

The Mysterious Galactic Rings Caught by Space Telescope

The Galactic Heart's Chronicle: Chemodynamical Archives of Galaxy Evolution Histories in Nuclear Rings

M. Steinmetz, S. Kwak, *Institute of Physics and Astronomy, University of Potsdam; Leibniz-Institut für Astrophysik Potsdam*

In Short

- NASA's James Webb Space Telescope has provided exceptionally detailed images of nearby galaxies, resolving at the finest scales observed to date. In particular, the striking presence of bright nuclear rings, where vigorous star formation activities are ongoing, has astonished even experts.
- Stellar bars are known to drive gas inflows, which is expected to result in the formation of gaseous substructures such as nuclear rings. This project will suggest the dynamical conditions and mechanisms governing their formation.
- By employing the SMUGGLE multiphase hydrodynamics model implemented with the AREPO moving mesh code, we perform high-resolution simulations to investigate the chemodynamical properties of nuclear rings.
- The anticipated results will offer theoretical predictions for forthcoming spectroscopic surveys using the 4MOST (4-metre Multi-Object Spectroscopic Telescope), for which the Leibniz Institute for Astrophysics Potsdam (AIP) serves as the leading institution.

About half of the disk galaxies in the local universe feature prominent stellar bars. These bars rotate rapidly and drive galactic evolution by exerting

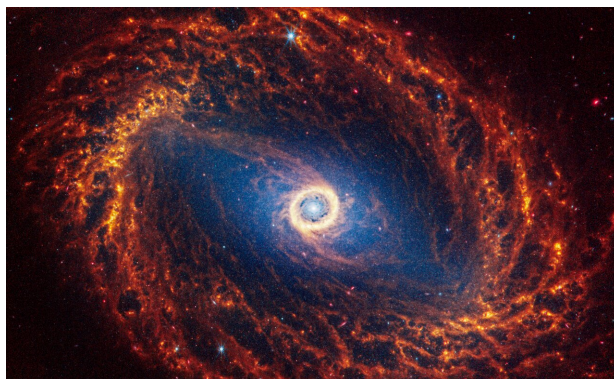


Figure 1: NGC 1512 observed by the James Webb Space Telescope in near- and mid-infrared light PHANGS (the **Physics at High Angular resolution in Nearby Galaxies**) program [1].

non-axisymmetric gravitational torques on gas, forming substructures such as dust lanes and nuclear rings in figure 1. Orbiting gas collides with the bar repeatedly, losing angular momentum and migrating inward to accumulate in a nuclear ring, where intense star formation occurs and chemodynamical history is recorded [2].

Literature on galaxy dynamics shows that bars emerge from gravitational instabilities in isolation or via tidal interactions with nearby galaxies. Bar properties and evolution are highly sensitive to initial conditions, with bar strength varying by over a factor of two. Once formed, bars evolve in strength, length, and pattern speed through angular momentum exchange between stars and dark matter. For instance, adopting fixed potential halos that do not simulate the angular momentum exchange can suppress bar formation entirely. As bars lengthen, imbalances in radial and vertical velocity dispersions trigger repeated vertical buckling instabilities, shortening the bar and creating X-shaped bulges, as observed in the Milky Way. Due to the complexity of realistic bar formation, most studies use fixed potential bars, which cannot capture time-dependent bar evolution, buckling, or resulting chemodynamical diversity—key imprints of galactic history. The only study, without fixed potentials, examining bar and nuclear ring formation and evolution, co-authored by S. Kwak [2], highlighted the role of gas component in redistributing young stars during bar growth. These simulations naturally produce star-forming nuclear rings at bar-forming galaxy centers, but they did not explain ring formation conditions and lack realistic star formation physics including chemical properties.

Future work must expand parameter spaces with broader initial condition variations, incorporate multiphase gas dynamics, increase resolution, and add stellar feedback and metallicity tracking. Simulating realistic galaxies is challenging due to vast dynamical ranges, from sub-pc supernova explosions to Mpc-scale halo assembly. Most simulations use sub-grid models for unresolved processes like star formation, stellar evolution, cooling, supernova feedback, and AGN feedback. Distinguishing resolution limits from physical modeling deficiencies is crucial, with star formation-ISM interactions being paramount beyond gravity and hydrodynamics.

Resolving the multiphase ISM—where hot, warm, and cold gas phases coexist and interact—requires detailed stellar feedback modeling, though this becomes computationally intensive at high resolutions,

especially in cold dense regions demanding short time-steps. Furthermore, traditional models with effective equations of state (e.g., polytropic two-fluid ISM) fail to resolve sub-pc scales, yielding overly smooth structures, unresolved vertical profiles, thicker/hotter disks than observed, and poor small-scale predictions.

