

## DESI Galaxy Quasar Physics 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

**What is DESI for galaxy science?** On top of all that DESI goodness, DESI will be great for galaxy science! Brief list of some exciting galaxy and quasar physics you can do with the DEIS BGS, QSOs, etc samples. **Current status of DESI** Comissioning about to start and SV data coming in a year. This is why a mock challenge timely.

**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 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

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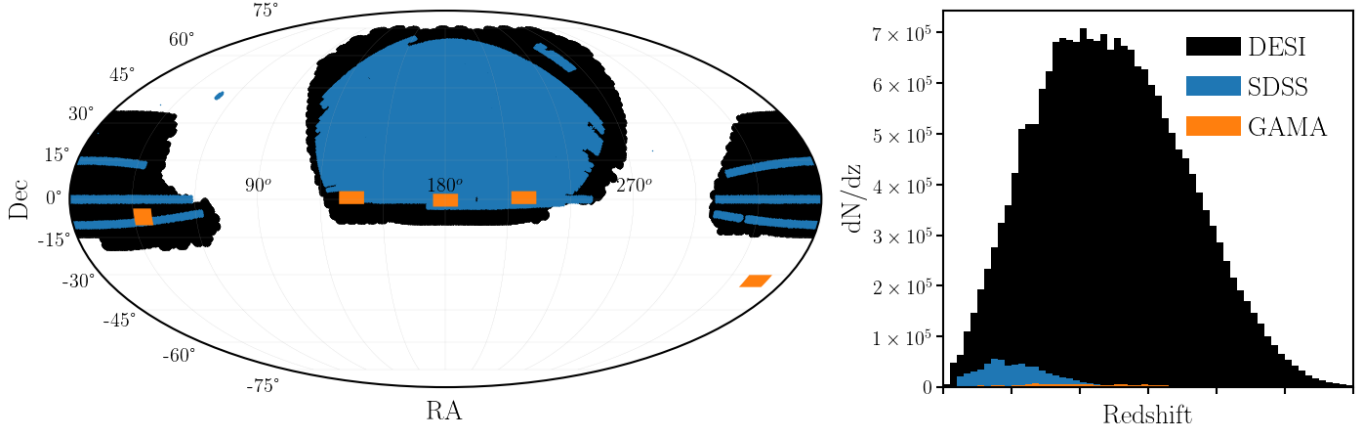
TODO

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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.

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

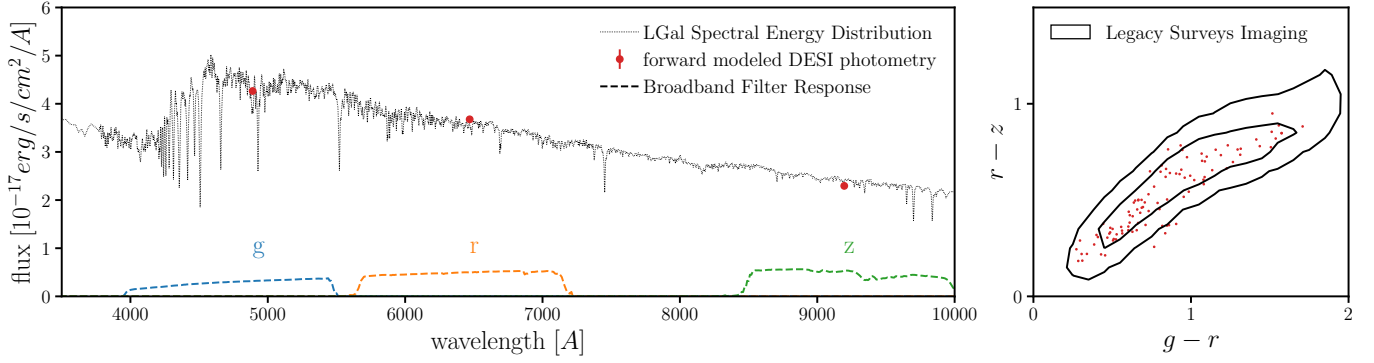
## 2. SIMULATIONS

**paragraph describing the DESI data before we talk about how we simulate it.** DESI will collect spectroscopy description: wavelength range, spectral resolution,

In addition to galaxy spectra, DESI will 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 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 spectroscopy and photometry for galaxies from state-of-the-art simulations.

### 2.1. $LGal$



**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).

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

TODO

## 2.3. Forward Modeled DESI Photometry

From the noiseless source spectra generated for the galaxies in our simulations (Section 2.1), we generate noiseless photometry by convolving the spectra with the broadband filters of DESI imaging:

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

$f(\lambda)$ ,  $R_X$  is the transmission.

