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ИЗВЕСТИЯ

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TWISTED COSMIC WEB AS THE ORIGIN OF SPIRAL STRUCTURE IN DISK GALAXIES

Abstract. The origin of spiral arms is one of the intriguing problems of modern galactic dynamics. Despite decades of research and routine reproducibility in computer simulations, the phenomenon of the spiral arms in disk galaxies remains not fully understood and is a real challenge in modern astrophysics. None of existing theories can give a comprehensive explanation of this phenomena for isolated disk galaxies. These theories successfully explain some elements of the spiral arms formation process, but fail to explain other key elements. We argue that this may hint at the existence of some more general mechanism for the formation of spirals, which embraces the existing theories as distinct components. We propose a draft idea of such theory and discuss how it might be verified.

Key words: disk galaxies, spiral arms, cosmic web, n-body simulations

1. Introduction. Two-thirds of all galaxies in the Universe are disk galaxies. One of the most conspicuous properties of disk galaxies is the presence of spiral density perturbations, known as spiral arms. The geometry of spiral structures is very diverse and varies from spirals with two global-scale arms to multi-tiered spirals having numerous segments and complex branches.

Despite considerable efforts in studying the phenomenon of galactic spiral arms, as well as their routine reproduction in computer simulations, the principle of the formation of spiral patterns is still not well understood. This situation represents an unprecedented challenge for modern astrophysics.

At the dawn of the study of spiral arms, with limited observational data, all studies of this dynamic phenomenon were analytical and of largely speculative character [1–3]. With the advent of computer simulations era, spiral arm researchers started to resort to controlled numerical experiments with equilibrium n-body models of disk galaxies [4–13]. In such experiments, it became possible to conclusively establish major reasons leading to the formation of spiral patterns. It was shown that the trigger of spiral pattern formation might come from tidal effects due to asymmetric potential of dark halos, galaxies flying nearby or even colliding with the host galaxy, as well as internal structures such as giant molecular clouds, globular star clusters, bars, etc. In addition, it was found that for certain combinations of initial parameters, in particular, large ratio of disk mass to the total mass of the galaxy and low random component of motion of stars in the disk, a spiral pattern can occur spontaneously without any external influences [6]. It should be noted that the knowledge of the triggers of the spiral pattern and of the specific conditions for its emergence though sheds some light on this phenomenon, however by no means fully explains it. It is important to understand the concrete mechanism of formation, establishing the chain of physical processes that lead to the formation of spirals, for whatever - external or internal - reason.

The first most developed theory of the origin of spiral arms is the theory of stationary density waves by Lin and Shu, which predicts long-lived and clear-shaped spiral structures [1]. In this model, the individual stars that comprise the spiral pattern move in and out of the arms, while the pattern itself propagates over the disc unchanged over many orbital periods. This theory seems most effective in explaining the formation of spiral arms under the influence of tidal forces. However, it is not consistent with computer simulations of isolated galaxies, in which observed spiral arms are far from stationary; rather, they are short-lived, but constantly reproducing structures with fuzzy edges [9,12]. Studies of these simulations have shown that spiral arms in isolated disks are not density waves, but rather structures arising from density fluctuations in a differentially rotating stellar disk [6,8,10].

Material theory explains spiral arms as formations of gravitationally bound stars that emerge from density fluctuations under the influence of self-gravity. As a result of differential rotation, such formations are aligned onto each other forming a spiral pattern. The distinctive feature of the theory of material arms is the constancy of the stellar composition of spirals: stars rotate in one direction with the arms, exchange energy with them, migrate along them, but remain within [8,10]. The weak point of the material theory is the winding problem - the differential rotation of the galaxy quickly turns all bound structures into tightly wound spirals, and this is observed neither in real galaxies nor in simulations. Thus, while this model can, in principle, account for flocculent spirals with their patchy patterns, it can hardly explain the origin of grand-design global-scale spiral arms.

Another theory - the theory of swing amplification - also relates the formation of spirals to density fluctuations, but it explains their amplification not only by gravitational contraction, but rather by the superposition of retrograde epicyclic motion of stars with the shear deformation of leading density perturbations [2,3]. This theory successfully explains the relationship of the initial parameters of the disk with the shape and number of spirals, through the minimum size of disturbances stabilized by rotation [4]. At the same time, the theory of swing amplification does not explain the subsequent extremely nonlinear evolution and regeneration of the spiral pattern [6].

The recent high-resolution simulations show that, in reality, both self-gravity and amplification of perturbations by the epicyclic motion of stars play an equally important role in the formation of spiral arms [6,8,9,13]. This may hint at the existence of some more general mechanism for the formation of spirals, which embraces the material theory and swing amplification theory as distinct components.

The purpose of this article is to outline a draft version of our own theory, which explains the spirals arms as a manifestation of well known physical phenomena in differentially rotating disks, in order to stake out a claim on this idea. Our theory is consistent with the swing amplification theory and the theory of material arms, but not reduced to them. The paper is organized as follows. In Section 2, we describe our theory in sketchy form, leaving more detailed and strict description for a follow up paper. Then, in Section 3 we discuss pros and cons of our theory, as well as ideas of how to further prove it or falsify. Finally, we conclude with a summary in Section 4.

2. Our Theory

Here we discuss our new theory, which explains spirals as structures forming in a co-rotation frame under the influence of residual irregular forces when the regular force such as the central gravitational pull is canceled out by the centrifugal force.

