ERC Advanced Grant 2023: Research proposal: Part B1

Order out of chaos: explaining the emergence and secular resilience of thin galactic discs

- *Acronym*: *CosmicEmergence*
- *Name of the Principal Investigator (PI)*: Christophe Pichon
- *Name of the PI's host institution for the project*: CNRS (Institut d'Astrophysique de Paris)
- *Proposal duration in months*: 60

An accurate *modelling of galactic morphological diversity over cosmic time is critical* to achieve high precision on cosmological parameter estimation with galactic surveys. A key missing piece of our understanding of the universe is the persistence of thin galactic discs. The operating assumption for their long-term dynamics has been that the Universe reached a quiet period about 10 Gyrs ago. Conversely, the standard cosmological model assumes a perturbed past environment, with traces of significant disturbances, e.g., found by Gaia within our own Milky Way. *CosmicEmergence* will test whether the tension between both assumptions can be resolved: how can galaxy formation conspire with cosmic flows to set up an efficient homeostatic[1] machine to produce the thin discs observed by JWST at high and low redshift?

Thanks to my earlier work on kinetic theory applied to collisionless systems, which captured the role of orbital diffusion on secular evolution, I am now in a position to implement *open dissipative* quasi-linear models to achieve a full understanding of homeostasis, likely achieved via gravitational-wake-accelerated feedback loops. These models will capture the orbital diffusion of self-gravitating discs as *emergent* dissipative structures, while simultaneously accounting for the regulating role of inflowing cold gas. When completed, *CosmicEmergence* will have *demonstrated* in detail how gravity 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. We will explain the appearance, and most importantly the resilience over cosmic time of such fragile galactic structures within the Hubble sequence. Our methodology will complement and enlighten standard numerical approaches.

As a *testbed for the emergence* of a scaling relation in a simple gravity-dominated context, *CosmicEmergence* will also prove enlightening for other astrophysical problems beyond the scope of galaxy formation, or, indeed, beyond astrophysics.

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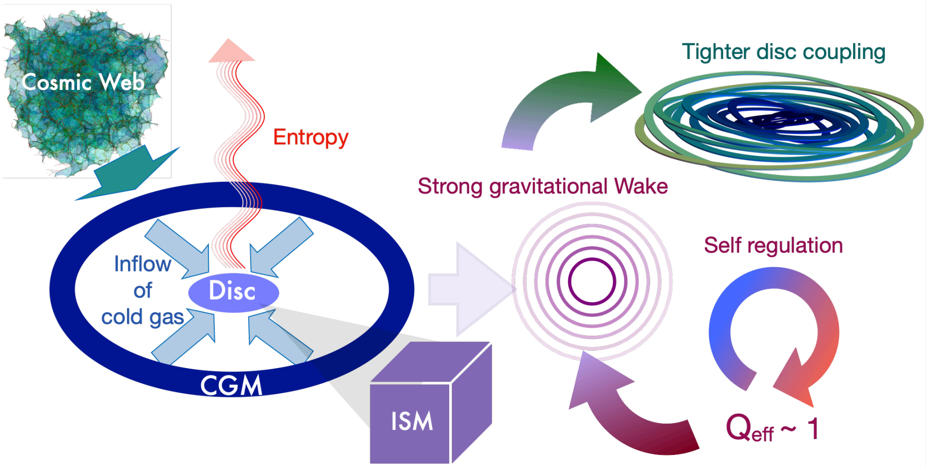
[1] The biologist Claude Bernard coined the concept in 1865 (from the Greek homoios, “similar,” and histemi, “standing still”), as the capacity of systems to maintain a stable, functionally adequate “internal milieu” through some mechanism of regulation.

Section a: Extended Synopsis

Galactic discs are observed everywhere by JWST. *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 *and* theoretical physics. It involves capturing gravity-driven baryonic processes operating on multiple scales, working to spontaneously set up a remarkably effective level of self-regulation, **whose robustness needs to be assessed now!**

CosmicEmergence will rely on the conjunction of analytic and numerical methods —calculation of linear response operators, finite element implementation of sourced and self-regulated quasi-linear equations— and the analysis of dedicated numerical simulations to quantify statistically the cosmic environment and validate the logistic parametrisation of feedback and star formation. The perturbations' environmental properties will be tabulated over the three relevant scales (a) circumgalactic medium (CGM), (b) disc and (c) interstellar medium (ISM), thanks to the production of suites of zoom-in simulations customised to each scales' boundaries.



Synopsis: The interplay between 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 Toomre $Q_{\rm eff}=(Q_{\rm gas}^{-1}+Q_{*}^{-1})^{-1}$, 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.

CosmicEmergence will then carry out a vertical analysis of disc growth and resilience, and identify the set of partial differential equations capturing the homeostasis of the disc. We will explain why self-regulation operates preferably around marginal stability, i.e. why a diverging gravitational susceptibility is a critical ingredient, together with free energy flowing from the angular momentum stored in the CGM. Having parametrised the source term via a logistic map, we will then implement the orbital diffusion via steps of increasing complexity/realism/risk. We will finally compare our kinetic estimates of the system's global secular response to cosmological simulations and observations. This will prove enlightening as an archetype of an emergent scaling relation, that can be analysed in details to quantify galactic morphological diversity.

Context: Most stars are born in galactic discs (Shu+'87). Major mergers destroy some of these discs recurrently in the history of the Universe (White+'91), but some have survived until today (see Fig 1), including our own Milky Way (MW). *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 convergence of the thickness of discs (thin and thick) in our galaxy is also a dynamical problem that has recently been revived in the light of the APOGEE and Gaia surveys (Prusti+'16). Star formation generally occurs on the circular (non-intersecting) orbits of the gas, so young stars typically form a very thin disc. However, chemo-dynamic observations of external galaxies have all shown that thick discs are very common (Gilmore+94). The simultaneous

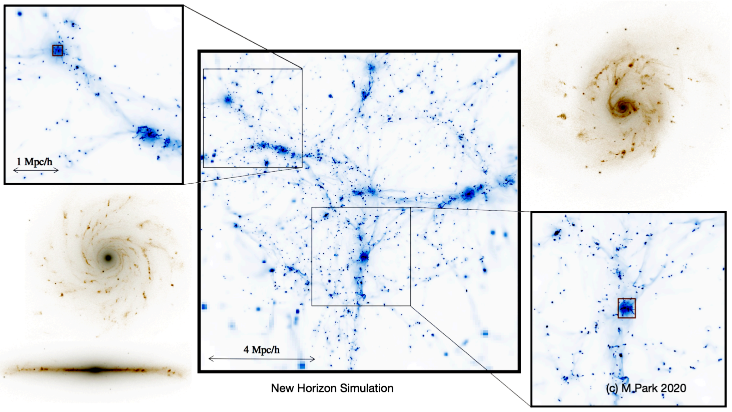


Fig.1: Simulations such as *NewHorizon (Park+'20)* are recently reproducing the formation of razor-thin discs in a full cosmological setting. These thin discs surprisingly survive down to redshift zero, given our choice of star formation and feedback. This program will model the driving process which produces these unlikely thin structures using *extended kinetic theory*. It will explain how convergence towards marginal stability operates via *wakes*, implying shorter dynamical times, hence a tighter control loop, and stiffer discs.

formation of thin and thick discs is therefore *an important puzzle for the theory of galaxy formation*.

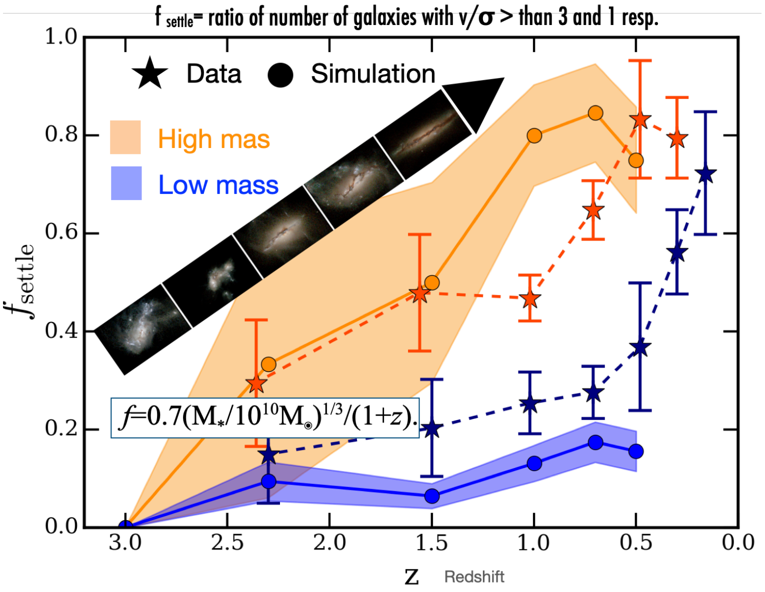


Fig 2: Settled disc fraction (measured from the Sins survey (Cresci+'9) and galaxies in *NewHorizon)* as a function of both mass and redshift. More evolved (or more massive) galaxies have settled into thin discs. This evolution is the observational counterpart to Toomre's $Q=\kappa\sigma/3.36\Sigma$ convergence towards one, which *Cosmic-Emergence* will explain.

Various dynamical mechanisms, internal or external, have been proposed to explain the observed thickening (Paczyńsky +'80) and rejuvenation, but their respective roles remain to be quantified. 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, cold and therefore fragile dynamical systems for which rotation provides an important reservoir of free energy, and where orbital resonances and wakes[2] 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 a small disturbance can lead to discs evolving towards a sequence of substantially distinct quasi-equilibria. Since discs are furthermore immersed in various sources of perturbations, their cosmic history must therefore include the common responses to all these stimuli (internal *and* external, Fouvry+'17).

CosmicEmergence will show that many of these processes, which in isolation would have a destructive impact on thin discs, in fact must *conspire* to limit the extent to which discs can grow vertically. 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 thin disc) is indeed paradoxically made possible by shocks and turbulence induced in the gaseous component, which can radiate most of the entropy generated from the open reservoir of free energy. They 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 (Fig 3).

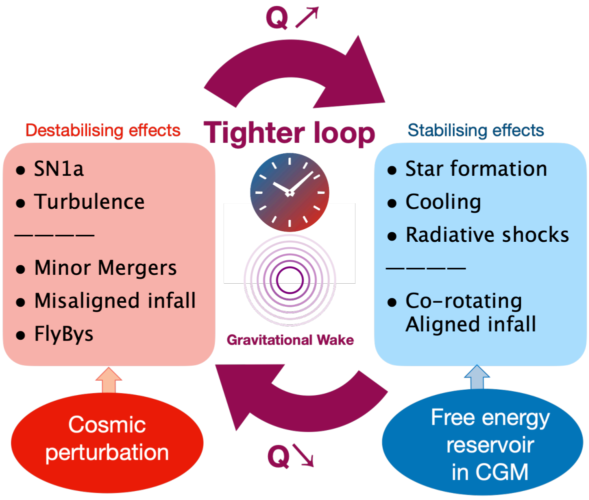


Fig 3: the control loop. In the secular regime, all perturbations generate strong wakes, shortening significantly the effective dynamical time. The induced tighter control loop drives Toomre's effective Q closer to 1, allowing for disc settling. It is an attractor because wakes yield a faster control loop for self-regulating processes (turbulence, supernovae, star formation), and efficient entropy radiation. The tightness of this loop is controlled by the amplitude of the fluctuating gravitational potential. This allows the disc to generate order through self-organisation.

Thin galactic discs are therefore the result of a homeostatic process emerging spontaneously from the hierarchical structure formation scenario. It is *remarkable* that stellar discs embedded in a stochastic environment can in fact get thinner with time, through locally gas-driven and wake-amplified self-regulation, in contrast to the standard expectation for collisionless systems. *CosmicEmergence* is uniquely well positioned to explain and model how this self-regulation accounts for the observed paradoxical behaviour: various processes which have typically only been described in isolation (angular momentum advection along cold flows, gravitational wakes, star formation, feedback, turbulence) *truly operate in a novel, non-linearly coupled manner when accounted for jointly* (Fig 3). While the resilience of thin galactic discs across cosmic time has been vindicated by

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[2] Perturbations in cold discs trigger strong gravitational deflections: they are effectively "*dressed"* by the disc's gravitational response: the wake, which qualitatively "pulls" stars which are orbiting out of plane back to the disc, increasing its internal coherence.

recent observations of JWST, and *seems* to occur generically in sufficiently resolved hydrodynamical zoom-in simulations, it was only very recently measured statistically that disc settling correlates with convergence towards Toomre's $Q_{\rm eff}\sim1$ (Toomre'81, e.g. within the unbiased sample of *NewHorizon* galaxies, Figs 1, 2). In turn this leads us to question how self-regulation operates, and why wakes, free energy dissipation and infall are *jointly* necessary ingredients to induce self-regulation near marginal stability. Having identified the relevant ingredients and their relationships, it is *now* of prime interest to re-analyse and theoretically understand hydro-dynamical simulations within that framework, focusing specifically on e.g. the strength of the wakes, the rate of orbital diffusion and turbulent energy cascades, etc. This will be the core science of *CosmicEmergence*. In short, my strategy will be:

What?	Galactic diversity as an emerging process: wakes and cosmic inflow drives self-regulation.
Why?	To account for the resilience of discs within the Hubble sequence and for a Hubble time, and understand the respective roles of the circumgalactic reservoir and intra-galactic dissipation on disc homeostasis.
Why me?	Unique *demonstrated* dual expertise of circumgalactic cosmic web dynamics, and open, rotating, self-gravitating quasi-linear systems, developed to answer the *very question* addressed by this proposal.
Why now?	The pieces of the puzzle (wake-controlled feedback) are finally falling into place; theory can now be put to the test against observations (JWST, Gaia) and simulations. It is critical for morphological diversity.
How?	Quasi-linear theory of a multi-component (incl. dissipative) galaxy. Explicit integration of feedback and star formation regulation via a logistic term. Link to maximum entropy production, energy cascading and self-organised criticality near marginal stability.