Fig. 2

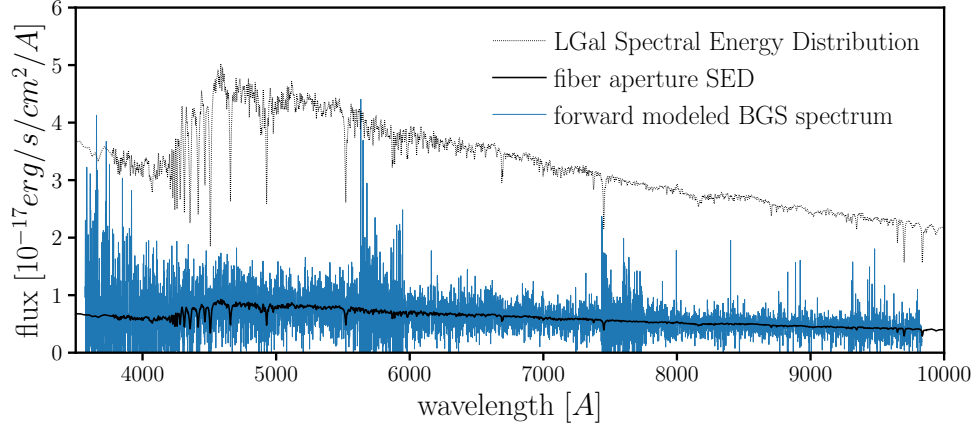
Next, we assign realistic photometric uncertainties to the simulated photometric fluxes using the Afterwards, we impose the target selection criteria of BGS:  $r < 20$ . This leaves us with **X** LGal galaxies.

TODO

## 2.4. Forward Modeled DESI Spectroscopy

fiber flux assigned when we assigned photometric uncertainty

- 'true' fiber aperture SED generated by scaling down the SED by the assigned  $r$ -band fiber flux.
- Meanwhile we add some noise to the fiber flux to have 'measured' fiber flux.
- Furthermore, we later jointly fit photometry and spectra we marginalize over  $f_{\text{fiber}}$ .



**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.

- run true fiber aperture SED through the DESI noise model to produce DESI-like spectra.
- describe the noise model in detail
- <sup>1</sup>

A paragraph on how we combine these to get the spectrophotometry with figure **figure** showing the spectra and photometry on top of each other

### 3. METHODS FOR INFERRING GALAXY PROPERTIES

Analysis of the mocks in section 2, using standard and newly developed codes.

Recover: stellar masses, ages, metallicities, star-formation histories.

#### 3.1. *Fitting Methods*

describe fiducial choices: IMF

describe Rita's SFH and ZH bases. cite paper.

description of firefly

description of iFSPS or FSPS emulator

description of Rita's VESPA

description of CIGALE

#### 3.2. *various set ups*

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

**Table 1.** Table of the different parameterizations for the spectro-photometric fitting. The changes in each setup with respect to default configuration, CIGALE D, are bolted.

name	SFH	dust	IMF
iFSPS A	vanilla		
iFSPS B	rita’s basis		
iFSPS C	rita’s basis		
iFSPS C’	rita’s basis		
Firefly	rita’s basis		
VESPA			
CIGALE A	<b>delayed SFH</b>	Charlot & Fall 2000, Draine et al. 2014	Salpeter
CIGALE B	delayed SFH + additional burst	<b>Calzetti et al. 2000, Dale et al. 2014</b>	Salpeter
CIGALE C	delayed SFH + additional burst	Charlot & Fall 2000, Draine et al. 2014	<b>Chabrier</b>
CIGALE D	delayed SFH + additional burst	Charlot & Fall 2000, Draine et al. 2014	Salpeter

**table:** table of all the different parameterizations of the fitters

iFSPS A: vanilla + simplest dust

iFSPS B: more complex SFH + simple dust

iFSPS C: more complex SFH + complex dust

iFSPS C’: more complex SFH + complex dust + different IMF

Firefly A (Firefly B?)

(VESPA B?)

