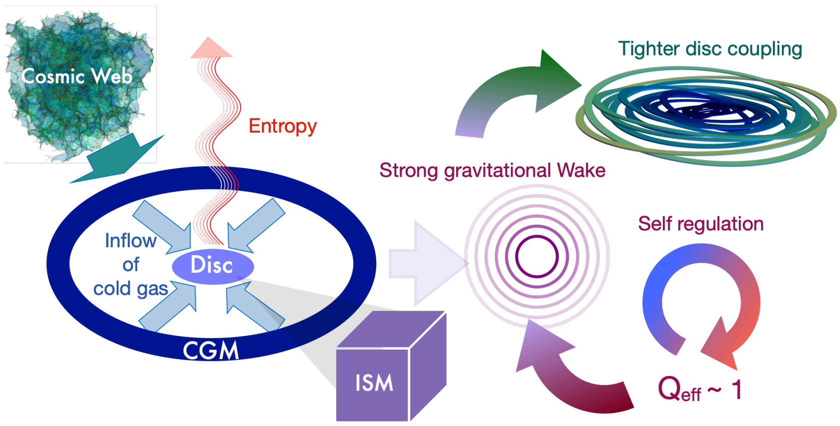
AAPG2025	Emergence	PRC
Coordonné par :	Christophe Pichon	60 mois
Axe G.2: Physique subatomique et astrophysique		

EMERGENCE of galactic scaling laws

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

Galactic discs are currently observed everywhere by the James Web telescope. *But why do such thin discs survive in the concordance model?* This question has long been set aside as an obvious consequence of angular momentum conservation. The true answer is more subtle and enlightening for astronomy. It involves capturing *gravity-driven* baryonic processes operating on multiple scales, working to spontaneously set up a remarkably efficient level of self-regulation. This regulation is responsible for disc resilience & the *tightness of observed scaling laws (Tully-Fisher, radial acceleration relations, etc.).*

An accurate modelling of galactic morphological diversity over cosmic time is critical to achieve high precision on cosmological parameter estimation with galactic surveys such as Euclid & LSST relying on morphology. A key missing piece of our understanding of the universe is the persistence of thin galactic discs and the role it plays in the emergence of tight scaling laws. The operating assumption for their long-term dynamics has been that the Universe reached a quiet period about 10 Gyrs ago. However, the standard cosmological model assumes a perturbed past environment, with traces of significant disturbances found by Gaia within the Milky Way.



The interplay between the three co-evolving galactic components, the ISM, the disc and the CGM (*bottom-left*) sets up an emerging dissipative machine, which, through wakes, achieves both self-regulation and stiffening (*right*). Inflowing cold gas lowers $Q_{eff}=(Q_{gas}^{-1}+Q_{\star}^{-1})^{-1}$, hence triggers wakes, which sources the turbulent cascade in the ISM. The thin disc inherits the coherence of the cosmic web's steadiness (*top left*) through gravitationally driven top-down causation, but the link is not finely tuned, thanks to the co-induced homeostasis towards marginal stability.

This ANR will test whether the tension between both assumptions can be resolved: how can galaxy formation conspire with cosmic flows to set up an efficient self-regulated machine to produce the thin discs that are observed with the James Web Telescope (JWST) at high and low redshifts? What are the implications of such self-regulation on the tightness of observed scaling relations? Why does it matter for morphological survey science?

Thanks to earlier validation of kinetic theory applied to stellar systems, which captured the role of heating via orbital diffusion on discs' secular evolution (Roule+'24, Fig. below), and very recent developments in large deviation theory (Feliachi+'24), 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 (aka thermal regulation), achieved via gravitational-wake-accelerated feedback loops. This ANR will capture the evolution of self-gravitating discs as emergent dissipative structures, while accounting for the regulating role of inflowing cold gas. When completed, the ANR will have demonstrated in detail how gravity with baryons provides top-down causation, from the cosmic web, via the circumgalactic medium (CGM), 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 co-jointly explain why most galactic scaling laws are so tight, thanks to this self-regulation.

Eventually, the success of this ANR will provide means to marginalize over the corresponding biases (e.g. intrinsic scatter, per type of environment) to improve cosmological parameter estimation. As a testbed for the emergence of scaling relations in a simple gravity-dominated context, this investigation will also prove enlightening beyond the scope of galaxy formation. ANR funding is therefore essential to fund a postdoc, a PhD and internships *now*, and organise meetings to support ongoing collaborative works with partner institutes in France (IAP, Strasbourg, Nice) and abroad (Oxford, Yonsei, KASI, Yale, Edinburgh, NY, UMass).

