

SCUOLA
NORMALE
SUPERIORE

Multi-tracer inference of Galaxy Properties During the 1st billion years of the Universe



Context

A little history of the Universe...

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Context



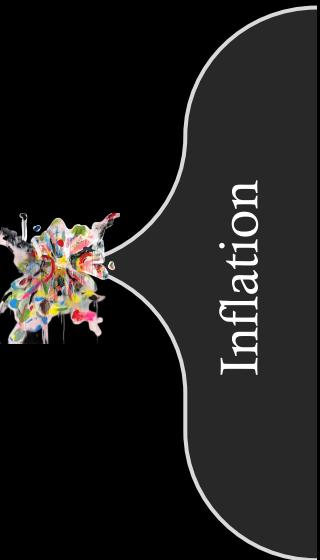
A little history of the Universe...

Context



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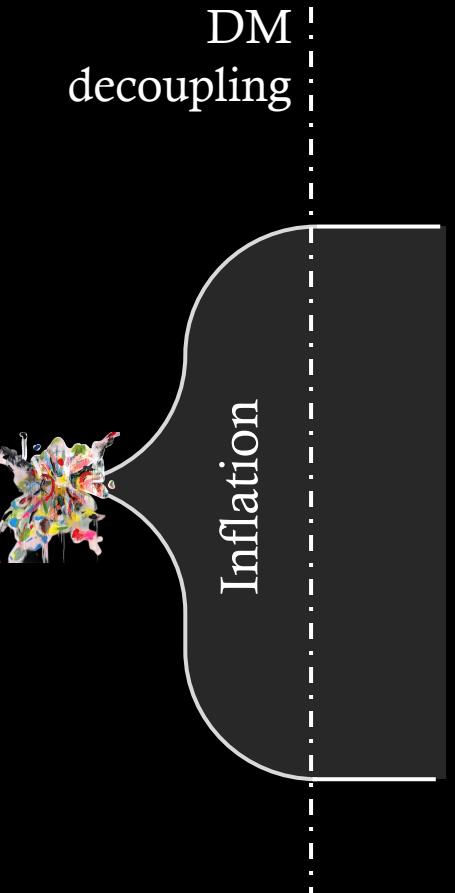
Context



Inflation

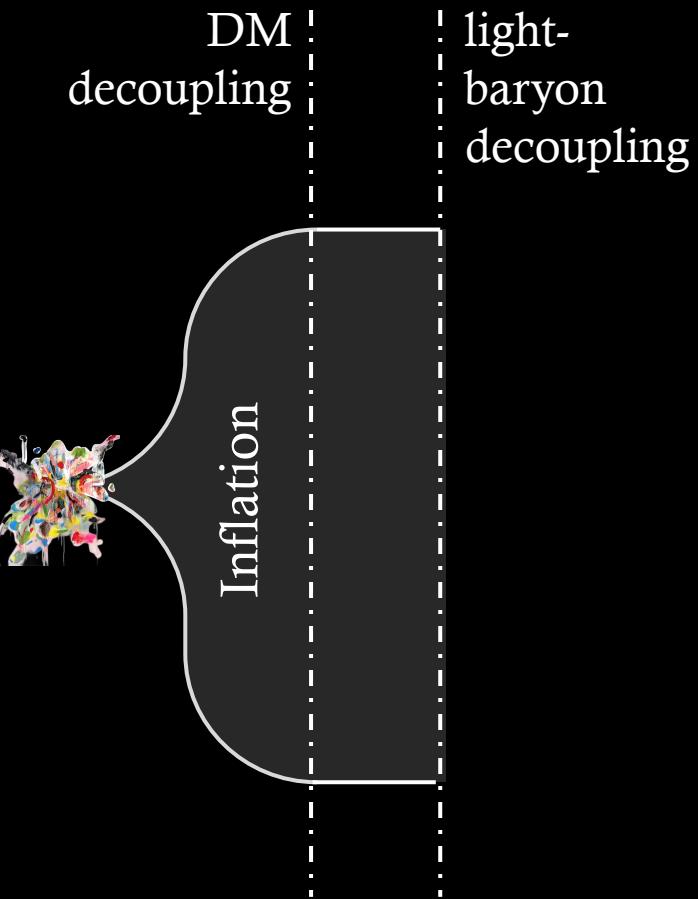
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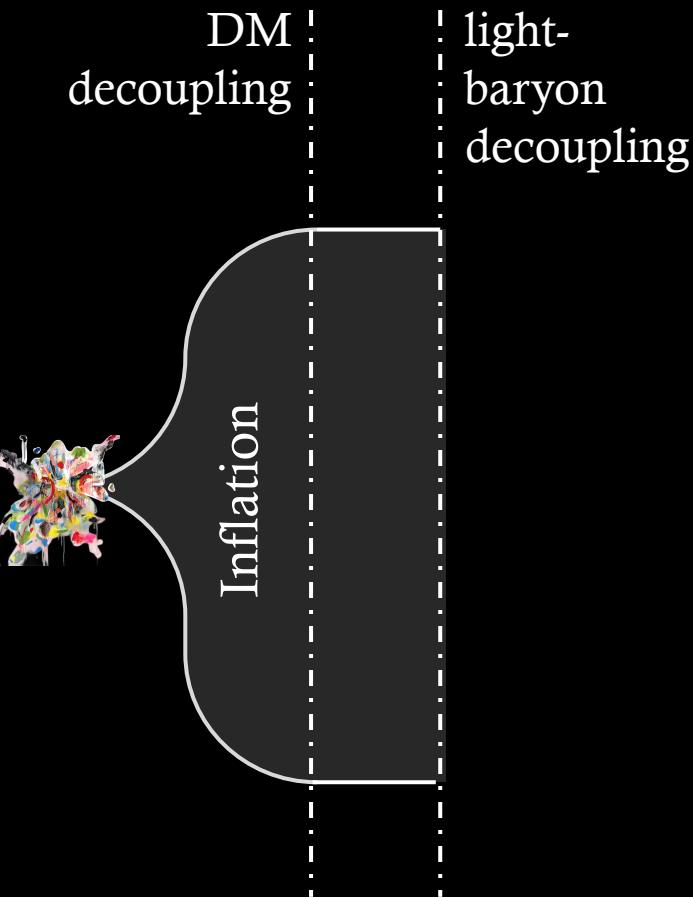
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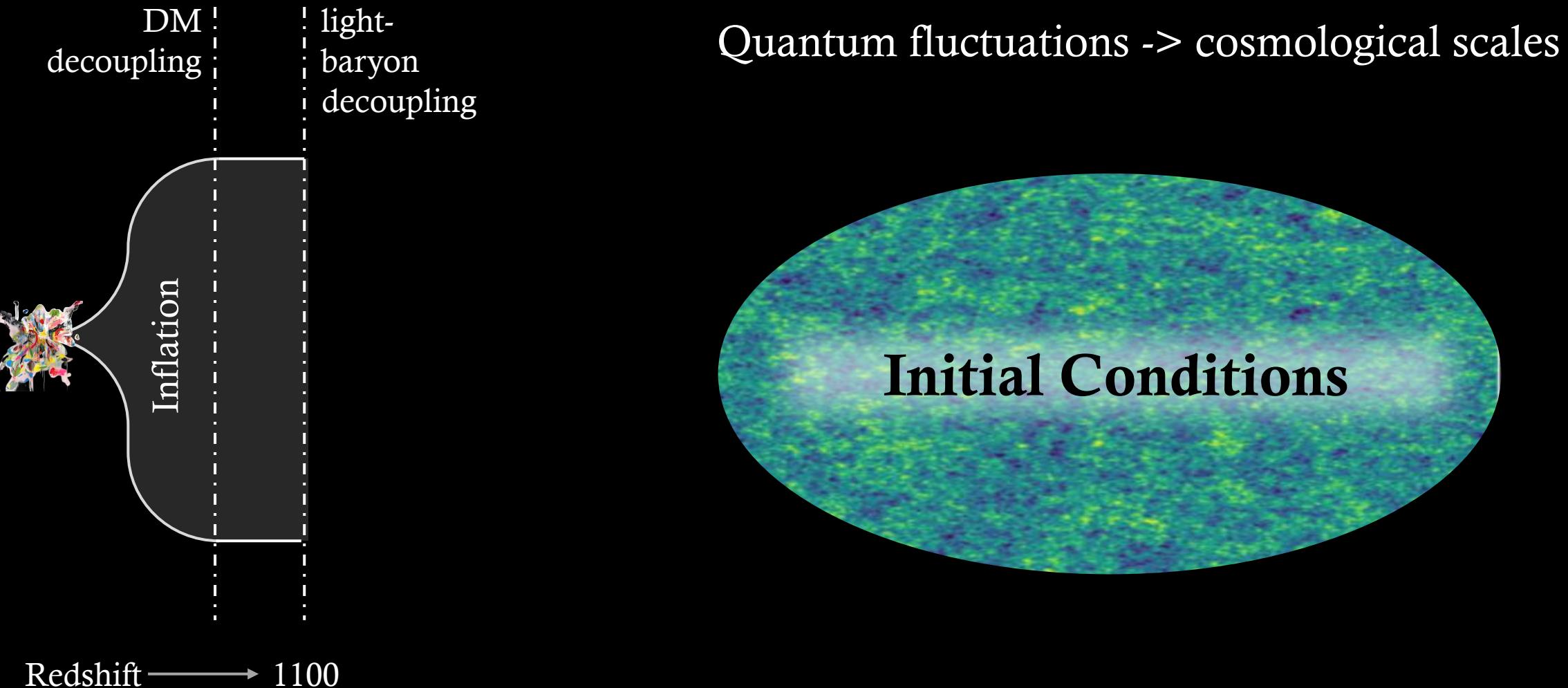


Quantum fluctuations -> cosmological scales

DM density distribution

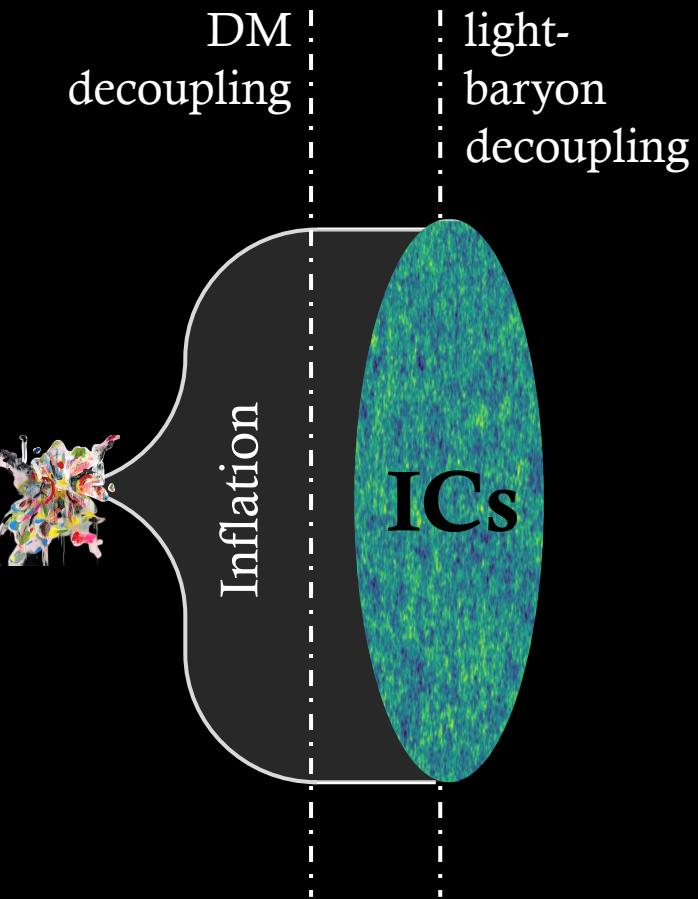
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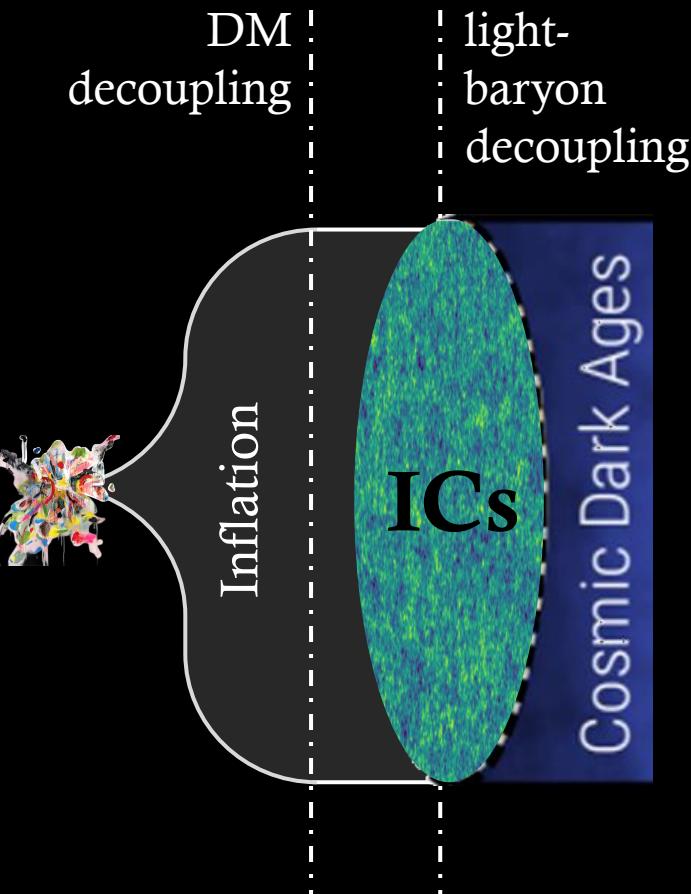
Context



Redshift → 1100

A little history of the Universe...

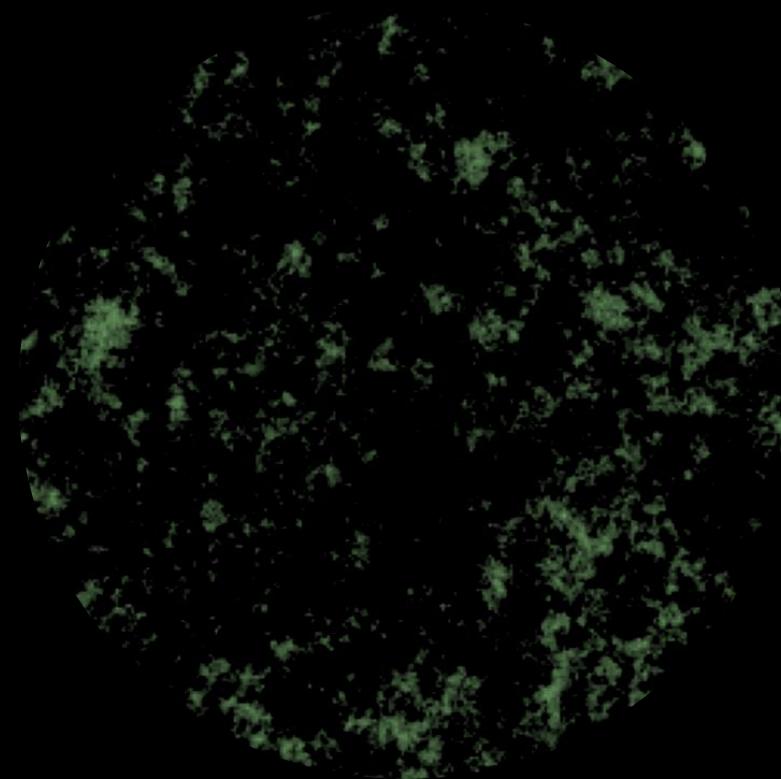
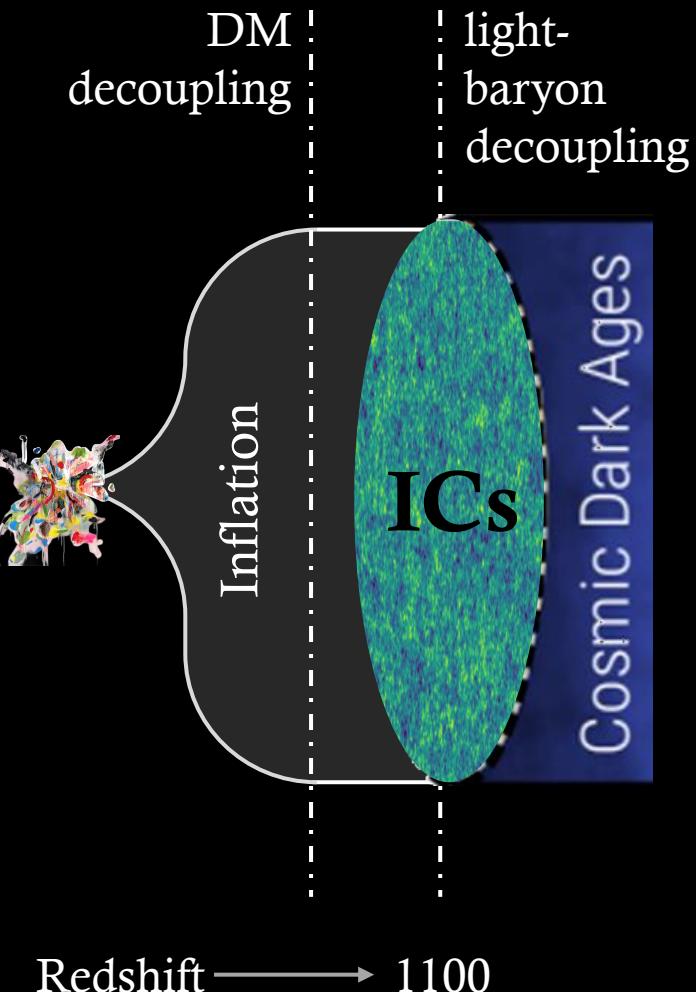
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Redshift → 1100

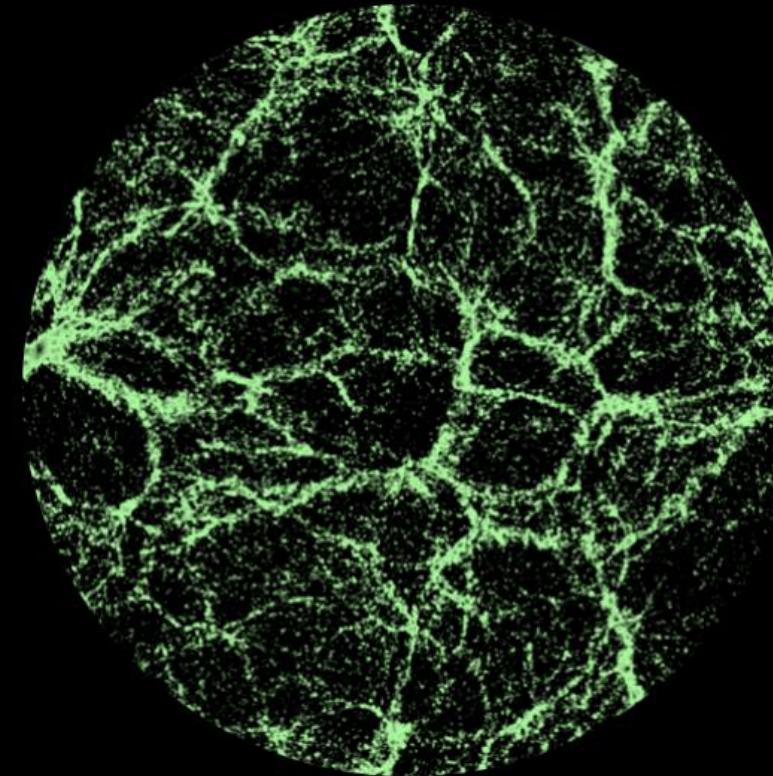
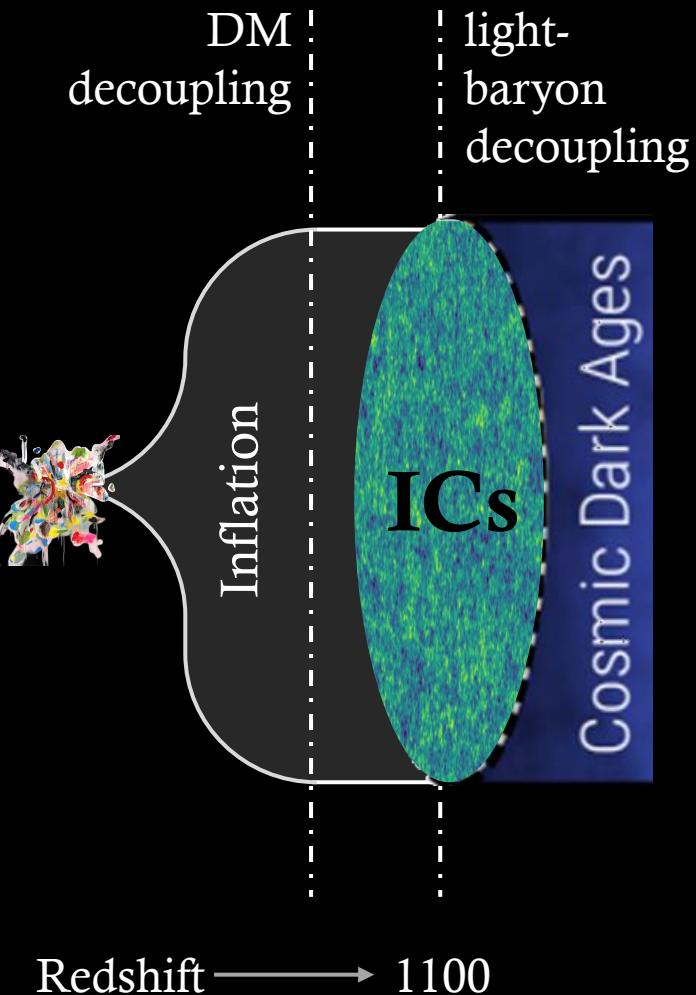
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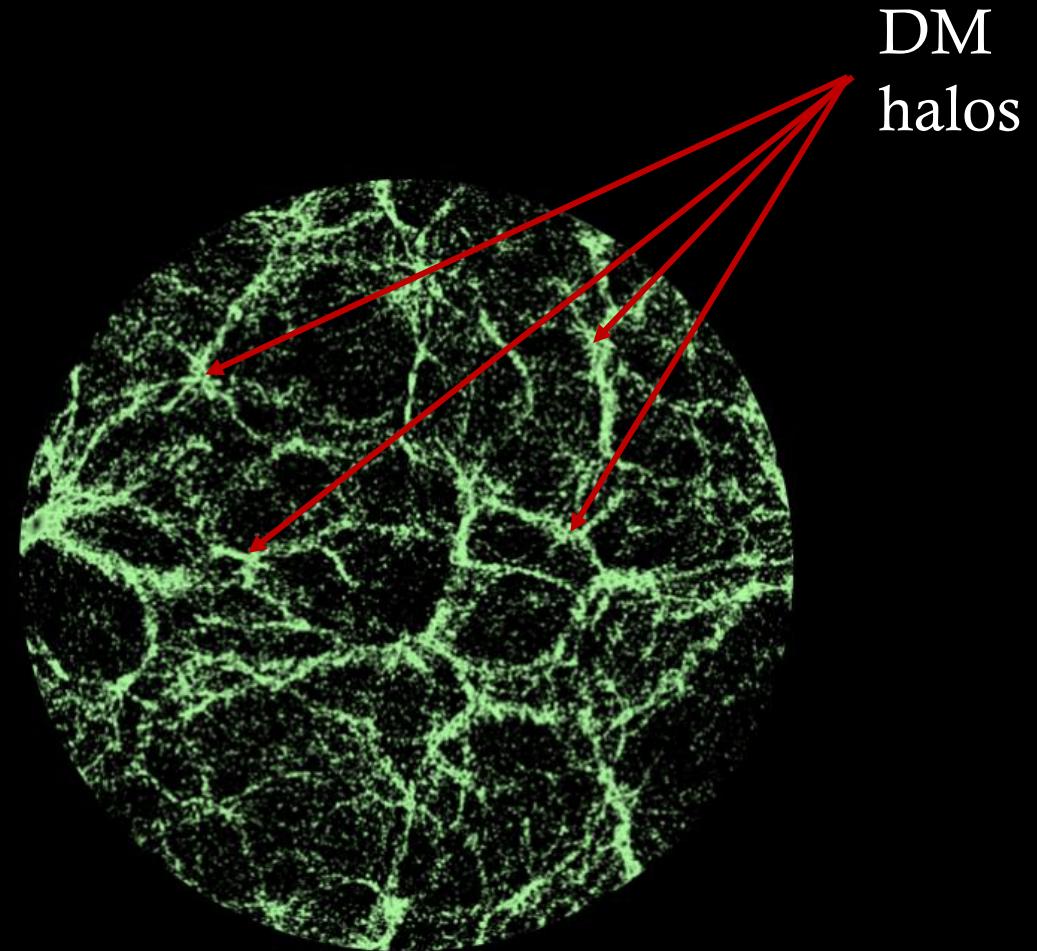
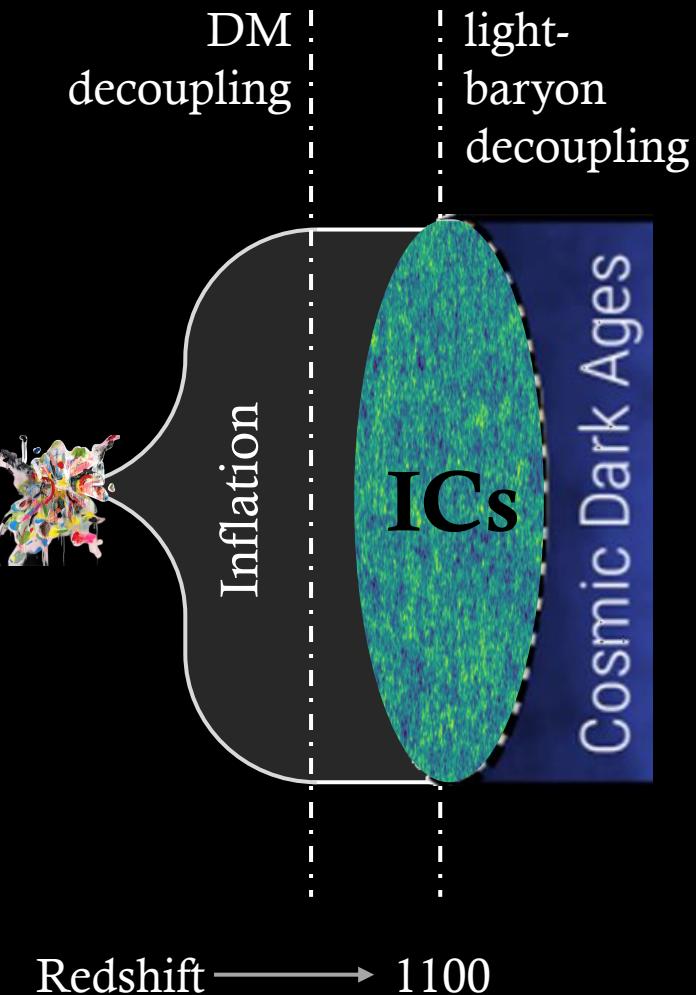
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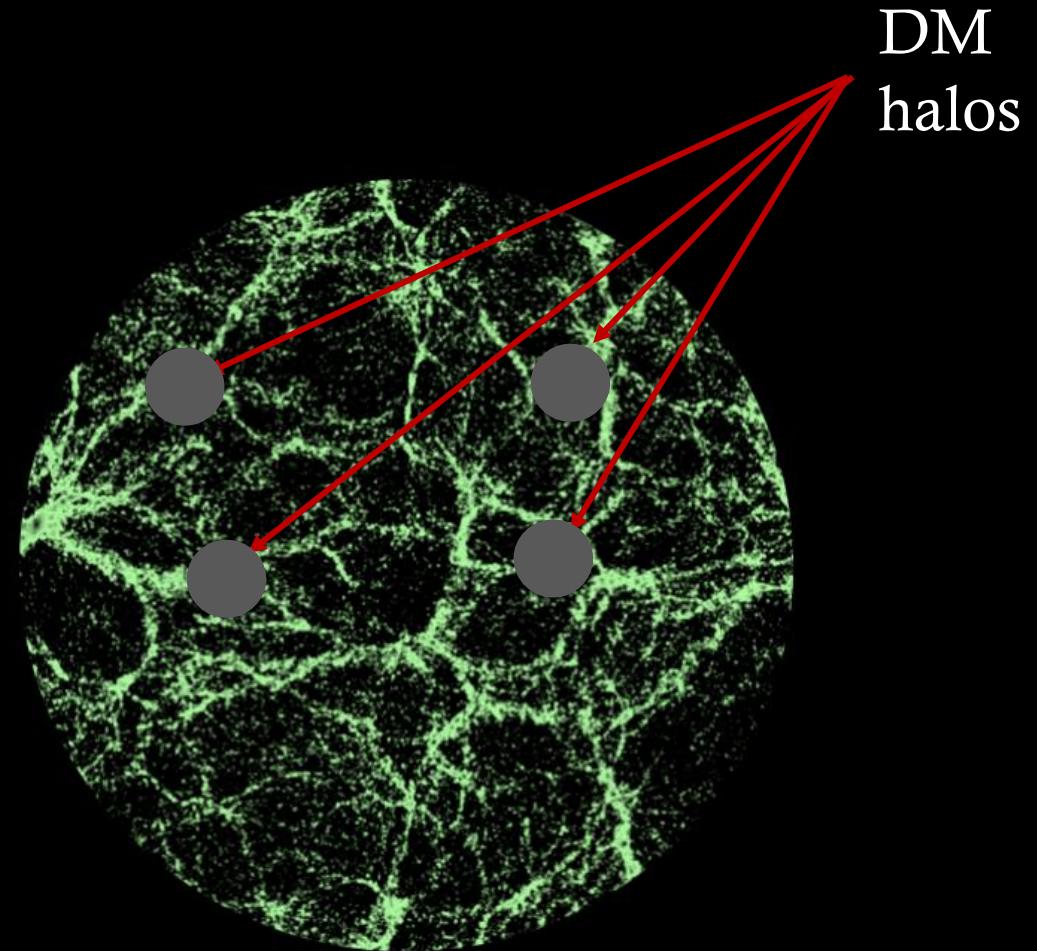
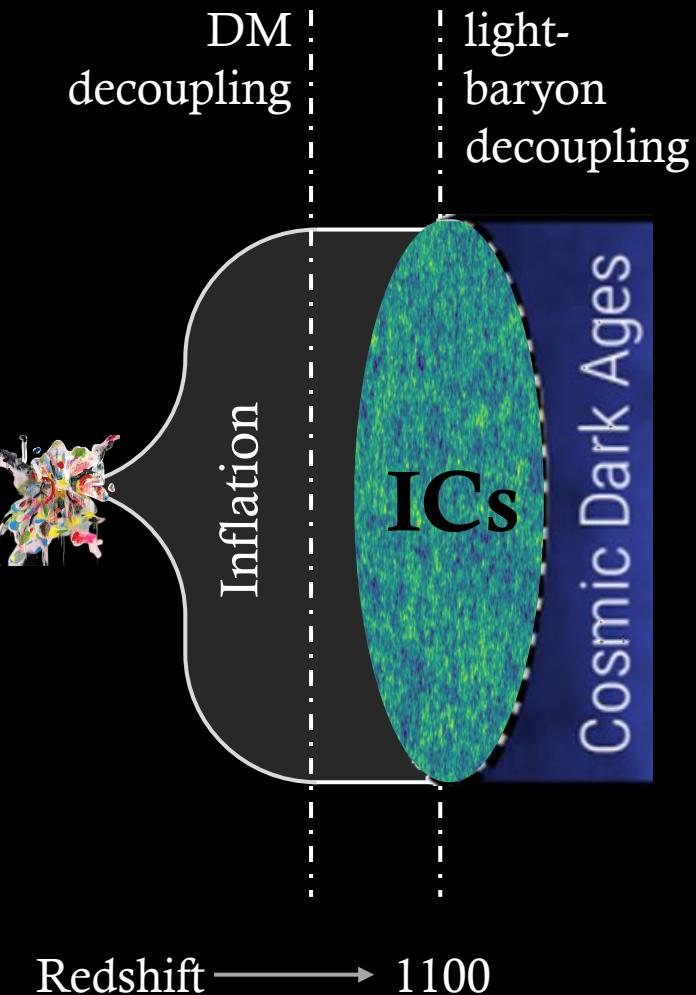
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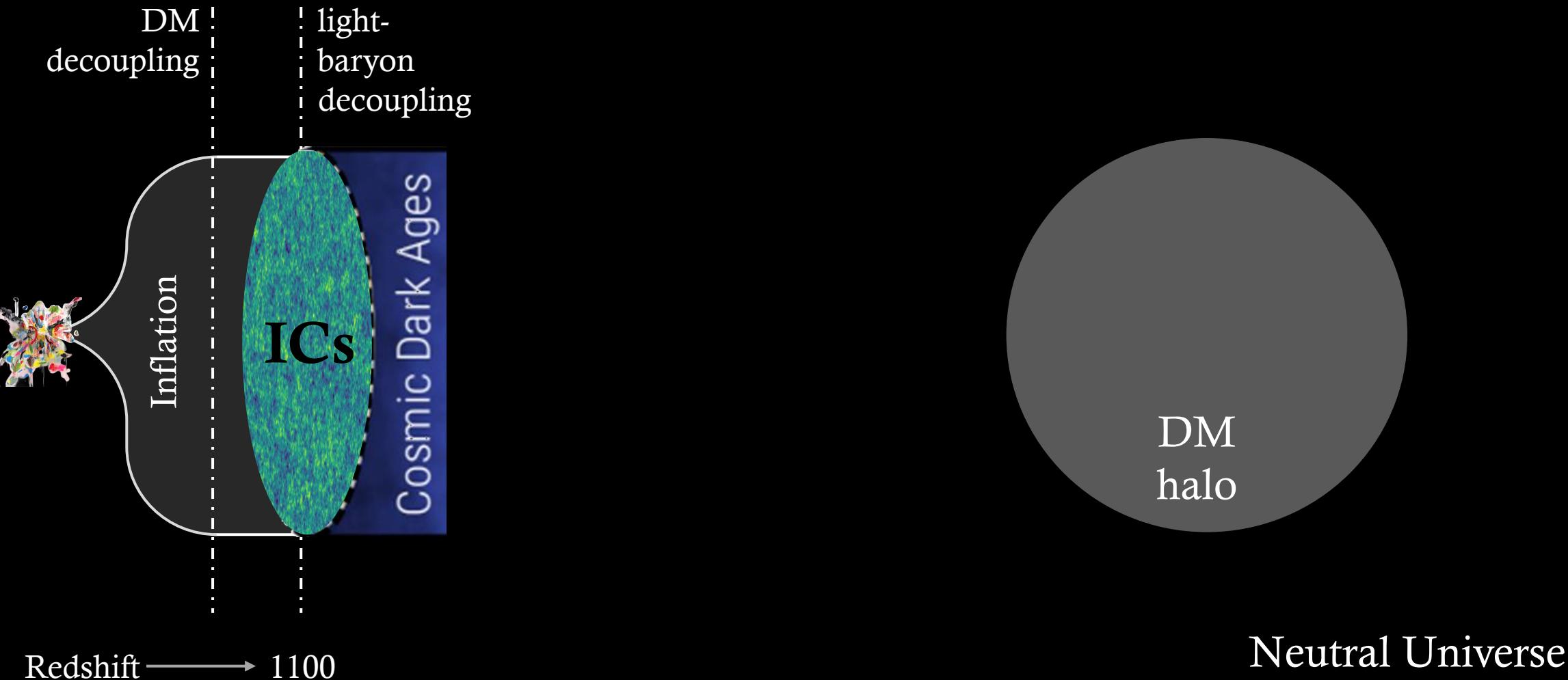
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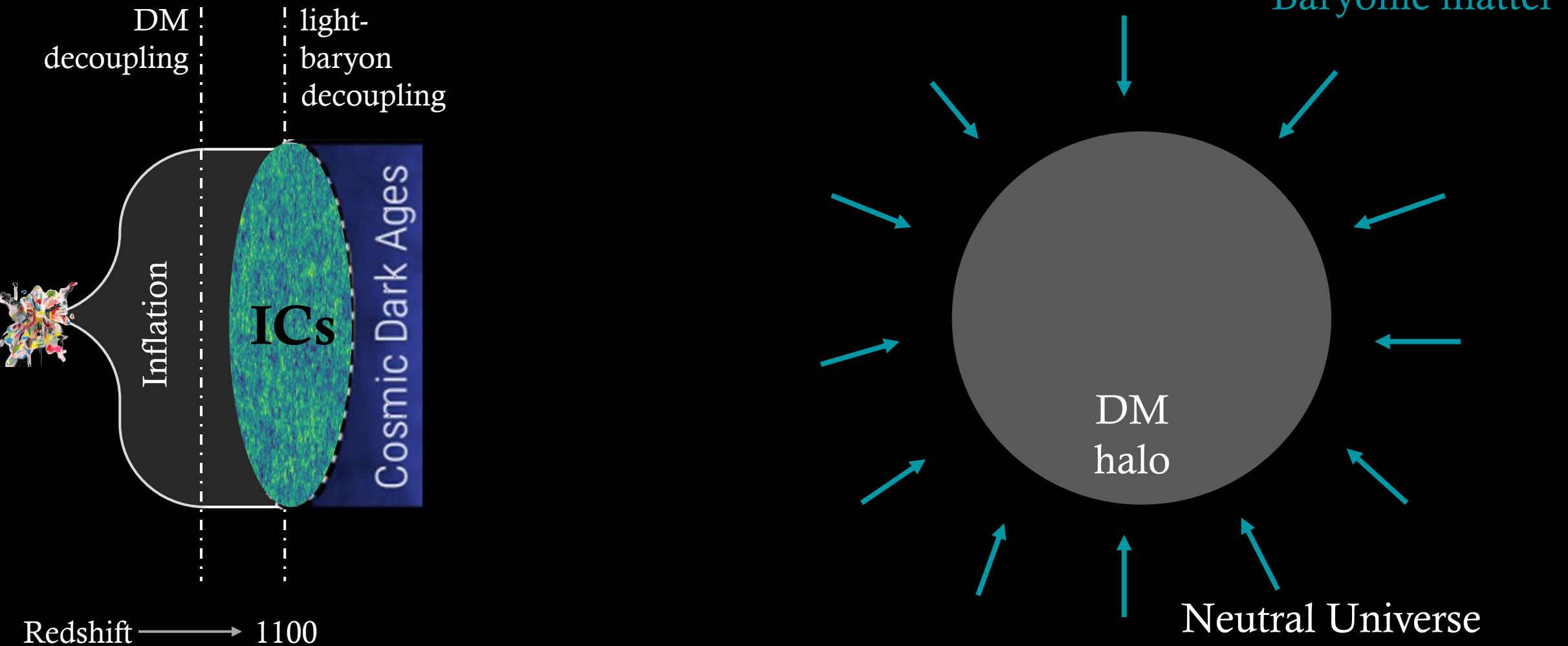
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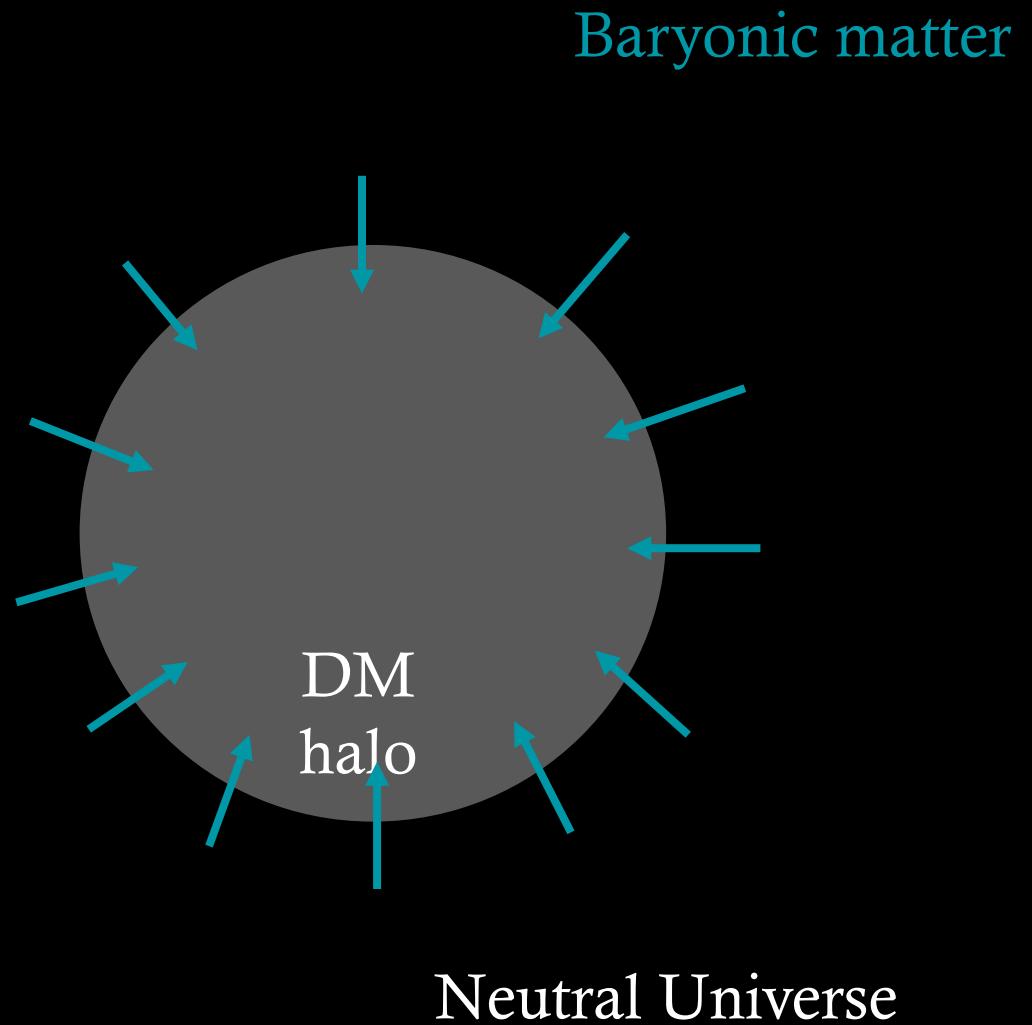
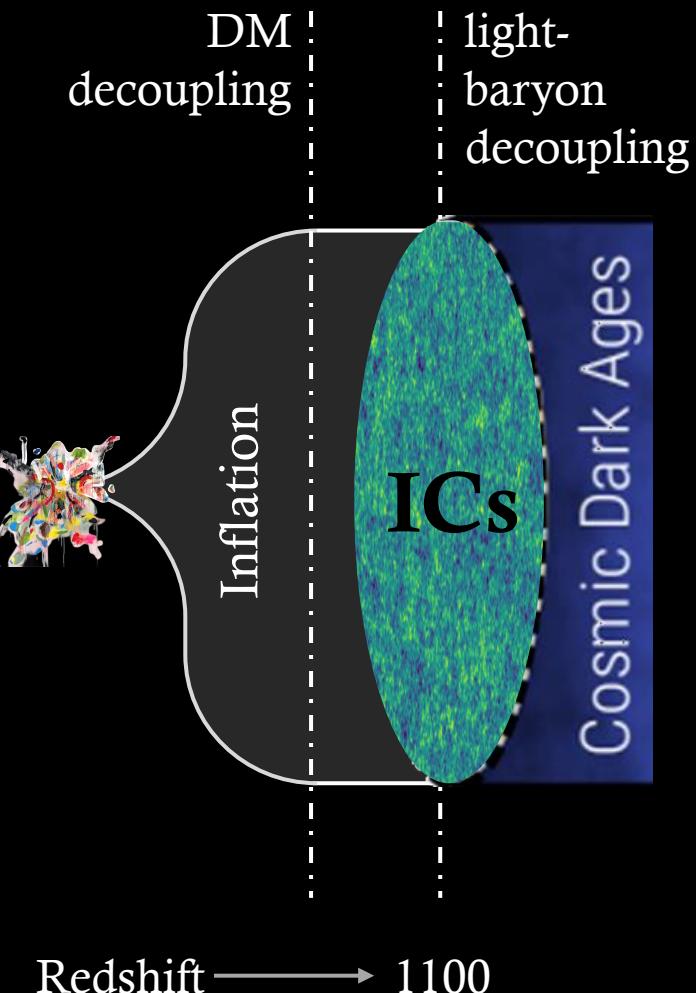
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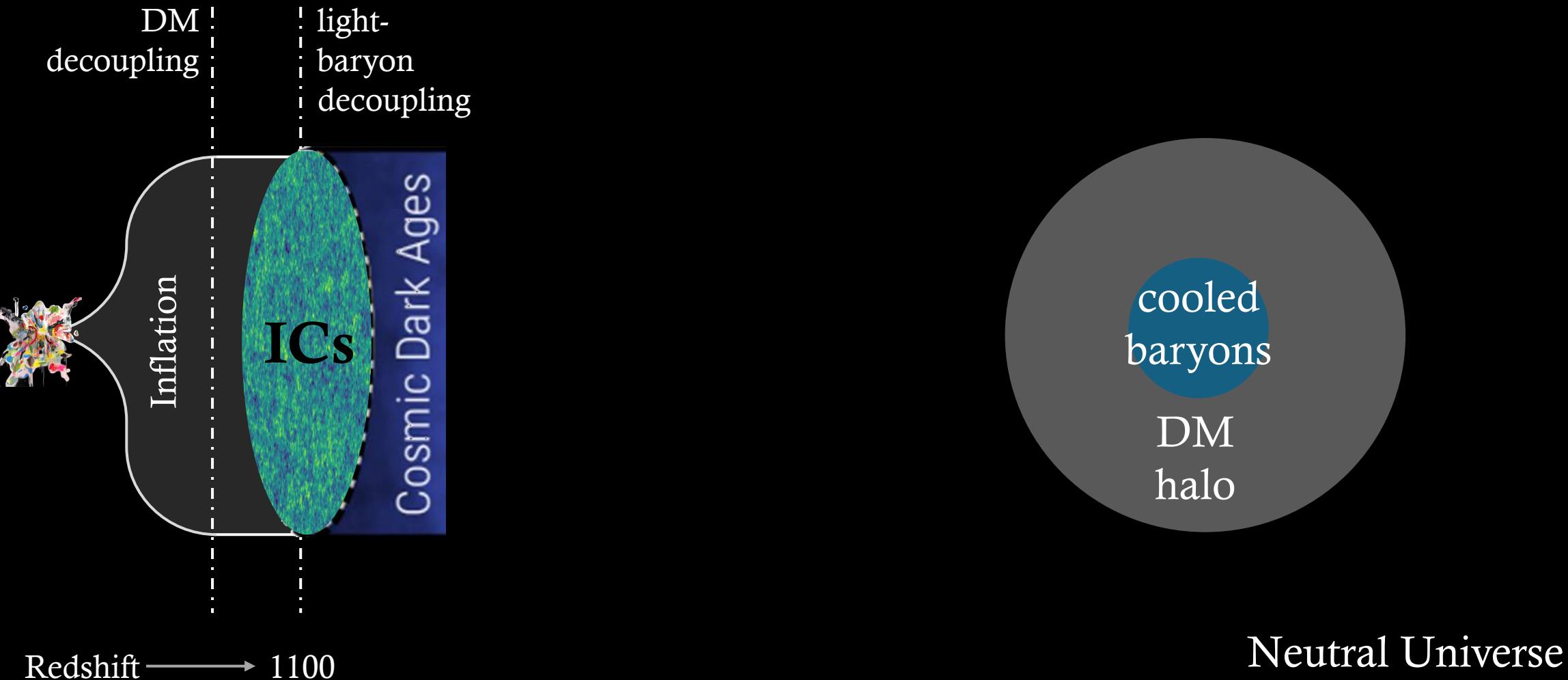
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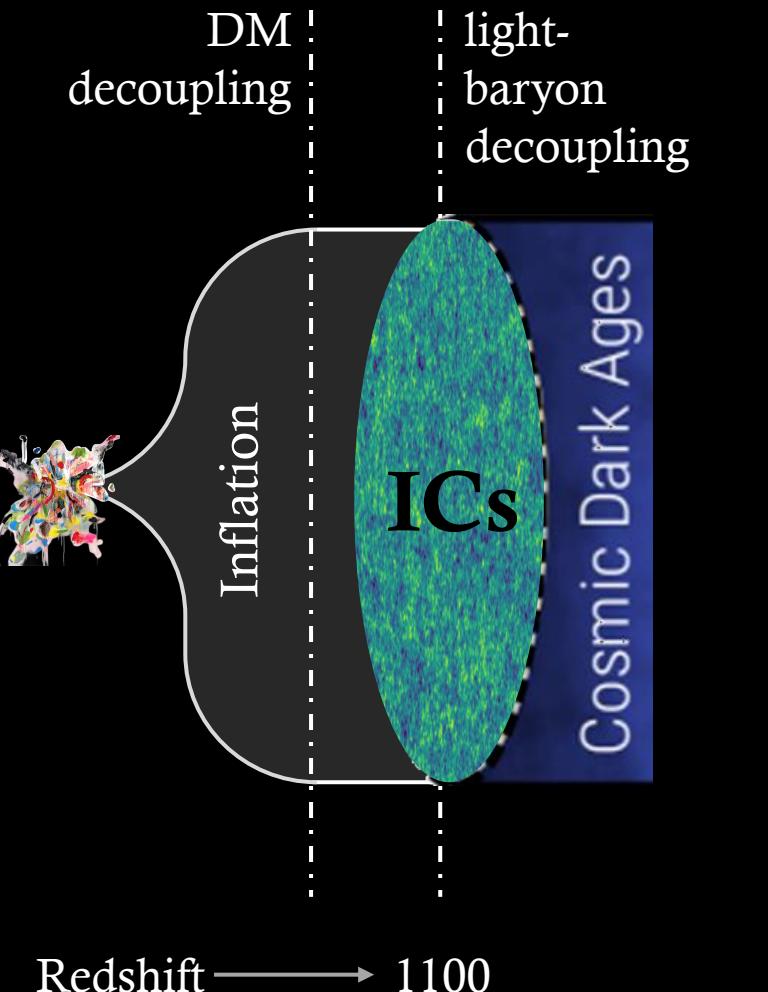
A little history of the Universe...