Method: Since the seminal works of Einstein (1905) and Perrin (1912), physicists have understood in the context of kinetic theory how ink slowly diffuses in a glass of water. The fluctuations of the stochastic forces acting on water molecules drive the diffusion of the ink in the fluid. This is the archetype of a process described by the fluctuation-dissipation theorem, which universally relates the *rate of diffusion to the power spectrum of the fluctuating forces*. For stars in galactic discs evolving over secular timescales, a similar process occurs, with three significant extensions: (i) for their orbital parameters to diffuse effectively, stars need to *resonate*, i.e. present commensurable frequencies to the perturbations; (ii) the amplitudes of the induced fluctuating forces are significantly *boosted* by collective effects, i.e. by the fact that, because of self-gravity, each perturbation generates a wake in its neighbours; (iii) new stars are produced continuously from the cold dissipative and turbulent inflowing gas, with an efficiency also regulated by the strength of wakes.

CosmicEmergence will study the resilience of thin galactic discs, relying on such extended kinetic theory, while further considering new sources of astrophysical fluctuations – both external (cold angular-momentum-rich gas inflow, flybys) *and* internal (star formation, SN feedback). The *key* methodological ingredients will be to i) parametrise a logistic (i.e. linear+quadratic) *source* term on the kinetic equations to account for star formation and feedback; ii) to properly account for the self-gravity of the centrifugally supported galactic disc and the inflow of free energy, so as to model *statistically* its secular evolution as a multi-component, dissipative system.

As an alternative to classical N-body/hydrodynamical approaches, which model given realisations, *CosmicEmergence* will propagate *statistics* of fluctuations top-down, from the cosmic web down to the interstellar medium (ISM) scales, while accounting for the self-regulating role of the dissipative inflow. Methodologically, such a kinetic formulation complements and challenges direct numerical methods, with the added value of *analytical insight*, *flexibility*, *universality* and *orders-of-magnitude* longer time steps (one 'particle' is one orbit, one 'interaction' is a full swing-amplified spiral sequence, where the impact of stochastic forces is encoded in the orbit-averaged power-spectra). Flexibility is achieved because the kinetic formulation includes explicit gravitational amplification and sourcing from the state-of-the-art linear and quasi-linear response theory, so that we can explore the effect of one ingredient at a time (e.g. vary the efficiency of star formation/feedback, switch off self-gravity, include swing amplification, etc.). The kinetic formulation also complements cosmological codes because it makes very different compromises in variance, bias, accuracy and efficiency. Recently demonstrated[3] convergence between the two methods provides solid ground for confidence in the robustness of the (ensemble average) sought solutions.

Goals and milestones: *CosmicEmergence's primary scientific goals are:*

1. To demonstrate how the appearance of an ordered thin disc within a stochastic environment is made possible by shocks and turbulence triggered by star formation and supernova explosions. As an open

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[3] Since the proposal was first submitted, we have published several papers (e.g. Fouvry+'20,21,22, Tep+'22, Giral+'21, Roule+'22) *demonstrating* how kinetic theory remarkably captures up to 95% of the *average* secular response of N-body systems (galactic centres, discs, globular clusters).

dissipative machine, the disc taps free energy from the circumgalactic medium, and radiates most of the generated entropy; it sets up an ever tighter self-regulating loop, operating in the vicinity of the disc's stability threshold, where secular times are (quadratically) shortened by tides.

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, multi-species, dissipative) via a parametric model for stellar injection; this will involve computing the relevant power spectra capturing fluctuations and fluxes at the two boundaries (ISM-disc, disc-CGM) and solving the induced sourced kinetic equations using stochastic differential equations (SDE) and finite element methods (FEM), to identify the asymptotic scaling relations (geometry of discs, bar/bulge fraction versus cosmic time etc).
3. To cast results in terms of observables[4], tailored to existing and future facilities, in order to guide the interpretation of datasets, and propose observational diagnostics to test theoretical predictions (metallicity-kinematic relation, radial profile of vertical velocity dispersion, bar/bulge fraction, etc).

To achieve these goals we will aim for this set of milestones and work packages:
WP-CGM: Quantify the statistics of 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 (in a steady state, all the extra free energy acquired by the disc from the CGM needs to be radiated away). Beyond this threshold, quantify how the disc chooses another path to sustain the stress imposed by its environment and redistribute the excess of angular momentum (via bar formation/radial transport of mass and angular momentum). *Deliverables*: inflow rates and power-spectra.
WP-ISM: Carry out a sub-parsec scale analysis of turbulence within simulated slabs of ISM with/without gravitational forcing on larger scales. Quantify how self-organised criticality describes the impact of Q on star formation and how star formation is controlled by the larger injection scale. *Deliverables*: calibrated star production rate via a logistic map; power spectra of potential fluctuations within the ISM.
WP-Linear: Build thick disc and spheroid bi-orthogonal bases; compute their linear-response matrix and the corresponding damped modes as a function of rotation rate. *Deliverables*: thick disc linear-response framework; bi-orthogonal bases; damped modes.
WP-Quasi: Extend Fouvry+'17-23 on the secular (dressed Fokker-Planck (FP), resp. Balescu-Lenard, BL) resonant thickening of self-gravitating discs, first with the logistic source term, and then while lifting the tightly wound limit, following four steps of increasing complexity/realism/risk: i) a strictly local vertical analysis; ii) a Laplace-Lagrange model of sets of coupled rings (linearised as a first step) iii) a dressed open FP formulation; iv) a dressed BL multi-component formulation. In the FP analysis, the disc's environment will be described as induced by external (fixed) perturbations, while in the BL, as a multiple component system. Understand how the disc settles, reflecting the modulation of both orbital diffusion and star formation by the same confounding factor: the proximity of galaxies to marginal stability. *Deliverables*: thick/thin disc fraction; diffusion timescales.
WP-Exit: Quantify when self-regulation breaks downs leading to compaction/instabilities. Understand when regulation *completely* fails and how this breakdown depends on merger rates or quenching of cold gas, triggering abrupt corrections that self-regulation cannot handle. More generally, characterise the qualitative difference in the secular evolution of open/closed, rotating/non-rotating, 1D,2D,3D systems, with/without dissipation. Eventually, stepping out of the specificities of self-gravitating discs, understand how the maximum entropy production principle in multiple component dissipative systems should be viewed as a process which selects stability thresholds and develops self-regulating loops around them via scaling relations (such as Tully Fisher's). *Deliverables*: disc/spheroid + bar/warp fraction & evolution;

Feasibility, risk assessment and mitigation: *CosmicEmergence* is an exploratory and challenging but *feasible* project: it involves addressing a central tenet in long-term galactic evolution, using novel theoretical and numerical developments involving kinetic theory and stochastic methods. These methods have recently been proven to complement, or indeed in some cases rival (as they predict statistical expectations) the well-established N-body methods. Gravitational dynamics, the PI's strong suit, remains the driving force, setting the pace for other processes. The main idea is that wakes are strong in dissipative centrifugally supported systems (linearly Toomre'81, and secularly Fouvry+'15). We have *demonstrated* via a series of forerunner papers that we have the expertise required to carry out this programme. This includes i) scientific leadership on the identification of the origin of disc 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 and validated the drift and diffusion coefficient of dressed secular equations (Fouvry+'15, 20, 21, Hamilton+'18, Tep+'21, Roule+'22); and iv) having successfully obtained the highly competitive French ANR research council funding (with pressure factors of 12) for the

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[4] Indeed, kinetic theory predicts the time evolution of the system's DF: any observable follows by taking its moments (e.g. velocity dispersions). Analysing critical thresholds corresponding to when self-regulation fails also provides threshold for the survival of discs and the build-up of spheroids.

precursor high-risk high-gain projects (Spine & Segal), which led to the intensive numerical (Dubois+'14,17) and analytical (Fouvry+'15-21) work that lay foundation for this proposal; v) having supervised and trained students and postdocs around this topic: many have tenure track or permanent positions in astrophysics (Fouvry, Laigle, Codis, Aubert, Ocvirk, Sousbie, Kimm, Dubois, Uhlemann, Musso, Chisari, Shin, Hwang, Song). Several are now leaders in the production of the corresponding state-of-the-art numerical simulations. In order to mitigate risks, we will invite D. Pogosyan, an expert on ISM turbulence and cosmic web dynamics for a 9 months sabbatical; we will continue to work in close connection with former students, postdocs and collaborators (Devriendt, Dubois, Famaey, Kraljic, De Rijcke, Rosier, Peirani, Yi, Heggie, Varri, Hamilton, Kaviraj, Weinberg, Petersen, Slyz, Tagger, Tep, Roule, Cadiou, Magorrian), and contact other experts beyond our own expertise (e.g., Lazarian, Hennebelle, Krumholz on turbulent star formation).

Since most work packages are independent, we do not expect any critical stumbling blocks. Many milestones are worthwhile in their own right (e.g. the linear response of rotating spheroids, extended kinetic theory of self-gravitating multi-component rotating systems). Extended kinetic theory has already recently proven effective in explaining the origin of ridges in action space in isolated galactic discs, and the behaviour of stars near our Galaxy's massive black hole. We therefore anticipate that the 19 FTE (3PhDs 2 Postdocs) we request will allow us to meet *CosmicEmergence's* targets within 5 years.

Timeliness and importance: Our community invests significant observational resources[5] to understand the evolution of galaxies over a Hubble time, both for its own sake (e.g. explaining the ubiquity of discs across redshift) and for the purpose of correcting biasses in cosmological surveys. Classical cosmological hydrodynamical simulations are of course heavily funded throughout[6]. Conversely, we *specifically need the ERC* to invest *now* in quasi-linear theory, a distinct yet solid 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. galactic centres). It is therefore high time to address upfront the more generic situation where the *inflowing baryons play a catalytic role* to set up and self-regulate disc growth (and more generally many observed scaling relations). From a technical perspective, the timing is optimal: cosmological hydrodynamical simulations now finally reach sub-galactic scales (in the '00s, cell resolution typically reached the Virial radius; in the '10s, the disc scale length, and in the '20s, the disc scale height: the realm of dissipative secular dynamics). However, these ultra-high resolution simulations are typically sparse, involving partially ad-hoc (sub-grid) parametrisation, with many entangled strongly stochastic processes, often failing to reproduce secular features (such as galactic bars, Reddish+'21). Their analyses must therefore be *enlightened by modular kinetic theory,* capturing explicitly the specific long-term effect of non-linear resonant mode coupling as ensemble averages, to provide in-depth understanding of the synergy between the relevant physical mechanisms leading to thin disc resilience. Strategically, this ERC programme stands neatly at the tipping edges of past projects, resp. on the role of the cosmic web in establishing the Hubble sequence on the one hand (spine), and the quasi-linear theory on the other hand, as a versatile toolbox to describe the long term evolution of collisionless systems (segal).

Perspectives: With the release of Gaia's data, a detailed theoretical modelling of the long-term evolution of the MW's internal structure is in order. *CosmicEmergence* will make clear predictions on its disc settling epoch (to be compared to Galactic archeology of e.g. Belokurov+'22). The comparison of simulations and kinetic theory to observations on secular timescales is now also of prime importance for existing and upcoming cosmological surveys, which rely heavily on *modelling the physics of galaxies to construct mock surveys*. Eventually, for the benefit of astronomy at large, it will also therefore be most important to predict the morphological properties of galaxy *populations*, and confront them against simulations and surveys (e.g. Euclid or 4MOST). *CosmicEmergence* will achieve this. While emergence has a strong history e.g. in chemistry and biology, it was less commonly identified in astronomy. *CosmicEmergence* will show that disc settling involves fairly simple processes, so that the onset of resilience can be analysed in details. *No fine tuning* is required: homeostasis operates within some range of sub-grid physics, because the key ingredients (self-regulated feedback loop and sustained reservoir of free energy) are both provided by gravity, through wakes and cosmic voids *resp*. This is an example of top-down causation, where the tiny galactic disc effectively inherits its resilience from the stability of large scale tides, via some non-trivial, yet tractable machinery, producing unexpected scaling relations. As a testbed for emergence in a simple gravity-dominated context, funding from the ERC will therefore provide a workable framework to model self-organised criticality and homeostasis, relying on novel, yet validated extensions of kinetic theory. Such a framework could also be used to explain the emergence of other scaling relations in galactic physics (e.g. baryonic Tully Fisher, Kennicutt Schmidt), or indeed *beyond the scope* of astrophysics!

