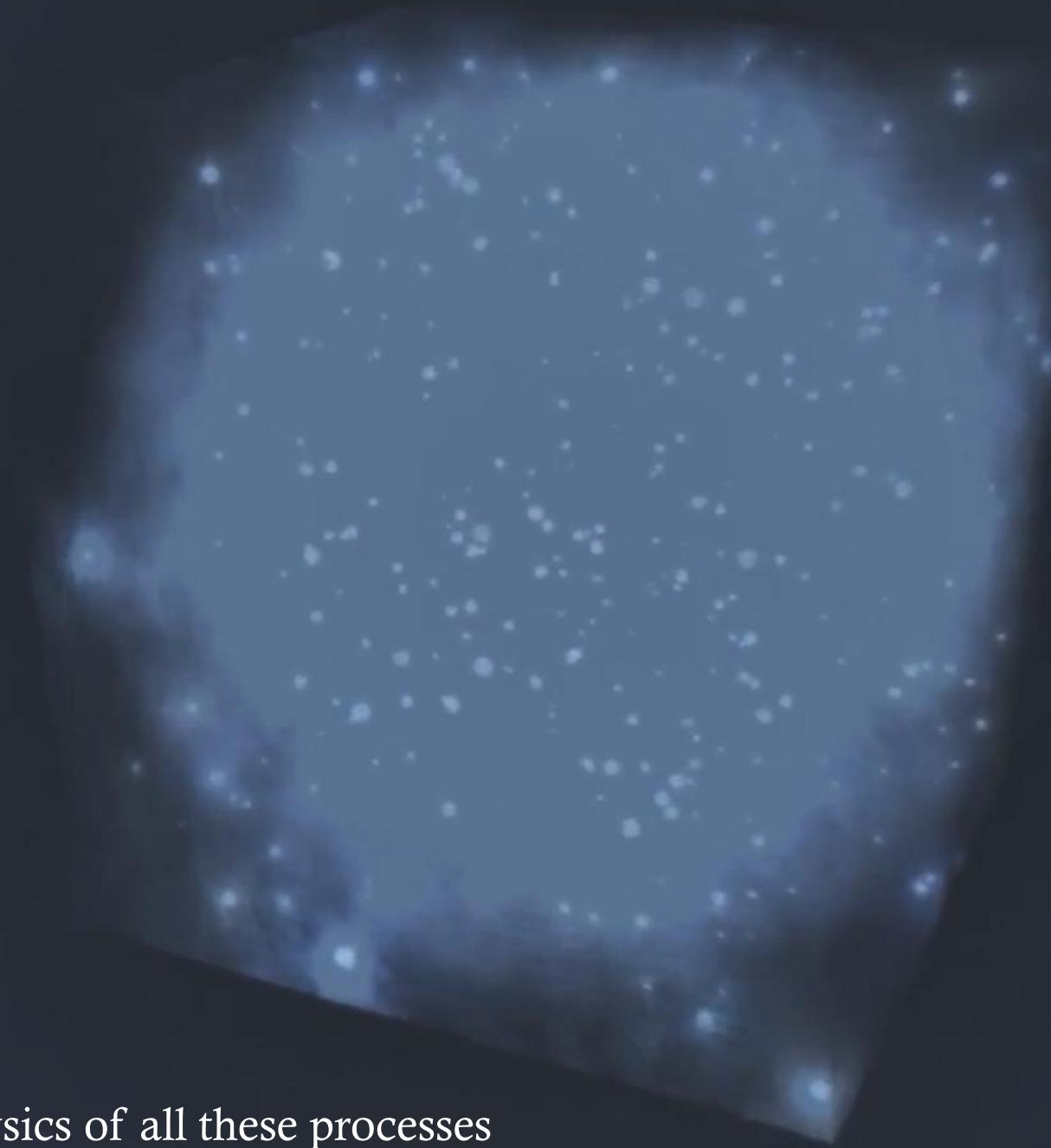


SCUOLA
NORMALE
SUPERIORE

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





We want to infer the physics of all these processes

Credit: ESO/L. Calçada

Observables







Cosmic 21-cm



Cosmic 21-cm



SKA



Cosmic 21-cm



Cosmic 21-cm

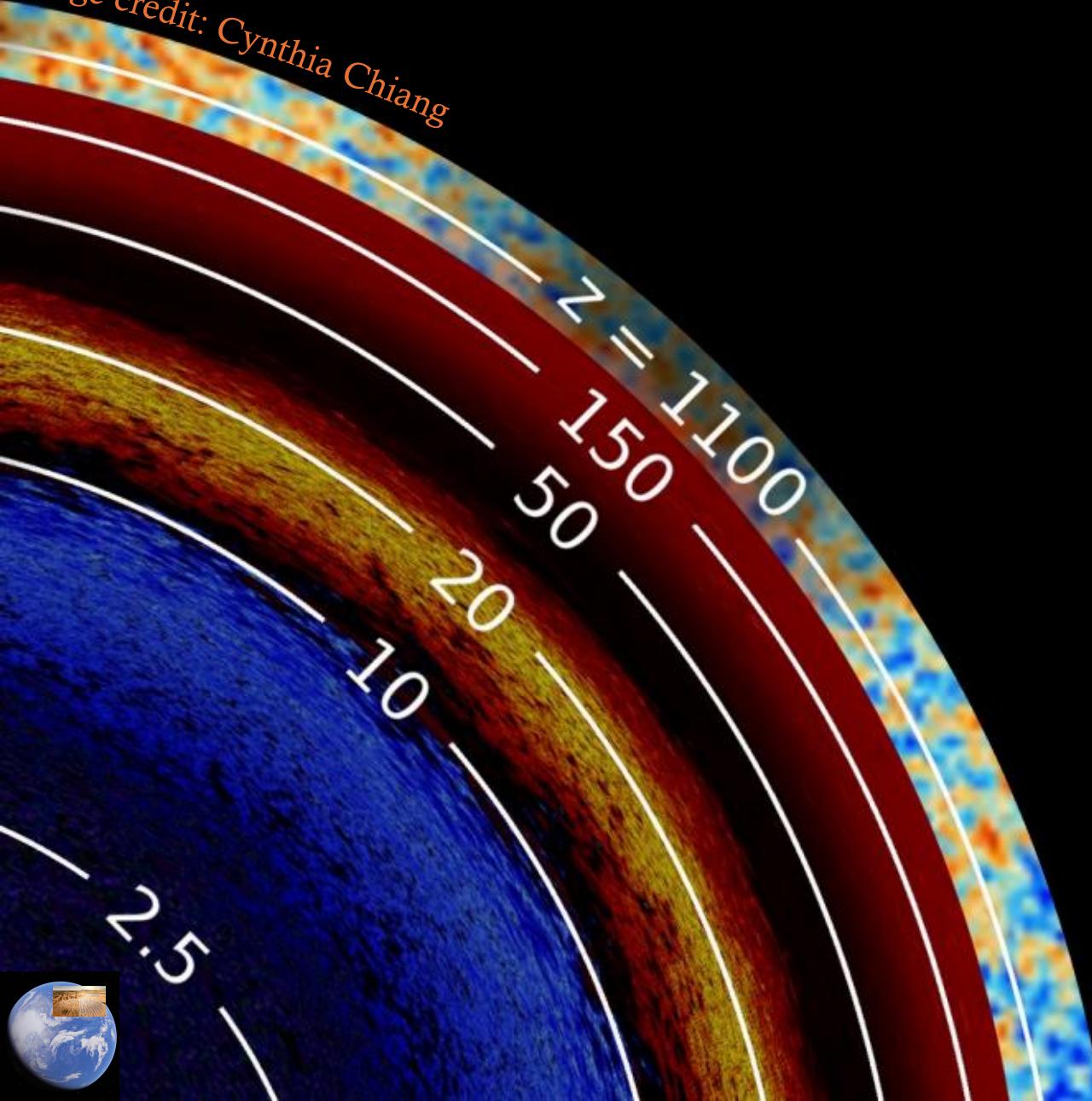


Cosmic 21-cm



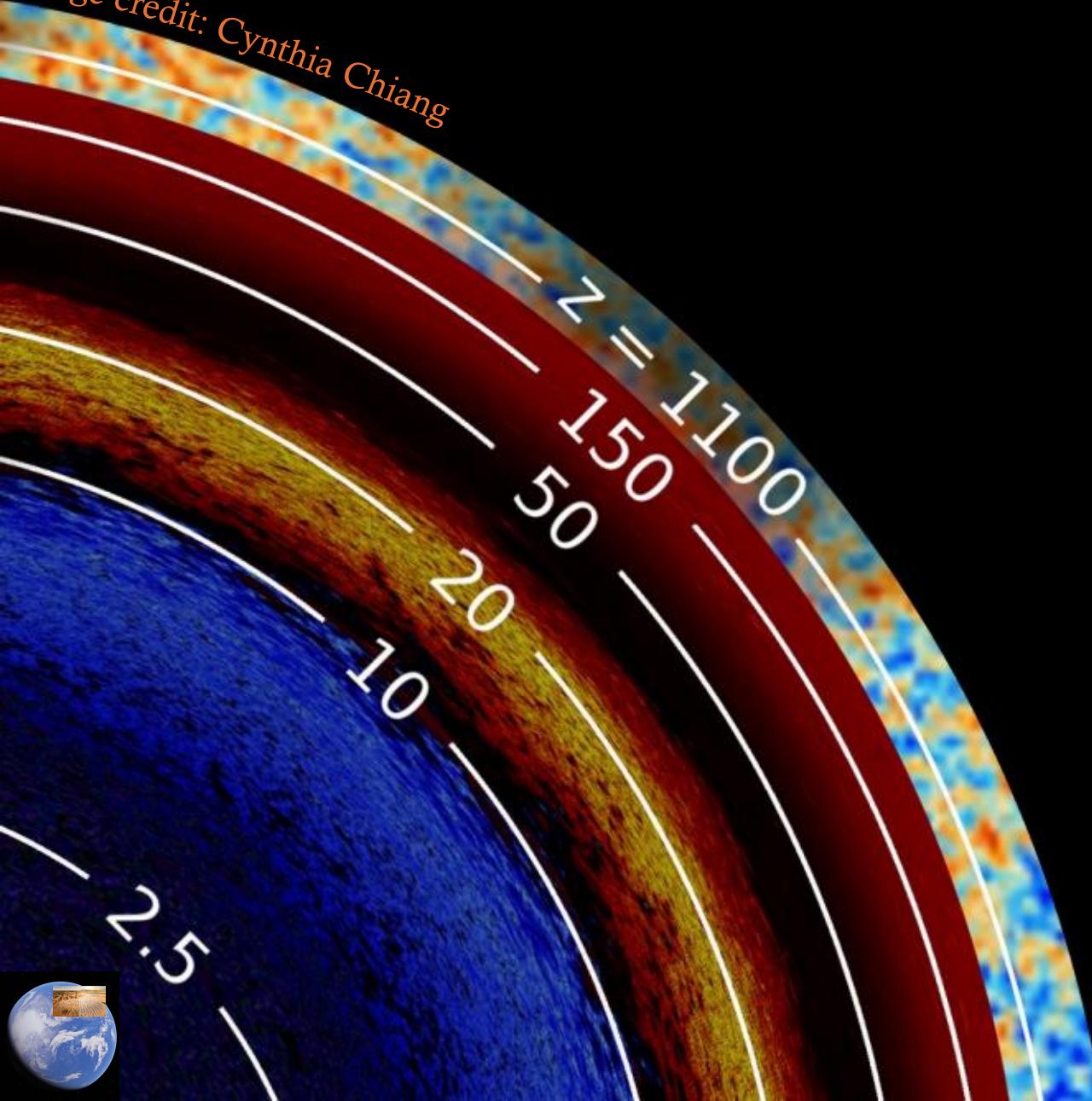
Cosmic 21-cm

image credit: Cynthia Chiang



Cosmic 21-cm

image credit: Cynthia Chiang

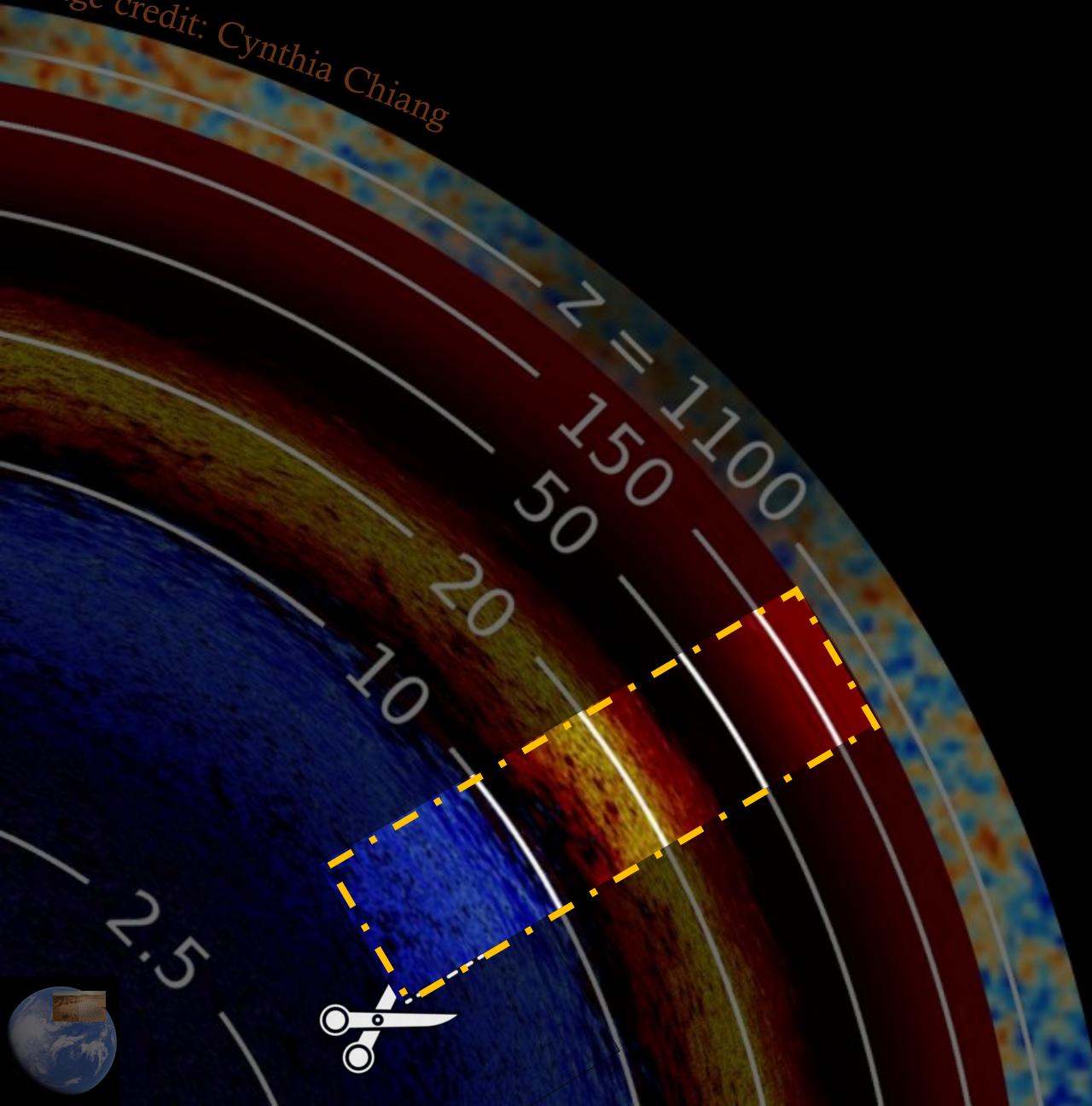


The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than **1/2 of our observable Universe**

Cosmic 21-cm

image credit: Cynthia Chiang

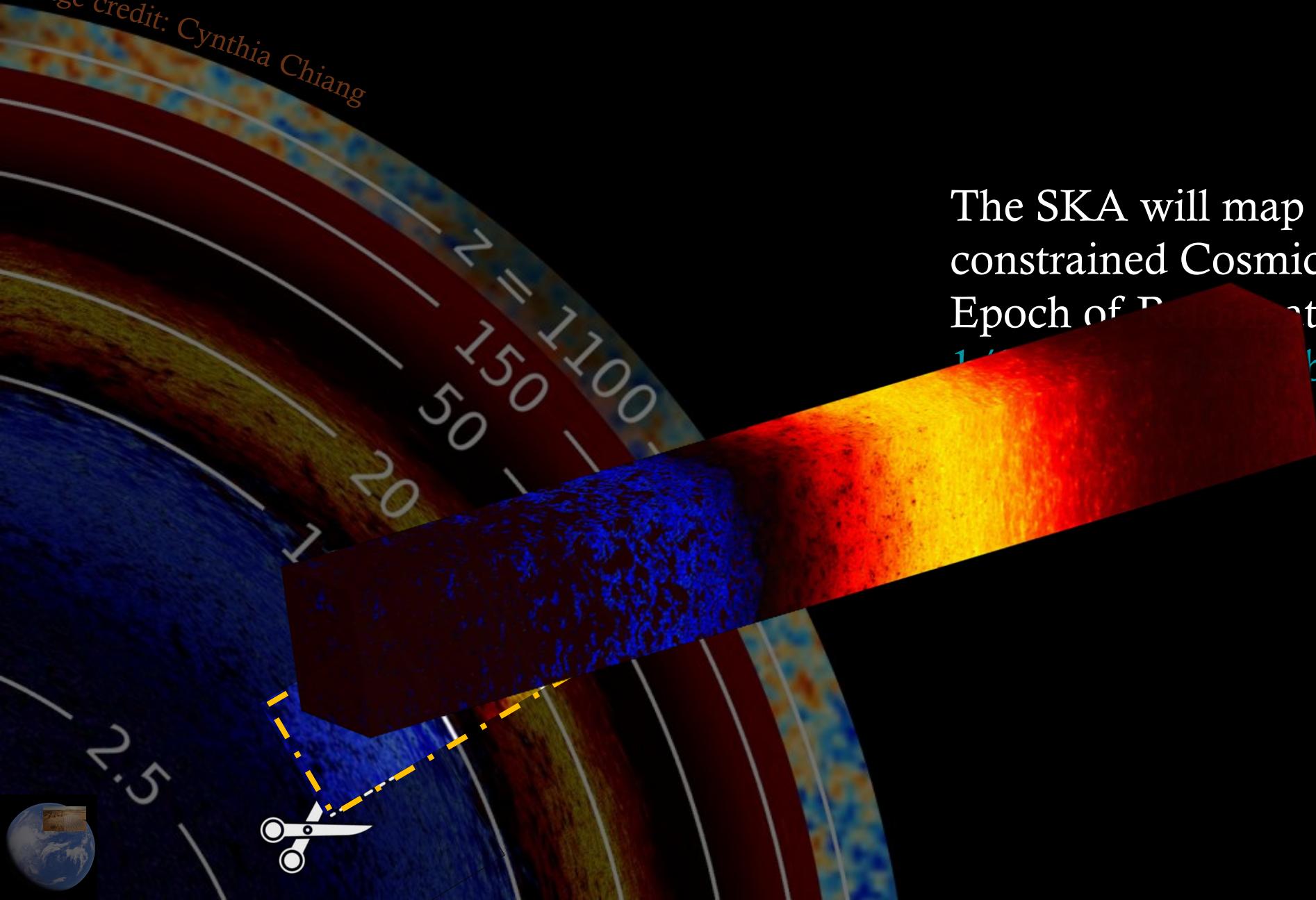
The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than 1/2 of our observable Universe



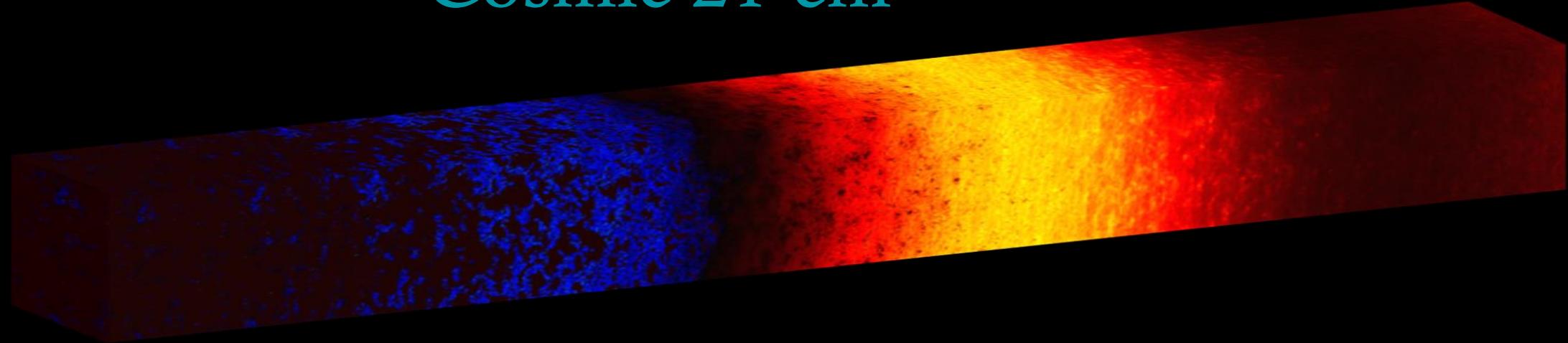
Cosmic 21-cm

image credit: Cynthia Chiang

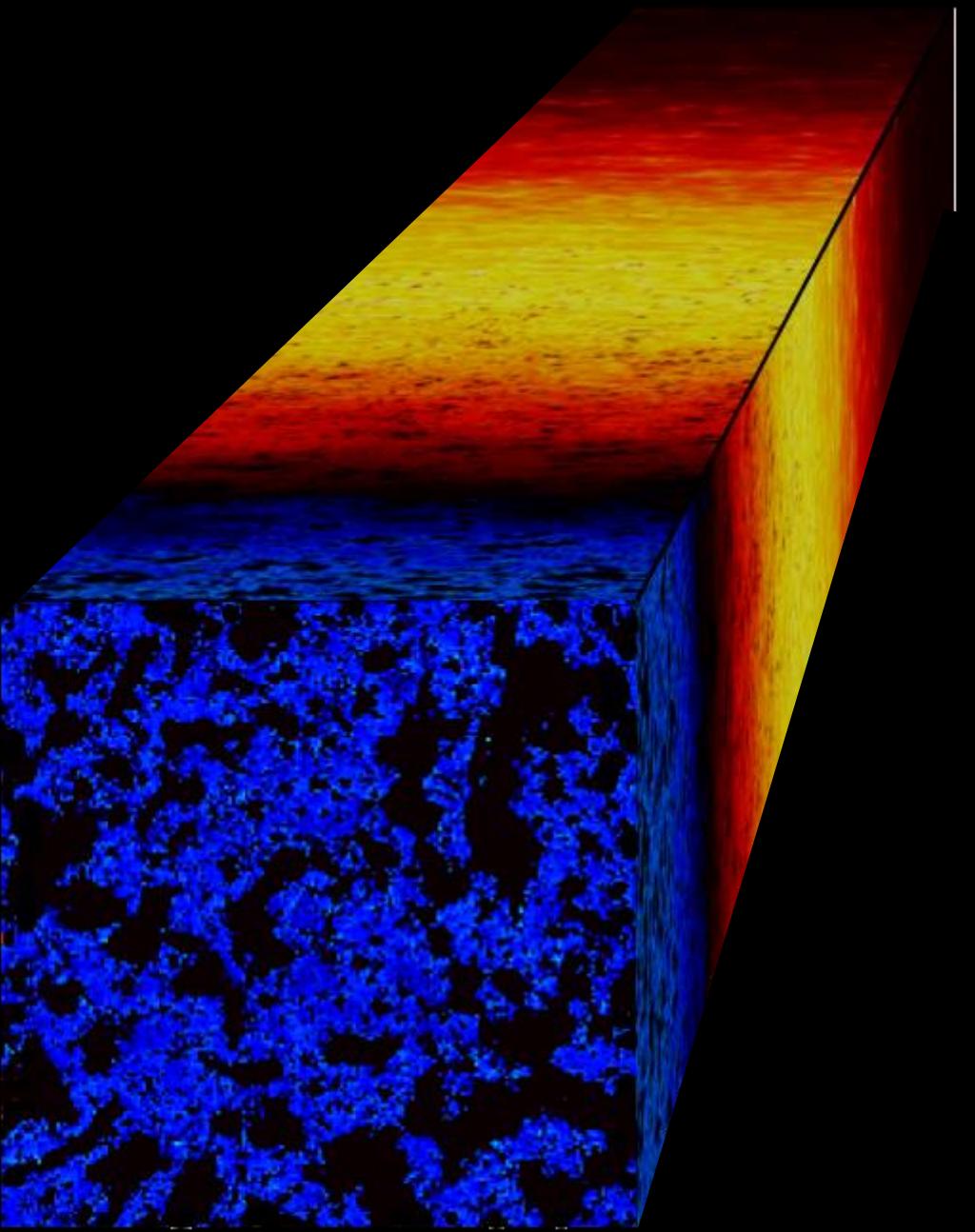
The SKA will map out the poorly constrained Cosmic Dawn and Epoch of Reionization: more than $1/6$ of the observable Universe



