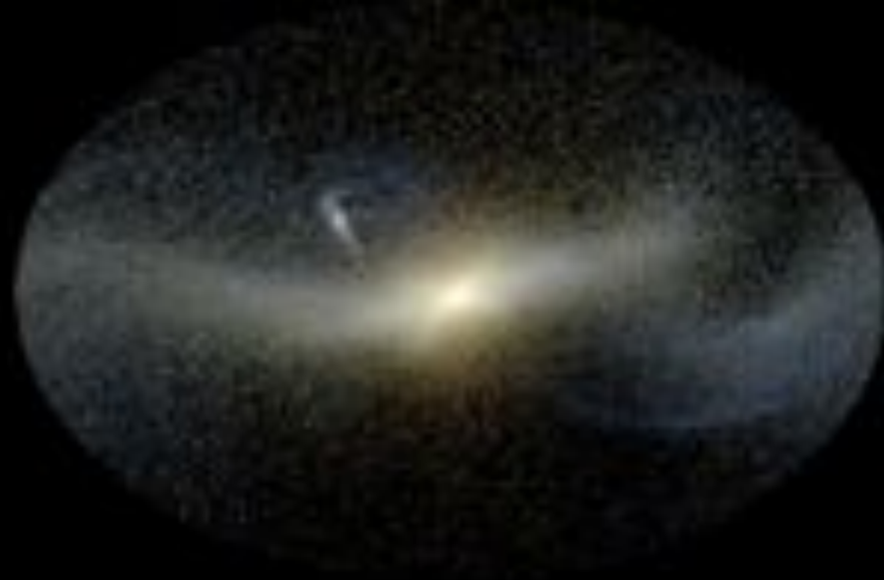


Prospects for dynamical modeling of the Galaxy: Gaia in the 2015 context

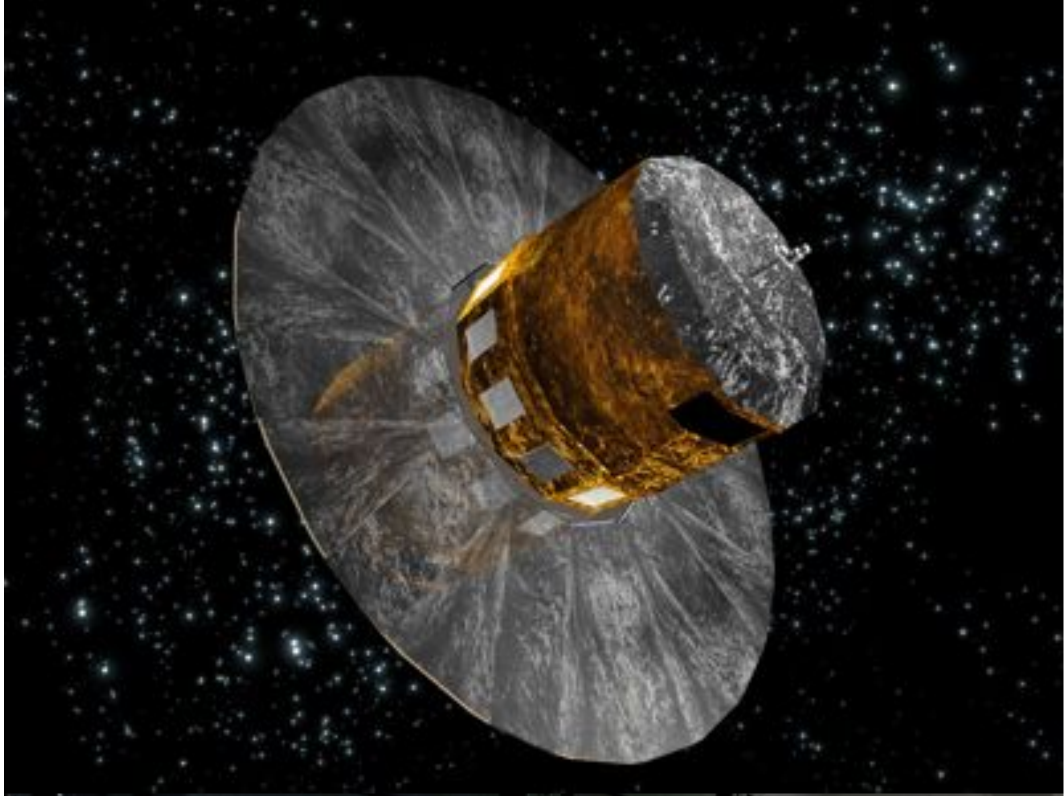
Daniel Pfenniger
Geneva Observatory

Introduction

Advances in observations and techniques, consequences:

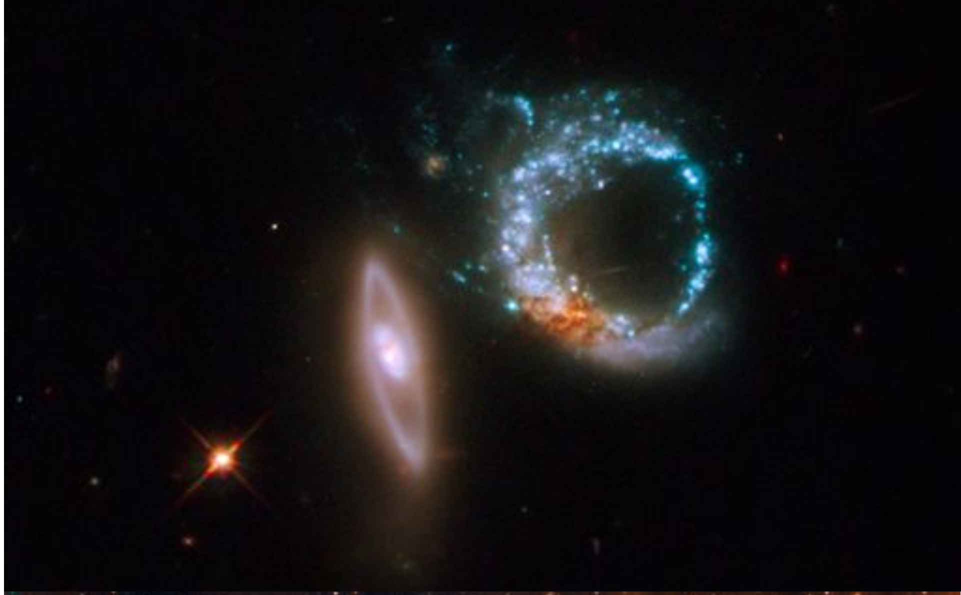
- Changes of perspectives
- Changes of methods

Modeling the Milky Way dynamics around 2015 will differ from past practices



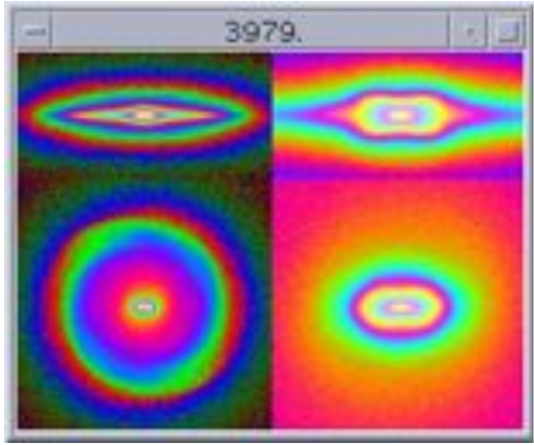
A brief reminder

- Gravitation and dynamics is THE dominant physical factor pervading the astrophysical scales, from the large scale universe down to asteroids and neutrons stars
- Gravitation is a long ranged force, so it leads to anti-thermo-dynamical behaviors, like the growth of density inhomogeneities and temperature gradients
- To be dynamically stable, astrophysical systems need ages >> dynamical time



A brief history of galactic dynamics

- The recognition that galaxies are Milky-Way like stellar systems occurred only in the 1920's, 170 yr after Kant (1755)
- It took at least 50 yr (1900-1950) to start recognizing the interstellar medium as an essential galaxy component
- For several decades (1920-1980) , galaxies were considered as stable, (axi)symmetric stellar systems
- Contrary to expectations, N-body simulations (> 1960) kept producing bars in disks, but were dismissed until about 1980's

