

# DESI: The PRObabilistic Value-Added Bright Galaxy Survey (PROVA-BGS) Mock Challenge

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## ABSTRACT

In this project, we present the methodology for inferring physical properties of galaxies from joint SED fitting of the DESI optical photometry and spectroscopy. We construct realistic forward modeled DESI data from star formation and chemical enrichment histories of galaxies in the L-GALAXIES semi-analytic model and the ILLUSTRIS TNG hydrodynamic simulations. Then, using these mock observations, we demonstrate that the stellar mass and SFR posteriors from our SED fitting are consistent with constraints from other SED fitting methods in the literature and, more importantly, the input stellar masses and SFRs from the simulations. The SED fitting we present and validate in this project will be used to construct the PRObabilistic Value-Added Bright Galaxy Survey (PROVABGS) from DESI observations.

*Keywords:* keyword1 – keyword2 – keyword3

## 1. INTRODUCTION

**What is DESI?** Provide an overview of DESI specifics, numbers, and science goals, which will mostly be cosmology (BAO, RSD, etc). DESI will be great

TODO

In addition to the impact DESI will have on cosmology, DESI will also provide a transformative data set for galaxy science. **emphasize DESI samples useful for galaxy science: magnitude complete sample of BGS, LRGs, QSOs.** With this statistically powerful sample of, **Brief list of some exciting galaxy and quasar physics you can do with the DEIS BGS, QSOs, etc samples.**

TODO  
TODO  
TODO

### Current status of DESI

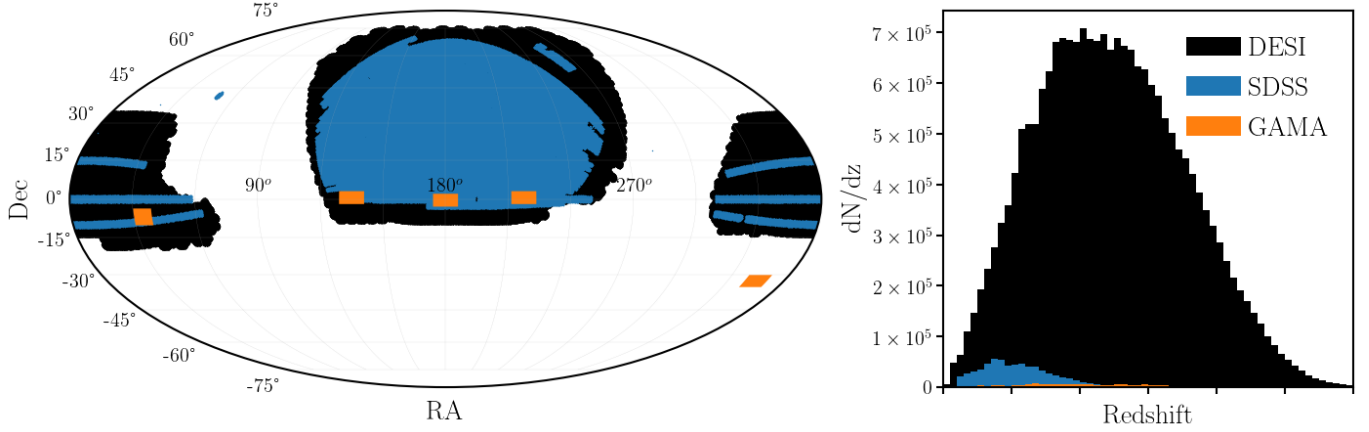
- Comissioning completed
- SV data by the end of the year

As we prepare for the imminent torrent of data, in this paper we present the timely mock challenge of the DESI Galaxy Quasar Physics (hereafter GQP) working group. **what is the mock challenge?**

TODO  
TODO

**Why do we need a mock challenge?** We want to test and cement our methodology specifically for our GQP analysis before SV data comes out. As part of the survey preparation, we have all the tools