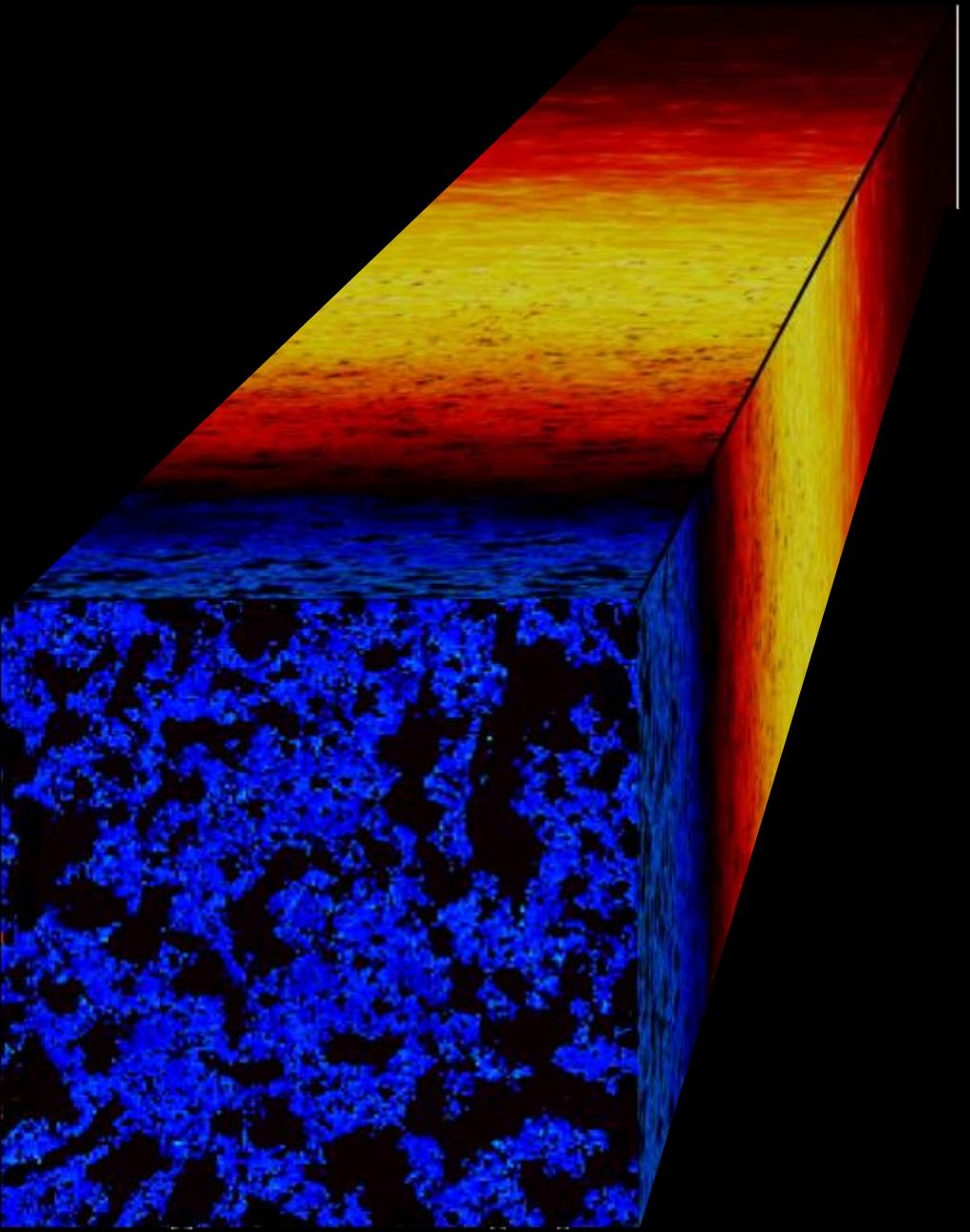
Cosmic 21-cm



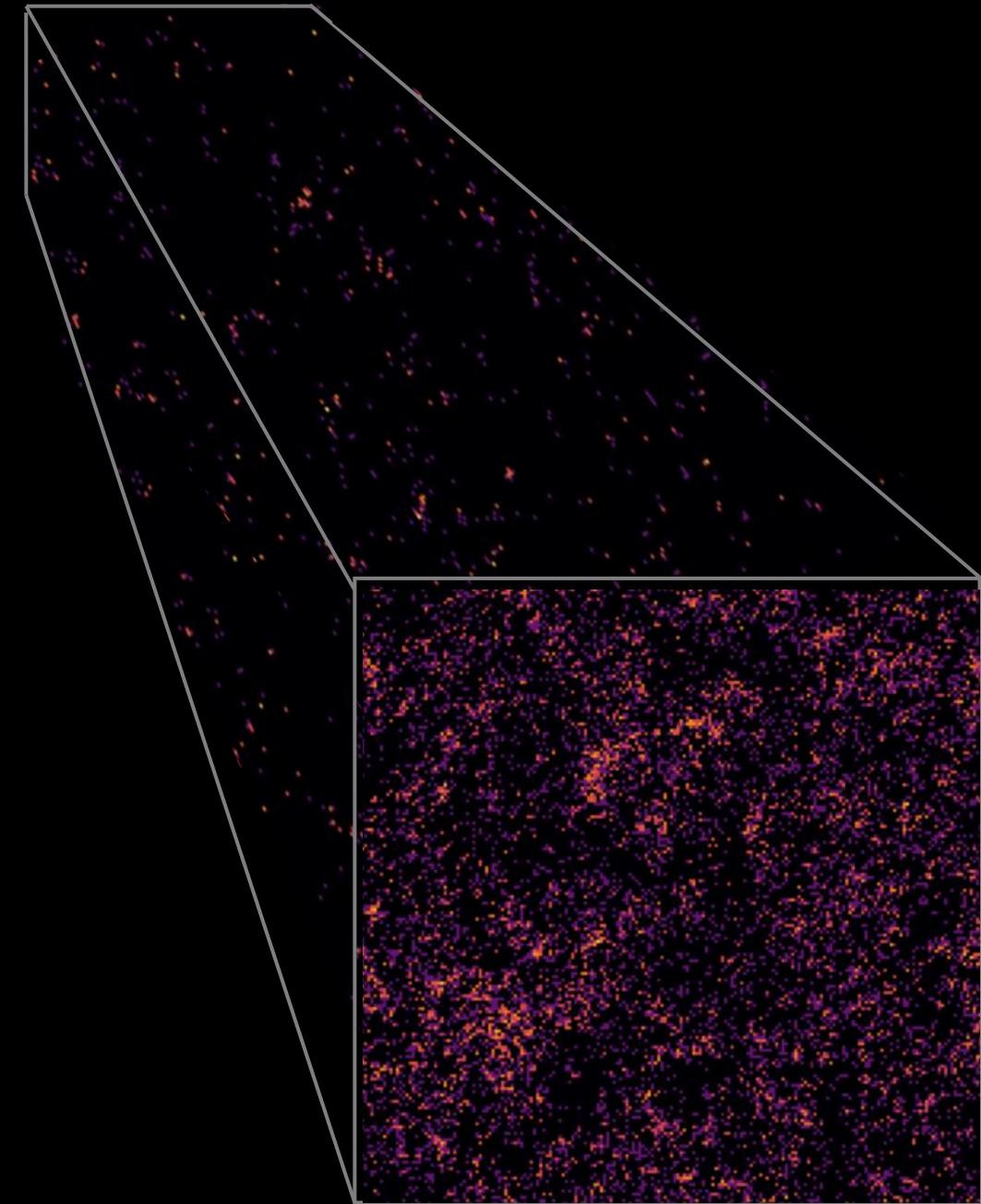
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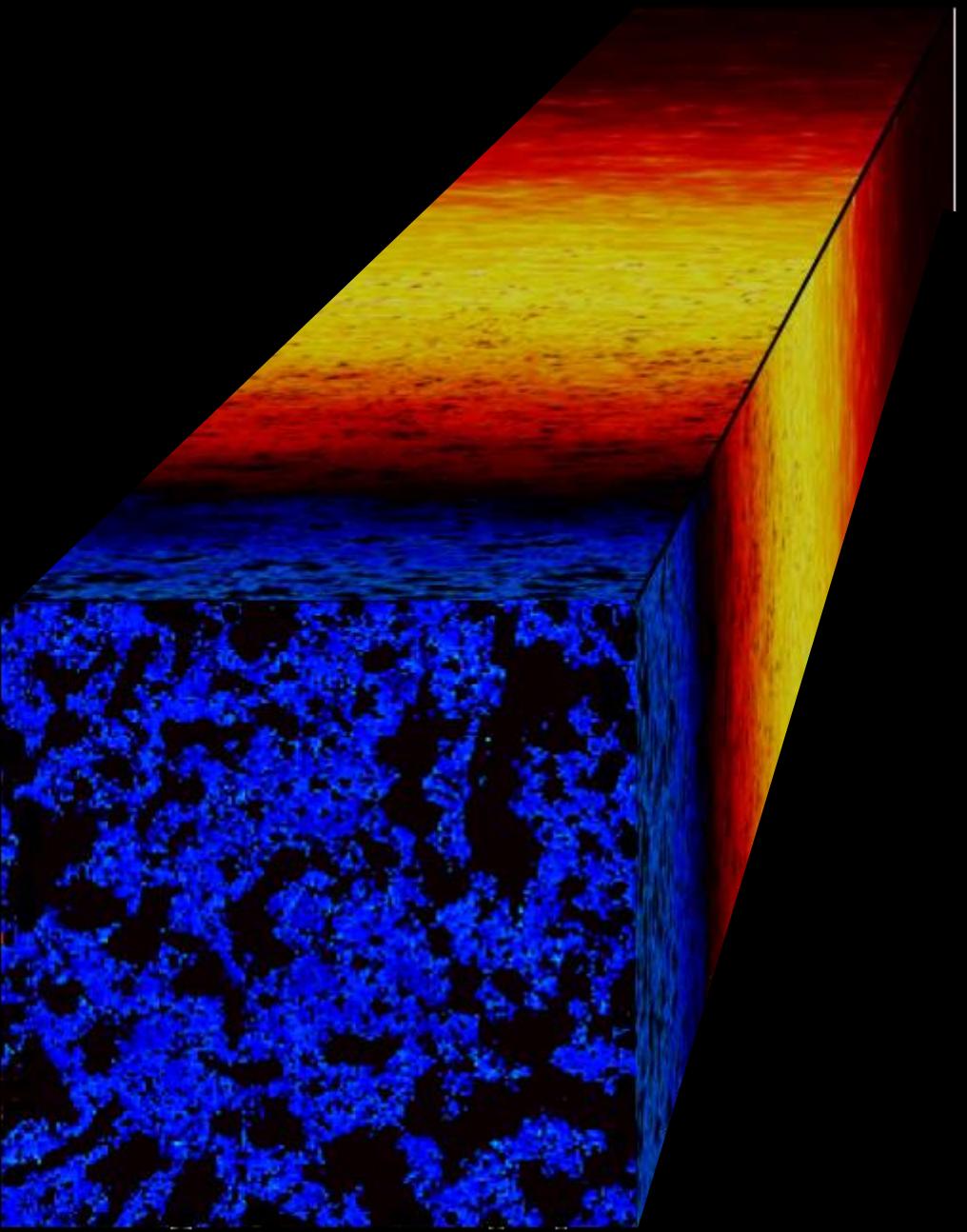
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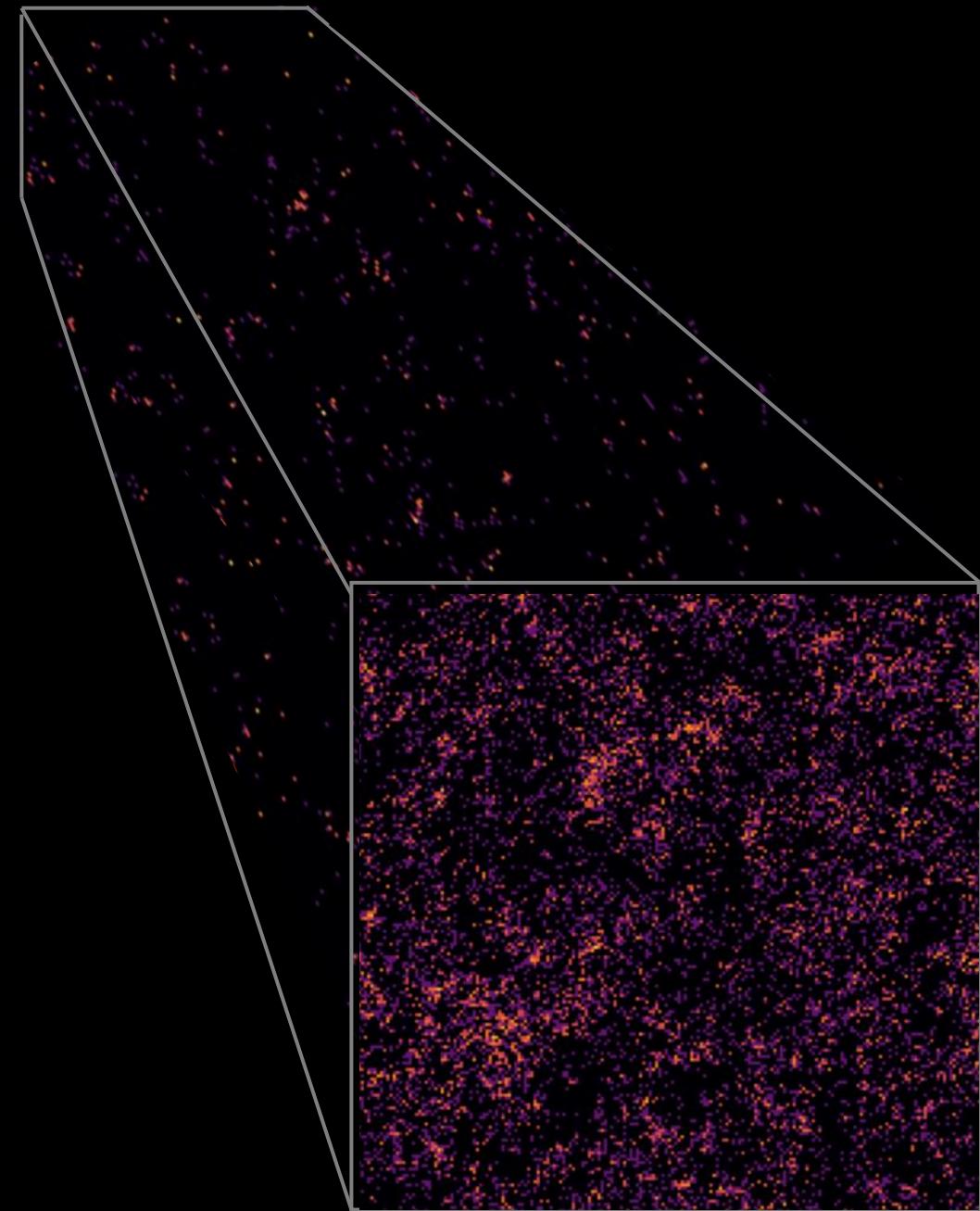
Galaxies



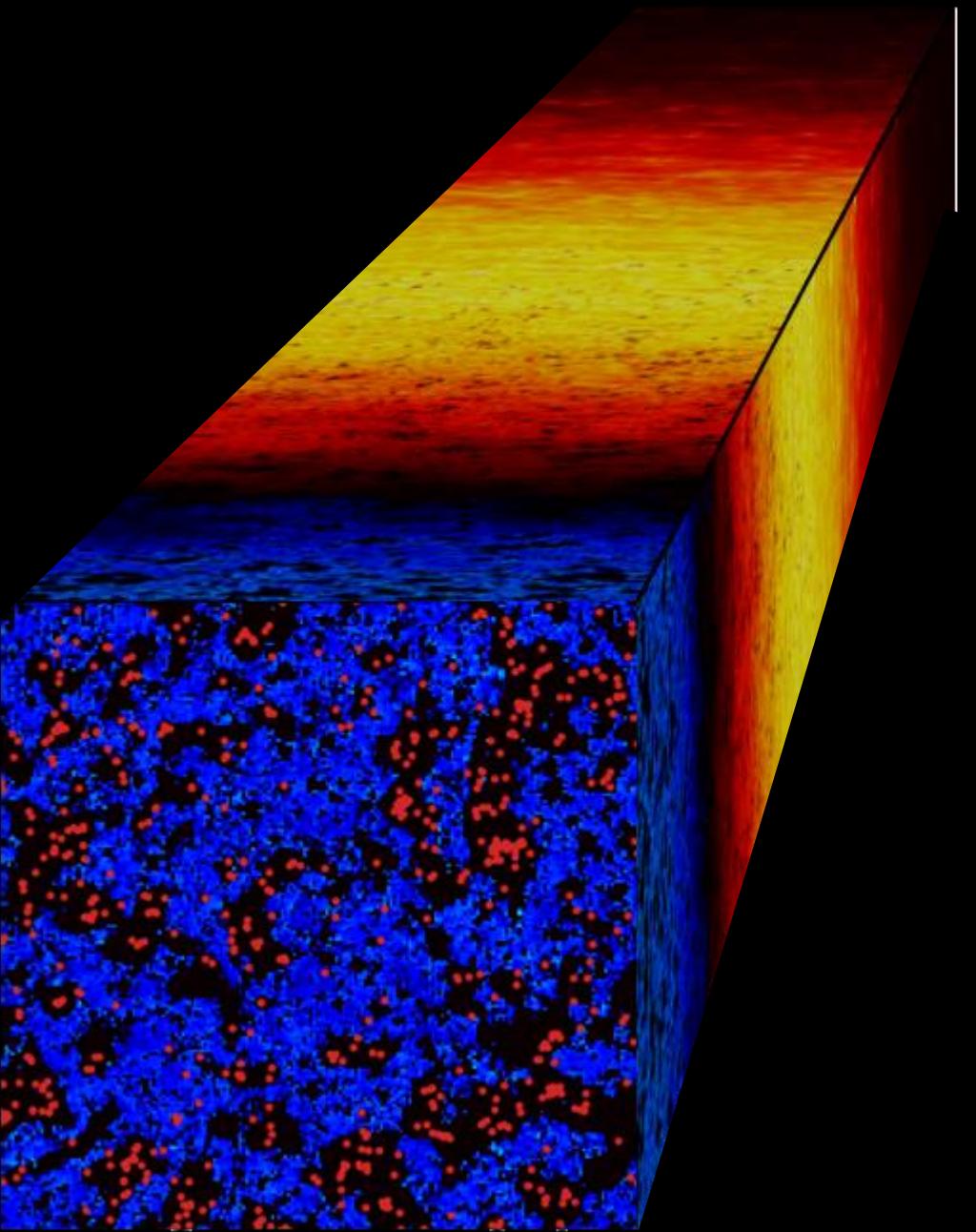
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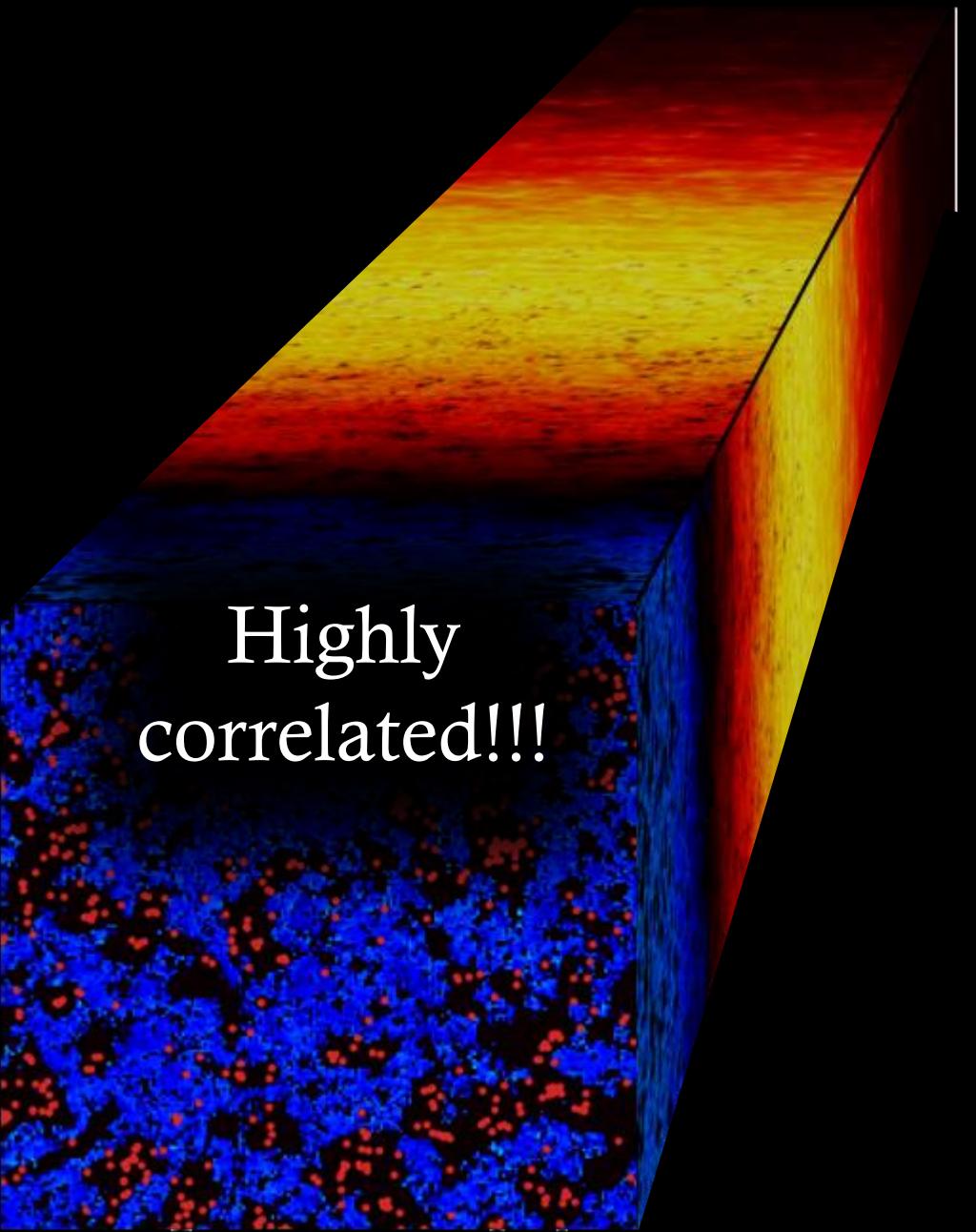
Galaxies



Cosmic 21-cm + Galaxies

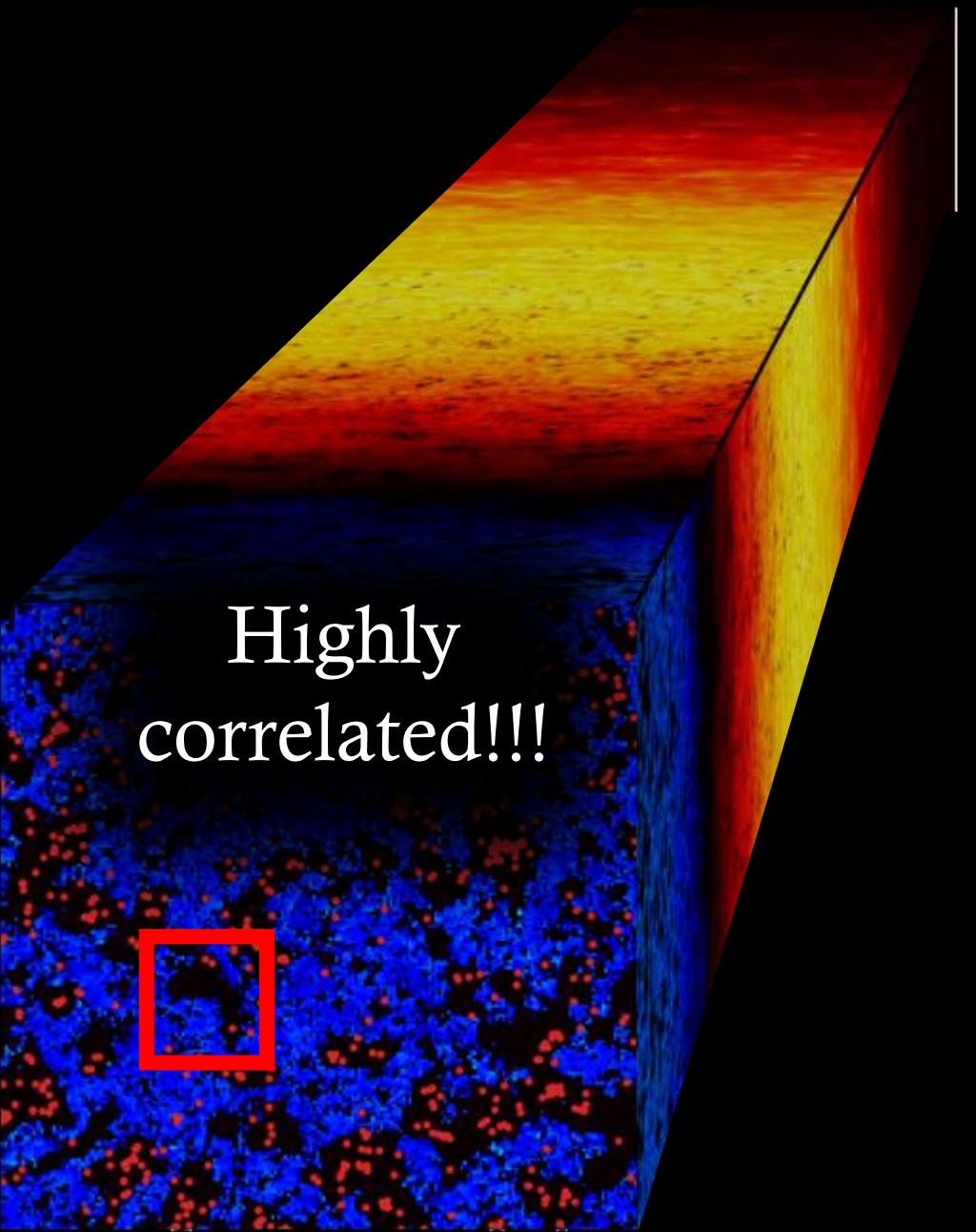


Cosmic 21-cm + Galaxies



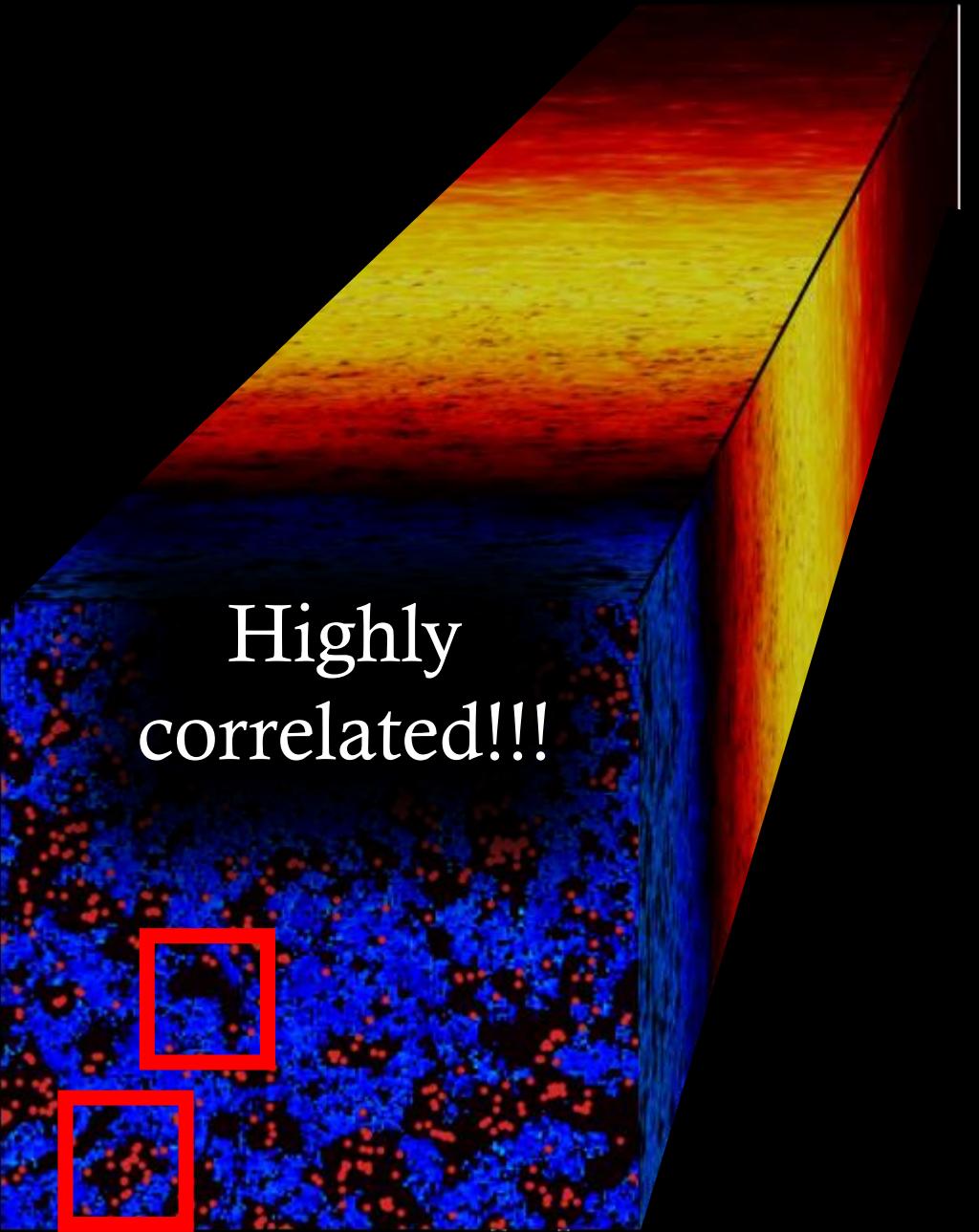
Highly
correlated!!!

Cosmic 21-cm + Galaxies



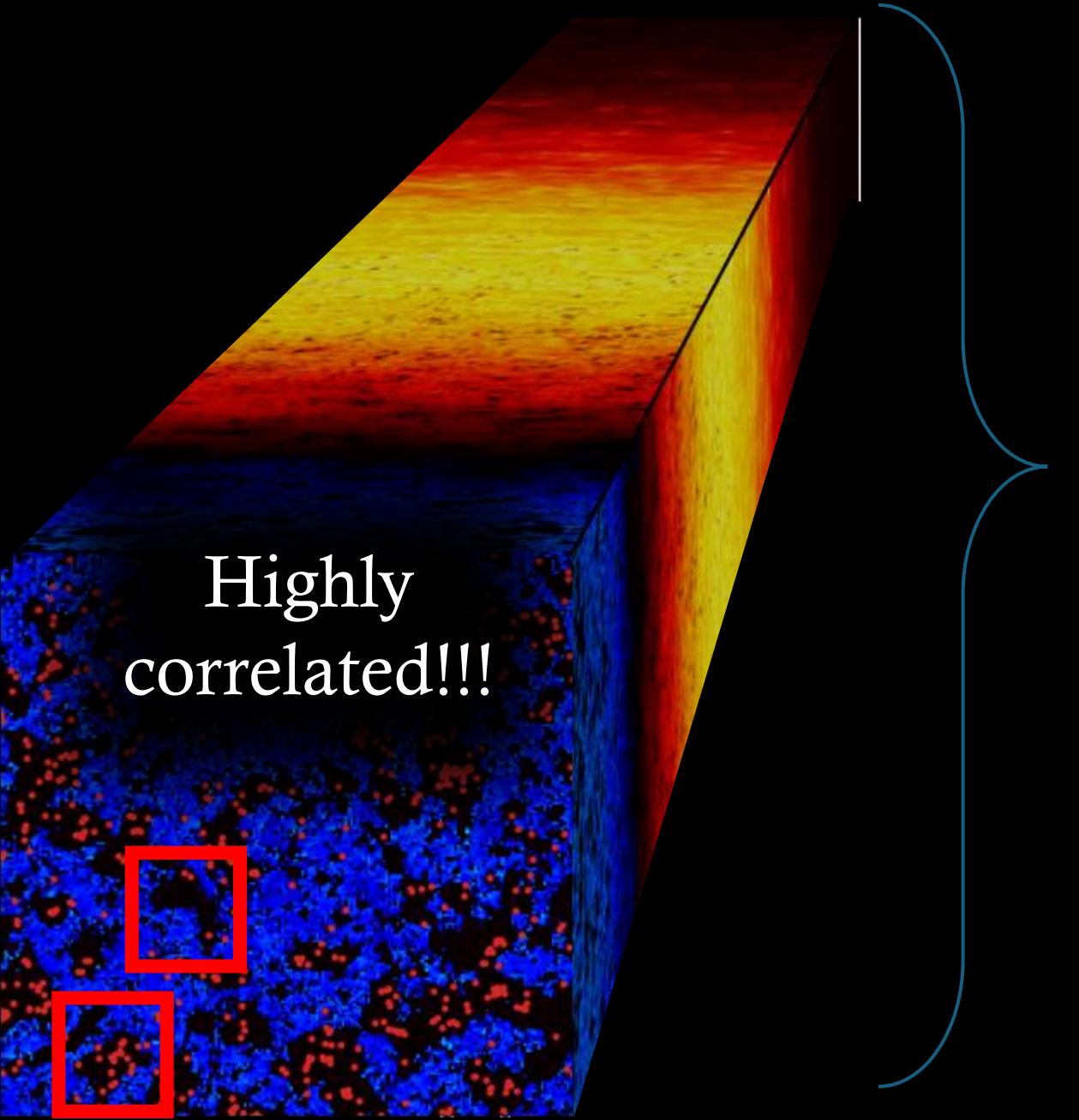
Highly
correlated!!!

Cosmic 21-cm + Galaxies



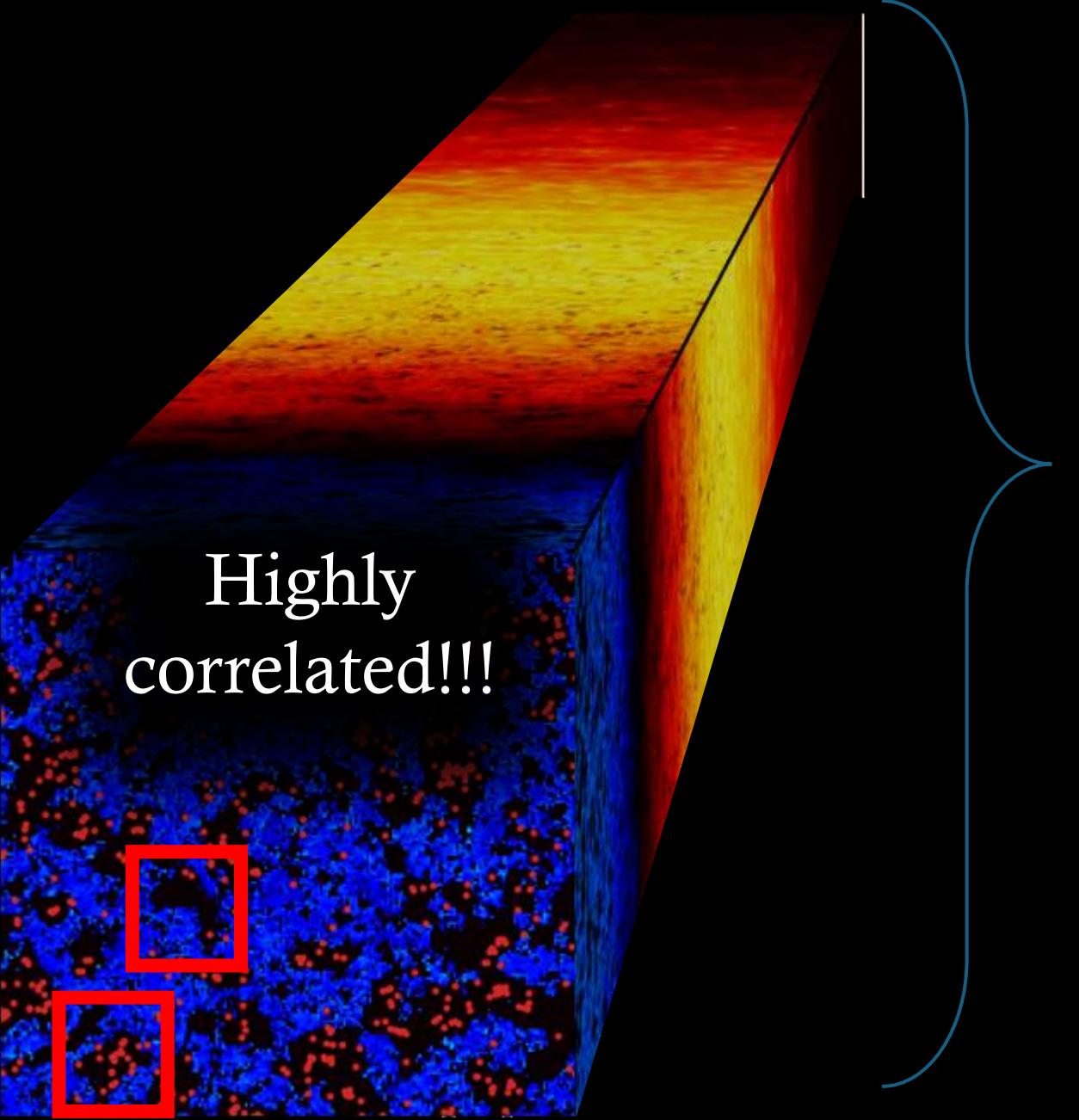
Highly
correlated!!!

