Analysis of the CMB and Cosmological Parameters

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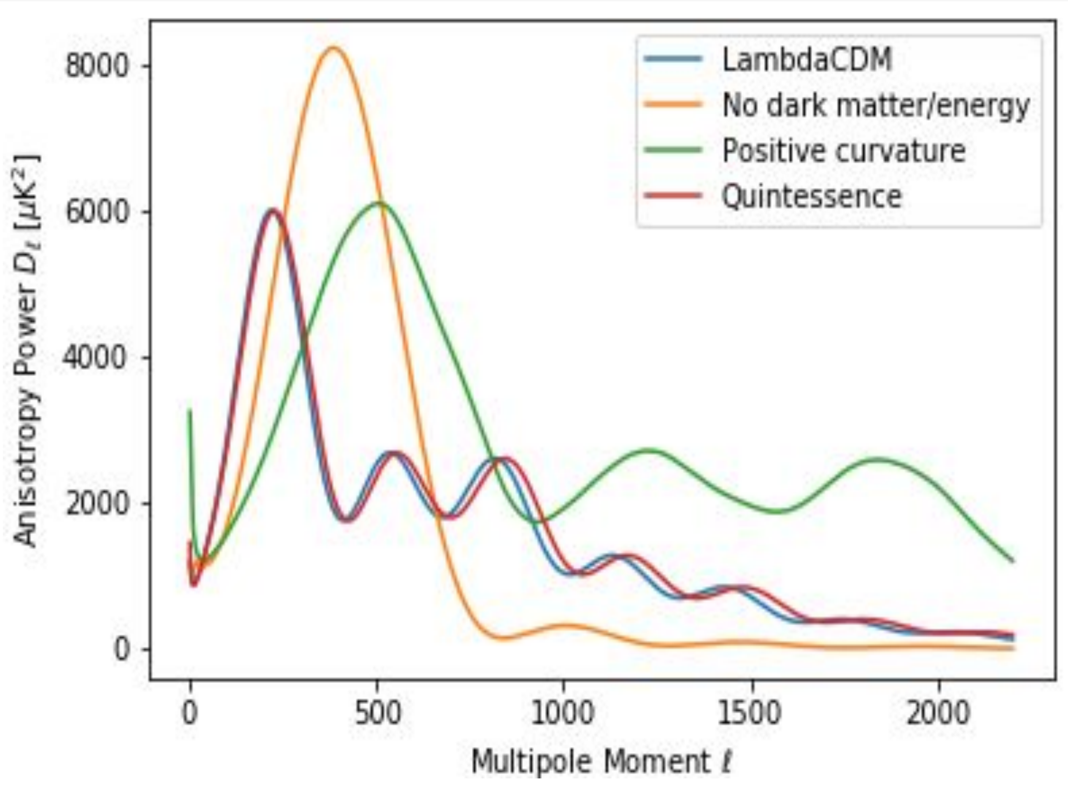
PHYS 250: Computational Physics

