SPIRAL STRUCTURES

Nature and comparison with observations

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Reference book:
Galactic Dynamics, J. Binney, S. Tremaine, 2ª Ed., Princeton, 2008 (Chapters 4 and 6)

The nature of spiral arms

70% of external disk galaxies show spiral structure (van Den Berg, 1998).

•Grand design (~10%)

Well defined arms. The arms are easily traced by one turn around the galaxy.

Grand Design
M100

•Multiarmed (~60%)

Combination of defined and flocculent arms.

Multiarmed
NGC6946

•Flocculents (~30%)

All arms are barely defined, and always fragmented.

Flocculent
NGC4414

The nature of spiral arms

The origin and nature of such structures remains uncertain.

Observations only show a snapshot of galaixes life time.

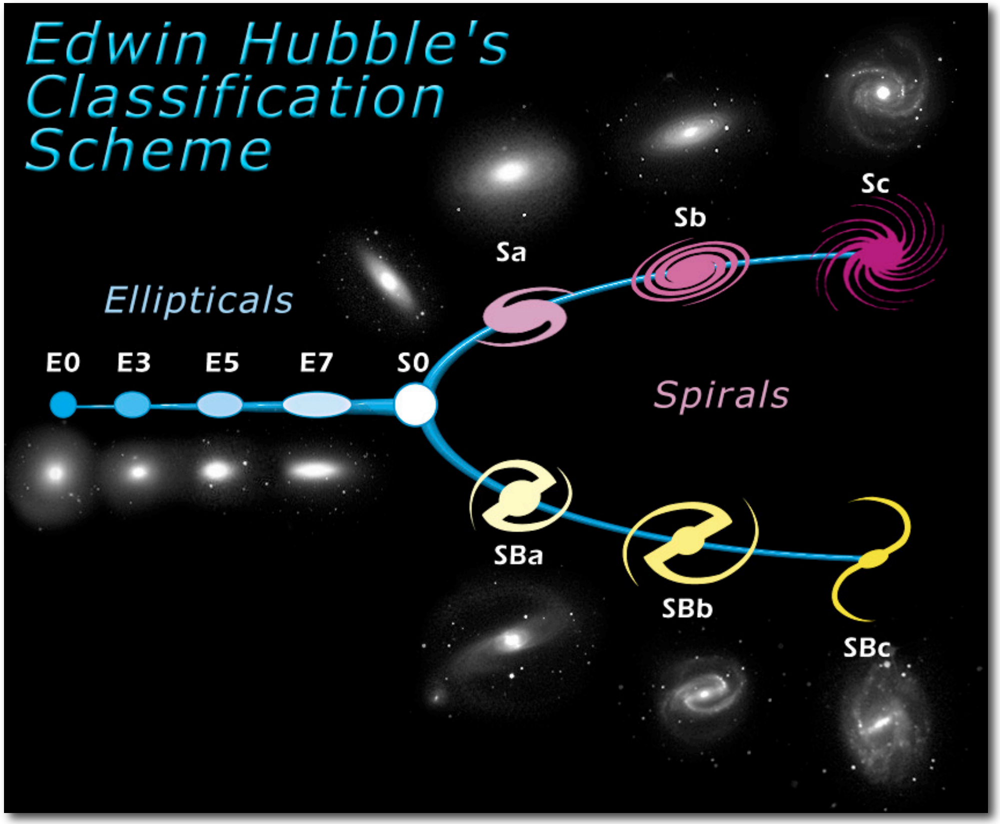
We need theoretical/numerical models to understand how they were formed and how they evolved to the current morphologies.

Theoretical/numerical models need of observables to be well calibrated.

E.g., if 70% of disk galaxies show spiral structure, this should be long-lived, or easy to generate. The models have to reflect this observation.

Observations of external galaxies

The morphology, density/luminosity contrast, number of arms changes from galaxy to galaxy but a coarse classification can be done. Many authors proposed variations of an original morphological classification, the Hubble sequence (Hubble, Sandage, Morgan, de Vaucouleurs).

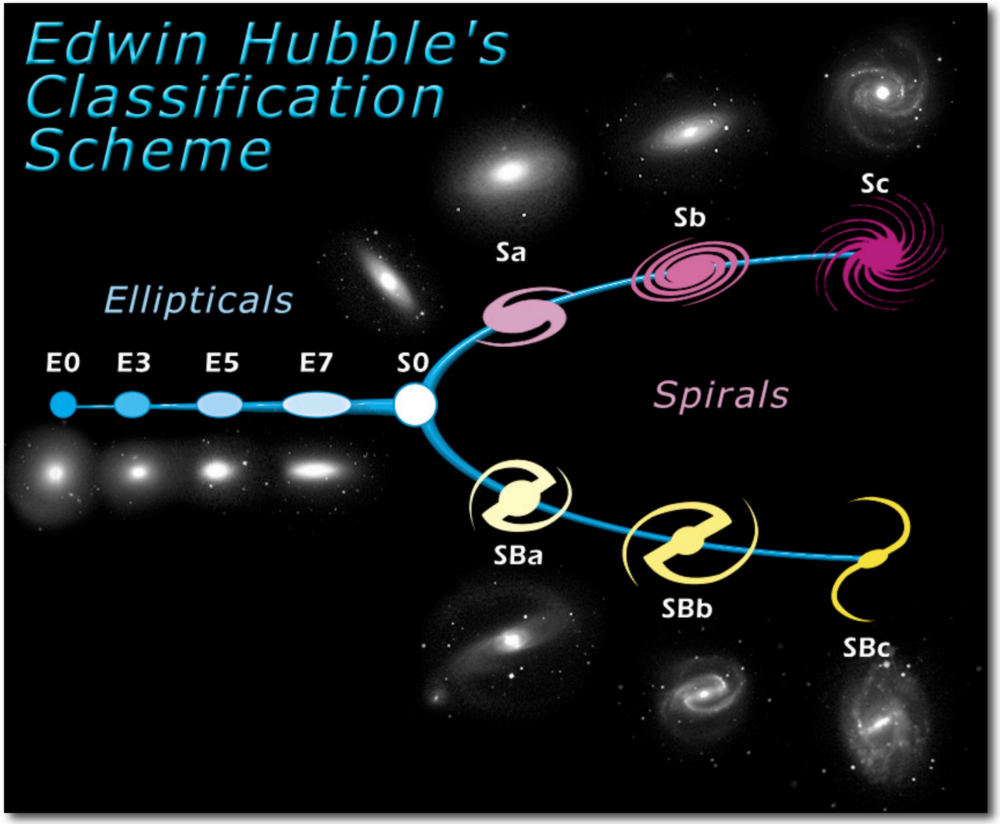


Observations of external galaxies

The morphology, density/luminosity contrast, number of arms changes from galaxy to galaxy but a coarse classification can be done. Many authors proposed variations of an original morphological classification, the Hubble sequence (Hubble, Sandage, Morgan, de Vaucouleurs).

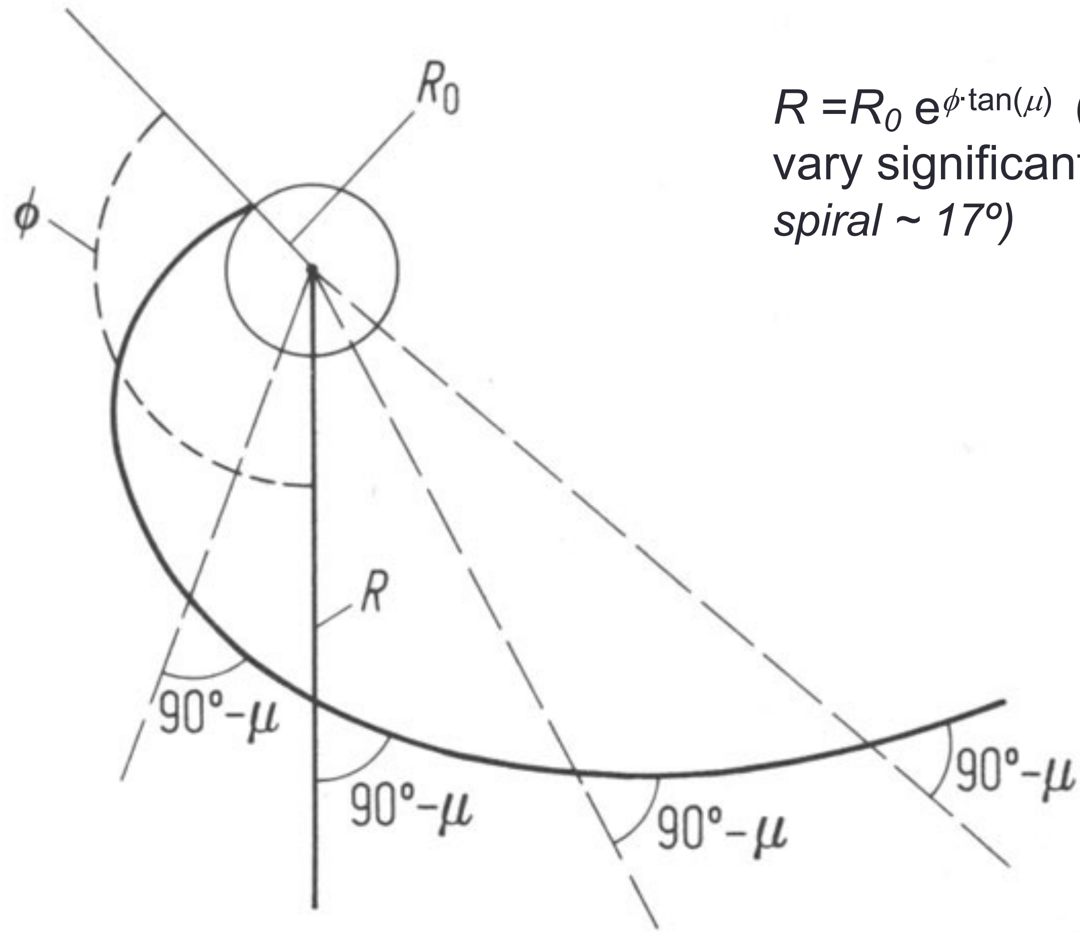
The basics of these clasifications are:

- Bulge to disk luminosity ratio.
- Winding angle (pitch angle)
- How well resolved are the spiral arms in stars and clusters.



Spiral arms properties – pitch angle

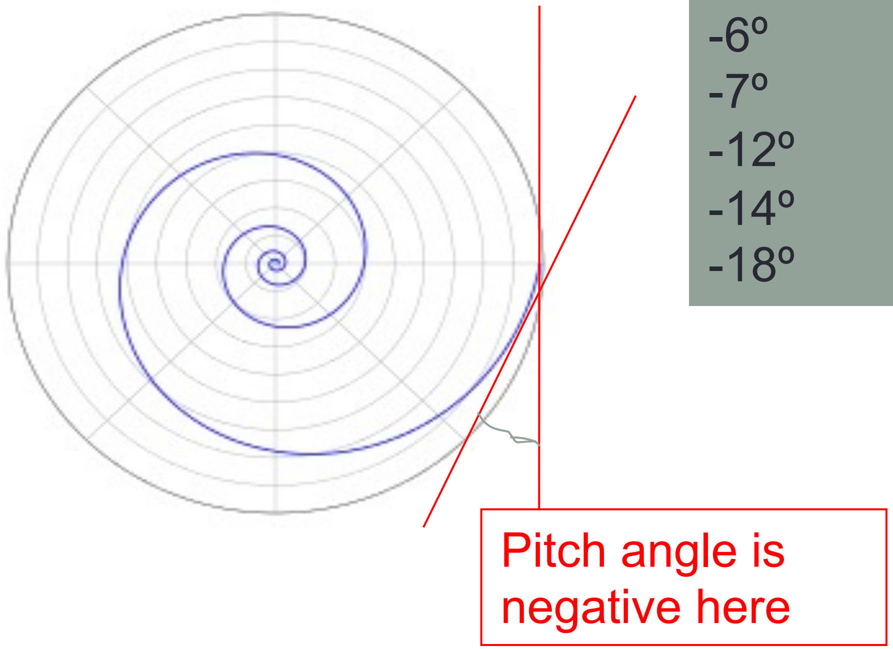
One of the first results obtained from observations of external galaxies is that spiral arms in galaxies can be well represented by a logarithmic function.



$R = R_0\, e^{\phi \cdot \tan(\mu)}$ (where the *pitch angle*, μ, does not vary significantly with R) *(pitch for the Fibonacci spiral ~ 17º)*

Spiral arms properties – pitch angle

Notice that the μ definition (and also the character used to define it) varies a lot in the (e.g., many works use just "i").
Furthermore, to obtain this angle requires of well defined spirals, something not easy to find in real galaxies.



Mean values for the "pitch angle":

-6º	Sa	
-7º	Sab	
-12º	Sb	
-14º	Sbc	- extreme values [-11º,-28º]
-18º	Sc	

Spiral arms properties – Amplitude

From the surface brightness it is not difficult to obtain a definition for the spiral arms' amplitude (A). This amplitude is usually derived from a Fourier series analysis, so, it depends on the number of spiral arms (m).

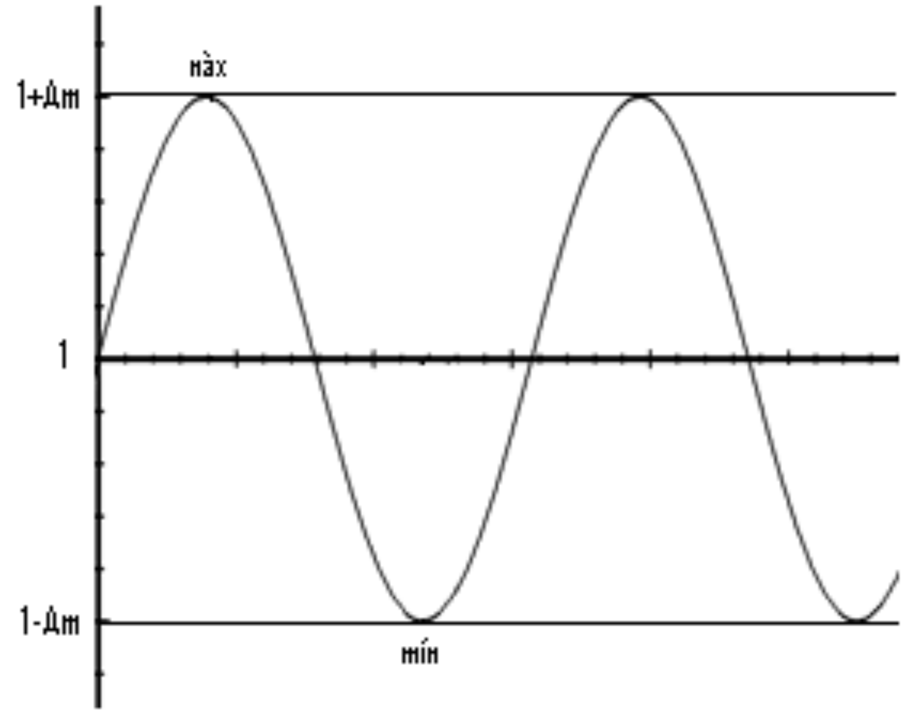
$$\frac{I(R,\Phi)}{\overline{\overline{I(R)}}} = 1 + \sum_{m=1}^{\infty} A_m(R)\cos\left[m(\Phi - \Phi_m(R))\right]$$

$$A_m(R) > 0 \;\; ; \;\; \overline{I(R)} = (2\pi)^{-1}\int_0^{2\pi} I(R,\Phi)\,d\Phi$$

Spiral arms properties – Amplitude

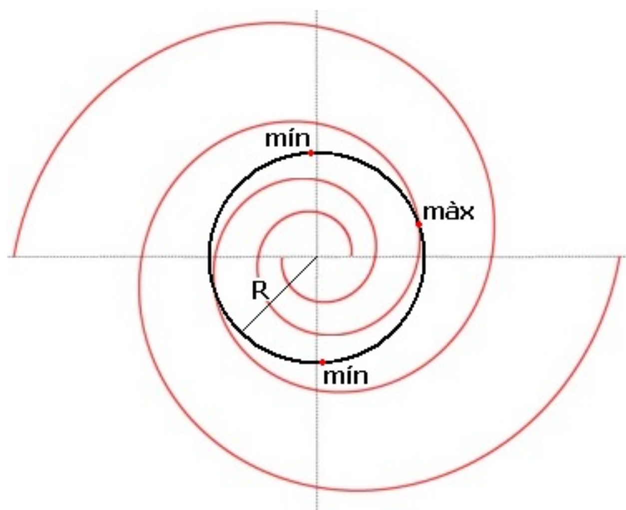
If the dominant mode is A_m, we can define:

$$K = \frac{1 + A_m}{1 - A_m}$$

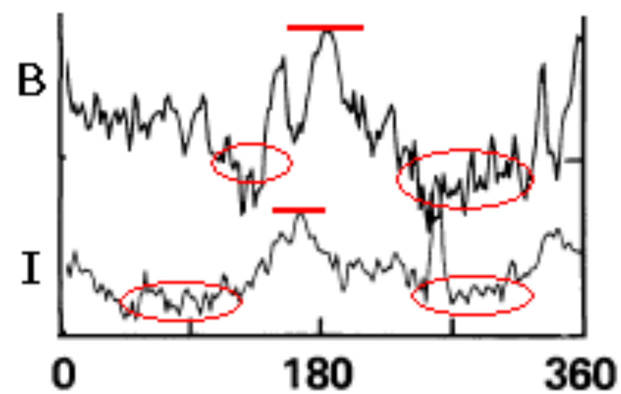


Spiral arms properties – Amplitude

From the relative surface brightness (m in magnitudes) of the B and I photometric filters (Elmegreen & Elmegreen 1984) we can define a new amplitude, now taking into account the difference between the arm and the interarm.



