Order out of chaos: the emergence of thin galactic discs

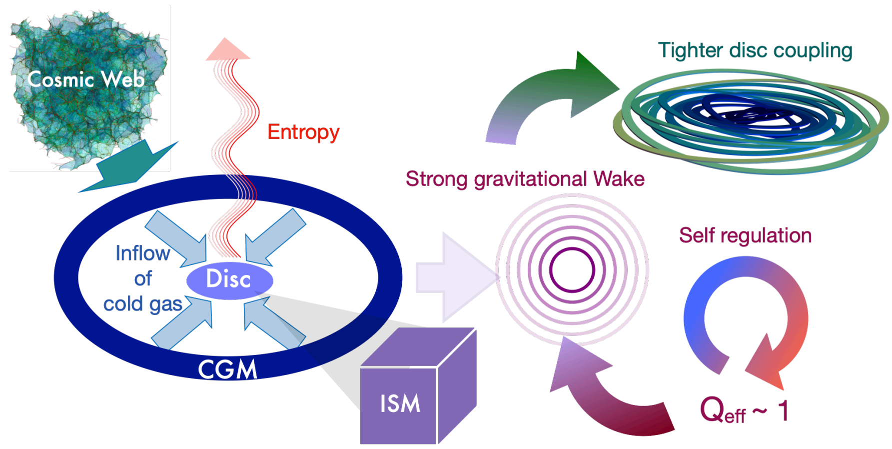
An accurate *modelling of galactic morphological diversity over cosmic time is critical* to achieve high-precision on cosmological parameter estimation with galactic surveys. A key missing piece of our understanding of the universe at large scale is the persistence of thin galactic discs. The operating assumption for their secular 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. The PhD candidate will test whether these tension can be resolved: how can galaxy formation conspire with cosmic flows to set up an efficient homeostatic machine?

Thanks to earlier work, we are now in a position to develop *novel quasi-linear models* for the secular evolution of galaxies to reflect this 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, the PhD candidate will have shown 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. He/she will explain the appearance, and most importantly the resilience of such fragile galactic structures within the Hubble sequence. As a *testbed for emergence of homeostasis* in a simple gravity-dominated context, it will also prove critical beyond the scope of galaxy formation, or indeed astrophysics.

Why do thin galactic discs survive in the concordance model? This question has long been set aside as an obvious consequence of angular momentum conservation. The true answer is more subtle and enlightening for astronomy. It must involve capturing gravity-driven processes operating on multiple scales, working to spontaneously set up a remarkably robust level of self-regulation, **which begs for an explanation now!**

Upshot: The PhD candidate will rely on the conjunction of analytic and numerical methods — calculation of linear response operators, stochastic/finite element implementation of sourced and self-regulated quasi-linear equations— and the analysis of dedicated numerical simulations to quantify statistically the environment and validate the logistic parametrisation. 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 scale.

The PhD candidate will then carry out a local vertical analysis of disc growth and resilience and identify the set of partial differential equations capturing the homeostasis of the disc. He/she 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, she/he will then implement the orbital diffusion via steps of increasing complexity/realism/risk. He/she will finally compare our stochastic estimates of the system's global secular response to cosmological simulations and observations.



The interplay between the three co-evolving galactic components, the ISM, the disc and the CGM (*bottom-left*) sets up an emerging dissipative machine, which, through wakes, achieves both self-regulation and stiffening (*right*). Inflowing cold gas lowers $Q_{eff}=(Q_{gas}^{-1}+Q_*^{-1})^{-1}$, 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.

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, including our own Milky Way. *Understanding the long-term survival of these discs is therefore an essential ingredient of modern cosmology, in order to account for the cosmic evolution of morphological diversity*. 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 formation of thin and thick discs is therefore *an important puzzle for the theory of galaxy formation*. The epoch of cosmic disc settling, a few Gyrs ago, *allows secular 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 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).

The PhD candidate 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 of increasing efficiency with cosmic time: the thinner the disc, the more self-regulated; the tighter the internal coupling, the thinner the disc. *Thin galactic discs are therefore the result of homeostatic processes 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. This PhD proposal will explain and model how this self-regulation accounts for this observed but 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 jointl*y.

While the resilience of thin galactic discs has been observed for decades, and seems to occur generically in sufficiently resolved hydrodynamical zoom-in simulations, it was only very recently measured statistically (e.g. within the unbiased sample of *NewHorizon* galaxies) that disc settling correlates with convergence towards Toomre's $Q_{\rm eff}{\sim}1$ (Toomre'81). 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 therefore of prime interest to re-analyse and theoretically understand hydro-dynamical simulations within that framework, focusing 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 this PhD.

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 differences: (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.