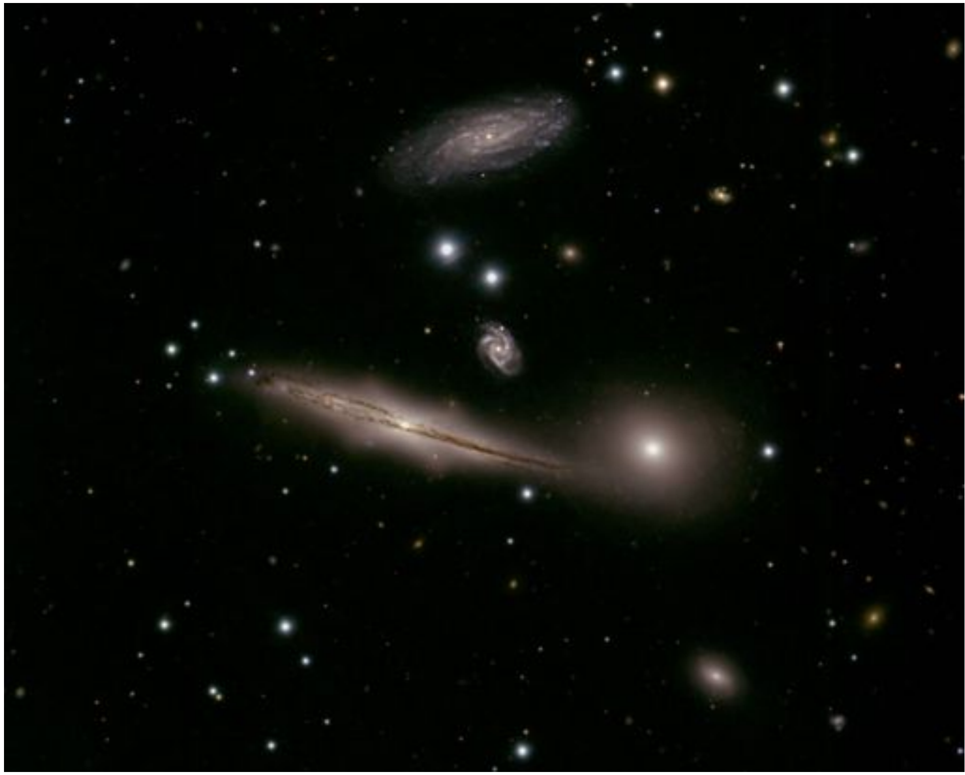


- Dark matter (1970's) was strongly motivated by the constant rotation curves

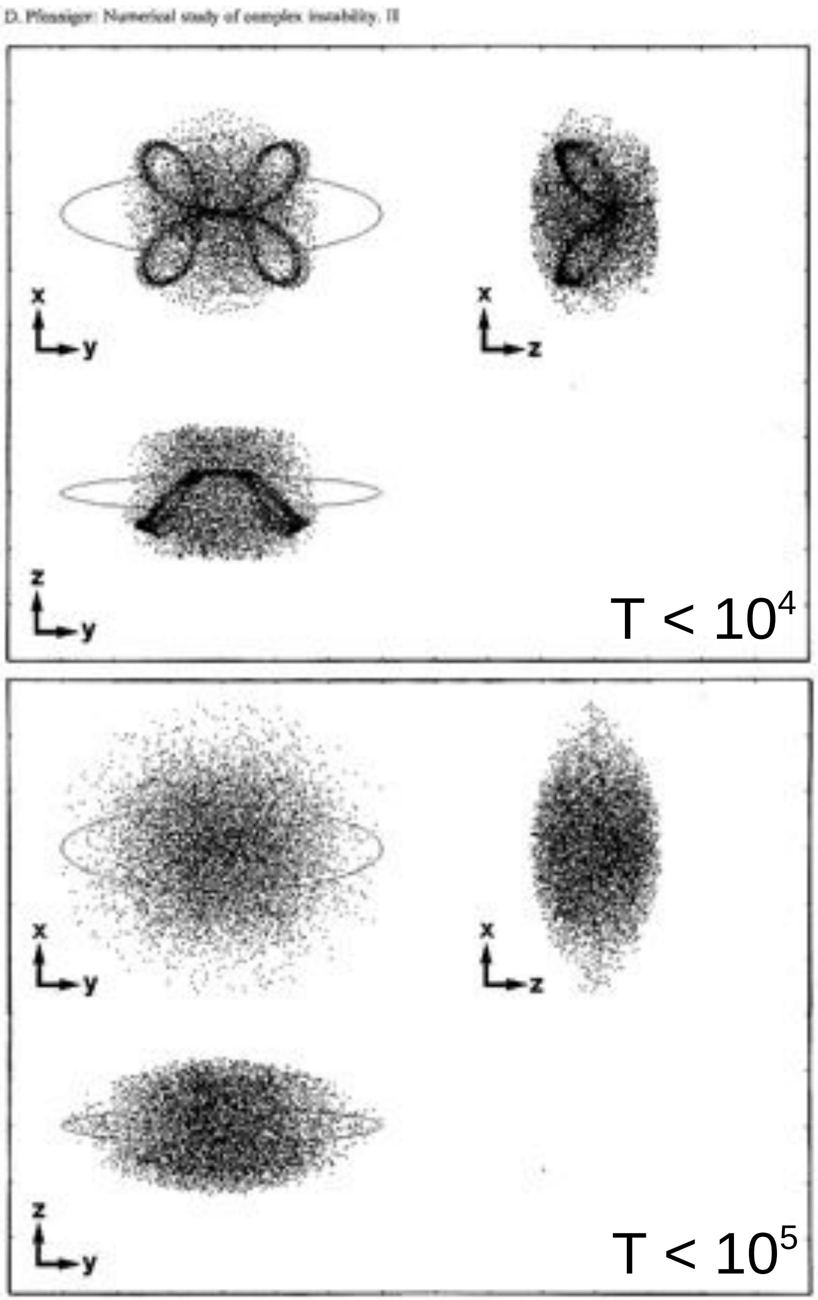
  and the wish to suppress bars

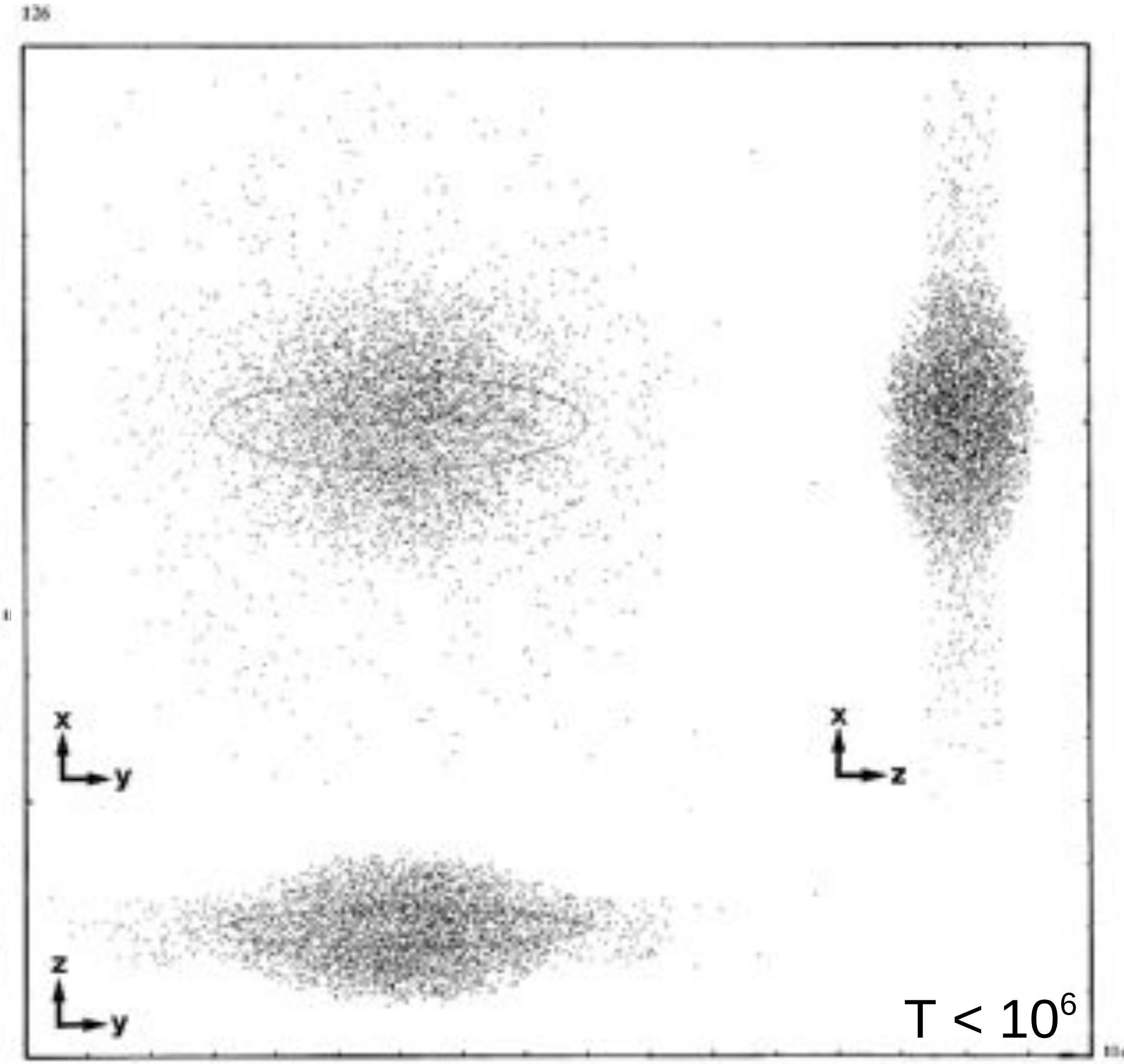
A brief history of galactic dynamics

- It took about 20 yr to accept Toomre's idea (1972) of galaxy type transformation by major mergers (S+S = E)
- It took about 20 yr to accept Kormendy's idea (1979) of galaxy secular evolution through internal processes like bars
- It took about 15 yr to accept that peanut-shaped bulges are actually bars (Combes & Sanders 1981)
- It will take some more years to accept that bars lead necessarily to enhanced diffusion and disk thickening (P 1984-1985)



Extended stellar diffusion around bars (Pfenniger 85)





Extended stellar diffusion around bars (Pfenniger 85)