At each radius we have:



$$\Delta m = m_{màx} - \overline{m}_{mín} \approx 2.5\log\left(\frac{N_{\text{braç}}}{N_{\text{interbraç}}}\right) \rightarrow \frac{N_{\text{braç}}}{N_{\text{interbraç}}} = A_i; \quad i = I, B$$

Spiral arms properties – Amplitude

Flocculent: high contrast arm-interarm in the blue band (strong star formation, but not a large stellar overdensity in the arm).
Grand design: similar contrast arm-interarm in both photometric bands (stars accumulate inside the arms, like a pressure wave).

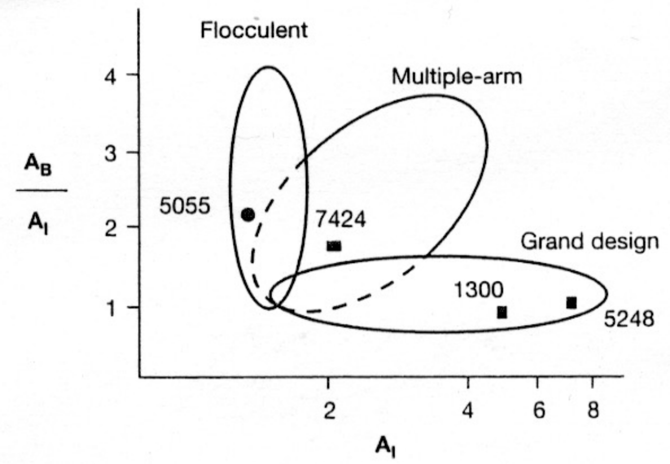
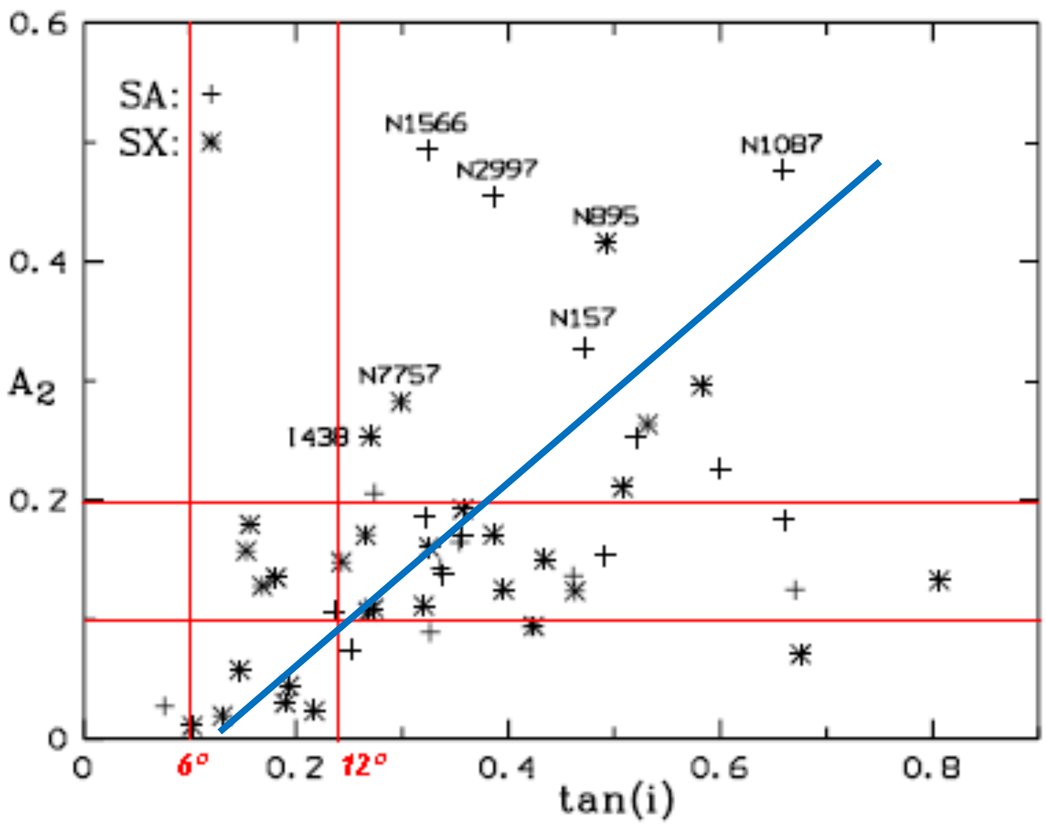


FIGURE 5.19 ***Arm-interarm contrasts in the B and I bands give an indication of the presence and strength of spiral density waves. Maximum contrasts measured for several galaxies are indicated.*** $A_B = 10^{0.4\Delta m_B}$, $A_I = 10^{0.4\Delta m_I}$. ***(Adapted from Elmegreen and Elmegreen 1984.)***

Spiral arms properties – pitch angle vs. Amplitude

- Grosbol (2004) observed 54 spirals in the K band
- Definition for the amplitude A2 = $\frac{k-1}{k+1} = \frac{I_{màx} - <I>}{<I>} = \%$



A2: amplitud in mag/arcsec2 of the second harmonic of the density profile obtained from the Fourier transform (Grosbol 1985, A&AS, 60, 261)

Spiral arms properties – pitch angle vs. Amplitude

To use the B photometric band is dangerous as it is highly affected by interstellar extinction.

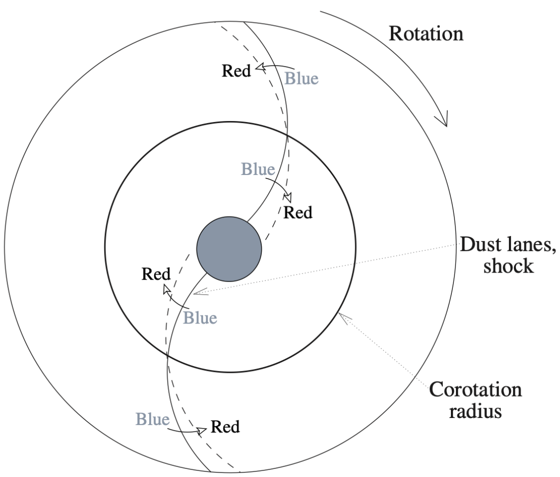
“On the amplitude of spiral arms, I never liked the contrast ratio defined by E&E. The main reasons are that the inter-arm brightness is difficult to determine while the arm intensity may be biased by young stars. Their 1984 paper is based on visual, photographic data which intrinsically have problems. I prefer NIR bands like K which is less affected by dust and young stars. Further, the amplitude of the m=2 FFT component seems to be a better, more robust measure (although also biased)”

Grosbol, 2009

Other spiral arms properties – dynamics (indirect)

The global dynamics of spiral arms structures has been observed in many occasions thanks to recent technological advances.

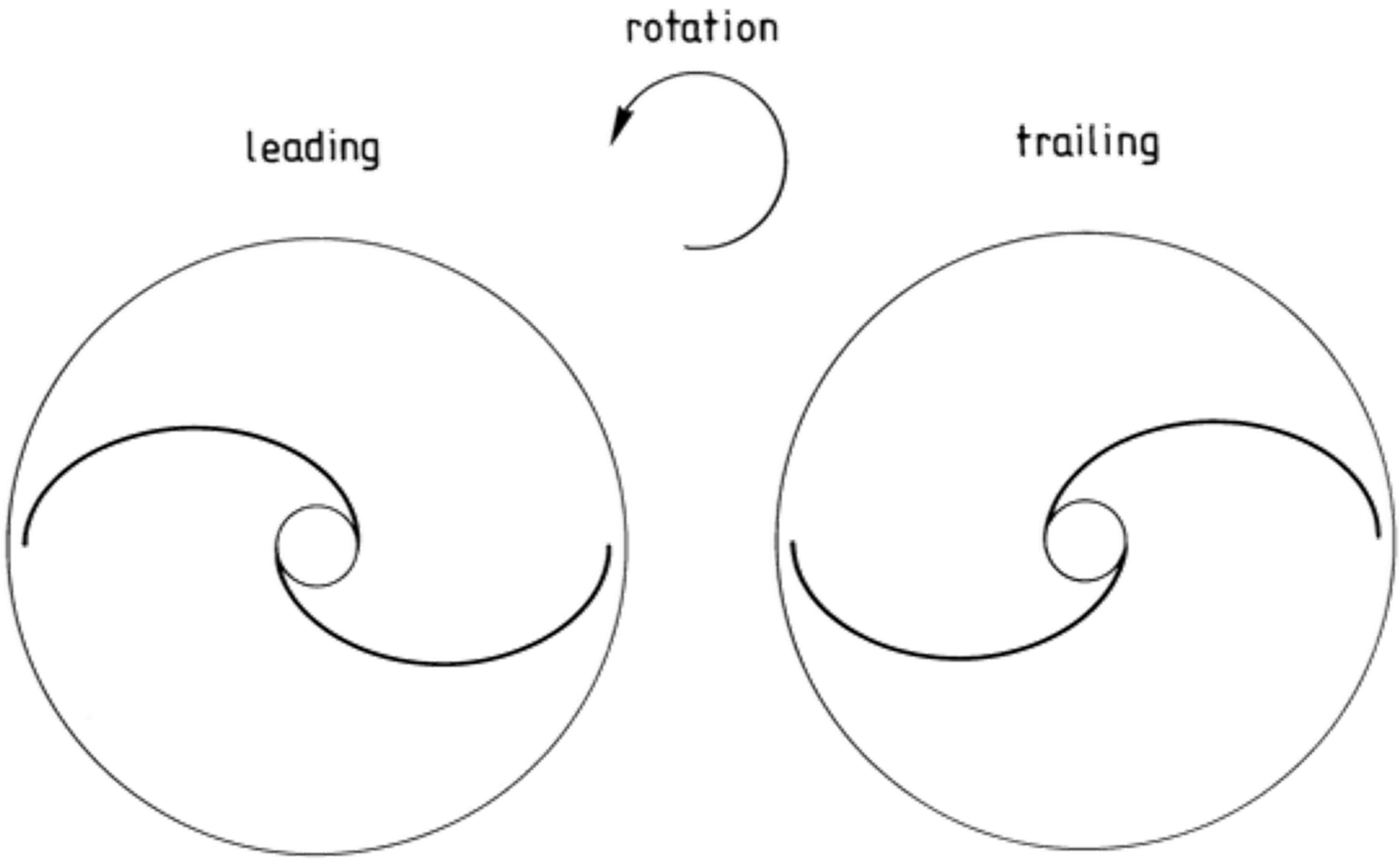
To study the dynamics of spiral arms we can use indirect methods which will give us information on the differences between disk and spiral arms rotation as a function of radius (e.g., observations in different photometric bands), or direct methods (Tremaine-Weinberg).
WARNING! Indirect methods require of theoretical models on the nature of the spiral arms, so results are model (e.g., density wave).



Martínez-García et al. 2009

Other spiral arms properties – dynamics - "Leading vs. trailing"

Depending on the direction of the relative motion of spirals with respect to the stellar disk we can have "*leading*" (the ending of spiral arms points towards the rotation direction) or "*trailing*" (opposite direction).



Other spiral arms properties – dynamics - "Leading vs. trailing"

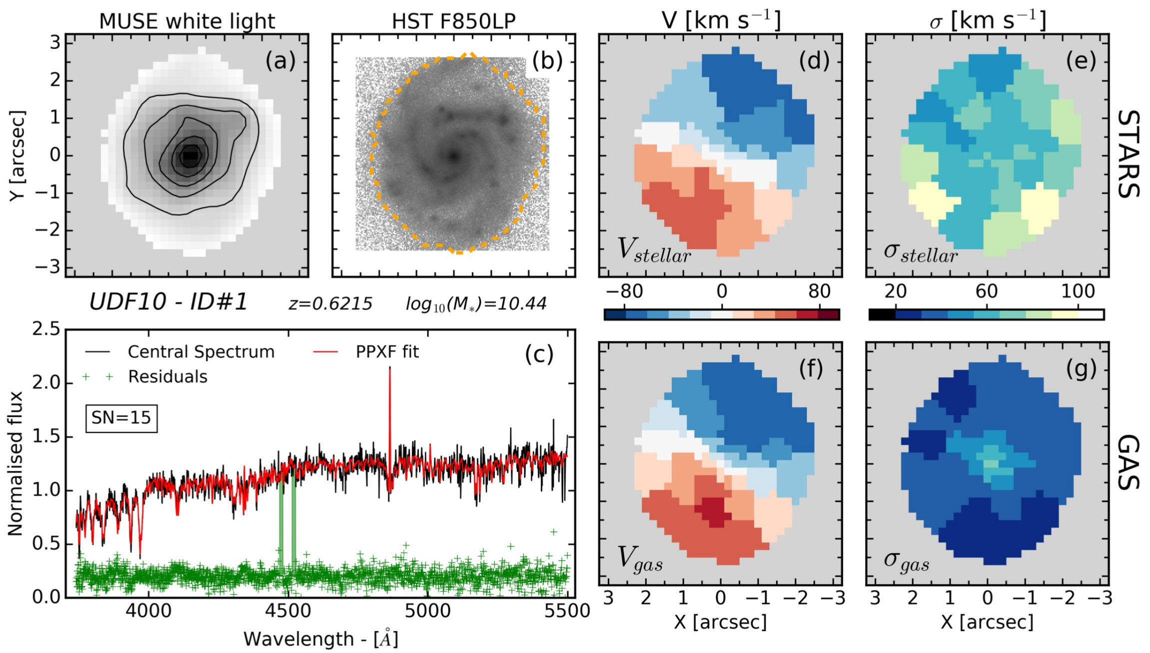
Most spiral arms are "*trailing*" (see Hubble 1943; de Vaucouleurs 1959; Pasha 1985), however, a few examples of "*leading*" spiral arms exist (Pasha 1985; Buta, Byrd, & Freeman 2003). "*leading*" spirals are usually in highly perturbed galaxies (e.g., retrogarde encounters Toomre & Toomre 1972.

