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VALIDATING THE LARGE SYNOPTIC SURVEY TELESCOPE'S CORE COSMOLOGY LIBRARY

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ABSTRACT

The Large Synoptic Survey Telescope Dark Energy Science Collaboration has developed the Core Cosmology Library (CCL) that aims to calculate cosmological observables to a high precision. Since this has only been validated for the fiducial cosmological parameter values, we want to make sure CCL has been validated for a wide range of cosmological parameter values. One of the observables is the matter power spectrum and we compared CCL to the Cosmic Linear Anisotropy Solving System (CLASS). The Validation Among Reasonable Routines Interface for Cosmology (VARRIC) is a powerful tool to visualize these comparisons and allows the users to find where CCL works and fails to meet the high precision. VARRIC has also been created such that it is not only to compare CCL and CLASS but any *reasonable routine in cosmology*, so VARRIC can be extended to consider other observables and programs.

1. INTRODUCTION

The Large Synoptic Survey Telescope (LSST) aims to take images of half of the entire sky at multiple wavelengths, resulting in hundreds of millions of galaxies being detected. Information gained from these galaxies will allow us to better understand the accelerating expansion of the universe, termed as dark energy (Perlmutter et al. (1999)). Therefore, the measurements need to be precise and accurate.

The LSST Dark Energy Science Collaboration developed a library called the Core Cosmology Library that aims to calculate these cosmological quantities to better than 0.01% precision (LSST DESC (2016–)). However, this has only been validated for the PLANCK fiducial values for the cosmological parameters. Since the LSST will take more precise data in the future and that CCL will be used for those measurements, CCL needs to be accurate for different sets of many possible cosmological parameters. As CCL is still in development, a challenge in making sure CCL meets this accuracy is the visualization of this data.

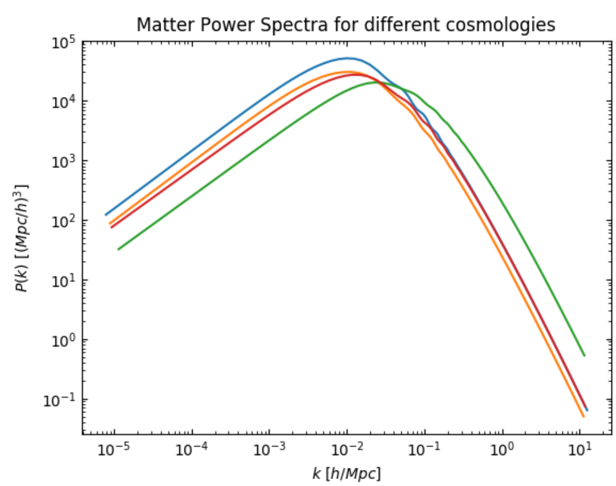

Figure 1. Plotted is the Matter Power Spectrum for different sets of cosmological parameters. The x-axis is k, which is similar to inverse distance. The y-axis is $P(k)$

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2. METHODS

2.1. *Core Cosmology Library (CCL)*

The Core Cosmology Library is a Python library that aims to create consistency between LSST analyses. By receiving data from the LSST, CCL can then calculate cosmological observables.

An example of an observable is the Matter Power Spectrum (mPk). By measuring the distances between galaxies, we can calculate the matter correlation function $\xi(r)$. Taking the Fourier transform of this function gives us the mPk $P(k)$, which describes the clustering of galaxies at different scales of the universe. As seen in the **Fig.** 1, different cosmological parameters leads to different mPk. So from the measurements by LSST, we use parameter estimation. This technique finds the cosmological parameters that produce the theoretical power spectra that best fits the one observed. This will be very difficult to fine tune the cosmological parameters

Table 1. Cosmological Parameters varied, the fiducial (default) values and the ranges.

Cosmological Parameters	Fiducial	Ranges
h	0.67	[0.5, 0.9]
Ω_{cdm}	0.27	[0.1, 0.4]
Ω_b	0.045	[0.018, 0.052]
A_s	2.1e-9	[1.5e-9, 2.5e-9]
n_s	0.96	[0.93, 0.99]

to fit the observed mPk. CCL streamlines this process.