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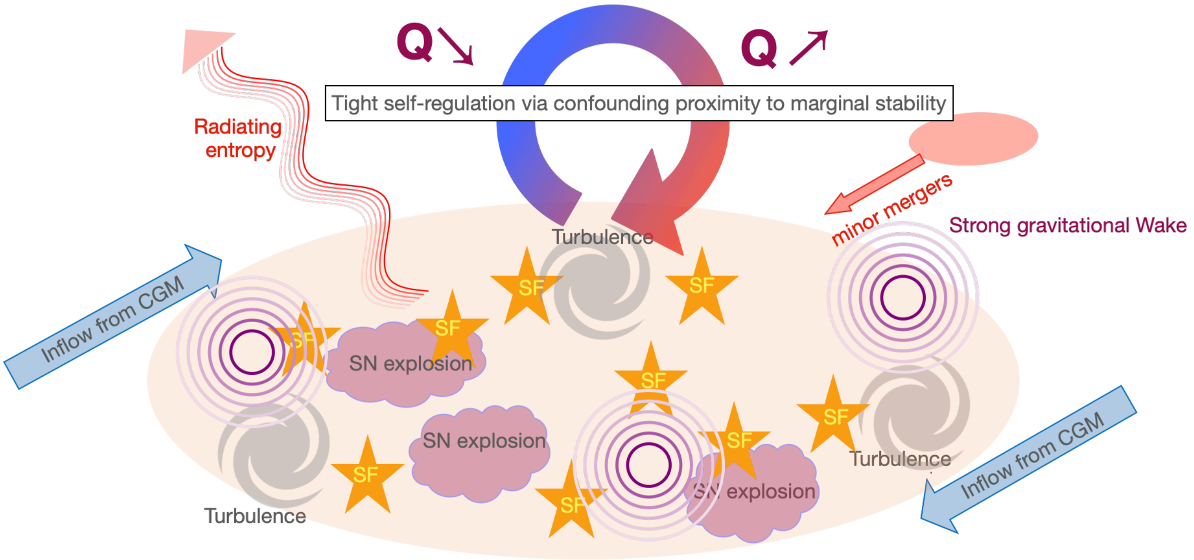
[5] existing: *SDSS, MUSE, SAMI, MANGA, COSMOS, CLAMATO, CALIFA, DES, WEAVE*, or upcoming: JWST, *Euclid, LSST, PFS, WFIRST, SDSS-V, SPHEREx, DESI, Hector, 4MOST, MOONS, SKA, CONCERTO, CDIM, COMAP, JPASS,, MOSAIC, MSE.*

6 Marenostrum, MassiveBlack, Eagle, TNG, (New)Horizon, Fire, Apostle, Eris, Nihao, Auriga, Owls, Magicc, Mufasa, Magneticum…

ERC Advanced Grant 2023 Part B2

Order out of chaos: explaining the emergence and secular resilience of thin galactic discs



Synopsis Galactic disks observed by the James Webb telescope at all redshifts are an astrophysical illustration of the concept of emergence and downwards causation. They are 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: SN, star formation: SF). 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 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 to marginal stability, the stronger the wake, the shorter the effective dynamical time, the tighter the loop. This attractor allows the disc to generate and maintain order through self-organisation. This is a remarkable yet generic outcome.

Section A. State-of-the-art and objectives

An accurate accounting of morphological diversity over cosmic time is now critical to de-bias surveys and achieve high-precision cosmology. As shown by JWST, Galactic discs are observed throughout the history of the universe. The survival of such thin galactic discs in the Λ-CDM model has long been taken for granted as an obvious consequence of angular momentum conservation. The actual reason is more subtle and enlightening for astronomy: self-regulation is in fact essential to account for their survival. Galactic morphology is driven by angular momentum acquisition through secondary infall, coming from larger scales, which are less dense, hence more steady. Such infall sets up a reservoir of free energy in the circum-galactic medium (CGM), out of which discs spontaneously build a dissipative control loop near marginal stability. In *CosmicEmergence*, we will demonstrate using novel kinetic theories that thin galactic discs are indeed emerging structures (as in intrinsically distinct in nature), when secular processes take over. Their appearance is paradoxically *made possible* by shocks, feedback and turbulence in the inter-stellar medium. These processes jointly radiate entropy, pumping free (rotational) energy from the CGM. The proximity to marginal stability acts as confounding factor for star formation (SF), orbital diffusion and the strength of wakes, which stiffen the discs, explaining their resilience. This is an illustration of an emerging scaling relation.

State of the art: Most stars, perhaps all, are born in stellar discs. Major mergers destroyed some of these discs quite early in the history of the universe, but some thin discs are observed at all redshifts and have

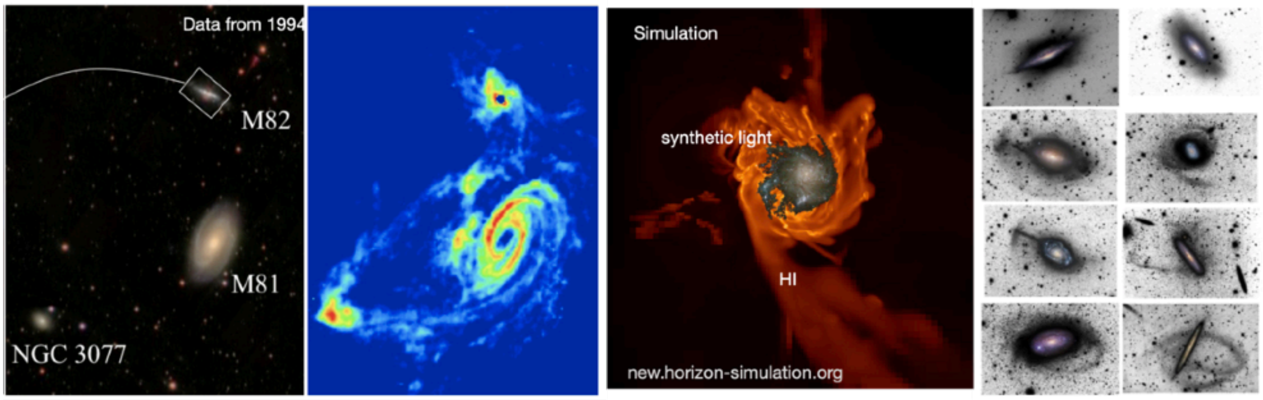
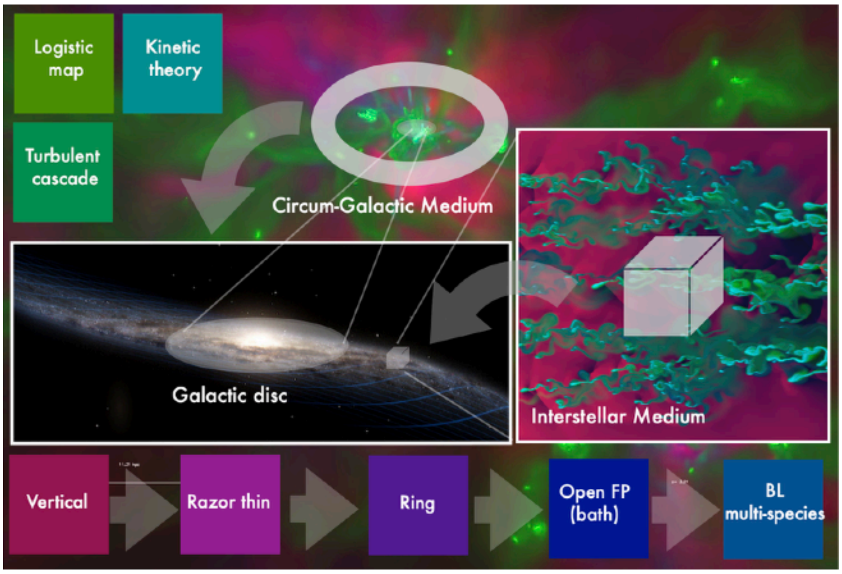


Fig 1: understanding the properties of the circumgalactic medium, a prime focus of this programme, is key to explaining the emergence of thin galactic discs. The circumgalactic medium is a multi-component, multi-process, complex interface, which plays a pivotal role between the large scale structures' cosmic web on the one hand, and the self-regulated galactic disc on the other hand.

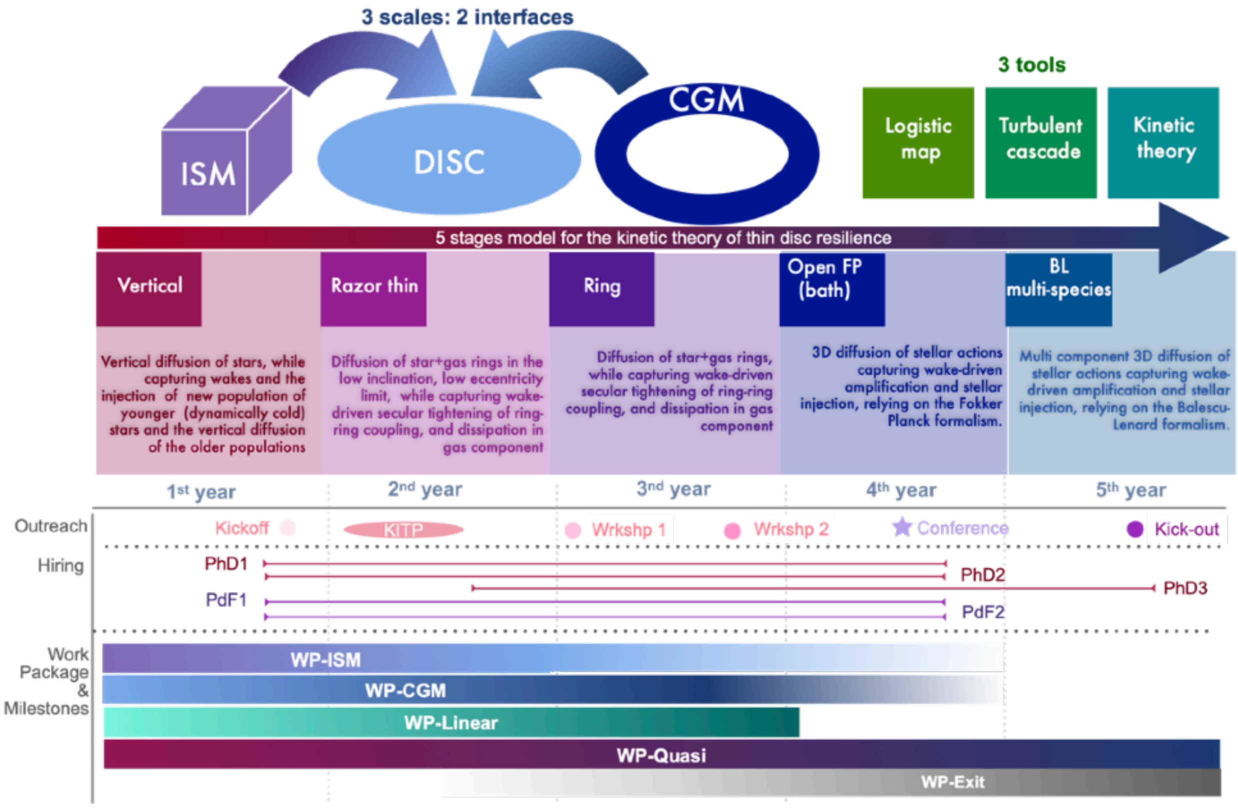


Synopsis of *CosmicEmergence,* as a *multi*-scale,-physics,-strategy approach. We will *sequentially* study the cosmic emergence of thin discs, in connection to the CGM and the ISM as sketched, relying on extended (multi component, open, dressed) kinetic theories (Fokker-Planck, FP and Balescu-Lenard, BL) involving self-regulation, feedback and turbulence. We will proceed in steps of increasing complexity, from a local toy model, through coupled rings, to an orbital diffusion framework (*bottom row*).

survived up to the present day, including the Milky Way. Understanding the secular dynamics of stellar discs therefore appears as an essential ingredient of cosmology, as the discs' cosmological environments are now firmly established in the ΛCDM model. Thin stellar discs are cold responsive dynamical systems in which rotation provides an important reservoir of free energy and where orbital resonances play a key role. The availability of this free energy leads to some stimuli being strongly amplified, while resonances tend to localise their dissipation, with the net result that even a very small perturbation can lead to discs evolving to significantly distinct equilibria. These discs are embedded in various sources of gravitational noise, from shot noise arising from the finite number of giant molecular clouds in the interstellar medium, to globular clusters and substructures orbiting around the galaxy. Clumps, supernovae explosions and spiral arms in the gas distribution also provide another source of fluctuations, while the central bar of the disc offers yet another coherent stimuli. The history of galactic discs likely comprises the joint responses to all these various stimuli (internal and external).

