Reconstructing the Initial Conditions using CAMELS Hydrodynamical Simulations and Diffusion Models

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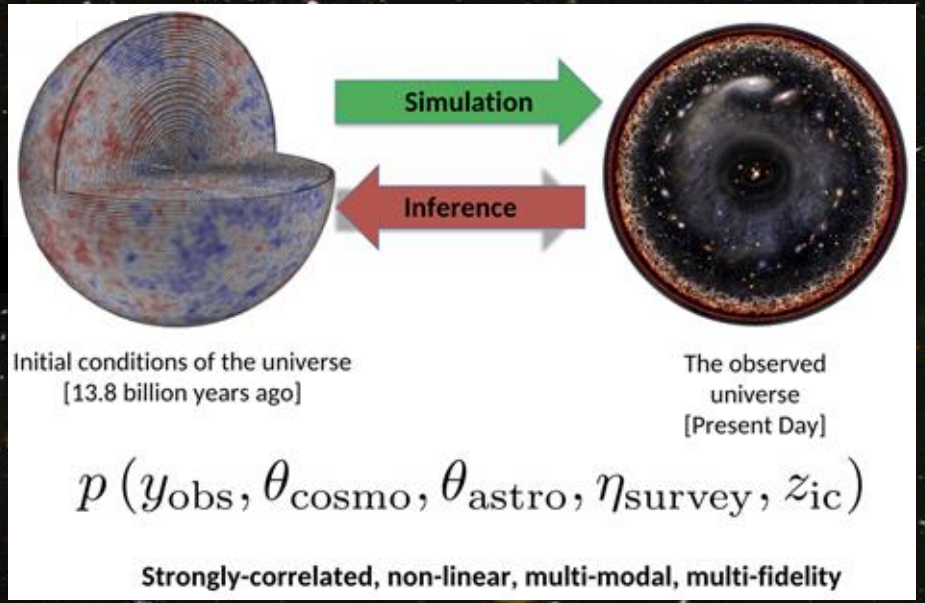
Motivation / Background

What is Initial Condition (IC) Reconstruction?

IC reconstruction is the process of figuring out the ICs from the modern day universe. Classically, this has been done with HMC / MCMC and differentiable simulators.

Motivation

If we know how our universe started, we can resimulate and create phase matched digital twins that show the formation of local structures.



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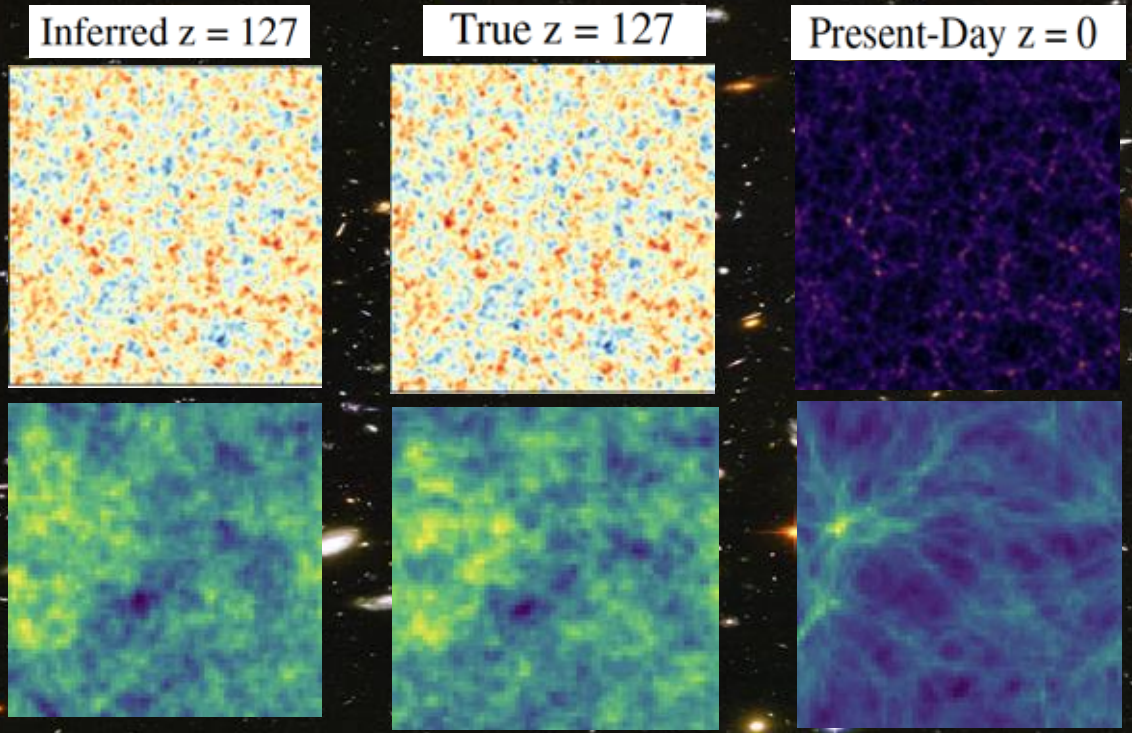
What we're doing | Objectives

