




# popkinmocks: mock IFU datacubes for modelling stellar populations and kinematics

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## Summary

Integral Field Units (IFUs) are a type of detector which measure both spatial and spectral information. These detectors output 3D data-products known as datacubes: 2D images with a spectrum associated with each image pixel. Beyond the very local Universe where individual stars can be resolved, IFU datacubes are our most information-rich datasets of galaxies, and large samples of these have been observed (e.g. [Croom et al., 2021](#)). Major results from galaxy IFU studies include the discovery of the fast versus slow rotator dichotomy ([Emsellem et al., 2011](#)), evidence for inside-out galaxy growth ([Pérez et al., 2013](#)), and the ubiquity of warm orbits across galaxy types ([Zhu et al., 2018](#)).

Galaxies are built from stars, gas, dust and dark matter. Stars are an especially useful observational probe as many physical properties can be inferred from their spectra. *Stellar populations* are intrinsic properties such as a star's age or chemical composition, which affect the strengths of spectral absorption lines. *Stellar kinematics* are the positions and velocities of stars within the galaxy. The component of velocity along the line-of-sight produces Doppler shifting of absorption lines. In the past, stellar populations and kinematics of external galaxies have been modelled separately; often thought of as distinct subfields. Recent work has demonstrated the power of moving beyond this dichotomy to study galaxy evolution (e.g. [Poci et al., 2019](#)). popkinmocks is software to create mock observations of IFU datacubes of galaxy stellar light for the era of combined population-kinematic analyses.

## Statement of need

Combined population-kinematic models require a framework that can self-consistently describe interactions between populations and kinematics. To this end, popkinmocks has been formulated in probabilistic language where the galaxy is represented as a joint probability density  $p(t, v, \mathbf{x}, z)$  over stellar age  $t$ , velocity  $v$ , position  $\mathbf{x}$  and metallicity  $z$ . This joint distribution can encode all interaction between these variables. Projections of this distribution are familiar quantities for any galactic astrophysicist, e.g. the 1D marginal  $p(t)$  is the *star formation history*, the 2D marginal  $p(t, z)$  is the *age-metallicity relation*, the conditional mean of  $p(v|\mathbf{x})$  is the *mean velocity map*. The popkinmocks API puts this unified, probabilistic formulation front-and-center, e.g.

```
mean_velocity_map = galaxy.get_mean('v_x')
```

This framework elucidates underlying connections between various quantities e.g. it is used in the [documentation](#) to explain a common assumption used in spectral modelling. Furthermore, this unified formulation may promote exploration of higher-order cross-moments which combine population and kinematics in novel ways.

Another unique feature of popkinmocks is the ability to create mock IFU observations of highly idealised galaxy models. Idealised models are useful as they provide a controlled setting to

develop new inference methods. All existing software to produce mock IFU observations (listed below) use stellar particles from simulations, which are inherently stochastic. In addition to simulation particles, popkinmocks can also create mock observations using smooth galaxy models based on analytic equations. These smooth models were used in Hinterer et al. (2023) to test a novel inference method, and ongoing development of this method will continue to make significant use of popkinmocks.

Existing software for mock IFU observations include `simspin` (Harborne et al., 2020), `RealSim-IFS` (Bottrell & Hani, 2022), and the (currently private) code behind the `iMaNGA` project (Nanni et al., 2022). A key functionality needed to create mock IFU datacubes is Doppler shifting of spectra. All three existing tools implement this functionality in the same way: using a particle-by-particle approach, shifting a particle's spectrum according to its velocity. By contrast, in popkinmocks we realise Doppler shifting via convolutions using Fast Fourier Transforms. This significantly different implementation of a key functionality makes popkinmocks a useful alternative which may be more computationally efficient in certain contexts.

