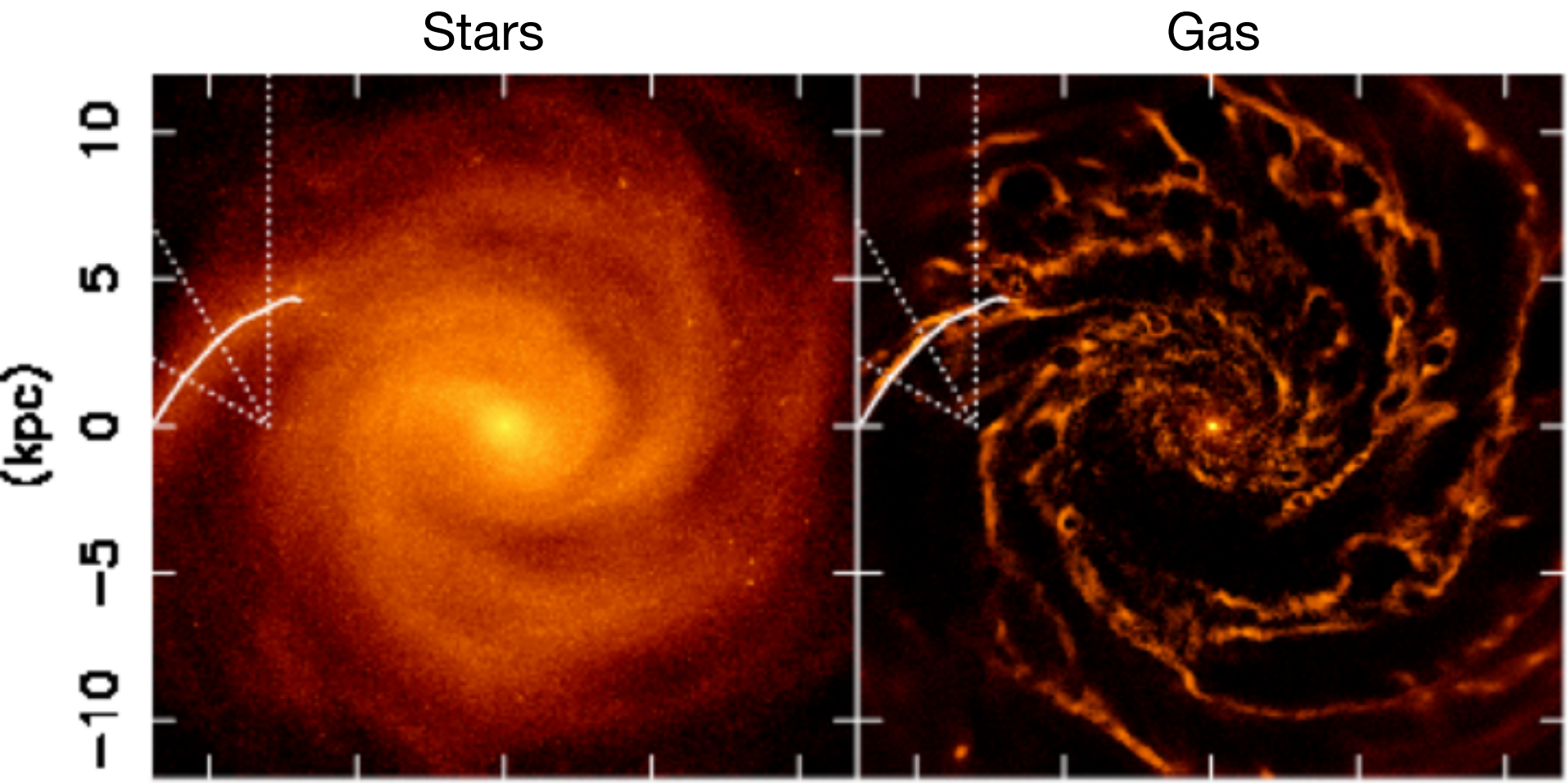


Gas

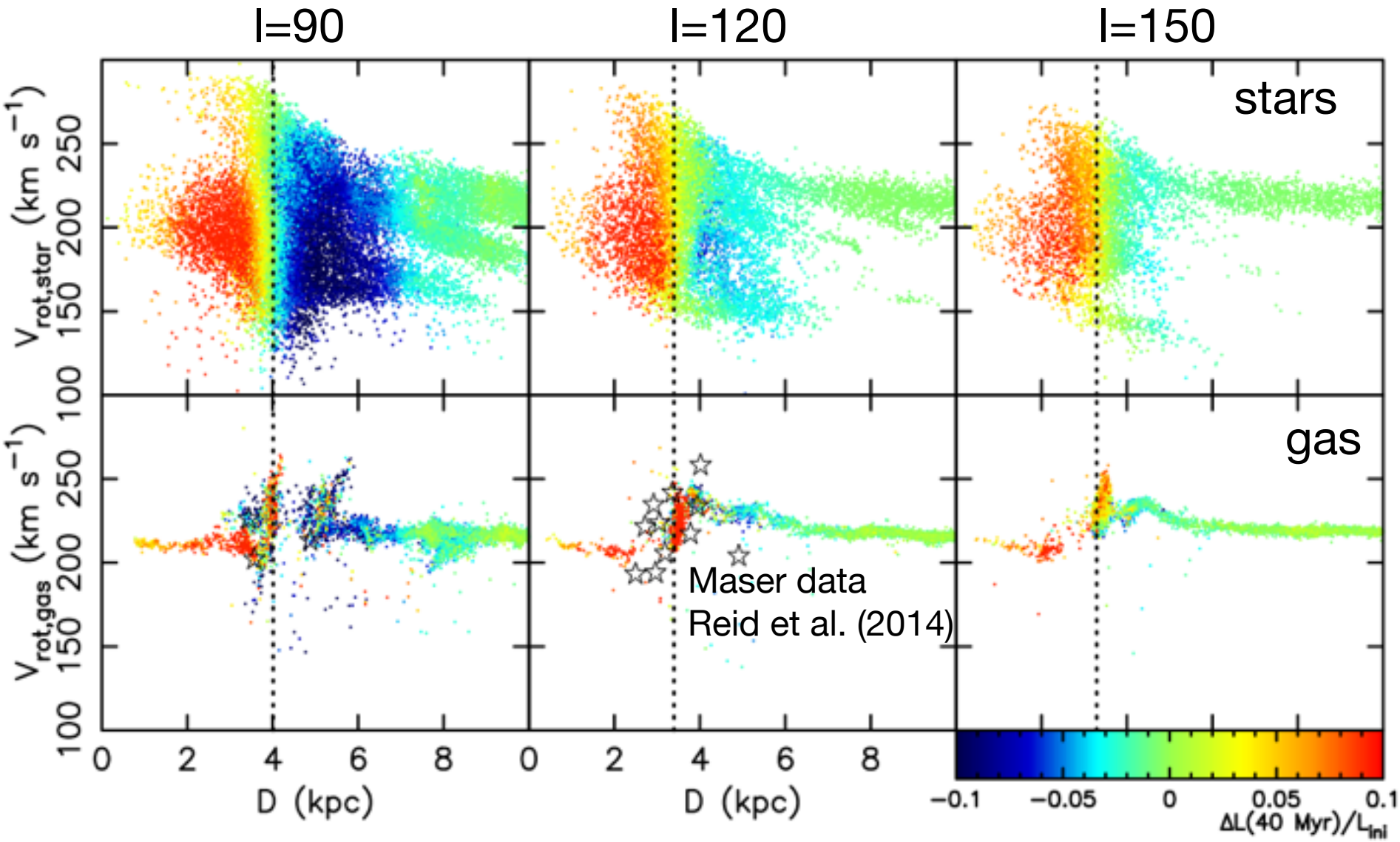


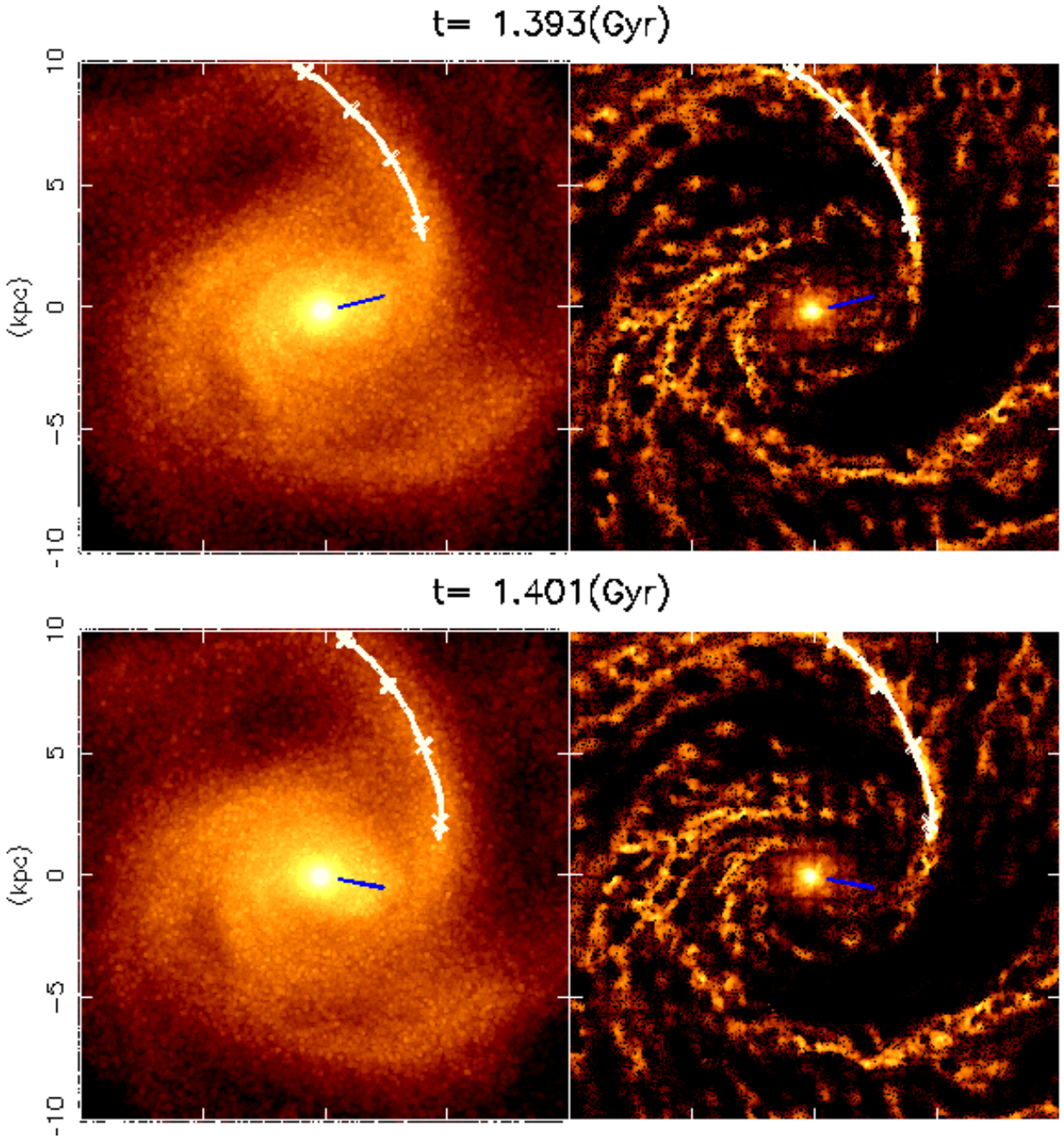
Grand, Kawata, Cropper (2014)

Stellar and gas kinematics around spiral arms in the Milky Way