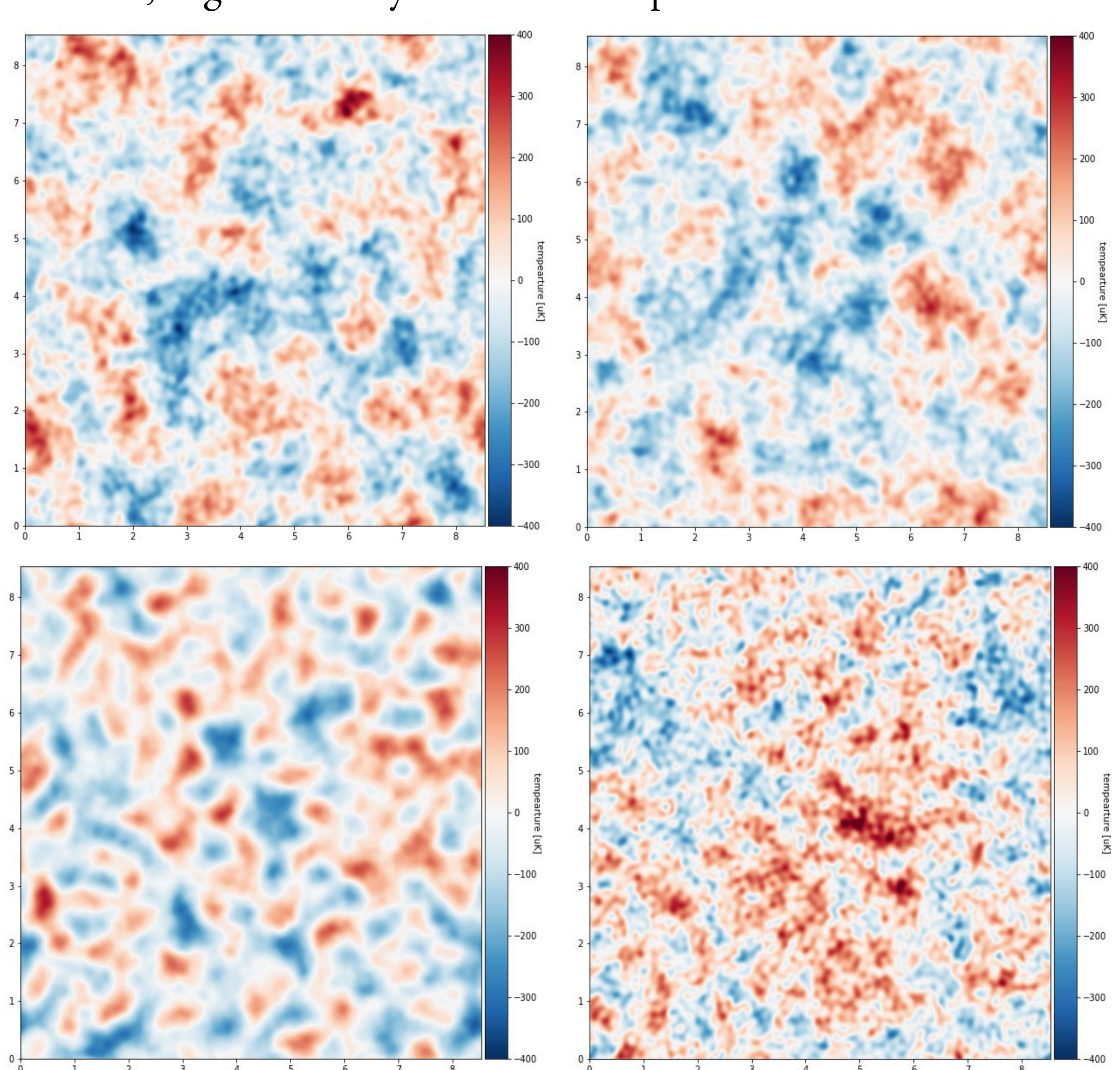
The CMB and its Power Spectrum

The Cosmic Microwave Background (CMB) is light emitted at the epoch of recombination, when the universe cooled enough to form neutral atoms and allow photons to travel freely rather than being scattered. The CMB is nearly uniform, with an average temperature of about 2.7 K, but it has tiny fluctuations across the sky resulting from small variations in the density of matter in the early universe.[1] The size of these fluctuations can be visualized through the angular power spectrum, which plots the amplitude of temperature variation against the "multipole moment," which corresponds to an inverse angle of separation.[2] Analyzing raw CMB data to produce sky maps and angular power spectra is a computationally challenging task, since it requires decomposing the map into spherical harmonics for a 3D Fourier transform, as well as accounting for instrumental and astrophysical effects.