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**Figure 1.** DESI will conduct the largest spectroscopic survey to date covering  $\sim 14,000 \text{ deg}^2$ . During dark time, DESI will measure  $>20$  million spectra of luminous red galaxies, emission line galaxies, and quasars out to  $z > 3$ . During bright time, DESI will measure the spectra of  $\sim 10$  million galaxies out to  $z \sim 0.4$  with the Bright Galaxy Survey (BGS). *Left:* With its  $\sim 14,000 \text{ deg}^2$  footprint (black), DESI will cover  $\sim 2\times$  the SDSS footprint (blue;  $\sim 7000 \text{ deg}^2$ ) and  $\sim 45\times$  the GAMA footprint (orange;  $\sim 300 \text{ deg}^2$ ). *Right:* Over this footprint, the BGS will provide spectra for a magnitude limited sample of  $\sim 10$  million galaxies down to  $r < 20$ , two orders of magnitude deeper than the SDSS main galaxy sample and 0.2 mag deeper than GAMA.

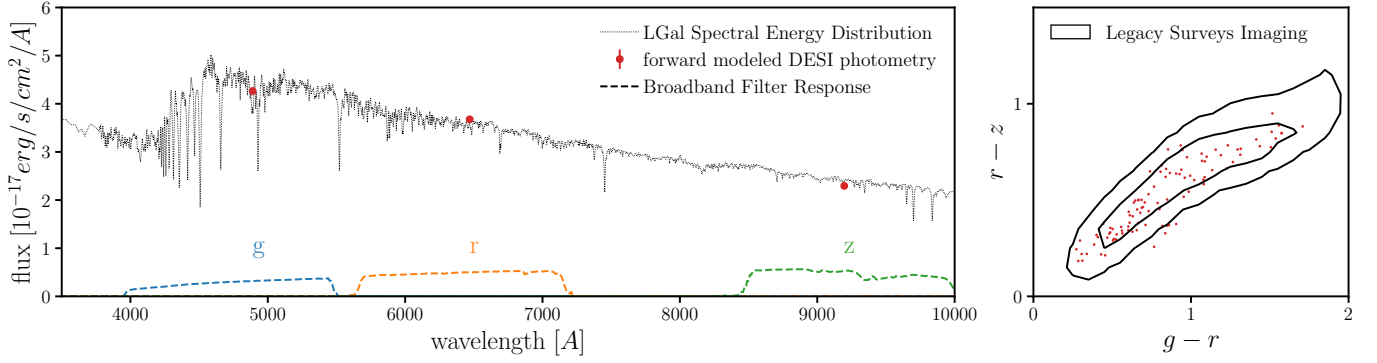
to accurately forward model observations. **details on some of the specific tools and what we're able to simulate: realistic spectroscopy. realistic photometry. realistic spectro-photometry** All of this gives us a rare opportunity to test our methodology on bespoke simulations.

A mock challenge is also great for testing new methodology. BGS is a bright time survey and will push the boundaries of low SNR spectra. But if we can find a way to infer robust galaxy properties the statistical payout is awesome. **Something also about LRGs** We're also trying to robustly fit spectra and photometry simultaneously. This has been done before (**citations**) but not extensively tested on simulations.

**broader impact of mock challenge** highlight some gqp science cases with a focus on mock challenge papers

## 2. SIMULATIONS

DESI, with its robotically-actuated and fibre-fed spectrographs, will collect 5000 spectra simultaneously. The spectra cover the wavelength range 3600 to 9800  $\text{\AA}$ , with a spectral resolution of  $R = \lambda/\Delta\lambda$  between 2000 and 5500. During its five-year operation, starting in 2020, it will measure over 30 million spectra over  $14,000 \text{ deg}^2$  of the sky (**cite**). In addition, these DESI targets also have optical and infrared imaging data from the DESI Legacy Imaging Surveys (hereafter Legacy Surveys **Dey et al. 2019**). The Legacy Surveys are a combination of three public projects (Dark Energy Camera Legacy Survey, Beijing-Arizona Sky Survey, and Mayall  $z$ -band Legacy Survey) that jointly imaged the  $\sim 14,000 \text{ deg}^2$  DESI footprint in three optical bands ( $g$ ,  $r$ , and  $z$ ). Furthermore, DR8 of the Legacy Survey also includes photometry in the WISE  $W1$ ,  $W2$ ,  $W3$ , and  $W4$  infrared bands. **The infrared**



