DOSSIER DE CANDIDATURE AAP 2025 DIM ORIGINES

# ALLOCATIONS DOCTORALES

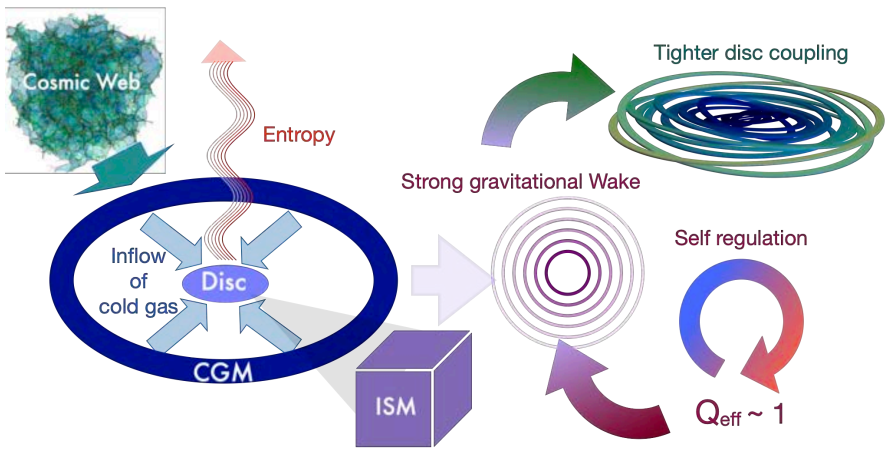
**Acronyme du projet :** **CosmicEmergence**

**Nom - Prénom du porteur du projet :** **Pichon Christophe**

**Laboratoire :** **Institut d'astrophysique de Paris**

**Dossier scientifique :**

## The emergence of Galactic Scaling Laws




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.

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

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

Under the supervision of Christophe Pichon (IAP), Corentin Cadiou (IAP) Maxime Trebitch (***Observatoire***), Julien Devriendt (Oxford) and Katarina Kraljic (Strasbourg), the student will address the following questions within the framework of the SEGAL project (https://www.secular-evolution.org):

- *How can galaxy formation conspire with cosmic flows to set up an efficient self-regulated machine which produces the thin discs that are observed with the James Web Telescope (JWST)?*
- *What are the implications of such self-regulation on the tightness of observed scaling relations?*
- *Why does it matter for morphological survey science?*

Galactic discs are immersed in various sources of perturbations and inflow. The PhD will show that these processes, which in isolation would have a destructive impact on thin discs, in fact conspire to maintain their responsiveness. The emergence —broadly defined as the "*arising of novel and coherent features through self-organisation in complex systems*"— of an improbable ordered structure (a massive yet thin disc) is indeed paradoxically made possible by shocks and turbulence induced in the sub dominant gaseous component, which can radiate most of the entropy generated from the Circum-Galactic Medium, acting as an open reservoir of free rotational energy. The interplay between gravity and baryonic physics set up a self-regulating loop near marginal stability, whose efficiency increases with cosmic time: *the thinner the disc, the more self-regulated; the tighter the internal coupling, the thinner the disc*. This spontaneously emerging self-regulation in turn tightens most galactic scaling laws, as it glues baryonic properties of the galaxies (sSFR, metallicity, stellar surface density etc.) to their dynamical properties (halo mass, angular momentum distribution etc.): disc spontaneously become maximal (MOND like, without MOND). Modelling this self-regulation will be the core science of this PhD. The student will in particular make clear predictions on the disc settling epoch; they will also explain why and how galactic discs conspire to sustain this unlikely state, and what are the corresponding observational signatures.