Cosmic 21-cm + Galaxies



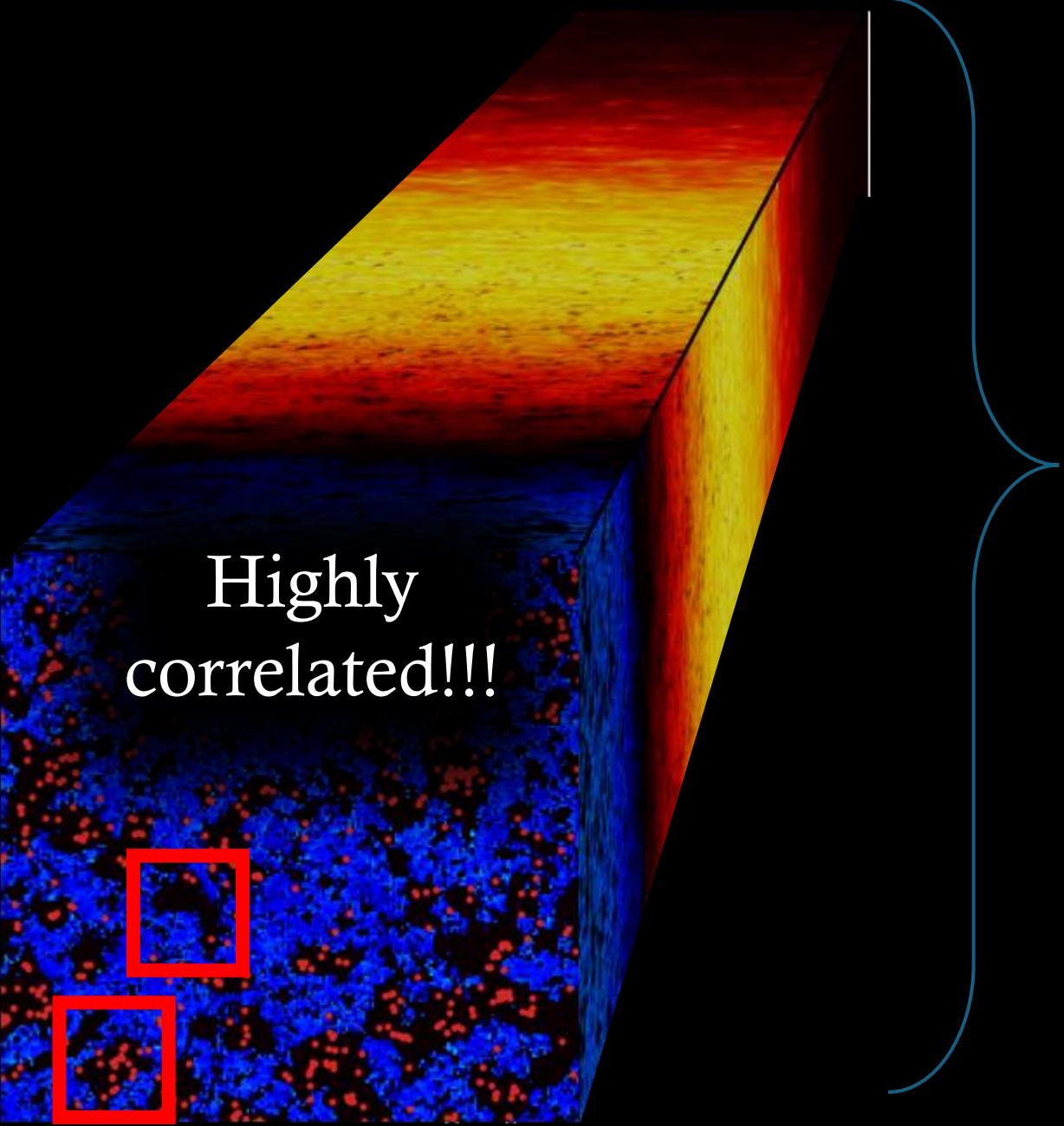
Highly
correlated!!!

Cosmic 21-cm + Galaxies



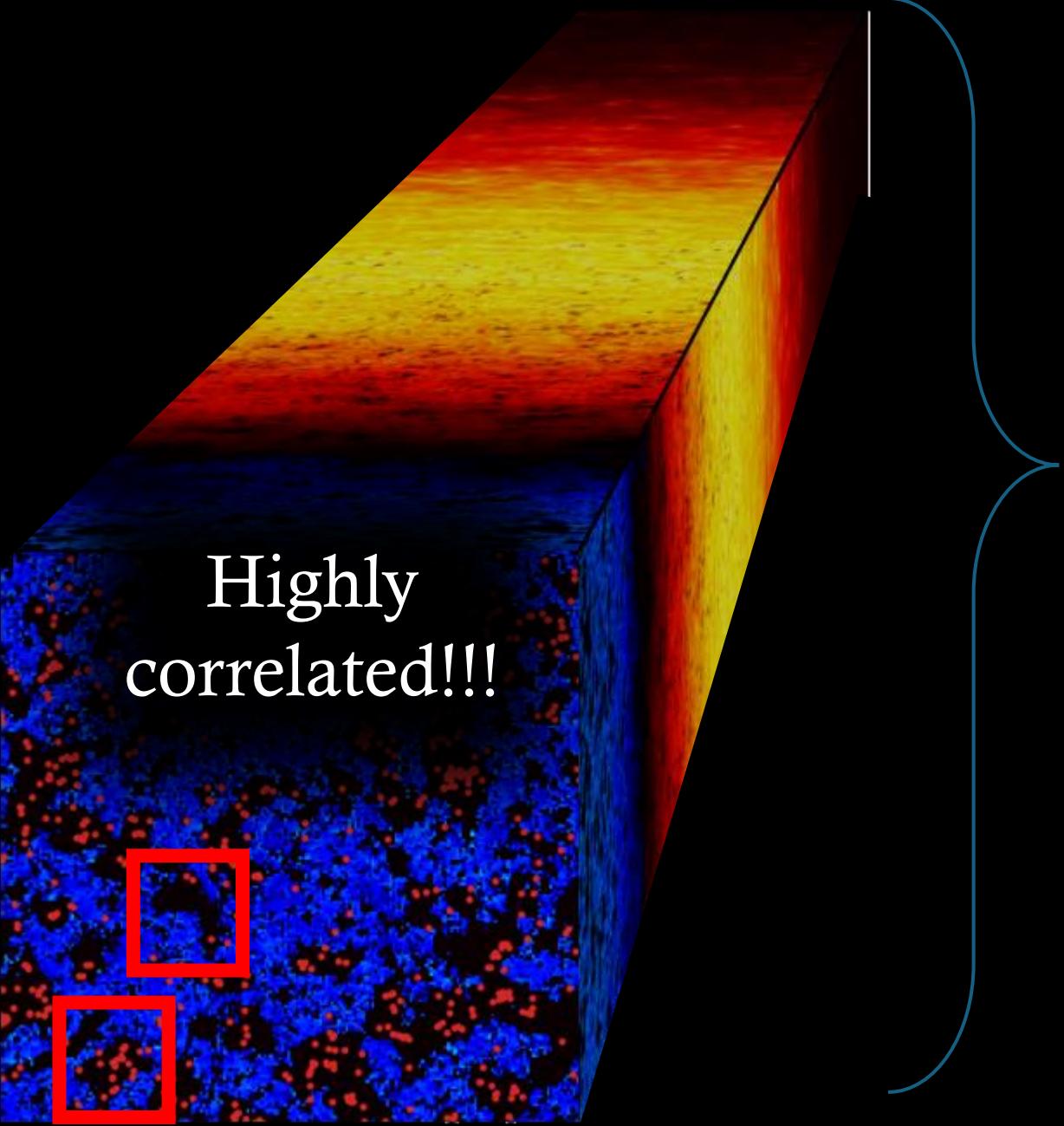
- Complementary info for the same volume

Cosmic 21-cm + Galaxies



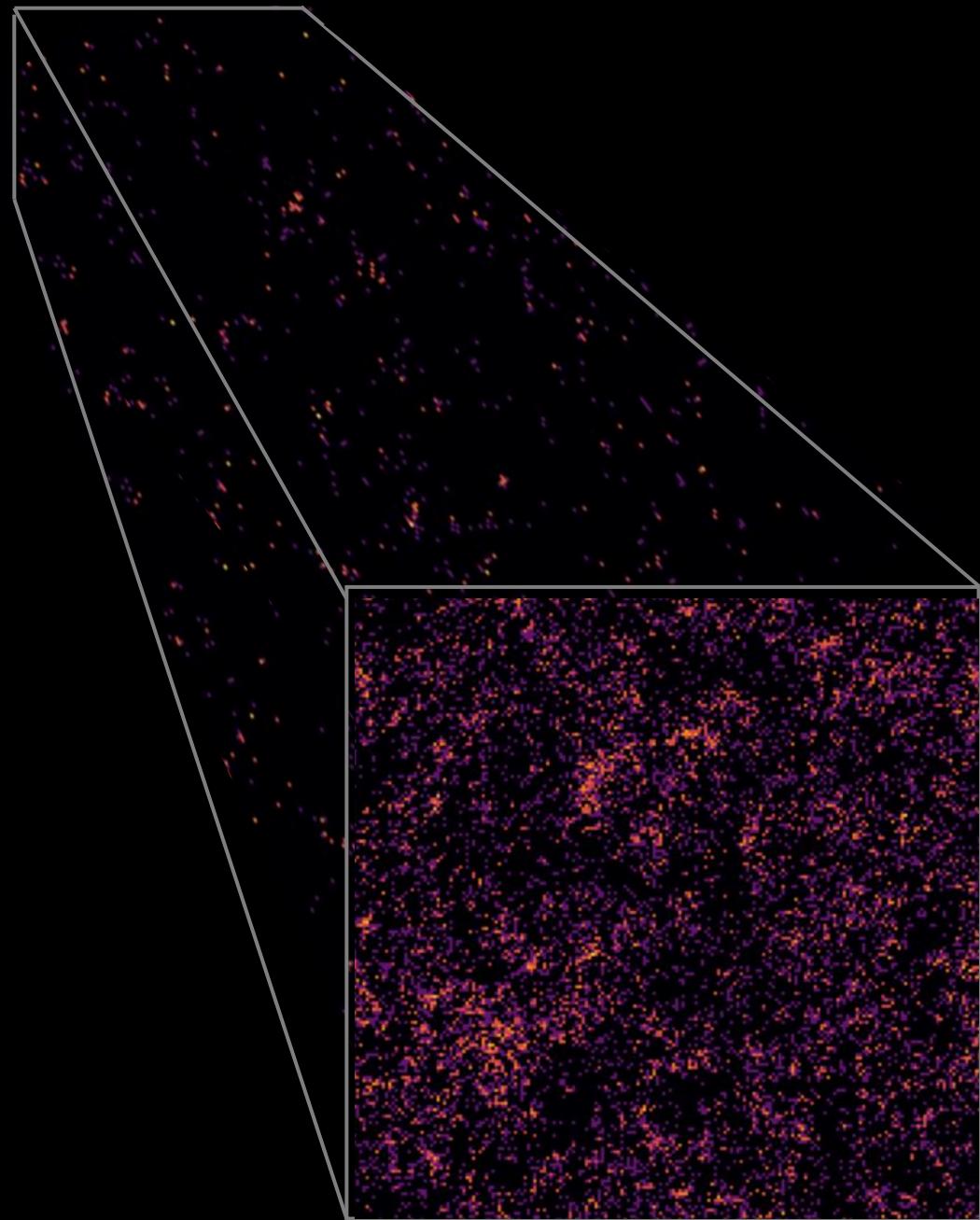
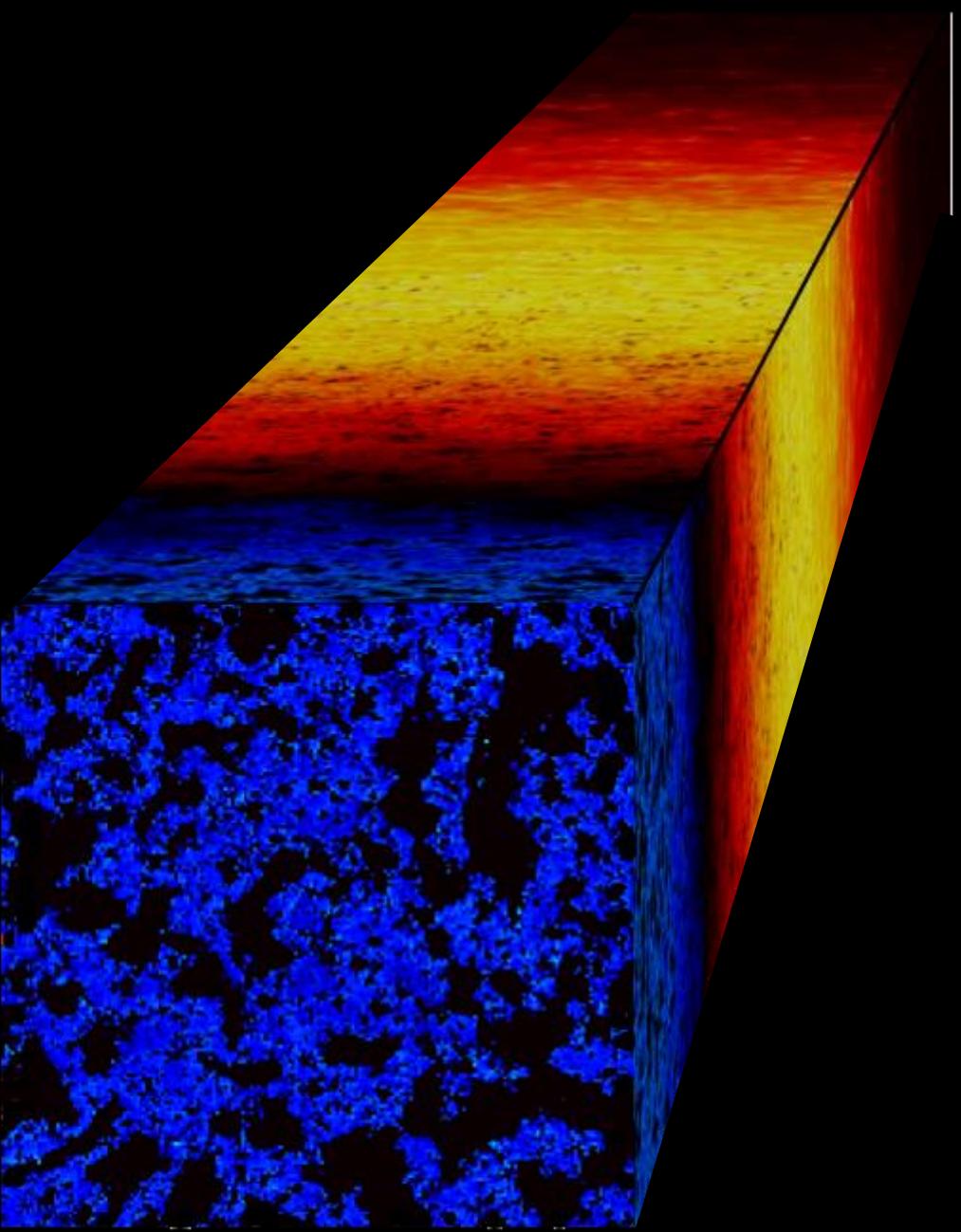
- Complementary info for the same volume
- Cross-correlations could be very powerful (systematics suppression)

Cosmic 21-cm + Galaxies

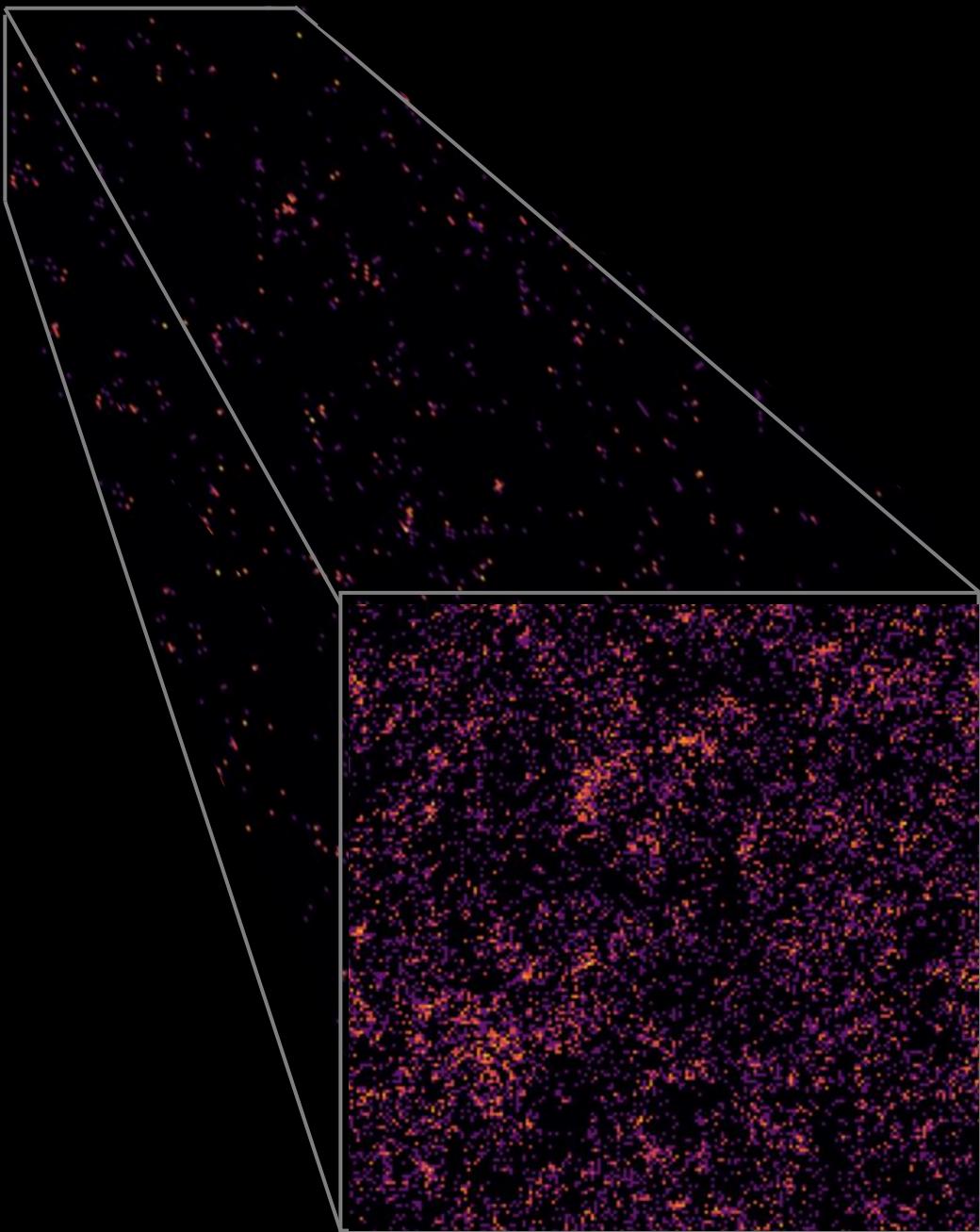
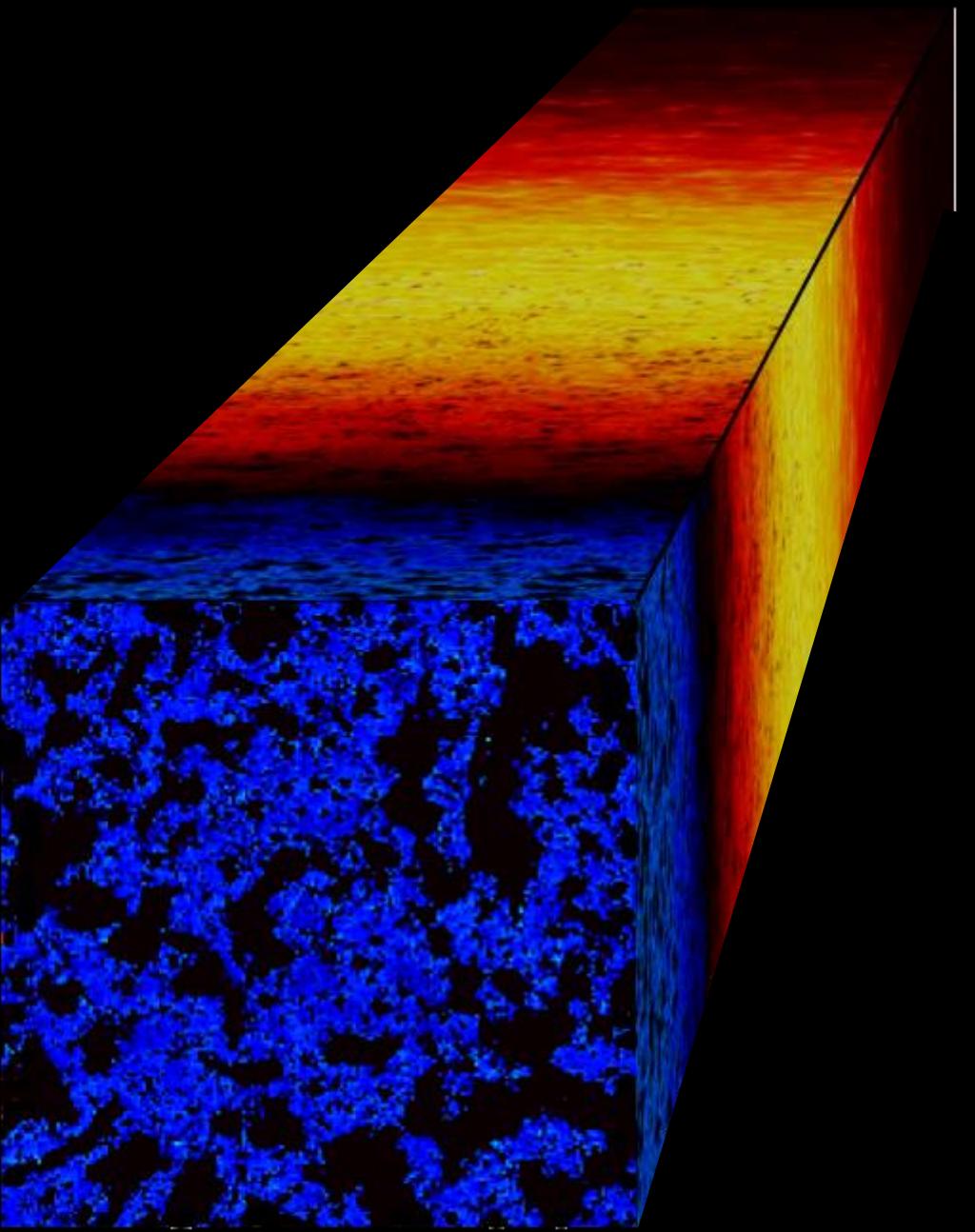


- Complementary info for the same volume
- Cross-correlations could be very powerful (systematics suppression)
- Info from PS upper limits came from multiple tracers

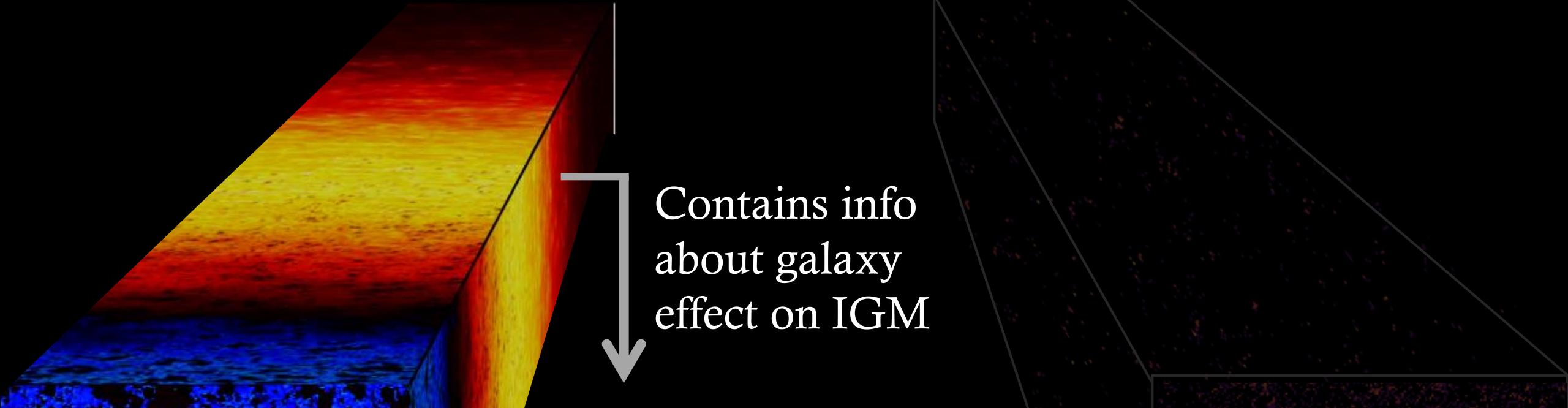
The HERA collaboration 2022



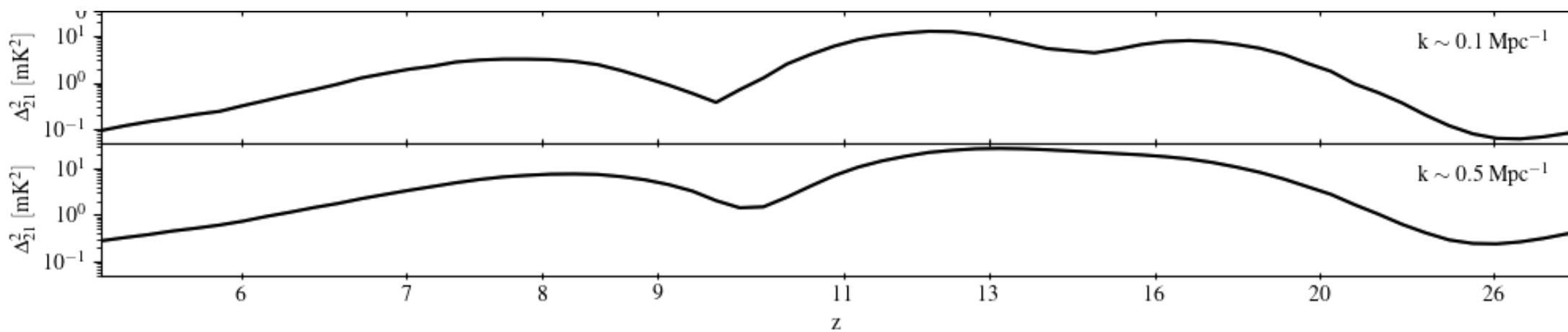
Summaries



Summaries



Summary 1: The Power Spectrum



Summaries

E.g.