(Kawata et al. 2014, Hunt et al. 2014)
3 lines of sight around “Perseus-arm like” feature.



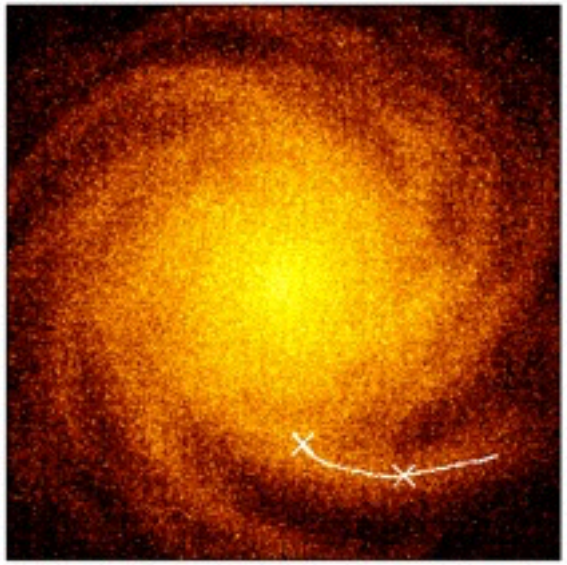
Distance vs. Vrot (Kawata et al. 2014)
co-rotating arm affects the kinematics at every radii