One can find in the solar neighbourhood at least three illustrations of such effects. First, the random velocity of each co-eval cohort of stars increases with the cohort's age (Wielen,'77; Aumer+'09). In addition, the velocity distribution around the Sun exhibits several '*streams*' of stars (Dehnen, '98). Each of these streams contains stars of various ages and chemistries, which are all responding to some stimulus in a similar fashion (Famaey+'05). Finally, in the two-dimensional action-space, resonant ridges form and play an important role in the secular dynamics of razor-thin stellar discs, as argued in Sellwood+'12.

The problem of explaining the origin of both thin and thick discs in our Galaxy has been around for some time (e.g. Gilmore+'83). First, some violent major events could be at the origin of the vertically extended distribution of stars in disc galaxies: accretion of galaxy satellites (Meza+'05; Abadi+'03), major mergers of gas-rich systems (Brook+'04), or even gravitational instabilities in gas-rich turbulent clumpy discs (Noguchi'98, Krumholtz+05) are all possible candidates. Violent mergers definitely have a strong impact on galactic structure, but thickened stellar discs could also originate from the slow and continuous heating of pre-existing thin discs, via for example galactic infall leading to multiple minor mergers (Toth+'92; Villalobos+'08). Spiral density waves (Sellwood+'84; Monari+'16) are also possible candidates to increase the disc's velocity dispersion, which can be converted into vertical motion through deflections



Gantt Chart for *CosmicEmergence.* The programme addresses the emergence and homeostasis of thin galactic discs as part of a three-component self-organised machine. The three *novel* focus points will be i) injection from the CGM to the disc ii) energy dissipation in the ISM and iii) the exact modelling of source term in the kinetic equations via generalised logistic maps. PdFs and PhDs will both devote significant amount of their research time to addressing these challenges through the WPs *CGM, ISM,* and *Quasi* resp. The five stages models are essentially independent, and will be investigated throughout the programme. Quasi-linear theory relies on the success of the linear response, which in itself is challenging for thick disc geometry. The *WP-exit* will focus on how/when thin disc regulation breaks down (e.g. spheroid formation). PhD-1's thesis will focus on linear stability, PhD-2 on ISM physics and PhD-3 on the CGM. We will benefit from the upcoming kinetic24 KITP program. We will organise a separate conference during year 4 on the topic of this ERC.

from giant molecular clouds (GMCs) (Spitzer+'53; Hänninen+'02). In addition, radial migration (Lynden-Bell +'72) could be induced by spiral-bar coupling (Minchev+'10), transient spiral structures (Barbanis+'67; Solway+'12), or perturbations induced by minor mergers (Bird+'12). All investigations can be broadly characterised as induced by an external or internal source of fluctuations to trigger a vertical orbital reshuffling in the disc.

It now appears that the dynamical (azimuthal instabilities, warps, accretion), physical (heating, cooling) and secular (radial migration) evolution of galactic discs are processes which are in part driven by the nature of their live components, in part by the boundary conditions imposed by their cosmic environment (e.g. Stewart+'16). It is therefore of prime importance to quantify the secular response of the disc induced by its interaction with this near circumgalactic environment. Interaction should be understood in a general sense and involves tidal potential interactions (like that corresponding to a satellite orbiting around the galaxy), shot noise (e.g. the population of globular clusters within the halo), *and* infall, where external components (virialized or not) are advected into the galaxy (Weinberg'93, Pichon+'06). Transmission and amplification can then foster communication between spatially separated regions through gravitational wakes (see e.g. Murali'99) and continuously excites the galactic structure. For example, spirals can be induced by encounters with satellites and/or by mass injection (e.g. Toomre +'72; Howard+'90), while warps may result from torque interactions with the surrounding matter (Jiang+'99).

In order to address these issues, over the last ten years we managed to secure funding for two programmes from the French *Agence Nationale de la Recherche* on resp. the connection between galaxy formation and the cosmic web in 2013 (cosmicorigin.org), and the secular evolution of self-gravitating systems in 2018 (secular-evolution.org). Through these, we have been able to show that galactic discs *form* because the large scale structures are large, dynamically young and partially an-isotropic: they induce persistent angular momentum advection of cold gas along filaments, which stratifies accordingly so as to (re)build discs continuously. Where galaxies form in the cosmic web therefore matters: a signature lays in correlation between the spin of discs and the internal kinematic structure of the cosmic web on larger scales.

This was formalised via a simple conditional extensions of tidal torque theory, subject to the larger tides of cosmic saddles (as a point process proxy for filaments), which also impact accretion rates, captured by an extension of excursion set theory, and galactic connectivity, modelled via the number count and clustering of saddles near peaks. Yet our programme made no clear prediction on the exact geometry of advection, nor its *long-term* impact on refilling the circumgalactic discs so as to feed the galactic disc (Fig 1), or indeed the survival of such discs. The fact that thin discs in cosmological simulations operate over cosmic times essentially as though they are isolated is indeed quite remarkable and needs explaining.

Conversely, the long-term evolution of self-gravitating *stellar* discs was studied through our second programme relying on recent breakthroughs in kinetic theory[1]. Such quasi-linear theories can gauge the respective roles of nature vs. nurture in establishing the galaxies' long term properties, using stochastic processes capturing internal and external sources of fluctuations. They allow for inclusive descriptions of the cumulative effects of long-range torques, resonances and cosmic inflow. We showed in particular how the rate of orbital diffusion is rescaled like the square of the gravitational susceptibility (since they involve the powerspectra of dressed potential fluctuations, Fig 2). Nonetheless, they were only implemented for dissipation-less isolated systems without gas, and as such obey an H theorem: their entropy can only increase, the disc can only thicken.

It is therefore now obvious that both approaches are *necessary but insufficient* to explain the long term resilience of thin discs observed by JWST. Within the context of the hierarchical clustering scenario, *how can we form razor thin discs in a stochastic environment? How come such fragile structures persist?*

Objectives: In *CosmicEmergence*, we will show how this cosmic resilience is indeed an emerging process (as in intrinsically distinct in nature) induced by self-regulation between cooling mechanisms (coplanar infall of dissipative gas), and heating processes (merging of small virialised satellites, turbulence, deflection on molecular clouds etc). Through this competition, a novel and fragile but robust structure survives, pumping free energy from a large reservoir of gas and angular momentum in the circumgalactic medium while efficiently radiating entropy in shocks and turbulence on smaller scales[2].

In order to demonstrate this, we propose to extend our current analytic quasi-linear models for the secular evolution of galaxies to reflect this homeostasis, achieved via gravitational-wake-accelerated feed-back loops within an open (cosmic) box model. The *Cosmic Emergence* programme will therefore capture the kinetic theory of *open* multi-component self-gravitating *partially dissipative* systems, while simultaneously accounting for the regulating role of inflowing cold gas. In connection with the results of Pichon+'11 and others, we will show that this is a case example of top-down causation (Ellis'12). Indeed the larger-scale less-dense more-slowly-varying large-scale filaments provides stability in the build up of the reservoir of the radially stratified cold gas in the circumgalactic medium (GCM). In turn, this reservoir regulates disc growth and ultimately, disc thinning.

As argued in the B1 document (Fig. 2), simulations *and* observations suggest that cosmic evolution conspire to promote a redshift-dependent disc mass between cosmic-driven morphology on the one hand (through mergers, strong feedback and turbulence), to secularly-driven morphology on the other hand, which promotes self-regulation around an effective Toomre Q number close to one. During the disc settling phase, the effective (star +gas) Q number becomes an attractor, because gravitational polarisation near marginal stability dresses fluctuations, which yields a tighter feedback loop, corresponding to turbulence-driven star formation (lower-ing Q) on the one hand, and SN feedback and turbulence (increasing Q) on the other hand. This allows for efficient stellar disc's growth, whose natural frequencies then detune from perturbations. This shorter feedback loop, fuelled by cold co-rotating gas infall from the CGM, drives Q closer to one (Fig 4). The homeostatic stellar disc dominates this later phase, and damps runaway instabilities within the gaseous disc. Also thanks to the wakes, the gravitational coupling between rings of stars at different radii becomes tighter, which damps relative oscillations above and below the mid plane, settling the disc.

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[1] The kinetic theory of self-gravitating systems is a very active and fruitful field of research (Villani's'10 Fields medal, or Mouhot's'16 Adams prize), to which we have contributed significantly over the last 20 years. In Fouvry+'15, we presented the first explicit implementation of this formalism in astrophysics, to explain the spontaneous formation of ridges in action space reminiscent of those observed by Gaia. Fouvry+17a showed how to derive the kinetic theory of galactic nuclei where a degenerate resonance condition is generically satisfied by all the orbits. Subsequently, in Fouvry+17b the foundation of this proposal, we extended this framework to discs to explore their spontaneous thickening. Benetti+'17 implemented the Balescu-Lenard equation for the HMF a proxy for orbital bar formation (see also Roule+22). These calculations were further investigated in Fouvry & Bar-Or '18 using stochastic theory, to highlight the peaked diffusion coefficients at the system's separatrix. Subsequently, Bar-Or+'18 Fouvry+21 applied it to galactic nuclei, and showed that the BL equation is the master equation for the scalar resonant relaxation for the S-stars observed around SgrA*. In Hamilton+18,21, we showed how the kinetic framework describes the slow relaxation of globular clusters, alleviating intrinsic limitations of the Coulomb logarithm, and accounting for the system's global inhomogeneity. One of the purposes of *CosmicEmergence* will be to continue stimulating theoretical physics with novel kinetic theories arising in the context of galactic dynamics to describe wider classes of dynamical processes, including dissipation and sourcing.

[2] Many dissipative systems rely on such control loops to produce complexity out of work. Here, large scale kinetic energy of the CGM is converted into thinning the disc, so disc settling is de facto the result of downwards causation.It illustrates the spontaneous appearance of a scaling relation.

Related issues have been previously discussed in the literature. Bertin+'88 have addressed the self-regulation of Toomre's Q number while postulating the shape of cooling and heating functions for the disc, but did not consider cosmic infall, which is also critical. Smolin'96 argued that structure formation in flocculent galaxies could operate as reaction-diffusion process. His emphasis was on morphogenesis (Turing'52) via percolation, without involving gravitational effects. Melnick+'04 have suggested that due to fine-tuned feedback processes, the ISM has on smaller scales reached a state of Self-Organised Criticality, qualitatively consistent with the slope of the observed IMF which imply spatio-temporal power law correlations, and an apparent self-tuning to a critical point and intermittency. We will claim it also operates dynamically on larger scales. In the context of the origin of extended thin discs, Kretschmer+'20 argues that such discs cannot launch galactic outflows anymore, allowing for the persistence of a thin, gently star-forming, extended disc. Recently, Peebles'20 argued that the width of galactic discs called for the introduction of non gaussian initial conditions to maintain massive galactic disc sufficiently isolated from their cosmic environment. The *onset* of disc settling has recently been addressed extensively in the literature (e.g. Dekel+'19, Park+'20), sometimes involving a so-called golden mass. Here, we *assume* that the CGM-disc connection is established somehow, so that the 'engine' is fed with the right amount of free energy to form stars with the relevant amount of angular momentum. Our focus is on the long term *survival* of such thin discs using kinetic theory.

