

GALAXY MODELING WITH PHYSICAL FORWARD MODELS AND GENERATIVE NEURAL NETWORKS

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Jeff Shen



Jared Siegel

Funding



<https://astro-data-lab.github.io>

GALAXIES ARE COMPLEX

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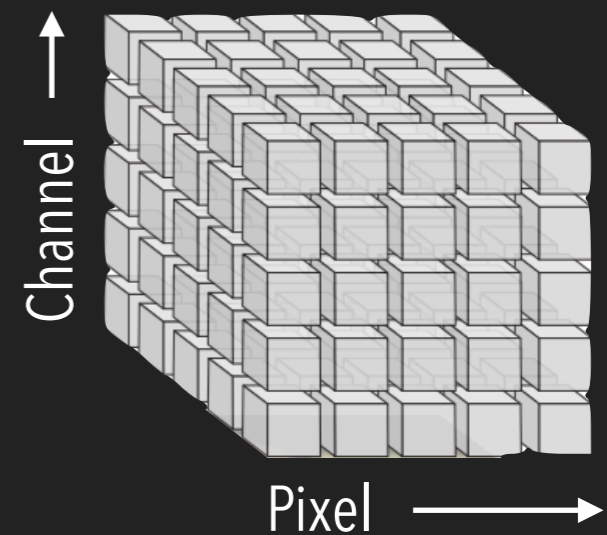


A FORWARD MODEL

Probabilistic model for the Hyperspectral Data Cube

$$\text{scene} = \sum_k \text{SED}_k \times \text{Morphology}_k$$

$$Y = A \cdot S + \text{noise} \quad \text{noise} \sim \mathcal{N}(0, \Sigma)$$



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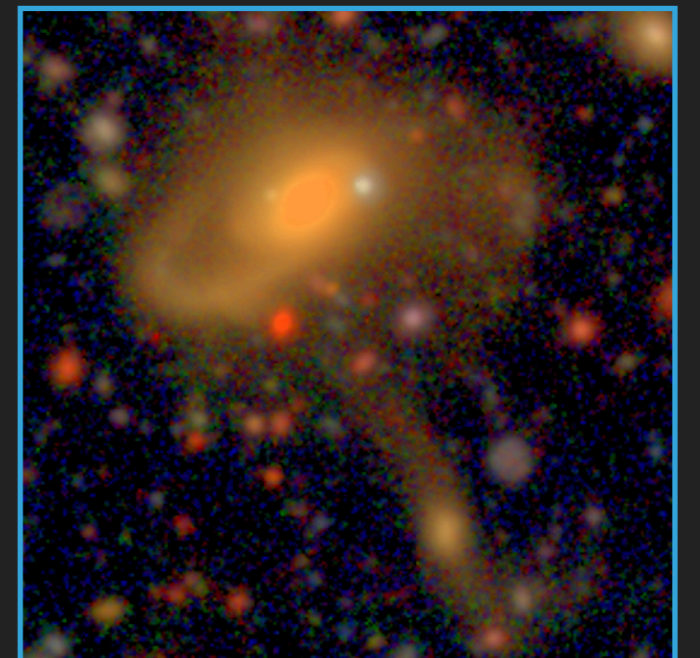
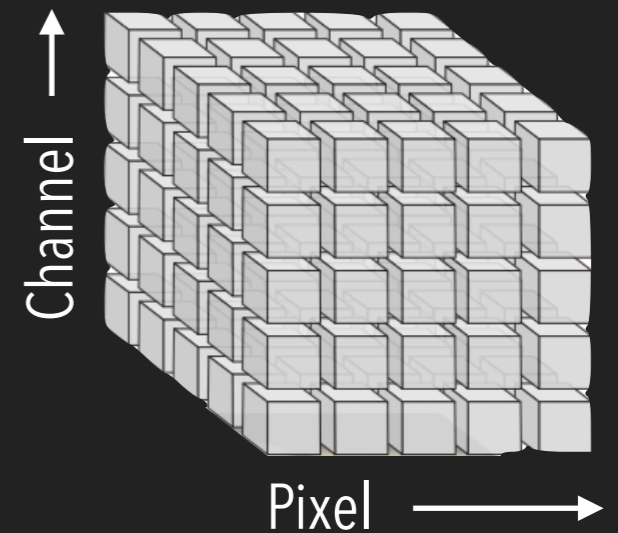
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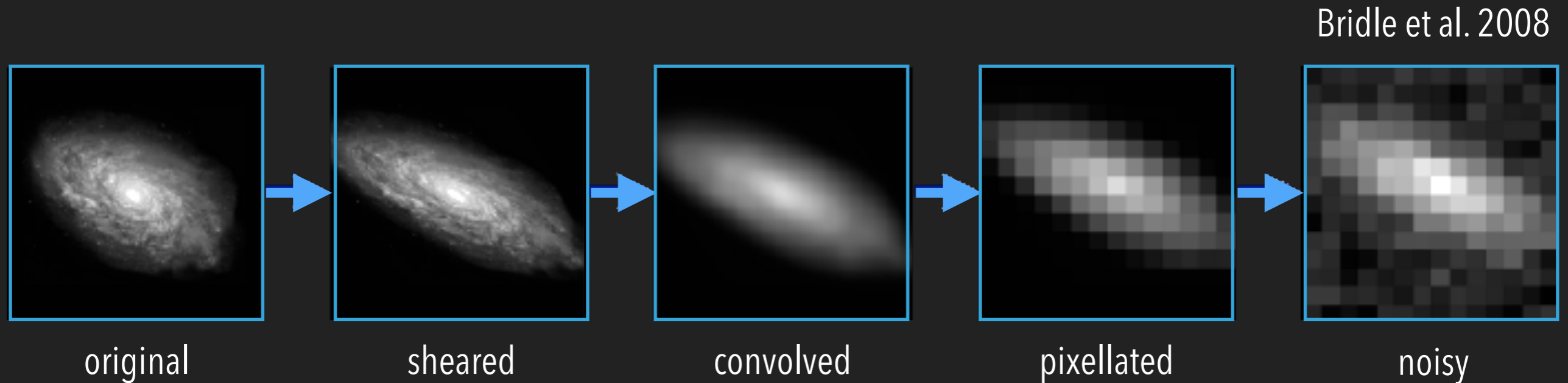
$$\log p(Y | A, S) \propto -\frac{1}{2} \|Y - A \cdot S\|_2^2$$