Cosmic Web: First we consider an expanding flat disk with unit radius and uniformly distributed unit mass, where all initial velocities are directed along the radius outwards and are proportional to the central distance with factor of $\sqrt{2}$. These conditions are effectively equal to initial conditions used to simulate large-scale structure formation in a flat universe with curvature $k = 0$. The primordial fluctuations are achieved by randomization of particle positions. Proceeding these initial conditions in time as a self-gravitating n-body system with $G = 1$ in collisionless mode with a non-zero softening length, we start to see formation of filament structures, the so called *Cosmic Web*, typically observed in cosmological simulations (see Fig. 1, top row). Certainly, this is only a rough approximation, it is two-dimensional only and does not account for periodic boundary conditions and many other details, but it reflects the mechanism behind the large-scale structure formation fair enough.

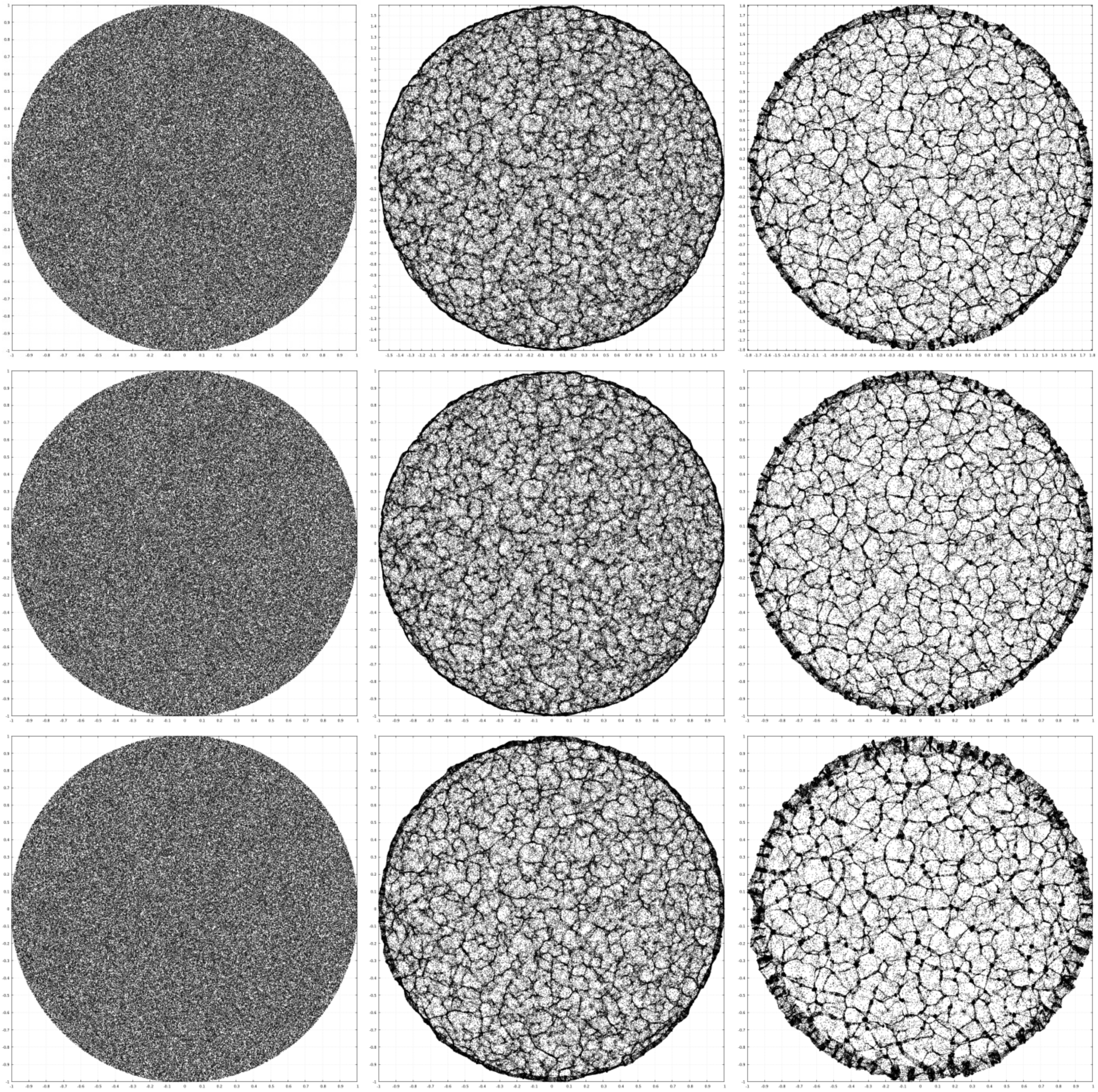

Figure 1. Expanding flat disk of self-gravitating particles when integrated in proper (top-row) and comoving coordinates (middle and bottom rows). The last row represents the co-moving integration with viscosity term taken out. Columns representing different times which increase from the left to right. Ranges of the plots in the first row are adjusted to fit the expanding disk. All simulations are 2D and carried out with direct n-body code with the following set of parameters: n = 262144 (number of particles), ε=0.01 (softening length), Δt=0.001 (timestep), R=M=G=1.

