Thesis subject

Name of the laboratory: LAM

Thesis advisor: Philippe AMRAM
Email and address: philippe.amram@lam.fr, 38 rue Frédéric Joliot-Curie, Marseille, France
Tel: 04 95 04 41 09

Co-advisor: Benoît EPINAT, LAM

Subject's title:

Kinematic and dynamic of high-z galaxies with PFS on the Subaru Telescope.

Quick Overview of the thesis objectives and methods:

- **For a large sample of high redshift galaxies**
  - Explore the Tully-Fisher Relation (TFR) in the redshift range 0.7<z<2.
  - Identify inner galaxy structures and of infalls/outflows in galaxies.
  - Detect signatures of fusion and interaction between galaxies.
- **Data and Analysis:**
  - Use imagery (HSC and COSMOS HST field) to extract morphological parameters
  - Use spectra (PFS) to extract the kinematical parameters
  - Use different sets of data and simulations to validate the method.

Subject description:

- **The PFS instrument on the SUBARU Telescope:**

The innovative forthcoming instrument PFS (https://pfs.ipmu.jp/) is a spectrograph system with a fiber positioner system to be mounted at the prime focus of the Subaru telescope. A single fiber of 1 arcsec of diameter will be positioned on each galaxy. The light from stars and galaxies are dispersed and recorded as spectra simultaneously covering a wide range of wavelengths ranging from the near-ultraviolet, through the visible, and up to the near-infrared regime, with a spectral power ranging from 2500 to 4500 from 0.38 to 1.30 μm.
The fiber positioner enables us to take exposures of 2,400 astronomical objects simultaneously on a large patch of sky as several times bigger than the full Moon (1.3-degree diameter at a time). The spectrographs of the instrument have been integrated at LAM and the galaxy redshift

measurements will also be done at LAM. PFS is supposed to be ready for scientific use in Fall 2024.

- **MOS versus IFU:**

The kinematic and dynamic study of galaxies ideally requires resolving the galaxies to have spatial information at each point of the galactic field. PFS is a multi-object spectrograph (MOS), it is not a spectro-imager (also called Integral Field Unit, IFU) like e.g. KMOS or MUSE on the VLT and no spatial information is available inside galaxies, so it is not possible to study with PFS the kinematics of individual resolved galaxies. However, in practice, multi-field spectro-imagers like KMOS or wide-field spectro-imagers like MUSE can only observe a small number of galaxies compared to MOS like PFS. The power of PFS is therefore its ability to observe a very large number of galaxies, PFS Galaxy Evolution Survey aims to observe half a million galaxies while the surveys carried out with spectro-imagers are rather limited to a few thousand galaxies for very large surveys (e.g. 740 galaxies for KMOS-3D, Wisnioski et al., 2015 – 1080 galaxies in the MUSE/MAGIC sample, Mercier et al. 2022). On the other hand, the wavelength ranges covered are not the same (MUSE works in the visible and therefore does not have access to the highest redshift).

The challenge that arises with PFS will be to extract the kinematic information from a single spectrum per galaxy, and its great advantage will be to study the kinematic of a large number of galaxies, never reached before, in particular to study the TFR and merger rate.

- **The PFS surveys:**

The PFS Galaxy Evolution Survey is described in Greene et al. (2022). The 130-night program will capitalize on the wide wavelength coverage and massive multiplexing capabilities of PFS to study the physics of galaxy evolution from cosmic dawn to the present. Beyond the measurement of galaxy redshifts which is the main goal of the instrument to study dark matter, dark energy and large-scale structures, medium-resolution PFS spectra could be used for complementary purposes. Redshifts are obtained from the measurement of the barycenters of the emission and absorption lines using gas and stellar populations templates.

However, the shape of the brightest nebular emission lines allows to extract kinematic information in measuring the amount of dark matter for more regular galaxies thanks to the Tully-Fisher Relation (TFR), or the mergers and/or interactions recent history between galaxies for the most disturbed objects. We propose in this thesis to study the kinematic and the dynamic of a large sample of emission line galaxies selected from the forthcoming SUBARU/PFS galaxy sample. The goal is to characterize the kinematic and dynamic properties of young galaxies in analyzing the shape of the main emission lines (Hα, NII, SII, OIII, OII) in different environments, the PSF galaxy survey being designed to probe galaxy evolution in different environments, from cosmic voids and filaments to clusters of galaxies.

- **Methods and goals:**

By using the images of the galaxies taken thanks to the complementary SUBARU/HSC (Hyper Suprime-Cam) survey in the 'g-r-i-z-y' bands complemented by four narrow-band filters, plus the COSMOS HST field which cover a part a part of the HSC survey, the disk scale-length (h) and the main galactic substructures (bulge, bars, spiral arms) will be characterized. For instance, morphological parameters for 8 million galaxies have been estimated in the HSC Wide Survey (Ghosh et al. 2022).