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## References

- Bottrell, C., & Hani, M. H. (2022). Realistic synthetic integral field spectroscopy with `RealSim-IFS`. *Monthly Notices of the Royal Astronomical Society*, 514(2), 2821–2838. <https://doi.org/10.1093/mnras/stac1532>
- Croom, S. M., Owers, M. S., Scott, N., Poetrodjojo, H., Groves, B., van de Sande, J., Barone, T. M., Cortese, L., D'Eugenio, F., Bland-Hawthorn, J., Bryant, J., Oh, S., Brough, S., Agostino, J., Casura, S., Catinella, B., Colless, M., Cecil, G., Davies, R. L., ... Vaughan, S. P. (2021). The SAMI Galaxy Survey: the third and final data release. *Monthly Notices of the Royal Astronomical Society*, 505(1), 991–1016. <https://doi.org/10.1093/mnras/stab229>
- Emsellem, E., Cappellari, M., Krajnović, D., Alatalo, K., Blitz, L., Bois, M., Bournaud, F., Bureau, M., Davies, R. L., Davis, T. A., Zeeuw, P. T. de, Khochfar, S., Kuntschner, H., Lablanche, P.-Y., McDermid, R. M., Morganti, R., Naab, T., Oosterloo, T., Sarzi, M., ... Young, L. M. (2011). The ATLAS3D project - III. A census of the stellar angular momentum within the effective radius of early-type galaxies: Unveiling the distribution of fast and slow rotators. *Monthly Notices of the Royal Astronomical Society*, 414(2), 888–912. <https://doi.org/10.1111/j.1365-2966.2011.18496.x>
- Harborne, K. E., Power, C., & Robotham, A. S. G. (2020). SIMSPIN - Constructing mock IFS kinematic data cubes. *Publications of the Astronomical Society of Australia*, 37, e016. <https://doi.org/10.1017/pasa.2020.8>
- Hinterer, F., Hubmer, S., Jethwa, P., Soodhalter, K. M., Ven, G. van de, & Ramlau, R. (2023). A projected nesterov–kaczmarz approach to stellar population-kinematic distribution reconstruction in extragalactic archaeology. *SIAM Journal on Imaging Sciences*, 16(1), 192–222. <https://doi.org/10.1137/22M1503002>
- Nanni, L., Thomas, D., Trayford, J., Maraston, C., Neumann, J., Law, D. R., Hill, L., Pillepich, A., Yan, R., Chen, Y., & Lazarz, D. (2022). `iMaNGA`: mock `MaNGA` galaxies based on `IllustrisTNG` and `MaStar` SSPs – I. Construction and analysis of the mock data

- cubes. *Monthly Notices of the Royal Astronomical Society*, 515(1), 320–338. <https://doi.org/10.1093/mnras/stac1531>
- Pérez, E., Cid Fernandes, R., González Delgado, R. M., García-Benito, R., Sánchez, S. F., Husemann, B., Mast, D., Rodón, J. R., Kupko, D., Backsmann, N., de Amorim, A. L., van de Ven, G., Walcher, J., Wisotzki, L., Cortijo-Ferrero, C., & CALIFA Collaboration. (2013). The Evolution of Galaxies Resolved in Space and Time: A View of Inside-out Growth from the CALIFA Survey. *The Astrophysical Journal Letters*, 764(1), L1. <https://doi.org/10.1088/2041-8205/764/1/L1>
- Poci, A., McDermid, R. M., Zhu, L., & Ven, G. van de. (2019). Combining stellar populations with orbit-superposition dynamical modelling: The formation history of the lenticular galaxy NGC 3115. *Monthly Notices of the Royal Astronomical Society*, 487(3), 3776–3796. <https://doi.org/10.1093/mnras/stz1154>
- Zhu, L., van de Ven, G., van den Bosch, R., Rix, H.-W., Lyubenova, M., Falcón-Barroso, J., Martig, M., Mao, S., Xu, D., Jin, Y., Obreja, A., Grand, R. J. J., Dutton, A. A., Macciò, A. V., Gómez, F. A., Walcher, J. C., García-Benito, R., Zibetti, S., & Sánchez, S. F. (2018). The stellar orbit distribution in present-day galaxies inferred from the CALIFA survey. *Nature Astronomy*, 2, 233–238. <https://doi.org/10.1038/s41550-017-0348-1>