The Local Spiral Arm of the Galaxy explained by trapping of stars in the corotation resonance

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The Dynamical Origin of the Local Arm and the Sun's Trapped Orbit

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Modelling resonances and orbital chaos in disk galaxies. Application to a Milky Way spiral model

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Lund 2017

FAPESP

Basics of the model

1) Totally observationally constrained, based on generally accepted description of the gravitational potential of the local region of the galaxy

$$\Phi = \Phi_0 \quad + \Phi_1$$

disk + spiral arms perturb.

2) Use objects with precise distance, proper motion and radial velocity to integrate their orbit (masers observed with VLBI)

3) Work in frame of reference rotating with the spiral arms

4) integrate the orbits and discover librating stars in the local arm

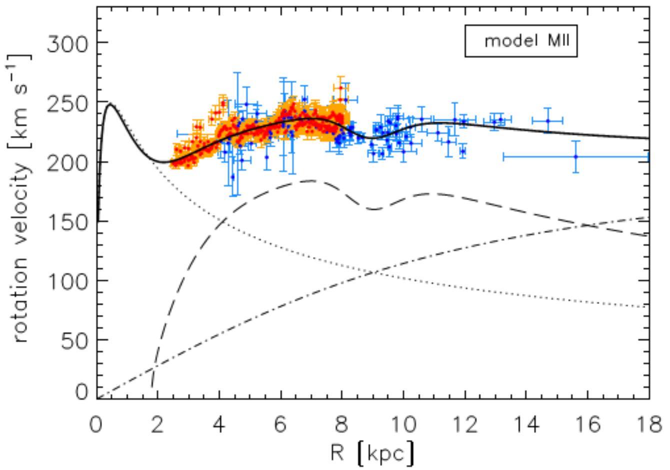
Φ_0 potential of the disk (potential of the Galaxy)

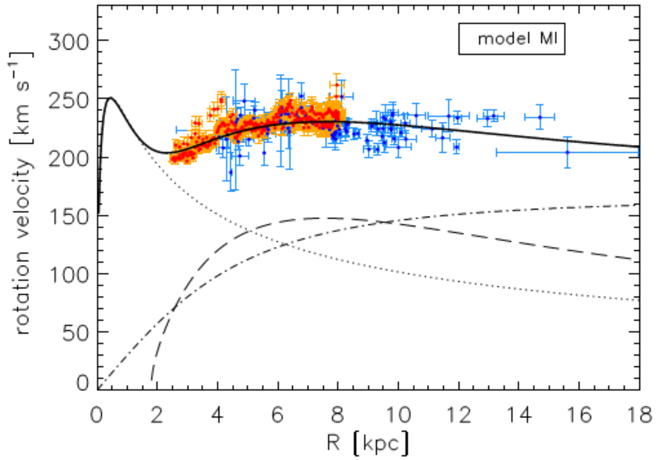
- The rotation curve is observable; it gives direly the force acting on the stars

$$\frac{\partial \Phi_0}{\partial R} = \frac{V_{\rm rot}^2}{R}$$

We avoid to use models and discussions about what is the contribution of a dark halo or any other component.

- The results of the present model do not depend on taking into account or not the local dip

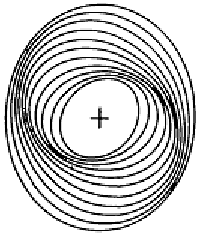




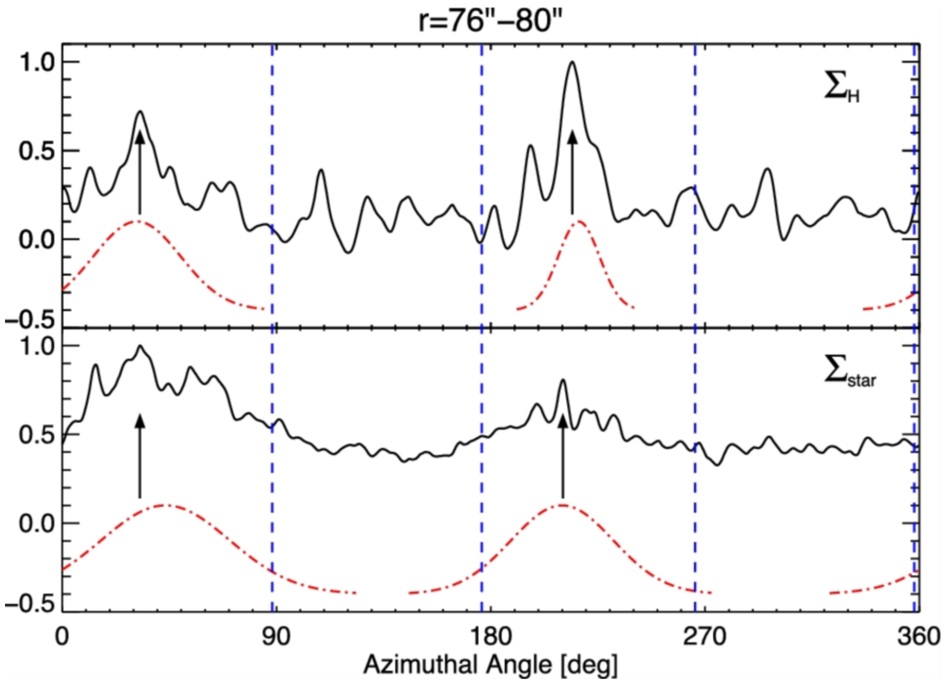
Barros et al. 2016 A&A

Spiral Arms ϕ_1

What is the best mathematical description of a spiral arm?



A.J. Kalnajs (1973) ideas explain the arms And show that they are potential valleys

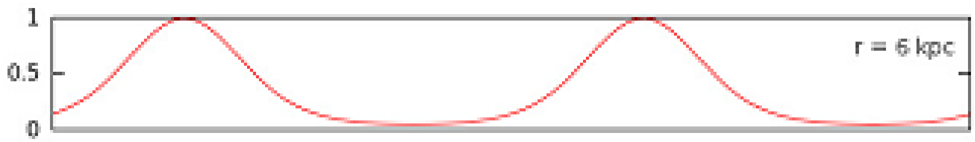


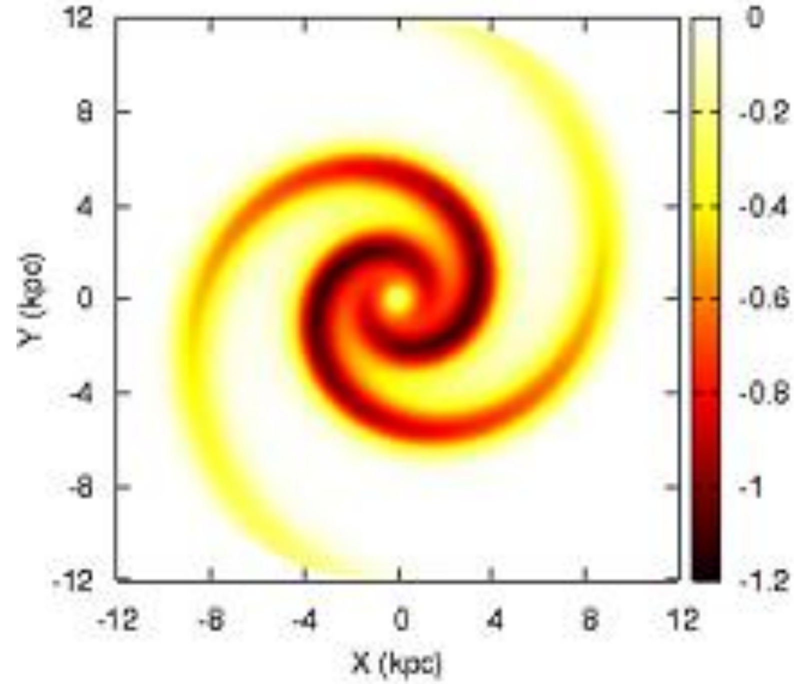
Gas and stellar spiral arms and their offsets in the grand-design spiral galaxy M51
Fumi Egusa Erin Mentuch Cooper Jin Koda Junichi Baba
MNRAS, Volume 465, Issue 1, 11 February 2017, Pages 460–471,