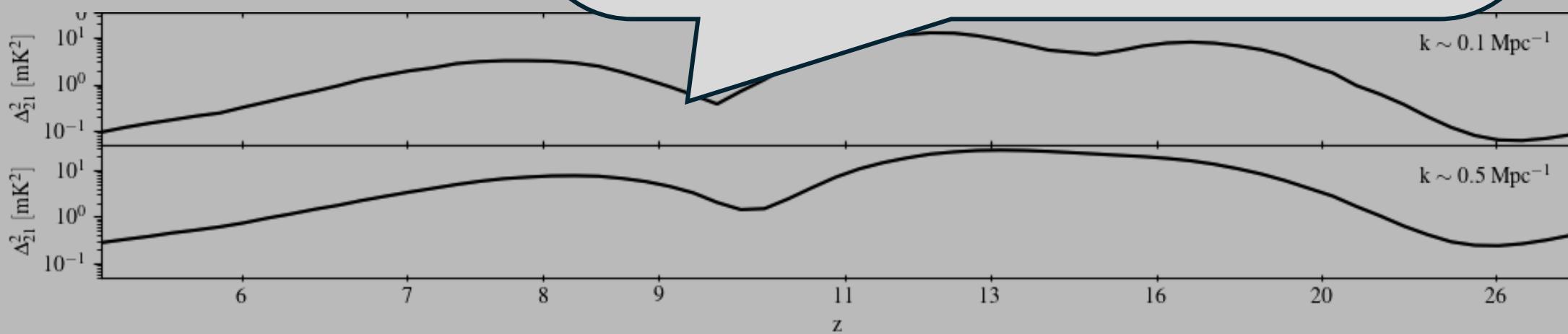


Summa

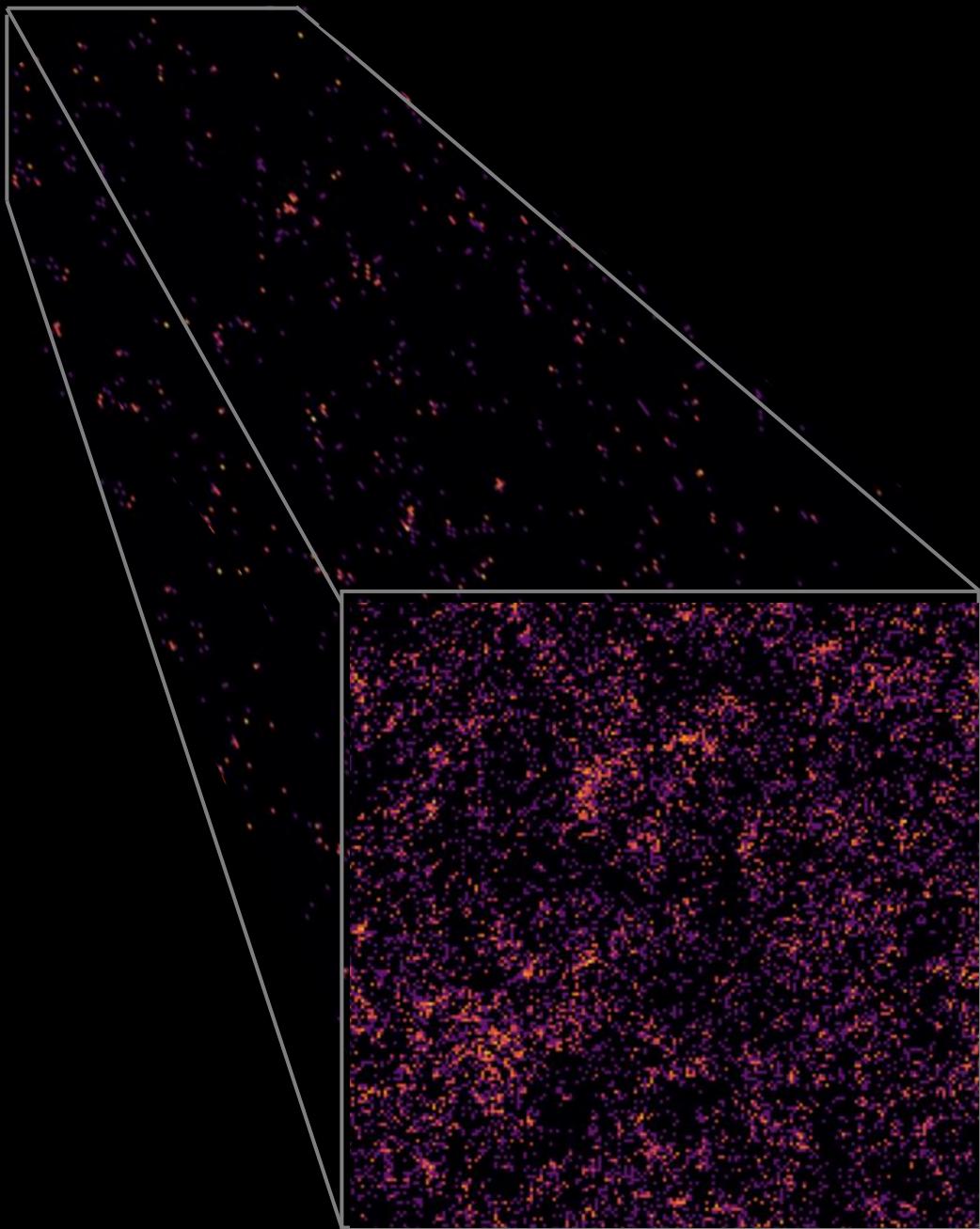
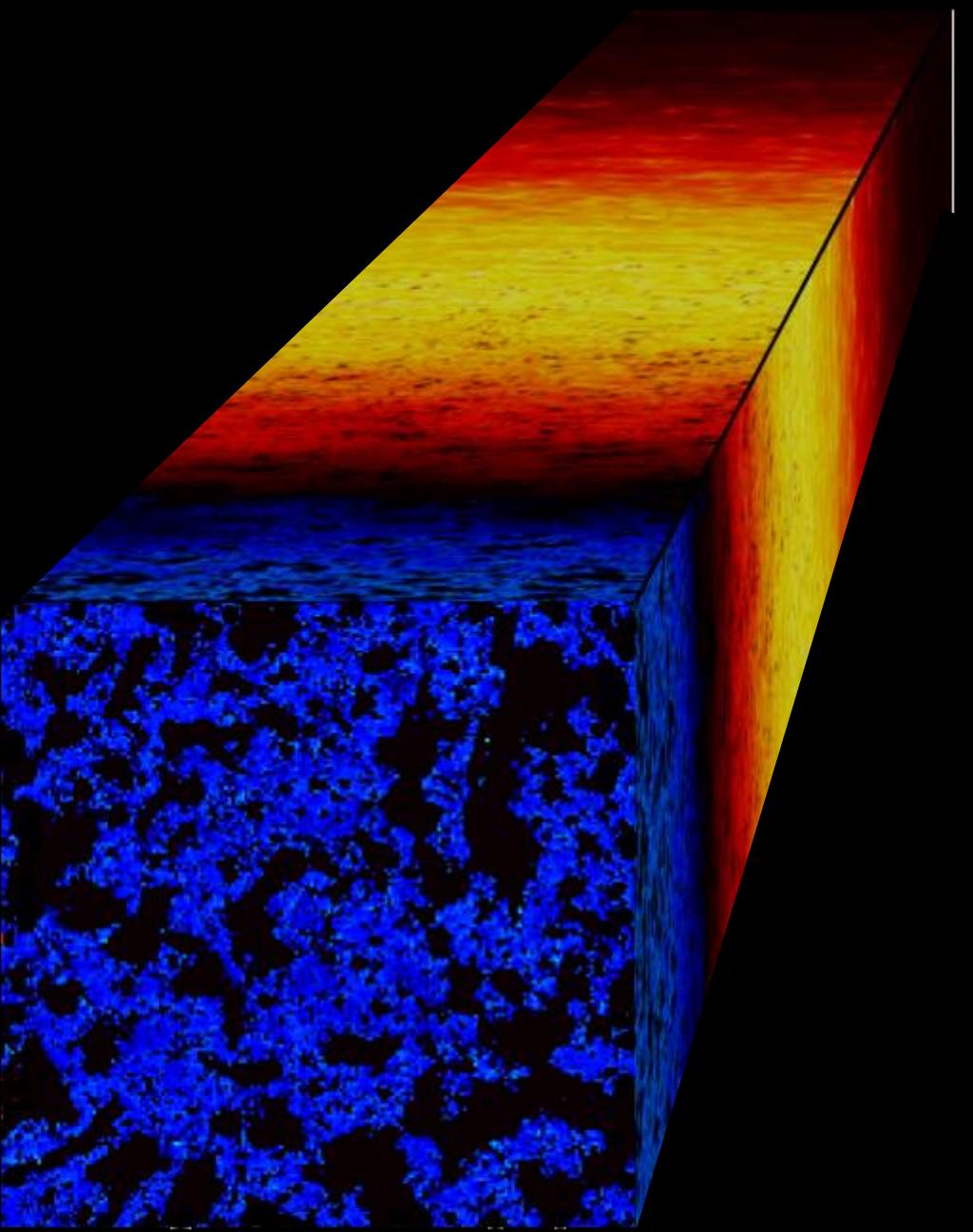
HERA



MWA

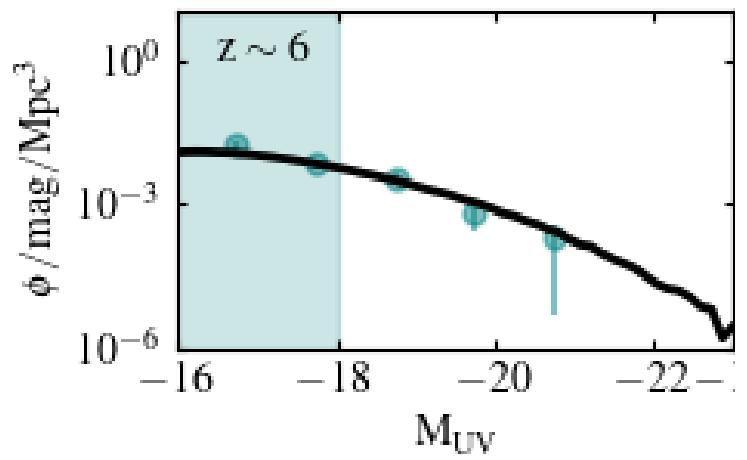


Summaries



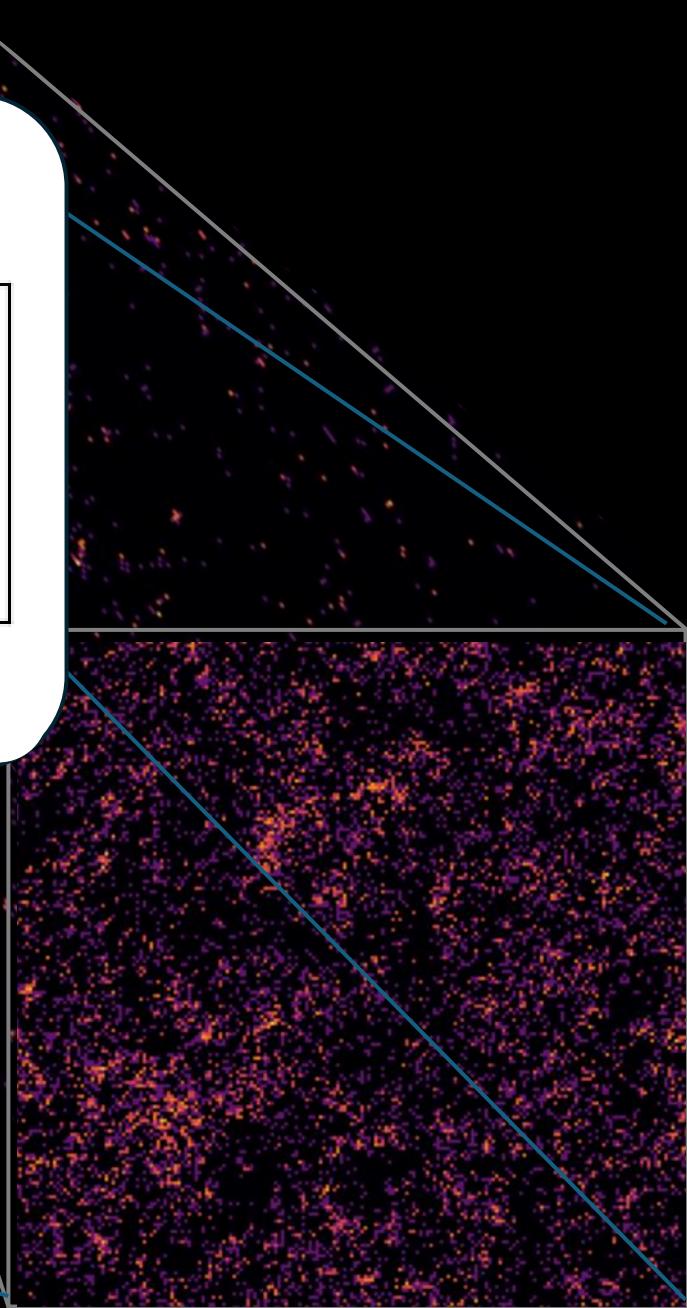
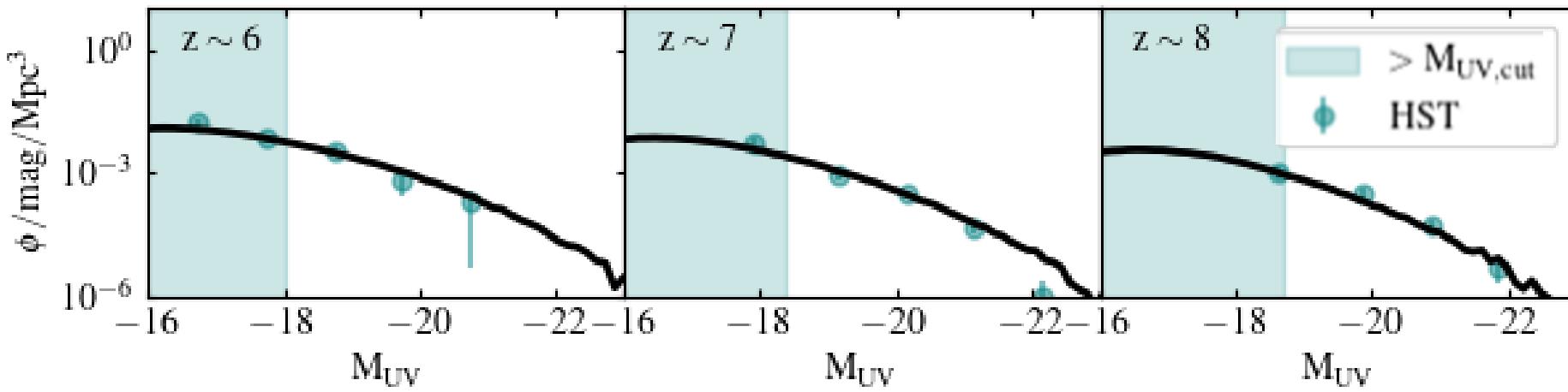
Summaries

Summary 2: UV Luminosity Functions



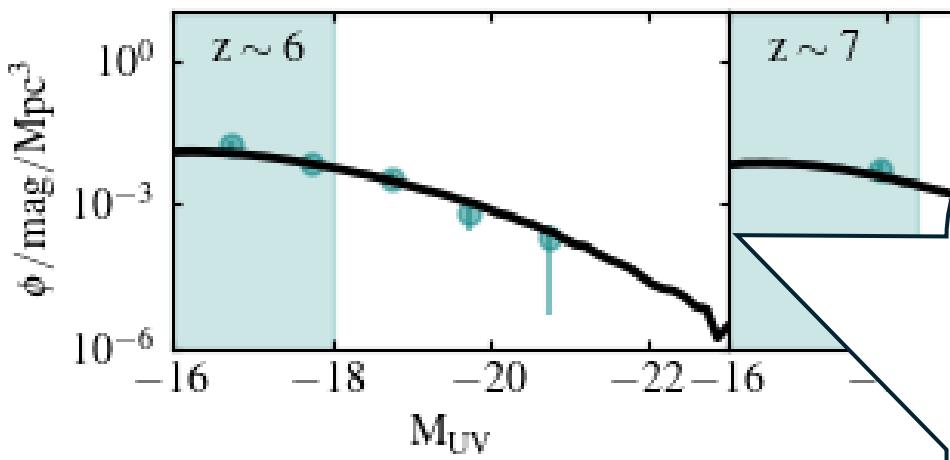
Summaries

Summary 2: UV Luminosity Functions

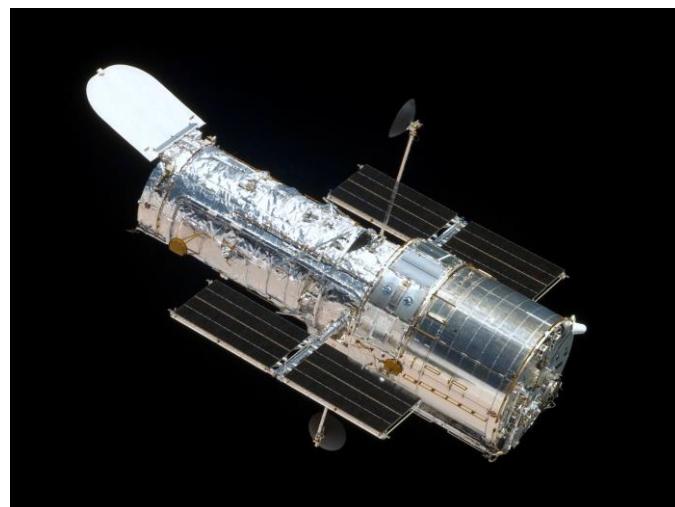


Summaries

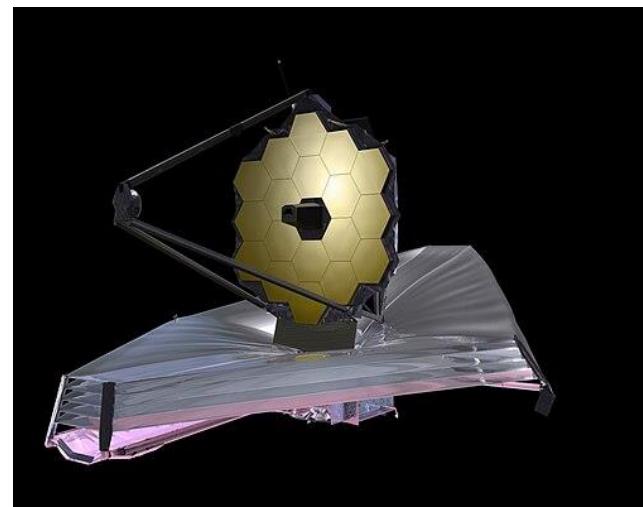
Summary 2: UV Luminosity Functions



E.g.

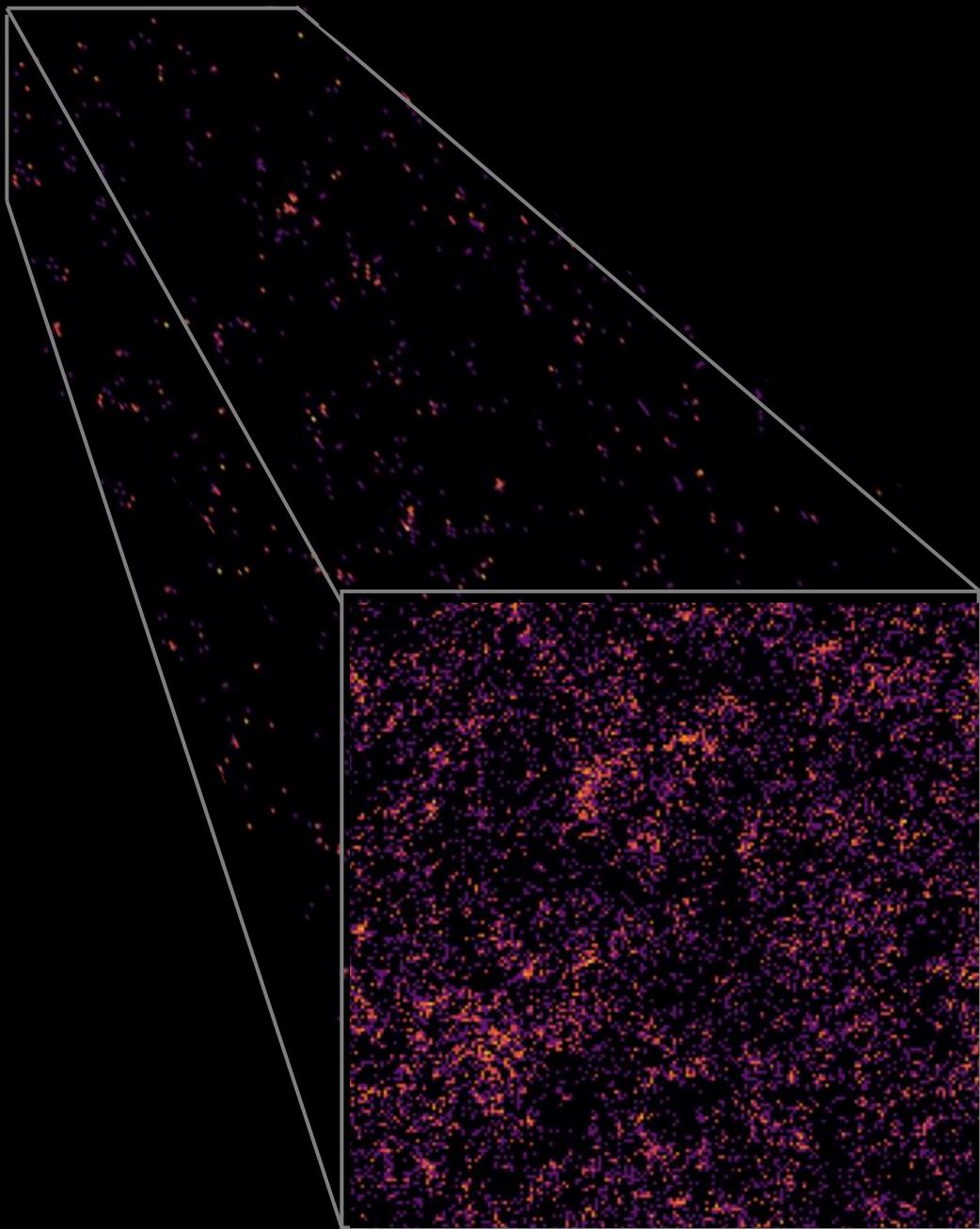
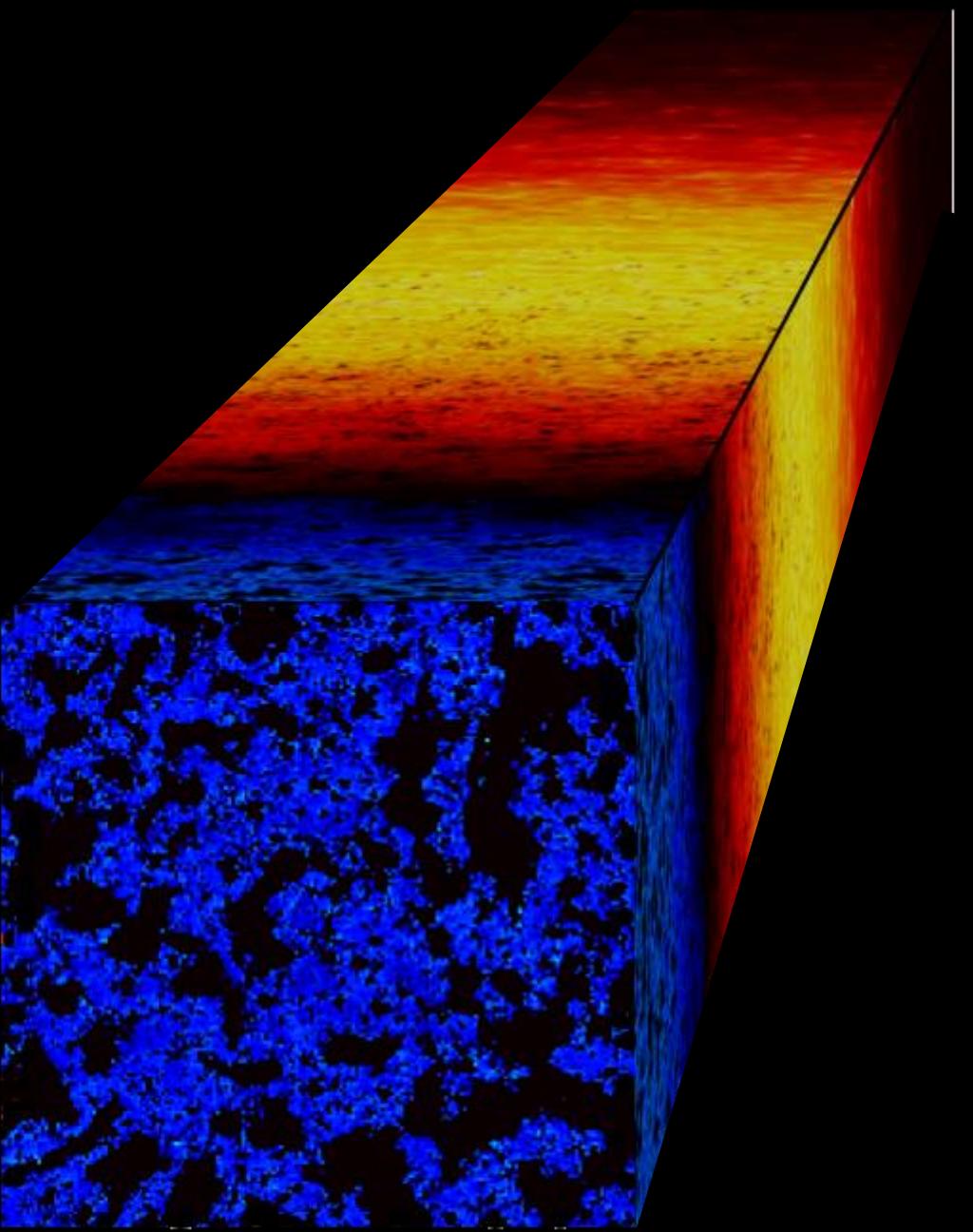


HST



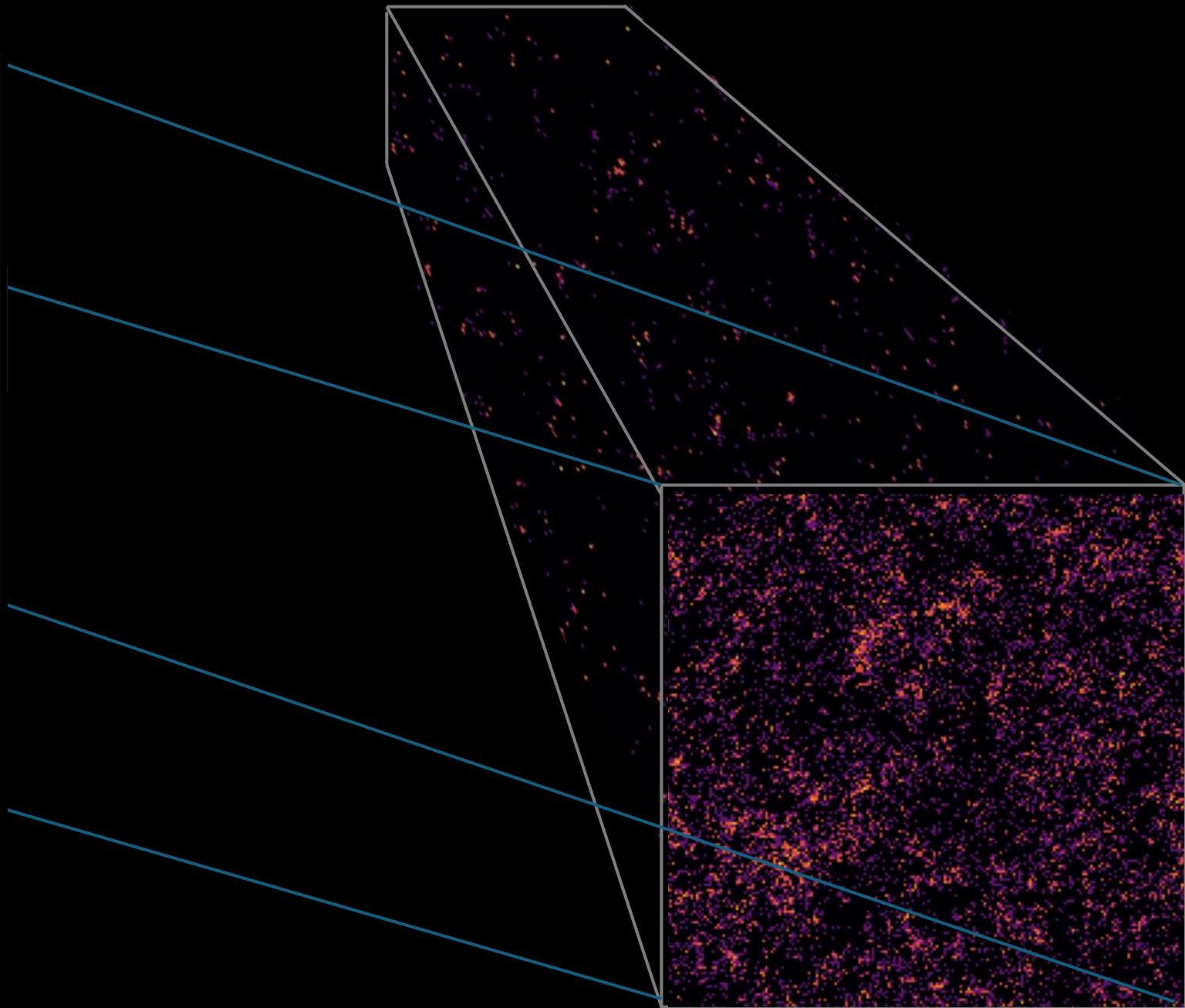
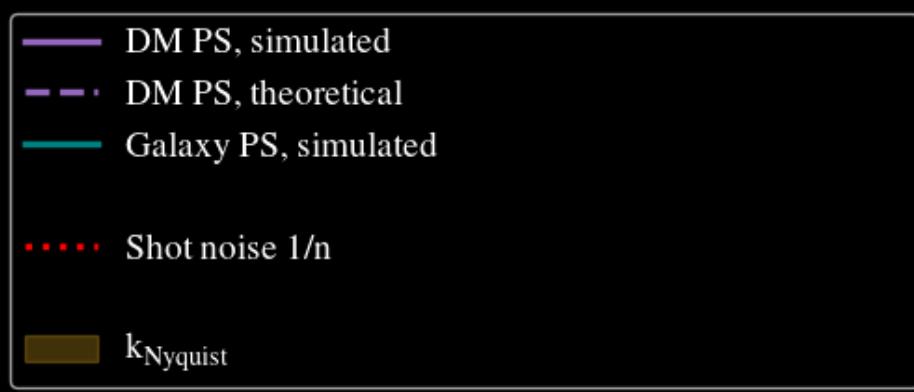
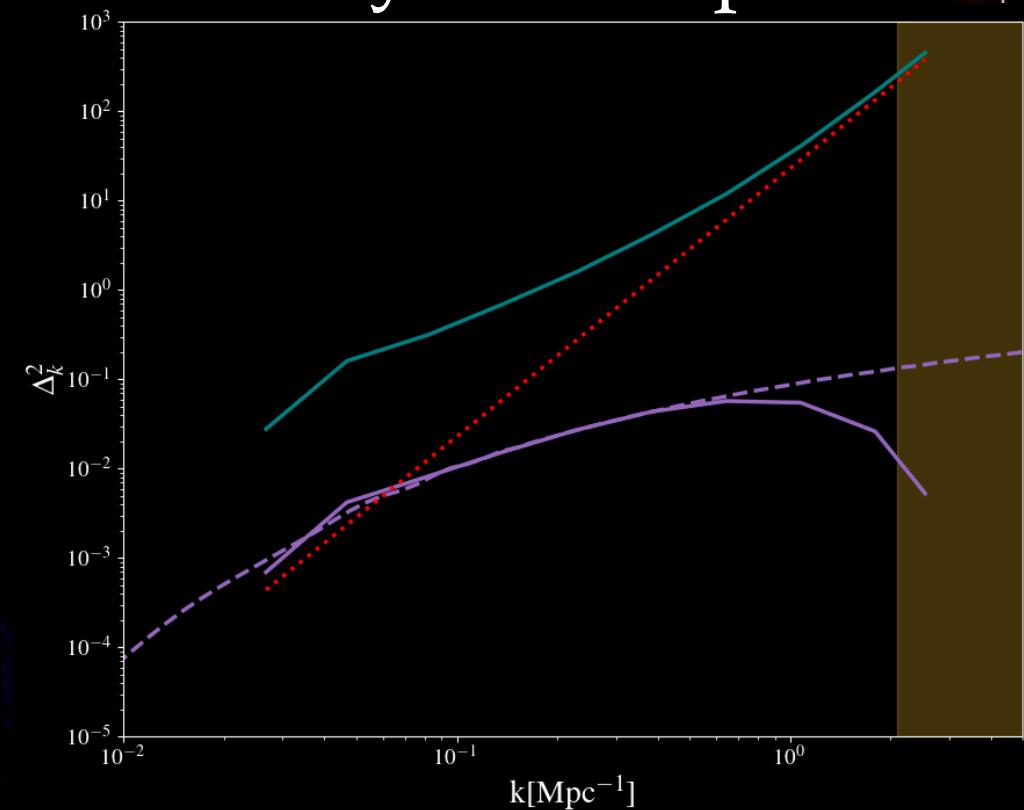
JWST

