Spirals Matter:

The emergence of Galactic Morphology & Scaling Relations

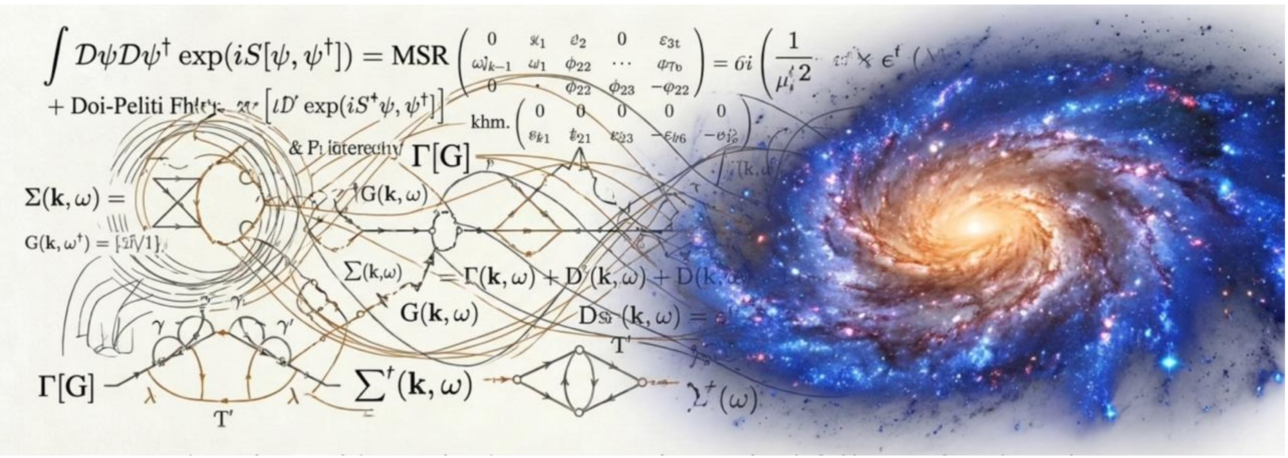
- *Acronym*: *SpiralsMatter*
- *Name of the Principal Investigator (PI)*: Christophe Pichon
- *Name of the PI's host institution for the project*: CNRS (Institut d'Astrophysique de Paris)
- *Proposal duration in months*: 60

Thin stellar discs dominate the star-forming population of the Universe, yet their remarkable stability and star-forming efficiency remain among the most persistent puzzles in galaxy formation.

We posit a *transformative* new paradigm: thin discs emerge and persist naturally through dynamical self-regulation, driven by the interplay between **spiral** wakes, coherent gas inflows, and star formation. Once a stellar disc becomes sufficiently massive to resist disruption, it enters a *homeostatic* state where orbital heating—driven by perturbations—is precisely balanced by cooling from new stars formed on nearly circular orbits. This loop maintains discs close to marginal gravitational stability, enabling them to remain thin, long-lived, and highly efficient at converting gas into stars. This self-regulated attractor state explains the ubiquity, resilience, and tightness of observed galaxy scaling relations, such as the Tully-Fisher laws, without recourse to any finely tuned feedback prescriptions.

To rigorously validate and quantify this framework, *SpiralsMatter* will derive from statistical field theory a novel dressed reaction-diffusion **equation for galactic morphology**, and produce dedicated simulations capturing the emergence and resilience of discs accros cosmic times. These theoretical predictions will then be directly compared to morphological and star-formation data from JWST, Euclid, and LSST.

By enabling precise differential marginalisation over galactic systematics, this ERC will sharpen cosmological parameter estimation. It will shift the field from local empirical calibration to a top-down, gravity-driven theory, and establish galactic discs as benchmarks for self-organised criticality.



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

Spirals are not ornemental, they are the most common galaxies, which
- host strong spiral wakes
- are hosted in thin (improbable & fragile) discs
- are fuelled by cold gas which shocks
- form stars recurrently
- obey galactic scaling laws
- are dominated by their self-**gravity.**

Spirals are the signature of a gravity-driven **homeostat** that arises spontaneously when collisionless dynamics of stars couples with collisional physics of cold gas: it allows gravity to globally control morphology, star formation hence galactic scaling laws.

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

In this context, *SpiralsMatter* will address a set of fundamental questions: *how does galaxy formation interact with the large-scale cosmic flows to build an efficient, self-regulating system that produces these ubiquitous thin discs? How does this gravity-driven regulation compare with the widely used picture of galaxies shaped mainly by stellar or black hole feedback? And why does the persistence of these fragile discs matter for the precision of galaxy surveys?*

