What?	Galactic diversity as an emerging process: gravity-driven wakes and cosmic inflow drive self-regulation.
Why?	Account for the resilience of discs and explain the emergence of tight scaling laws.
Why now?	Cosmic surveys require physically motivated debiasing. Galaxy formation requires refocussing.
How?	Reaction-diffusion of multi-component galaxies, accounting for top-down regulated stellar cooling & heating.

I. Contexte, positionnement et objectif(s) de la pré-proposition

Understanding the diversity of galaxy shapes across cosmic history is essential for making the most of major sky surveys such as Euclid and LSST. These surveys rely heavily on galaxy morphology (their shapes and structures) to extract precise information about the universe. Yet one of the main unsolved puzzles is why thin galactic discs, delicate structures of stars and gas, persist over billions of years, and why they so consistently obey tight scaling laws (the regular patterns that link galaxy properties together).

In this context, *CosmicEmergence* will address a set of fundamental questions: *how does galaxy formation interact with the large-scale cosmic flows to build an efficient, self-regulating system that produces these ubiquitous thin discs? How does this gravity-driven regulation compare with the widely used picture of galaxies shaped mainly by stellar or black hole feedback? And why does the persistence of these fragile discs matter for the precision of galaxy surveys?*
We will challenge the mainstream[59,61,78] understanding of galactic disc formation and stability. We posit that thin galactic discs are not sustained by fine-tuned feedback mechanisms, but rather represent emergent systems driven by gravity and baryonic processes to a state of homeostasis[1] near marginal gravitational stability. *CosmicEmergence* will provide quantitative analytical insight into "why" galaxies behave as they do, complementing the "what" shown by simulations, and ultimately improve cosmological parameter estimation by reducing biases related to galaxy morphology.

With *CosmicEmergence*, we will model galactic discs as self-organising structures that are constantly fed and regulated by streams of cold gas flowing in from the cosmic web. The outcome will be a detailed explanation of how gravity, acting together with normal matter, imposes (twice) a top-down order on galaxies via shocks: from the largest scales of the cosmic web[92], through the circumgalactic medium surrounding galaxies, down to the shock-driven processes of star formation inside discs. This framework will explain not only the emergence of thin discs, but also their remarkable resilience over cosmic time – and why galactic scaling laws are so tight. Beyond galaxy formation itself, this investigation will also shed light on how complex, self-regulating structures emerge in nature under the simple yet universal influence of gravity.

Galactic discs observed by the James Webb telescope at most redshifts are an astrophysical illustration of the concept of emergence and downwards causation. They are seemingly fragile, yet dynamically stable structures that emerge spontaneously from hierarchical clustering when secular dissipative processes take over. The shielding from the cosmic environment operates via self-reinforcing wakes on mesoscales (the thin disc) which are coupled both to larger scales (via the gravitational field, and cosmic flows of cold gas from the circumgalactic medium), and a control loop on smaller scales (supernovae feedback, star formation). This is typical of open dissipative systems with feedback loop, which provides resilience to the environment: the disc is homeostatic. Emergence operates because gravity dominates. Hence the shortening of gravitational relaxation times via wakes impacts both the control loop (indirectly), the rate of dissipation, and the tightening of the disc (directly). Indeed, the closer the disc is to marginal stability, the stronger the wake, the shorter the relaxation time, the tighter the loop. This attractor allows the disc to generate and maintain order through self-organisation. This is a remarkable widespread outcome. While this qualitative scenario is compelling, the detailed quantitative demonstration and astrophysical implications is still lacking, and is the goal of this ANR.

Context: Since we formulated it in 2021[89] to explain the stratification in stellar age and height of simulated galactic discs (driven by the cofounding factor of proximity to marginal stability), the emergent scenario has been vindicated by most recent observations on distinct scales and epochs (JWST[117], ALMA, SAMI, MANGA GAIA,

[1] The key insight is that stellar discs are dynamically cold, which means that stellar orbits are not eccentric. In turn, this low eccentricity makes them very responsive: because the relative motion of co-rotating stars is weak, gravity has time to build up. On the one hand, this responsiveness makes them very sensitive to perturbations, which increases their eccentricity. In effect, because they are dynamically cold, they heat up. Conversely, this responsiveness also boosts recurrent episodes of star formation when spirals unwind. When perturbed, they efficiently form new stars with low eccentricity, i.e., they cool. The net effect of these opposite responses is a robust attractor. The disc self-regulates in a cold dynamical state, a thin disc, while efficiently forming stars. This dynamical **homeostasis** naturally explains many puzzles that the standard paradigm of galaxy formation fails to address.