Legin et.al 2023



Previous work:
Legin et.al 2023
Cube size 1 Gpc^3

Current work:
CAMELS
Cube size 25 Mpc^3

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Science Questions

1) Can we do IC reconstruction at this scale?
2) Is IC reconstruction cosmology limited or cosmic variance limited?
3) Which simulation parameters have the strongest impact on IC reconstruction?
4) Is gas, or dark matter a better IC tracer?

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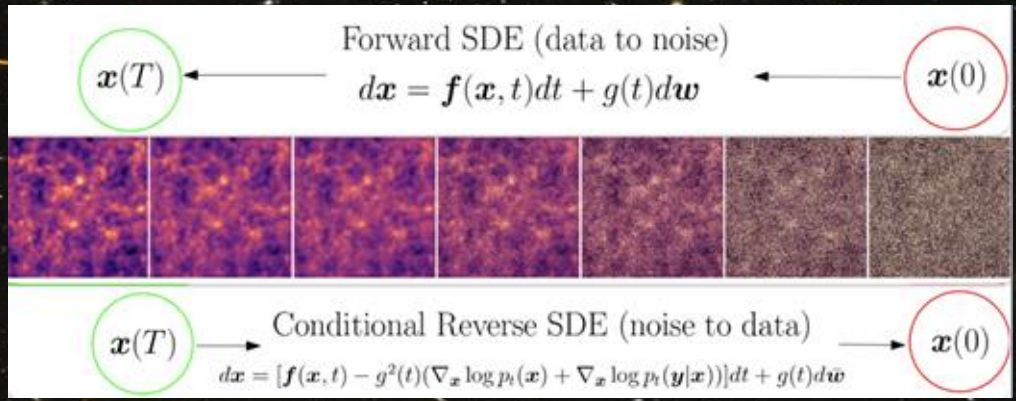
Methods

We use an accelerated forward diffusion model with a U-net architecture to train on the latin hypercube CAMELS hydro simulations (CDM + gas density)

We take trained weights to sample posteriors, generating power spectra + cross power to determine resolution scale at which these initial condition reconstructions hold up.

U-Net

(arXiv:2502.13242)



Bonab et. al, in prep

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CAMELS Datasets

Dataset	Usage	Initial Conditions	# of Samples
Latin Hypercube (LH)	Training	Varied	1000
Cosmic Variance (CV)	Sampling	Varied	27
1 Parameter (1P)	Sampling	Fixed	30