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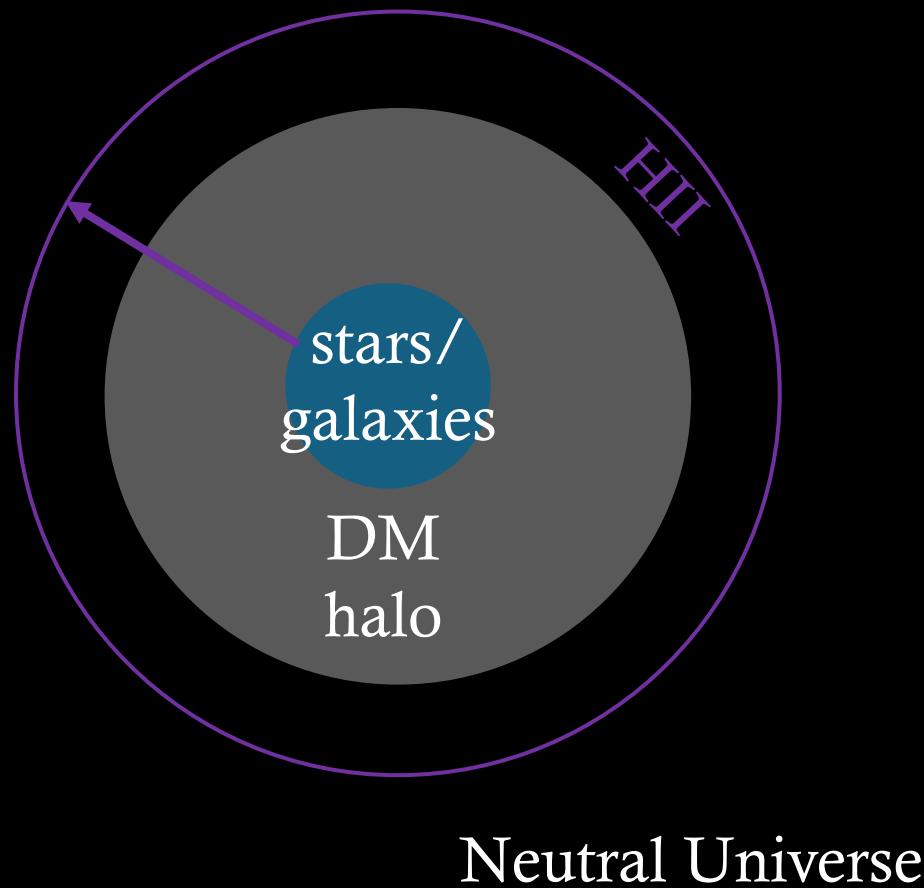
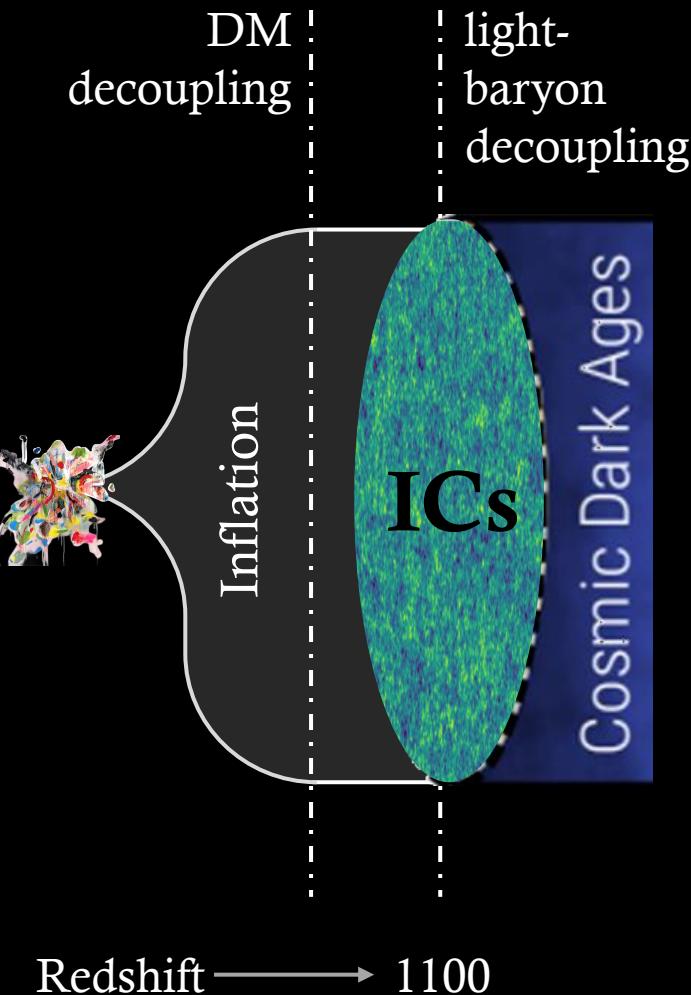
Context



Neutral Universe

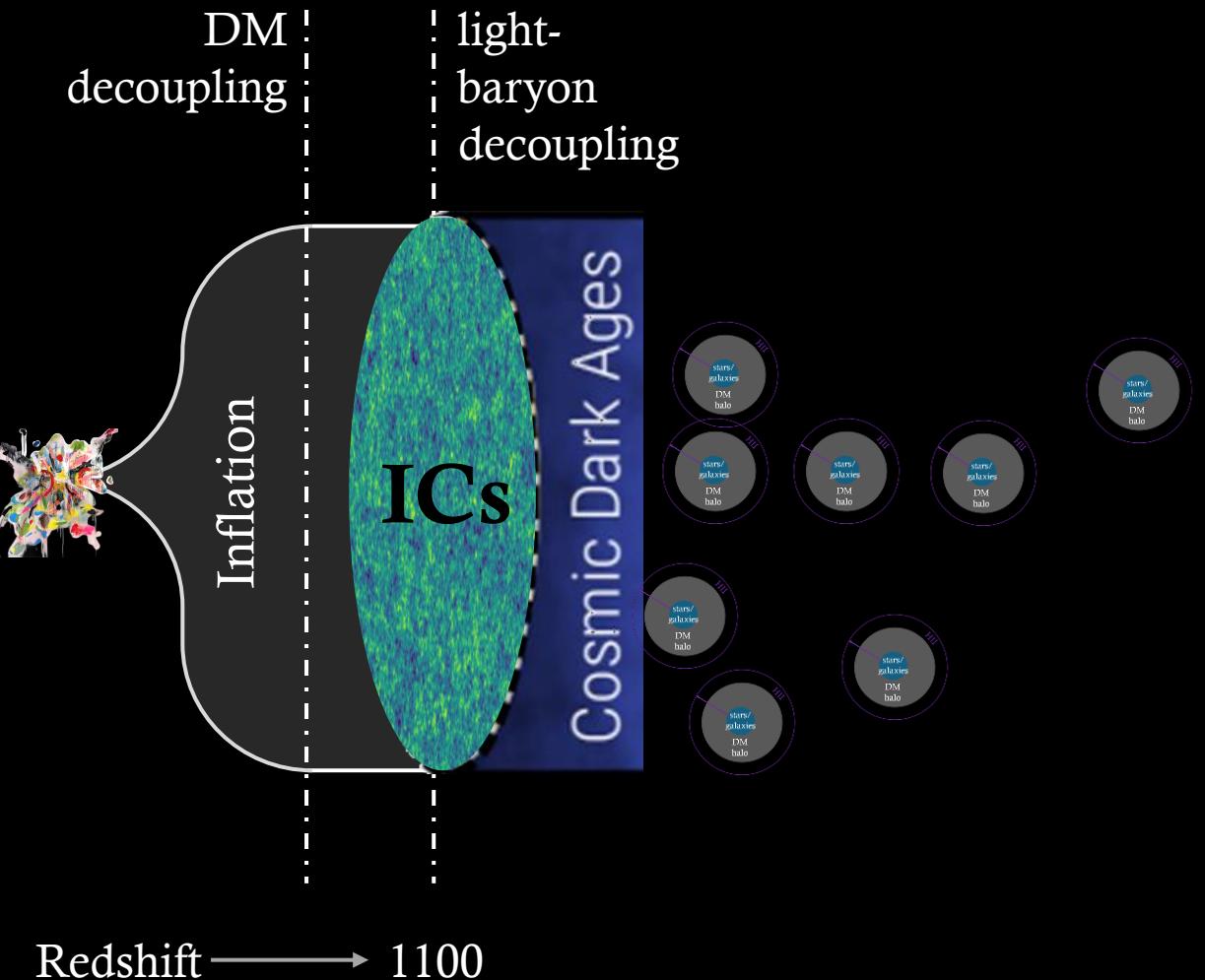
A little history of the Universe...

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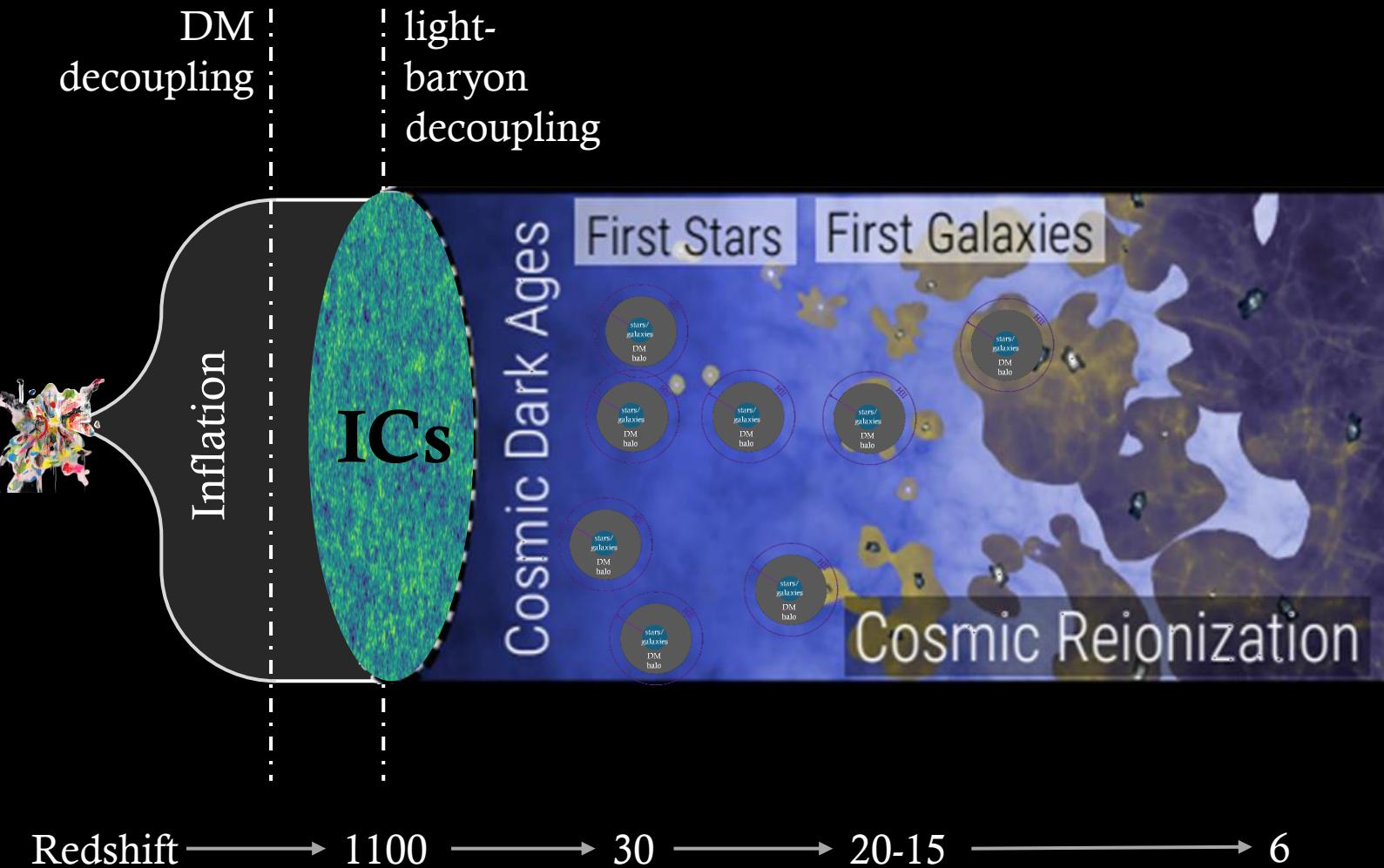
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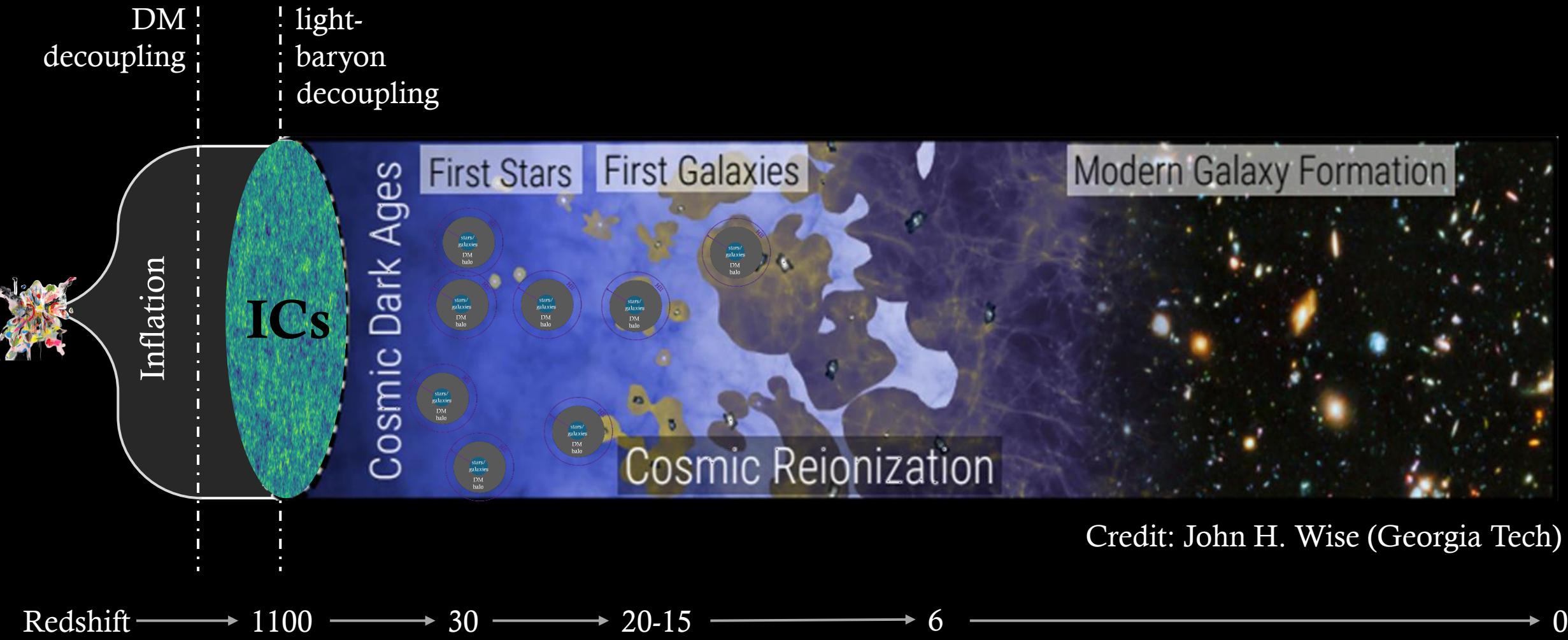
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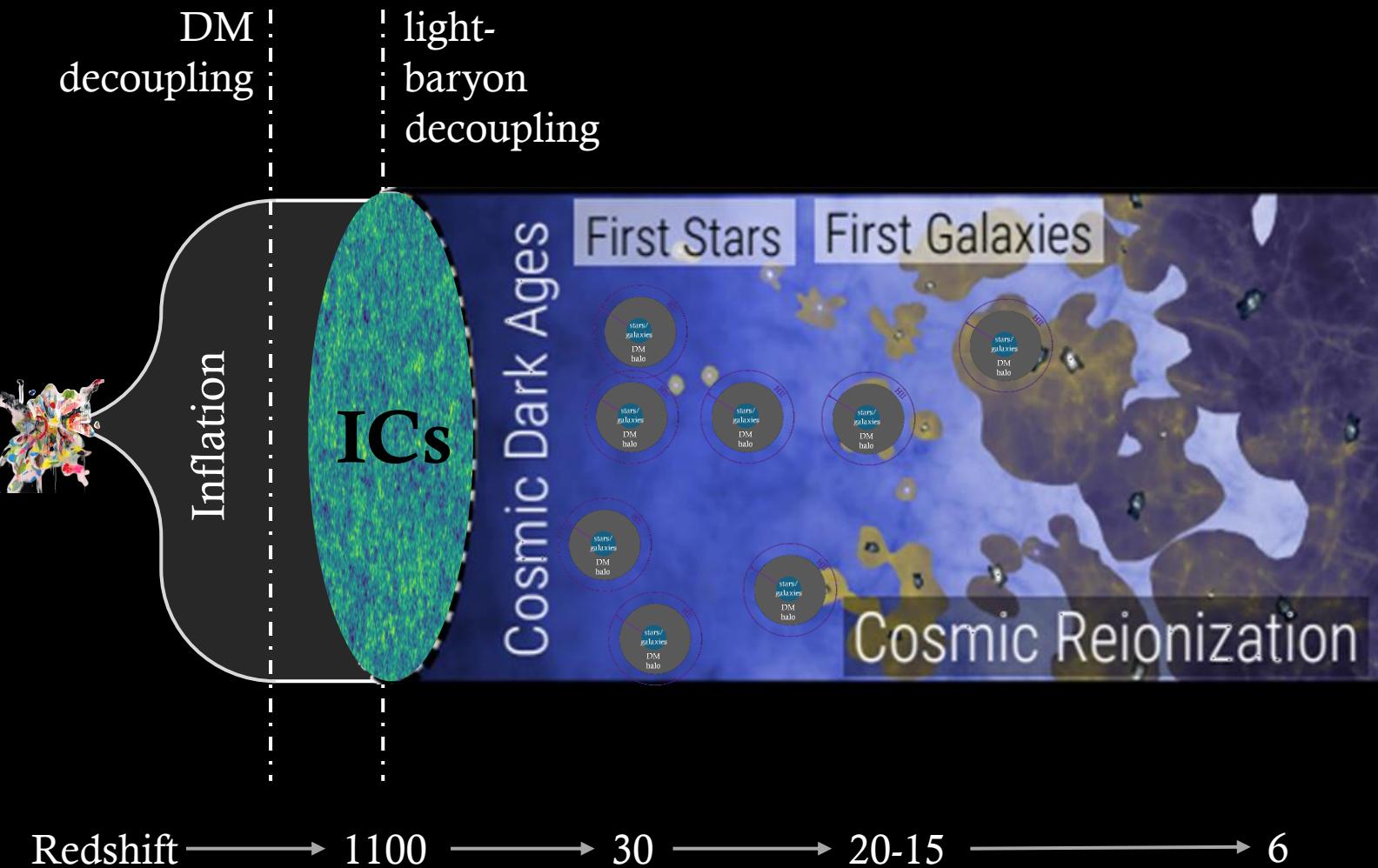


Cosmic 21-cm

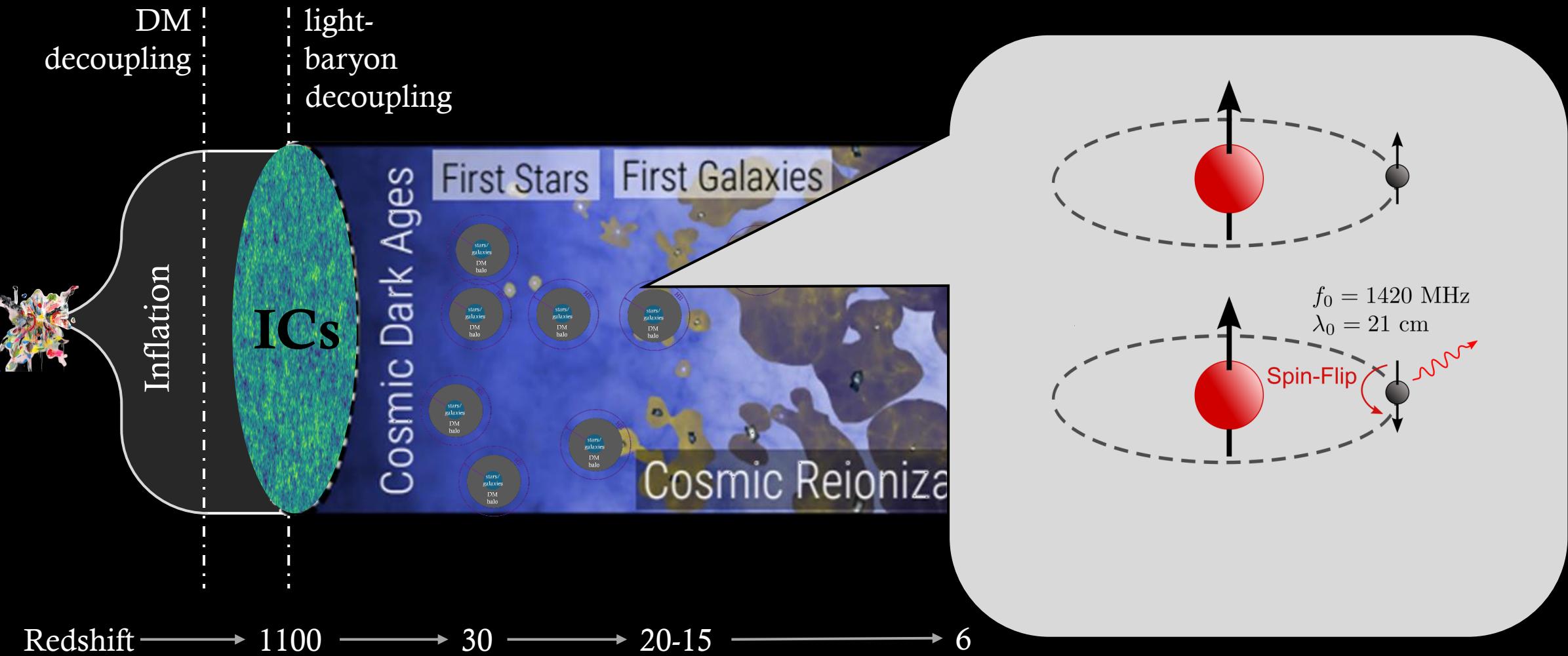


Redshift → 1100 → 30 → 20-15 → 6 → 0

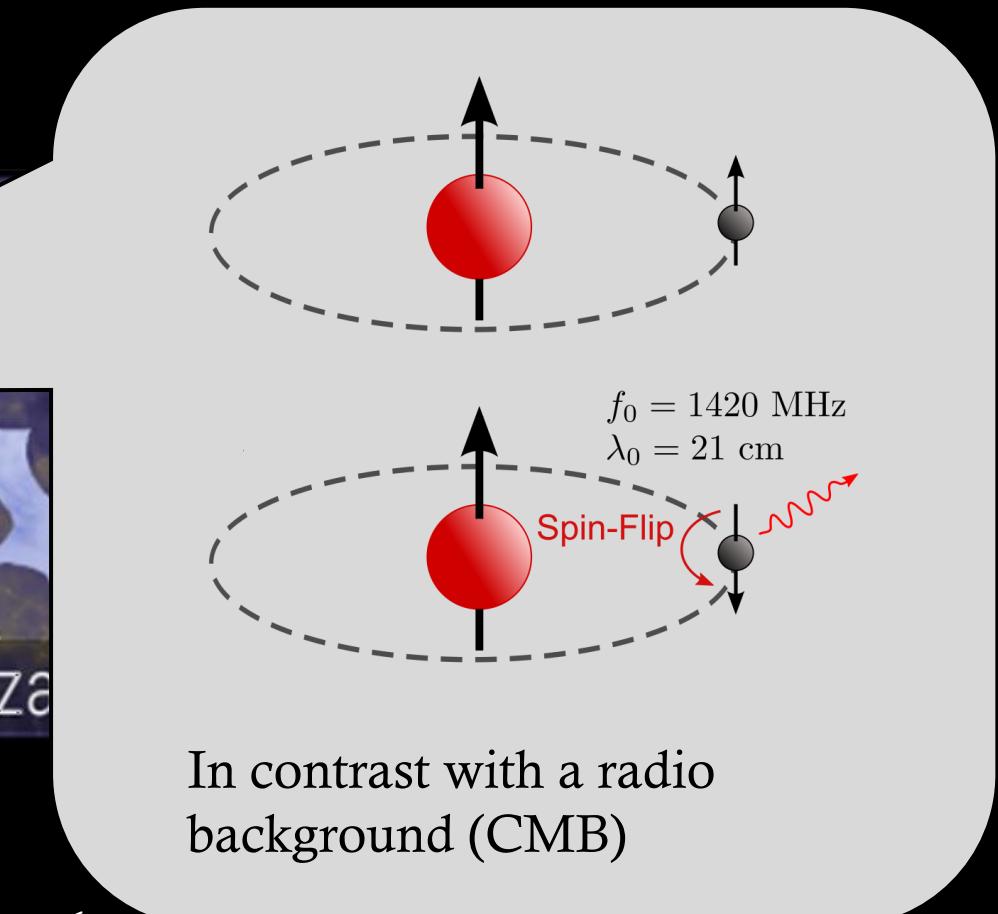
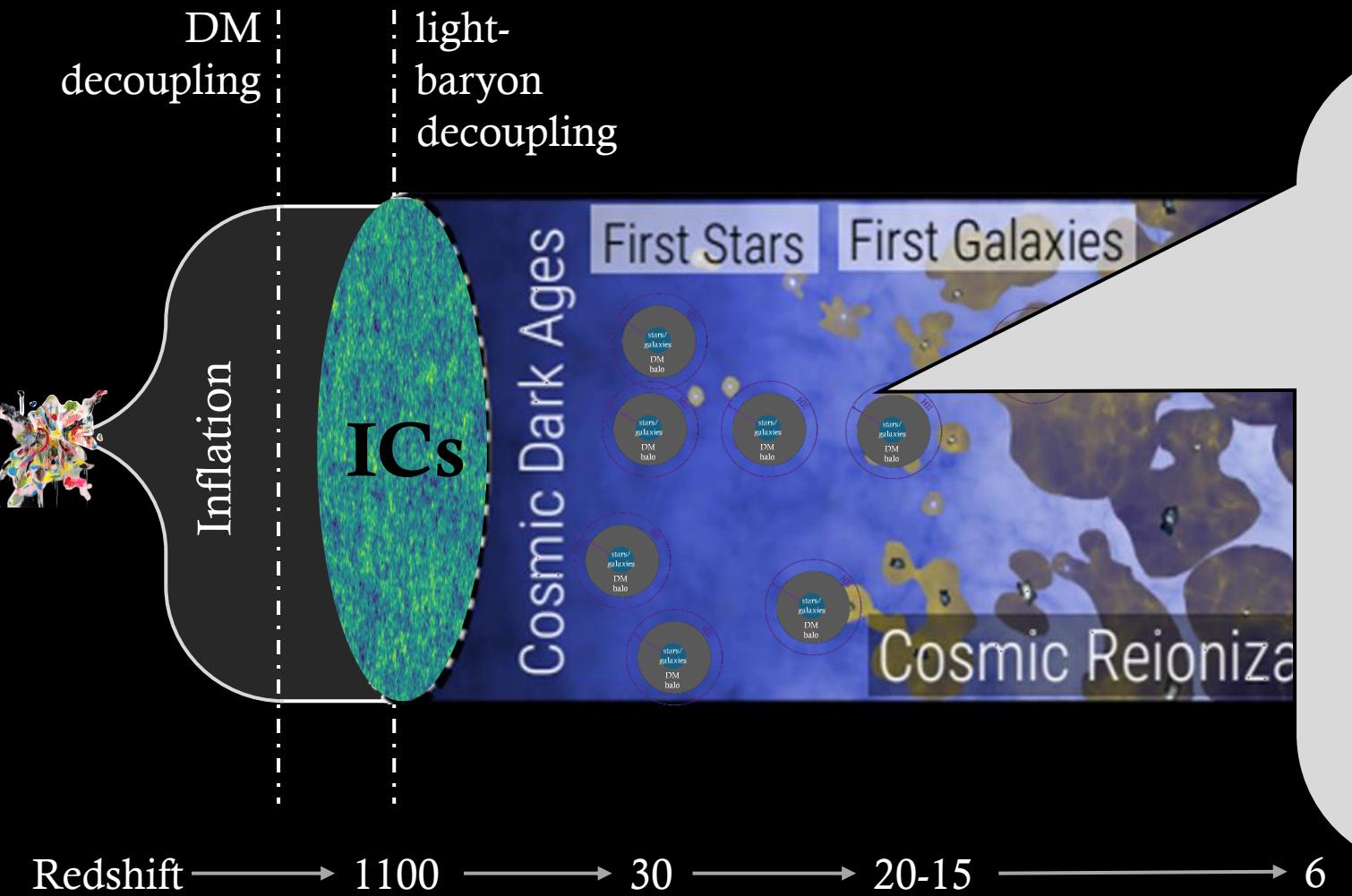
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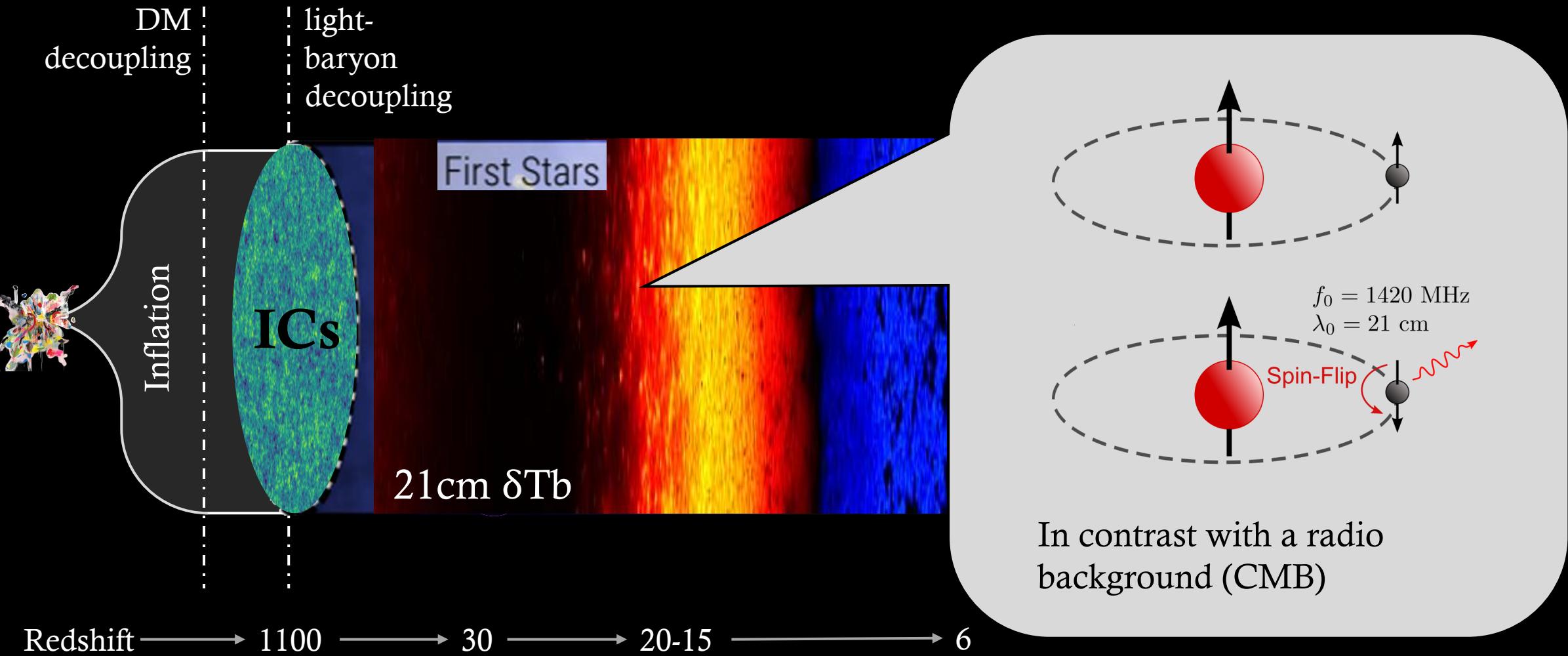
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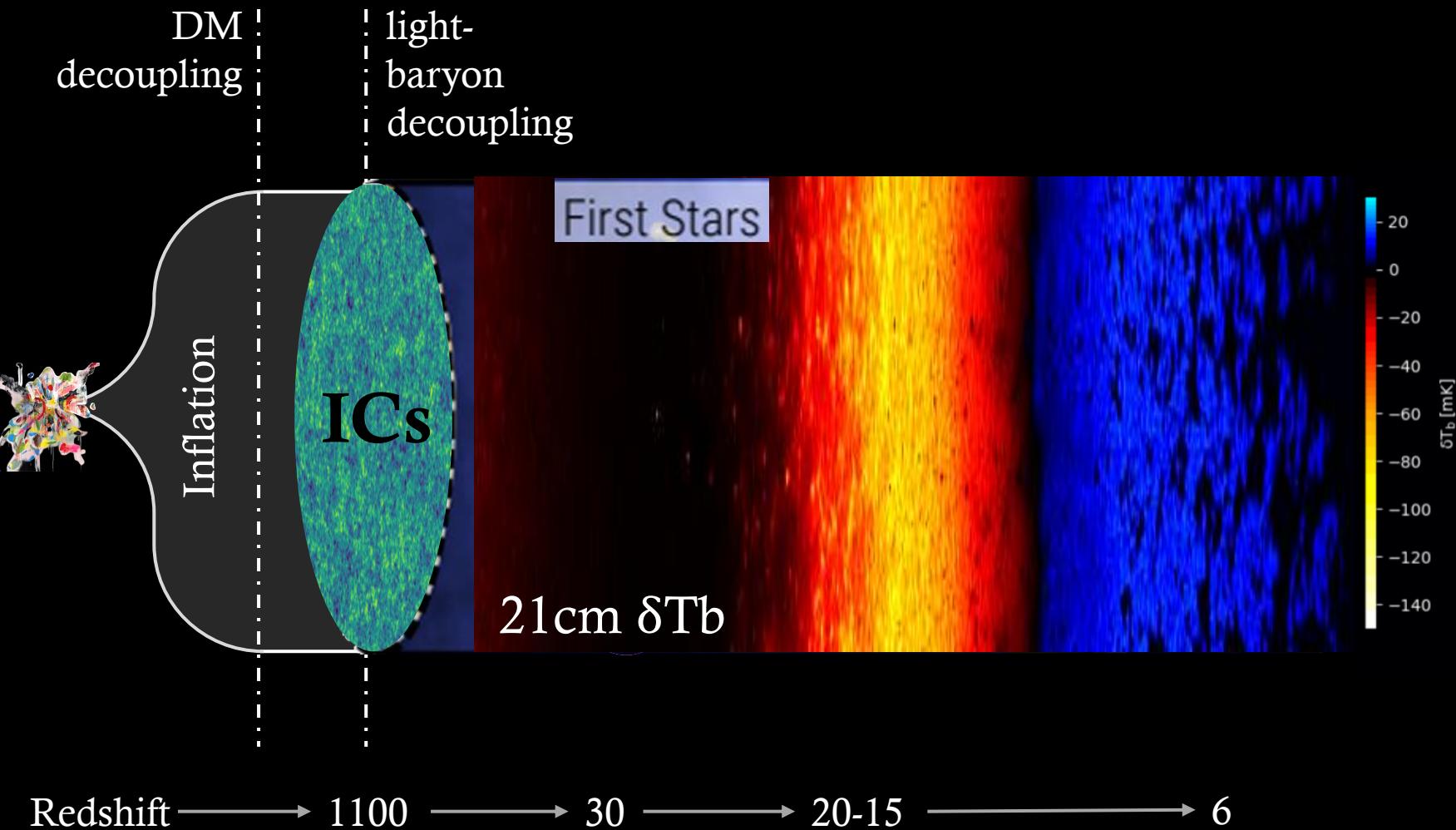
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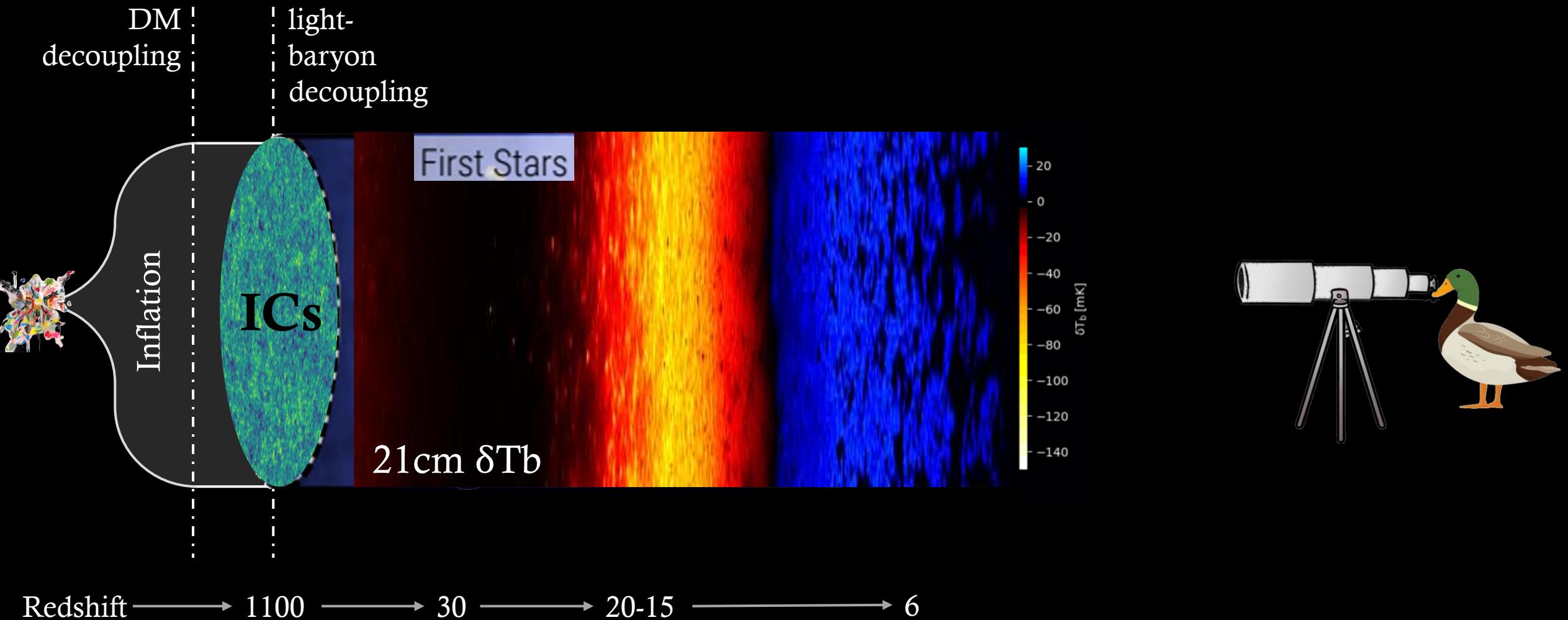
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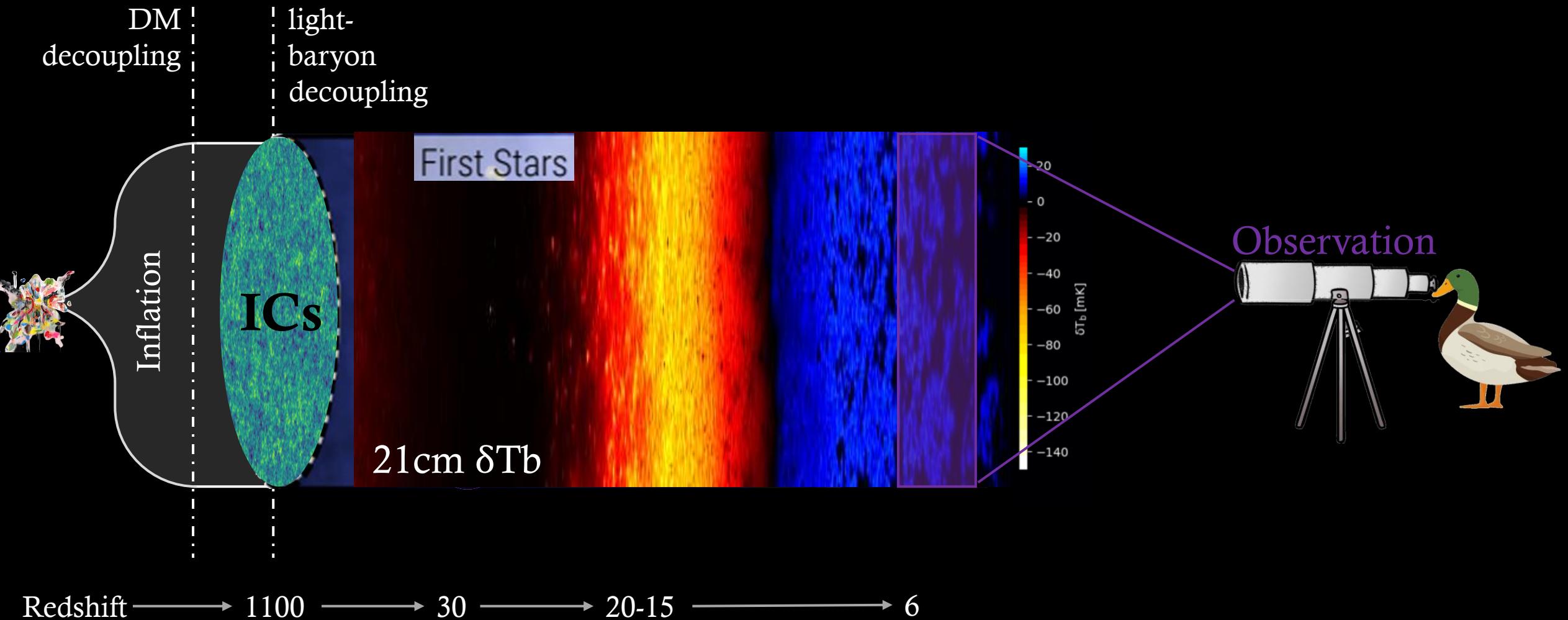
Cosmic 21-cm



Cosmic 21-cm



Cosmic 21-cm



Aims

Aims

We want to infer the physics of all these processes

Observables







Cosmic 21-cm



Cosmic 21-cm



SKA



Cosmic 21-cm



Cosmic 21-cm

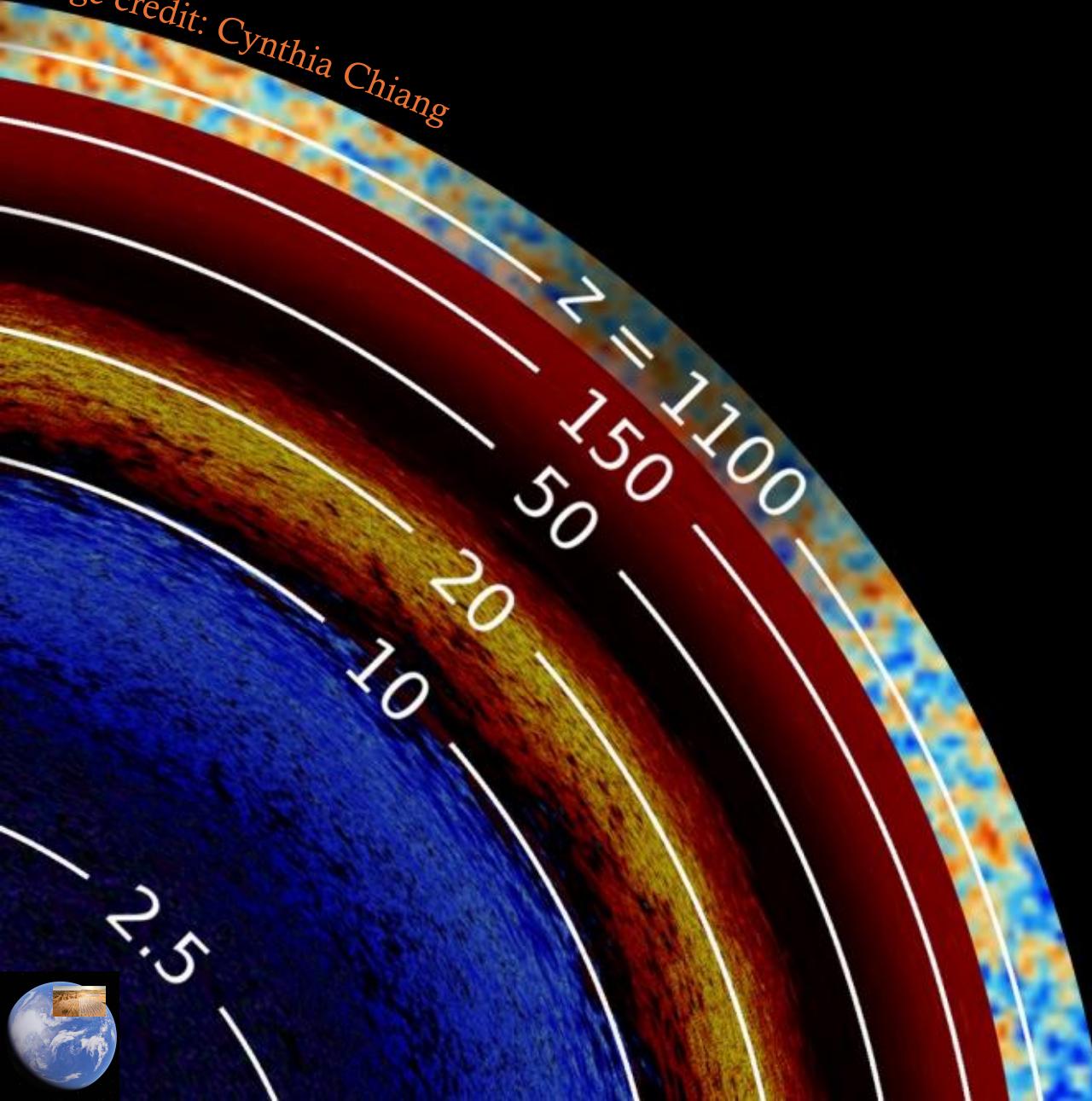


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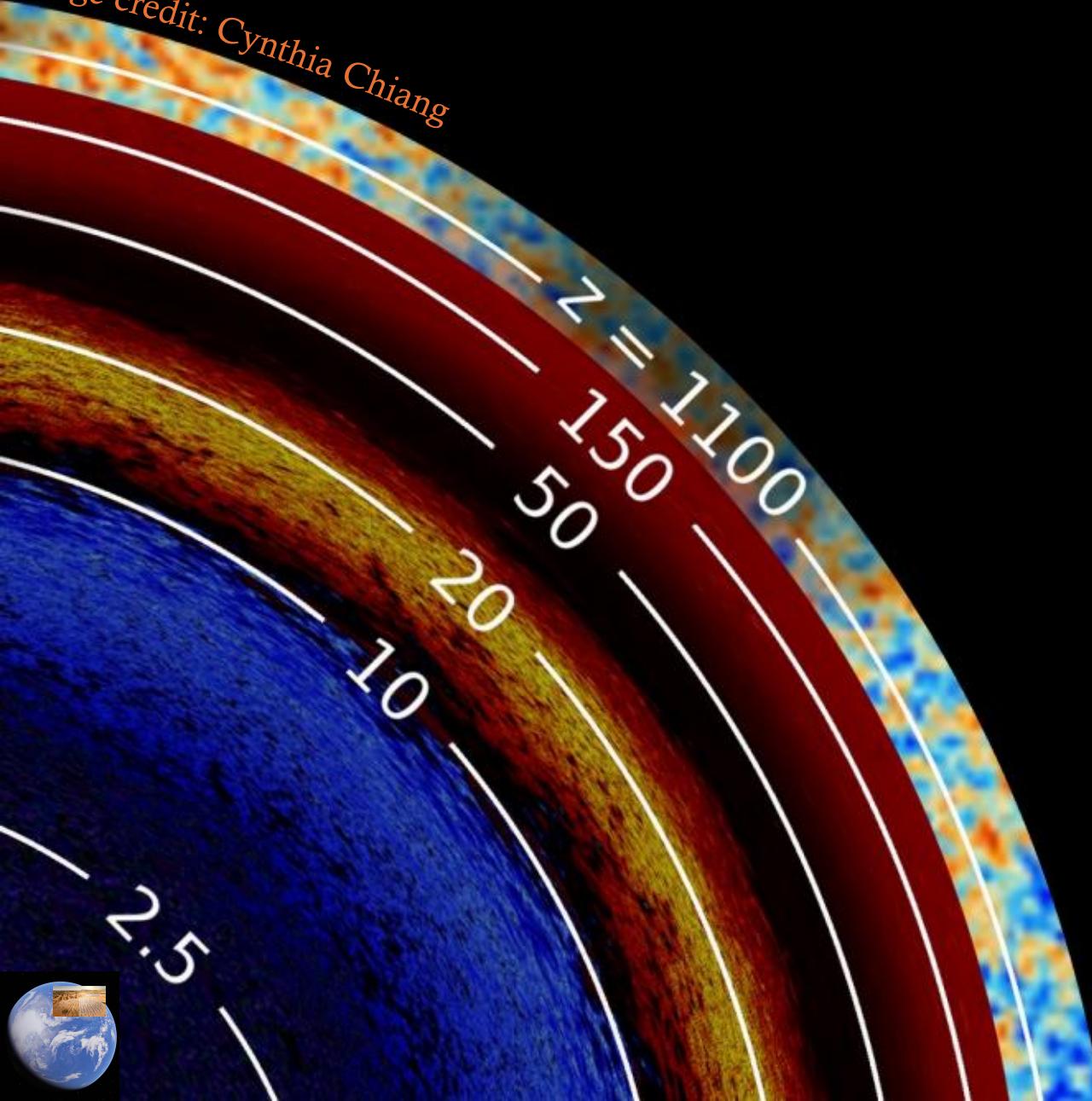
Cosmic 21-cm

image credit: Cynthia Chiang



Cosmic 21-cm

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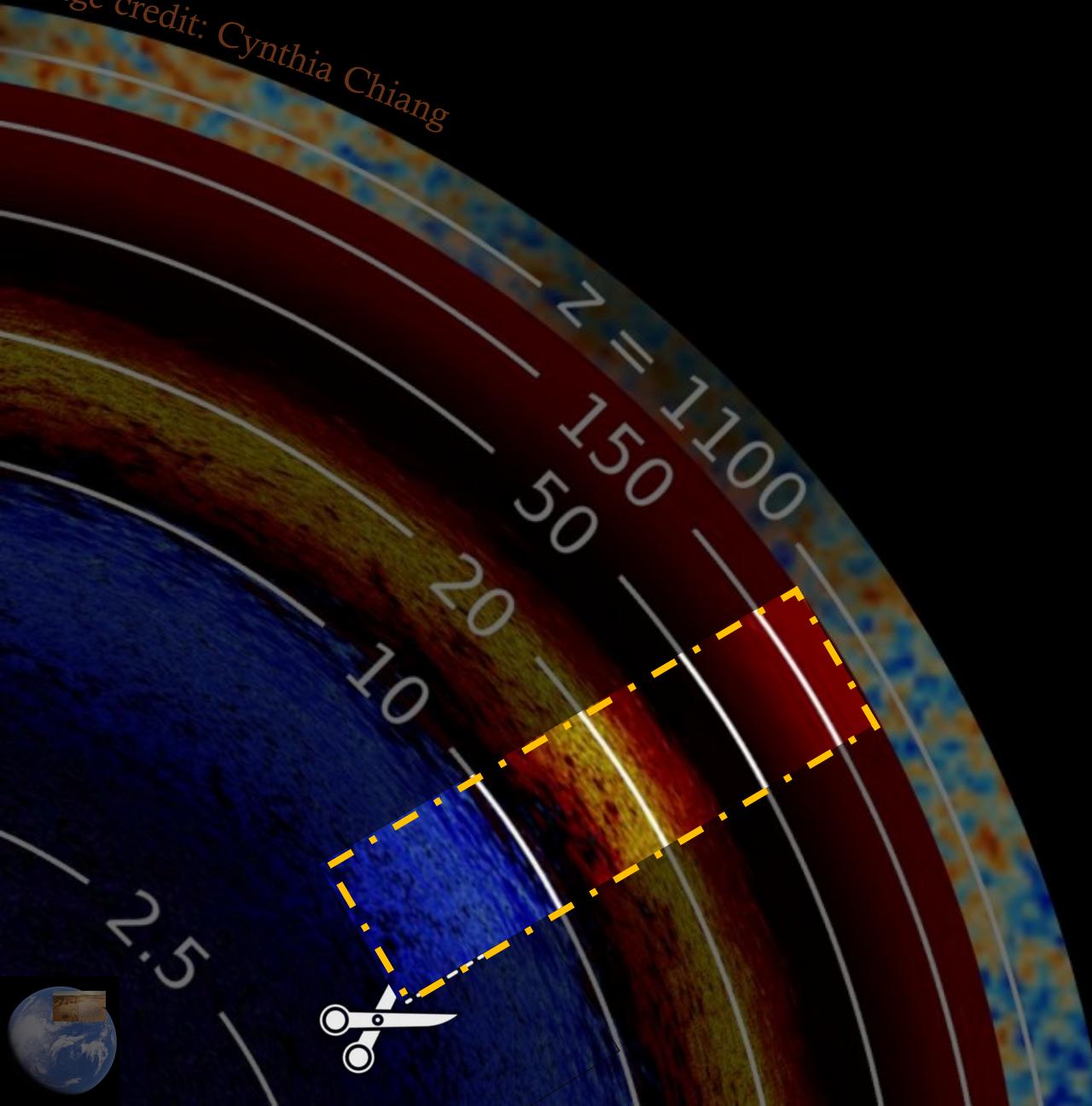