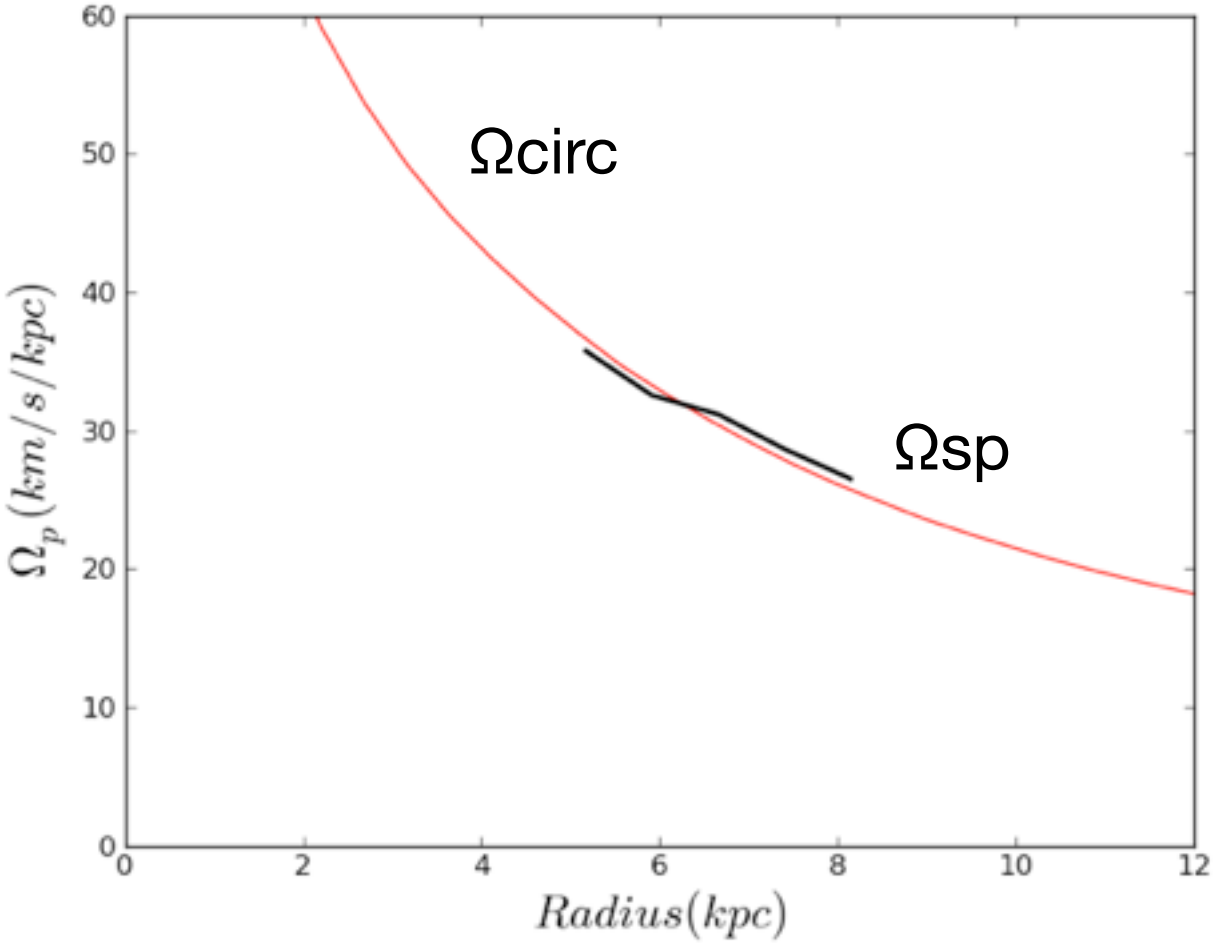




Spiral pattern speed from 2 snapshots

Non-barred case
(Grand et al. 2012a)

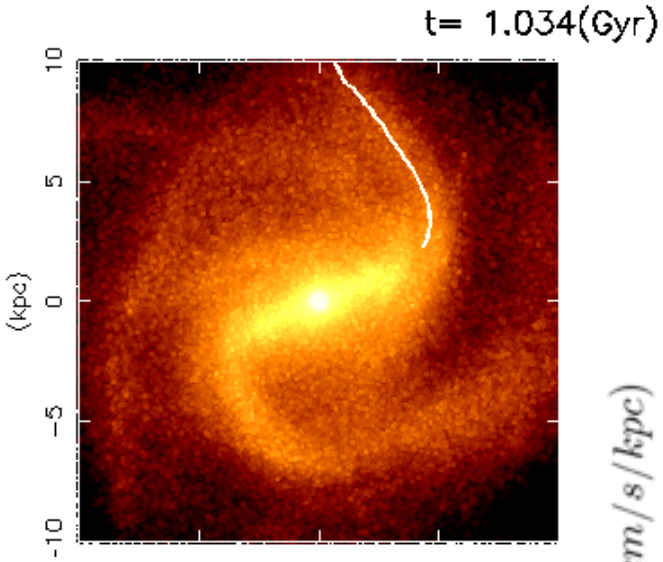


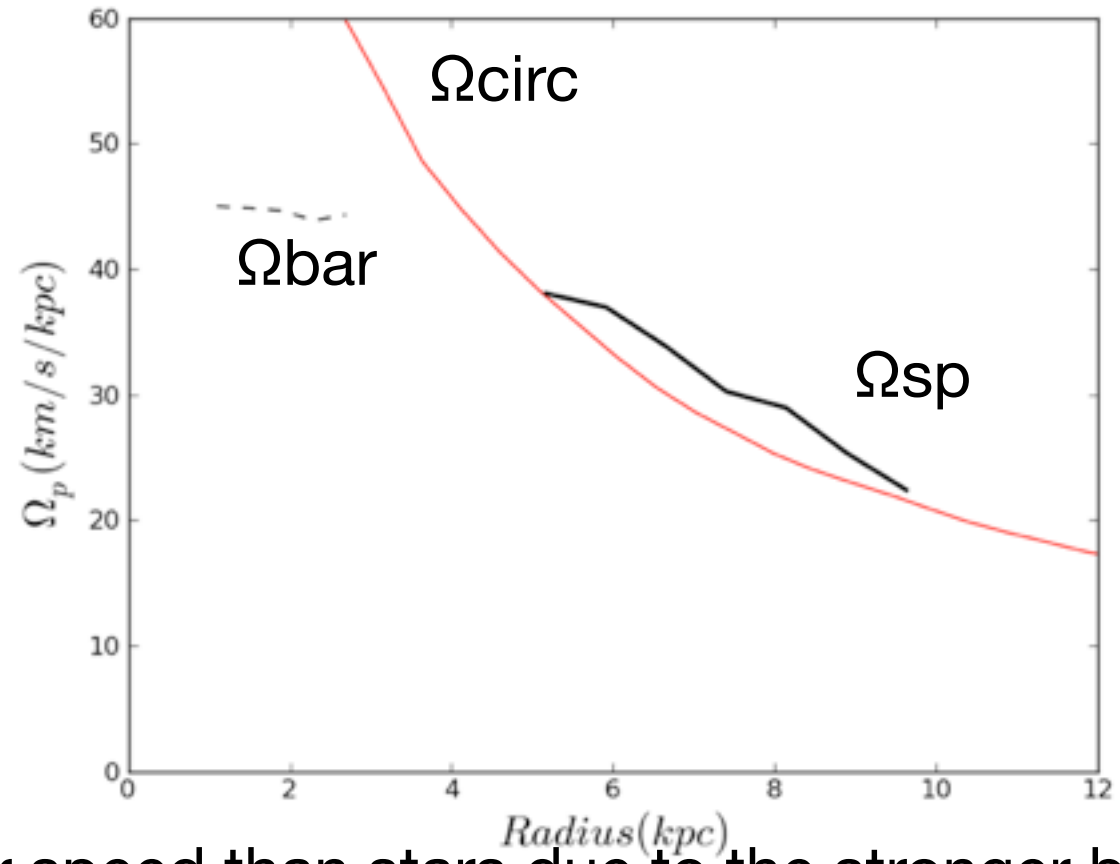


The pattern speed is consistent with the circular speed,
i.e. co-rotating.

Pattern speed of the spiral arms: stronger bar

still decreasing with radius and similar to the circular speed.