CCL also calculates other power spectra, necessary for dark matter and dark energy analyses. And since LSST is not just used to understand dark energy, CCL also has tools for other analyses such as supernovae analysis.

We need to validate this program, so that there's no bias when we make our measurements. From **Fig. 1**, and the cosmological parameters used, we can infer the wrong values for the cosmological parameters if we don't have an accuracy of 0.01%.

2.2. *Latin Hypercube Sampling*

As the LSST takes more data, the fiducial cosmological parameters can change. To account for these shifts, we want to make sure that CCL is validated for a large area of parameter space. A good way of sampling most of the parameter space is through Latin hypercubes formulated by McKay et al. (1979). Latin hypercube sampling (LHS) is used to generate parameter values from a multidimensional function. This sampling scheme can yield more precise estimates of the values compared to Monte Carlo sampling. Since these are multidimensional functions, this leads to exponentially increasing sample sizes. LHS remedies that.

To better understand Latin hypercubes, we consider the case of the Latin square, which is a 2 dimensional Latin hypercube. So this means we vary 2 parameters. Say we want five samples. We then look at the probability distribution functions of the 2 parameters, then we bin them, such that in each bin there is a $1/N_{samples}$ probability of finding the point in that range. Then we pair up the 2 parameters randomly, such that each bin is not used again. Refer to **Fig. 2**. Then after pairing them, we choose a point randomly inside each of those bins.

Extending this to the 5 cosmological parameters that we

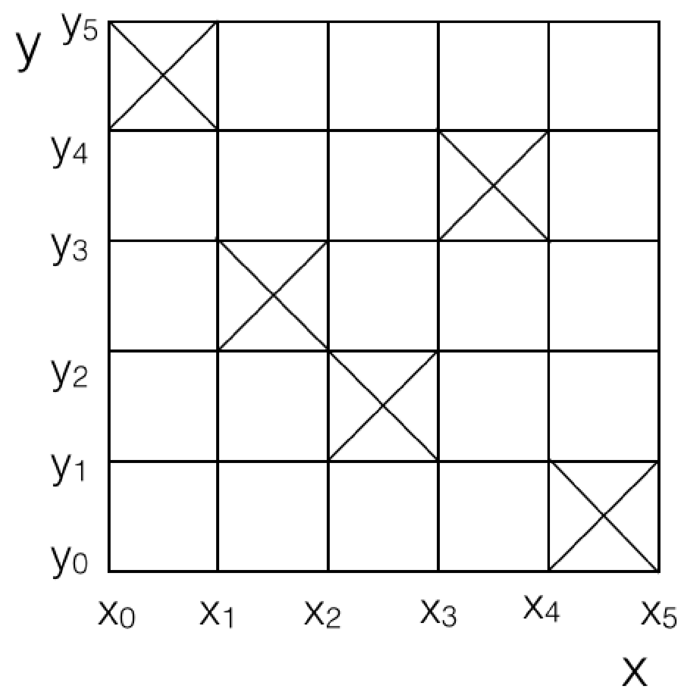

Figure 2. An example of a Latin square, with the paired bins marked.

varied:

h	Hubble's constant
Ω_b	density parameter of baryonic matter
Ω_{cdm}	density parameter of cold dark matter
A_s	amplitude of the primordial power spectrum
n_s	tilt of the primordial power spectrum

For these parameter values, we assumed a uniform distribution in the ranges given in **Table 1**. We perform LHS for 100 samples, since we find that to be a good enough number to sample the parameter space. So instead of pairing 2 parameters in the case of a Latin square, we pair the 5 parameters randomly. And instead of choosing a point randomly inside the bins, we choose the midpoint of those bins, since what we want is just a point in the parameter space.

2.3. *CLASS*

The Cosmic Linear Anisotropy Solving System (CLASS) has been shown to reach the 0.01% accuracy threshold for many cosmological observables, one of them being the matter power spectrum (Blas et al. (2011) and Lesgourgues (2011)). CCL actually uses the default version of CLASS to calculate the mPk. CLASS can also calculate the linear and nonlinear mPk.