The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than **1/2 of our observable Universe**

Cosmic 21-cm

image credit: Cynthia Chiang

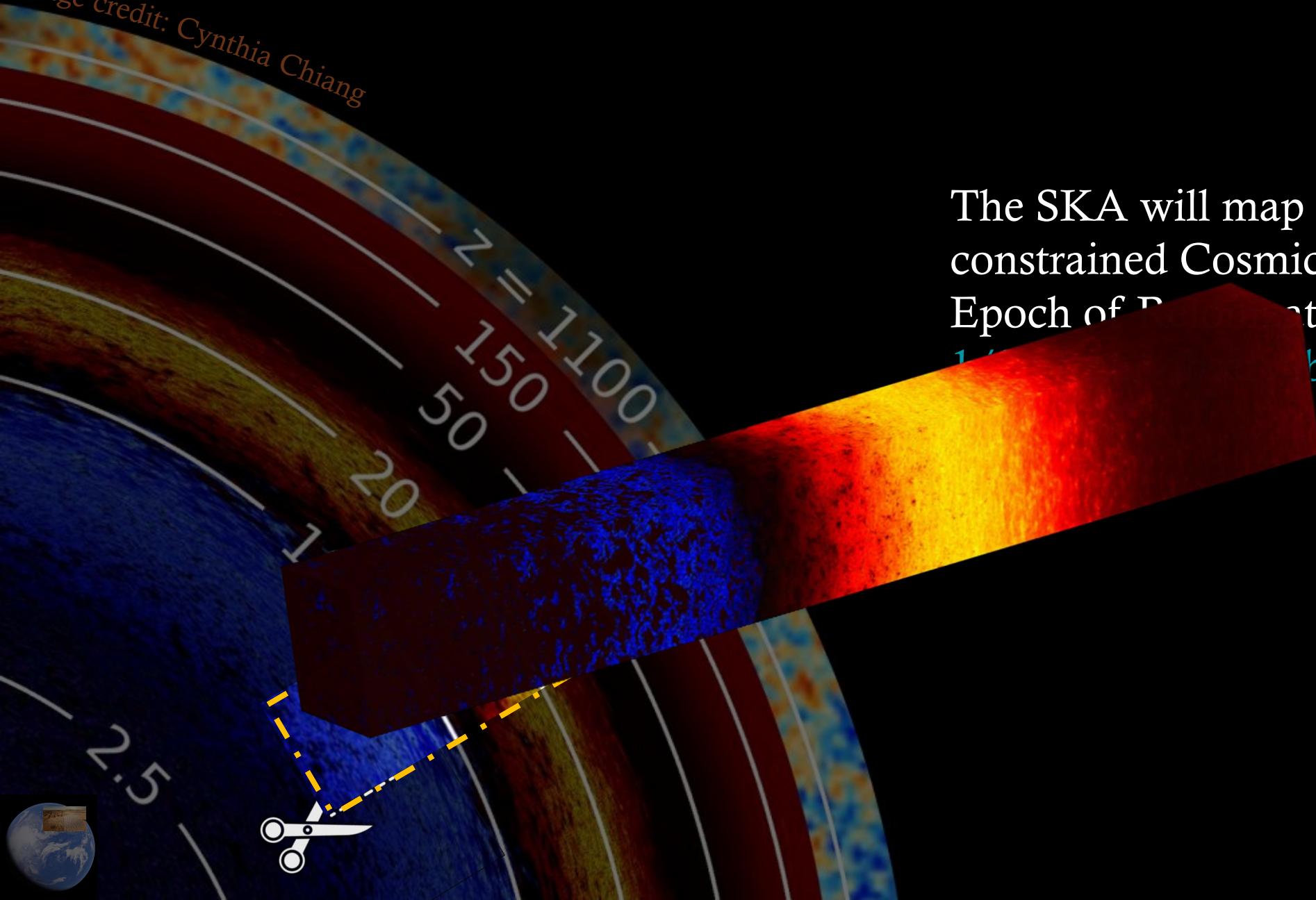
The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than 1/2 of our observable Universe



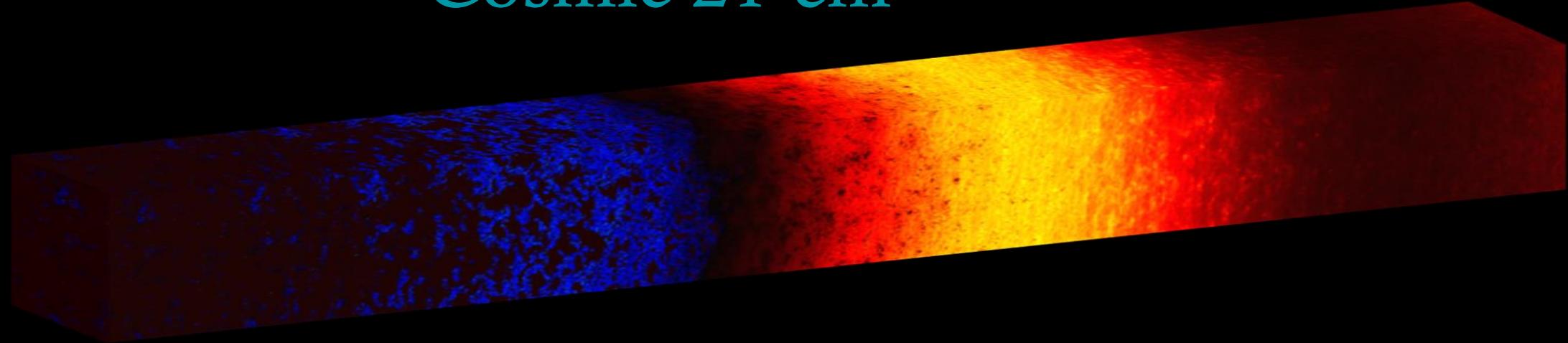
Cosmic 21-cm

image credit: Cynthia Chiang

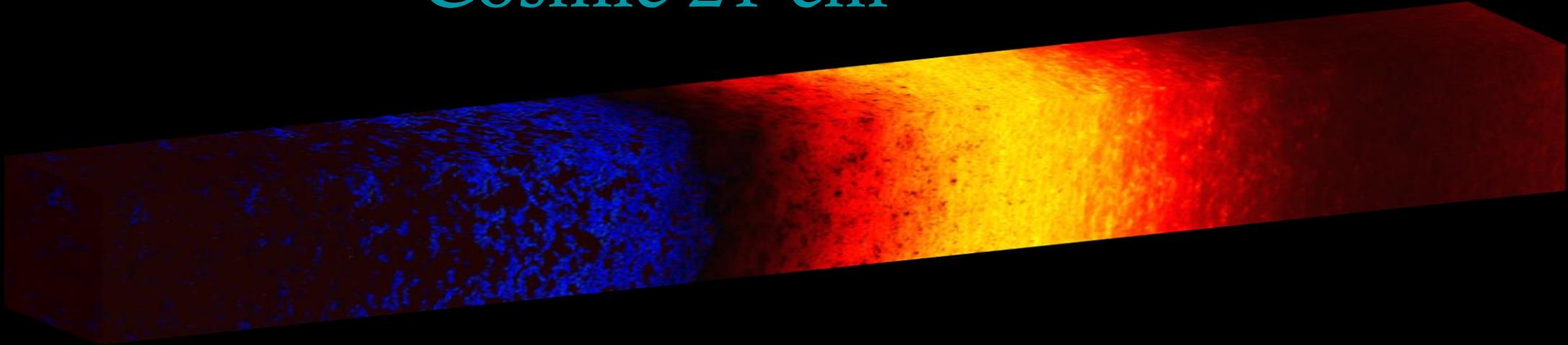
The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than $1/6$ of the observable Universe



Cosmic 21-cm



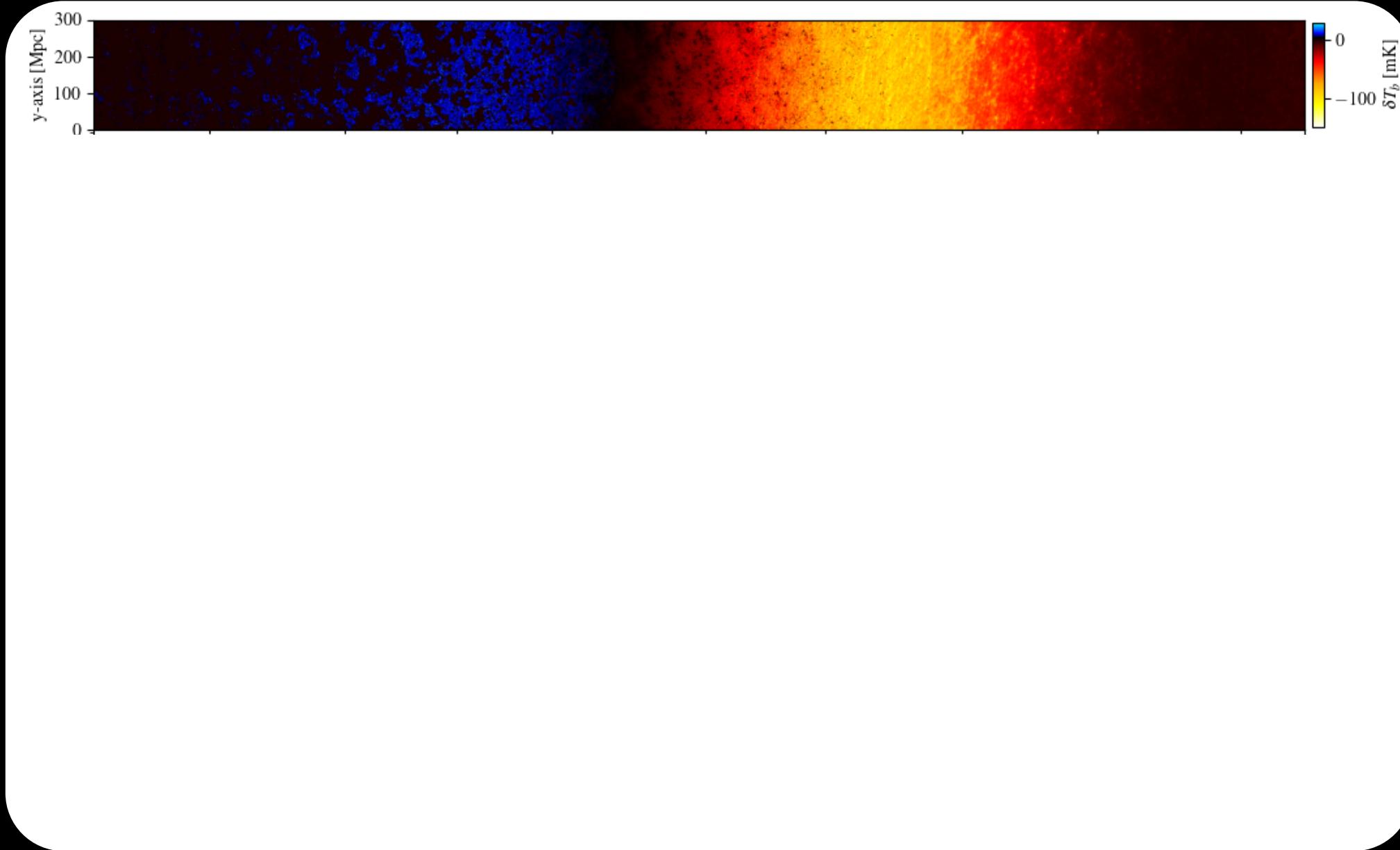
Cosmic 21-cm



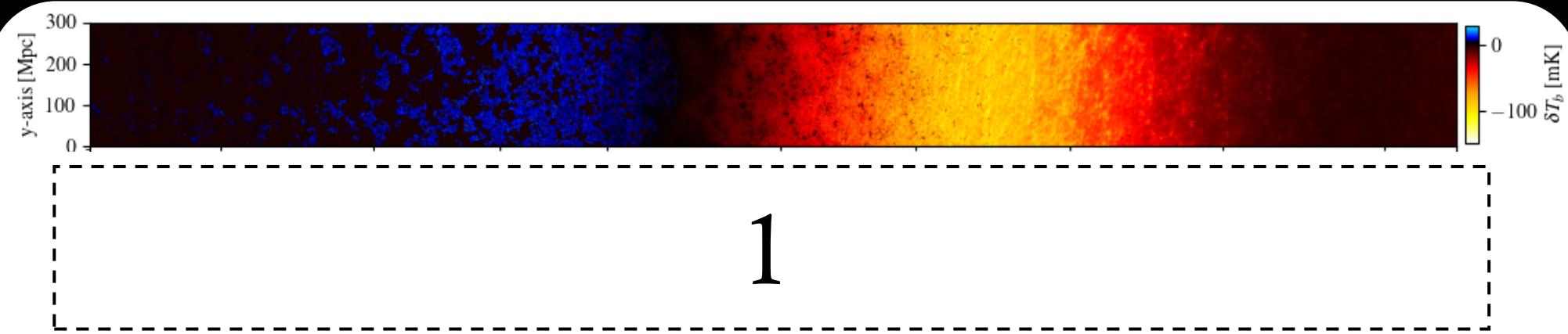
Card of Observables



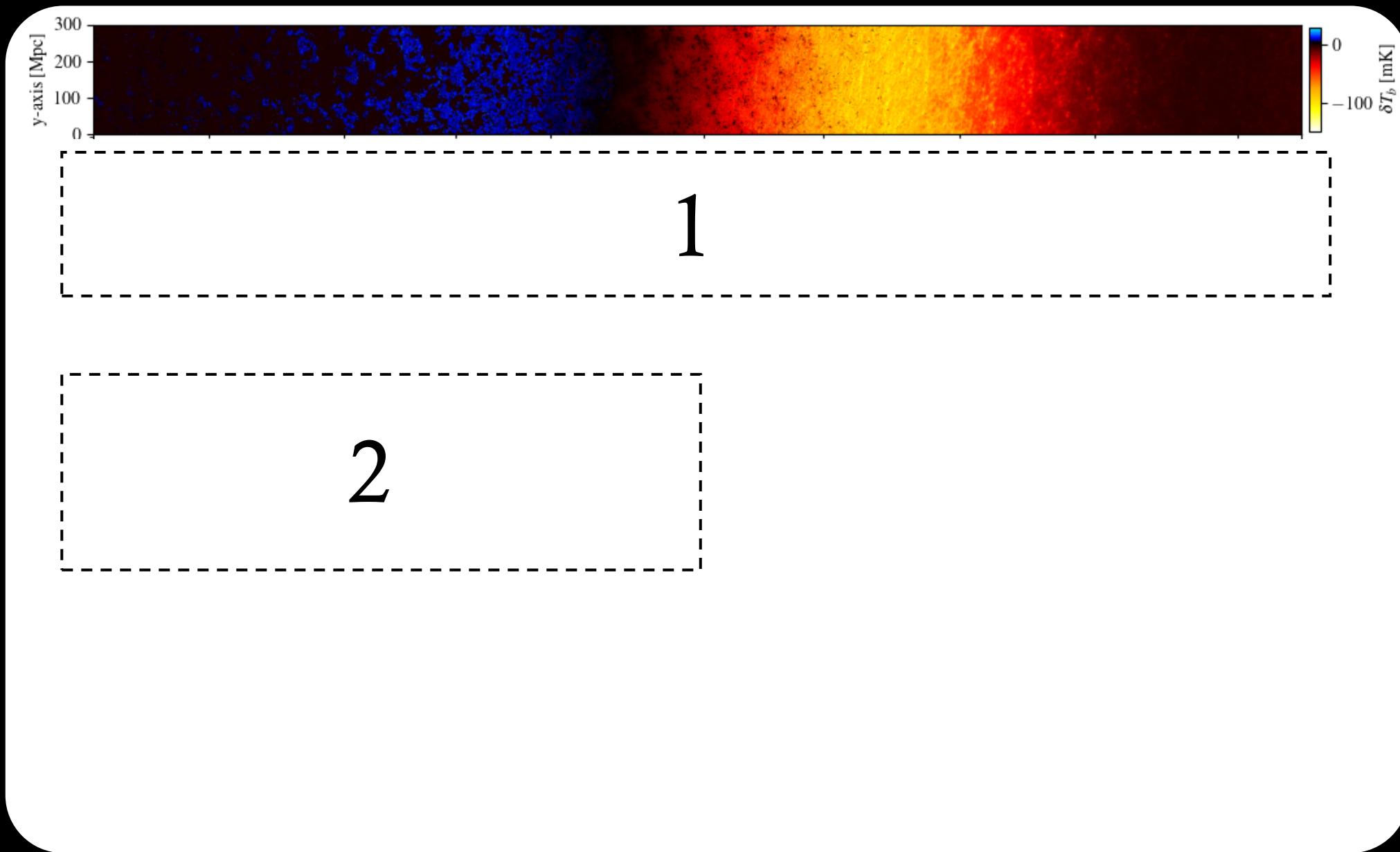
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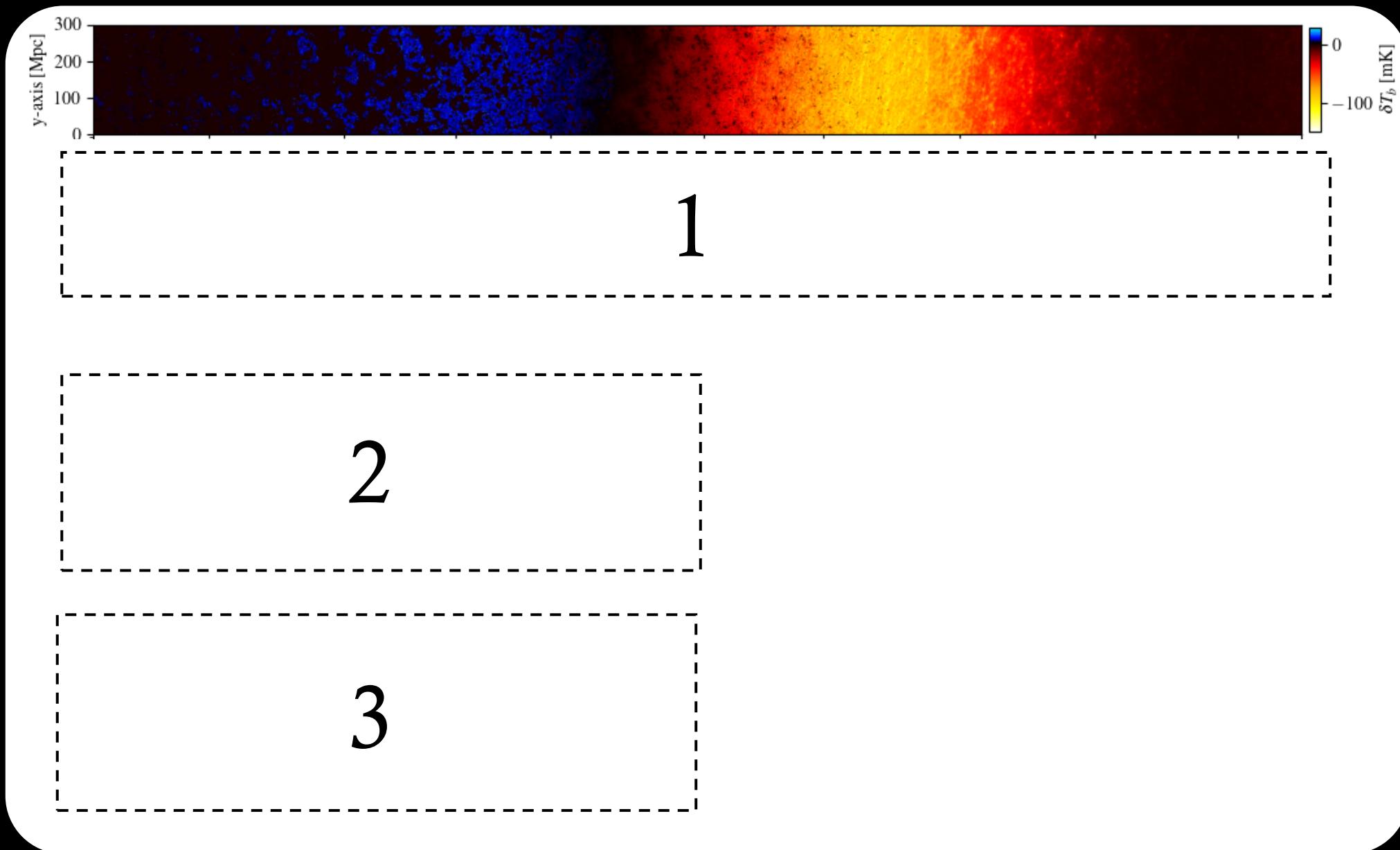
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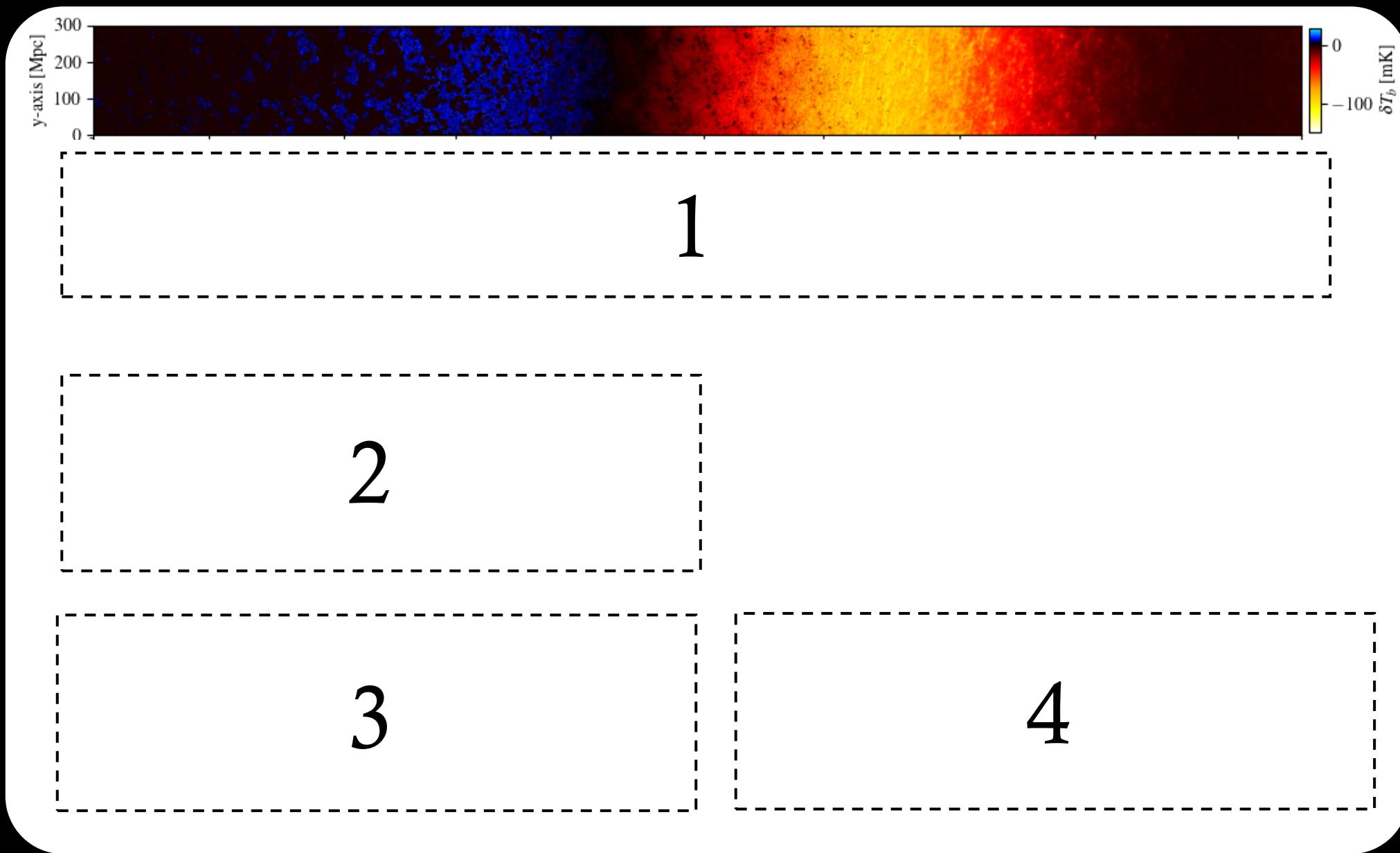
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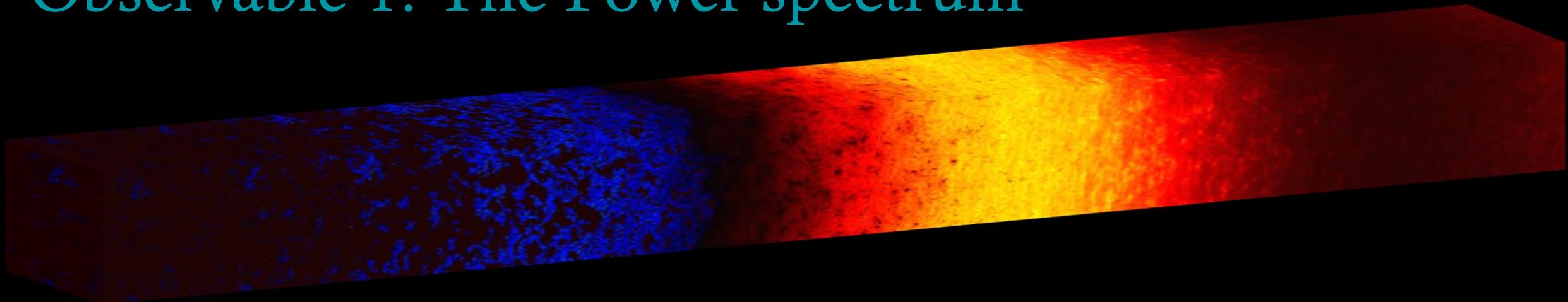
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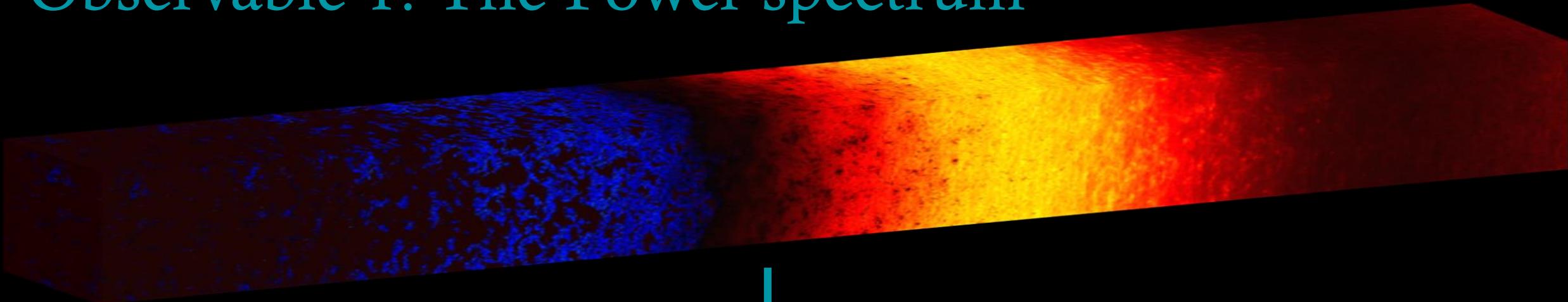
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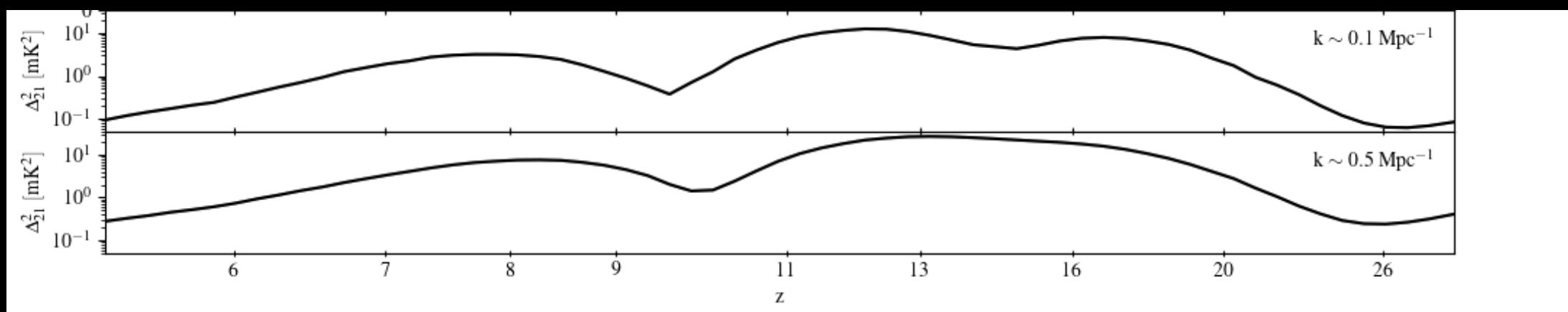
Observable 1: The Power spectrum



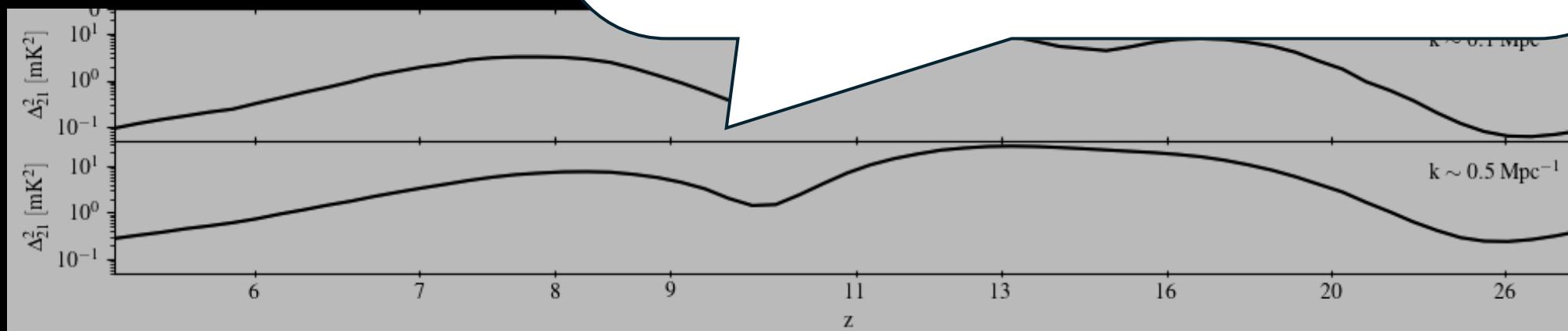
Observable 1: The Power spectrum



Contains info about
galaxy effect on IGM

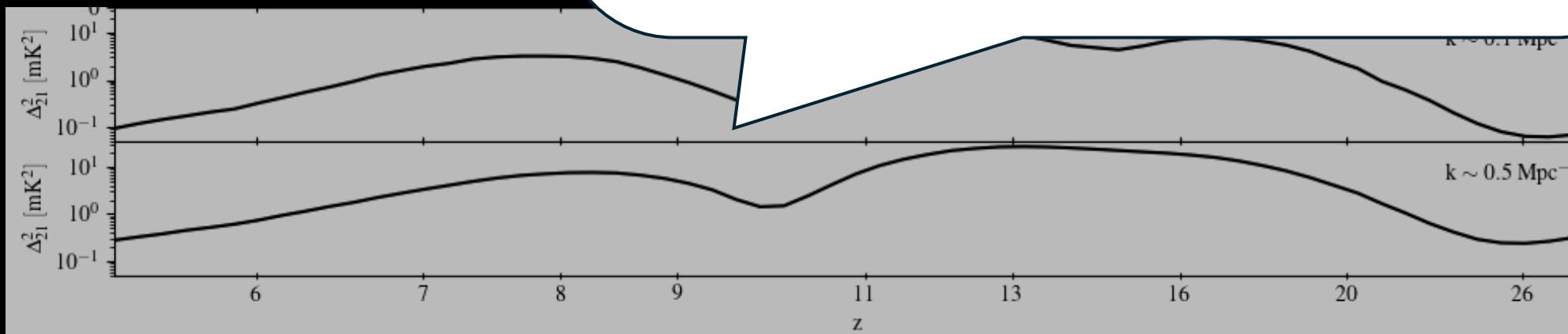


Observable 1: The Power spectrum



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E.g.

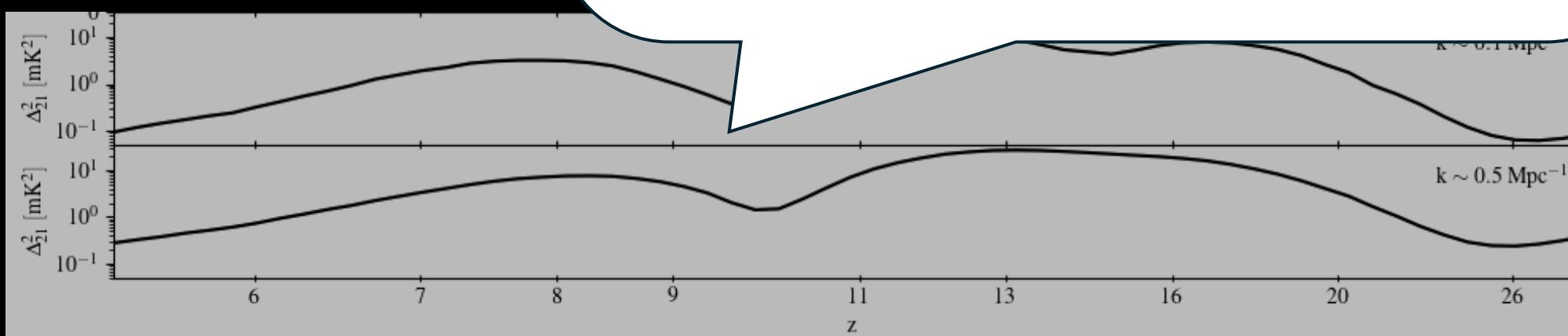


Observable 1: The Power spectrum

E.g.



HERA



Observable 1: The Power spectrum

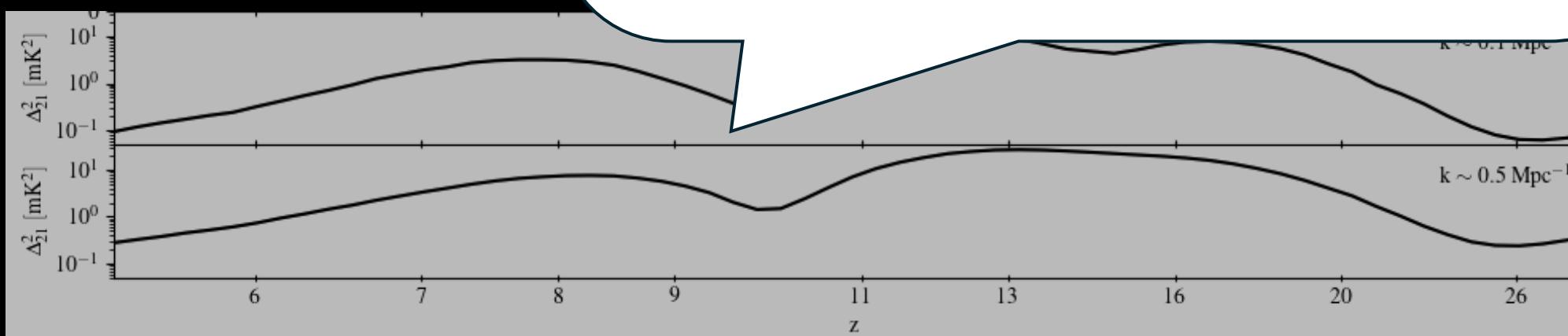
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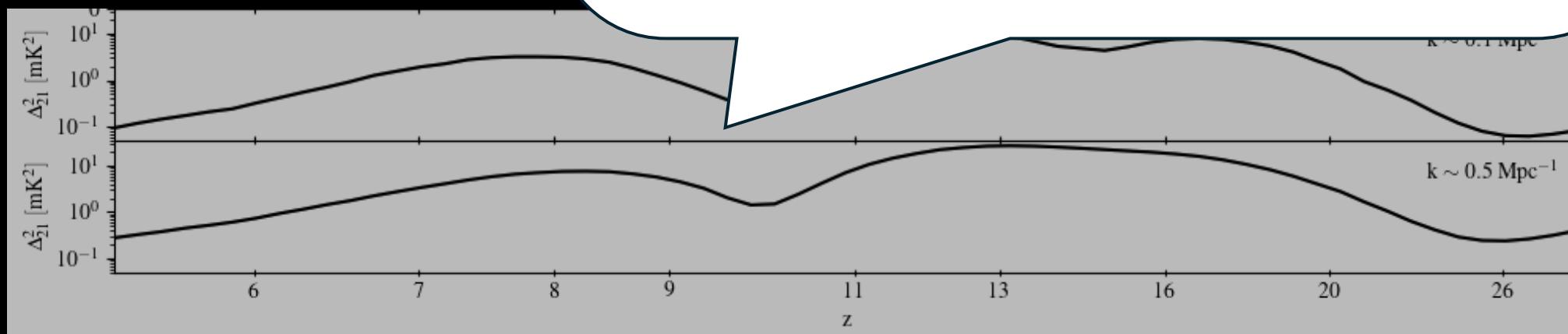
HERA



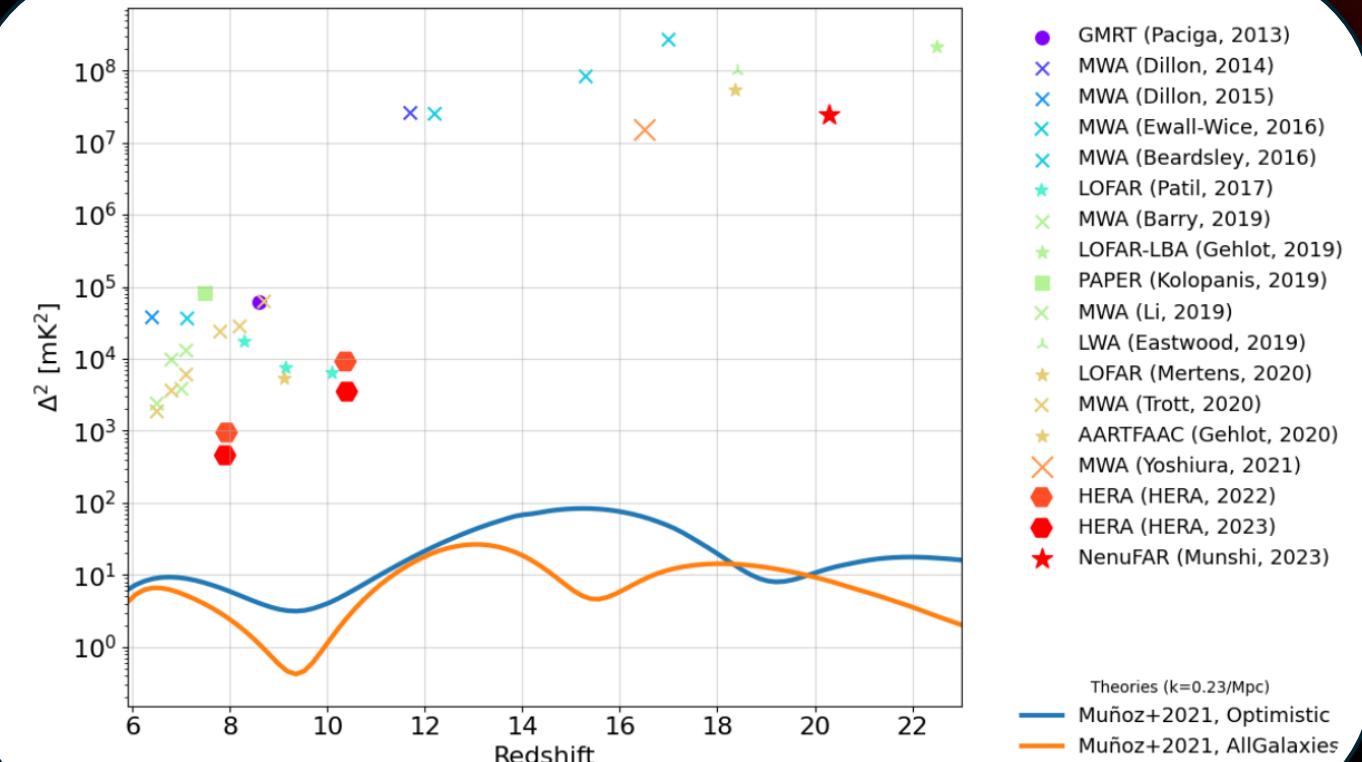
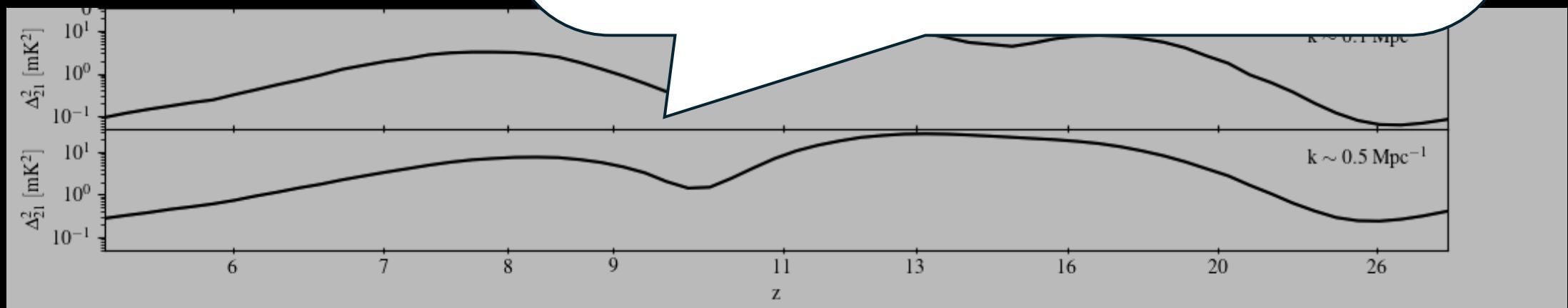
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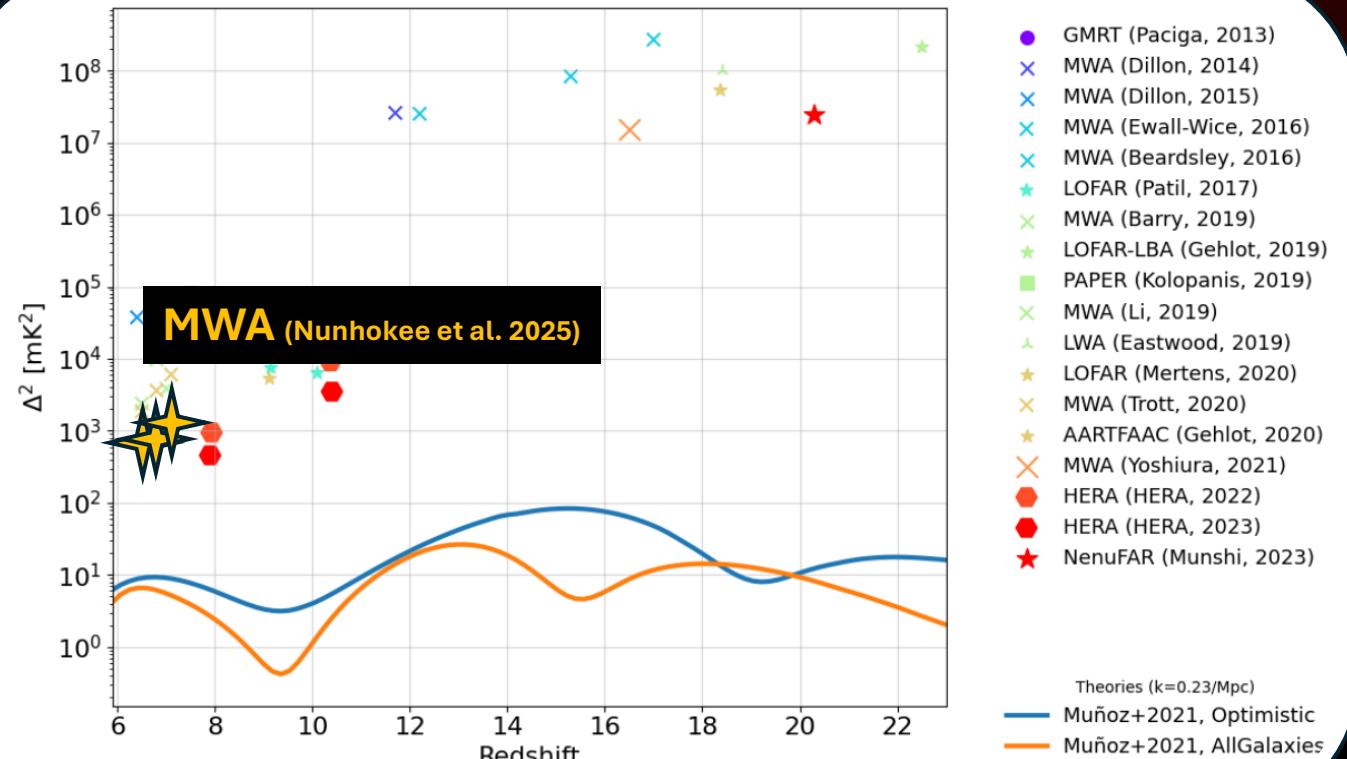
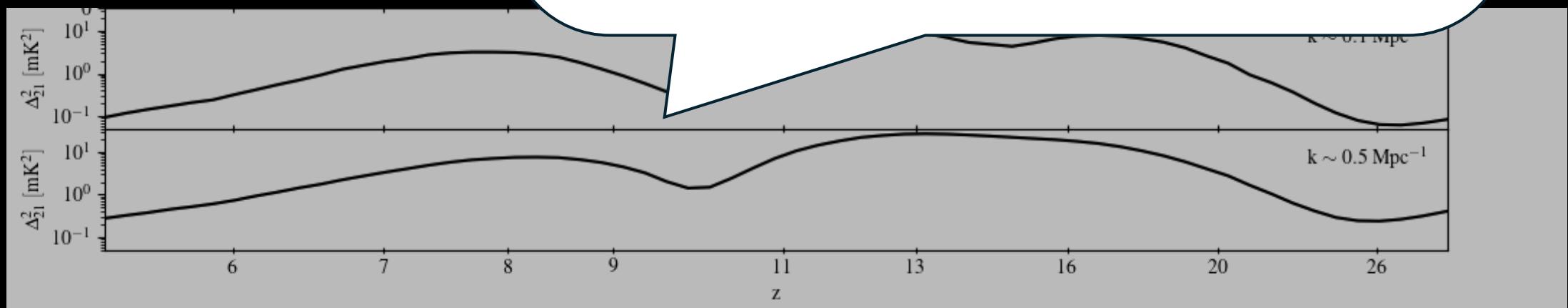
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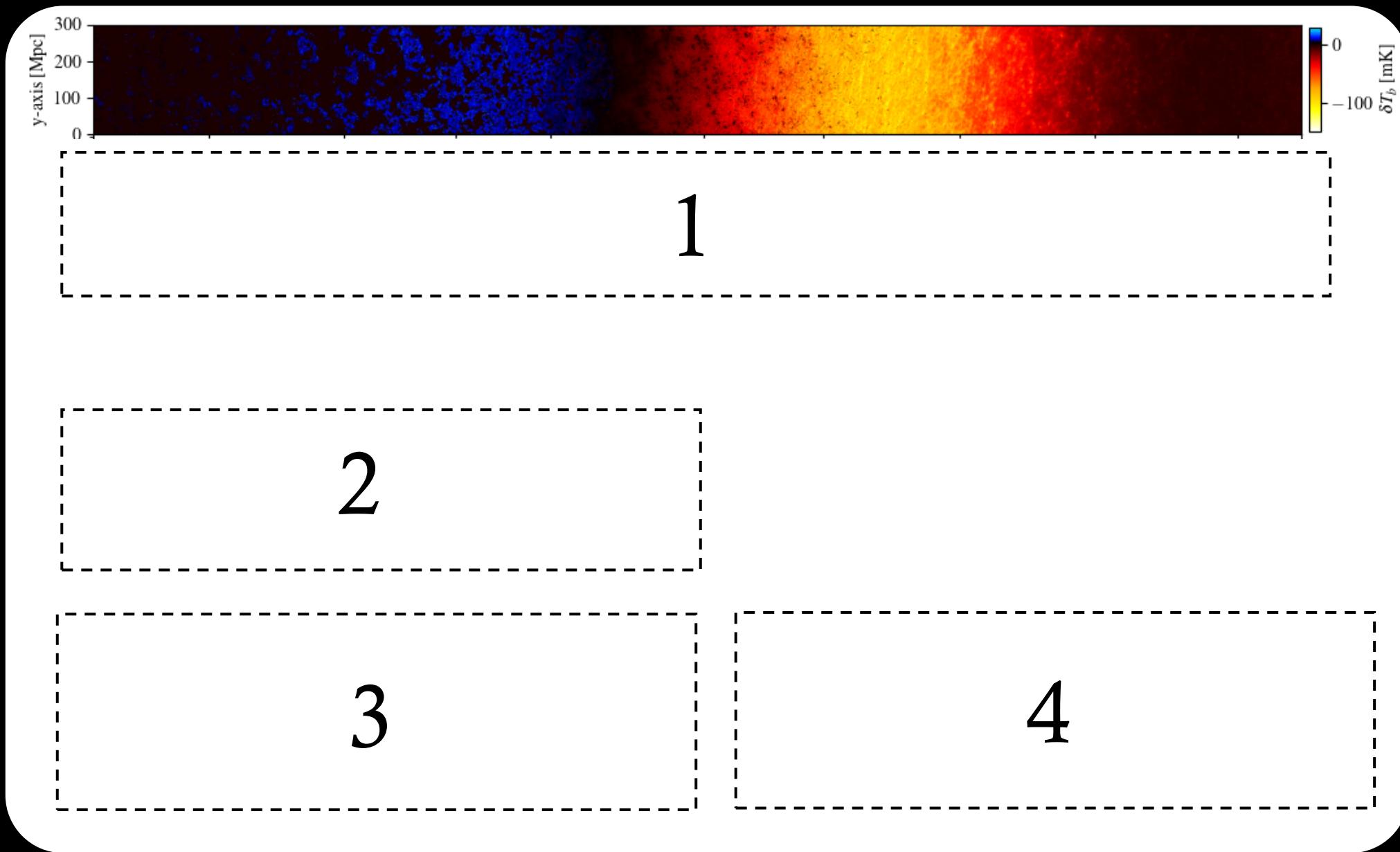
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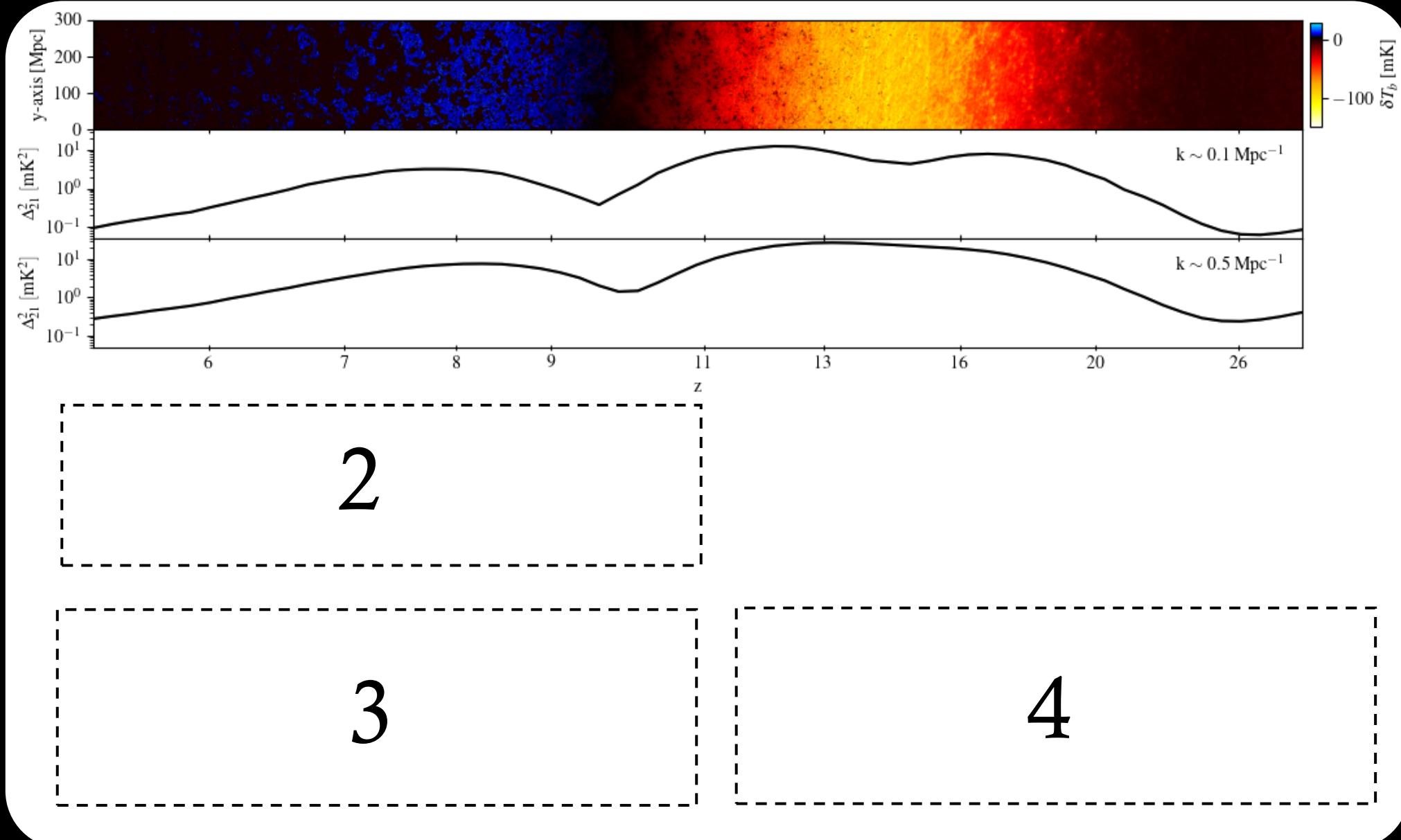
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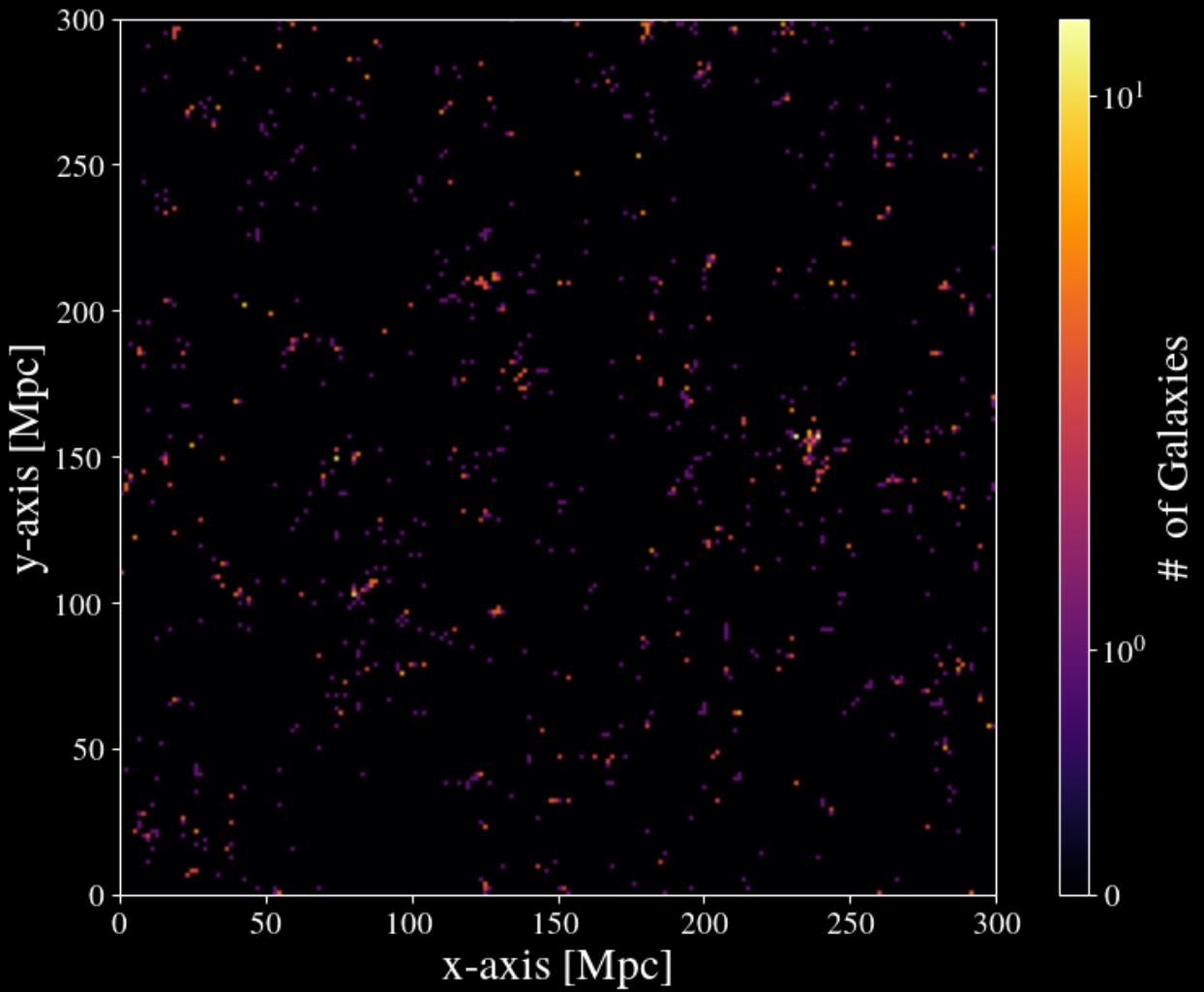
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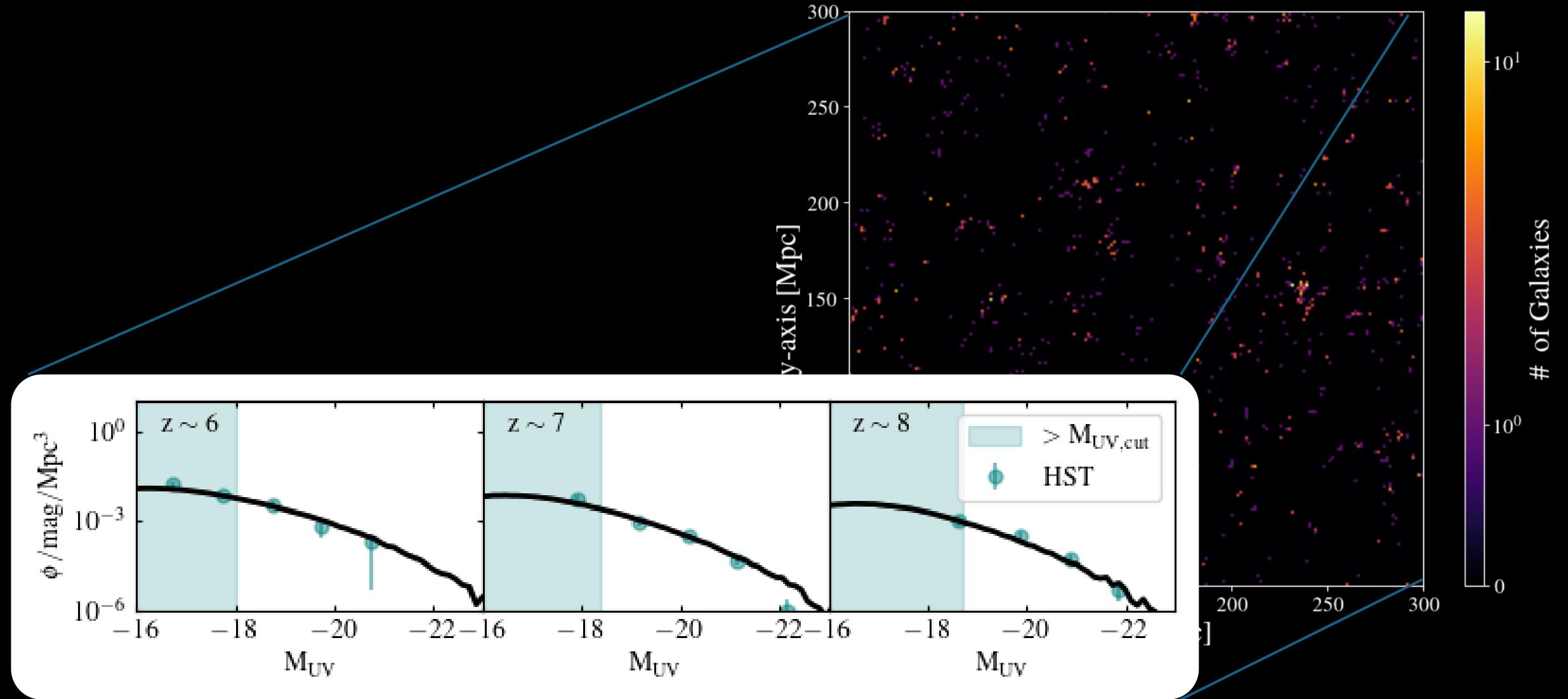
Card of Observables