$$\text{loss} = f(A, S) + g(A, S)$$

Optimization with Constraints / Priors



RENDERING OPERATORS

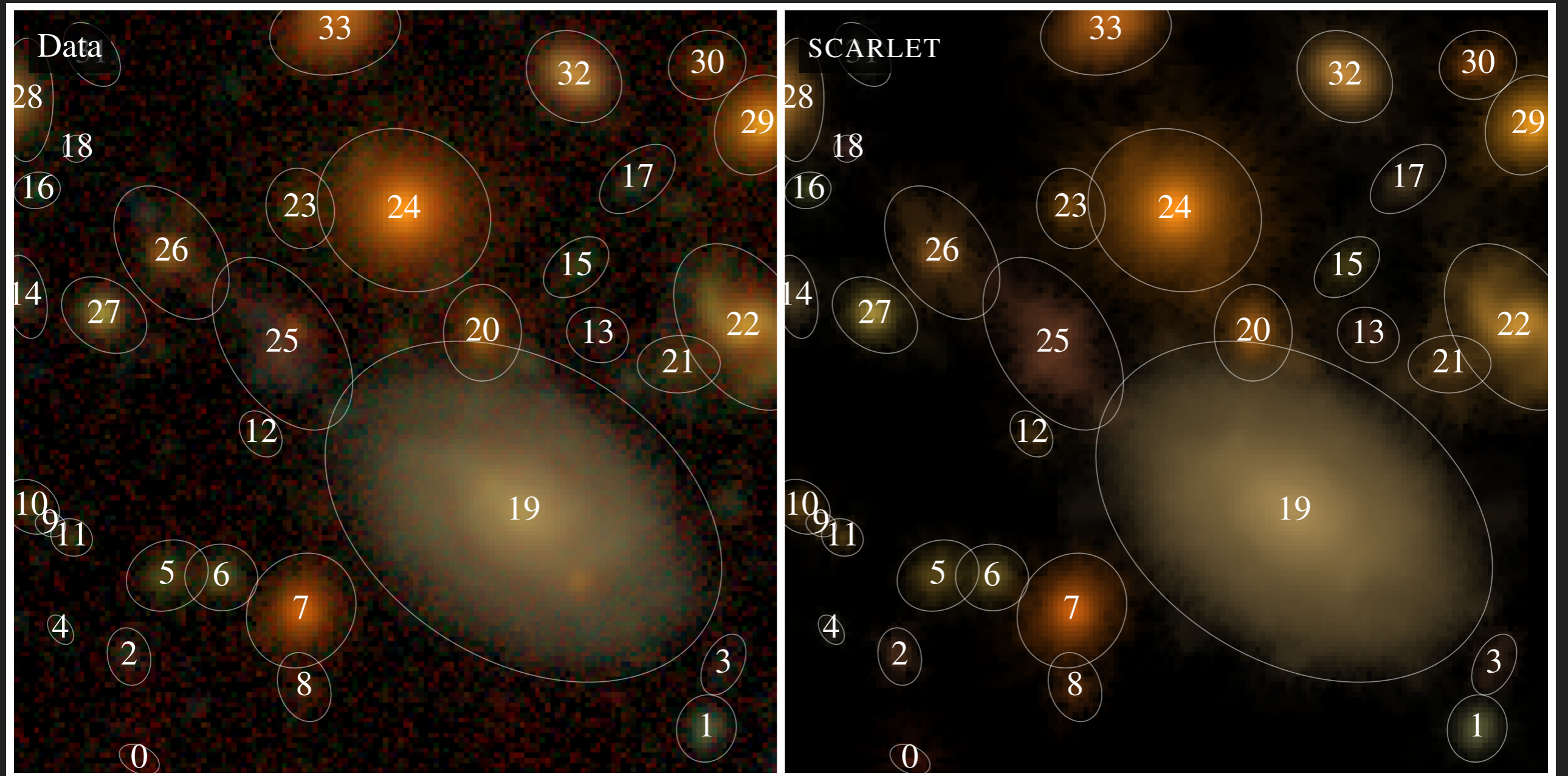


$$f(A, S) = \frac{1}{2} \|W \odot (Y - P \cdot A \cdot S)\|_2^2$$

SCARLET

code: <http://github.com/pmelchior/scarlet>

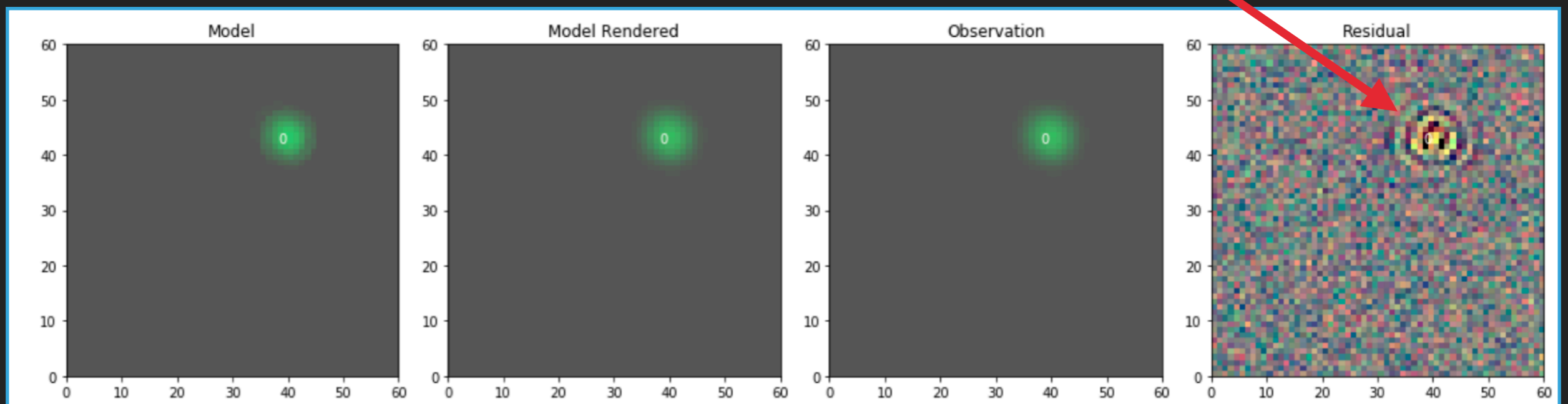
Melchior et al. (2018)



5-band HSC

PROBLEMS

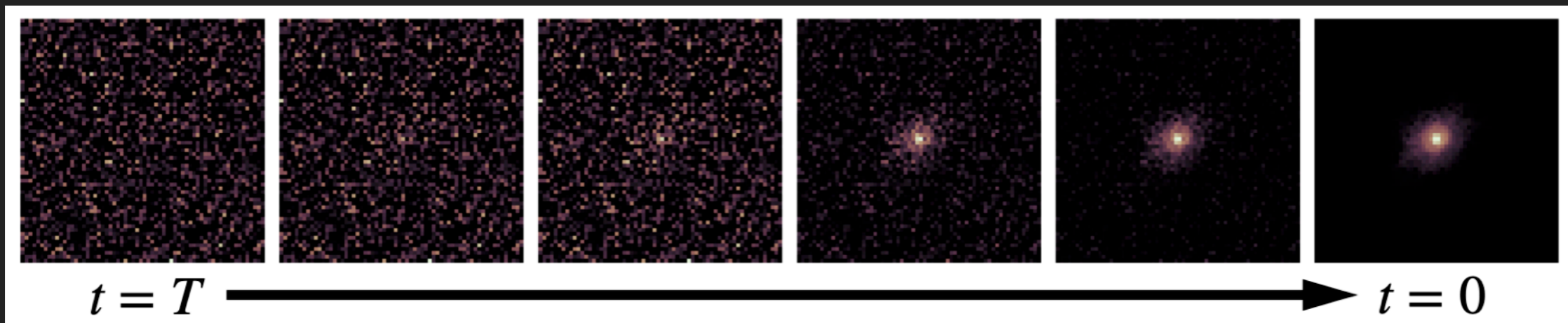
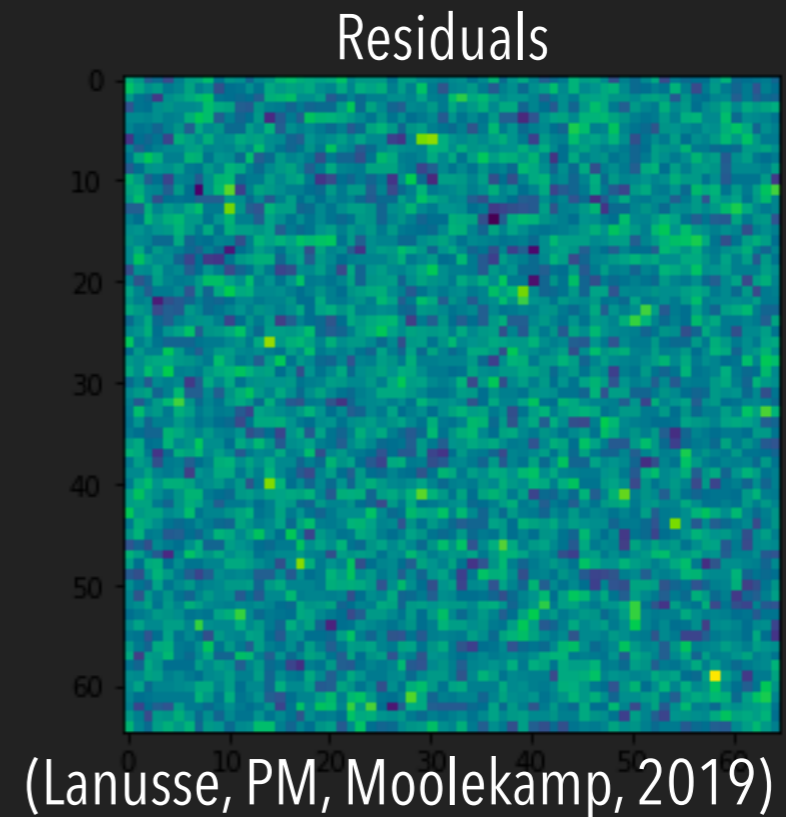
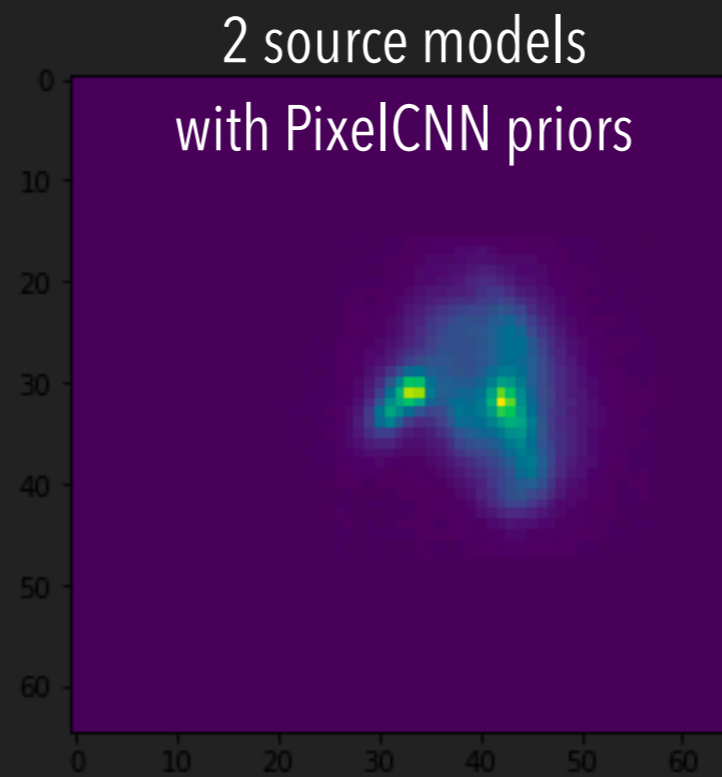
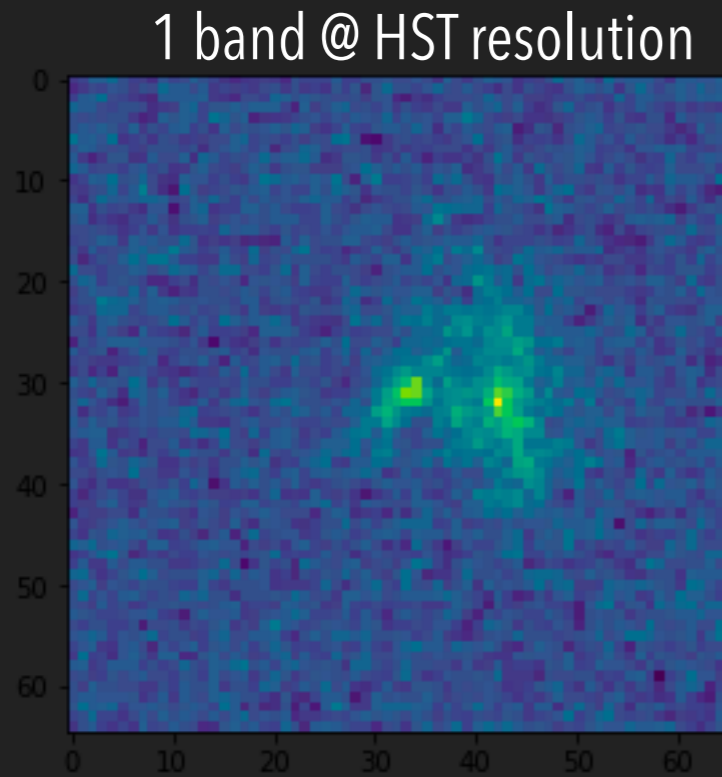
- ▶ Proximal Gradient Method: $x^{k+1} = \text{prox}_{\lambda g}(x^k - \lambda \nabla f(x^k))$
$$\text{prox}_{\lambda g} : x \rightarrow \text{argmin}_u g(u) + \frac{1}{2\lambda} \|x - u\|^2$$
- ▶ Not differentiable
- ▶ Realistic galaxy constraints not trivial
- ▶ Can get trapped in very suboptimal minima *en route*



