Modelos dinámicos de la Vía Láctea y aplicaciones a problemas abiertos de dinámica de galaxias

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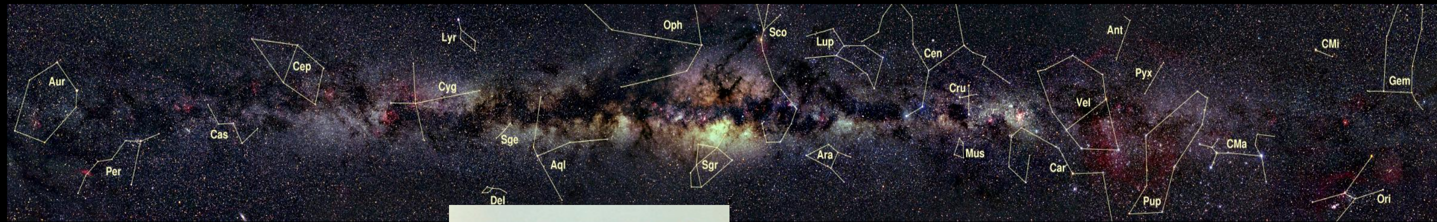
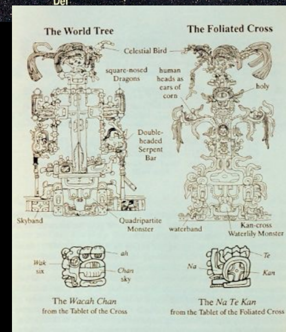
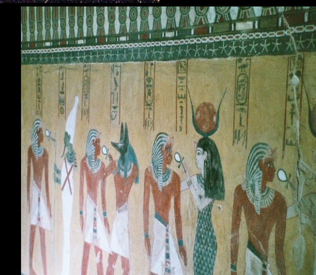
CNA 2018





The Milky Way was called *Wakah Chan*, and it was related with *Xibalbá*, the Kiche' from Guatemala even call it yet *Xibalbá be* or path to the underworld.



Egyptians. Hathor, the celestial cow (Luxor). Milky Way personification. Master of the sky, mother of egiptians and creator of the Universe.

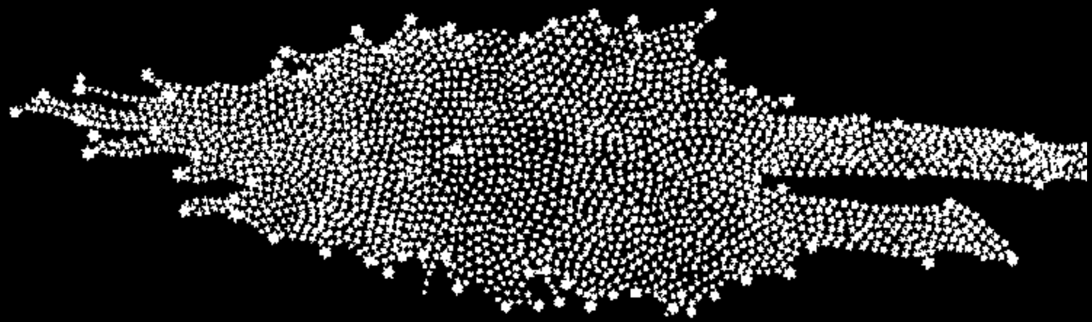
Mesopotamians. Slicing Tiamat in half, he made from her ribs the vault of heaven and earth. Her weeping eyes became the source of the Tigris and the Euphrates, her tail became the Milky Way.

Greeks and Romans. La Creación de la Vía Láctea, por Rubens (1637)

Coatlicue for the Mexicas (Aztecs): Earth goddess, mother of the Sun, the Moon, stars and of all gods.

The discovery of the Milky Way

•1785. The first attempt to describe the whole galaxy was performed by William Herschel (and his sister Caroline, his maid and assistent) with stellar counting methods. He locates the Sun too close to the center of the distribution (ignoring the ISM presence).



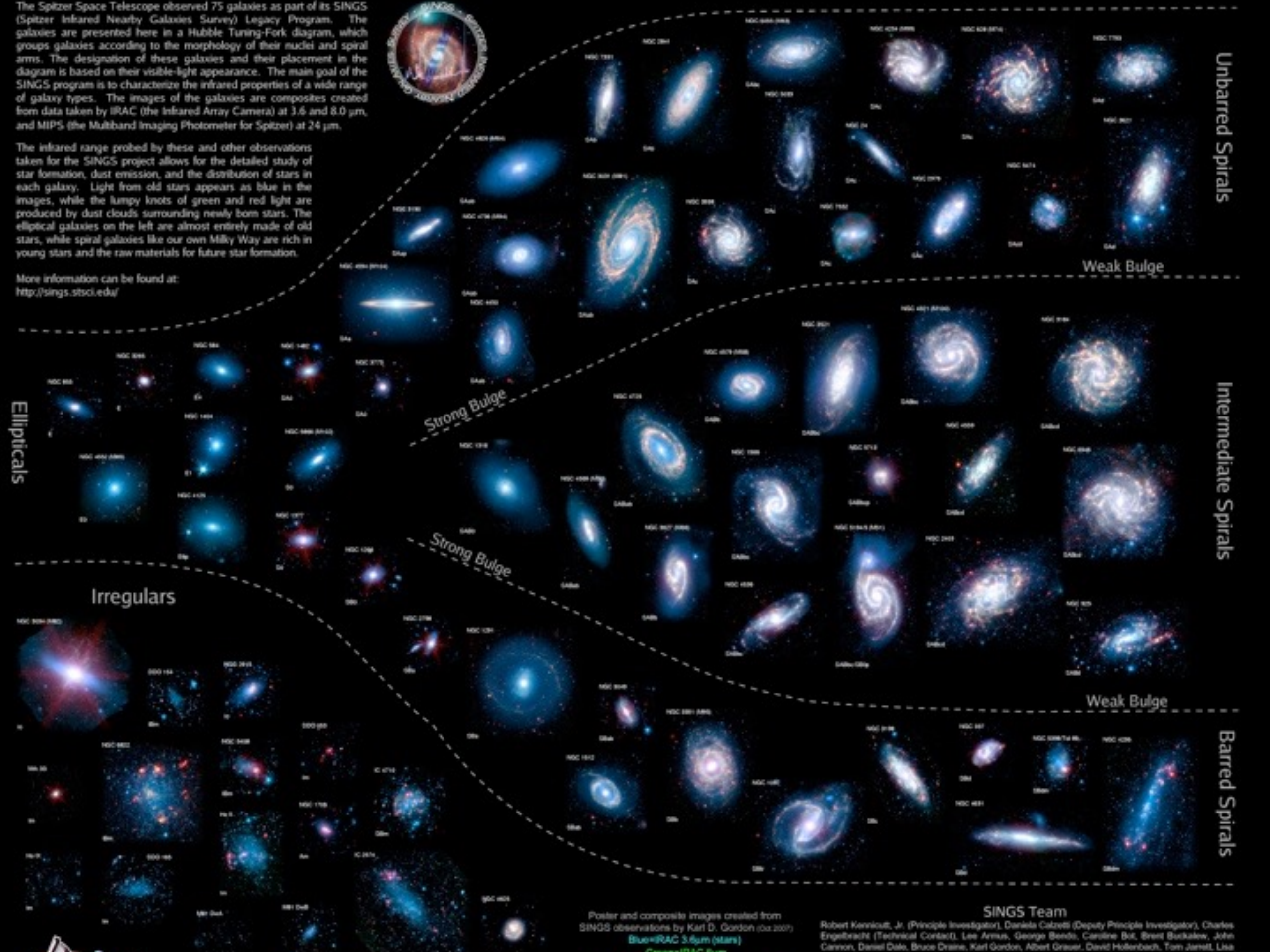
William Hershel
(1738-1822)

Caroline Hershel
(1750-1848)

•Edwin Hubble solves finally the problem in 1920 , by calculating the distance with cepheids (Leavitt´s method) to the galaxy of Andromeda.

Edwin Powell Hubble
(1889-1953)

Henrietta Swan Leavitt
(1868-1921).



The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 µm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 µm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Unbarred Spirals
Weak Bulge
Strong Bulge
Intermediate Spirals
Ellipticals
Strong Bulge
Weak Bulge
Irregulars
Barred Spirals
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6µm (stars)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa

• 1930. With the observational knowledge of spiral galaxies obtained in this decade and large-scale gas observations, it is accepted the idea that the MW is a spiral galaxy.

• 1932. Oort analyses the local kinematics and builds the first dynamical model to explain it. Galactic dynamics is born here.

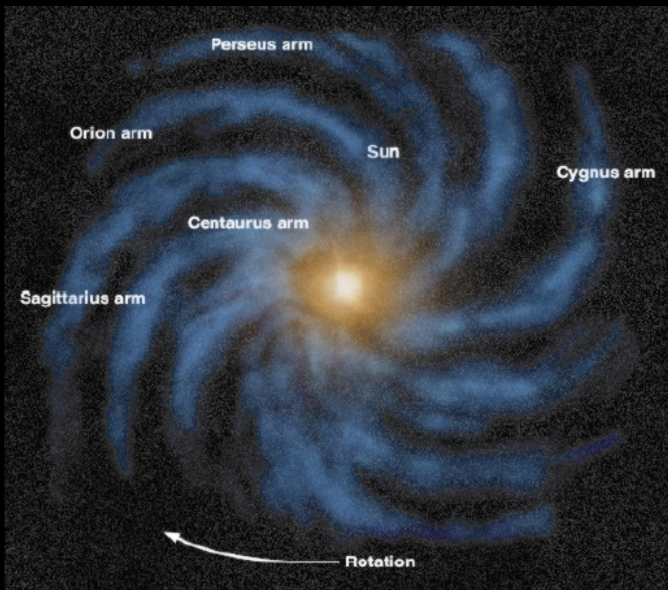
Jan Hendrik Oort
(1900-1992)

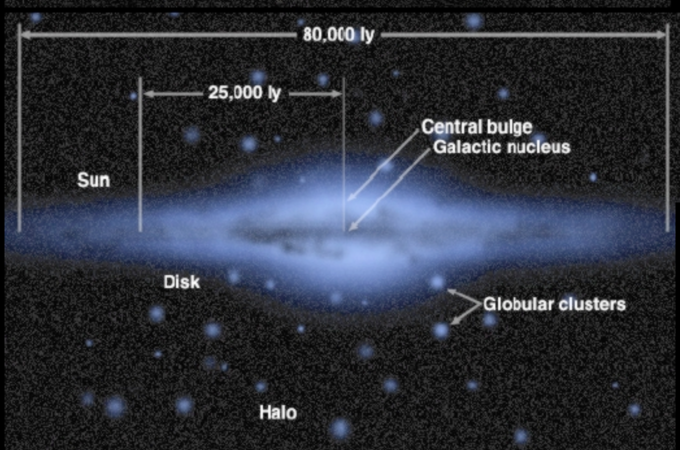
★ 1952. Morgan, Sharpless and Osterbrock find that even at large scale observations of the gaseous component of the Galaxy, the HI distribution shows a strong azimuthal dependence (with concentrations at some given regions that they divide in three spiral arms close to the solar neighborhood).

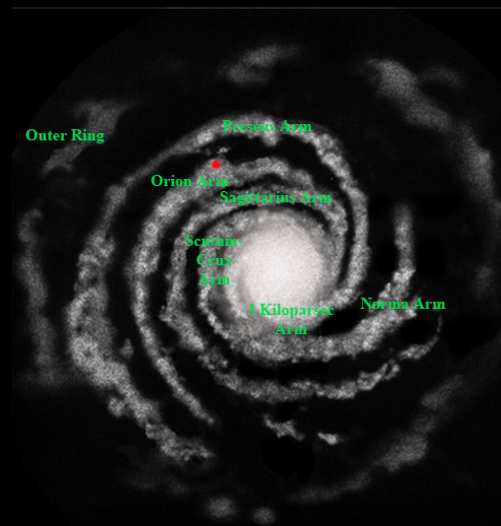
★ 1954. Kwee et al. presents the first rotation curve with 21 cm.

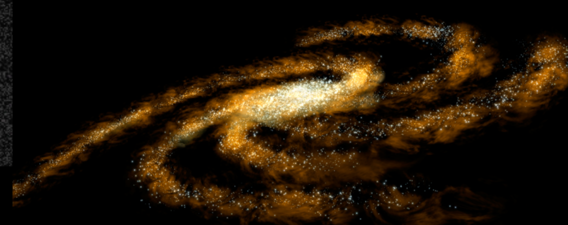
The unbarred Milky Way

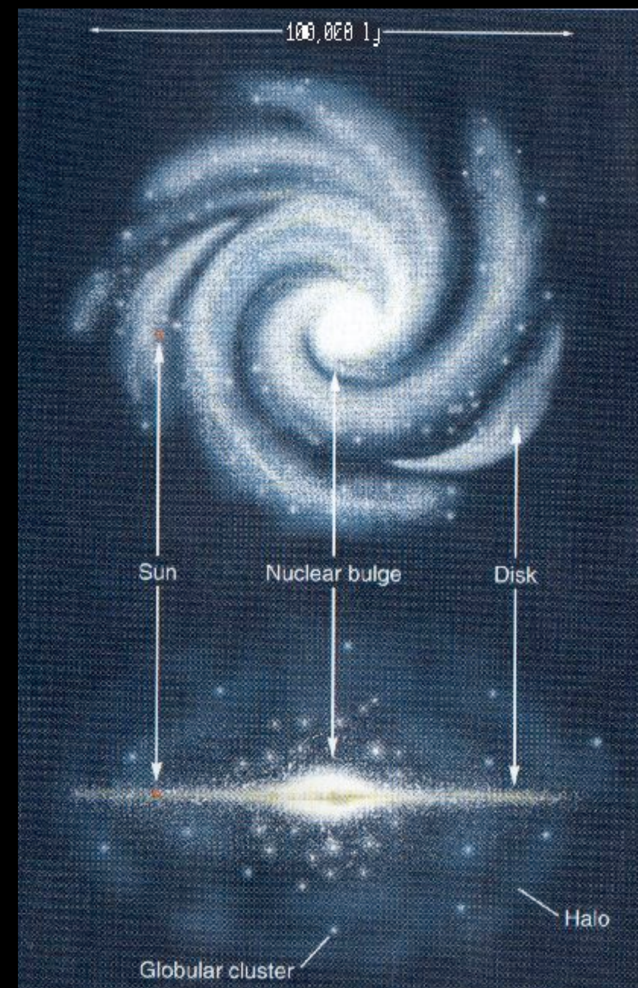
(70's tarantulas)





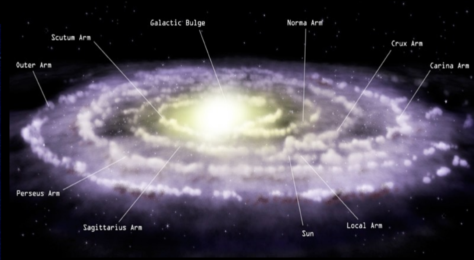




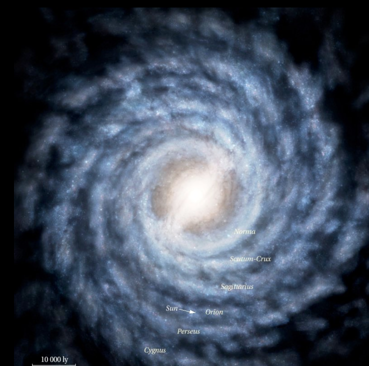


The Barred Milky Way
(from 90's)

Encyclopedia of Science

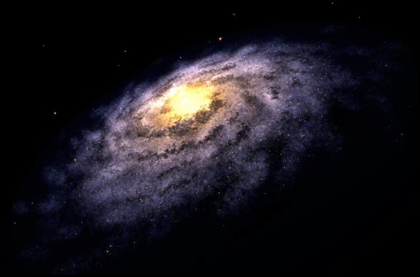


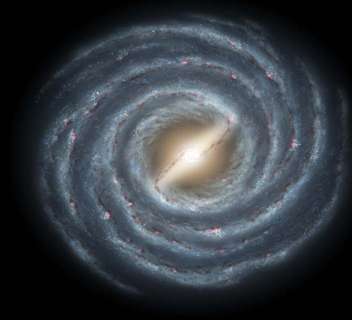
NASA



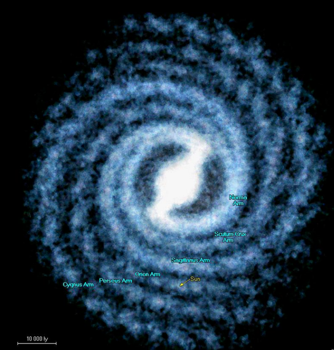
Atlas of the Universe (Obs. Sidney)

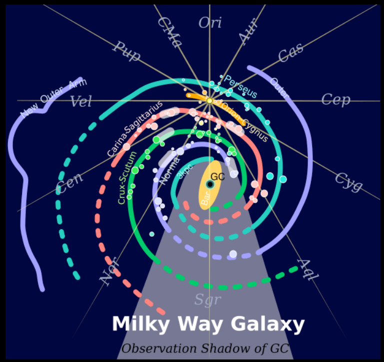
National Geographic

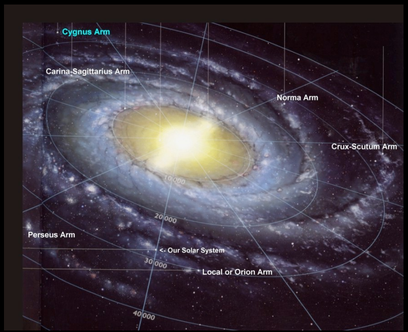




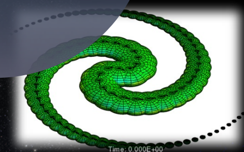
Wisconsin, Spitzer (SST)







"from an Abducted woman by Aliens from Zeta 2 Reticuli"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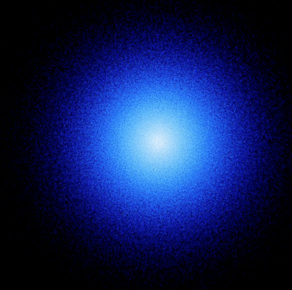
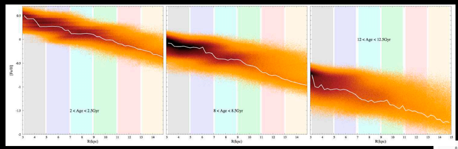
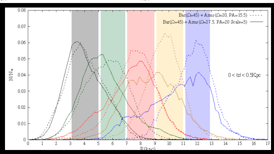
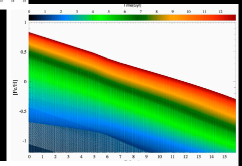
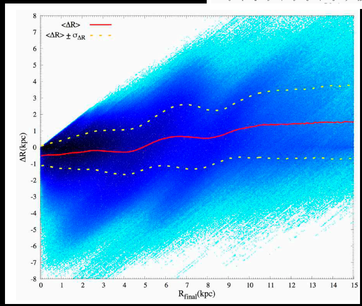
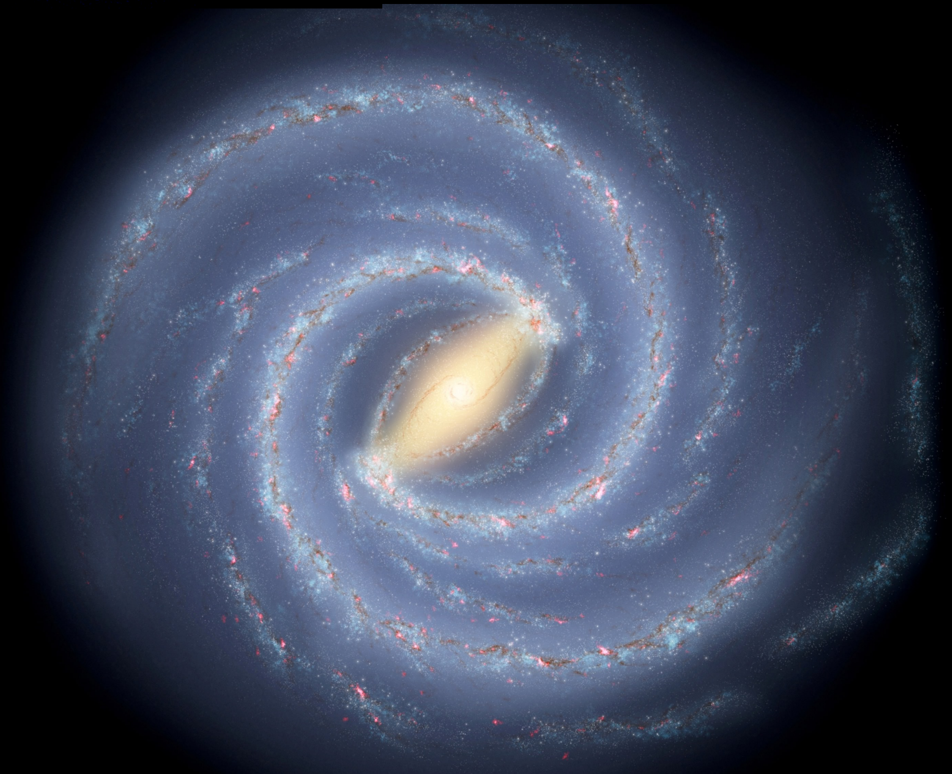
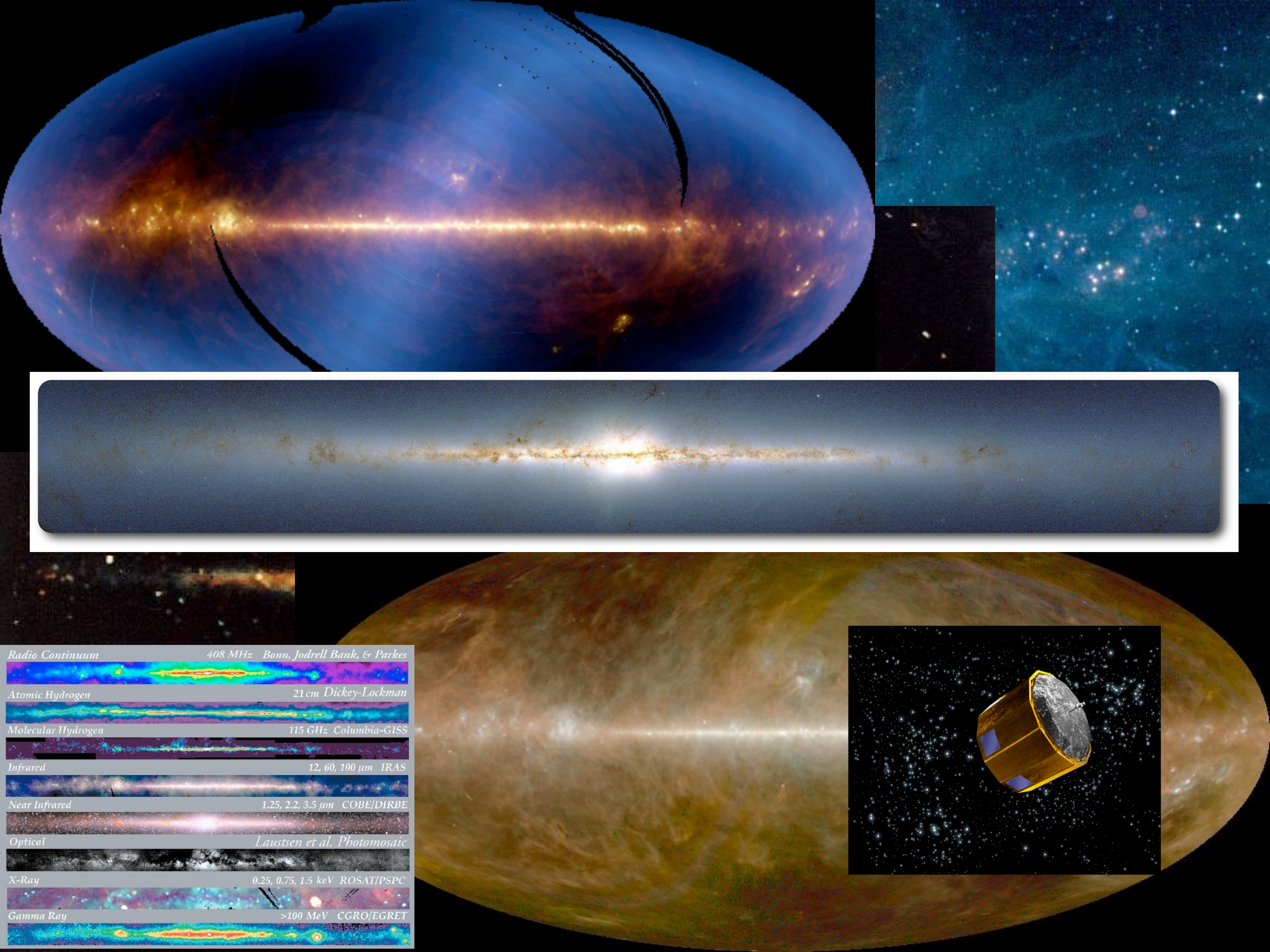





$\langle\Delta R\rangle$
$\langle\Delta R\rangle \pm \sigma_{\Delta R}$
ΔR(kpc)
R_{final}(kpc)



Radio Continuum 408 MHz Bonn, Jodrell Bank, & Parkes
Atomic Hydrogen 21 cm Dickey-Lockman
Molecular Hydrogen 115 GHz Columbia-GISS
Infrared 12, 60, 100 μm IRAS
Near Infrared 1.25, 2.2, 3.5 μm COBE/DIRBE
Optical Laustsen et al. Photomosaic
X-Ray 0.25, 0.75, 1.5 keV ROSAT/PSPC
Gamma Ray >100 MeV CGRO/EGRET

In particular, understanding the large scale structure of the MW would help to model its dynamics and that would help to understand things like:

1. The origin of the MW.

2. Origin and evolution of the non-axisymmetric structures: spiral arms and bar(s)

3. Bar and spiral arms kinematics (independent or the same velocity?), chemical distribution produced by their dynamical influence.