With the generated sets of parameter values, we calculate the mPk using CLASS and CCL and see how well CCL works, an example of which is in **Fig. 3**. And we compare them for the different modes:

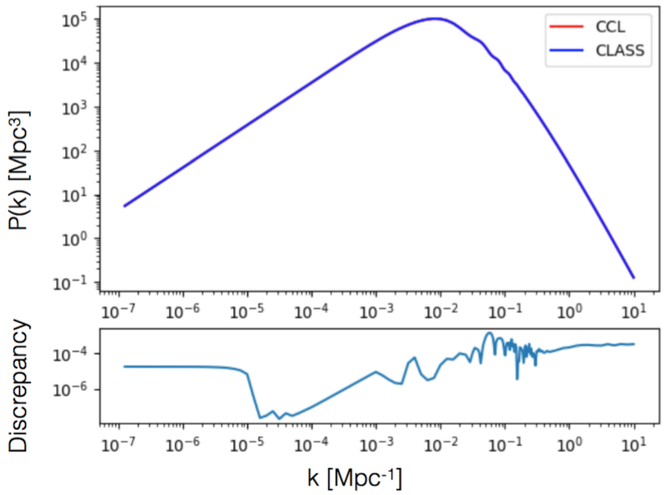

Figure 3. An example of a comparison between CCL and CLASS. The matter power spectrum calculated by CLASS and CCL are plotted in the first plot. The fractional difference is plotted on the second plot.

- Linear mPk
- Nonlinear mPk
- Linear mPk, Precision
- Nonlinear mPk, Precision

The precision means that we are running CLASS with the 0.01% accuracy settings. We also performed the calculations for redshifts, z = {0, 0.5, 1, 1.5, 2, 2.5}. Since we have 100 samples, it would be difficult for the developers of CCL to go through each of the different modes for each of the different redshifts.

The purpose of VARRIC is to allow the developers to easily visualize how well CCL meets the accuracy threshold, as in which z values and in what scales (e.g. Linear Scales, Nonlinear Scales). As seen in **Fig.** 3, CCL fails to meet it at k > 10^{-2}, but it is very difficult to see it on the plots of the mPk. So we would like this interface to have more interactivity compared to a regular plot. This is were VARRIC comes in.

2.4. *Bokeh and Flask*

Bokeh is a Python module that enhances the visualization experience and interactivity to plots (Bokeh Development Team (2014–)). It adds tools for your plots, such as allowing the user to zoom at points, select points of interest, and save the plots for later use. Bokeh also adds widgets, so that the user can easily change what is being plotted. In the case for VARRIC for example, the user can choose which mode to be plotted. Bokeh allows for integration to web interfaces, which is what we aim VARRIC to become.

The tools that we have implemented from Bokeh include:

HoverTool	the user can hover over a point on a plot and information about that point will be shown, such as x, y
TapTool	the user can click on points and based on what is coded an event will occur, e.g. a new tab is opened
PanTool	the user can click and drag to pan the plot
BoxTool	the user can click and drag a box to select a region in which the plot will zoom in to
ResizeTool	the user can click and drag on the plot to make it larger or smaller
WheelZoomTool	the user can use the wheel on their mouse (or the equivalent) to zoom in and out of the plot
SaveTool	the user can save the plots as a .png file
ResetTool	the user can click on this to reset the plot to what it was originally

We also use widgets from Bokeh. These include:

Dropdown	The user can choose from a selection what argument they would like
Slider	The user can choose the value for the slider
RangeSlider	The user can choose a range a values from the ones given
Checkbox	The user can check/uncheck boxes based

We use widgets because Bokeh can utilize JavaScript code to change the values plotted based on the values chosen in the widgets in real time.

Because of its integration to web interfaces, we utilize Flask to create the website in our local servers (Flask Development Team (2010–)). Flask is a Python-like module for creating web frameworks.

3. RESULTS

3.1. *Summary Page*

When VARRIC first loads up, a corner plot is shown of the cosmological parameters that we varied. The points are plotted as squares with its color corresponding to how badly the CCL points fail to meet the threshold, as seen in **Fig.** 4.