DATA-DRIVEN PRIOR: SCORE MODEL

- ▶ Computes gradients of morphology prior

$$\nabla f \rightarrow \nabla f + \nabla p$$

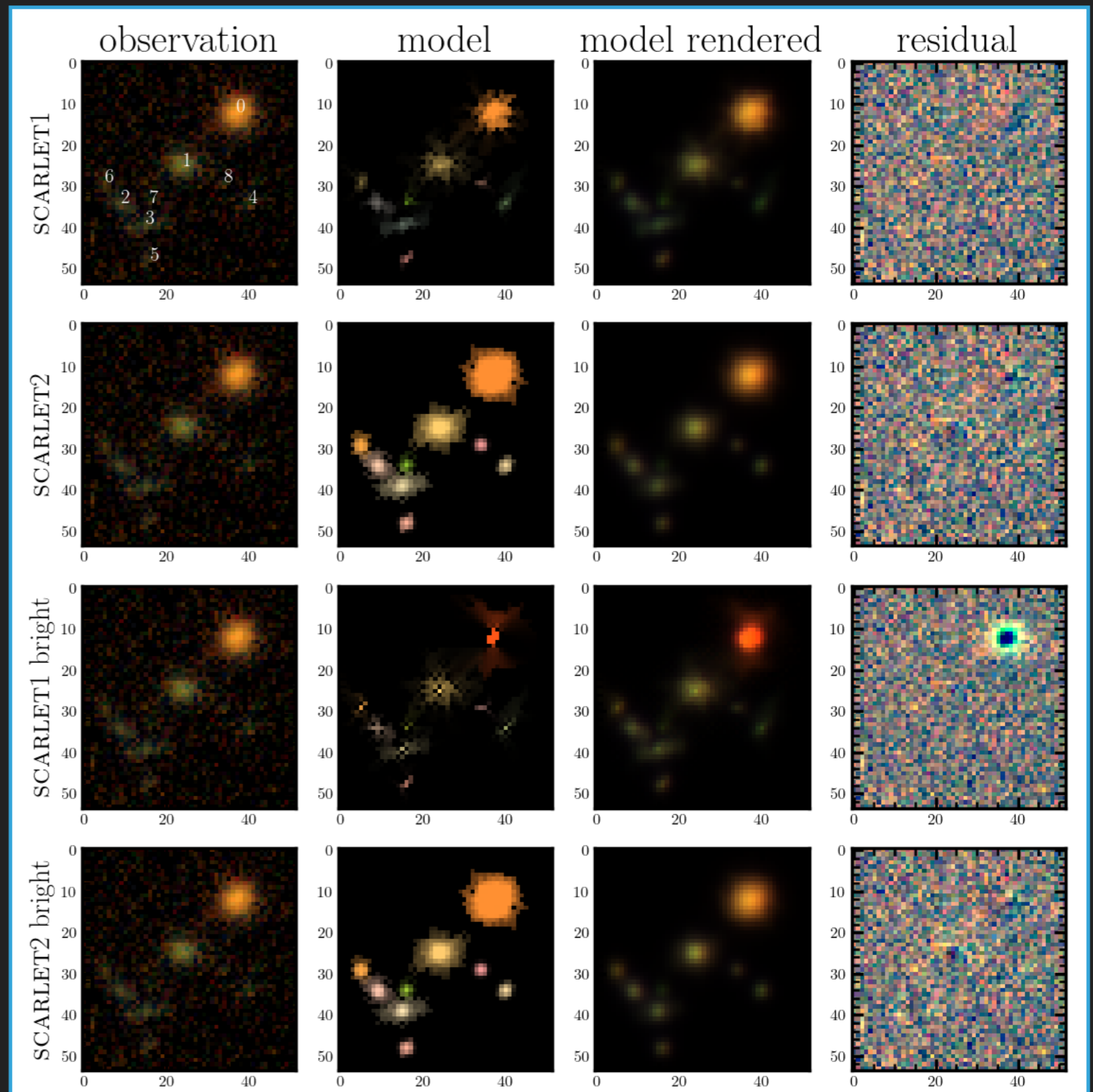


Sampson+ (in prep.)

SCARLET2

Code: <https://github.com/pmelchior/scarlet2>

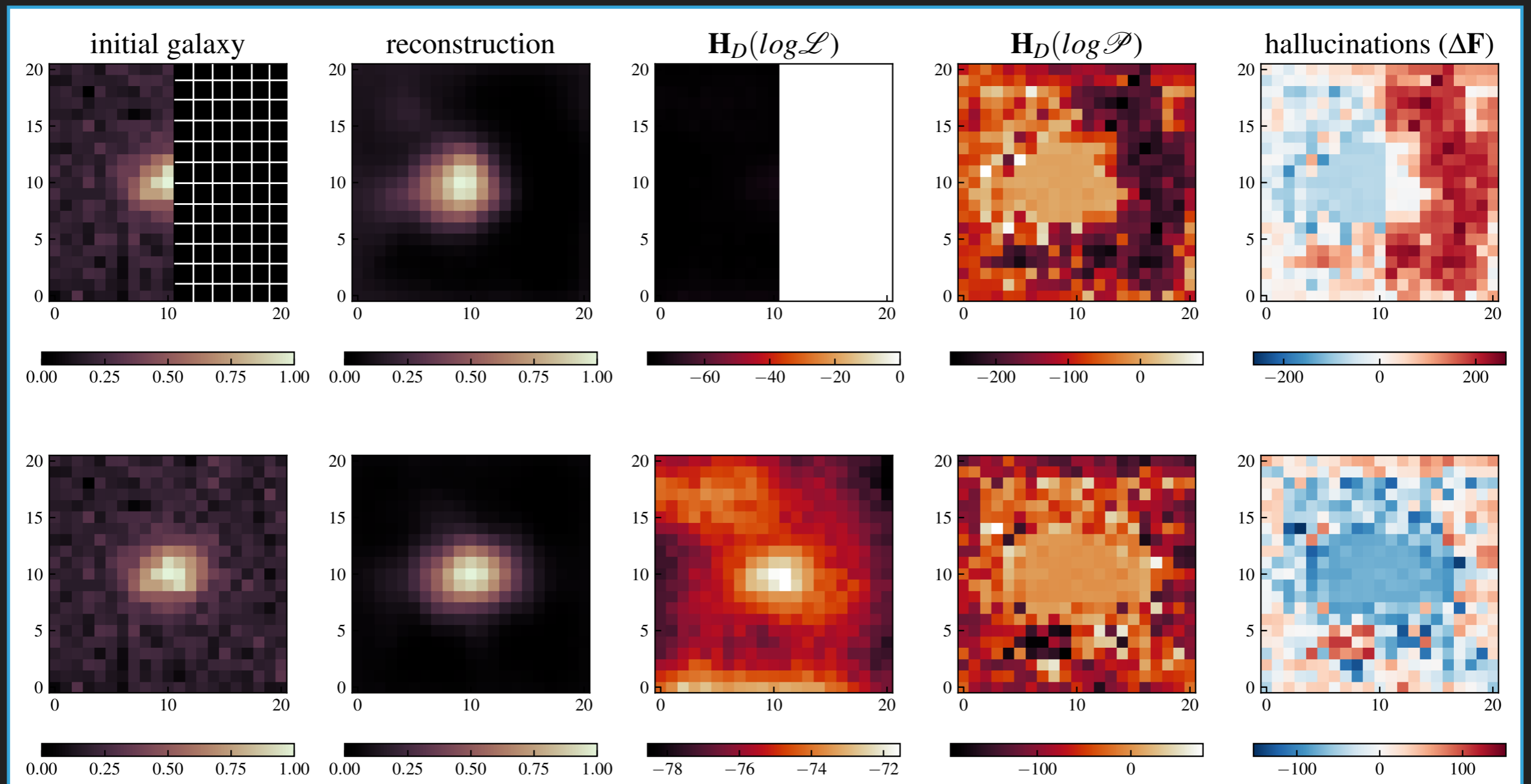
- ▶ JAX + Equinox
- ▶ More modular/flexible
- ▶ Continuous optimization
- ▶ HMC sampling
- ▶ Integration of NNs



Sampson+ (in prep.)