4. Quantity and distribution of dark matter (specially toward the center, dark matter?, some "type of MOND"?) Interaction barion-dark matter (dynamical feedback).

5. Properties of the interestelar medium linked to large scale structures and how its kinematics constraints the mass distribution?

7. Large scale motion phenomenologies: disk heating, radial migration, chemical gradients, moving groups, clusters destruction, etc.

etc...

To model the Milky Way, some components are used to build the potential and some other as restrictions. The Milky Way is the galaxy best known, that makes it the most complicate to model.

Steady Models

These models are based on potential theory, they are analytical or semi-analytical: spherically symmetric, spheroids and triaxial figures.

Disadvantages:
They are steady (they do not evolve in time), this means, they are not self-consistent in the "traditional" way.

Advantages:
-Conserve "hardly" motion integrals, no resolution problems. Chaos, detailed orbital studies.
-Fast (computationally cheap). Statistical studies.
-ADJUSTABLE.
-They can be approximately, orbitally tested for self-consistency.

Galactic Potential Model

Axisymmetric Potential: Bulge, Disc, Supermassive spheric halo (Miyamoto-Nagai, NFW, Hernquist, logarithmic, exponential, etc).

<u>Constraints satisfied:</u>

-Rotation curve

-Perpendicular force (z) at the Solar neighborhood

-Local escape velocity

Adopted parameters:

- R_0 (7.5 to 8.5 kpc); $V(R_0)$=220 to 254 km/s (Reid et al. 2009)
- ρ_0 (0.15 $M_\odot$ /pc^3)
- $A = -(r/2)\, d\Omega/dr$ (12.95 km/s kpc): shear ratio

  $B = -(1/2r)\, d(r^2\Omega)/dr$ (-12.93 km/s kpc): local vorticity

- In the density wave theory (Lin & Shu 1964), the solution (TWA), was modelled as a periodic perturbation given by a simple formula:

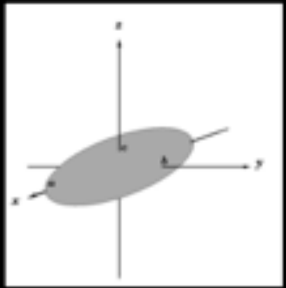
$$\Phi = g(r)\cos(m\varphi + f(r))$$

- This model is widely used in the literature to represent this spiral arms in 2D.

Tres modelos de barra

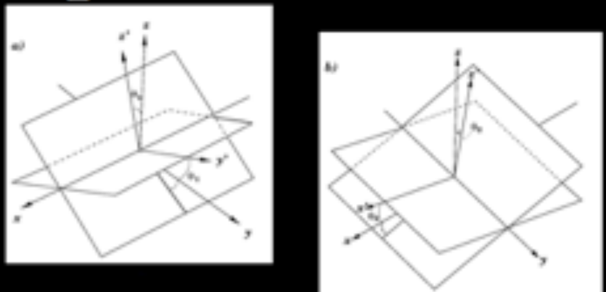
(+ potencial axisimétrico Allen y Santillán 1991)

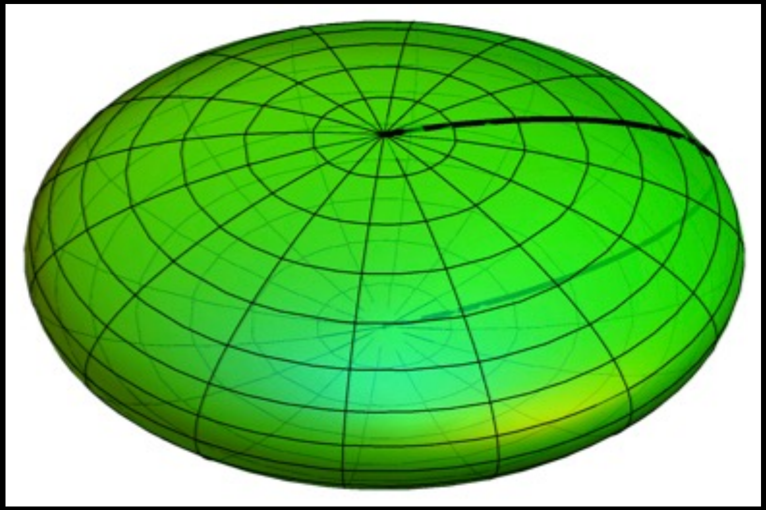
Modelo 1: Triaxial (elipsoidal) inhomogéneo.

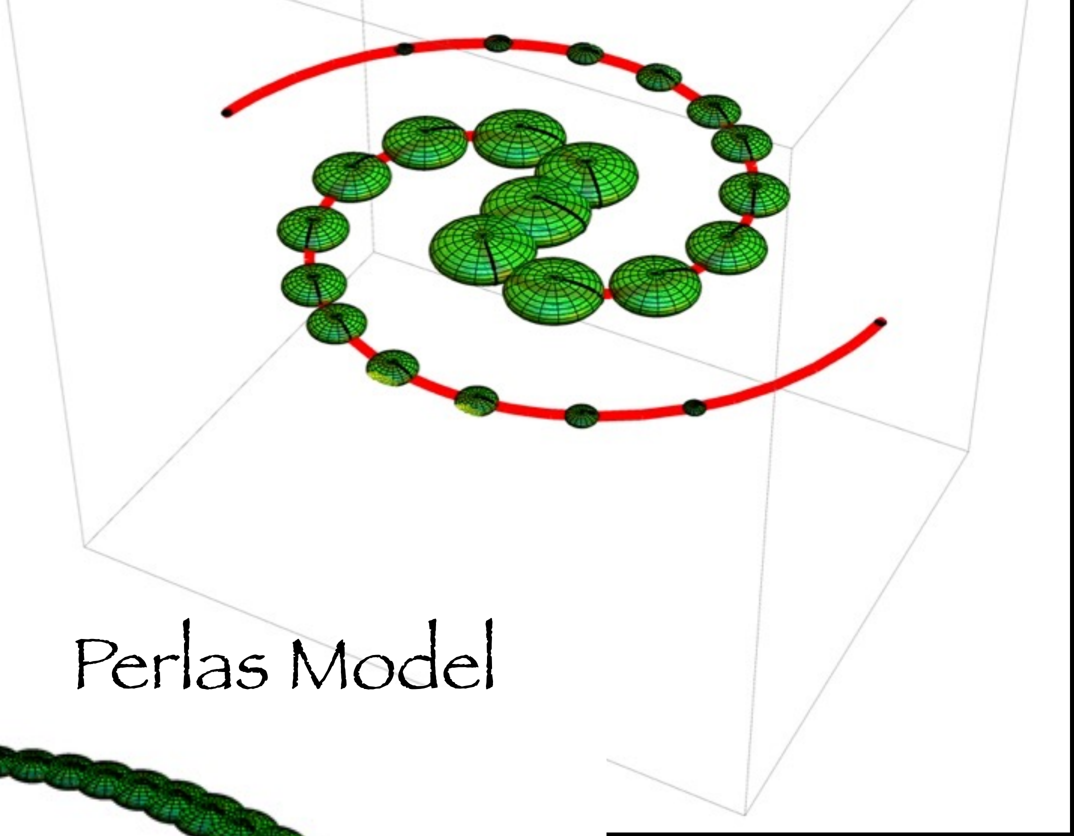


Modelo 2: Prolato inhomogéneo.

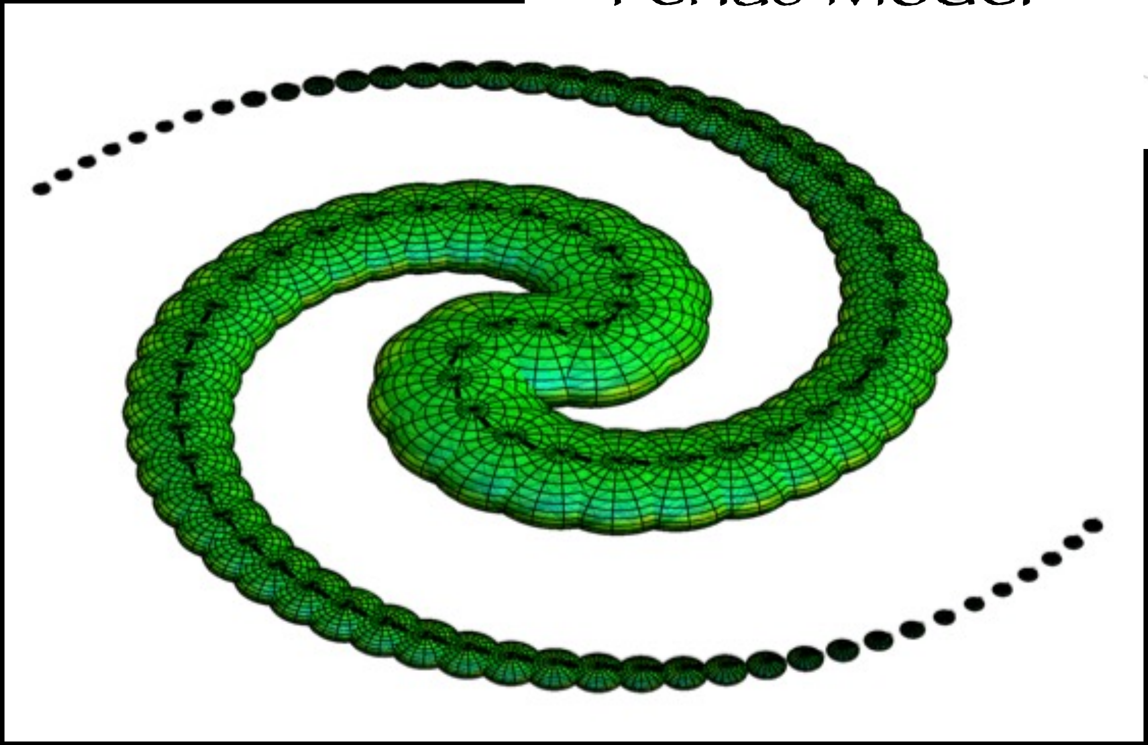
Modelo 3: Superposición de elipsoides inhomogéneos.

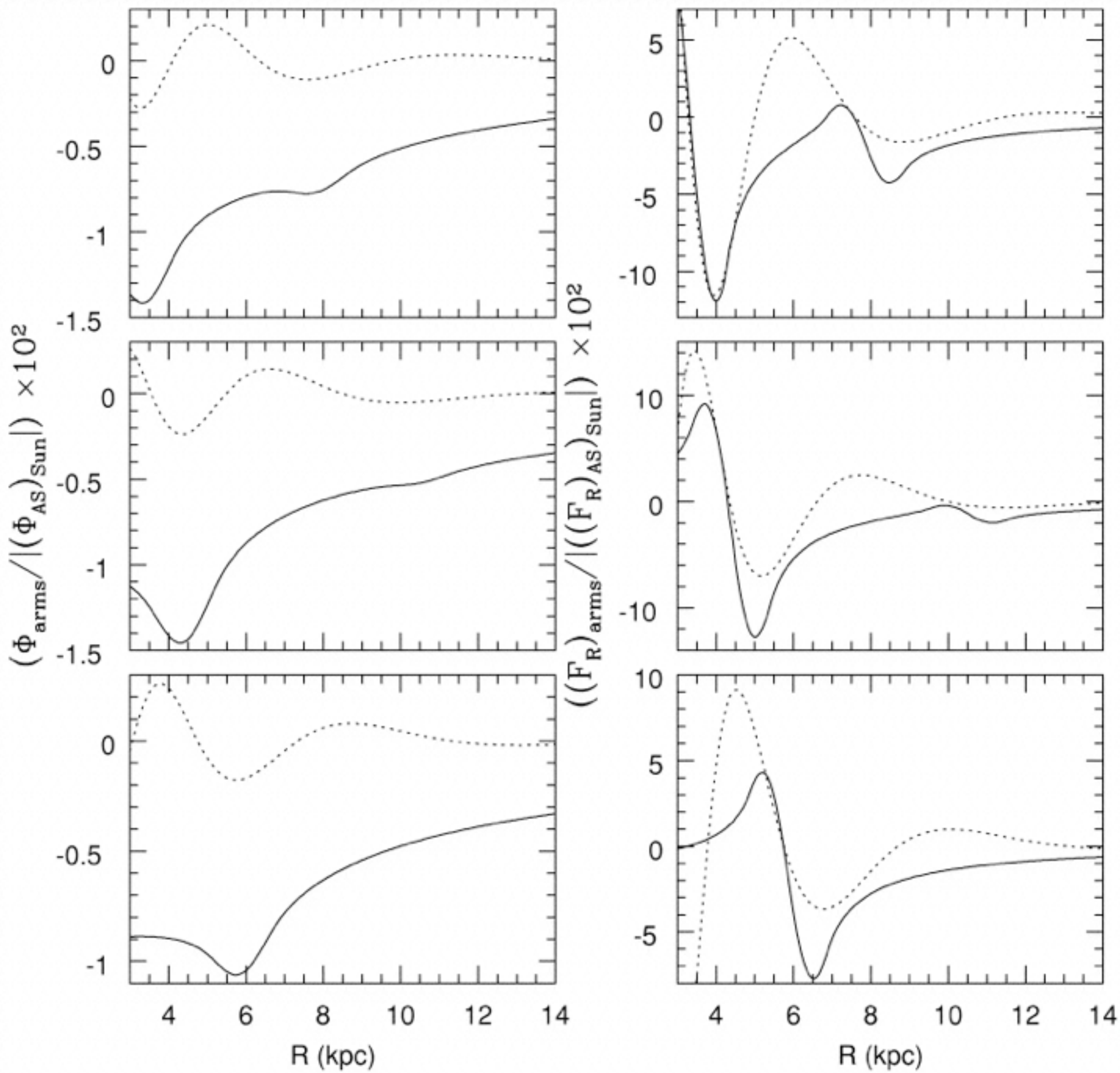






Perlas Model

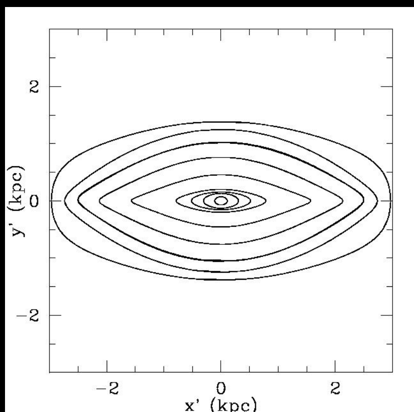



0
-0.5
-1
-1.5
$(\Phi_{arms}/|(\Phi_{AS})_{Sun}|)\ \times 10^2$
5
0
-5
-10
$((F_R)_{arms}/|((F_R)_{AS})_{Sun}|)\ \times 10^2$
4
6
8
10
12
14
R (kpc)

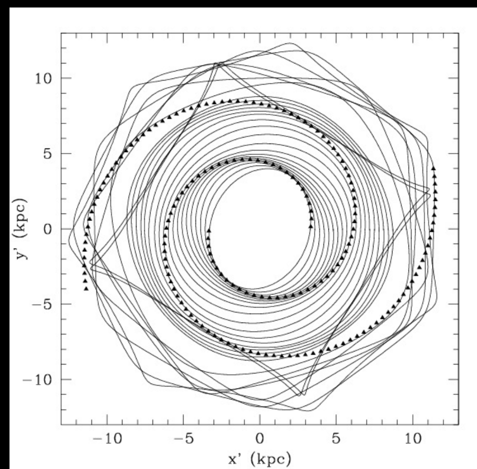
Steady Models

BAR

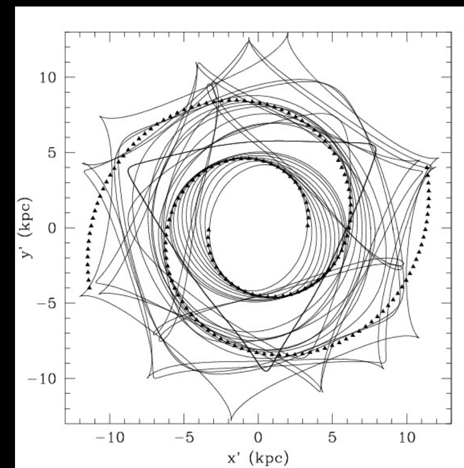
SPIRAL ARMS



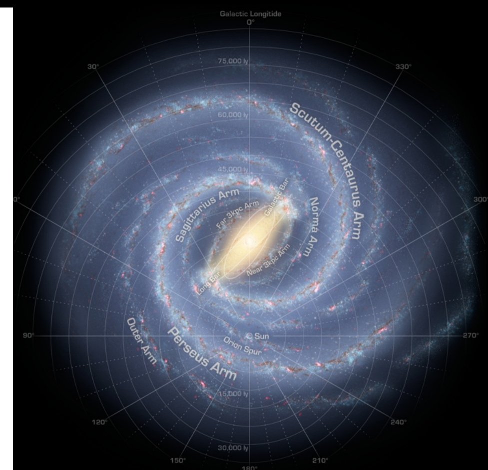
* X_1 orbits

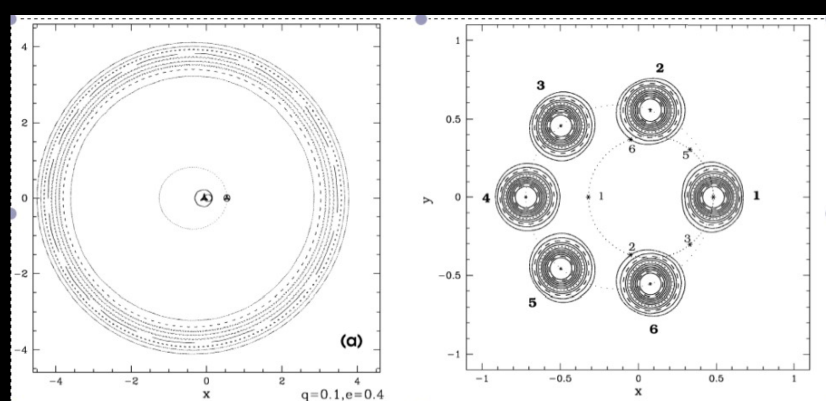


M_B/M_D=0.0175



M_B/M_D=0.05





Alpha Cen A and B

What we know

MILKY WAY:

- No. of spiral arms: 2 (Vallée 2005, IR banda K), Benjamin 2010; Churchwell et al. 2010.
- Pitch angle: i_p=15.5° (Drimmel y Spergel 2001).

4 brazos, 12° (Vallée 2005).

- Width and height: unknown in our Galaxy. Kennicutt y Hodge (1982). Study of spirals: width ~2 kpc. height 0.5 kpc (medium heigth between the thin and the thick disk).
- Density Law: Exponential.
- Outer limit: R ~ 12 kpc (Caswell & Hanes 1987, Drimmel 2000).

- Radial force and mass: Patsis, Cotopoulos & Grosbol (1991) find a correlation between i_p and radial force of spiral arms. They calculate for the Milky Way radial force ratios between 4 y 10% that are translated to a mass for *PERLAS* of M_B/M_D=[0.0175,0.5].
- Ω_p: 20-25 Obtained from a self-consistency analysis.

Milky Way Galaxy

Bar:

Length: R_f = 3.1-3.5 kpc based en maps IR, COBE/DIRBE
(Freudenreich 1998; Binney, Gerhard & Spergel 1997;
Bissantz & Gerhard 2002).

Axial ratio: 10:3.8:2.6 (Freudenreich 1998).

Density and scalelengths: $\rho_B = \mathrm{sech}^2(R_S)$.
$a_x=1.7$, $a_y=0.64$, $a_z=0.44$ (Freudenreich 1998).

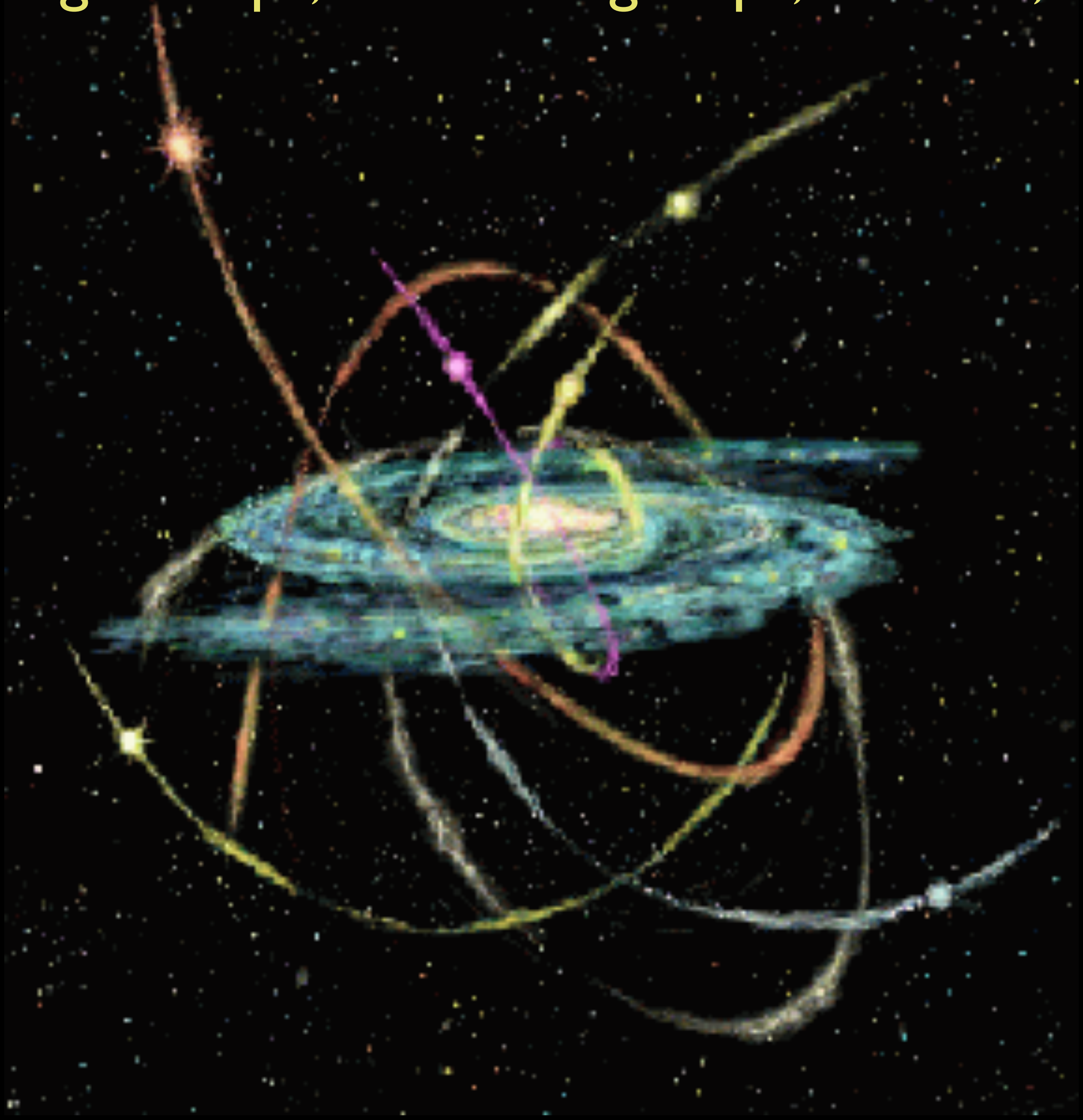
Mass: ~10^{10} M (Weiner & Sellwood 1999), HD and Ferrers' bars to reproduce *l,v* diagrams.