Observable 2: UV Luminosity function

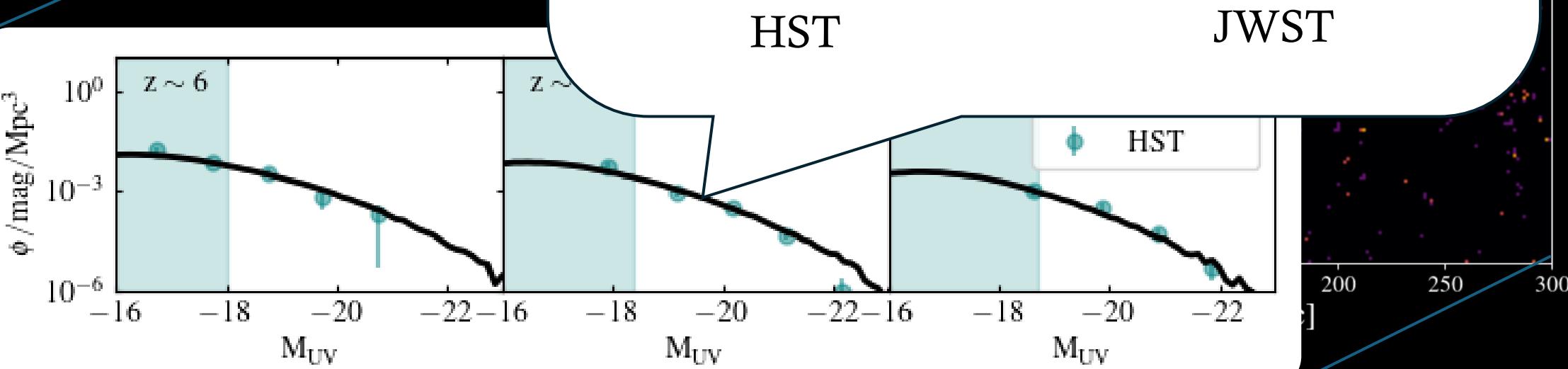
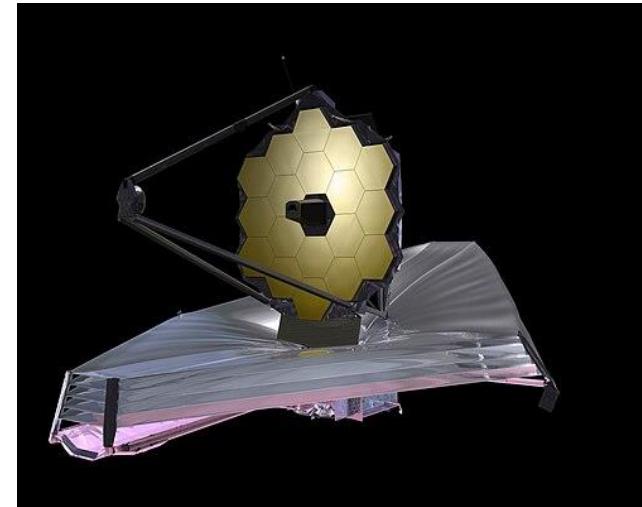
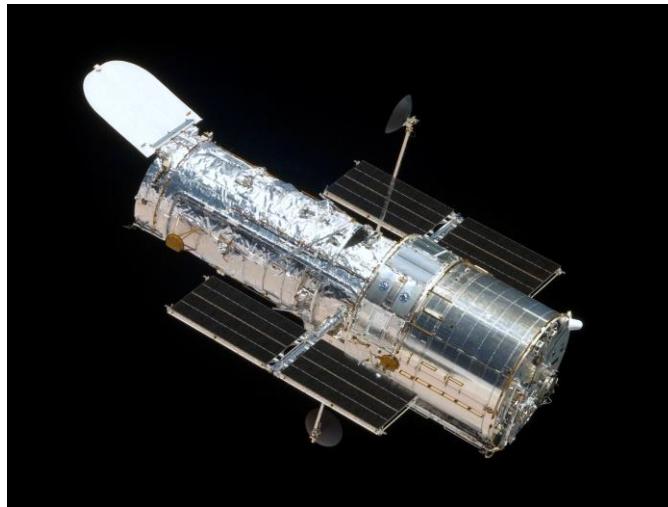


Observable 2: UV Luminosity function



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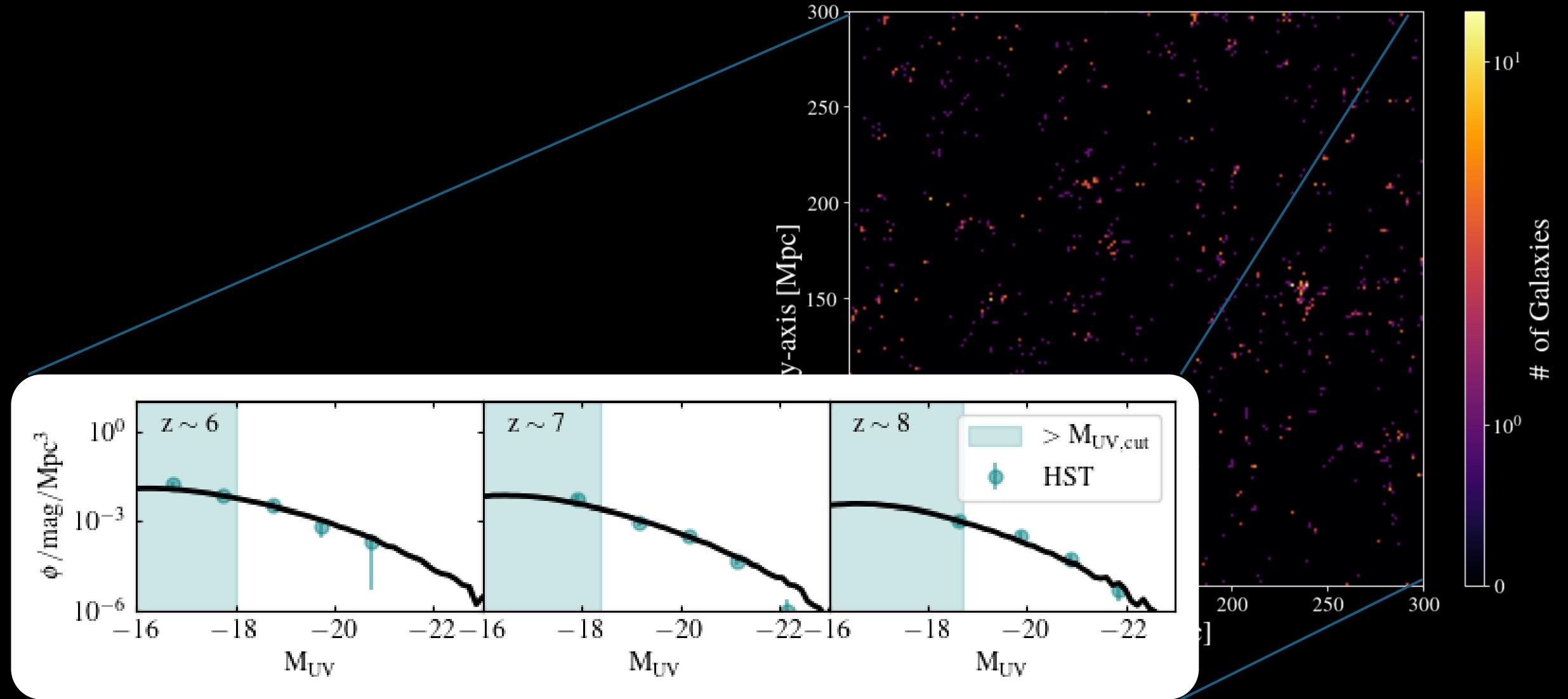
e.g.



of Galaxies

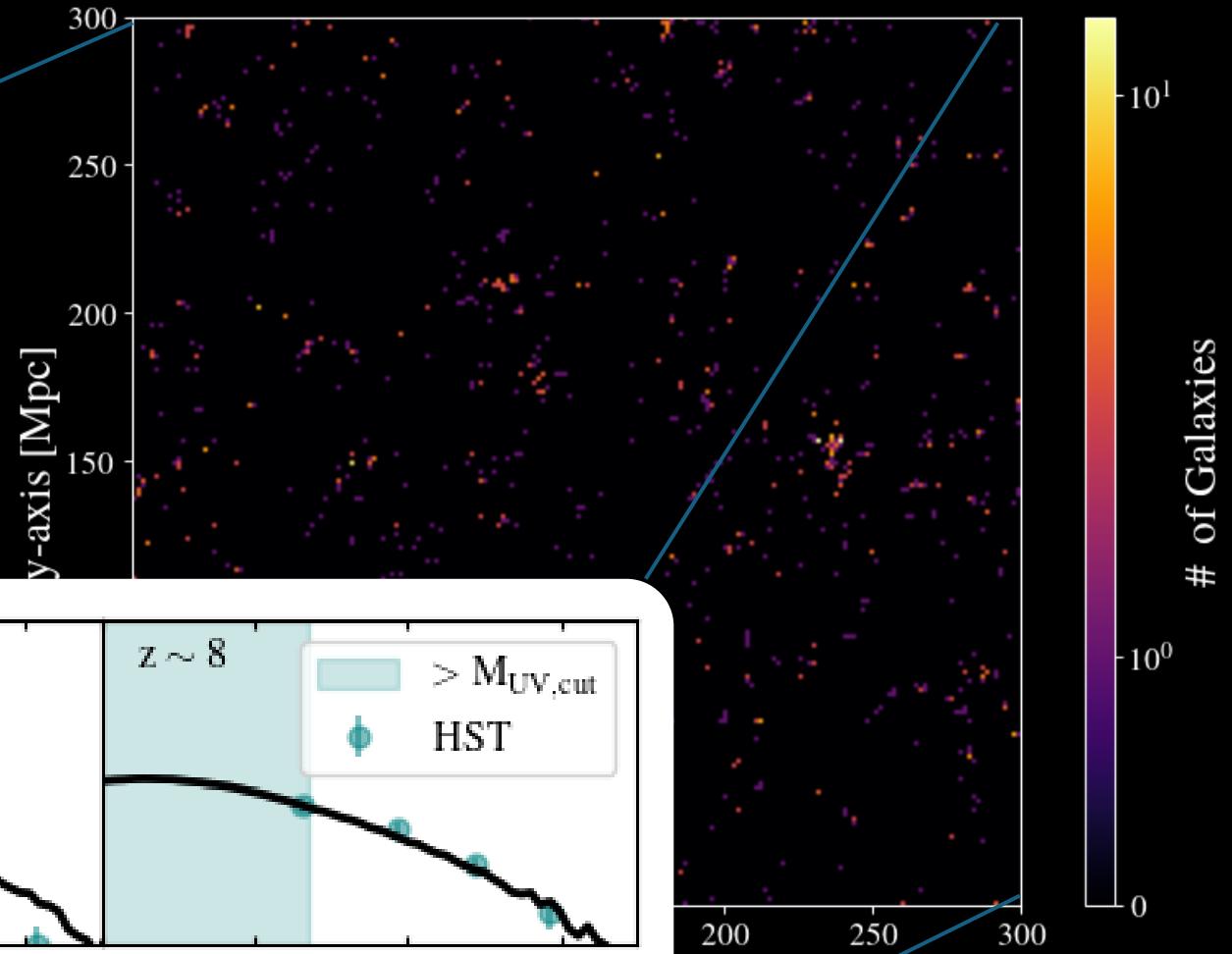
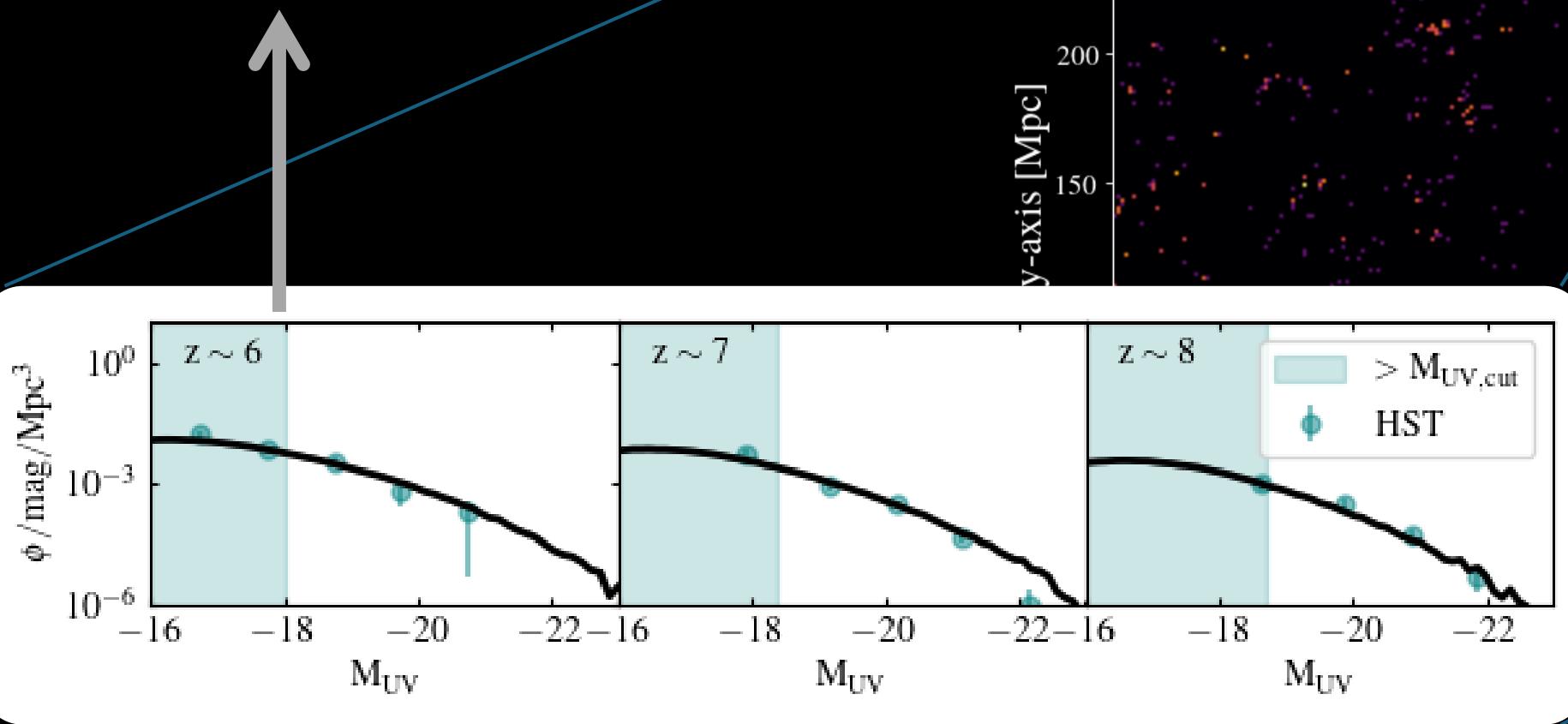
10^1
 10^0
0

Observable 2: UV Luminosity function

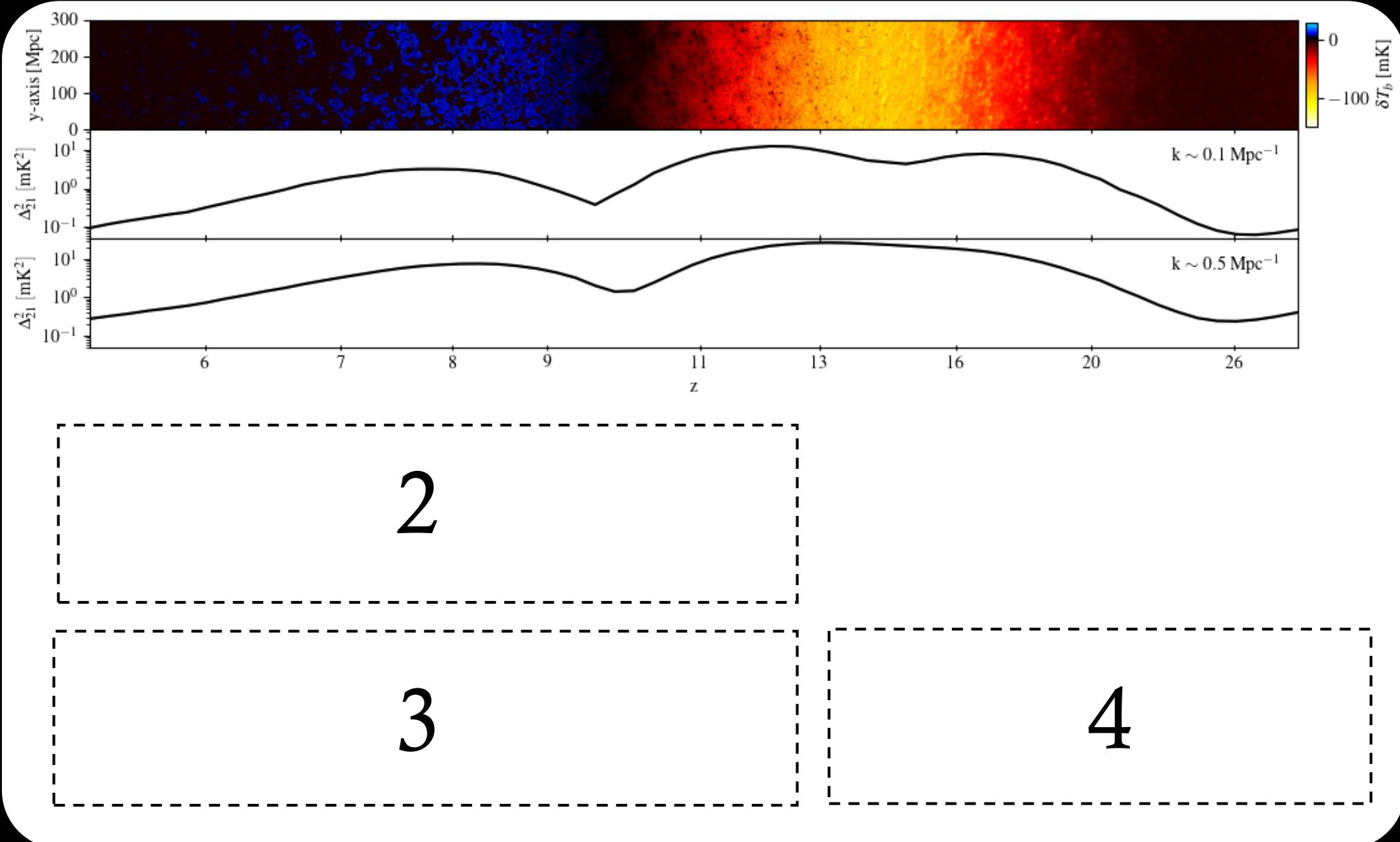


Observable 2: UV Luminosity function

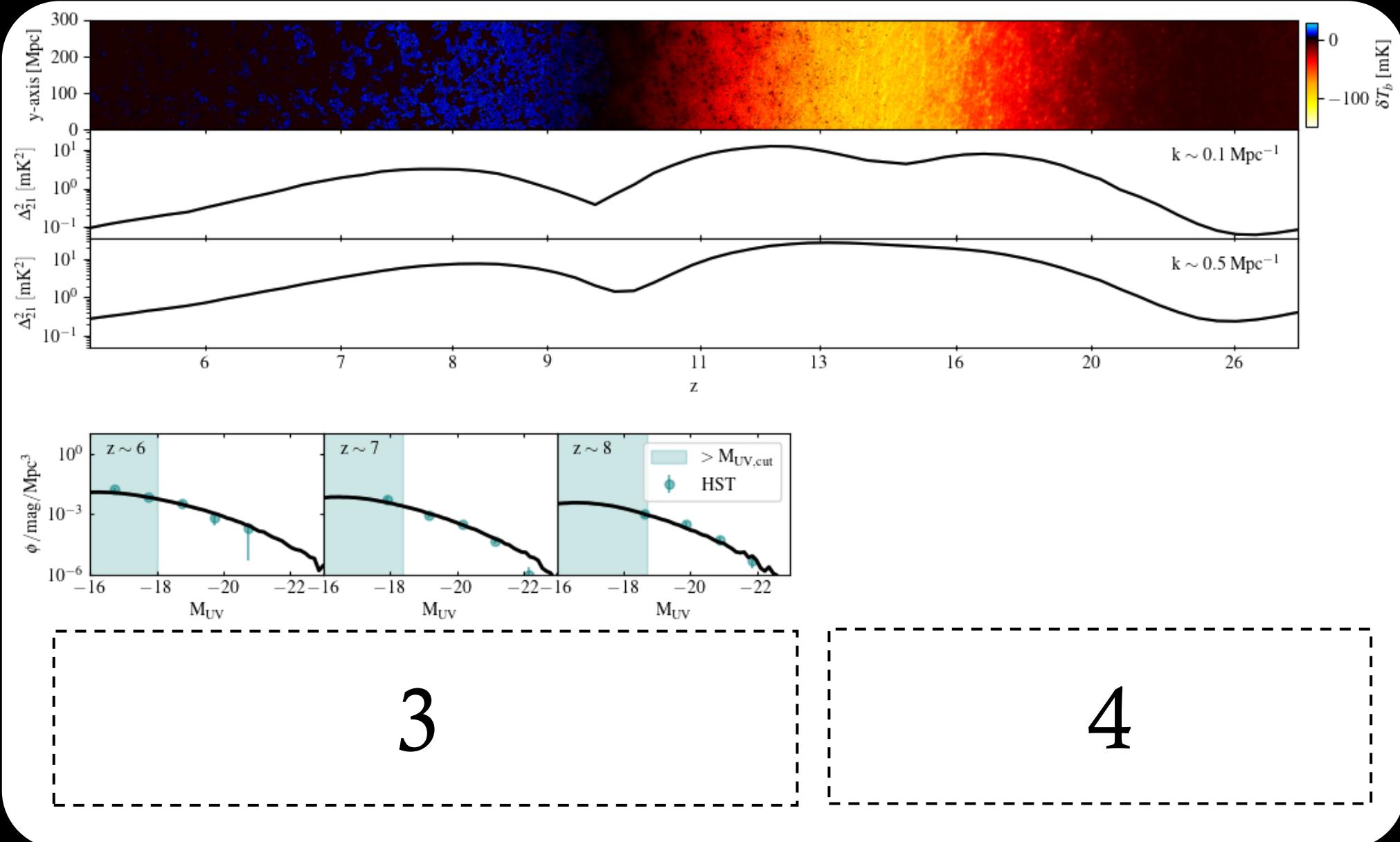
the completeness limit of UVLFs
from Umeda+2024



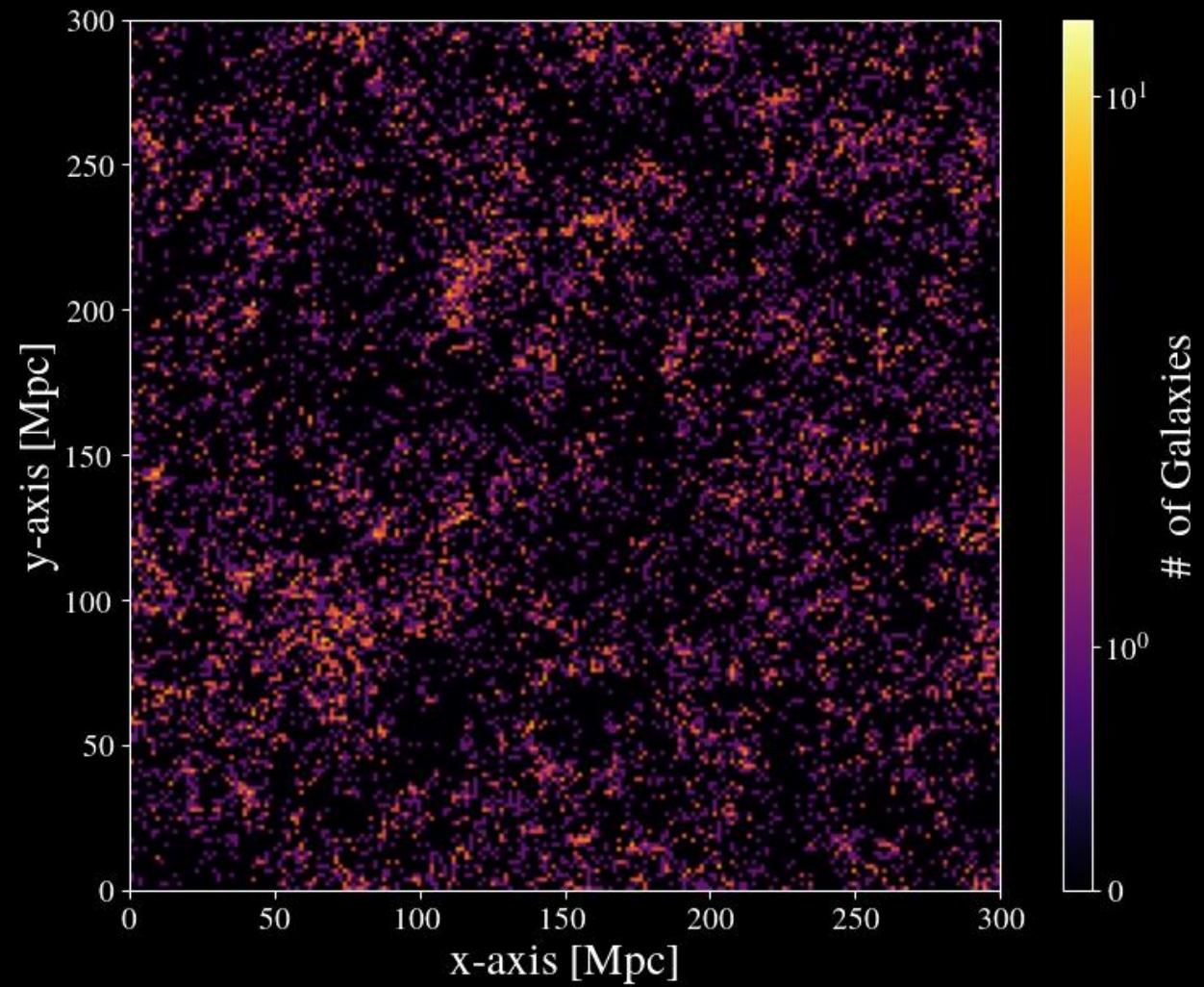
Card of Observables



Card of Observables

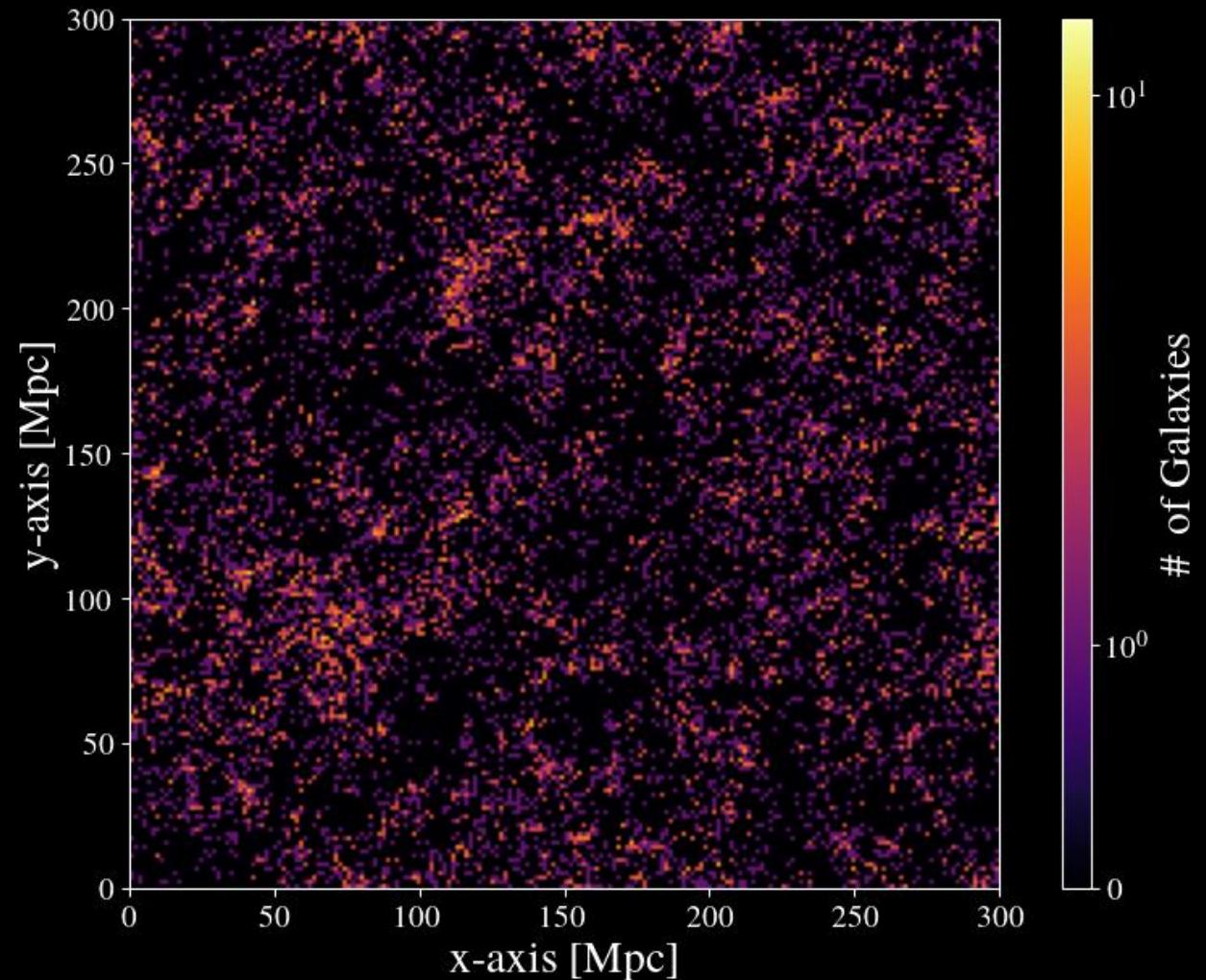
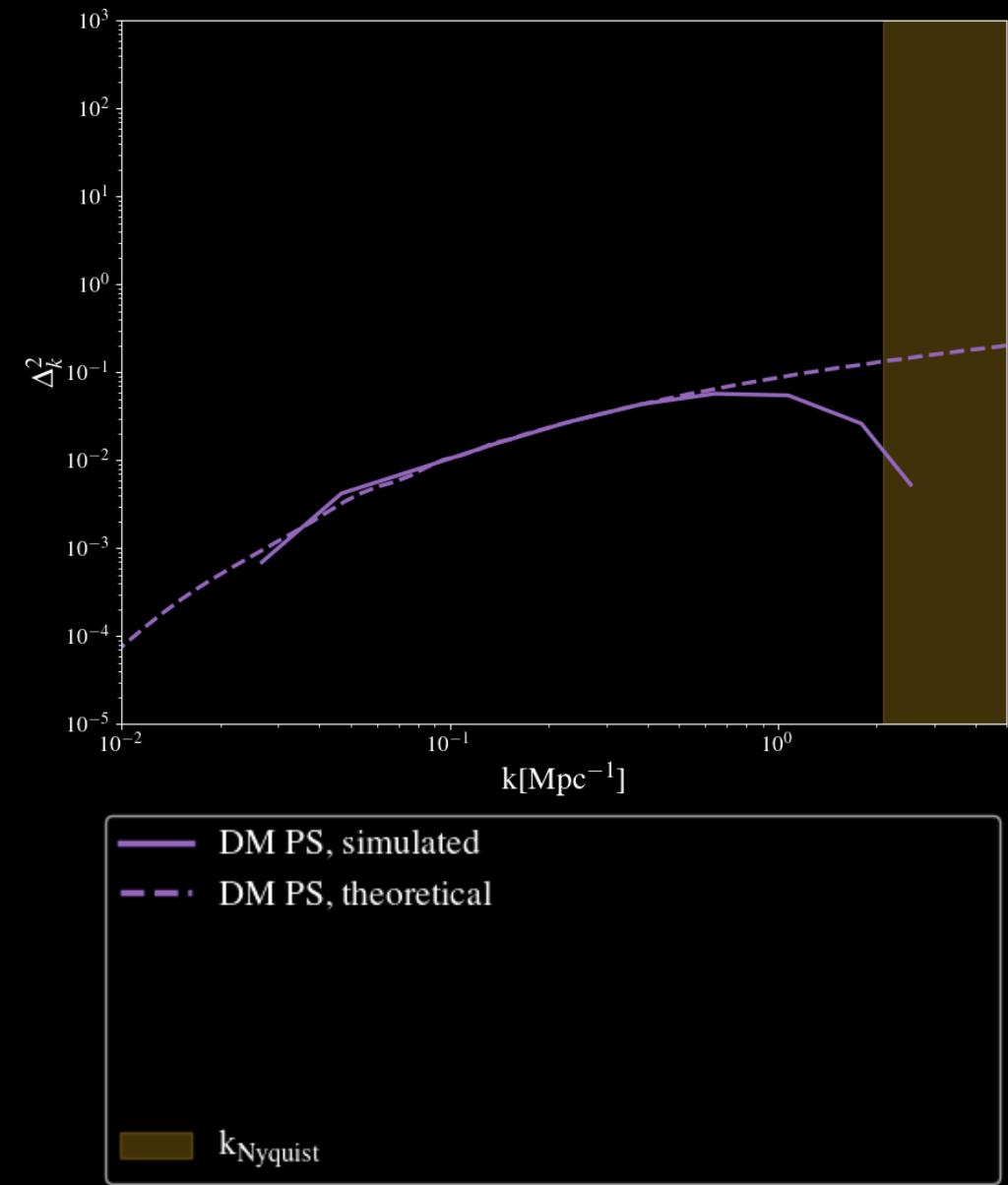


Observable 3: Galaxy Power Spectrum



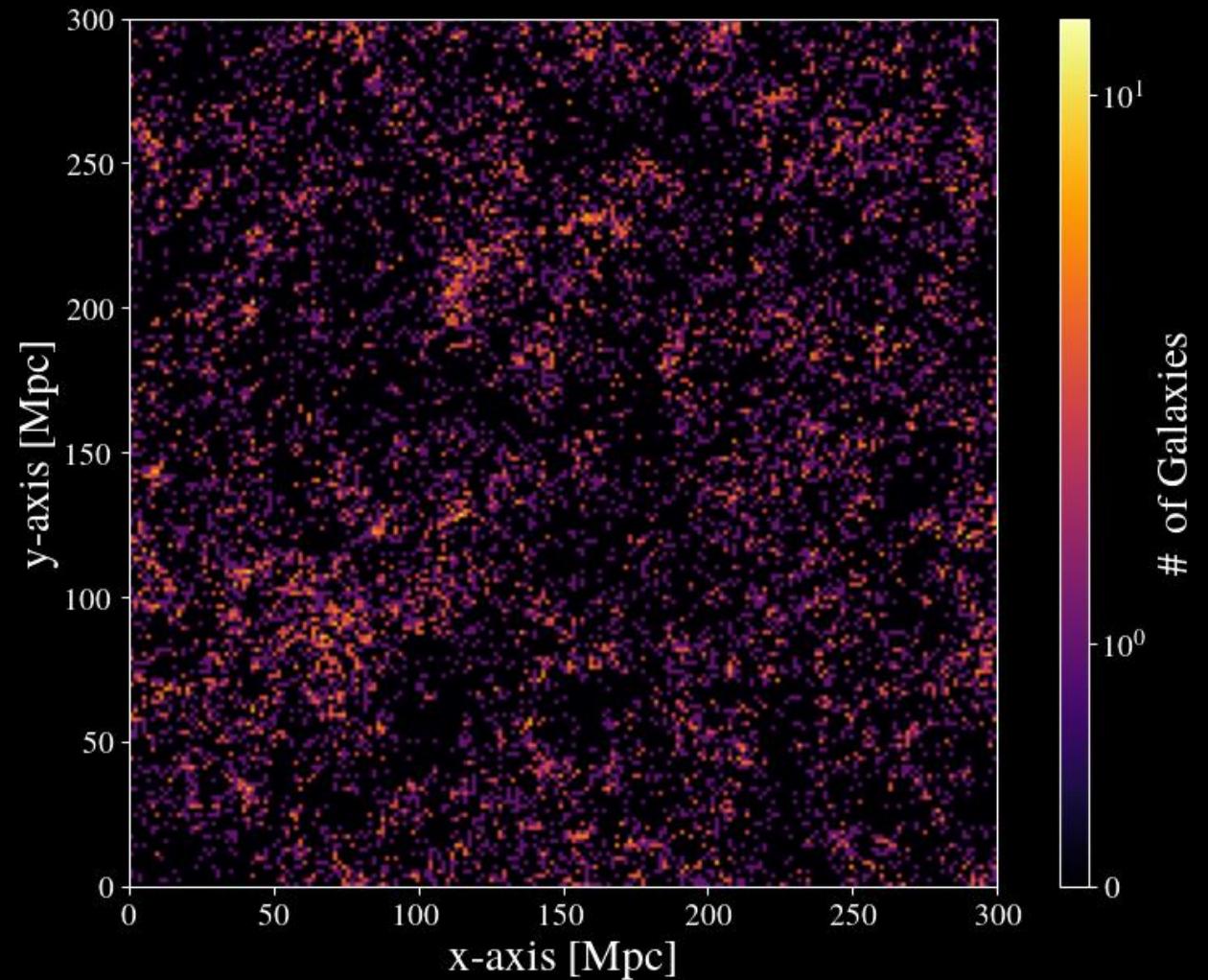
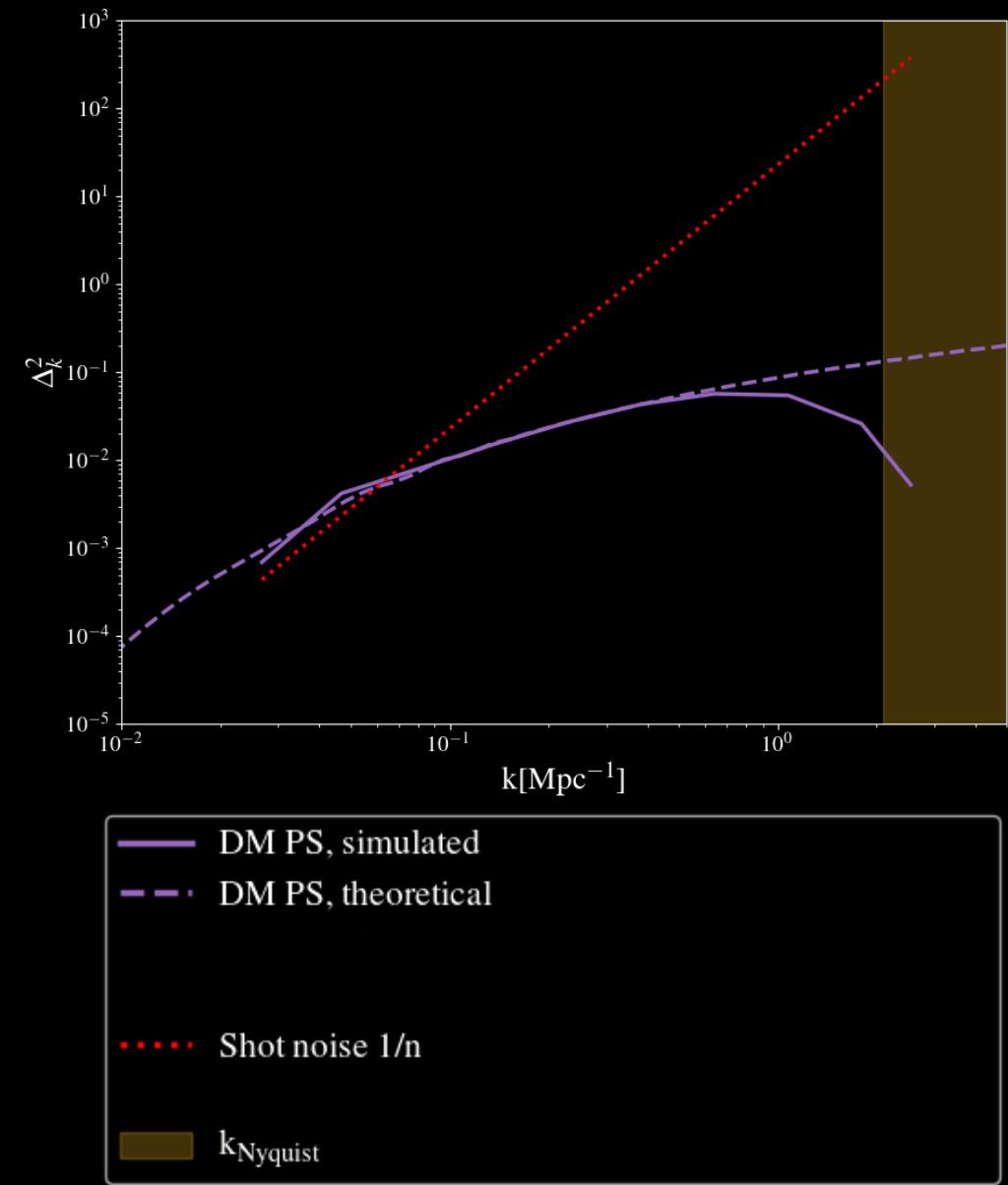
Slice -> project -> Muv cut