We chose the color scales such that large failures are more visually striking, hence bright red, and small failures are lighter. The failure is characterized as

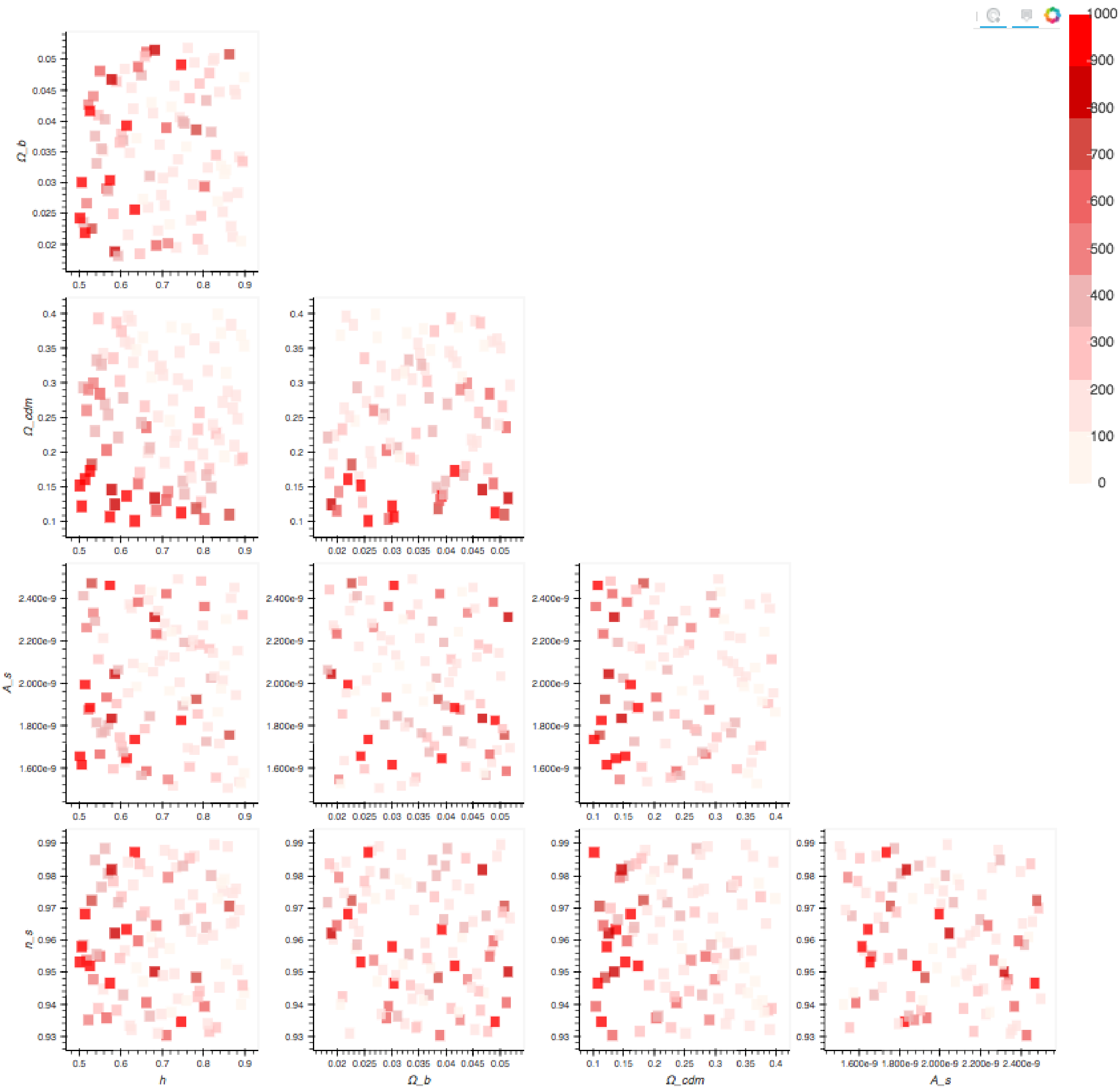

Figure 4. This is a corner plot of the cosmological parameters that we varied. It is essentially the cosmological parameters plotted against one another. The color corresponds to how well CCL works in those parameter values

$$\Delta = \sum_{ij} log_{10}\left(\frac{|P_{CCL}(k_i,z_j)-P_{ref}(k_i,z_j)|}{P_{ref}(k_i,z_j)\Delta_{thres}}\right) \quad (1)$$

where P_{CCL} corresponds to the matter power spectra calculated by CCL, P_{ref} corresponds to the reference matter power spectra (i.e. CLASS), and Δ_{thres} corresponds to the accuracy we want (i.e. 0.01%).