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Context: Most stars are born in galactic discs (Shu+'87) where gravity is the dominant force. Major mergers destroy some of these discs recurrently in the history of the Universe (White+'91), but some have survived until today, including our own Milky Way. Understanding the long-term survival of these discs is therefore an essential ingredient of modern cosmology, in order to account for the cosmic evolution of morphological diversity. The epoch of cosmic disc settling, a few Gyrs ago, allows secular, hence resonant processes to take over to define the morphology of galaxies. Discs are old, yet star forming and dynamically cold, and therefore fragile systems, for which rotation provides an important reservoir of free energy, and where orbital resonances and wakes play a key role (Goldreich+'78). The availability of this free energy leads to a strong amplification of certain stimuli, with the net result that even small disturbances (internal and external, Fouvry+'17) can lead to discs rapidly self-regulating. Such level of self-regulation can be quantified thanks to recent advances in large deviation theory (Feliachi+24) which allows us to predict, within the context of kinetic theory, the expected variance in the statistical properties of galactic discs.

Galactic discs are immersed in various sources of perturbations and inflow. EMERGENCE will show that these processes, which in isolation would have a destructive impact on thin discs, in fact *conspire* to maintain their responsiveness. The emergence —broadly defined as the *"arising of novel and coherent features through self-organisation in complex systems*"— of an improbable ordered structure (a massive yet thin disc) is indeed paradoxically made possible by shocks and turbulence induced in the sub dominant gaseous component, which can radiate most of the entropy generated from the CGM, acting as an open reservoir of free rotational energy. The interplay between gravity and baryonic physics set up a self-regulating loop near marginal stability, whose efficiency increases with cosmic time: the thinner the disc, the more self-regulated; the tighter the internal coupling, the thinner the disc. This spontaneously emerging self-regulation in turn tightens most galactic scaling laws, as it **glues** baryonic properties of the galaxies (sSFR, metallicity, stellar surface density etc.) to their dynamical properties (halo mass, angular momentum distribution etc.). Such a framework therefore naturally explains the induced emergence of tight scaling relations.

Accounting for this self-regulation will be the core science of EMERGENCE. It will make clear predictions on the disc settling epoch (vz Galactic archaeology, e.g. Belokurov+'22). It will also explain *why* and *how* galactic discs conspire to sustain this unlikely state, and what are the corresponding *observational signatures* (as recently seen e.g. by JWST).

What?	Galactic diversity as an emerging process: gravity driven wakes and cosmic inflow drives self-regulation.
Why?	Account for the resilience of discs for a Hubble time, and understand the emergence of tight scaling laws.
Why now?	Euclid and LSST require debiasing. Large deviation theory provides **now** means to achieve this critical step.
How?	Quasi-linear theory of multi-component galaxies, accounting for self-regulated cooling & heating processes.

Method: EMERGENCE will rely on the conjunction of analytic and numerical methods —calculation of linear response operators, stochastic and finite element implementation of sourced and self-regulated quasi-linear equations— and the analysis of dedicated ensemble of numerical simulations to i) quantify statistically the cosmic environment ii) validate the parametrisation of cooling and heating and iii) quantify the mean and variance of the corresponding observables. The perturbations' environmental properties will be tabulated over the three relevant scales (a) circumgalactic medium, (b) disc and (c) interstellar medium (ISM). EMERGENCE will then carry out a secular analysis of disc growth and resilience, solving for the set of partial differential equations capturing the homeostasis of the disc. It will explain why self-regulation operates preferably around marginal stability, i.e. why a large gravitational susceptibility is a critical ingredient, together with free energy flowing from the angular momentum stored in the CGM. Having parametrised the source term, we will then study orbit production and diffusion via steps of increasing complexity/realism/risk. Large deviation theory will be implemented to quantify how cooling, which leads to self-regulation, tightens the dispersions. We will finally compare our kinetic estimates of the system's global secular response to observed scaling laws (radial acceleration relations (RAR), baryonic Tully-Fisher (TF), Kennicutt-Schmidt (KS), etc) and cosmological simulations. This will prove enlightening as an archetype of emergent tight scaling relations that can be analysed in detail, while also explaining galactic morphological diversity.

