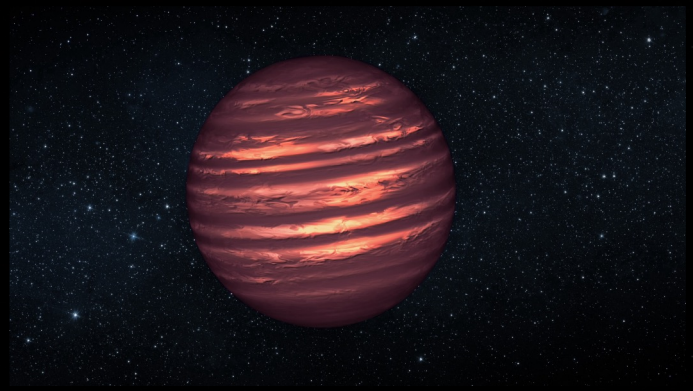
Using Variational Autoencoders to Accelerate Atmospheric Analysis for Brown Dwarfs



UC San Diego

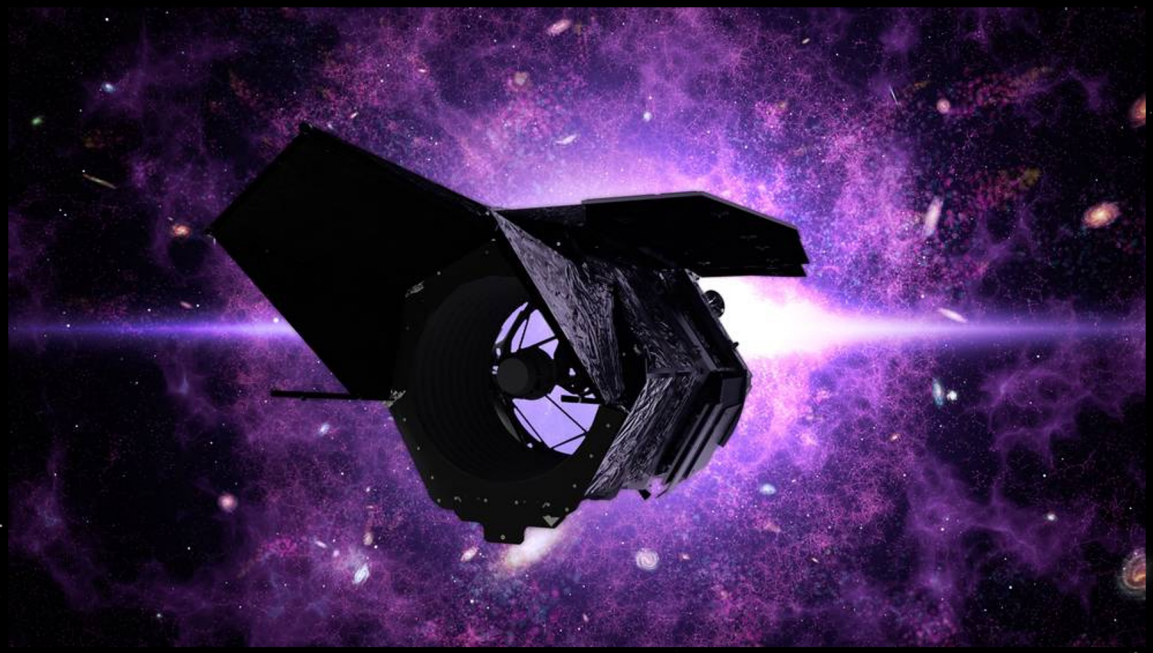
Julia Haynes | Data Science Masters Graduate