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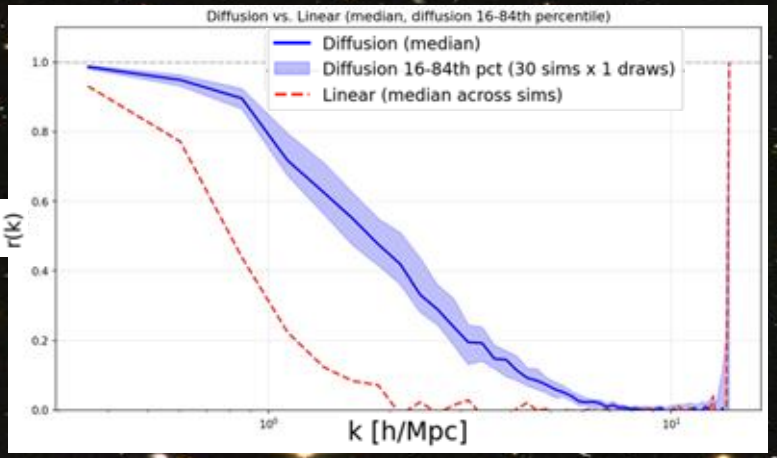
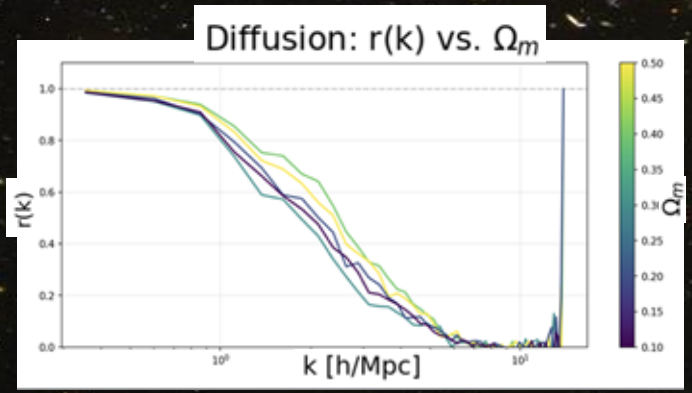
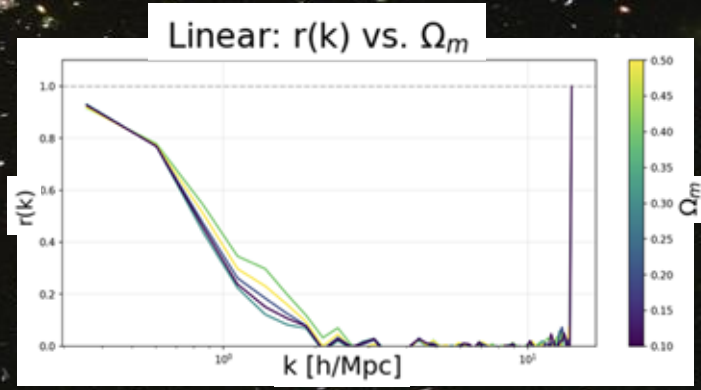
Science Results

We can do it, and significantly better than linear reconstruction!

We present the first known analysis to marginalize over cosmology and train on only gas density + cdm fields at 25 Mpc/h scale, with consistently high cross power fidelity at >6 Mpc/h.