Impact: Gravity is the driving force in spiral galaxies, from their outskirts to their very core. Understanding the long-term resilience of spirals is a subject of intensive numerical research, with massive upcoming instrumental investments. With *CosmicEmergence*, we will rely on *new extensions of kinetic theory* to show *how* wake-driven self-regulation operates during the emergence of thin discs, and how remarkable this is, since it only involves simple processes, so that the onset of resilience can be analysed in details. Through self-organisation, an overall order arises via local interactions between components of an initially disordered galactic disc. This process is amplified by positive feedback relying on available free energy from the circumgalactic medium, which acts as an external agent. The resulting self-organisation is wholly decentralised, distributed in wakes throughout the disc. As such, it is *generically robust.*

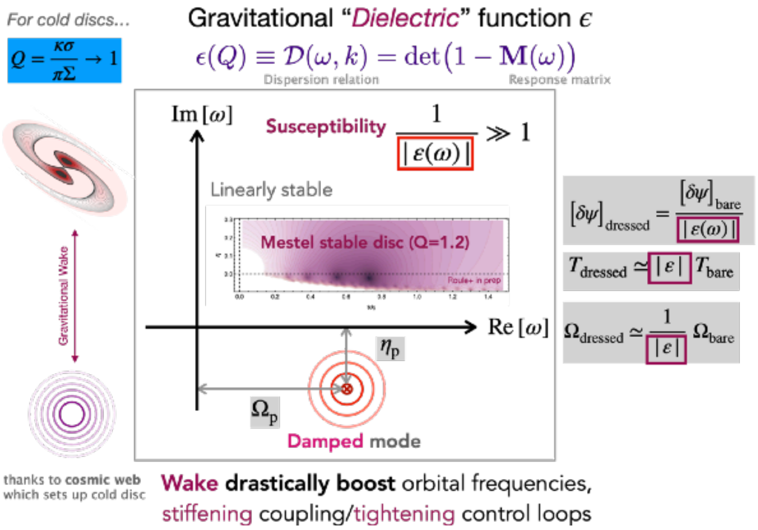

Fig 2: The impact of gravitational wakes is captured by the linear response of the disc (Goldreich+'78). Typically the inverse "*susceptibility*", ϵ, which corresponds to the dispersion relation of the modes in the disc, can become quite close to zero, in the limit of marginal stability, because of the existence of very weakly damped modes. A rule of thumb sets $\epsilon \sim (Q-1)/25$ for a flat rotation curve. The corresponding division by almost zero near weakly damped modes (dark pink inset) is boosting dynamical frequencies, which in turn accelerates self-regulation. In layman's term, perturbations in colds disc are effectively "*dressed*".

One of the highlight of this investigation will therefore be to show that *no fine tuning* is required for thin galactic discs to emerge from the large scale structures. Gravity provides both the initial raw setup, *and* the engine necessary to stiffen discs via wake-accelerated regulation: as argued below, the self-catalysis robustly operates over a range of circumstances. This is sticking both *conceptually*, as a tractable example of spontaneous self-organisation in an otherwise fairly stochastic context, and *practically*, because it provides an understanding of a subtle but real connection between late-time galaxy morphology and cosmology, which astronomers will be able to include in their modelling of galactic surveys.

Section B. Methodology

Galactic discs are unique laboratories to test the universal law of gravity, the driving force from their inner cores to their outskirts. As they are found at all redshift, astronomers have recently focussed significant amounts of theoretical, computational and observational efforts to understand and explain their cosmic evolution. This rising interest can be explained by the conjunction of three factors:

i) First, new ground-based or space instruments like JWST, SDSS, Vipers, GAMA, MUSE, SAMI, MANGA, COSMOS, CLAMATO, CALIFA, DES, DESI, WEAVE, and GAIA are collecting an unprecedented wealth of observations probing the dynamical state of galaxies on all scales. Upcoming instruments such as Euclid, LSST, PFS, WFIRST, SDSS-V, SPHEREx, Hector, 4MOST, MOON, SKA, CONCERTO, CDIM, COMAP, JPASS, WAVE, TIME, HERA, MOSAIC, MSE, HARMONI, will continue to stimulate upcoming investigations. We now have high precision data on the state of our Milky Way (literally billions of stars), but also statistical samples of kinetic information on large populations of neighbouring galaxies;

ii) Second, the Cold Dark Matter (CDM) paradigm provides a well-established cosmic framework for the formation of such discs. On various scales, their interaction with the environment can now be quantified statistically. Depending on redshift and configurations, it will contribute differently to galaxy assembly. Together with the steady increase in computing power, this allows for simulations of ever greater resolution and complexity[3]. This applies not only for isolated and idealised setups, but also to account statistically for the fluctuating environment on different scales, from the ISM to the outskirt of the CGM. These self-gravitating astrophysical systems can therefore now be considered nested, embedded in their own lively environment, with which they interact throughout their lifetime;

iii) Finally, recent theoretical breakthroughs in our understanding of the kinetic theory of self-gravitating systems allow us to follow the effects of gravitationally-amplified disturbances on the orbital structure of galactic discs over cosmic time. In particular, we now have self-consistent integro-differential equation describing the secular evolution of given systems under the effect of potential fluctuations. These kinetic theories define a computational framework to quantify statistically the long-term evolution of the orbital structure of self-gravitating stellar systems, complementing (commonly used) N-body methods.

Qualitatively, they all involve diffusion coefficients in orbital (action) space, $D_{\boldsymbol{m}}(\mathbf{J})$, scaling like the power spectrum of the potential fluctuations (with $\mathbf{m}$ the harmonic number of the resonance, $\mathbf{J}$ the action and $\boldsymbol{\Omega}$ the frequencies):

$$D_{\boldsymbol{m}}(\boldsymbol{J}) = \overset{\substack{\textbf{Dressed}\text{ fluctuations}\\ \downarrow}}{\big\langle\big|\psi^{\mathrm{tot}}_{\boldsymbol{m}}(\omega)\big|^2\big\rangle}(\omega=\boldsymbol{m}\cdot\boldsymbol{\Omega}) = \frac{\overset{\substack{\textbf{Nurture}\\ \downarrow}}{\big\langle\big|\psi^{\mathrm{ext}}_{\boldsymbol{m}}(\omega)\big|^2\big\rangle}}{\underset{\substack{\uparrow\\ \textbf{Nature}}}{\big|\varepsilon_{\boldsymbol{m}}(\boldsymbol{J},\omega)\big|^2}}\overset{\substack{\text{At }\textbf{resonance}\\ \swarrow}}{(\omega=\boldsymbol{m}\cdot\boldsymbol{\Omega})}$$

In such a stellar “fluid”, this diffusion coefficient (which drives the secular distortion of its orbital structure, following the dissipation-fluctuation theorem) is *amplified* by the *square* of its gravitational susceptibility, 1/ε, evaluated at the natural frequencies of the system (see Fig 2). If the fluctuations hit these natural frequencies while the system is not far from marginal stability, diffusion along that resonance can be *very* efficient and cause rapid changes. Our state-of-the-art understanding of galaxy formation within the concordance model now offers a consistent paradigm in which to statistically characterise the potential fluctuations on all relevant scales, hence to compute the corresponding power spectra. The long-term resonant effects of potential fluctuations can therefore now be accounted for, by quantifying their spectral properties *along* the orbits.

Technically, our purpose in *CosmicEmergence* is to make use of ii) and iii) to make predictions for i). *Specifically we will write the relevant sourced & dressed kinetic equations and then solve the set of partial differential equations capturing the homeostasis of the disc as a self-regulating Reaction-Diffusion system.*

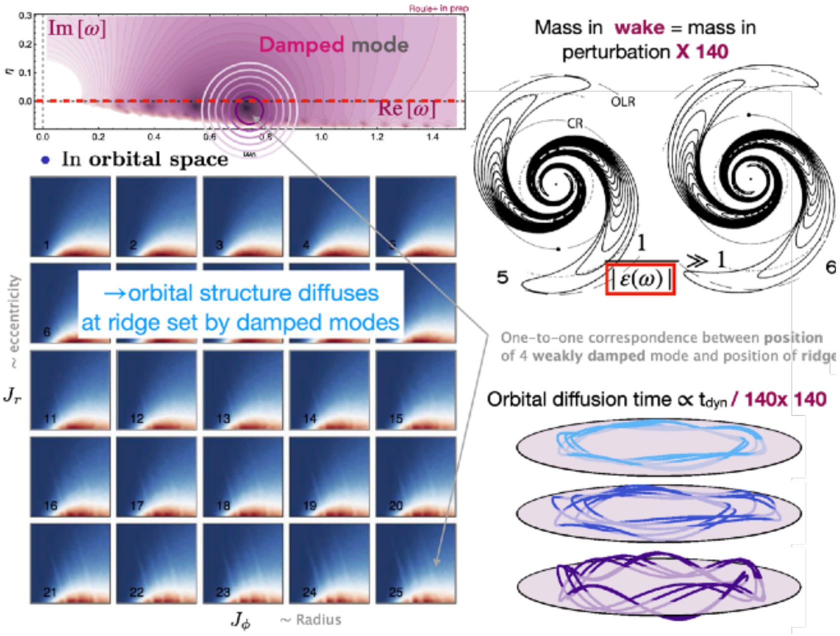

Fig 3: Near marginal stability, the weakly damped modes (top) induce quadratically faster orbital diffusion (bottom). Jointly with its impact on star formation and feedback, this contributes to the tighter self-regulation, which is responsible for emergence, as it accelerates all processes.

Main Work-Package **WP-QUASI:** In practice, depending on how the system is formally split (e.g. the stellar disc alone, or the gas and stellar disc and their environment as multiple components system), the

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[3] Yet simulations of Milky-Way-like galaxies with ~10^{11} particles remain extremely expensive, and have been only attempted once on one of the largest super-computers today. Multi-scale kinetic theory provides *independent* checks relying on different *prejudices*, making directly *statistical* predictions corresponding to the *average* of many such simulations. It restricts the effect of tides to the neighbouring encapsulating scales: this is a different *Variance-Bias-Accuracy-Efficiency* balance from N-body or hydrodynamics.

relevant potential fluctuations can be considered to be external or internal. The corresponding distinction between *self*- and *externally*-induced fluctuations will allow us to disentangle their respective roles in sourcing secular evolution, as we will quantify the diffusion signatures and the characteristic timescales associated with each source of fluctuations. In practice, we will indeed investigate the relative diffusive efficiency of shot noise triggered by Giant Molecular Clouds (GMCs), clumps within the turbulent disc, etc. as transient components of the system. Alternatively, we will also quantify *external* powerspectra of fluctuations: turbulence, SN explosions, flybys, infall etc. We will finally quantify the system's reservoir of free energy impacting the transformation of the underlying stellar disc through infall (WP-CGM), regulating its effective 'temperature'. We will then connect the gravity-driven secular mechanisms at play on galactic scales, relying in turn on both sets of extended kinetic theories. We will start from an easier Fokker Planck (FP) formulation *and* eventually implement a more realistic but more complex Balescu-Lenard (BL) one.

Starting from Fouvry+'17, we will i) lift the tightly wound assumption using the matrix method (Kalnajs'76), ii) account for cold gas inflow and the birth (and death) of stars, i.e. for the possibility of sources and sinks of particles (Pichon+'06); iii) follow up on the self-regulation of the disc's heat content (via its response matrix) while capturing *implicitly* (FP) or *explicitly* (BL) the multiple components of the disc. The perturbations' environmental properties will be tabulated over the three relevant scales: (a) CGM, the source, (b) the disc and (c) ISM, the sink, thanks to the production of suites of zoom-in simulations customised to each scale (Synopsis). Once all these mechanisms are statistically characterised and quantified, kinetic theory will allow us to carry out a detailed analysis of *disc growth, resilience and failure.* We will finally compare our estimates of the system's global secular response to cosmological simulations. The long-term evolution of the disc's thickness or the age-dispersion relations within discs will finally be also compared to e.g. JWST and GAIA+APOGEE observations, e.g. to the structure of our Galaxy's distribution function (DF).

Sourcing orbital diffusion: As illustrated in B1-Fig 3, the preservation of the disc vertical density profile over very long periods of time can only arise through a high degree of synchronisation between star formation and vertical diffusion (Park+'20). This is a very important observational and numerical result, as this apparent fine tuning is made possible by the discs hovering closer around Toomre Q = 1 as they settle. It is very difficult (not to say impossible) to tightly tie together the star formation timescale in the thin disc and the vertical diffusion timescale *unless they have the same 'cause'*: gravitational (in)stability. Star formation itself is mitigated via the dynamics of the turbulent gas disc (Tasker+'09), explaining the observed correlation between stellar age and height. When $Q_{\rm eff} \to 1$, kinetic theory (Fouvry+'17) predicts that the vertical diffusion coefficient increases (quadratically), which will both heat up the disc in the plane, induce radial migration, and vertical heating. Concurrent spiral waves will trigger cold gas inflow, turbulence hence star formation, and cooling of the stellar component (by injection of newly formed stars), which will maintain $Q_{\rm eff} \sim 1$. *CosmicEmergence* will investigate quantitatively this line of reasoning and build source terms for the extended kinetic theory accordingly (WP-ISM).