Observable 3: Galaxy Power Spectrum



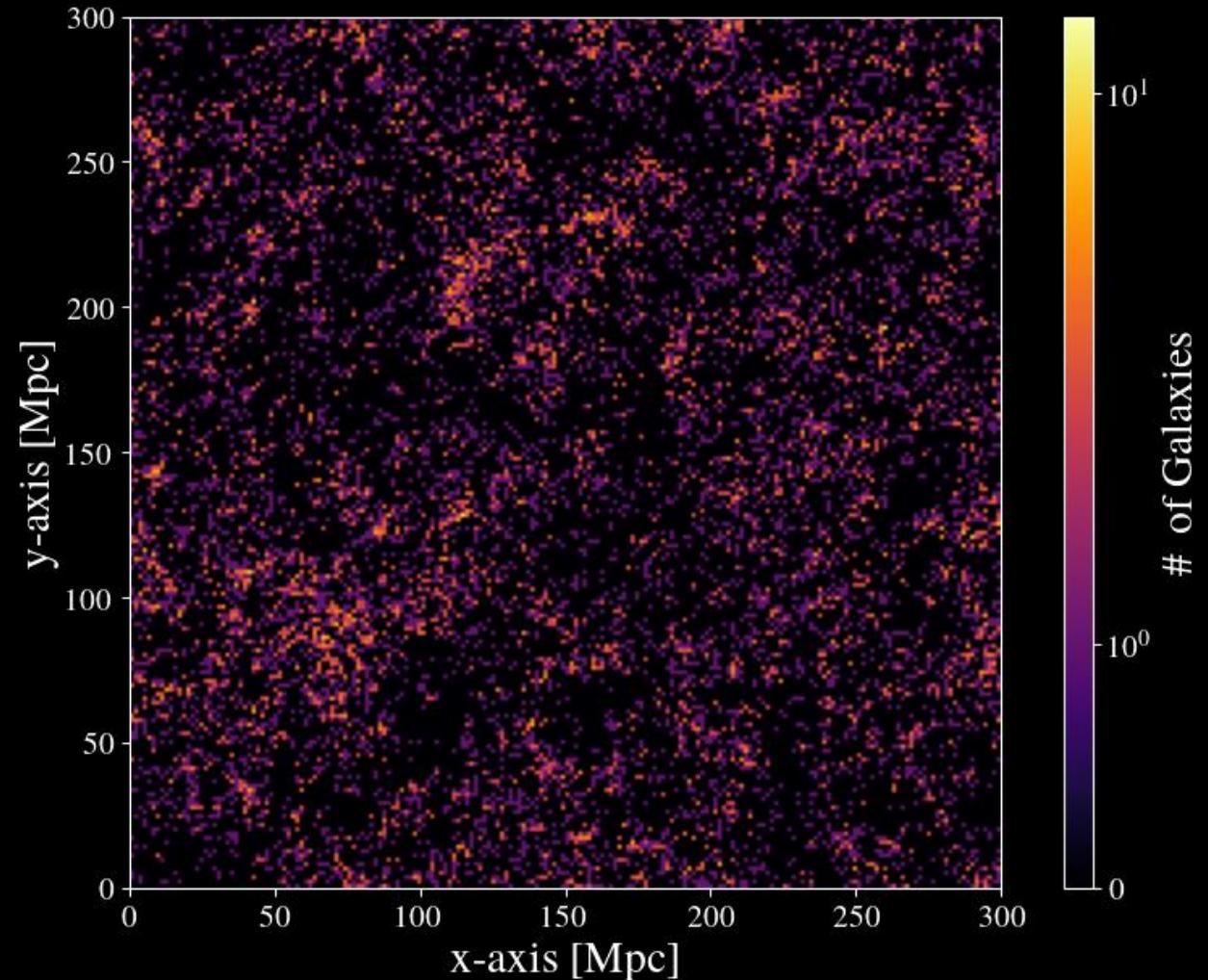
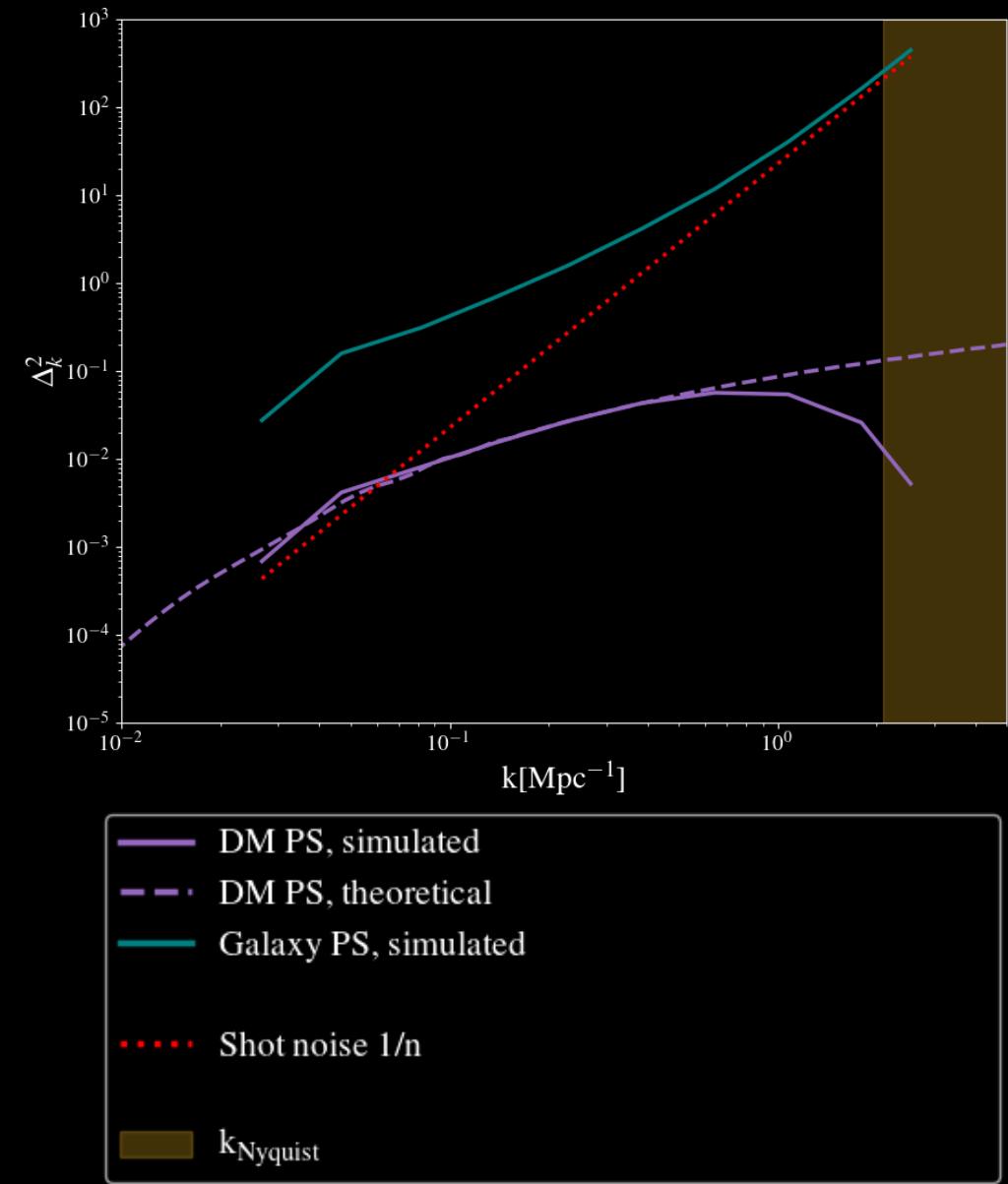
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Observable 3: Galaxy Power Spectrum



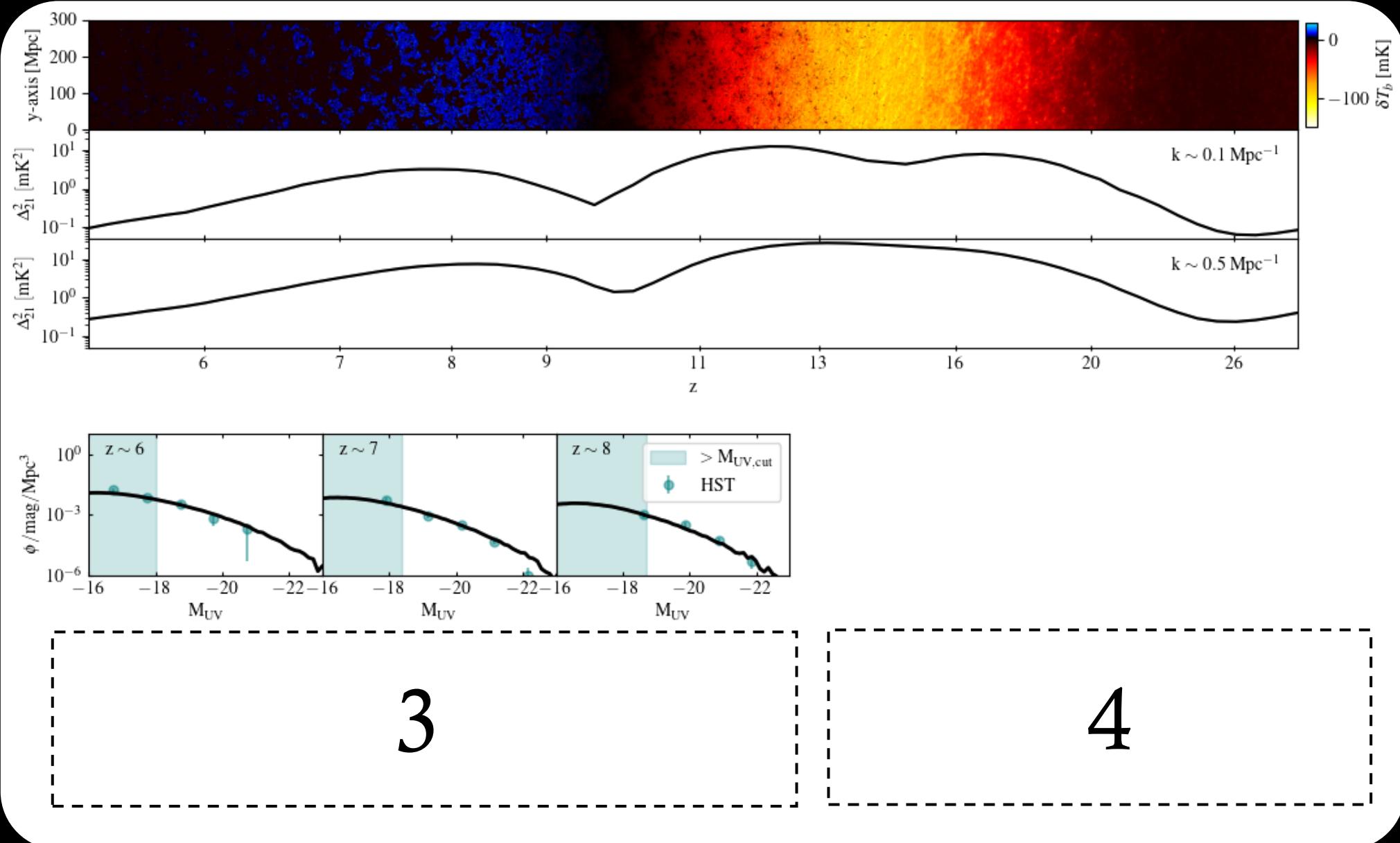
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Observable 3: Galaxy Power Spectrum

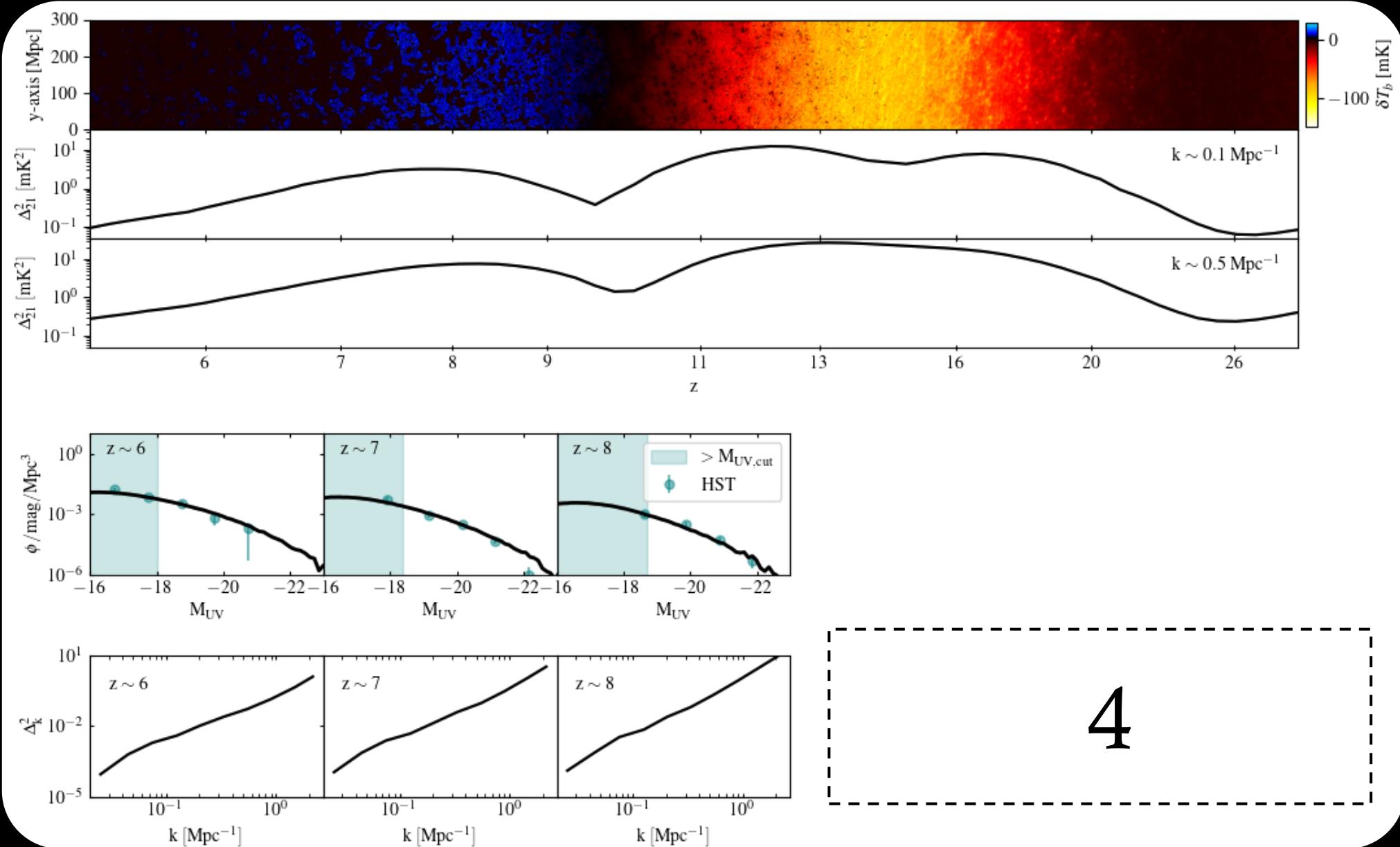


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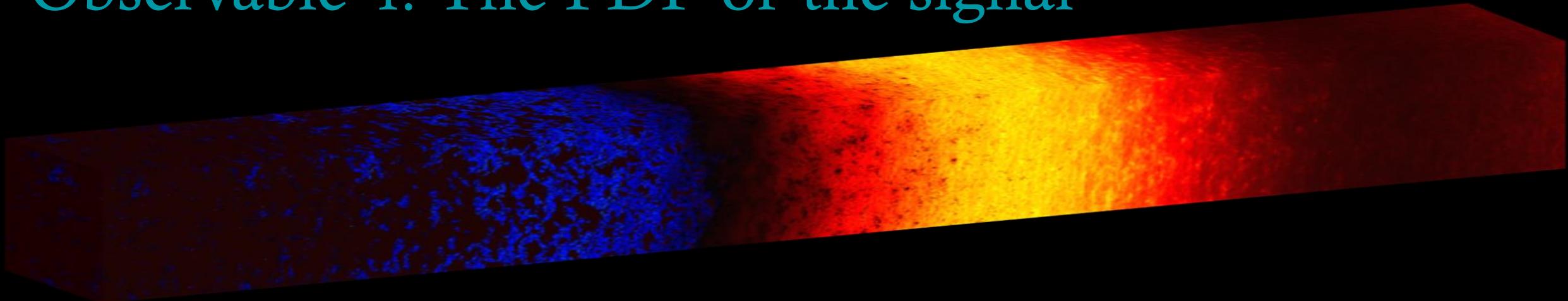
Card of Observables