Thanks to earlier validation of kinetic theory applied to stellar systems, which captured the role of heating via orbital diffusion on discs' secular evolution (Roule+'24), and very recent developments in large deviation theory (which predict scatters, Feliachi+'24), we are indeed *now* in a position to implement open dissipative quasi-linear models to also account for gas cooling, so as to reach a coherent understanding of homeostasis (a.k.a thermal regulation), achieved via gravitational-wake-accelerated feedback loops. The PhD student will therefore model the evolution of self-gravitating discs as emergent dissipative structures, while accounting for the regulating role of inflowing cold gas. When completed, the student will have demonstrated in detail how gravity with baryons provides top-down causation, from the cosmic web, via the circumgalactic medium, down to wake-controlled turbulent star formation and feedback in the intra-galactic medium. The PhD student will explain the appearance, and most importantly the *resilience* over cosmic time of such fragile galactic structures. The student will *co-jointly explain why most galactic scaling laws are so tight*, thanks to this self-regulation which locks halo and galactic properties on attractors.

This will prove enlightening, as an archetype of the emergence of tight scaling relations that can be analysed in detail, while also explaining galactic morphological diversity.

## II Plan de recherche et calendrier : https://tinyurl.com/cosmicemergence

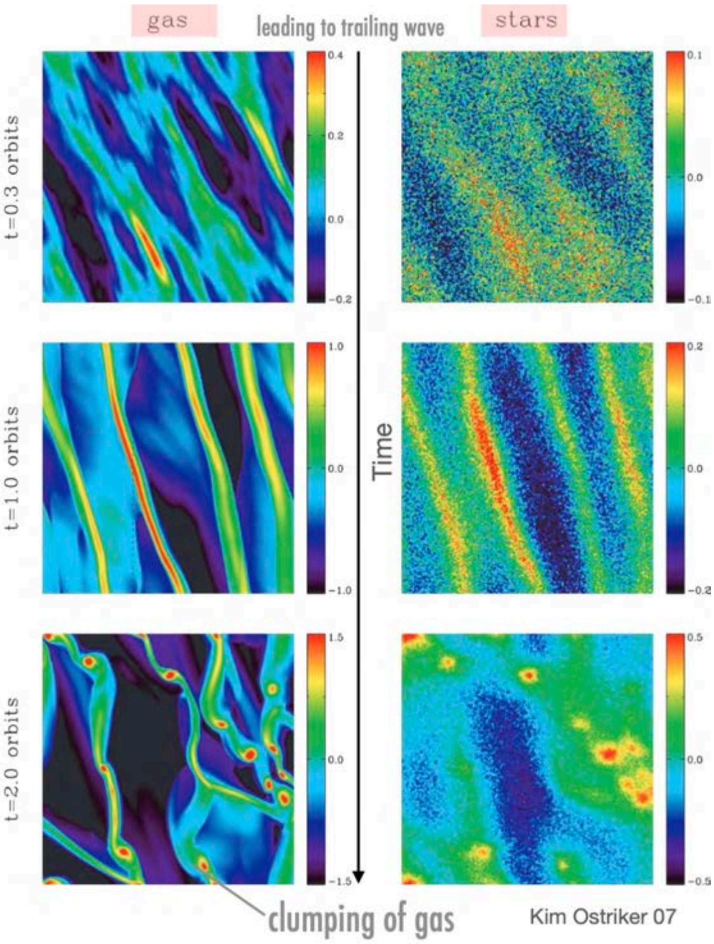
**Goals and milestones**: The PhD' scientific goals are:

I. To demonstrate how gravity-driven baryonic processes operate on multiple scales to spontaneously set up a remarkably efficient level of self-regulation, tightening galactic scaling laws.
II. To develop the theoretical models and the computational algorithms to follow the thinning of discs over cosmic (secular) times, using extended kinetic theories (open, dissipative, large deviation).
III. To cast results in terms of observables (bar/bulge fraction, disc thickness, scaling laws and dispersions of metallicity-kinematic or radial acceleration relation, baryonic Tully-Fisher, Kennicutt-Schmidt, etc) tailored to existing and upcoming facilities.