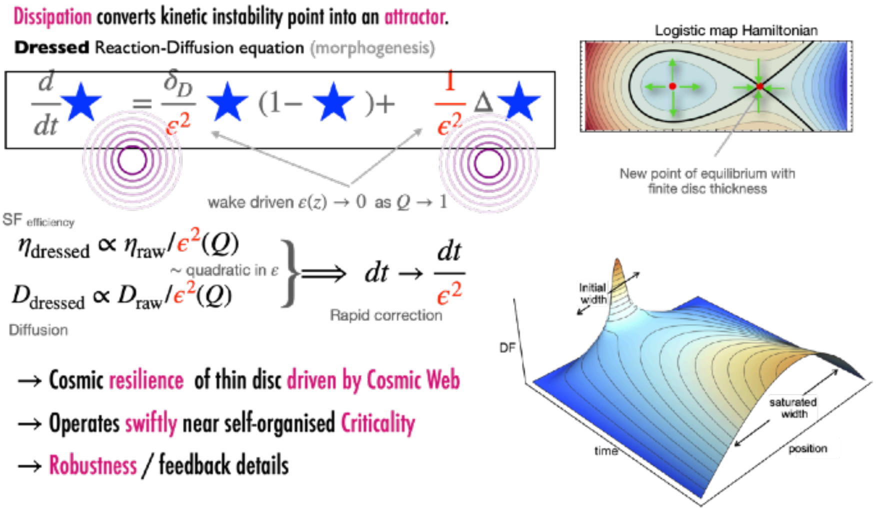

Fig 4: Toy model for the diffusion of the vertical profile of the disc towards a new attractor as a function of cosmic time, regardless of the exact level of wake amplification. Since both dissipative and diffusive processes are quadratically driven by the same confounding factor, proximity to marginal stability, self-correction is robust. A range of α = η/D, yields the same fixed width disc. No fine tuning for feedback or star formation is required, as it is wake and infall driven.

Why does convergence towards Q = 1 dynamically drives the galaxy towards a thinner disc?

Let us *illustratively* consider a simple toy model (Fig 4) for the sourced diffusion of the disc's stellar distribution, f: $\partial f/\partial t = D\Delta f + \eta\delta_{\rm D}(z)f(f_0 - f)$, where the orbital diffusion rate, D, is modelled by a constant, while the source of stars is modelled via an in plane logistic map (the archetypical differential equation for the emergence of stochasticity, population growth, pandemic propagation, reaction models, and even the diffusion of innovation!), with a star formation efficiency, η. This quadratic functional form captures the expected self-regulating features of the star formation/feedback processes: it sources the rate of change of the distribution with a linearly growing and quadratically saturating component, so that at small *f*, it triggers growth, whereas above f_0 it damps it.

The fate of this toy model is controlled by the parameter α = η/D. The asymptotic (late time) solution will be given the solution to the corresponding non-linear Poisson-like equation nulling the r.h.s. of that equation. The right amount of diffusion stabilises the latter solution, which in its absence would be an unstable point (fig 4). While the thin disc self-regulates towards $Q = 1$, it can in fact robustly maintain a finite vertical extent, and, remarkably, the rate of star formation or feedback does not need to be fine-tuned to the rate of diffusion to preserve its vertical extent: a full range of values for α yields the same width. Since both the star formation rate[4], $\eta_{\rm dressed} \propto \eta_{\rm raw}/\epsilon^2(Q)$, and the stellar diffusion rates, $D_{\rm dressed} \propto D_{\rm raw}/\epsilon^2(Q)$, are boosted with secular time, as the disc settles and $\epsilon(Q) \to 0$, the control parameter α will enter the insensitive regime and the evolution of *f* will rapidly pick the asymptotic solution (Fig. 4).

This toy model formalises the above confounding factor argument (see also Park+'20) while providing a robust (untuned) saturation of the growth of the disc's width. This incidentally explains why self-regulation operates preferably around criticality: a diverging gravitational susceptibility $1/\epsilon(Q)$ is a critical ingredient (Fig 3), together with free energy flow from angular momentum stored in the CGM.

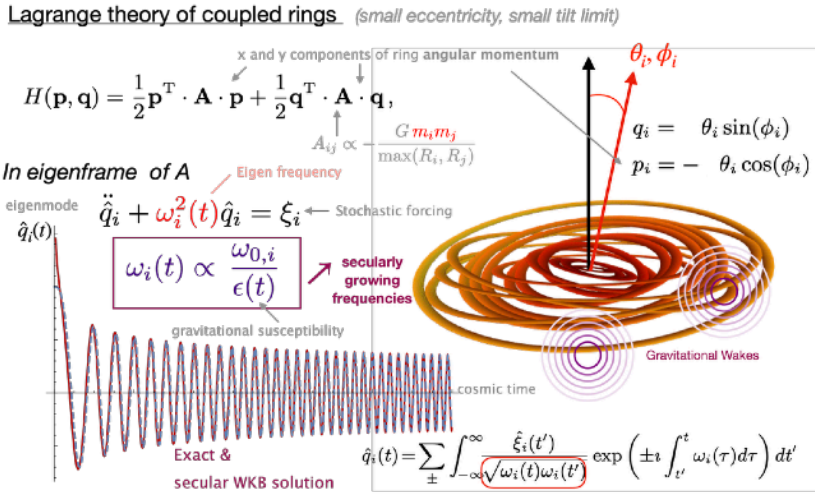

Fig 5: *Proximity to marginal stability accelerates stellar disc settling.* Consider a set of rings representing the perturbed stellar disc, at various radii, and use as canonical variables, the x and y components of angular momenta, in the small-eccentricity small-tilt limit. Lagrange theory implies that the corresponding Hamiltonian is quadratic, with coupling terms involving the masses of the two rings. Each oscillator forced mode can be described independently. The net effect of the wake is to boost all frequencies by a significant and secularly growing factor, as convergence towards marginal stability proceeds. Hence the ring's relative oscillation amplitude decreases and the disc stiffens.

Operationally, *CosmicEmergence* will therefore rely on *sourced* FP and BL kinetic equations to follow up on this toy model, in steps of increasing complexity.

To understand this relaxation, as a geometric alternative, *CosmicEmergence* will also consider a set of concentric gravitationally self-interacting rings depicted in Fig 5. Each ring represents a set of orbits with a given set of actions, which are coupled together by gravity. Since we are concerned by departure from a settled disc, we will assume without loss of generality that the equation of motions describing the different rings are linearised w.r.t. an unperturbed co-planar configuration. After linearisation, the set of N coupled oscillators obeys a matrix equation. The equations of motions governing the oscillators can be decoupled by moving to their eigen-frame.

This is best described in the so-called Lagrange theory (Kocsis +'11). The net effect of the cosmic convergence towards Q ~ 1 and disc growth will be that the effective mass of each ring gets boosted by the gravitational polarisation that it triggers within the unperturbed disc. Hence the secular growth of the gravitational susceptibility (driven by the convergence toward Q ~ 1) will induce a stiffening of the restoring force between rings, and therefore damping of all oscillations. *This is a striking result*: a stellar disc can and does realign itself through polarisation, provided it is embedded in an open dissipative compound. The emergent behaviour operates through long-range collective modes: a form of top-down causation operates, which may appear to defy entropic principles and the second law of thermodynamics, but does not since the disc can extract information and order out of its environment.

This WP will also consider the dynamics of the set of coupled gas+star eigenmodes for the stars, and

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[4] (Dressed) potential perturbations on sub-GMC scales will stir the clouds and generate turbulence on smaller scales (Lazarian+'00,Tasker+'09). Gravitational perturbations cascade down to the relevant scales for SF. Hence the SFR will be strongly enhanced near marginal stability so long that a sufficient flux of cold gas from the CGM exists to refurbish the consumed gas. Increased star formation will contribute to increasing $\Sigma_\star(t)$ and decreasing $\sigma_\star(t)$ momentarily, hence decreasing $Q_{\rm eff}$ via a stronger stellar contribution, up to the point where the more massive stars explode in super-novae, induce more turbulence within the gas, which in turn will increase $\sigma_{\rm gas,turb}$, hence increase $Q_{\rm eff}$. But assuming that the disc is dense enough, the key bring-home feature of this cycle is that it self regulation is globally driven by the (quadratic) shortening of *relaxation* time with proximity to marginal stability.

the gas components. We will consider that each eigen mode has its own natural frequency, $\omega_\star$ and ω_g resp, a coupling term, $\omega_{\star g}$ and a driving ξ and damping η term specific to the gas component. The amplitude of each mode then obeys the set of coupled equations, shown in Fig 6b, which also illustrates the damping of two modes when one increases the drag on the gas component. With cosmic time all frequencies will stiffen (through increased stellar mass, and gravitational polarisation), while the amplitude of the secular stochasticity will decrease, so that the alignment within and between the two discs will increase.

In the tightly wound, continuous number of rings limit, *CosmicEmergence* will finally revisit Hunter+'69 to describe the warps of a two-components (gas+star) disc, and model accordingly the damping of the waves (through the corresponding quartic dispersion relation with negative imaginary roots) when the stellar disc grows. The generalised dispersion relation will involve the coupling frequency between the two discs, $\omega_{\star g}^4 = (2\pi G k)^2 \Sigma_g \Sigma_\star$, and the damping rate $\eta \propto k^2$ quantifying the effectiveness of the energy dissipation on small scales. The coupling frequency will stiffen with cosmic time, so that oscillation of the stellar disc will damp away more vigorously.

Whatever the toy model, settling is driven by four complementary processes: *quieter environment, convergence towards marginal stability, dissipation in the injected gas and increased stellar disc mass.*

Strategy: Starting from the various kinetic equations, *CosmicEmergence* will therefore first generically *introduce the source term*, and proceed to orbital diffusion modelling via steps of increasing complexity/realism/risk, as discussed above (see also Gantt chart): i) a strictly local vertical analysis; ii) a linearised sets of coupled discrete rings (Fig 5,6), then in the continuous limit) iii) a Laplace-Lagrange model of sets of coupled ring iv) a dressed open Fokker-Planck formulation; v) a dressed Balescu-Lenard multi-component formulation (see Gantt chart). In the FP analysis, the disc's environment will be described as induced by external perturbation, while in the BL, as a multiple component system. For iv) and v) we will follow up on Fouvry+'15 and evolve both kinetic equations (either Fokker-Planck, resp. Balescu-Lenard), accounting for mass and angular momentum inflow within the disc, and modelling self-consistently churning (drift in guiding centre), thickening (vertical extension) and blurring (in plane heating). Extending the resonant thickening of self-gravitating discs presented in Fouvry+'17, *CosmicEmergence* will quantify the expected cosmic evolution of the structure of the disc and its population, relying on the multi-component generality of the kinetic formalism. This will involve building perturbatively thickened equilibria with a mapping in action-space from an integrable to a non-integrable model via fits of generating functions (Kaasalainen+'94). We will then solve the exact fields equations, construct an appropriate basis of potentials, and deal with the full response matrix (WP-linear) in order to solve for the corresponding BL and FP equations[5]. Integrating such a partial differential equation will be a challenging numerical calculation, which can involve complex finite elements methods (FEM, e.g. Tep+21) .

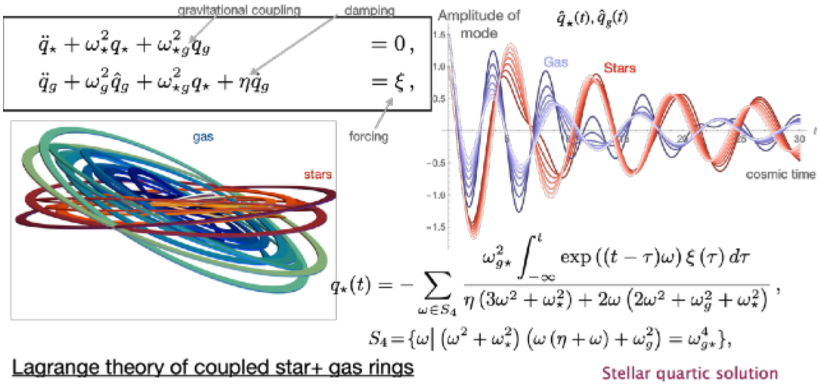

Fig 6: *Coupling to dissipative component accelerates stellar disc settling.* Given a double set of gas-like and stellar-like rings, we can diagonalise jointly both of them. Within that frame, only the gas disc is subject to forcing (through turbulence, SN explosions) and damping through shocks. The coupling yields a damped linear response for both components, involving four secularly growing frequencies associated with a quartic dispersion relation. Dissipation in the gas brings down the amplitude of the stellar oscillatory modes. All relevant processes (stochastic forcing, inflow, dissipation, drift in frequencies) operate jointly to settle the disc.