We chose this metric because it is based on how many orders of magnitude the CCL is off compared to the reference mPk, in this case CLASS. To make sure the points that meet the threshold do not affect the value of Δ, we set those points to 0. The different indices of k correspond to the 3 scales, Ultra-large, Linear, and Nonlinear. The different indices of z correspond to which redshift value is chosen. The advantage of this metric is also that one big failure is equivalent to many small failures.

Some of the other widgets available for the user to change is the Threshold slider. It is set at the default value for 0.01% Moving the slider to the left makes the threshold value tighter, so in principle, the points should become redder. And moving the slider to the right, makes the threshold value looser, making the points become paler.

There is also a Dropdown menu for the mode chosen. So if the user wants to look at the Nonlinear mPk or the precision version of Linear mPk, the user can do so. One of the advantages of Bokeh, is that the changes are real time, and do not need to recalculate the matter power spectra or reload the web interface.

Another widget is the z slider. This is a RangeSlider in terms of Bokeh widgets, since we want to choose which range of the z values we want being included in the calculation of Δ. For example, if we are looking at data from the LSST, we are only interested in the range of 0.5 to 1.5. This allows the user to choose those ranges and observe how well CCL works.

Lastly, we have a Checkbox of the k scales. This allows the user to choose which k scales we want being included in the calculation of Δ. Say again, we are looking at data from the LSST, we are only interested in the Linear Scales, the user can click on the checkboxes to *uncheck* the Ultra-Large Scales and the Quasi-Linear Scales. This should, in principle, make the dots paler.

Any changes being made to any of the widgets changes the plots in real time. So rather than, reloading the website every time, VARRIC has been coded to make the changes in real time.

Looking at the plots, we implemented the Hover tool. The information shown is the index of the point, the location on the x-y plane, and Δ of that point.

Another tool that we have implemented is the TapTool in terms of Bokeh widgets. This allows for the user to select on points of interest. Varric has been coded, such that when the user finds a point that is of interest, the user can click on it. By doing so this opens a new tab showing the *Detailed Summary Page* of that set of parameter values.

3.2. *Detailed Summary Page*

After clicking on a data point of interest, a new tab will open. This new tab is the *Detailed Summary Page*. As its name implies, this part of VARRIC shows a more detailed representation of the sample chosen. The first plot, titled **Summary Statistic** plots Δ for different k scales and z values. But in this case the k indices correspond to the k values used to make the mPk. We chose these, so the user can observe which z values and k ranges CCL works well in meeting the accuracy threshold.

To the right of the plot we have the parameter values used to generate the matter power spectra.

Below these are 2 plots. The first plot, titled **Discrepancy mPk, MODE** plots $(P_{CCL} - P_{ref})/P_{ref}$ against k value. We plotted these for different z values used. In this we used the *Interactive Legend* from Bokeh. So again, say the user is only interested in z values between 0.5 and 1.5, the user can click on the points in the legend, to make the lines on the plot appear and disappear corresponding to the z value. To