Advisor: Adam Burgasser

Collaborators: Emma Softich, Evan Pritchard

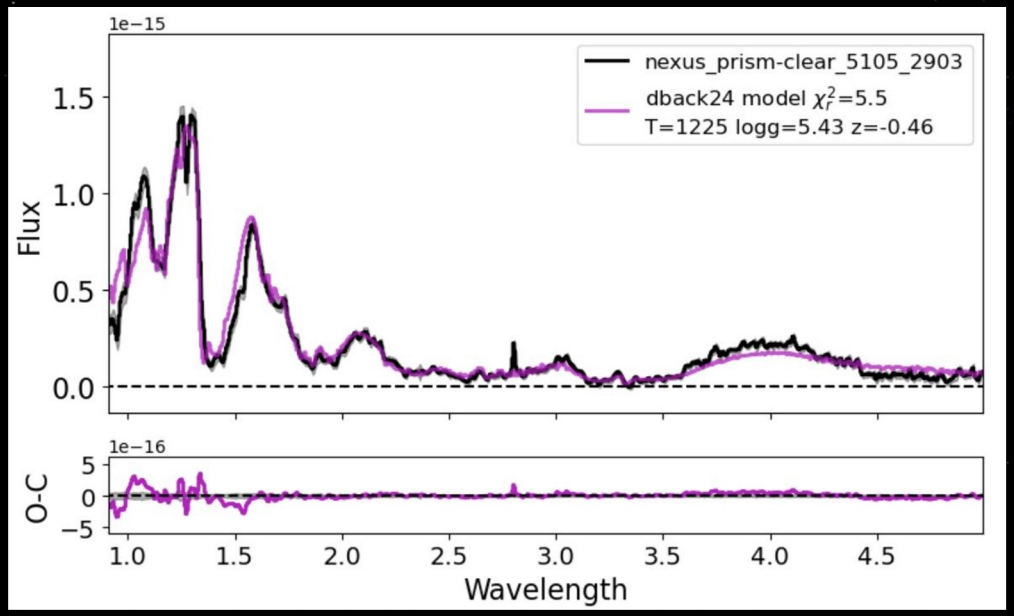
Artist's rendering of a brown dwarf Credit: NASA

Roman is expected to find thousands of brown dwarfs (Street et al. 2023). We want to use brown dwarfs to study the Milky Way, because they are abundant, live forever, and evolve with time.



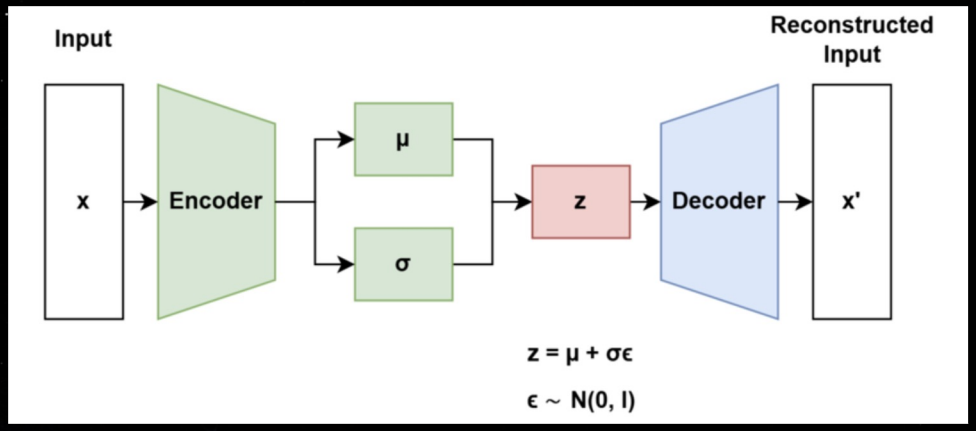
Artist's rendering of Roman Telescope Credit: NASA

Standard MCMC approaches for spectral modeling are too slow for large spectral datasets



Generate 10,000 models = 27 min
MCMC fit with 10,000 steps = 70 min

Variational autoencoders are a generative neural network that can be used to compress information, and generate new data. The encoder maps the data to a lower dimensional latent space, and the decoder recreates the original data from the latent variables.