The PhD candidate will study the resilience of thin galactic discs, relying on such extended kinetic theory, while simultaneously considering 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 *source* term on the set of kinetic equations to account for stellar formation; ii) to properly account for the self-gravity of the centrifugally supported galactic disc and the flow of free energy, so as to model *statistically* its secular evolution as a multi-component, dissipative system. By relying on an orbital diffusion framework as an alternative to classical N-body/hydrodynamical approaches, The PhD candidate will propagate statistics top-down, from the cosmic web down to the interstellar medium (ISM) scales, while accounting for the self-regulating role of the dissipative component.

Goals and milestones: *The PhD candidate'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 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 dynamical times are 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) and a parametric model for stellar injection; to compute the relevant power spectra capturing fluctuations and fluxes at the two boundaries (ISM-disc, disc-CGM); to solve the induced sourced kinetic equations using stochastic differential equations (SDE) and finite element methods (FEM), and identify the asymptotic solutions (geometry of discs and bar/bulge fraction versus cosmic time etc).
3. To cast results in terms of observables, 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, the PhD candidate will aim for a set of three milestones (one per semester):

1/ **MS-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.
2/ **MS-CGM:** Quantify the statistics of fluctuation in 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).
3/ **MS-Quasi:** Extend Fouvry+'17 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 five steps of increasing complexity/realism/risk: i) a strictly local vertical analysis; ii) and iii) a Laplace-Lagrange model of sets of coupled rings (linearised as a first step) iv) a dressed open FP formulation; v) a dressed BL multi-component formulation. Eventually, 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.

Feasibility, risk assessment and mitigation: This PhD proposal 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 should complement, or indeed in some cases rival the well-established hydrodynamical methods. Indeed, gravitational dynamics, the supervisors' strong suit, remains the driving force, setting the pace for other processes. The only critical assumption is that wakes are important for dissipative centrifugally supported systems. The supervisors, Slyz, Devriendt and Pichon have demonstrated via a series of forerunner papers that they control the expertise required to carry out this programme.

Timeliness and importance: Our community invests significant observational resources to understand the evolution of galaxies over a Hubble time, both for its own sake and for the purpose of correcting biasses in cosmological surveys. Classical cosmological hydrodynamical simulations are of course heavily funded throughout. Conversely, we *specifically need* 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 such approaches in specific contexts where the impact of baryons was ignored (e.g. galactic centres). It is high time through this joint supervision to address upfront the more generic situation where the *inflowing baryons play a catalytic role* to set up and self-regulate disc growth. 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 processes, often failing to reproduce secular features (such as galactic bars, Reddish+'21). Their analyses must therefore be *enlightened by modular kinetic theory*, to provide in-depth understanding of the synergy between the relevant physical mechanisms leading to thin disc resilience.

Supervision leadership: The joint research activity of Slyz, Devriendt and Pichon has focused on gravitational dynamics, with a special emphasis on the statistical characterisation of matter. The applicant, Christophe pichon is an expert in theoretical galactic dynamics. His expertise will be complemented by Adrianne Slyz's expertise in ISM turbulence, and Julien Devriendt's in numerical galaxy formation. Our long standing collaboration has led us to explore various topics such as the dynamics of the large-scale structure, the intergalactic and interstellar media and the secular dynamics of galaxies and black holes. We have promoted novel tools and theories to trace and understand the cosmic web in simulations and observations. *This has proven extremely fruitful to understand galaxy formation*.
We have a *proven track record of leading scientific projects* on related topics (3 majors grants: Horizon(-UK) '07, Spine '13, Segal '19), involving training and supervising jointly many PhDs and postdocs and successfully promoting collaborations amongst scientists across the globe.

Perspectives: With the public release of Gaia's data, a detailed theoretical modelling of the long-term evolution of the Milky Way's internal structure is in order. The comparison of simulations and kinetic theory on secular timescales is now also of prime importance for 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 is therefore most important to predict the morphological properties of galaxy *populations* and confront them against simulations and surveys.

While emergence has a strong history e.g. in chemistry and biology, it has less commonly been identified in astronomy. The PhD candidate will show how it operates during disc settling, remarkably only involving fairly simple processes, so that the onset of resilience can be analysed in details. She/he will aim to show that *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 illustration 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.

This proposal overlaps with the following themes of IPI: Formation et dynamique des galaxies – Grandes structures de l'Univers – Matière Noire – Physique de l'Univers – Physique de la gravitation.

arXiv:2009.12373,MNRAS,471,2642, 2017MNRAS.471.2642F, 2021arXiv210501371F, A&A (2015) 584 129 MNRAS (2018), 481.2041H 2012, MNRAS, 427, 3320 2011, MNRAS 418, 2493, 2006, MNRAS, 368, 1657