**Figure 2.** *Left:* We forward model DESI photometry (red) for our simulated galaxies (Section 2.1) by convolving their SEDs with the broadband filters (dashed). We construct the SEDs **CH: using the star formation and metallicity histories** (Section 2.2). We assign uncertainties to the forward modeled photometry by **CH: matching the colors to the Legacy Survey imaging for BGS** (Section 2.3). *Right:* The  $g-r$  and  $r-z$  color distribution of the forward modeled LGal photometry is consistent with the color distribution of BGS targets from Legacy Survey imaging (black contours).

photometry is from all imaging through year 4 of NEOWISE-Reactivation force-photometered in the unWISE maps at the locations of Legacy Surveys optical sources (cite). Below we describe how we simulate realistic DESI-like galaxy spectra and photometry from state-of-the-art simulations.

### 2.1. LGal

@rita

overview of Lgal. small volume semi-analytic and cosmo-hydro simulations

describe what galaxy properties (SFH, ZH, etc) are available

TODO

### 2.2. Spectral Energy Distributions

describe how the SED is generated using the SFH and ZHs In Fig. 2,

TODO

### 2.3. Forward Modeled DESI Photometry

We generate realistic Legacy Survey-like photometry for the galaxies in our simulations using their noiseless source spectra or SEDs (Section 2.1). We first generate *noiseless* photometry by convolving the SEDs with the broadband filters of the Legacy Survey:

$$f_X = \int f(\lambda) R_X(\lambda) d\lambda \quad (1)$$

where  $f(\lambda)$  is the galaxy SED and  $R_X$  is the transmission for filter  $X$ . We generate photometry for the  $g$ ,  $r$ , and  $z$  optical bands as well as the  $W1$  and  $W2$  WISE infrared bands.

Next, to assign photometric uncertainties, we match each simulated galaxy to a Legacy Survey DR8 galaxy (**specify how I'm defining galaxies here**) with the nearest  $g$ ,  $r$ , and  $z$  magnitudes as well as  $g-r$  and  $r-z$  colors. These uncertainties are then used to generate Gaussian noise and added to  $f_X$  to assign “measured” photometry to the simulated galaxy.

TODO

Finally, we impose the target selection criteria of BGS:  $r < 20$ . This leaves us with **X** LGALAXIES galaxies. In the left panel of Fig. 2, we plot the forward modeled photometry (red error bars) and the SED (black) for a LGALAXIES galaxy. For reference, we also plot  $R_X$  for the three optical bands of the Legacy Survey. On the right panel, we compare the  $g - r$  and  $r - z$  color distribution for the forward modeled LGALAXIES galaxies (red) to the color distribution of Legacy Survey galaxies (black contour). The two distributions show good agreement.

TODO

#### 2.4. Forward Modeled DESI Spectroscopy

We're interested in exploiting the detailed information in DESI spectra in addition to the photometry to improve constraints on the inferred physical parameters. We therefore also construct forward model DESI-like spectra for our simulated galaxies. DESI fibers have 1" radii, which means only the light within this aperture is collected by the fiber. To simulate this fiber aperture, we apply an aperture correction to the SEDs.

Legacy Survey provides fluxes of objects within a 1" radius aperture,  $f_X^{\text{fiber}}$ . This serves as an estimate the flux that passed through to the fibers. Similar to how we assigned photometric uncertainties above, for each simulated galaxy we identify a Legacy Survey galaxy with the nearest  $g$ ,  $r$ , and  $z$  magnitudes and  $g - r$  and  $r - z$  colors. Then, we assign it the ratio of the  $r$ -band fiber flux to the total  $r$ -band flux ( $f_r^{\text{fiber}}/f_r$ ) of this LS galaxy. We use the assigned  $f_r^{\text{fiber}}/f_r$  as the aperture correction for the SED:

$$f^{\text{spec}}(\lambda) = \left( \frac{f_r^{\text{fiber}}}{f_r} \right) f(\lambda). \quad (2)$$

This correction assumes there is no significant color dependence, we confirm that this is the case for LS galaxies. We assume that there are no significant biases in the LS  $f_X^{\text{fiber}}$  measurements from miscentering of objects. **Do we want to say more about this assumption?**

Besides the aperture correction, we also assign to each simulated galaxy a "measured"  $\hat{f}_r^{\text{fiber}}$  with the LS  $f_r^{\text{fiber}}$  plus a Gaussian noise based on the measured LS uncertainty for  $f_r^{\text{fiber}}$ .  $\hat{f}_r^{\text{fiber}}$  will later be used to set the prior for when we marginalize over the aperture correction later in Section 3.