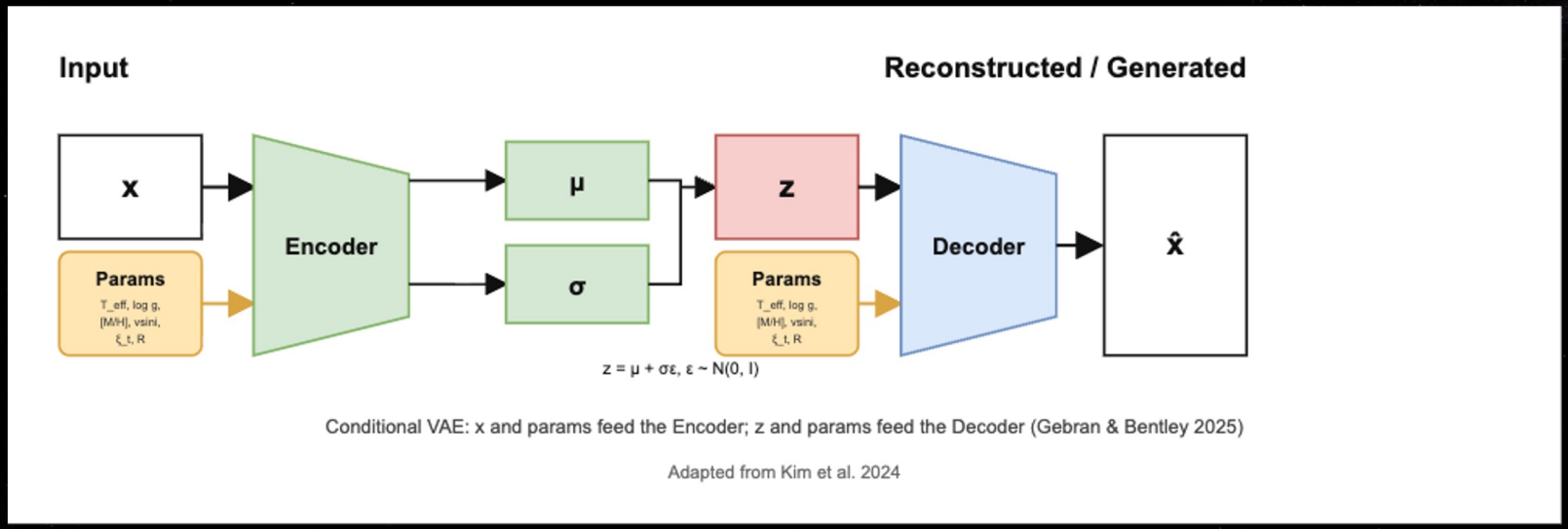
(Kim et al. 2024)

$$L = L_{MSE} + L_{KL}$$

reconstruction loss + KL divergence

Latent variables (z): Parameters not directly observed in the data that represents/ describes the data.

Conditional variational autoencoders (CVAEs) take in parameter values along with training data, allowing the parameter range of generated data to be controlled.