The qualitative reason for the initial heterogeneity to growth in this way lies in the interplay of expansion and gravity. Overdense regions expand slower than rarefied areas because their gravity is working more strongly against the expansion. As a result, a dense region tends to become denser and smaller, while a low density region becomes more diffuse and bigger. The expanding regions of lower density, so-called voids, acquire the topology of inflating bubbles [14]. Matter appears “pushed” to their periphery/outskirts and becomes more concentrated in the spaces between the bubbles. As the expansion continues, the bubbles contact each other and the matter is further “displaced” to the contact interfaces, forming so-called filaments that connect regions of maximum matter concentration in the inter-bubble space. Thus, the matter distribution starts to resemble a foam-like Voronoi mesh [15].

The easiest way to understand the main driving forces behind this phenomenon in a quantitative way is to switch to the co-moving coordinate frame. In this frame of reference, the gravitational force acting on a particle of mass *m*, that sits in position $\mathbf{x}'$ and has a velocity $\mathbf{v}'$, can be decomposed into three terms

$$\mathbf{F}' = \frac{1}{a}\left(\,\mathrm{F} - m\ddot{a}\mathrm{x}' - 2m\dot{a}\mathbf{v}'\,\right)\ . \tag{1}$$

where *a* is the radius of the expanding sphere also known as the *scale factor*. The first term in the brackets represents the gravitational force that acts on a body in a proper coordinate system, while the second is the regular force coming from the imaginary mass enclosed within the body radius if it were distributed absolutely uniformly in accordance with the averaged density of the entire system. The last term which is proportional to the velocity of the body can be understood as a friction force. The second and third terms are “fictitious” forces that show up themself when we switch to a non-inertial frame of reference related to an expanding system of self-gravitating bodies. Altogether, it works like this: the second term basically cancels out the central gravitational pull caused by the first term and thus prevents gravitational collapse of resting bodies that they will experience otherwise. Since the real gravity force is lampy due to irregularities of body positions, what is leftingover after such cancelation is only residual peculiar forces, also known as irregular forces. The third term accounts for interparticle space growth, that “decreases” the values of particle’ velocities in a co-moving frame and causes the particles to experience a viscosity. Using these forces and starting from the same space distribution but zero velocities, it is entirely possible and, in fact, is a common practice, to simulate an expansion of gravitating particles without the expansion, so that the result of simulations would be indistinguishable from the simulation in proper coordinates (see Fig. 1, the second row). This illustrates the full validity of such treatment and gives “a sense of reality” to fictitious forces acting in a comoving frame.

Integration in co-moving coordinates has a lot of advantages, among them - the ability to detect the force primarily responsible for cosmic web formation. If we remove the friction term and repeat integration, the results are somewhat changed but the formation of the cosmic web is not prevented (see Fig. 1, the bottom row). Due to this fact we can safely conclude that the main prerequisite for the structure formation to occur is a situation when the regular part of gravitational force acting on a particle is taken out and the self-consistent evolution is mainly driven by irregular forces.

Rotating Disk: There is another situation when such elimination of the central gravitational force takes place and the particle evolution is governed by residual peculiar and fictitious forces. This is rotationally supported self-gravitating disk systems. Hence we can expect the formation of structures similar to the cosmic web in these disks as well. Indeed, if we put a uniformly and randomly distributed particle disk in potential that ensures an *r*-independent angular speed and initialize the disk particles with circular velocities and then let them evolve in a self-consistent manner, we will find a familiar structures that look pretty much the same as the cosmic web (see Fig.2).

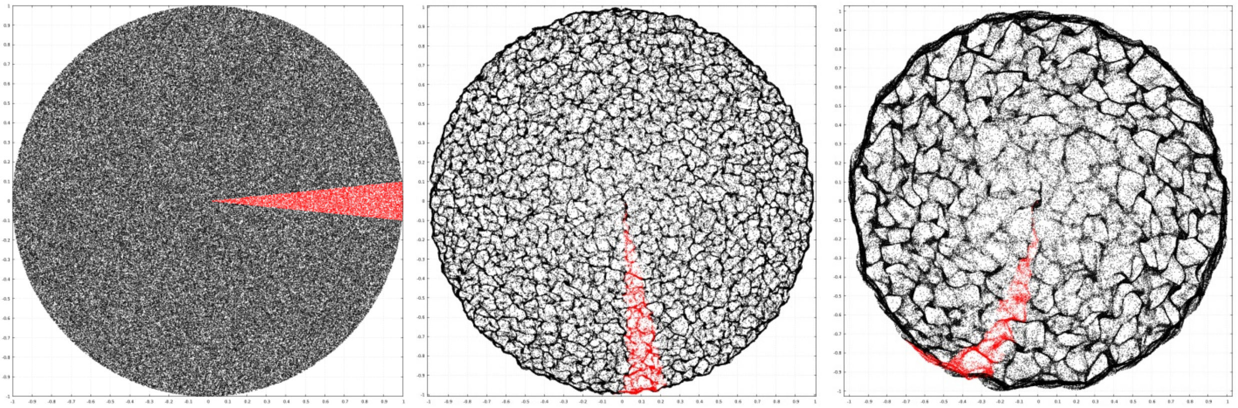

Figure 2. Rotating n-body disk with zero thickness placed in the halo (not shown) the potential of which provides near rigid-body rotation (when angular velocity is constant over radius). As before, the different plots show the different times, starting from a homogeneous distribution at the left and proceed in time in the middle and right plots. Elapsed time and actual rotation speed can be seen from the motion of the red marked particles. Disk-to-halo mass ratio is M_d / M_h = 0.08, ε=0.02, n=262144.