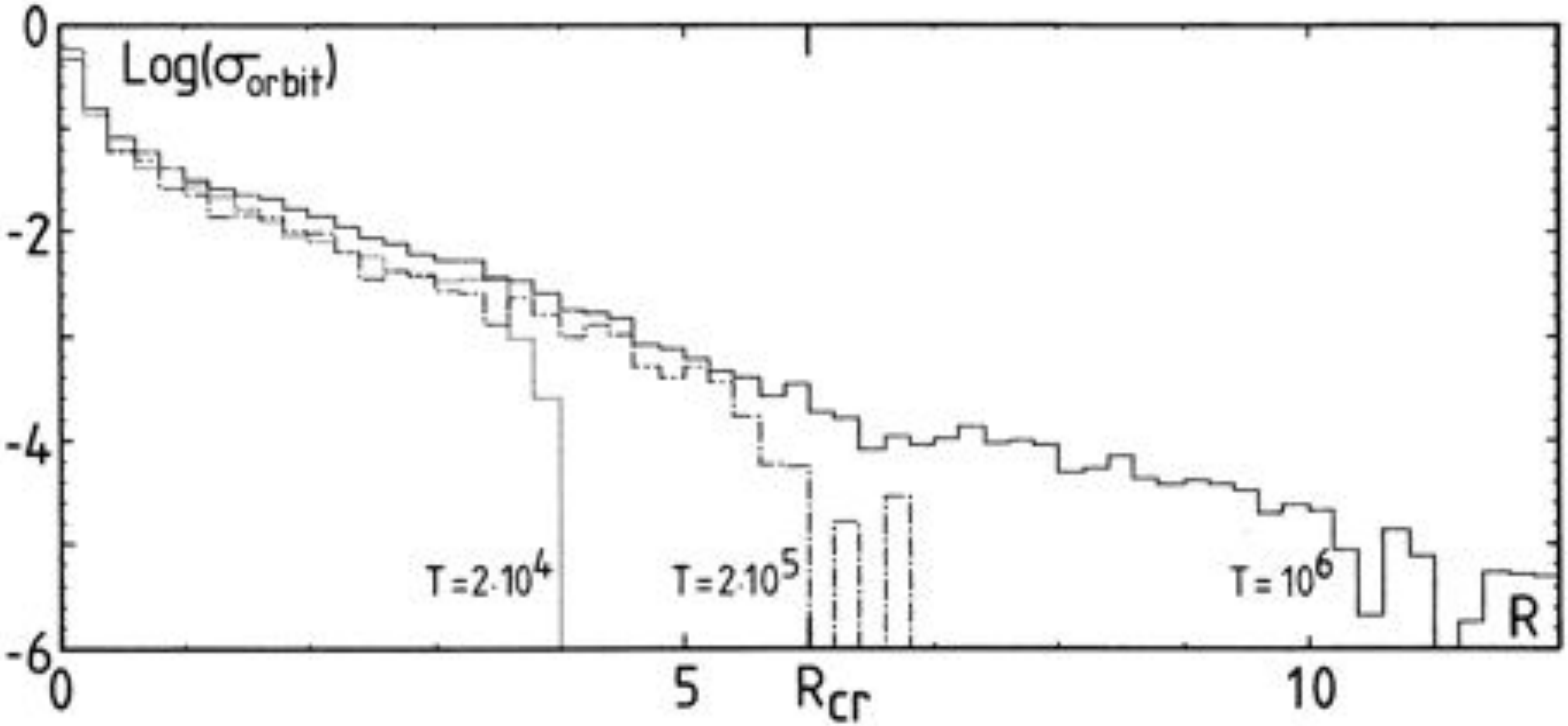


Fig. 12. Angularly averaged surface density in function of *R* of the orbit shown in Fig. 11. The final shape is slightly less steep than exponential, but about 2.5 times steeper than the model surface density

A single chaotic orbit averaged over a very long time represents the invariant distribution of a population of stars in the chaotic phase space

=> substantial stellar diffusion inescapable

Theoretical understanding of spiral galaxies
(Sellwood & Sparke 88)

Mon. Not. R. astr. Soc. (1988) **231**, *Short Communication*, 25P–31P

Pattern speeds in barred spiral galaxies

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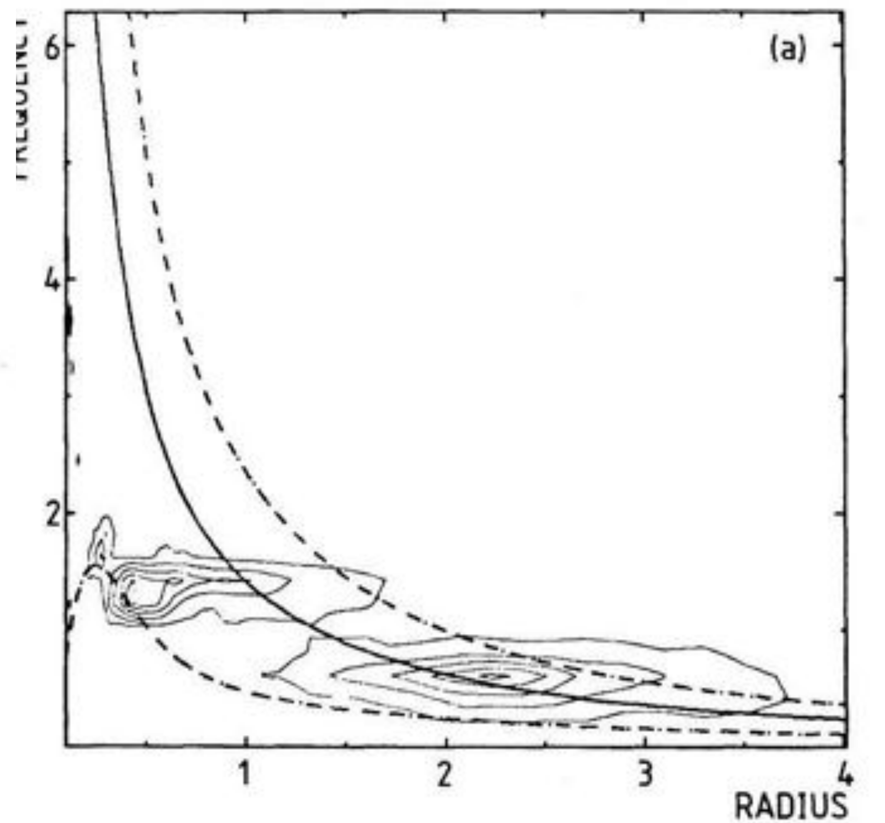
Accepted 1988 January 4. Received 1987 December 23

Summary. Current theoretical ideas of the pattern speeds of the bar and spiral arms in SB galaxies appear to conflict with the observational evidence. This difficulty can be avoided if the spiral arms have a lower pattern speed than the bar. We present evidence of multiple pattern speeds in our *N*-body simulations, and show that, though the spiral continually breaks from and reconnects to the bar, the morphology of the pattern at all times resembles that of barred galaxies in the sky. We briefly discuss how the gas might respond to the multiple patterns.



=> necessarily time-dependent galactic potentials

Evidence for a box-shaped bar in the Galaxy (Blitz & Spergel 91)

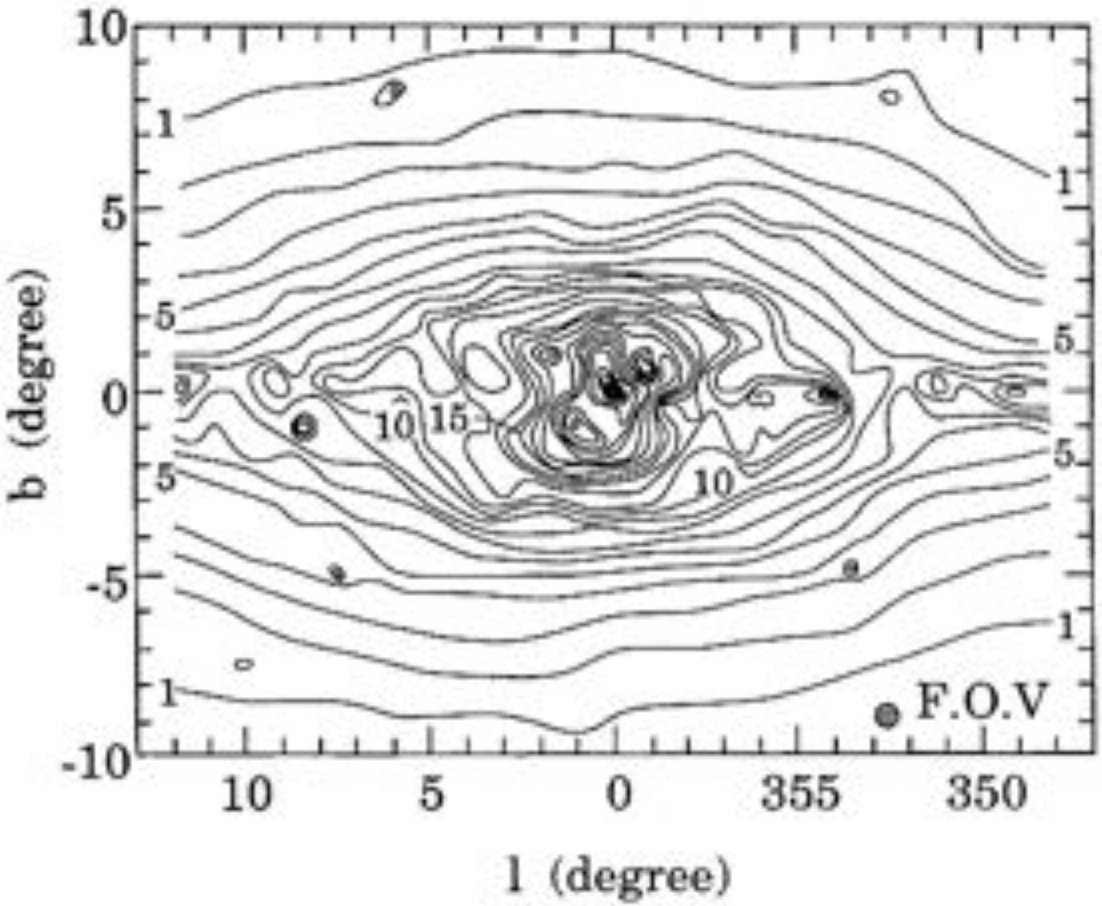
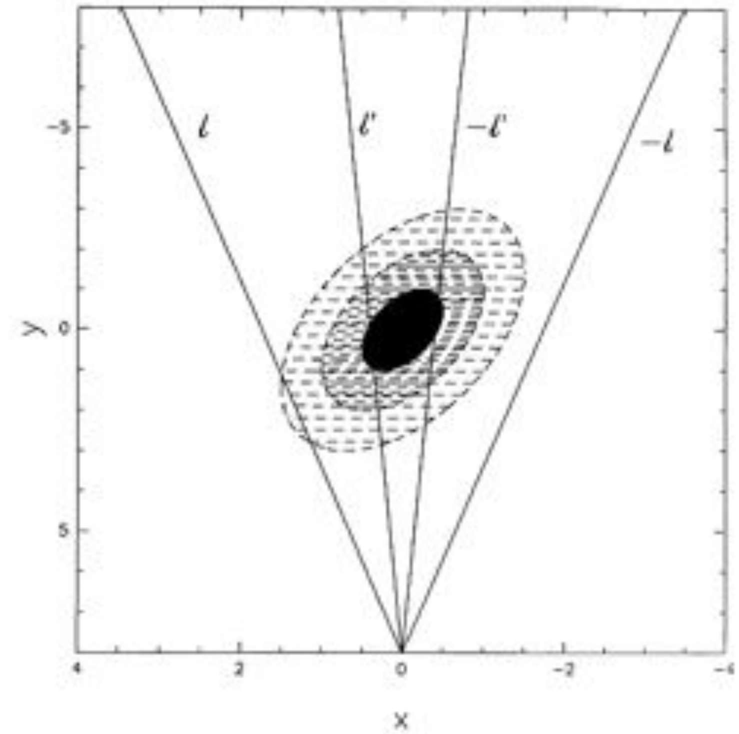


FIG. 2.—Contour map of 2.4 μm surface brightness of the region around the Galactic center taken from Matsumoto et al. (1982). The lowest contour and the contour interval are in steps of 1.0×10^{-10} W cm^2 μm^{-1} sr^{-1}.