TODO

Next, we generated realistic DESI-like spectra from the aperture corrected SEDs using a forward model that simulates the DESI instrument response and realistic observing conditions. **details on desi instrument model. details on bgs observing conditions. table of bgs observing conditions?**<sup>1</sup>

TODO

In Figure 3, we present **conclude by emphasizing the fact that our simulations cover the full expected observable space of DESI BGS and therefore if the pipeline works on our mocks, then it should work for every expected type of galaxies in the observations**

TODO

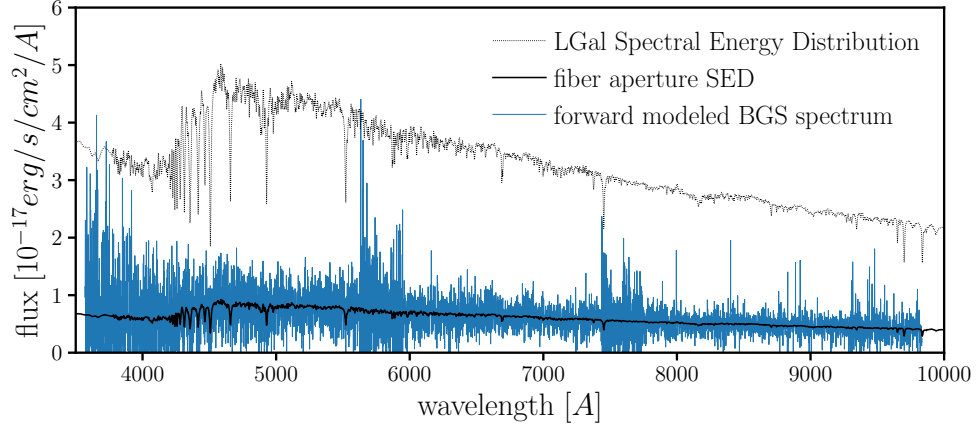
TODO

TODO

### 3. INFERRING GALAXY PROPERTIES FROM PHOTOMETRY AND SPECTRA

- overview of SED fitting
- refer to appendix about different set ups

<sup>1</sup> <https://specsims.readthedocs.io>



**Figure 3.** We construct forward model DESI spectra (blue) for our simulated galaxies by first applying a fiber aperture correction to the SED (black solid), then applying a DESI noise model. We apply a fiber aperture correction by scaling down the SED based on the  $r$ -band aperture flux we assign from the Legacy Surveys imaging. The noise model includes a DESI instrument model, which accounts for the DESI spectrograph response, and an atmosphere model, which accounts for the bright time observing conditions. We construct simulated DESI spectra for 8 different bright time observing conditions. For more details, we refer readers to Section 2.4.

- be explicit about what physical properties are inferred from our SED fitting: stellar masses, ages, metallicities, star-formation histories. Explain how we derive SFRs from the SFHs (i.e. our choice of 100Myr)
- brief description of other standard SED fitting methods we include for comparison: firefly, VESPA, CIGALE

description of our speculator SED model (Alsing et al. 2019), which is based on FSPS. We use Chabrier IMF **CH: do we need to justify htis?**.