Of course, this similarity alone does not fully prove the similarity of the underlying process, but, together with the fact that our model predicted it, it testifies in favor of the idea that this resemblance is not a coincidence, but rather a manifestation of the same mechanism governed by irregular forces. Leaving a more robust proof for the later, let us now consider the case of a differentially rotating disk, where angular speed varies with radius. In this case we see the same structures, but now they are squeezed and stretched by differential rotation (see Fig. 3). The cell walls are aligned in such a way that they start to form long spiral arms extending from the center to the periphery and spiral structure begins to be seen.

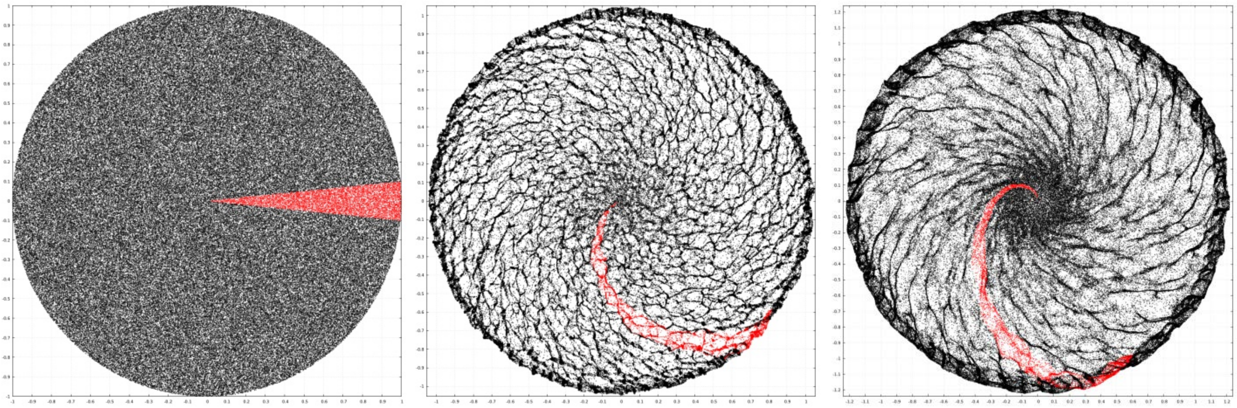

Figure 3. Rotating n-body disk in Hernquist potential with the same disk-to-halo mass ratio 0.08, same softening length ε=0.02 and number of particles n=262144.

Thus, the gist of our idea is that the spiral arms observed in self-gravitating disk systems are essentially a cosmic web distorted by differential rotation. Sure enough, the spiral patterns seen on Fig. 3 are far from the real spiral structures observed in real and simulated disk galaxies, but thus far we have been using unrealistic uniform disk distribution to illustrate the idea. Let’s now switch to a more realistic non-uniform disk distribution with density increasing toward the center, while keeping all other parameters like disk-to-halo mass ratio, shape of the halo potential, softening length, etc. completely unchanged. The Fig. 4 shows the time evolution of such a disk in sequence of time-snapshots over regular time intervals. As one can see, the cosmic web-like structures show up here as well, and, as before, they start to be differentially stretched forming the spiral patterns, but in contrast with previous uniform disk simulation the resulting structures become thicker toward the center and are more robust to the central twisting.