HALLUCINATION SCORE

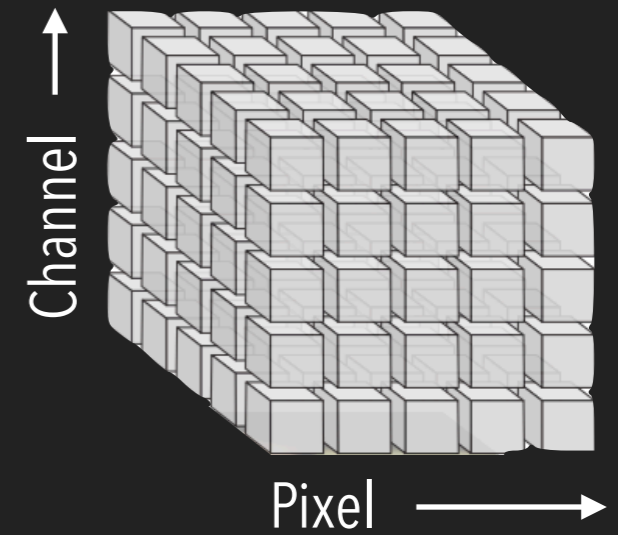
$$\Delta\mathbf{F} = \text{Diag}(\mathbf{F}_{\log \mathcal{P}}) - \text{Diag}(\mathbf{F}_{\log \mathcal{L}})$$



DUST MODELING

- ▶ Single Component

Spectrum \times Morphology



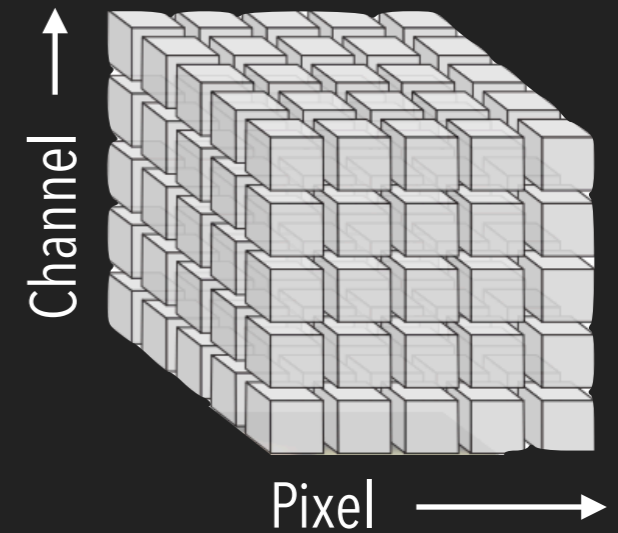
DUST MODELING

- ▶ Single Component

Spectrum \times Morphology

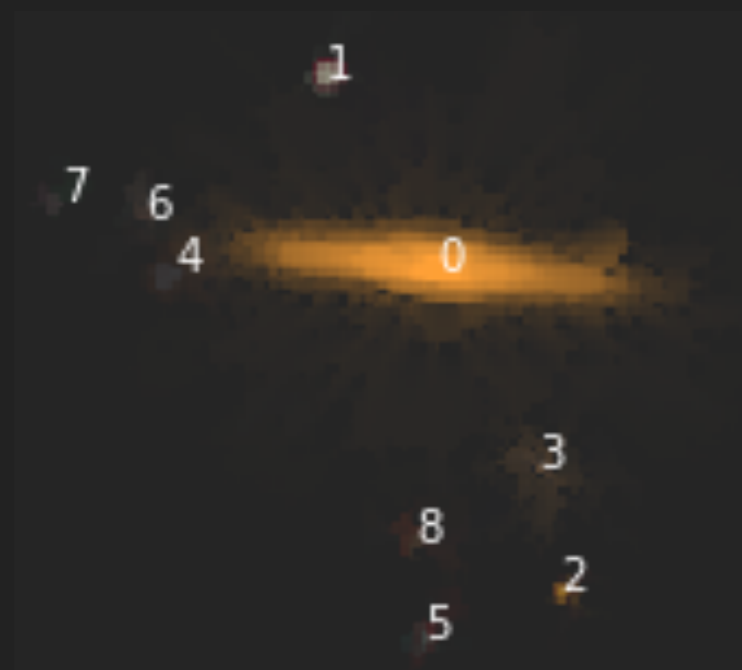
- ▶ Single attenuated component

Spectrum \times Morphology $\cdot e^{-\text{Spectrum}_{\text{dust}} \times \text{Morphology}_{\text{dust}}}$