Φ_1 Potential perturbation of the arms

Two-armed Logarithmic Gaussian Potential

Junqueira et al. 2013, A&A 550, A91





In the present work m = 4

Reference frame of spiral arms

$$\varphi = \theta - \Omega_p t$$

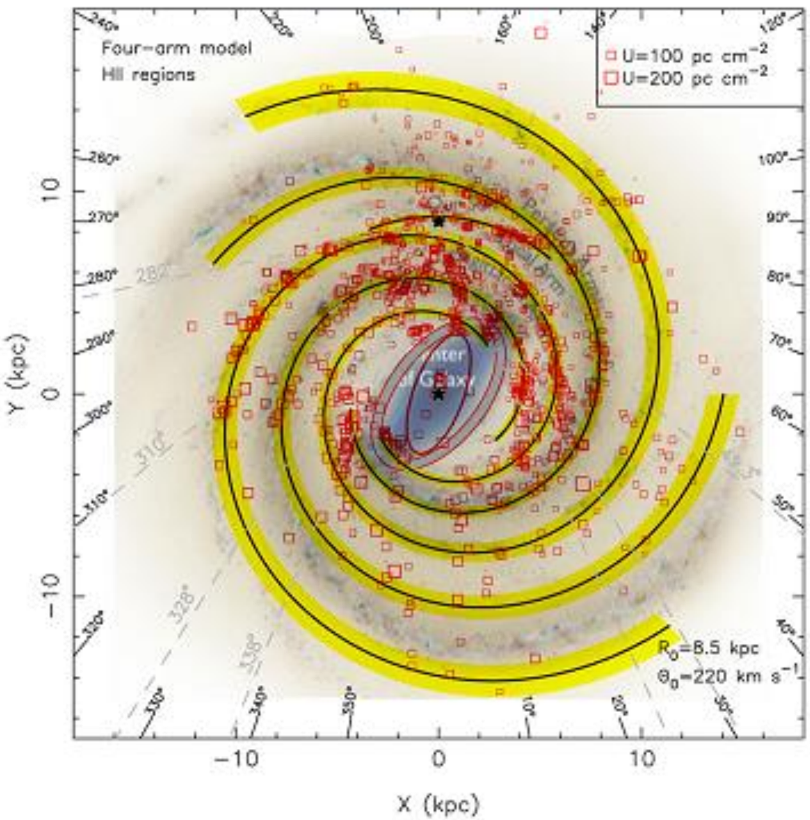
Classical

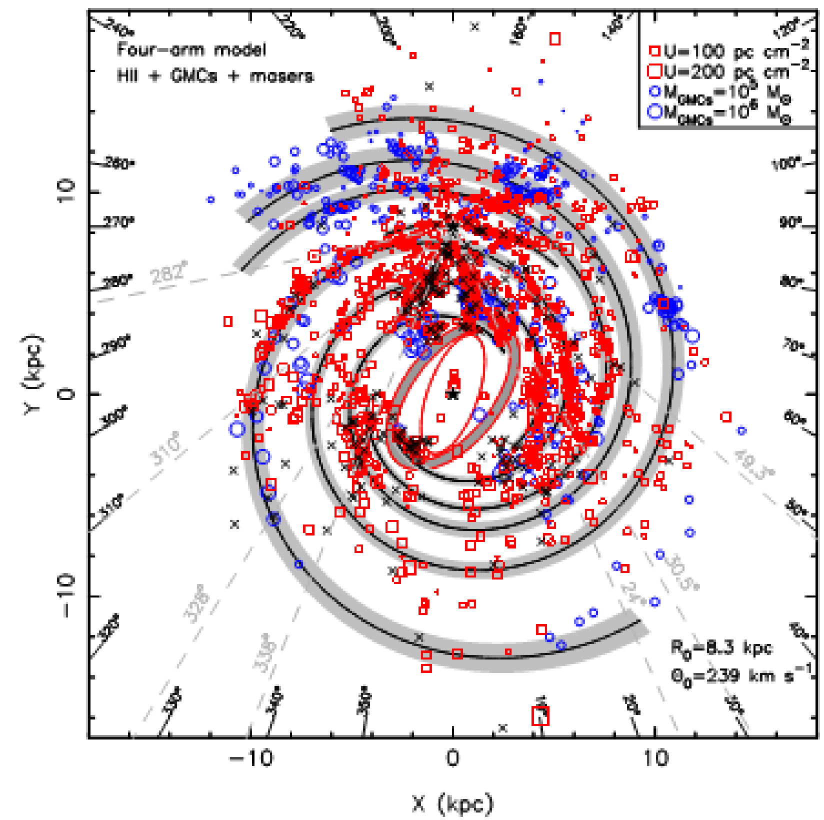
$$\phi_1(R, \varphi) = \phi_D e^{i[m\varphi + f_m(R)]}$$

Junqueira´s

$$\phi_1(R, \phi, z) = -\zeta_0 R \, exp[-\frac{R^2}{\sigma^2}[1 - \cos(m\varphi - f_m(R))] - \epsilon_s R - k\,|z|\,]$$

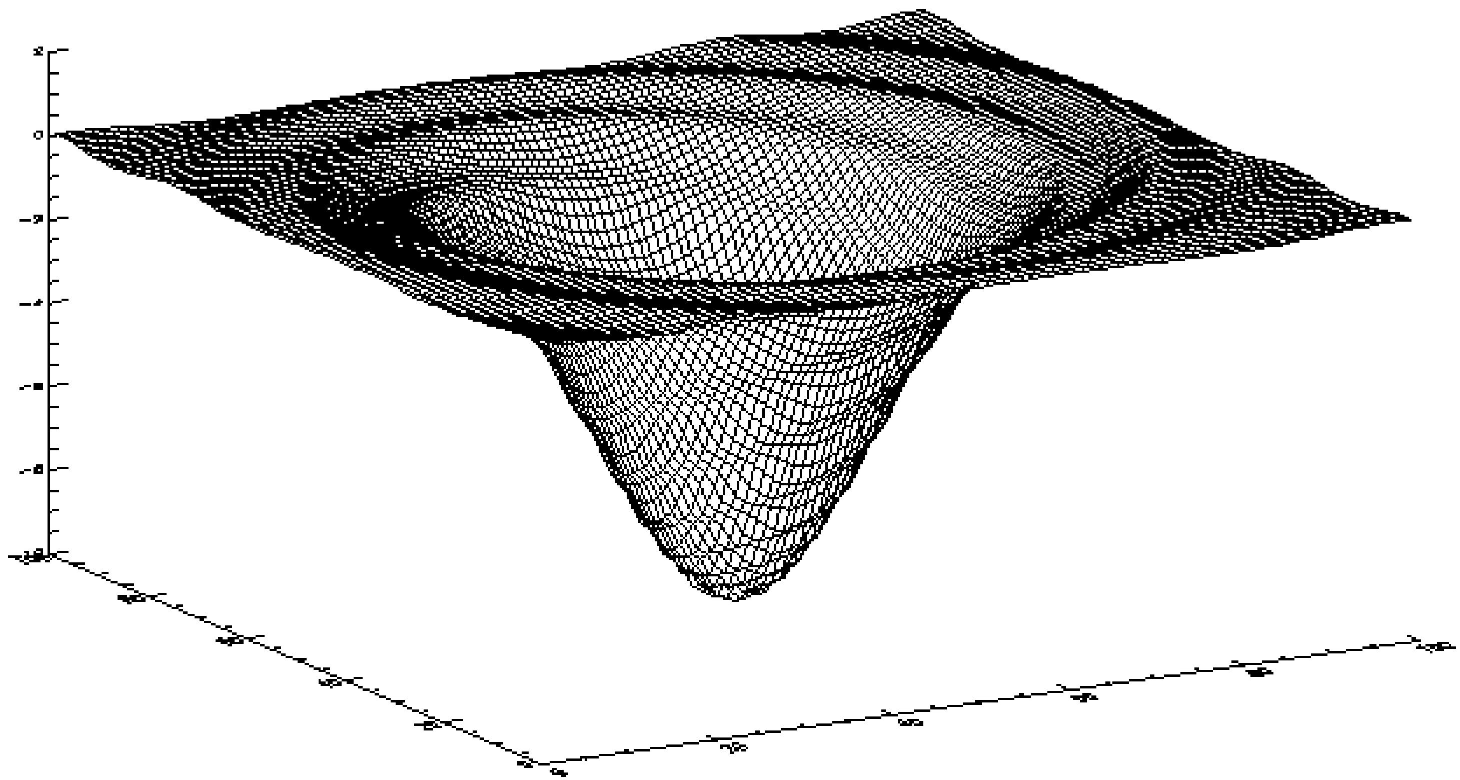
Φ₁ **Where are the arms? How many arms?**