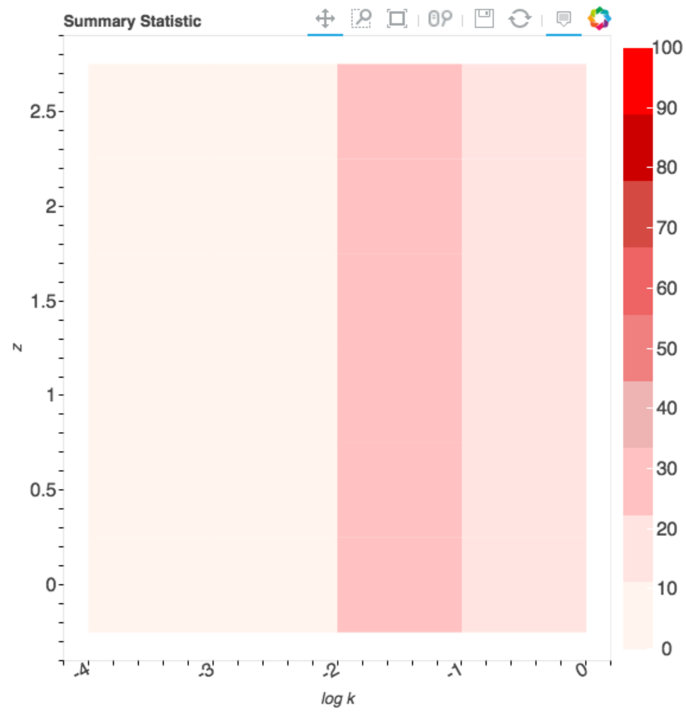

Figure 5. This summary statistic plots the $log_{10}(k)$ on the x-axis and the redshift on the y-axis. The color corresponds to how badly it failed.

the right, of this is the plot of the mPk for both CCL and CLASS and the different z values. This plot also implements the *Interactive Legend*, so clicking on the points in the legend can make the lines disappear/reappear.

These two plots have the interactivity that we wanted to have for our validation interface. We have implemented the HoverTool, PanTool, BoxTool, ResizeTool, WheelZoomTool, SaveTool, and ResetTool to these two plots, so that the user can zoom in on points of interest, as well as save the plots for later use.

If the user wants to recreate the plots, we have provided the .ini file that CLASS uses to generate the mPk. And we need these first, since our CCL code utilizes the k values from the CLASS data files. We have also provided the CCL code, which the user can run on Python.

VARRIC has a Detailed Summary Page for the four modes we have.

4. CONCLUSION

The Validation Among Reasonable Routines Interface for Cosmology (VARRIC) is a powerful tool for developers of CCL to visualize where CCL works and fails in meeting the accuracy of 0.01%. A manual is currently being written for users to update the data sets being plotted, since CCL will be updated because it is in development. VARRIC has also been created such that it is not only used to validate the mPk. Comparing observables, such as those for dark energy analyses, can be done so easily. It also does not have to be CCL, other cosmological routines can be compared with VARRIC.