CIGALE A

CIGALE B

CIGALE C

CIGALE C’: with different IMF

## 4. RESULTS

### 4.1. *Inferred Galaxy Properties*

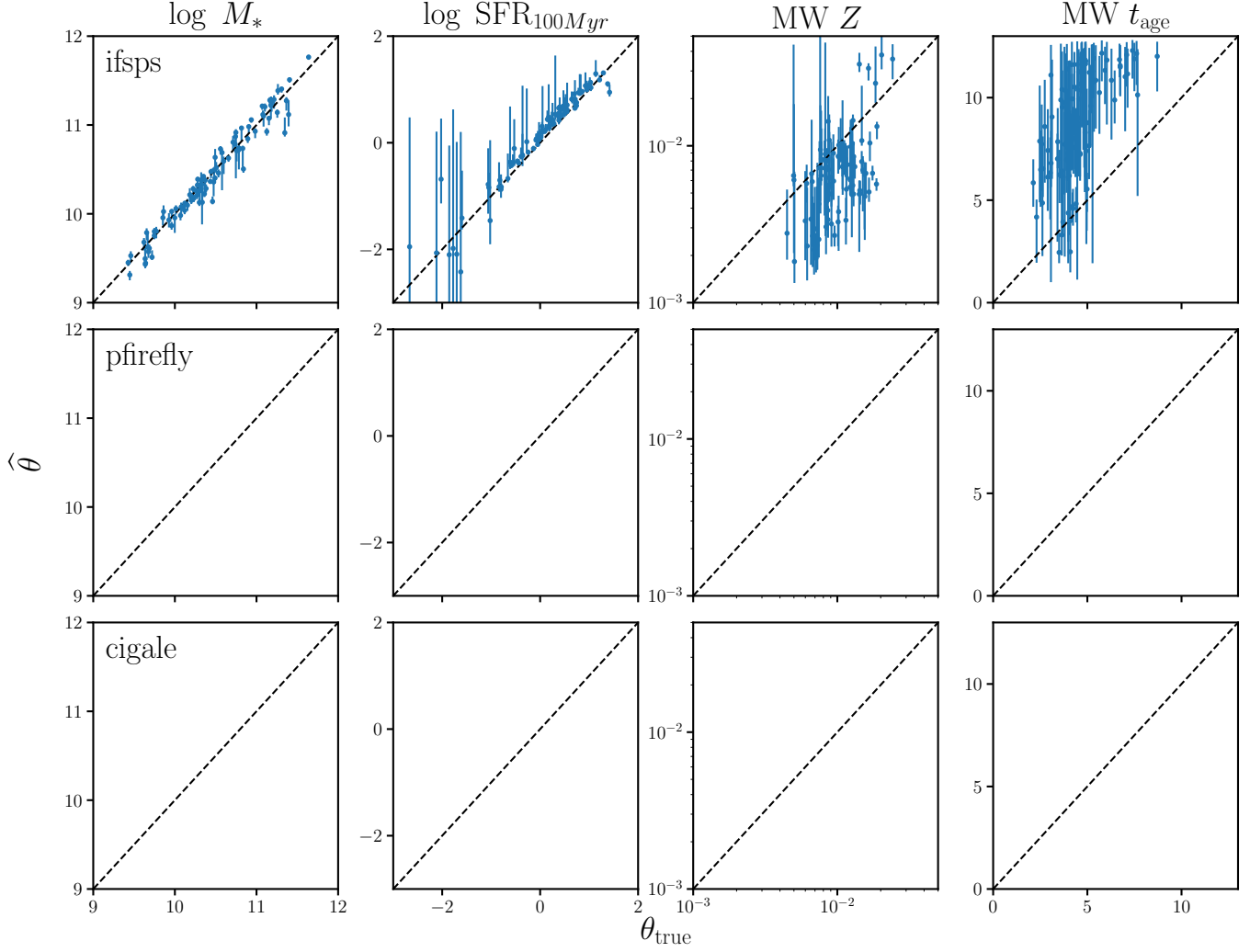
Figure 4

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  $\Delta_{\theta,i}$ )

$$\theta_i^{\text{inf}} = \theta_i^{\text{true}} + \Delta_{\theta,i} \quad (2)$$

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

$$\Delta_{\theta,i} \sim \mathcal{N}(\mu_{\Delta_{\theta}}, \sigma_{\Delta_{\theta}}). \quad (3)$$