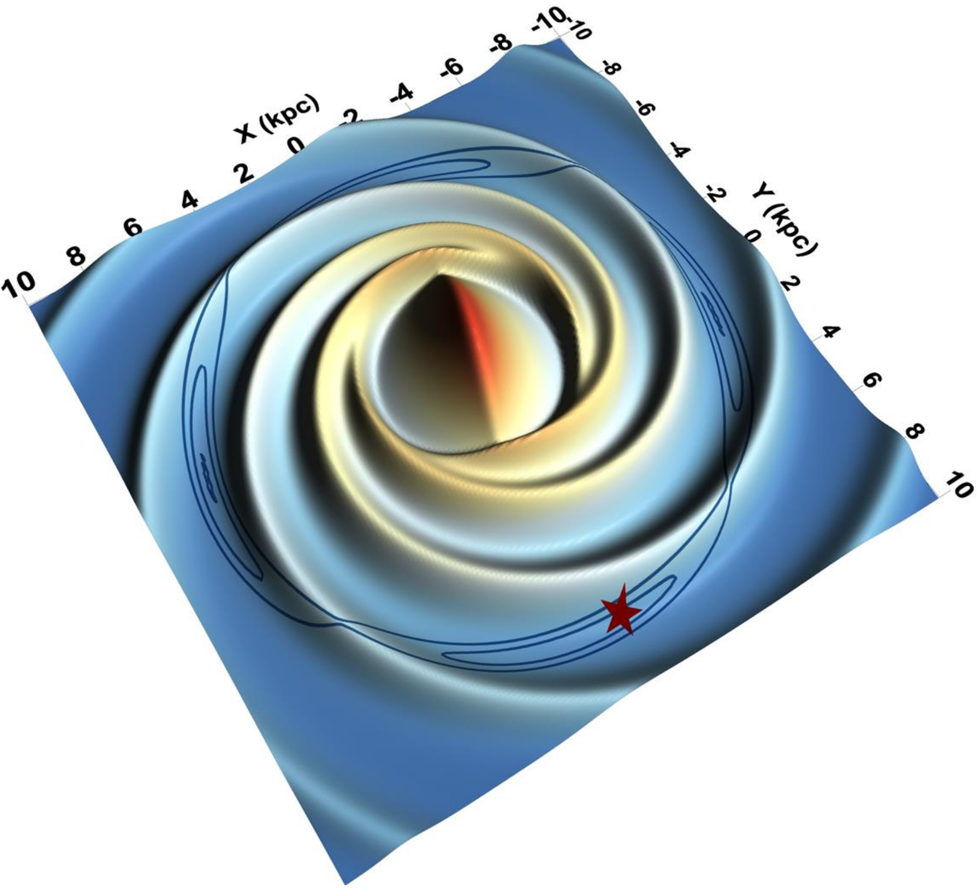




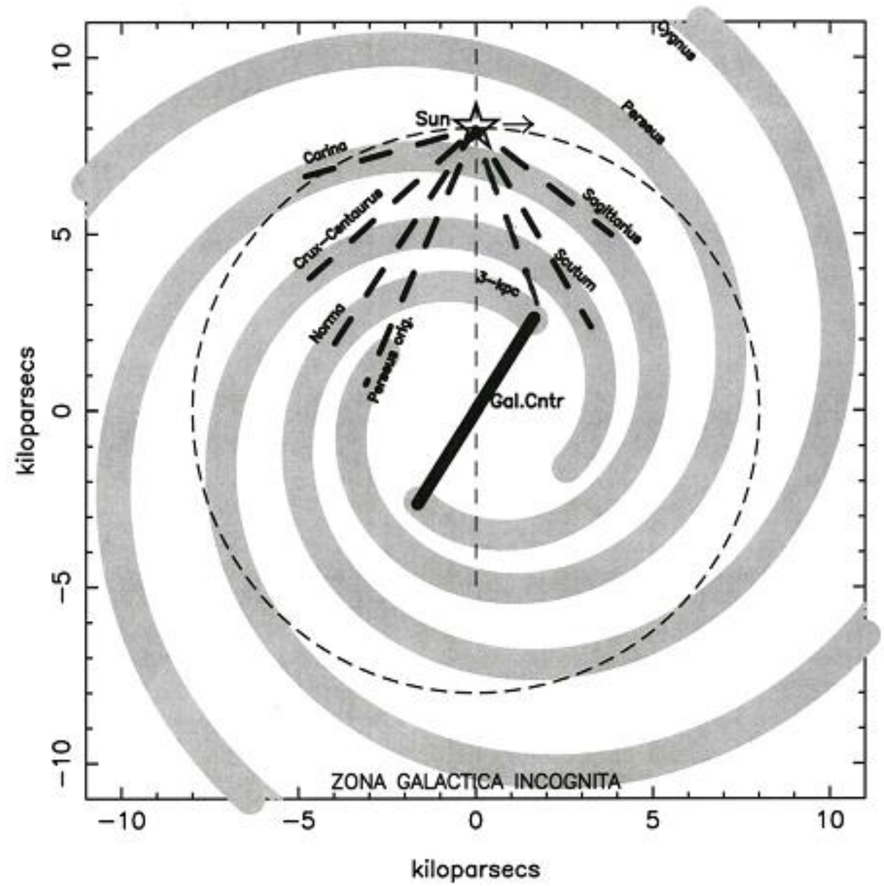
L. G. Hou and J. L. Han A&A 569, A125 (2014)

4 arms is the best fit!





Potential of the disk removed, only perturbation
Shown, with negative potential (arms are positive)



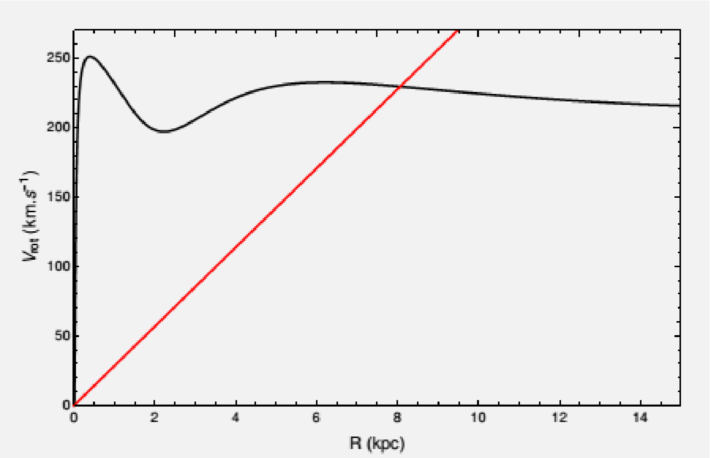
Vallée 2014 Tangential directions

Last parameter to be decided: Ω_p

$$\Omega_p = V_c / R_C$$

~ 28. 4 km/s/kpc = 230 km/s / 8.1 kpc

Pattern speed



Rotation curve

Yes, the Sun is located near the corotation circle

Yu.N. Mishurov and I.A. Zenina Astron. Astrophys. 341, 81–85 (1999)