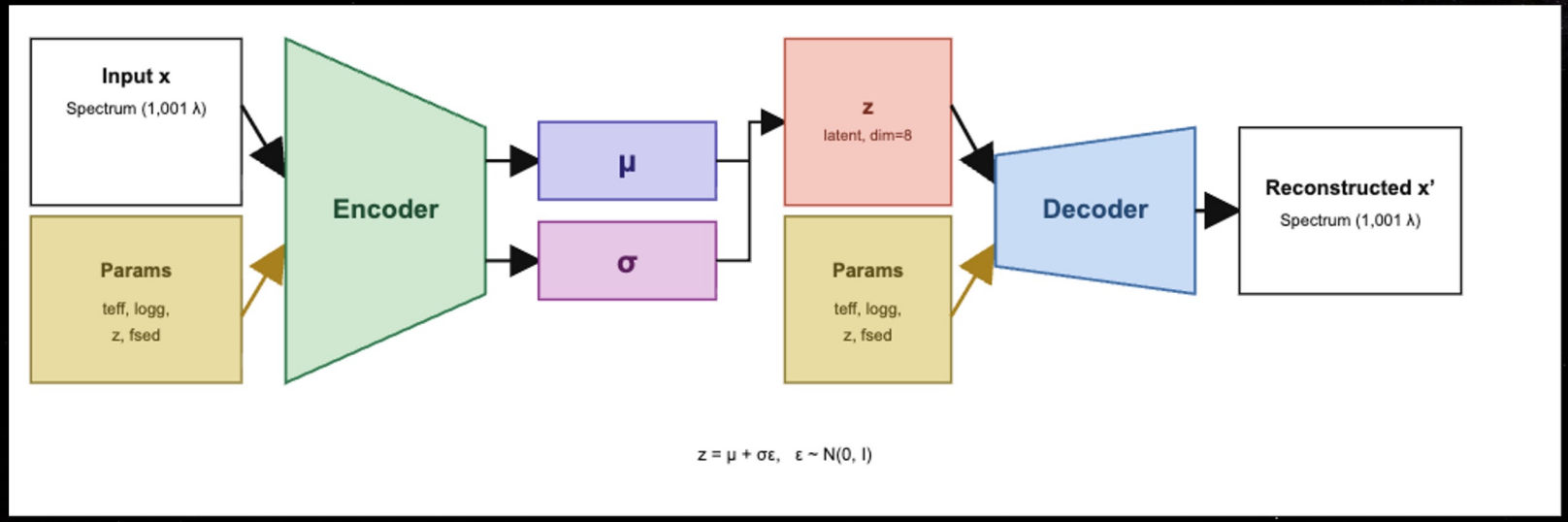


Conditional VAE: x and params feed the Encoder; z and params feed the Decoder (Gebran & Bentley 2025)