Cosmological Parameters



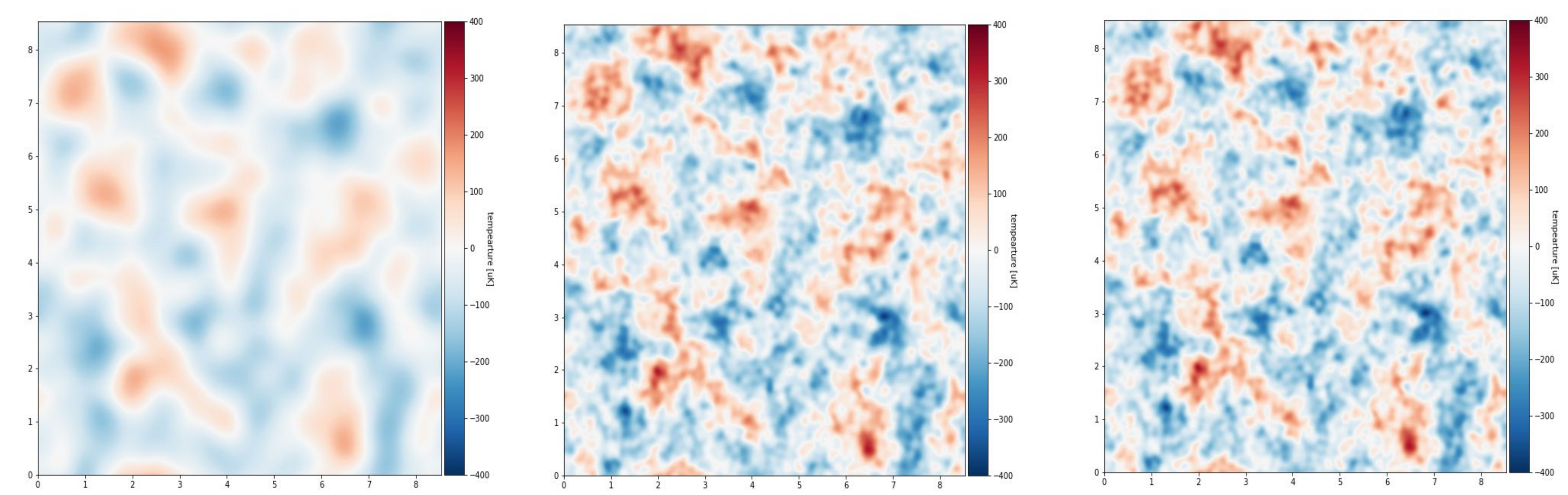
CMB anisotropies encode a variety of cosmological parameters describing the composition and dynamics of the universe. The locations and heights of the acoustic peaks of the power spectrum are closely related to features like spatial geometries and baryon density.[3] The plot above shows the power spectra of four model universes, as generated by the WMAP experiment CAMB code.[4]



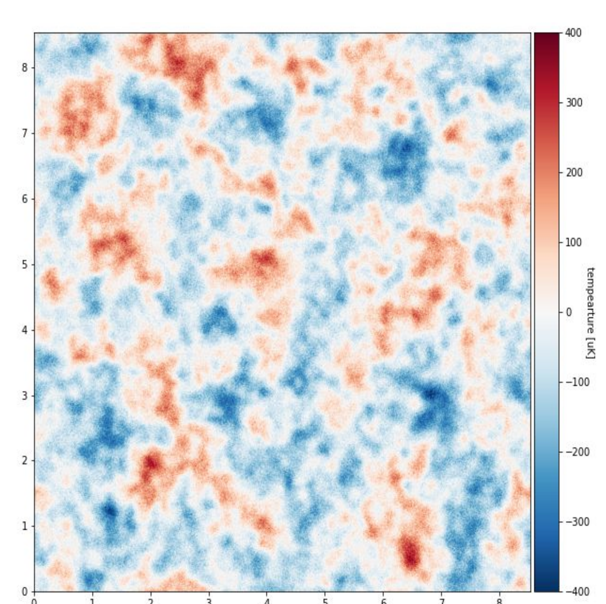
Clockwise from the top left, these are CMB sky maps of **(a)** a Lambda-CDM universe, **(b)** a universe where dark energy isn't the cosmological constant but rather a variable equation of state (quintessence), **(c)** a universe with positive curvature (k=1), and **(d)** a universe without any dark matter or dark energy (baryonic density = 1).