Ω_{P}.: ~50-70 km/s kpc (Binney et al. 1991; Fux 1999; Englmaier & Gerhard 1999; Weiner & Sellwood; Bissantz & Gerhard 2002; Debattista 2002).

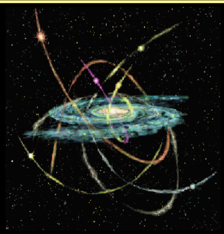
Potential models for galactic dynamics:

N body models.

"Moving Groups, kinematic groups, Streams, etc"



The origin of Moving groups



Hércules

Arturo

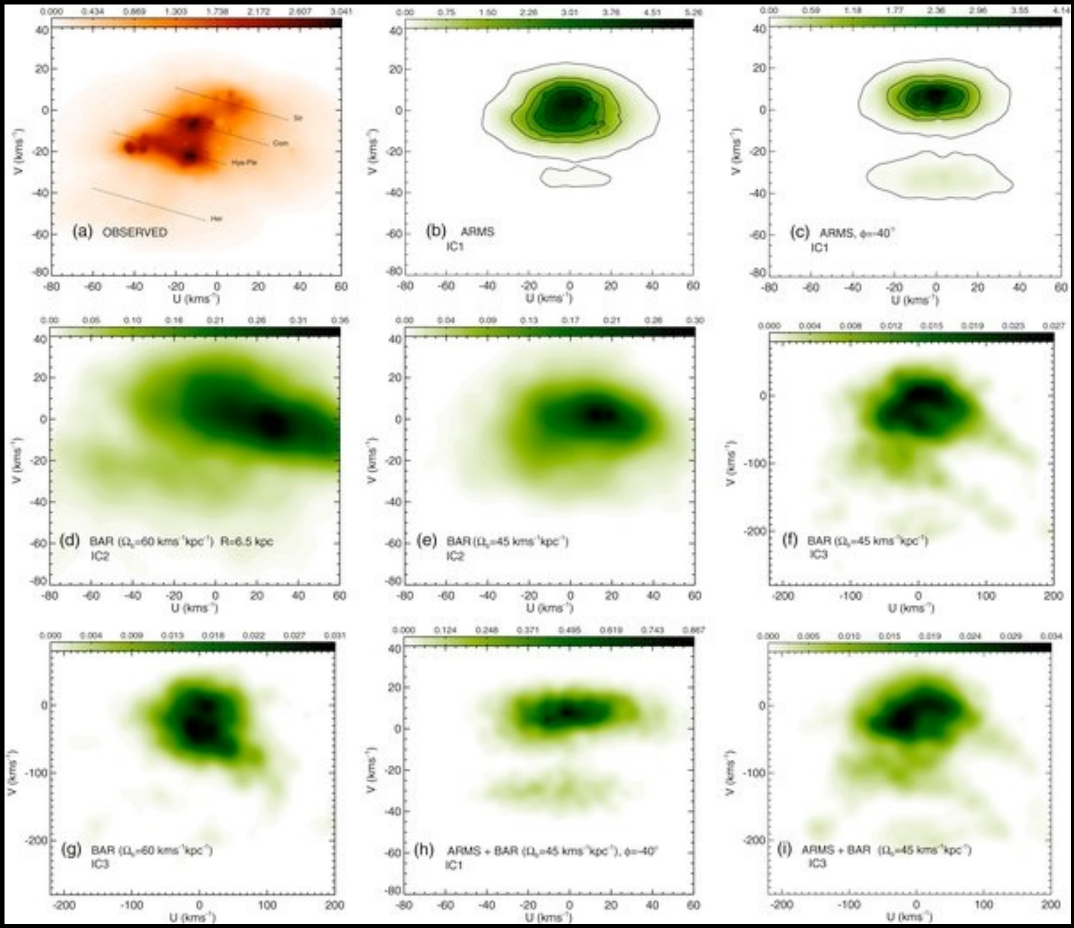
Disco de MO

Discovery of the Hyades and Ursa Major groups (Proctor 1869).Eggen identifies in 1959 several stellar groups and proposes that those are disperse rests of stellar formation in a cloud (v.g. Hercules stream). However, the stars have very different ages (1 to 2 Gyr), Caloi et al. (1999) y Famaey et al. (2005) conclude that they do not come from a common origin since they present a wide range in metallicities (Raboud et al. 1998).

Some could be induced dynamically by resonant periodic orbits of the bar (Dehnen 1999, Fux 2001 among others), or spiral arms if they are formed in an estocastic way (de Simone et al 2004), both can cause lumpy structure in the velocity distribution of the disc stars.

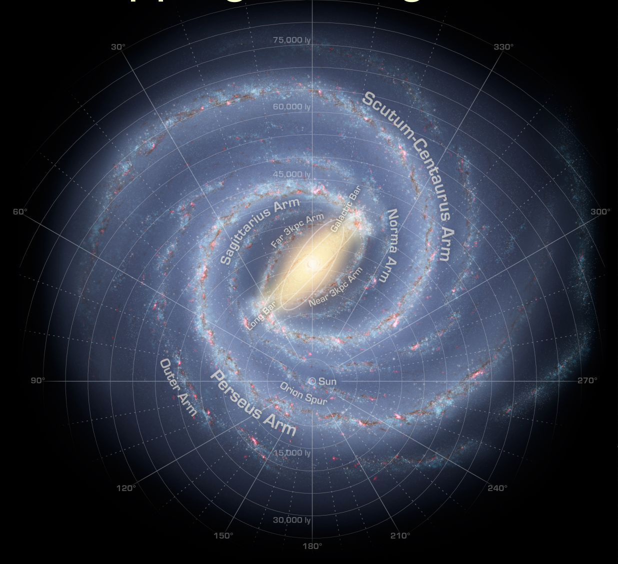
Stellar chaos in resonances overlap (Raboud 1998, Fux 2001, Chakrabarty 2007)

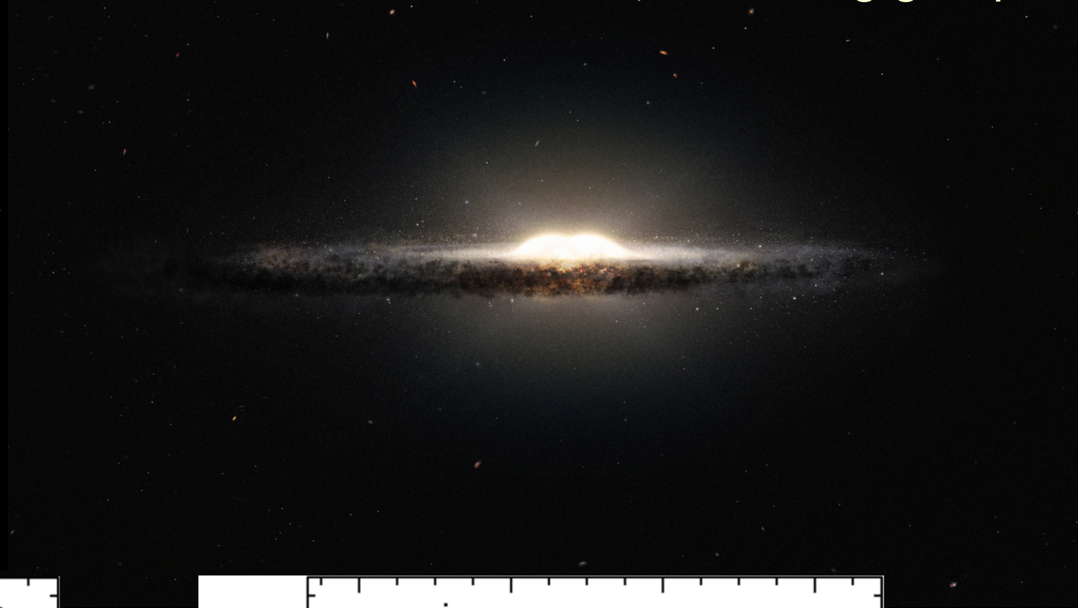
With the use of the potential described, the phase space available to the local stellar distribution is studied. The introduction of spiral arms induce phase space structure has several observable consequences.

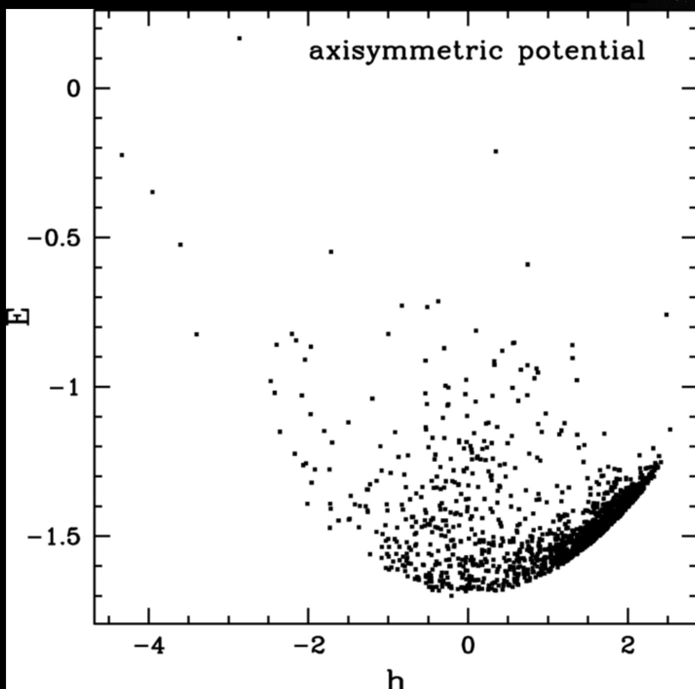


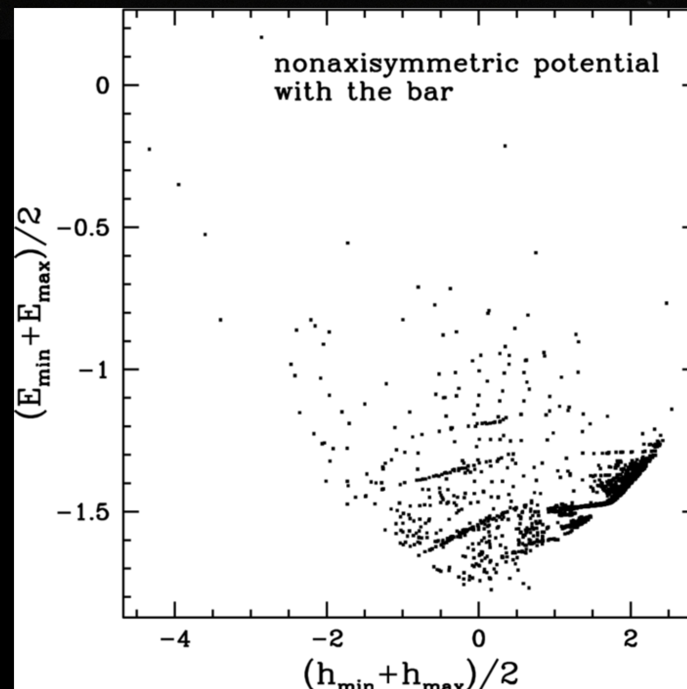
Antoja, Valenzuela, Pichardo, Moreno, Figueras, Fernández 2008

Resonant trapping in the galactic disc and halo and its relation with moving groups

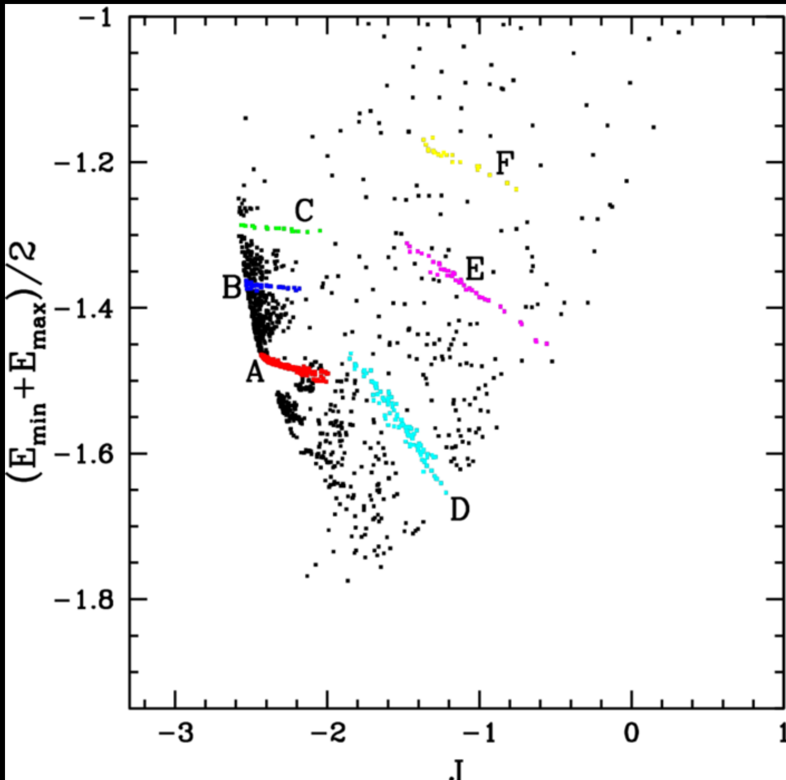


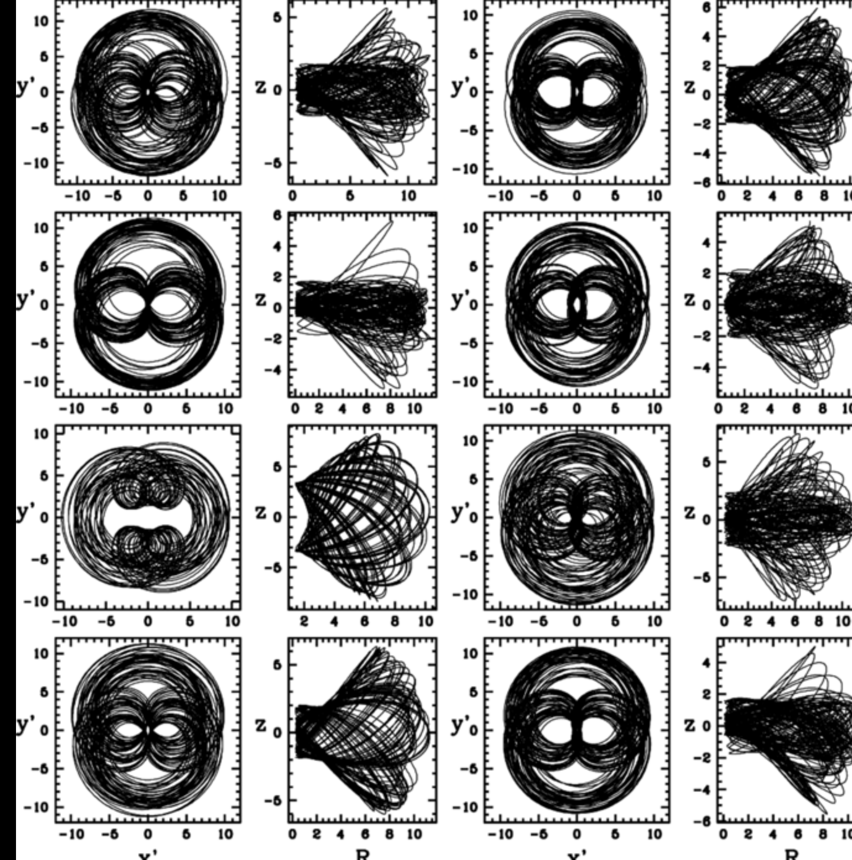


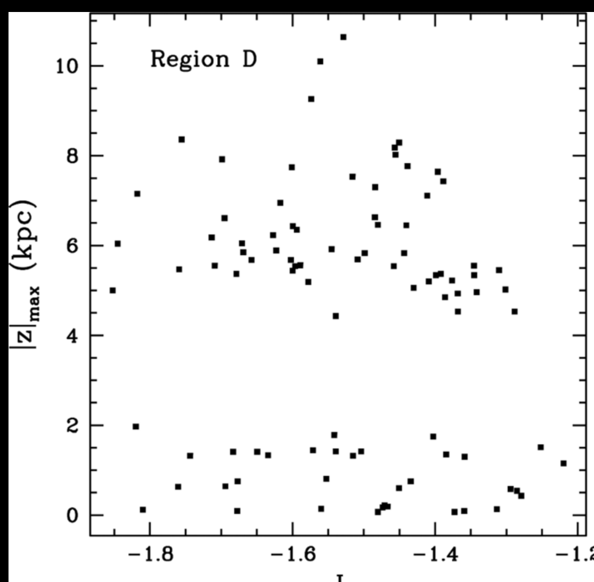


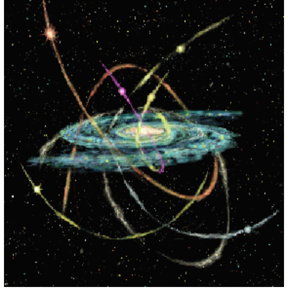


Moreno, Pichardo & Schuster 2015


$(E_{min}+E_{max})/2$
J
A
B
C
D
E
F
-1
-1.2
-1.4
-1.6
-1.8
-3
-2
-1
0
1


y'
z
x'
R


Region D
$|z|_{max}$ (kpc)
J
0
2
4
6
8
10
-1.8
-1.6
-1.4
-1.2



Detecting Triaxiality in the Galactic Dark Matter Halo through Stellar Kinematics

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ABSTRACT

Assuming the dark matter halo of the Milky Way as a non-spherical potential (i.e. triaxial, prolate, oblate), we show how the assembling process of the Milky Way halo, may have left long lasting stellar halo kinematic fossils only due to the shape of the dark matter halo. In contrast with tidal streams, associated with recent satellite accretion events, these stellar kinematic groups will typically show inhomogeneous chemical and stellar population properties. However, they may be dominated by a single accretion event for certain mass assembling histories. If the detection of these peculiar kinematic stellar groups is confirmed, they would be the smoking gun for the predicted triaxiality of dark halos in cosmological galaxy formation scenarios.

Subject headings: Galaxy: halo — Galaxy: kinematics and dynamics — Galaxy: structure —

1. Introduction

The standard cosmological model (ΛCDM) has reached a development stage in which cosmological tests at the scale of galaxies become possible (e.g. Van den Bosch 1998; Courteau & Rix 1999; Gnedin et al. 2006; Pizagno et al. 2007). However, a lack of understanding in the complicated physics that mediates the evolution of baryonic matter has meant that these tests are hard to implement, as their application depends on this physics. In some cases, controversial results are found out of these studies (e.g. Klypin et al. 1999; Moore 1994), stimulating suggestions of modifications for the model, but probably also the need of more accurate comparisons between theory and observations (e.g. Valenzuela et al. 2007; Simon & Geha 2007).

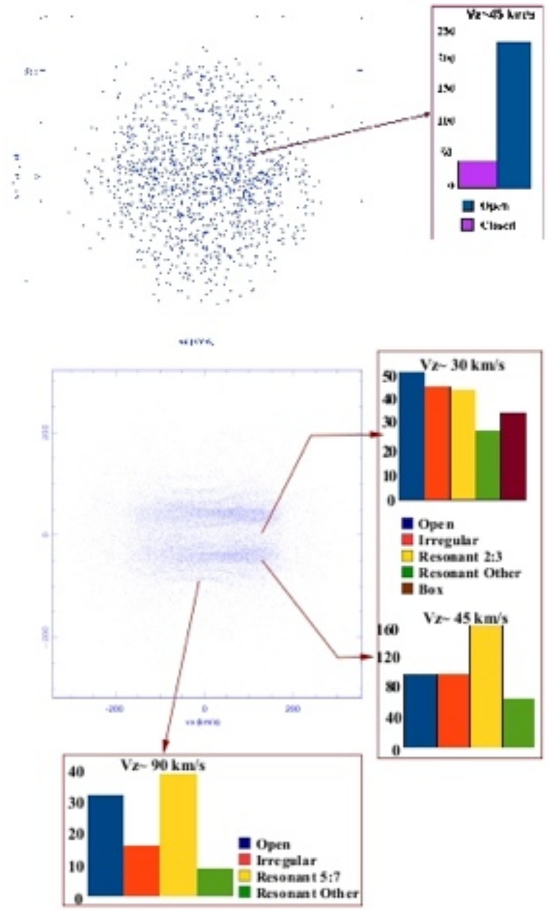


Fig. 3.— Kinematic structure in spherical (top panel) and triaxial
models. We show the vx-vz projection of the velocity space measure
observer inside the spherical model, the projection is basically feature
a histogram of the orbital types, the contribution of resonant orbits
hand panel shows the vx-vz diagram corresponding to an observer ins
model. We recover the structure related to the fish-like orbits as in
experiment, and other structures, regardless that in this case we rand
orbital distribution. We present three insets in the triaxial halo case:
that shows almost a nearly even distribution of all orbital species, the
shows a distribution clearly dominated by resonant orbits (2:3), the lower
in another kinematic structure, again the 5:7 resonant is dominant. W

Conclusions 1

- In particular, we find that the Hercules structure may be produced by the spiral arms and not exclusively by bar resonances as traditionally believed.

- The spiral arm contribution to the resonant structure in the solar neighborhood may be comparable to that of the Galactic bar.

- We develop a structure resembling the Arcturus kinematic group. The required condition seems to be a relatively hot stellar disk population similar to the thick disk in kinematics..

- The dependence of the stellar kinematics in the solar neighborhood on the structure, dynamics, and initial conditions of our experiments suggests that kinematic groups may provide a useful constraint on nonaxisymmetric MW models..

- There is a strong trapping of stars by resonances on the Galactic plane created by the Galactic bar plane resonances. Our aim is to relate this mechanism with moving groups in our Galaxy, especially with moving groups in the Galactic halo. A new method is presented to delineate the trapping regions.

- The influence of these resonant families can extend several kpc from the Galactic plane, explaining the observed coincidence in the halo region.

- An orbital study of a stellar system under the influence of the gravitational potential generated by a steady triaxial dark matter halo shows that, independently of the nature of dark matter, a non-spherical shape of the Milky Way dark matter halo strongly influences the stellar halo kinematic structure, producing lots of kinematic groups in the stellar halo.


“Spiral Arms”

On Spiral arms and bars:

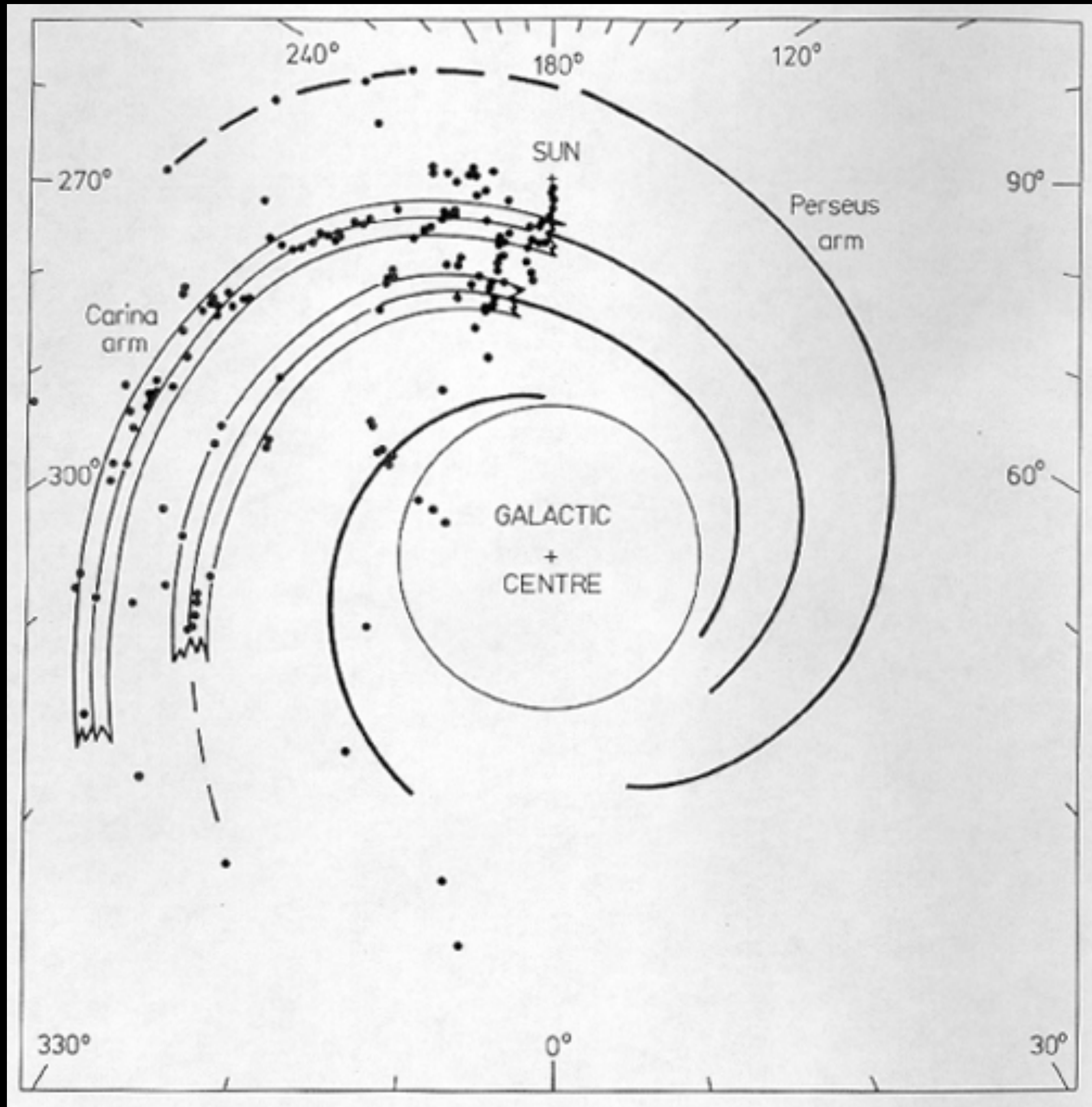
How are they excited? How do they maintain?
How do they affect dynamics?
What are their observed parameters (MW)? (from the number)
How do they look like in the Milky Way?
Are they short or long-lasting structures? How long?
Do they rotate rigidly?
What´s their angular speed? Do they run at the same angular velocity?