We don't use tau model for SFH because it biases the physical parameters inferred. citation. **TODO**

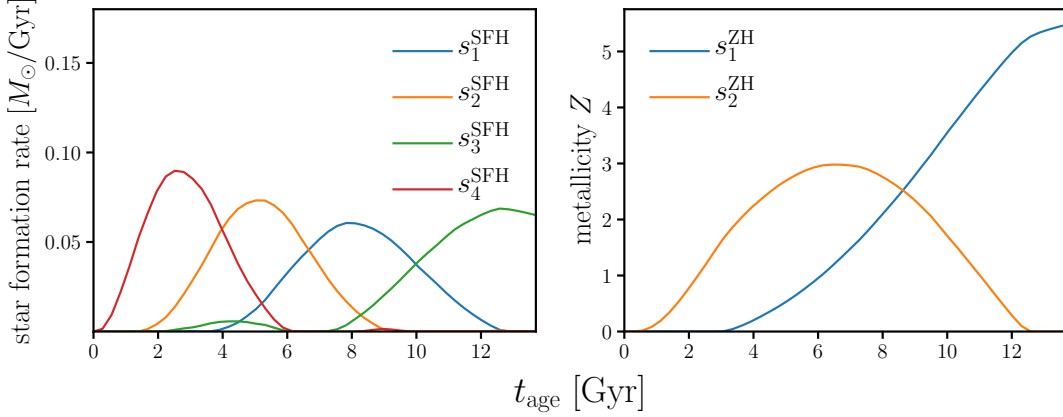
Instead we use the following SFH bases from Rita in prep.

$$\text{SFH}(t, t_{\text{age}}) = \sum_{i=1}^4 \beta_i^{\text{SFH}} \frac{s_i^{\text{SFH}}(t)}{\int_0^{t_{\text{age}}} s_i^{\text{SFH}}(t) dt} \quad (3)$$

Similarly for ZH, we use the following ZH bases

$$\text{ZH}(t) = \sum_{i=1}^2 \gamma_i^{\text{ZH}} s_i^{\text{ZH}}(t) \quad (4)$$

$$\text{SFR}_{100\text{Myr}} = \frac{\int_{t_{\text{age}}-100\text{Myr}}^{t_{\text{age}}} \text{SFH}(t) dt}{100 \text{ Myr}} \quad (5)$$



**Figure 4.** speculator bases

see Figure 4.

Calzetti dust attenuation curve

Rather than evaluating the SPS directly using FSPS we use SPECULATOR, an emulator for FSPS. Brief explanation of the PCA neural net. motivate why we're using speculator by reiterating Alsing et al. (2019)s speed profiling.

describe our MCMC sampling. James's work in convergence here. talk about how in principle speculator can easily be used with HMC because you can get derivatives with backpropagation. provide detailed profiling of SED fitting and projections for full 10million galaxy BGS sample.

In Figure XXXX we present the posterior as well as the best-fit photometry and spectroscopy using speculator + emcee.

## 4. RESULTS

Figure 5

In order to quantify the precision and accuracy of the inferred physical properties for our simulated galaxy population, we begin by assuming that the discrepancy between the inferred and true parameters for each galaxy  $\Delta_{\theta,i}$

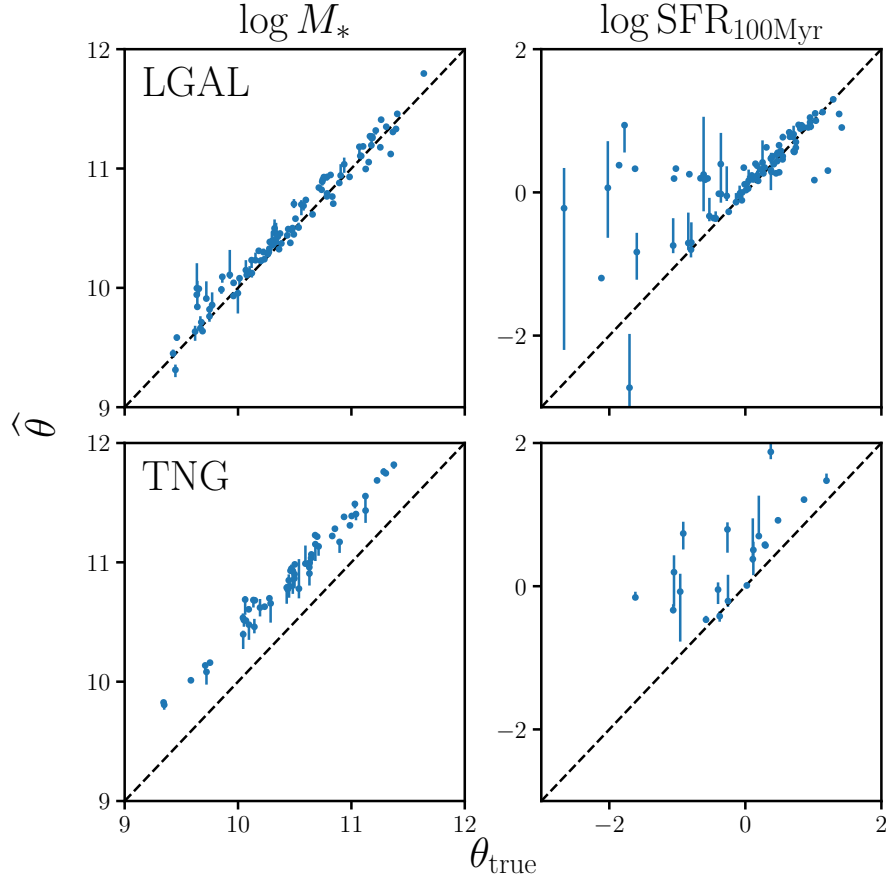
$$\theta_i^{\text{inf}} = \theta_i^{\text{true}} + \Delta_{\theta,i} \quad (6)$$

