Roman CCS White Paper

Figures of Merit for Roman Studies of Galaxy Evolution with Lookback Time

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Abstract: *Rather than advocating a particular survey strategy, this white paper discusses a framework for assessing survey strategies for their ability to contribute to our knowledge of galaxy formation and evolution. Two suggested figures of Merit (FoM) can be used to assess different observational strategies for the High Latitude Wide Area Survey with respect to key measurements that are used to constrain models of galaxy evolution. These FoM are chosen to be complementary to those used for assessing the survey ability to constrain Dark Energy (DE), and in the same spirit as capturing Roman's ability to measure Dark Energy in a single DE FoM.*

Background
The consensus view is that galaxies form at dark-matter over-densities. The initial baryon fraction within dark matter halos is expected to have minimal scatter. Virialized galaxy dark-matter halos have nearly universal profiles. Nonetheless these simple initial conditions result in a rich diversity of properties of present-day galaxies. The fundamental challenge of galaxy-evolution physics is to identify the physics responsible for this diversity. Gas cools, fragments, and forms stars, as well as black holes. The feedback of energy from stars, supernovae, and black-hole accretion processes acts to regulate the rate of star formation and hence the mass distribution and age distribution of galaxies and the stars within them. While this general picture matches observations very well, many aspects of the models (particularly for feedback) are poorly constrained by observations and stress our ability to consistently model physics from sub-parsec scales to scales of megaparsecs.

Roman combines excellent optical and near-infrared sensitivity with sub-kpc spatial resolution (at any redshift) with the ability to survey large volumes. Compared to HST and JWST, it offers orders-of-magnitude improvement in the ability to measure the evolution with redshift of galaxy clustering and (more generally) galaxy environment.

From Data to Constraints on Physical Models

Data Space: Roman measures galaxy positions, fluxes, sizes, morphologies, spectral-energy distributions, redshifts, and line strengths. For any given survey strategy, one can compute uncertainties on the measurement of these quantities as a function of exposure time for a single galaxy. One can also compute uncertainties on suitably parametrized summary statistics of the distributions of these parameters and the correlations between them, in one or more dimensions, (given relatively broad prior assumptions on the plausible distributions and correlations).

Theory Space: Galaxy formation involves highly non-linear processes that span many orders of magnitude in physical scale. It is currently impossible to include all the relevant physics for star-formation and feedback and radiative transfer in a simulation of a single galaxy, not to mention cosmologically relevant collections of galaxies. Theory space thus includes various intermediate approximations to describe the behavior of the "sub-grid" physics on progressively larger scales. There is no one universal approach to doing this translation between small and large scales. As most models adopt the same assumptions for dark matter and cosmology, the differences between galaxy evolution models are all due to the different treatment of the physical processes on various scales within galaxies and in the surrounding gas.

The intermediate space: Translating data to *theory space* generally involves so many assumptions that inferences about the underlying physical processes are suspect. But, it can be prohibitively expensive to translate models into the *data space* for a useful range of choices for the sub-grid physics. It is perhaps most practical to meet in an intermediate space of *derived quantities* from both the data and models. Derived quantities for individual galaxies (or pixels within galaxies) include redshifts (spectroscopic and photometric) stellar masses, star-formation rates, metallicities, mass surface densities (from lensing). Derived quantities for collections of galaxies include correlation functions, projected mass surface densities (from lensing) and distributions and trends of individual quantities (e.g. mass functions, mass-metallicity relations, etc). The relations generally used for testing galaxy evolution models are different projections of the distribution of such derived quantities. For all such distribution functions and trends, the unique aspect of Roman as a survey mission is the prospect of constraining the distributions precisely via large samples across a large span of cosmic time.

Survey Strategy Space: Within a fixed fraction of the Roman core mission devoted to surveys at high galactic latitude, a myriad of possibilities exists for optimizing the observations to satisfy not only the cosmology science objectives but objectives across a wide range of astrophysics. The observing-strategy space includes trading depth, area, wavelength coverage and spectral resolution to optimize the science return. It includes changing the mix of spectroscopy vs. imaging and weighs uniform depth vs. combining surveys with different depth. These trades should be considered not in isolation but in combination with (at least) survey data from the nearly contemporaneous Rubin and Euclid surveys as well as the dedicated Subaru time.

Constructing figures of merit to quantify the constraints on parameters in the *intermediate space* seems like it might be the most practical way to fold galaxy-evolution science into the evaluation of the observing strategies. The challenge is to choose just a few figures of merit that span the wide variety of measurements and the complexity of galaxy evolution.