By now the strength and pattern speed of the Milky Way bar seem reasonably well established, both on the basis of photometry (Binney et al. 1997 ; Bissantz & Gerhard 2002) and on the basis of dynamics (Dehnen 1999; Minchev et al. 2007).

We know much less about spiral structure in the stellar disk. While the location of the nearby Galactic spiral arms have long been known on the bases of the dense gas geometry and distance measurements to young stars, the existence and properties of dynamically-important stellar spiral structure is completely open: neither has there been a known measure of a spiral stellar over-density that should have dynamical effects, nor has there been direct evidence for any response of the Disk to stellar spirals. Clarifying the dynamical role of spiral arms in the Milky Way has probably to await Gaia (Rix & Boby 2013).

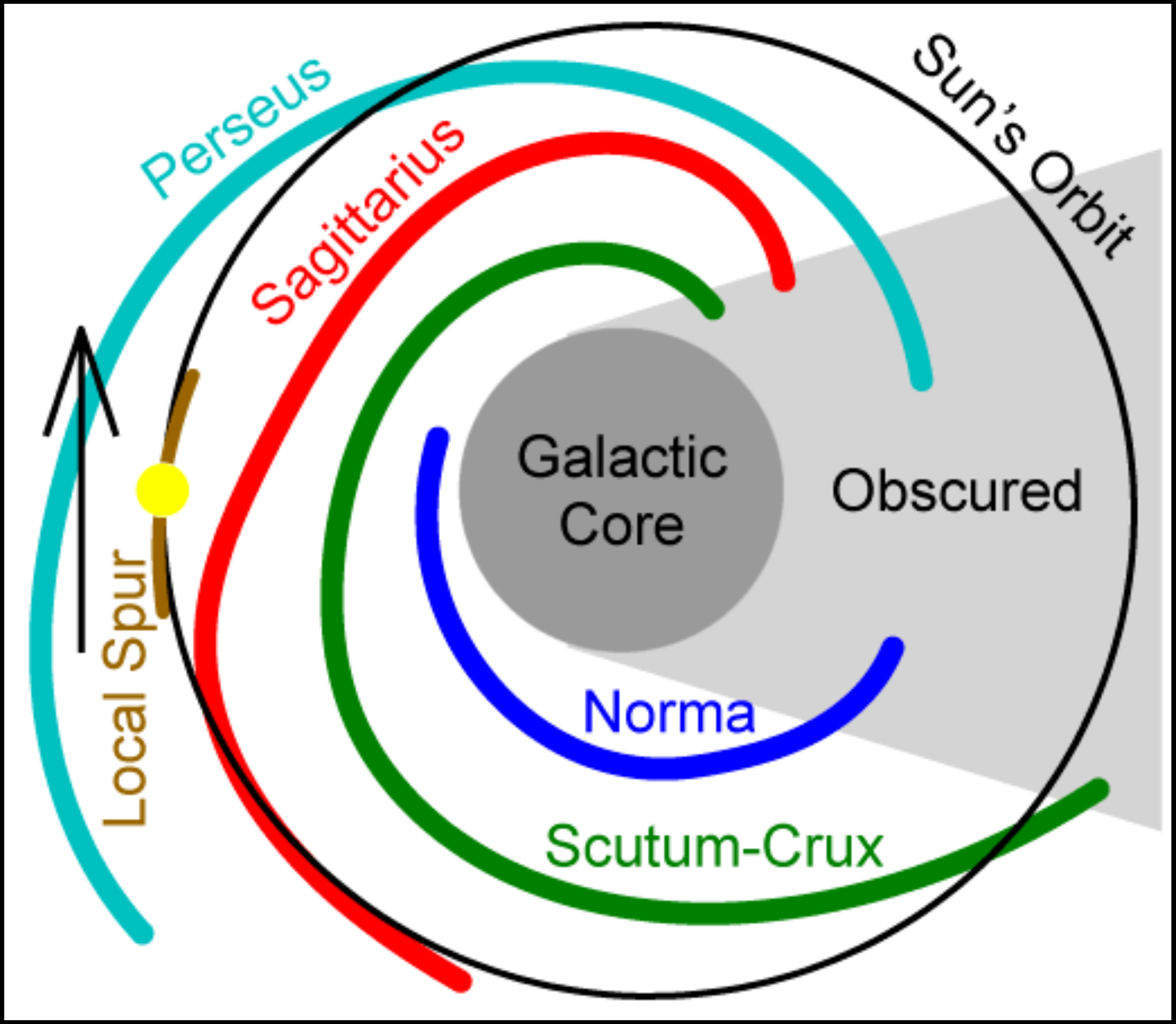
Chemical gradient, radial migration, thick disk, halo and disk velocity structure: moving groups (galactic satellites or intrinsic dynamics), the double bar, chaos effects.

Spiral Model of the MW from HII Regions (Georgelin & Georgelin 1976; Caswell & Hanes 1987)



Spiral Model of the MW from HII Regions (Georgelin & Georgelin 1976; Caswell & Hanes 1987)

Optical arms 4: Valleé 2002.



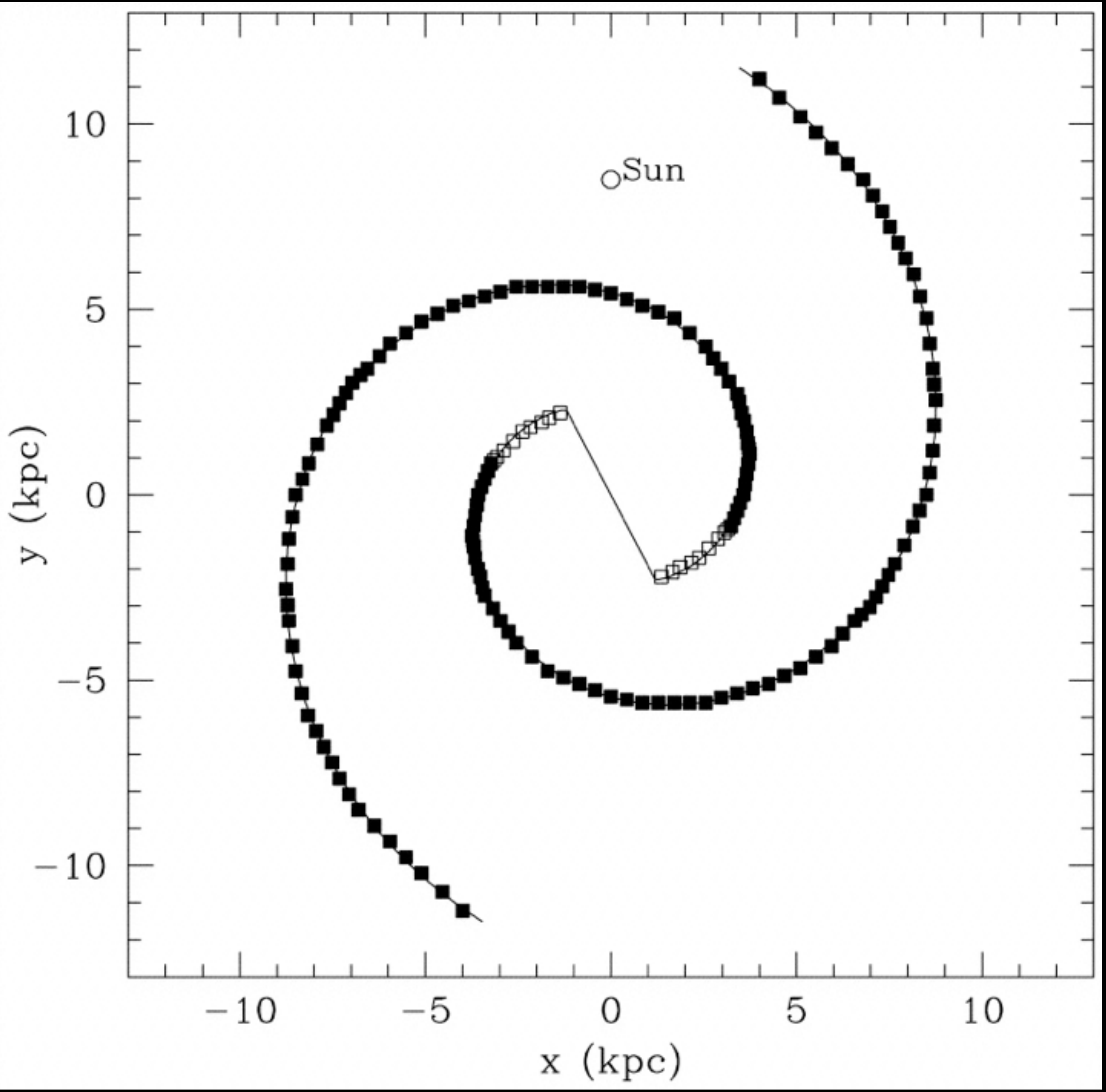
Galactic models using a superposition of two- and four-armed spirals have been proposed by Amaral & Lépine and Lépine et al. (2001).

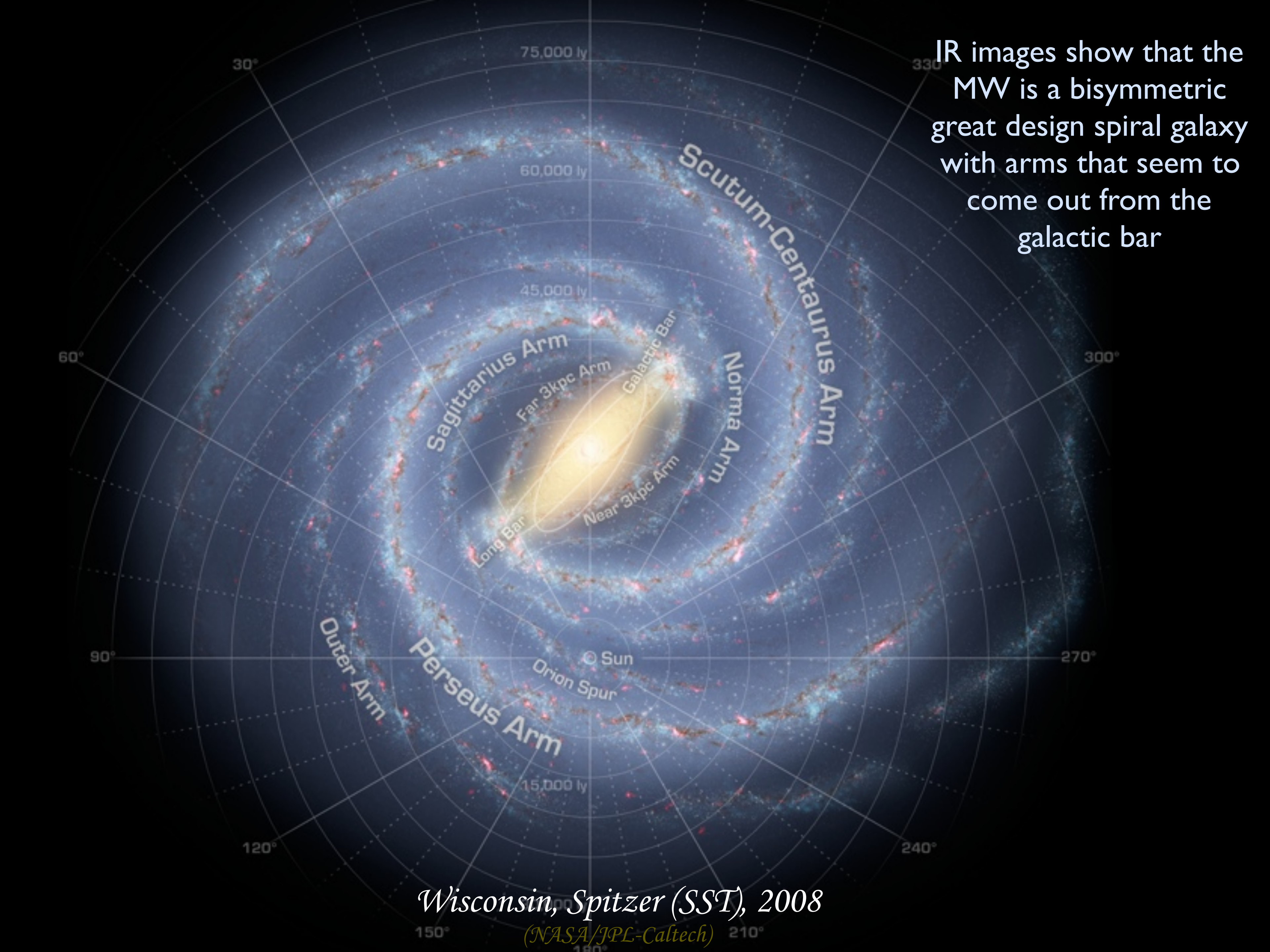
Spiral Model of the MW from HII Regions (Georgelin & Georgelin 1976; Caswell & Hanes 1987)

Optical arms 4: Valleé 2002.

K band arms + Optical: Drimmel 2000.

Galactic models using a superposition of two- and four-armed spirals have been proposed by Amaral & Lépine and Lépine et al. (2001).



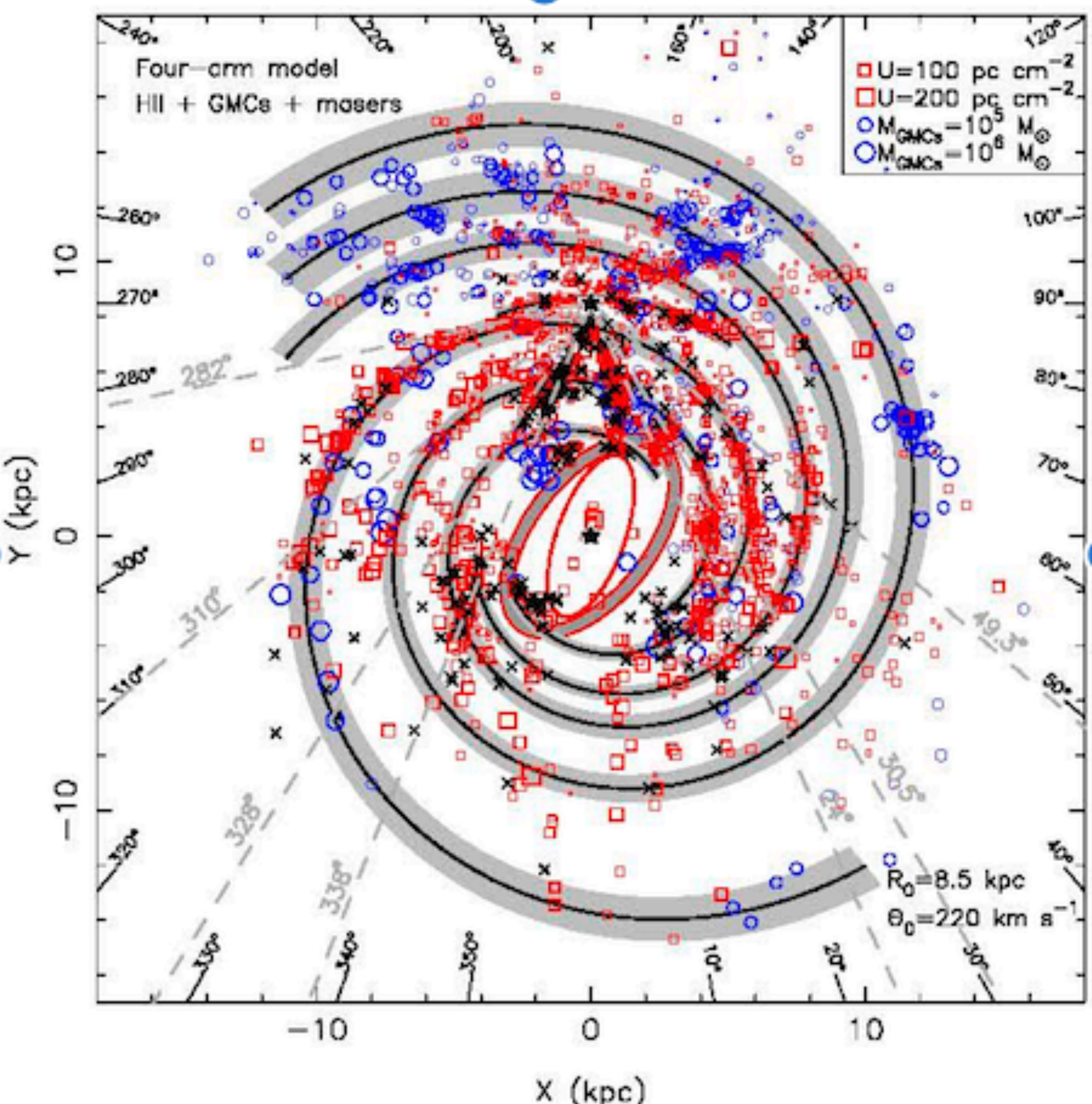


IR images show that the MW is a bisymmetric great design spiral galaxy with arms that seem to come out from the galactic bar

Wisconsin, Spitzer (SST), 2008

(NASA/JPL-Caltech)

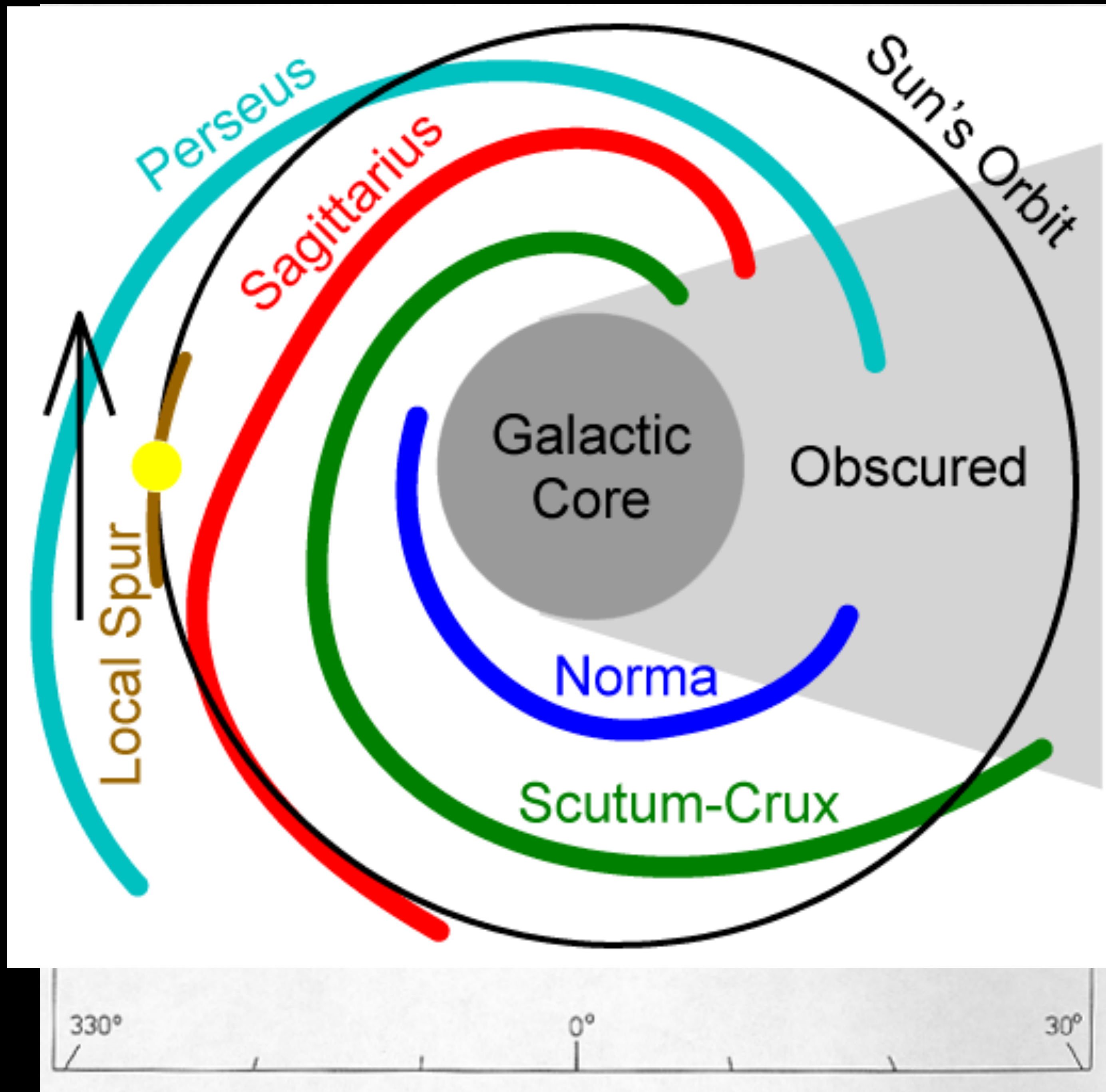
Hou, Han, 2014



Four-arm model
HII + GMCs + masers
U=100 pc cm^{-2}
U=200 pc cm^{-2}
$M_{GMCs}=10^5$ $M_\odot$
$M_{GMCs}=10^6$ $M_\odot$
R_0=8.5 kpc
Θ_0=220 km s^{-1}
Y (kpc)
X (kpc)

Spiral Model of the MW from HII Regions (Georgelin & Georgelin 1976; Caswell & Hanes 1987)

Optical arms 4: Valleé 2002.

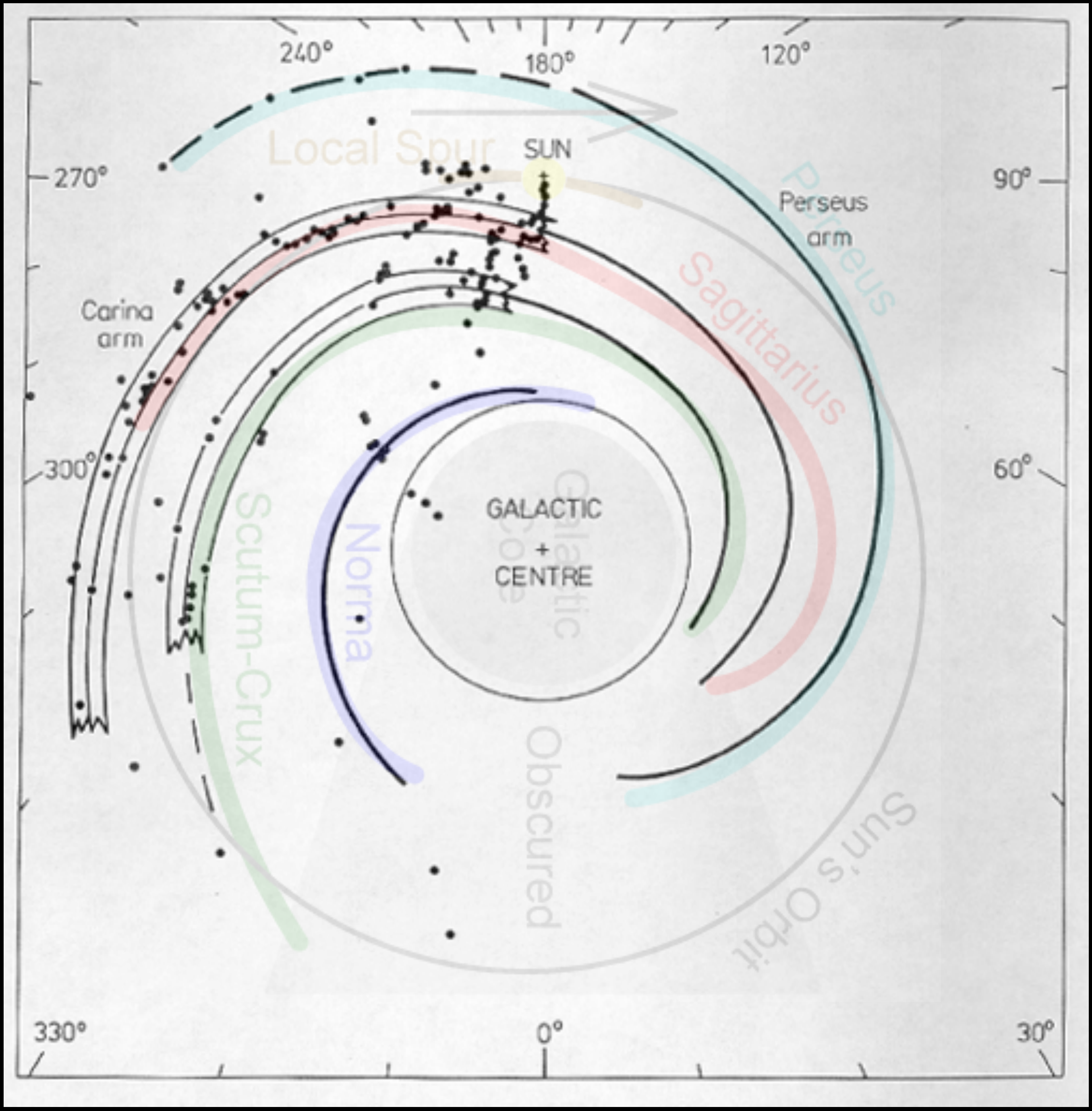


Galactic models using a superposition of two- and four-armed spirals have been proposed by Amaral & Lépine and Lépine et al. (2001).