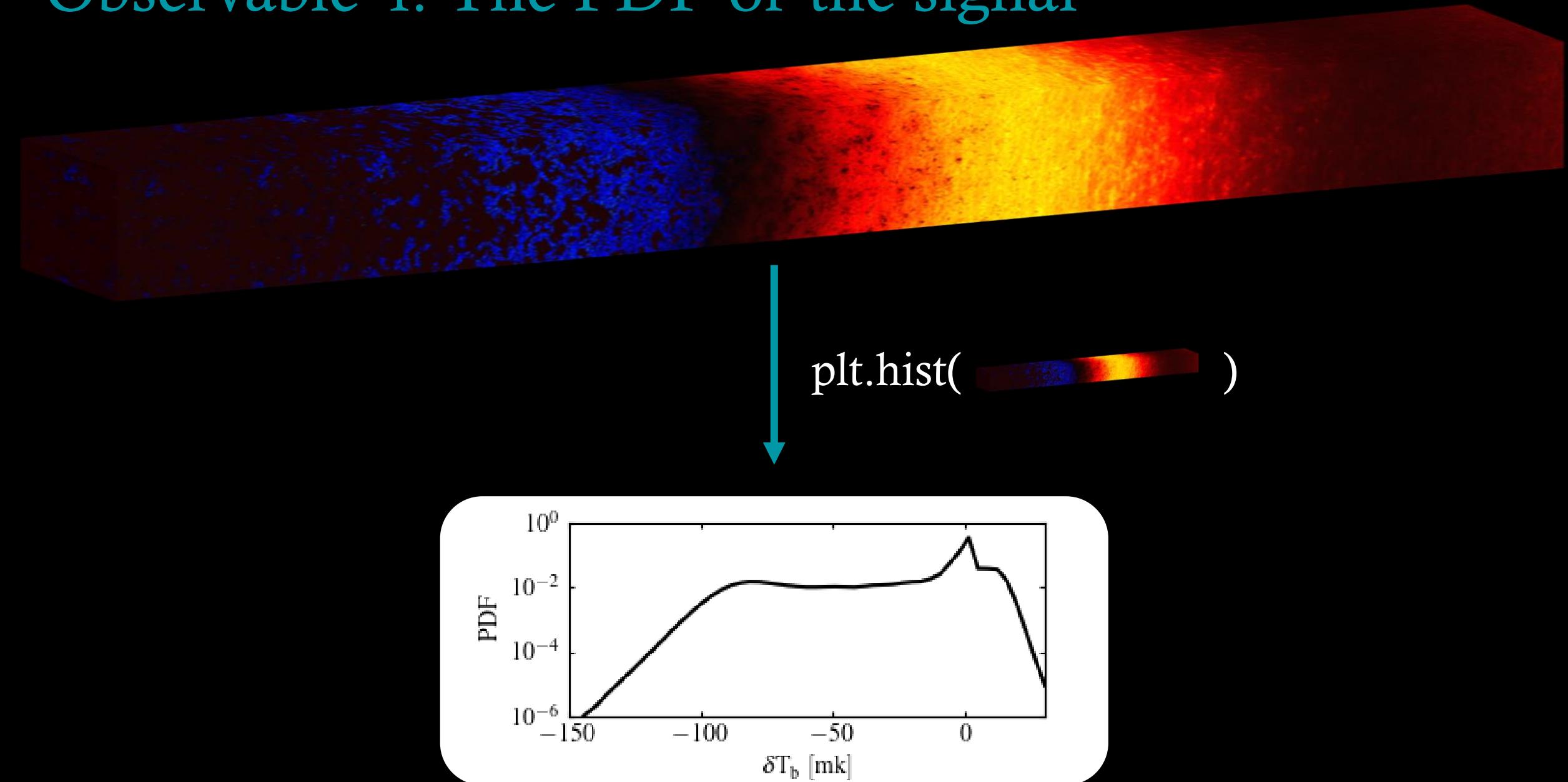
Card of Observables



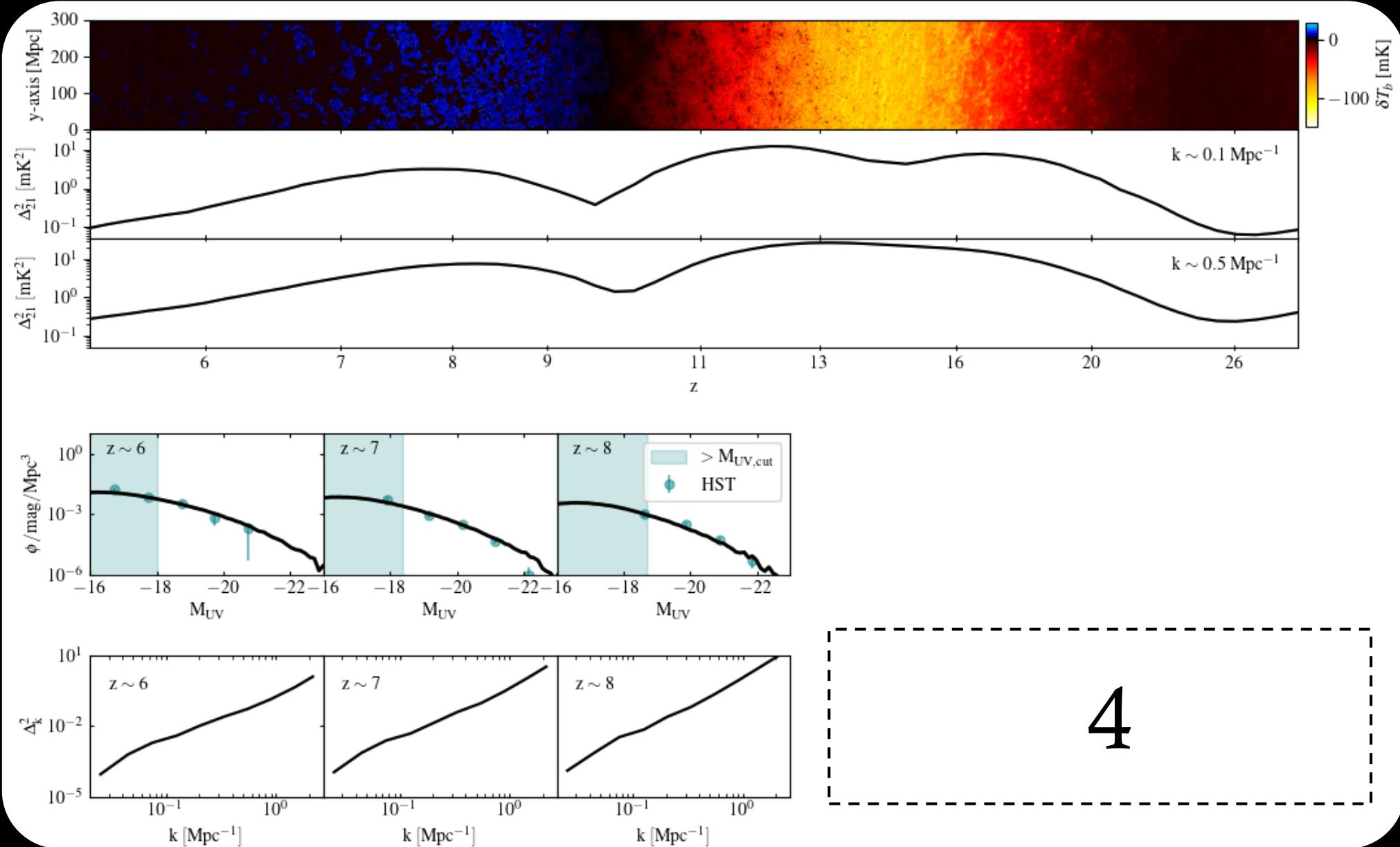
Observable 4: The PDF of the signal



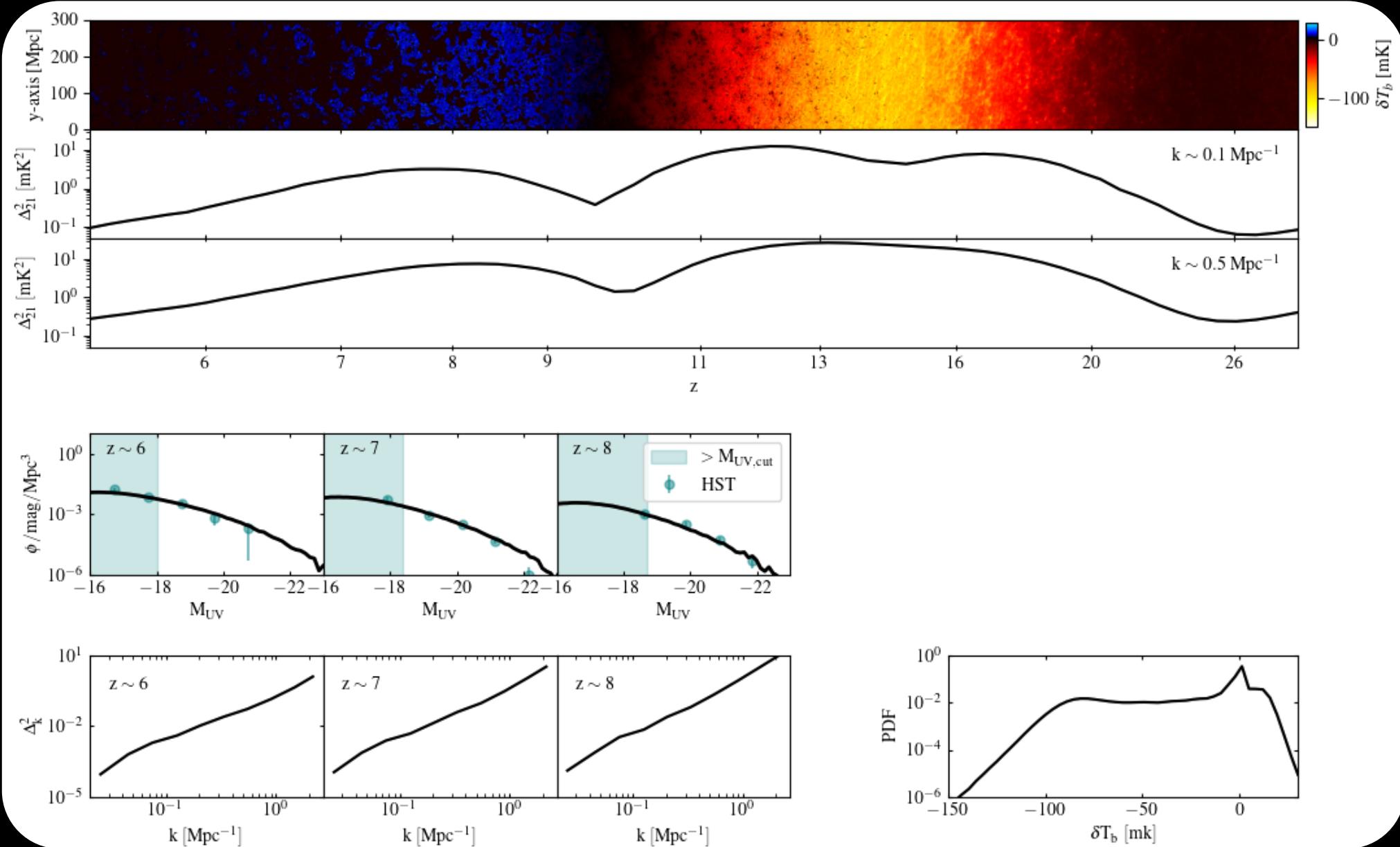
Observable 4: The PDF of the signal



Card of Observables



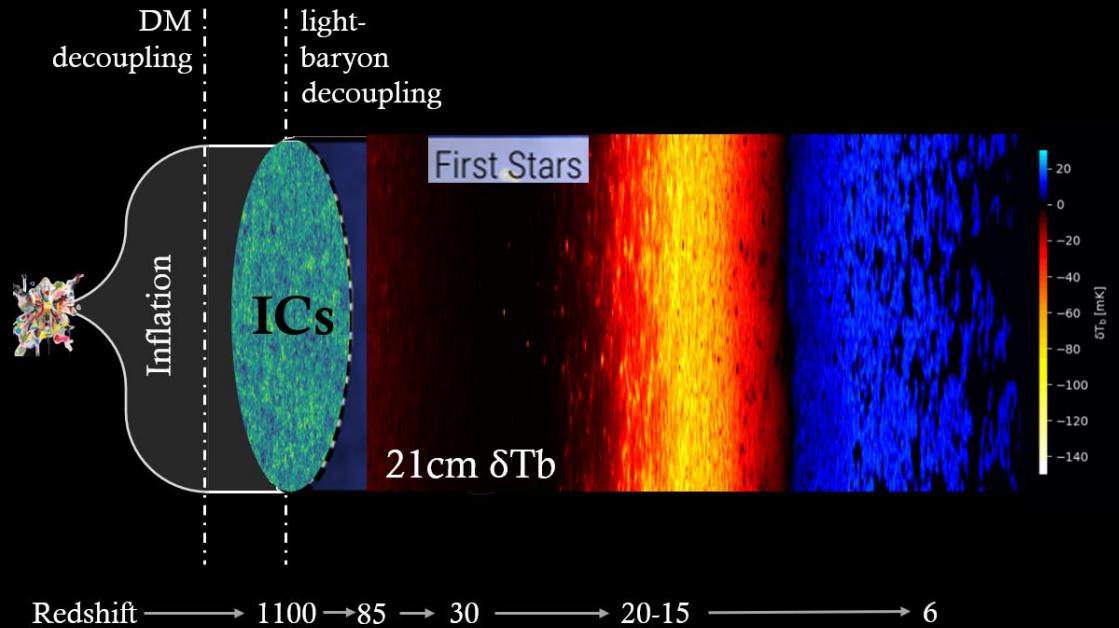
Card of Observables



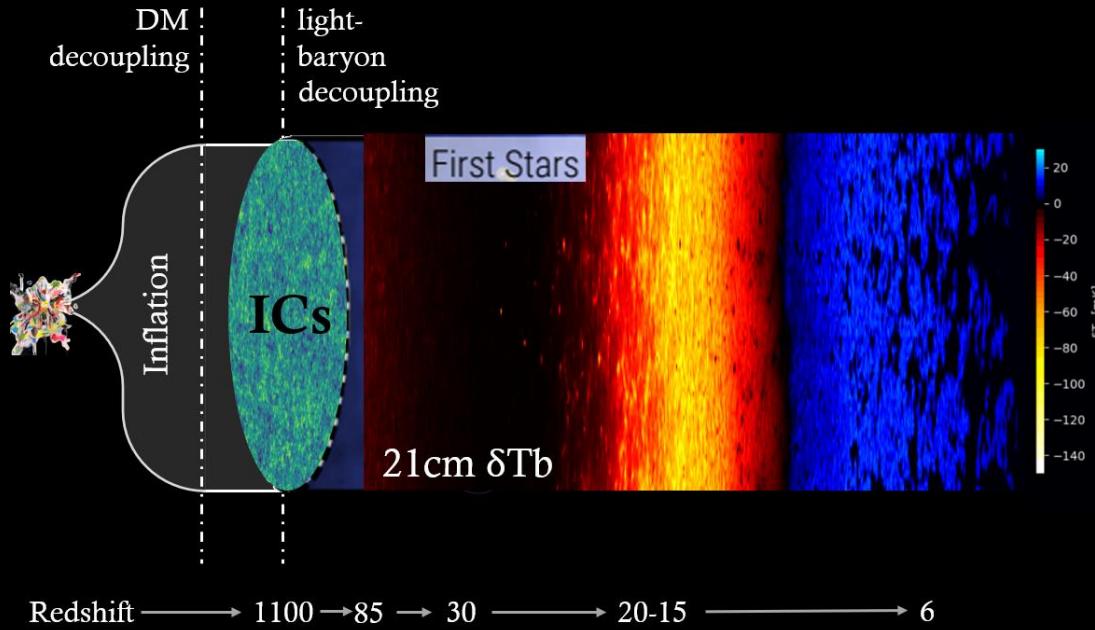
Aims

Aims

Physics ← Observables

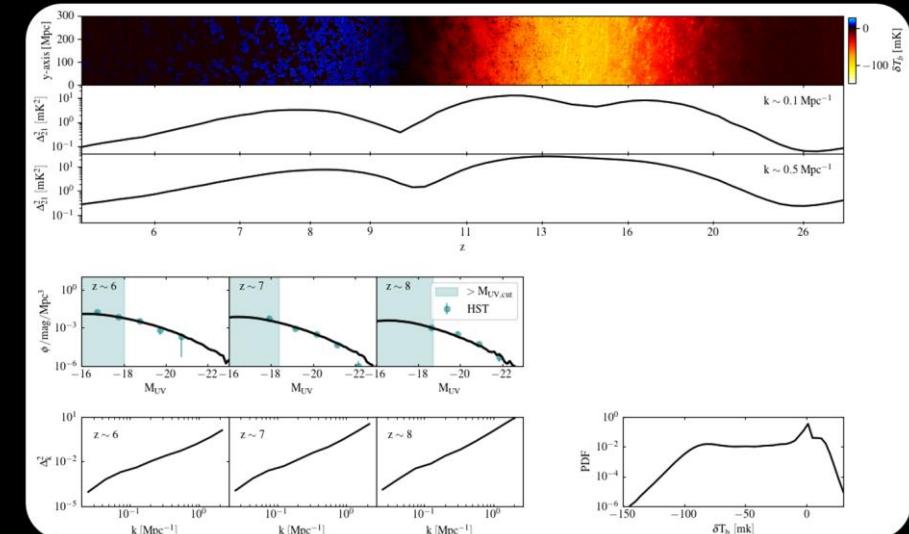


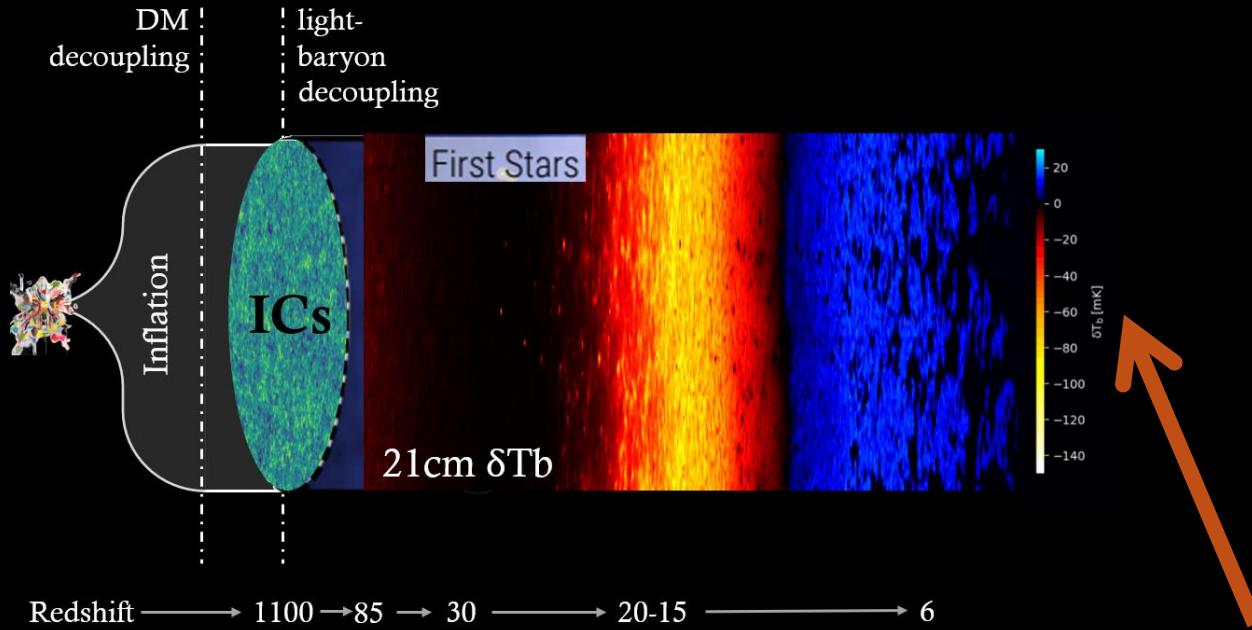
Parameters encoding physics



Parameters encoding physics

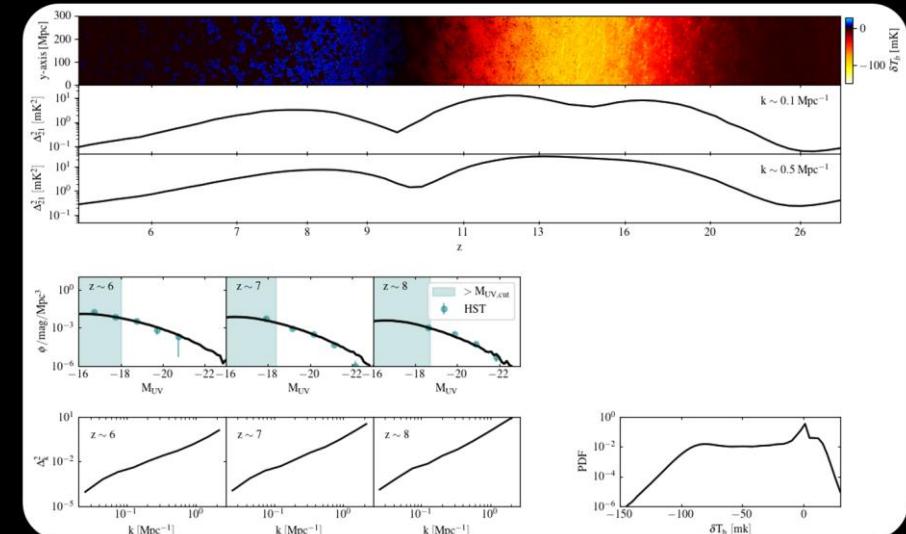
Observables



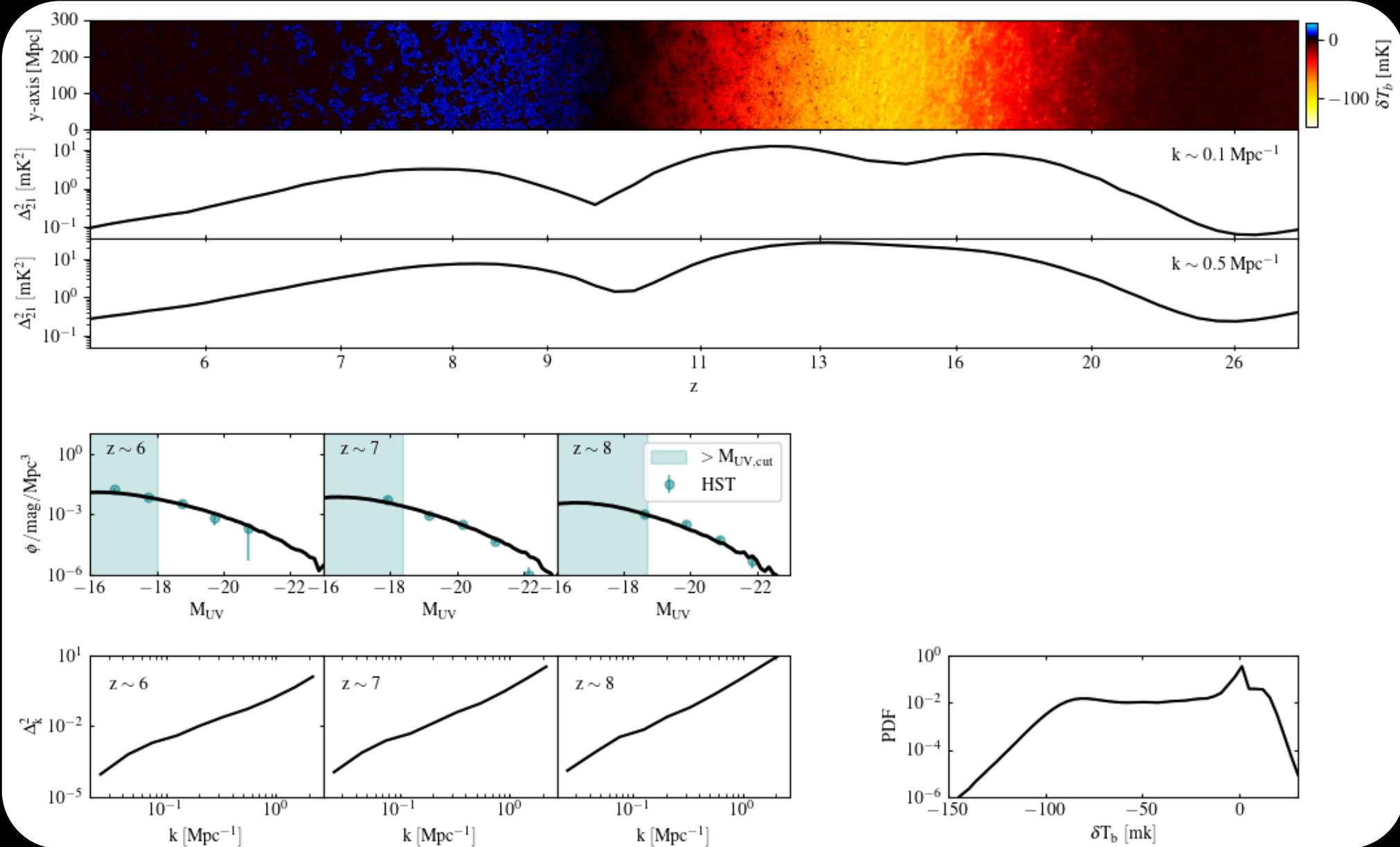


Parameters encoding physics

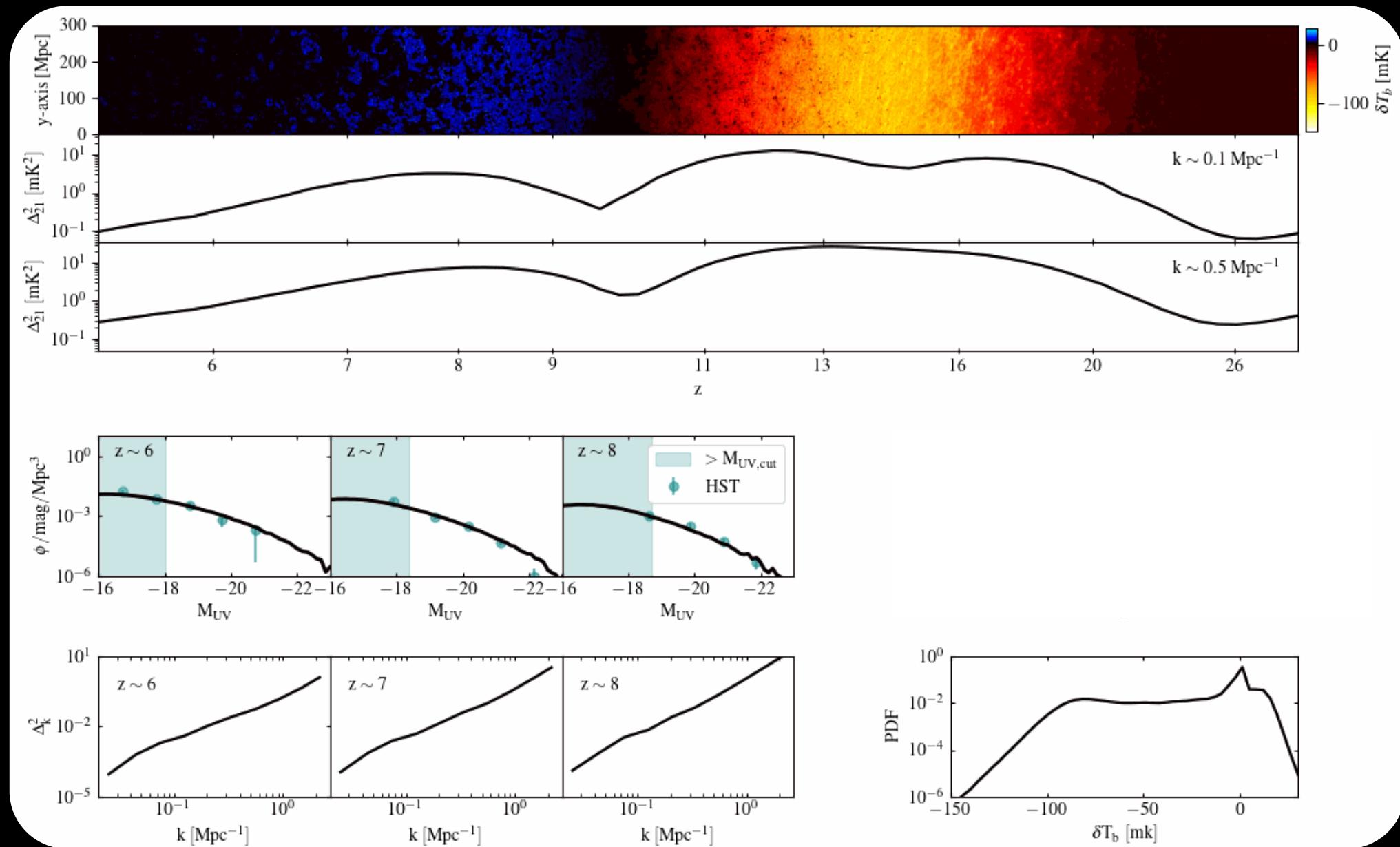
Observables



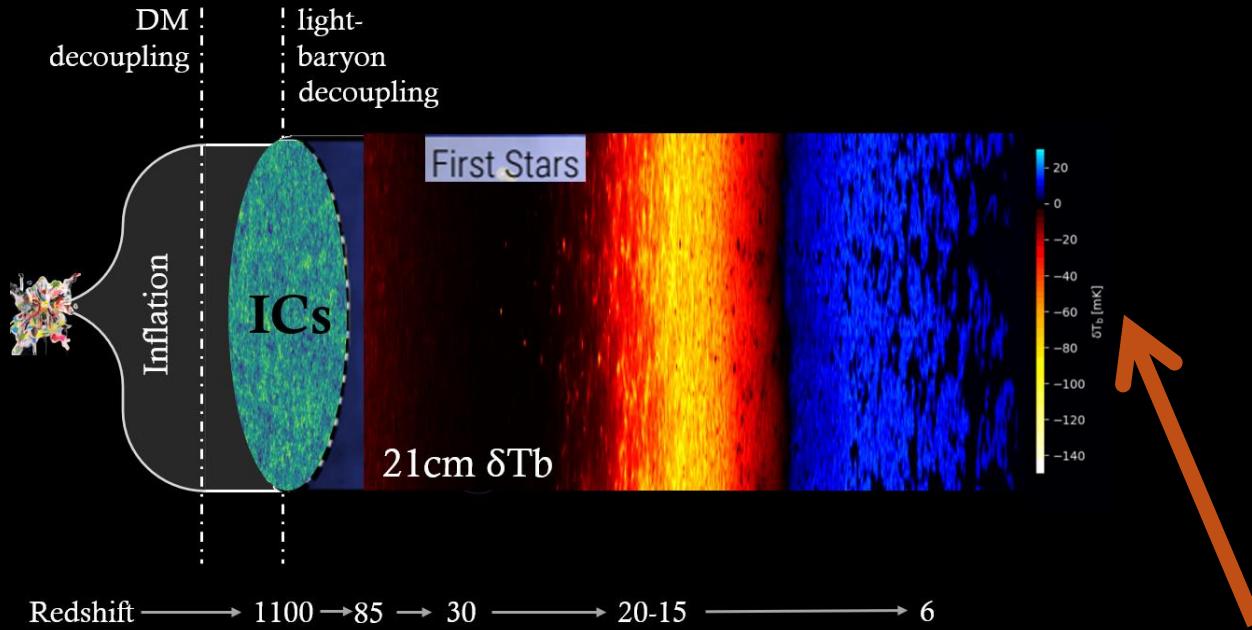
Card of Observables



SOS: Multi- tracer approach

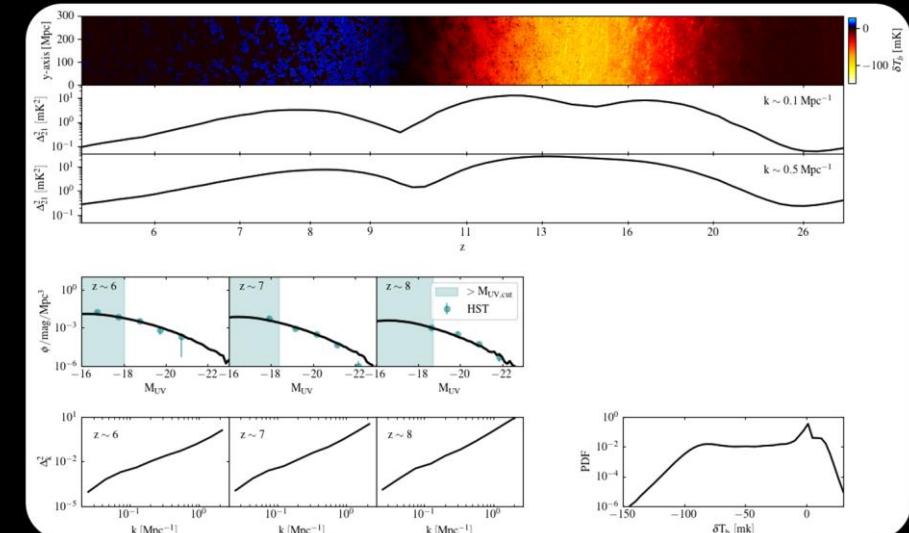


SBI

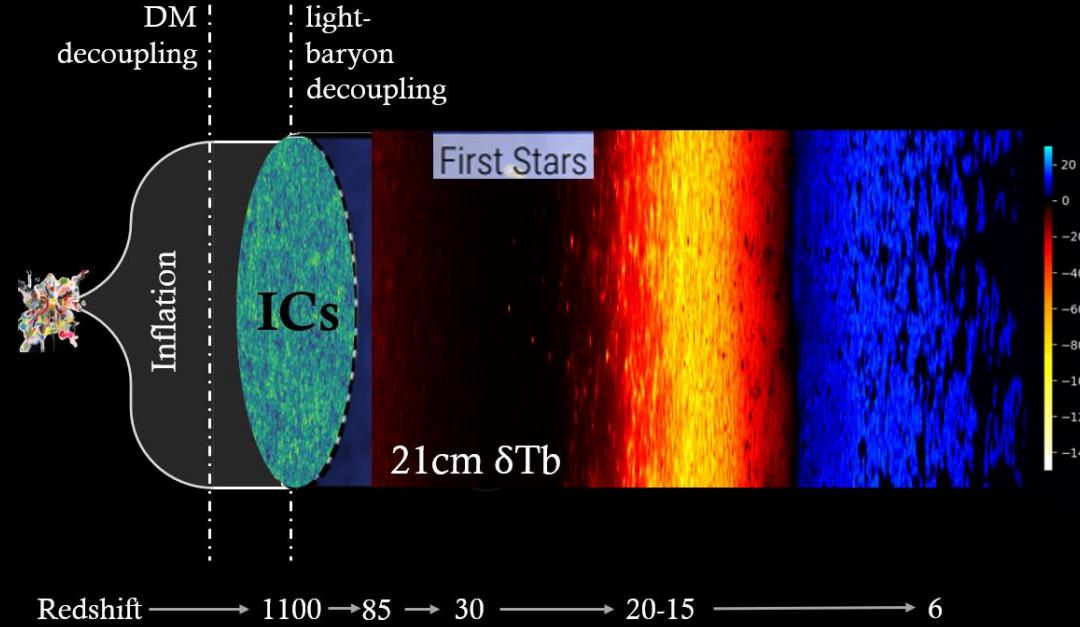


Parameters encoding physics

Observables

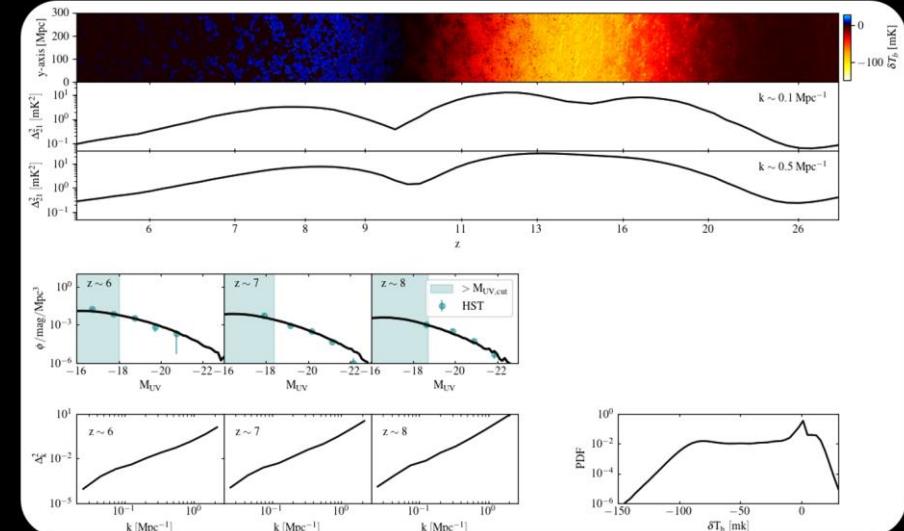


Simulation: 21cmFAST



Parameters encoding physics

Observables



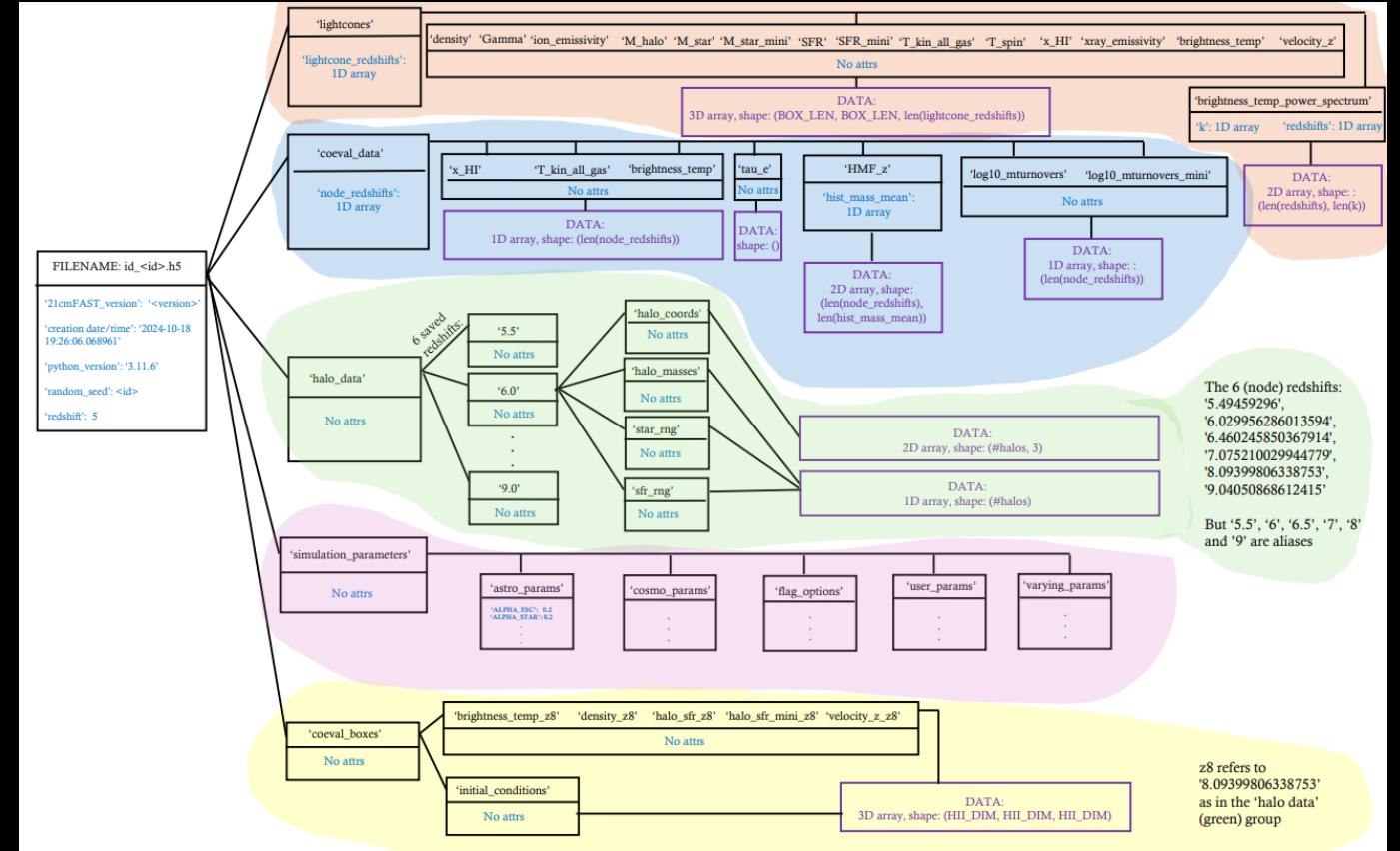
Simulation: 21cmFAST



Simulation: 21cmFAST



Database:
~100,000
simulations



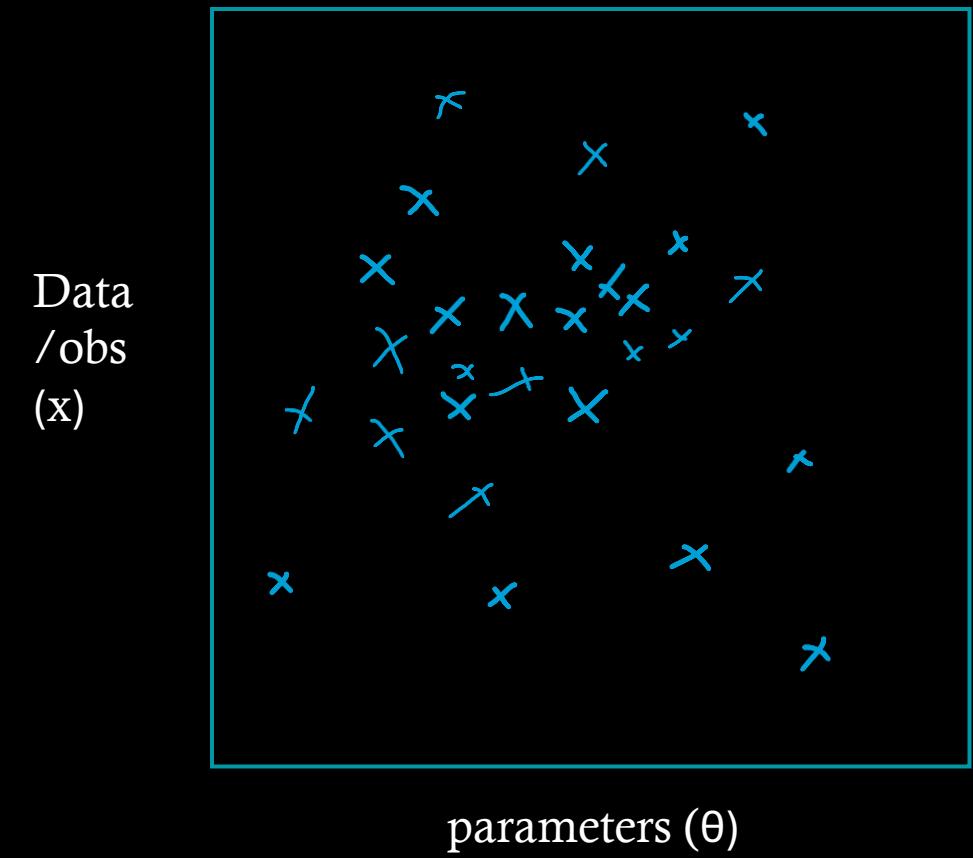
Method

Simulation Based Inference

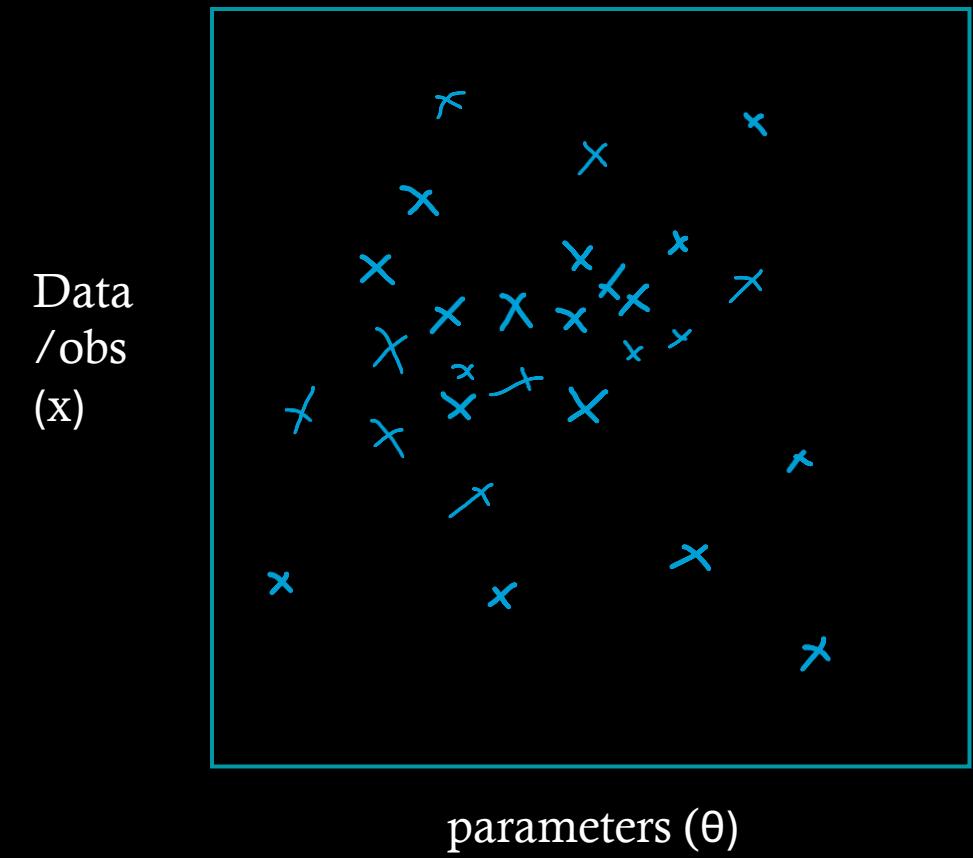
Data
/obs
(x)

parameters (θ)

Simulation Based Inference

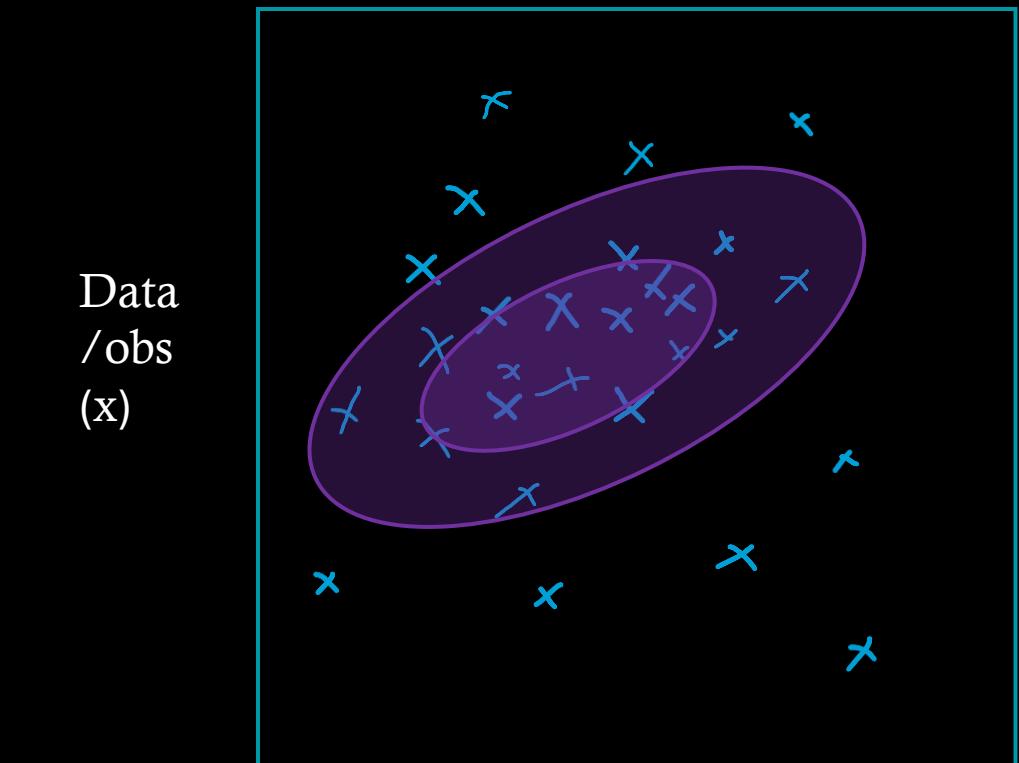


Simulation Based Inference



Simulation Based Inference

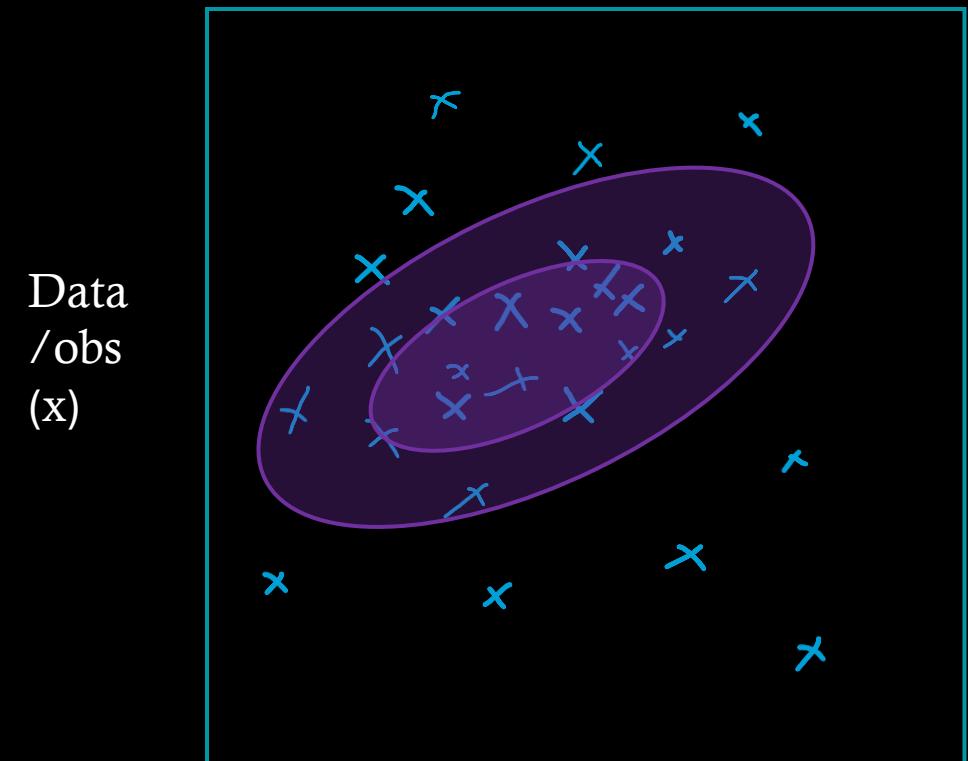
$$p(\theta \mid x)$$



parameters (θ)

SBI: Neural Ratio Estimation (NRE)

$$p(\theta \mid x)$$



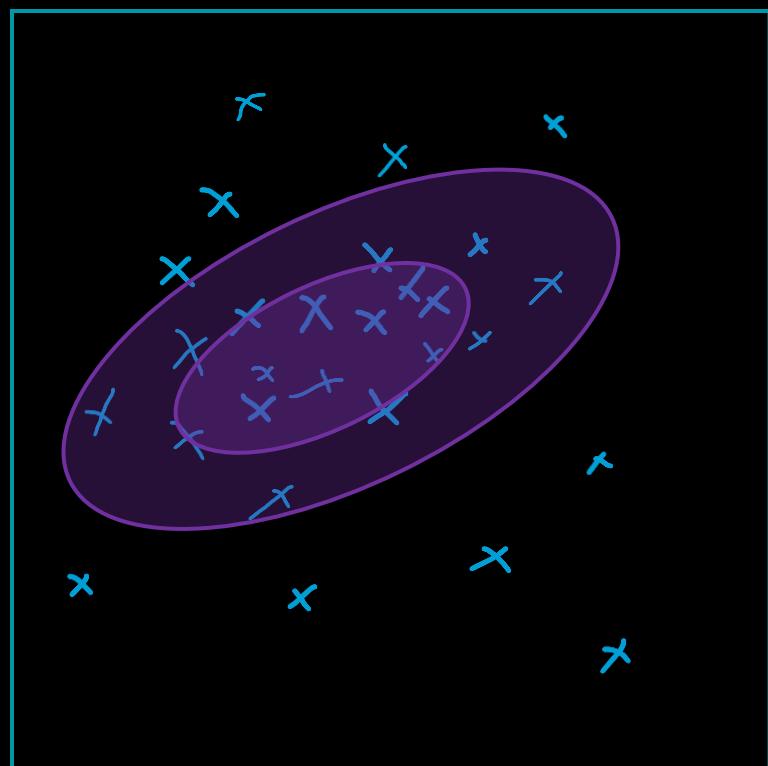
parameters (θ)

SBI: Neural Ratio Estimation (NRE)

$$p(\theta \mid x)$$

Jointly drawn $p(x, \theta)$

Data
/obs
(x)



parameters (θ)

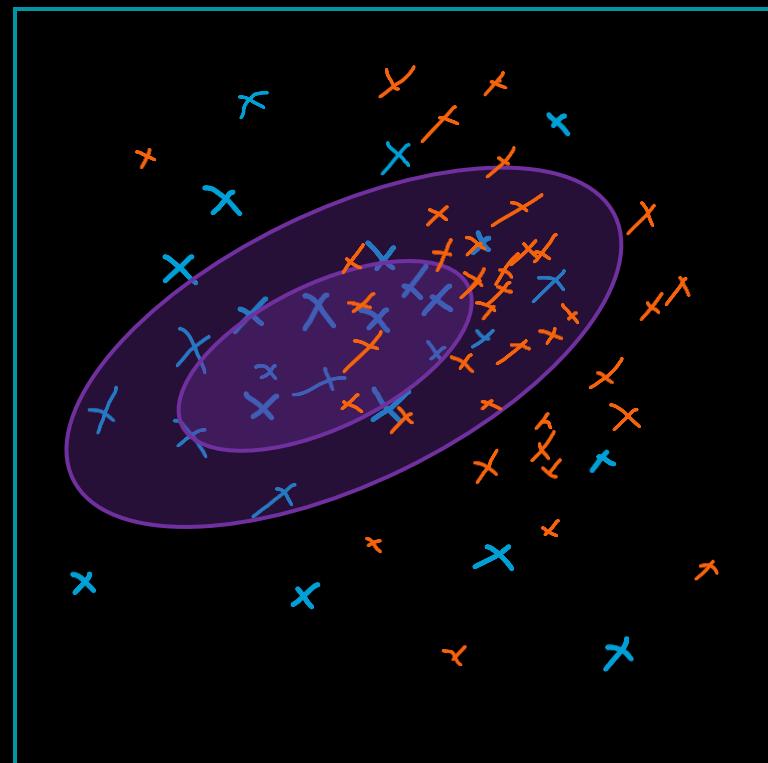
SBI: Neural Ratio Estimation (NRE)

$$p(\theta \mid x)$$

 Jointly drawn $p(x, \theta)$

 Independently drawn $p(x)p(\theta)$

Data
/obs
(x)



parameters (θ)

SBI: Neural Ratio Estimation (NRE)

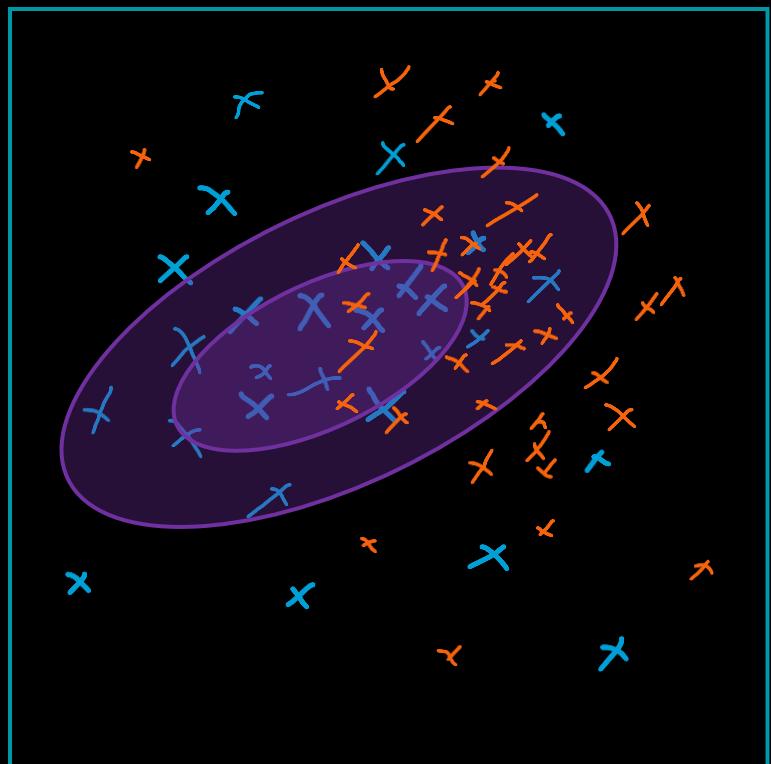
$$p(\theta \mid x)$$

Jointly drawn $p(x, \theta)$

Independently drawn $p(x)p(\theta)$

Neural Network (\times ?)

Data
/obs
(x)



parameters (θ)

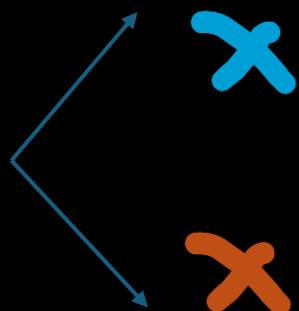
SBI: Neural Ratio Estimation (NRE)

$$p(\theta \mid x)$$

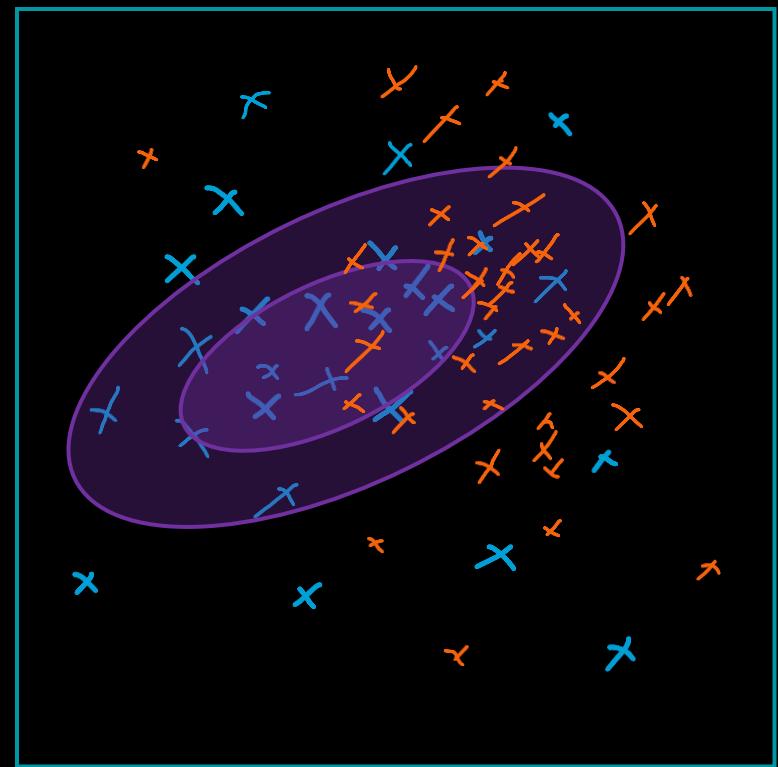
Jointly drawn $p(x, \theta)$

Independently drawn $p(x)p(\theta)$

Neural Network ($\text{X} ?$)



Data
/obs
(x)

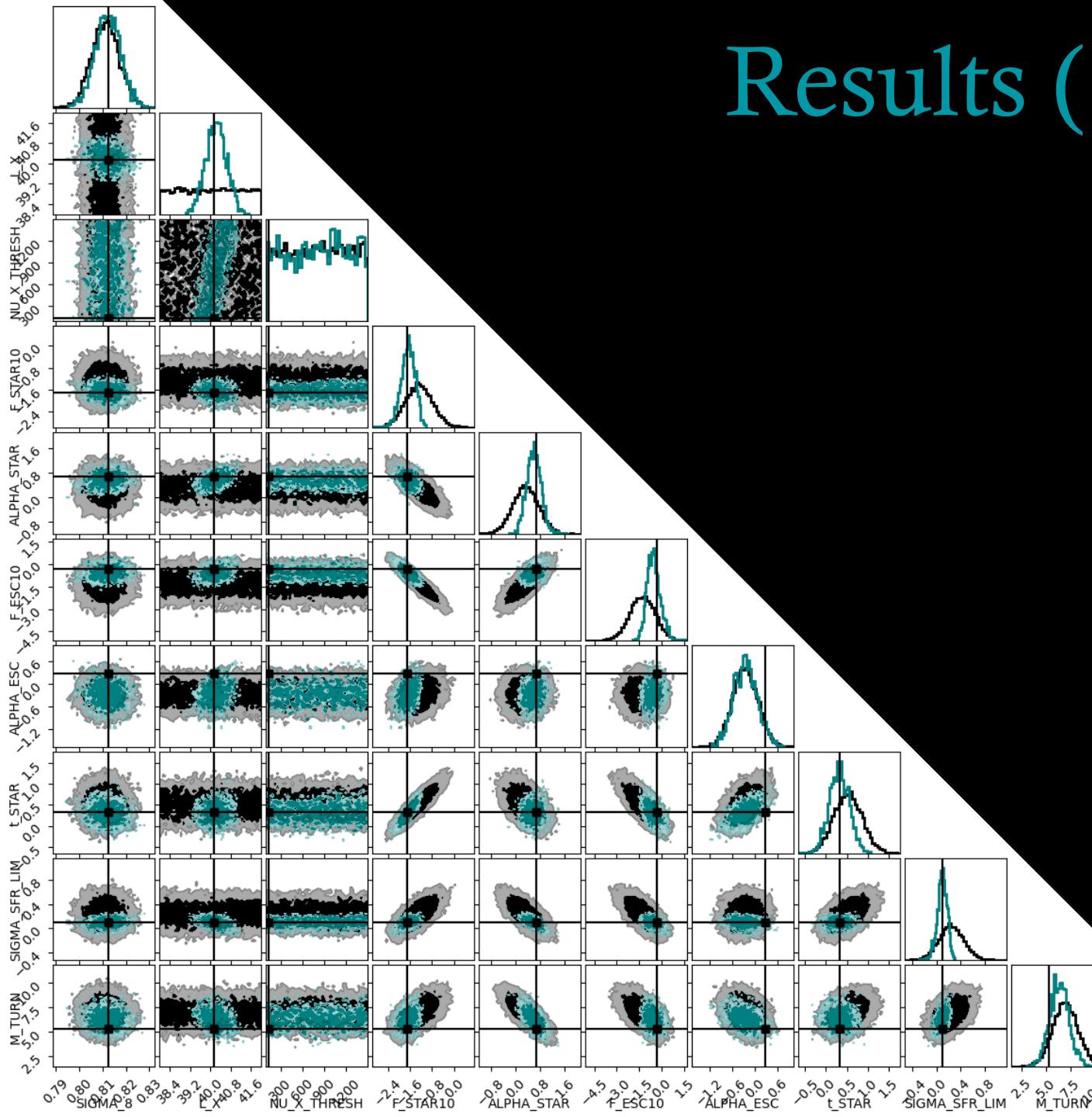


parameters (θ)

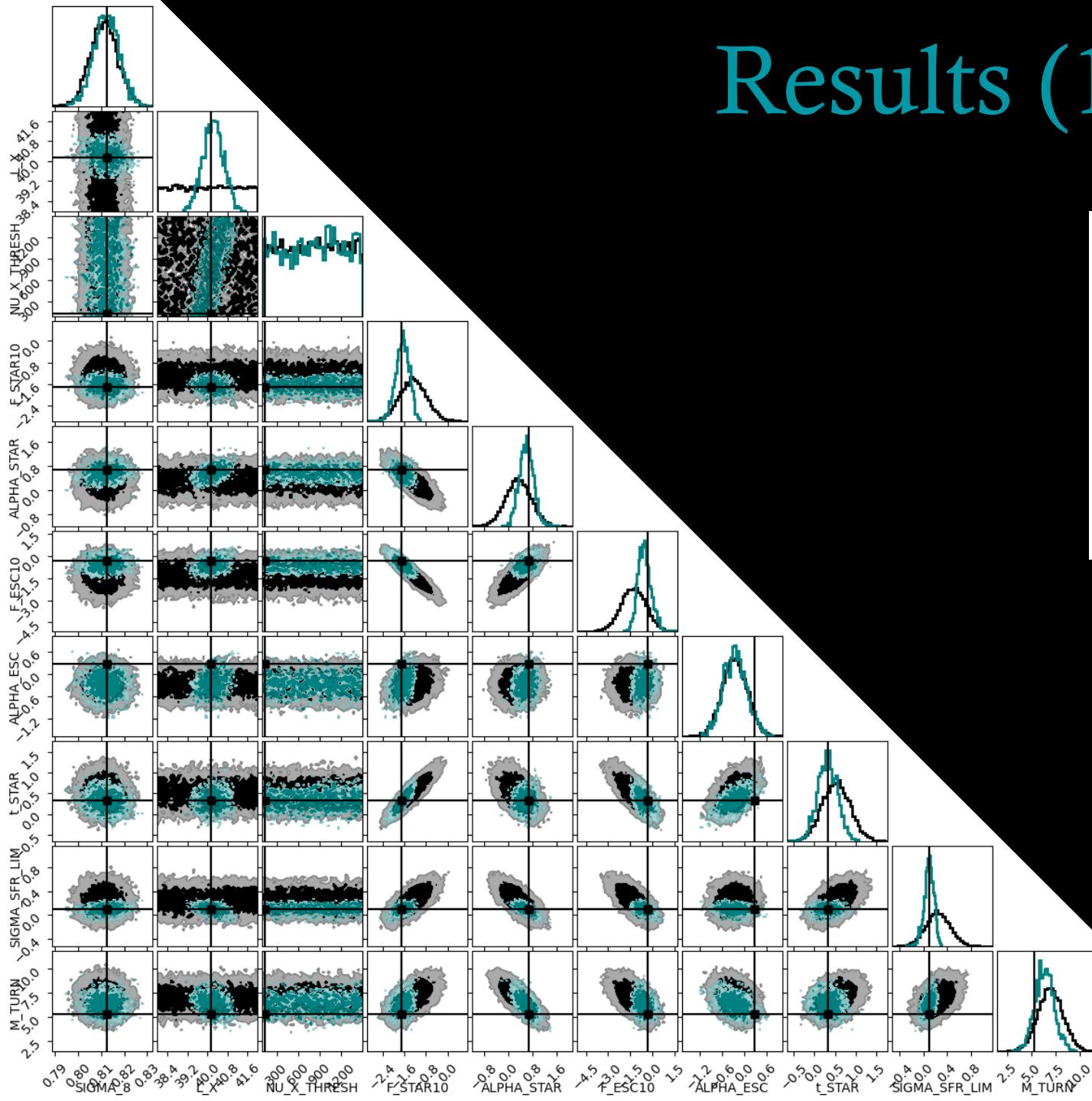
Results (1/2)

Results (1/2)

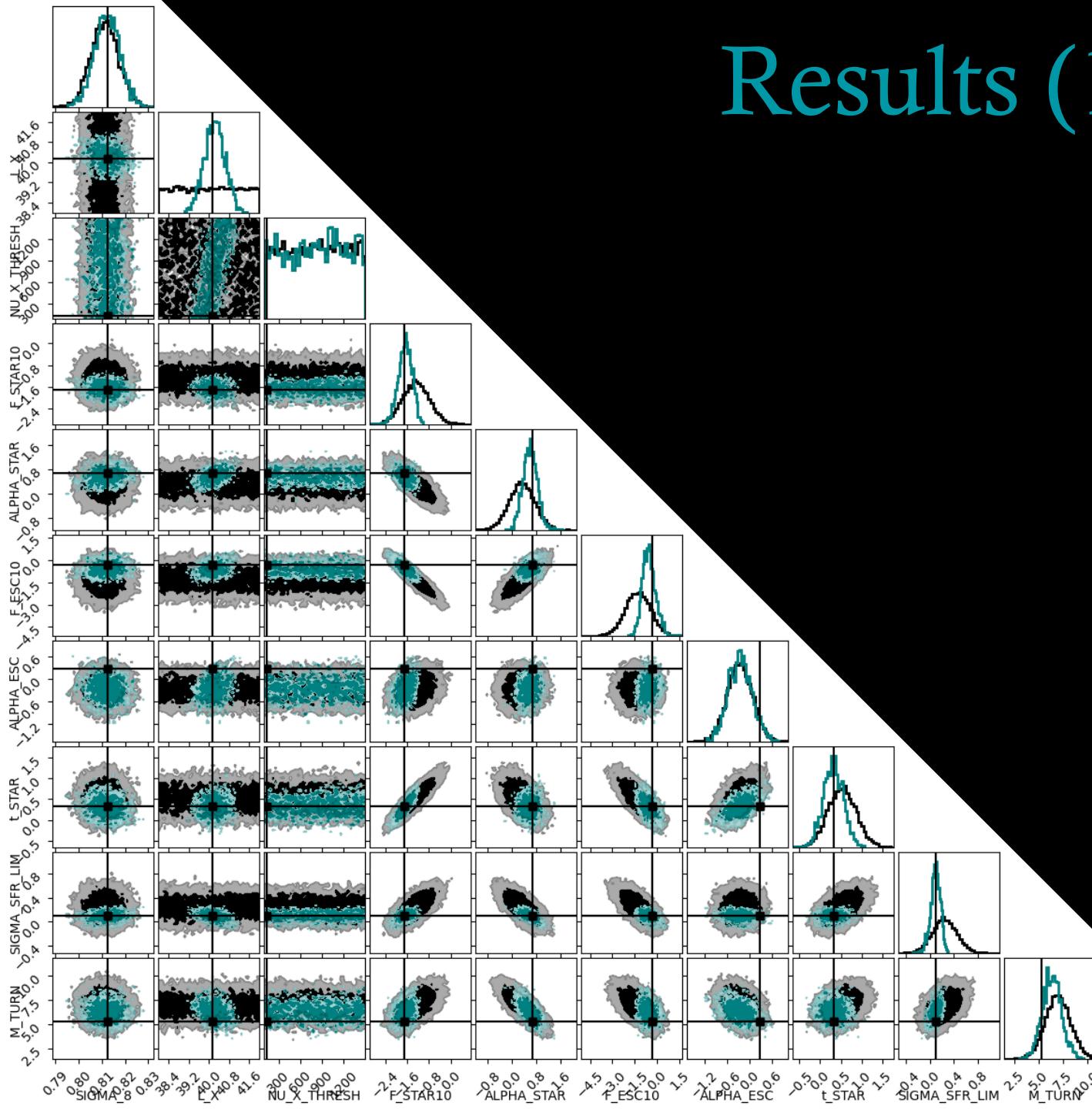
Results (1/2)



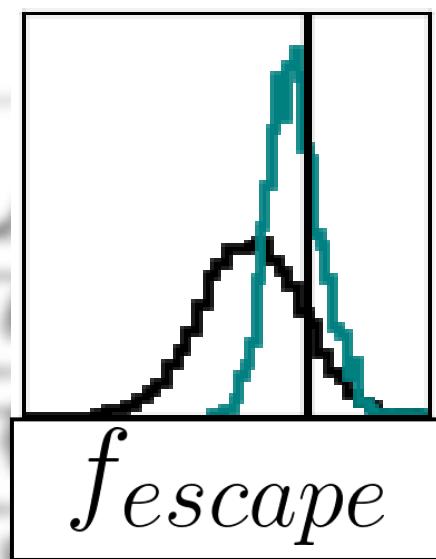
Results (1/2)



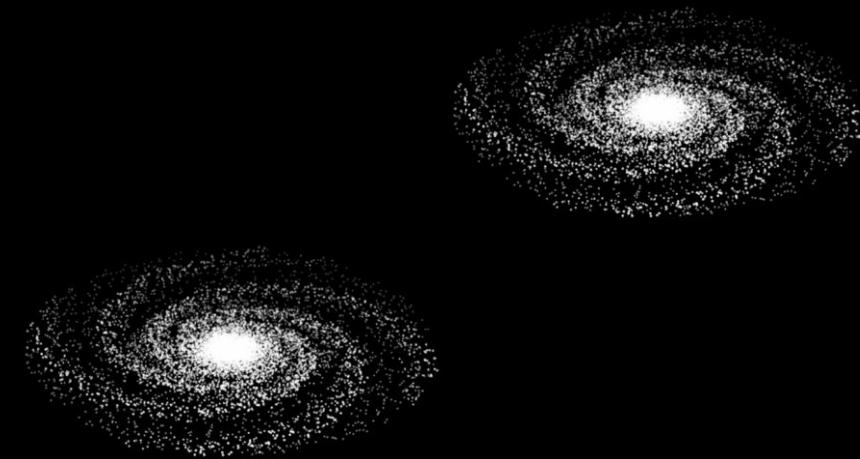
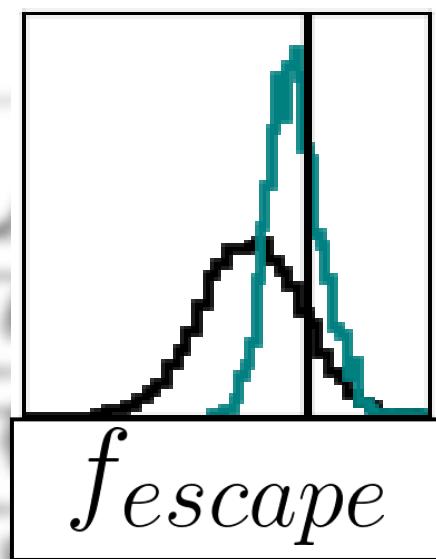
Results (1/2)



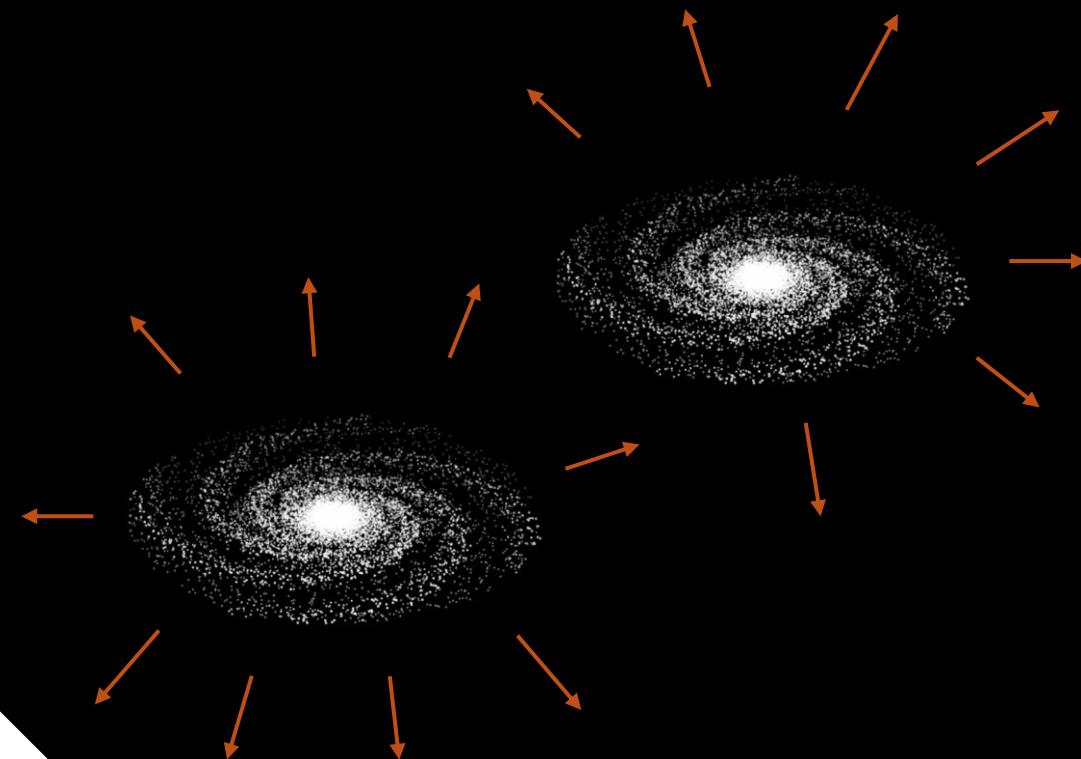
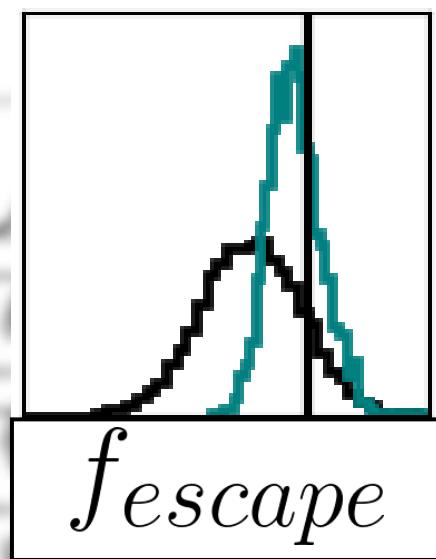
Results (1/2)



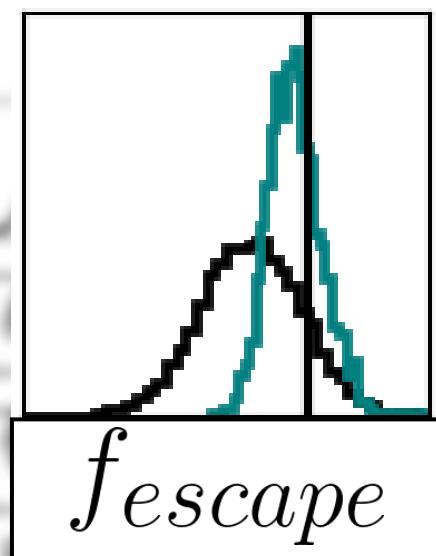
Results (1/2)



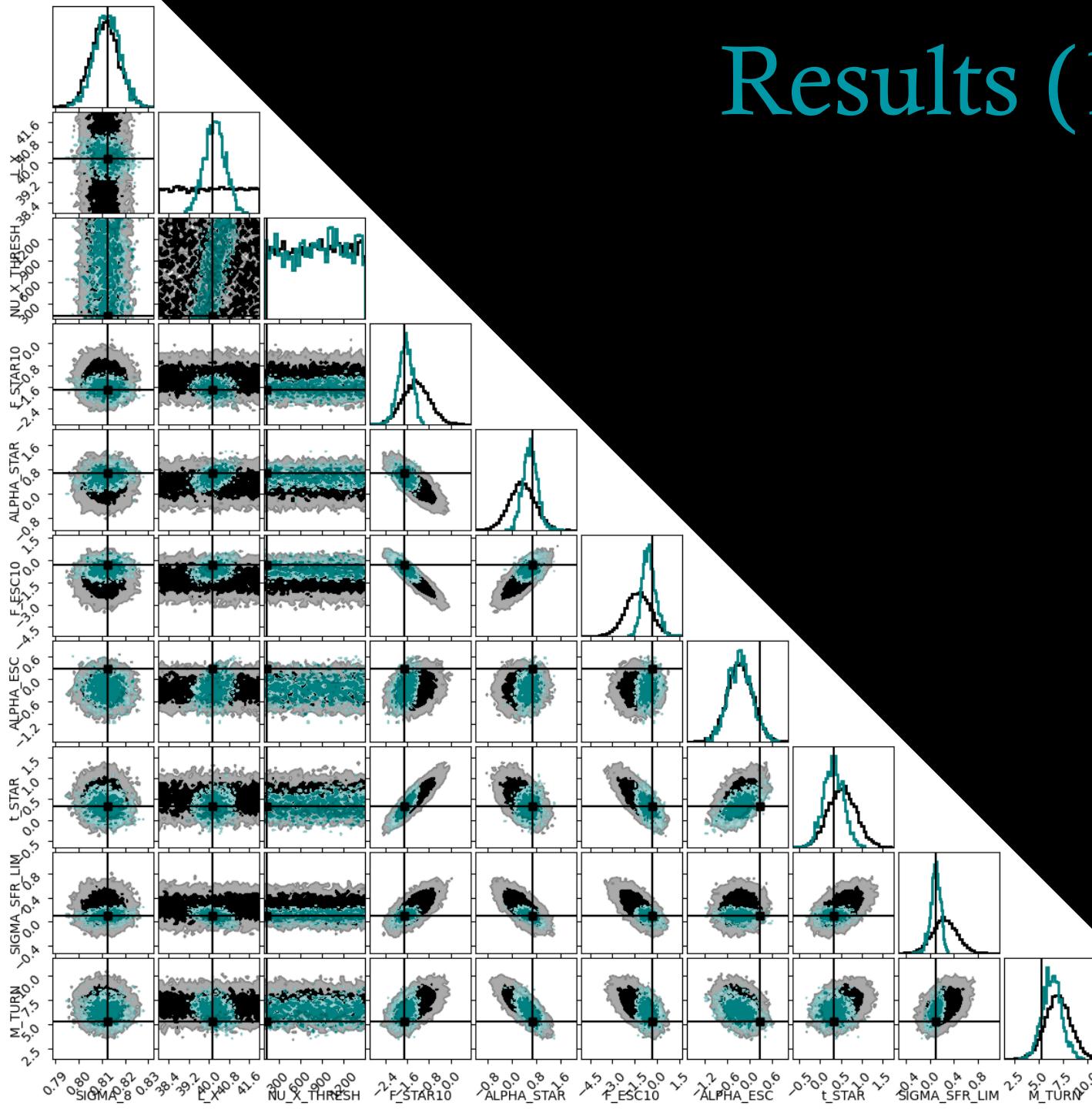
Results (1/2)



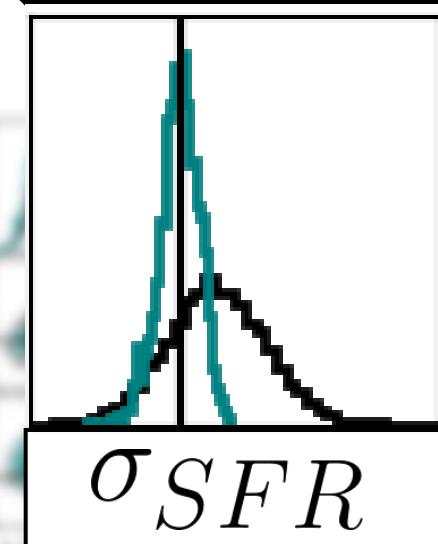
Results (1/2)



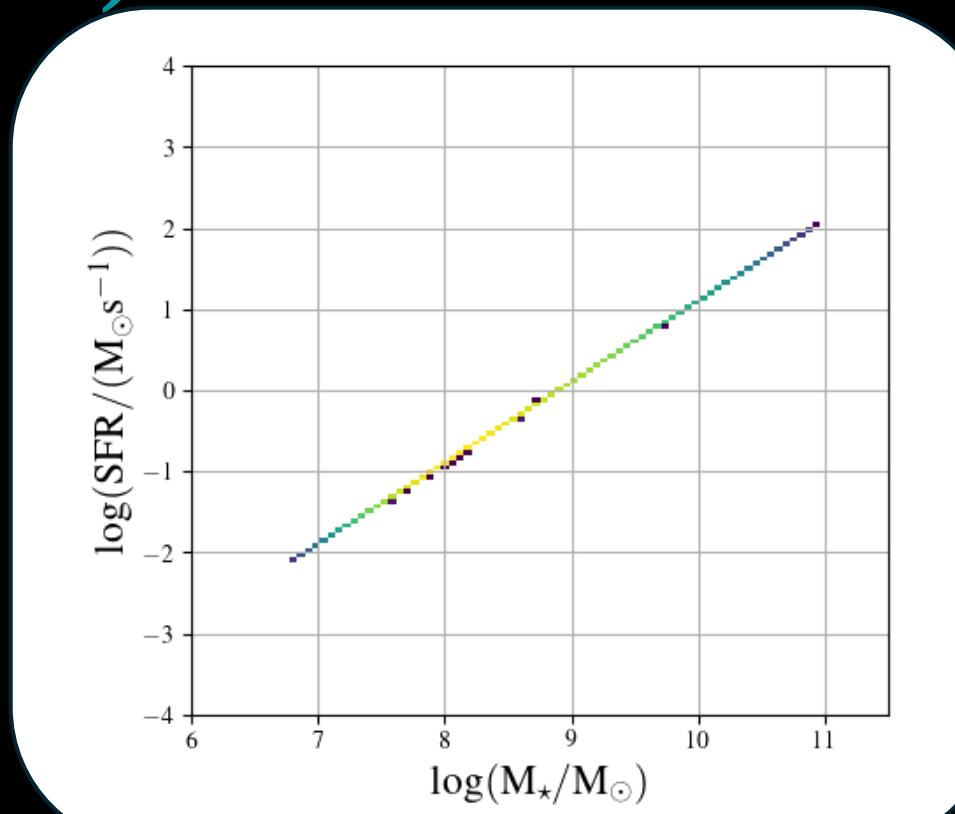
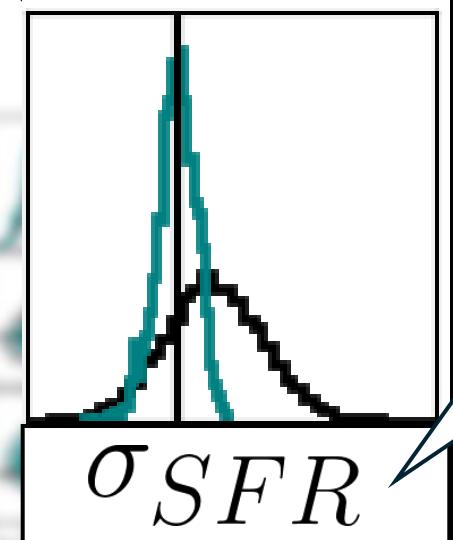
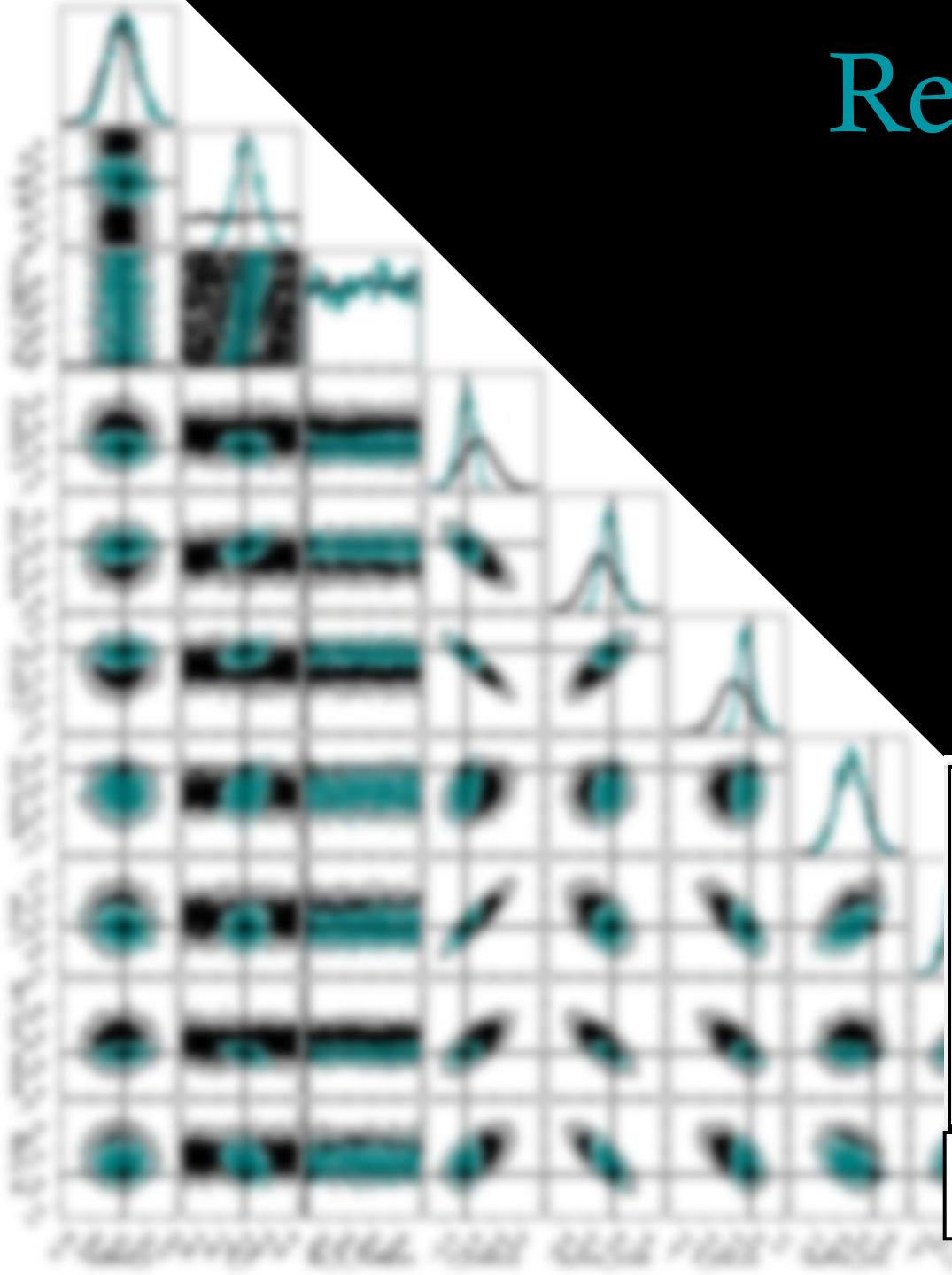
Results (1/2)