where  $\Delta_{\theta,i}$  is sampled from a Gaussian distribution

$$\Delta_{\theta,i} \sim \mathcal{N}(\mu_{\Delta_{\theta}}, \sigma_{\Delta_{\theta}}). \quad (7)$$

This Gaussian distribution is described by population hyperparameters  $\mu_{\Delta_{\theta}}$  and  $\sigma_{\Delta_{\theta}}$ , the mean and standard deviation, which quantify the accuracy and precision of the inferred physical properties for the population.

Given the photometry and spectrum of our galaxies,  $\{\mathbf{D}_i\}$ , we can get the posteriors for these population hyperparameters  $\eta_{\Delta} = \{\mu_{\Delta_{\theta}}, \sigma_{\Delta_{\theta}}\}$  using a hierarchical Bayesian framework (Hogg et al.



**Figure 5.** The properties inferred from ifspS spectrophotometry fit as a function of true properties.

2010):

$$p(\eta_{\Delta} | \{\mathbf{D}_i\}) = \frac{p(\eta_{\Delta}) p(\{\mathbf{D}_i\} | \theta_{\Delta})}{p(\{\mathbf{D}_i\})} \quad (8)$$

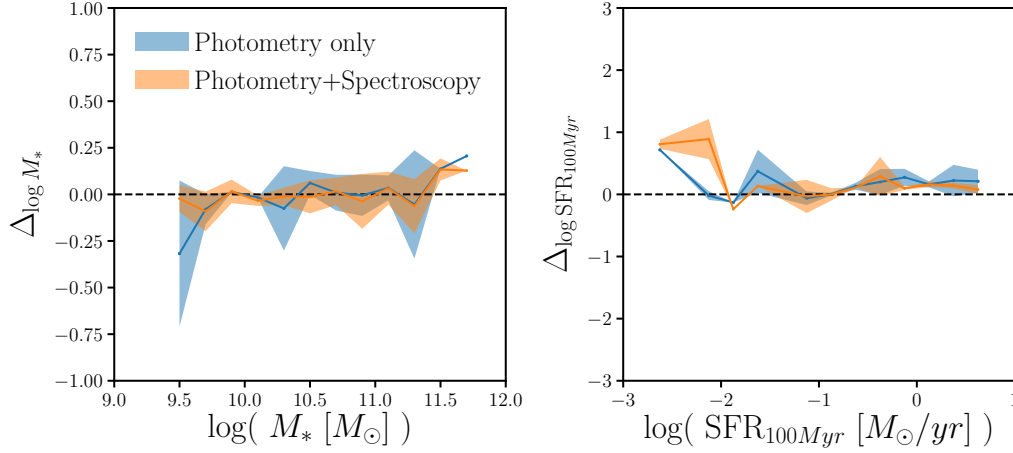
$$= \frac{p(\eta_{\Delta})}{p(\{\mathbf{D}_i\})} \int p(\{\mathbf{D}_i\} | \{\theta_i\}) p(\{\theta_i\} | \eta_{\Delta}) d\{\theta_i\}. \quad (9)$$