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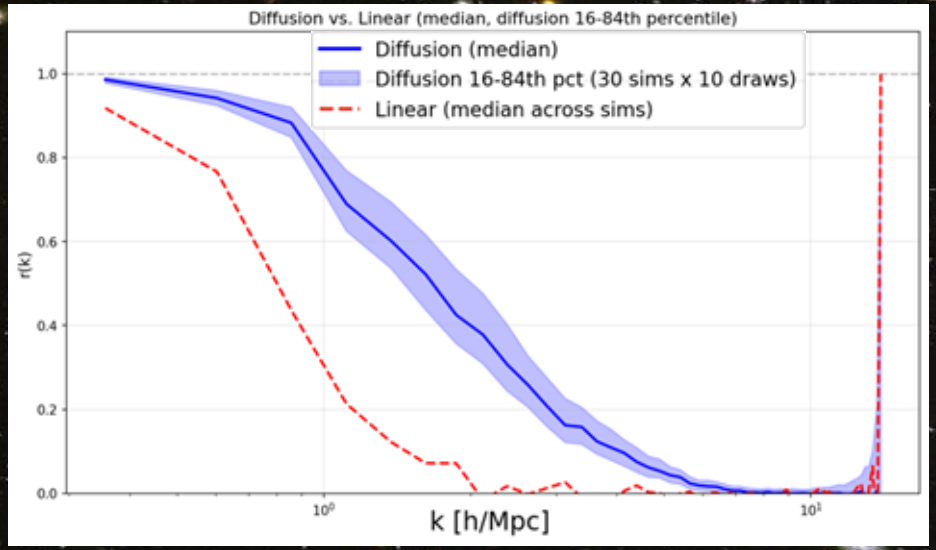
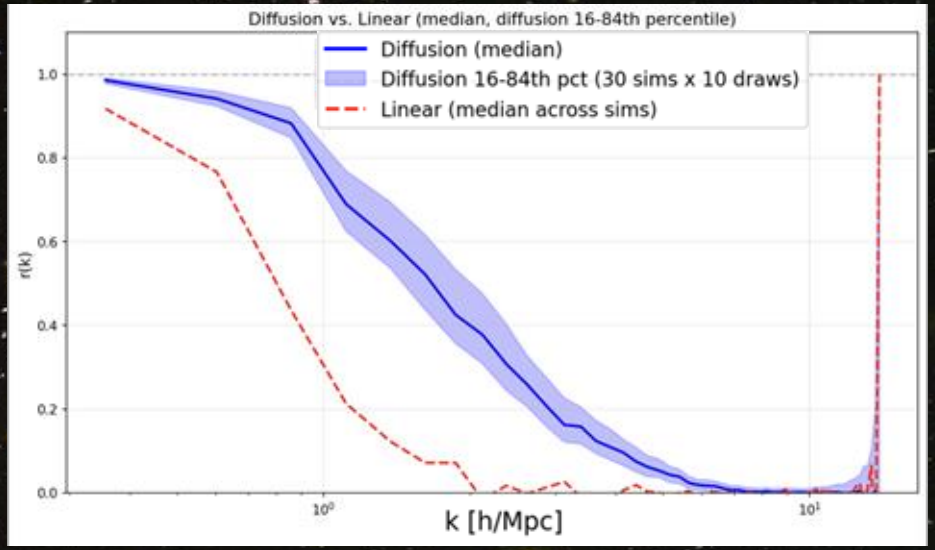
Science Results: 1P



Gas input



CDM input

Result: Gas and CDM inputs reconstruct roughly the same!