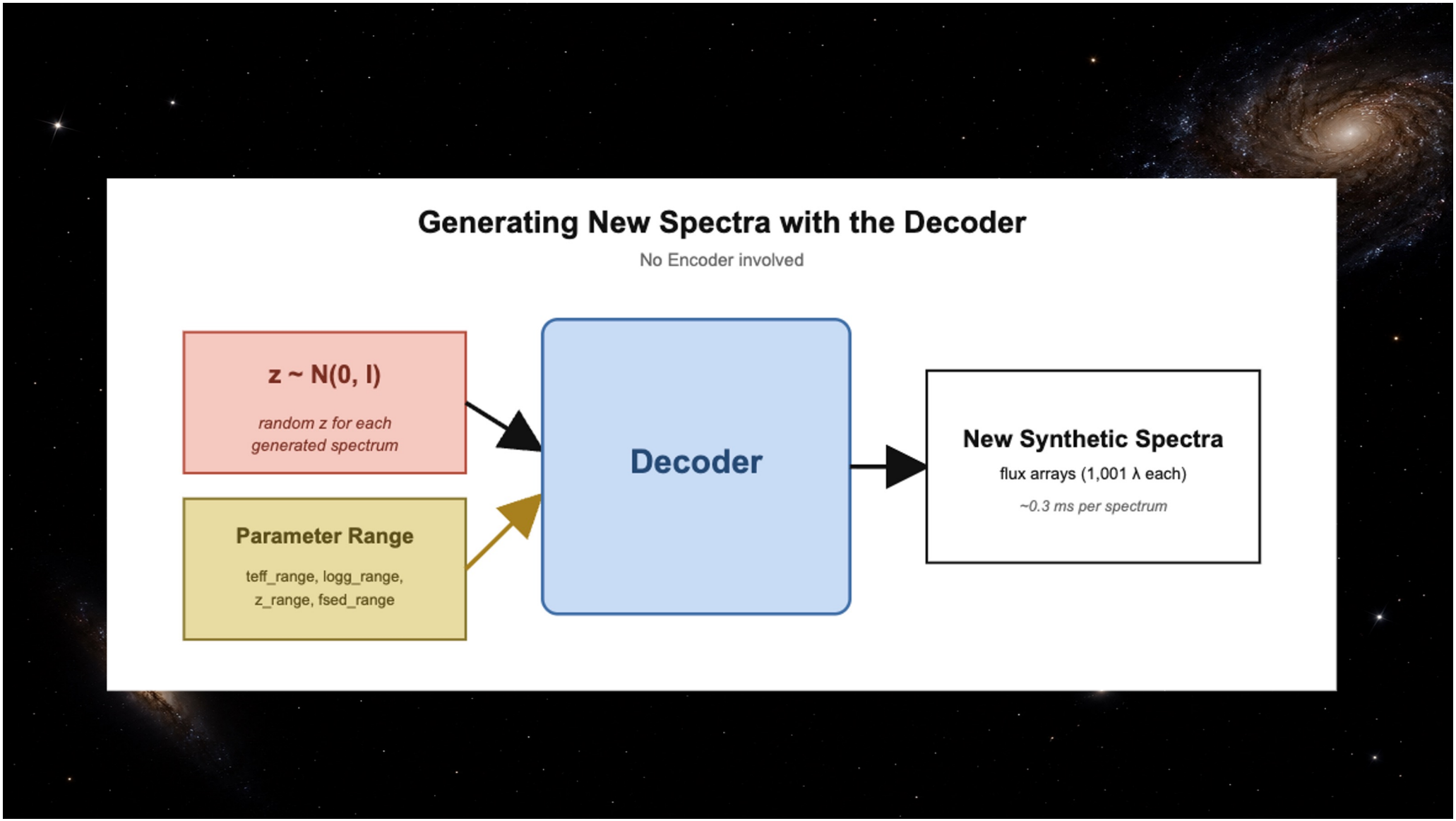
Adapted from Kim et al. 2024

Similar Astrophysical use case: Gebran and Bentley in 2025 used CVAEs to generate stellar spectra.