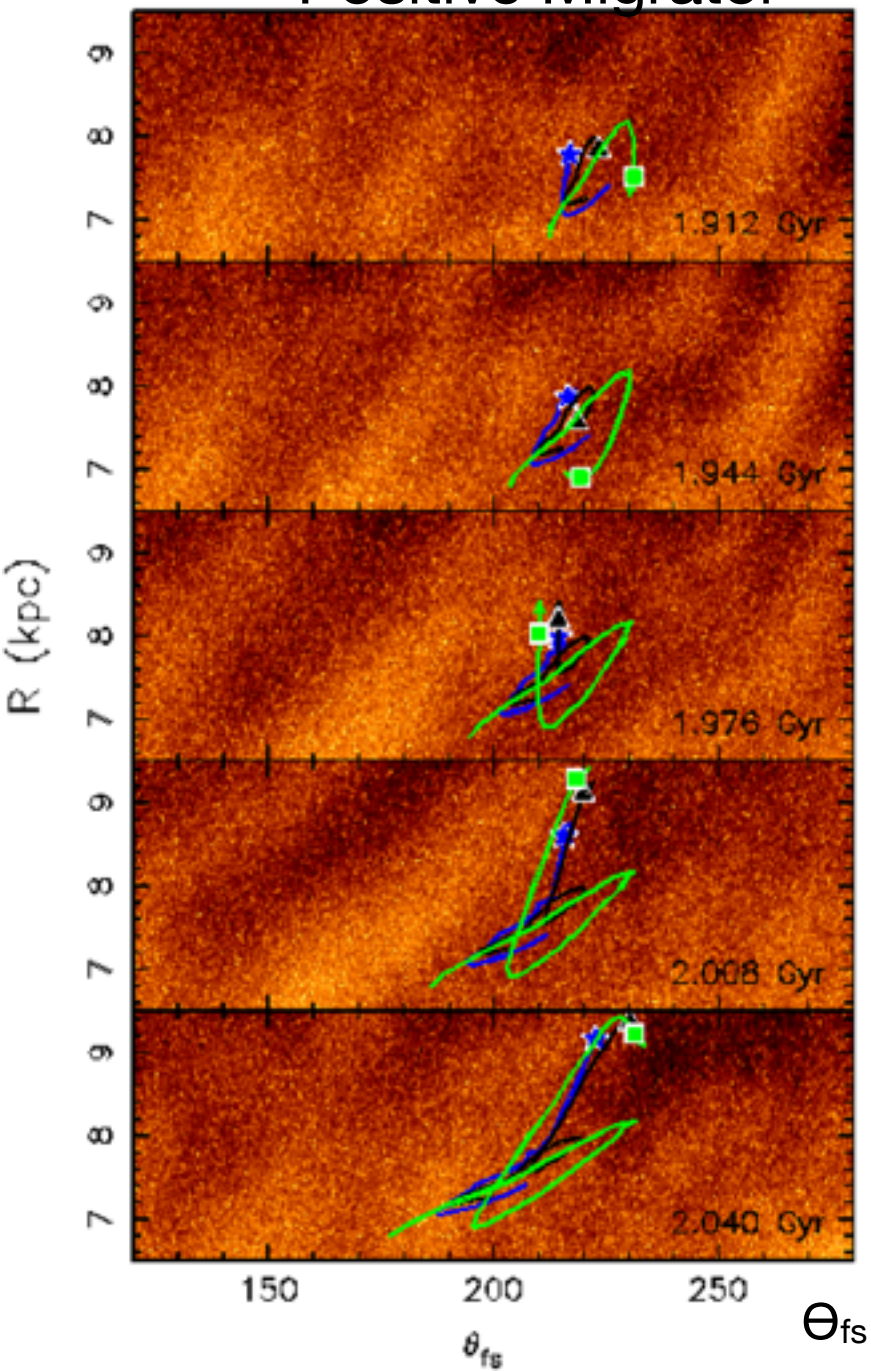


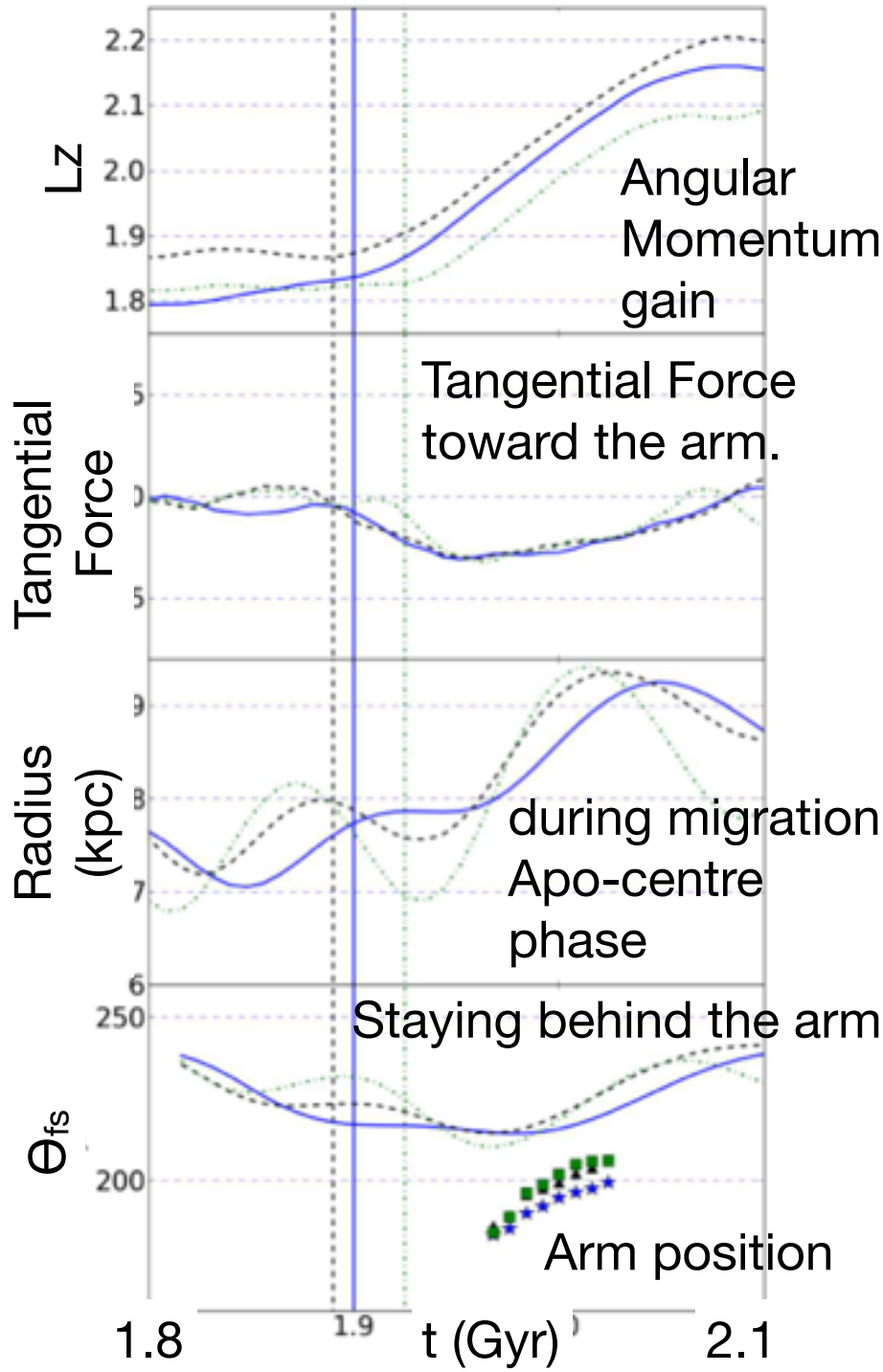


Grand, Kawata, Cropper (2012b)