Generating Maps from Power Spectra: FFTs and Convolution

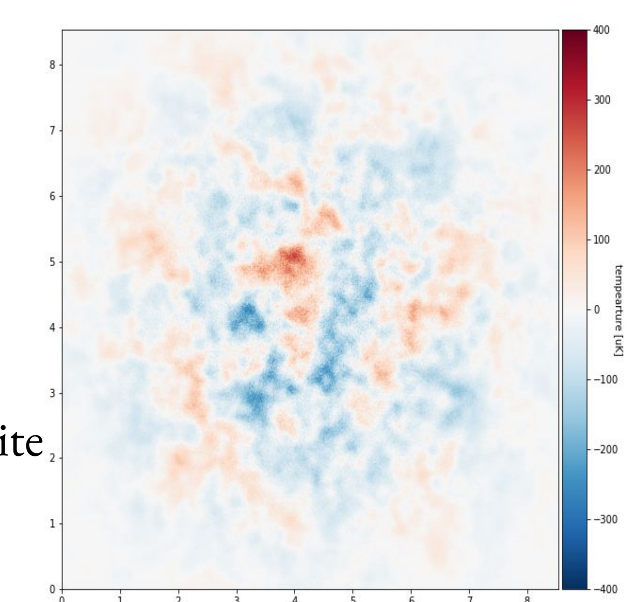
Using the flat sky approximation, the Fourier transform required is simplified to two dimensions only. A 2-D power spectrum is generated and convolved with a Gaussian random realization to return a real space CMB map. To account for instrumental beam effects, the map is convolved (multiplied by a Gaussian beam pattern and inverse Fourier transformed).



From left to right, beam convolution with a 30 arcminute beam, 3 arcminute, and 1 arcminute.