As validation, *CosmicEmergence* will use methods inspired from Monte Carlo simulations, which follow from the Langevin rewriting of the sourced diffusion equation. One samples the system's DF with individual particles, and integrates the first-order stochastic ordinary differential equations describing the dynamics of

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[5] All the existing published works on self-gravitating kinetic theory, with the noticeable exception of Weinberg's'01 paper, were restricted to computing the initial diffusion flux of the kinetic equations. In order to probe later stages of secular evolution, *Cosmic Emergence* will have to integrate forward in time the secular diffusion equations. There are a few anticipated difficulties. The first arises from the self-consistency of the diffusion equations. Since the response matrix encapsulates the self-gravity of the system, it intrinsically involves a double integration over phase-space. The system's drift and diffusion coefficients depend on the current global value of the system's DF and have to be updated as the system evolves. For the BL equation, the dependency is explicit and quadratic, *and* implicit via the response matrix. For the explicitly linear FP equation, there is again implicit dependency via the response matrix. The integration in time has to be made step-by-step, with successive updates of the system's DF, potential, and diffusion flux.

such test orbits[6]. All our results (the DFs) will be cast in terms of direct observables (e.g. velocity dispersion), tailored to existing and future facilities, in order to guide the interpretation of such datasets. These observables are typically *marginals* of the underlying DF($\mathbf{J}$,τ) and are therefore straightforwardly computed (see Fig.7). Depending on scale, the signatures of our stochastic differential equations (SDE) solutions on galactic cosmic evolution will be quantified in terms of the evolution of the age-dispersion relations in the Milky Way's disc, its vertical gradient, and the stellar dynamical evolution of the Galactic centre's cluster.

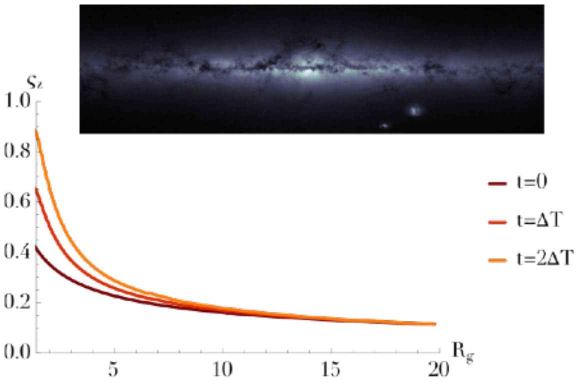

Fig 7: *Top panel:* GAIA stellar counts of the Milky Way. *Bottom panel:* time dependent disc thickening predicted by Fokker-Planck diffusion (Fouvry+'17).

Implications: While the self-regulation operates close to marginal stability by design (to warrant rapid correction of the control loop, in direct analogy with faster electronics controlling modern drones), this implies that it will be subject to two types of failures which we will study in *CosmicEmergence*: i) those impacting too strongly/rapidly directly the disc, not allowing the regulating loop to operate against large amplitude variations, and throwing it off it stability boundary; ii) those impacting the engine (within the disc or within the free energy reservoir) so that self-regulation is made impossible.

The former category implies that the polarisation fails to operate fast enough to correct for the crossing of some boundary threshold. In this category, a major/or strong-minor merger will of course have a dramatic effect on the disc. The long-term impact of minor mergers is less straightforward to anticipate. Our own Milky-Way has swallowed Sgr about 5 Billion years ago. The GAIA data shows stellar kinematic evidence for this past accretion event (including a bar and winding spirals in (z,v_z)-space and indirect traces of disc settling in the metallicity of stars, Belokurov+'22), though our disc still falls into the thin category, suggesting that the merger was not disruptive enough to permanently stop the loop.

The latter quenching mechanisms can be split in subcategories: cosmic infall can break the loop by breaking the engine, providing too much/to little vorticity in CGM (Song+'23), quenching gas infall all-together (Pichon+'06), while a change in star formation efficiency can break the cascade between meso- (disc scale height) and microscopic (GMCs) scales. If the environment temporally (e.g. while passing the caustics of large scale filaments, Song+'20) boosts the vorticity content of the CGM, the cold gas will not reach the inner regions of the disc, and cooling via star formation will stop, breaking the loop. Conversely, if the vorticity content of the CGM is momentarily too low, the inside-out build up of the disc will stop, triggering accretion, bar formation, compaction, and eventually possibly bulge formation via bar dissolution or buckling. From the point of view of the above-mentioned control parameter, the new values of α do not allow for homeostasis anymore. Studying when such failure occurs will be the topic of the WP-Exit below.

Results & Deliverables: characteristic timescales for churning and blurring; prediction for radial and cosmic variation of metallicity-age-dispersion; thick/thin disc fraction versus cosmic time; marginals of DF($\mathbf{J}$,τ) & corresponding estimators; self-consistent model for cosmic disc settling. Sourced kinetic codes on GitHub.
Involvement: as the main WP all participants will be involved throughout (PhDs towards the end).

Secondary WorkPackages: In order to achieve *CosmicEmergence's* milestones, we also need to complete the following sub-Work-Packages:

WP-ISM: In *CosmicEmergence*, the first step will be to characterise potential fluctuations on small scales. To do so, we will rely on our understanding of turbulence on small scales and hydrodynamical simulations. In order to characterise these fluctuations, we will implement supernova feedback allowing for the release of energy from the supernova into the interstellar medium. Figure 8 illustrates two snapshots of such a hydro-dynamical simulation. In this figure, one can note that because of supernova feedback, the gas density fluctuates. These fluctuations in the potential due to the gas will be felt by the stars and will therefore drive

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[6] With this formulation, the involved timesteps are commensurable with a fraction of a Hubble time. After a few timesteps, the DF is resampled using cloud-in-cell, and the new matrix response, drift and diffusion coefficients are computed. Some regularisation must be imposed on the estimated (noisy) DF since the matrix and the coefficients involve derivatives of this distribution. Finally, one must take into account changes in the DF induced by infall. For instance, the radial distribution of cosmic cold gas accretion directly impacts the metallicity of the new stars, which are the chemical clocks within the disc. This is a prime example of scale coupling that *CosmicEmergence* will address. Asymptotic solutions to the kinetic equation should correspond to the observed quasi-stationary states of the corresponding secular process, given final mitigations between environmental and intrinsic effects.

resonant secular diffusion. We will ensemble-average various realisations of this same physical setup. The same approach will allow us to investigate how much this diffusion depends on the strength and type of the feedback, while changing the recipes (e.g. cooling/heating, etc.) used in the hydro-dynamical simulations. We will quantify the typical fluctuation power spectrum and find quantitative bounds on feedback strengths sufficient to induce significant diffusion. We will also carry out sub-parsec scale RAMSES simulations and analysis of the potential component of turbulence within simulated slab of ISM with/without gravitational forcing on larger scales. We will check how valid is the assumption that star formation is controlled by the larger injection scale, and how effectively self-organised criticality describes the impact of Q on star formation. *Pogosyan's sabbatical in Paris will prove essential for the successful completion of this WP.*

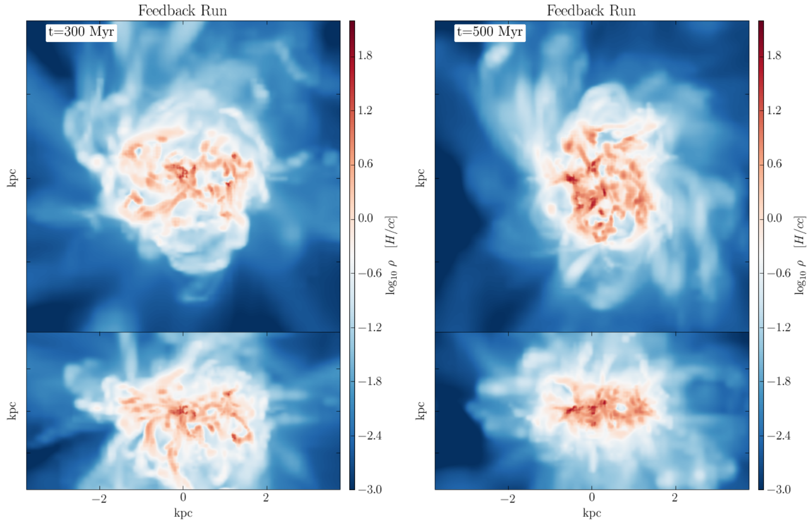

Fig 8: Gas density in hydro-dynamical simulations. The gaseous discs and are seen from the top (*top pane*l) and the edge (*bottom panel*). Different star formation and supernova feedback recipes will be implemented, leading to distinct fluctuations in the gas density, which may resonantly couple to the stellar disc and induce orbital diffusion therein. *CosmicEmergence* will carry out many such simulations to quantify the induced powerspectra of fluctuations.

Results & Deliverables: calibrated reaction rate via a logistic parametrisation; temporal and spatial power spectra of potential fluctuations within the ISM. *Involvement*: PhD-3+PI+PdF1+Pogosyan.

WP-CGM: We will rely on *CosmicEmergence's* computing resources to produce sets of simulations to account statistically for the specific fluctuating environment on the boundary of that scale, from galactic centres to the outskirts of dark halos. The assumption will be that while the detailed long-term results of hydrodynamical simulations should be considered with the appropriate level of skepticism, their short-term ensemble-average on the larger scales are more robust. Within *CosmicEmergence* we will focus only on canonical angular power spectra (involving the Fourier transform of the potential fluctuations w.r.t. the angle coordinates conjugated to the actions – labelling orbits), since the fluctuation-dissipation theorem tells us they are the relevant quantity. We will use multi-scale, zoomed-in simulations that include stellar and AGN feedback. We pioneered such measurements using over 15k dark halos at the Virial radius in Aubert+'07, and over 50k virtual galaxies in Pichon+'11 and Welker+14, see Fig. 9. The theorem provides us with a significant compression of the full statistics: from the point of view of the

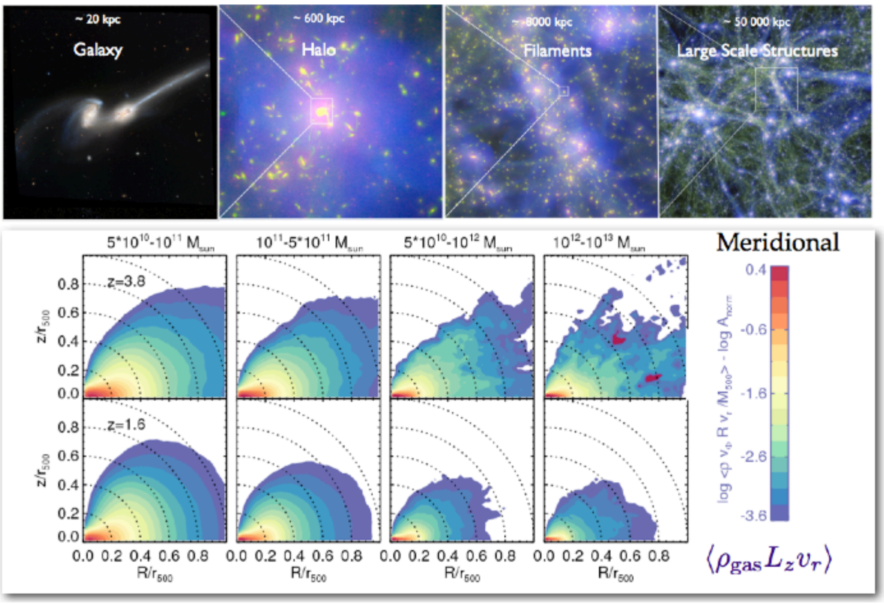

Fig 9: *Top-panels*: Illustration of the multi-scale cosmic environment in which galaxies secularly evolve. On larger scales, the environment is anisotropic, which impacts the long-term evolution of galaxies. *Bottom-panels*: median meridional advected angular momentum over 50,000 galaxies in the Horizon-Mare nostrum simulation as a function of host mass and redshift (Pichon+'11). Angular momentum is advected coplanar to the host's spin. The fluctuations around the mean flow will drive secular evolution.

underlying orbital structure, only the power spectrum of the potential fluctuations matter[7]. This is a significant compression of the full statistics![8] We will rely on zoom-in on multiple resolutions in order to fit and extrapolate these power spectra. These fits will be deliverables of the project and made available to the community. We will show how cosmic web-induced rotation of the CGM is structurally important because it sources spontaneous work through self-reorganisation: a rotating disc has small heat content to counter-balance large-scale coherent waves. This in turn is favourable to long range gravitational interactions inducing significant changes (smaller inertial response, given small relative motion). Following Pichon+'06, the kinetic equations will then be extended in *CosmicEmergence* and applied to systems open to their cosmic environment. Under the assumption of ergodicity, we will relate the corresponding source, drift and diffusion coefficients of the ensemble-average distribution to the underlying cosmic two-point statistics of the infall. We will also account for the slow evolution of the *underlying* equilibrium over half a Hubble time (see also Aubert+'07), and quantify cold gas infall towards the disc.

Results and deliverables: inflow rates and powerspectra at the interfaces; *Involvement*: PhD-2+Co-PI+PdF2.