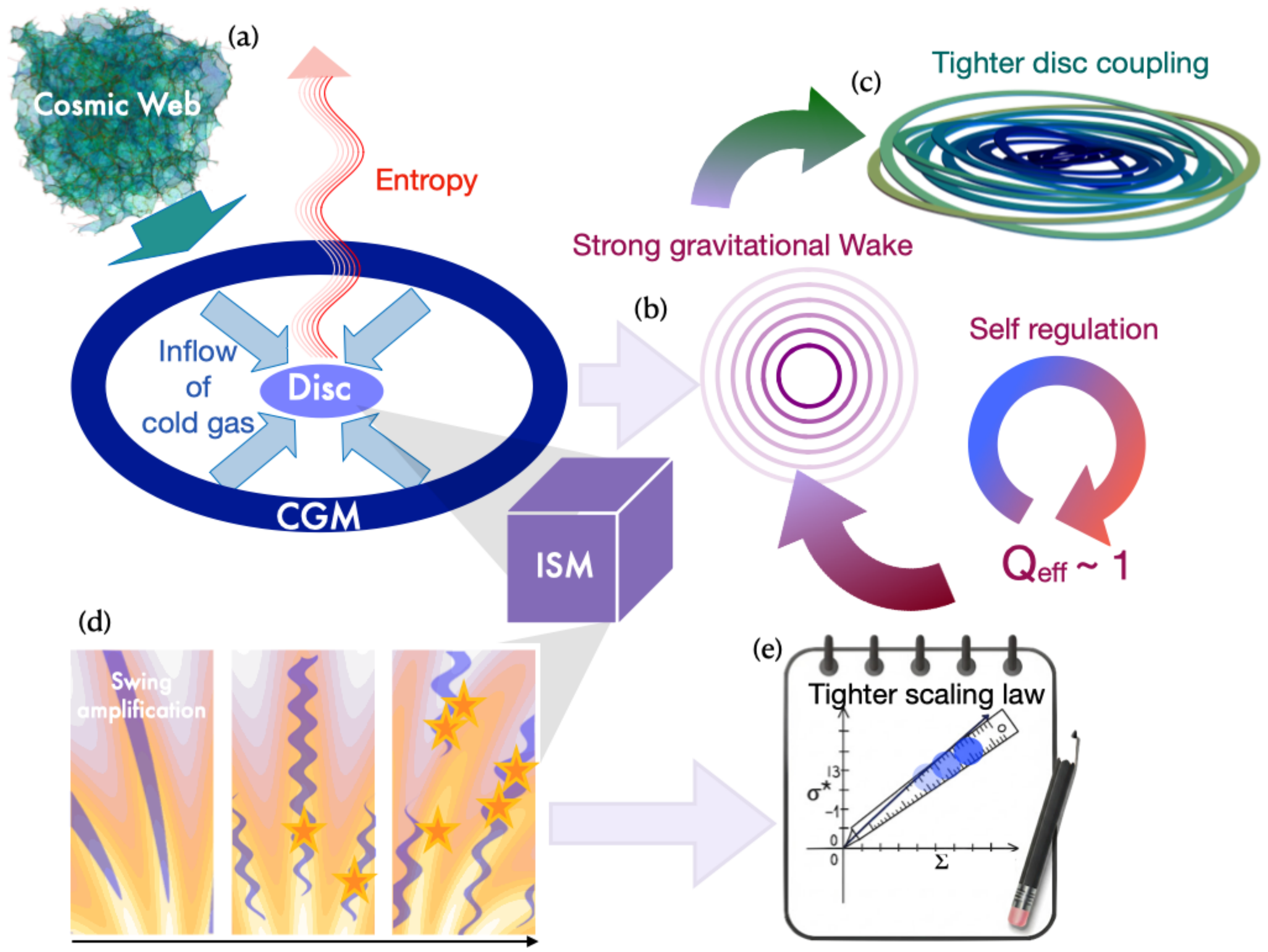
We will challenge the mainstream[59,61,78] understanding of galactic disc formation and stability. We posit that thin galactic discs are not sustained by fine-tuned feedback mechanisms, but rather represent emergent systems driven by gravity and baryonic processes to a state of homeostasis near marginal gravitational stability [fig 1]. *SpiralsMatter* will provide quantitative analytical insight into "why" galaxies behave as they do, complementing the "what" shown by simulations, and ultimately aim to provide models for galactic morphology which will be used to improve cosmological parameter estimation by reducing the corresponding biases.

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

1. Context: Since we formulated it in 2019[89] to explain the stratification in stellar age and height of simulated galactic discs (driven by the cofounding factor of proximity to marginal stability), the emergent scenario has been vindicated by most recent observations on distinct scales and epochs (JWST[117], ALMA, SAMI, GAIA, MUSE), most cosmic simulations resolving spiral structures[1], and our recent extended kinetic theories.

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

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



Synopsis: The interplay between three co-evolving galactic components (a), the interstellar medium (purple), the disc (light blue) and the circum-galactic medium (dark blue), sets up an emerging dissipative machine (b), which, through spiral wakes, achieves both self-regulation and stiffening, (c). Inflowing cold gas lowers the disc's effective temperature, hence triggers wakes and shocks, which sources the turbulent cascade in the ISM through sequences of stellar swing amplifications[51,116], (d), leading to recurrent star formation. The thin disc inherits the coherence of the cosmic web's steadiness[92] (a), through gravitationally-driven top-down causation, but the link is not finely tuned, thanks to the co-induced homeostasis towards stellar marginal stability[89]. The effect of the induced attractor is to "glue" baryonic and dynamical properties together, explaining the ubiquity of tight scaling laws[96], (e). Feedback is not fine-tuned to reach bottom-up baryonic regulation, because it is achieved by the dominant stellar component.

in thin-disc galaxies[117] reflects quiescent, predictable evolution tied to the regulatory attractor[88;]; 7/ the existence of super-spirals in quieter environments[93].

Numerical evidence includes: 1/ simulations of coupled stellar–gas discs confirm that mutual gravity can destabilise an otherwise stable system, with star formation triggered when the two-fluid stability parameter[50,95,73] falls below a critical threshold [fig 4]; 2/ self-gravitating, multi-component simulations show that swing amplification generates transient spiral arms, whose gas fragmentation yields a GMC mass spectrum matching observations[99], linking galactic-scale dynamics to star-forming clouds; 3/ high-resolution cosmological simulations reveal that discs can grow thinner and dynamically colder over time[89], even in chaotic environments, demonstrating the homeostatic resilience predicted by the emergent scenario.

SpiralsMatter aims to *complete the paradigm shift*, and steer the field towards a theoretical predictive understanding of galaxy evolution, which will prove quantitatively useful for cosmology.