NGC 4622 a leading arm spiral (Buta et al 2003)

Physics 315 Spring 2007

Other spiral arms properties – dynamics (~indirect)

Using integral field spectroscopy (IFU) we can find which is the global rotation of the galaxy and from it, applying theoretical models, extract the spiral arms rotation profile.



MEGARA using the IFU

Guérou et al. 2017

Other spiral arms properties – dynamics (direct?)

The only direct method currently available to obtain the spiral arms' rotation radial profile from observations of external galaxies is the Tremaine-Weinberg method (T&W1984):

It is possible to measure the pattern speed Ω_p of a barred disk galaxy without employing any particular dynamical model. The main assumption required is that the luminosity density of the tracer (stars, neutral hydrogen, etc.) obey a continuity equation, i.e., that the total mass of tracer remain fixed and the apparent luminosity per unit mass be constant. In its simplest form, the method requires measuring the surface brightness and radial velocity along a strip parallel to the line of nodes. If position and velocity are measured relative to the galactic center, then the luminosity-weighted mean velocity in the strip, divided by the component of the luminosity-weighted mean position vector which is parallel to the line of nodes, is equal to $\Omega_p \sin i$ (cf. eq. [7]).

https://ui.adsabs.harvard.edu/abs/1984ApJ...282L...5T/abstract

Deriving spiral arms' pattern speed

The method uses an analytical derivation of the relation between the mean velocity along the minor axis (mass-weighted), the mean position along the major axis, and the non-axisymmetric structure (spiral arms) angular velocity Ω_p. This relation only occurs if the stars follow the continuity equation, i.e., if they have long life compared with their orbital period.

$$\Omega_\mathrm{p} = \frac{\int_{-\infty}^{\infty} \mathrm{d}x\,\Sigma v_y}{\int_{-\infty}^{\infty} \mathrm{d}x\,\Sigma x}$$

where $v_y = v_\parallel / \sin i$

It can be re-writen as:

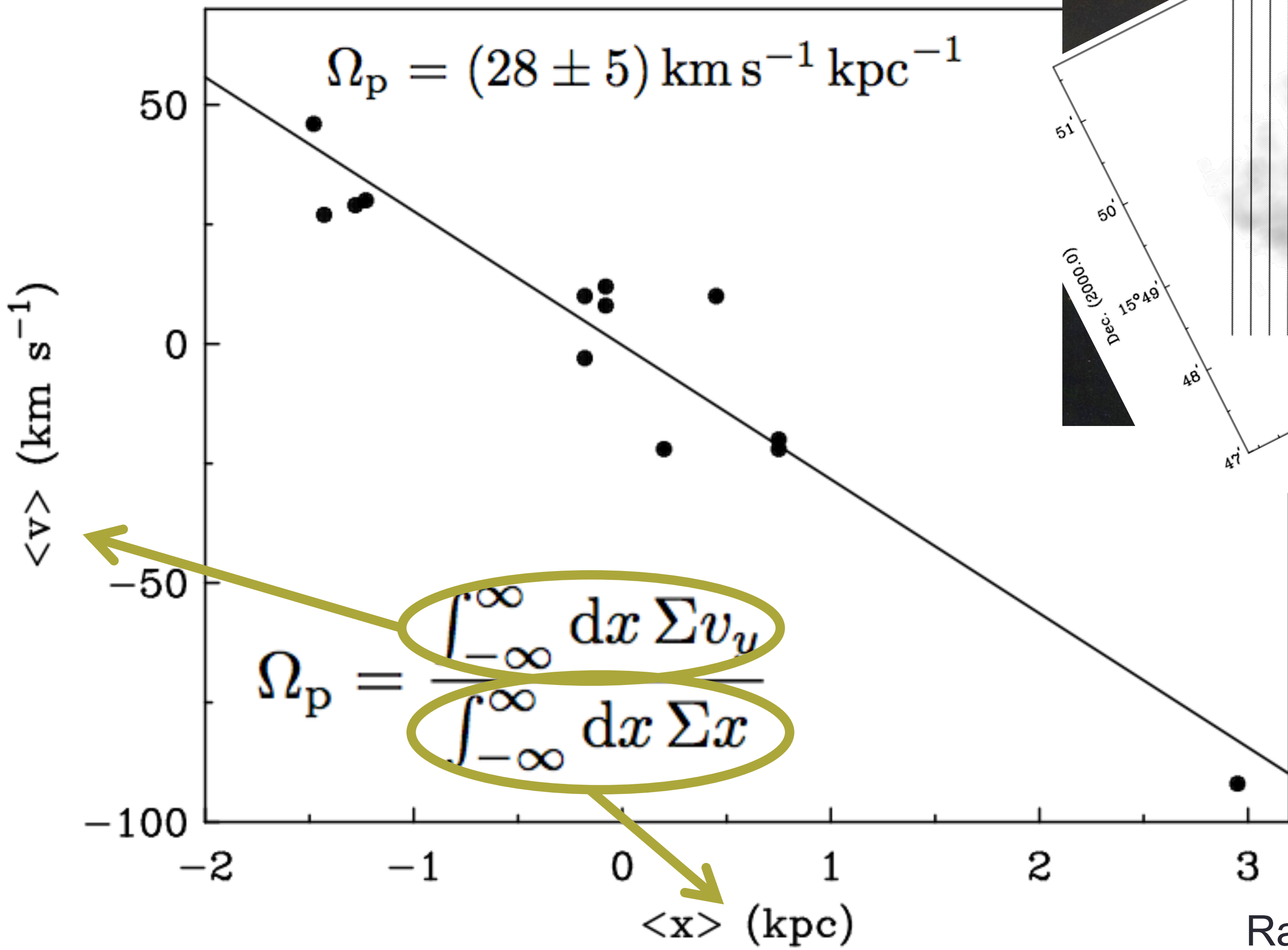
$$\Omega_p \sin i = \frac{\int_{-\infty}^{\infty} \Sigma(X,Y) V_\parallel dX}{\int_{-\infty}^{\infty} \Sigma(X,Y) X dX}$$

If the light from these stars traces the total mass surface density Σ, then:

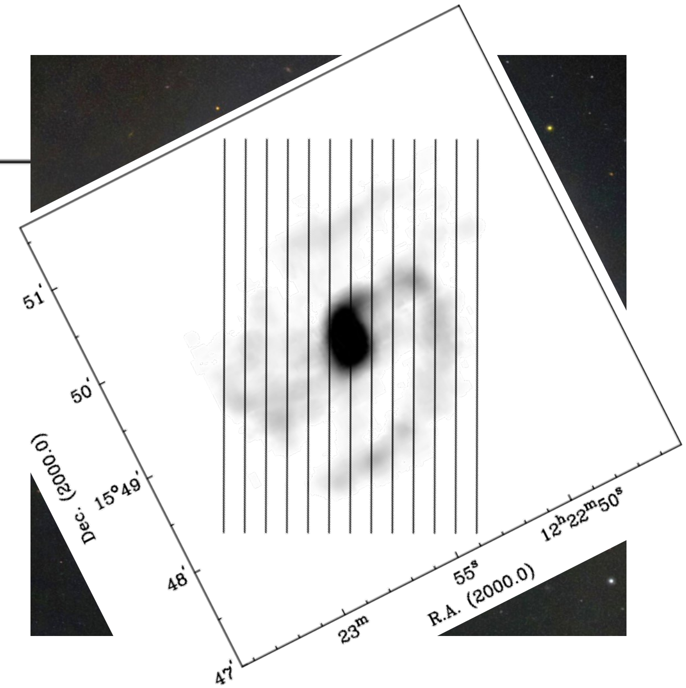
$$\Omega_p = \frac{1}{\sin i} \frac{\int_{-\infty}^{\infty} I(X) V_\parallel dX}{\int_{-\infty}^{\infty} I(X) X dX}$$

Deriving spiral arms' pattern speed

4) Tremaine & Weinberg (1984):



$$\Omega_p = \frac{\int_{-\infty}^{\infty} dx\, \Sigma v_y}{\int_{-\infty}^{\infty} dx\, \Sigma x}$$



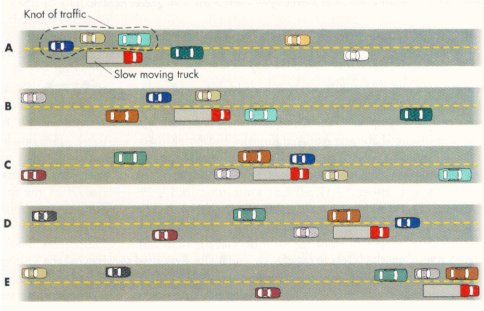
Rand & Wallin (2004)

Other spiral arms properties – kinematics (stellar)

To obtain **observations of local stellar kinematics** in external galaxies, and how spiral arms affects it **is still difficult, impossible in many cases**.

Using spectroscopy and high precision proper motions has been possible, recently, to get a global distribution of stellar kinematics in Local Group galaxies.

In any case, **results are not conclusive** on the kinematic differences between stars that move inside, close, and outside the spiral arms. Currently we **only have theoretical predictions** on how kinematics could help us to understand the **spiral arms nature and evolution**.



Which is the nature of spiral arms?

The nature of spiral arms

“The nature of spiral arms” can be defined by a combination of physical properties including its effect over the stellar disk of their host galaxy.

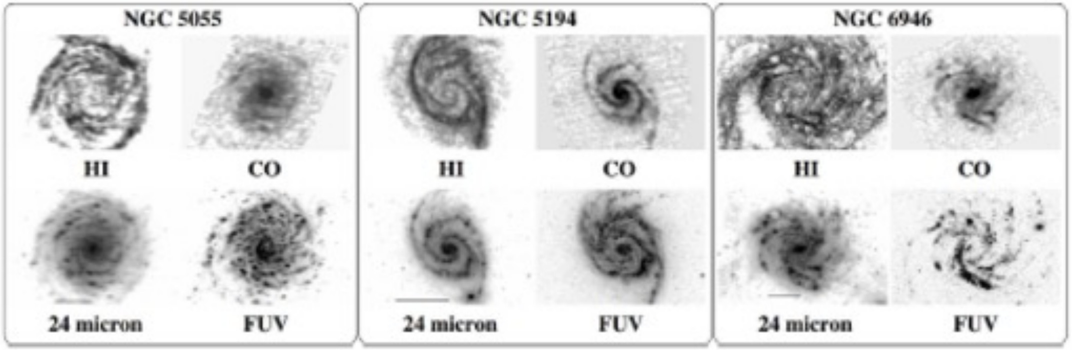
We can distinguish between three broad definitions of spiral arms’ nature predicted by theories and numerical models :

- Material
- Density wave (material vs. non-material)
- Star forming

The nature of spiral arms *(trailing)*

It is usual that external galaxies show many spiral structures with evident differences in morphology and physical properties. This makes the study of spiral arms' nature more complicated. However, some characteristics of those individual structures allow us to determine their nature:

- Stellar kinematics (stars inside the spiral arm vs. all following disk kinematics)
- Dynamics (radial rotation profile)
- Lifetime
- Arm-interarm contrast / amplitud (as a function of photometric band)



Martínez-García et al. (2014)

The nature of spiral arms (trailing) – Stellar kinematics

- Material:
  - A single kinematic stellar population: Stellar disk. Stars that cross the spiral arm.

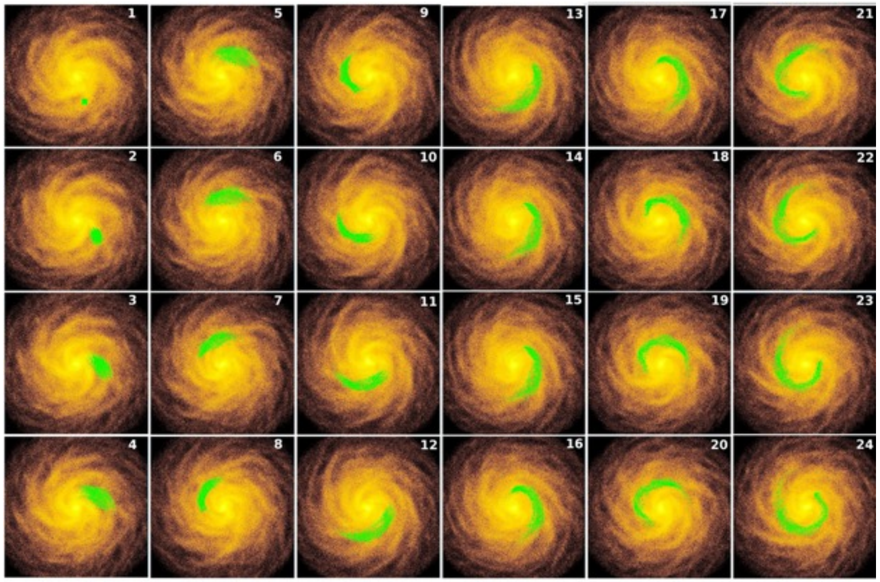
- Density wave - materials:

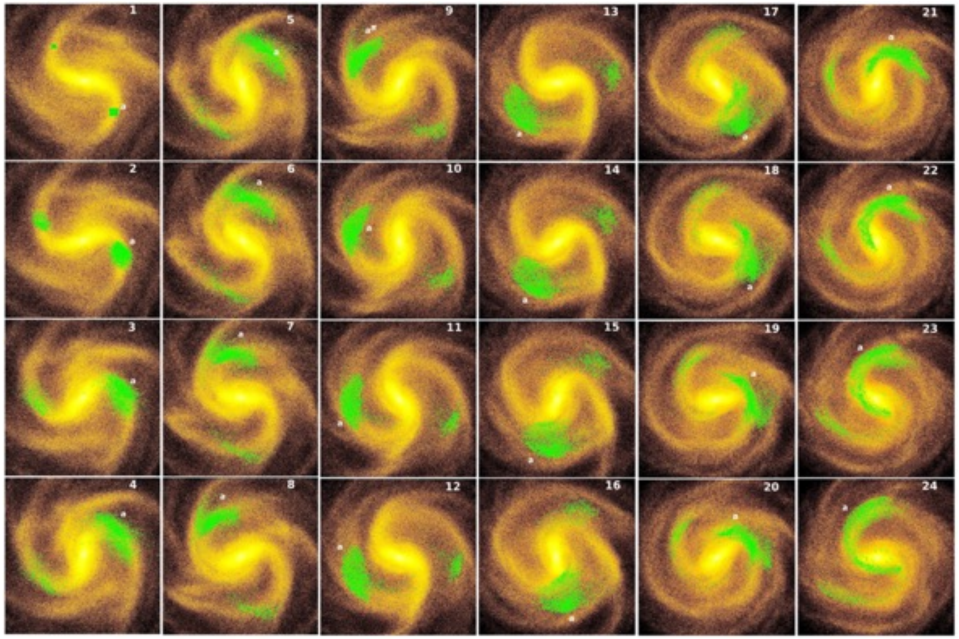
  - Two kinematic stellar populations coexist in the arm region:
    a) Stellar disk. Stars that cross the spiral arm.
    b) Stars that truly belong to the spiral arm. They move along the spiral structure towards the external regions of the galaxy.

- Density wave - pure:
  - A single kinematic stellar population: Stellar disk. Stars that cross the spiral arm.

- Star forming:
  - A single kinematic stellar population: Stellar disk. Stars that cross the spiral arm.

The nature of spiral arms (trailing) – Stellar kinematics



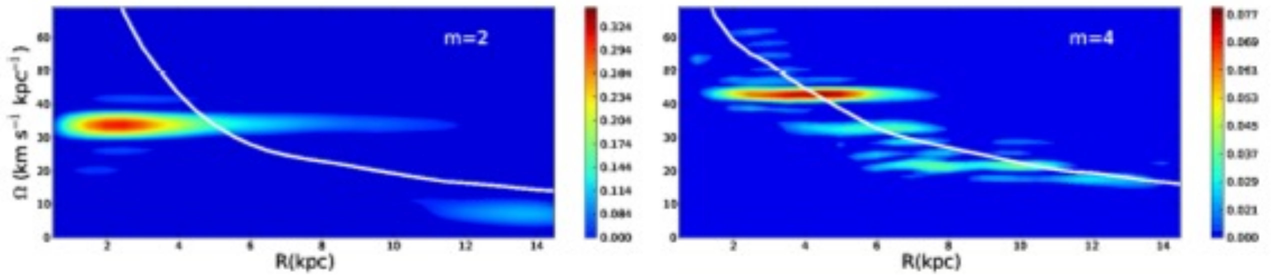


The nature of spiral arms *(trailing)* – *Dynamics*

- Material:
  - Its radial rotation profile is the same as the one of the stellar disk (corotation).