Summaries

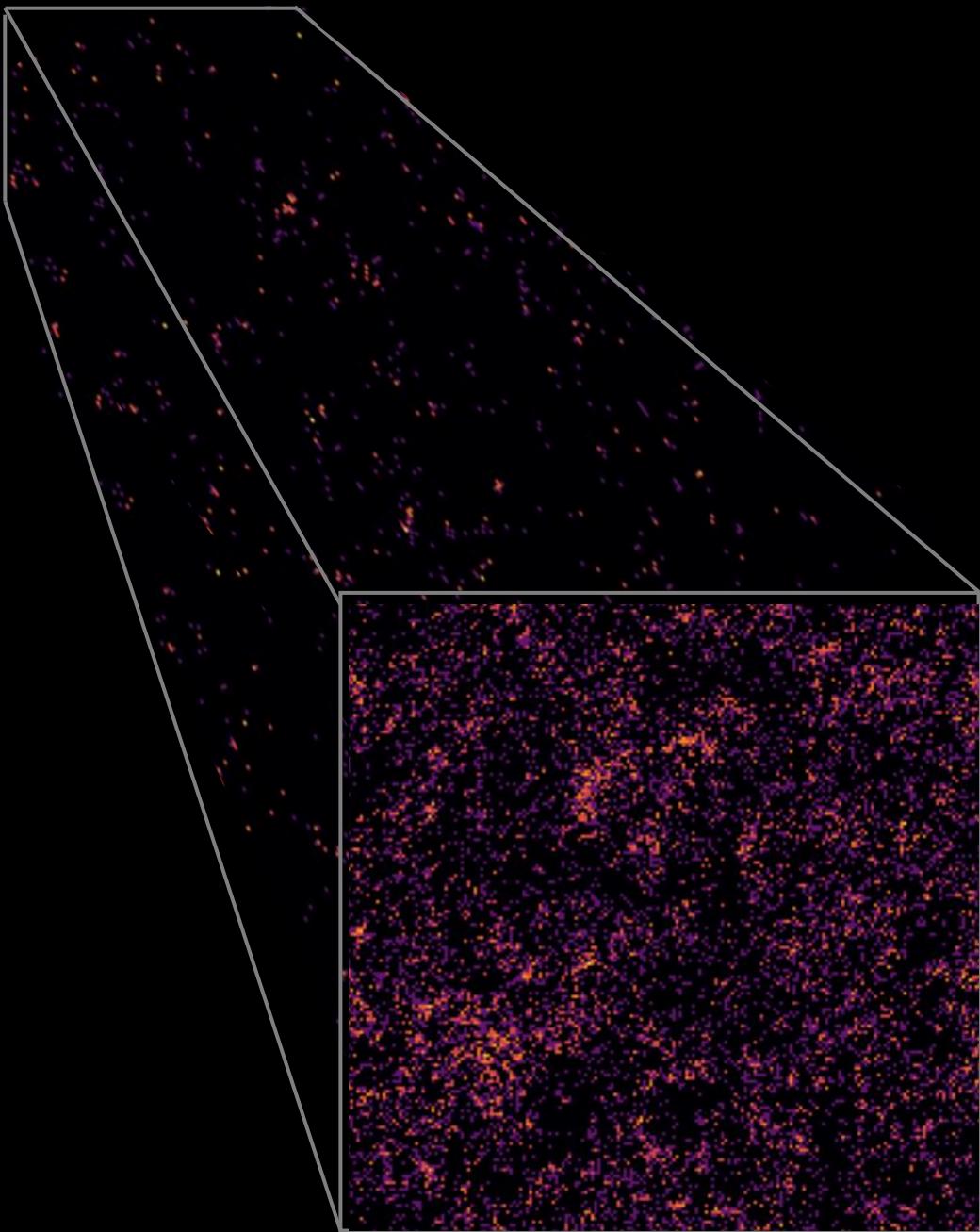
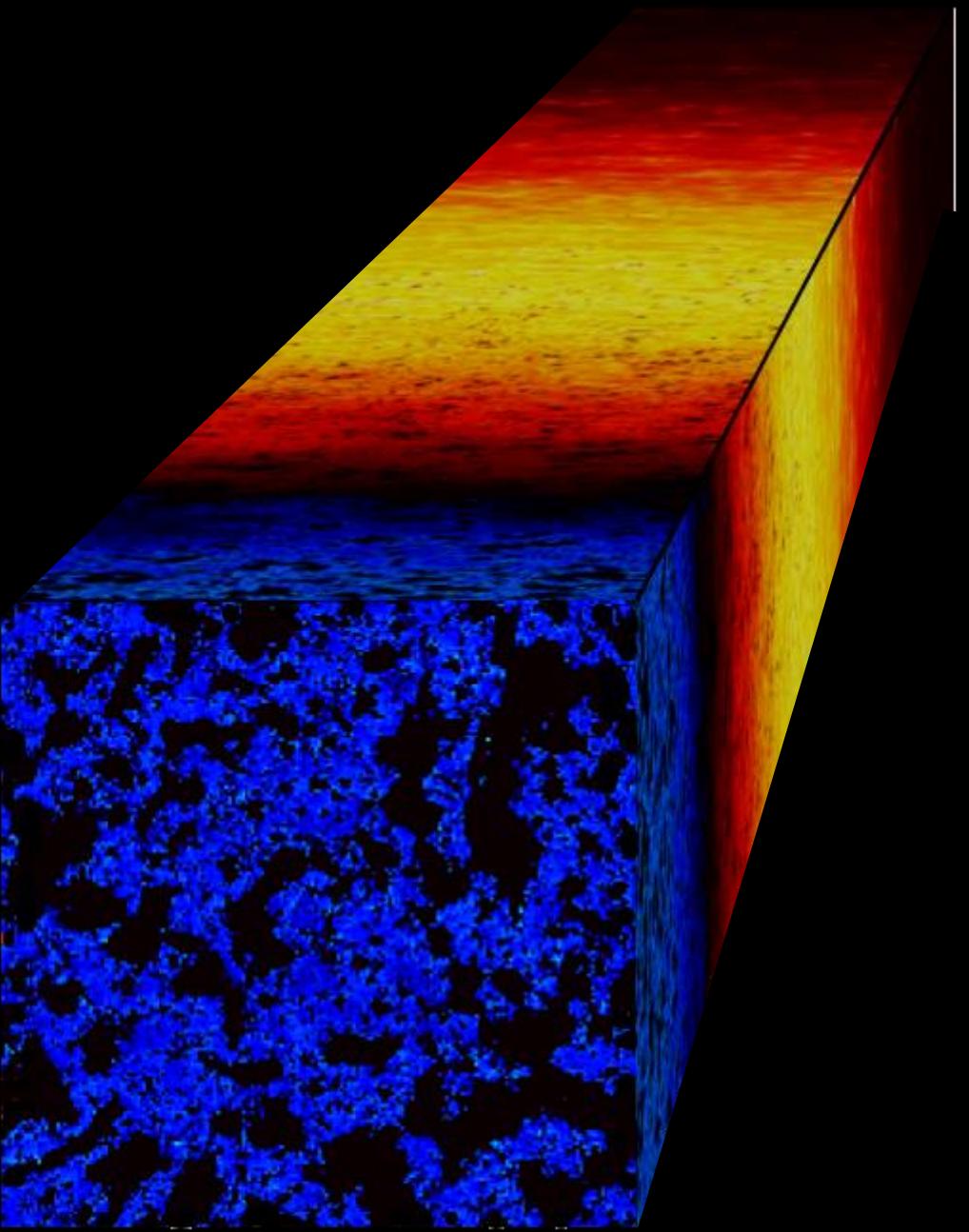


Summary 3: Galaxy Power spectra

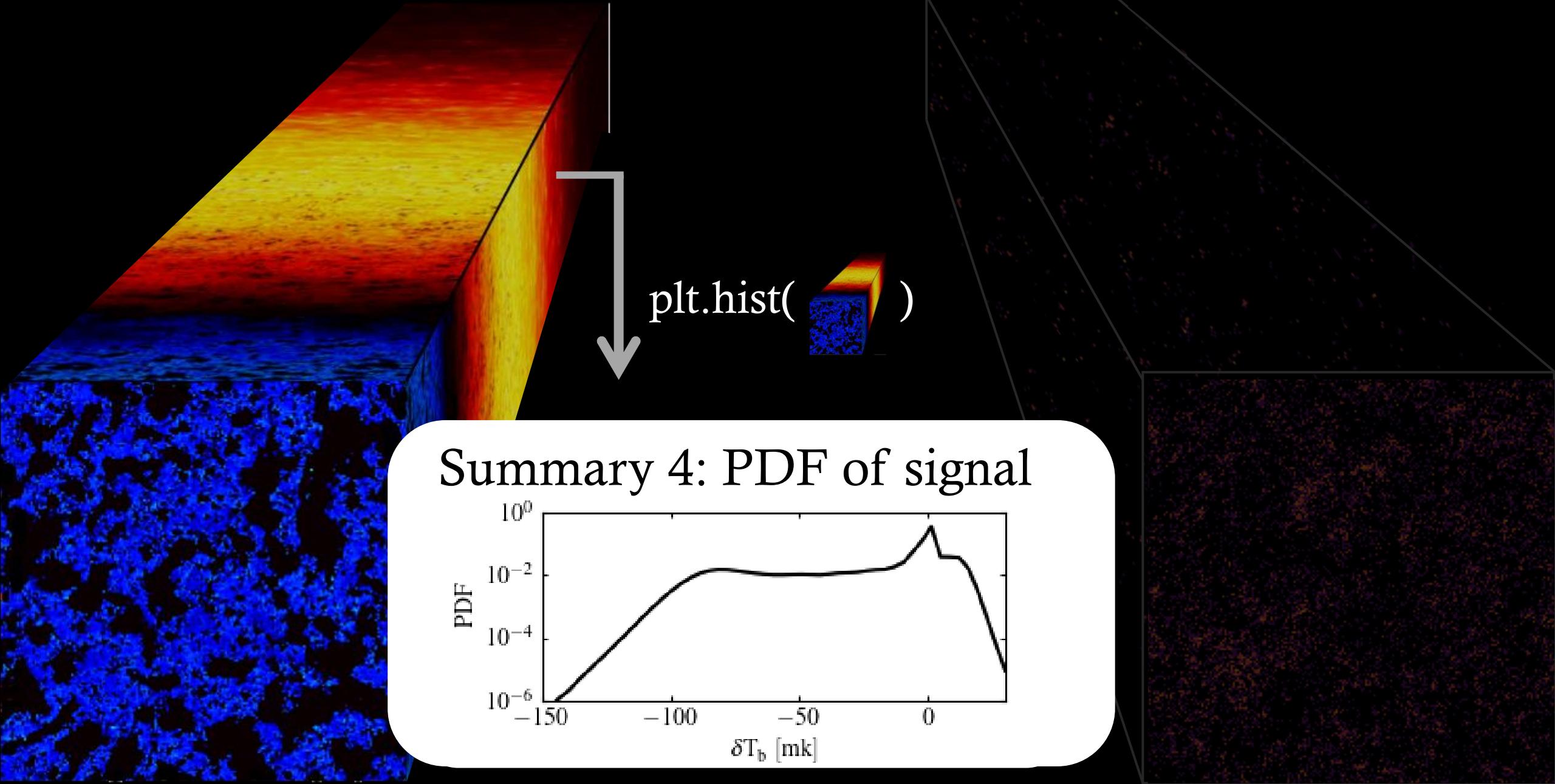
Summaries



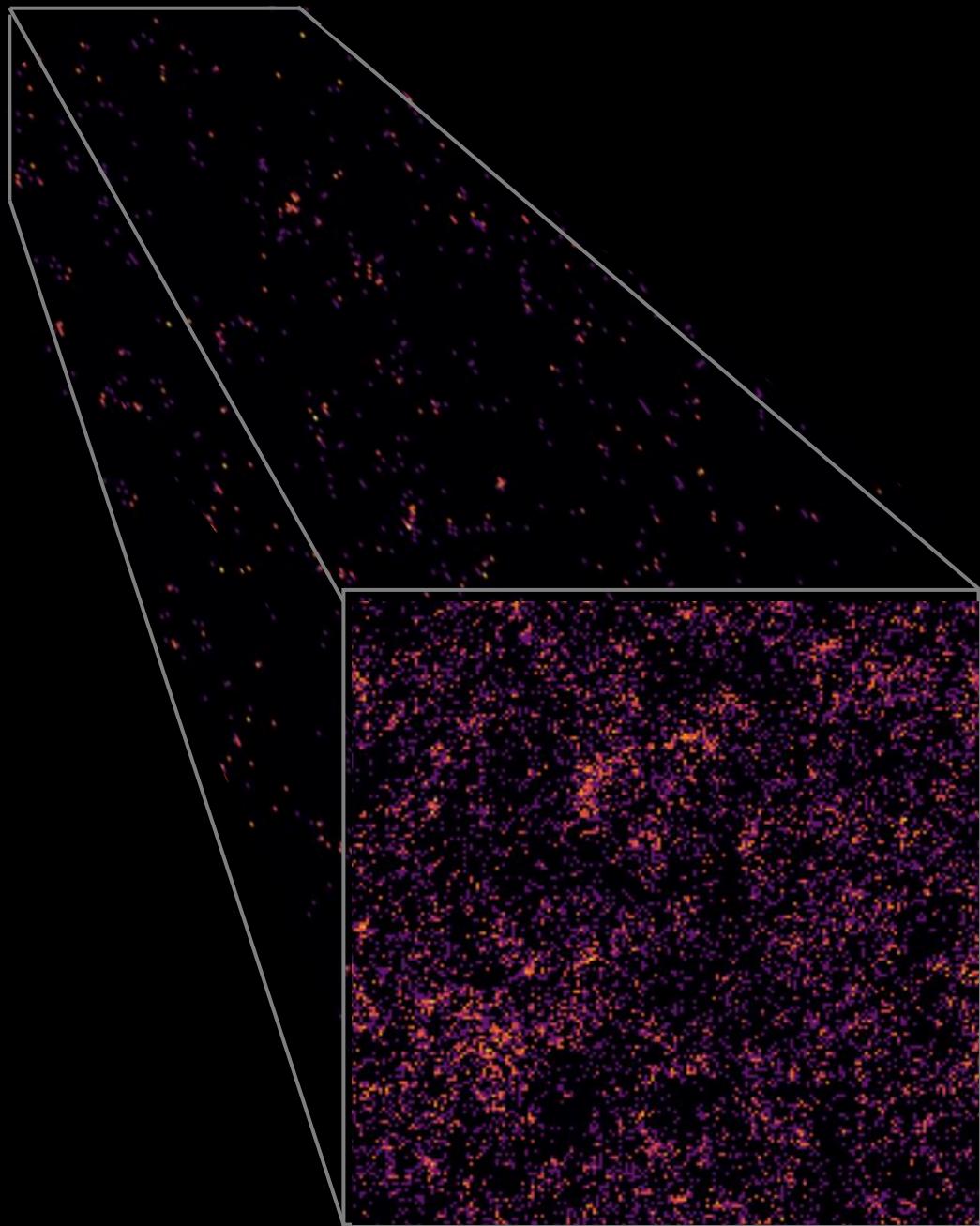
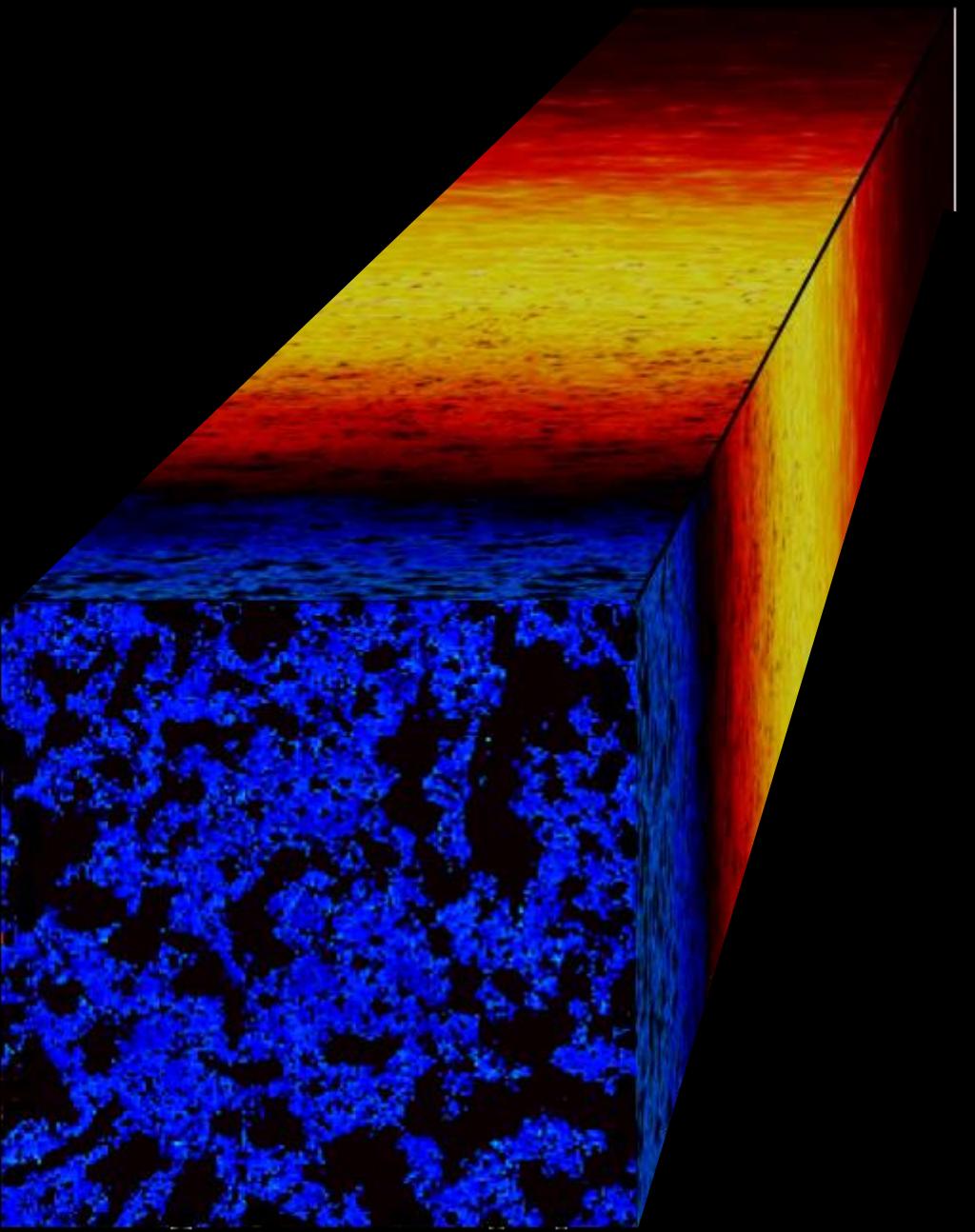
Summaries



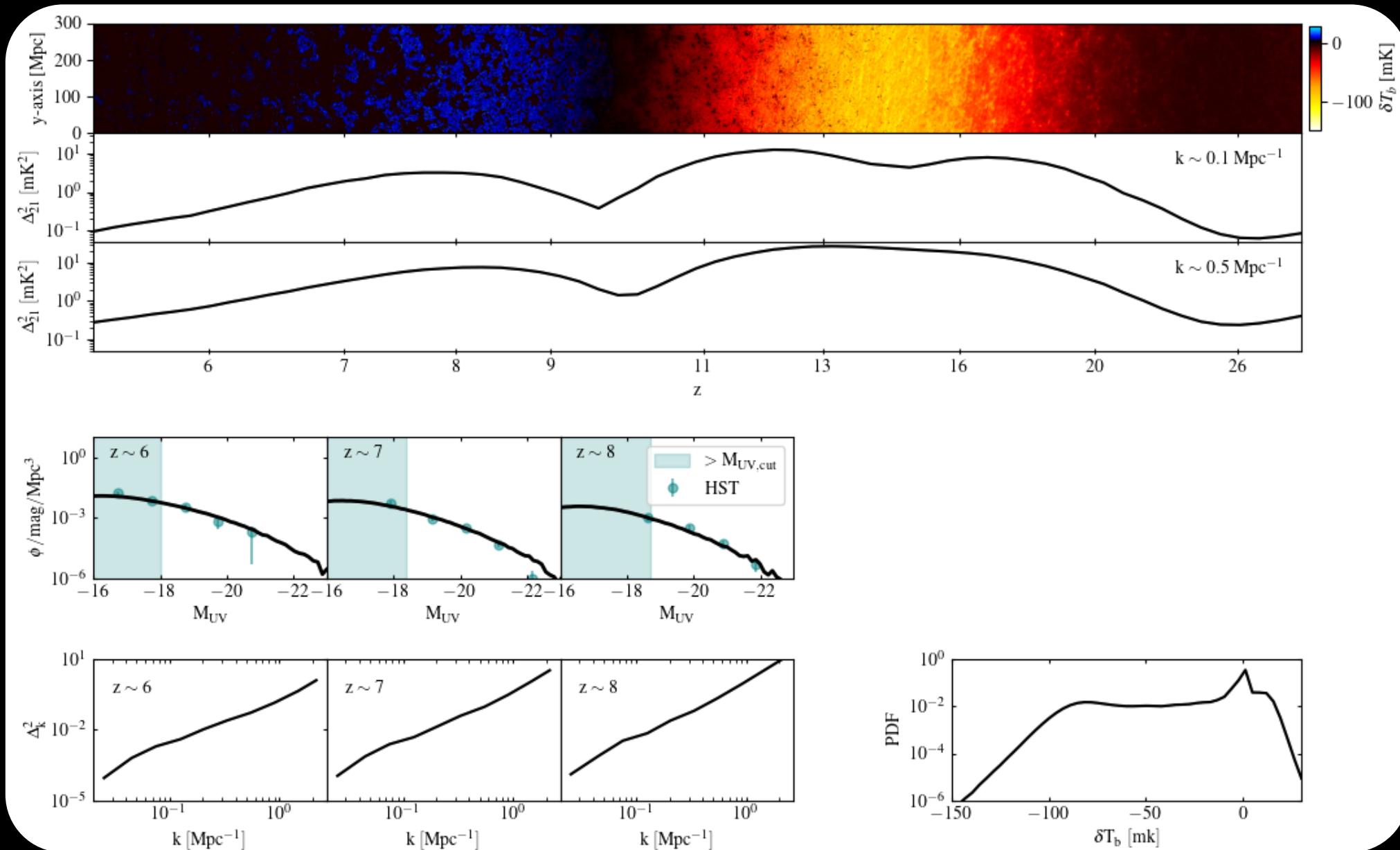
Summaries



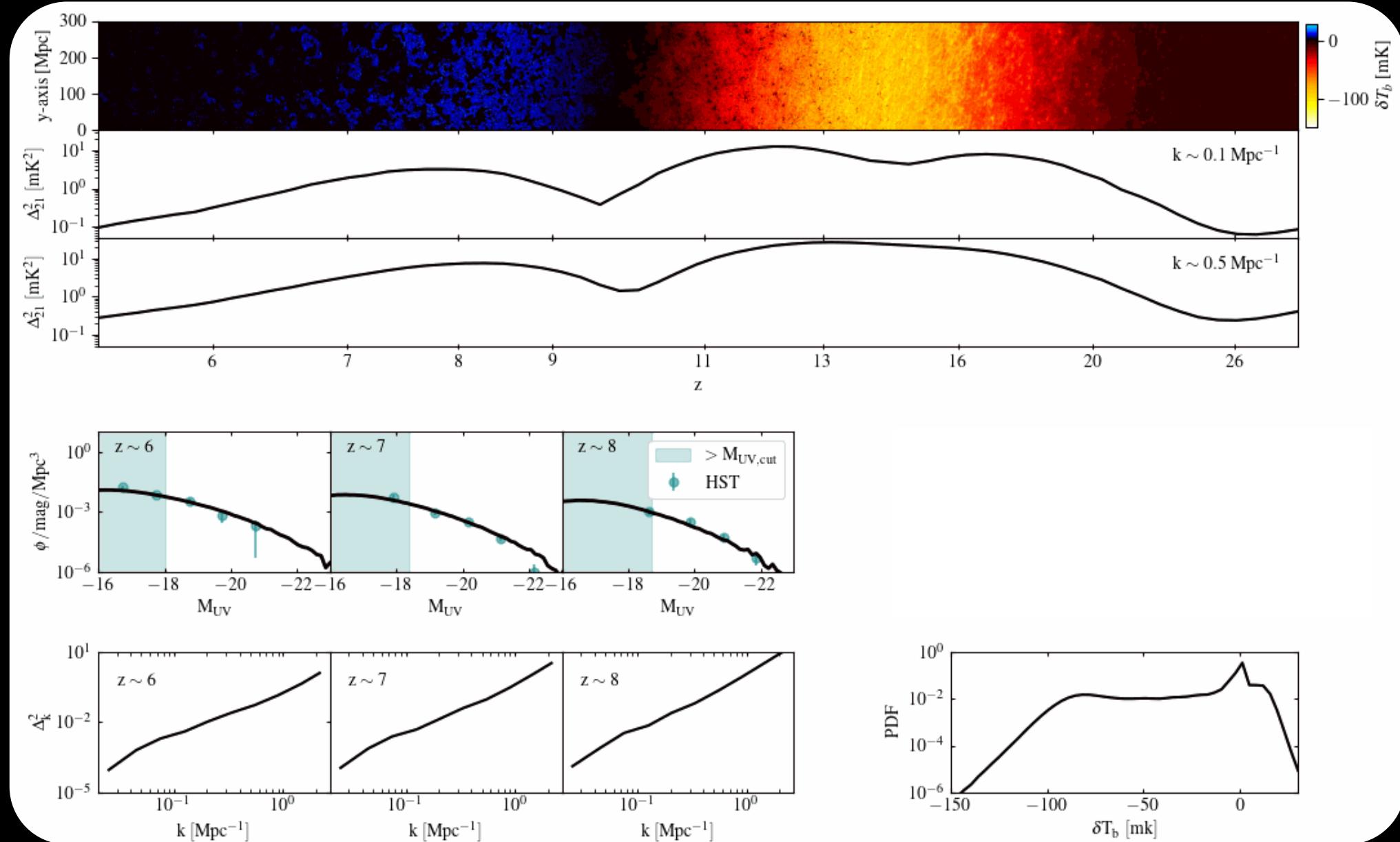
Summaries



Card of Summaries



Highly correlated



Aims

Physics ← Observables

Method

Bayesian inference

• Bayesian inference

• Bayesian vs frequentist

Bayesian inference

$$p(\theta|d) \propto p(d|\theta) \cdot p(\theta)$$

$\theta \rightarrow$ parameters
 $d \rightarrow$ data

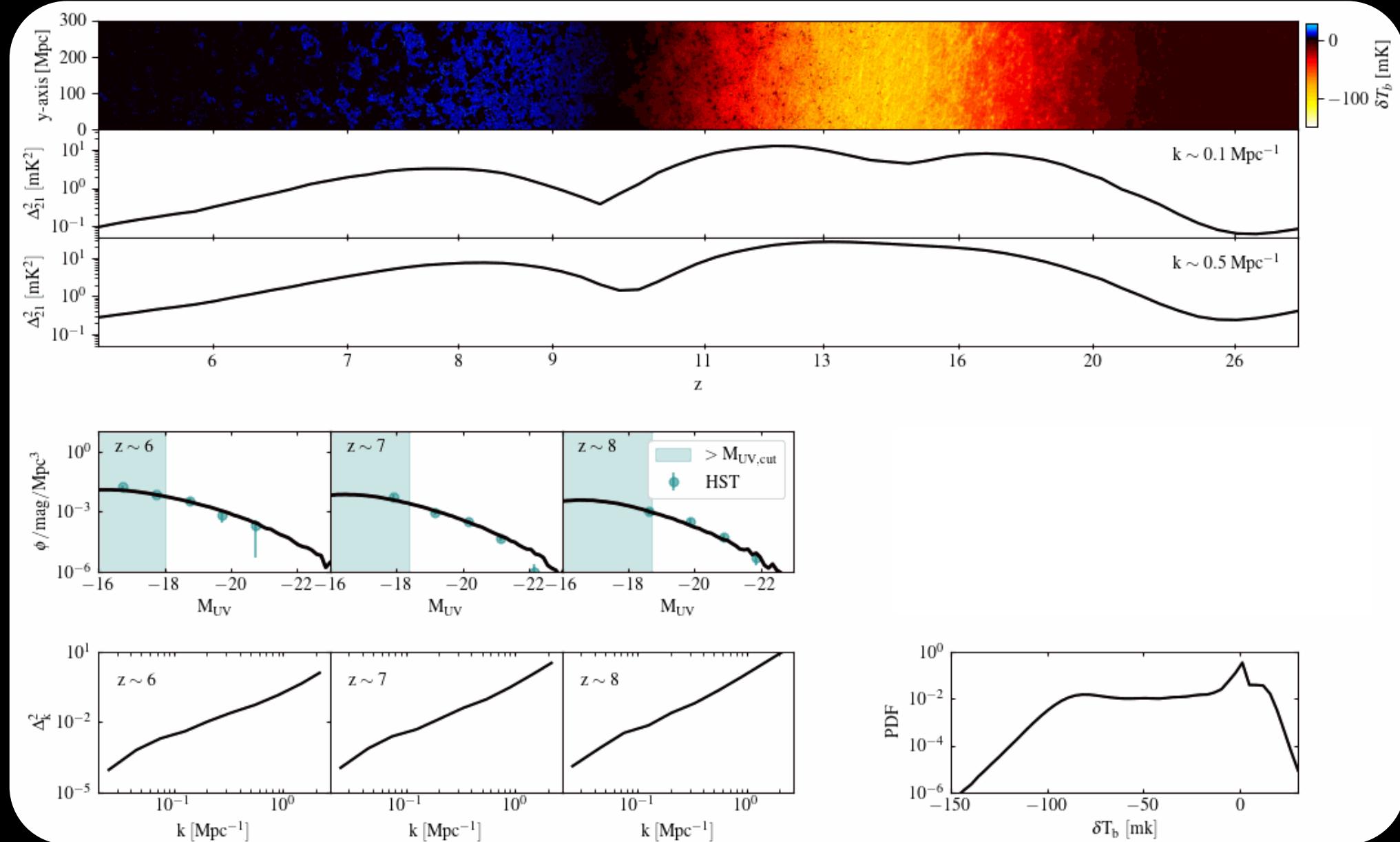
Bayesian inference

$$p(\theta|d) \propto \boxed{p(d|\theta)} \cdot p(\theta)$$

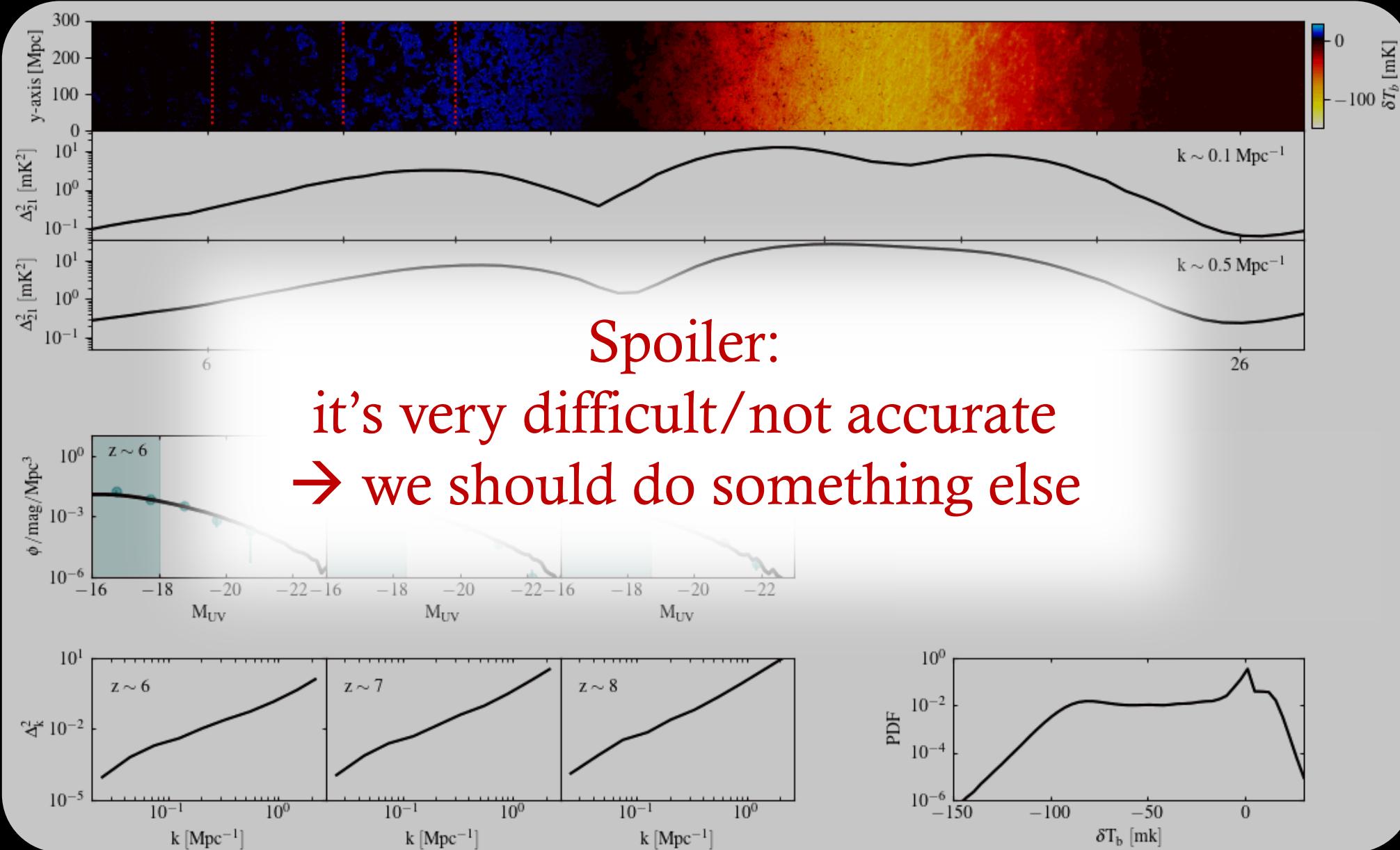
likelihood

$\theta \rightarrow$ parameters
 $d \rightarrow$ data

How do we write a likelihood?