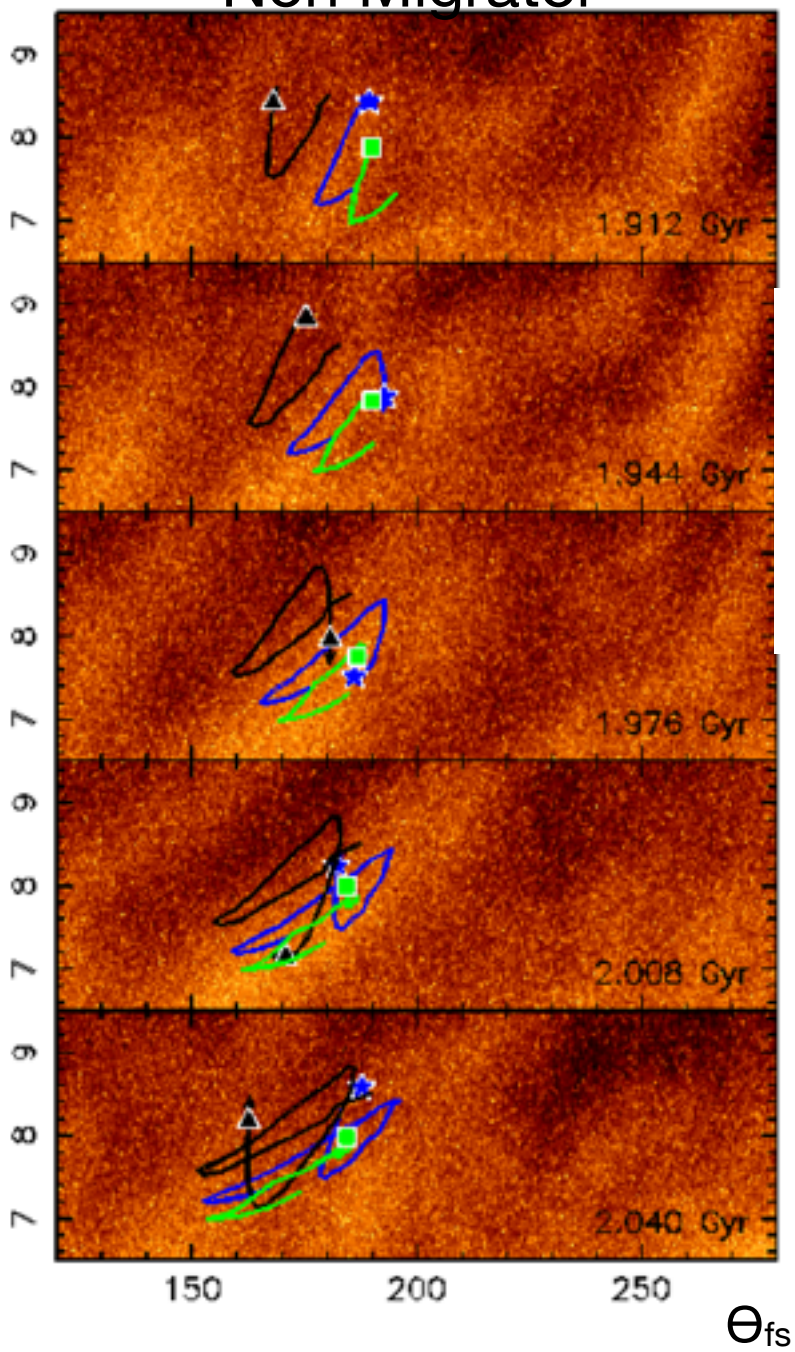
Faster arm patter speed than stars due to the stronger bar?
(see also Roca-Fàbrega et al. 2013)