- Density wave - (material and pure):
  - The spiral structure moves across the disk in a rigid body rotation (slower than stars inside corotation and faster than stars in the outer regions)

- Star forming:
  - Its radial rotation profile is the same as the one of the stellar disk (corotation).



Roca-Fàbrega+13

The nature of spiral arms (trailing) – Lifetime

- Material:
  - Short lived, less than one galactic rotation (“winding problem”)

- Density wave - material:
  - Their lifetimes are linked with the lifetime of the perturbation that generated them (bar, merger, ...).

- Density wave - pure:
  - They can live forever if the perturbation that generated them is kept active.

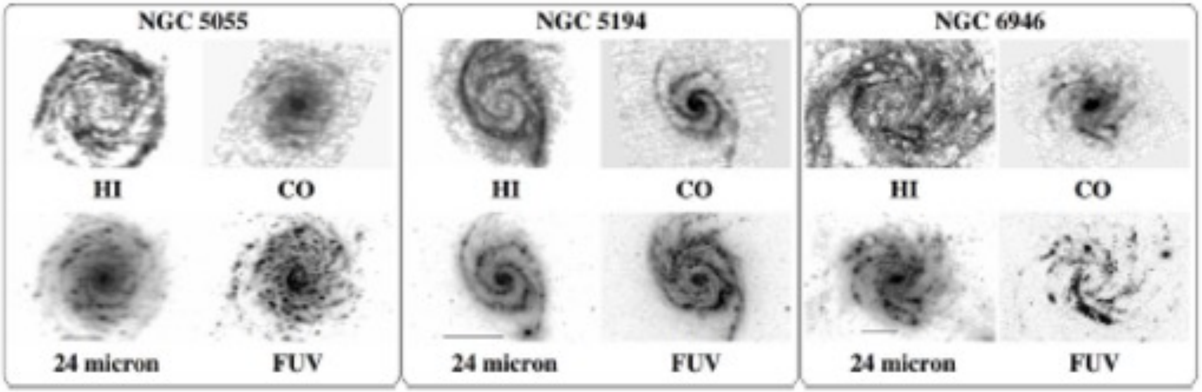
- Star forming:
  - Short lived, less than one galactic rotation. In addition, these only show up while star formation is active in the region.

The nature of spiral arms (trailing) – Arm-interarm contrast

- Material:
  - Low contrast both in the blue and red photometric bands.

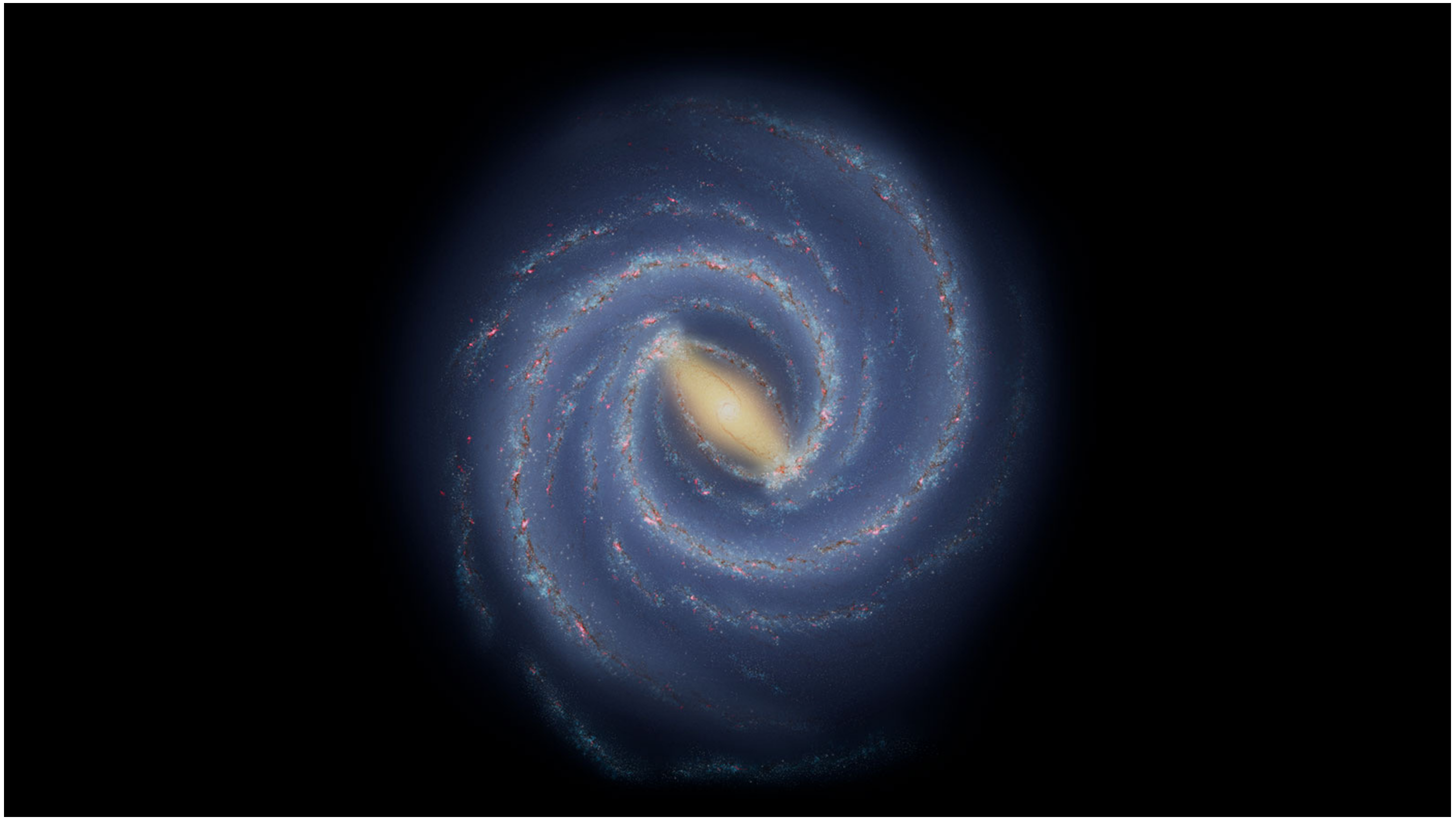
- Density wave (material and pure):
  - Strong contrasts in both, the blue and the red photometric bands. The blue peak is not in phase with the red peak (star formation in shocks vs. density peak).

- Star forming:
  - Strong contrast in the blue, no contrast in the red.



Martínez-García et al. (2014)

The Milky Way's spiral arms



MW spiral arms – pre-Gaia

First detection of a density structure compatible with spiral arms in the Milky Way by **Oort, Kerr and Westerhout** in **1958**. They observed it from **HI gas emission**.

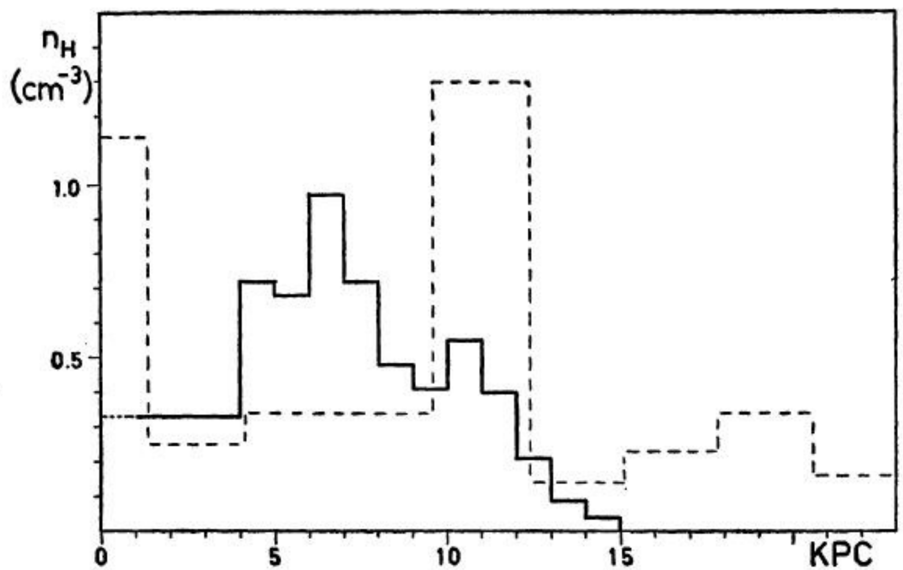


FIG. 5.—*Variation of average density in the galactic plane with distance from the centre* (6), *and comparison with the Andromeda nebula* (17) (*dotted line*).

Oort, Kerr and Westerhout (1958),

"The galactic system as a spiral nebulae"

Distances obtained from radial velocities assuming that the gas velocity comes from circular motions in an axisymmetric potential at a distance r from the Galactic center.

MW spiral arms – pre-Gaia

The results by Oort et al. were polemic. **Uncertanties in distances** were so big that no conclusion could be obtained from the HI density radial profile.

Nowadays to get **distances** is still one of the largest problems in galactic astrophysics as we need them to determine properties and position of the large scale structures in the Milky Way.

In 2022, still with Gaia-DR3 we are far to determine the position of all stellar density structures in our Galaxy.

The current picture of the Milky Way's large scale structures comes mainly from **observations of emission lines from ionized gas, the position of young bright OB stars, and the position of variable stars (e.g., cepheids).** These methods have shown useful to detect the **position of the star forming regions,** but not to get a direct confirmation of where the overdensities are.

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2005AJ....130..659A/abstract

Stellar extinction empirical model by Amores & Lapine 2005

After the publication of a large number of observations of gas and dust in the Milky Way it was proposed to create an extinction model of the Galaxy.

The aim was to get a map of the MW gas structures and also of the large scale motions in the Milky Way.

Available observations:

→survey HI (Berkeley & Parkes)

→survey CO (Columbia Unversity),

→IRAS 100 μm

→Radial velocities of the HII regions

Models:

combination of logarithmic spirals

Conclusion:

The Milky Way is a complex system with bifurcations ,spureous spirals, etc.

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2005AJ....130..659A/abstract

Stellar extinction empirical model by Amores & Lapine 2005

<u>Results</u>

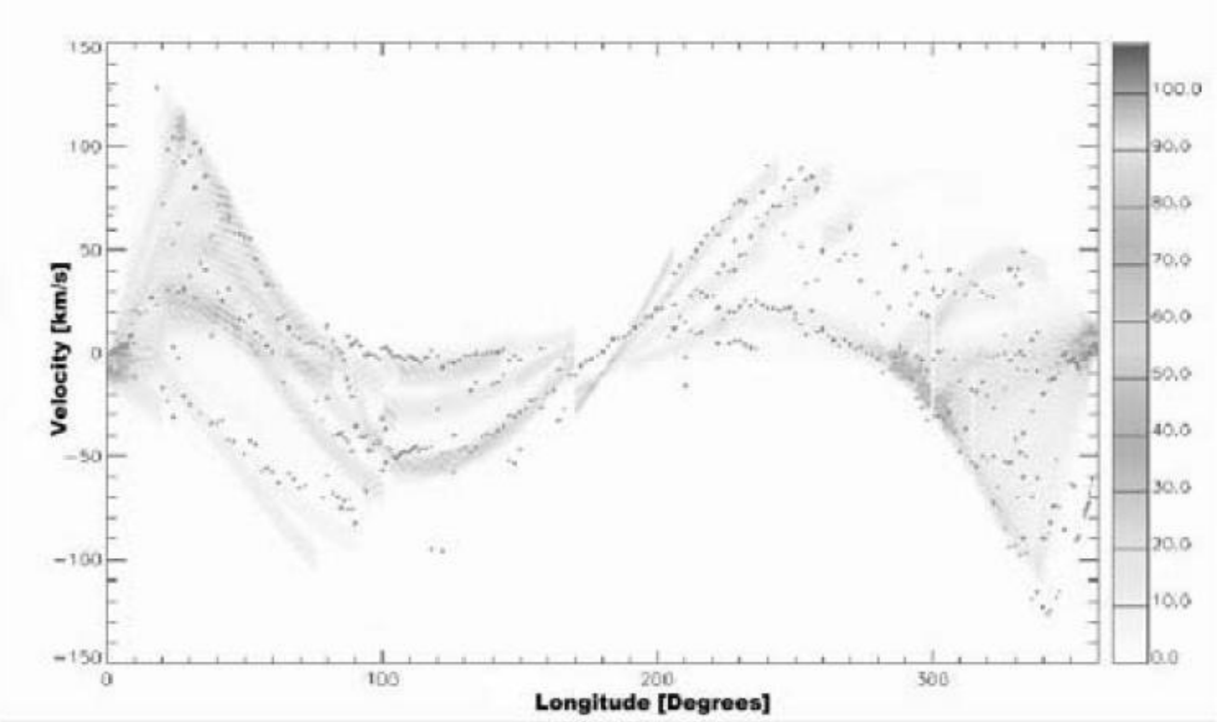


Figure 2. Comparison between the l-v diagram predicted (map) and the observed (the points represented adjusting realized from observed spectra at each one degree in longitude and represent the velocities which the great peaks in intensity of the gas for each longitude).

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2005AJ....130..659A/abstract

Stellar extinction empirical model by Amores & Lapine 2005

Results

Galactic longitude vs. Radial velocity

HII regions

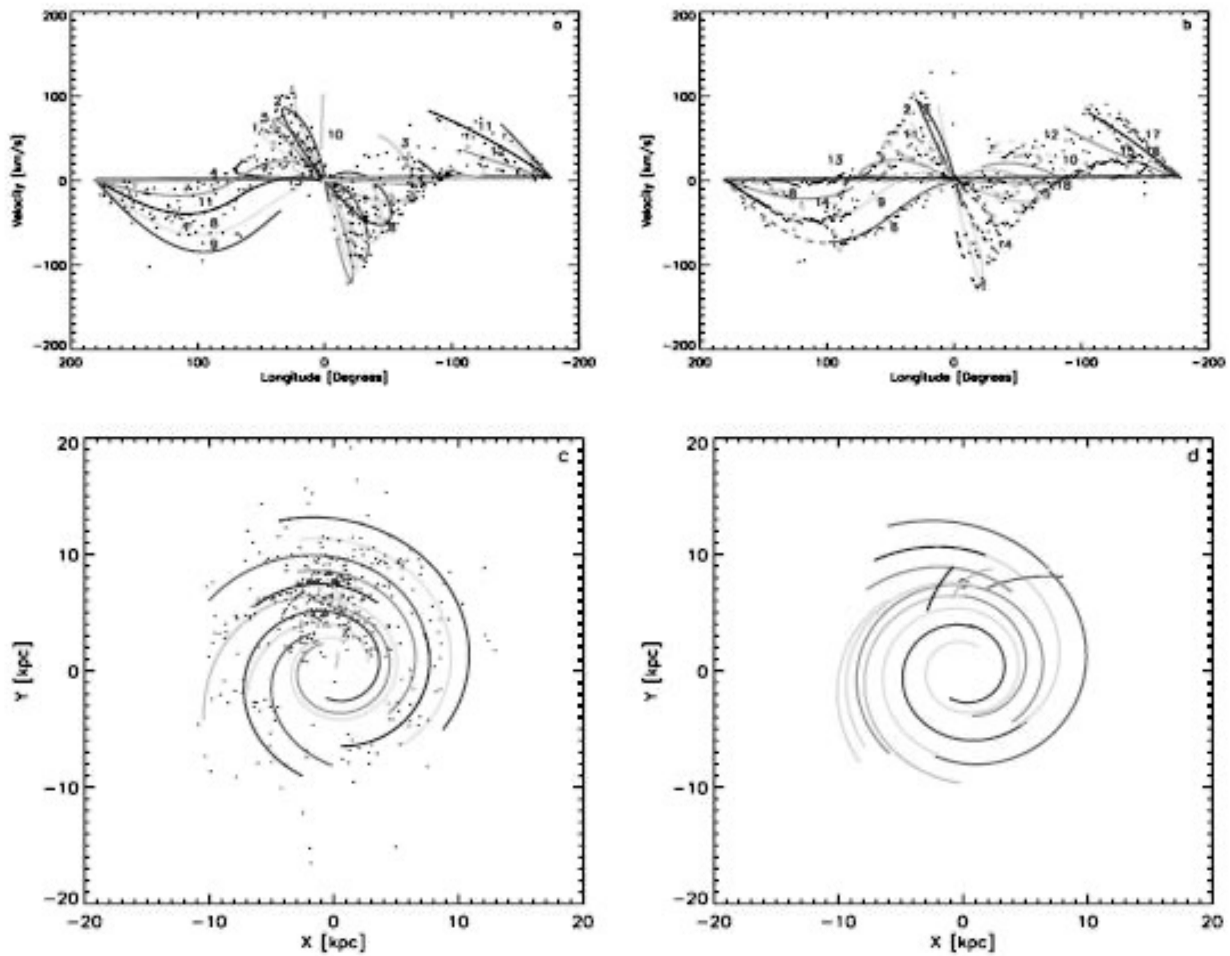


FIG. 6.—*Top*: *l*-*v* diagrams for (*a*) H II regions and (*b*) H I. *Bottom*: Face-on (*c*) H II regions and (*d*) H I. The lines represent the spiral arms, and the points are described in the text. The parameters of the arms are given in Tables 2 and 3.