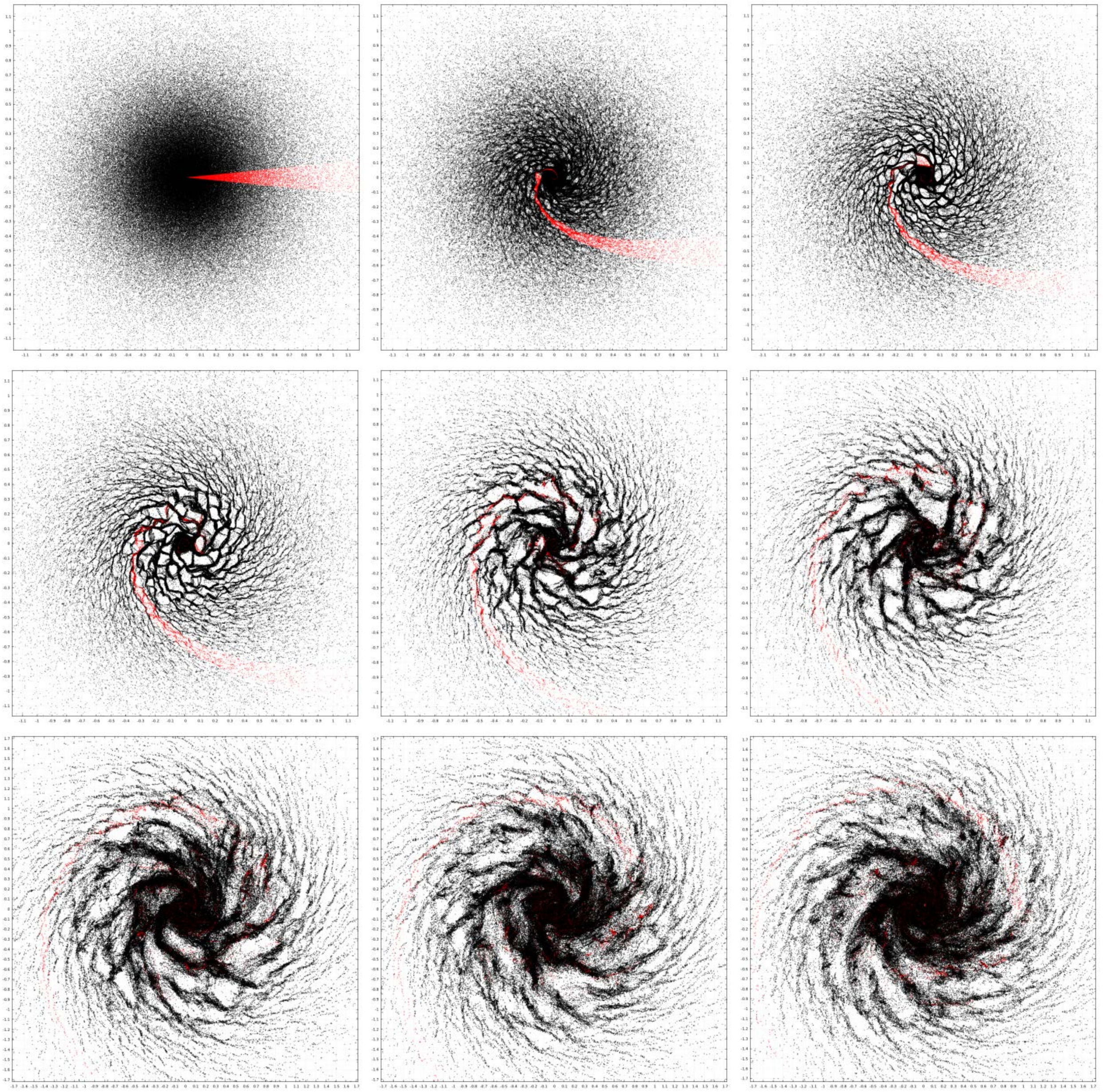

Figure 4. The same as in Figure 3, but now with non-uniform disk density distribution and time evolution is depicted in 9 snapshots starting from top-left and moving progressively to bottom-right.

As the time goes by, the cells get larger and larger, while their walls thicker and thicker (second row on the Fig.4), something that was seen before in our previous runs. There is no twisting issue because cellular structures show a certain degree of stiffness and decouple from the differential rotation flow constantly rearranging themself and thus sustain pitch angles much larger than those dictated by differential flow (see and compare the spiral pattern formed by red-marked particles and spiral patterns formed by the system as a whole). At some point, the cells get so large and their walls so thick that they become comparable with the scale of the whole system, and we start to see the classical spiral galaxy structures (see the last row on Fig.4 and left image on Fig.5). At this point cellular structure becomes barely recognizable by eye, but in fact still present. It is visible in the kinks of the spiral arms, in the splitings of their ends, even the whole cells can still be outlined (see Fig. 6). Amazingly enough, these features are recognizable in real galaxies as well (see the right image on Fig 5 and 6).

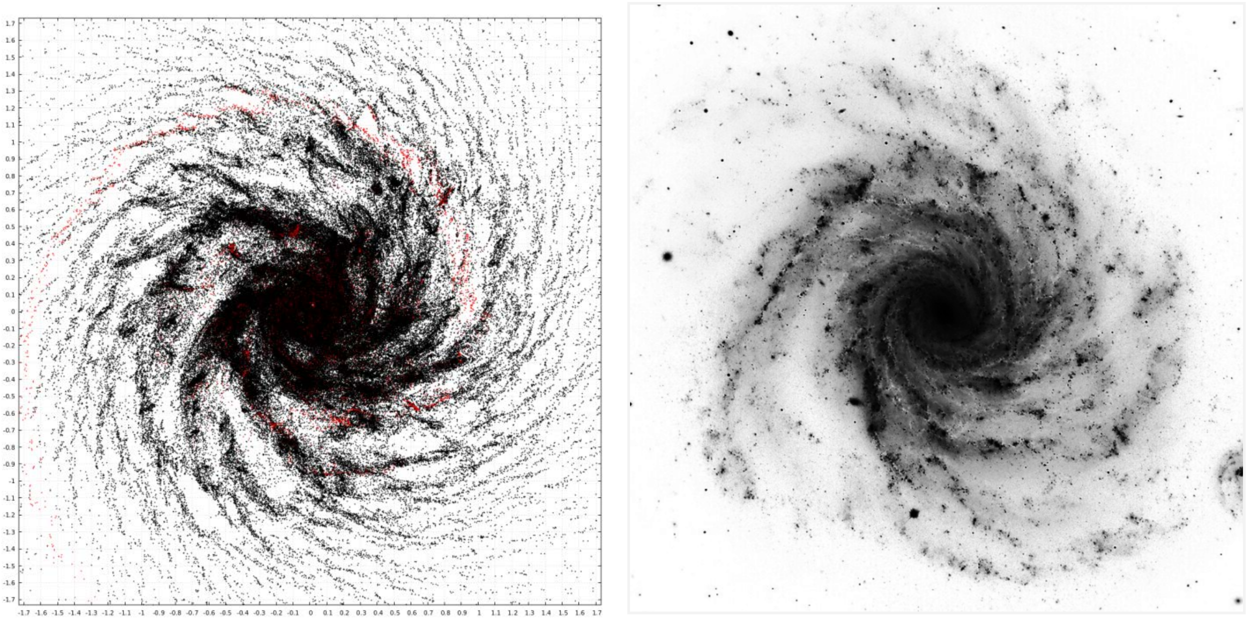

Figure 5. Side by side comparison of our simulated galaxy (left column) and the real galaxy M101 (right column).