How do we write a likelihood?



SBI

Simulation Based Inference

SBI

Simulation Based Inference

Hasn't been done for Multi-Tracer (only for 21cm)
e.g. Prelogović+2023

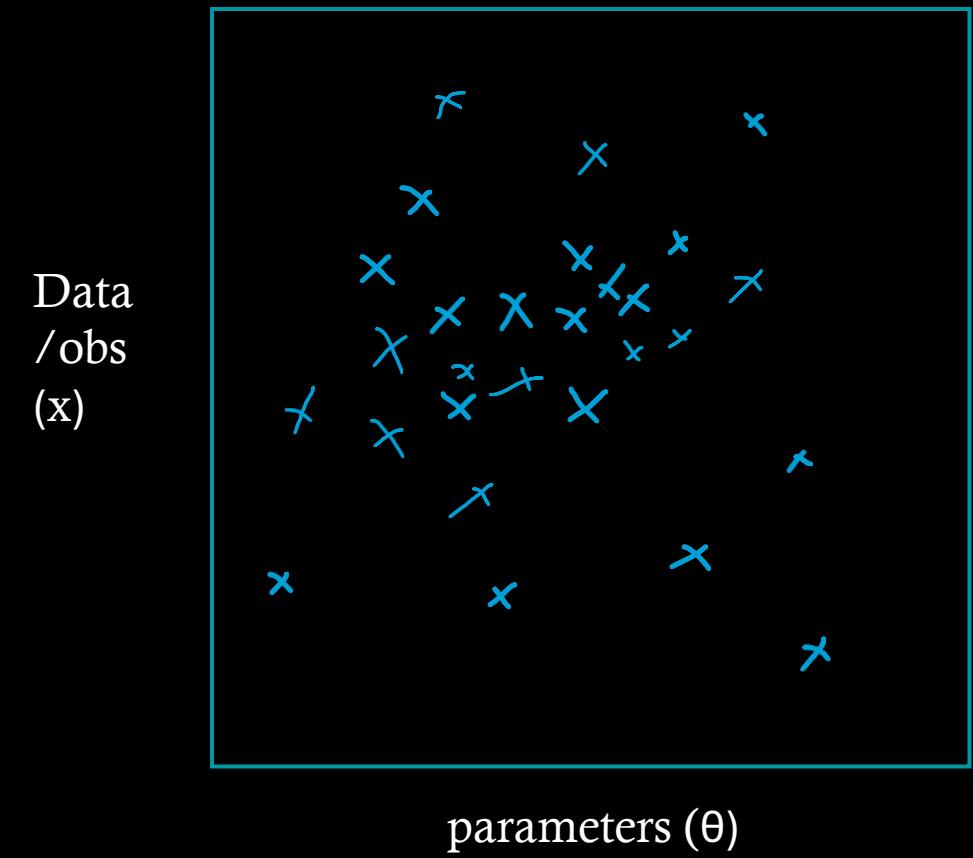
Simulation Based Inference

Simulation Based Inference

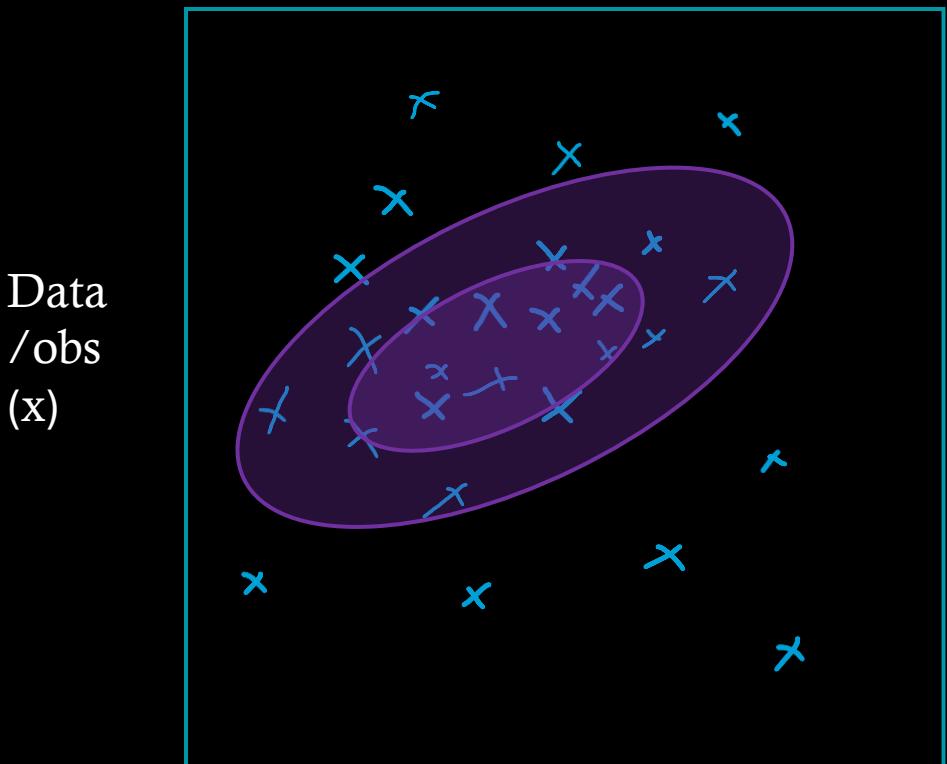
Data
/obs
(x)

parameters (θ)

Simulation Based Inference

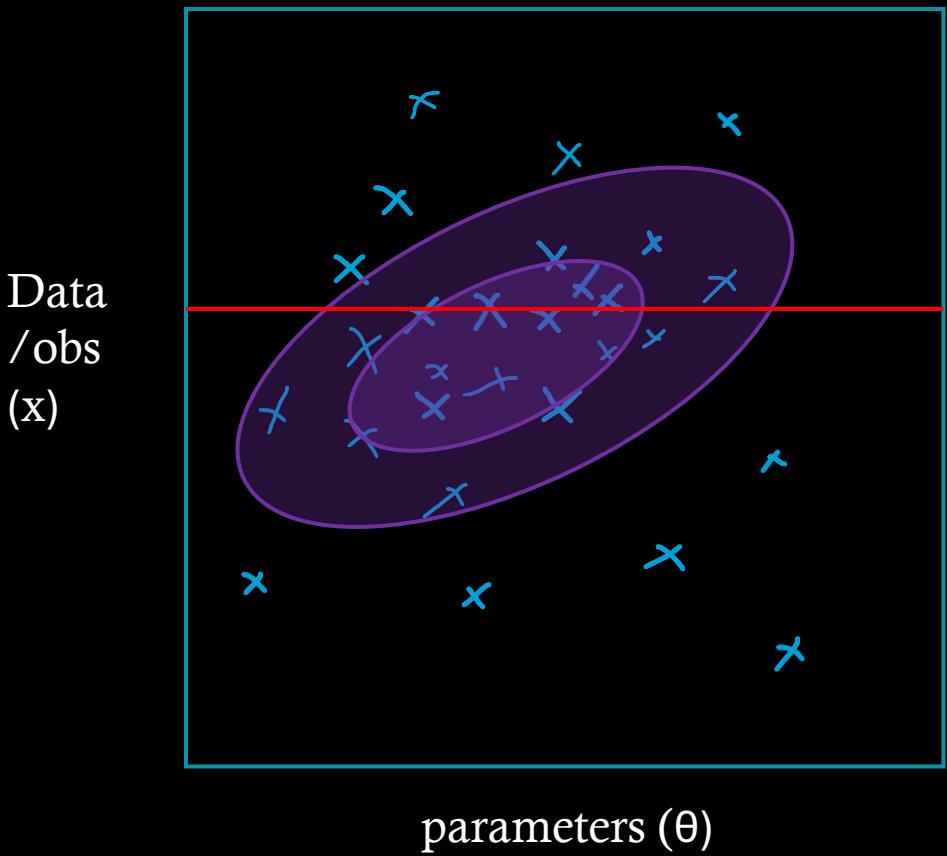


Simulation Based Inference

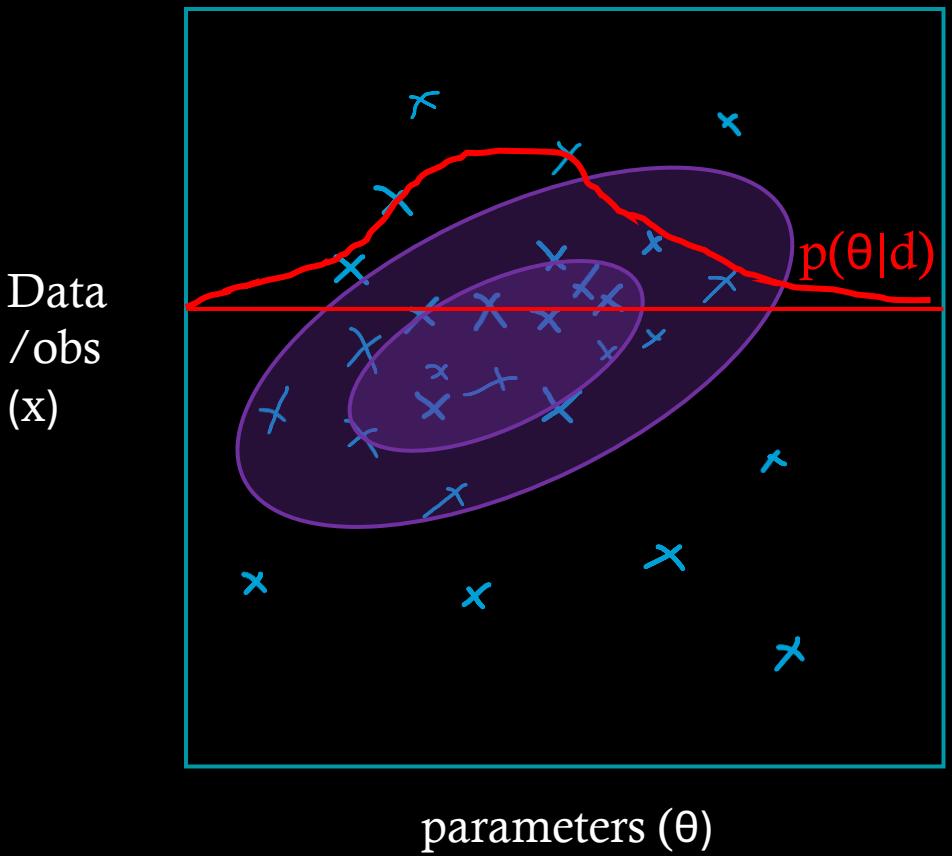


parameters (θ)

Simulation Based Inference



Simulation Based Inference



SBI: Neural Ratio Estimation (NRE)



parameters (θ)

SBI: Neural Ratio Estimation (NRE)

Jointly drawn $p(x, \theta)$

Data
/obs
(x)



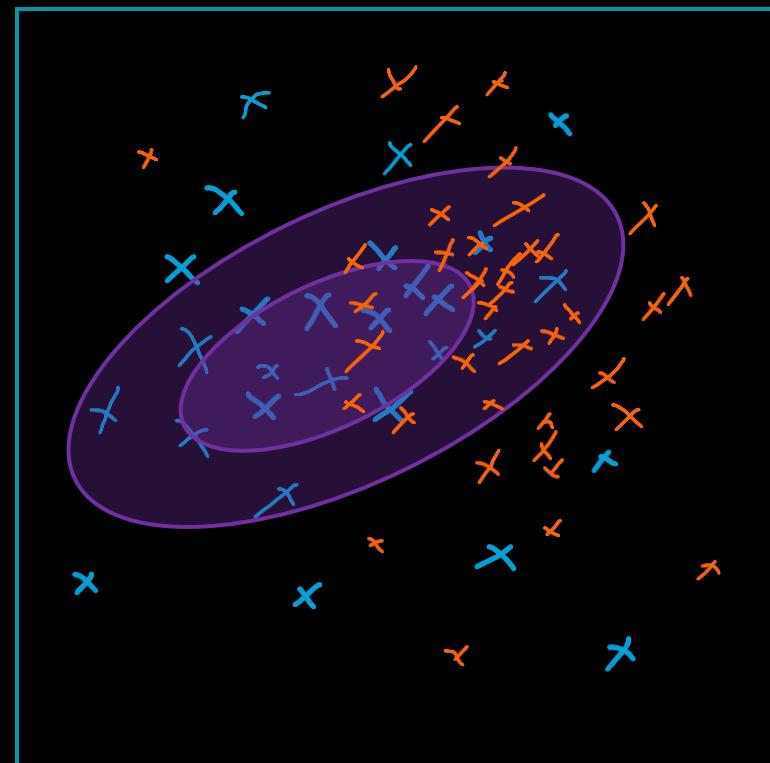
parameters (θ)

SBI: Neural Ratio Estimation (NRE)

 Jointly drawn $p(\mathbf{x}, \boldsymbol{\theta})$

 Independently drawn $p(\mathbf{x})p(\boldsymbol{\theta})$

Data
/obs
(x)



parameters ($\boldsymbol{\theta}$)

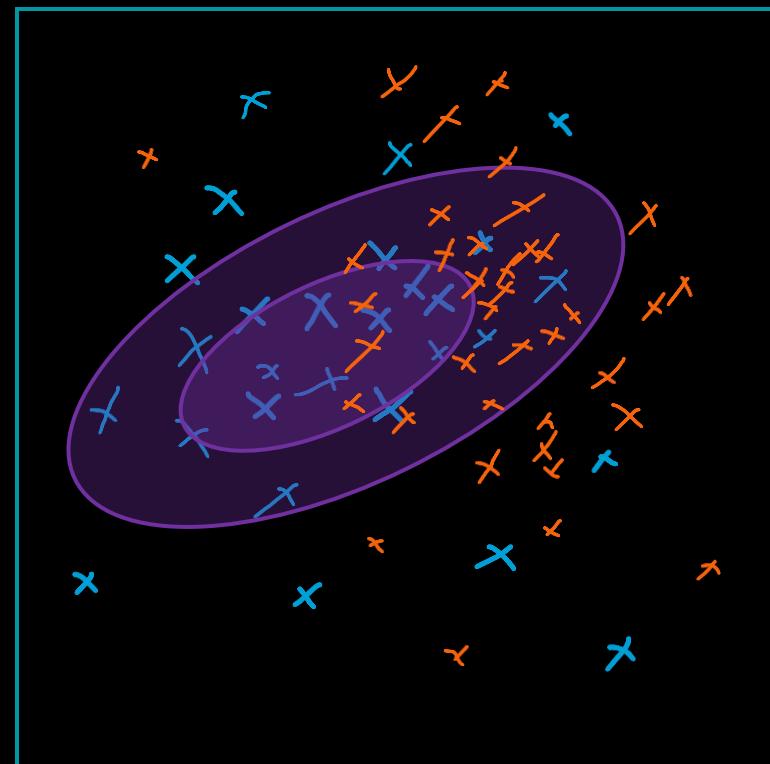
SBI: Neural Ratio Estimation (NRE)

Jointly drawn $p(\mathbf{x}, \boldsymbol{\theta})$

Independently drawn $p(\mathbf{x})p(\boldsymbol{\theta})$

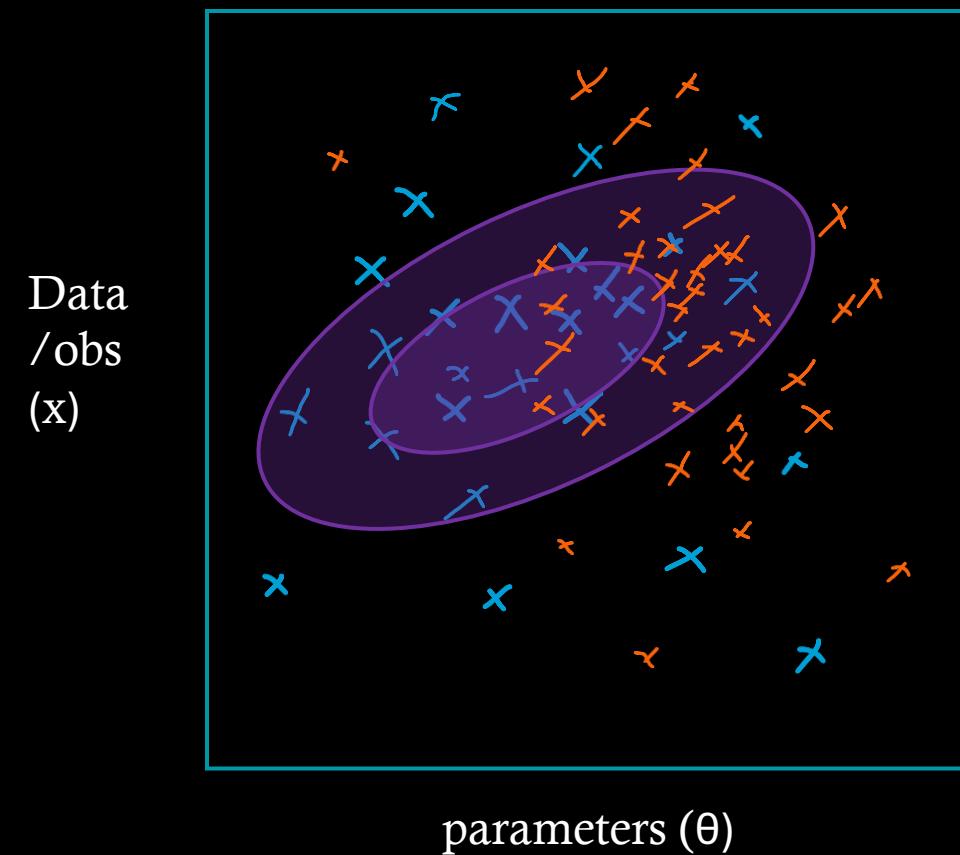
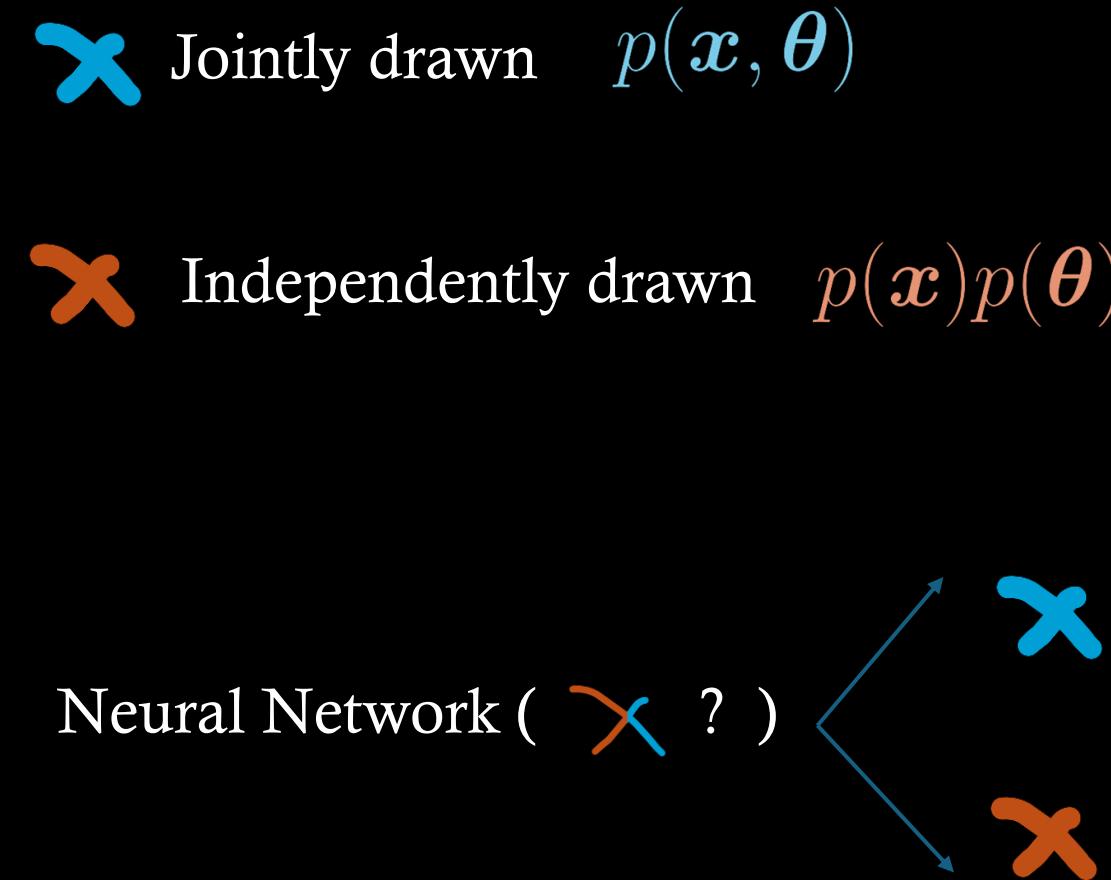
Neural Network ($\mathcal{X} ?$)

Data
/obs
(x)



parameters ($\boldsymbol{\theta}$)

SBI: Neural Ratio Estimation (NRE)



We need a simulation

We need a simulation

So let me introduce you to...



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025

Built for:



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025

Built for:

High dimensional



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025

Built for:

High dimensional, field level



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025

Built for:

High dimensional, field level, multi-tracer



The new

21cmFASTv4

Davies, Mesinger & Murray, 2025

Built for:

High dimensional, field level, multi-tracer
Bayesian inference of the 1st Billion Years