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2005AJ....130..659A/abstract

Stellar extinction empirical model by Amores & Lapine 2005

Results

TABLE 2
MAIN PARAMETERS OF THE SPIRAL ARMS TRACED BY MOLECULAR HYDROGEN (DUST) USED IN THE SPIRAL MODEL

Arm	Tangential Directions (deg)	Pitch Angle (deg)	Initial Radius (kpc)	Initial Phase (deg)	Arm Extension (deg)	Peak Density (cm^{-3})	Width (kpc)
1	32.07/−52.6	12.3	2.40	165.0	360	2.05	0.14
2	49.0/−26.1	7.0	2.70	340.0	380	0.1	0.13
3	−70.0	13.8	6.50	353.0	120	6.0	0.08
4	−34.2	13.5	3.65	30.0	150	10.0	0.14
5	−21.4	7.5	2.50	20.0	345	0.50	0.06
6	24.1/−44.7	11.7	2.90	285.0	180	1.00	0.08
7	71.0/−88.0	6.0	6.80	330.0	80	24.0	0.04
8		10.1	7.10	240.0	140	0.8	0.13
9		7.0	8.40	220.0	140	2.0	0.13
10		8.0	7.50	330.0	40	4.0	0.08
11	−57.13	10.0	7.90	290.0	130	10.0	0.15
12		10.0	5.70	5.0	150	1.25	0.14
13		55.0	5.10	345.0	15	10.0	0.13
14	41.1	6.2	6.50	185.0	110	30.0	0.13

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2008ASPC..387..375B/abstract

Infrared observations (Spitzer – Benjamín et al. 2009)

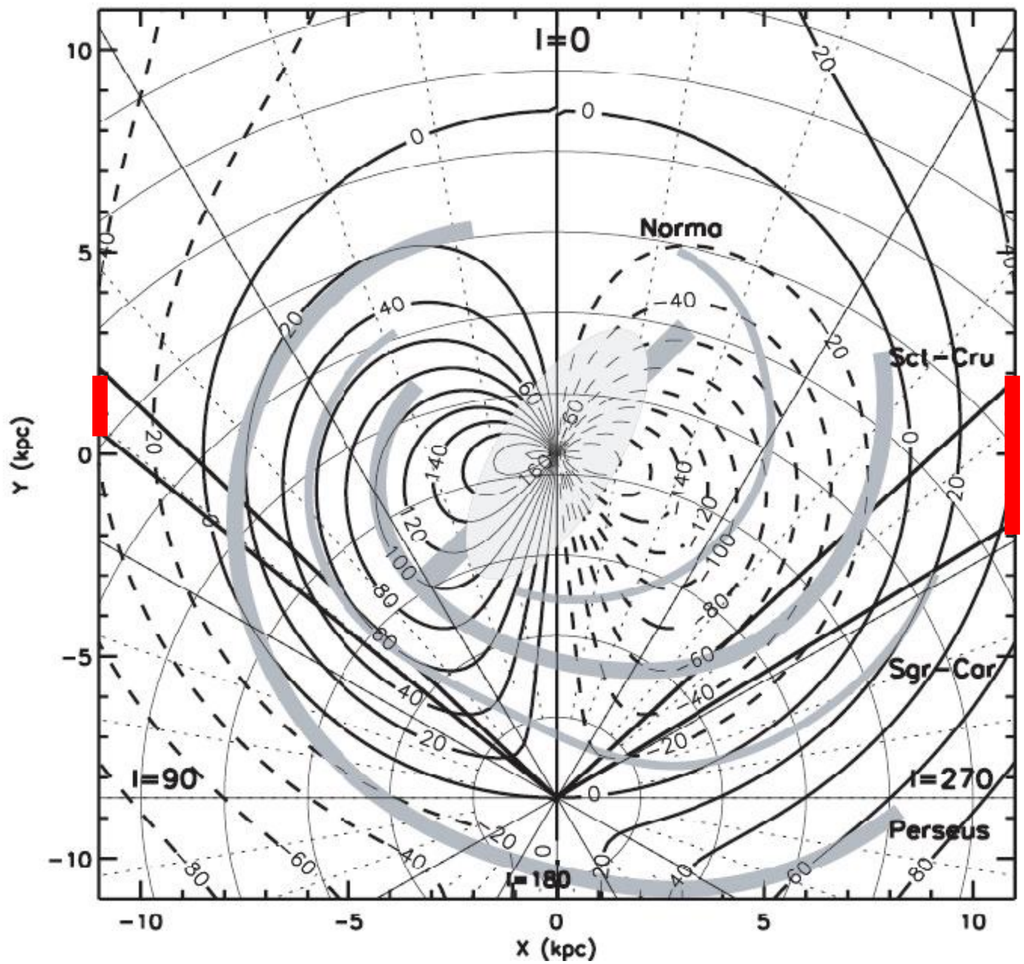
<u>Optical vs. Infrared</u>

MW spiral arms – pre-Gaia

https://ui.adsabs.harvard.edu/abs/2008ASPC..387..375B/abstract

Infrared observations (Spitzer – Benjamín et al. 2009)

Results



MW spiral arms – pre-Gaia

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Infrared observations (Spitzer – Benjamín et al. 2009)

Results

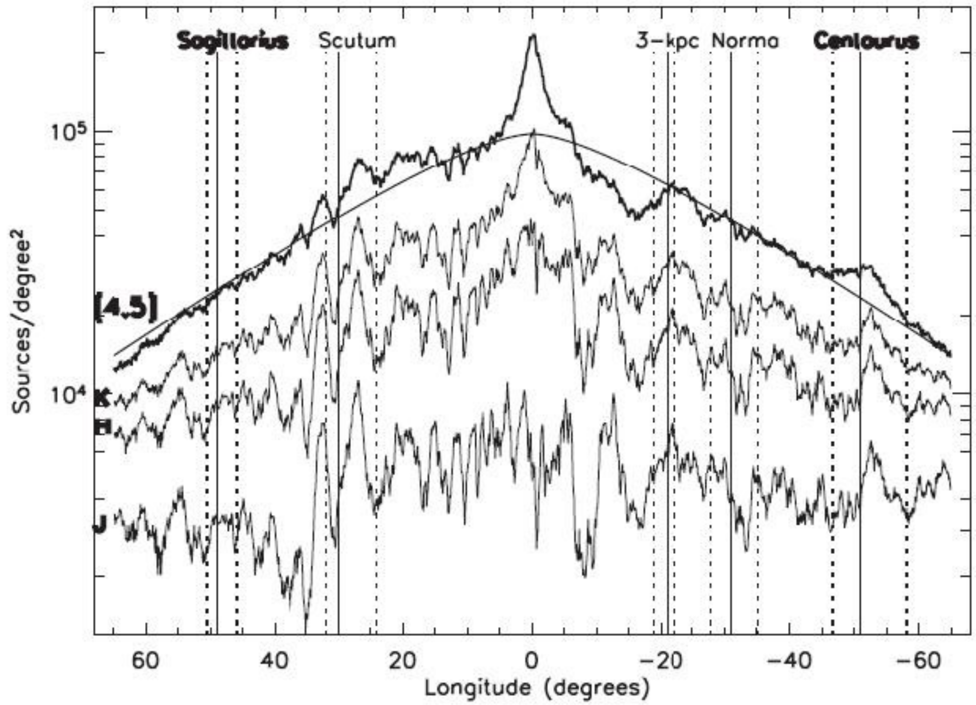


Figure 2. Density of sources in the Galactic plane ($|b| < 1^\circ$) for near and mid-infrared bands (J, H, K, and *Spitzer/IRAC* [4.5], as labeled) in the magnitude range m =6.5 to 12.5 averaged over $2^\circ \times 0.1^\circ$ strips. Note in particular the presence of an enhancement in star counts in the $l = 302 - 313^o$ Centaurus arm tangency directions, but the lack of an enhancement for the expected $l = 46 - 50.5^o$ Sagittarius arm tangency. The smooth line is the best-fit model (Benjamin et al. 2005).

MW spiral arms – pre-Gaia

https://arxiv.org/pdf/1808.00015.pdf

Dust observations (SDSS APOGEE DR14– Rezaei Kh. et al. 2018)

Results

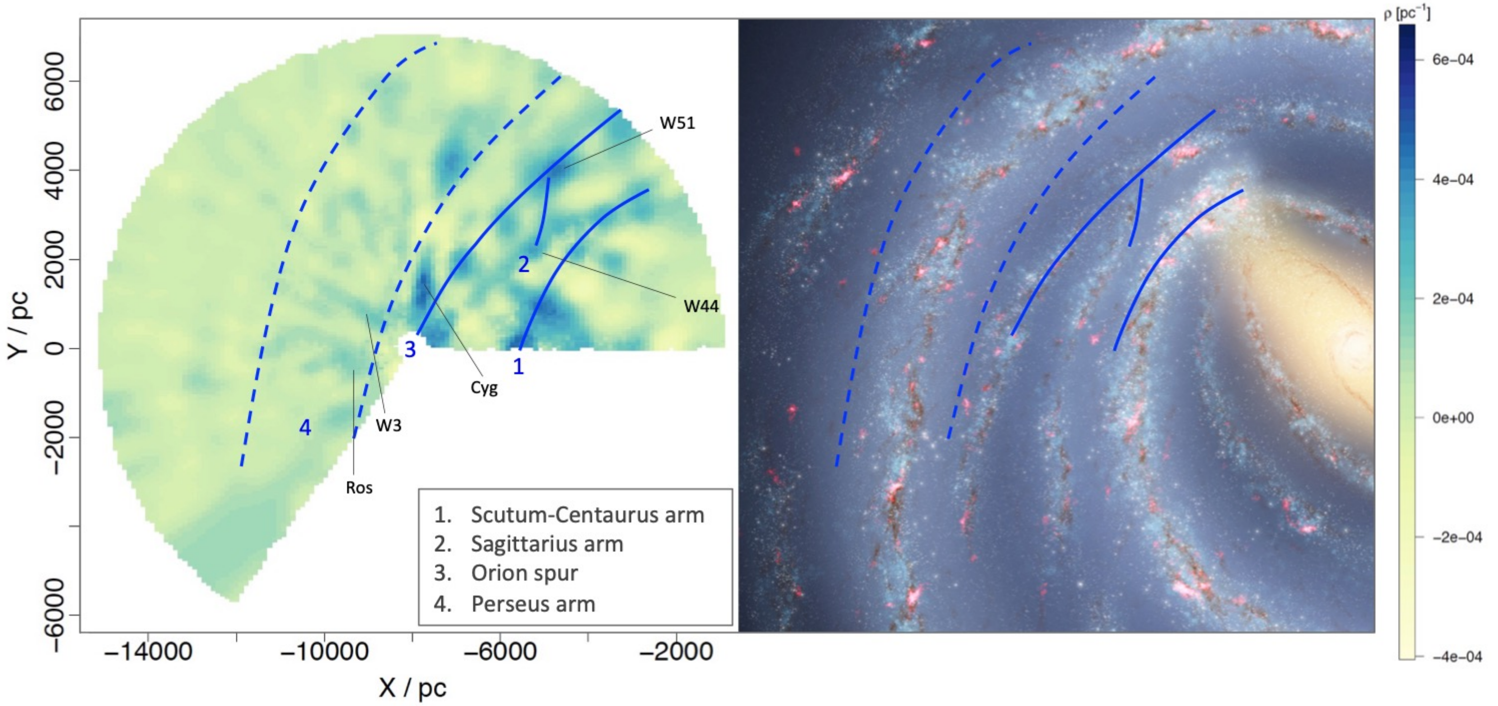


Fig. 4. Left panel: our dust density predictions as in Fig. 2 (left panel), but now over-plotting with blue lines the approximate locations of the arms as we deduce them from this dust map. The dashed lines show an area in which relatively high density dust clouds are seen, but which do not lead to as such a distinct pattern as seen for the other three lines. The known giant molecular clouds detected in the map are also labelled. Right panel: our estimated location of the arms (blue lines) from the left panel plotted on top of the Spitzer sketch of the Galactic arms (by Robert Hurt, courtesy of NASA/JPL-Caltech/ESO).

MW spiral arms – pre-Gaia

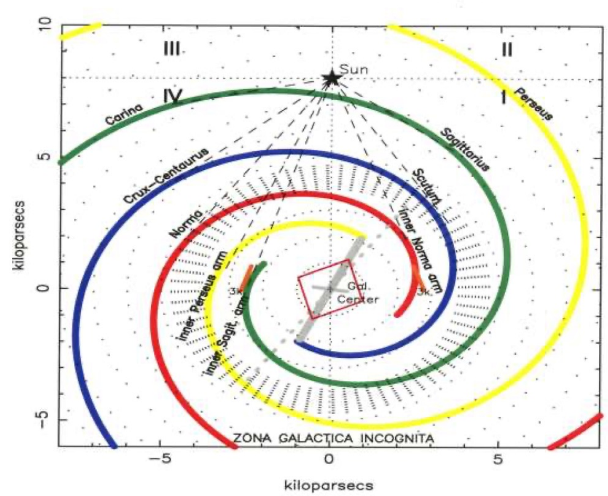
A good review of the MW spiral arms topic was given by **J.P. Vallé en 2014, 2017** (Catalog of observed tangents to the spiral arms in the Milky Way Galaxy and A guided map to the spiral arms in the galactic disk of the Milky Way).