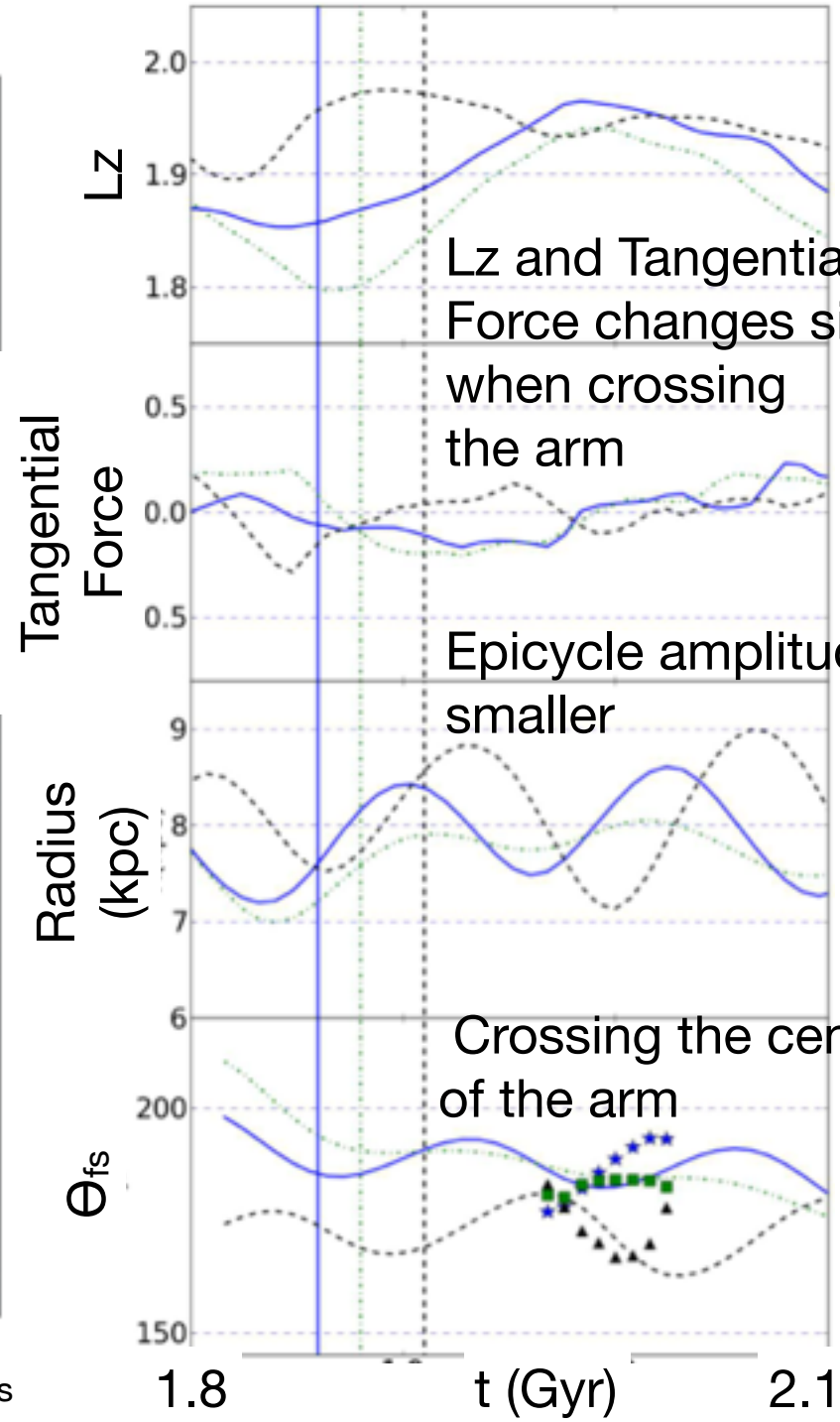
Positive Migrator





Non Migrator



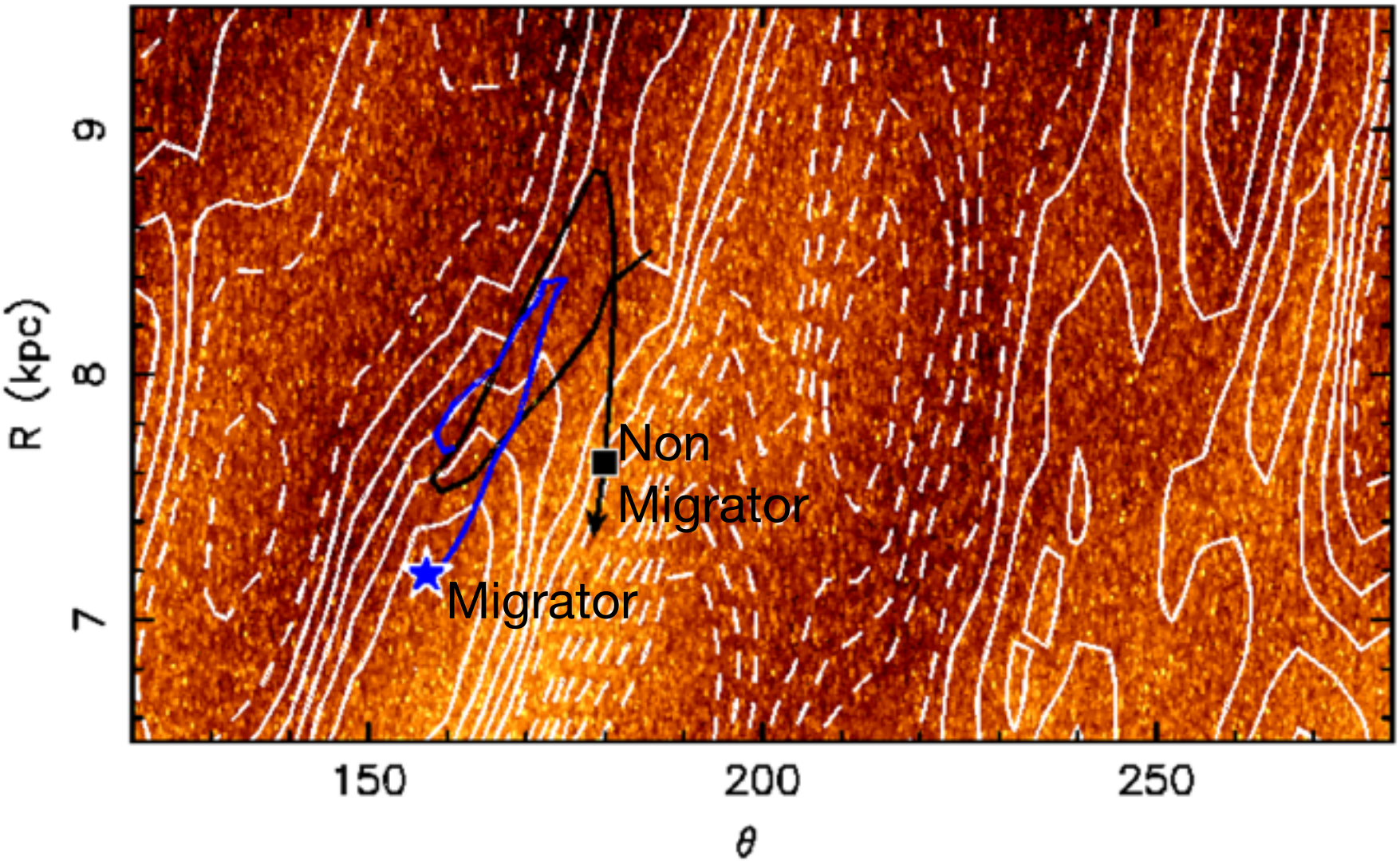


Lz and Tangential Force changes sign when crossing the arm

Epicycle amplitude smaller

Crossing the centre of the arm

Migrators surf along the edge of the arm where tangential force is strong

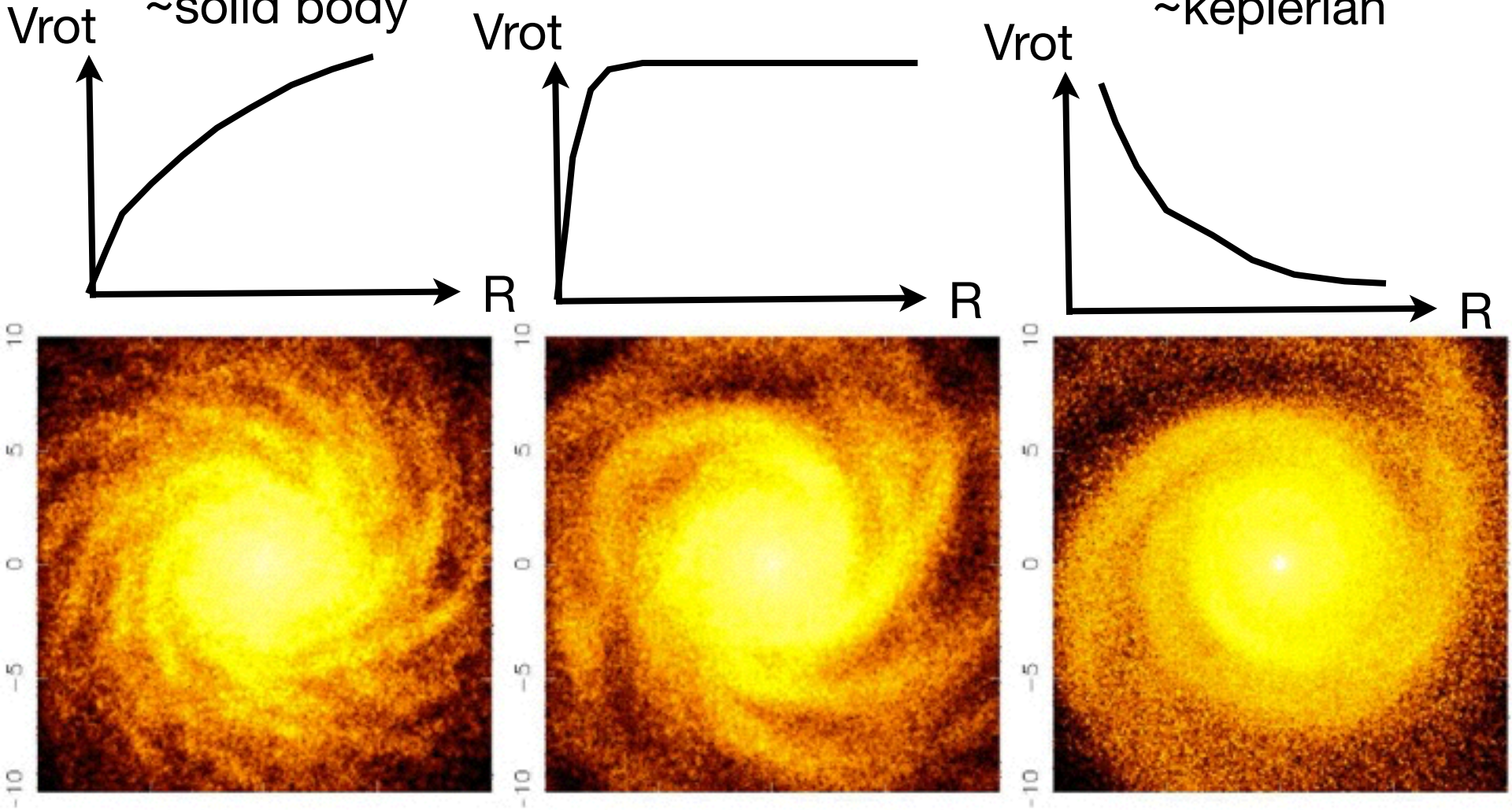


Pitch Angle vs. Galactic Shear Rate

(Grand, Kawata, Cropper 2013)