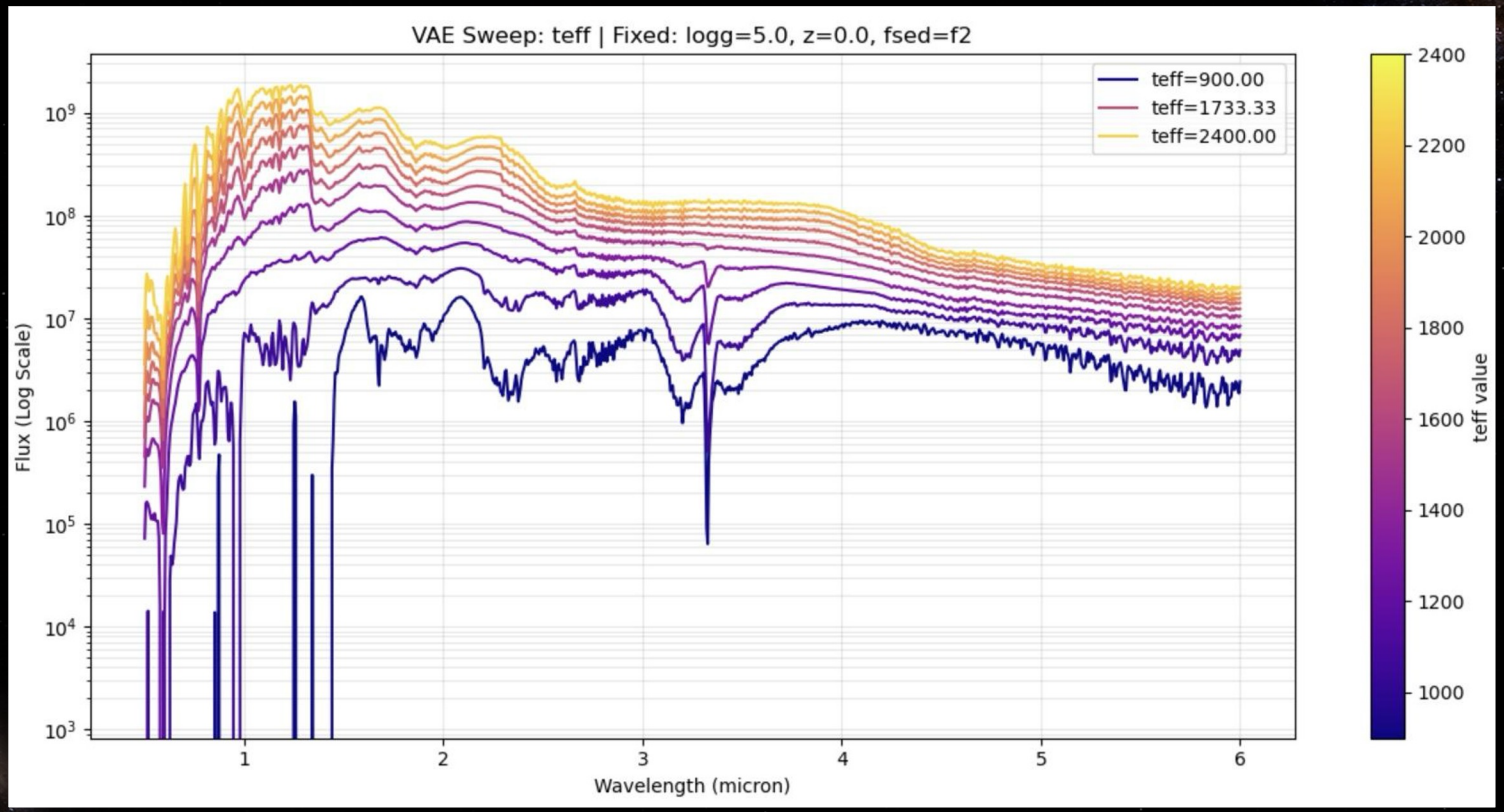
We trained a CVAE on the Sonora Diamondback model grids