Table 1
Catalog of Published Different Spiral Arm Tracers (Since 1980), with Only One Mean Tracer Value for Each Arm

Arm Name	Chemical Tracer	Gal. Longit. of Arm Tangent[a]	Ang. Dist.[b] to ^{12}CO	Linear Separation Inside Arm[c] from ^{12}CO	References[d]
Carina	^{12}CO at 8′	282°	0°	0 pc, at 5 kpc[c]	Bronfman et al. (2000b, Table 2); see Table 3
	Thermal electron	283°	1°	87 pc	Taylor & Cordes (1993, Figure 4)
	H II complex	284°	2°	174 pc	Russeil (2003, Table 6); see Table 4
	Dust 240 μm	284°	2°	174 pc	Drimmel (2000, Figure 1)
	Dust 60 μm	285°	3°	262 pc	Bloemen et al. (1990, Figure 5)
	FIR [C II] & [N II]	287°	5°	435 pc	Steiman-Cameron et al. (2010, Section 2.1)
Crux-Centaurus	^{12}CO at 8′	309°	0°	0 pc, at 6 kpc[c]	Bronfman et al. (2000b, Table 2); see Table 3
	Thermal electron	309°	0°	0 pc	Taylor & Cordes (1993, Figure 4)
	H II complex	309°	0°	0 pc	Russeil (2003, Table 6); see Table 4
	FIR [C II] & [N II]	309°	0°	0 pc	Steiman-Cameron et al. (2010, Section 2.1)
	H I atom	310°	1°	105 pc	Englmaier & Gerhard (1999, Table 1)
	^{26}Al	310°	1°	105 pc	Chen et al. (1996, Figure 1)
	Sync. 408 MHz	310°	1°	105 pc	Beuermann et al. (1985, Figure 1)
	Dust 240 μm	311°	2°	209 pc	Drimmel (2000, Figure 1)
	Dust 60 μm	311°	2°	209 pc	Bloemen et al. (1990, Figure 5)
	Dust 870 μm	311°	2°	209 pc	Beuther et al. (2012, Figure 2; another peak at 305°)
Norma	H II complex	325°	–3°	–366 pc	Downes et al. (1980, Figure 4); see Table 4
	^{26}Al	325°	–3°	–366 pc	Chen et al. (1996, Figure 1)
	^{12}CO at 8′	328°	0°	0 pc, at 7 kpc[c]	Bronfman et al. (2000b, Table 2); see Table 3
	Thermal electron	328°	0°	0 pc	Taylor & Cordes (1993, Figure 4)
	H I atom	328°	0°	0 pc	Englmaier & Gerhard (1999, Table 1)
	Sync. 408 MHz	328°	0°	0 pc	Beuermann et al. (1985, Figure 1)
	Dust 60 μm	329°	1°	122 pc	Bloemen et al. (1990, Figure 5)
	Methanol masers	331.5°	3.5°	427 pc	Caswell et al. (2011, Section 4.6.2); see Table 5
	Dust 240 μm	332°	4°	488 pc	Drimmel (2000, Figure 1)
	Dust 2.4 μm	332°	4°	488 pc	Hayakawa et al. (1981, Figure 2(a))
	Dust 870 μm	332°	4°	488 pc	Beuther et al. (2012, Figure 3)
Start of Perseus	^{12}CO at 8′	337°	0°	0 pc, at 8 kpc[c]	Bronfman et al. (2000b, Table 2); see Table 3
	FIR [C II] & [N II]	338°	1°	140 pc	Steiman-Cameron et al. (2010, Section 2.1)
	Dust 870 μm	338°	1°	140 pc	Beuther et al. (2012, Figure 3)
	Methanol masers	338°	1°	140 pc	Green et al. (2011, Section 3.3.1); see Table 5
	Sync. 408 MHz	339°	2°	279 pc	Beuermann et al. (1985, Figure 1)
	Dust 2.4 μm	339°	2°	279 pc	Hayakawa et al. (1981, Figure 2(a))
	Dust 60 μm	340°	3°	419 pc	Bloemen et al. (1990, Figure 5)
Near 3 kpc arm	^{12}CO at 8′	026°	0°	0 pc, at 6 kpc[c]	Cohen et al. (1980, Figure 3); see Table 3
	H II complex	025°	1°	105 pc	Russeil (2003, Table 6); see Table 4
	Warm ^{12}CO cores	024°	2°	209 pc	Solomon et al. (1985, Figure 1(b)); Bania (1980, Figure 7)

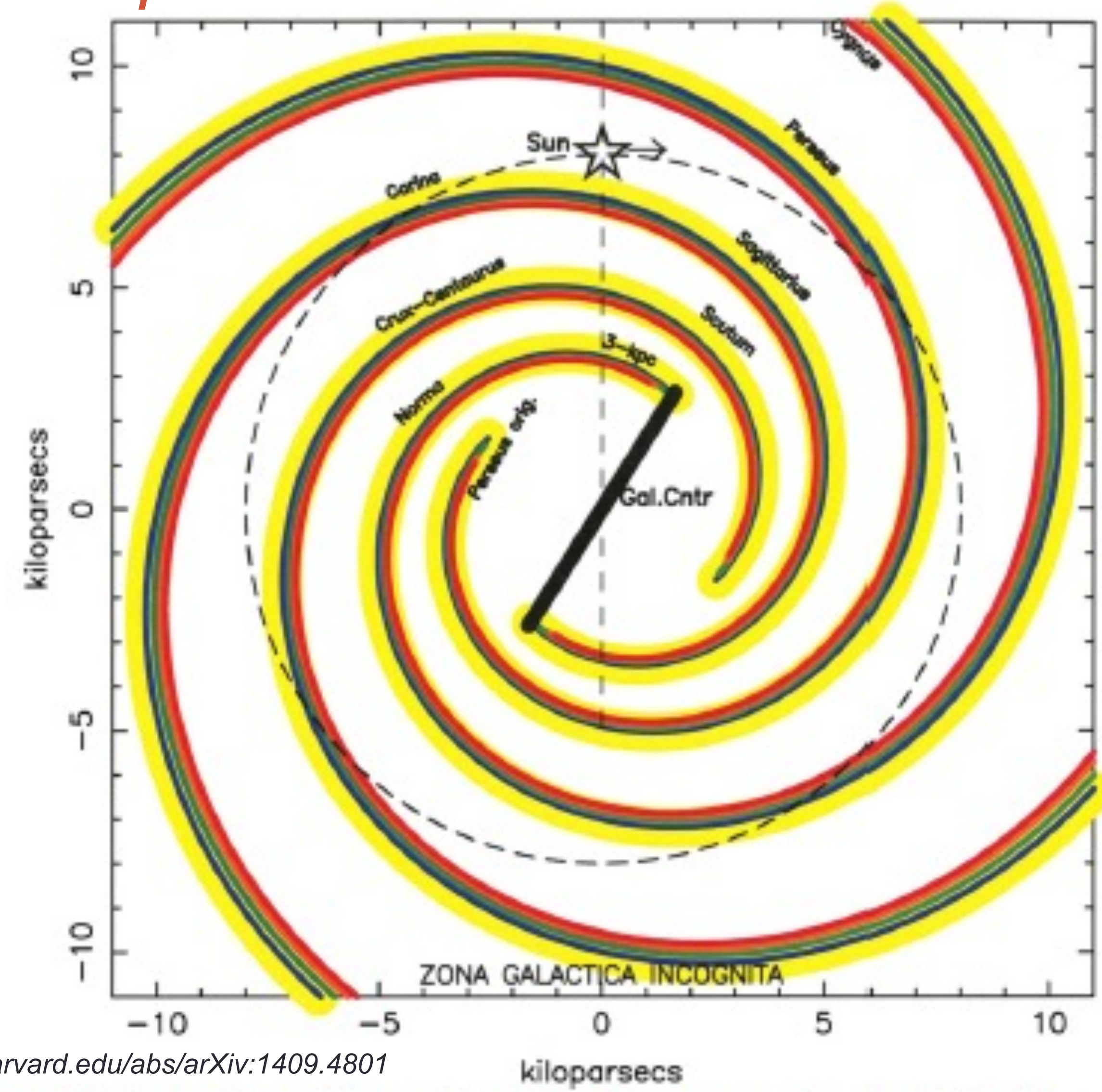
https://ui.adsabs.harvard.edu/abs/2017AstRv..13..113V/abstract

Tracers of t he MW spiral arms (1980-2014)



MW spiral arms – pre-Gaia

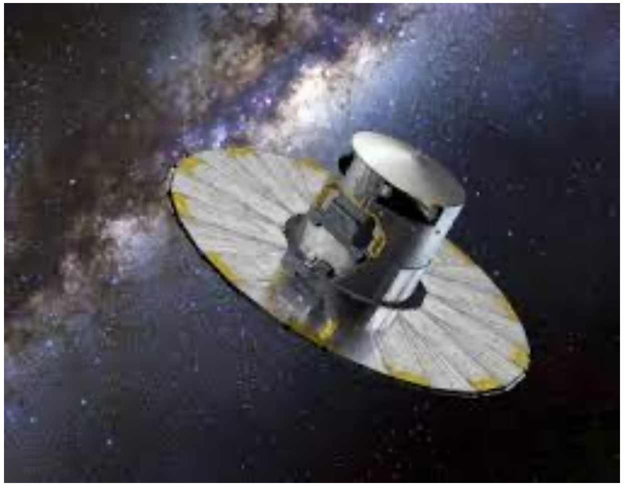
"Average Cartographic Model" coherent with observations to 2014.



https://ui.adsabs.harvard.edu/abs/arXiv:1409.4801

Figure 3. New galactography. Besides stars all over spiral arms, spiral arms harbor different components (tracers) at slightly at different (parallel) locations. Stars (yellow) are all over the arms. The ^{12}CO (and H_2) molecules peak near the middle of the arm (blue), while the hot dust (with masers and newborn stars) peak near the inner arm edge (red). Other intermediate tracers peak in between: thermal and relativistic electrons and H I atoms (green), and cold dust with FIR cooling lines (orange). Same color coding used as in Figure 2. Updated from Vallée (2014a).

MW spiral arms – in the Gaia era



The new astronomy:

Billions of stars with good distances

The release of Gaia data (DR1-DR2-DR3) was a revolution for many fields in astrophysics.
In particular, this data allowed us to study with unpreceded detail the density structures in the solar neighbourhood and up to more than 5kpc.
Gaia data also allowed us to confirm the position of the gas and dust emission regions.

In the following slides we give you some examples of the most recent works on the study of spiral arms using Gaia data.

Although our knowledge on the position and properties of the closest spiral arms has improved a lot, it is important to take in mind that we still need more observations to get a final picture of which is (or are) the nature(s) of the MW's spiral arm(s).

Spiral structure and Cepheids (young component/kinematically cold)

Skowron et al. 2019, Science, Volume 365, Issue 6452, pp. 478-482

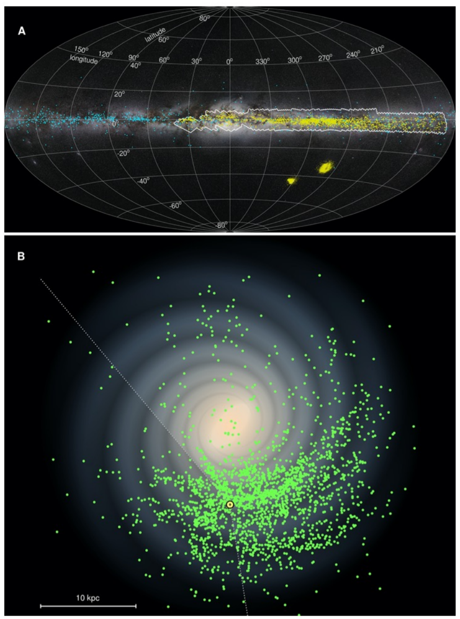


Figure 1: **Distribution of Galactic classical Cepheids.** (**A**) On-sky view of the Milky Way in Galactic coordinates (l, b), with our sample of classical Cepheids in the Milky Way and in the Magellanic Clouds. Cepheids from the OGLE Collection of Variable Stars are shown with yellow dots, other sources with cyan dots (*10*). The white contour marks the OGLE survey area in the Galactic plane ($190° < l < 360°, 0° < l < 40°; -6° < b < +6°$). The background image is a Milky Way panorama (by Serge Brunier). (**B**) Face-on view of our Galaxy with all 2431 Cepheids in our sample marked with green dots. The background image represents a four-arm spiral galaxy model consistent with neutral hydrogen measurements in our Galaxy (with the spiral structure modeled as the logarithmic spirals (*29*)). The Sun is marked with a yellow dot; the dashed lines show the angular extent of the OGLE fields ($190° < l < 360°, 0° < l < 40°$).

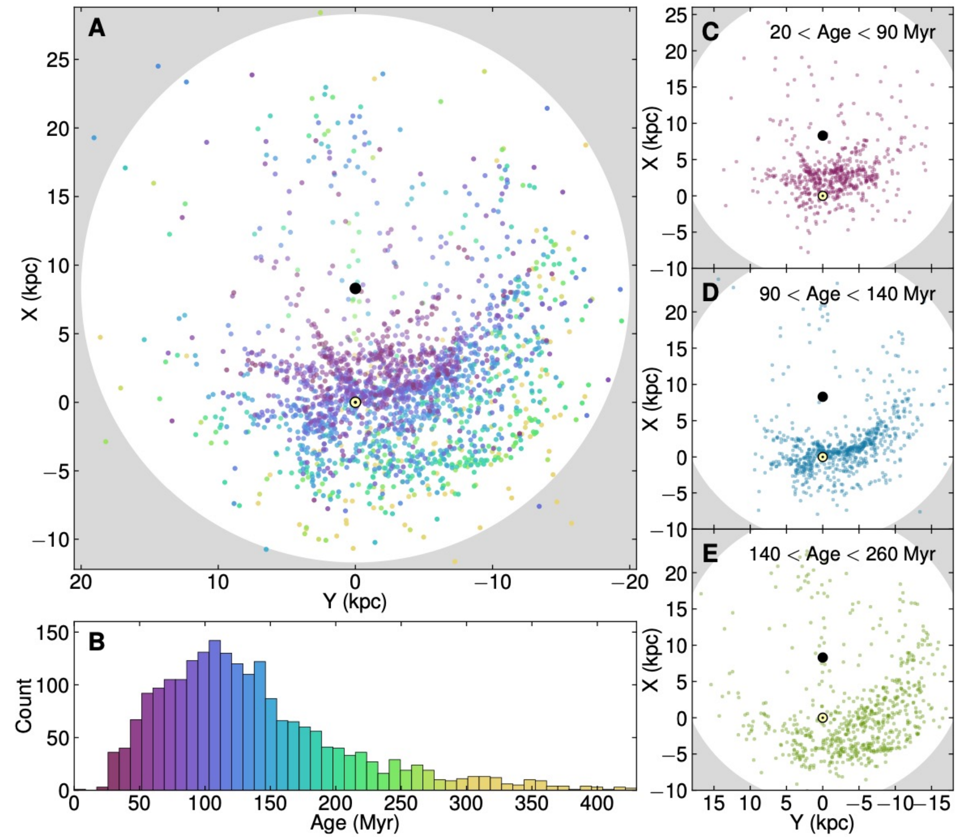


Figure 3: **Ages of Galactic classical Cepheids.** (**A**) Face-on view, showing the Cepheid distribution in the Galaxy, with colors corresponding to Cepheid ages as indicated in (B). The Sun is marked with a yellow dot, the Galactic center with a black dot. (**B**) Age histogram of Galactic classical Cepheids in our sample. (**C** to **E**) Age tomography of the Milky Way Cepheids in three selected age bins, as indicated. Each age bin reveals Cepheid overdensities.

https://ui.adsabs.harvard.edu/abs/2019Sci...365..478S/abstract

Spiral structure traced by O and B stars (¿star forming spirals?)