Space Research Department, Rostov State University, 5 Zorge, 344090, Rostov-on-Don, Russia (e-mail: mishurov@phys.rnd.runnet.ru)

$$\Delta R \approx 0.1\,\text{kpc}$$

DIRECT DETERMINATION OF THE SPIRAL PATTERN ROTATION SPEED OF THE GALAXY

Wilton S. Dias[1] and J. R. D. Lépine[2]

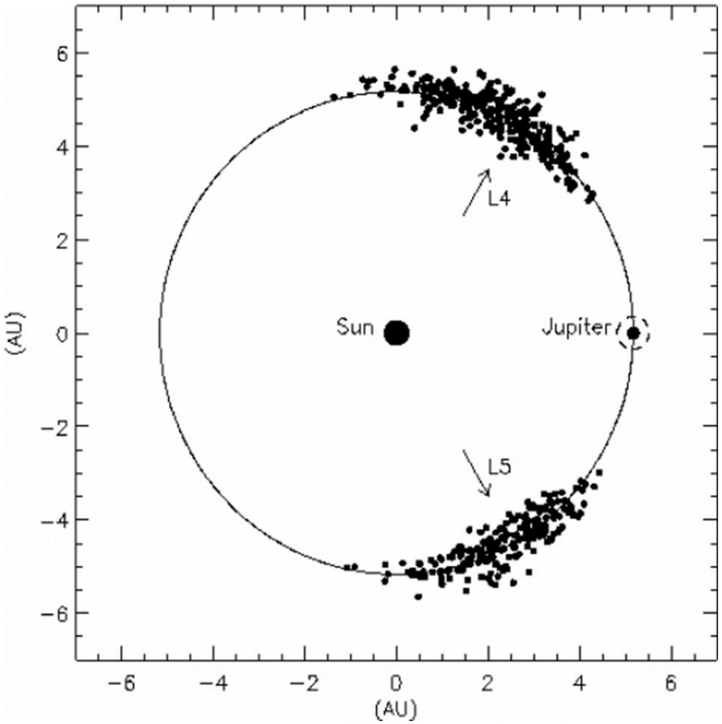
Received 2005 February 11; accepted 2005 April 28

The Astrophysical Journal, 629:825–831, 2005 August 20

$$(R_c/R_0 = 1.06 \pm 0.08)$$

Once a spiral arm emerges in a galaxy, the **corotation zone** appears in **phase space!** (Contopoulos 1973 ApJ)

The same physics and equations of the Lagrangean points L4 and L5 where the Trojan asteroids are trapped in the orbit of Jupiter.



Trojan asteroids

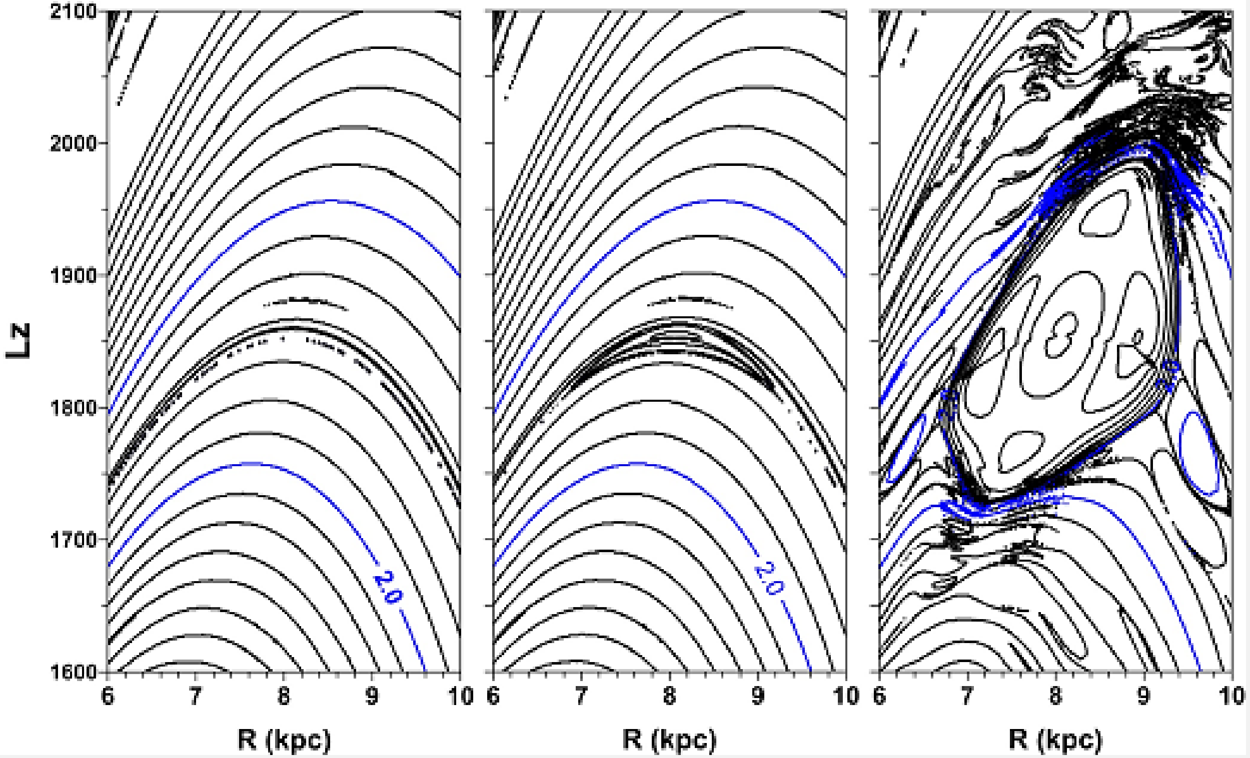
$$\Phi_{\rm eff}(R,\,\varphi) = \Phi_0(R) + \Phi_{\rm s}(R,\,\varphi) - \frac{1}{2}\Omega_p^2 R^2$$

Size of corotation zone depends on spiral arm strenght

No arms: no co-rotation zone.

Small amplitude: The CR zone is small

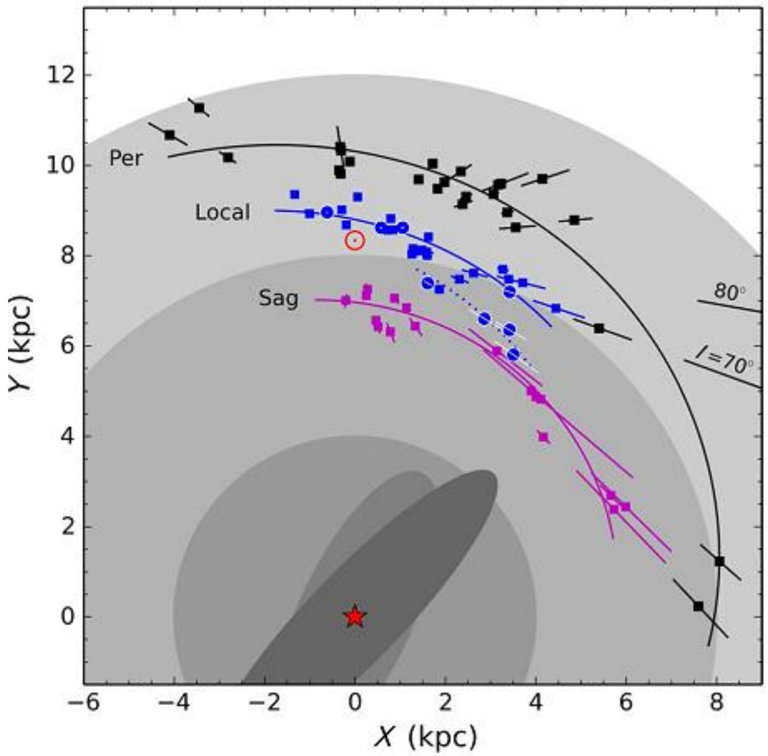
Larger amplitudes: CR zone grows a lot!