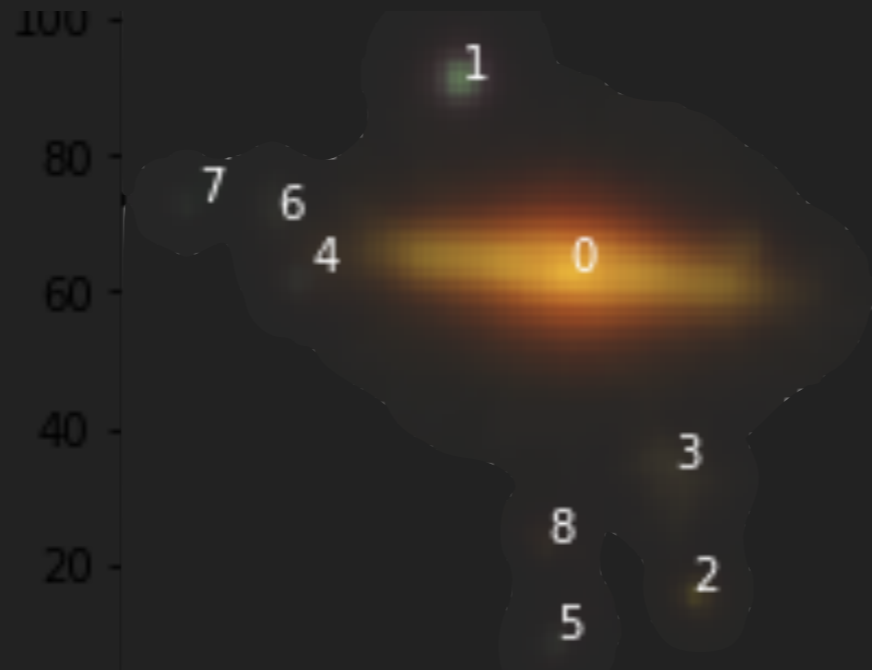


EXAMPLE IN HSC DATA

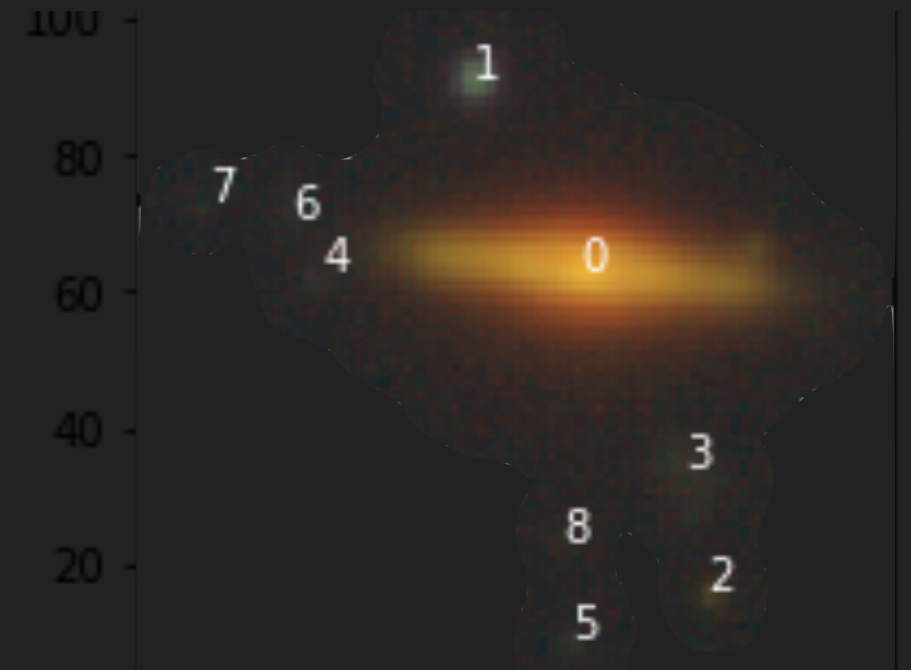
Deconvolved model



Convolved model



HSC

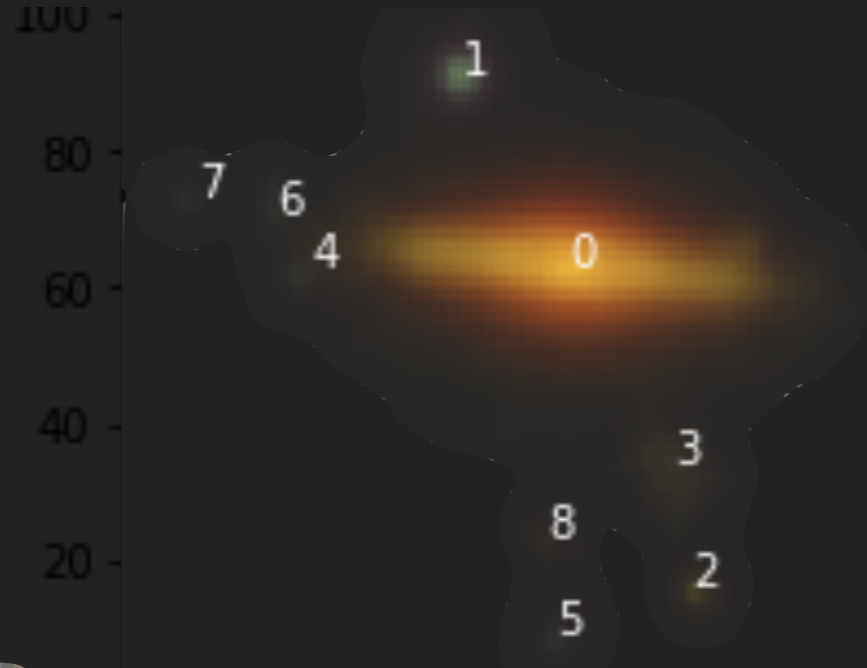


EXAMPLE IN HSC DATA

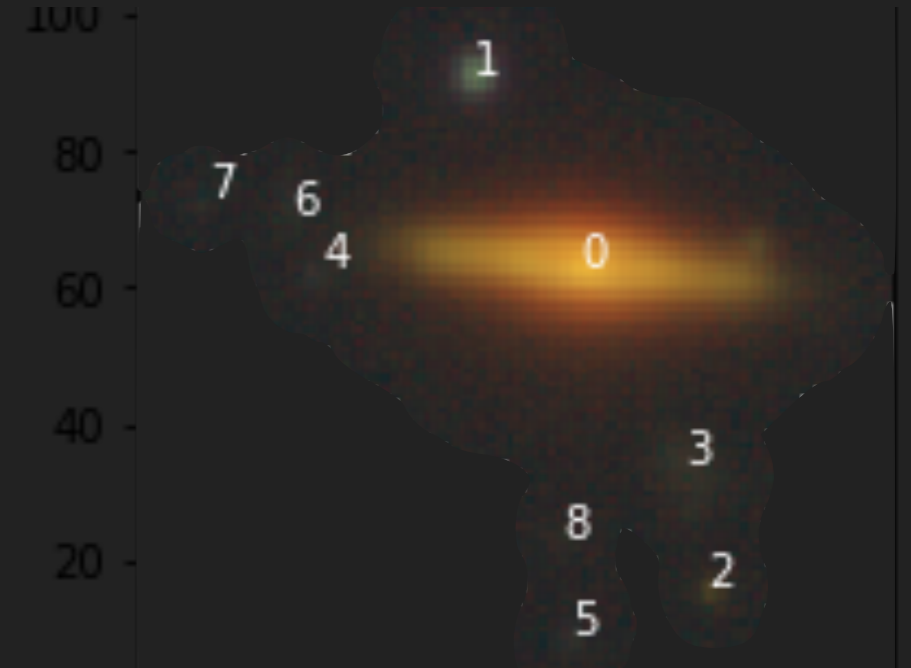
Deconvolved model