SpiralsMatter's approach, formalised via a "dressed" reaction-diffusion equation, will stand in stark contrast to the classical model of galaxy formation, which relies on "bottom-up" feedback, where small-scale events like supernovae explosions were thought to regulate the entire galaxy[6,119]. This methodology, though effective, has clear limitations. First, tuning parameters to match one cosmic epoch undermines predictive power at others, reflecting flexibility rather than physical accuracy. Second, complex sub-grid models entangle processes, obscuring causal interpretation. Third, physically motivated values tied to specific force scales clash with scale-invariant gravity. Finally, the high computational cost of high-resolution runs prevents full exploration of parameter space or the generation of large ensembles needed to quantify intrinsic variance in galaxy properties. In this new framework, small-scale processes do not counteract the infall of gas from above; they resonantly excite heating and star formation within the disc, with a global amplitude which self-tunes to the dynamical cold state of the disc[91]. This explains why, in high-resolution simulations, the specific details of feedback recipes do not matter much, whereas in low-resolution simulations, they must be constantly tuned.

SpiralsMatter will argue that the persistent engine of star formation in disc galaxies is a self-regulating cycle driven by the stellar disc itself, while it remains in a globally dynamically stable state. The stellar disc acts as a pacemaker, generating a continuous sequence of density waves. These waves are powerfully amplified by the disc's self gravity, and their gravitational influence is transferred to the colder, more responsive interstellar gas[106]. It is within this dynamically-coupled gaseous component that instabilities are triggered post shock, leading to a turbulent cascade down to molecular clouds and subsequent episodes of star formation [fig 4]. Because the stellar disc itself never becomes globally unstable, this mechanism can be sustained over cosmological timescales, providing a robust explanation for the long-lived, self-regulated nature of star formation in disc galaxies.

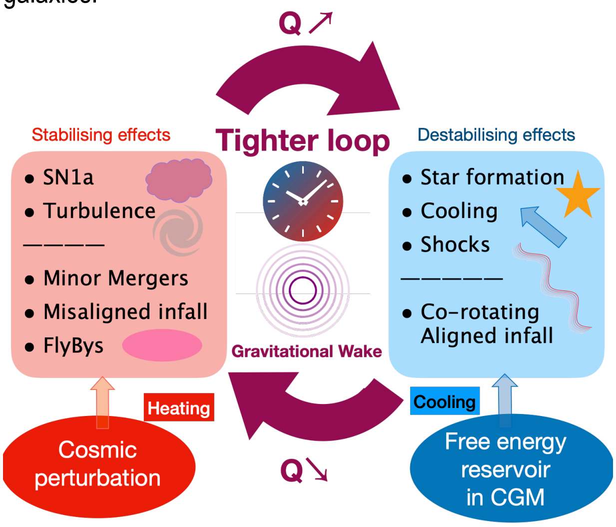


Fig 1: The control loop: in the secular regime, all perturbations generate strong spiral wakes, shortening significantly the effective dynamical time. The induced tighter control loop drives Toomre's effective Q closer to 1, allowing for disc settling. It is an attractor because wakes yield a faster control loop for regulating processes (turbulence, supernovae). This allows the disc to generate order through self-organisation.

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

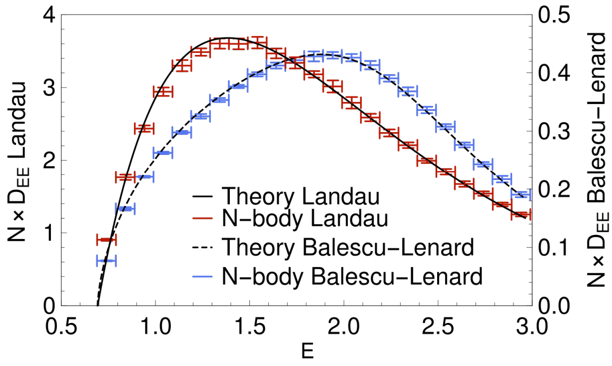


Fig 2: Validation of kinetic theory[101] for the 1D model of vertical oscillation of N planes near the isothermal distribution. Both the predicted Landau (solid) diffusion coefficient and its Balescu-Lenard counterpart (dashed) match the average of many simulations very well (5%). Wakes **stiffens** the disc by a factor of 10. *SpiralsMatter* will revisit this with a 3D model.

2. Method: Because the stellar component usually dominates the baryonic mass and gravity is a long-range force, the amplitude of perturbations is typically weak compared to the galaxy's overall gravitational field. This means their statistical impact can be handled perturbatively, which is a theoretical game-changer. This project's key insight is that the model's corresponding master equation can be given as a "dressed" reaction-diffusion equation derived from kinetic theory. The secular evolution of stellar discs has been studied for decades through the lens of kinetic theory.[2] Foundational concepts include the heating of the stellar disc and the increase of stellar velocity dispersions over time, driven by scattering off gravitational perturbations like giant molecular clouds. These processes are formally described as a form of orbital diffusion. The dressed reaction-diffusion framework proposed in *SpiralsMatter* is a natural extension of this formalism. The diffusion term in the master equation directly corresponds to the established heating and scattering processes that drive orbital diffusion. The novel reaction term reflects the countervailing processes of gas cooling, accretion, and subsequent star formation, which act to reduce the disc's dynamical temperature. The last crucial physical element is the spontaneous dressing of the equation, which incorporates quadratically the collec-