Naively the posteriors for each of the galaxies are not correlated, so we can factorize the expression above

$$p(\eta_{\Delta} | \{\mathbf{D}_i\}) = \frac{p(\eta_{\Delta})}{p(\{\mathbf{D}_i\})} \prod_{i=1}^N \int p(\mathbf{D}_i | \theta_i) p(\theta_i | \eta_{\Delta}) d\theta_i \quad (10)$$

$$= \frac{p(\eta_{\Delta})}{p(\{\mathbf{D}_i\})} \prod_{i=1}^N \int \frac{p(\theta_i | \mathbf{D}_i) p(\mathbf{D}_i)}{p(\theta_i)} p(\theta_i | \eta_{\Delta}) d\theta_i \quad (11)$$

$$= p(\eta_{\Delta}) \prod_{i=1}^N \int \frac{p(\theta_i | \mathbf{D}_i) p(\theta_i | \eta_{\Delta})}{p(\theta_i)} d\theta_i. \quad (12)$$



**Figure 6.** The discrepancies between the inferred and input/“true”  $M_*$ s (left) and SFRs (right) for our LGAL galaxies. In blue, we infer  $M_*$ s and SFRs using only photometry; in orange, we infer  $M_*$ s and SFRs by jointly fitting both photometry and spectroscopy. *Jointly fitting spectroscopy and photometry improves constraints on galaxy properties.*

$p(\theta_i | \mathbf{D}_i)$  is the posterior for galaxy  $i$ . Hence, the integral can be which means the integral can be estimated using the MCMC sample from the posterior

$$p(\eta_\Delta | \{\mathbf{D}_i\}) = p(\eta_\Delta) \prod_{i=1}^N \frac{1}{S_i} \sum_{j=1}^{S_i} \frac{p(\theta_{i,j} | \eta_\Delta)}{p(\theta_{i,j})}. \quad (13)$$

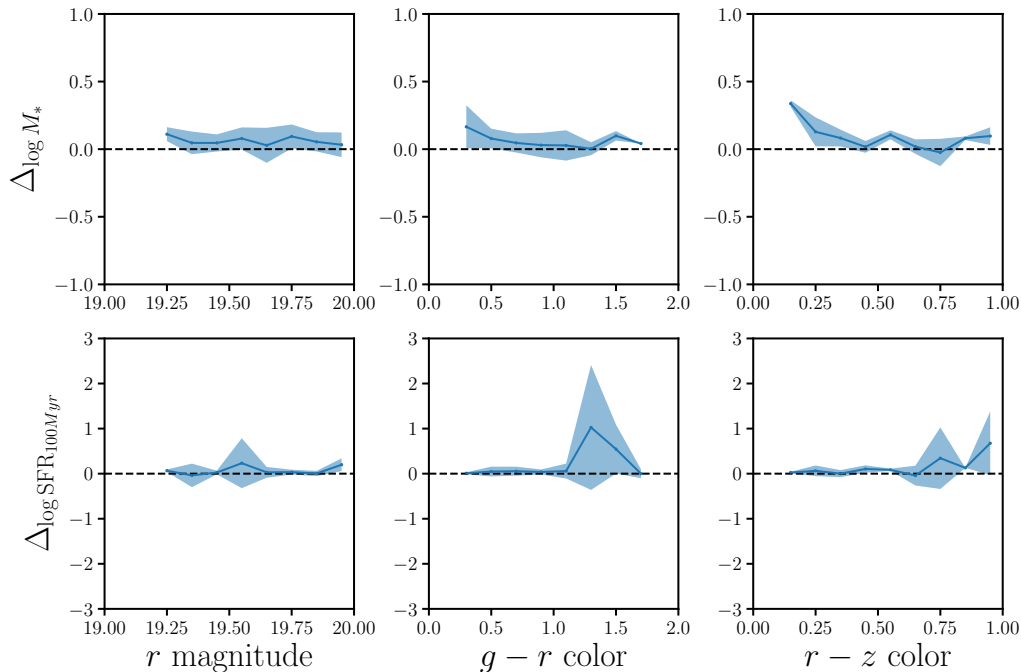
$S_i$  is the number of MCMC samples and  $\theta_{i,j}$  is the  $j^{\text{th}}$  sample of galaxy  $i$ . We present the maximum a posteriori (MAP) estimates of  $\eta_\Delta$  for  $\log M_*$  and  $\log \text{SFR}$  in Figure 6.