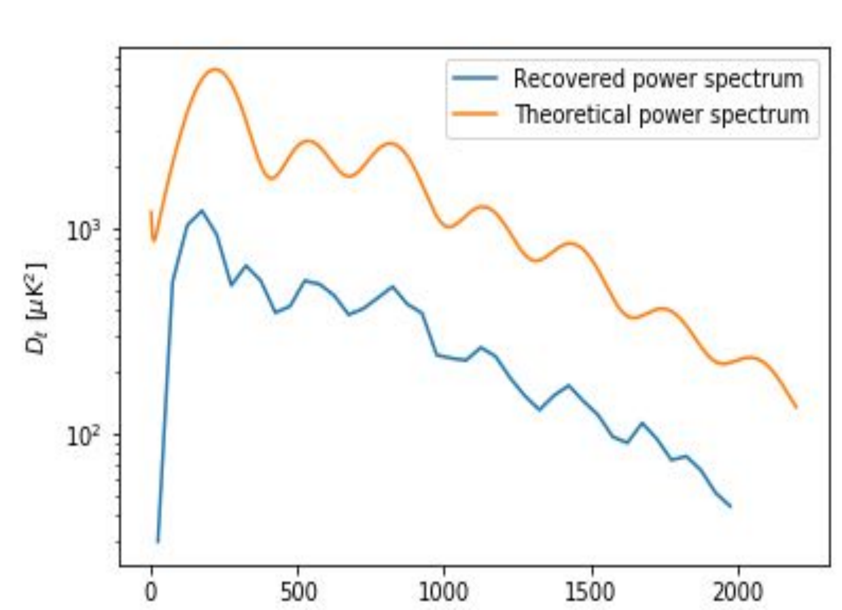
30 μK of white noise added

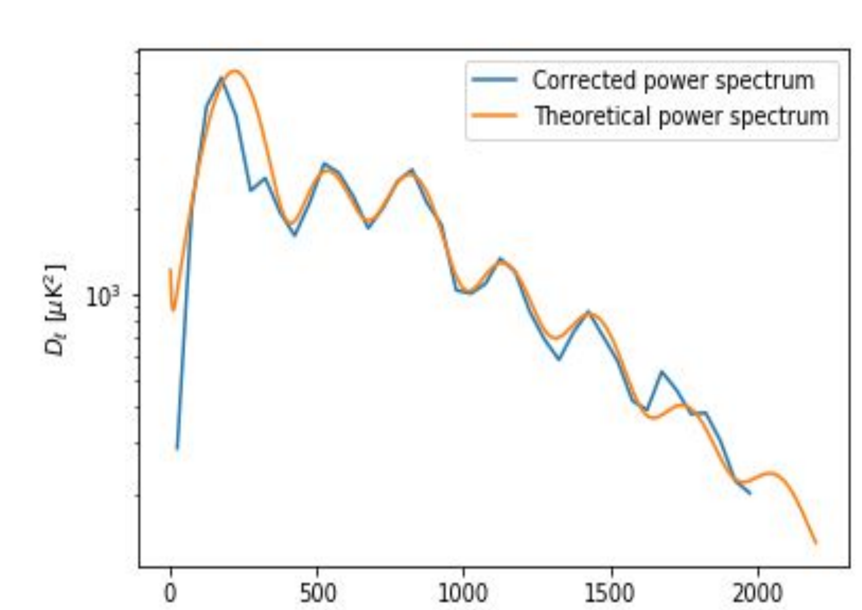


Gaussian apodization window to eliminate edge effects

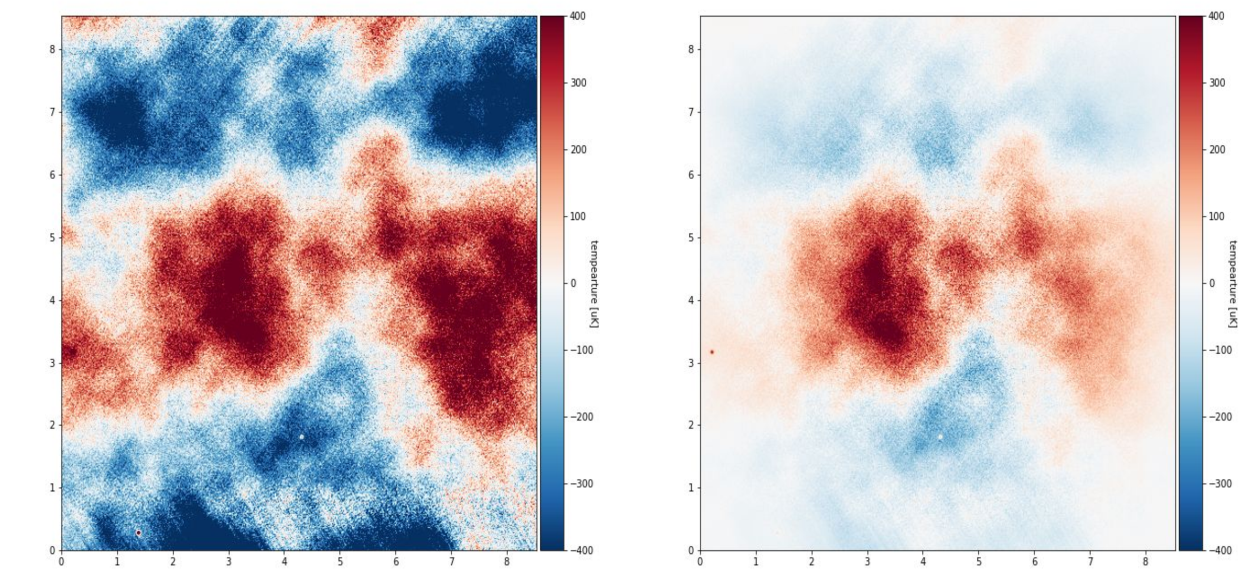
Recovering Power Spectra from Maps: Monte Carlo Methods

To recover the power spectrum from a realistic CMB map, we take the 2D Fourier transform, average the signal in radial bins, and convert back to a multipole scale. However, this power spectrum is biased with white noise, beam effects, and apodization filtering. In order to correct this, Monte Carlo simulations are run to calibrate the multiplicative and additive bias terms in the equation $D_\ell=(\hat{D}_\ell-N)/T$ that relates the actual spectrum to the measured spectrum.