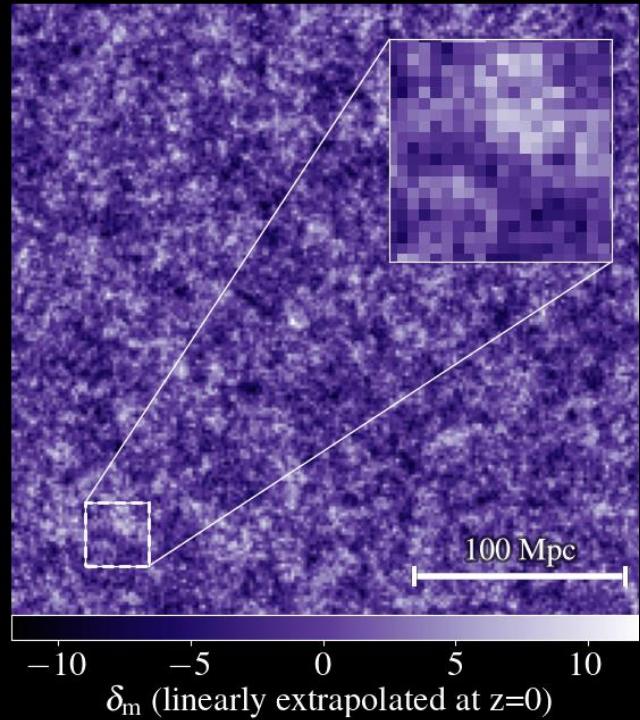
21cmFASTv4

Davies, Mesinger & Murray, 2025

21cmFASTv4

Davies, Mesinger & Murray, 2025

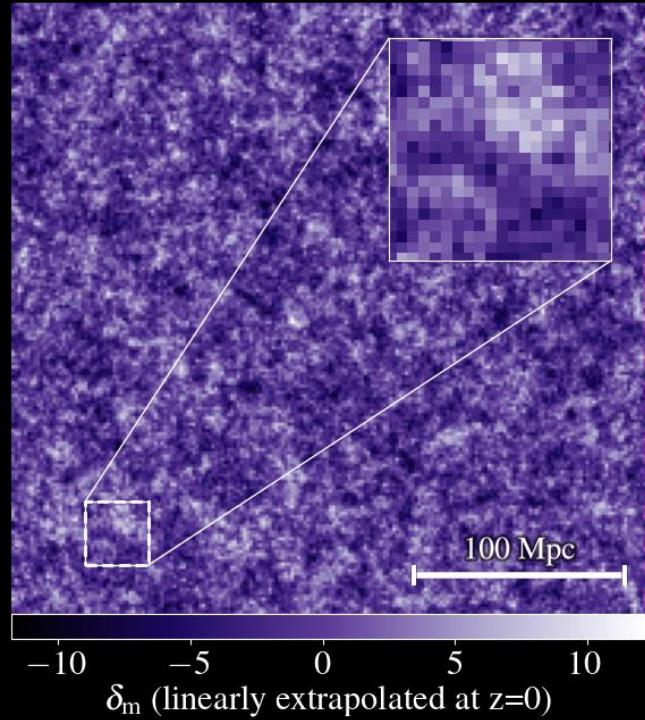
Initial Conditions



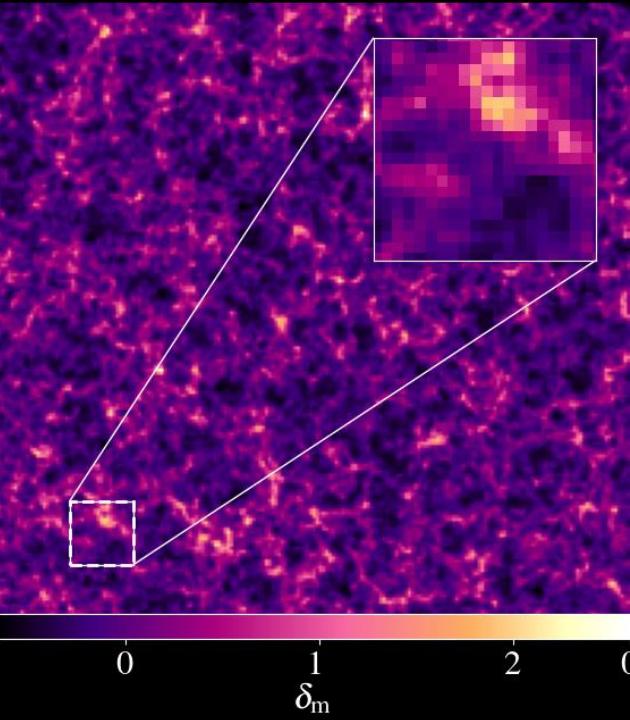
21cmFASTv4

Davies, Mesinger & Murray, 2025

Initial Conditions



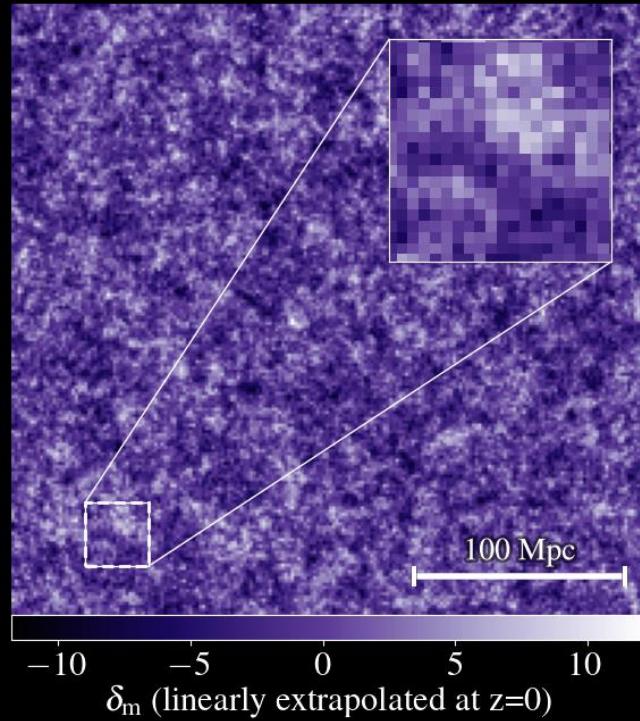
Density $z=8$



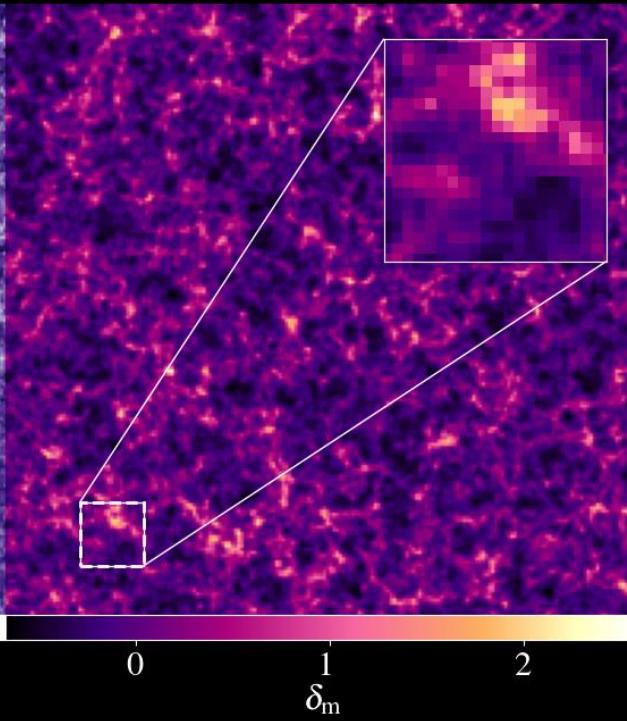
21cmFASTv4

Davies, Mesinger & Murray, 2025

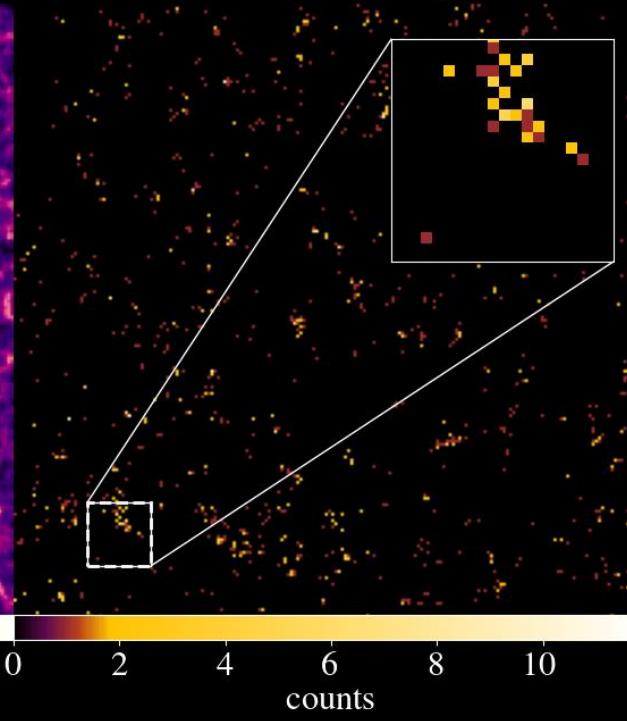
Initial Conditions



Density $z=8$



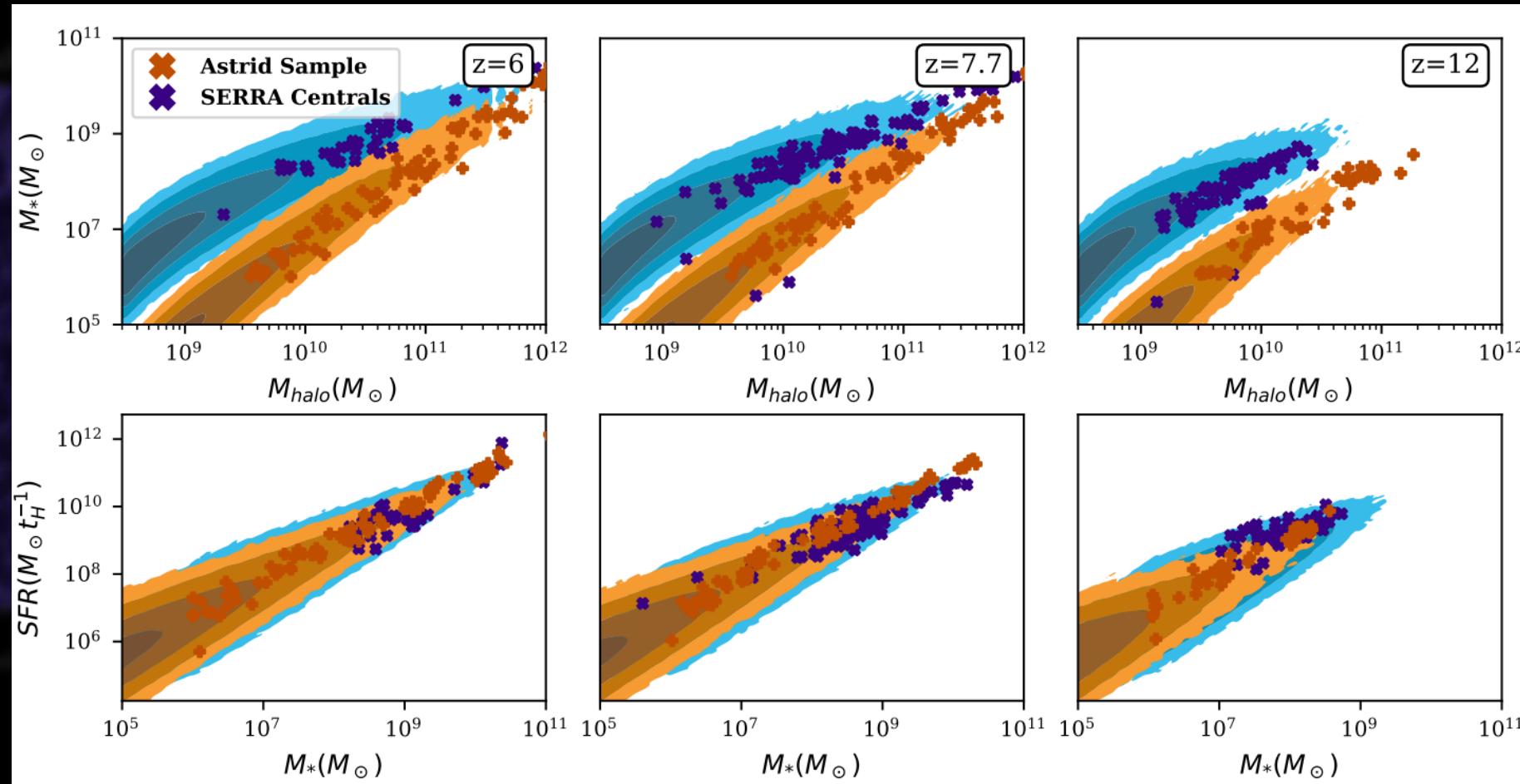
Galaxy counts $z=8$



21cmFASTv4

Davies, Mesinger & Murray, 2025

Davies+2025



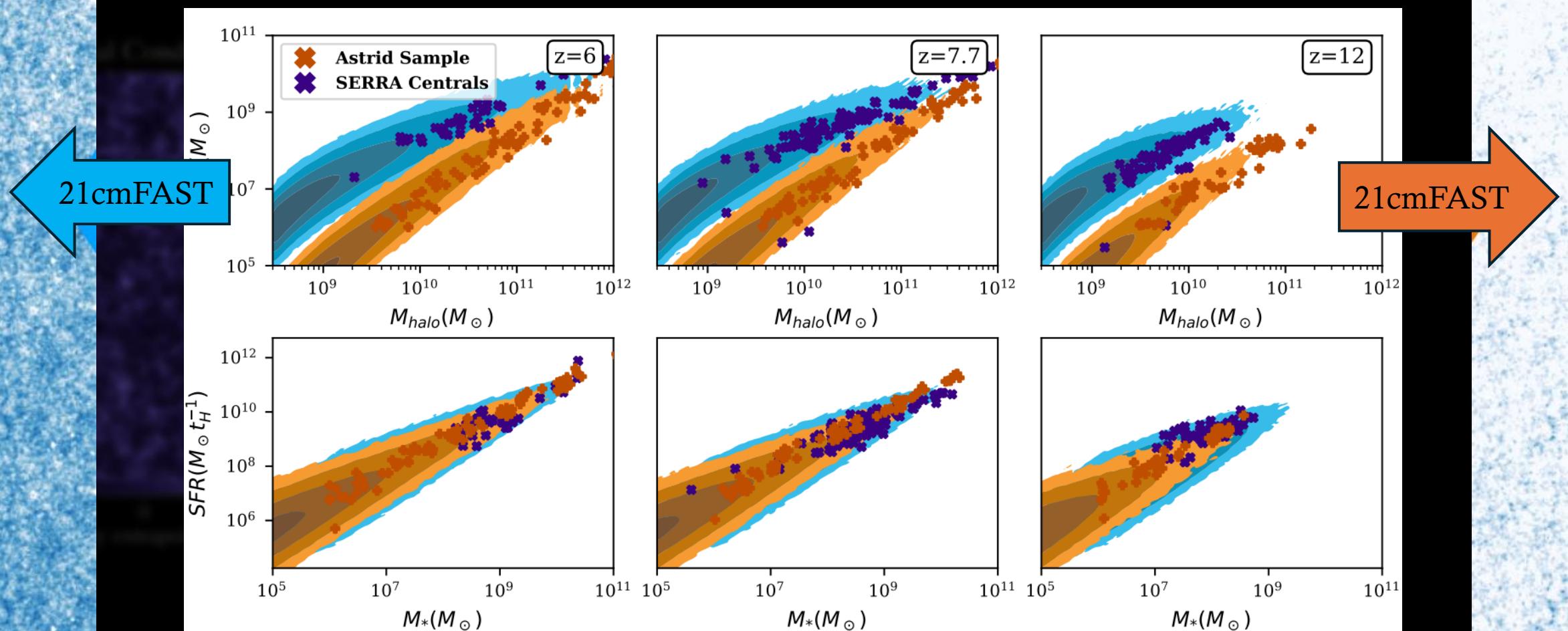
SFRD

SFRD

21cmFASTv4

Davies, Mesinger & Murray, 2025

Davies+2025



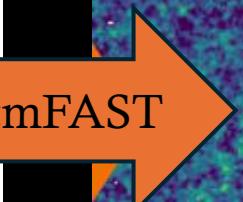
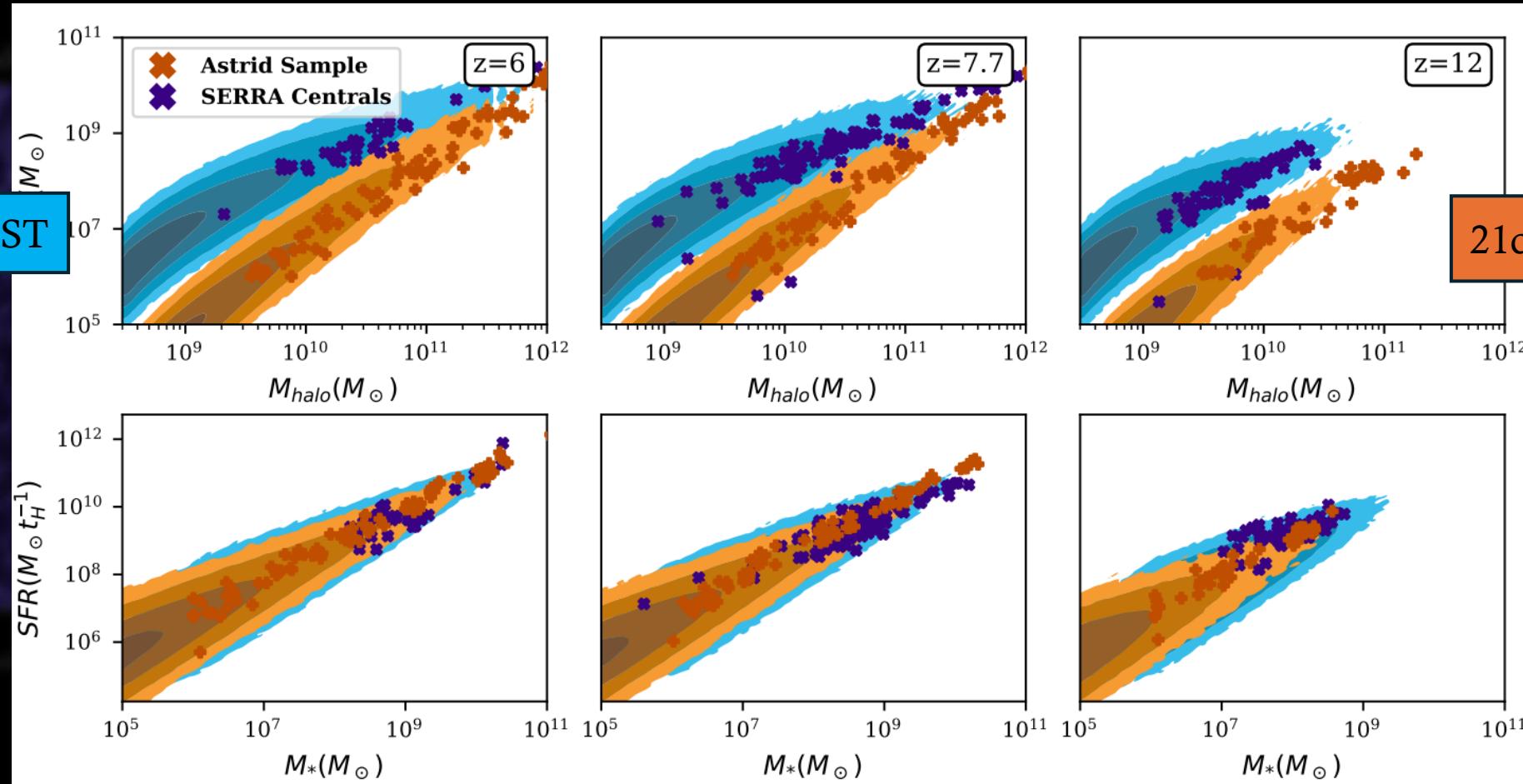
[CII]

21cmFASTv4

[CII]

Davies, Mesinger & Murray, 2025

Davies+2025



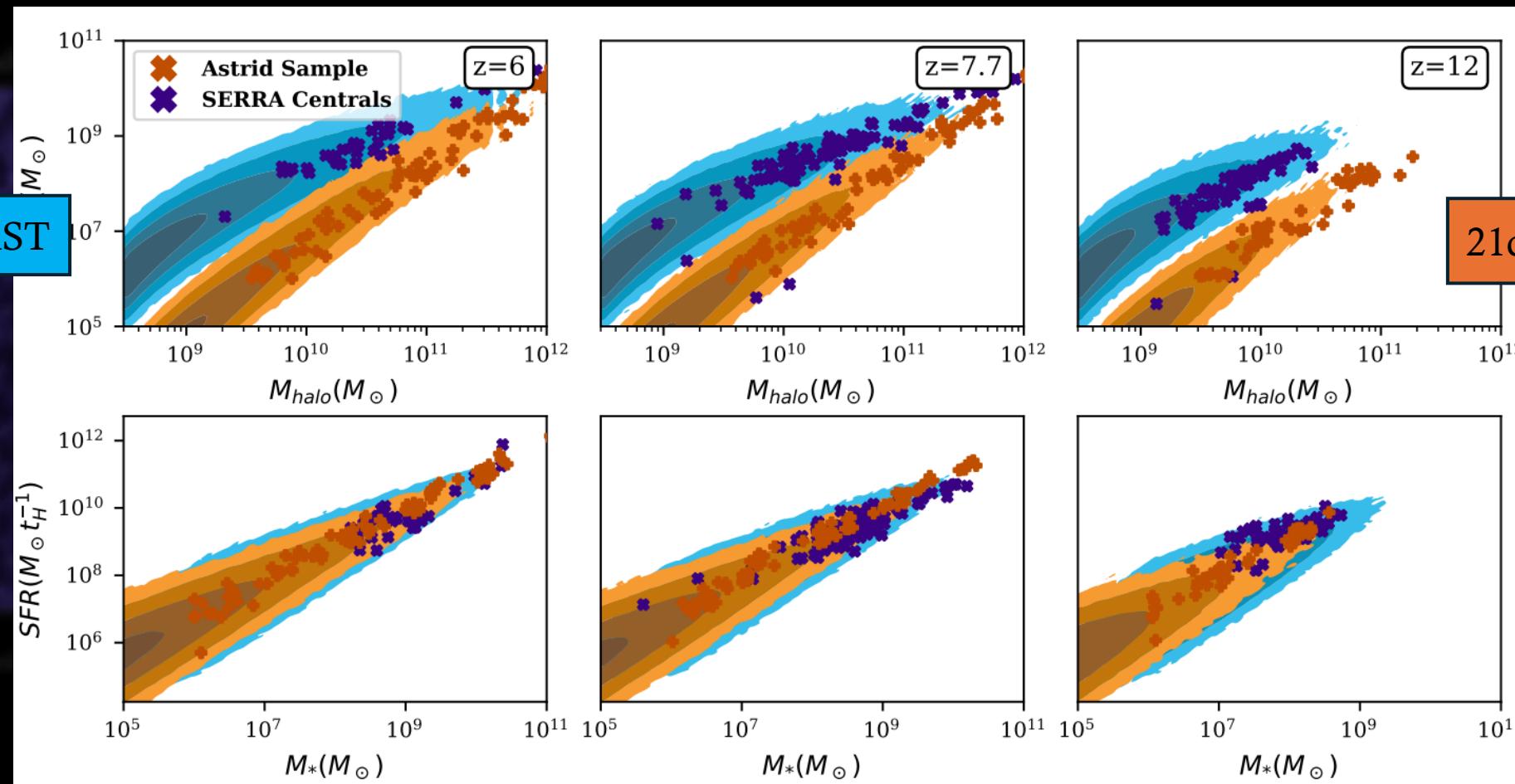
21cm

21cmFASTv4

21cm

Davies, Mesinger & Murray, 2025

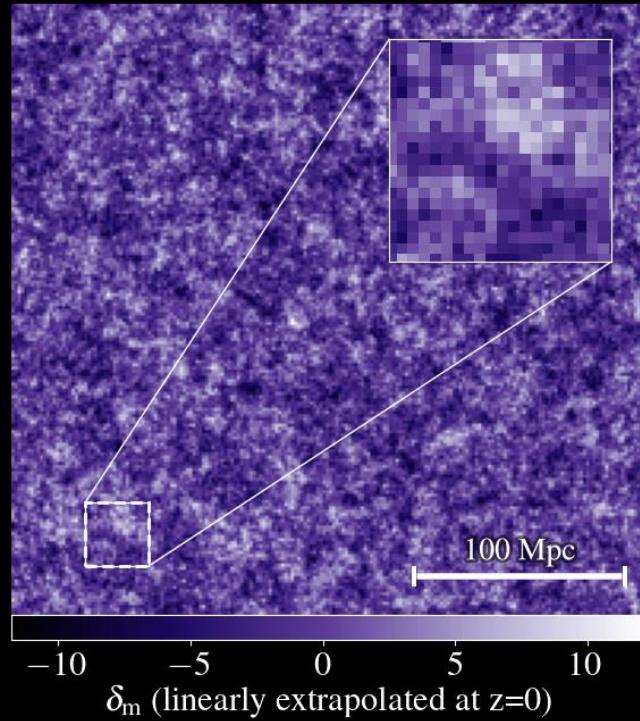
Davies+2025



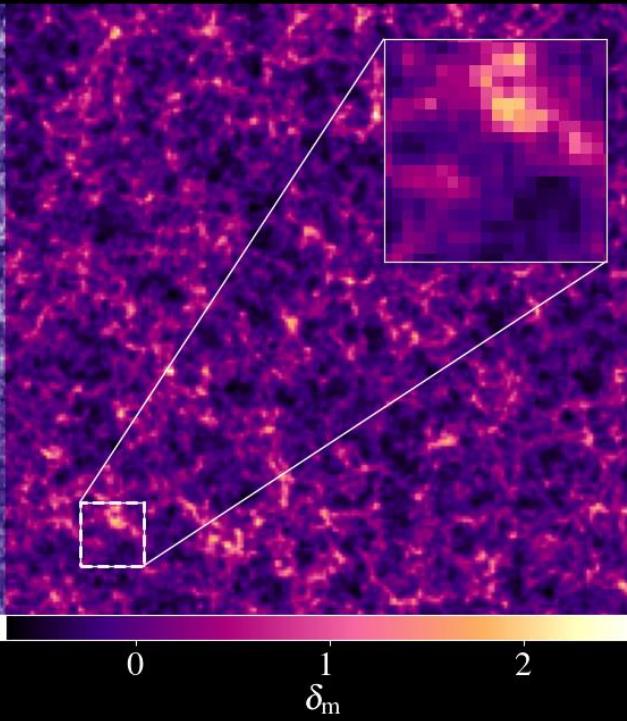
21cmFASTv4

Davies, Mesinger & Murray, 2025

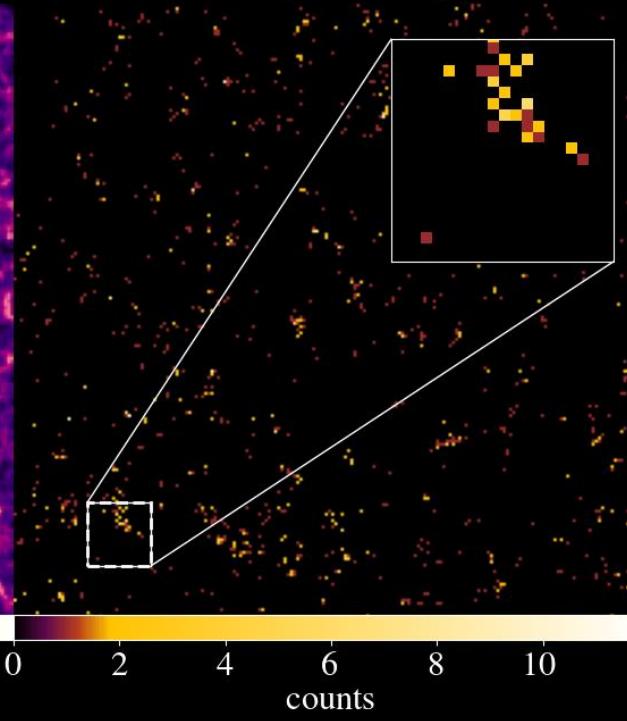
Initial Conditions



Density $z=8$

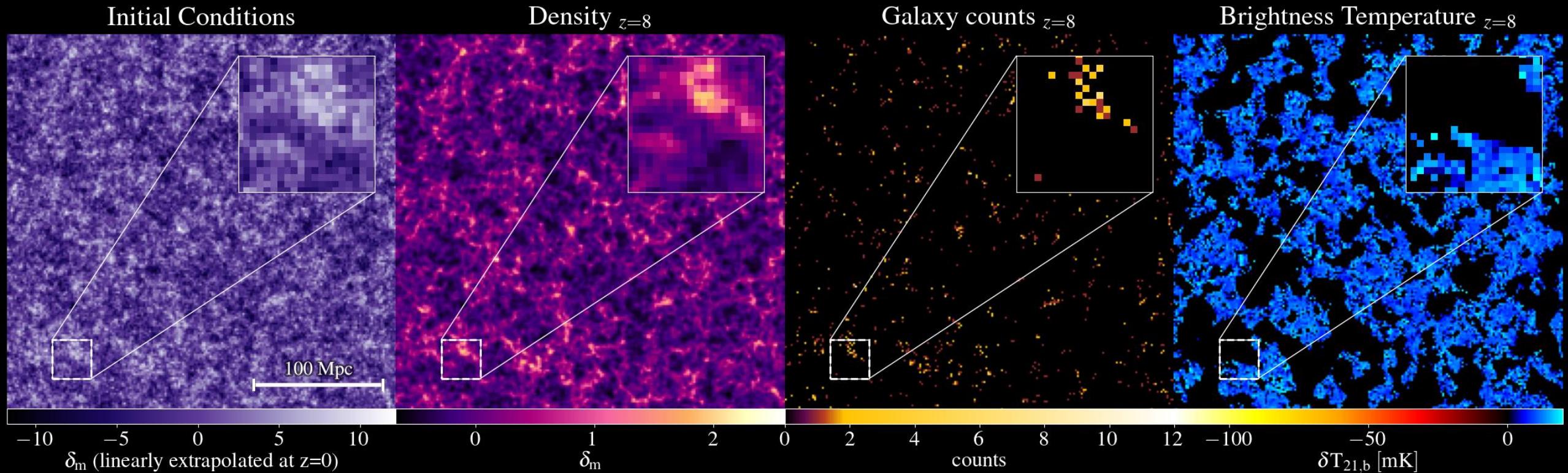


Galaxy counts $z=8$



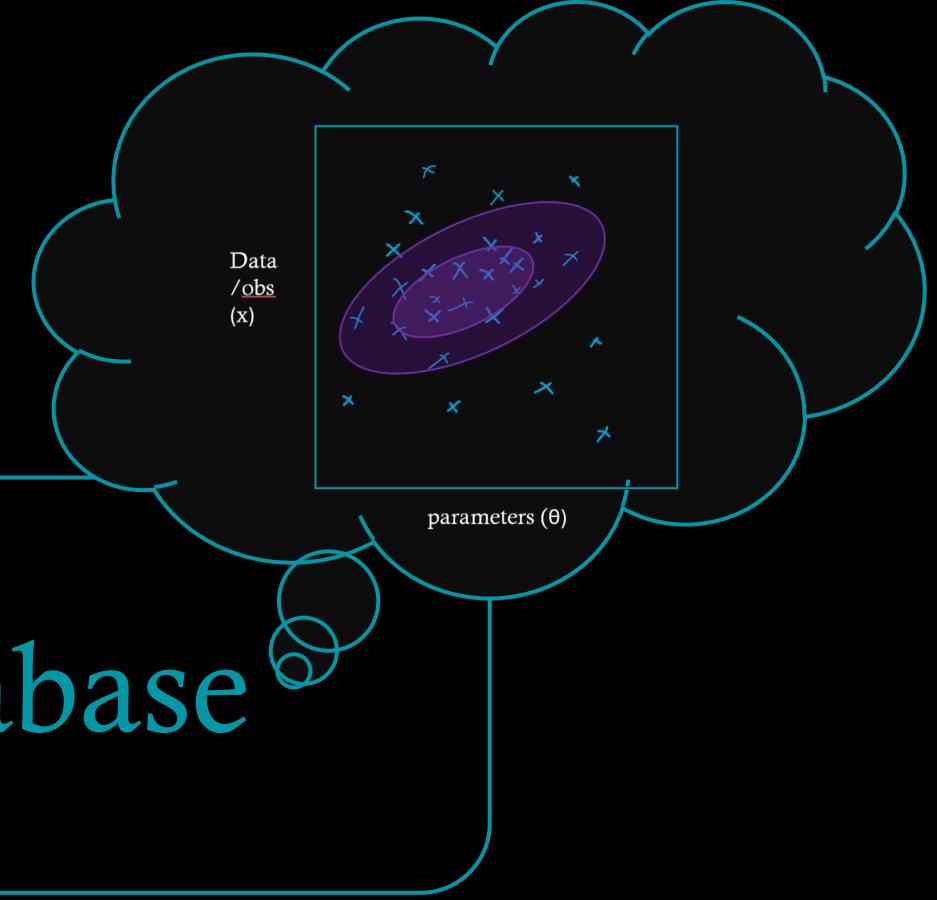
21cmFASTv4

Davies, Mesinger & Murray, 2025



We need a database

We need a database



21cmDATABASE



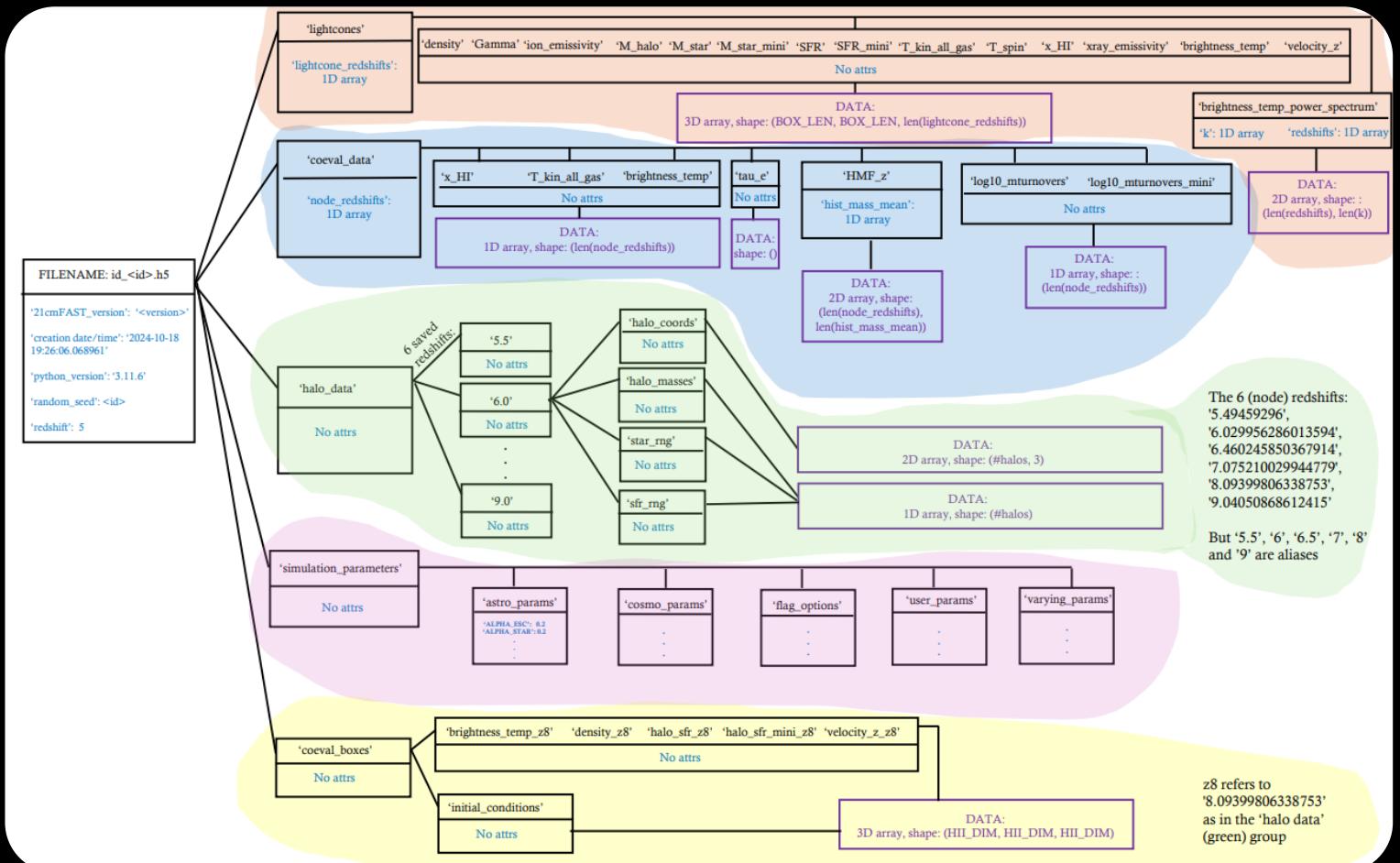
21cmDATABASE

aiming for ~100,000 simulations

21cmDATABASE

aiming for $\sim 100,000$ simulations

Example file structure

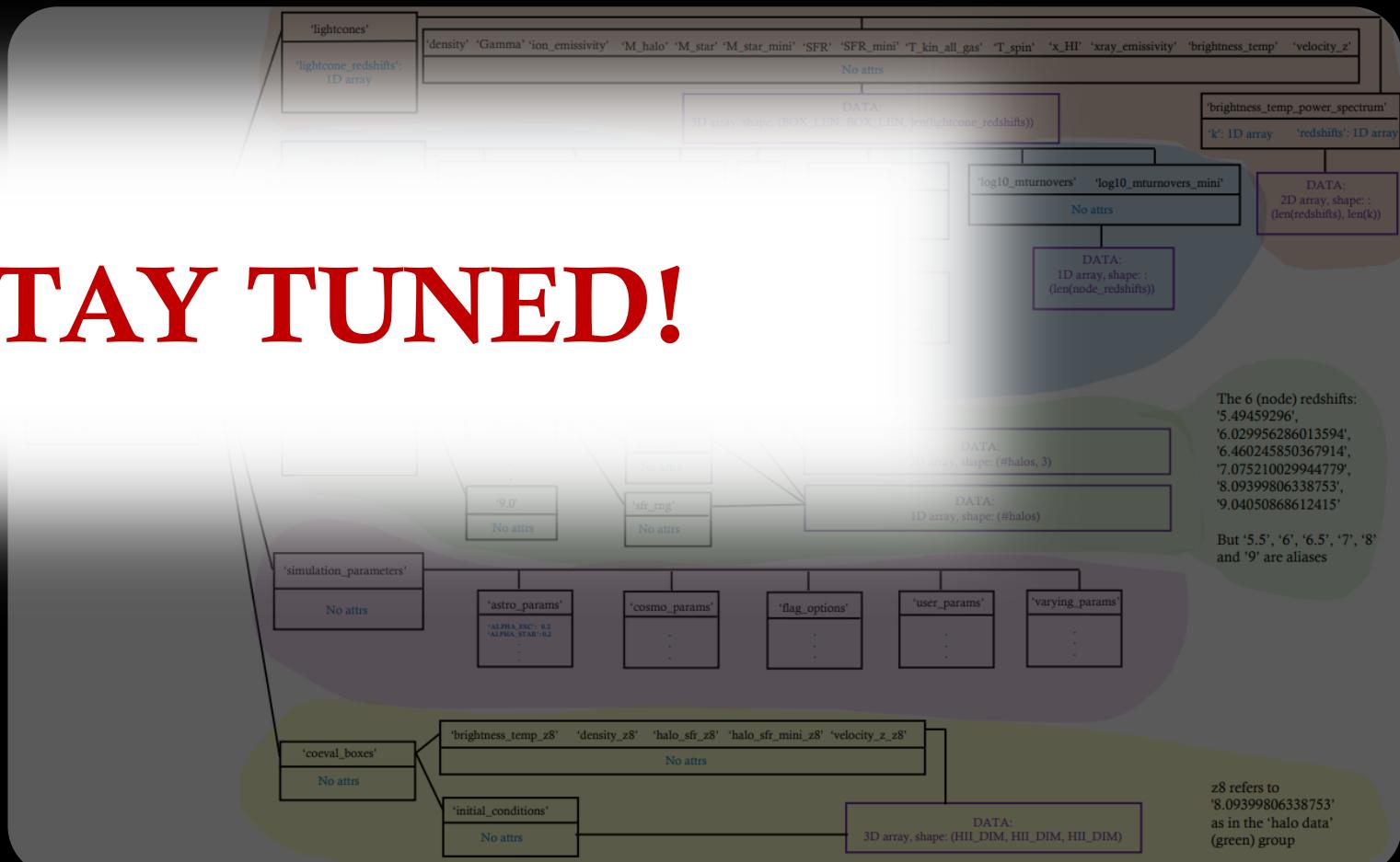


21cmDATABASE

aiming for ~100,000 simulations

Example structure

STAY TUNED!