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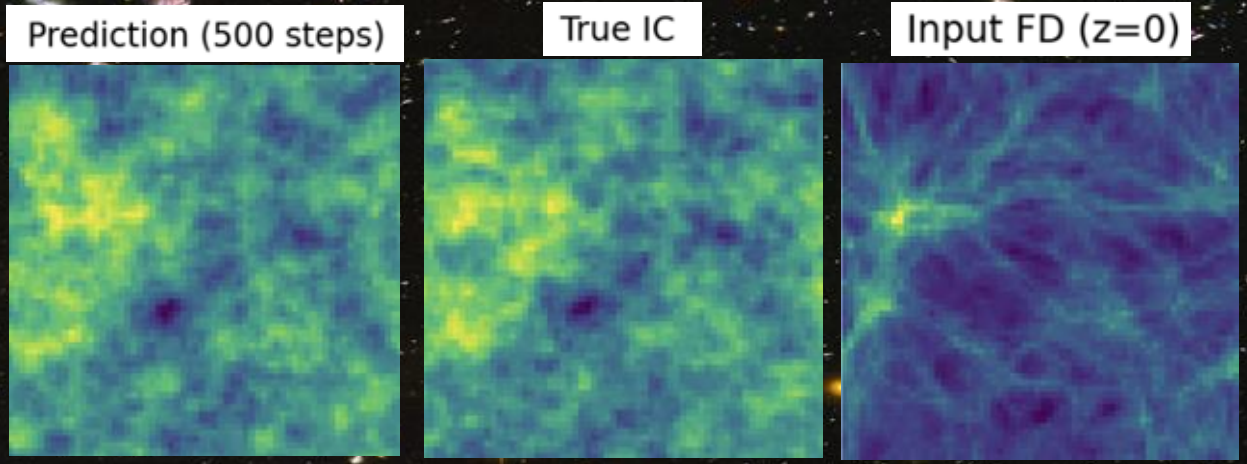
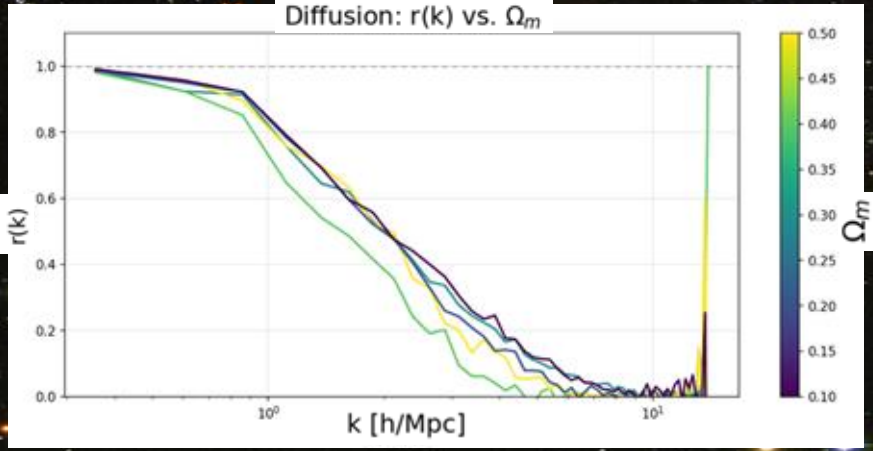
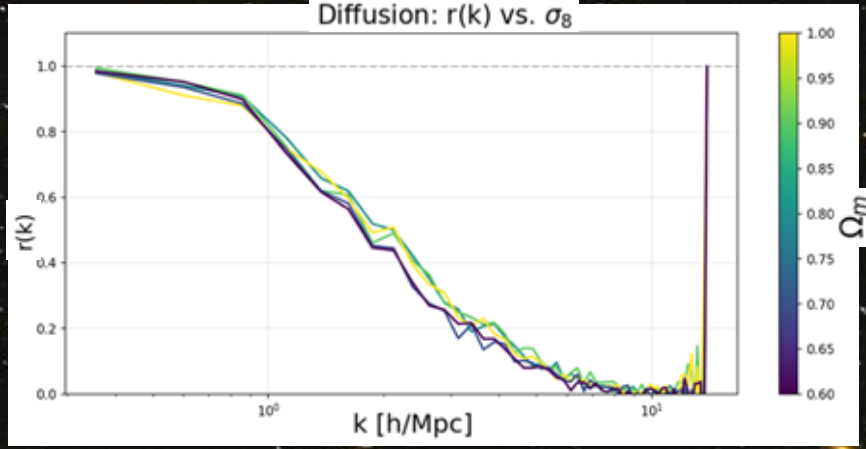
Science Results