=> the boxy bulge is essentially a bar

Infrared view of the spiral stellar content
(Seigar & James 98)

Mon. Not. R. Astron. Soc. 299, 685–698 (1998)

The structure of spiral galaxies – II. Near-infrared properties of spiral arms

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ABSTRACT
We have imaged a sample of 45 face-on spiral galaxies in the *K* band, to determine the morphology of the old stellar population, which dominates the mass in the disc. The *K*-band images of the spiral galaxies have been used to calculate different characteristics of the underlying density perturbation such as arm strengths, profiles and cross-sections, and spiral pitch angles. Contrary to expectations, no correlation was found between arm pitch angle and Hubble type, and combined with previous results this leads us to conclude that the morphology of the old stellar population bears little resemblance to the optical morphology used to classify galaxies.

The arm properties of our galaxies seem inconsistent with predictions from the simplest density wave theories, and some observations, such as variations in pitch angle within galaxies, seem hard to reconcile even with more complex modal theories. Bars have no detectable effect on arm strengths for the present sample.

We have also obtained *B*-band images of three of the galaxies. For these galaxies we have measured arm cross-sections and strengths, to investigate the effects of disc density perturbations on star formation in spiral discs. We find that *B*-band arms lead *K*-band arms and are narrower than *K*-band arms, apparently supporting predictions made by the large-scale shock scenario, although the effects of dust on *B*-band images may contribute towards these results.

Key words: galaxies: fundamental parameters – galaxies: spiral – galaxies: structure – infrared: galaxies.

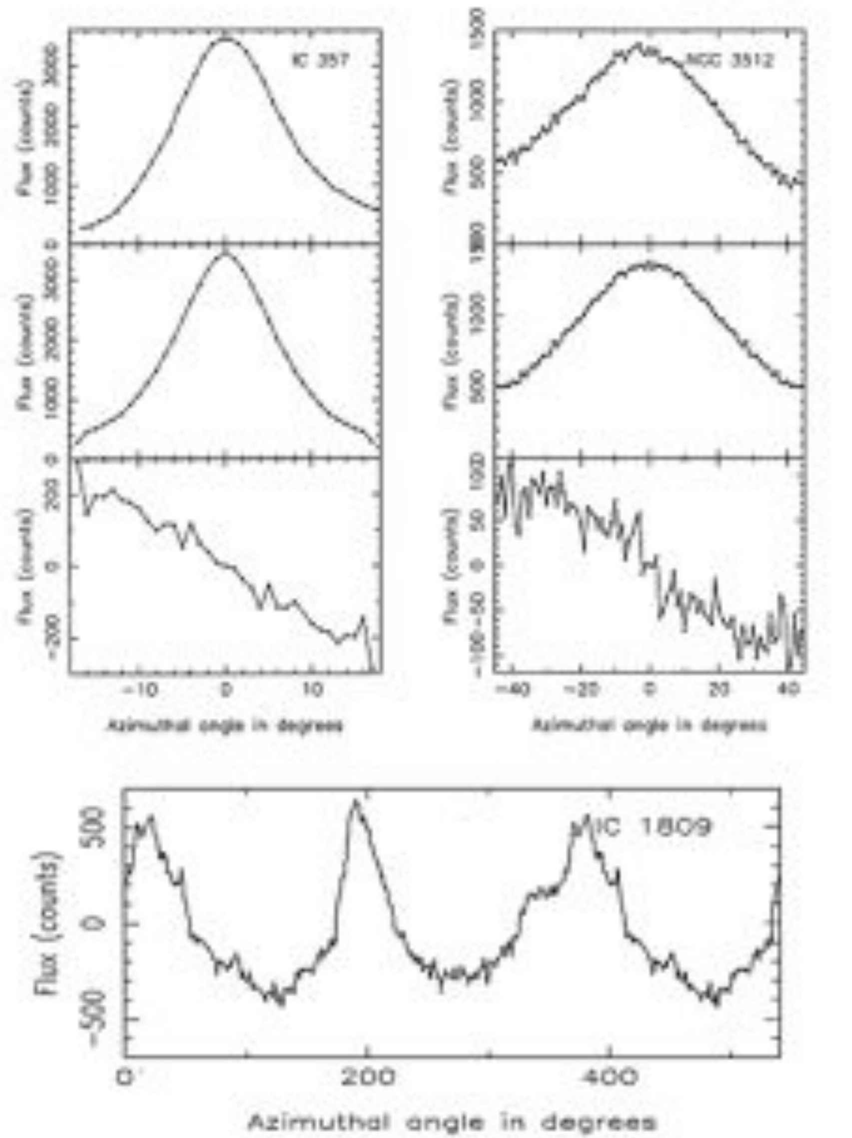


Figure 3. Upper panels: arm cross-sections (top), symmetric components (centre) and antisymmetric components (lower). Leading edges of arms are plotted on the right. Lower panel: a 540° cut of IC 1809.

=> bars and spiral arms are strong non-linear density perturbations, self-gravity is locally dominant

Local stellar kinematics from Hipparcos (Dehnen 1998)

=> Complicated, non-smooth phase space structure
=> use of Boltzmann equation not granted

No. 6, 1998 DISTRIBUTION OF NEARBY STARS 2391

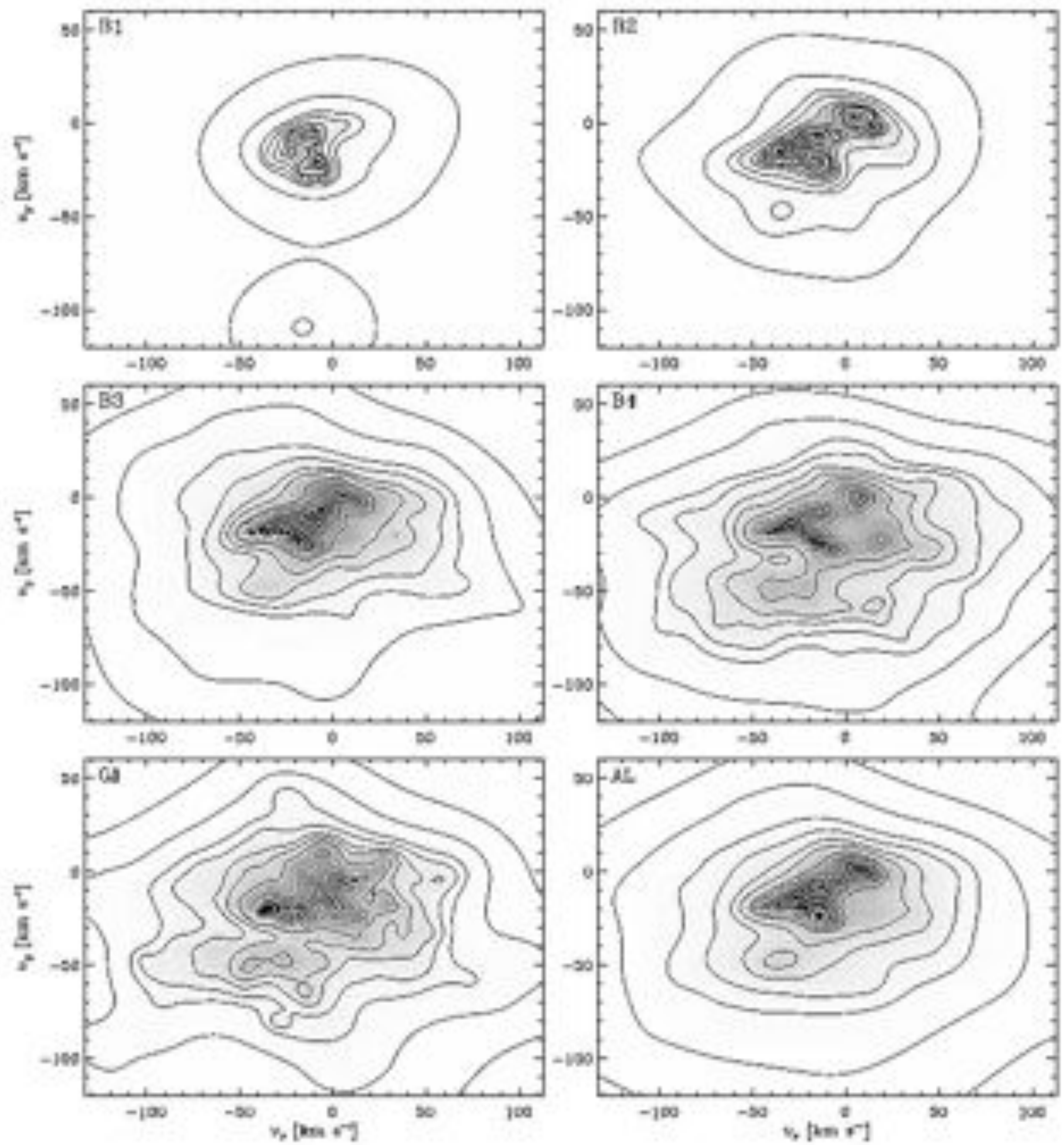
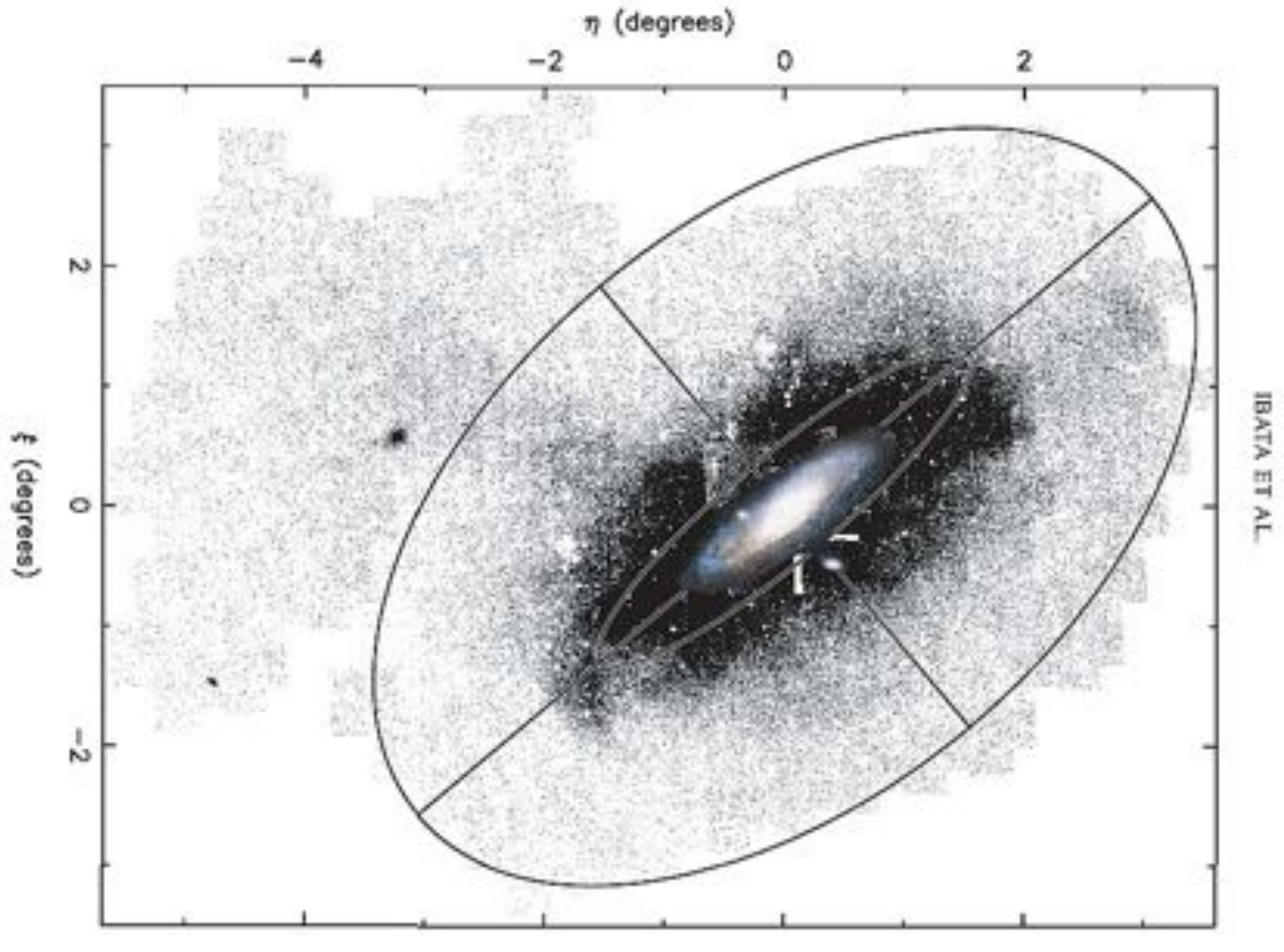