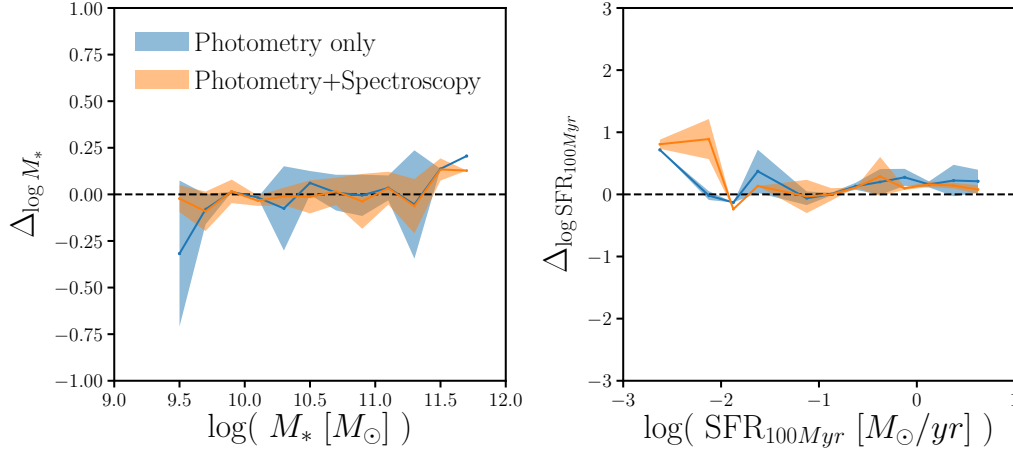
**Figure 4.** The properties inferred from ifsp spectrophotometry fit as a function of true properties.

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 parameters  $\theta_\Delta = (\mu_{\Delta_\theta}, \sigma_{\Delta_\theta})$  using a hierarchical Bayesian framework (Hogg et al. 2010):

$$p(\theta_\Delta | \{\mathbf{D}_i\}) = \frac{p(\theta_\Delta) p(\{\mathbf{D}_i\} | \theta_\Delta)}{p(\{\mathbf{D}_i\})} \quad (4)$$

$$= \frac{p(\theta_\Delta)}{p(\{\mathbf{D}_i\})} \int p(\{\mathbf{D}_i\} | \{\theta_i\}) p(\{\theta_i\} | \theta_\Delta) d\{\theta_i\}. \quad (5)$$



**Figure 5.** 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.*

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

$$p(\theta_\Delta | \{\mathbf{D}_i\}) = \frac{p(\theta_\Delta)}{p(\{\mathbf{D}_i\})} \prod_{i=1}^N \int p(\mathbf{D}_i | \theta_i) p(\theta_i | \theta_\Delta) d\theta_i \quad (6)$$

$$= \frac{p(\theta_\Delta)}{p(\{\mathbf{D}_i\})} \prod_{i=1}^N \int \frac{p(\theta_i | \mathbf{D}_i) p(\mathbf{D}_i)}{p(\theta_i)} p(\theta_i | \theta_\Delta) d\theta_i \quad (7)$$

$$= p(\theta_\Delta) \prod_{i=1}^N \int \frac{p(\theta_i | \mathbf{D}_i) p(\theta_i | \theta_\Delta)}{p(\theta_i)} d\theta_i. \quad (8)$$

$p(\theta_i | \mathbf{D}_i)$  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

$$p(\theta_\Delta | \{\mathbf{D}_i\}) = p(\theta_\Delta) \prod_{i=1}^N \frac{1}{S_i} \sum_{j=1}^{S_i} \frac{p(\theta_{i,j} | \theta_\Delta)}{p(\theta_{i,j})}. \quad (9)$$