What objects to use to test the model? (waiting for GAIA DR2)

The local spiral structure of the Milky Way

Ye Xu,[1]* Mark Reid,[2] Thomas Dame,[2] Karl Menten,[3] Nobuyuki Sakai,[4] Jingjing Li,[1,3]
Andreas Brunthaler,[3] Luca Moscadelli,[5] Bo Zhang,[6] Xingwu Zheng[7] Sci. Adv. 2016;2:e1600878

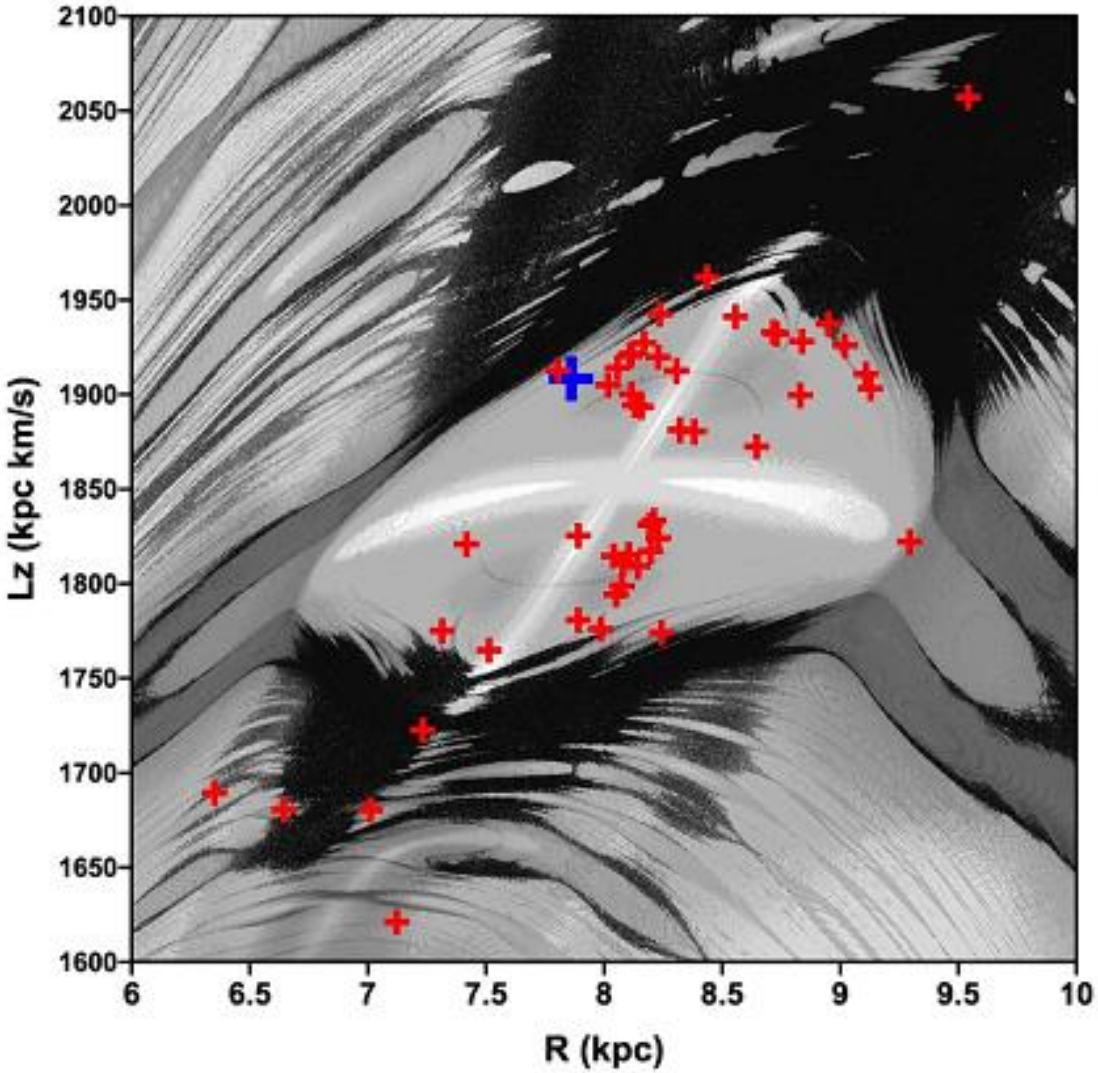


Methanol Masers associated with massive stars, short lifetime, not able to move away from their birthplace

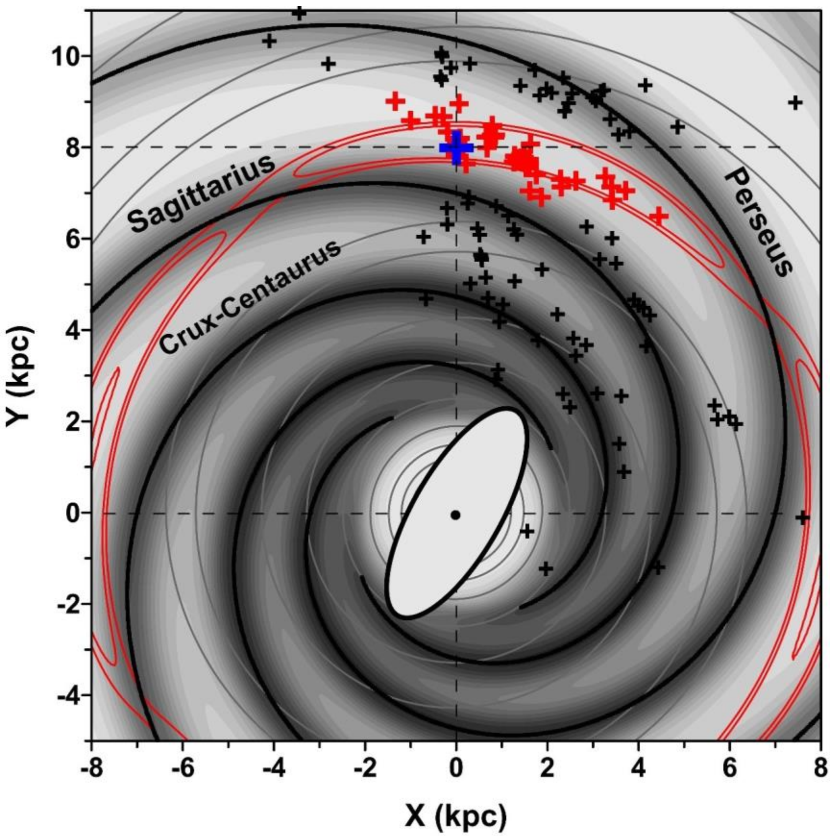
Paralaxes typically of the order of 1 mas
For distances of 2 kpc typically errors are of the order of 0.2 kpc
Errors in velocities in the U, V components typically 5 km/s

We adopted R0 = 8 kpc Vo= 230 km/s, within the determination by Schoenrich 2012 (MNRAS) R0 = 8.27± 0.029 kpc and V0= 238 ± 9 km/s

The results found in this work are robust. Small changes in R0 , V0,
pitch angle, strength of the arms, do not change the existence of a corotation zone