To simulate realistic hydrodynamics and feedback, we adopt the Stars and Multiphase Gas in GaLaxies (SMUGGLE) model [3] (figure 2). This explicit stellar feedback framework, designed for the moving-mesh code AREPO, resolves multiphase ISM structure and self-consistently drives gaseous outflows. It incorporates photoionization, radiation pressure, and energy/momentum from stellar winds and supernovae, tested in high-resolution Milky Way-like simulations and featured in recent literature. SMUGGLE regulates star formation to observed levels, reproduces the Kennicutt-Schmidt relation (converged across resolutions), generates outflows with mass loading factors, and links strong outflows to star formation peaks. Much ejected gas recycles via galactic fountains, sustaining late-time star formation and yielding a multiphase ISM with coexisting cold, warm, and hot phases.

We are entering an exciting era swamped by revolutionary discoveries of hidden galactic regions and remote high-redshift periods, made possible by technological progress that provides unmatched observational resolutions. However, the speed and quantity of these discoveries surpass existing theories and simulations, since numerous researchers continue to rely on conventional methods. In particu-

lar, next year will bring a surge of chemodynamical properties observed through the 4MOST survey (the 4-metre Multi-Object Spectroscopic Telescope). This advanced spectroscopic survey instrument is installed on ESO's VISTA telescope and is engineered to collect spectra for as many as 2400 objects at once over broad fields. The consortium is led by the Leibniz Institute for Astrophysics Potsdam (AIP). The instrument is vital for research on galaxy evolution and formation via its extensive surveys that determine redshifts, velocities, and chemical abundances for millions of sources beyond our galaxy. These measurements allow for the rebuilding of assembly histories and the examination of interactions between dark matter halos and baryonic processes.

To account for the observed fine details of galaxies and get ready for the upcoming deluge of observational data, our simulations will incorporate realistic hydrodynamics and chemistry to examine the chemodynamical development of rings. Our setups include (1) high-resolution simulations, (2) responsive dark matter halo particles, (3) parameter surveys of models that form unique bars, (4) multiphase gas dynamics featuring realistic feedback and chemistry, and (5) the inclusion of a realistic circumgalactic medium (CGM) and tidal forcing.

Our objectives address:

- What are the formation conditions of nuclear rings?
- How do bar characteristics influence chemodynamical properties of nuclear rings?
- From the future spectroscopic data by the 4MOST survey, what can we address about the galaxies' early phase from their nuclear rings and bars?

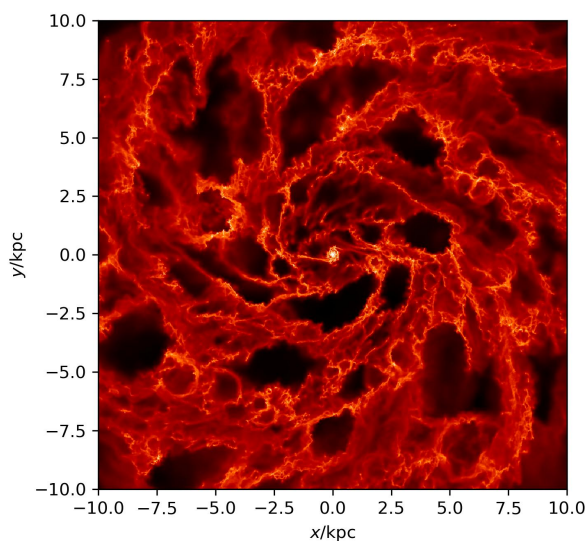


Figure 2: Surface density distribution of gas disk from a simulated galaxy in SMUGGLE.

More Information

- [1] NASA's Webb Depicts Staggering Structure in 19 Nearby Spiral Galaxies
<https://science.nasa.gov/missions/webb/nasas-webb-depicts-staggering-structure-in-19-nearby-spiral-galaxies/>
- [2] W.Y. Seo, W.T. Kim, S. Kwak, P.Y. Hsieh, C. Han, P.F. Hopkins, *ApJ* **872**, 5S (2019). doi:10.3847/1538-4357/aafc5f
- [3] F. Marinacci, L.V. Sales, M. Vogelsberger, P. Torrey, V. Springel, *MNRAS* **489**, 4233M (2019). doi:10.1093/mnras/stz2391

DFG Subject Area

311-01 Astrophysics and Astronomy