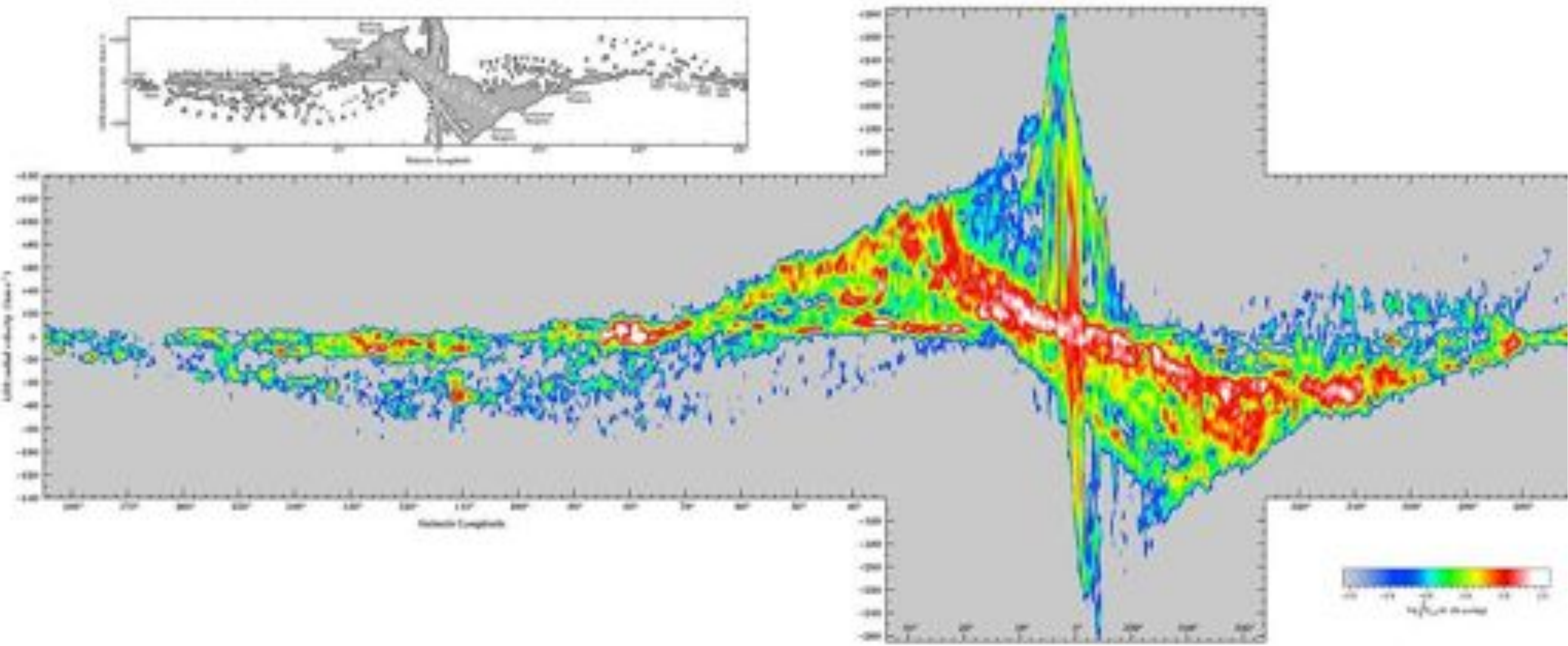
FIG. 3.—Distributions in v_x (toward the Galactic center) and v_y (in direction of Galactic rotation): projection of $f(v)$ obtained as MPLE for the sets listed in Table 1. Gray scales are linear and the contours contain, from inside outward, 2, 6, 12, 21, 33, 50, 68, 80, 90, 95, 99, and 99.9 percent of all stars; i.e., half the stars are within the innermost dark contour. The origin is at the solar velocity, while the velocity derived for the LSR in Paper I is indicated by a triangle. Note that the smoothing is optimal for the full sample (AL) only, while the results for the subsets are undersmoothed. However, since the subsets are distinct, any feature common to more than one of them is likely to be real.

Milky Way and Andromeda stellar halos (Ibata et al. 2005)



=> Complicated non-virialized (time-dependent) stellar halos

Milky Way CO survey (Dame et al 2001)



=> Complicated clumpy molecular gas and kinematics
=> time-dependence over a wide range of timescales

Theoretical understanding of spiral galaxies (Fux 97,99)

Astron. Astrophys. 327, 983–1003 (1997)

ASTRONOMY AND ASTROPHYSICS

3D self-consistent N-body barred models of the Milky Way

I. Stellar dynamics

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Received 23 April 1997 / Accepted 20 June 1997

Astron. Astrophys. 345, 787–812 (1999)

ASTRONOMY AND ASTROPHYSICS

3D self-consistent N-body barred models of the Milky Way

II. Gas dynamics

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Received 26 November 1998 / Accepted 5 February 1999

(Fux 99)

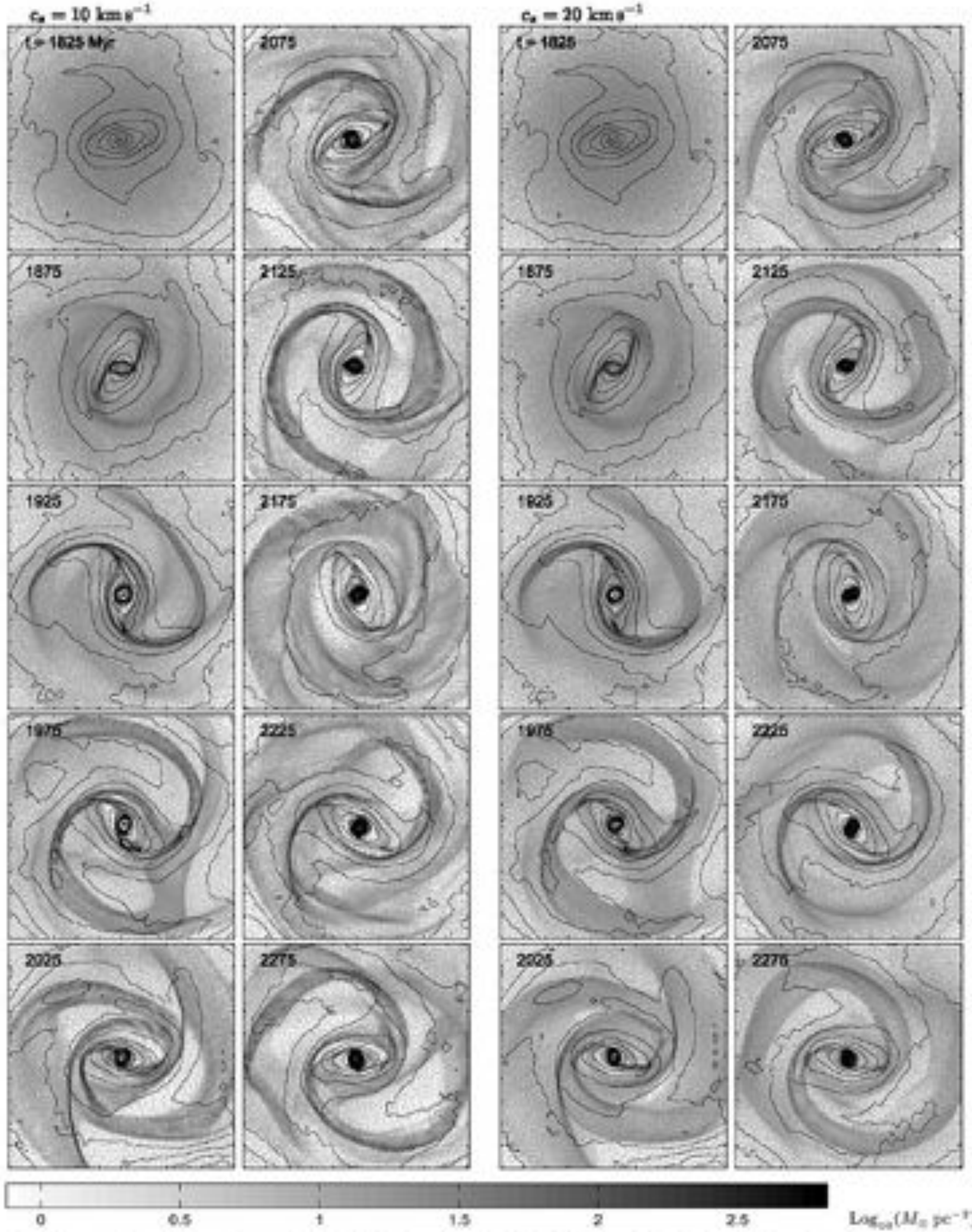


Fig. 12. Face-on view of the gas flow evolution in simulations I10 and I20, which differ only by the value of the sound speed c_s. Each frame is 20 kpc on a side in initial units. The dotted lines indicate the stellar surface mass density contours spaced by 0.75 magnitude.