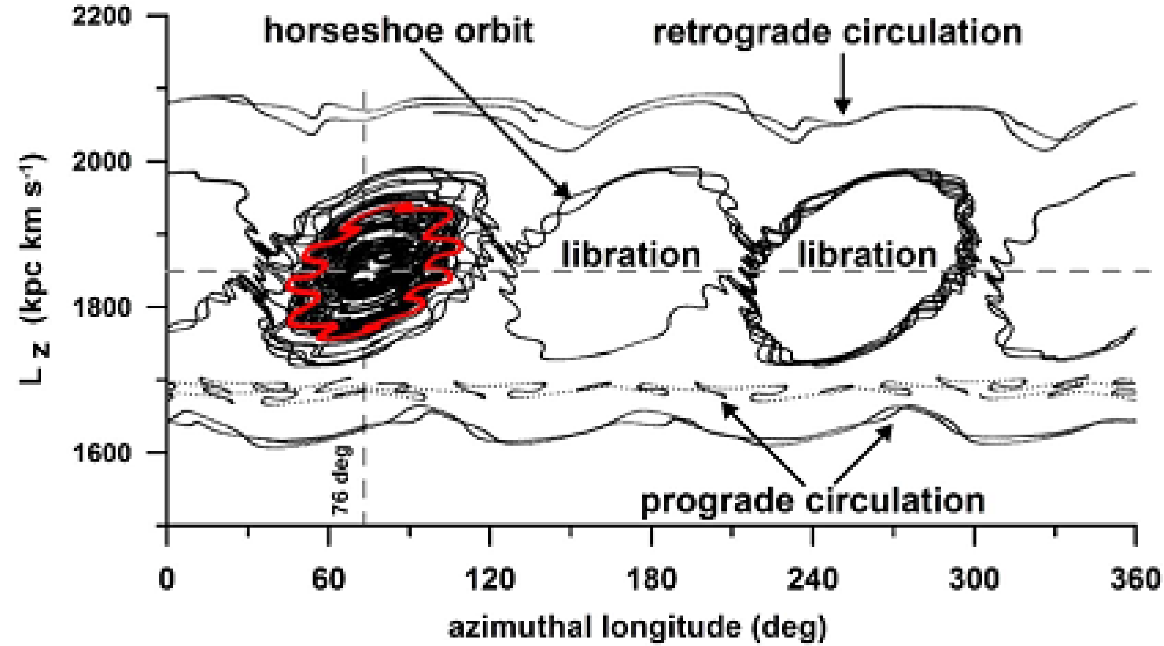
The dynamical map of the corotation zone. Stars in clear regions have stable orbits, dark regions are regions of chaotic orbits. Masers in red color



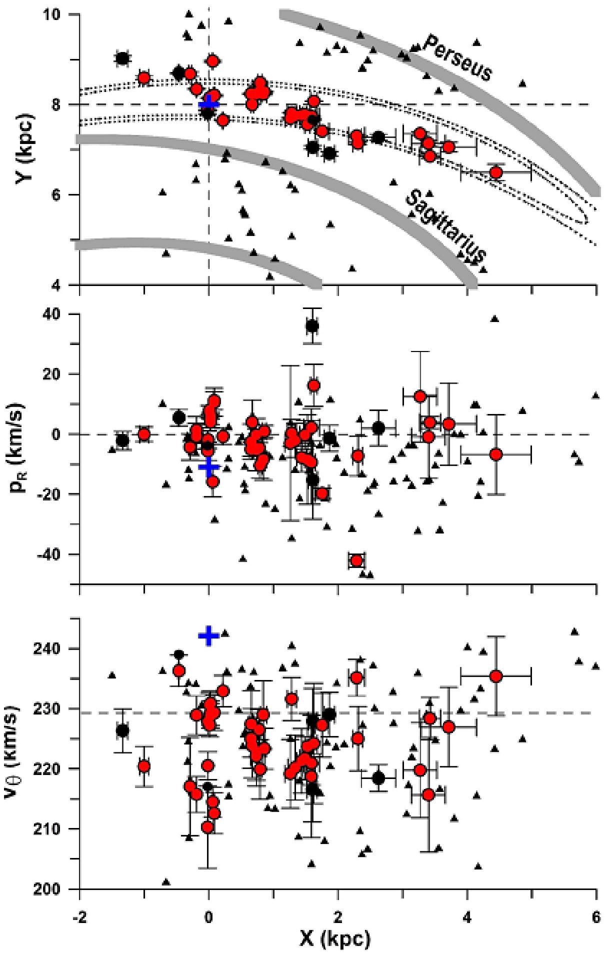
+ Masers that librate (allways stay in the corotation zone)

+ Masers that will circulate in the Galaxy

(Some masers from other references where added)



horseshoe orbit
retrograde circulation
libration
libration
prograde circulation
76 deg
2200
2000
1800
1600
L z (kpc km s-1)
0
60
120
180
240
300
360
azimuthal longitude (deg)


Perseus
Sagittarius
Y (kpc)
p_R (km/s)
v_θ (km/s)
X (kpc)