1P set : Affected by the parameters







Science Results : CV

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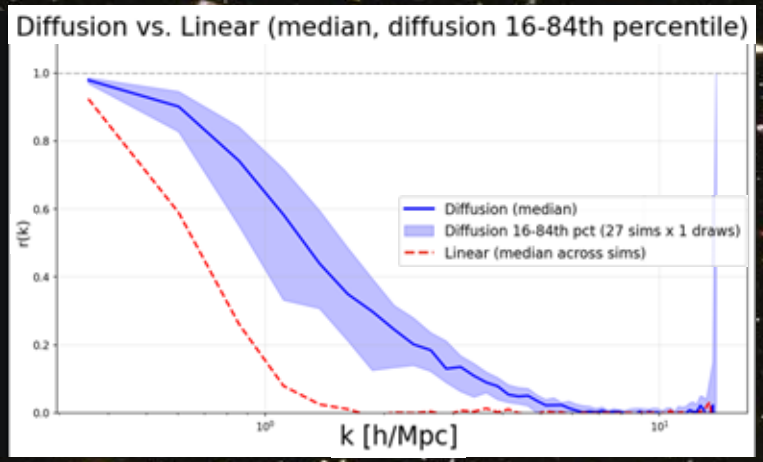
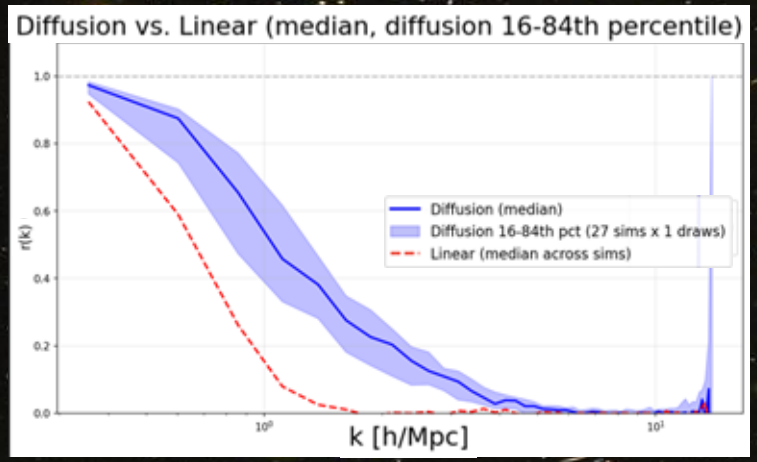
CV set fluctuates in performance more than 1P set



Gas only input