Modelo espiral de la Galaxia obtenido de RHII (Georgelin & Georgelin 1976; Caswell & Hanes 1987)

Optical arms 4 (Valleé 2002).

Galactic models using a superposition of two- and four-armed spirals have been proposed by Amaral & Lépine and Lépine et al. (2001).

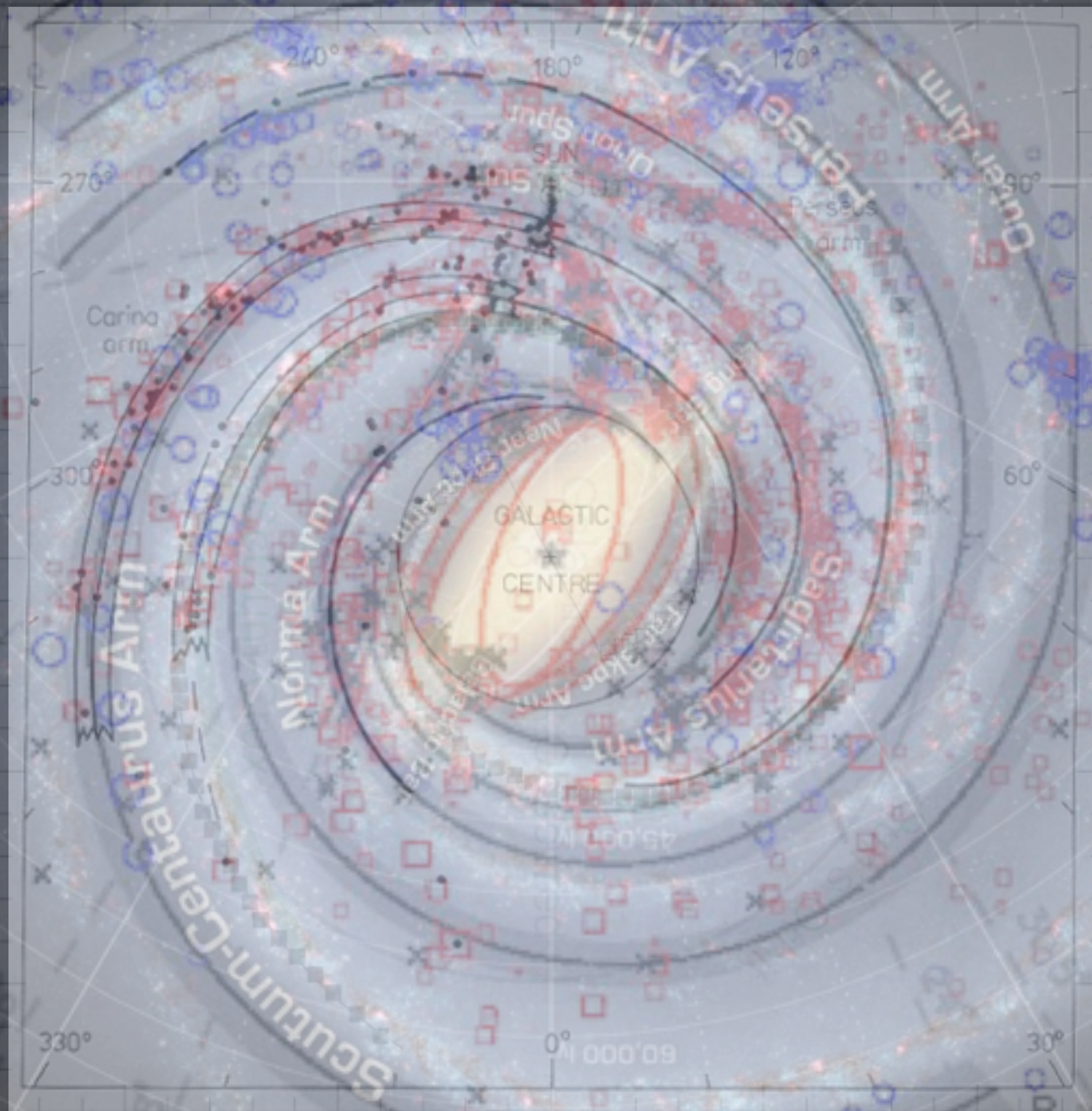


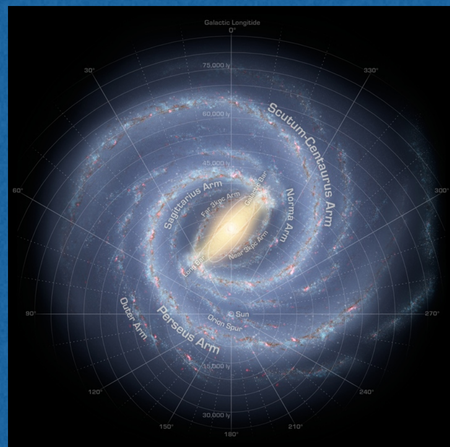
Modelo espiral de la Galaxia obtenido de RHII (Georgelin & Georgelin 1976; Caswell & Hanes 1987)

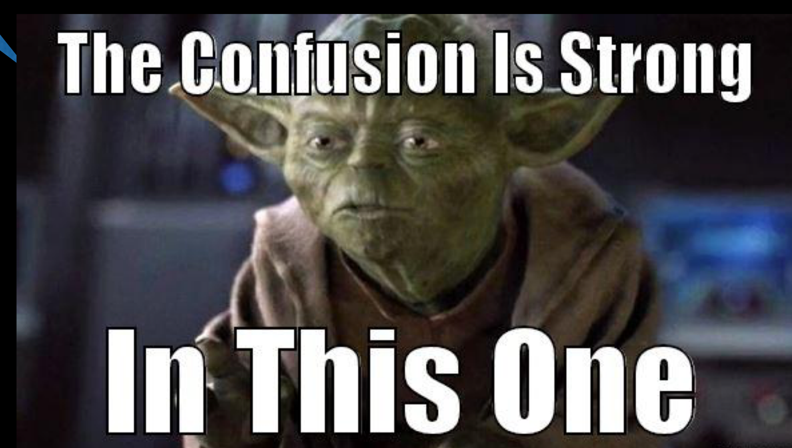
Optical arms 4 (Valleé 2002).

K band arms + Optical (Drimmel 2000).

Galactic models using a superposition of two- and four-armed spirals have been proposed by Amaral & Lépine and Lépine et al. (2001).




Galactic Longitude
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Sun
Orion Spur


The Confusion Is Strong
In This One
quickmeme.com

- Radial Migration

Exchange of angular momentum: Radial migration and radial heating

In the rotating frame of a steady spiral perturbation there is an "energy" invariant, Jacobi's integral E_J (Binney & Tremaine, 1987)

$$\boldsymbol{E_J = E - \Omega_p L_z} \qquad \textbf{(1)}$$

where E and L_z are the specific energy and z-angular momentum of the star in a non-rotating frame, and Ω_p is the pattern speed of the non-axisymmetric perturbation.

Hence, changes in energy and angular momentum are related by

$$\boldsymbol{\Delta E = \Omega_p \Delta L_z} \qquad \textbf{(2)}$$

If J_R is any parameter that quantifies radial kinetic energy, we can write

$$\boldsymbol{dE = \frac{\partial E}{\partial J_R} dJ_R + \frac{\partial E}{\partial L} dL} \qquad \textbf{(3)}$$

Radial Migration

Exchange of angular momentum: Radial migration and radial heating

If J_R is chosen to be the 'radial action', those partial derivatives become the angular frequencies, $\boldsymbol{\omega_R}$ and $\boldsymbol{\Omega}$, of the radial and azimuthal motion of the star. Eliminating $\boldsymbol{\Delta E}$ between equations (2) and (3), we obtain

$$\boldsymbol{\Delta J_R = \frac{\Omega_p - \Omega}{\omega_R} \Delta L} \qquad \textbf{(4)}$$

While changes in $\boldsymbol{L}$ at corotation $(\boldsymbol{\Omega = \Omega_p})$ does not cause changes in J_R, those away from corotation do. At more general locations energy is exchanged between random and angular motion.

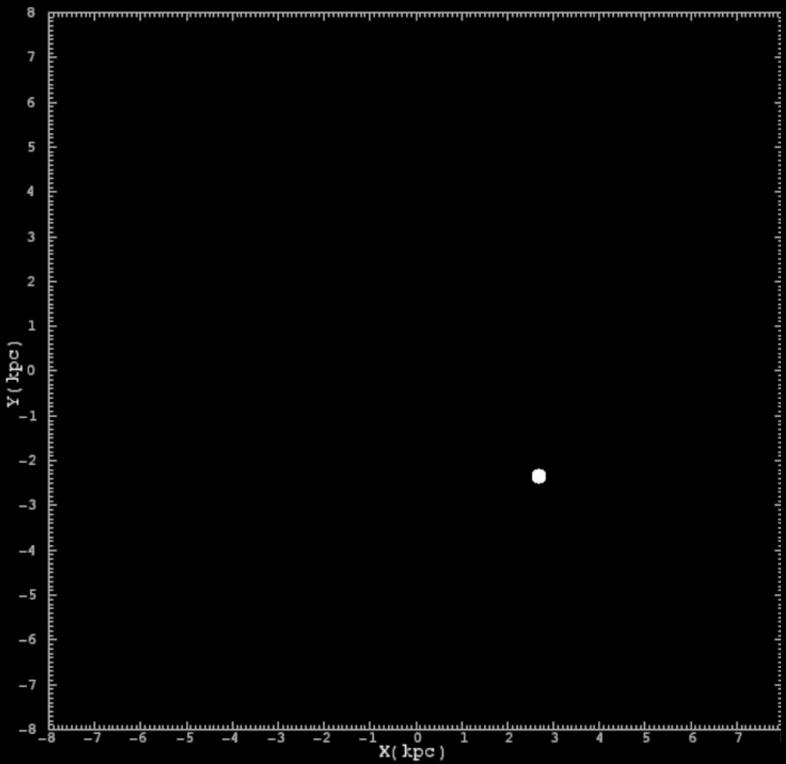
When a star is in Lindblad resonance with an m-armed spiral, its frequencies satisfy

$$\boldsymbol{\omega_R = \pm m(\Omega - \Omega_p)} \qquad \textbf{(5)}$$

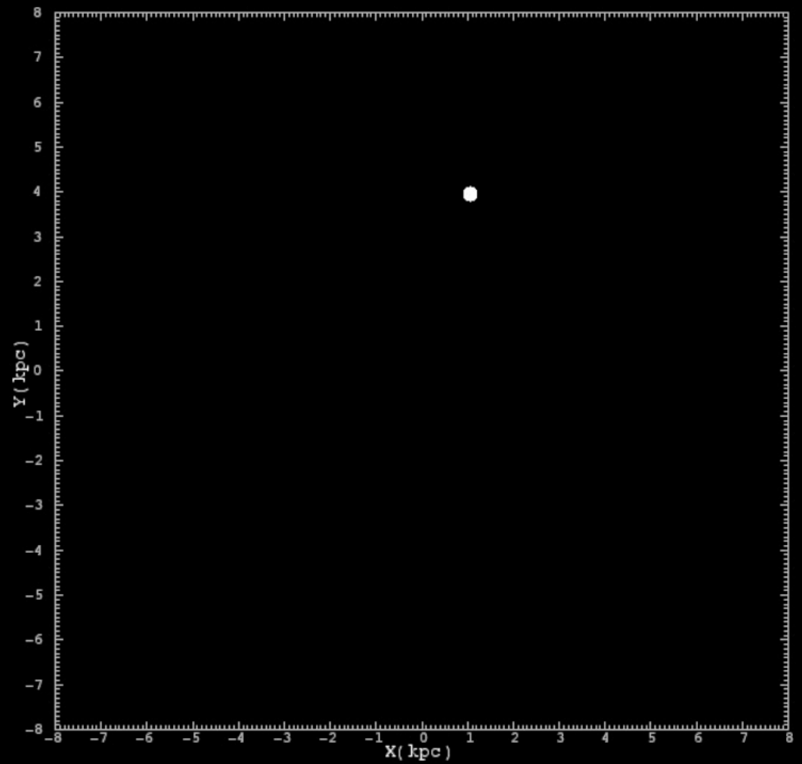
Combining equations (4) and (5) we obtain the simple result

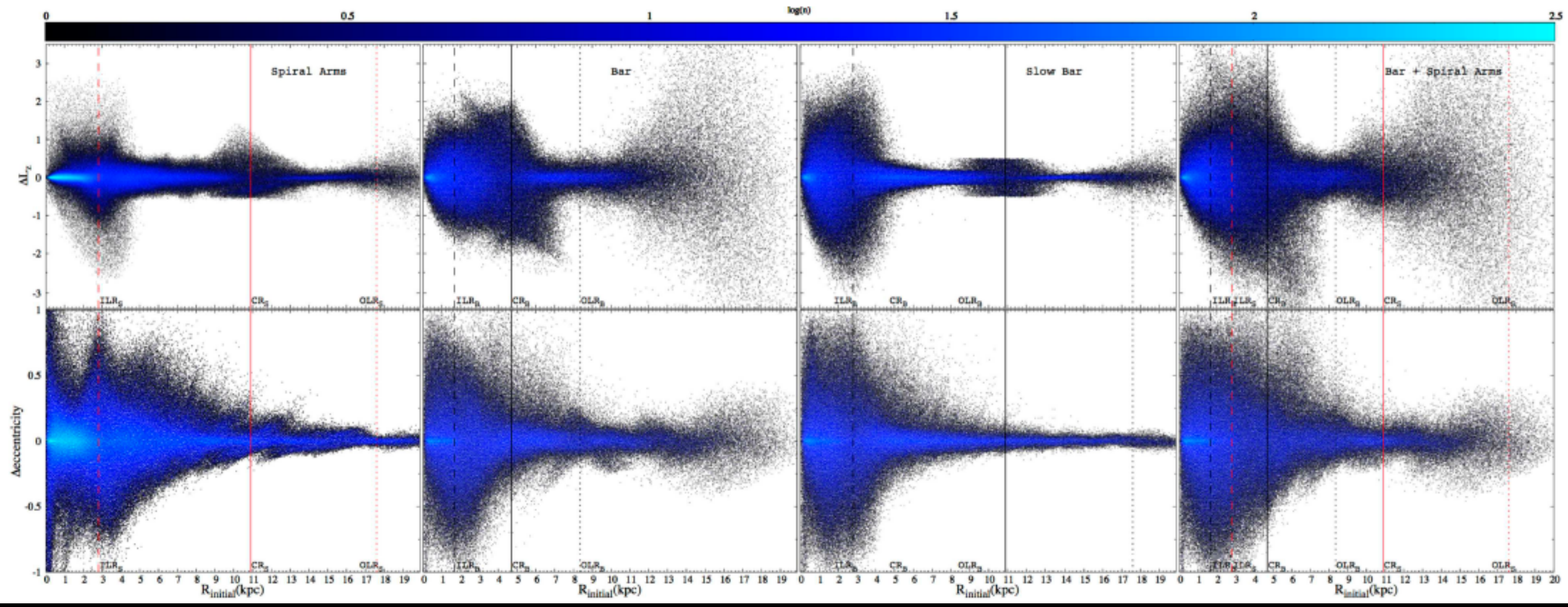
$$\boldsymbol{\Delta J_R = \mp \frac{1}{m} \Delta L} \qquad \textbf{(6)}$$

- Heating



- Radial Migration





Martínez-Medina, Pichardo, Moreno, Peimbert 2016

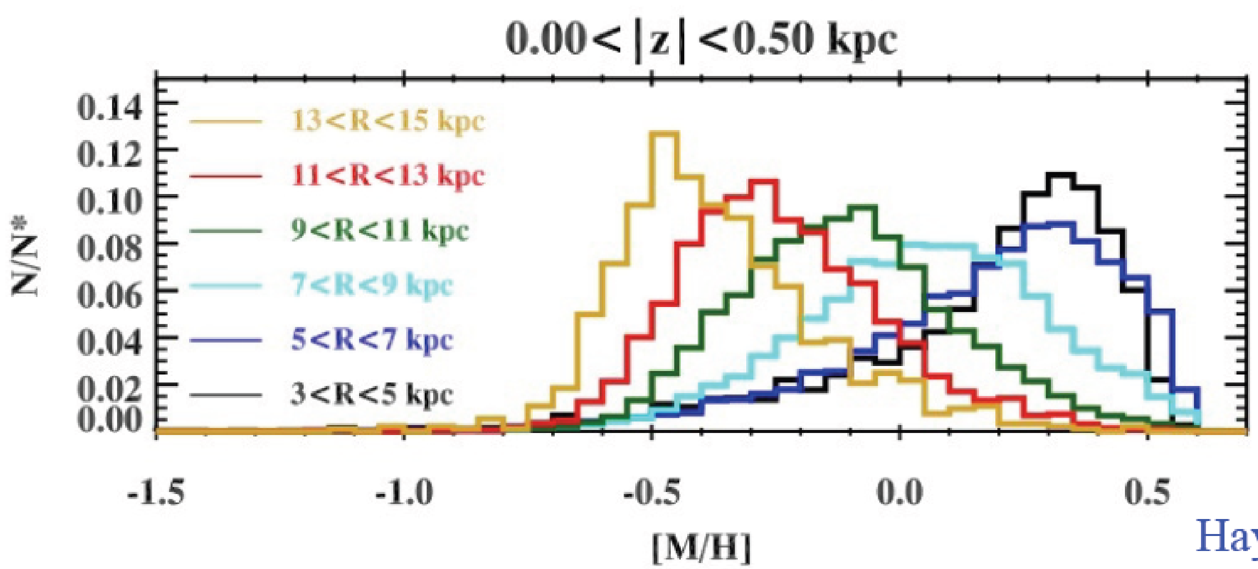
• Radial Migration and Metallicity Distribution Function

Metallicity Distribution Functions

69,919 red giants from the SDSS-III / APOGEE Data, Release 12

MDF shape change with radius

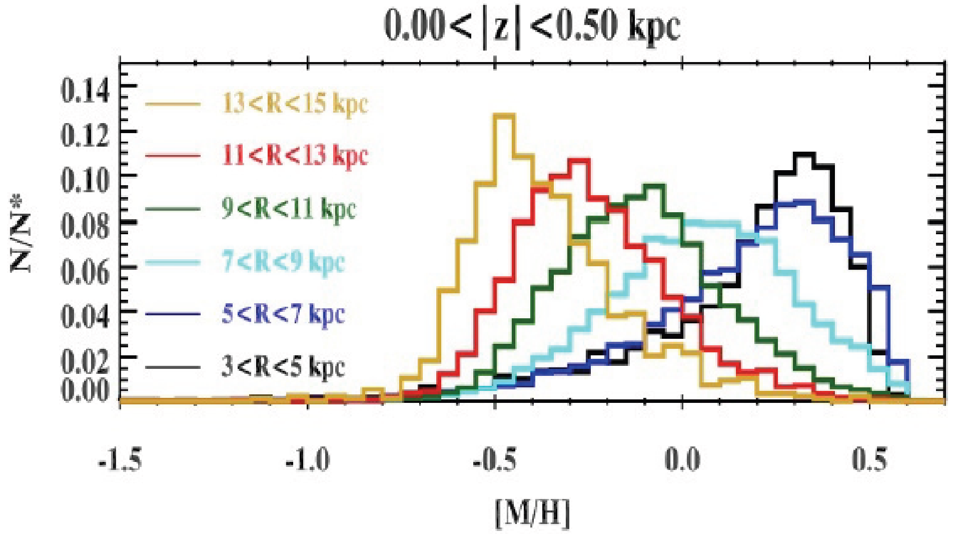
- Skew-negative in inner galaxy
- Roughly Gaussian at solar circle
- Skew-positive in outer galaxy



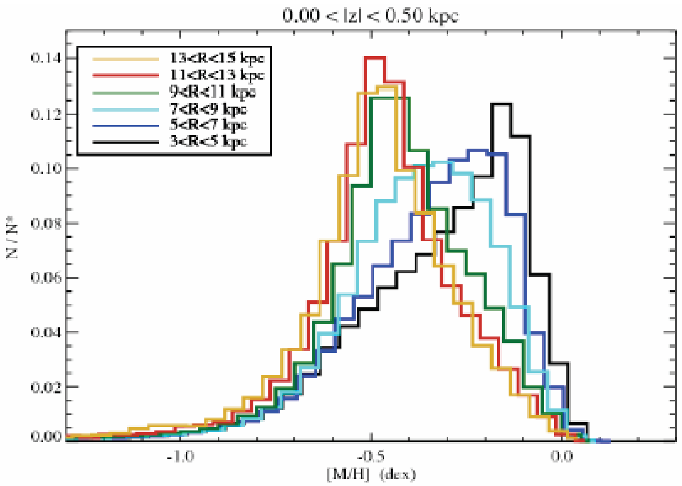
Hayden et al. (2015)

Simulations

Observations



Simulation



- Radial migration in simulation qualitatively reproduces the observed change in MDF skewness in MW midplane

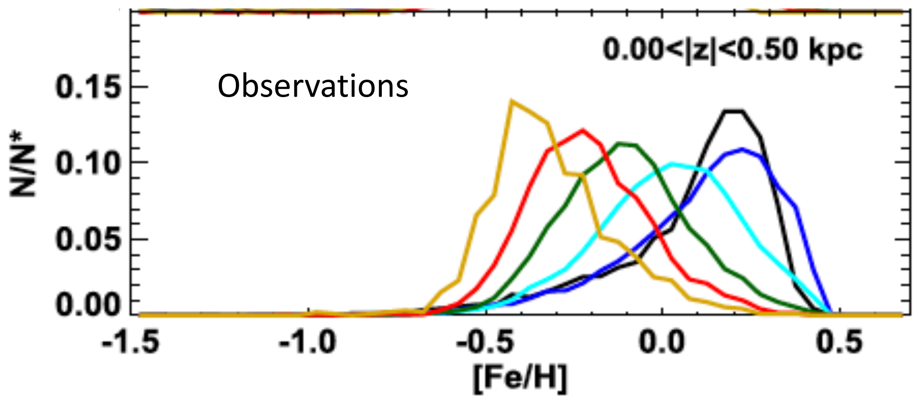
Loebman, DeBattista, Nidever et al. (2016)

Morphology !

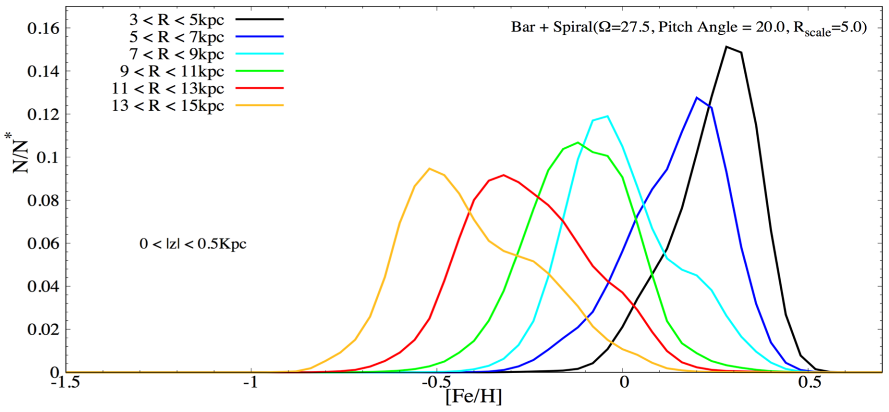
STELLAR DYNAMICS IMPRINTED IN THE METALLICITY DISTRIBUTION

The MDFs contain information about the spiral arms.