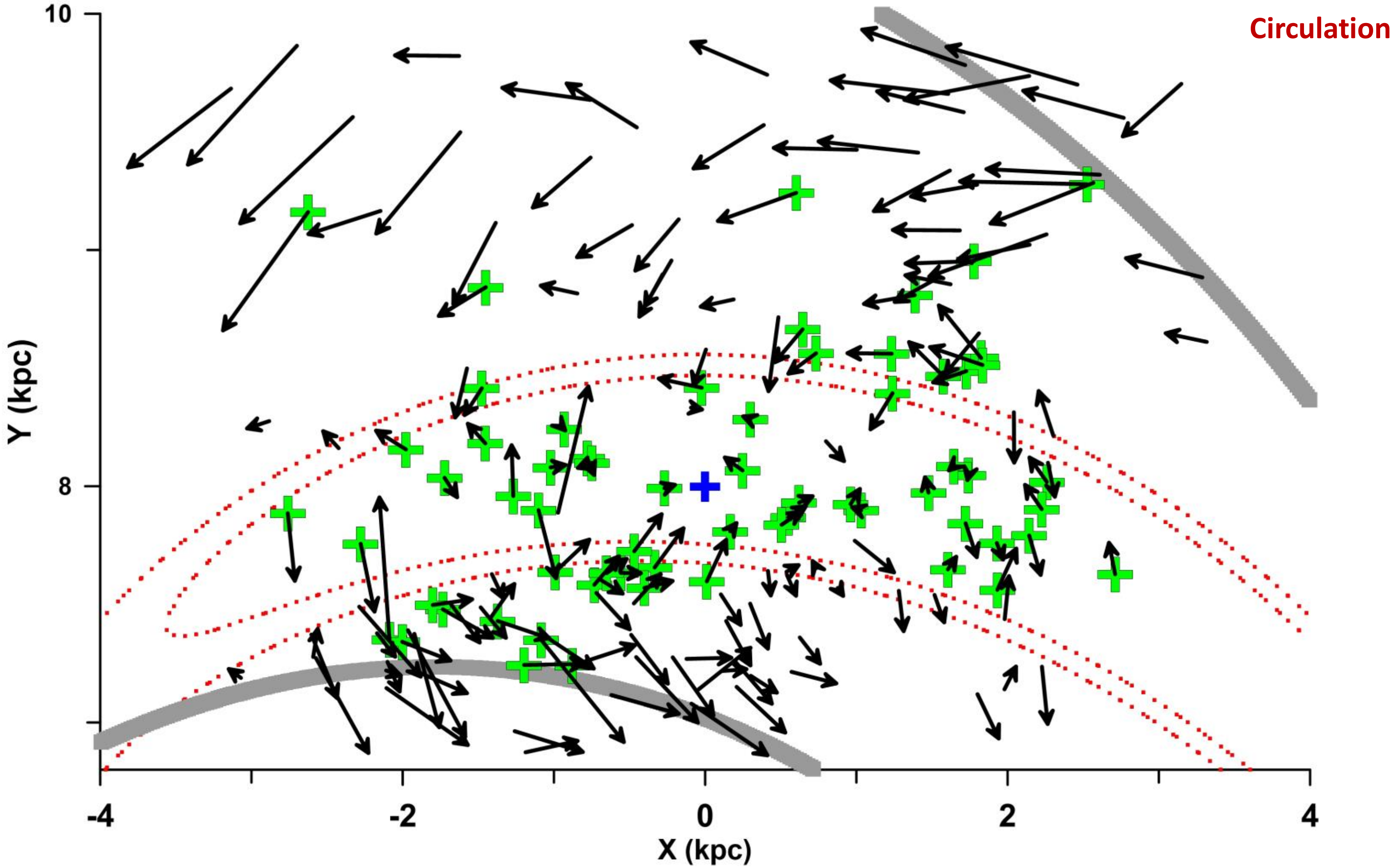
Observed consequences

Circulation of stars

Minimum of U velocity at corotation

Metallicity of Young stars

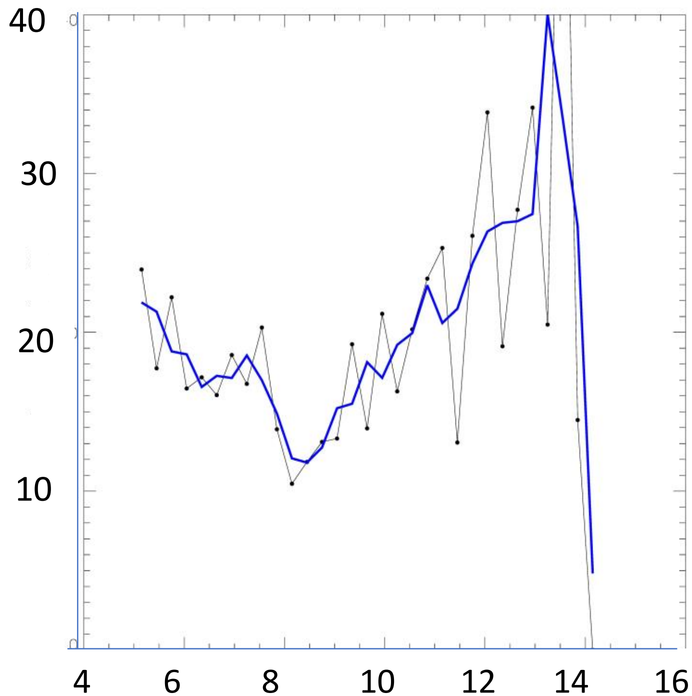
The dip in the rotation curve

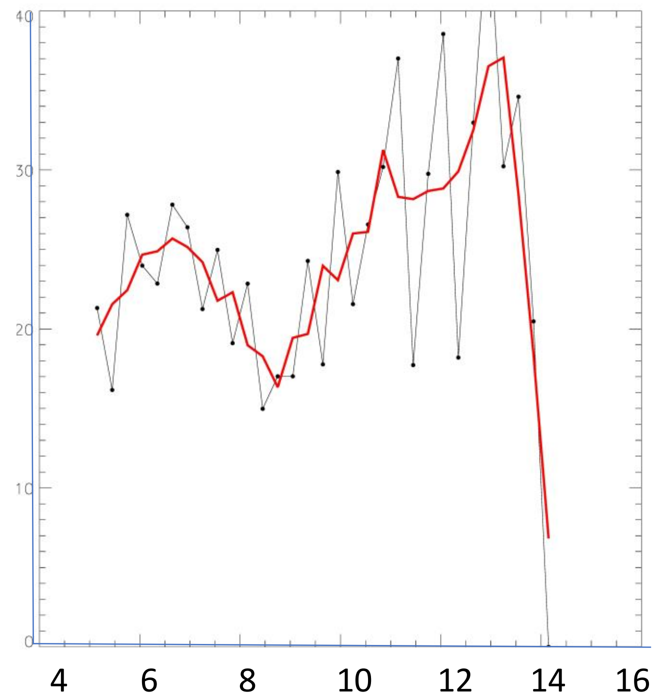


Circulation
10
8
Y (kpc)
-4
-2
0
2
4
X (kpc)

Sample of Cepheids   (available from Vizier)

Average of modulus of U component of velocity and dispersion rms of U component of velocity

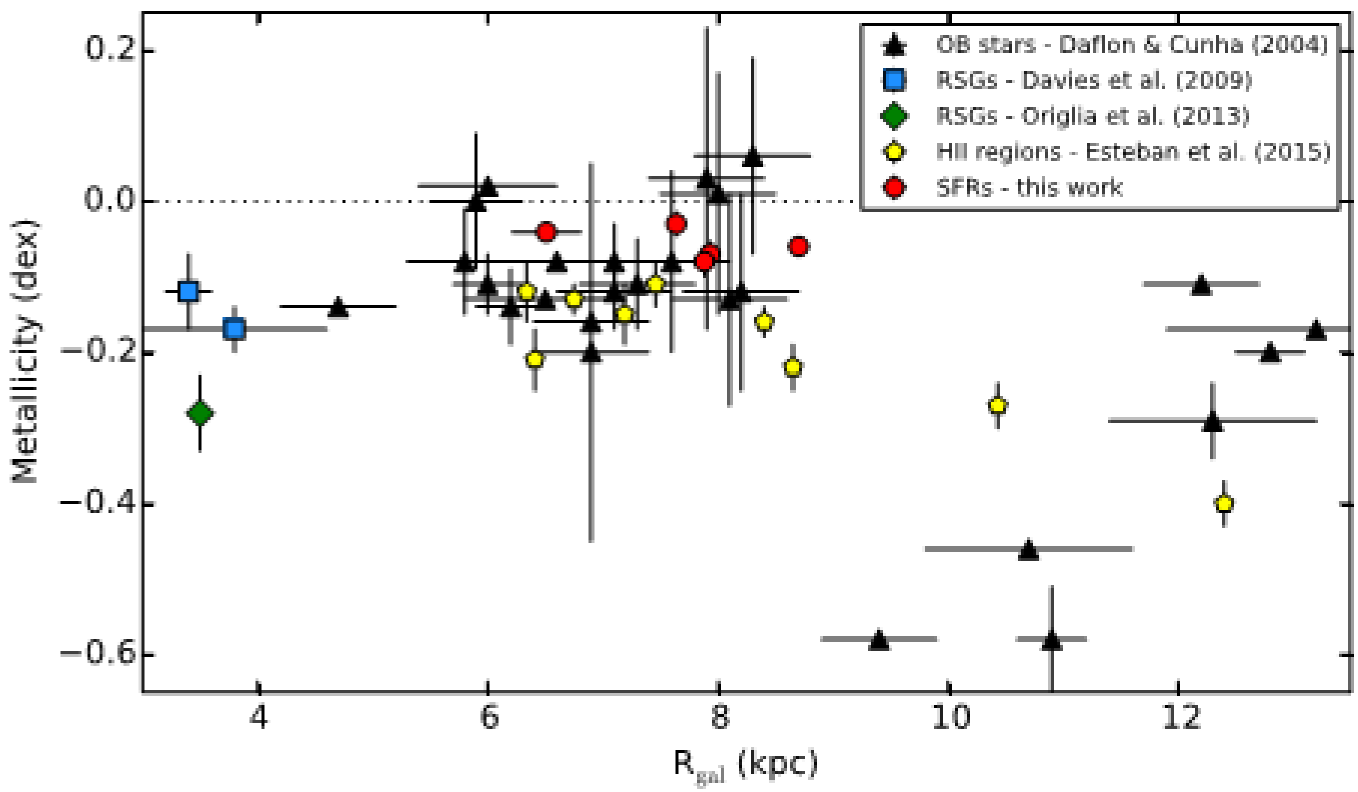




We defined U as the velocity in the galactic radial direction. The circular rotation of the stars does not affect the motion in the radial direction. The minimum at 8 kpc is due to The trapped stars.