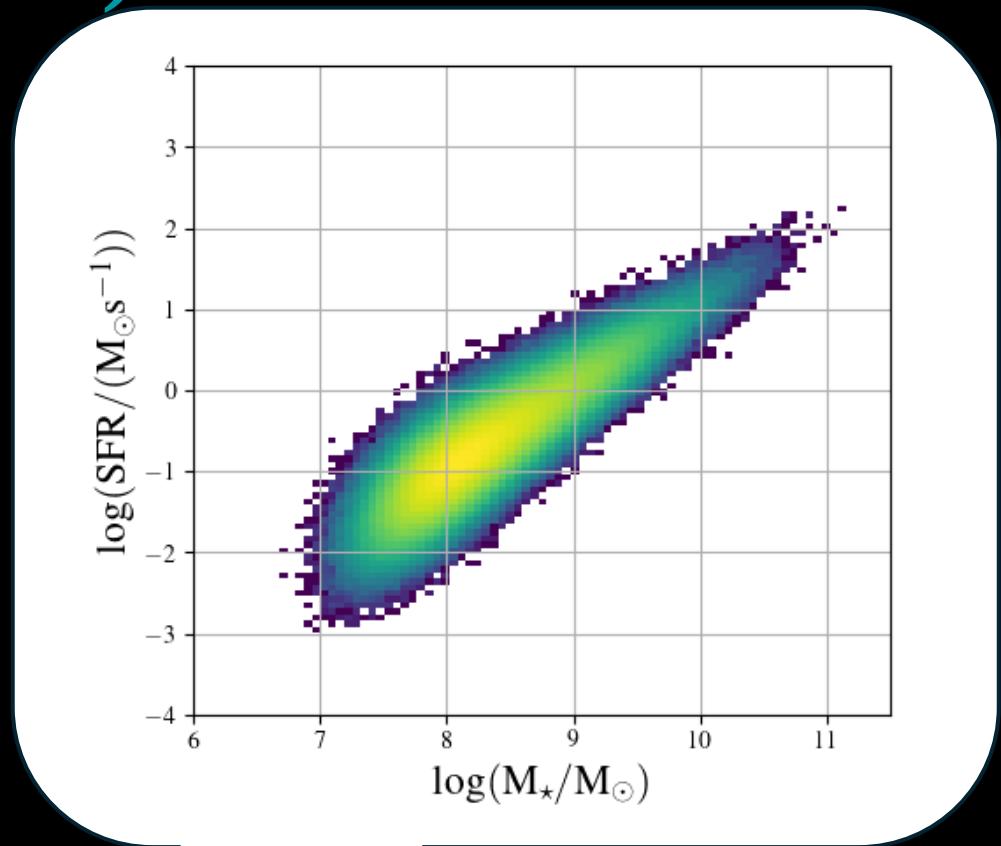
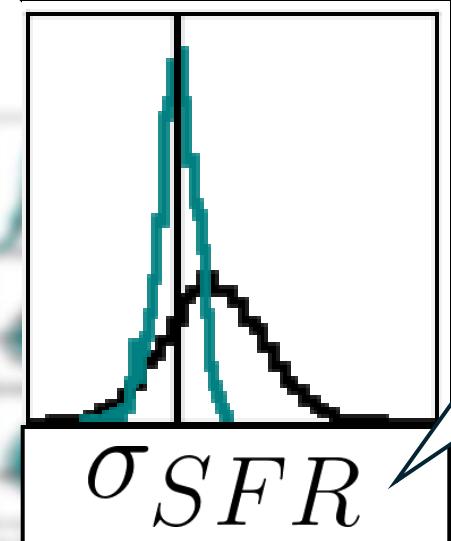
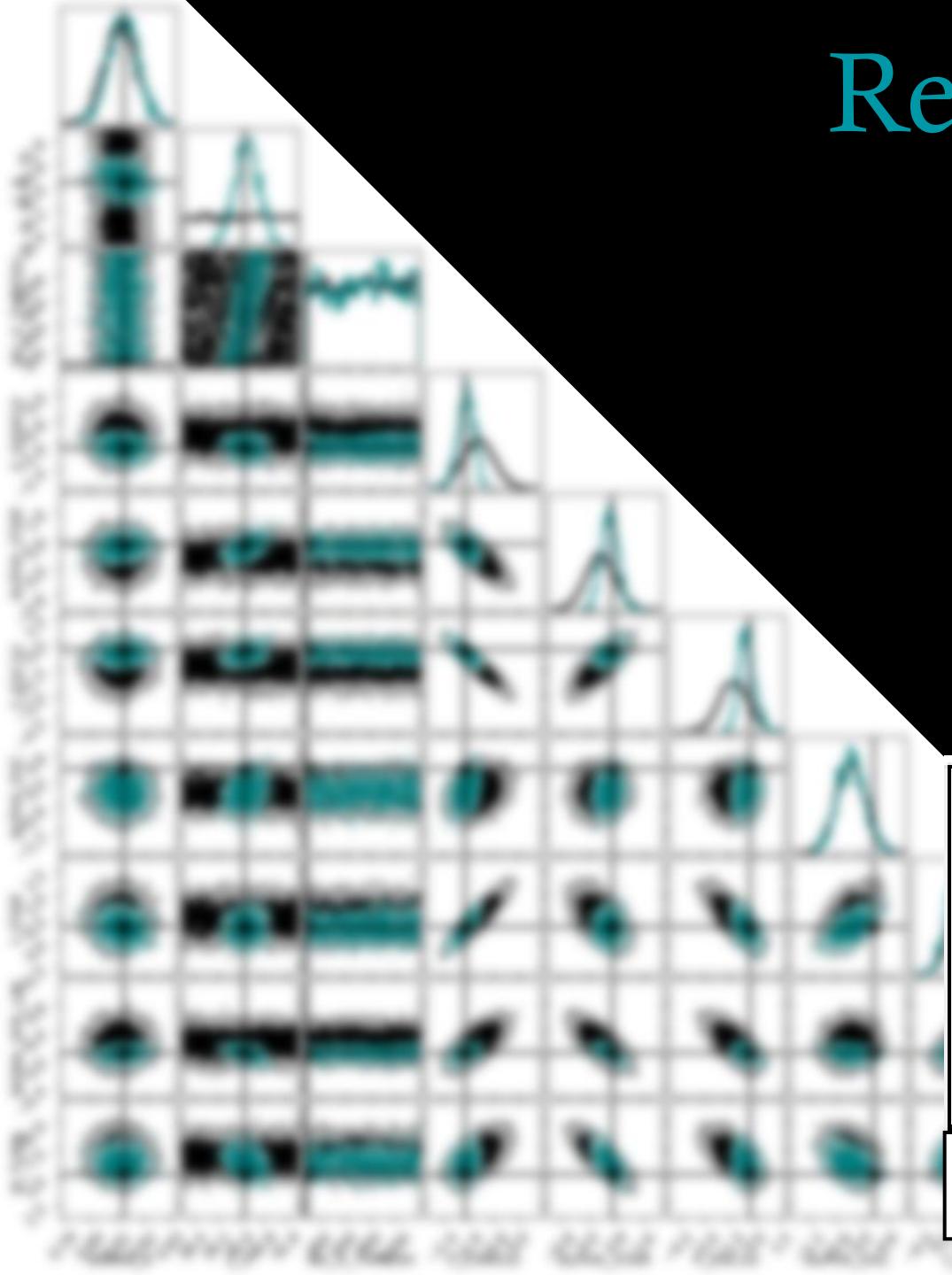
Results (1/2)



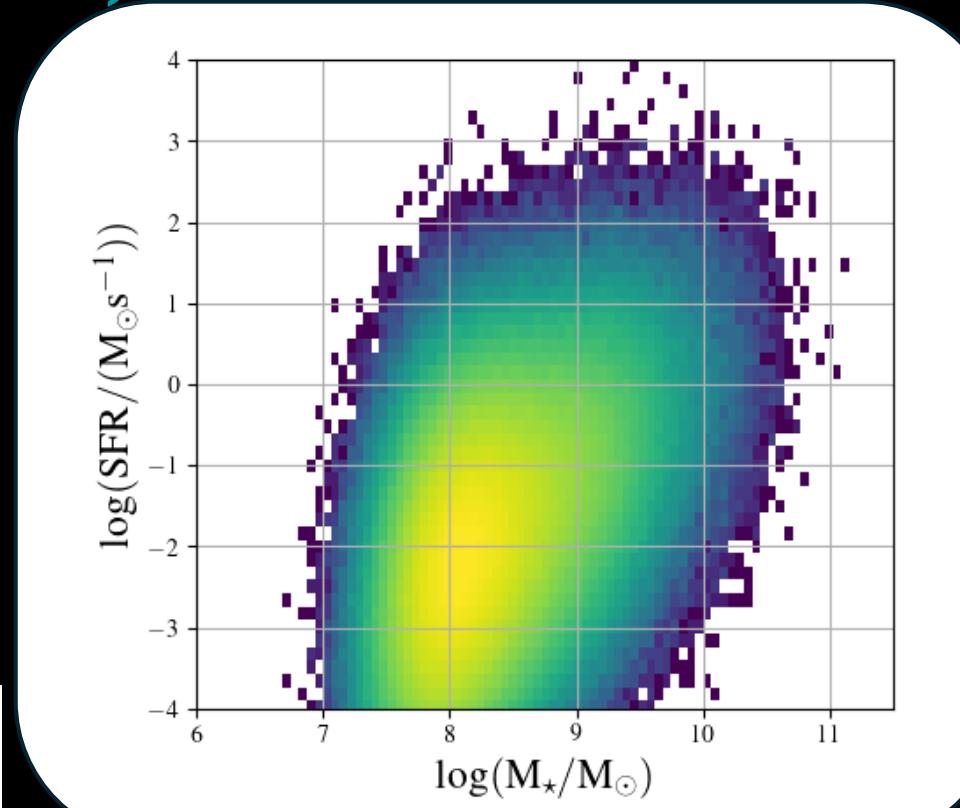
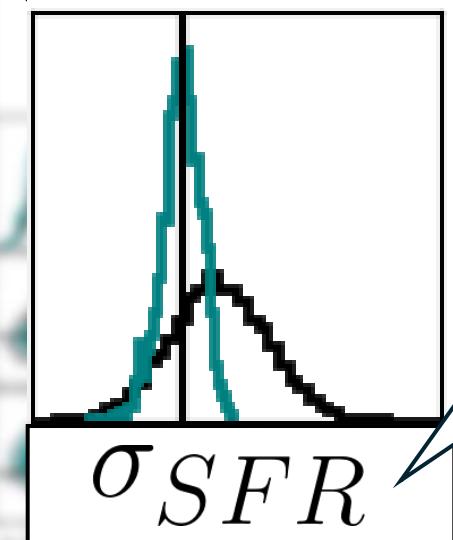
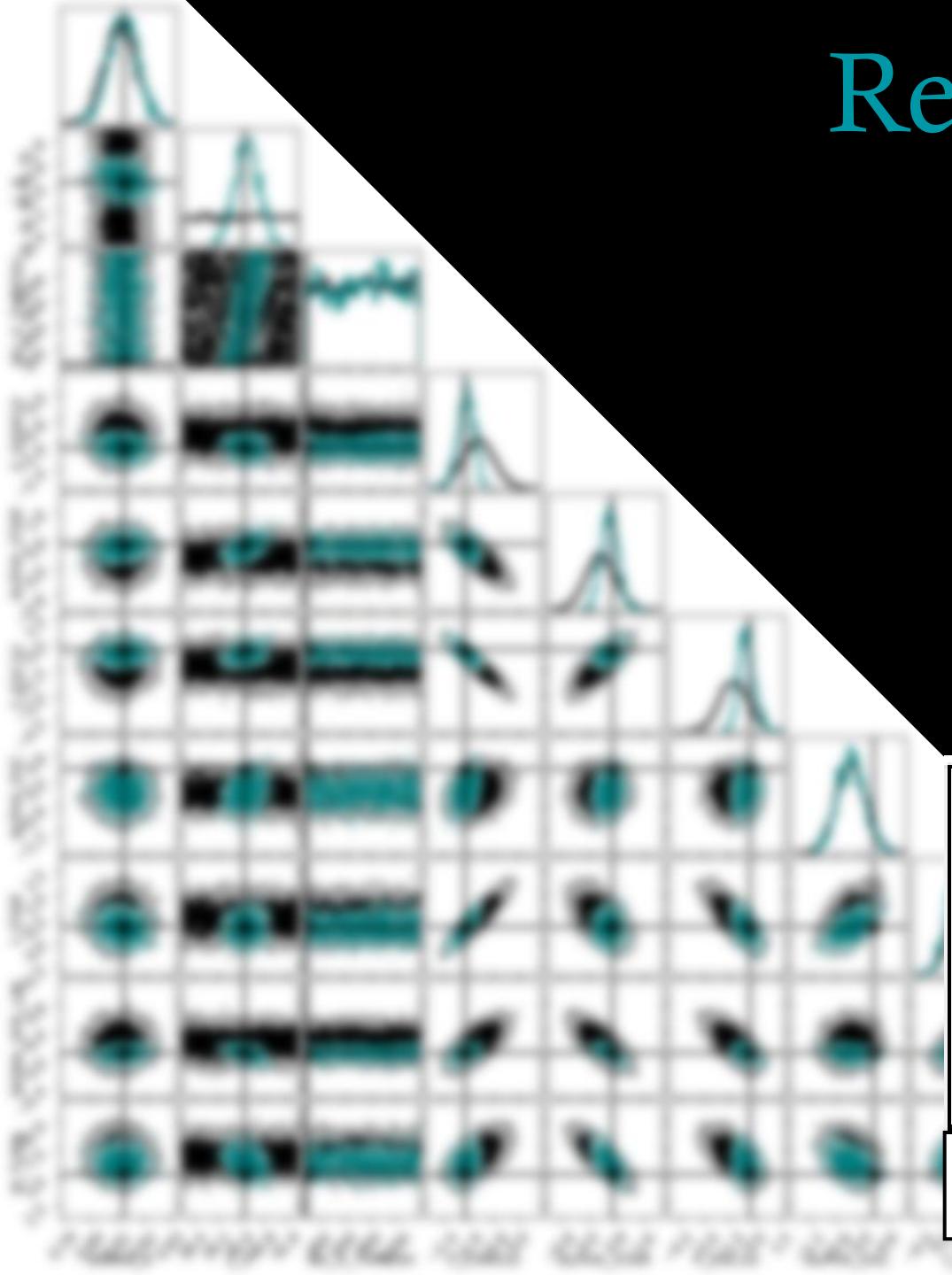
Results (1/2)



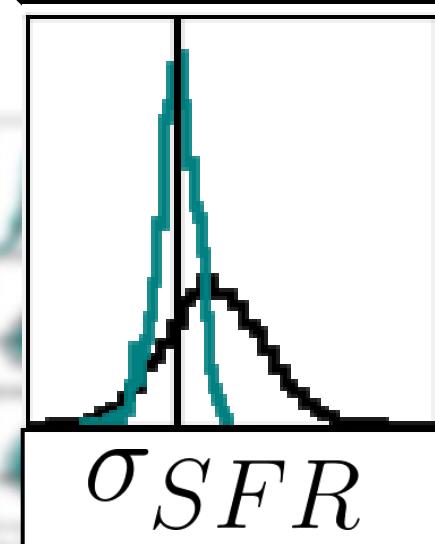
Results (1/2)



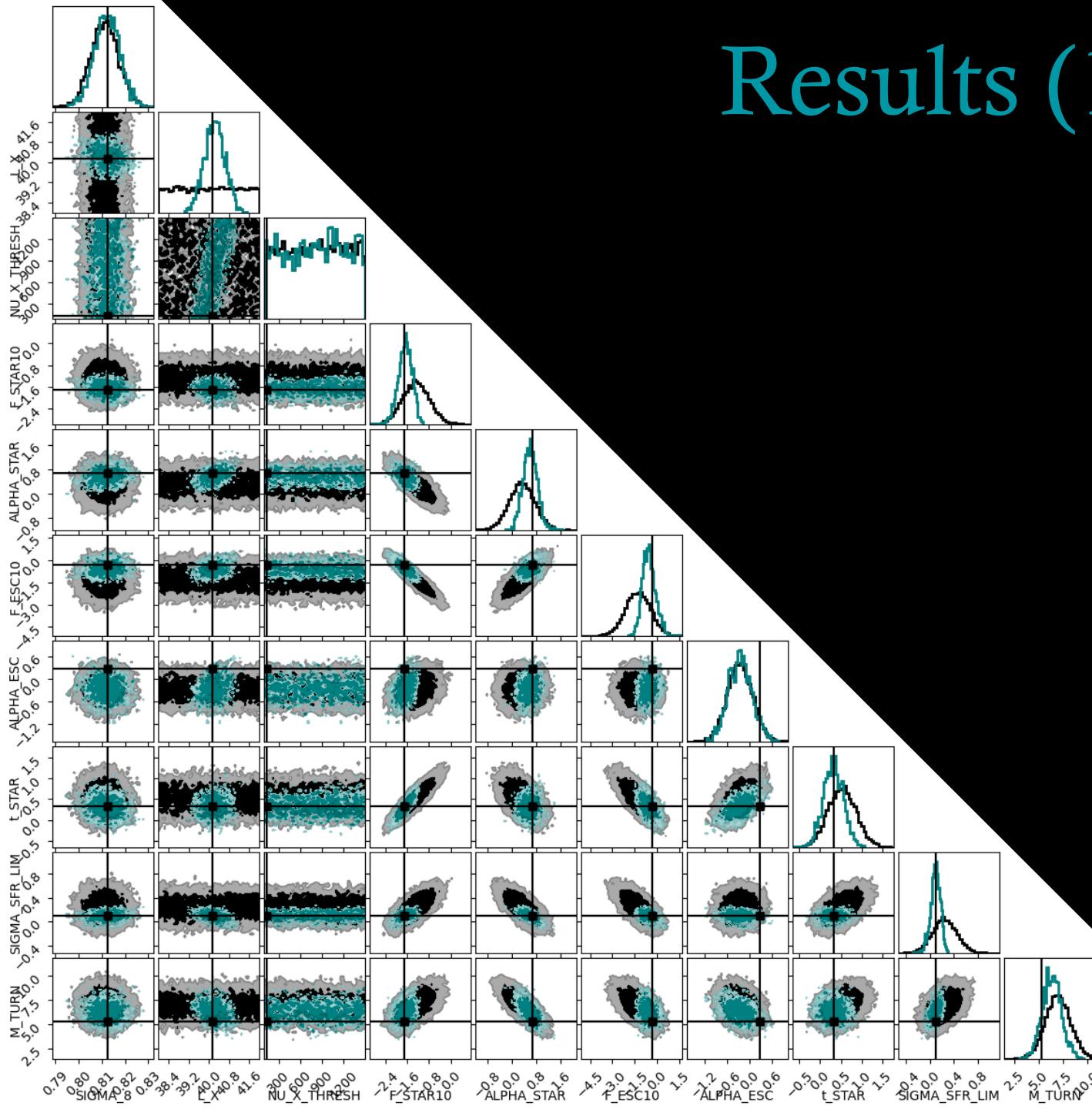
Results (1/2)



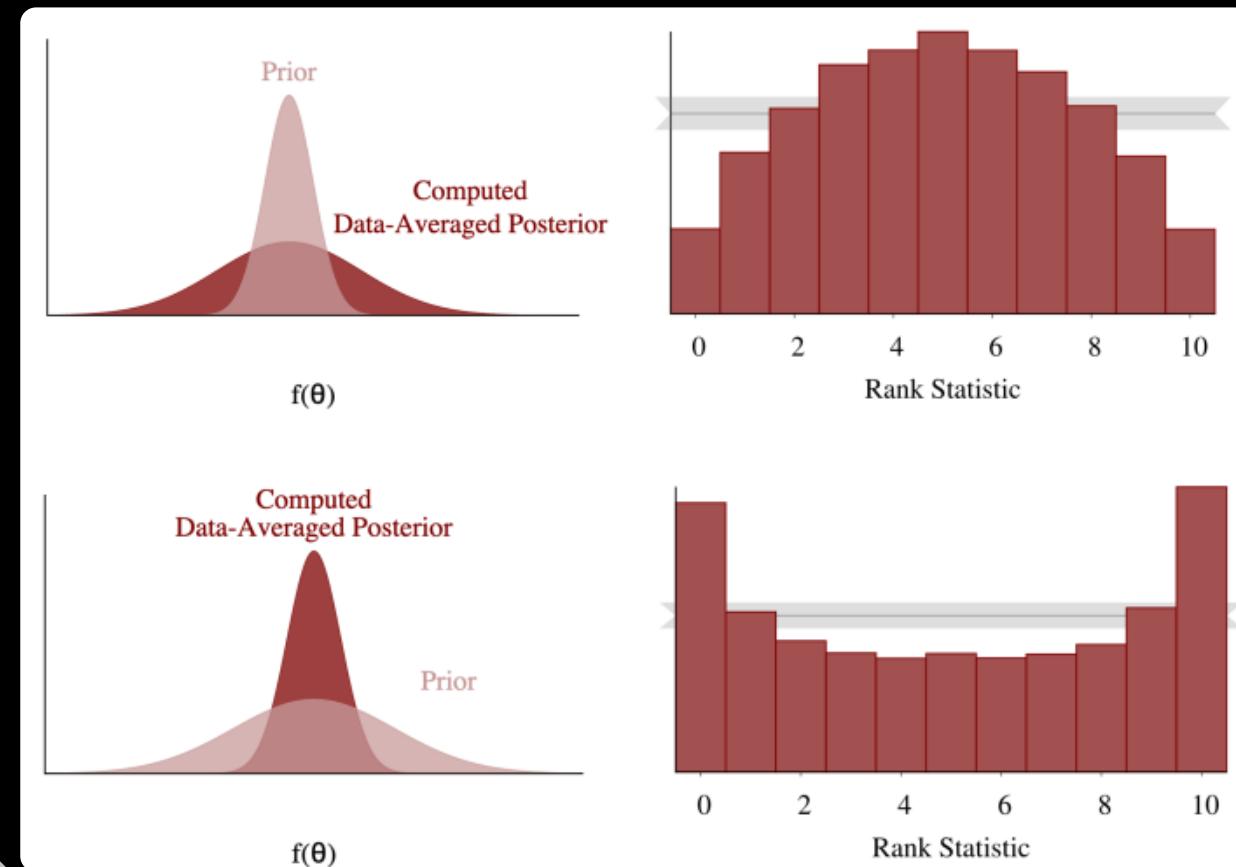
Results (1/2)



Results (1/2)

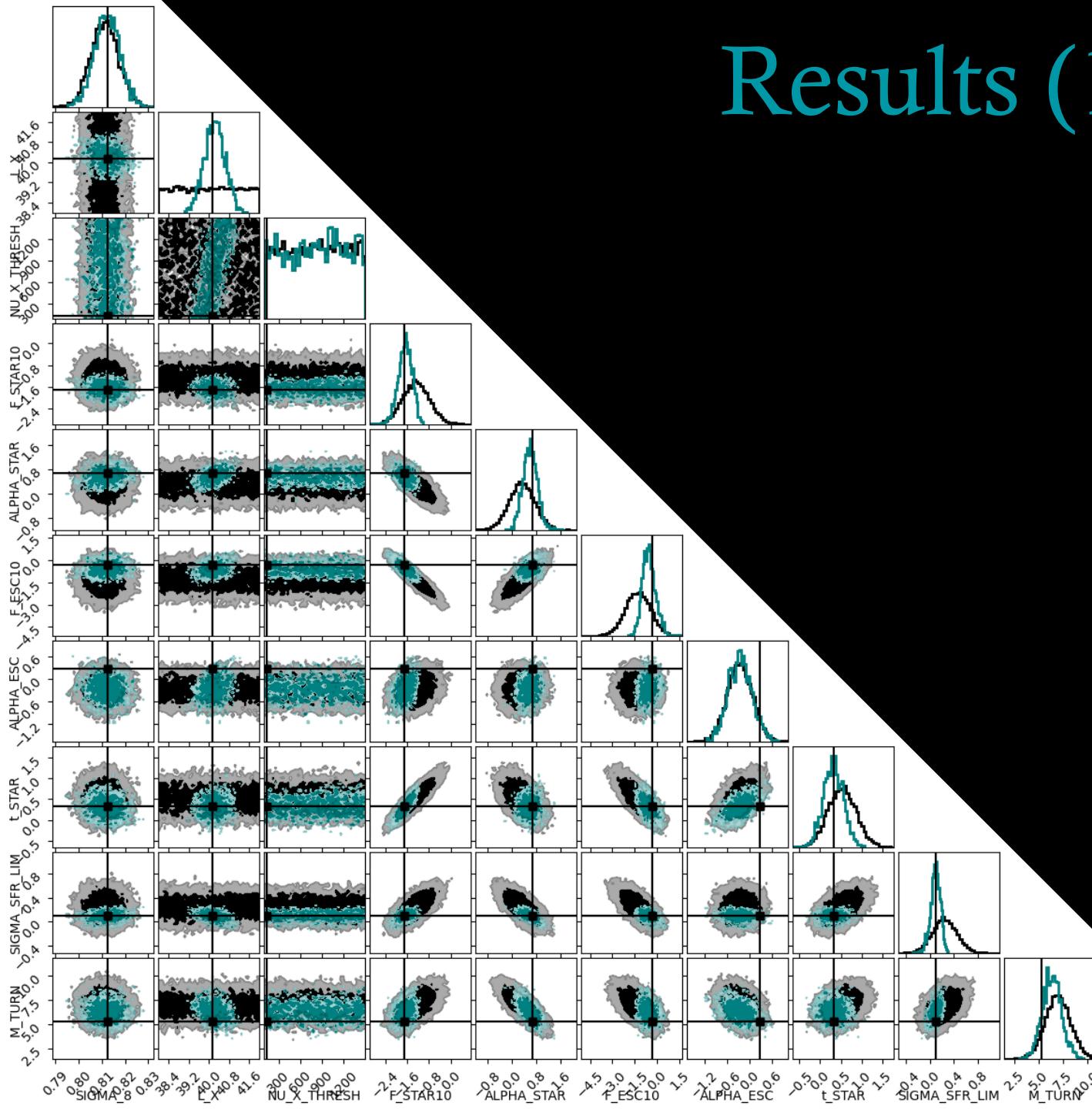


Results (1/2)

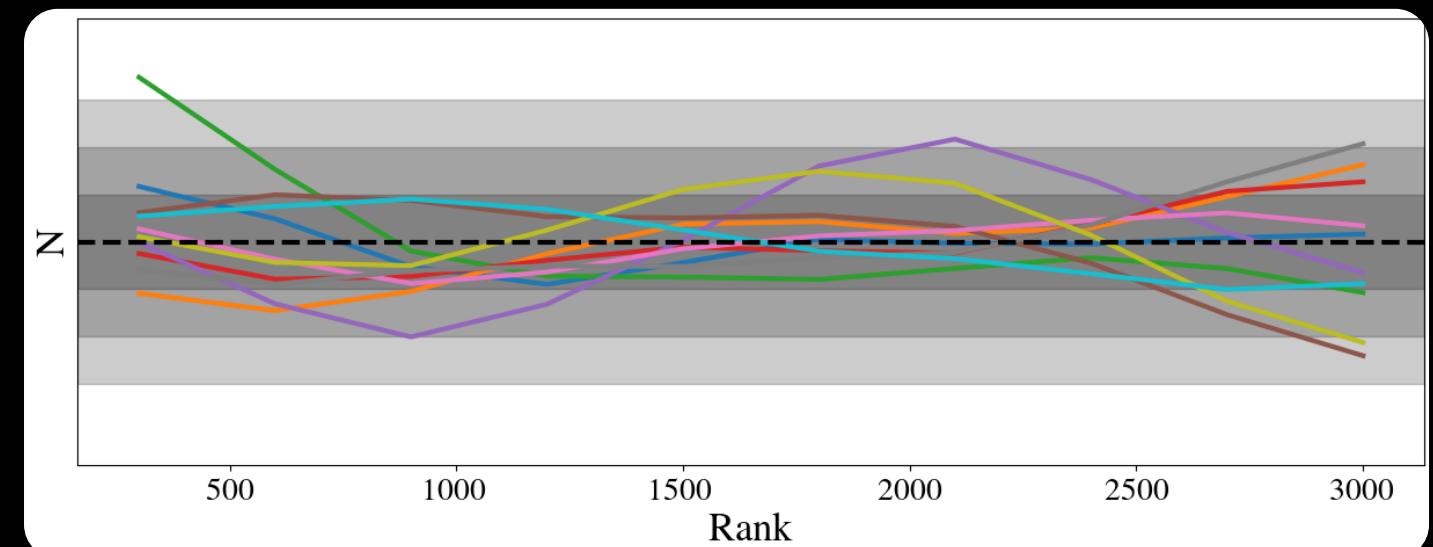
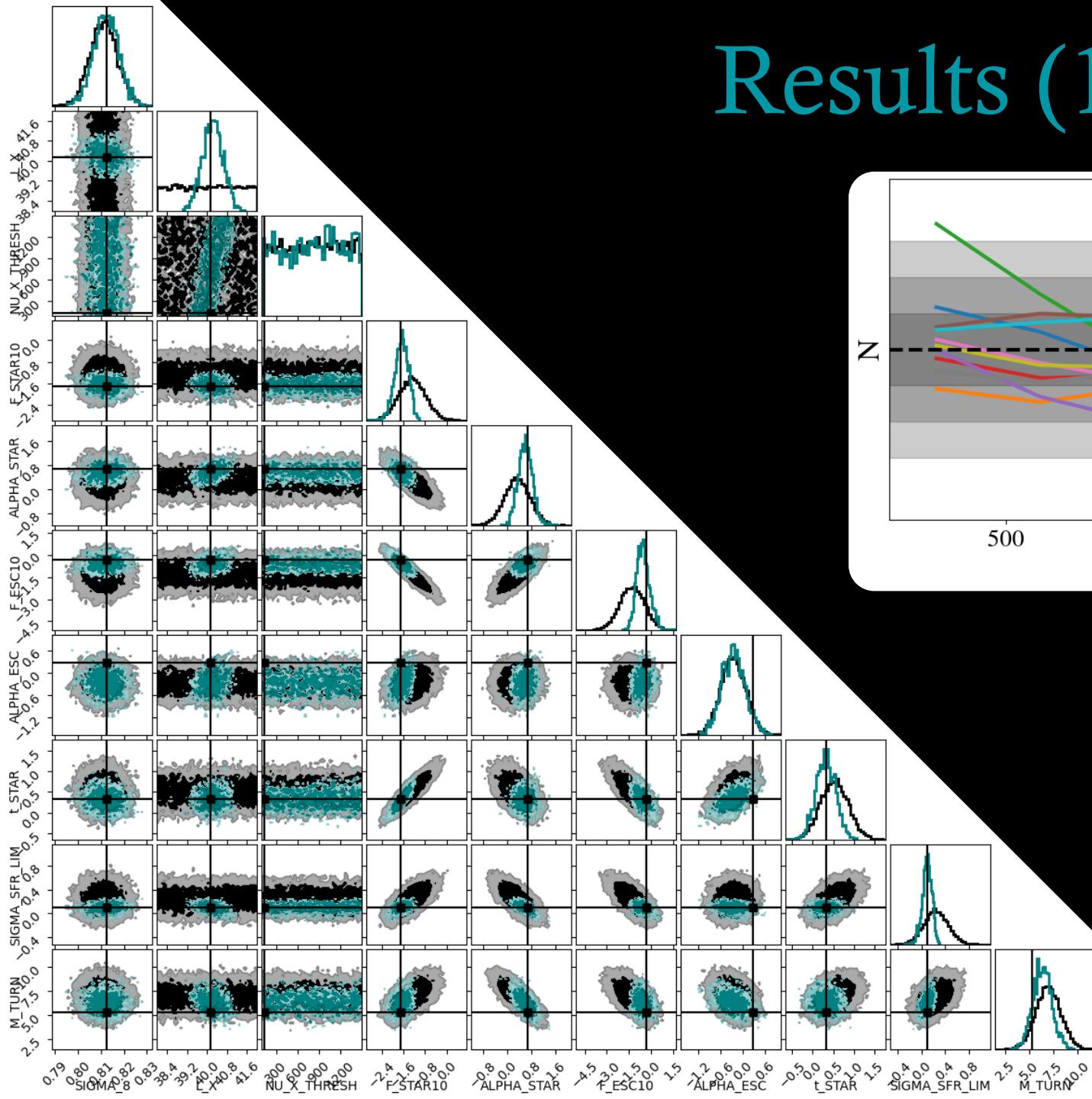


Talts+2018

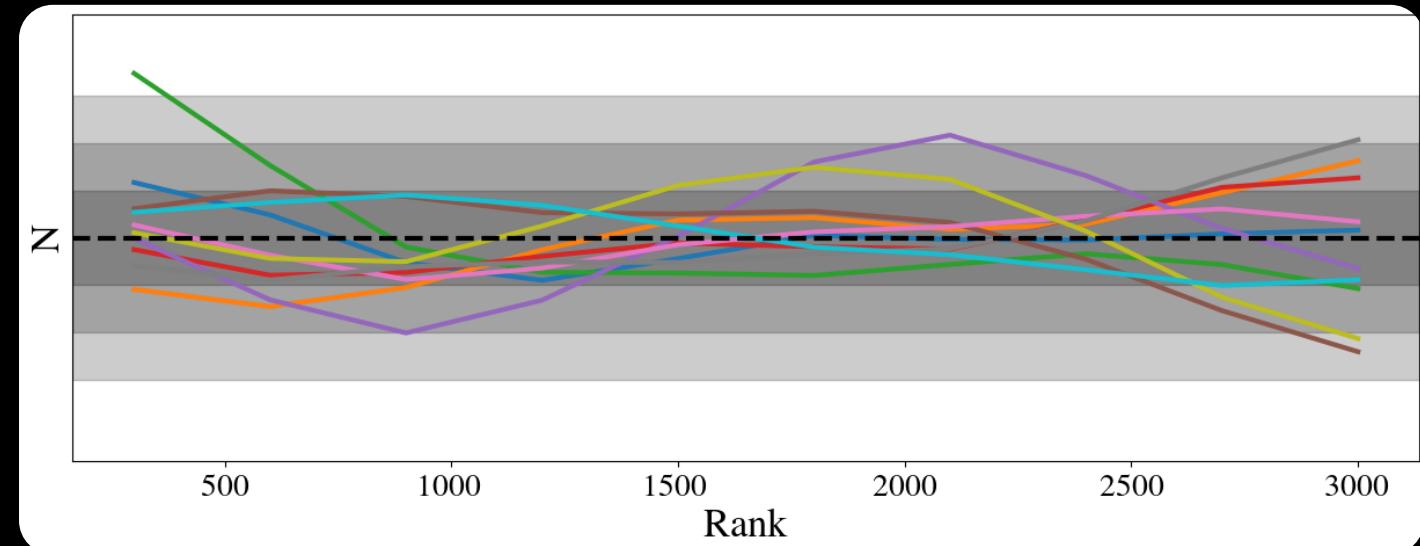
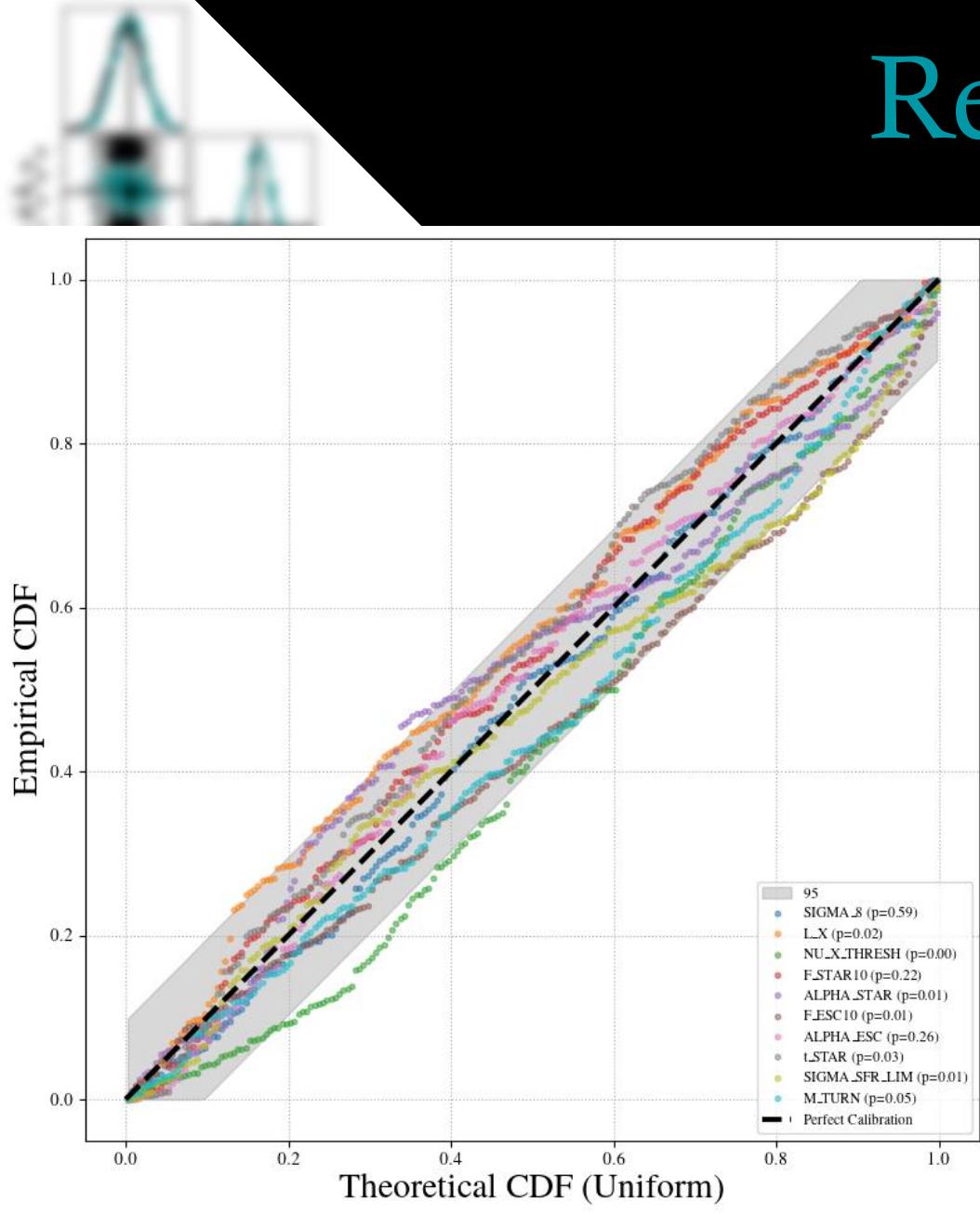
Results (1/2)



Results (1/2)



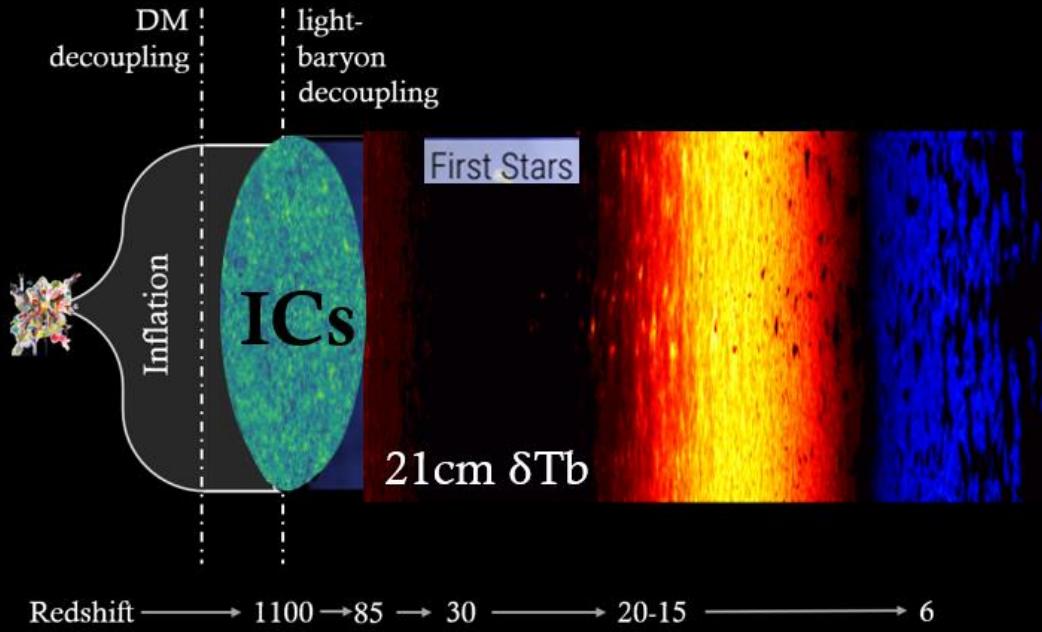
Results (1/2)



Recap

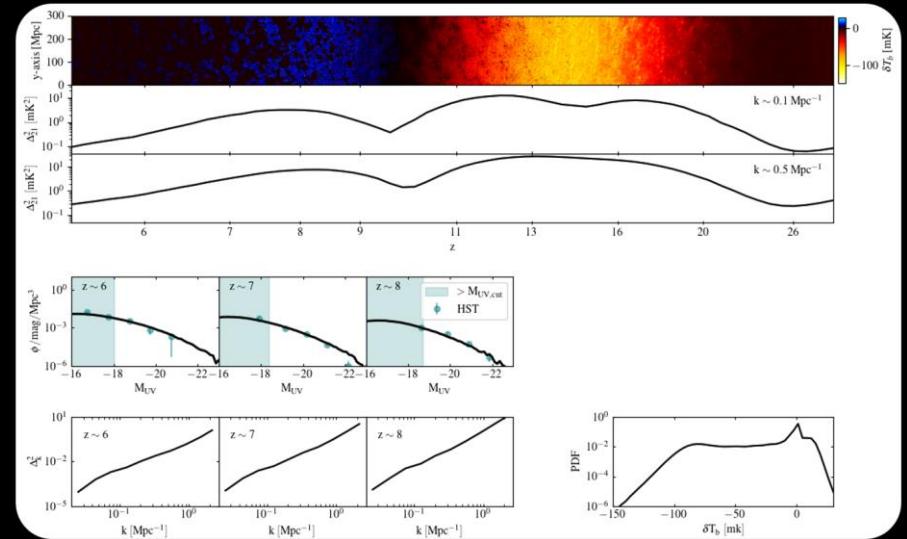
Recap

Recap

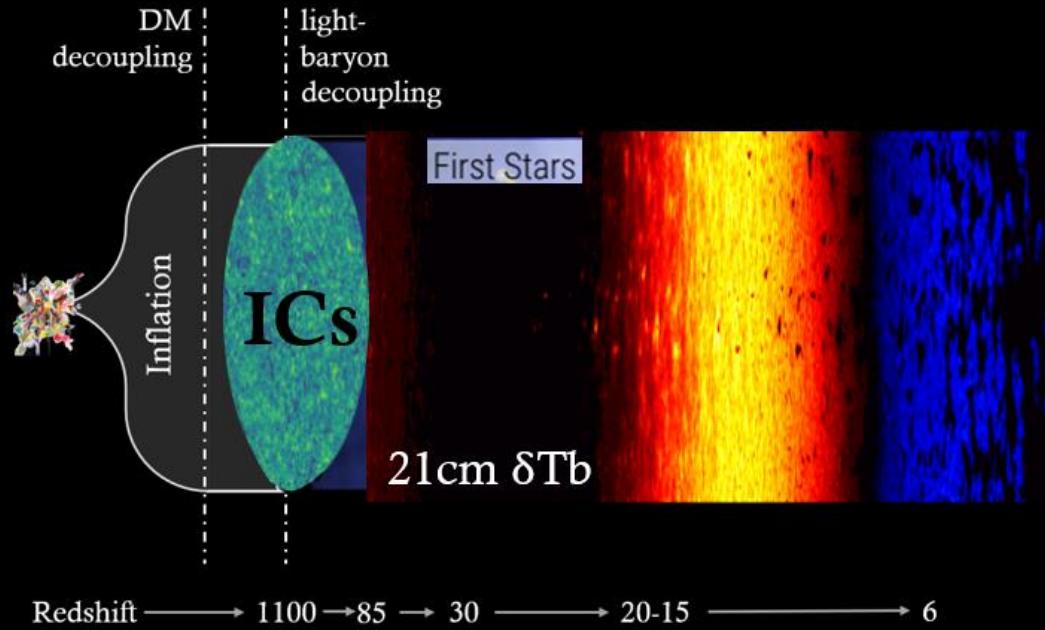


Parameters encoding physics

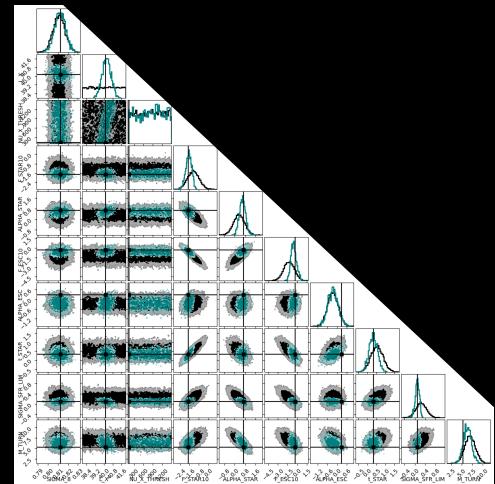
Observables



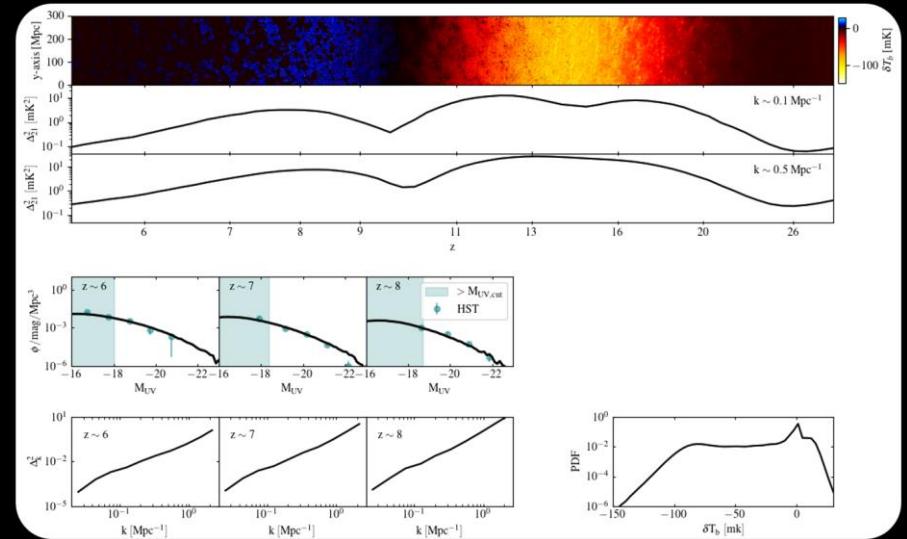
Recap



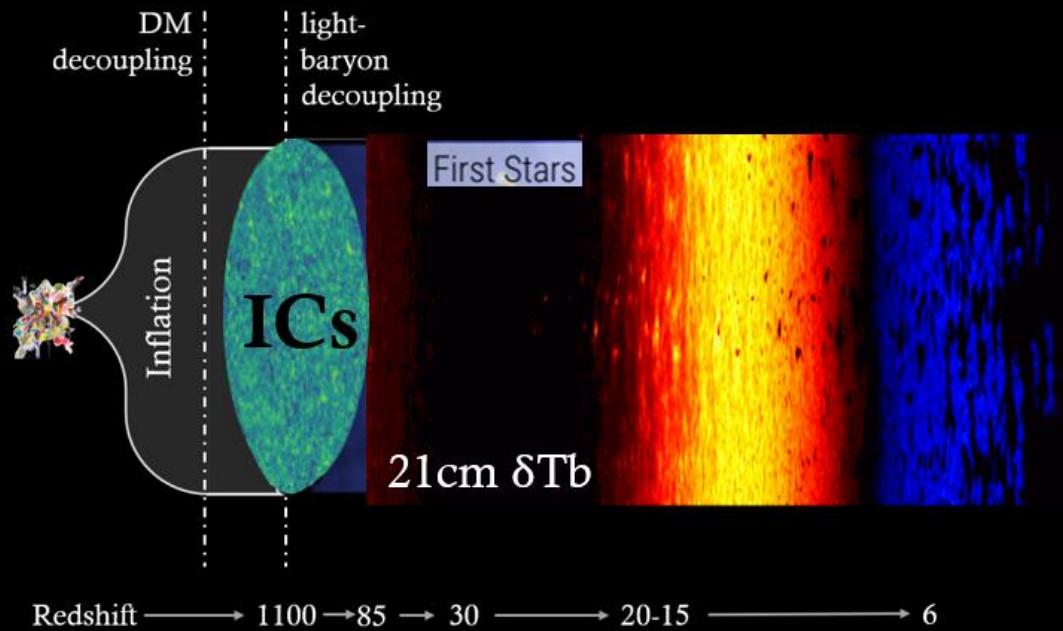
Parameters encoding physics



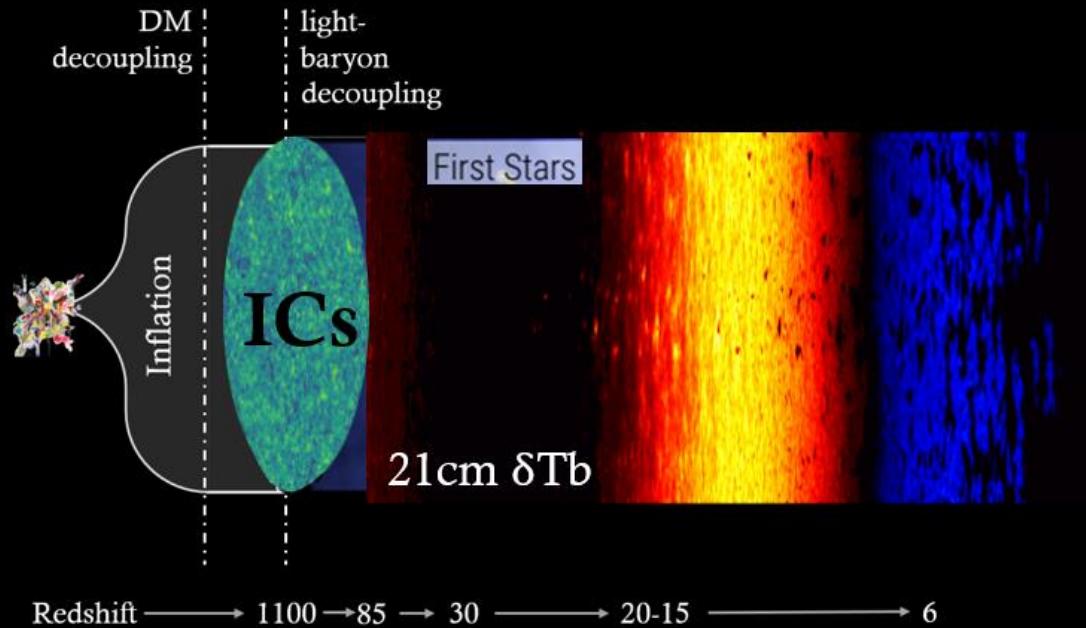
Observables



Recap

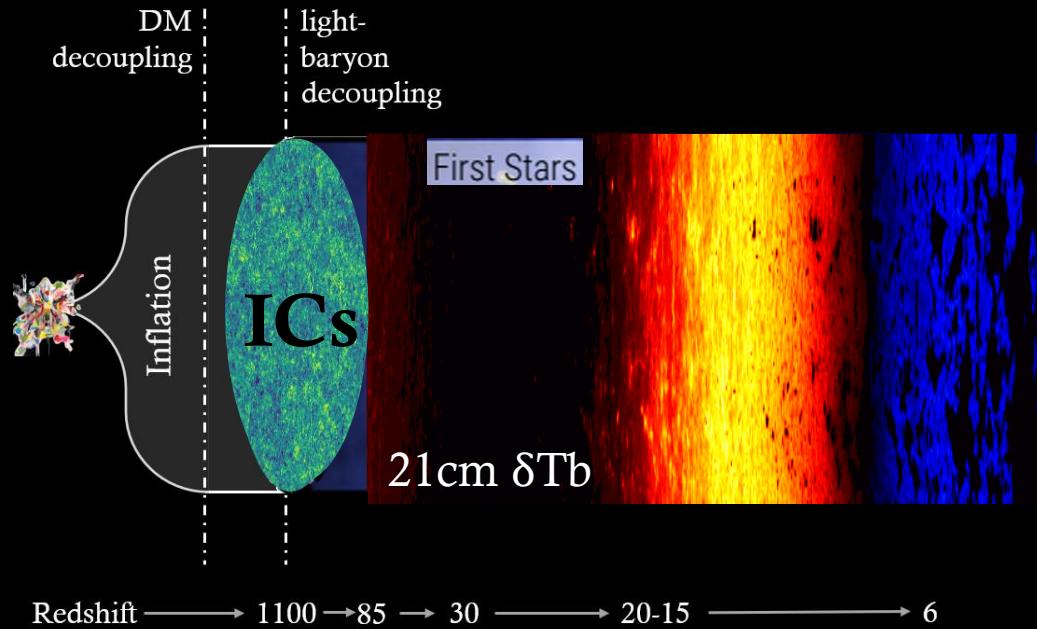


Recap



What about ICs?