Possible Figures of Merit (FoM)

The stellar-mass to halo-mass relation SMHM: The SMHM is a powerful way to quantify the efficiency of converting baryons into stars and connect that to a key parameter of dark matter – the depth of the gravitational potential well. It is a good place to look for a galaxy-evolution FoM because on the measurement side it requires translating photometry and/or spectroscopy into redshifts and stellar masses and requires some inference of halo masses. The halo-mass estimates can come from clustering (correlation functions), gravitational lensing, or abundance matching. All benefit from large areas, but there is a tension between getting the large area and getting deeper photometry or spectroscopy to go further down the mass functions or improve the mass estimates. Behroozi et al. 2018 have proposed parametrizing the SMHM as a double powerlaw plus a Gaussian with a smooth model for the variation of each of the parameters (M_1, α, β, γ, and δ) with redshift:

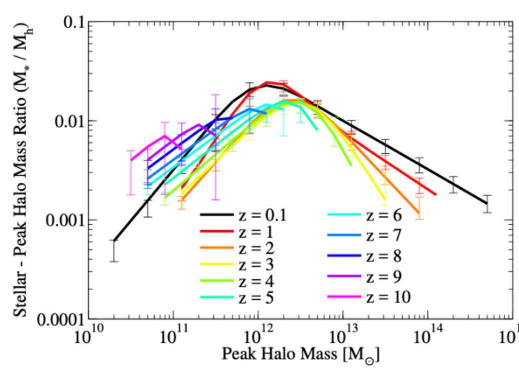

Figure 1: SMHM evolution with redshift from Behroozi et al. 2018.

$$\log_{10}\left(\frac{M_*}{M_1}\right) = \varepsilon - \log_{10}\left(10^{-\alpha x} + 10^{-\beta x}\right) + \gamma \exp\left[-0.5\left(\frac{x}{\delta}\right)^2\right]$$; with $$x \equiv \log_{10}\left(\frac{M_{\mathrm{peak}}}{M_1}\right)$$

The resulting function has 19 parameters to be constrained by the data.

The FoM that could be used to compare one survey strategy vs. another would be the volume enclosed within the 68%- confidence hypersurface of these 19 parameters. It is not necessary to use this exact parameterization. It may be useful to do some transformations to avoid degeneracies. The point here is that having parameterized the relation and its evolution, we can evaluate the surveys based on their ability to constrain the parameters. It should be possible to calibrate approximately how the uncertainties in the individual parameters vary with uncertainties in the stellar-mass estimates and in photometric redshifts, with sizes of the samples in different mass and redshift bins, and with the survey geometry on the sky, so that the FoM can be calculated without an end-to-end simulation of each potential survey.

This figure of merit offers several advantages:

- Comprehensive Characterization: The multi-dimensional hyper-surface captures the joint constraints on the SMHM parameters, considering the interdependence between them. It provides a holistic view of the parameter space, accounting for the correlations among the parameters and their uncertainties.
- Dimensionality Reduction: Condensing the information into a single number facilitates the comparison of different survey strategies. It provides a quantitative measure of the overall performance of the telescope in constraining the SMHM relation.
- Standardization: Having a single figure of merit allows for easy comparison across different surveys and observational programs. It provides a standardized metric to evaluate the telescope's capability to constrain the SMHM relation, irrespective of the specific survey strategy or observational details.

The joint distribution of galaxy specific star-formation rates, morphologies, and local environment. Galaxies in the local universe show strong correlations between structure and stellar populations. Elliptical galaxies generally have low rates of star formation per unit stellar mass. Spiral galaxies have higher specific star-formation rates. Elliptical galaxies are found in denser environments than spiral galaxies. These correlations between structure, star-formation, and environment evolve over time. Matching these observed relations is one of the great challenges for models of galaxy evolution. Often the comparisons between models and data are carried out on one projection of this parameter space. In the spirit of the first FoM, we suggest standardizing on specific measures of each measured parameter. For example, the ability to measure morphology could be represented by the uncertainties on the Sersic parameter n, which can be calibrated as a function of galaxy flux and size without needing to do a full galaxy evolution model or make simulated images of galaxies with more detailed substructure. Local density, ρ, can be estimated from N-nearest neighbors. The distribution in the 3D plane of SSFR, n, and ρ in slices of redshift will be different for different galaxy evolution models. In the spirit of the treatment of the SMHM relation, the task would be (1) to parametrize the distribution at fixed redshift and the evolution of this distribution as a function of redshift, ideally with a relatively small number of parameters chosen to be flexible enough to represent trends from different theoretical models, (2) quantify the sensitivity of the parameters to the measurement uncertainties and sample sizes and (3) define the FoM as the volume of the 68%-confidence within this parameter space for any given survey strategy. If the work to define this FoM can be accomplished over the coming months, it could be a valuable complement to one based on the ability to constraint the SMHM, because it emphasizes Roman's spatial resolution.

In summary, both theory space and survey strategy space are exceptionally large. While figures of merit cannot substitute for thorough discussion and analysis, it may be useful to have a *small* number of figures of merit to help characterize the ability of any possible survey strategy to constrain the evolution of galaxies and their relation to dark matter. We have proposed (conceptually) two FoM, both of which are based on the concept of estimating the volume of the 68% confidence intervals in an intermediate space of inferred galaxy distributions, similar in spirit to Dark Energy figures of merit (Albrecht et al. 2006, 2009). The distributions proposed here emphasize galaxy-evolution science and Roman's unique survey capabilities.

References:
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