[2] Beyond linear response, statistical physics tells us that the evolution of the mean field and of the system's susceptibility must be considered jointly. At this level of nonlinearity, when coupled to a dissipative component, self-regulation can emerge spontaneously, through the adjustment of this susceptibility, which simultaneously accelerates orbital diffusion (heating) and star production (cooling). The attractor corresponds to a thin dynamically robust disc, precisely because it is locked in to be susceptible. Only global three-loop perturbative theory—based on a bi-orthogonal 3PI projection—can rigorously capture this regime, because it broadens resonances and inherits dynamical robustness from the halo (only the gaseous component is unstable). The so-called *Doi-Peliti nPI formalism*[6], developed extensively in condensed-matter and quantum chemistry from a path integral perspective, provides a quantitative framework to describe the coupled evolution of mean fields, propagators and third-order correlations in a self-consistent manner. In this ERC, we will transpose this framework in *global angle actions,* to construct an analogous description of the long-term evolution of galaxies, in which the host galaxy and internal fluctuations within the disc generated by new stars evolve self-consistently over cosmic time. The nPI theory will provide a framework to add non-conservative reaction vertices and predict the stable, self-regulated morphologies observed in deep-field surveys, while avoiding the mathematical singularities and breakdowns that limit traditional analytical approaches. The objective of *SpiralsMatter* is to implement and validate this perturbative theory, translate it into an effective reaction-diffusion equation and confront it with the data. This demonstration will firmly establish the associated paradigm shift. Spiral patterns are not merely ornamental: they are the signature of a global emergent process arising when gravitational forces couple to the gas!

tive gravitational response (the susceptibility) of the disc, capturing the secular effect of a series of swing amplified spirals.

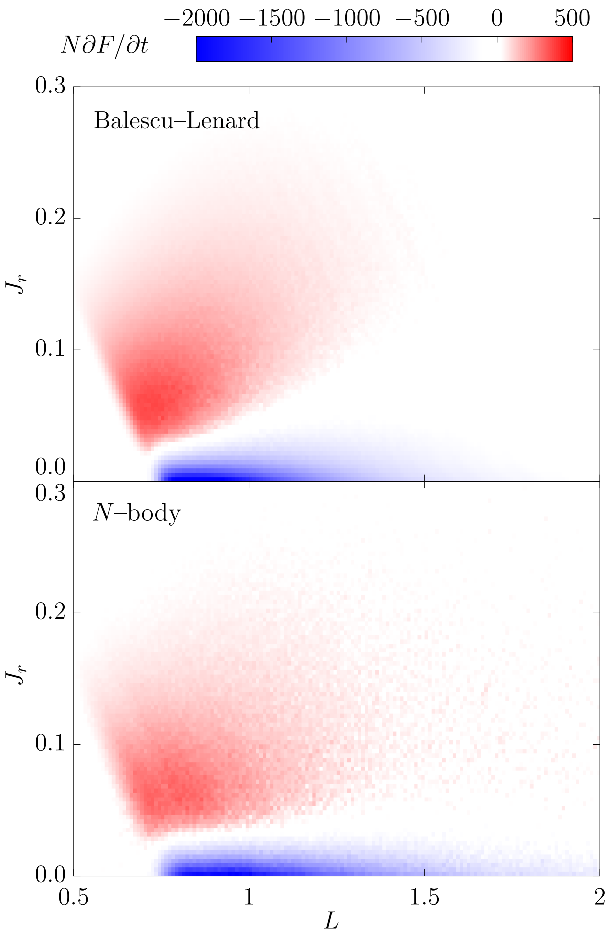


Fig 3: *Top*: kinetic predictions[102] of the mean rate of change for the distribution of stars, ∂F/∂t, from kinetic equations for the long-term evolution of a disc in orbital space in actions space. *Bottom*: Average flux over N body 1000 realisations. The agreement in this shot noise-driven regime is remarkable, as is the **quadratic** boost in amplitude driven by the wakes, which renormalise fluctuations: it's amplitude reflect the global disc state *without fine tuning*! *SpiralsMatter* will account for a) external heating, b) cooling, c) self-regulation & d) expected variations beyond the mean.

This self-consistently accounts for how the disc's own self-gravity mediates the interplay between heating (diffusion) and cooling (reaction), allowing for a fully analytical description of the approach to the homeostatic attractor state. Once validated, this equation will be a major break-through in a field that has almost exclusively relied on computationally expensive N-body Monte Carlo simulations to model gravity. It is an essential tool for providing a deeper understanding that N-body simulations alone cannot offer. The core strategy is to shift the narrative from merely simulating observations, to explaining why galactic evolution occurs, through analytical insights into self-regulation operating in a distinct regime.
The stationary solutions of the reaction-diffusion equation will be computed explicitly. Consequently, galaxy morphology or metallicity[44] will be predicted conditional to a given environment [fig 5] or redshift, and incorporated into physically motivated bias models (e.g., in the context of the cosmic web, clusters, etc.). This will improve the accuracy of standard rulers in cosmology. It will also provide a physical model for galaxy bias. By incorporating this physically motivated understanding of how shape and orientation connects to mass and environment, it is for instance possible to generate more accurate corrections for systematic effects in weak lensing data[49]. This leads to more robust and precise cosmological constraints on the nature of dark energy.

3. Objectives: The goal of *SpiralsMatter* will first be to validate the dressed reaction diffusion framework via idealised models of increasing complexity, relying on the modularity of the perturbative framework:
i) open/closed loop, ii) active/passive potential, iii) with, w/o new stars, iv) with, w/o external noise, v) as a local/global model, 1,2, and 3D vi) conditional to larger scale environment (cluster, group, cosmic web), vii) or while varying the adiabatic parameters of the model (Bulge/disc ratio, M_*/M_{halo} etc).
In doing so, we will investigate the domain of efficiency of the self-regulation and contrast it to the standard paradigm. We will also investigate when it fails, quenching star formation and inducing disruptive morphological transformation. This defines thresholds for unregulated or quenched galaxies, ellipticals, bulges and bars. We will explore the possibility that the two pathways to regulation may not be mutually exclusive but may describe different, complementary phases of a galaxy's life. The bottom-up narrative may explain the chaotic early formation of galaxies while the emergent explanation applies to the remarkably ordered and stable nature of the mature, star-forming disks which are observed later.