To achieve these goals, the PhD candidate will aim for a set of three milestones (one per semester):

1rd semester/ **MS-Quasi:** Extend Fouvry+'17, on the secular resonant thickening of self-gravitating discs, while accounting for galactic infall, first with a logistic source term, following steps of increasing complexity/realism/risk: i) within the shearing sheet model; ii) via a Laplace-Lagrange model of sets of coupled rings iii) via a dressed open multi-component Fokker Planck formulation.
2st semester/ **MS-LDP:** using large deviation theory, understand how, while the discs settle, the scaling laws tighten, reflecting the modulation of both orbital diffusion and star formation by the same confounding factor, proximity of galaxies to marginal stability, which acts like an attractor.
3nd semester/ **MS-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. 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 and radial transport of mass and angular momentum). Quantify how this impacts morphological diversity.




An unwinding gas +star spiral in a metastable disc clumps strongly at maximum amplification; this connects disc scales to the onset of the turbulent cascade leading to star formation. The closer the disc to marginal stability, the stronger the effect.

**Feasibility, timeliness and importance:** 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 perturbative theory and stochastic methods. The expertise of Maxime will be critical to help the student develop the computational algorithms to follow the thinning of discs over cosmic (secular) times, and measure the ingredients entering extended kinetic theories (open dissipative). This will involve quantifying the mean field, the actions and the distribution function of the galactic disks extracted from the cosmological simulation **NewHorizon** in order to carry out a statistical analysis (ensemble average, cosmic variance). The student will also characterise the spectral properties of the galactic cosmic environment (power spectrum of the fluctuations in the force field and fluxes at the two boundaries: ISM-disc, disc-CGM). The induced orbital scattering will be quantified independently in simulations. A 30 000 000 CPU hours application has been submitted to GENCI (TMP33736, PI Renaud). The present PHD project is a natural follow-up of Aubert, Fouvry, Rozier, Cadiou, Welker, Tep and Roule's PhDs, who addressed various aspects of the premises of this work.

**Impact sociétal :** Understanding emergence, a fairly universal process (snowflakes, hurricanes, life, etc) in the context of such a simple system (where gravity drives the show) is clearly of general societal interest, because it can be studied both at a microscopic (the stars) and mesoscopic (the homeostatic machine obeying open kinetic theory) level. Sharing this knowledge has proven popular with the general public. This aspect of the work will therefore continue to be advertised (such as this public lecture, the RER-B exhibit below, or online https://www.cosmic-evolution.org). We will aim to present


our simulations in the La Villette planetarium (in collaboration with A. Riazuelo). All aspects of this work are of course open science. Note that this line of research also provides means of studying the long-term evolution of galaxies without relying exclusively on energy intensive hydrodynamical simulations.

**Impact économique :** The economic implications of this line of work are indirect yet significant. Self-regulation operates throughout many aspects of robotics and automation, hence understanding how and when it occurs spontaneously in nature is of interest, if only to understand how robust a given system can be. Galactic disc's cosmic resilience provides a specific simplified playground where the nature and limitation of self-regulation can be studied in details to address generic questions such as "*when and why does the self-regulation break down?*", "*How to anticipate the corresponding bifurcations?*". Emergence generically operates near phase transition, as the result of non-trivial solutions to reaction-diffusion processes. The mathematics of such processes has tight connection to chaos theory, and is of interest in the context of modeling complex systems (solid state physics, electronics, climate change, cybernetics, etc). As such, the mid-term economic impact of the applicant's work should be significant.

## CV du directeur de thèse :

Born: 7 May 1968 (56 years old) http://www.iap.fr/users/pichon ORCID: 0000-0003-0695-6735

I have spent most of my career at *Institut d'Astrophysique de Paris* after a 5 years period at *Observatoire de Strasbourg* and sabbaticals at Oxford, Cambridge, Edinburgh and Seoul. My research is focused on theoretical and computational gravitational dynamics, from black holes to the large-scales structure of the Universe. I have published 210 refereed publications (150 in the last 10 years), 46 of which have over 100 citations. My papers have over 20 000 citations (H=65).