MUSE)[2], most cosmic simulations resolving spiral structures[3], and our recent extended kinetic theories[4].
This ANR aims to complete the paradigm shift, and steer the field toward a theoretical predictive understanding of galaxy evolution, which will prove quantitatively useful for cosmology.

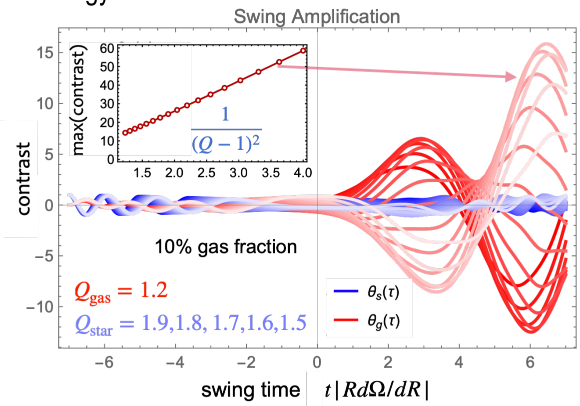


***Fig 1**:* The joint evolution of gas (red) and stellar (blue) spiral contrast, as a function of unwinding time for a sequence of spirals[50] with different gas and star "temperature" labelled by Q. As the noise-driven spiral unwinds, the gravitational coupling between the two components drives a very strong transient amplification of the gas contrast (left), which will non-linearly **shock**[87] and fragment, triggering a turbulent cascade down to star formation scales. *Inset:* the maximum contrast versus gravitational susceptibility of the stellar component, suggesting a quadratic scaling. This *preliminary* result validates within the shearing sheet model the closure of the dressed reaction-diffusion framework. CosmicEmergence will extend this work to a global secular criterion for the reaction term.

The central idea is that massive stellar discs are not just collections of stars, but self-regulating (homeostatic) attractors. Their evolution is primarily governed by the large-scale, long-range force of gravity, which organises the disc into a stable, star-forming attractor. This approach, formalised via a "dressed" reaction-diffusion equation, stands in stark contrast to the classical model of galaxy formation, which relies on "bottom-up" feedback, where small-scale events like supernovae explosions were thought to regulate the entire galaxy[6,119]. This methodology, though effective, has clear limitations. First, tuning parameters to match one cosmic epoch undermines predictive power at others, reflecting flexibility rather than physical accuracy. Second, complex sub-grid models entangle processes, obscuring causal interpretation. Third, physically motivated values tied to specific force scales clash with scale-invariant gravity. Finally, the high computational cost of high-resolution runs prevents full exploration of parameter space or the generation of large ensembles needed to quantify intrinsic variance in galaxy properties.

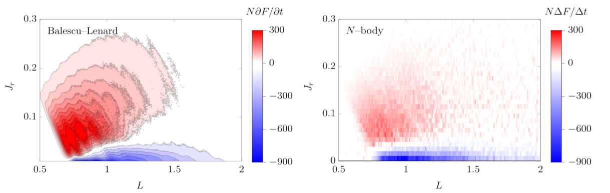


Fig 2: Left: predictions of the mean-field changes, ∂F/∂t, from kinetic equations for the long-term evolution of the Toomre disc in action space (L,Jr). Right: Average flux over 1000 realisations (Roule+'24). The agreement in this shot noise-driven regime is remarquable. CosmicEmergence will now account for a) external heating (SN, turbulence, mergers), b) cooling (SF), c) self-regulation & d) expected variations beyond the mean.

In the *CosmicEmergence* new framework, small-scale processes do not counteract the infall of gas from above; they resonantly excite heating and star formation within the disc, with a global amplitude which self-tunes to the dynamical cold state of the disc[91]. This explains why, in high-resolution simulations, the specific details of feedback recipes do not matter much, whereas in low-resolution simulations, they must be constantly tuned.

CosmicEmergence argues that the persistent engine of star formation in disc galaxies is a self-regulating cycle driven by the stellar disc itself, while it remains in a globally dynamically stable state. The stellar disc acts as a pacemaker, generating a continuous sequence of density waves[86]. These waves are powerfully amplified by the disc's self-gravity, and their gravitational influence is

[2]Recent observational evidence includes: 1/ abundant thin discs at high redshift[68]; their survival in merger-driven eras is naturally explained by self-regulating homeostasis. 2/ tight galactic scaling laws[71,72,79]; minimal scatter arises from a dynamical attractor state, with correlations tied to kinematics (v/σ)[114,96] rather than star formation history. 3/ star formation occurs even where gas alone appears stable[99,100], due to stellar–gas gravitational interaction. 4/ arms organise molecular gas[112,73] but do not increase intrinsic star formation efficiency; 5/ slow, inefficient star formation (1–2% per orbit) indicates a multi-scale regulatory mechanism[22]; 6/ minimal scatter in thin-disc galaxies[117] reflects quiescent, predictable evolution tied to the regulatory attractor.