Chen et al. 2019, MNRAS Volume 487, Issue 1, p.1400-1409

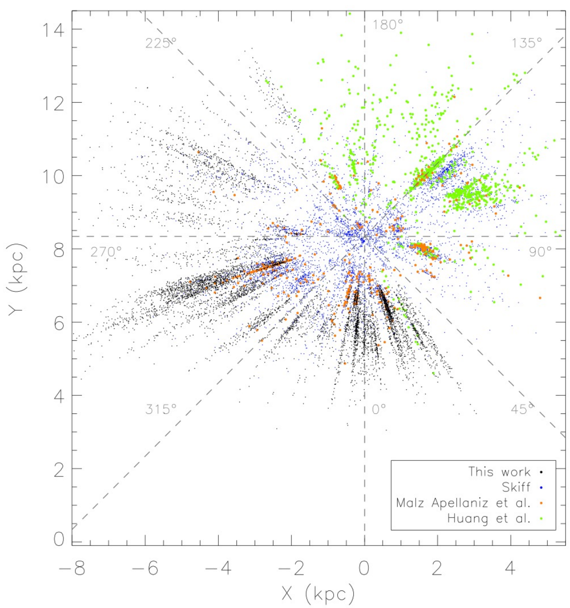
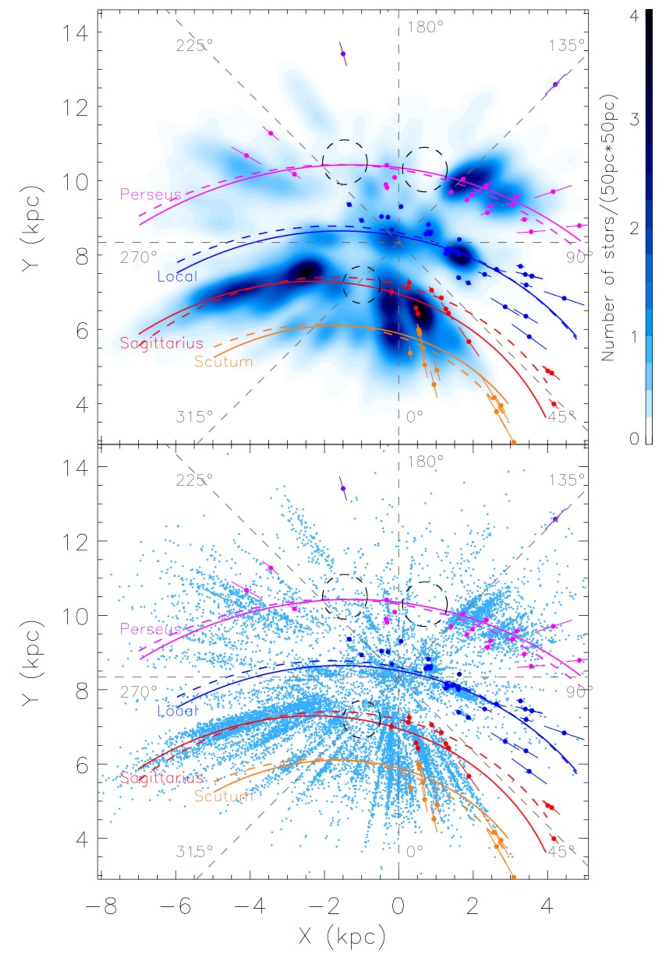


Figure 3. Spatial distribution of the combined OB sample stars in the XY plane. Black, blue, orange and green dots correspond to OB star candidates selected in this work, those from Skiff (2014), Maíz Apellániz et al. (2013) and Huang et al. (in prep.), respectively. The Sun, assumed to be at 8.34 kpc from the Galactic center, is located at the centre of the plot ($X = 0$ kpc and Y=8.34 kpc). The directions of $l = 0°, 45°, 90°, 135°, 180°, 225°, 270°$ and $315°$ are also marked in the plot.

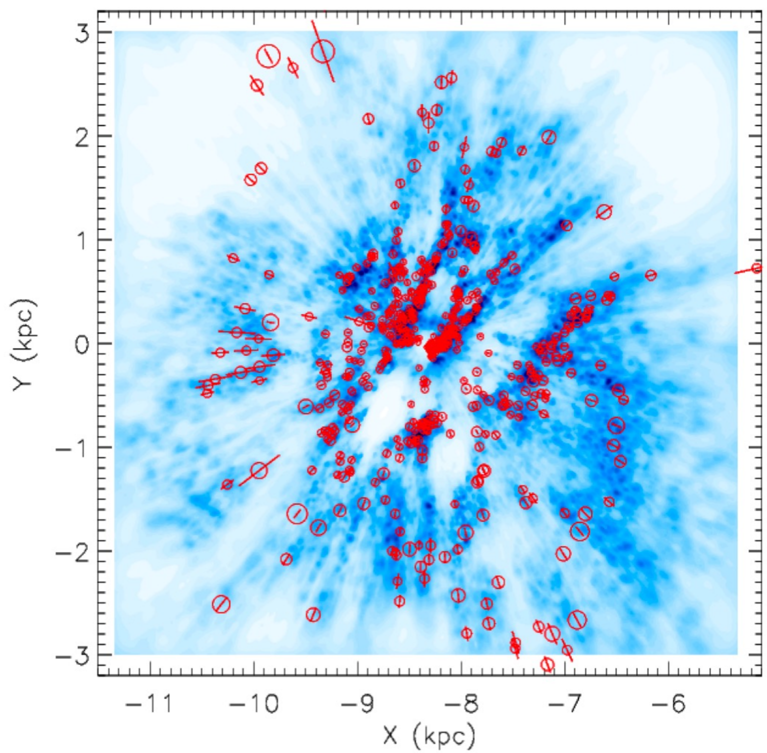


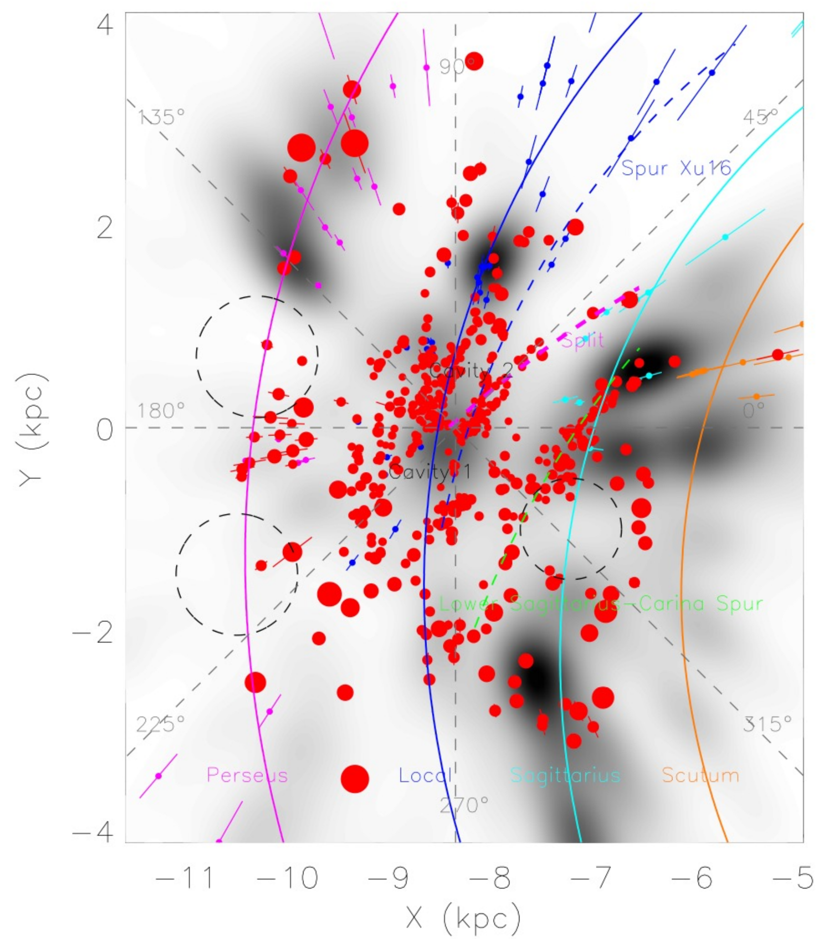
https://ui.adsabs.harvard.edu/abs/2019MNRAS.487.1400C/abstract

Spiral arms structure and molecular clouds (¿star forming spiral arms?)

Chen et al. 2020, MNRAS Volume 493, Issue 1, p.351-361

Error in distance below 5%!





https://ui.adsabs.harvard.edu/abs/2020MNRAS.493..351C/abstract

Spiral arms structure and young open clusters (¿star forming spiral arms?)

Castro-Ginard et al. 2021, A&A Volume 652

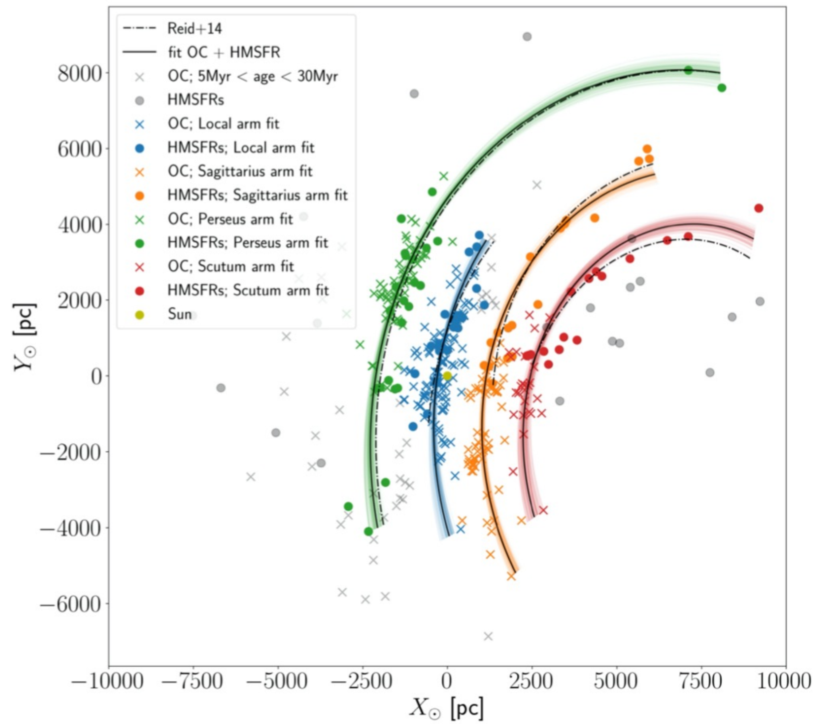


Fig. 3: Heliocentric *X* - *Y* distribution of OCs (crosses) younger than 30 Myr and HMSFRs (dots) from Reid et al. (2014), used to fit the spiral arms. Different colours correspond to different arms. The assignments to each arm is computed using a Gaussian Mixture Model. Solid black lines are the fitted spiral arms with the parameters in Table 1, while shaded regions account for 1σ uncertainties. Dash-dotted lines correspond to the spiral arms defined by HMSFRs only. The Galactic centre is towards positive *X* and the Galactic rotation direction is towards positive *Y*.

Spiral structure Gaia DR3

Gaia Collaboration et al. 2022, eprint arXiv:2206.06207

Confirmation of the neighbouring spiral arms location

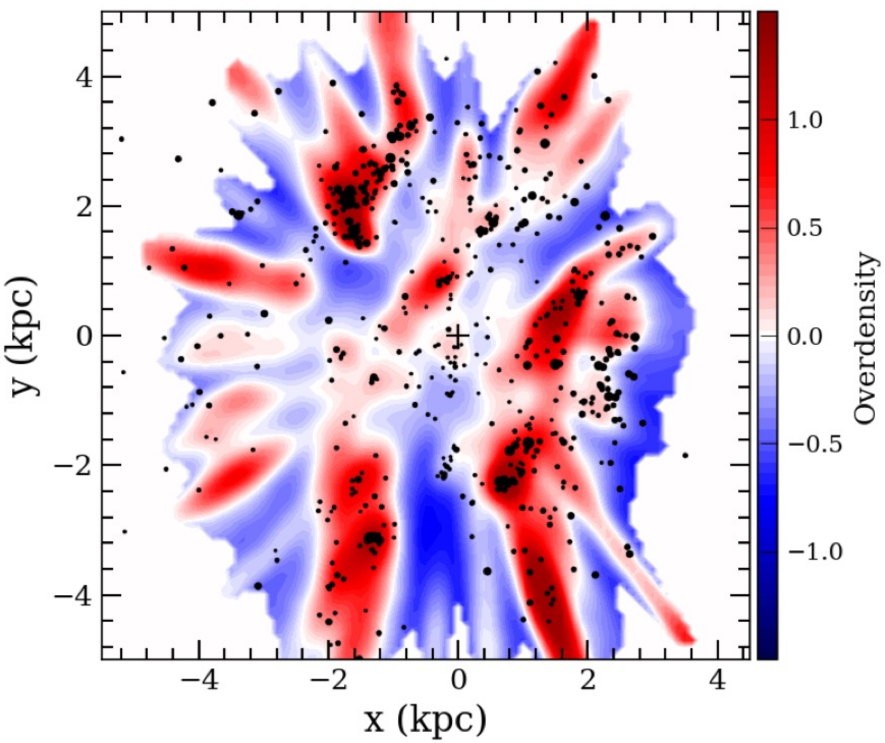


Fig. 13. Overdensity map of the OB stars over plotted with the positions of the open clusters younger than 63 Myr and with $n_0 > 5$, plotted with filled circles whose size is proportional to $\sqrt{n_0}$. The cross indicates the position of the Sun.

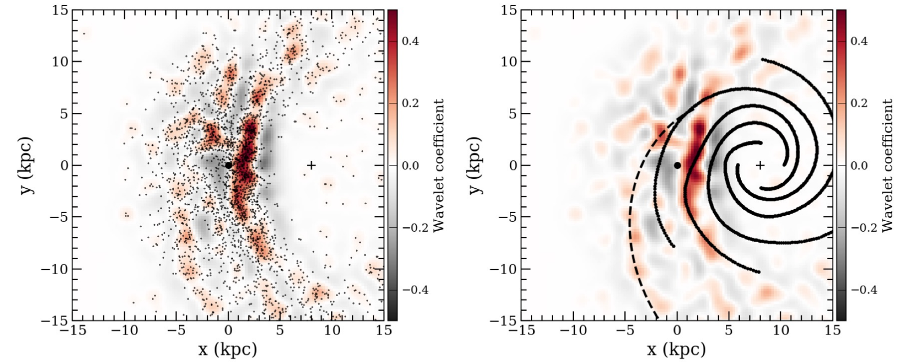


Fig. 15. Wavelet transformation of the Cepheids with age < 200 Myr. Black dots in the left panel show the positions of the single sources, while the right panel shows, on a larger scale, an overlay of the model from Taylor & Cordes (1993) (solid lines) and the one from Levine et al. (2006) (dashed line).

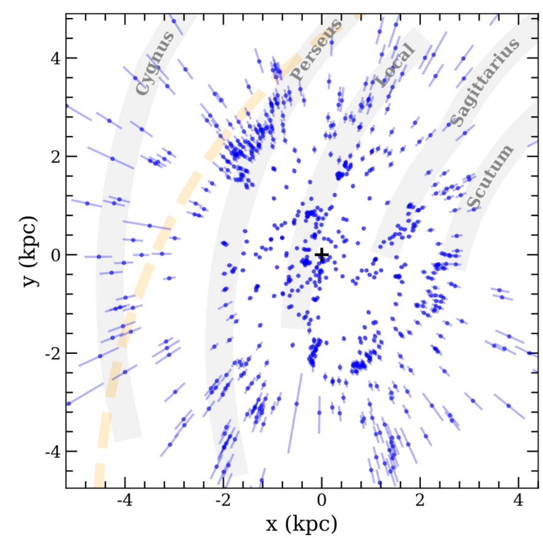
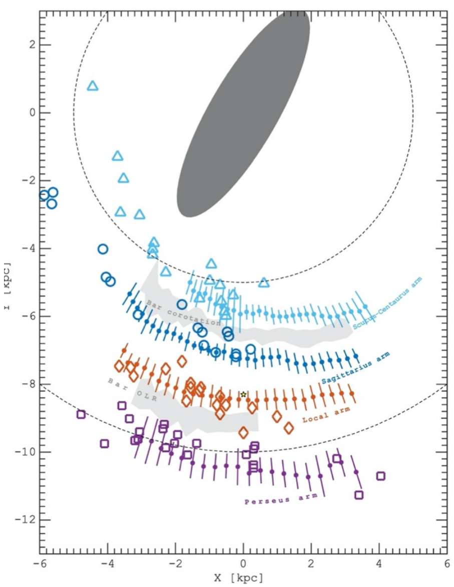


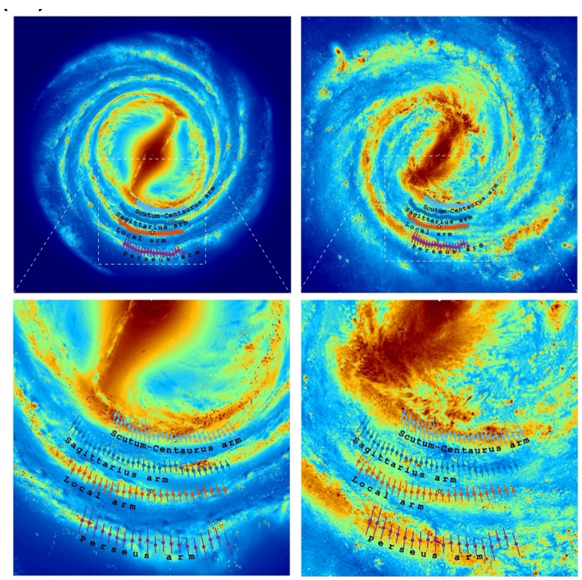
Fig. 14. Heliocentric coordinates of the clusters younger than log t=7.6 (63 Myr). Thick grey lines are the spiral arm model of Reid et al. (2019), and the dashed line is the trace of the Perseus arm modelled by Levine et al. (2006). The bars represent the 1-σ uncertainty on the distance, taking into account statistical and systematic parallax errors.