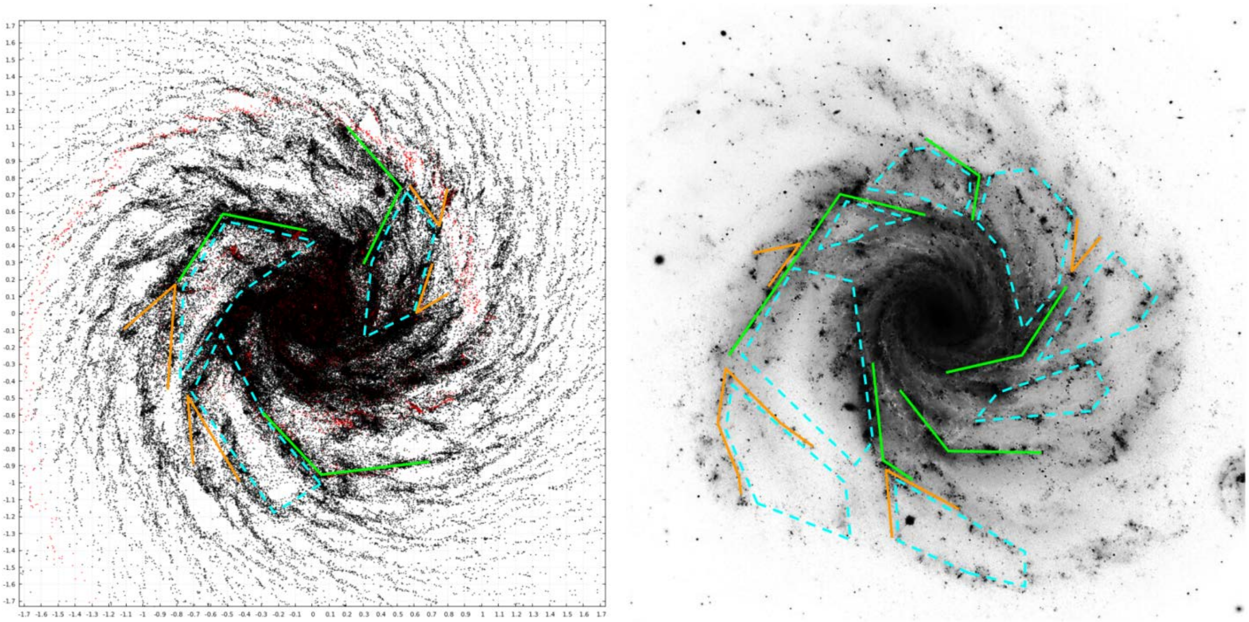

Figure 6. Same as Fig. 5, but now on both images the signatures of cellular structure, such as kinks (green lines), splittings (orange lines) and cells (dashed blue) are marked.

The striking example of visible cellular structure is the spiral galaxies NGC 5468 and IC 342, where you can clearly see dozens of recognizable cells (see Fig. 7).