WP-Linear: In order to include self-gravity in our kinetic equation we will need to build thick disc and spheroid bi-orthogonal basis, compute their linear-response matrix and the corresponding damped modes as a function of rotation rate. I will be important to study the stability of rotating spheroids to quantify disc-halo torquing (Rozier+21). At first order, we will assume integrability, i.e. the existence of global Stackel angle-action coordinates. It can be either guaranteed by the system's symmetry (spherical halo, razor-thin discs) or by additional assumptions, such as the epicyclic approximation. When it does not hold, the system's dynamics may become partially chaotic and its secular evolution may need to be described via explicit stochastic diffusions, which we will need to calibrate from simulations. For example, chaos is likely to play a role in the central bar. In CosmicEmergence, we will rely on perturbation theory (Goldstein'50) to build new (fast and slow) angle-actions customised to each resonance, using as a perturbation the departure from symmetry of the sought system: this strategy, known as Torus Mapping (Binney+'16), yields new actions with which secular diffusion for rotating systems will be reformulated. We will in particular build secular diffusion equations for thickened discs models and possibly triaxial halos.

Results & Deliverable: Thick disc linear-response framework; bi-orthogonal basis; sets of damped mode as a function of the geometry of the disc. *Involvement*: PhD-1+PI+PdF1.

WP-Exit: So as to maintain a stationary process, the level of energy dissipation within the turbulent gas must match the energy input from inflow. This requirement puts constraints both on the galaxy and its environment. Beyond the impact of mergers, *CosmicEmergence* will study how any process that breaks the control loop e.g. by quenching cold gas infall, or changing the influx of angular momentum, may temporally or permanently damage the disc. We will quantify the statistics of fluctuation in the CGM and the variation of inflow that the disc's homeostasis can tolerate before the disc becomes unstable, i.e. the more realistic generalisation of the control parameter α. We will estimate the maximum rate of entropy production allowed by the configuration (in a steady state, all the extra free energy acquired by the disc from the CGM needs to be radiated away). Beyond this threshold, we will understand how the disc chooses another path to sustain the stress imposed by its environment and redistribute the excess of angular momentum (via contraction, bar formation, buckling, bar dissolution via diffusive separatrix crossing, radial transport of mass and angular momentum). Finally we will qualify when regulation *completely* fails: impact of merger rates, quenching of CGM, triggering abrupt corrections that self-regulation cannot handle. Our astrophysical goal will be to explain the redshift evolution of morphological diversity as traced by JWST, and other upcoming surveys like 4MOST, DESI or Euclid. More generally, we will aim to understand the qualitative difference in the secular evolution of open/close, rotating/non rotating, 1D,2D,3D systems, with/without dissipation, so as to trace the minimal sets of ingredients for homeostasis and the emergence of scaling relations.

Results & Deliverables: Statistics of broken discs: e.g. bar/bulge fraction. *Involvement*: PhDs+PI+PdF2.

Quantitative assessment of success: Building up on the practical advantage of kinetic theories capturing the long-term effect of self-gravity in an open multi-scale environment, the research in *CosmicEmergence* will rely on the conjugation of analytic and numerical methods – calculation of linear response operators, stochastic/finite element implementation of sourced and self-regulated quasi-linear equations – and the

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[7] As such, the expected accuracy is not as demanding as what is required for a fully self-consistent zoom-in simulation.

[8] On the other hand, as the orbital structure diffuses, the underlying mean field varies. Hence the angles over which the power spectrum must be computed have to be updated. This requires significant storage (see section resources), as the two-point function must be retained before it is transformed over angles.

analysis of dedicated simulations to quantify the statistics of the various components, and validate the parametrisation. We will show how the thickening of the existing stellar disc and the continued formation of young stellar thin-disc, the vertical distribution of stars does not change much after the disc settles, reflecting the modulation of both orbital diffusion and star formation by the same confounding factor: the proximity of galaxies to marginal stability. At the technical level, *CosmicEmergence*'s deliverables will include new public routines for solving extended kinetic equations as stochastic Langevin processes, using finite element methods (see Fig. 10 for a preliminary validation/distribution). *CosmicEmergence* will also deliver sets of estimators for standard observables, and a novel understanding of the effect of self-induced regulation.

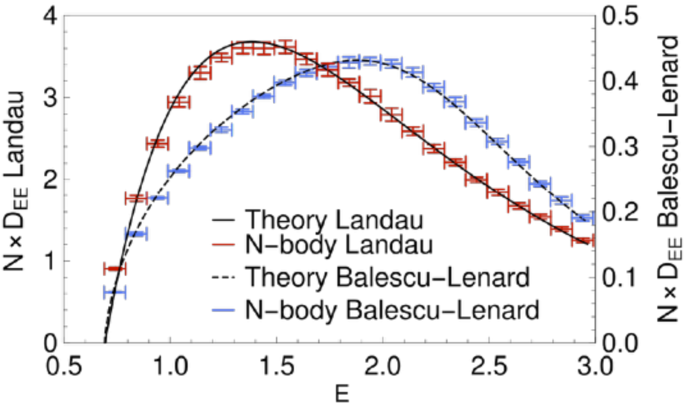

Fig 10: Validation of kinetic theory for the 1D model of vertical oscillation of N planes near the isothermal distribution. Both the predicted FP (solid) diffusion coefficient and its BL counterpart (dashed) match the average of many simulations very well (5%). Wakes reduce significantly vertical diffusion (Roule+'22*)*.

A measure of the impact of this programme – beyond our detailed understanding of galactic disc resilience – will be i) a statistical understanding of when disc homeostasis operates *and why it fails*, and ii) the promotion of quasi-linear theories as a general universal and powerful means to rival/ complement brute force simulations. As a bi-product of homeostasis failure, we will also predict statistical estimates for the cosmic evolution of bar fraction, disc to bulge fraction, etc. While cosmological hydrodynamical simulations have been extremely successful in experimentally improving our understanding of galaxy evolution in general, and at reproducing the observed fraction of thin disc in particular (see e.g. Park+'20 and Fig 2 of B1), they will still definitely benefit from validation through independent methods. *CosmicEmergence*'s programme will address this via analytical and numerical work of an intrinsically novel nature, by solving the corresponding sourced SDEs and seeking finite element methods solutions. Conversely, when implementing complex kinetic theories with self-regulation via wakes and inflow, validation is essential. We will demonstrate that the kinetic formulation accurately describes the *ensemble average secular* response of the modelled disc components. Relying on a state-of-the-art hydro solvers like RAMSES, we will compare the effect of secular evolution captured by such codes to the prediction of idealised dedicated zoom-ins on the one hand, and kinetic theory using SDE on the other hand. We will rely on FEM for comparison, relying on the (hired) expertise of the PdFs, and the PI and CoI upcoming investment in this technology. In closing, this work could also be generalised to the emergence of other related scaling relations, such as the baryonic Tully-Fisher, Kennicutt-Schmitd, etc.

Conclusions: *CosmicEmergence* presents a well-balanced framework to explore the emergence of thin discs *using novel kinetic theories*, which offers unique physical insights into the competing dynamical processes at play, while explicitly accounting for dissipation-driven self-regulation. On the conundrum of nature versus nurture being responsible for the state of thin galactic discs, *CosmicEmergence* will demonstrate how the answer seems to be both, in a somewhat unexpected manner. The cosmic environment quietens and detunes itself, but most importantly the disc self-shields, thanks an ever tighter wake-regulated control loop running on the (cosmically refurbished) large reservoir of free energy in the circumgalactic medium. Hence the tiny galactic disc effectively inherits its coherence from the stability of small and large scale tides, via some non trivial, yet tractable machinery: the cosmic web sets up the CGM, which in turns feeds the loop.

CosmicEmergence will bring quantitative understanding to the stability threshold for thin disc resilience hence on morphological diversity, which will be of prime importance for upcoming cosmological surveys, which rely more and more heavily on modelling the physics of galaxies to construct mock surveys.

As a testbed for emergence of homeostasis in a simple-enough gravity-dominated context, funding from the ERC will also prove critical *beyond the scope of galaxy formation*, or indeed astrophysics: it will provide a workable framework to model top-down causation, self-organised criticality and emergence, relying on novel *rigorous extensions* of kinetic theory. Together with the *public release* of the new kinetic codes, this will truly be one of the high-gain general outcomes of this outstanding research programme.

Let us finally conclude with summary of the main aspects of the proposal.

- To what extent does the proposed research address important challenges?
  - Characterising the top-down gravity-controled causation linking the cosmic web and the CGM to the ISM via the disc is both enlightening and useful, in order to de-bias upcoming estimators for cosmology and explain the JWST-observed ubiquity of thin galactics discs throughout cosmic age.

- Understanding emergence and homeostasis in a trackable framework is of critical importance in general, and for galaxy formation in particular, as an example of spontaneous occurrence of a scaling relationship.
- Developing the relevant extended kinetic theories as a competitive alternative to hydrodynamical simulations is also totally worthwhile, as sanity checks *and* also to provide detailed understanding of the underlying physics: the resilience of thin discs needs explaining both conceptually and practically.

• To what extent are the objectives ambitious and beyond the state of the art?

- While logistic maps in particular and the concept of emergence have widely been used across many fields (e.g. ecology, epidemiology, chemistry, demography, economics, sociology, cybernetics) the specific framework of galactic discs thinning offers a unique opportunity to track down its transforming role.
- The BL kinetic equation has almost never been applied to multiple species, nor in an open framework.

• To what extent is the proposed research high risk/high gain?

- *CosmicEmergence* is relatively high-risk, given the (non integrable) geometry of thin discs and the induced technical challenges involved, since quasi-linear theories embrace much of the unavoidable complexity required to capture self-regulation. The work-plan is nonetheless conceived to alleviate the risks via our set of milestones and lack of deadlocks.
- It is also high-gain for the *very same* reason: it captures the minimum amount of complexity required for emerging homeostasis! This will prove enlightening and useful for our understanding of the physics of complexity beyond the scope of astrophysics. It will complement upcoming hydrodynamical zoom-ins.

• To what extent is the outlined scientific approach feasible?

- *CosmicEmergence* is certainly exploratory *and* challenging but is *feasible within 5 years*: it addresses a central tenet in galactic evolution, using novel and *efficient* theoretical and stochastic methods which will complement the classical hydrodynamical methods, while predicting ensemble average expectations. These theories are not significantly less CPU/memory intensive than direct N-body: in the end they must also implement double integrals over the full 6D phase-space to reflect the long reach of gravity. Yet they makes different compromises in variance, bias, accuracy and efficiency: convergence between both methods will prove invaluable. Various validations of dressed kinetic theory have recently been published by us and others.
- The feasibility of the project is guaranteed both by its structure and by the skillsets of the applicants. Having identified the issue (why thin discs are observed in a cosmic framework?) many years ago, they have assembled and published all the bricks necessary for the programme's completion over the ERC's period, with recent critical technical breakthroughs (e.g. implementing rotation in the linear response, Rozier+'19, computing dressed vertical diffusion coefficients Roule+'22) as well as conceptual ones (e.g. sustaining proximity to marginal stability via dissipation-driven auto-catalysis).

• To what extent is the research methodology & working arrangements appropriate to achieve its goals?

- The proposed work-plan is detailed, incremental *and* realistic. The human resources requested are appropriate given the set of identified WPs. The sabbatical will address the important issue of small scale cascades. Complementary expertise on hydrodynamical zoom-in simulations are available both at IAP and beyond, within the group of existing collaborators (e.g., in Seoul, Oxford). The work-plan is also timely: given the sought precision on cosmological surveys, we *must* understand now what drives galactic morphology in general, and the resilience of thin discs in particular.
- The only critical established assumption is that wakes are important for dissipative centrifugally-supported systems. Hence, gravitational dynamics, the PI's strong suit, remains the driving force, setting the pace for other processes (turbulence, SF, Feedback).

• To what extent does the proposal involve the development of novel methodology?

- The methodology is novel, both when contrasted to the field as a whole (which overwhelmingly relies on simulations) and to the community of secular dynamicists specifically, who mostly focus on collisionless dynamics: *CosmicEmergence* will embrace the impact of hydrodynamical processes explicitly but differently, since it is self-catalytic in this context. It will also capture gravity-driven processes operating differently on multiple scales, working to spontaneously set up the observed remarkable robust level of self-regulation, operating within some range of sub-grid physics.
- This line of investigation will conversely likely prove complementary to cosmo-hydrodynamicists who struggle to produce statistical sets of simulations which cover all relevant scales simultaneously.

• To what extent are the proposed timescales, resources & PI commitment adequate and properly justified?

- Within the proposed timescale, all WPs (valuable as such) will be completed, since the incremental structure of the modelling in *WP-Quasi* greatly limits the impact of stumbling blocks.
- The requested resources (FTE, hardware, mobility), together with our existing access to other computational resources and numerical expertise, are both necessary and sufficient to warrant success. The PhDs will work on complementary pillars of the programme (resp. linear stability, CGM science, ISM science). The PdFs will co-supervise and tackle with the PI the more challenging aspects of the proposal, helped by our collaborators and visitors (including Pogosyan's sabbatical). They will also provide complementary numerical expertise.
- Having invested in this science since early 90s, the PI is fully committed to making the project a success!

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