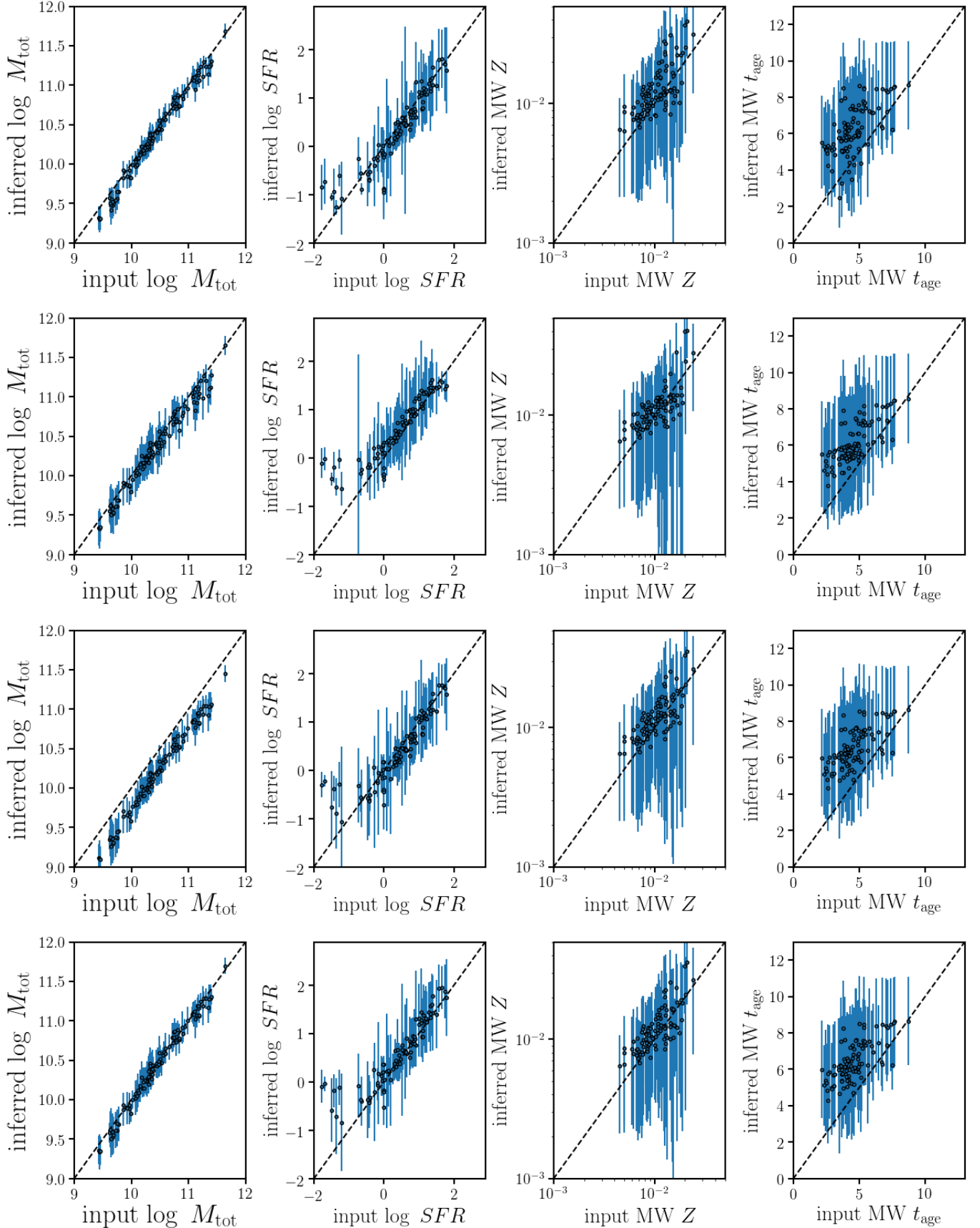
$S_i$  is the number of MCMC samples and  $\theta_{i,j}$  is the  $j^{\text{th}}$  sample of galaxy  $i$ . We present the maximum a posteriori (MAP) estimates of  $\theta_\Delta$  for  $\log M_*$  and  $\log \text{SFR}$  in Figure 5.

Quantify precision and accuracy as a function of SNR/mag/colour.

**figure:**  $\theta_{\text{inf}}$  vs  $\theta_{\text{true}}$  plot for final fitting methods. Money plot of the mock challenge

**figure:** delta(galaxy properties) as a function of r-mag, SNR, color for different fitters for spectral fitting

**figure:** delta(galaxy properties) as a function of r-mag, SNR, color for different fitters for photometric fitting



**Figure 6.** The properties inferred from CIGALE photometry fit as a function of true properties. Configuration CIGALE A, B, C, and D