[3]Numerical evidence includes: 1/ simulations of coupled stellar–gas discs confirm that mutual gravity can destabilise an otherwise stable system, with star formation triggered when the two-fluid stability parameter[50,95,73] falls below a critical threshold; 2/ self-gravitating, multi-component simulations show that swing amplification generates transient spiral arms, whose gas fragmentation yields a GMC mass spectrum matching observations[99], linking galactic-scale dynamics to star-forming clouds; 3/ high-resolution cosmological simulations reveal that discs can grow thinner and dynamically colder over time[89], even in chaotic environments, demonstrating the homeostatic resilience predicted by the emergent scenario.

[4]The kinetic theory[5] of self-gravitating systems has been a fruitful field of research over the last 20 years[97]. We first presented the formalism[97,91], and a first explicit implementation[29] to explain the spontaneous formation of ridges in action space reminiscent of those observed by Gaia. Subsequently, we explored their spontaneous secular thickening[33]. We applied it to galactic nuclei[35], and showed that the Balescu-Lenard equation is the master equation for the scalar resonant relaxation for the S-stars observed around SgrA*[117]. We showed how the kinetic framework describes the slow relaxation of globular clusters[117], alleviating intrinsic limitations of the Coulomb logarithm. Finally we very recently showed how wakes in cold galaxies stiffen the disc[101]and drastically accelerate orbital diffusion[102] [fig 2].

transferred to the colder, more responsive interstellar gas. It is within this dynamically-coupled gaseous component that instabilities are triggered post shock, leading to a turbulent cascade down to molecular clouds and subsequent episodes of star formation [fig 1]. Because the stellar disc itself never becomes globally unstable, this mechanism can be sustained over cosmological timescales, providing a robust explanation for the long-lived, self-regulated nature of star formation in disc galaxies.

This framework naturally explains[71,72,79] several new key observations: the ubiquity of thin stellar discs, the corresponding kinematically-driven tightness of the baryonic Tully-Fisher (the thiner, the tighter), Kennicutt-Schmidt, or radial acceleration relations (without MOND), and the colour and kinetic properties of local spiral galaxies, which are shaped by swing amplification and orbital diffusion.

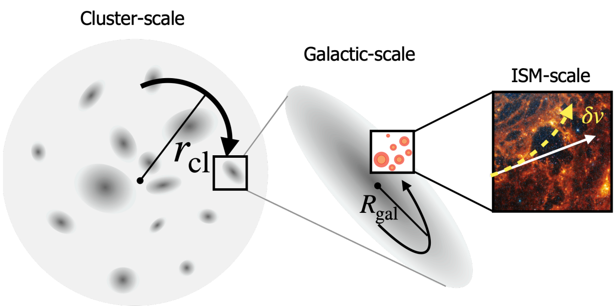
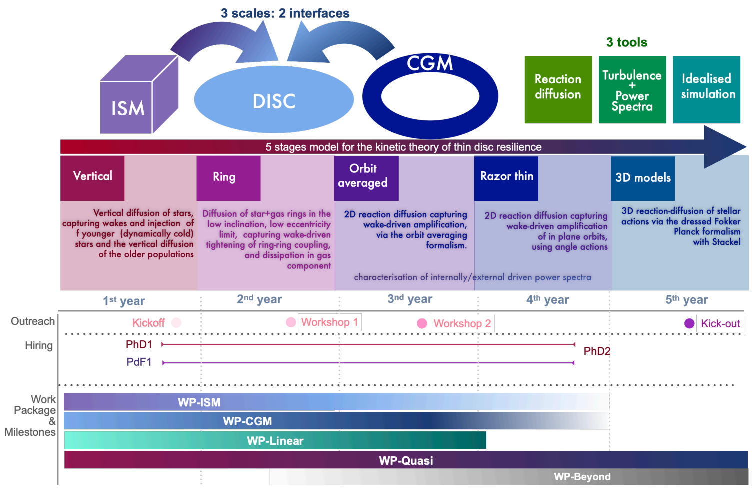


Fig 3: Diffusion coefficients will be computed conditional to a multi-scale environment[44]. Each component contributes to its own power spectrum of fluctuations, which are modulated by the frequencies of the convoluted motion of the stars in the total potential. Jointly with a conditional reaction term, the corresponding reaction-diffusion solution will yield a measure of **morphology** as a function of cosmic environment, in order to debias e.g. intrinsic alignments.