By correlating this HSC photometric sample with the PFS spectroscopic sample, starting at a redshift z=0.7, the galaxies presenting the most regular line profiles can be used to establish the TFR in the early universe. Indeed, in the low-redshift universe (SDSS), irrespective of passband and galaxy morphology, concentration, and asymmetry, depending on the galaxy mass, the average r-band disc scale-length is h=3.8+-2.1 kpc (Fathi et al. 2010). On the other hand, the best measure of the TFR is done at 2.2h (Courteau & Rix, 1999) i.e., from 3.8 kpc for low mass galaxies to 12.8 kpc for massive ones and we expect that those disk scale-lengths decreases at higher redshift. The size of an optical fiber on the sky being one arcsec, low and median mass galaxies are embedded in the fiber up to 2.2h from a redshift z=0.7 and 1.0 respectively. In addition, galaxies with complex or/and multiple line profiles cannot be used to study the TFR but, alternatively, at all redshifts, will be massively used to detect galaxy merger and/or interaction (Maschmann et al. 2022) and to trace internal galactic structure likes bars and spiral arms, or events related to star formation (outflows), or to gas accretion (inflows). The galaxy merger rate is a fundamental constraint of cosmological and galaxy evolution models as well as the gas exchanges between galaxies and the circum- and intergalactic media.

An Algorithm for Massive Automated Z Evaluation and Determination called AMAZED (e.g. Schmitt et al. 2019) and developed at LAM will be adapted and used. High resolution data (GHASP, e.g. Epinat et al. 2008; HRS/VESTIGE e.g. Gomez-Lopez et al. 2019), resolved MUSE intermediate-redshift data (e.g. Mercier et al., 2022), SDSS spectral analysis, toy models and possibly numerical simulations and machine learning - deep learning technics will be used to reinforce the extraction methods on the PFS spectra.

References: Courteau S. & Rix, H-W, 1999, A.J. 513, 561 -- Epinat B, Amram P., Marcelin M, 2008, MNRAS, 390, 466 -- Fathi K., Allen M., Boch T, et al., 2010, MNRAS, 406, 1595 – Ghosh A., Urry C.M., Mishra A., et al., 2022, arXiv:2022.00051 -- Greene J.E., Bezanzon R., Ouchi M. et al., arXiv :2206.149008 -- Gomez-Lopez J, Amram P., Epinat B., et al, 2019, A&A, 631, 71 -- Maschmann D., Halle A., Melchior A-L, et al, 2022, A&A in press, arXiv:2212.02529 -- Mercier W., Epinat B., Contini T., et al., 2022, A&A, 665, 54 – Schmitt A., Arnouts S., Borges R. et al., 2019, in Astronomical Data Analysis Software and Systems XXVI ASP conference Series, Vol. 521 -- Wisnioski E., Forster-Schreiber N., Wuyts S., et al., 2015, ApJ, 799, 209

Thesis subject

Name of the laboratory: LAM

Thesis advisor: Philippe AMRAM
Email and address: philippe.amram@lam.fr, 38 rue Frédéric Joliot-Curie, Marseille, France
Tel: 04 95 04 41 09

Co-advisor: Benoît EPINAT, LAM

Subject's title:

Angular Momentum and Torques in nearby galaxies.

Quick Overview of the thesis objectives and methods:

- **Angular Momentum and Torques in nearby galaxies**
  - Explore the resolved (specific) angular momentum properties for a large sample of nearby spiral and irregular galaxies
  - Compare it to intermediate redshift star-forming galaxies to probe galaxy evolution.

- **Data and Analysis**
  - Use near-IR imagery to extract morphological parameters
  - Use spectro-imagery (Fabry-Perot) data to extract the kinematical parameters
  - Use different sets of data and simulations to validate the method.

Subject description:

- **Angular momentum and torques in galaxies:**

The angular momentum **J** is a physical quantity representing the cross product of the position **R** and velocity **V** vectors multiplied by the mass M: **J** = **R** x M **V**. The angular momentum is thus the moment arm **R**, times the amount of inertia M, times the amount of displacement **V**.

The torque τ, defined by the cross product of **R** and the gradient of the potential ϕ, i.e. the force **F** = $\nabla\phi$, acting on the body of mass M, determines the rate of change of the body's angular momentum **J**, it is thus the time derivative of the angular momentum that can change with time, which cannot occur for masses, and represents the capability of a force to produce change in the rotational motion of the body.

For a galaxy, most of the angular momentum is found in its outer disk. In the central bulge or in the dark halo, due to random motion of the components, the resulting angular momentum is lower. It is useful to consider the specific angular momentum vector **j** = **J**/M, to remove the implicit mass scaling dependence, thus specific angular momenta and masses become major parameters to describe galaxy properties. The specific angular momentum is a universal parameter defined for all galaxies which is conserved for isolated galaxies, but which varies during galaxy formation, galaxy interaction and galaxy merger. Galaxies being not isolated systems, torques are in action and angular momentum is expected to evolve and to be exchanged between their different components (disk and bulge) during their evolution. This universality also motivates the use of the angular momentum as parameter to describe and classify galaxies.