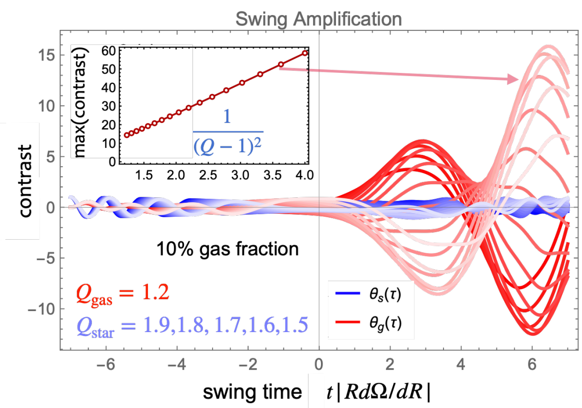


Fig 4: The joint evolution of gas (red) and stellar (blue) spiral contrast, as a function of unwinding time for a sequence of spirals[50] with different gas and star "temperature" labelled by Q. As the noise-driven spiral unwinds, the gravitational coupling between the two components drives a very strong transient amplification of the gas contrast (left), which will non-linearly **shock**[87] and fragment, triggering a turbulent cascade down to star formation scales. *Inset:* the maximum contrast versus gravitational susceptibility of the stellar component, suggesting a quadratic scaling. See also Fig. 6.

4. Expected achievements Within this novel framework, the ERC's 2 postdocs and 3 PhDs will derive and implement these kinetic reaction-diffusion models to predict key observables, which will be compared to the corresponding JWST, Euclid, and LSST data (bar and bulge to disc fractions, scale heights/length, tightness of scaling relations, epoch of disc settling, etc.).

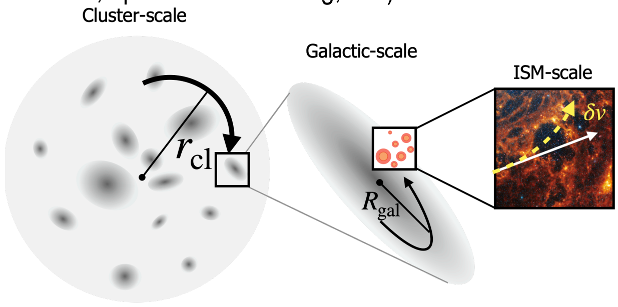


Fig 5: Diffusion coefficients will be computed conditional to a multi-scale environment[44]. Each component contributes to its own power spectrum of fluctuations, which are modulated by the frequencies of the convoluted motion of the stars in the total potential. Jointly with a conditional reaction term, the corresponding reaction-diffusion solution will yield a measure of morphology as a function of cosmic environment.

They will model galactic systematics across different environments and cosmic epochs, sharpening the distance ladder, and correct for morphological biases in dark energy estimates.

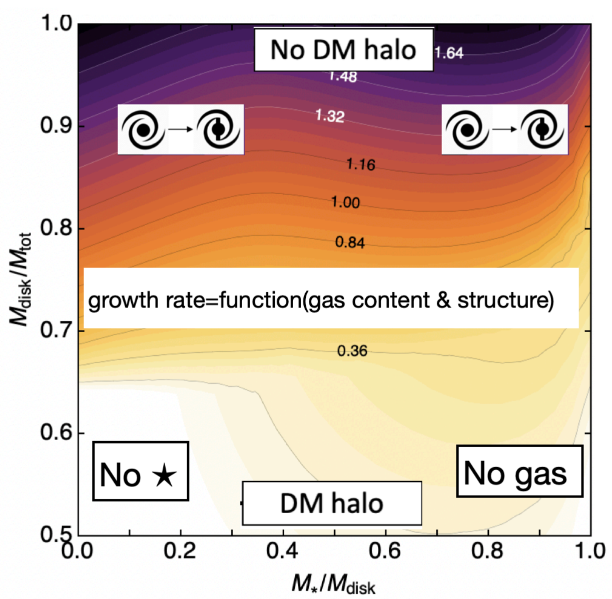


*Fig 6: Linear response of a disc made of stars and gas as a function of the global structure of the galaxie.*This *preliminary* result extends Fig 4 and illustrates how *local* star formation will be impacted by the *global* galactic properties, explaining scaling relations.

Many components of our model are already validated against simulations with remarkable agreement [figs 2,3,6,7]. Thanks to our earlier work on kinetic theory applied to stellar systems, which captured the role of heating via orbital diffusion on discs' secular evolution, we are now in a position to implement open dissipative quasi-linear models to also account for gas cooling, so as to reach a coherent understanding of homeostasis, achieved via spiral-wake-accelerated feedback loops.

When completed, *SpiralsMatter* will capture the evolution of self-gravitating discs as emergent dissipative structures, while accounting for the regulating role of inflowing cold gas[92]. The enduring star formation in disc galaxies is not the product of catastrophic, global instabilities but the result of a subtle and remarkably persistent dynamical engine. The key lies in treating the galaxy as a coupled two-fluid system, where the gravitationally stable stellar disc provides the impetus for instability in the more responsive interstellar gas. Through the mechanism of swing amplification [fig 4], the disc transforms its own noise into a sequence of transient density waves. These waves organise the gas into the dense structures needed for star formation, creating a self-regulating, homeostatic cycle that can be sustained over the lifetime of a galaxy

This model provides a compelling physical explanation for the longevity of star formation, resolving the paradox of how galactic discs can be both stable enough to survive for eons and active enough to continuously create new generations of stars. We will have demonstrated in detail how gravity with baryons provides *top-down causation*, from the cosmic web, via the circumgalactic medium, down to wake-controlled turbulent star formation and feedback in the intra-galactic medium. It will explain the appearance, and most importantly the resilience over cosmic time of such fragile galactic structures. It will also jointly explain why most galactic scaling relations are so tight, thanks to this self-regulation.