We propose a fit to the MDFs as a method to obtain information on the morphology and dynamics of the spiral arms



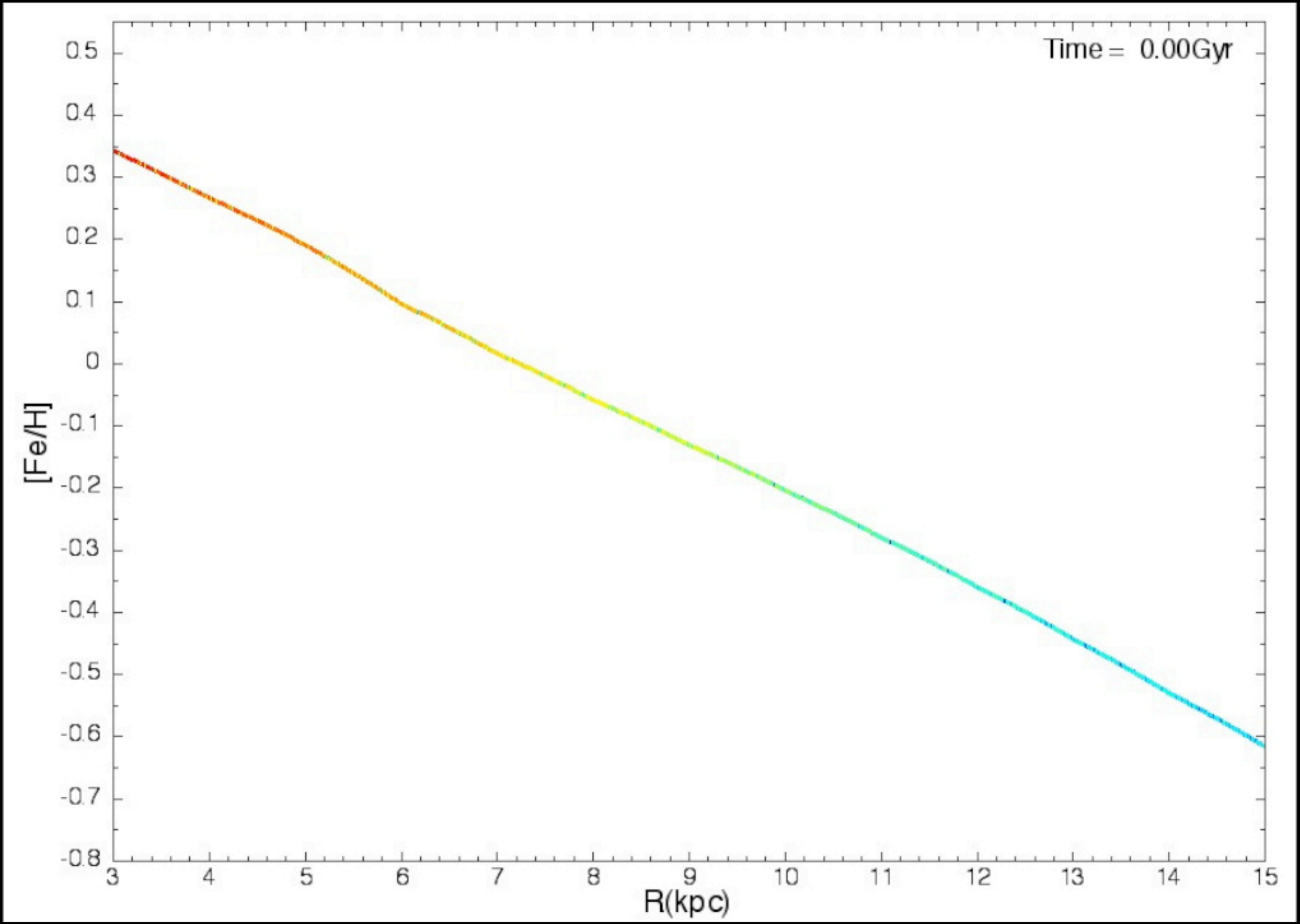
Simulation



The method gives us the next optimal outputs:

- Pattern speed of the MW spirals.
- Pitch angle of the MW arms.
- Scale radius of the MW arms density.
- The metallicity gradient across the MW disk.

Martínez-Medina, Pichardo, Peimbert, Carigi 2017


Time = 0.00Gyr
[Fe/H]
R(kpc)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
3
4
5
6
7
8
9
10
11
12
13
14
15

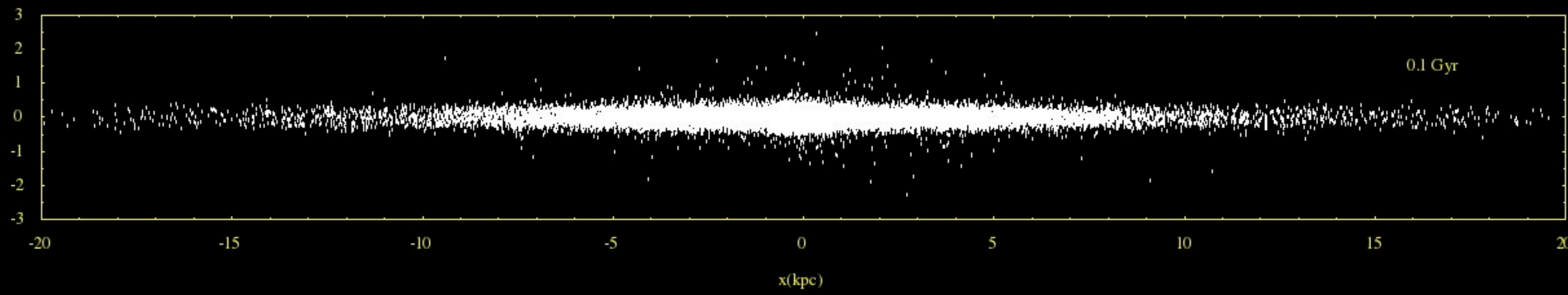
Conclusions 2

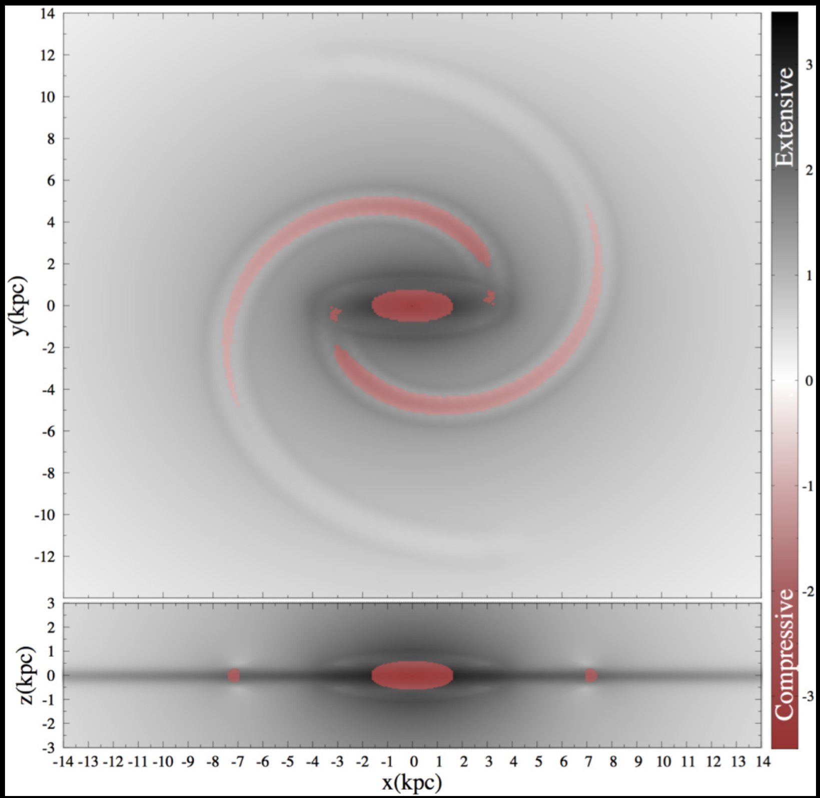
- Recent observations show that the Milky Way's metallicity distribution function (MDF) changes its shape as a function of radius. This new evidence of radial migration within the stellar disc sets additional constraints on Galactic models.
- By performing controlled test particle simulations in a very detailed, observationally motivated model of the Milky Way, we demonstrate that, in the inner region of the disc, the MDF is shaped by the joint action of the bar and spiral arms, while at outer radii the MDF is mainly shaped by the spiral arms.
- We show that the spiral arms are able to imprint their signature in the radial migration, shaping the MDF in the outskirts of the Galactic disc with a minimal participation of the bar.
- Conversely, this work has the potential to characterize some structural and dynamical parameters of the spiral arms based on radial migration and the shape of the MDF.
- The resemblance obtained with this approximation to the MDF curves of the Galaxy as seen by APOGEE, show that a fundamental factor influencing their shape is the Galactic potential. This means that the imprint of the spiral arms may be identified even in the presence of the strong influence of the massive bar.

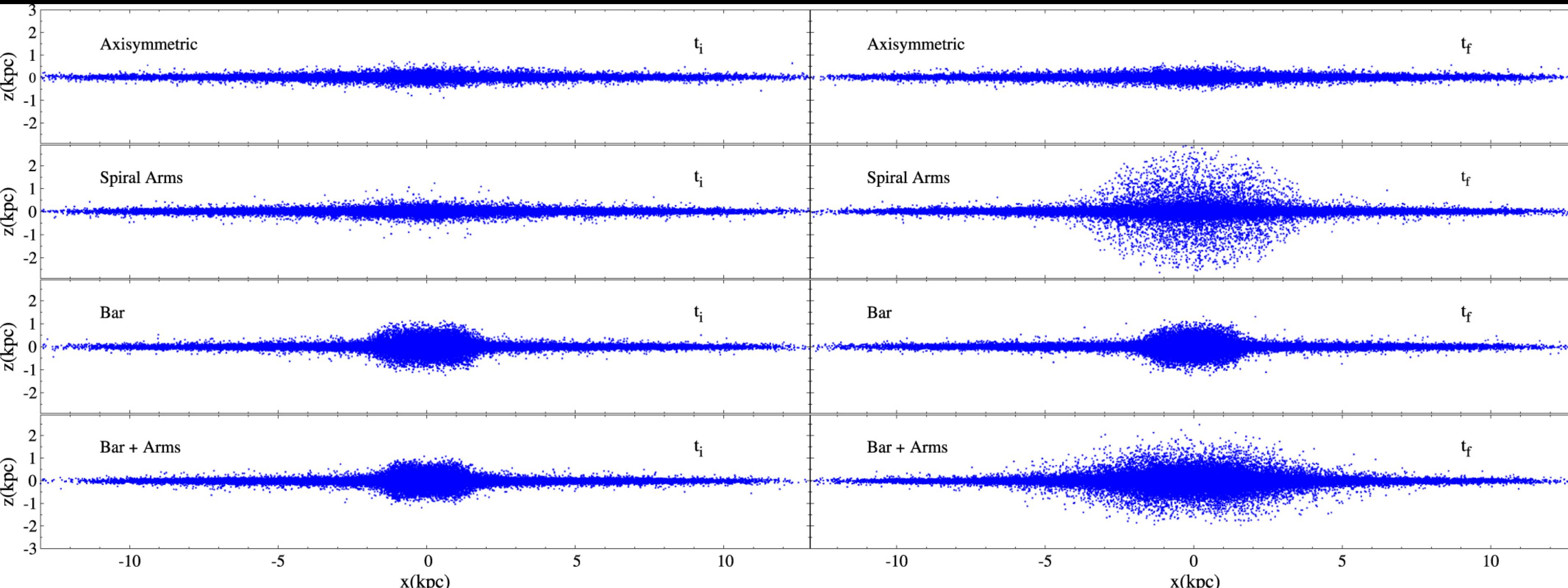
Conclusions 2

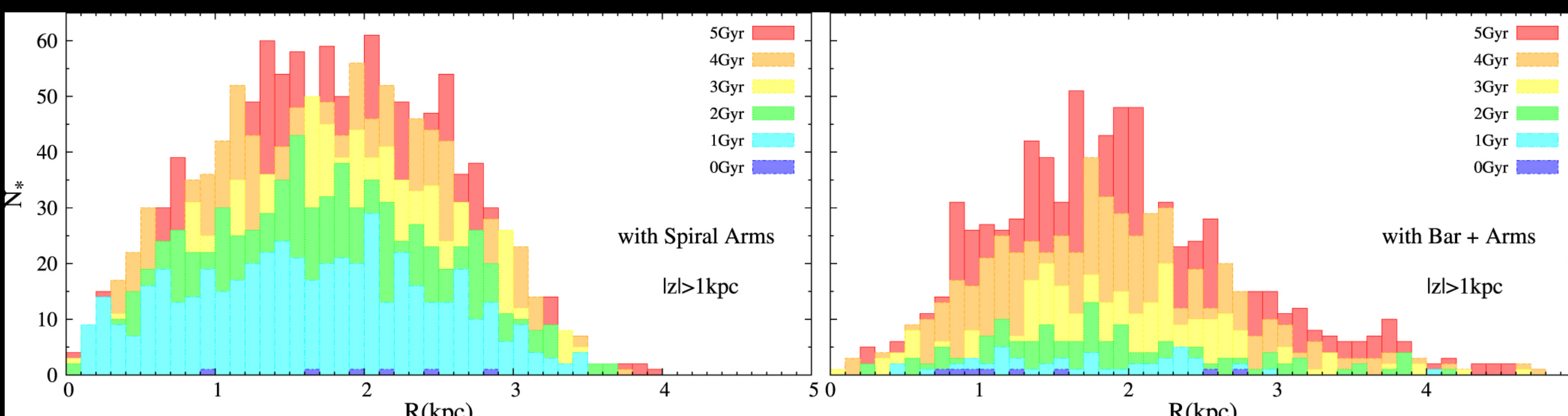
- Also, by tuning our simulated MDFs as close as possible to the observed ones, we introduce a method to set further constrains to chemical evolution models. This is helpful along the whole disc, but specially in the central region, where currently models do not provide information about the chemical content and its evolution.

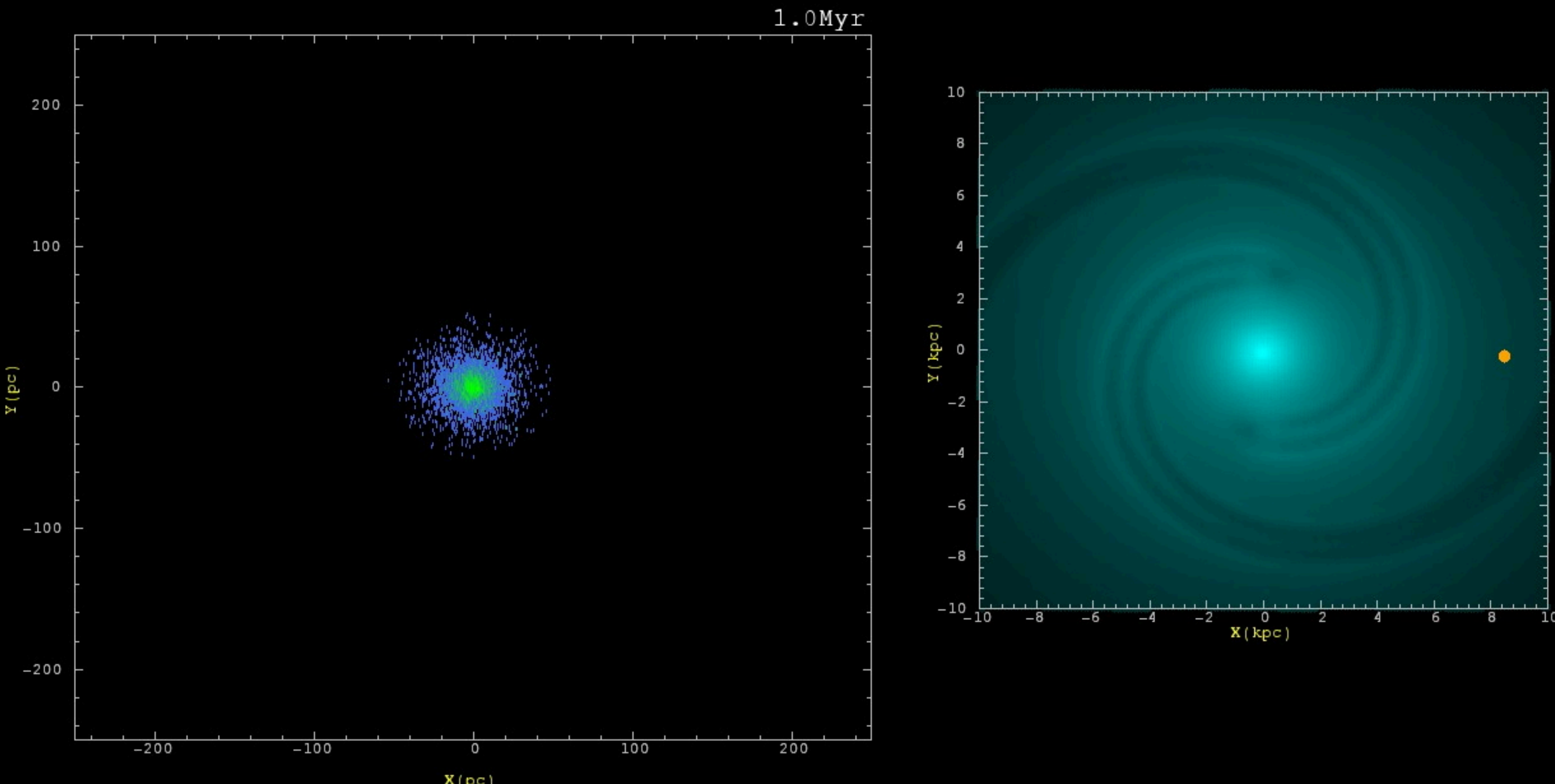
- We found that a dynamically evolved stellar population can exhibit a clear metallicity gradient regardless of the presence of important radial migration and heating in the disc. This means that the presence of important radial migration does not imply necessarily a substantial flattening of the metallicity gradient. Therefore, looking for flattened metallicity gradients is not a trustworthy method to establish the presence and importance of radial migration in galaxies.

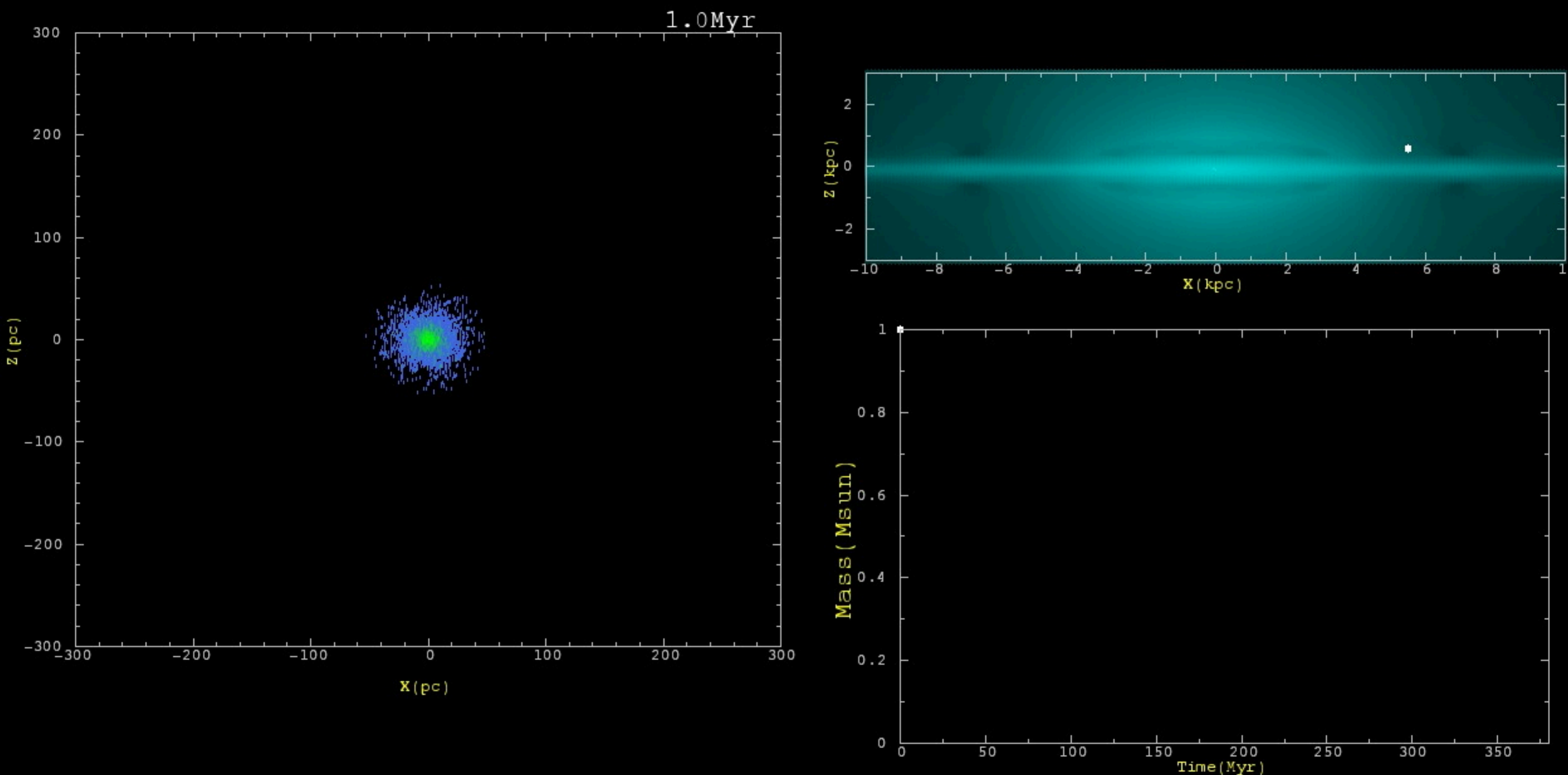

0.1 Gyr
x(kpc)


y(kpc)
z(kpc)
x(kpc)
Extensive
Compressive

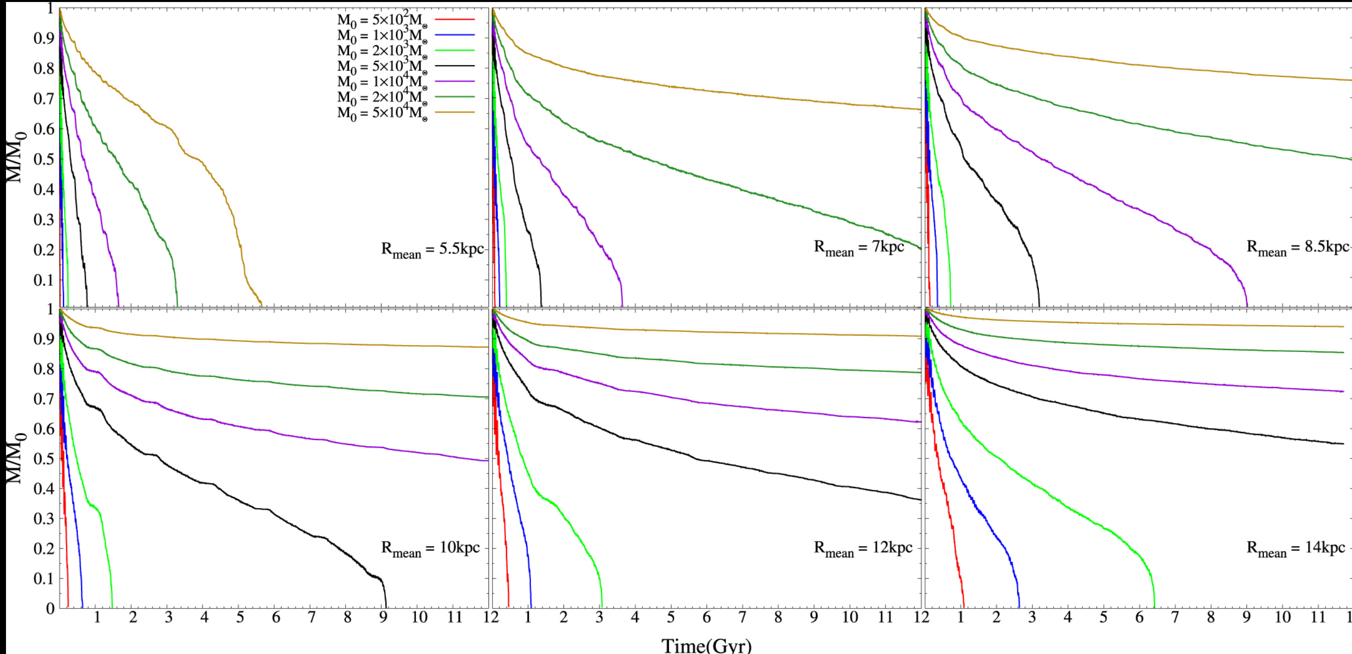

Axisymmetric
t_i
t_f
Spiral Arms
Bar
Bar + Arms
z(kpc)
x(kpc)