CDM only input

Science Results : CV vs 1P

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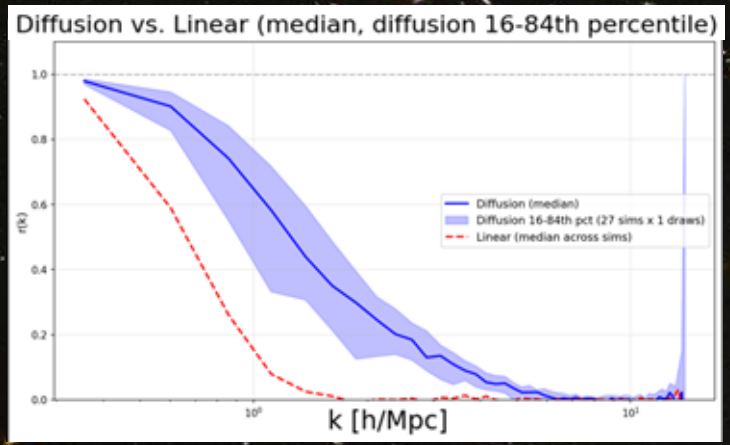
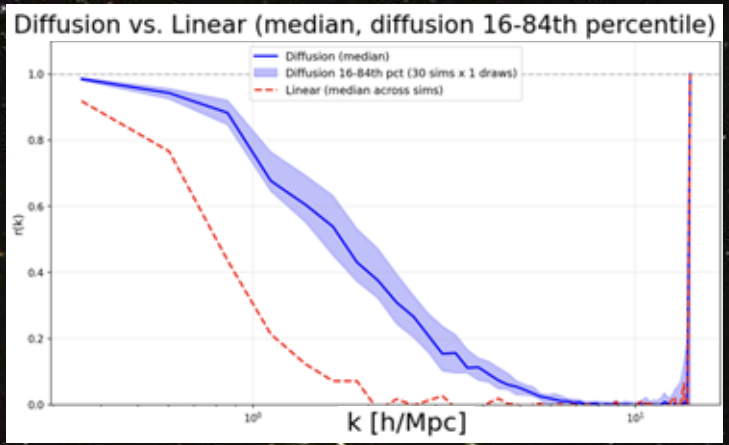
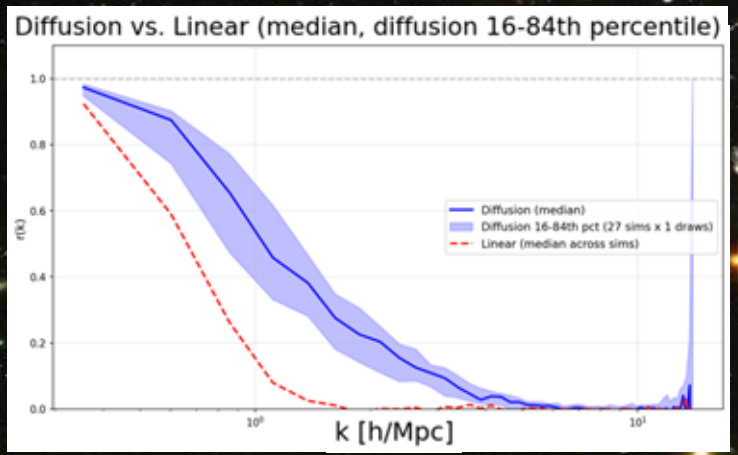
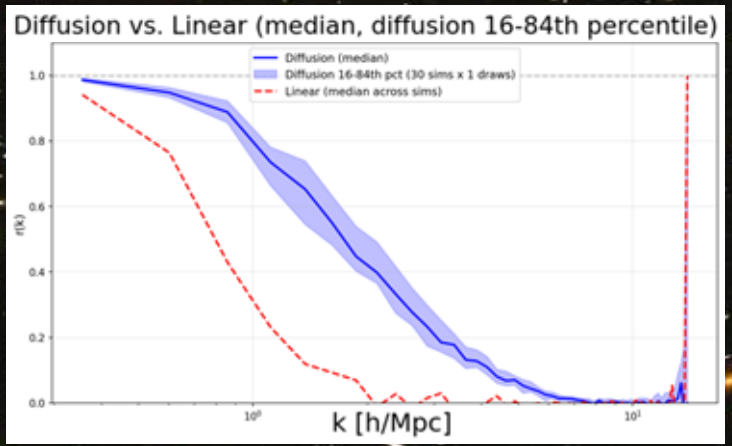