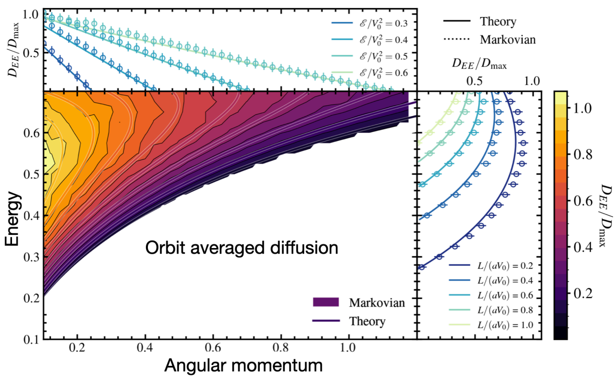


Fig 7: Predicted and measured orbit averaged diffusion induced by exploding supernovae as a function of energy and angular momentum (preliminary). *SpiralsMatter* will include their diffusive impact to account for the corresponding baryonic physics in driving the secular evolution of galaxies.

SpiralsMatter will also help the community to move away from a dependence on empirical calibration and towards embracing the physics of complexity. The current practice of using sub-grid models will be superseded by a methodology derived from statistical field theory. Our approach will predict ensemble averages and statistical dispersions, an important capability for interpreting large surveys. This ERC will have addressed the most pressing questions in galaxy evolution by offering tools to create physically motivated models of galaxy morphology, to mitigate systematic biases in large-scale surveys like Euclid and LSST. It finally will reframe the theory of gravity where it belongs, at the heart of galactic astrophysics.

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ORCID: 0000-0003-0695-6735

My research is focused on theoretical and computational gravitational dynamics, from black holes to the large-scales structure of the Universe. I have published 235 refereed publications (150 in the last 10 years), 50 of which have over 100 citations. My papers have over 23 000 citations (H=70).

EDUCATION

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)

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.
2015-2025	(First astronomy) KIAS Scholar, Korean Institute of Advanced Studies, Seoul, Korea.
2018	Sabbatical at Institute for Astronomy, Royal Observatory University of Edinburgh, UK.
2015	Sabbatical at Churchill College, Institute of Astronomy, University of Cambridge, UK.
2010	Sabbatical at Merton College, Astrophysics, Department of Physics, Oxford, UK.
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

2025	Kyung Hee Eminent scholar Korea.
2018	Research supervision award CNRS.
2018	Scottish University Physics Alliance distinguished visitor Edinburg.
2015	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.
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 16 predoctoral and 20 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 Prix de la fondation CFM (120k€) le Prix de la Chancellerie (10k€). Codis got in 2018 the Prix Merac de la société européenne d'astronomie (110k€). J. Giral was granted Médaille L.E. Rivot.

1. M. Iancu   : "On the emergence of thin discs" 2026-
2. E. Ko   : "The impact of superbubbles on dark matter cusps" 2023-
3. M. Roule   : *"Kinetic theory of self-gravitating stellar systems"* with J.B. Fouvry, 2024, Paris,
4. K. Tep   : *"Secular evolution of stellar clusters "* with J.B. Fouvry, 2023, Paris,
5. S. Rozier   : *"Linear Stability of Rotating Stellar Clusters"* with J.B. Fouvry, 2020, Paris,
6. C. Cadiou* : "*The impact of the LSS on galaxy formation* ", with Y. Dubois 2019,
7. C. Gouin* : "Lensing probing the mass content of the Universe" with R. Gavazzi, 2018, Paris
8. C. Laigle*   : "*Constraints on galaxy evolution"* with H.J. McCraken, 2016, Paris.
9. J.B. Fouvry*: "*Secular evolution of self-gravitating systems"*, with J. Binney, 2016, Paris.
10. C. Welker*   : "*Gas inflows and mergers shape galaxies*" with J. Devriendt, 2015, Paris.
11. S. Codis*   : "*Que nous apprennent les grandes structures ?*" with D. Pogosyan, 2015, Paris.
12. C. Gay   : "*L'évolution cosmique du squelette de l'Univers*", with D. Pogosyan, 2011, Paris.
13. J. Thiébaut : "*Reconstruction de champs magnétiques*" with S. Prunet, 2011, Paris.
14. T. Sousbie* : "*Le Squelette de l'univers*" with H. Courtois, 2009, Lyon.

15. S. Caucci : "*La topologie du Milieu intergalactique*" with P. Petitjean, 2009, Paris.
16. B. Aracil : "*Étude du milieu intergalactique*" with P. Petitjean, 2007, Paris.
17. E. Rollinde*: "*La physique du milieu intergalactique*" with P. Petitjean, 2006, Paris.
18. D. Aubert* : "*Étude des flux cosmologiques au travers de la sphère du viriel Galactique*", 2004, Paris.
19. P. Ocvirk* : "*Évolution spectro-dynamique des galaxies*" with A. Lançon, 2004, Strasbourg.
20. A. Siebert* : "*Structure et dynamique des disques de la Galaxie*" with O. Bienaymé, 2003, Strasbourg.

My past students' expertise ranges from the analytical (Fouvry, Tep, Gay, Codis, Rozier, Roule, Ko) to the highly numerical (Aubert, Welker, Laigle, Gouin), with expertise in inverse problems (Thiébaut, Ocvirk, Siebert, Aracil) or computational geometry (Sousbie, Cadiou).
I have co-supervised 20 postdocs: Scannapieco, Ocvirk, Le Borgne, Kimm, Peirani, Sousbie, Dubois, Chisari, Feix, Uhlemann, Codis, Benoit-Levy, Musso, Shim, Lee, Shin, Hwang, Song, Kraljic and Rhee.
My students and postdocs have pioneered the largest simulations in cosmology using dark matter (Horizon, 6144 cores,'07), hydrodynamics (Marenostrum 2048 cores, '08, Horizon-AGN, 4096 cores,'14, NewHorizon 4096 cores,'18, HR5 131 072 cores,'21), and ray tracing (18,688 cores, Cosmic Dawn,'15).