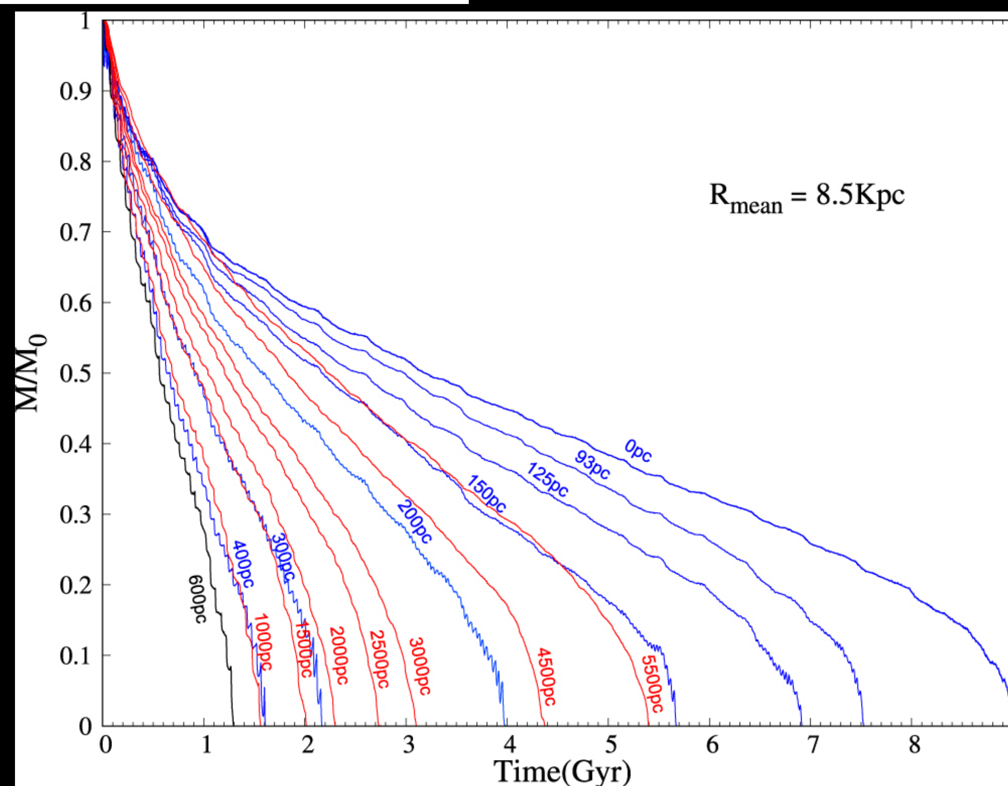

5Gyr
4Gyr
3Gyr
2Gyr
1Gyr
0Gyr
N_*
with Spiral Arms
with Bar + Arms
|z|>1kpc
R(kpc)

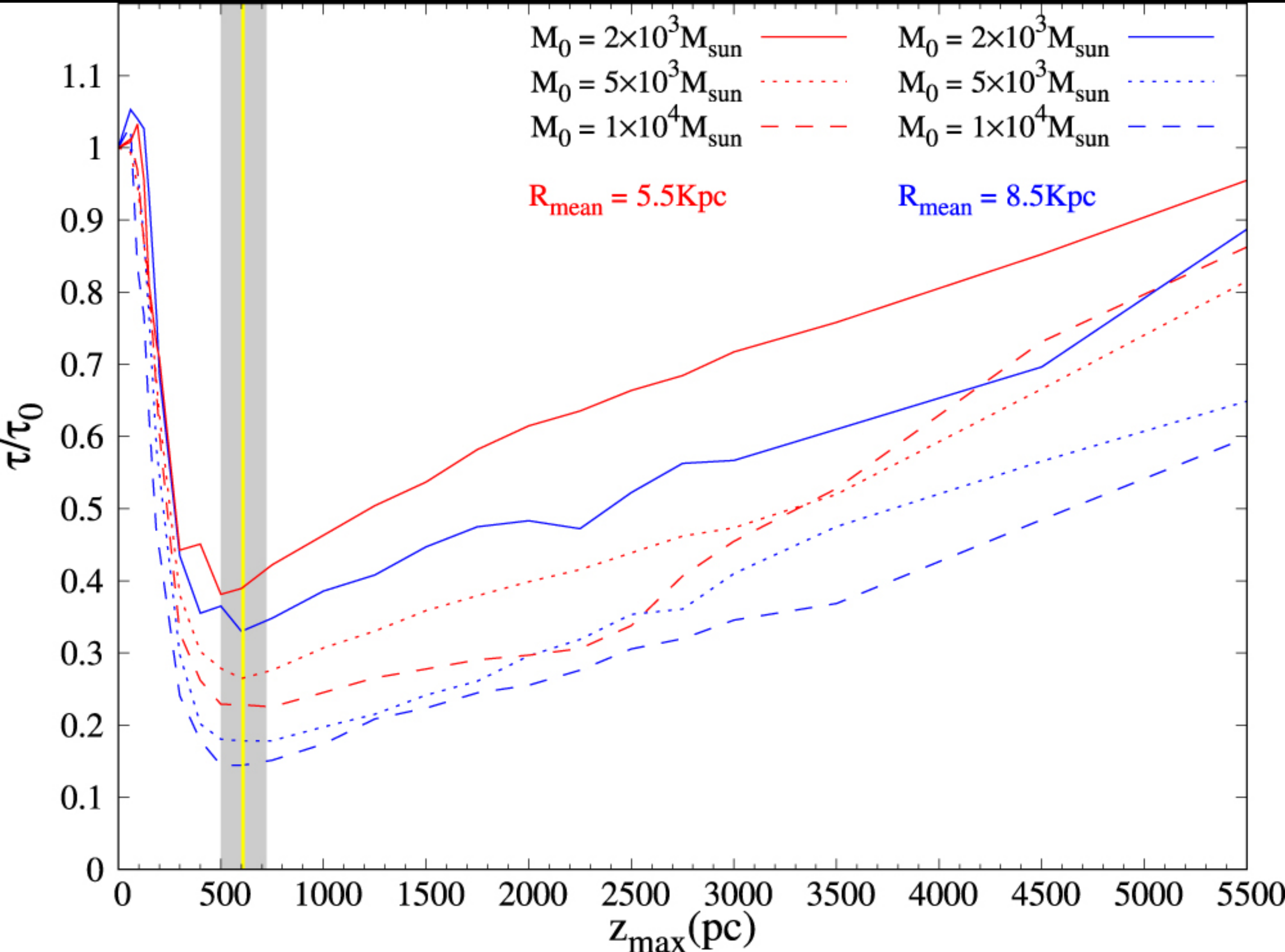

1.0Myr
Y(pc)
X(pc)
Y(kpc)
X(kpc)



1.0Myr
Z(pc)
X(pc)
Z(kpc)
X(kpc)
Mass(Msun)
Time(Myr)


M0 = 5×10^2 M⊙
M0 = 1×10^3 M⊙
M0 = 2×10^3 M⊙
M0 = 5×10^3 M⊙
M0 = 1×10^4 M⊙
M0 = 2×10^4 M⊙
M0 = 5×10^4 M⊙
Rmean = 5.5kpc
Rmean = 7kpc
Rmean = 8.5kpc
Rmean = 10kpc
Rmean = 12kpc
Rmean = 14kpc
M/M0
Time(Gyr)


Rmean = 8.5Kpc
M/M0
Time(Gyr)
0pc
93pc
125pc
150pc
200pc
300pc
400pc
600pc
1000pc
1500pc
2000pc
2500pc
3000pc
4500pc
5500pc



$M_0 = 2\times10^3 M_{sun}$
$M_0 = 5\times10^3 M_{sun}$
$M_0 = 1\times10^4 M_{sun}$
$M_0 = 2\times10^3 M_{sun}$
$M_0 = 5\times10^3 M_{sun}$
$M_0 = 1\times10^4 M_{sun}$
R_{mean} = 5.5Kpc
R_{mean} = 8.5Kpc
τ/τ_0
z_{max}(pc)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500

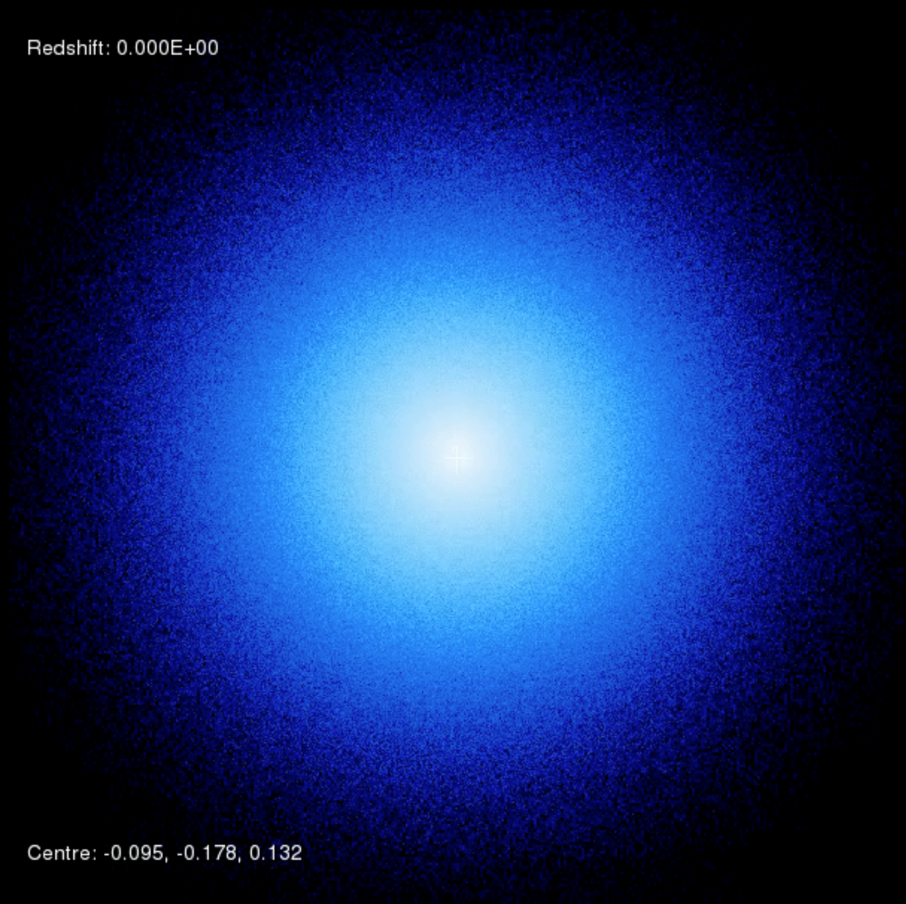
Conclusions 3

- We construct a tidal map from our Milky Way model. We find important zones where the tides are fully compressive within the bar and spiral arms. By their nature, fully compressive tides would magnify the binding of stellar clusters, preventing them from being disrupted as fast as clusters moving into any other region of the Galaxy.

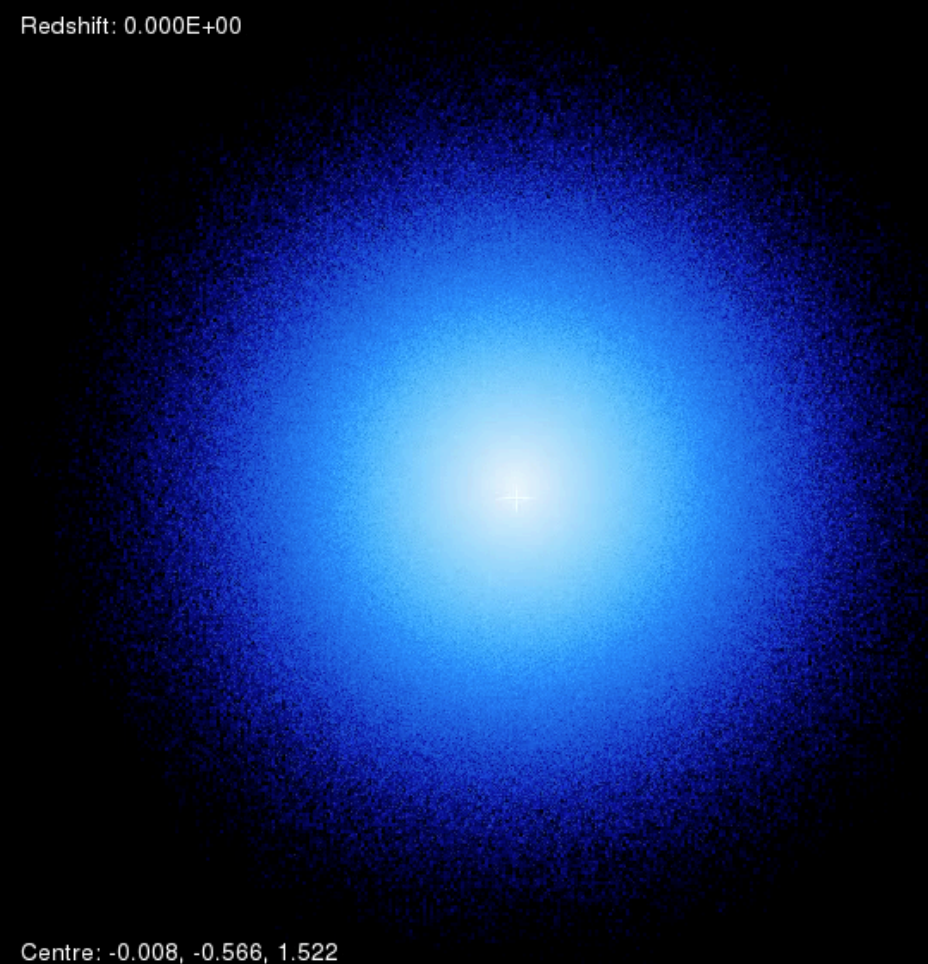
- Fully compressive regions have interesting implications on the evolution of clusters within the Galactic plane, especially on the time small clusters last inside the spiral arms in comparison to other locations of the Galaxy, i.e., small clusters would be more abundant in the spiral arm zone, not only because of the density contrast or because of an enhancement by the star formation, but because of the protective binding by tides. Preliminary calculations show that clusters inside the compressive region of the arm live almost twice as long as the ones outside.

- Contrary to common knowledge, high-altitude open clusters (those over 200 pc) experience severe tidal destruction when they pass through the disk. In this respect, we find that, up to a certain altitude away from the disk plane (between 0 and 600 pc) , the lifetime of clusters decreases as its maximum orbital altitude increases because tidal shocks with the disk are stronger; clusters confined to the Galactic plane live longer because they do not experience vertical tidal shocks from the Galactic disk (even in the presence of strong arms and bar).

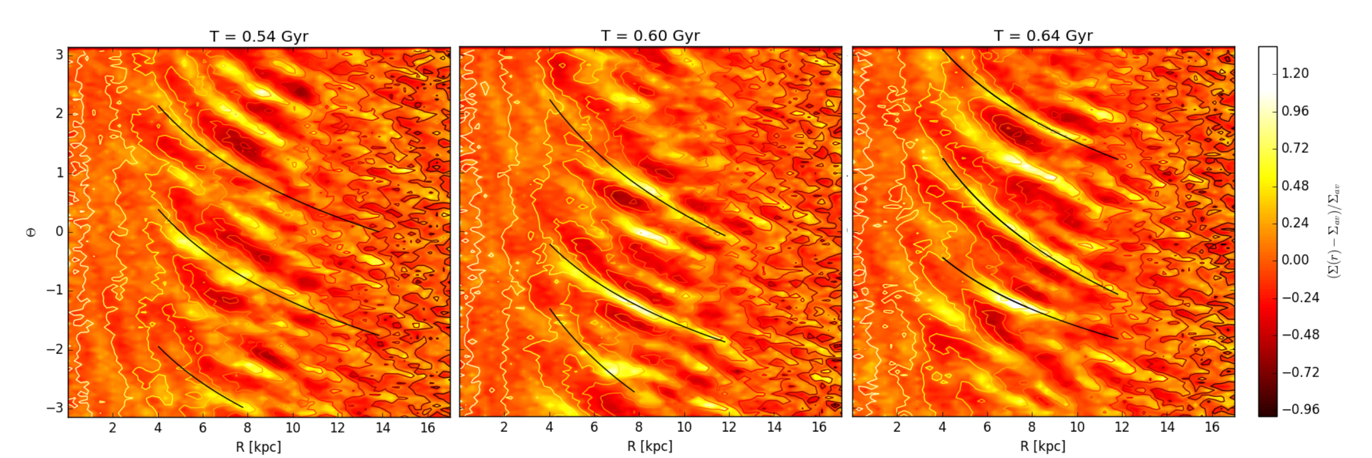
- For clusters that rise higher than ~ 600 pc, lifetimes increase again, as a function of the maximum altitude, due to the lower number of encounters with the disk. We parameterized the survival time for high-altitude open clusters as a function of height away from the plane, average galactocentric radius and the mass of the cluster.

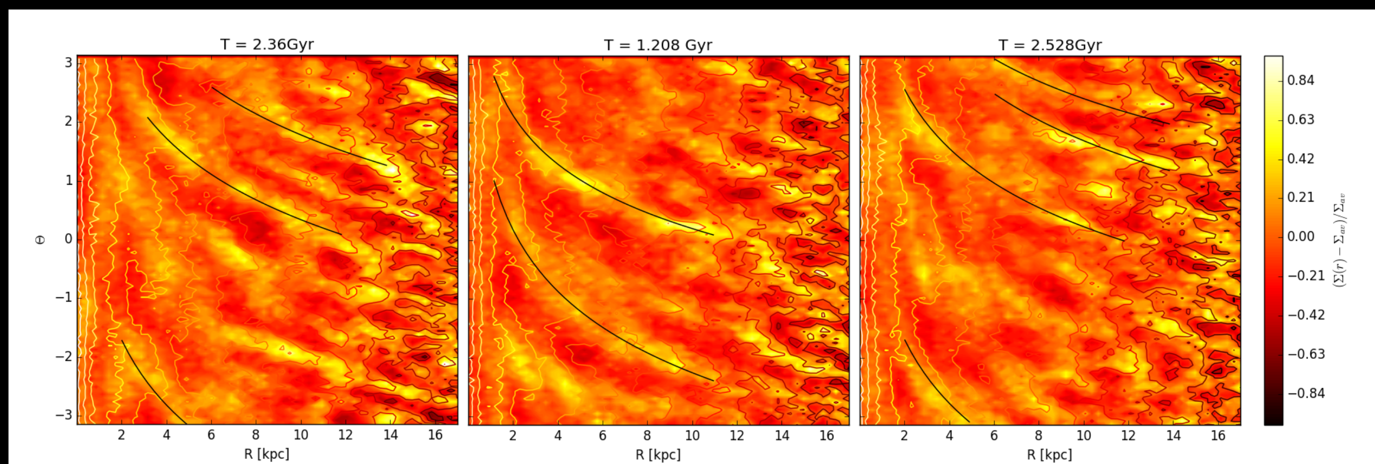


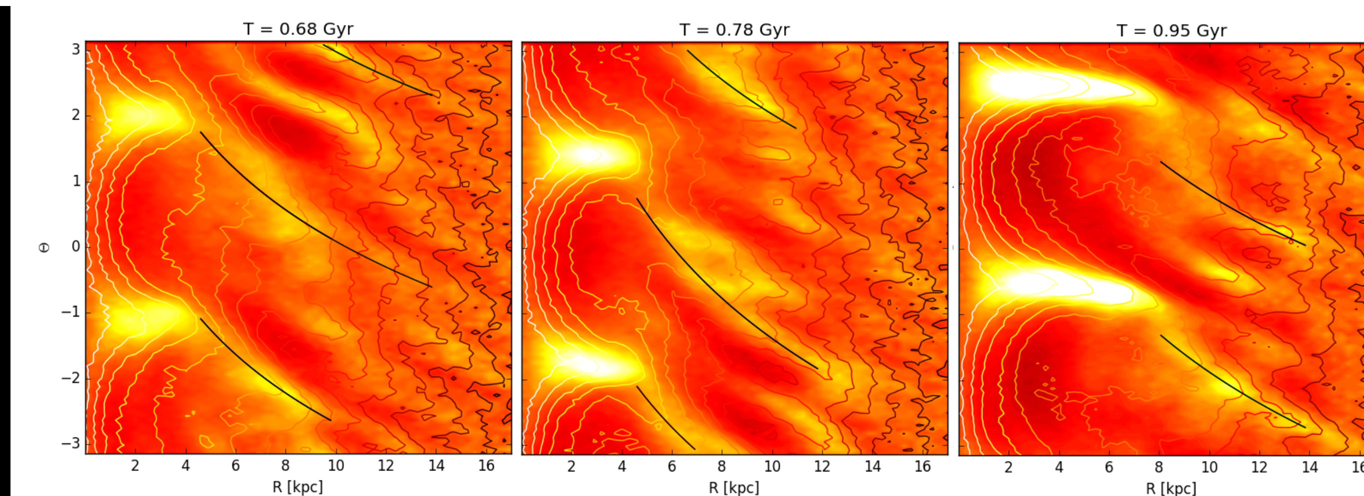
Non-barred

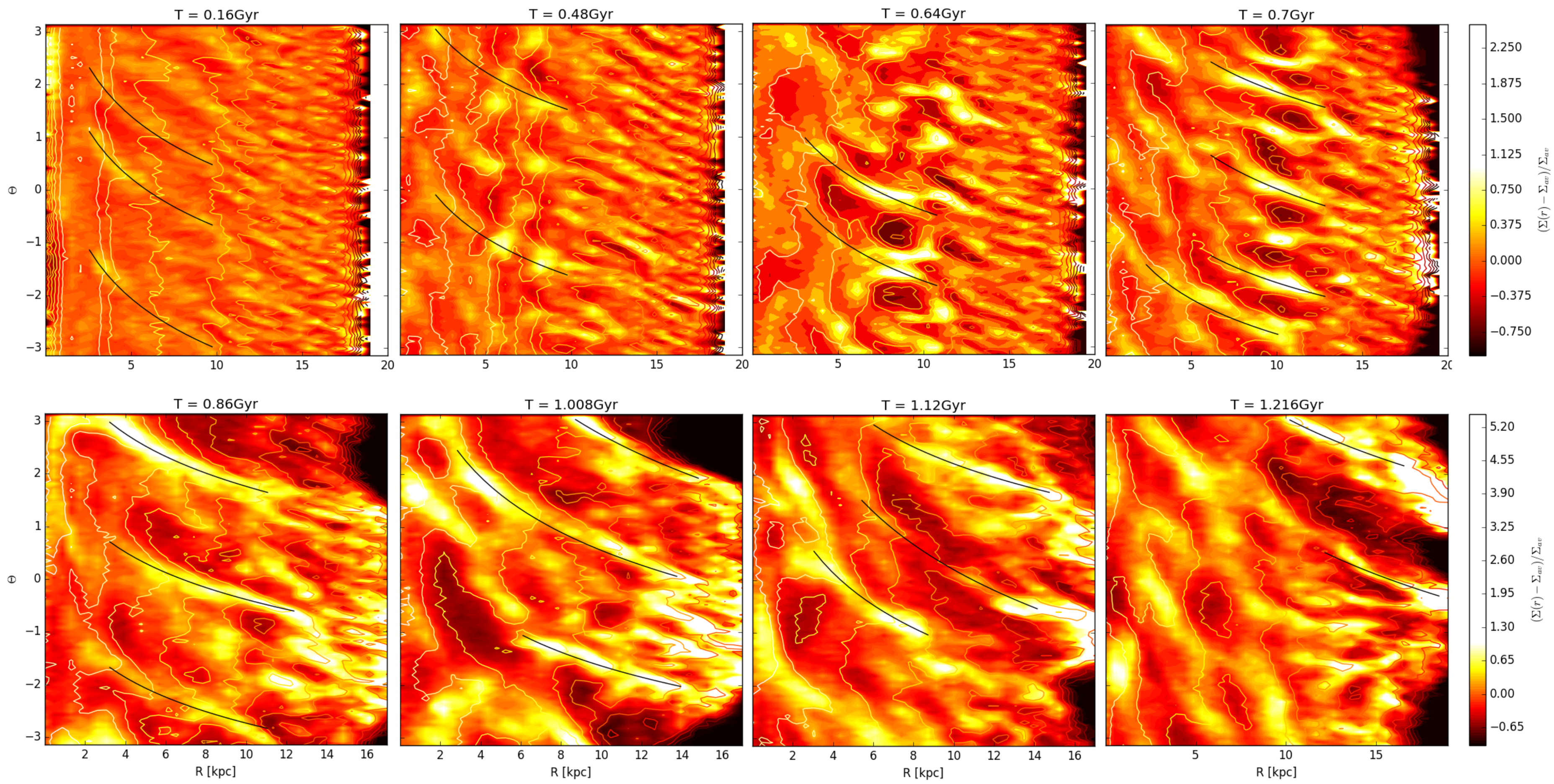


Barred

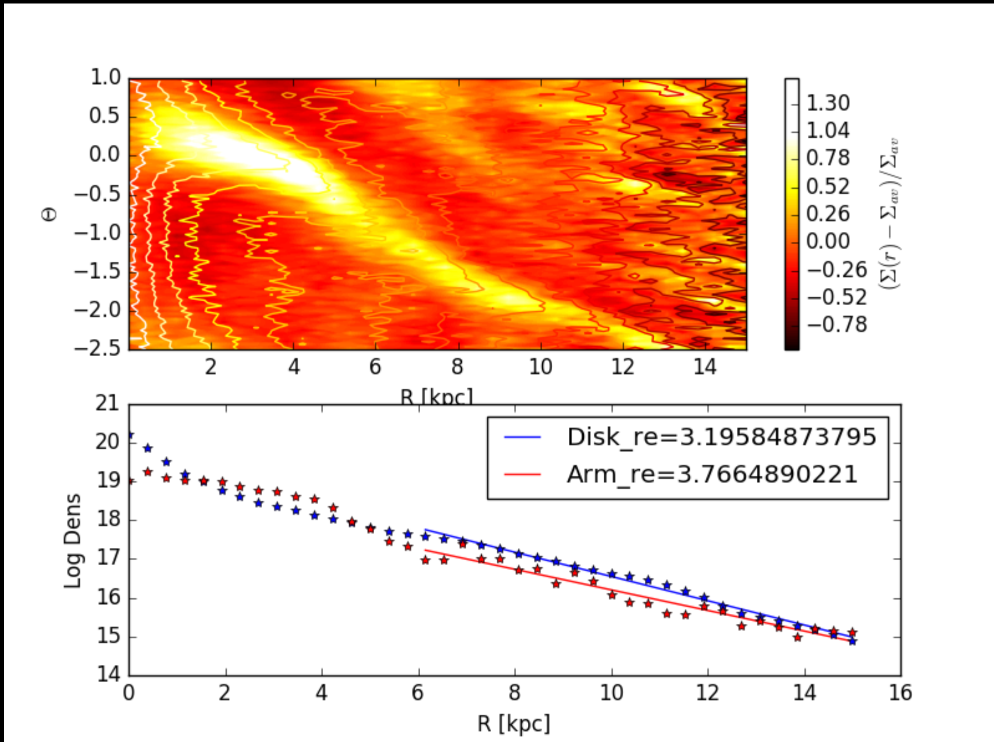

T = 0.54 Gyr
T = 0.60 Gyr
T = 0.64 Gyr
Θ
R [kpc]
1.20
0.96
0.72
0.48
0.24
0.00
−0.24
−0.48
−0.72
−0.96
$(\Sigma(r)-\Sigma_{av})/\Sigma_{av}$