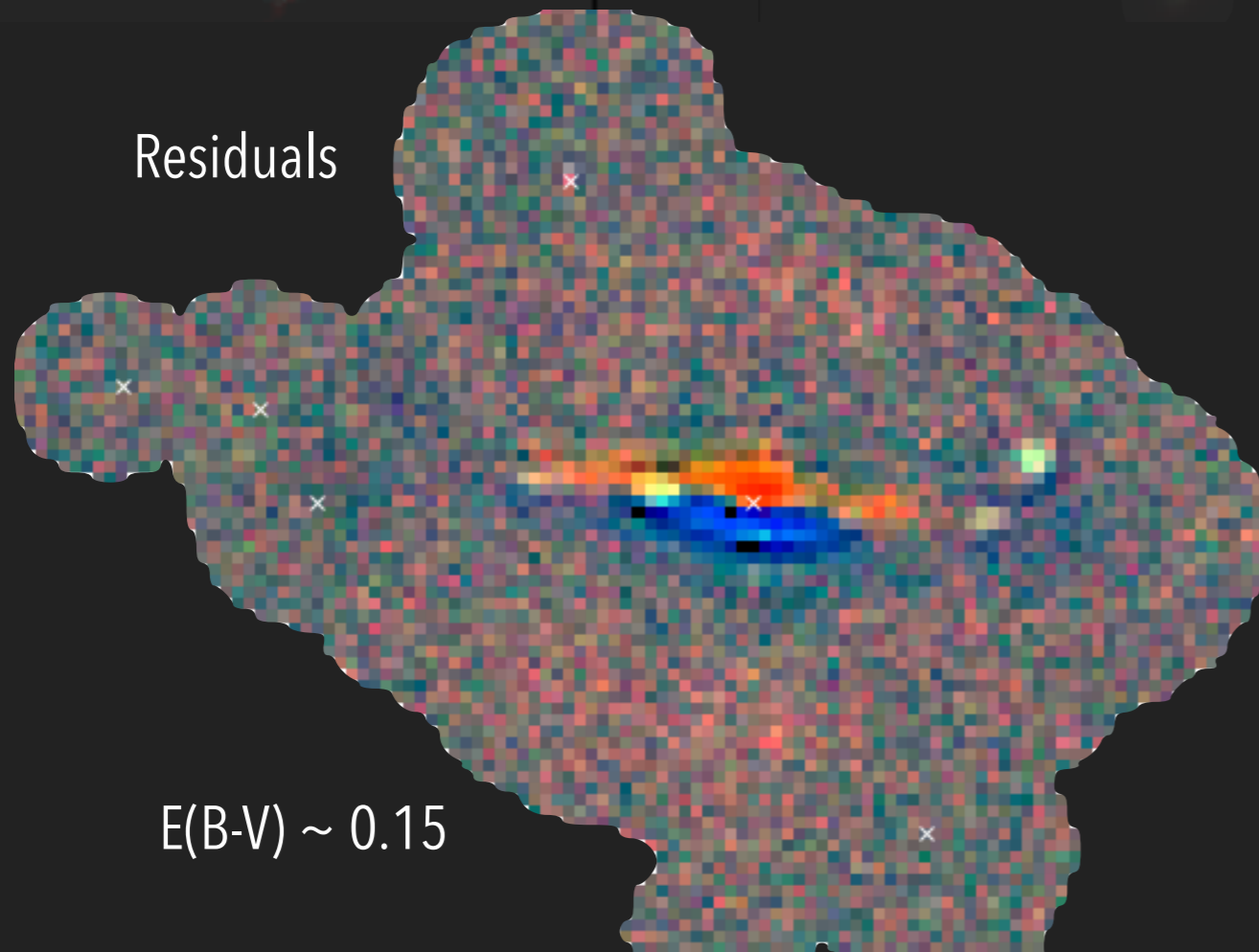
Convolved model



HSC

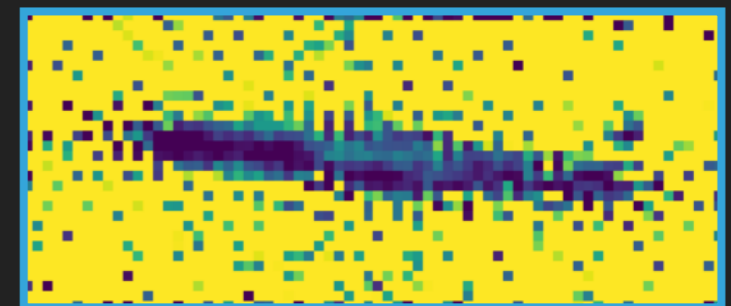


Residuals



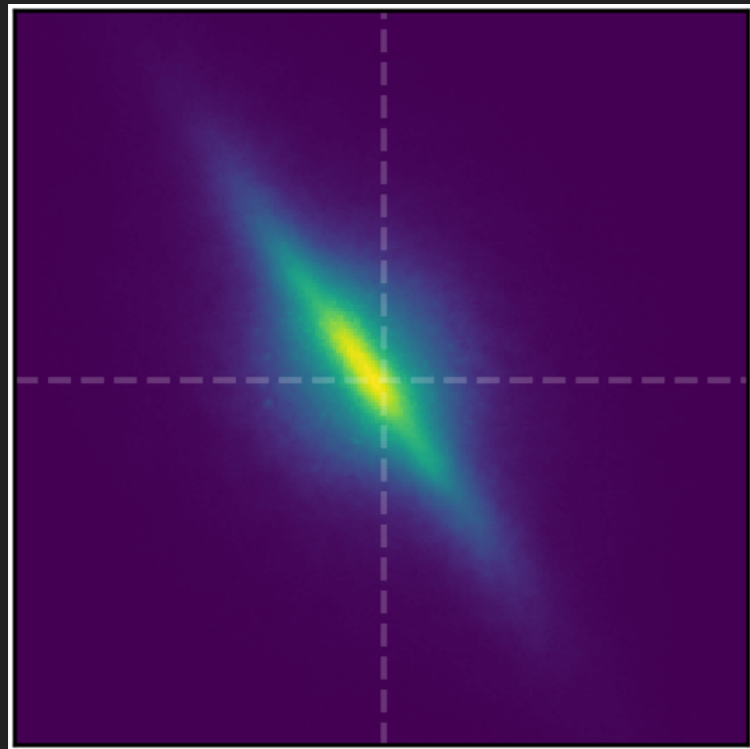
$E(B-V) \sim 0.15$

Dust Model

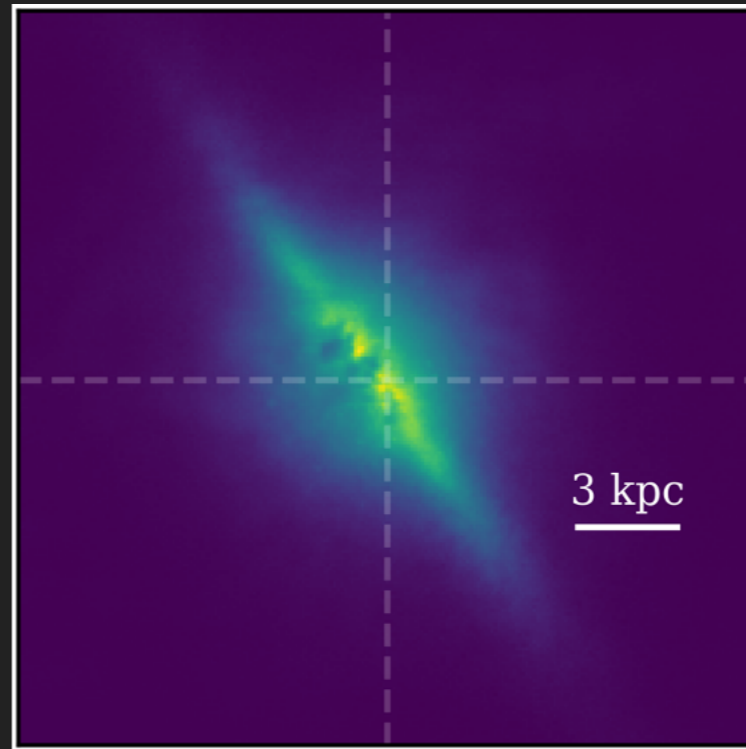


Siegel+ (in prep)