TEACHING ACTIVITIES

2016 – 2024	Lecturer – Large Scale Structures statistics and dynamics, Korea
2009	Lecturer – LSS dynamics, Physics Department, University of Oxford, UK
2006 – 2014	Lecturer – Gravitational dynamics, *Astrophysics graduate studies* UPMC Fr
2006 – 2007	Lecturer – Inverse methods, *Astrophysics graduate studies* UPMC Fr

ORGANISATION OF MEETINGS & INSTITUTIONAL RESPONSIBILITIES

2024	"*Segal ANR meeting in Nice 2024*" https://nice.secular-evolution.org/ 30 pers. Chair Fr.
2023	"*New simulations for problems in galaxies*" https://iapsymposium2023.org 125 pers.
2023	"*Cosmic Web 2023*" https://www.cosmicweb23.org 145 pers. Chair US.
2020 –	"*Segal ANR virtual bi-monthly recurrent meeting*"; secular-evolution.org 20 pers. Chair Fr.
2018	"*Spine ANR Farewell meeting*"; cosmicorigin.org/farewell 25 pers. Chair Fr.
2017	"*Spine ANR Kickout meeting*"; cosmicorigin.org/kickout 25 pers. Chair Fr.
2016	"*Mapping the cosmic web*" UCL-France conf: map.cosmicorigin.org 40 pers. Chair, UK.
2016	"*Secular evolution of self-gravitating systems*" secular.cosmicorigin.org Chair; 60 pers.
2015	"*Spine ANR Cambridge meeting*" Chair; cosmicorigin.org/cambridge 40 pers. Chair UK.
2015	"*Spine ANR Kickoff meeting*" Chair; cosmicorigin.org/kickoff 40 pers. Chair Fr.
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

2020 – 2024	Member 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)
2013 –	Referee for European Research Council ERC, Prace (HPC), and french ANR

MEMBERSHIPS OF SCIENTIFIC SOCIETIES & MAJOR COLLABORATIONS

2026 –2030	CoI of ANR GalBar Fr (590k€) ANR-25-CE31-4684.
2020 –2025	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 .
2005 –2008	Co-I of ANR Horizon (500k€) Fr (Cosmological simulations)

TRACK RECORD

As a theoretician I have always had as a priority to connect measurements with the underlying *physical processes*, relying on extensive *mathematical* descriptions and state-of-the-art cosmological simulations. My publication-record reflects this dual expertise.

My research activity has focused on *gravitational dynamics*, with a special emphasis on the *statistical* characterisation of matter. I have in particular analysed the instability and secular mechanisms driving the evolution of galaxies embedded in their environment. This investigation has led me 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. I have developped novel tools and theories to trace and understand the cosmic web in *simulations* and observations. This has proven extremely fruitful, both from the point of view of cosmology (using the web as a ruler), but also to understand galaxy formation (quantify statistically how the large-scale structures impact embedded galaxies). I have also published ~25 papers on alternative probes of dark energy relying on topology, theory of extrema, spherical count-in-cells in the large deviation limit and redshift distortion. I am now a recognized expert in galaxy formation and numerical simulations. I have a proven track record of leading scientific projects, involving training and supervising many PhDs and postdocs, and successfully promoting collaborations amongst scientists across different institutions. I have directly supervised five PhD students who developed state-of-the-art filament tracers (Sousbie), the corresponding theory (Gay) or applied it to understand how cold flows build up the angular momentum of high-redshift galaxies (Codis, Welker, Laigle).

I have explored the impact of this *large-scale* cosmic web on the origin of the so-called Hubble sequence, which classifies galaxies based on their shape. I relied on observations and numerical expertise to automate the extraction of filaments and morphological parameters of galaxies from mock, public and proprietary catalogues. I interpreted galaxy evolution within the complex anisotropic 3D structure of this web, and demonstrated that filamentary flows feed specifically the angular momentum of discs (Pichon+'11).

I provided a critical assessment of the respective roles of merger/interaction history, and the evolution driven by instabilities, stellar and AGN feedback as a function of cosmic time. I co-produced state-of-the-art "full-physics" cosmological simulations (Marenostrum'07, Horizon'08, Horizon-AGN'14, New Horizon'18), theoretical priors, and surveys to disentangle the relative effects of all these interconnected influences, which are crucial for a detailed understanding of the acquisition of angular momentum driving the morphology of galaxies. The highlights of my work in this field of research are novel theories for conditional spin alignment (see Codis+'12,15, Laigle+'15), conditional excursion set (Musso+17', Kraljic+18'), critical events (Cadiou+20'24'), and cosmic web connectivity (Codis+18', Kraljic+'19,'20, Laigle+'20,'26). This field has become very popular. The corresponding extensive numerical expertise enables me to rigorously *disentangle* and assess the respective contributions of subgrid physics and gravity to the secular evolution of galaxies.

In parallel, I worked on *smaller scales* on the secular evolution of stellar systems driven by discreteness, and their cosmic environment (with Aubert, Kimm). With Fouvry, Rozier, Tep, Roule and Ko, I have investigated *analytically* the secular transformation of cusps into cores, radial migration, Galactic centre and globular cluster dynamics and disc thickening. This work is both original, as it relies on very recent breakthroughs in kinetic theory, some of which I initiated[3], but also the natural consequence of a recurrent focus of my research: to promote these statistical approaches – which have been the successful backbone of large-scale structure cosmology – to galactic scales, in order to follow their evolution as a population over cosmic time. My outstanding past contributions to this field of research have been accounting for the secular evolution of open systems (Pichon+'06) and implementing the Balescu-Lenard equation to stellar thin discs for the first time (Fouvry+'15-21, Rozier+'22,24), and in the process demonstrating *why* swing-amplified sequences need not be correlated to account for the formation of ridges in action space.