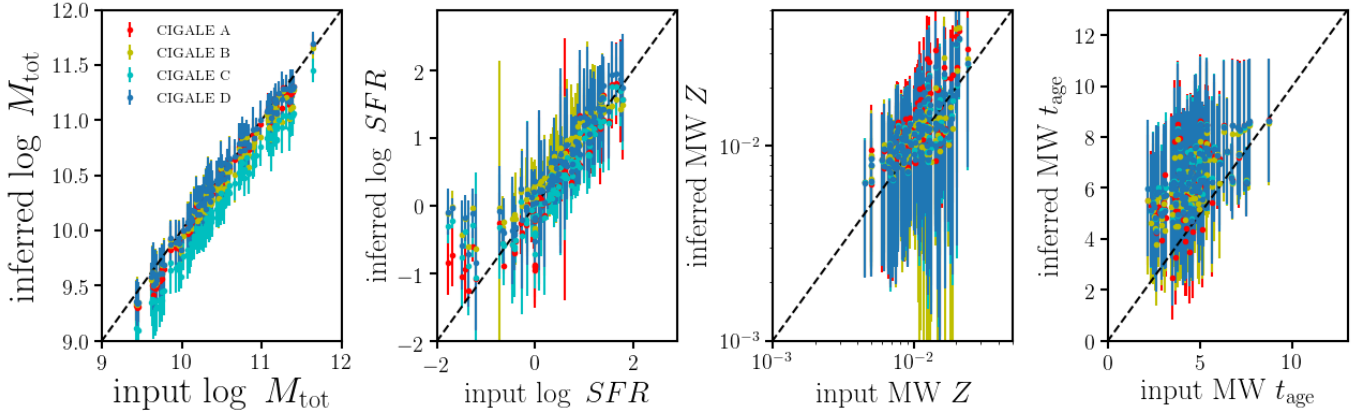


**Table 2.** Table of  $\theta_{\text{inf}} - \theta_{\text{true}}$  and uncertainties for different sets of data fitted with ifsp

set	photometry	spectroscopy	specphot
$\Delta M_{\text{tot}}$	0.13	0.11	0.09
$M_{\text{err}}$	0.10	0.08	0.07
$\Delta \text{Age}$	4.05	3.84	4.33
$\text{Age}_{\text{err}}$	1.83	2.37	2.03
$\Delta Z$	0.0546	0.0126	0.0063
$Z_{\text{err}}$	0.0291	0.0203	0.0050

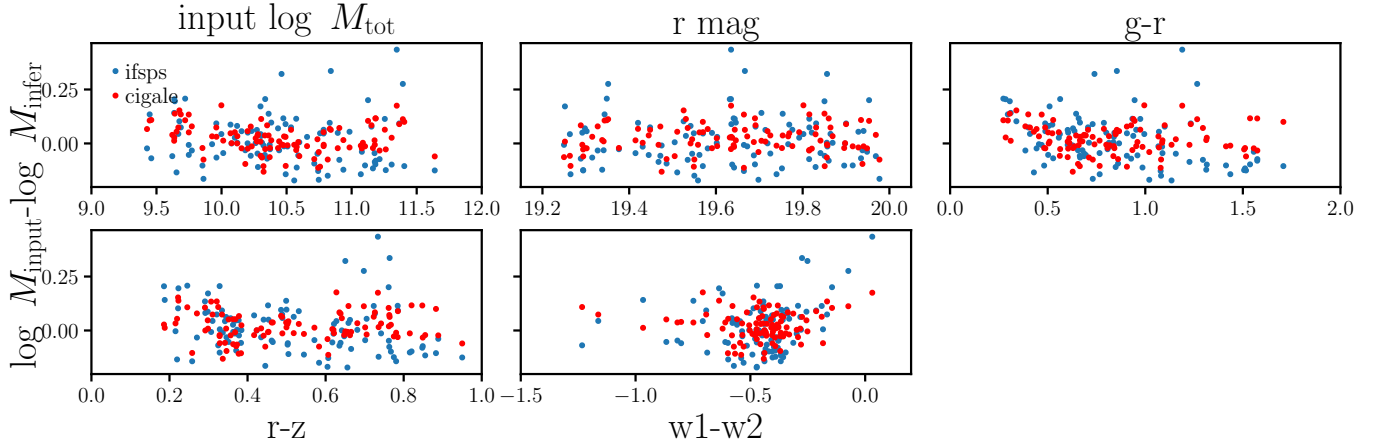
**Table 3.** Table of  $\theta_{\text{inf}} - \theta_{\text{true}}$  and uncertainties for different CIGALE setups

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

**figure:** delta(galaxy properties) as a function of r-mag, SNR(?), color for different fitters for spectro-photometric fitting

#### 4.2. Comparison of Galaxy Properties



**Figure 8.** delta(galaxy properties) as a function of  $M_{tot}$ ,  $r$  mag and colors for ifsp(spectrophotometry) and CIGALE (photometry, CIGALE D).

comparison of the different fitting set ups

**figure:**  $\theta_{inf}$  vs  $\theta_{true}$  plot for multiple fitting methods

**figure:** more quantitative comparison of accuracy and precision  $\theta_{inf}$  vs  $\theta_{true}$  for multiple fitting methods

## 5. SUMMARY

DESI is great.

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

## ACKNOWLEDGEMENTS

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## APPENDIX

## REFERENCES

Dey A., et al., 2019, [AJ](#), 157, 168

Hogg D. W., Myers A. D., Bovy J., 2010, [The Astrophysical Journal](#), 725, 2166