Spiral structure and radial velocities (GaiaDR2 + radial velocities)

Khoperskov et al. 2020, A&A Volume 634, Issue 8

Detecting resonance and corrotation radius could give us information on the nature of the non-axisymmetric structures in the galaxy.





Roca-Fabrega et al. 2014

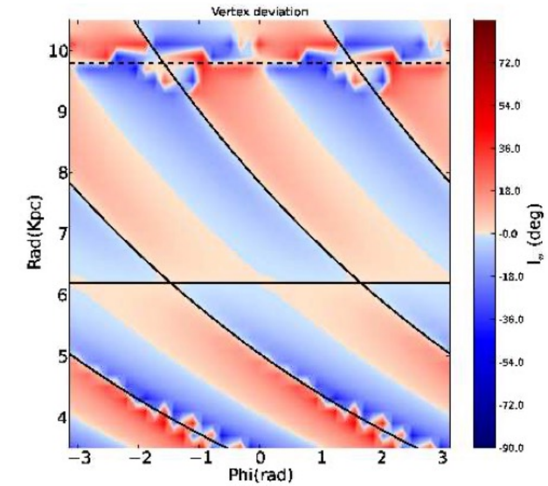


Figure 2. Vertex deviation polar plots in a color scale (red for positive values, blue for negative) for the TWA analytical solution (see Sect. 3.1). The solid and the dashed horizontal black lines show the position of CR and OLR radius, respectively. The curved black solid lines show the position of the spiral arms locus. The galaxy rotates from left to right.

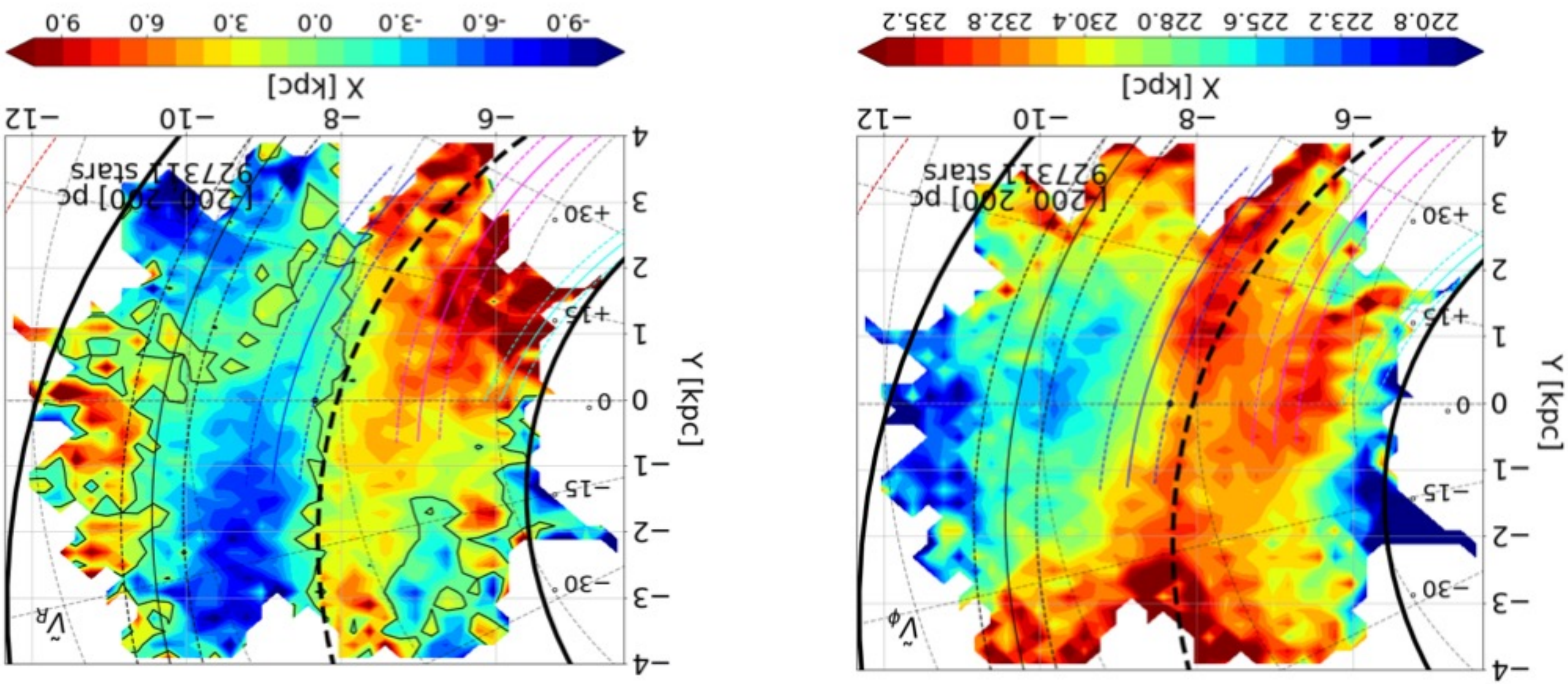
https://ui.adsabs.harvard.edu/abs/2020A%26A...634L...8K/abstract

Spiral structure and stellar kinematics

Gaia Collaboration et al. 2018, A&A Volume 616, Issue 11

Changes on the radial velocity (left) and angular (right), and its relationship with the currently most accepted position of the spiral structures.

Sample: Giants sample (sub-selection of the main sample that includes only giant stars selected on their absolute magnitude in *G* band *MG* < 3.9 and intrinsic colour (*G*BP − *G*RP)0 > 0.95)



https://ui.adsabs.harvard.edu/abs/2018A%26A...616A..11G/abstract

Spiral structure Gaia DR3

Gaia Collaboration et al. 2022, eprint arXiv:2206.06207

First maps of stellar kinematics of the RGB population

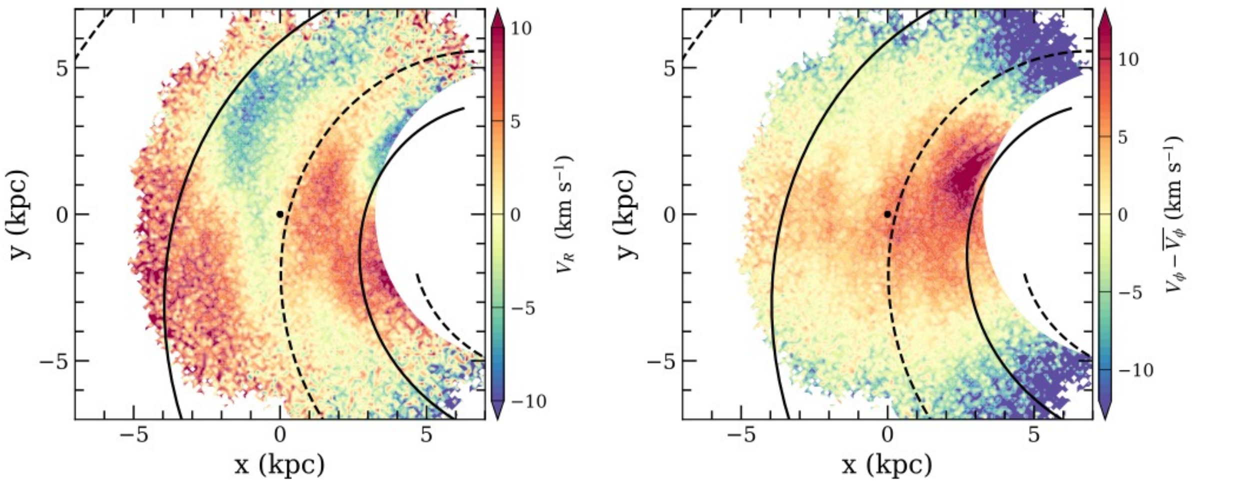
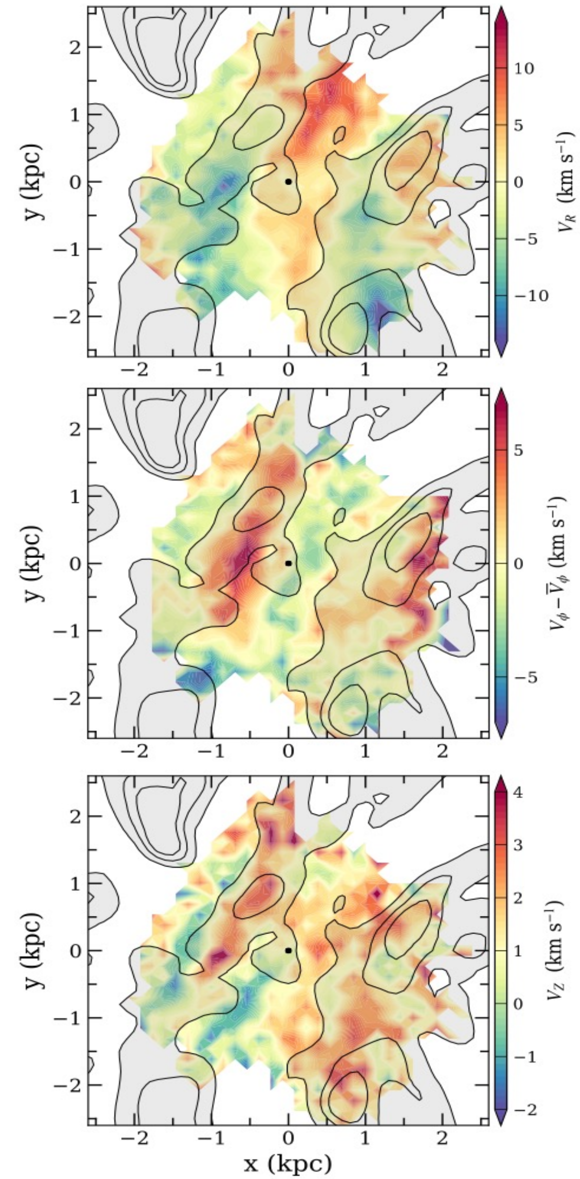


Fig. 22. Velocity maps for the RGB sample. The left panel shows the inferred radial velocity, V_R. The right panel shows the map for $V_\phi - \overline{V_\phi}$, i.e., the residual azimuthal velocity. Overlaid on both maps is the 2-arm *NIR* spiral model from Drimmel (2000), shown as solid lines. The dashed lines correspond to the minimum interarm density (see text). The position of the Sun is marked by a black dot.



MW spiral arms – in the Gaia era

PHANGS-ALMA

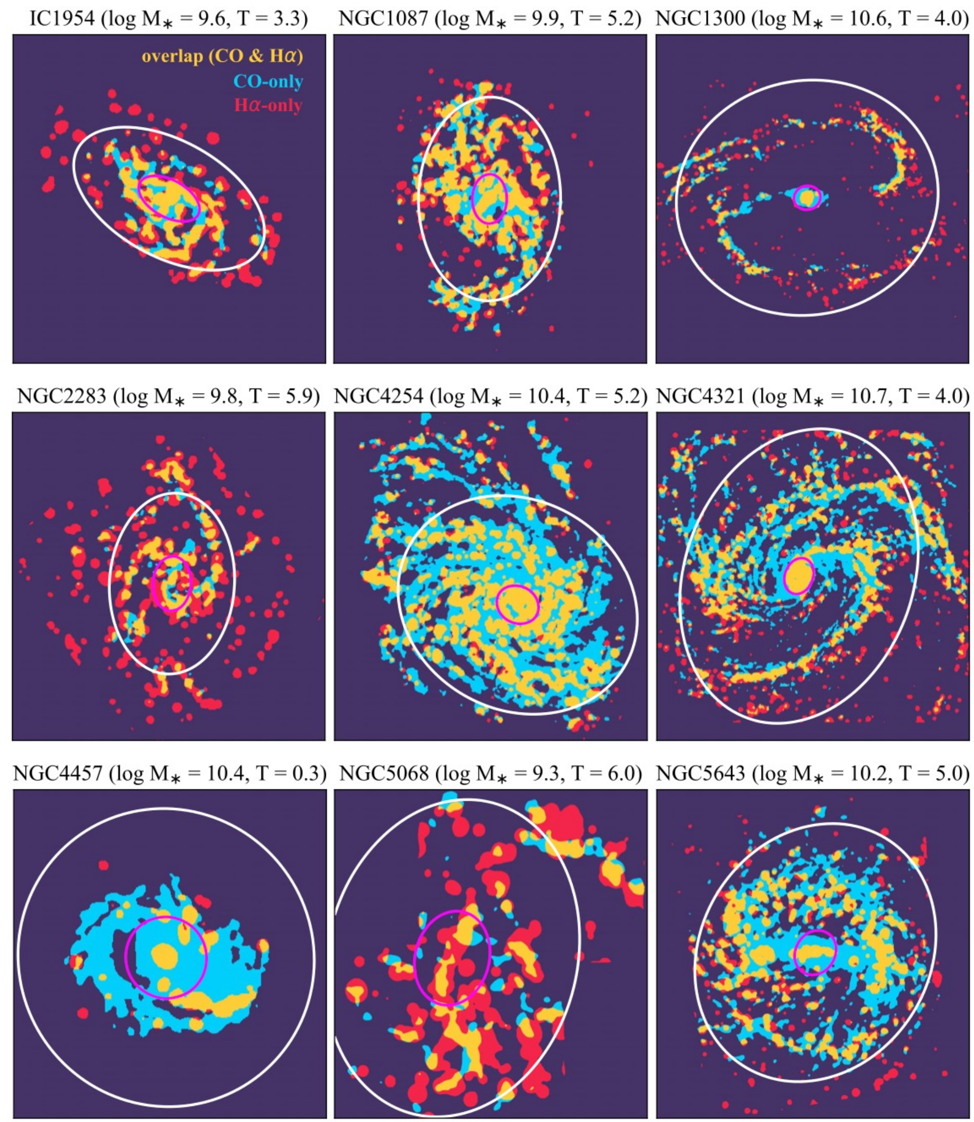


Figure 2. Examples of the spatial distribution of different sight lines. Galaxy maps show the regions of *CO-only* (blue), *Hα-only* (red), and *Overlap* (yellow) sight lines at 150 pc resolution. The inner ellipses (magenta) mark the central region, defined as the central 2 kpc in deprojected diameter. The outer ellipses (white) indicate the $0.6R_{25}$ regions where we measure the global sight-line fractions. The M_* (in units of solar mass in log scale) and Hubble type of each galaxy are given at the top of each panel.

Comparing the position of molecular gas and young stars tracers we can test theories of spiral arms' nature

Pan et al. 2022

Spiral structure: Gaia-DR4, Gaia-NIR

“The journey of a thousand miles begins with one step”

Lao Tzu