SpiralsMatter groundbreakingly builds up on coalescing these large and small-scale works. In Park+'19, Pichon+'23, Hong+'24, Jackson+'25, Oh+'25, I indeed recently identified in observations and simulations the cosmic appearance of thin galactic discs as an emerging process. We now must capitalise on these findings. The current state of affairs has revealed challenges that cannot be overcome by computational power alone; it requires new analytical insights. *SpiralsMatter* presents a path forward, offering a first-principles theory for how the universe's most ordered structures sustain themselves. By doing so, *SpiralsMatter* will not only resolve long-standing questions in galaxy formation but will also provide the robust theoretical toolkit needed to fully capitalise on the next generation of cosmological surveys.

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[3]The kinetic theory[5] of self-gravitating systems has been a fruitful field of research. In our group at the institut d'astrophysique de Paris first presented the formalism[91], and a first explicit implementation[29] to explain the spontaneous formation of ridges in action space reminiscent of those observed by Gaia. Subsequently, we explored their spontaneous secular thickening[33]. We applied it to galactic nuclei[35], and showed that the Balescu-Lenard equation is the master equation for the scalar resonant relaxation for the S-stars observed around SgrA*[117]. We showed how the kinetic framework describes the slow relaxation of globular clusters[117], alleviating intrinsic limitations of the Coulomb logarithm. Finally we very recently showed how wakes stiffen the disc[101] [fig 3] and drastically accelerate orbital diffusion[102] [fig 2].

Research achievements.

I have chosen the most novel papers relevant to this proposal, *not* the most cited ones. This work is done in collaboration with my students and postdocs (underlined) they are therefore first authors by tradition within our group. The last two, beyond the 10 years period, are central to this proposal.

1. Roule, M, Fouvry, J.B, **Pichon**, C, & Chavanis, P.H "The long-term evolution of razor-thin galactic discs: Balescu-Lenard prediction and perspectives" 2025, Astronomy and Astrophysics
This key recent paper shows that self gravity dramatically accelerates secular evolution in thin discs [fig 2]. It validates quantitatively the corresponding secular kinetic equation against ensemble averaged simulation.
2. Petersen, M., Roule, M., Fouvry, J.B, **Pichon**, C., & Tep, K. Predicting the linear response of self-gravitating stellar spheres and discs with LinearResponse.jl 2024, Monthly Notices of the Royal Astronomical Society
This paper presents a versatile public toolbox to compute rigorously the linear response of self gravitating discs, which we developed for the purpose of this programme.
3. Roule, M., Fouvry, J. B., **Pichon, C**, Chavanis, P.H. "Long-term relaxation of one-dimensional self-gravitating systems", Physical Review E, Volume 106, Issue 4, (2022)
This paper shows that self-gravity stiffen discs in the secular regime [fig 3]. It validates quantitatively at 5 % level the corresponding secular kinetic equation against ensemble averaged simulation.
4. Park, M. ; Yi, S K. ; Peirani, S; **Pichon, C** ; Dubois, Y; Choi, H; Devriendt, J; Kaviraj, S; Kimm, T; Kraljic, K; Volonteri, M. "Exploring the Origin of Thick Discs Using the NewHorizon and Galactica Simulations" ApJS, 254, pp. May (2021)
This paper first presented the argument behind gravitational self-regulation, the premise of SpiralsMatter.
5. *Fouvry*, J-B, **Pichon, C,** Chavanis, P.-H., and Monk, L.: Resonant thickening of self-gravitating discs: imposed or self-induced orbital diffusion in the tightly wound limit, MNRAS,471,2642 (2017)
This paper presents theoretical premisses of this proposal, focusing on the secular growth of disc thickness.
6. *Fouvry*, J.B; **Pichon, C**.; Magorrian, J.; Chavanis P.H. "Secular diffusion in discrete self-gravitating tepid discs **II**: accounting for swing amplification via the matrix method" A&A (2015) 584 129
This paper is the first implementation of the inhomogeneous Balescu-Lenard equation in science: this proof of concept paper was the paradigm around which this proposal operates (linear & quasi-linear response).
7. *Hamilton,C.; Fouvry*, J.B; Binney J. ; **Pichon, C**.; "Revisiting relaxation in globular clusters" MNRAS (2018).481.2041H
Together with Fouvry 2021+ this is the first implementation of the Balescu-Lenard equation to a spherical cluster. It derives the generalization of Chandrasekhar's formula when accounting for its self-gravity.
8. *Fouvry*, J.B; **Pichon, C**.; Chavanis P.H. "The secular evolution of discrete quasi-Keplerian systems. **II**. Application to a multi-mass axisymmetric disc around a supermassive black hole" A&A, 2017
This paper is the first presentation of the inhomogeneous Balescu-Lenard equation near a massive Black Hole. It predicts from first principle the loci of the Schwarzschild Barrier.
9. *Codis*, S., **Pichon, C.**, Devriendt, J., Slyz, A., Pogosyan, D., Dubois, Y., Sousbie, T., "Connecting the cosmic web to the spin of dark haloes: implications for galaxy formation", 2012, MNRAS, 427, 3320
This paper quantifies spin alignment in dark halos w.r.t. the cosmic web, explains the origin of the transition and its implication for galaxy formation (250 citations).
10. **Pichon, C.**, *Aubert*, D., "Dynamical flows through dark matter haloes: inner perturbative dynamics, secular evolution and applications", 2006, MNRAS, 368, 1657
This paper presents the first linear and secular equations for ***open*** *galactic halos, the precursor paper of this ERC.*

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