Galactic Radial gradient of metallicity from very Young objects

Dramatic drop of about 4 dex at 9 kpc - but not really “galactic Radial”



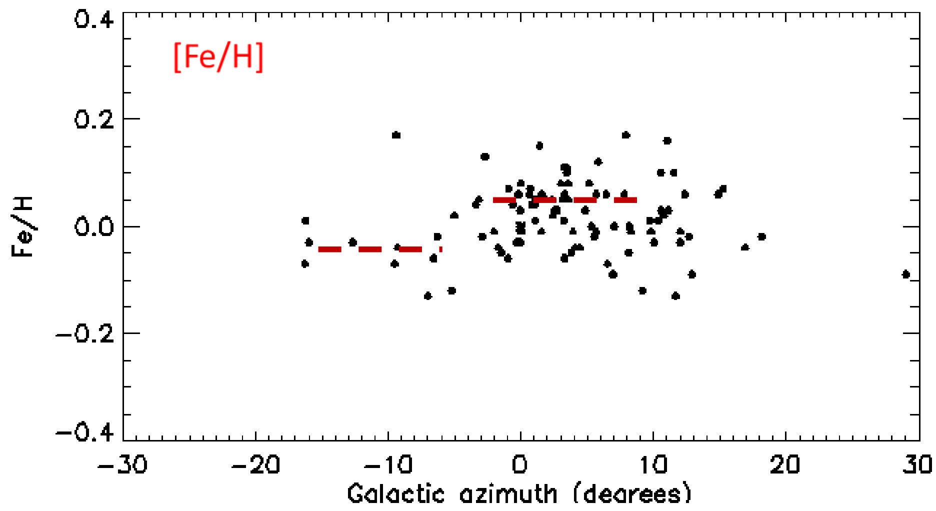
The Gaia -ESO Survey: the present-day radial metallicity distribution of the Galactic disc probed by pre-main-sequence clusters, **L.Spina et al.**, A&A 601, A70 (2017) (Sao Paulo Univ.)

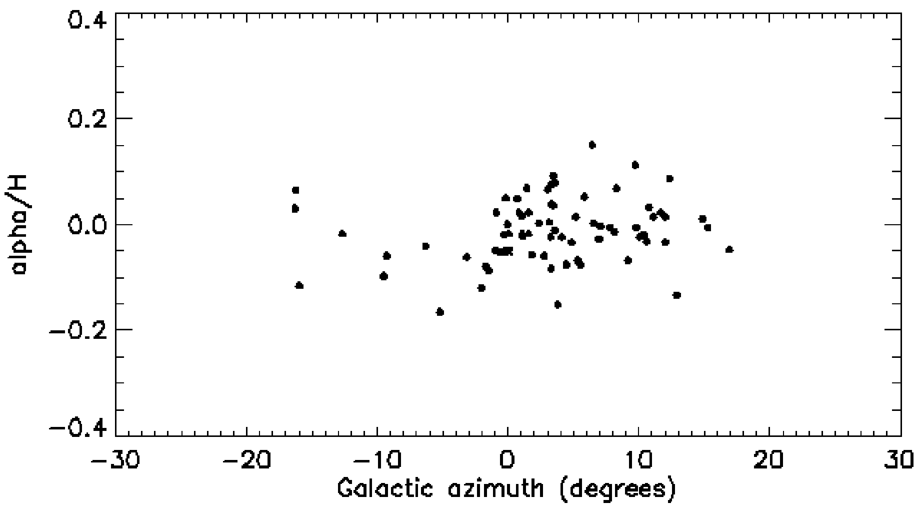
Azimuthal gradient of metallicity

Sample of Cepheids
Azimuth measured from Galactic center
Angle 0 = Direction of anticenter
Analysed: ring from 7 to 9 kpc

[Fe/H]-[Fe/H]solar

Inside corotation stability zone the metallicity is higher



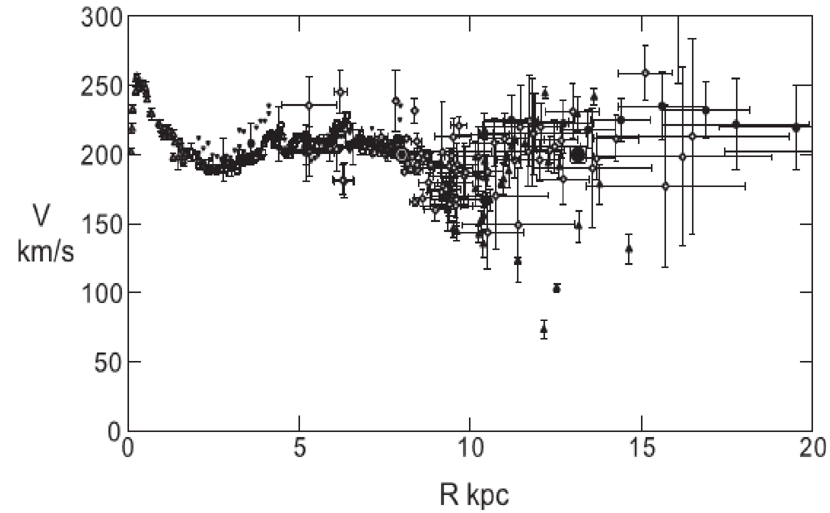


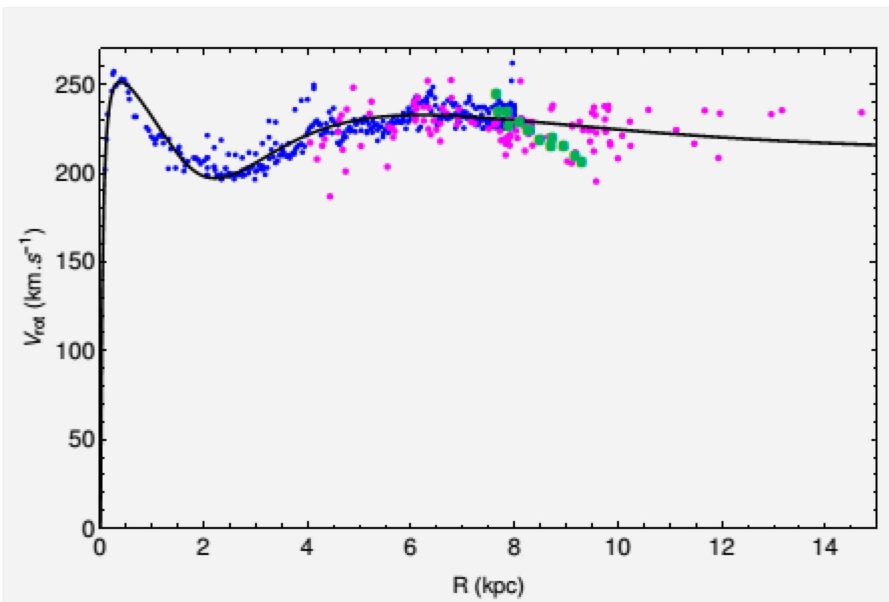
The dip 1) an example of the deep seen by other authors

Unified Rotation Curve of the Galaxy
— Decomposition into de Vaucouleurs Bulge, Disk, Dark Halo, and the 9-kpc Rotation Dip —

Yoshiaki SOFUE,[1,2] Mareki HONMA,[3] and Toshihiro OMODAKA[1]

PASJ: Publ. Astron. Soc. Japan 61, 227–236, 2009





- Blue: HII and CO
- Magenta: masers
- Green: Masers that are liberating In the corotation zone

But it is not a "galactic " dip, only local

Conclusions

Many stars of the solar vicinity and tracers of the Local Arm are trapped in a banana-shaped island of stability around the Lagragian point L4

The results that we obtained are robust, as they remain practically the same if we perform small changes in the adopted parameters of the Galaxy, within the accepted range of uncertainties.

With the parameters adopted, the Sun is also trapped!

We believe that from now on, it will be impossible to ignore the corotation zone, to correctly interpret stellar orbits in the solar vicinity, metallicity gradients, etc.

Future with Gaia
LSR?
Moving groups?
Much more!