(Fux 99)

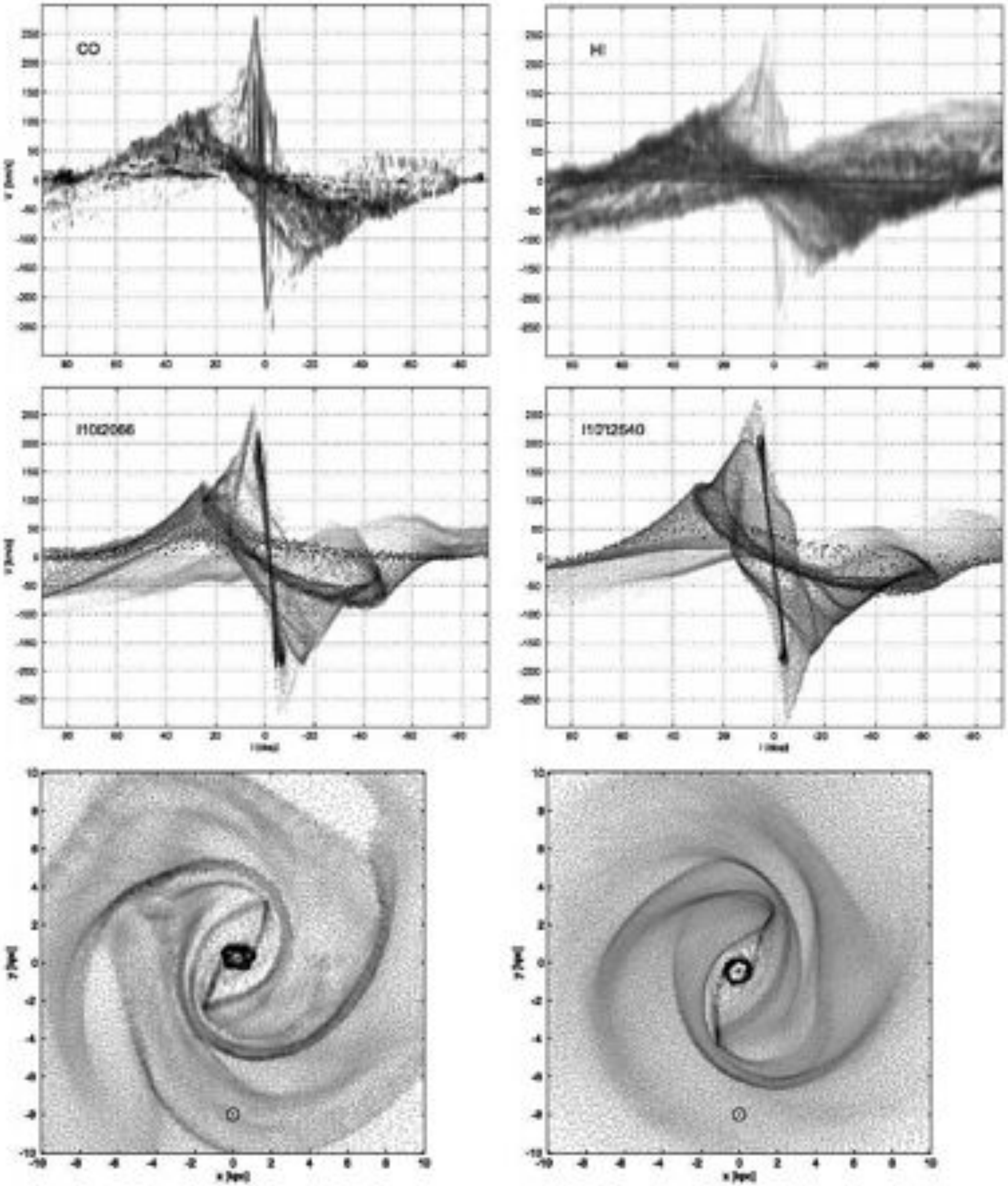


Fig. 15. Confrontation of a selection of two models with observed gas kinematics. *Top:* ^{12}CO and HI $\ell - V$ diagrams integrated over $|b| \le 2°$ and $|b| < 1.25°$ respectively; the data are from Dame et al. (1999) for the CO, and Hartmann & Burton (1997), Burton & Liszt (1978) and Kerr et al. (1986) for the HI. *Middle:* synthetic $\ell - V$ diagrams of models l10t2066 and l10't2540 for a bar inclination angle $\varphi_{\rm b} = 25°$, including all particles within $|b| < 2°$. *Bottom:* face-on projections of the gas spatial distribution in these models, rescaled such as to put the observer at $(x, y) = (0, -8)$ kpc (⊙ symbol). In these units, corotation lies at $R_{\rm L} = 4.5$ kpc (l10t2066) and 4.4 kpc (l10't2540). The model on the left reproduces almost perfectly the connecting arm, while the model on the right provides a fair global qualitative agreement to the data.

=> only substantially time-dependent models at different spatial scales can match observations

All these works and others point to the need to consider the Milky-Way as a time-dependent and asymmetric system

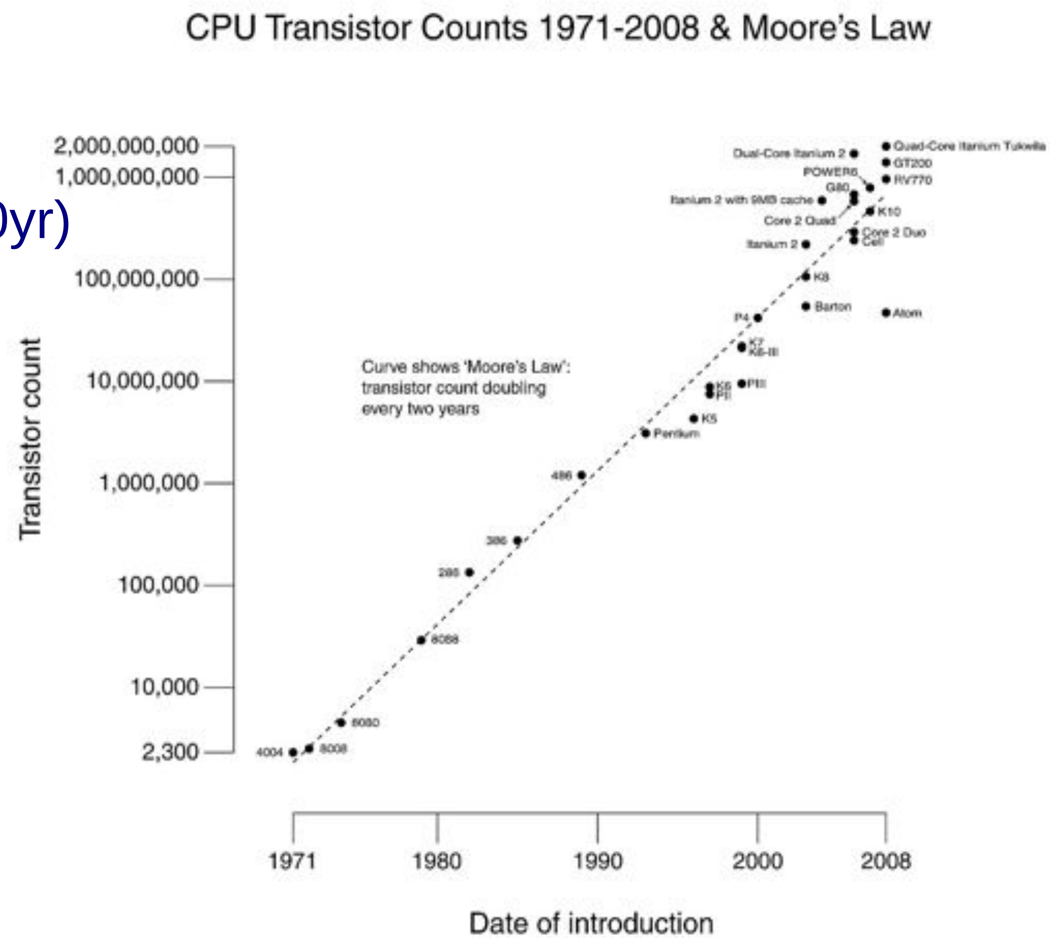
Only fully self-consistent N-body models can achieve the level of detail required by future observational data such as those of GAIA

Gordon E. Moore's law (1965)

- Historically unprecedented technological revolution (~10x performance every 5yr over 60yr)
- For complex sciences (biology, astronomy, earth-sciences, chemistry, ...), high performance computing plays the rôle that maths have fullfilled over last centuries for physics
- Perfomance of the present top computers becomes easy to access

  ~ after 5-15 yr for average scientists

  ~ after 20-30 yr for the public



=> as in other sciences, advances in computer technology have a major impact in astronomy

Moore's law @ Top 500 (top500.org)

Change of paradigm

- For galaxies, computer simulations are more and more providing more faithfull models than traditional models based on calculus (like Boltzmann's equation)
- Indeed: with $\sim 10^{11}$ stars

=> with 100 stars/phase space cell to represent a reasonably smooth distribution function: 10^9 cells

=> $(10^9)^{1/6}$ ~ 32 bins / coordinate only

=> the smooth phase space flow model used in Boltzmann equation is not a better description of galaxies than a N-body model with $N \sim 10^9$

Today $N > 10^{10}$ becomes increasingly accessible
(Teyssier et al 2009, Springel et al 2005, Boylan-Kolchin et al 2009)