Method: Because the stellar component usually dominates the baryonic mass and gravity is a long-range force, the amplitude of perturbations is typically weak compared to the galaxy's overall gravitational field. This means their statistical impact can be handled perturbatively, which is a theoretical game-changer. This project's key insight is that the model's corresponding master equation can be given as a "dressed" reaction-diffusion equation derived from kinetic theory[5]. Once validated, this equation will be a major break-through in a field that has almost exclusively relied on computationally expensive N-body Monte Carlo simulations to model gravity. It is an essential tool for providing a deeper understanding that N-body simulations alone cannot offer. The core strategy is to shift the narrative from merely simulating observations, to *explaining* why galactic evolution occurs, through analytical insights into self-regulation operating in a distinct regime.

The stationary solutions of the reaction-diffusion equation can be computed explicitly. Consequently, galaxy morphology or metallicity[44] can be predicted conditional to a given environment [fig 3] or redshift, and incorporated into physically motivated bias models (e.g., in the context of the cosmic web, clusters, etc.). This improves the accuracy of standard rulers in cosmology. It also provides a physical model for galaxy bias. By incorporating this physically motivated understanding of how shape and orientation connects to mass and environment, it is for instance possible to generate more accurate corrections for systematic effects in weak lensing data[49]. This leads to more robust and precise cosmological constraints on the nature of dark energy.

Objectives: The goal of *CosmicEmergence* will first be to validate the dressed reaction diffusion framework via idealised models of increasing complexity, relying on the modularity of the perturbative framework:
i) open/closed loop, ii) active/passive potential, iii) with, w/o new stars, iv) with, w/o external noise, v) with different noise power spectra, vi) with w/o gas, vii) assuming infinite/finite resolution, viii) as a local/global model, conditional to larger scale environment (cluster, group, cosmic web), ix) or while varying the adiabatic parameters of the model (Bulge/disc ratio, $M_*/M_{\rm halo}$ etc).



In doing so via a set of work-packages (above), we will investigate the domain of efficiency of the self-regulation and contrast it to the standard paradigm. We will also investigate when it fails, quenching star formation and inducing disruptive morphological transformation. This defines thresholds for unregulated or quenched galaxies,

[5] The secular evolution of stellar discs has been studied for decades through the lens of kinetic theory[93]. Foundational concepts include the heating of the stellar disc and the increase of stellar velocity dispersions over time, driven by scattering off gravitational perturbations like giant molecular clouds[5].These processes are formally described as a form of orbital diffusion. The dressed reaction-diffusion framework proposed in CosmicEmergence is a natural extension of this formalism. The diffusion term in the master equation directly corresponds to the established heating and scattering processes that drive orbital diffusion. The novel reaction term is introduced to model the countervailing processes of gas cooling, accretion, and subsequent star formation, which act to reduce the disc's dynamical temperature. The last crucial physical ingredient is the spontaneous dressing of the equation, which incorporates quadratically the collective gravitational response (the susceptibility) of the disc[97], capturing the secular effect of a series of swing amplified spirals. This self-consistently accounts for how the disc's own self-gravity mediates the interplay between heating (diffusion) and cooling (reaction), allowing for a fully analytical description of the approach to the homeostatic attractor state.

ellipticals, bulges and bars. We will explore the possibility that the two pathways to regulation may not be mutually exclusive but may describe different, complementary phases of a galaxy's life. The bottom-up narrative may explain the *chaotic* early formation of galaxies while the emergent explanation applies to the remarkably ordered nature of the mature, star-forming disks we observe later.

Expected achievements: Within this novel framework, the ANR's postdoc and PhD will also implement these kinetic reaction-diffusion models to predict key observables, which will be compared to the corresponding JWST, Euclid, and LSST data (bar and bulge to disc fractions, scale heights/length, tightness of scaling laws, epoch of disc settling, etc.). They will model galactic systematics across different environments and cosmic epochs, sharpening the distance ladder, and correct for morphological biases in dark energy estimates.