Recap

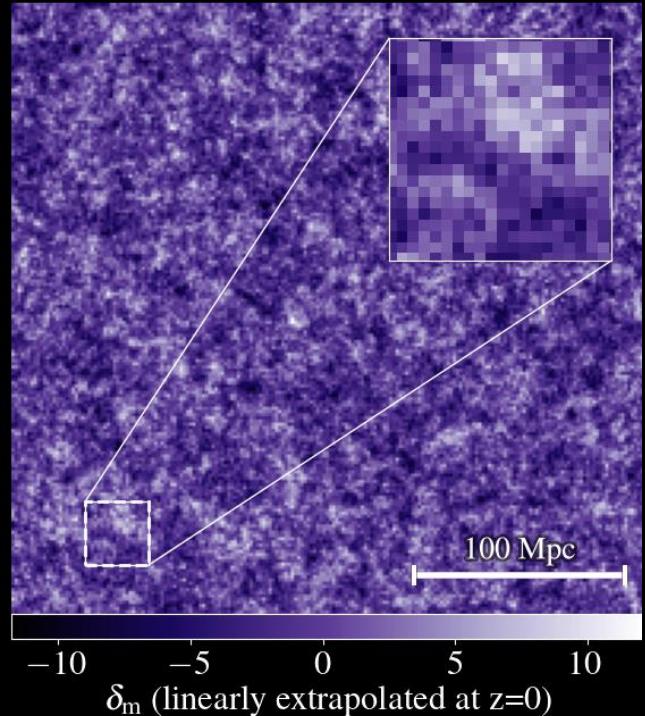


What about ICs?

Extra: ICs

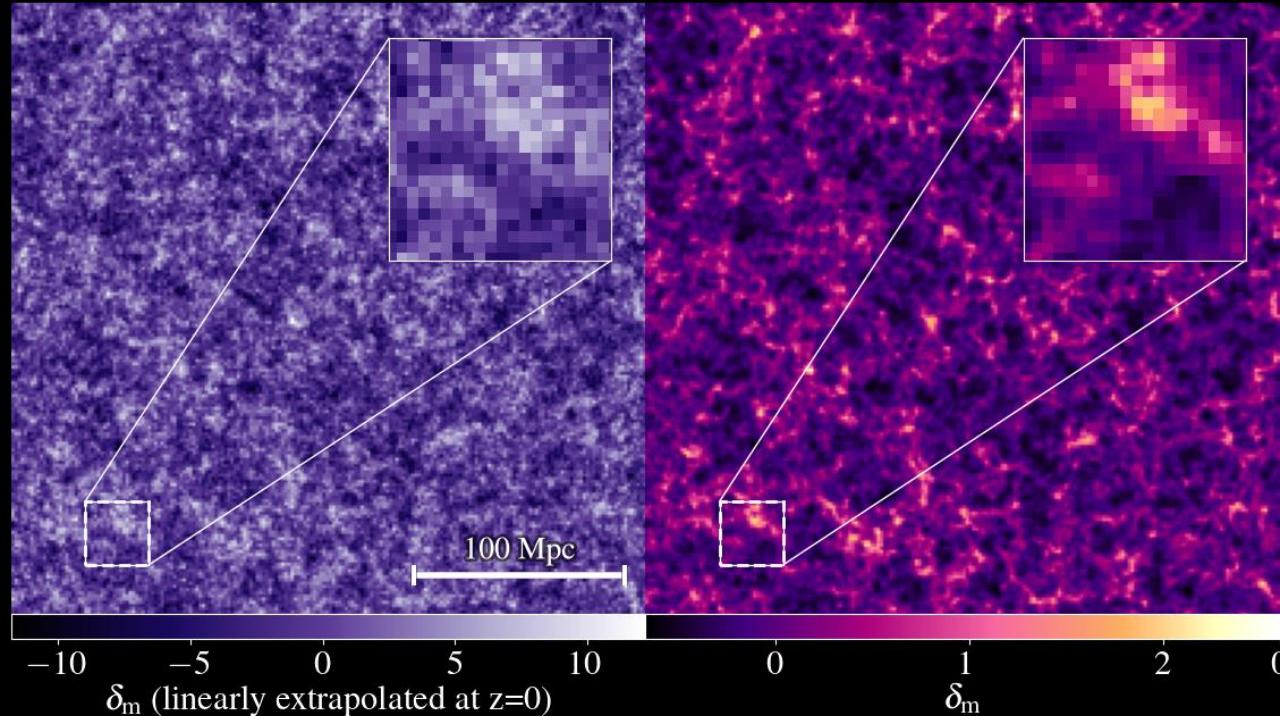
ICs

Initial Conditions



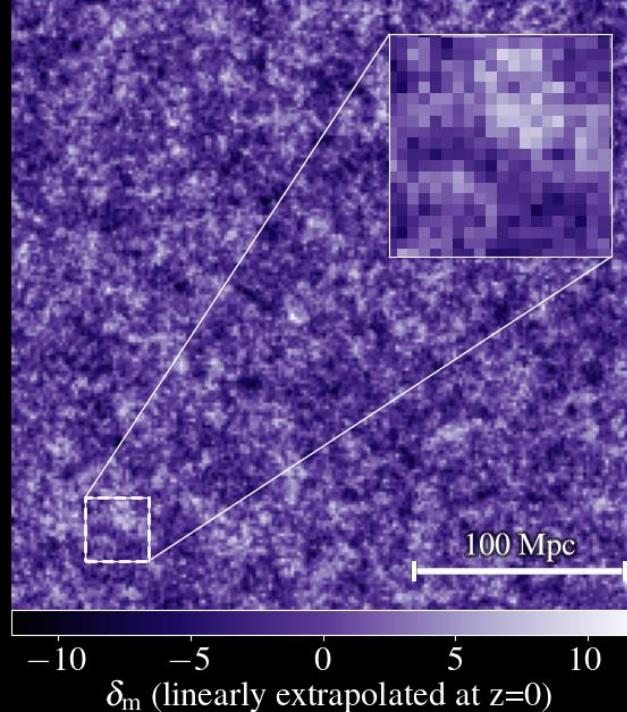
ICs

Initial Conditions

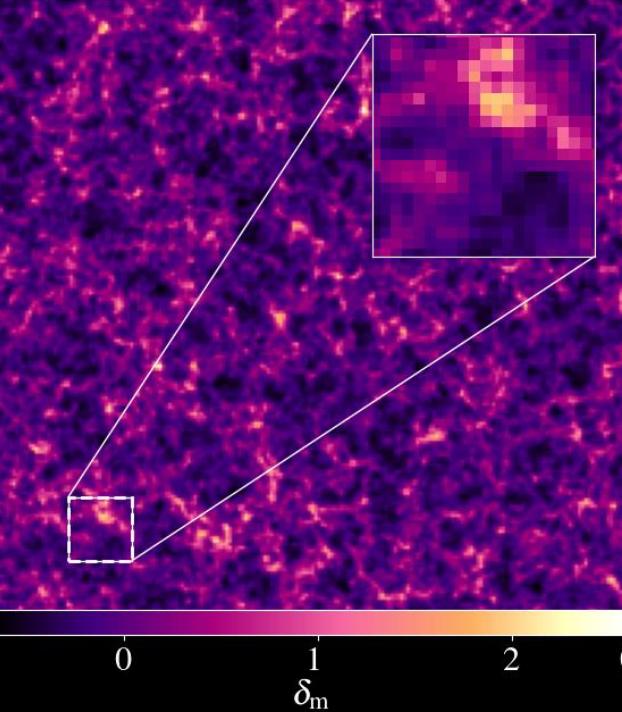


ICs

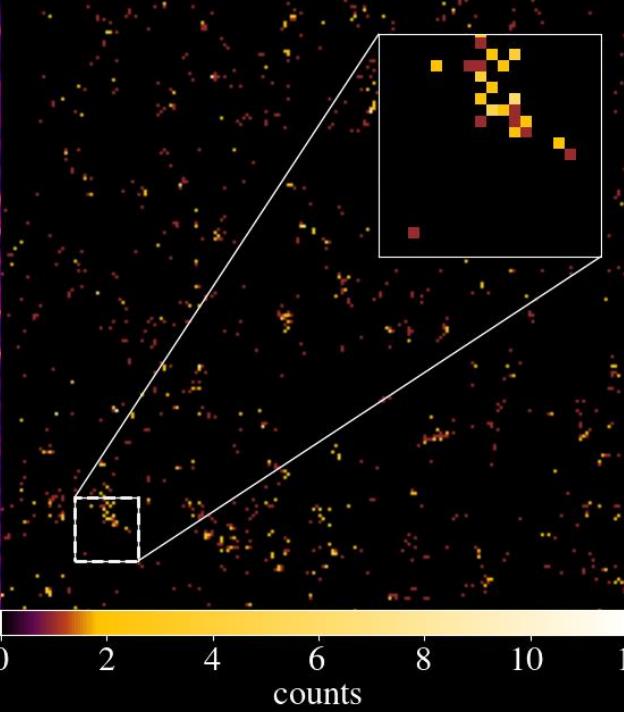
Initial Conditions



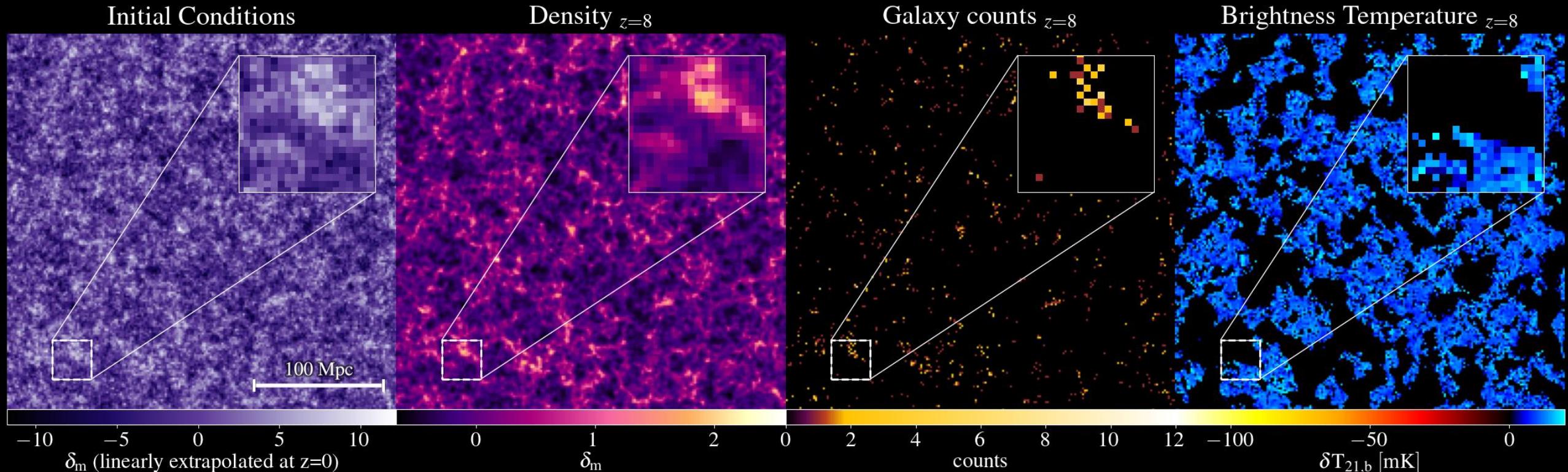
Density $z=8$



Galaxy counts $z=8$

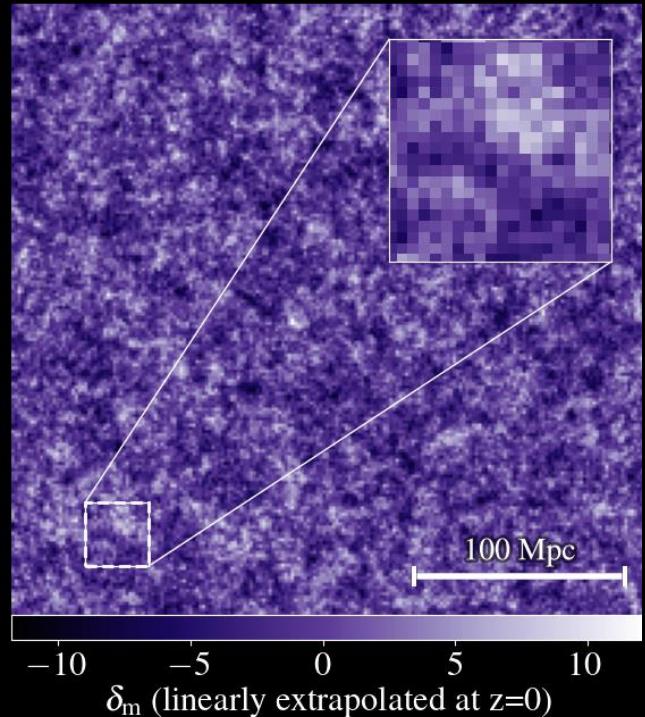


ICs

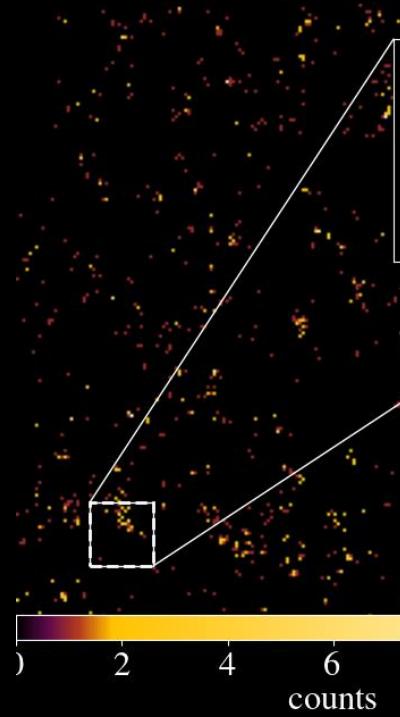


ICs

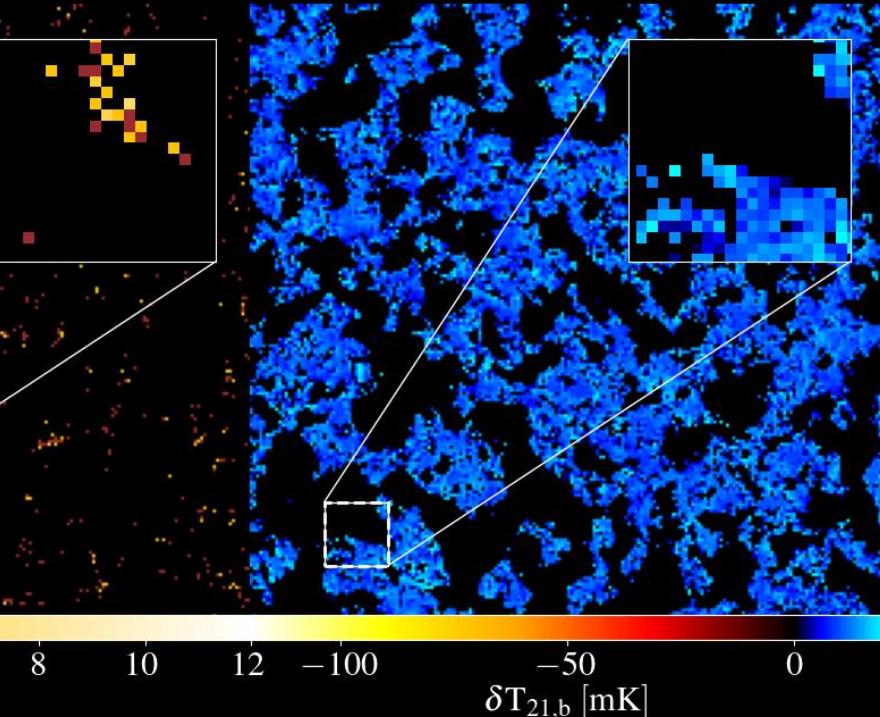
Initial Conditions



Galaxy counts $z=8$



Brightness Temperature $z=8$



Method

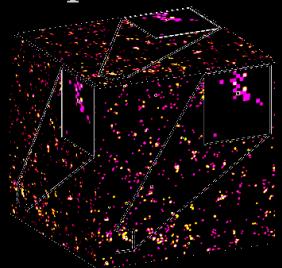
Training

Inference

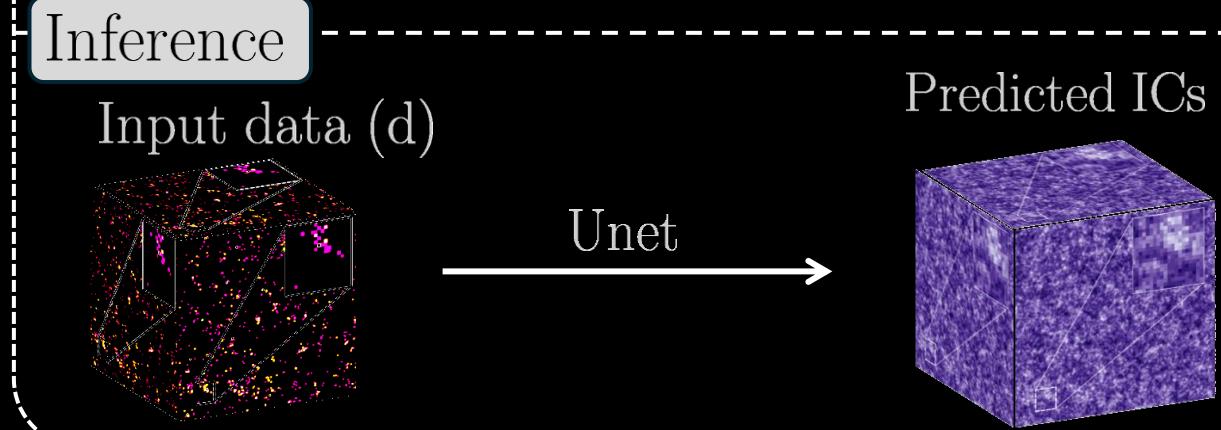
Training

Inference

Input data (d)



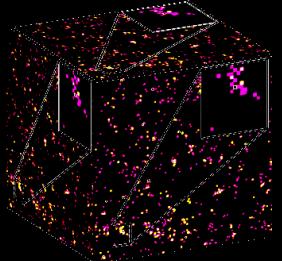
Training



Training

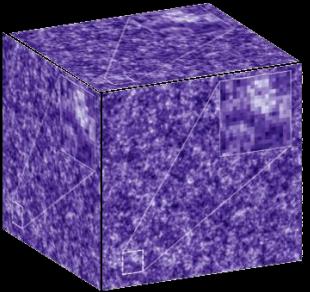
Inference

Input data (d)



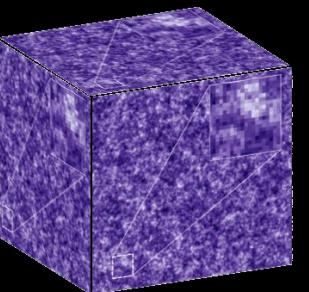
Unet

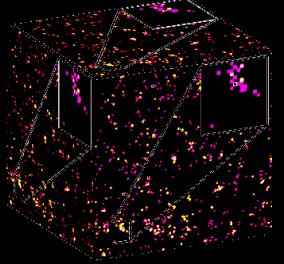
Predicted ICs



+

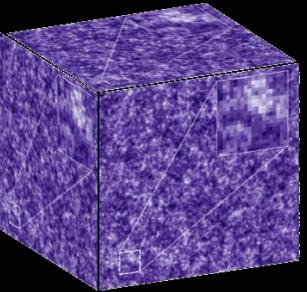
Uncertainty realization



Training**Inference**Input data (d)

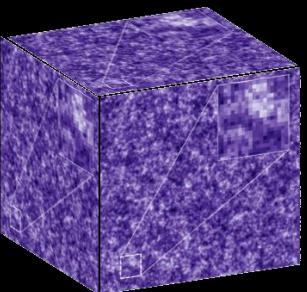
Unet

Predicted ICs



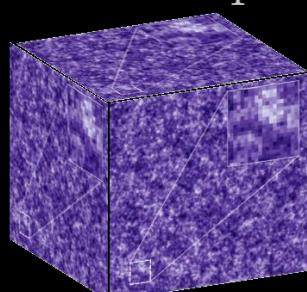
+

Uncertainty realization



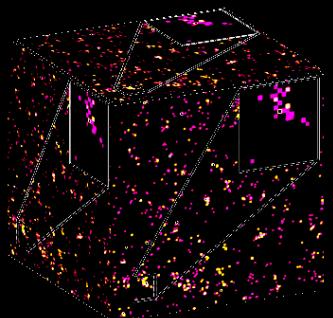
→

ICs sample



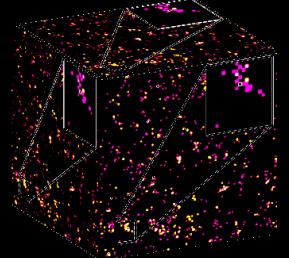
Training

Input data (d)



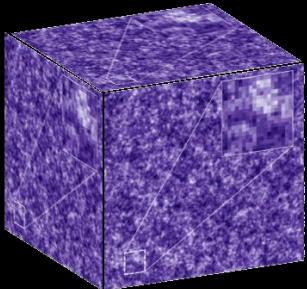
Inference

Input data (d)



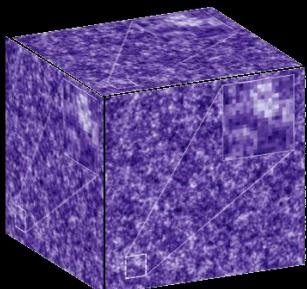
Unet

Predicted ICs



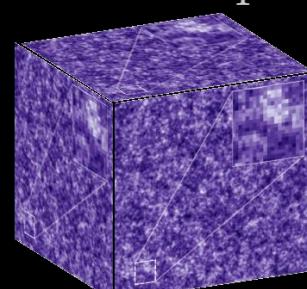
+

Uncertainty realization



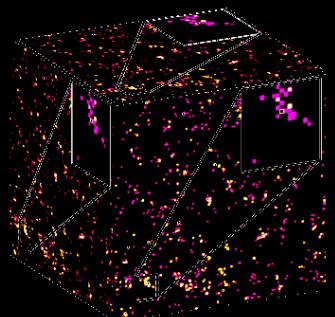
→

ICs sample



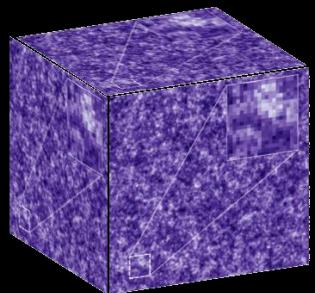
Training

Input data (d)



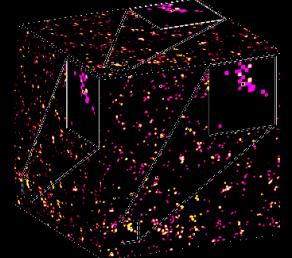
Unet

Predicted ICs



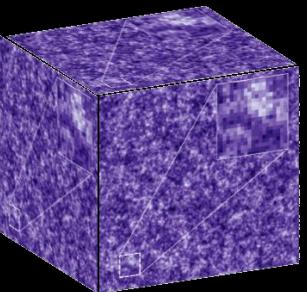
Inference

Input data (d)



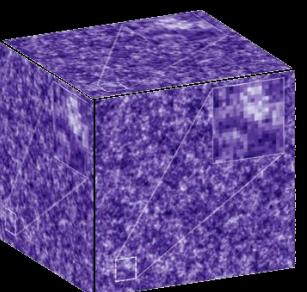
Unet

Predicted ICs



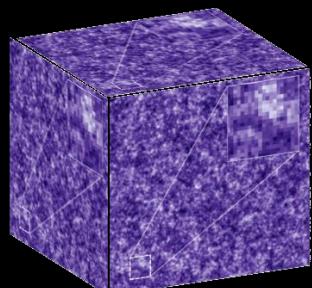
+

Uncertainty realization



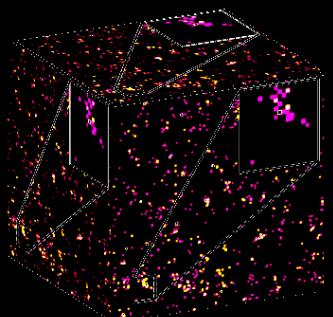
→

ICs sample



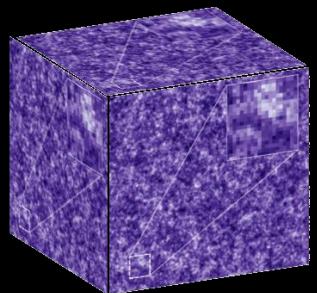
Training

Input data (d)



Unet

Predicted ICs

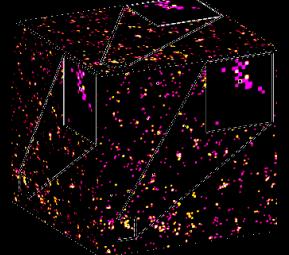


$P(\mathbf{k})_{\text{predicted}}$

$\phi(\mathbf{k})_{\text{predicted}}$

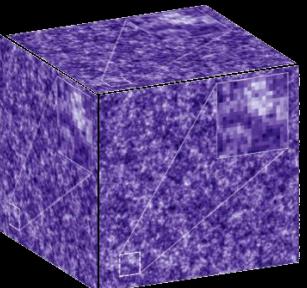
Inference

Input data (d)

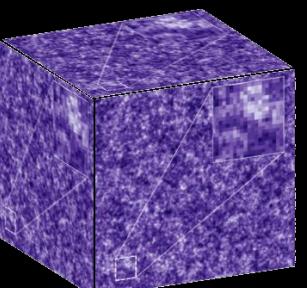


Unet

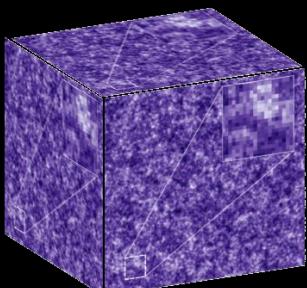
Predicted ICs



Uncertainty realization



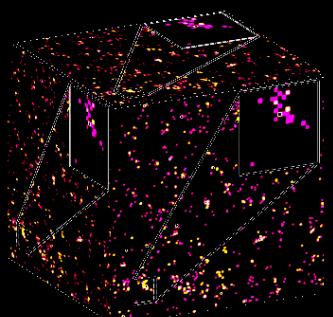
ICs sample



+

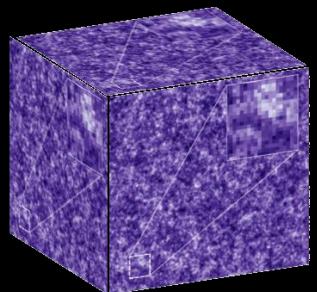
Training

Input data (d)

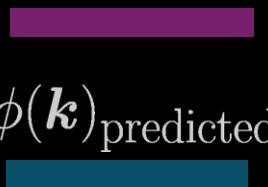


Unet

Predicted ICs



$P(\mathbf{k})_{\text{predicted}}$



$\phi(\mathbf{k})_{\text{predicted}}$



$P(\mathbf{k})_{\text{uncertainty}}$

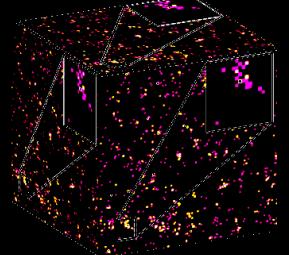


$\phi(\mathbf{k})_{\text{uncertainty}}$



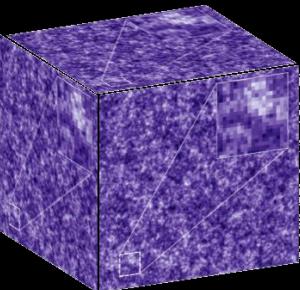
Inference

Input data (d)

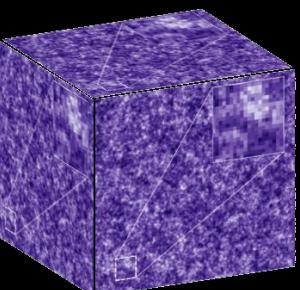


Unet

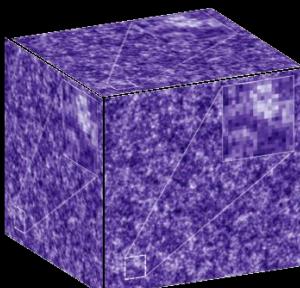
Predicted ICs



Uncertainty realization

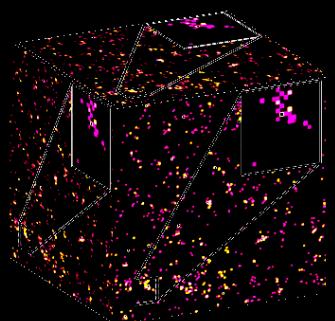


ICs sample

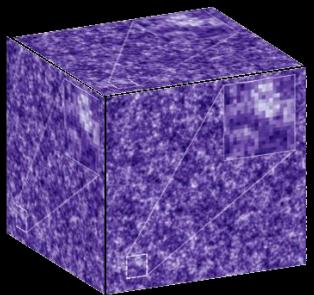


Training

Input data (d)



Predicted ICs



Unet

Conditioned or
unconditioned?

$P(\mathbf{k})_{\text{predicted}}$

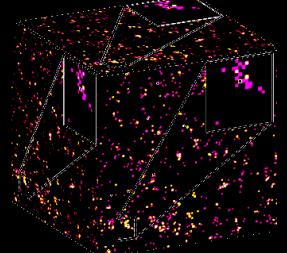
$\phi(\mathbf{k})_{\text{predicted}}$

$P(\mathbf{k})_{\text{uncertainty}}$

$\phi(\mathbf{k})_{\text{uncertainty}}$

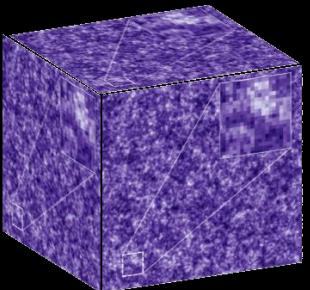
Inference

Input data (d)

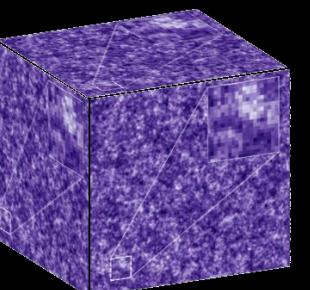


Unet

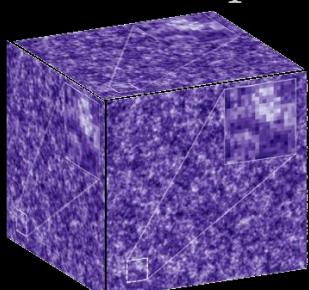
Predicted ICs



Uncertainty realization



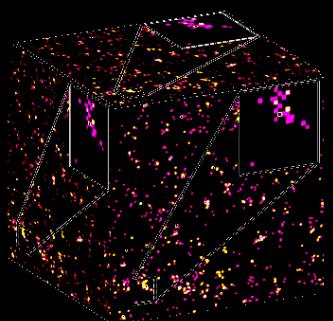
ICs sample



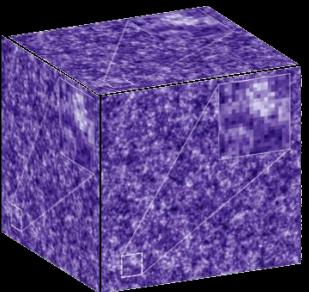
+

Training

Input data (d)



Predicted ICs



Unet

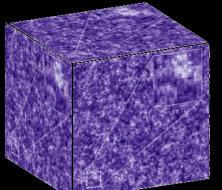
Conditioned or
unconditioned?

$P(\mathbf{k})_{\text{predicted}}$

$\phi(\mathbf{k})_{\text{predicted}}$

$P(\mathbf{k})_{\text{uncertainty}}$

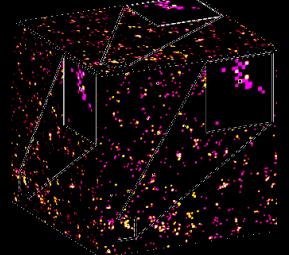
$\phi(\mathbf{k})_{\text{uncertainty}}$



True ICs

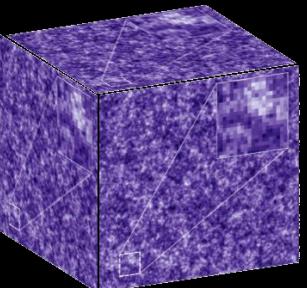
Inference

Input data (d)

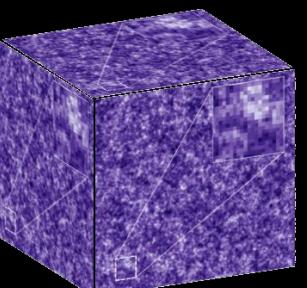


Unet

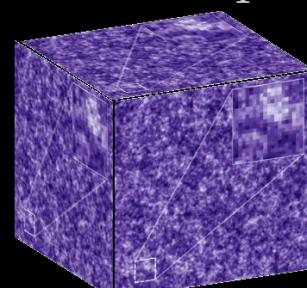
Predicted ICs



Uncertainty realization

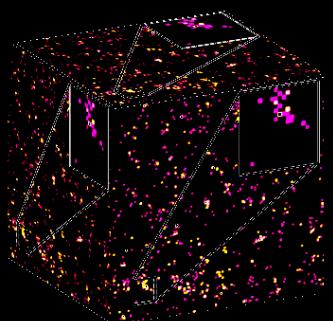


ICs sample

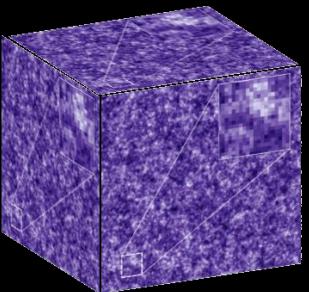


Training

Input data (d)



Predicted ICs



Unet

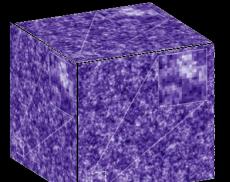
Conditioned or
unconditioned?

$P(\mathbf{k})_{\text{predicted}}$

$\phi(\mathbf{k})_{\text{predicted}}$

$P(\mathbf{k})_{\text{uncertainty}}$

$\phi(\mathbf{k})_{\text{uncertainty}}$



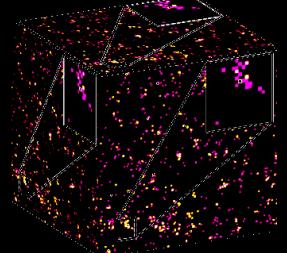
True ICs

$P(\mathbf{k})_{\text{true}}$

$\phi(\mathbf{k})_{\text{true}}$

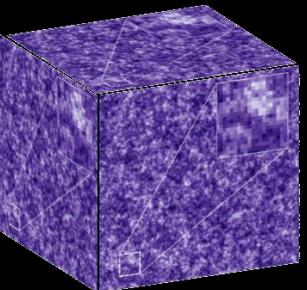
Inference

Input data (d)

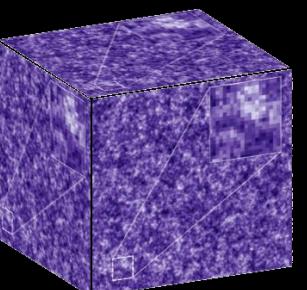


Unet

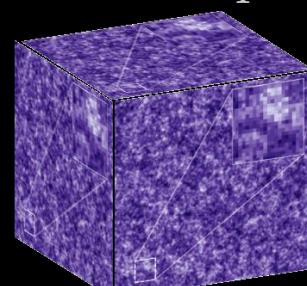
Predicted ICs



Uncertainty realization



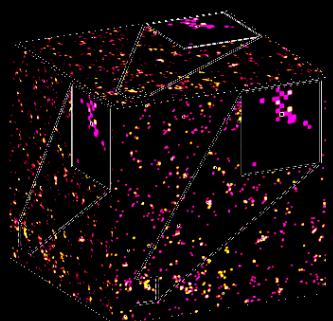
ICs sample



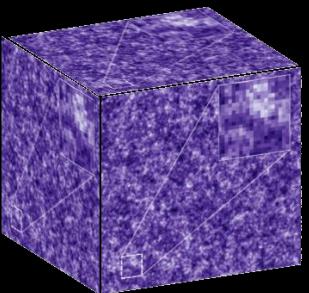
+

Training

Input data (\mathbf{d})



Predicted ICs



Unet

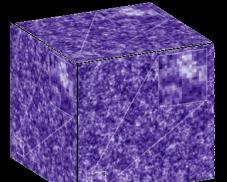
Conditioned or
unconditioned?

$P(\mathbf{k})_{\text{predicted}}$

$\phi(\mathbf{k})_{\text{predicted}}$

$P(\mathbf{k})_{\text{uncertainty}}$

$\phi(\mathbf{k})_{\text{uncertainty}}$



True ICs

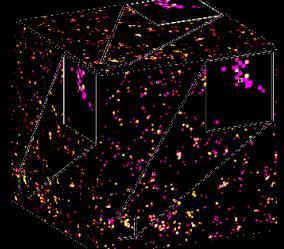
$P(\mathbf{k})_{\text{true}}$

$\phi(\mathbf{k})_{\text{true}}$

$$\mathcal{L}_{\text{oss}} = -\log[p(\boldsymbol{\theta}|\mathbf{d})]$$

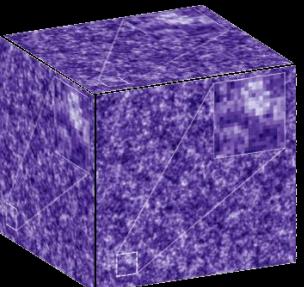
Inference

Input data (\mathbf{d})

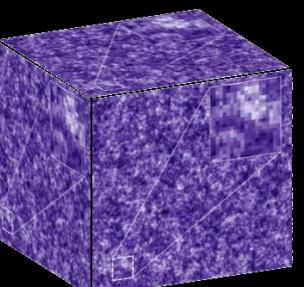


Unet

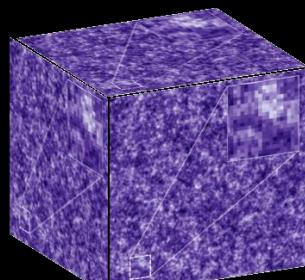
Predicted ICs



Uncertainty realization

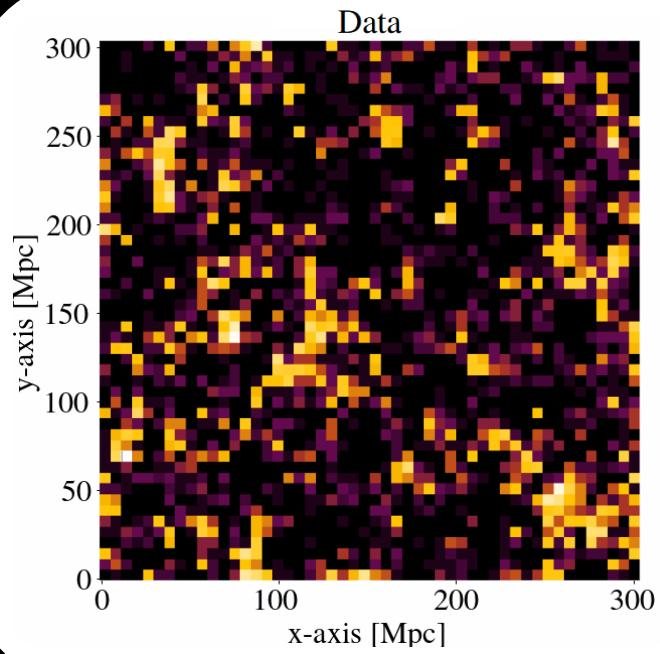


ICs sample

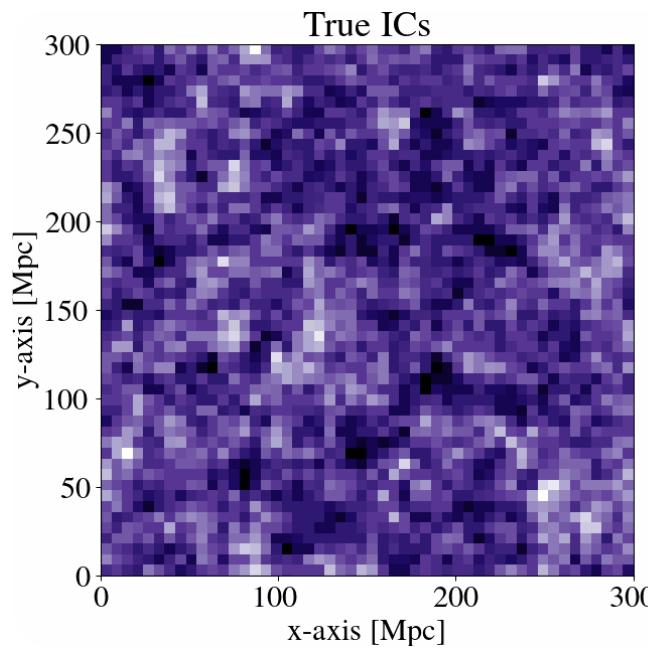
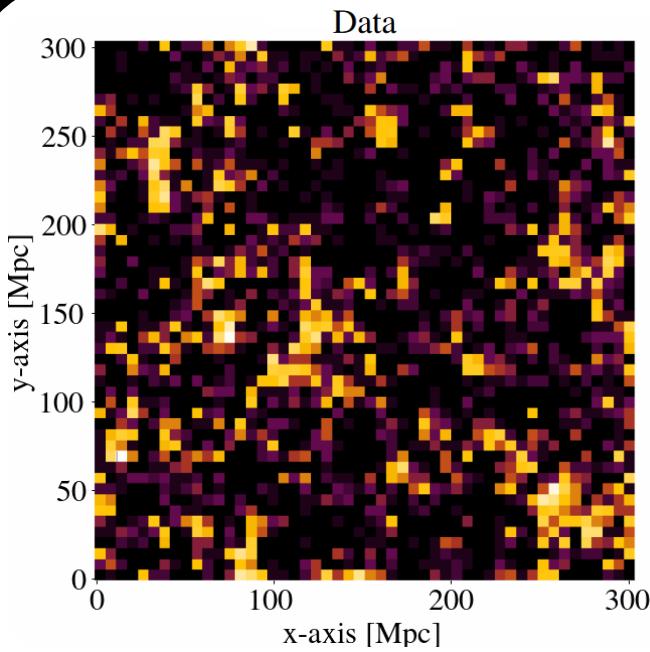


Results (2/2)

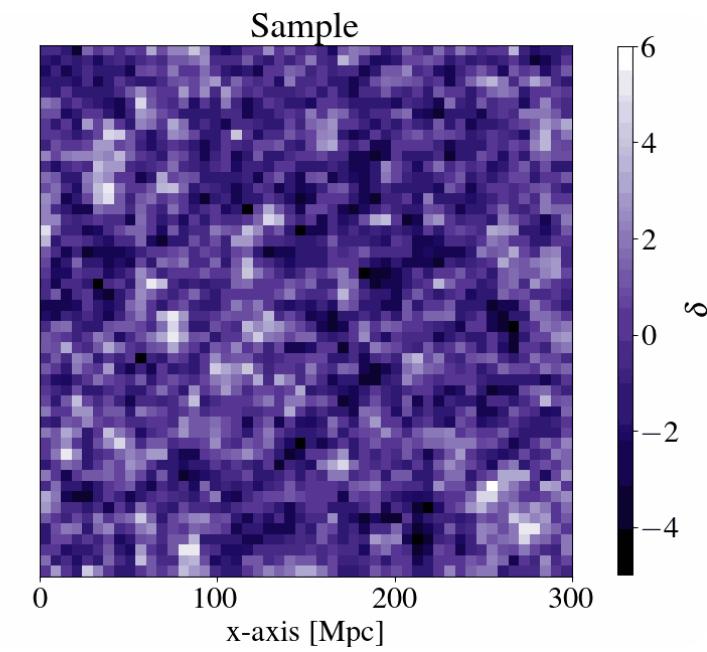
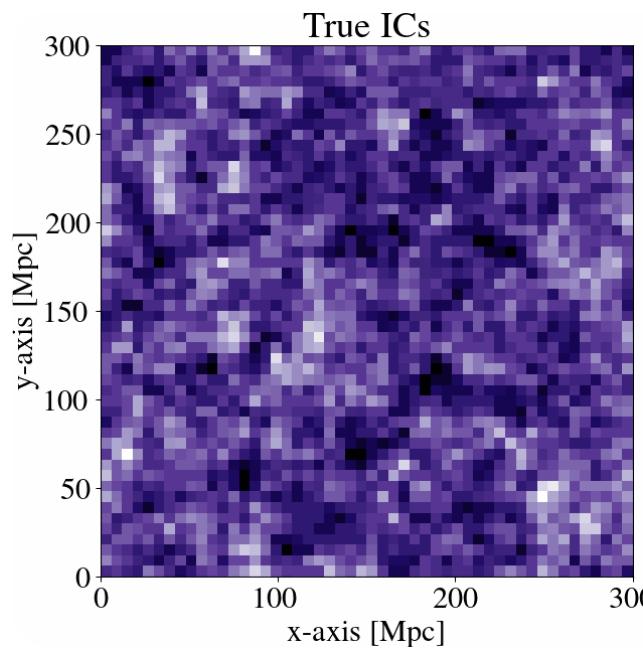
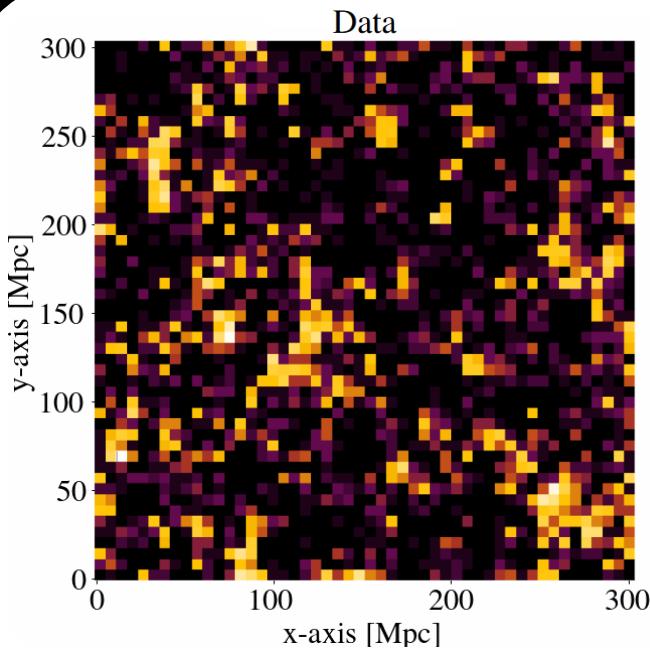
ICs



ICs



ICs



Key-takeaways...



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- Very exciting times for 21cm cosmology

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- Very exciting times for 21cm cosmology
 - Multiple tracers are a very powerful probe
 - Initial conditions are degenerate with observables but they can be probed