Training time: 5 minutes

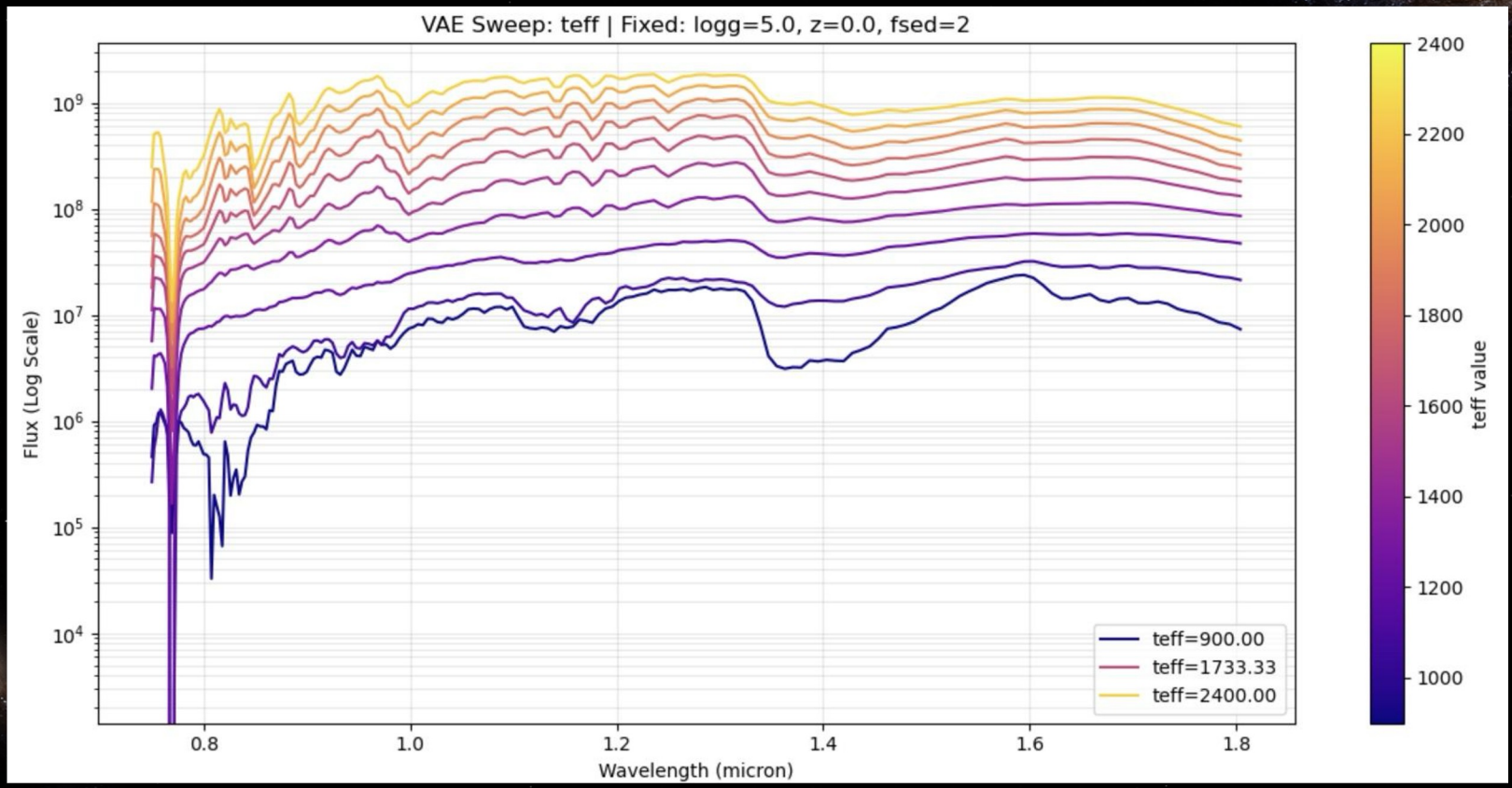

Generating New Spectra with the Decoder
No Encoder involved
z ~ N(0, I)
random z for each generated spectrum
Parameter Range
teff_range, logg_range, z_range, fsed_range
Decoder
New Synthetic Spectra
flux arrays (1,001 λ each)
~0.3 ms per spectrum