### EDUCATION

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| 2008 | Habilitation: Gravitational structuration mechanisms : theory and estimation. |
| 1994 | PhD : *Dynamics of self gravitating disc* with D. Lynden-Bell, Cambridge University, UK |
| 1989 | Master: DEA d'Astrophysique Graduate school of Ile-de-France. |
| 1988 | Selected at Ecole Normale Superieure de Lyon, France. |

### CURRENT & PREVIOUS POSITION(S)

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| 2021- | Research director, first class, CNRS, UMR 7095, Institut d'astrophysique de Paris, Fr. |
| 2011-2020 | Research director, 2nd class, CNRS, UMR 7095, Institut d'astrophysique de Paris, Fr. |
| 2004-2010 | Researcher, CR1, CNRS, UMR 7095, Institut d'astrophysique de Paris, Fr. |
| 1998-2004 | Junior Researcher, CR2, CNRS, UMR 7550, Observatoire de Strasbourg, Fr. |

### FELLOWSHIPS AND AWARDS

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| 2018 | Research supervision award CNRS. |
| 2018 | Scottish University Physics Alliance distinguished visitor Edinburg. |
| 2015-2025 | Korean Institute of Advanced Studies Scholarship Seoul. |
| 2014 | Churchill College-CNRS fellowship, University of Cambridge. |
| 2014 | Excellence research reward CNRS. |
| 2013 | Sackler visiting fellowship, University of Cambridge. |

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| 2010 | Merton College visiting Professorship, University of Oxford. |
| 2009 | Leverhulme Professorship, University of Oxford. |
| 1992 | Knight Prize * University of Cambridge. |

## SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS

I have (co-)supervised 17 predoctoral and 19 PhD students (two ongoing), ***eleven*** of whom have now permanent positions in astronomy. Aubert is recipient of the SF2A young researcher, while Codis and Fouvry are best PhD in astronomy respectively. Fouvry is also mention SFP and Springer Verlag outstanding PhD. He was nominated to the Lindau Nobel Laureate meeting. He is also the recipient of le Prix de la Chancellerie (10k€) and ANR tremplin (SESS). Codis got the Prix Merac de la société européenne d'astronomie (110k€) and an ANR grant (Cosmic Spheres 350k€); J. Giral was granted Médaille L.E. Rivot.

E. Ko : "The emergence of thin discs in a cosmic framework" 2023-
M. Roule : *"Kinetic theory of self-gravitating stellar systems"* with J.B. Fouvry, 2024, Paris,
K. Tep : "Secular evolution of stellar spheres" with J.B. Fouvry, 2020-2023, Paris
S. Rozier : "Linear Stability of Rotating Stellar Clusters" with J.B. Fouvry, 2020, Paris,
C. Cadiou : "*The impact of the LSS on dark matter halo and galaxy formation* ", with Y. Dubois 2019,
C. Gouin : "Lensing probing the mass content of the Universe" with R. Gavazzi, 2018, Paris
C. Laigle : "*Constraints on galaxy evolution"* with H.J. McCraken, 2016, Paris.
J.B. Fouvry: "*Secular evolution of self-gravitating systems"*, with J. Binney, 2016, Paris.
C. Welker : "*Gas inflows and mergers shape galaxies*" with J. Devriendt, 2015, Paris.
S. Codis : "*Que nous apprennent les grandes structures de l'Univers*?" D. Pogosyan, 2015, Paris.
C. Gay : "*L'évolution cosmique du squelette de l'Univers*", with D. Pogosyan, 2011, Paris.
J. Thiébaut : "*Reconstruction de champs magnétiques*" with S. Prunet, 2011, Paris.
T. Sousbie : "*Le Squelette de l'univers*" with H. Courtois, 2009, Lyon.
S. Caucci : "*La topologie du Milieu intergalactique*" with P. Petitjean, 2009, Paris.
B. Aracil : "*Étude du milieu intergalactique*" with P. Petitjean, 2007, Paris.
E. Rollinde: "*La physique du milieu intergalactique*" with P. Petitjean, 2006, Paris.
D. Aubert : *"Étude des flux cosmologiques au travers de la sphère du viriel Galactique*", 2004, Paris.
P. Ocvirk : "*Évolution spectro-dynamique des disques galactiques*" with A. Lançon, 2004, Strasbourg.
A. Siebert : "*Structure et dynamique des disques de la Galaxie*" with O. Bienaymé, 2003, Strasbourg.