Future simulations

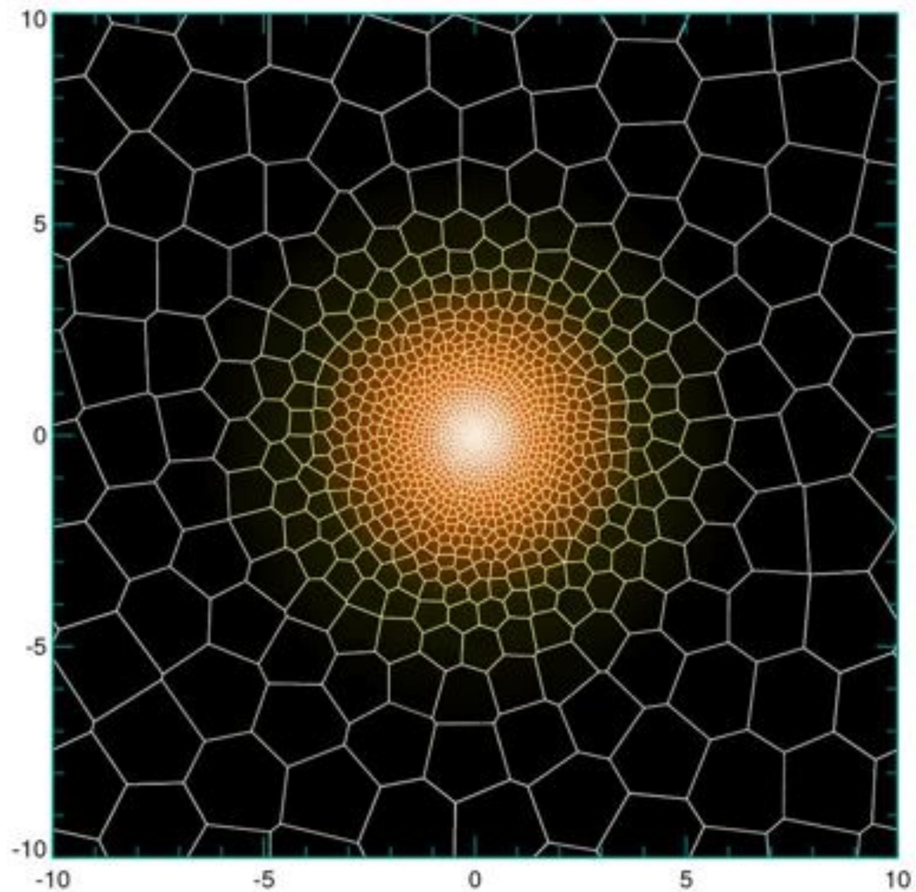
- With N=10^{10} -10^{11} particles each (bright) star can be represented in a Milky Way N-body model where particles can represent at least all the massive stars, and groups of low mass stars/binaries

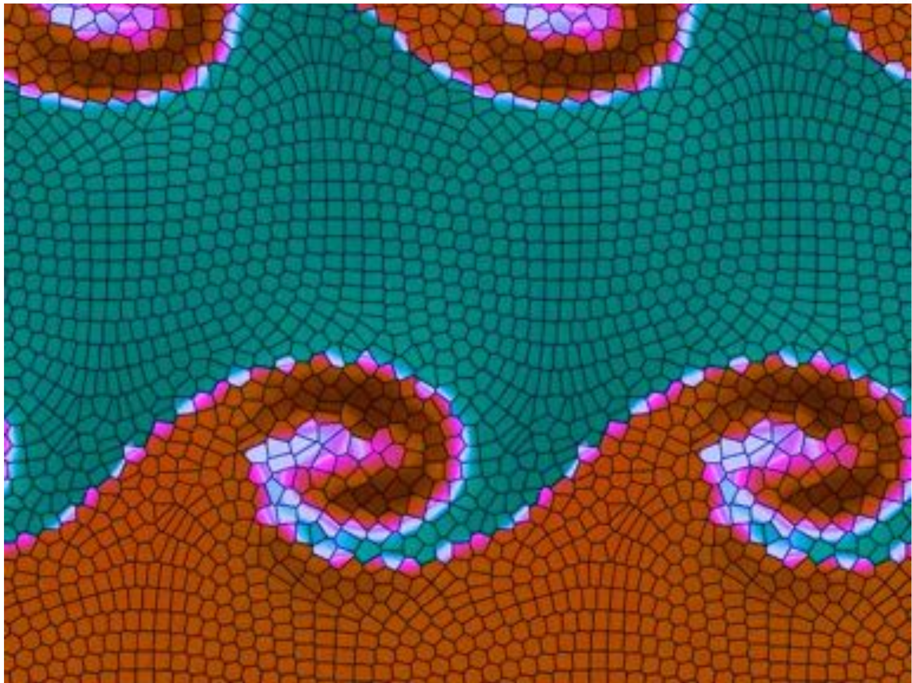
  => Phase space correlations (streams) can be studied and compared
- The problem of softening almost disappears
- Large sets of smaller N-body models with different initial conditions can be performed
- Precise simulations of observations are possible at a level matching GAIA results

Galactic gas dynamics is still a very hard problem though

Springel (2009) using computational geometry (Voronoi space decomposition + volume preserving scheme) solve several problems:

- The respective shortcomings of AMR and SPH methods
- Natural evolution of Lagrangian meshes without cell stretching
- Refining and de-refining Lagrangian schemes while conserving integrals





AREPO software (Springel 2009)

However

simple modeling

remains useful

Where in the Milky-Way are

the largest proper motions induced

by galactic rotation ?

The largest proper motions induced by galactic rotation in the Milky-Way

Brunetti & P 2010

- Differential velocity field of an axisymmetric galaxy:

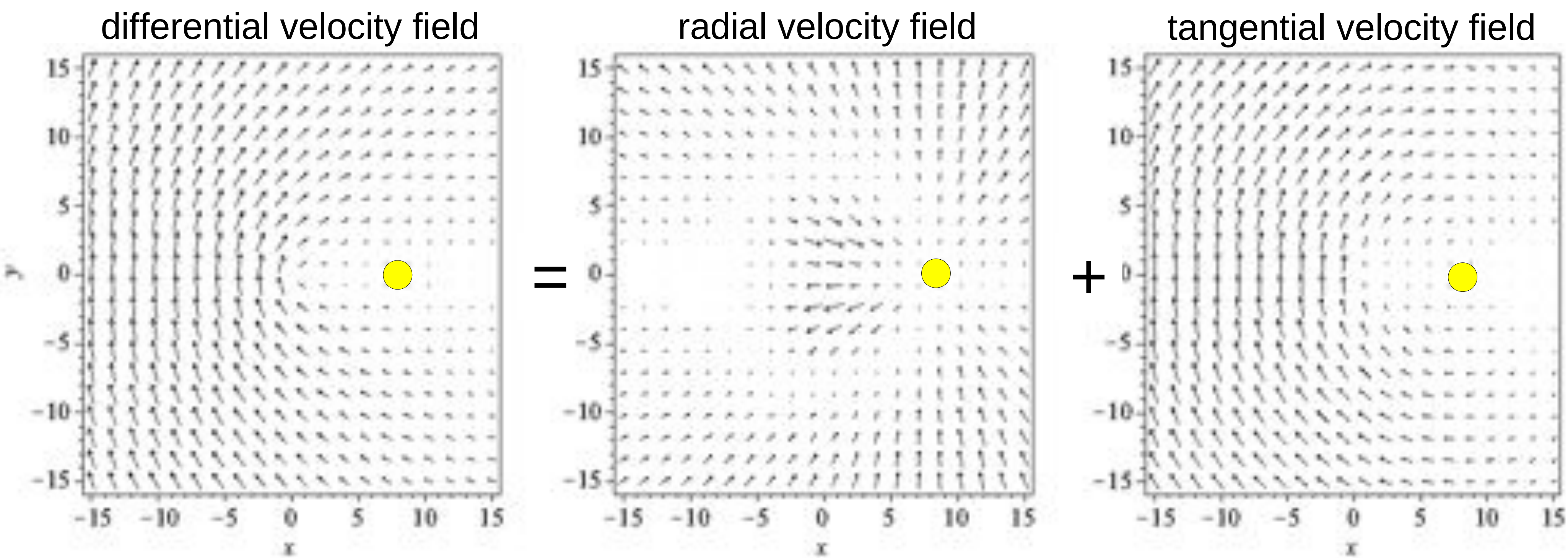


Fig. 1. The differential velocity field for $h = 1$, $p = -0.05$, $x_0 = 8$, $y_0 = 0$ (left) and its decomposition in radial (middle) and tangential (right) components.

The largest proper motions induced by galactic rotation in the Milky-Way

Brunetti & P 2010

- Amplitudes of the radial and tangential velocity fields

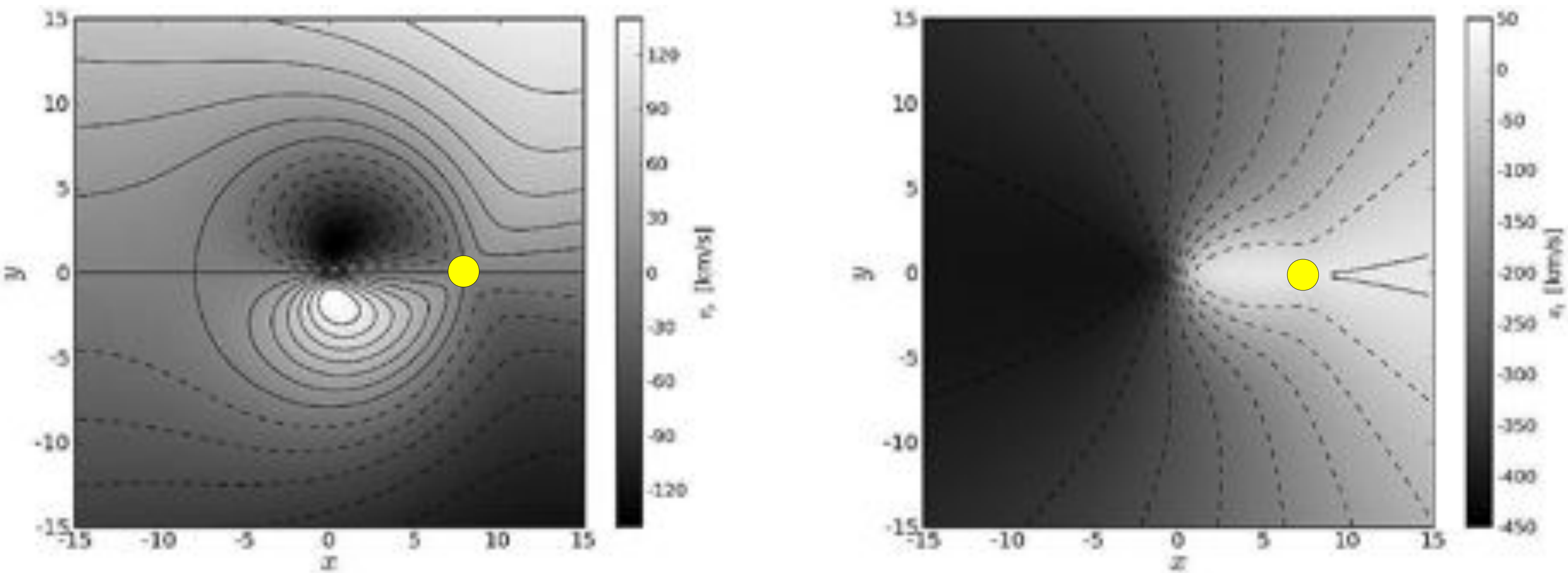


Fig. 2. Contour and gray map of the magnitude of the differential velocity field as in Fig. 1 decomposed in its radial (left) and tangential (right) components. The dark/light grays correspond to low/large values.