In the scenario of the cold dark matter hierarchical Universe (ΛCDM), the galaxies were born in halo of dark matter from collapsing baryonic matter, thus, from torques, the angular momentum have been transferred to the developing proto-galaxy by the gravitational interaction of the system with the tidal field of the matter becoming concentrated in neighboring proto-galaxies (Peebles 1969). The specific angular momentum is one of the most fundamental galaxy properties that determines the disk properties, typically the galaxy size, but also the pressure, instabilities and gas fractions (Fall & Efstathiou, 1980). Galactic disks grow with cosmic time, accreting corotating cold gas from the circumgalactic medium, bringing fresh material for star formation but also angular momentum.

The relation between the angular momentum **j** and the mass **M** is such that $j \propto M^{\alpha}$, with $\alpha = 2/3$ is a prediction of the ΛCDM and has been studied first by Fall (1983) what gave it the name of Fall's relation. Understanding this Fall relation allows to restraint models about galaxies formation and mass dependence. Several simulations can predict the angular momentum for high mass galaxies but are still uncertain for low mass galaxies as observed recently by Bouché et al (2022) for intermediate redshift galaxies. Recent observations have highlighted the relation between the fraction of mass in the bulge and the specific angular momentum.

- **Study inner angular momenta and gravitational torques in spiral and irregular galaxy samples.**

This thesis will focus on angular momentum of spiral and irregular galaxies of nearby galaxies to be compared to high redshift galaxies. The nearby galaxy sample that will be used is the world largest three-dimensional (3D, i.e. 2 spatial dimensions plus a velocity component for each galaxy line-of-sight) resolved and extended sample of galaxies for which kinematic data are available for the ionized gas component, which traces the galaxy velocity and mass distributions. Combining the GHASP sample, the HRS/VESTIGE sample, the Hickson Compact Group sample, the full sample contains about 600 galaxies, spanning in a very different environments, from isolated galaxies to very dense structure, comprising cluster (essentially the Virgo Cluster) and compact groups of galaxies. The properties of those nearby galaxies will be compared to high redshifts sample, mainly obtained thanks to MUSE surveys. When neutral gas kinematic will be available, the outer HI velocity fields will complement the optical velocity fields. When molecular gas kinematic will be available, CO and Hα velocity fields will be compared and possibly combined.

The impact of environment is underlined by present-day torques exerted by non-axisymmetric structure in the disk. The constraints supplied by gravitational torques allow to define the dynamical environment. A strong correlation between present-day torque and gaseous depletion time is expected in some spiral galaxies (e.g. M51, Meidt et al. 2013). Corotation radius are located for radius where the angular speeds of the disk and non-axisymmetric structure are the same. Inside (outside) corotation, negative (positive) torques drive gas radially inward (outward), carrying the gas from the different galaxy components, spiral arms, and bars.

- **Methods**

High resolution Fabry-Perot 3D data (GHASP, e.g. Epinat et al. 2008; HRS/VESTIGE e.g. Gomez-Lopez et al. 2019) will constitute the dataset to be analysed. Resolved MUSE intermediate-redshift data (e.g. Mercier et al., 2022) will be used to study galaxy evolution.

Thanks to Near infrared imagery, the stellar mass distribution of the galaxies will be computed from the surface brightness distribution. The mass-to-light ratio M/L will be estimated using simple stellar population models for the whole sample. For a subsample for which multiple wavelengths data are available, SED algorithm like CIGALE could be used to compute more accurate stellar mass distributions. Morphological modelling will be done for a part of the sample for which it is not yet done.

The two-dimensional (2D) stellar mass distributions will be combined to the 3D ionized gas velocity distributions to obtained 2D angular momentum maps for the whole sample.

For a subsample, for which in addition the spatial resolution is high enough, we can compute the gravitational potential from these maps and compute the torques.

An algorithm for computing the angular momentum of galaxies developed by W. Mercier (Mercier et al., 2022) will be adapted and used. Toy models and possibly numerical simulations and machine learning - deep learning technics will be used to reinforce the morphological and kinematical parameters determination.

References: Bouché N., Genel S, Pellisier A, et al., 2021, A&A 654, 49 -- Epinat B, Amram P., Marcelin M, 2008, MNRAS, 390, 466 -- Fall S. M. 1983, IAU, 100, 391 -- Fall S. M., & Efstathiou G. 1980, MNRAS, 193, 189 -- Gomez-Lopez J, Amram P., Epinat B., et al, 2019, A&A, 631, 71 – Meidt S.E., Schinnerer E., Garcia-Burillo S. et al., 2013, ApJ, 779, 45 -- Mercier W., Epinat B., Contini T., et al., 2022, A&A, 665, 54 – Peebles P.J.E., 1969, AJ, 155, 393