Many components of our model are already validated against simulations with remarkable agreements[100-1] [fig 1]. Thanks to our earlier work on kinetic theory applied to stellar systems, which captured the role of heating via orbital diffusion on discs' secular evolution, we are now in a position to implement open dissipative quasi-linear models to also account for gas cooling, so as to reach a coherent understanding of homeostasis, achieved via gravitational-wake-accelerated feedback loops. CosmicEmergence will capture the evolution of self-gravitating discs as emergent dissipative structures, while accounting for the regulating role of inflowing cold gas[92]. When completed, *CosmicEmergence* will have demonstrated in detail how gravity with baryons provides *top-down causation*, from the cosmic web, via the circumgalactic medium, down to wake-controlled turbulent star formation and feedback in the intra-galactic medium. It will explain the appearance, and most importantly the resilience over cosmic time of such fragile galactic structures. It will also jointly explain why most galactic scaling laws are so tight, thanks to this self-regulation.

Upon completion, *CosmicEmergence* will help the community to move away from a dependence on empirical calibration and towards embracing the physics of complexity. The current practice of using sub-grid models will be superseded by a methodology grounded in *renormalised effective field theory*. We will predict ensemble averages and statistical dispersions using very recent developments in large deviation theory[45], an important capability for interpreting large surveys. This ANR will also address the most pressing questions in galaxy evolution by offering tangible tools to create physically motivated analytic models for galaxy morphology *conditional* to a given environment [fig 3], in order to mitigate systematic biases in large-scale surveys like Euclid and LSST. Beyond astrophysics, it will act as a unique laboratory for studying universal concepts like emergence and self-organisation near a phase transition, maximising its intellectual return.

II. Partenariat (consortium/équipe)

Applicant's skills: The PI, Pichon (70%*), is an expert in theoretical galactic and large-scale structure dynamics[6].

Feasibility, risk assessment and mitigation: *CosmicEmergence* is an exploratory and challenging but feasible, useful and timely project: It involves addressing the central tenet in long-term galactic evolution. We have demonstrated that we have the expertise required to carry out this ANR. This includes i) leadership on the identification of the origin of disc's homeostasis and on the timely techniques needed to model it, starting with Pichon+'06; ii) having pioneered the statistical description of the cosmic environment of galaxies at their interface, first as dark matter flows[2], then as baryonic flows[121-3]; iii) having computed diffusion coefficient of dressed secular equations[33,112,100-1] (iv) having transposed large deviation theory to the realm of kinetic theory[45] and v) having successfully obtained funding for the precursors (Spine & Segal), which led to the intensive numerical[61,4] and analytical[28,35] work that lay foundation for this proposal. We therefore anticipate that funding from the ANR will allow us to meet *CosmicEmergence*'s science goals.

Available resources: The success of this project relies on dedicated manpower, hardware and mobility. Supervision of 1PhD+1Postdoc will provide the synergies within the collaboration. Our access to simulations such as NewHorizon(1,2)/Cluster, HR5, Darwin, is made possible via CoI-ships and, practically, via the PI's management of the infinity cluster. Another PB of storage will be requested via *CosmicEmergence*'s funding, to upload other publicly available simulations, and Monte Carlo our own sets. Conversely, we will also have access to ~10 Mhours of CPU on site, to analyse statistically these simulations and carry out validations of kinetic theories.

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[6] Within the ANR, the joint research activity of PhD (dynamics, 100%*), Fouvry (secular & large deviation theory, 20%*), Leborgne (galaxy formations, 20%*), Rhee (Groups, 20%), Marcos (Kinetic theory,10%), Petersen (linear response 10%), Rozier (time response 10%), Prunet (statistics, 20%), Ko (secular,20%*), Tep (secular theory,10%), Aubert (open self-gravitating systems,10%), Boily (stellar dynamics,10%), Cadiou (CGM science 20%*),Varri (rotation,10%) Weinberg (secular theory, 10%), and Famaey (MOND,10%), focuses on theoretical gravitational dynamics, with a special emphasis on the statistical characterisation of matter. Their expertise will be complemented by PostDoc (ISM + galaxy formation,100%*), Slyz (galaxy formation,10%), Devriendt (CGM,10%), and Kraljic (galaxy evolution,15%)'s expertise in ISM turbulence, and Peirani (baryons,10%), Van den Bosch (galaxy formation,10%), Welker (CGM, 10%), Shin (dwarfs,10%), Dubois (feedback,10%*), Yi (disc settling,10%), Atek (JWST,20%*), Guillard (JWST,20%*) and Laigle (Euclid,20%*)'s knowledge in numerical and observational galaxy formation. [* means at IAP]