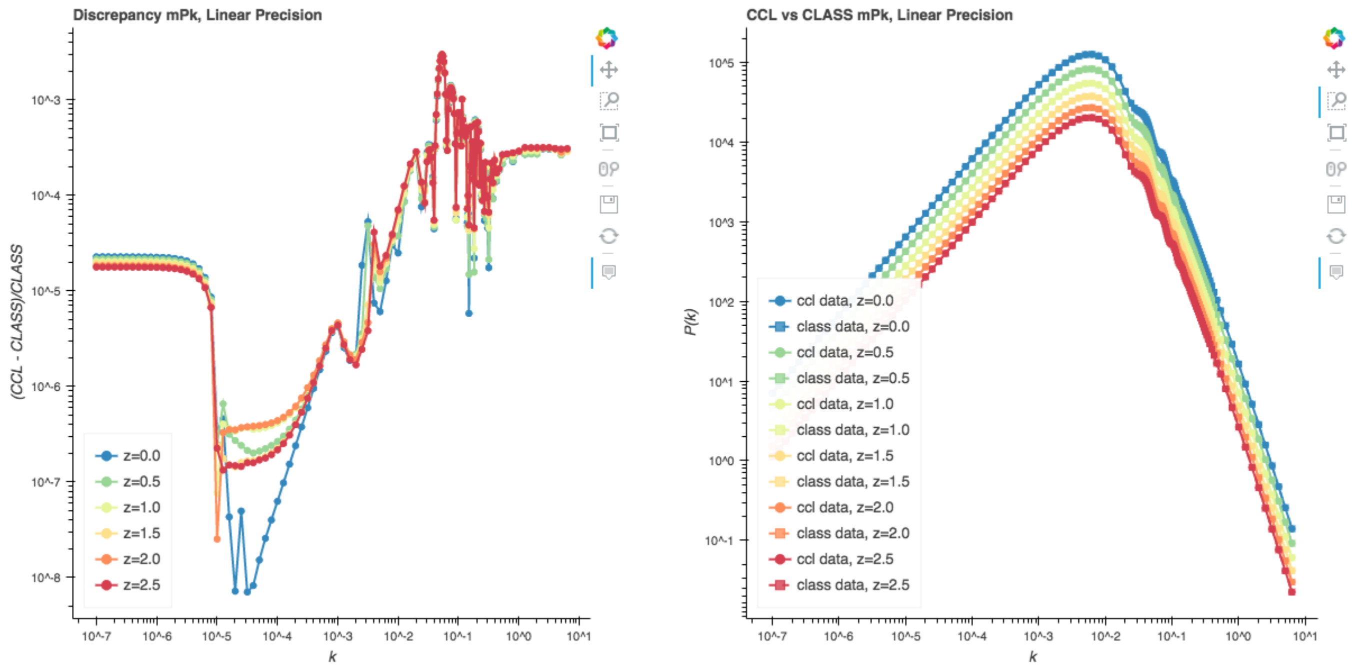

Figure 6. These are the plots of the fractional difference and the mPk calculated by CLASS and CCL, for the range of z values, as seen in VARRIC.

Some more examples are discussed in *Future Work*.

5. FUTURE WORK

The adaptability of VARRIC makes it a powerful tool for visualizing comparisons. For example, we have only considered varying 5 cosmological parameters, but we can extend the number of cosmological parameters to 8, by considering the time evolution of dark energy and the curvature of the universe (Bull et al. (2016)). Simply running CLASS and CCL for these parameter values and adjusting the code for VARRIC, can recreate these plots for a larger set of cosmological parameters.

Another possible extension is to validate other cosmological observables such as the Lensing Power Spectrum and others associated with dark energy and dark matter analyses. CCL has been developed to calculate these as well, however, CLASS was not. One of the cosmological routines that also calculates these observables is CosmoLike (Krause & Eifler (2017)). With VARRIC, we can simply change the data sets being plotted.

Lastly, another work considered, is to use VARRIC to compare cosmological observables generated by CosmoLike to its fiducial values. In this work, CosmoLike considers more than 20 nuisance parameters in addition to the cosmological parameters to model the Lensing Power Spectrum. We are interested in studying how varying these nuisance parameters affects the observable.

6. PERSONAL COMMENT

I have never been to JPL before my internship. I initially expected JPL to be hardworking robot-like humans that constantly perform their work. However, setting foot and meeting the workers and my advisors proved otherwise. Though these people are hardworking, the workers I've met were far from robots.

From my experience, last summer at CERN, I gained a better understanding of what the European laboratory atmosphere is like. I also had an idea of what the working atmosphere is like in Academia. And it is much different at JPL, in the sense of regulations and the working atmosphere. There are considerably more regulations at JPL. For example, I didn't particularly liked wearing a badge all the time, but I understood its necessity. I also gained a better understanding of how working in a laboratory is different from working in academia, in the sense of the constant need to fund your research in JPL.

The several postdocs and employees were very approachable. For example, I was able to meet with the section manager, Leonidas Moustakas and discuss research and what it's like working in JPL. I was also able to ask other postdocs for advice and help on my project and Final Presentation.

I enjoyed the sense of camaraderie in my group. For example, every week we host a hack session, where people in our group meet for 3 hours and work on our own code, and if we need help or want to collaborate with others, we can.

I particularly enjoyed the group of interns I worked with. They were very friendly and how our division set it up, we performed our final presentations in a sort of weekly colloquia, where 8-9 interns present on Thursday on the last 3 weeks of our internship.

Also, my main research interest is dark matter. I have mainly been working on the particle physics side of the topic.

However, dark matter is a topic of intersection between cosmology and particle physics. All the evidence we have of dark matter comes from cosmological observations. My group hosted weekly lectures and workshops on cosmological topics that helped me gain a better understanding of the cosmological frontier on studying dark matter.

Overall, I believe that this was an incredible experience that made me want to continue pursuing my PhD in physics to study dark matter. However, I am actually considering a postdoc position in JPL.

I would like to thank Phil Bull and Tim Eifler for their mentorship throughout the internship. I would like to thank Elizabeth Kimura, an intern I worked with, who designed some of the aspects of VARRIC. I would also like to acknowledge the Dark Sector group for their time and advice. This research was supported by the National Aeronautics and Space Administration's Minority University Research and Education Project (MUREP), and the Fellowships and Internships in Extremely Large Data Sets (FIELDS) research project.

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