## ORGANISATION OF MEETINGS & INSTITUTIONAL RESPONSIBILITIES

| | |
|---|---|
| 2023 | "*Cosmic Web 2023*" https://www.cosmicweb23.org 145 pers. Chair US. |
| 2014 | "*Magnetic fields from the sun to black holes*" www.iap.fr/heyvaerts2014, 110 pers. Fr. |
| 2013 | "*The origin of the Hubble sequence*" www.iap.fr/col2013 150 pers, Chair, Fr. |
| 2021 – | System manager of "*Infinity cluster"* infinity-cluster.projet-horizon.fr (850k€). |
| 2015 – | Head of "*Numerical simulations*" at IAP (25 pers.). |
| 2005 –2015 | Head of "*Universe & large-scale structures*" research group at IAP (45 pers.). |
| 2005 –2021 | System manager of "*Horizon cluster*" (1M€). cluster.projet-horizon.fr |

## COMMISSIONS OF TRUST

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| 2020 – | Steering committee of Institut de la Physique des infinis. |
| 2020 | Evaluator for Marie Curie fellowships MSCA-IF. |
| 2016 | Member of Section 17 of CNRS (National Hiring committee) |

## MEMBERSHIPS OF SCIENTIFIC SOCIETIES & MAJOR COLLABORATIONS

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| 2020 –2024 | PI of ANR Secular evolution of galaxies Fr (550k€) ANR-19-CE31-0017. |
| 2014 –2018 | PI of ANR Cosmic origin of Hubble sequence Fr (550k€) ANR-13-BS05-0005 . |

## Liste des publications les plus pertinentes : 1 page maximum


Aubert, D., & Pichon, C. 2007, MNRAS, 374, 877
Balescu, R. 1960, Physics of Fluids, 3, 52
Bar-Or, B., & Alexander, T. 2014, Class. Quantum Grav., 31, 244003
Bar-Or, B., Fouvry, J.-B., 2018, ApJ, 860, 23
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Breen, P.G., Varri A.L., Heggie, D.C. 2017 MNRAS 471, 2778
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Dubois, Y., Peirani, S., Pichon, C., et al. 2016, ArXiv, arXiv:1606.03086
Dubois, Y., Pichon, C., Welker, C., et al. 2014, MNRAS, 444, 1453
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Fouvry, J.-B., Binney, J., & Pichon, C. 2015a, ApJ, 806, 117
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Hamilton, C., Fouvry, J.-B., Binney, J., Pichon, C., 2018, MNRAS, 481, 2041
Heggie, D., & Hut, P. 2003, The Gravitational Million-Body Problem (CU Press)
Heggie, D.C., Breen, P.G., Varri, A.L.2019 MNRAS in press
Heyvaerts, J. 2010, MNRAS, 407, 355
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Peirani, S., Kay, S., & Silk, J. 2008, A&A, 479, 123
Pichon, C., & Aubert, D. 2006, MNRAS, 368, 1657
Pichon, C., & Cannon, R. C. 1997, MNRAS, 291, 616
Pichon, C., Pogosyan, D., Kimm, T., et al. 2011, MNRAS, 418, 2493
Rauch, K. P., & Tremaine, S. 1996, New A, 1, 149
Rozier, S., Fouvry, Breen, P., Varri, Pichon, Heggie, 2019 MNRAS,
Sellwood, J. A. 1984, J. Comput. Phys., 50, 337
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Sellwood, J. A., & Carlberg, R. G. 2014, ApJ, 785, 137
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Varri, A.L et al., 2018 Computational Astrophysics and Cosmology, 5, 2
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Volonteri, M., Dubois, Y., Pichon, C., & Devriendt, J. 2016, ArXiv, 1602.01941
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