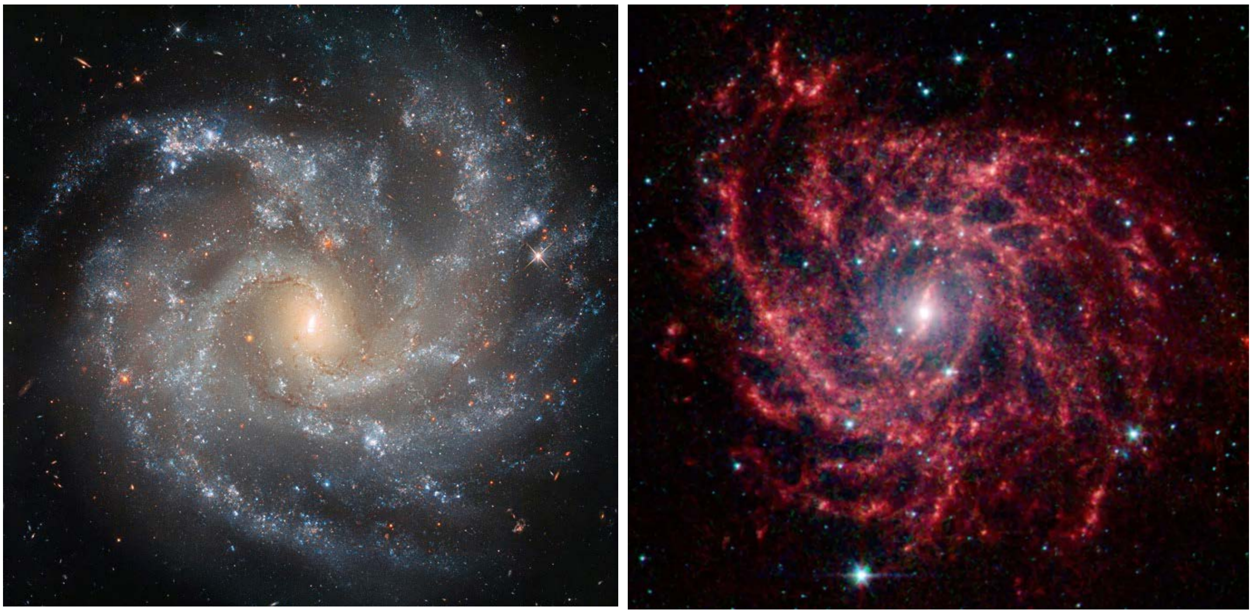

Figure 7. Left: The spiral galaxy NGC 5468 presents a face-on view as seen in this image from the Hubble Space Telescope. Right: Infrared image of IC 342 from NASA's Spitzer Space Telescope which reveals a spider-web like dust distribution pattern visible throughout the galaxy's disk.

3. Discussion

Here we discuss our new theory, in particular its pros and cons, as well as methods for its further verification and falsification.

First of all, we point out that our theory does not contradict the theory of swing amplification or/and material arms theory, but rather considers them as particular manifestations of one physical process that we have exposed. For example, in our simulations, the particles indeed have a tendency to stay together in intercellular interfaces and move along them (see dynamic of red-marked particles in Fig. 4), which is quite in line with the material arm vision, however there is no winding issue because cells are constantly rearranging their segments due to differential rotation. In their turn, the segments that form cellular walls have different orientation relative to the direction of rotation, some of them are trailing, some are leading, which allows a swing amplification to occur in the latter case.

Second, we emphasise the preliminary nature of our conclusions that were drawn from extremely simple 2D n-body models with a relatively small number of particles. We understand that more appropriate full 3D simulations need to be carried out before we can make certain conclusions. This is a subject for our subsequent publications. It is worth noting that we have unique tools that will allow us to do this, namely GALIC/GALIC-3D [16,17] codes for creating fully 3-dimensional n-body galaxy models in a high-quality equilibrium state with advanced control of initial velocity structure. This will allow us to study the spiral arms phenomenon in full 3D in a clean environment largely free of intrinsic instabilities.

One of the direct implications of our idea is the existence of a stage in the process of galaxy formation during which the cellular structure has a pronounced appearance and the sizes of individual cells are much smaller than the scale of the galactic disk (see Fig.4, first and second rows). Then, it is reasonable to ask why one does not observe these early stages that should feature a clear cellular structure in real galaxies. It is well known that spiral arms are unambiguously related to enhanced star formation rates and have more young stars than inter-arm regions [18]. It could mean that the formation of cells initially occurs in galaxies during their gas dominant phase [19], when there are simply no light sources available to illuminate these structures. Later, when the cellular structure gets larger and denser the process of star formation is triggered along the intercellular interfaces and the entire structure is illuminated, but by this time the cells become so large and distorted by differential rotation that the cellular structure becomes poorly visible. Also one should not forget that the process of galaxy formation is much more violent and complex than we model it and the structures are constantly disturbed by new falling gas and various feedback processes. Nevertheless, in self-consistent numerical hydrodynamic simulations, where the visibility of structures is not limited by available light sources, almost all disk galaxies pass through such a phase, even though the gas is constantly falling and supernova blasts and other feedback process are constantly disturbing the galactic disk (see Fig. 8).

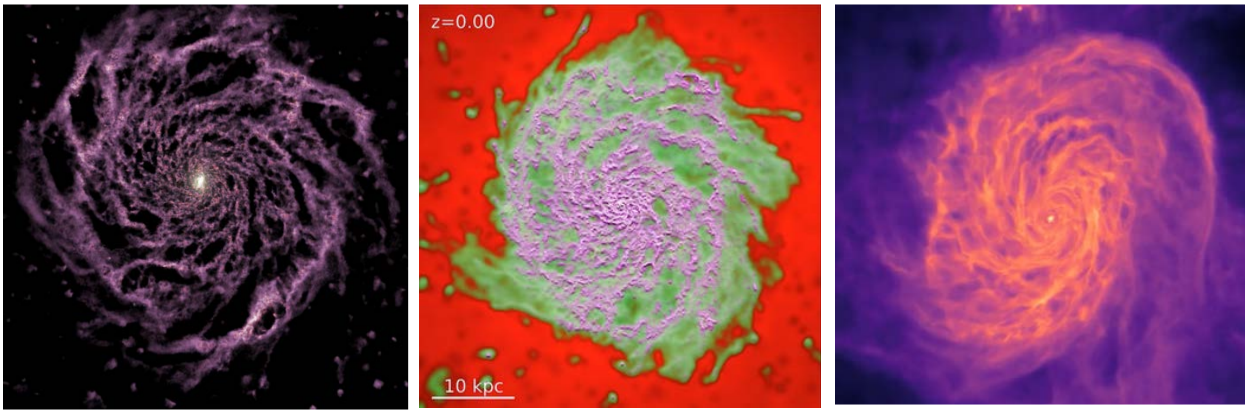

Figure 8. Gas density distribution of self-consistently formed late-type disk galaxies observed in different cosmological simulations: ERIS Simulation, 2011 [20] (left), FIRE Simulation [21] (middle) and TNG50 Simulation [22] (right).