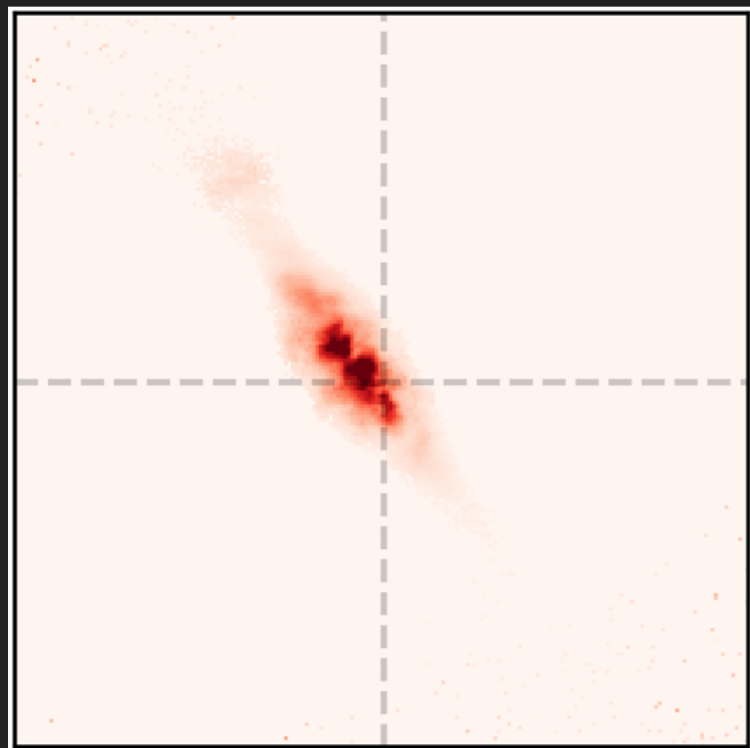
RESULTS IN NIHAO+SKIRT SIMULATIONS



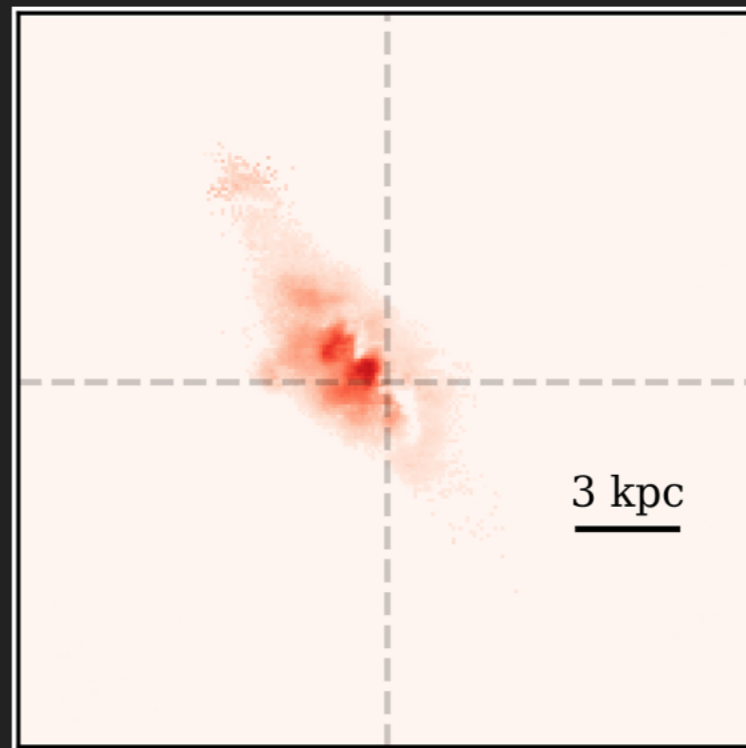
i-band:
No Dust



i-band:
With Dust

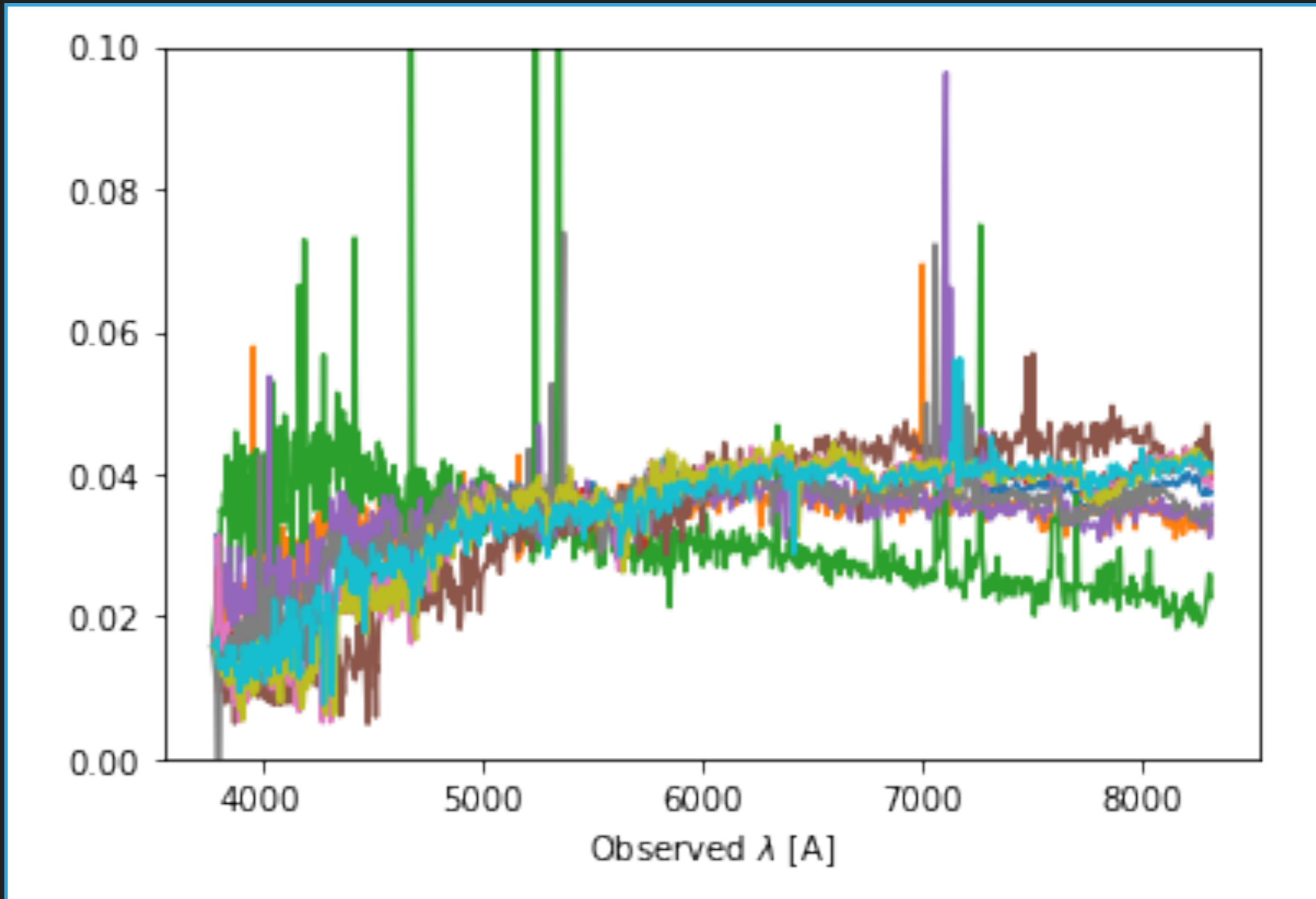


True Dust



Inferred Dust

SPECTRUM PRIORS

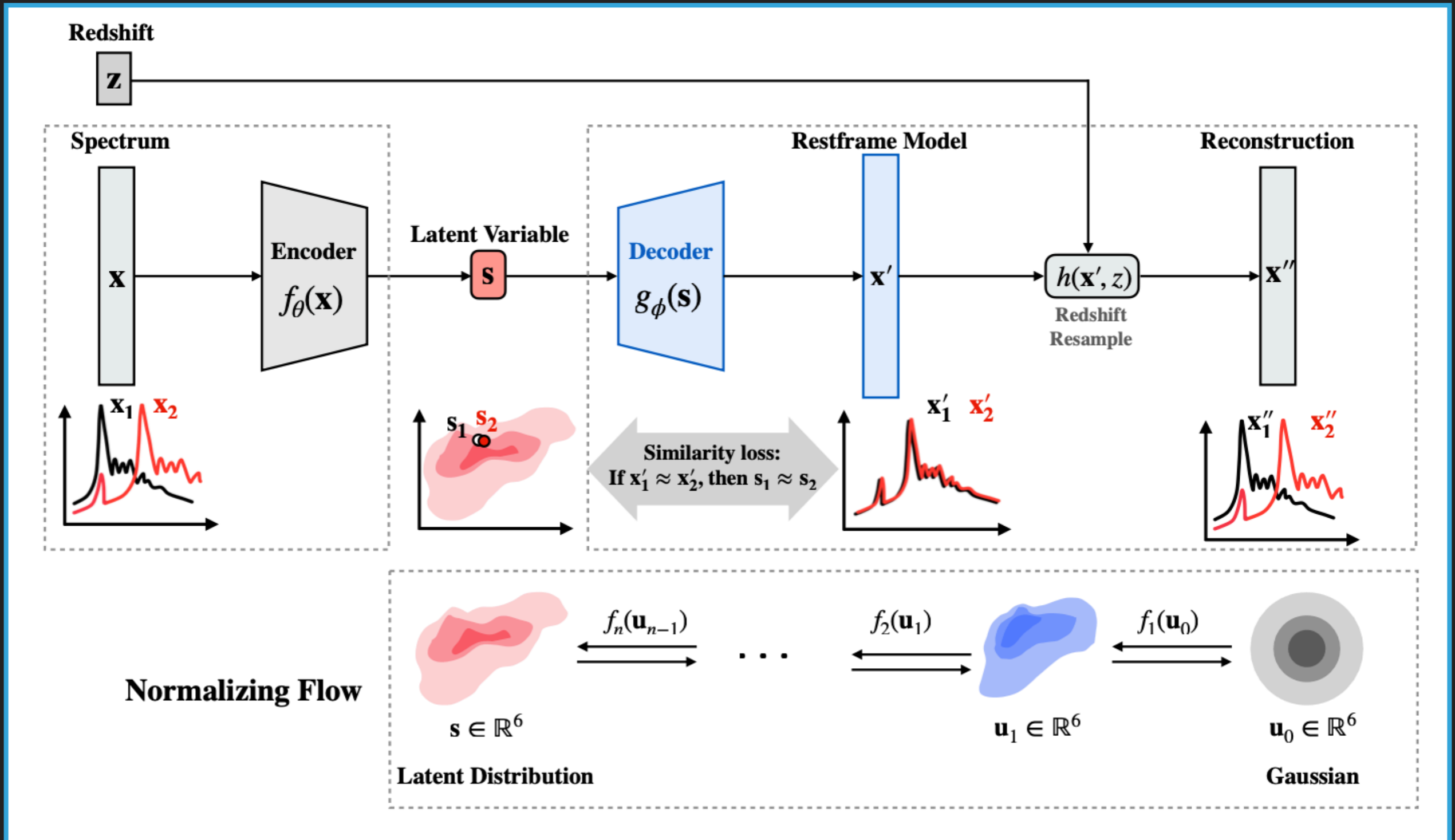


SPECTRUM AUTOENCODER

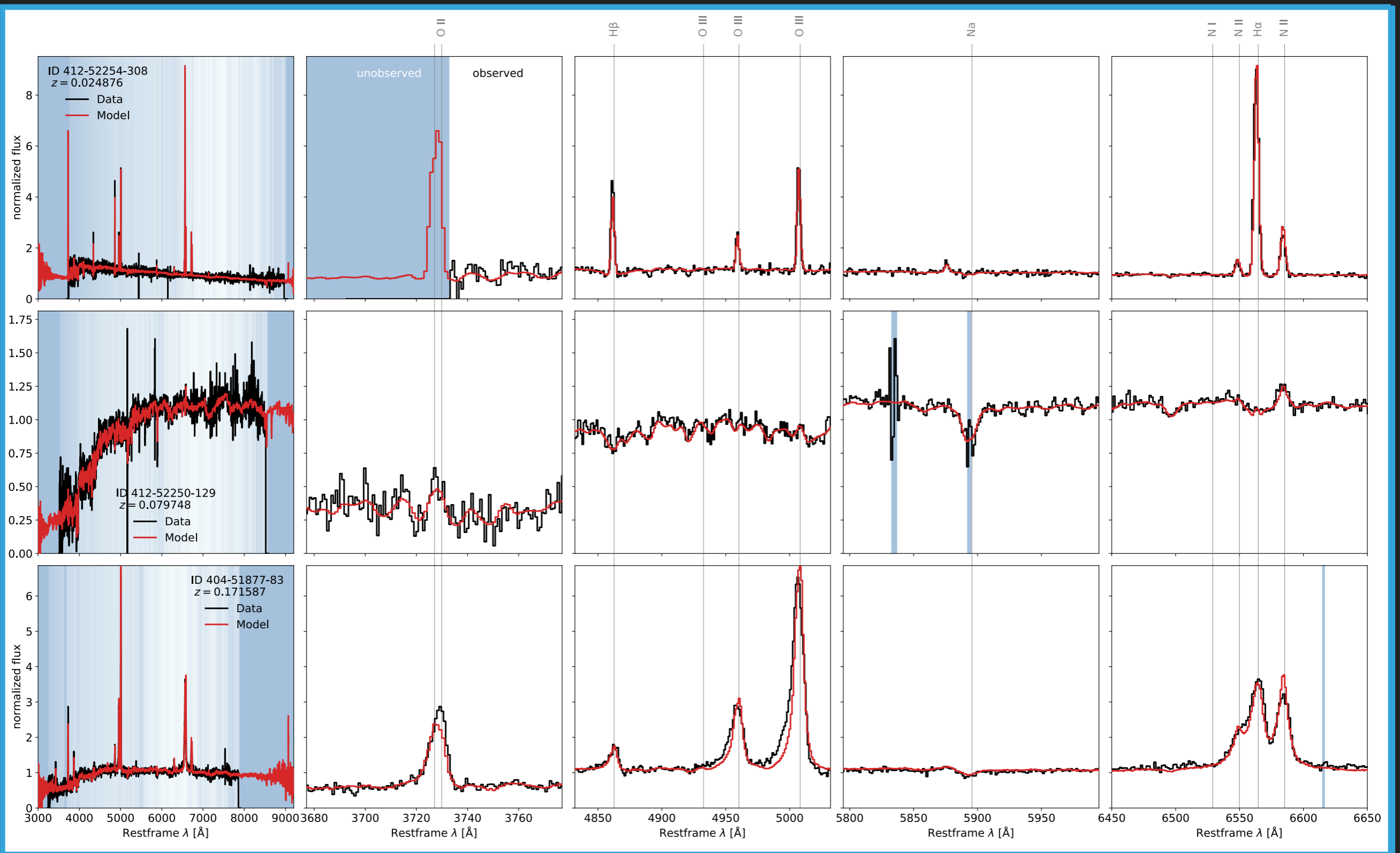
Melchior, Liang, Hahn & Goulding, AJ (2023)

Spender: github.com/pmelchior/spender

Liang, Melchior, Goulding, Ward, AJ (2023)