Sonora Diamondback Models Generated for JWST

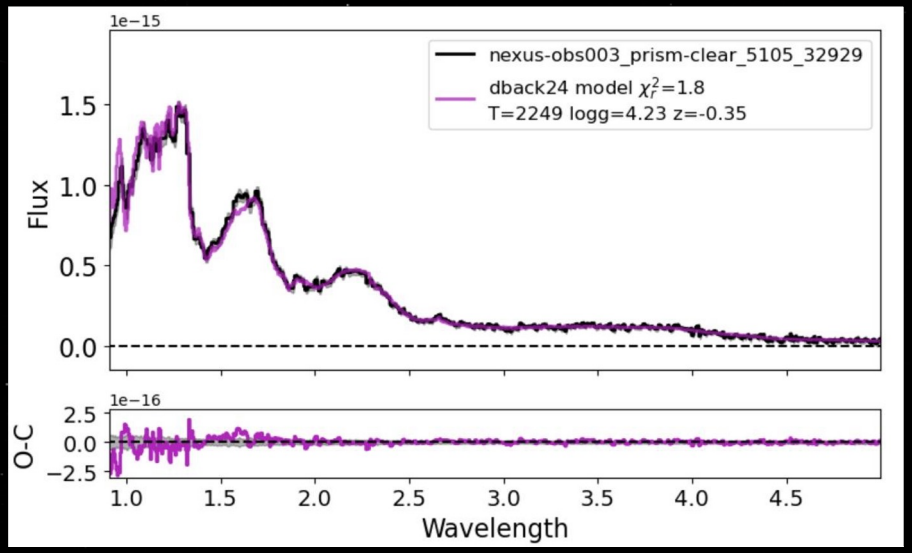


Generated 10,000 spectra in 1.6s: 1000 times faster than linear interpolation

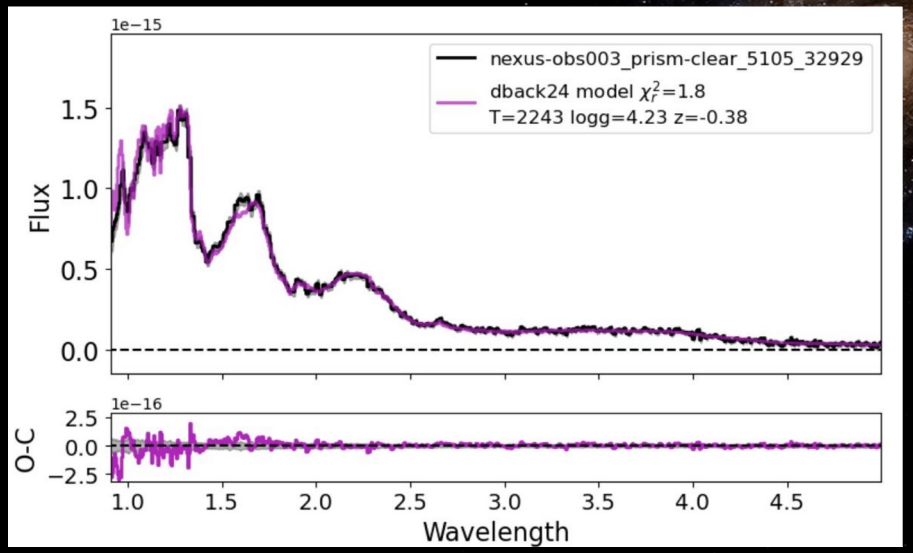
Sonora Diamondback Models Generated for Roman Prism



MCMC fit



VAE grid fit



The MCMC fit took 70 minutes while the VAE grid fit took 6 minutes, a speed up of over 10x!

MCMC vs. VAE Grid Fit

Parameter Uncertainties

Parameter	MCMC	VAE Grid Fit
T_{eff} (K)	2293.43 +77.74 / −79.48	2250 ± 3.31
log g (cm/s²)	4.52 +0.44 / −0.54	4.38 ± 0.07
[M/H] / z	−0.06 +0.34 / −0.31	−0.31 ± 0.04

Next Steps

- Train the model on all brown dwarf atmospheric model grids, including a framework that allows anyone to train a CVAE on any model grid
- Explore incorporating VAEs into the MCMC framework
- Explore applying this to random forest retrieval frameworks
- Explore applying this framework to atmospheric retrievals

Key takeaways

- Variational Autoencoders accelerated the model generation process for the brown dwarf atmospheric model Sonora Diamondback by over 1000 times.
- After training for 5 minutes, performing a fit with the VAE grid showed evidence of being faster than running an MCMC fit.
- We will explore applying this to retrieval frameworks as well as MCMC.
- Applying to other models for Roman Prism and Grism modes, as well as other fitting frameworks beyond MCMC.

Acknowledgements / References

Gebran, M., & Bentley, I. (2025). The use of conditional variational autoencoders in generating stellar spectra. *Astronomy*, *4*(3), 13. https://doi.org/10.3390/astronomy4030013

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