The *key* methodological ingredients will be to i) parametrise a *source* term in the kinetic equations to account jointly for cooling and heating; ii) to model the disc's self-gravity and the inflow of free energy, so as to model *statistically* its self-regulated secular evolution as a multi-component, dissipative system; iii) to compute the net expected **dispersion** above and below the mean kinetic prediction.

Goals and milestones: EMERGENCE's primary scientific goals are:

1. To demonstrate how the appearance of an ordered thin disc within a stochastic environment seems paradoxically made possible by shocks and turbulence triggered by star formation and supernova explosions, thanks to self-regulation.
2. To develop the theoretical models and the computational algorithms to follow the thinning of discs over cosmic (secular) times, using extended kinetic theories (open, dissipative, large deviation) via a parametric model.
3. To cast results in terms of observables (scaling laws and dispersions of metallicity-kinematic relation or RAR, TF, KS, bar/bulge fraction, etc) tailored to existing and upcoming facilities.

To achieve these goals, we will aim for a set of milestones and work-packages (WPs) to reach our final goal:
+**WP:CGM**: Quantify and model the statistics of potential fluctuation in the CGM, and the variation of inflow that the disc's homeostasis can tolerate before the disc becomes unstable. Estimate the maximum rate of entropy production allowed by the configuration. [CC,CW,JS,CP,SR,EK] Deliverables: inflow rates and power-spectra per process (SN, turbulence, etc..).
+**WP:ISM**: Carry out a multi-scale analysis of turbulence within simulations of ISM, with/without gravitational forcing on larger scales. Quantify how self-organised criticality describes the impact of marginal stability on star formation, and how star formation efficiency is controlled by the larger injection scale. [AS,JD,JS,YD,KK,Postdoc] Deliverables: calibrated star production rate via a logistic map; feedback driven power spectra of potential fluctuations.
+**WP:Open-Quasi**: Extend Fouvry+'17-24 on the secular (dressed Fokker-Planck (FP), resp. Balescu-Lenard, BL) resonant evolution of self-gravitating discs, while accounting for inflow, following four steps of increasing complexity: i) local vertical analysis; ii) a Laplace-Lagrange model of coupled rings iii) a dressed open FP and iv) dressed BL multi-component formulation. Understand how the disc settles, reflecting the modulation of both orbital diffusion and star formation by the same confounding factor: proximity to marginal stability. [CP,DA,MP,KT,SY] Deliverables: thick/thin disc fraction;
+**WP:Scaling**: Quantify the expected tightening of dispersion on observables derived from large deviation estimates, thanks to the induced level of self-regulation.[CP,JBF,KT,FVdB,BF,PhD] Deliverables: scaling laws per environment.
+**WP:Exit**: Quantify when self-regulation breaks downs, leading to compaction/instabilities. Understand when it completely fails, and how this breakdown depends on merger rates or quenching of cold gas, triggering abrupt corrections that self-regulation cannot handle. [MW,CB,BF,S,ALV] Deliverables: disc/spheroid, bar/warp fraction & evolution.

After the completion of these interconnected WPs, i) the link between the emergence of galactic morphology and the tightness of galactic scaling relations will be predictable, to be marginalised over, so as to de-bias large scale structure surveys; ii): we will understand theoretically how maximum entropy production in dissipative systems selects stability thresholds.