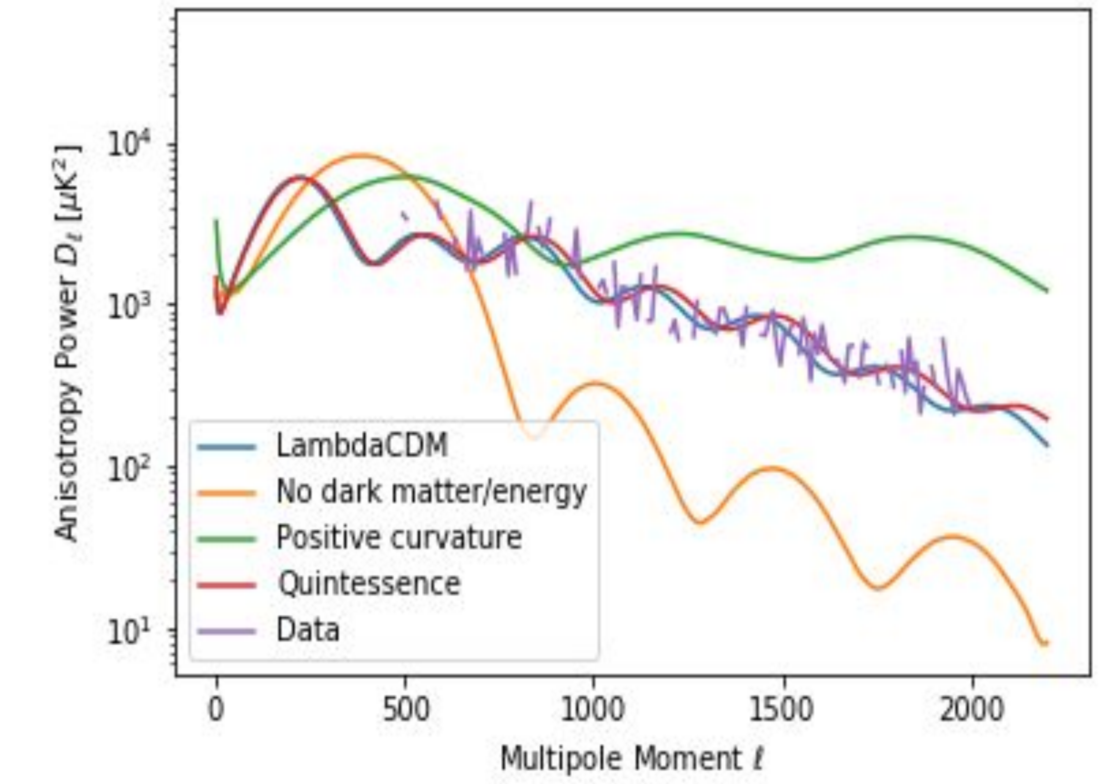




Comparing Data to Theory



Patch from ACT sky map: raw data on the left, apodized on the right.



When the power spectrum of public ACT data is plotted alongside theory power spectra, it is clear that 2 of the 4 model universes do not align with the data. However, the data seems to be similar to both the Lambda-CDM universe and the quintessence universe (due to parameter degeneracy), which is why additional tests like measurements of type-IA supernovae are useful in studying dark energy and "cosmic coincidence."[5]

Fitting Parameters

While we've compared data to theory visually, in order to actually fit cosmological parameters to measured power spectra, Monte Carlo methods are utilized to optimize the likelihood function in a parameter space with high-dimensionality. However, this process can be computationally demanding and slow even with MCMC analysis, so machine learning is beginning to be implemented to derive accurate theoretical predictions from a training set and validation.

References

[1] Filippini, Jeff. "The Cosmic Microwave Background." UC Berkeley Cosmology Group. August 2005. http://cosmology.berkeley.edu/Education/CosmologyEssays/The_Cosmic_Microwave_Background.html.

[2] Kavli Institute for Cosmology, Cambridge. "CMB Power Spectra, Likelihood, and Cosmological Parameters." https://www.kicc.cam.ac.uk/research/cosmic-microwave-background-and-the-early-universe/CMB-cosmological-parameters.

[3] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018). https://doi.org/10.1103/PhysRevD.98.030001.

[4] Lewis, Antony. "CAMB Notes." DAMTP/CITA/IoA/Sussex, April 2, 2014. https://cosmologist.info/notes/CAMB.pdf.

[5] Steinhardt, Paul J. "A Quintessential Introduction to Dark Energy." *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 361, no. 1812 (November 15, 2003): 2497–2513. https://doi.org/10.1098/rsta.2003.1290.

The code for this project is available in this Github repository: https://github.com/ananyakaranam/PHYS250_Final_Project Much of it is based on Jeff McMahon and Renee Hlozek's CMB School interactive notebooks and ACT data .