$\eta_\Delta$  as a function of SNR/mag/colour.

discussion:

- sfh basis improves SFH accuracy?
- advantage of mcmc over MAP
- non-Gaussian posteriors
- science applicatoinis
- comparison to other methods
- different observing condition doesn't impact our results?
- we use super simple dust mmodel. **CH:** more sophistiicated dust models doesn't matter?
- the simulated spectra and the fitting are generated using the same SED. **CH:** We try with different libraries.
- **CH:** we try fitting with a different IMF





**Figure 7.** do we want to test bias against other properties? (e.g. obs condition?)

## 5. SUMMARY

DESI is great.

Also advertise science papers with specific focus on mock challenge science papers.

## ACKNOWLEDGEMENTS

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## APPENDIX

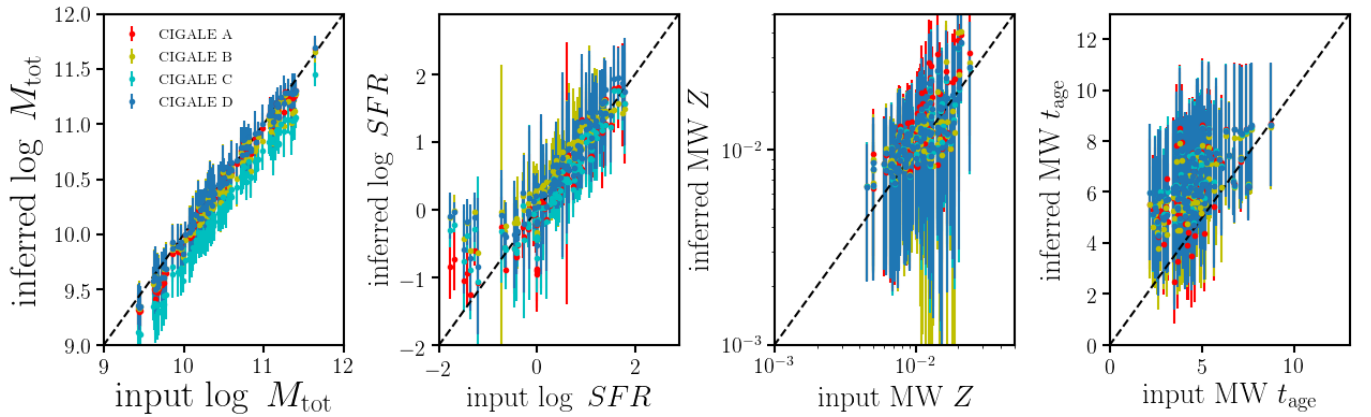
### A. COMPARISON TO OTHER METHODS

## REFERENCES

- Alsing J., et al., 2019, arXiv:1911.11778 [astro-ph]  
 Hogg D. W., Myers A. D., Bovy J., 2010, [The Astrophysical Journal](#), 725, 2166  
 Dey A., et al., 2019, [AJ](#), 157, 168

**Table 1.** Table of  $\theta_{\text{inf}} - \theta_{\text{true}}$  and uncertainties for different CIGALE setups

set	CIGALE A	CIGALE B	CIGALE C	CIGALE D
$\Delta M_{\text{tot}}$	0.07	0.09	0.27	0.05
$M_{\text{err}}$	0.13	0.20	0.16	0.16
$\Delta \text{Age}$	1.78	1.59	1.97	1.92
$\text{Age}_{\text{err}}$	2.36	2.63	2.47	2.47
$\Delta Z$	0.0037	0.0026	0.0027	0.0027
$Z_{\text{err}}$	0.0091	0.0085	0.0089	0.0089

**Figure 8.** The properties inferred from CIGALE photometry fit as a function of true properties. Configuration CIGALE A, B, C, and D on one plot.