II. Partenariat (consortium ou équipe)

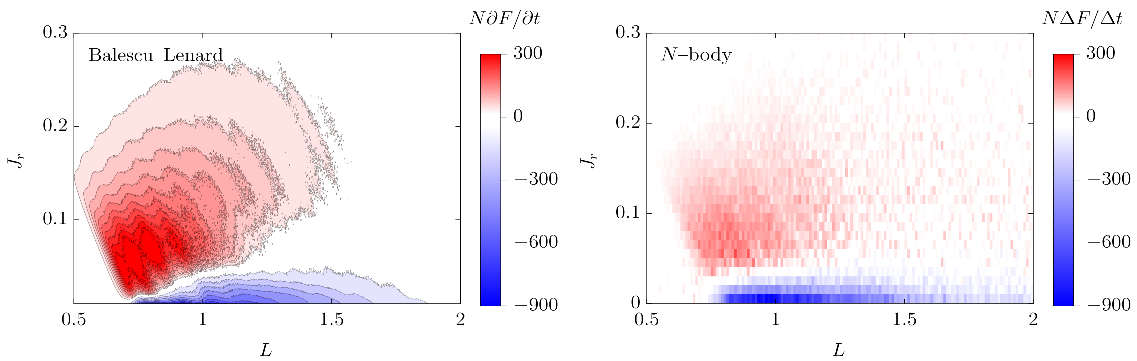
Applicant's skills: The PI, Pichon ([CP]60% ETPR), is an expert in theoretical galactic and large-scale structure dynamics. The joint research activity of **PhD** (dynamics, 100% ETPR), Fouvry (secular & large deviation theory,[JBF]20% ETPR), Marcos (Kinetic theory Col, [BM]30% ETPR), Petersen (linear response [MP]10% ETPR), Rozier (time response [SR]10% ETPR), Prunet (statistics, [SP]20% ETPR), Ko (secular,[EK]20% ETPR), Tep (secular theory,[KT]10% ETPR), Aubert (open self-gravitating systems, [DA]10% ETPR), Boily (stellar dynamics, [CB]10% ETPR), Cadiou (CGM science [CC] 15% ETPR), Varri (rotation [ALV] 10% ETPR) Weinberg (secular theory [MW]10% ETPR), and Famey (MOND, [BF]10% ETPR), 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% ETPR), Slyz (galaxy formation [AS]10% ETPR), Devriendt (CGM, [JD]10% ETPR), Renaud (ISM, [FR]10% ETPR), and Kraljic (Col, galaxy evolution [KK]25% ETPR)'s expertise in ISM turbulence, and Peirani (baryons, [SP]10% ETPR), Van den Bosch (galaxy formation [FVdB]10% ETPR), Welker (CGM [CW]10% ETPR), Shin (dwarfs, [JS]10% ETPR), Dubois (feedback, [YD]10% ETPR), Yi's (disc settling, [SY]10% ETPR), Atek (JWST, [HA], 5% ETPR) and Laigle (Euclid [CL] 5% ETPR)'s knowledge in numerical and observational galaxy formation. Our collaborations led us to explore various topics, such as the dynamics of the large-scale structure, the intergalactic and interstellar media and the secular dynamics of galaxies and black holes. We have promoted novel tools and theories to trace and understand galaxies in simulations and observations to carry through the main goal of this ANR.

Timeliness and importance: Our community has invested significant observational resources to understand the evolution of galaxies over a Hubble time, both for its own sake (e.g. explaining the ubiquity of discs across redshifts, or understand the tightness of scaling laws, without reference to MOND) and for the purpose of correcting biases in cosmological surveys. Classical cosmological hydrodynamical simulations are of course heavily funded throughout. Conversely, we specifically need the ANR to invest now in sourced quasi-linear theory, a distinct yet solid (tailored to the perturbative regime, therefore more carbon-efficient per ensemble average of simulations) alternative to address key challenges of the concordance model. We have demonstrated leadership in promoting and validating such approaches in specific contexts where the impact of baryons can be ignored (*e.g.* heating in nuclear and globular clusters, or pure stellar discs). It is now time to address upfront the more generic *and fruitful situation* where the inflowing baryons play a catalytic role to set up and self-regulate disc growth. We must in particular make use of very recent breakthroughs in large deviation theory (which predict the variation of observables, sourced by the competition between heating and cooling processes) to *explain* the tightness of the corresponding observed scaling relations (TF, RAR, KS).

Feasibility, risk assessment and mitigation: EMERGENCE 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 (e.g. Aubert+'04), then as baryonic flows (e.g. Kimm+'11, Welker+'15); iii) having computed diffusion coefficient of dressed secular equations (Fouvry+'15, 20, 21, Hamilton+'18, Pichon'19, Tep+'21,23, Roule+'22,24); iv) having transposed large deviation theory to the realm of kinetic theory (Feliachi+24) and v) having successfully obtained funding for the precursors (SPINE & Segal), which led to the intensive numerical (Dubois+'14,17) and analytical (Fouvry+'15-24) work that lay foundation for this proposal. We therefore anticipate that funding from the ANR will allow us to meet EMERGENCE's science goals.

Available resources: The success of this project relies on dedicated manpower, hardware and mobility. Supervision of PhD+Postdoc 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 EMERGENCE'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 implementation and validations of kinetic theories.

III. Bibliographie



Left: predictions of the mean-field changes, $\partial F/\partial t$, from kinetic equations for the long-term evolution of the Toomre disc in action space. *Right*: Average flux over 100 realisations (Roule+'24). The agreement in this shot noise-driven regime is remarquable. *EMERGENCE* will now account for a) external heating (SN, turbulence, mergers), b) cooling (SF), c) self-regulation & d) expected variations beyond the mean.

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