T = 2.36Gyr
T = 1.208 Gyr
T = 2.528Gyr
Θ
R [kpc]
0.84
0.63
0.42
0.21
0.00
−0.21
−0.42
−0.63
−0.84
$(\Sigma(r)-\Sigma_{av})/\Sigma_{av}$

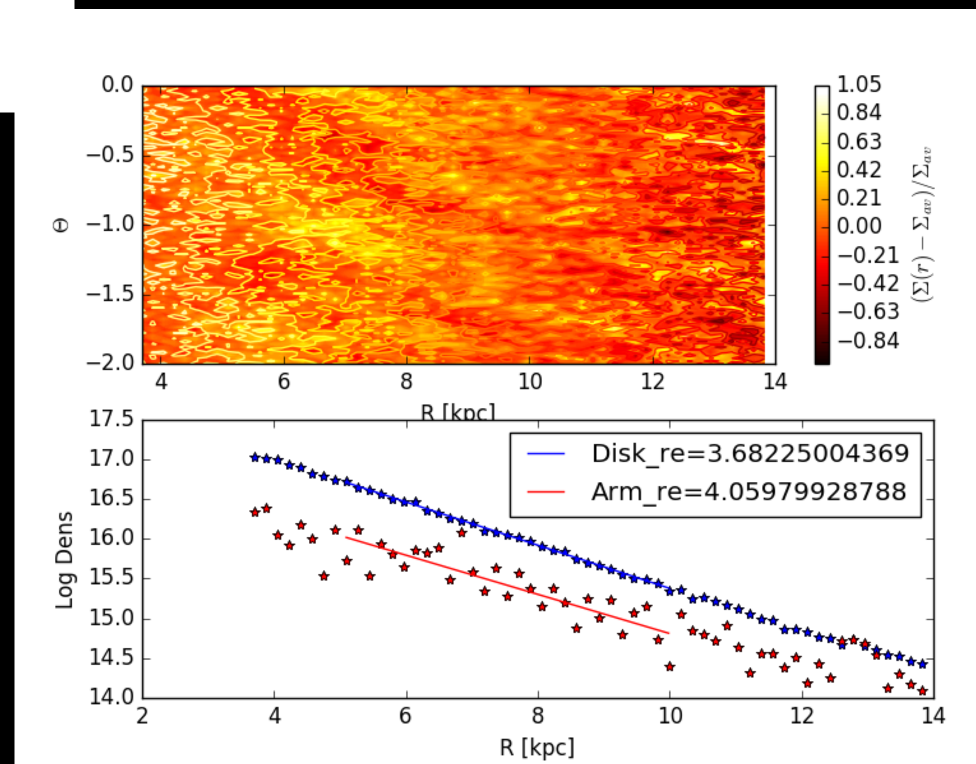

T = 0.68 Gyr
T = 0.78 Gyr
T = 0.95 Gyr
Θ
R [kpc]



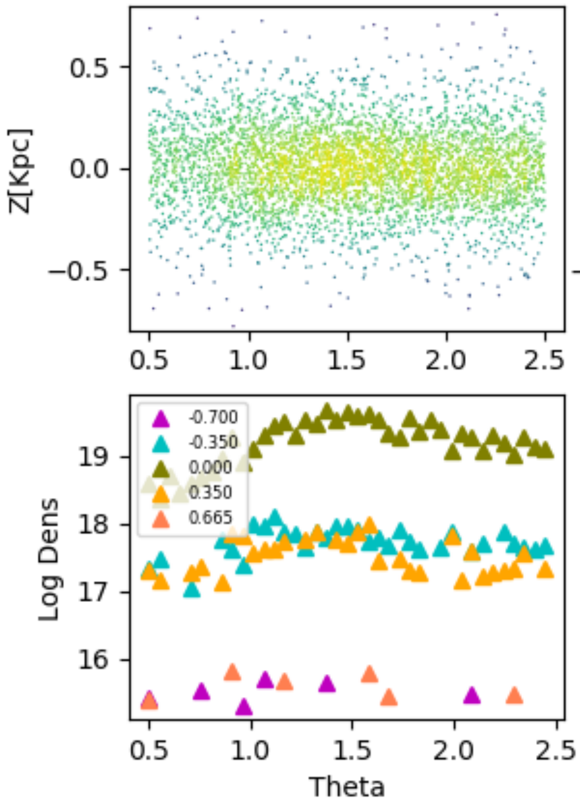
T = 0.16Gyr
T = 0.48Gyr
T = 0.64Gyr
T = 0.7Gyr
T = 0.86Gyr
T = 1.008Gyr
T = 1.12Gyr
T = 1.216Gyr
Θ
R [kpc]
$(\Sigma(r) - \Sigma_{av})/\Sigma_{av}$

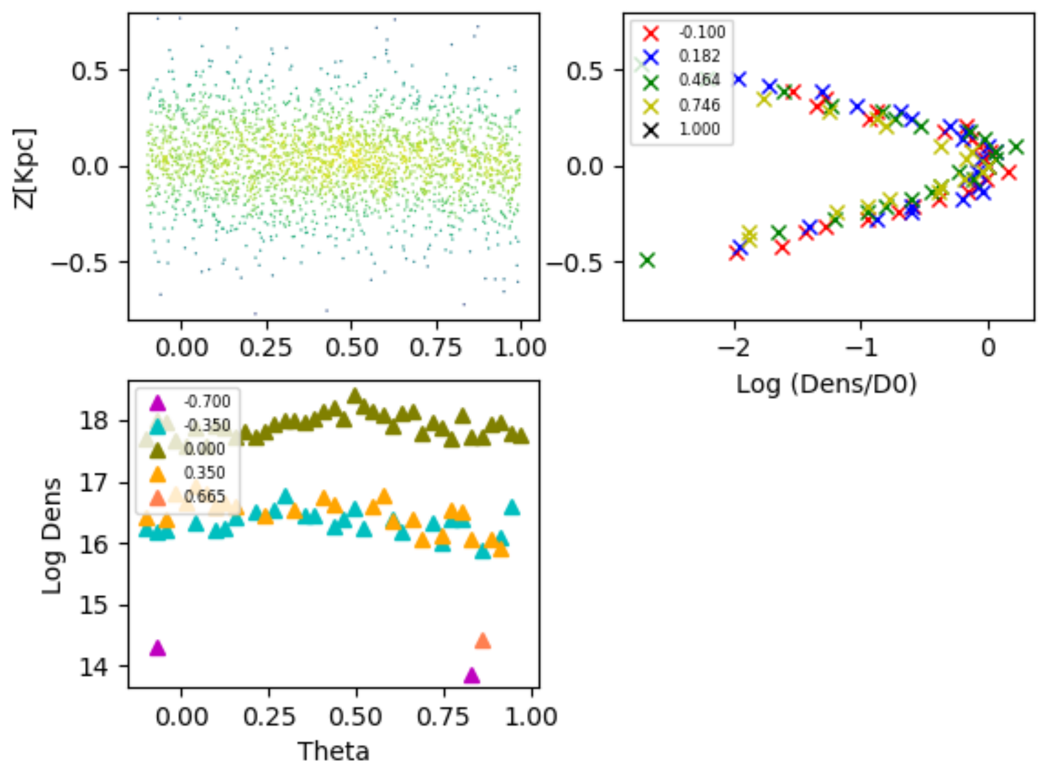


$(\Sigma(r)-\Sigma_{av})/\Sigma_{av}$
Θ
R [kpc]
Log Dens
R [kpc]
Disk_re=3.19584873795
Arm_re=3.7664890221



$(\Sigma(r)-\Sigma_{av})/\Sigma_{av}$
Θ
R [kpc]
Log Dens
R [kpc]
Disk_re=3.68225004369
Arm_re=4.05979928788





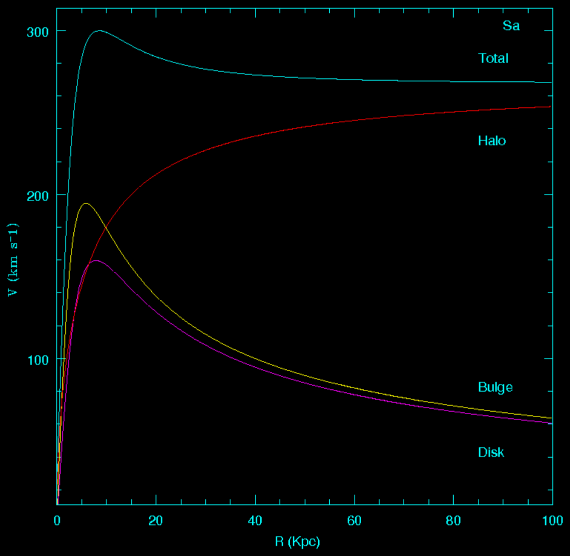
Mata-Chávez, Velázquez, Pichardo, Valenzuela, Hernández-Toledo, Roca-Fábrega, in prep. 2018

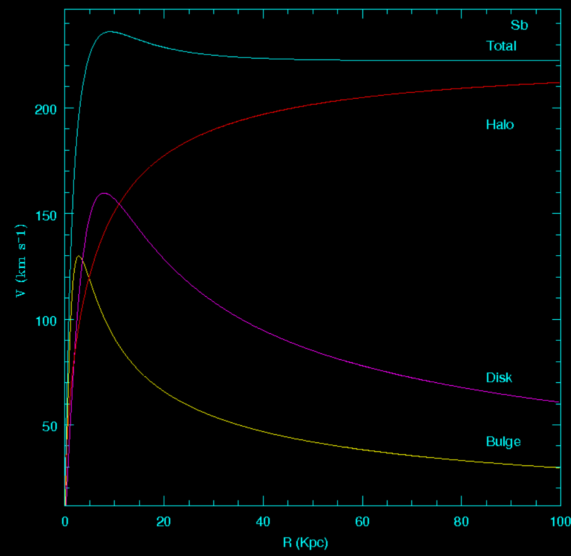
GRACIAS

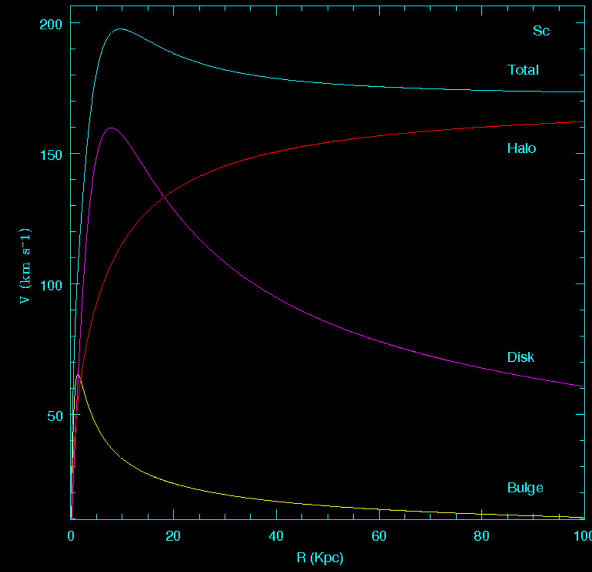
Order and Chaos

And the lord stood upon Tiamats hinder parts, and with his merciless club he smashed her skull. He cut through the channels of her blood, and he made the north wind bear it away into secret places."

Modelos dinámicos para galaxias espirales



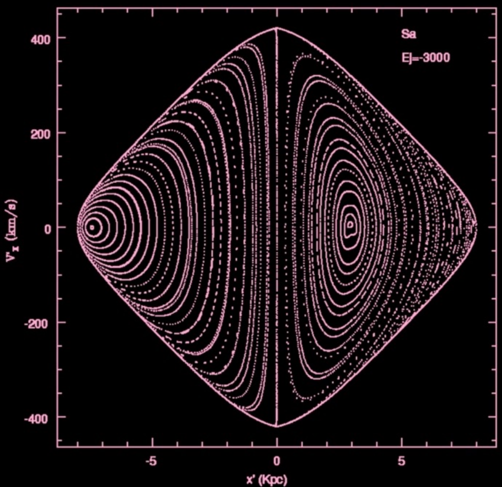


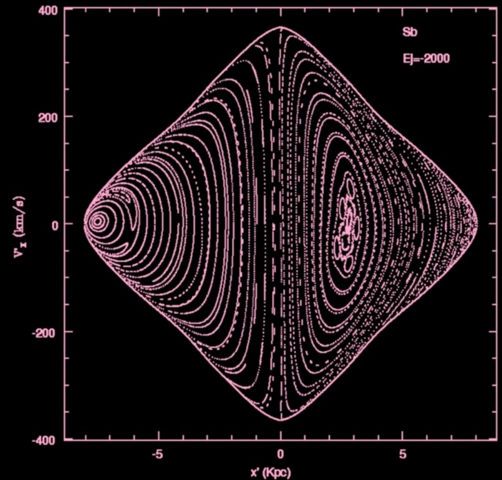


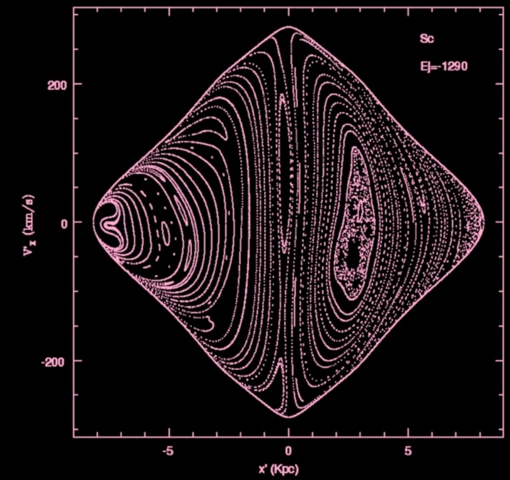
Sa **Sb** **Sc**

order and orbital chaos in the Hubble sequence

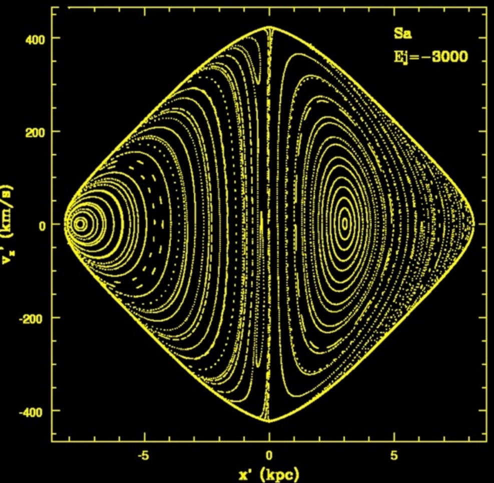
Cosine

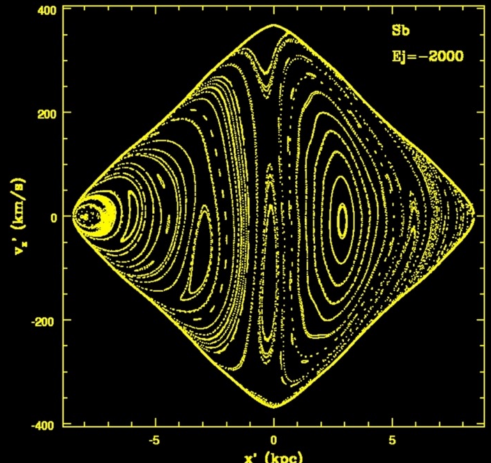


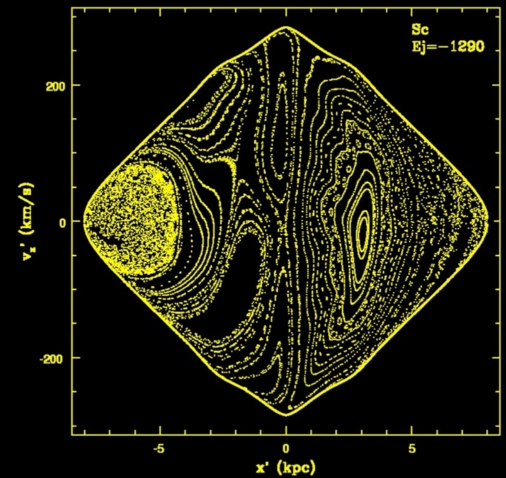


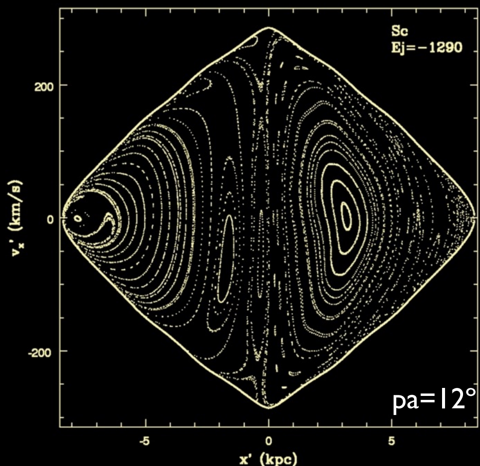


PERLAS

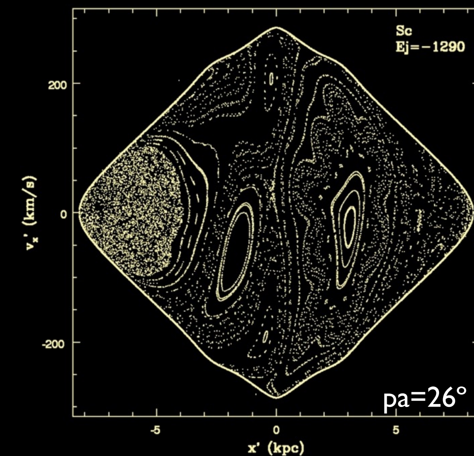




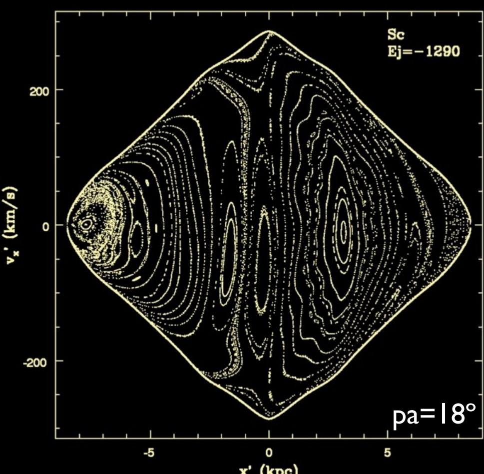




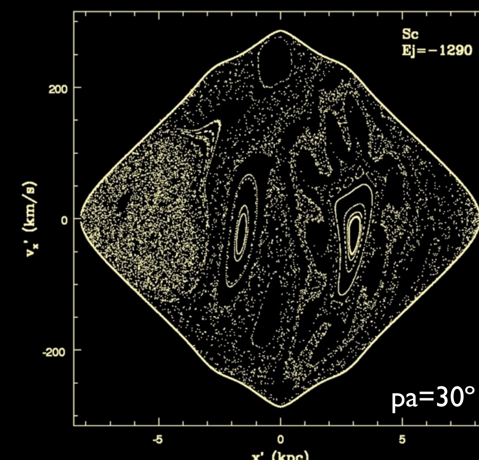
NGC 3938 pa=°12±3°



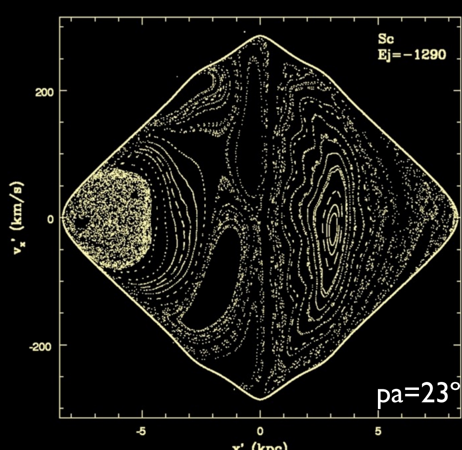
NGC 5457, pa=26°±4°



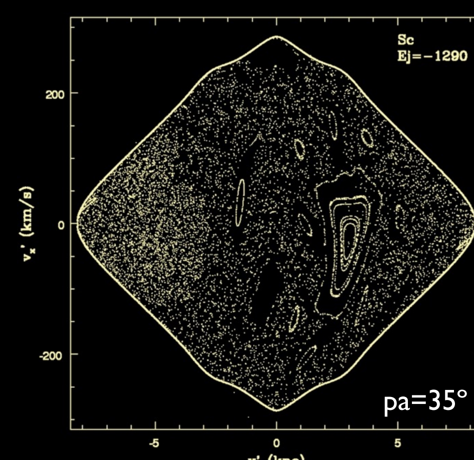
NGC 4535, pa=18°±3°



NGC 598, pa=31°±5°



NGC 1566, pa=22°±2°



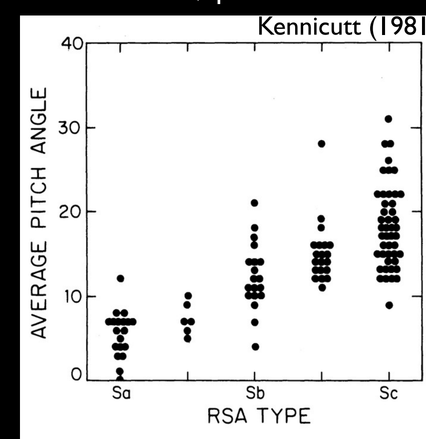


FIG. 7. Measured pitch angle vs Hubble type, the latter from Sandage and Tammann.