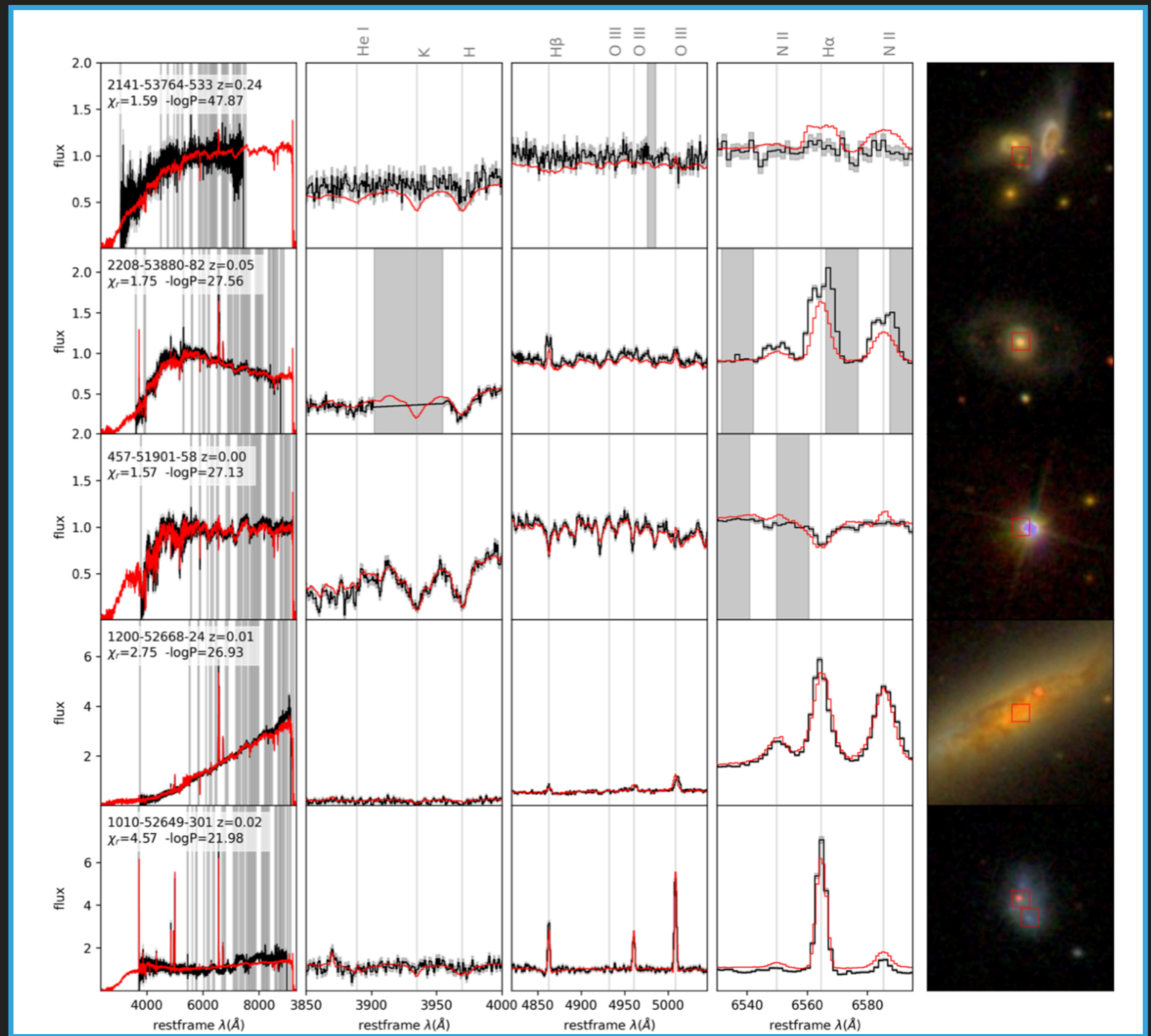
EXAMPLE SPECTRA



SPECTRUM OUTLIERS

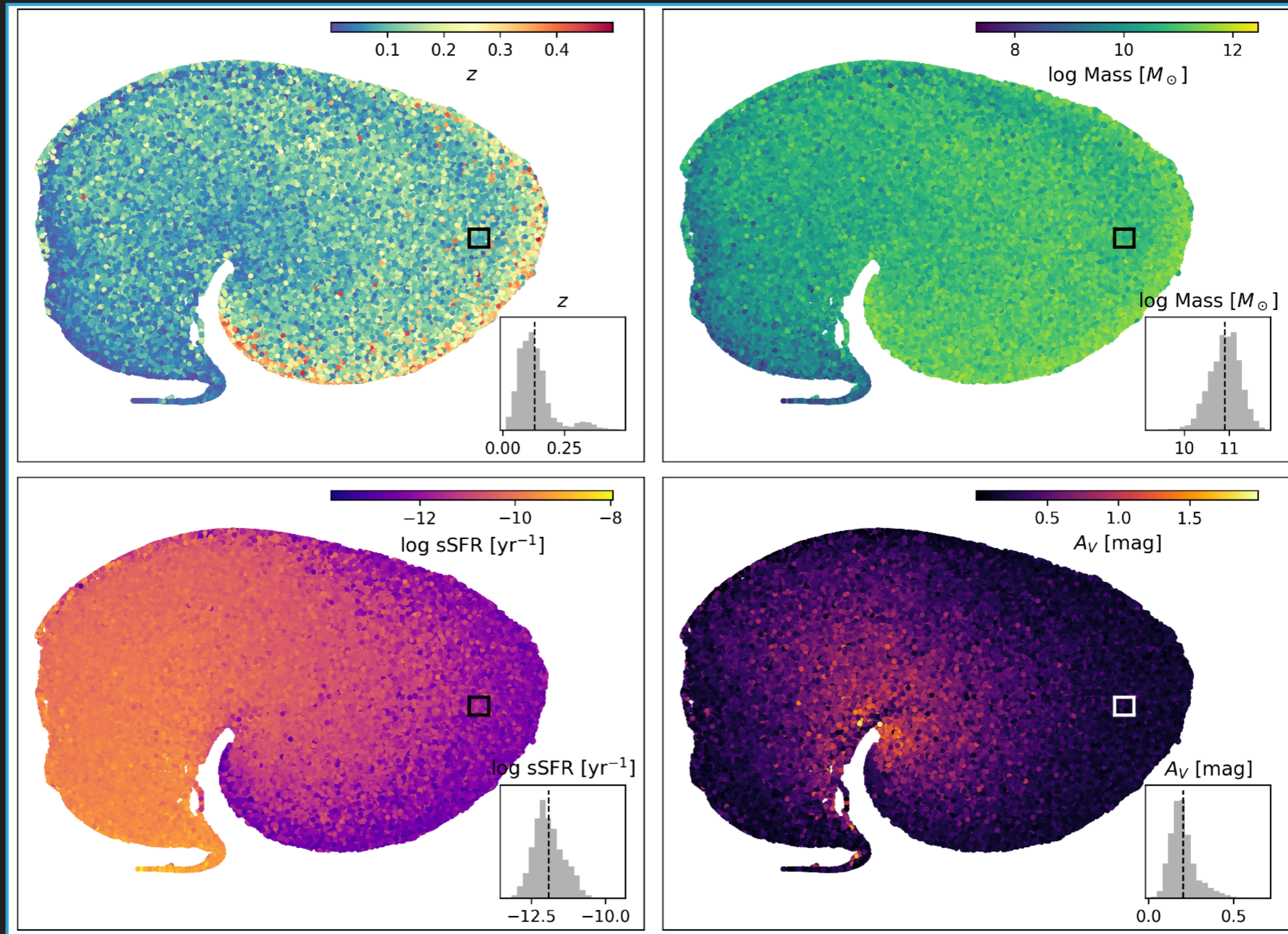
SDSS:
Liang, Melchior, Goulding, Ward
AJ (2023)

DESI EDR:
Liang+ AJ (2023)



LATENT SPACE STRUCTURE

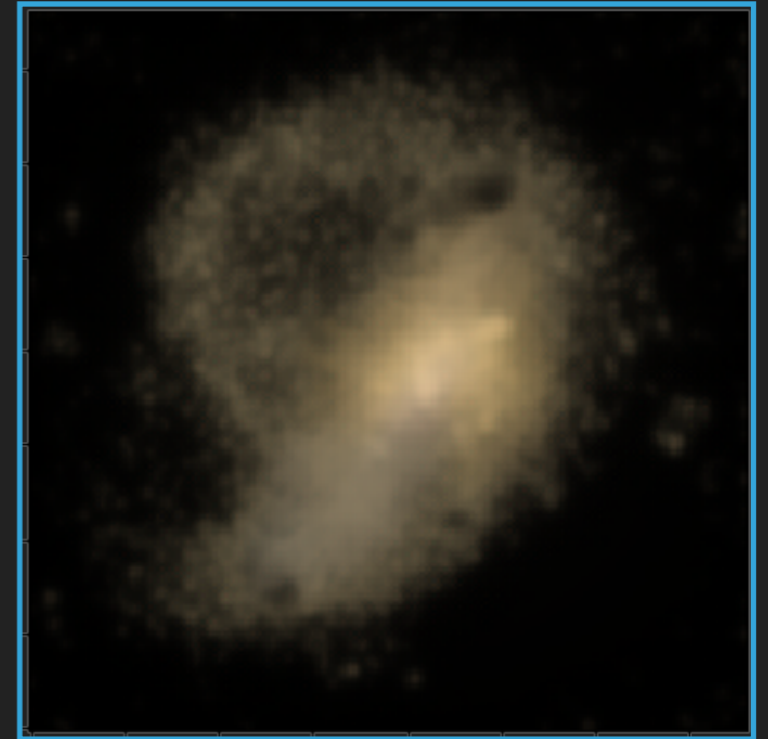
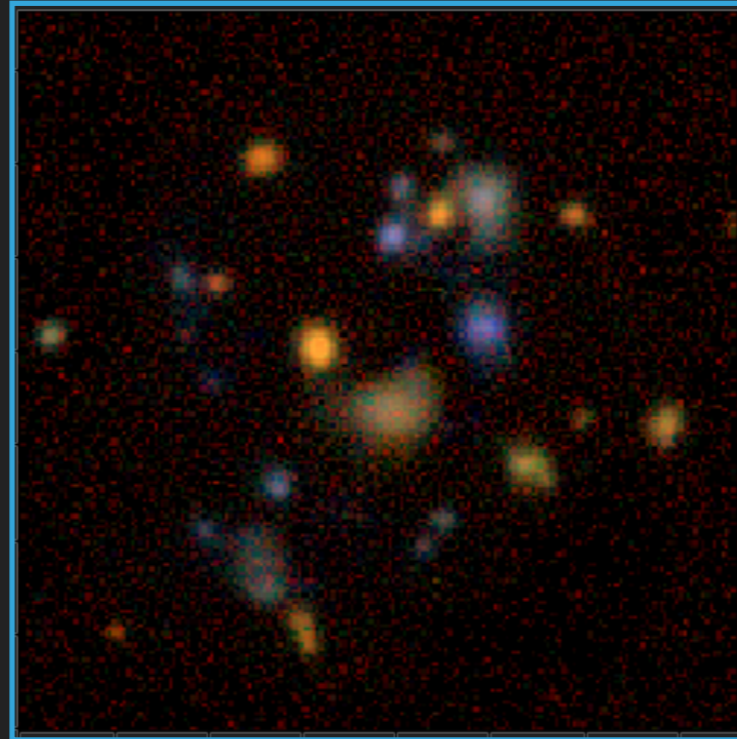
Liang, Melchior, Goulding, Ward, AJ (2023)



ARE GALAXIES COMPLEX?



MIX & MATCH PARAMETERIZATIONS



▶ PointSource

▶ ExtendedSource

▶ BlackBodySpectrum

▶ WaveletMorphology

▶ SersicMorphology

SED MODELING RESULTS

SEDFlow: Hahn & Melchior (2023)