Gas only input





CDM only input

Science Results: CV

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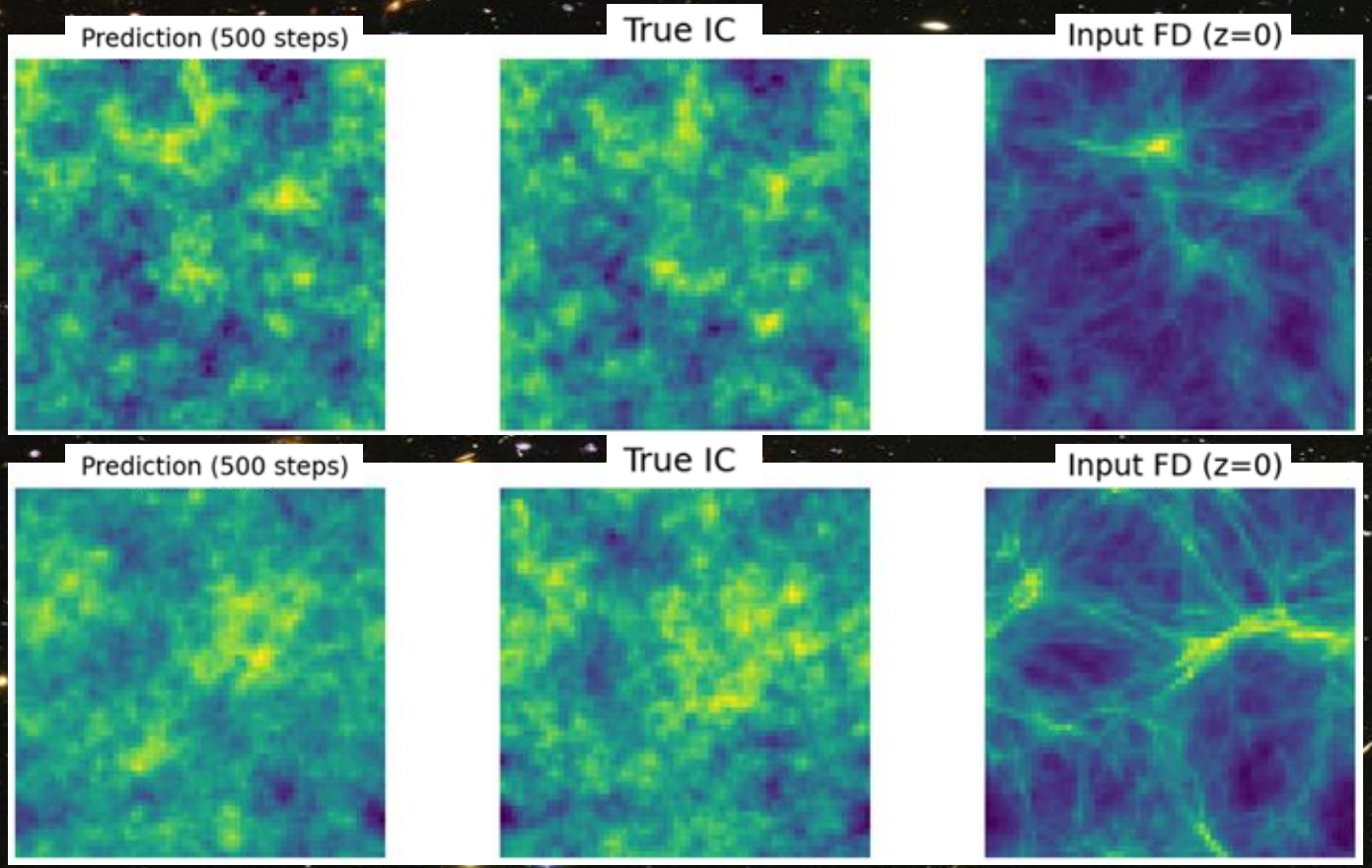

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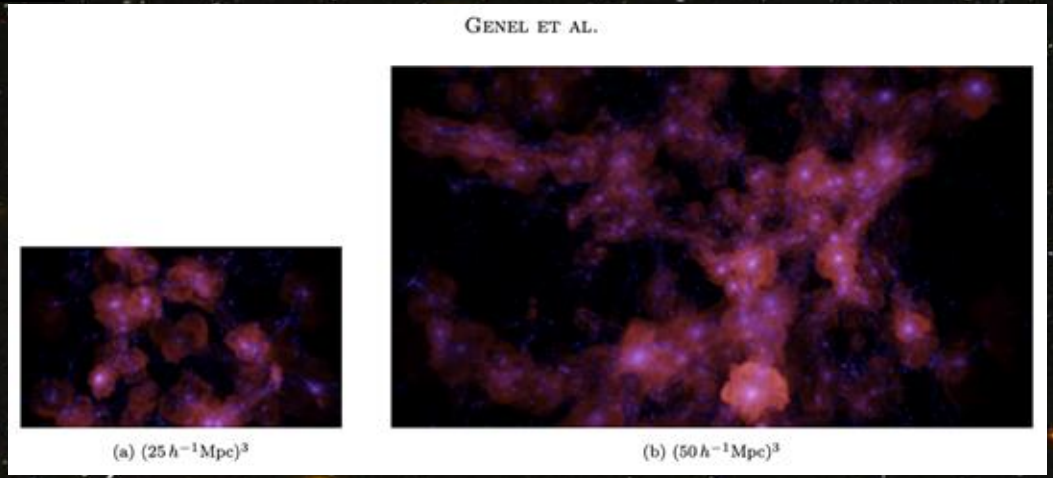
Future Work / Conclusion

Re-simulating our generated samples to test reconstruction fidelity

Expanding to new CAMELS 50 Mpc/h cubes

Mock observables (X-ray, eRosita)



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Preliminary | Future Work

Extending Analysis to 128^3