The largest proper motions induced by galactic rotation in the Milky-Way

Brunetti & P 2010

- Proper motion field

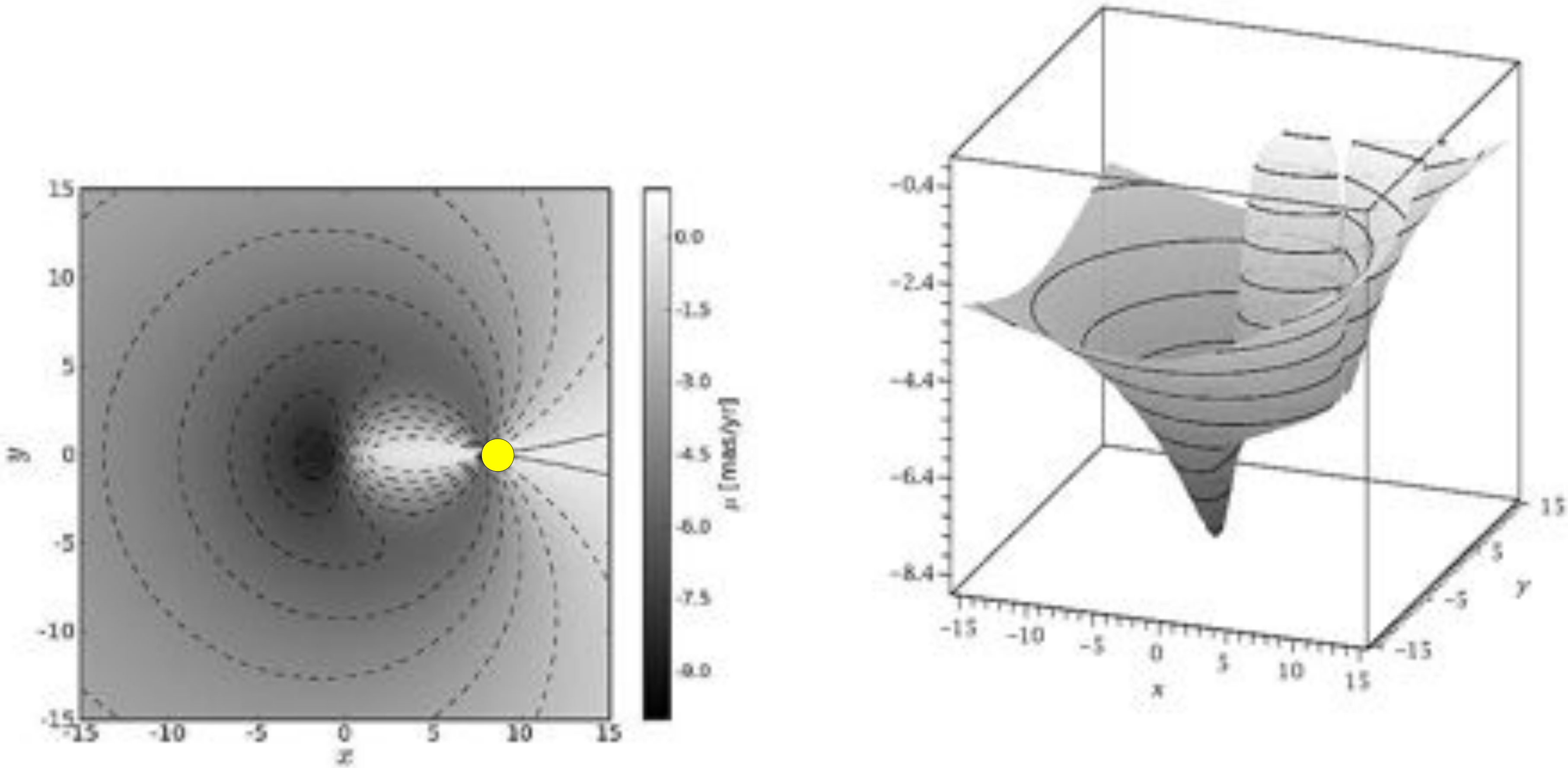


Fig. 3. On the left, contour map of the magnitude of the proper motion μ as observed from the observer's position at $x_0 = 8, y_0 = 0$ as in Fig. 1. The dark/light grays correspond to low/large values. On the right, the side view of the same contour map shows the relative importance of proper motion, with the most negative, largest absolute value slightly beyond the Galactic center as seen from the observer's position.

The largest proper motions induced by galactic rotation in the Milky-Way

Brunetti & P 2010

- Proper motion in the direction of the Galactic center

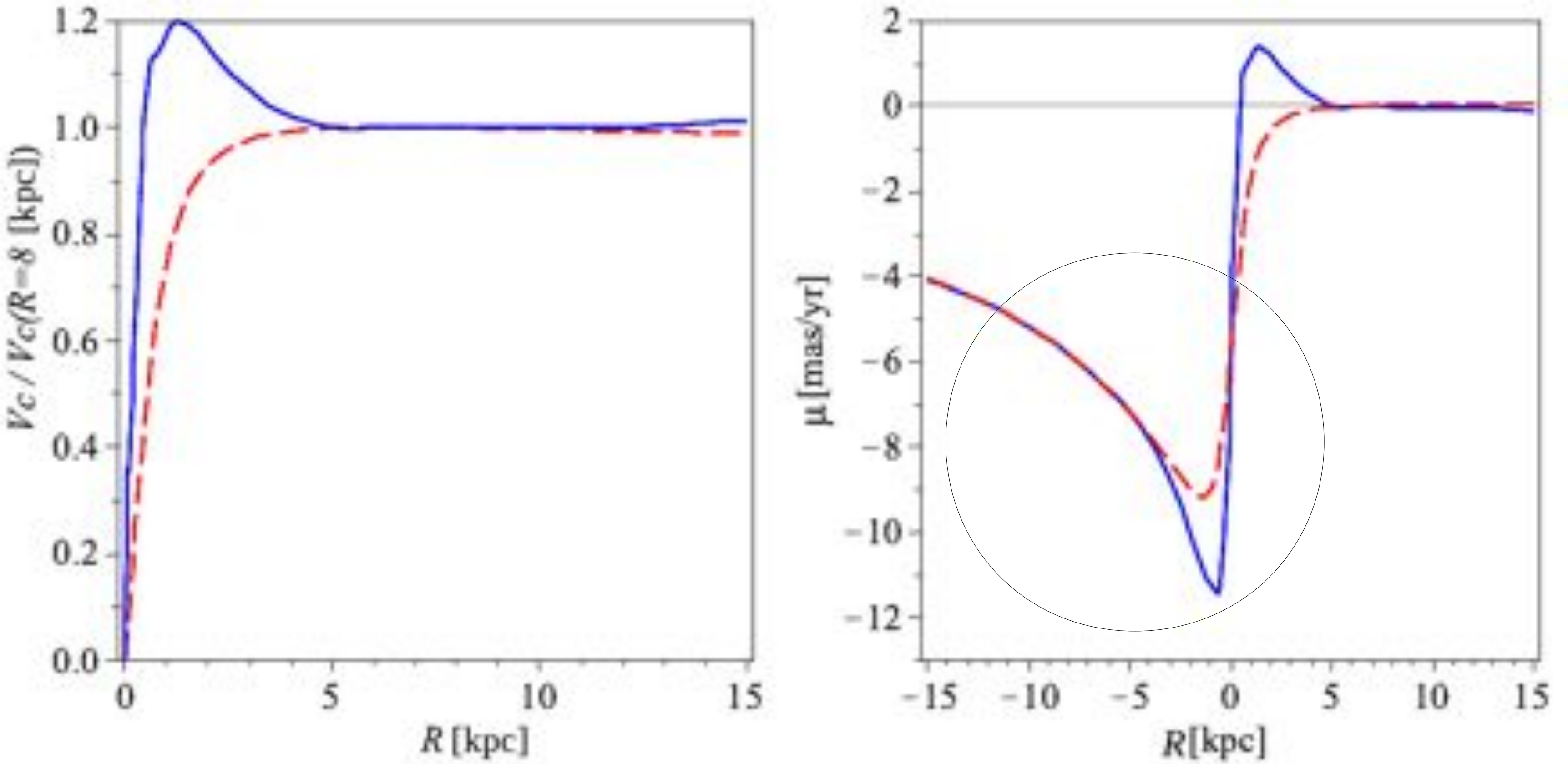


Fig. 4. On the left, rotation curve for the analytic model (dashed red line, same parameters as in Fig. 1) and the Kalberla model (solid blue line). On the right, proper motion μ_θ along the line passing through the Galactic center as observed from the observer's position at $R_0 = 8$, in mas yr^{-1} for $v_0 = 220$ km s^{-1} and kpc length unit, for the analytic model (dashed red line, same parameters as in Fig. 1) and the Kalberla model (solid blue line).

Conclusions

- The bar (= bulge) is an essential feature that introduces chaos and orbit diffusion, including the disk thickening
- At GAIA epoch disk galaxies must be seen as time-dependent structures with multiple patterns rotating at different speeds
- Modeling the optical part of the Milky-Way with fully consistent N-body models containing as much particles as stars will be feasible during the next decade
- Gas and dust modeling, as well as star formation, will remain a difficulty for a longer time