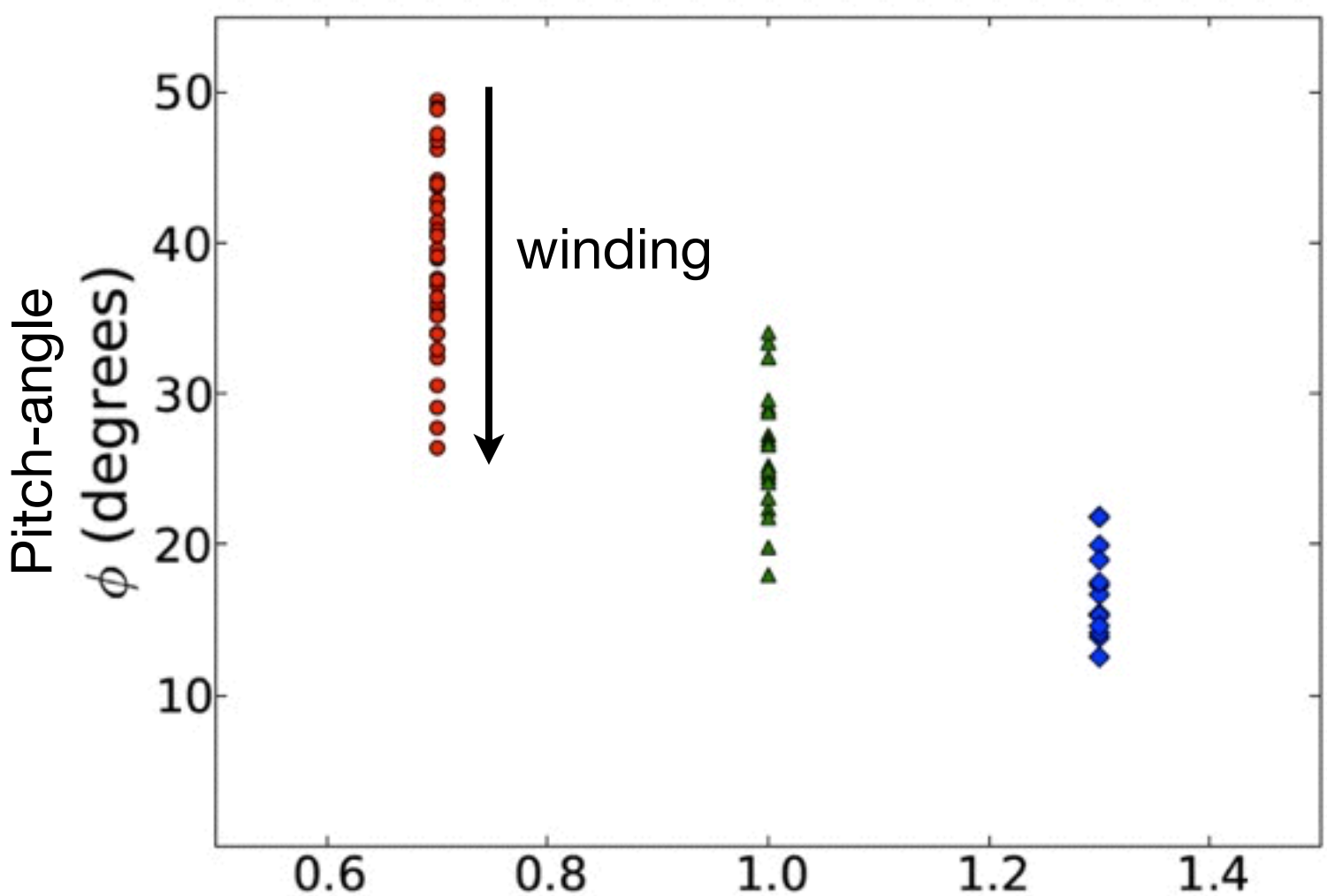
low shear
~solid body

high shear
~keplerian



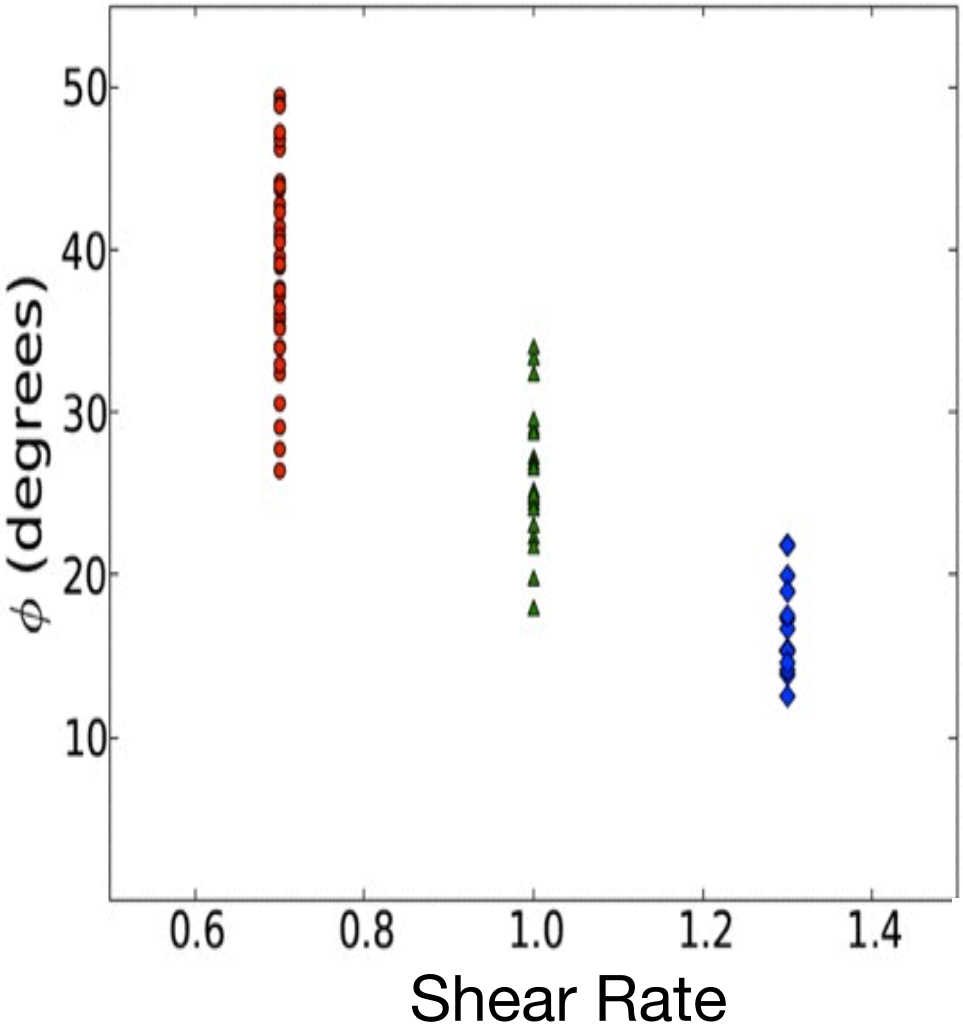
Higher Pitch Angle in disc with lower Shear Rate