Interestingly, these simulations have a fairly large diversity in their treatments of gaseous and feedback physics, but still systematically produce the cellular structures in their disks [20–22]. Thus, it may indicate that the formation of cosmic web-like structures in galaxies might define the numerous physical processes occurring in a disk galaxy, rather than be defined by them.

The origin of Grand Design spirals has always been considered to be distinct from that of multi-branched spiral structures; however, our tests show that with a certain combination of initial parameters, the process of cell enlargement goes so far that in fact there are only two huge cells and the interface between them remain in the form of Grand Design spirals. It could be that the bar is also a result of such growth, and is simply an enlarged intercellular interface. Certainly, these conjectures require additional studies.

The essence of our theory is that in the formation of spiral arms in dynamics, we observe a struggle between two processes, the process of formation of cellular structure under the influence of irregular forces similar to cosmic-web formation, and the process of shear deformation caused by differential rotation. There are several ways to confirm or refute this statement, and some of them were already tested by us. For example if our explanation is true then turning off differential rotation we have to see a comic-web-like structure formation, and this is already confirmed in our 2D simulation as demonstrated above. Turning off irregular forces should prevent formation of cellular structure, and this is also true. While this can be done in various ways, e.g. by smoothing out irregular forces using non-zero softening of the right scale, or suppressing irregular forces by regular ones, or making the disk "hotter" by increasing the pressure, the outcome is always the same: the formation of spiral structures is prevented.

Another possibility to further justify our theory is to perform unwinding of the spiral pattern and process the resulting structures with topological analysis to reveal its cellular nature even if it is not recognizable visually.

Alternatively, we can consider the possibility of switching to a co-rotating coordinate frame in order to carry out the integration using modified force of gravity as we did in the case of cosmological expansion. For example, we may try to turn off fictitious forces, for example the Coriolis force, and see how the resulting structures will react to that. We expect, that this should boost the cellular structures formation as we remove one of the distorting forces.

4. Conclusion. We presented in bare outlines our theory of spiral arms formation in self-gravitating n-body disk systems. This theory explains the spirals as an interplay between cellular structure formation under the influence of residual forces (with gravitational pull being canceled out by centrifugal forces in the co-rotating frame) on one side, and the differential rotation on the other side. This is somewhat similar to the mechanism that forms the large-scale structure of the Universe in a co-moving frame under the action of irregular forces, the only difference being that in the case of differentially rotating systems this process is accompanied and distorted by shear deformation.

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ДИСКІЛІК ГАЛАКТИКАДАҒЫ АЙНАЛДЫРЫЛҒАН ҒАРЫШТЫҚ ТОР СПИРАЛЬДЫ ҚҰРЫЛЫМЫНЫҢ ПАЙДА БОЛУЫНЫҢ ТҮСІНДІРМЕСІ

Аннотация. Шиыршықты жеңдердің пайда болуы қазіргі галактикалық динамиканың қызықты мәселелерінің бірі болып табылады. Ондаған жылдар бойы компьютерлік модельдеудегі жүргізілген зерттеулерге және күнделікті жаңғыртылуына қарамастан, дискілі галактикада шиыршықты жеңдердің феномені толық зерттелмеген. Бұл қазіргі астрофизика саласында нағыз сынақ. Қолданыстағы теориялардың ешқайсысы оқшауланған дискілік галактикалар үшін бұл құбылыс туралы толық түсінік бере алмайды. Бұл теориялар шиыршықты жеңдердің пайда болу процесінің кейбір элементтерін сәтті түсіндіреді, алайда басқа негізгі элементтерді түсіндіре алмайды. Біз бұл қолданыстағы теорияларды жеке компоненттер ретінде қамтитын спиральдарды қалыптастырудың неғұрлым жалпы механизмінің бар екенін білдіруі мүмкін деп санаймыз. Біз осындай теорияның алғашқы жобасын ұсынамыз және оны тексеру үшін қандай құралдар қажет болуы мүмкін екенін талқылаймыз.

Түйін сөздер: дискілі галактика, шиыршықты жеңдер, ғарыштық тор, N-денелі симуляциялар

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СКРУЧЕННАЯ КОСМИЧЕСКАЯ ПАУТИНА КАК ОБЪЯСНЕНИЕ ПРОИСХОЖДЕНИЯ СПИРАЛЬНЫХ СТРУКТУР В ДИСКОВЫХ ГАЛАКТИКАХ

Аннотация. Происхождение спиральных рукавов - одна из интригующих проблем современной галактической динамики. Несмотря на десятилетия исследований и рутинное воспроизведение в компьютерных симуляциях, феномен спиральных рукавов в дисковых галактиках остается не до конца понятым, что является большим вызовом для современной астрофизики. Ни одна из существующих теорий не может дать исчерпывающего объяснения этого явления для изолированных дисковых галактик. Существующие теории успешно объясняют некоторые элементы процесса образования спиральных рукавов, но не объясняют другие ключевые элементы. Мы считаем, что это может указывать на существование некоего более общего механизма образования спиралей, который охватывает существующие теории, как отдельные компоненты. Мы предлагаем черновой вариант теории такого механизма и обсуждаем как ее можно проверить.

Ключевые слова: дисковая галактика, спиральные рукава, космическая сетка, N-телесные симуляции.

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