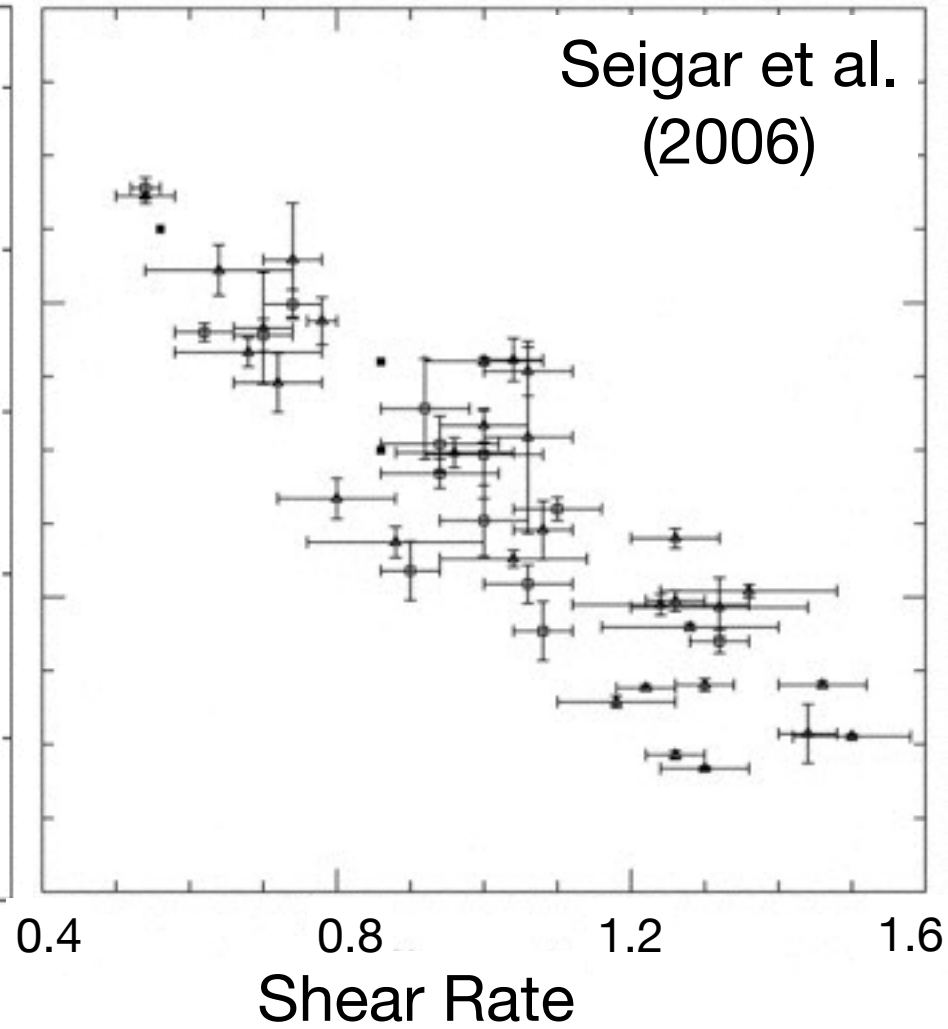
(Grand et al. 2013)



more solid body $\Gamma = 1 - (R/V_c)(dV_c/dR)$ more Keplerian

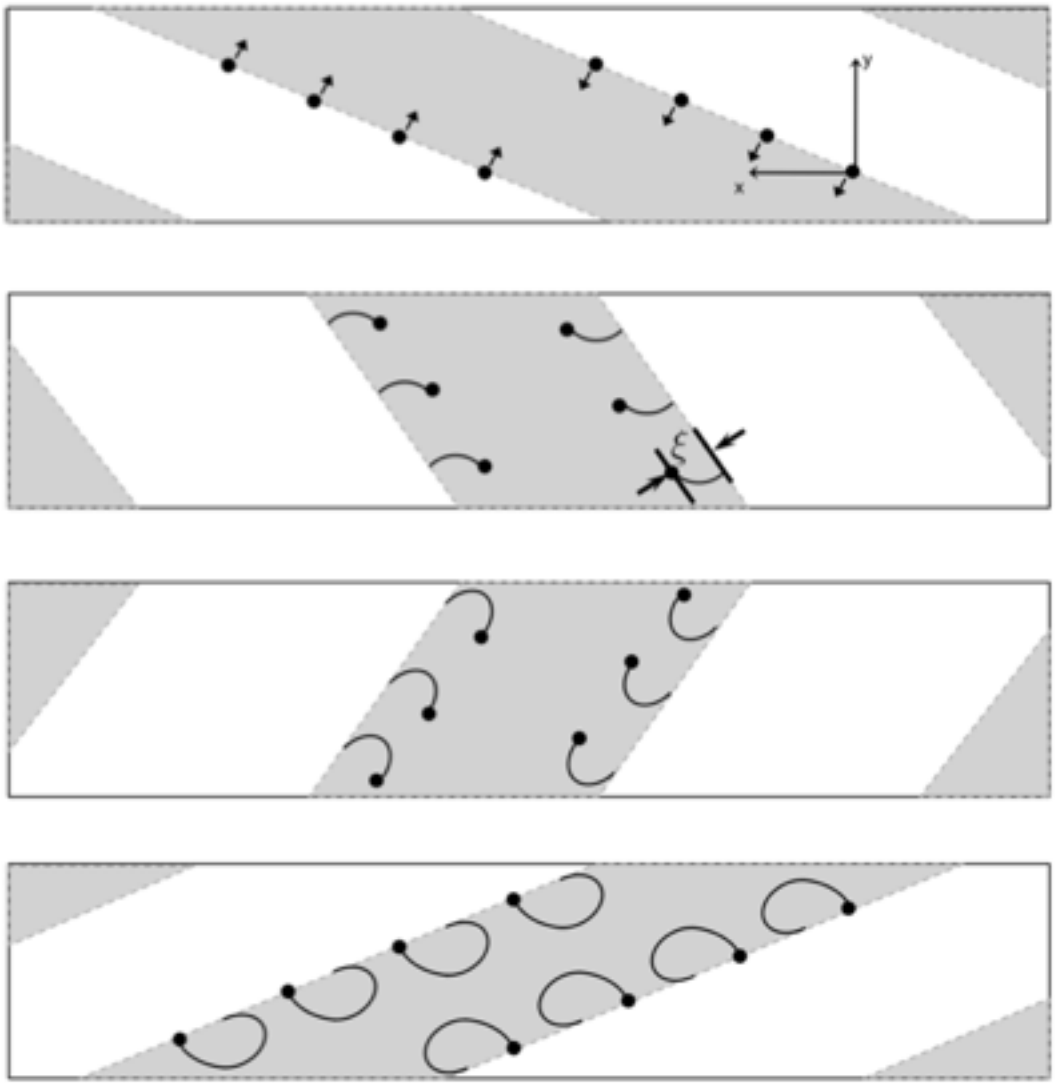
Consistent with the observed trend winding can explain the scatter, too?





Swing Amplification

(Julian & Toomre 1966, Toomre 1981)



N-body spiral arm seems to form by similar mechanism to Swing Amplification.
However, non-linear features, such as extreme migrators, are not described by linear perturbation theory.

Stellar motion

(example of different simulated galaxy)
trailing side going outward, and leading side going inward
private communication with Ivan Minchev (Beijing 2010)