Recap

Recap

1. Aim? → Infer Galaxy properties

Recap

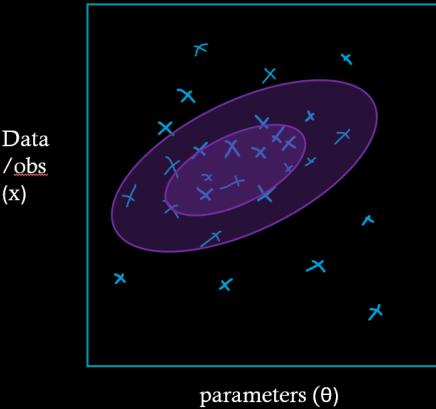
1. Aim? → Infer Galaxy properties
2. Method? → SBI (NRE)

Recap

1. Aim? → Infer Galaxy properties

$$p(\theta | x)$$

2. Method? → SBI (NRE)

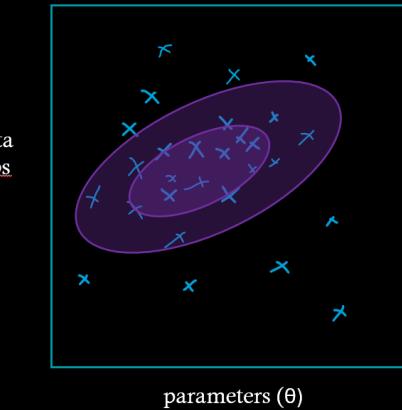


Recap

1. Aim? → Infer Galaxy properties

$$p(\theta | x)$$

2. Method? → SBI (NRE)



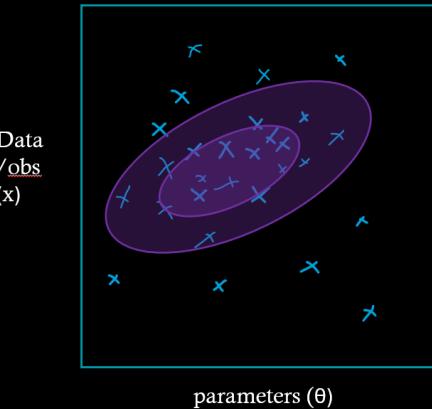
21cmFASTv4

Recap

1. Aim? → Infer Galaxy properties

$$p(\theta | x)$$

2. Method? → SBI (NRE)



21cmFASTv4

21cmDATABASE

Results

Results

1.1.1.

1.1.1.1.

1.1.1.1.1.

1.1.1.1.2.

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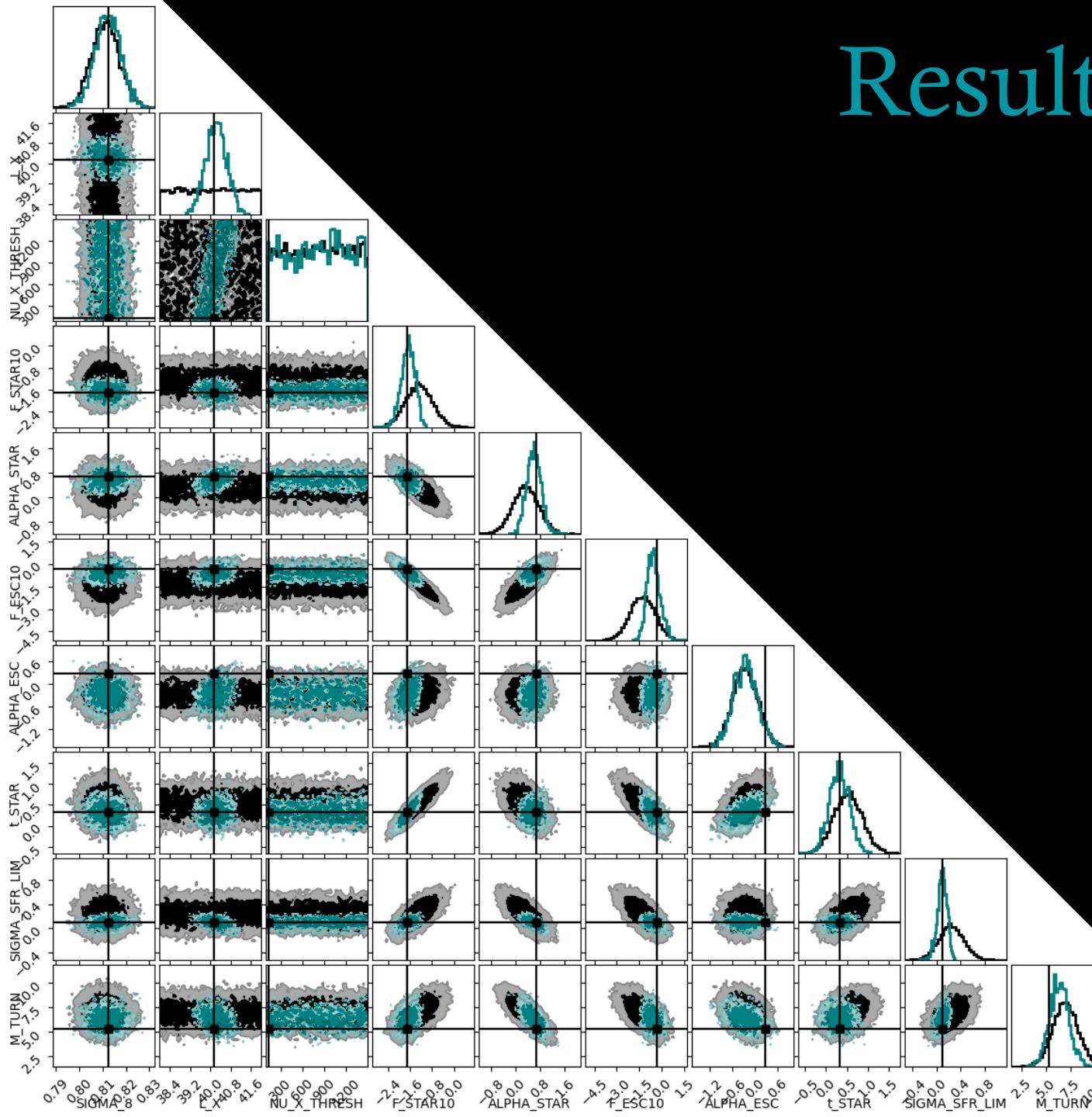
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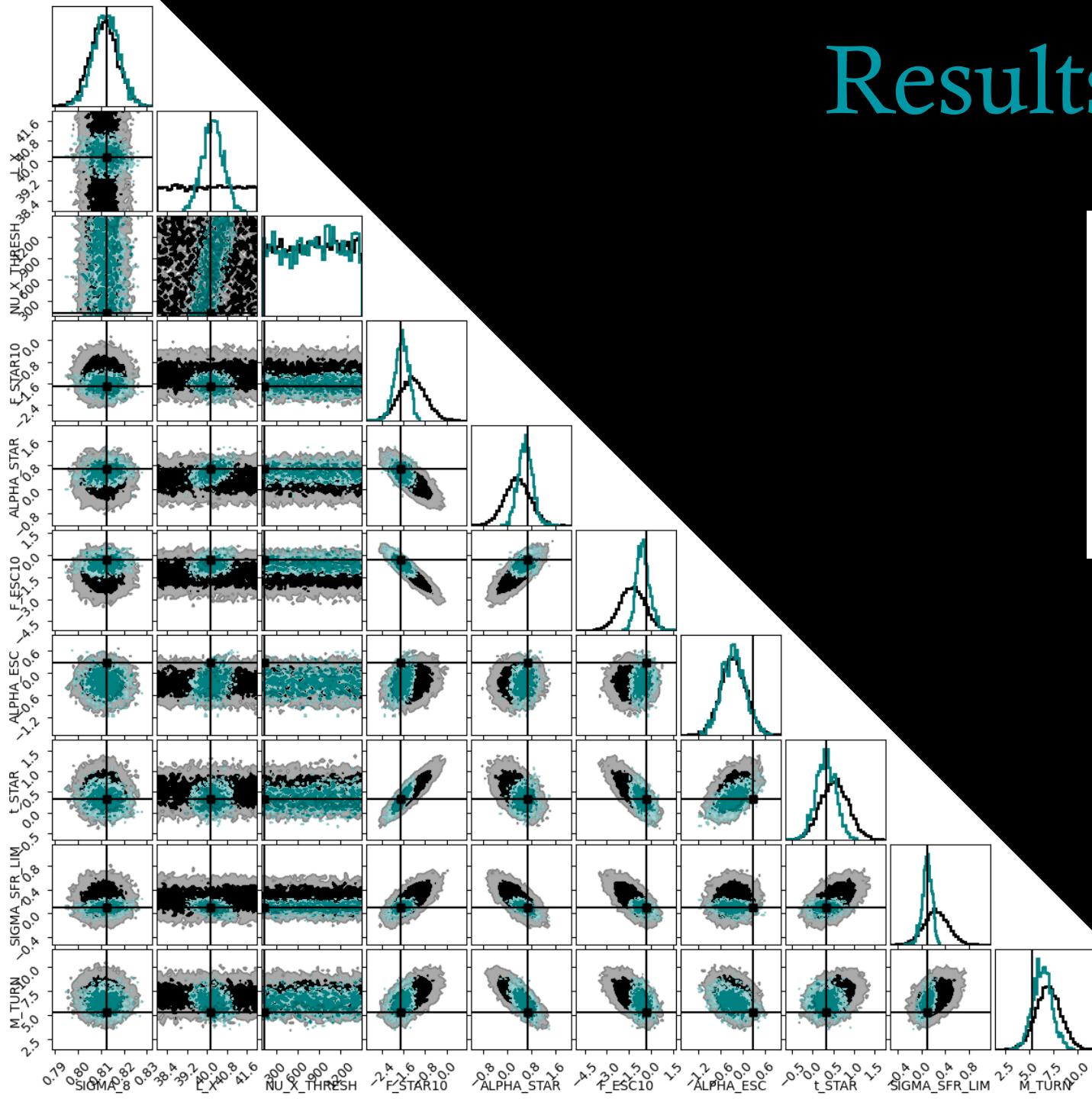
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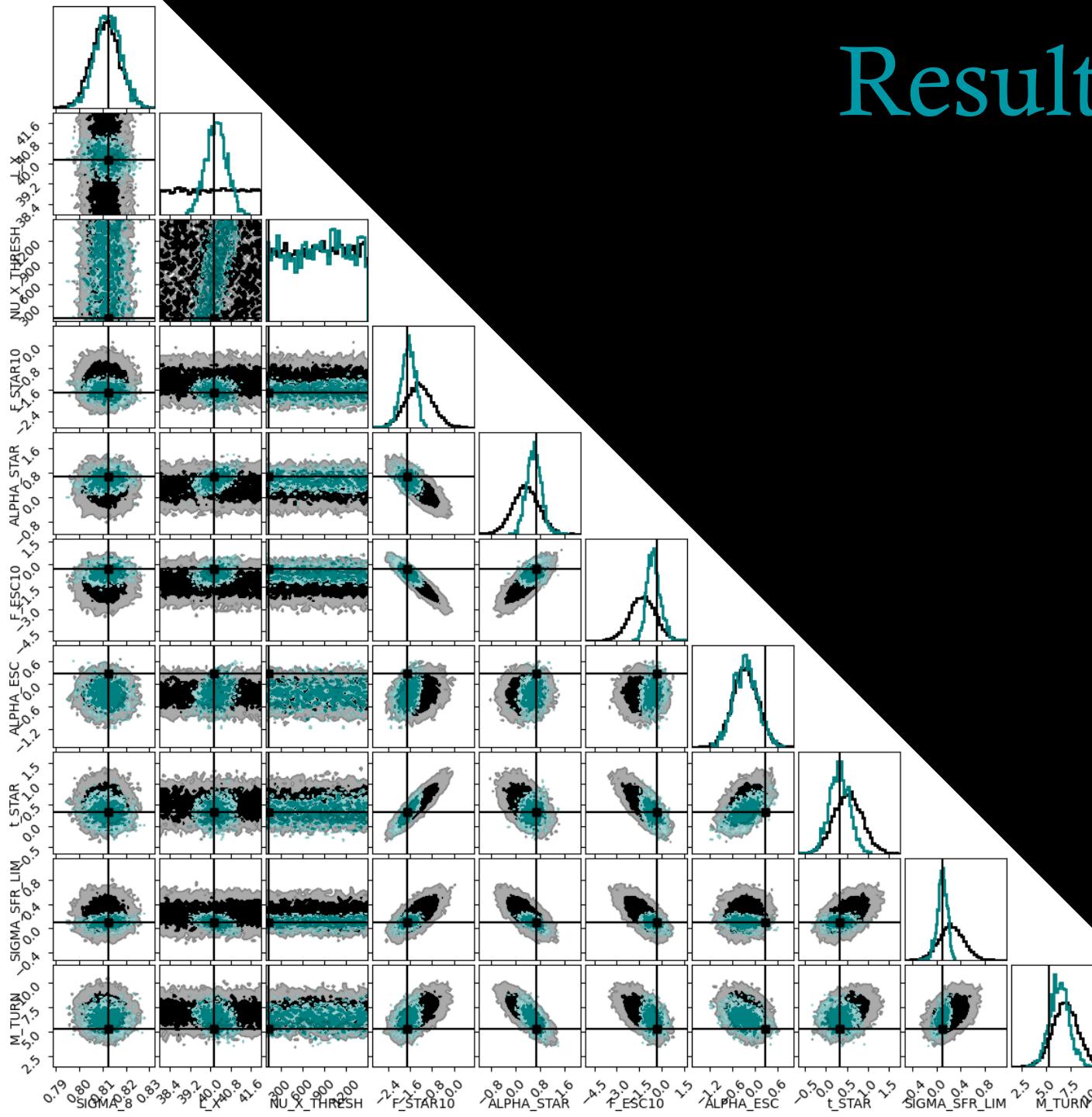
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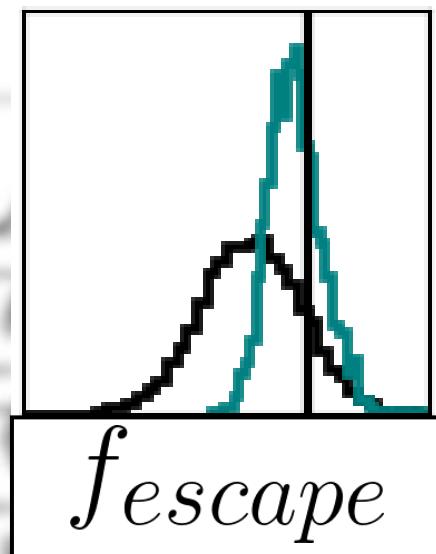
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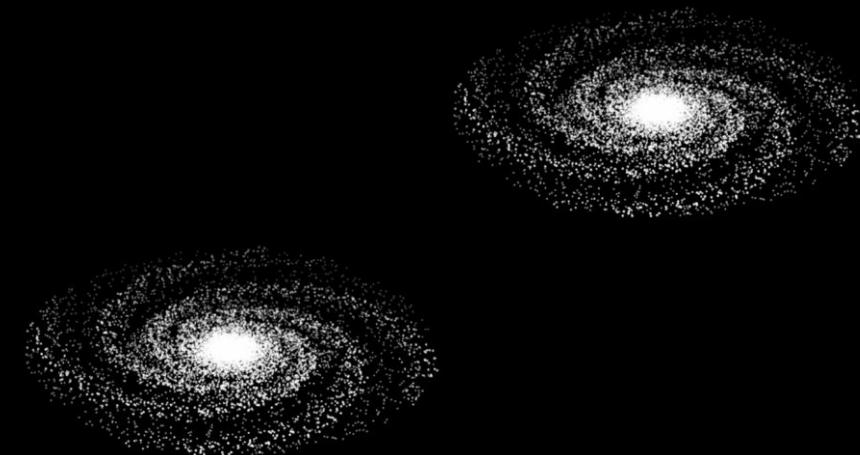
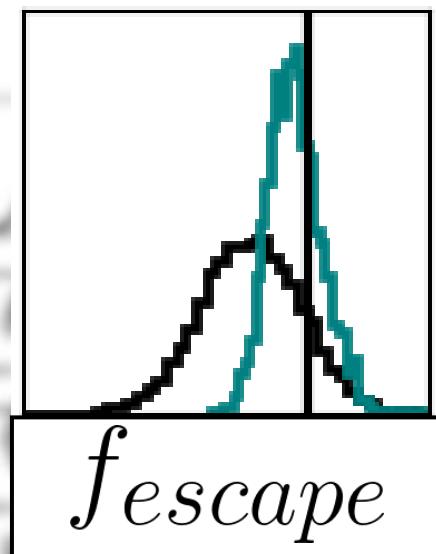
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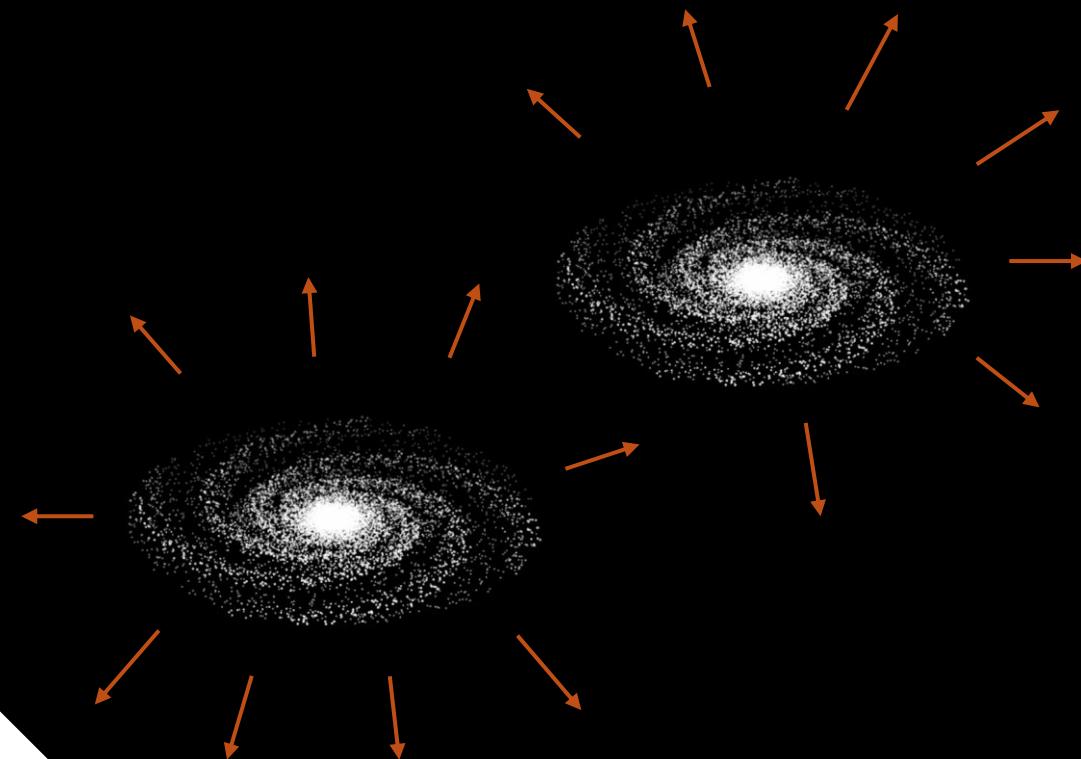
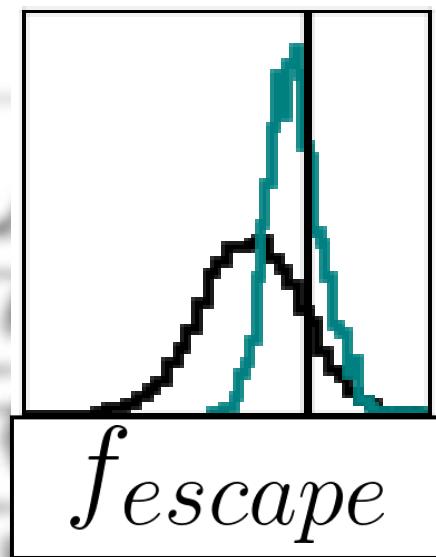
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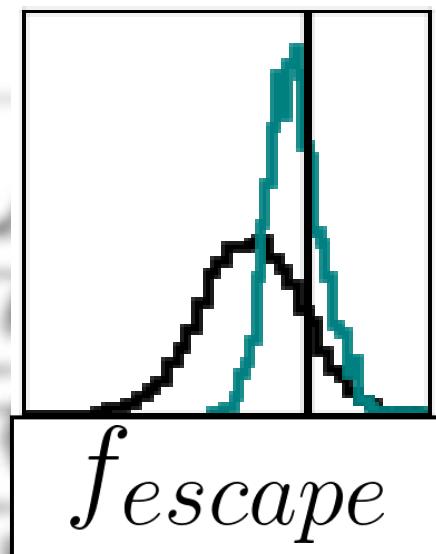
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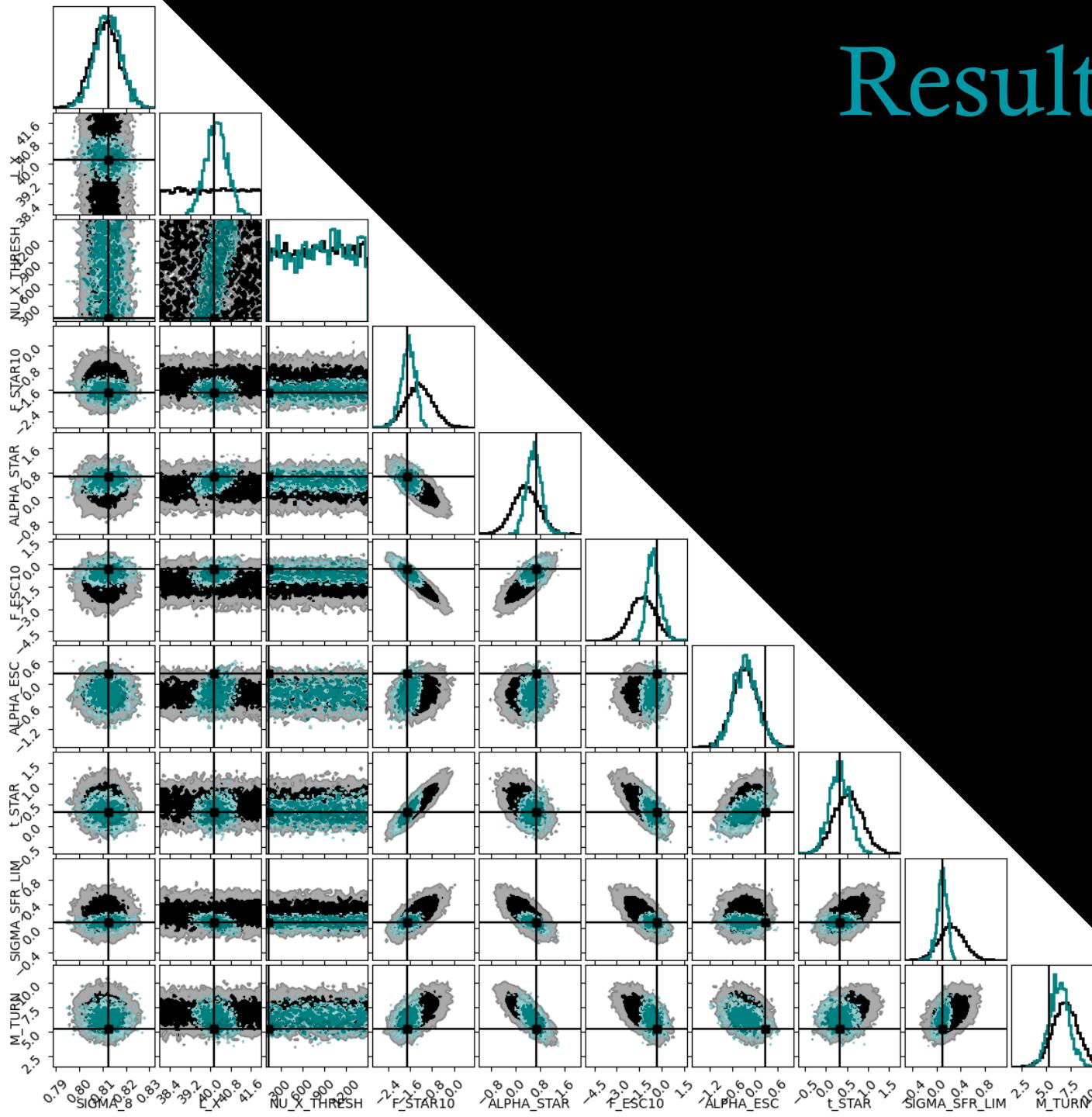
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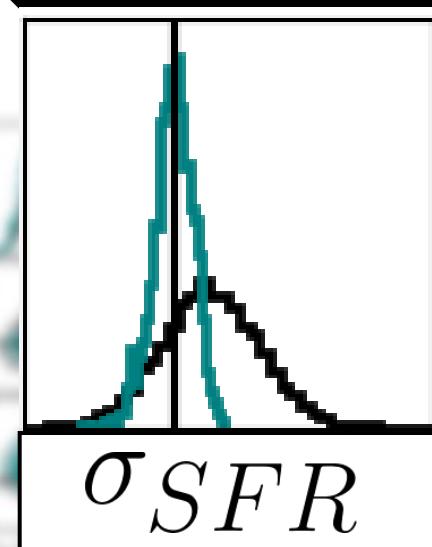
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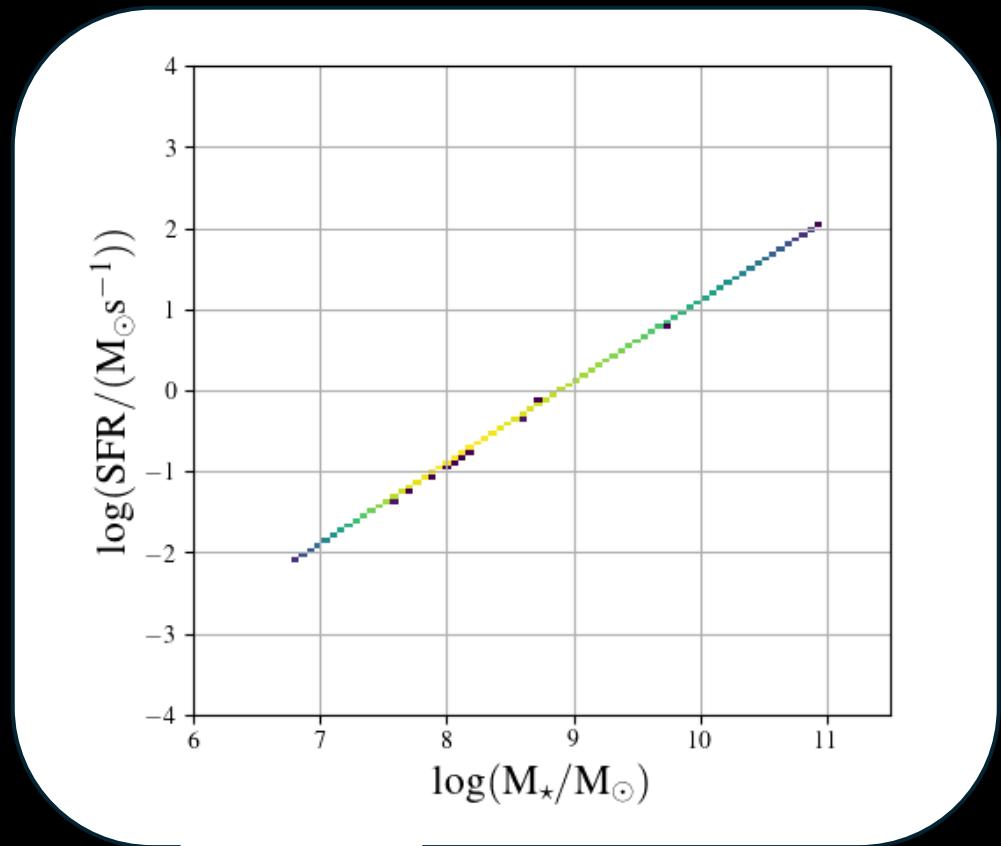
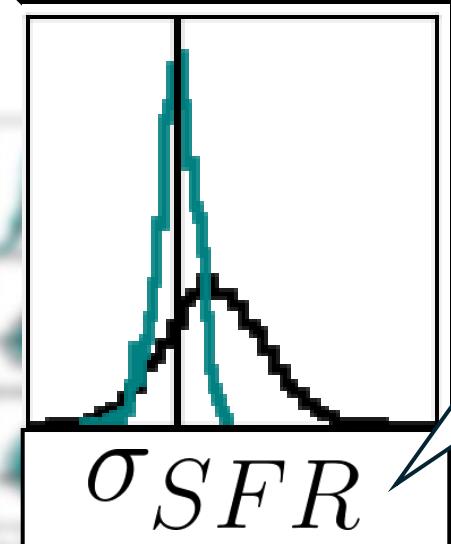
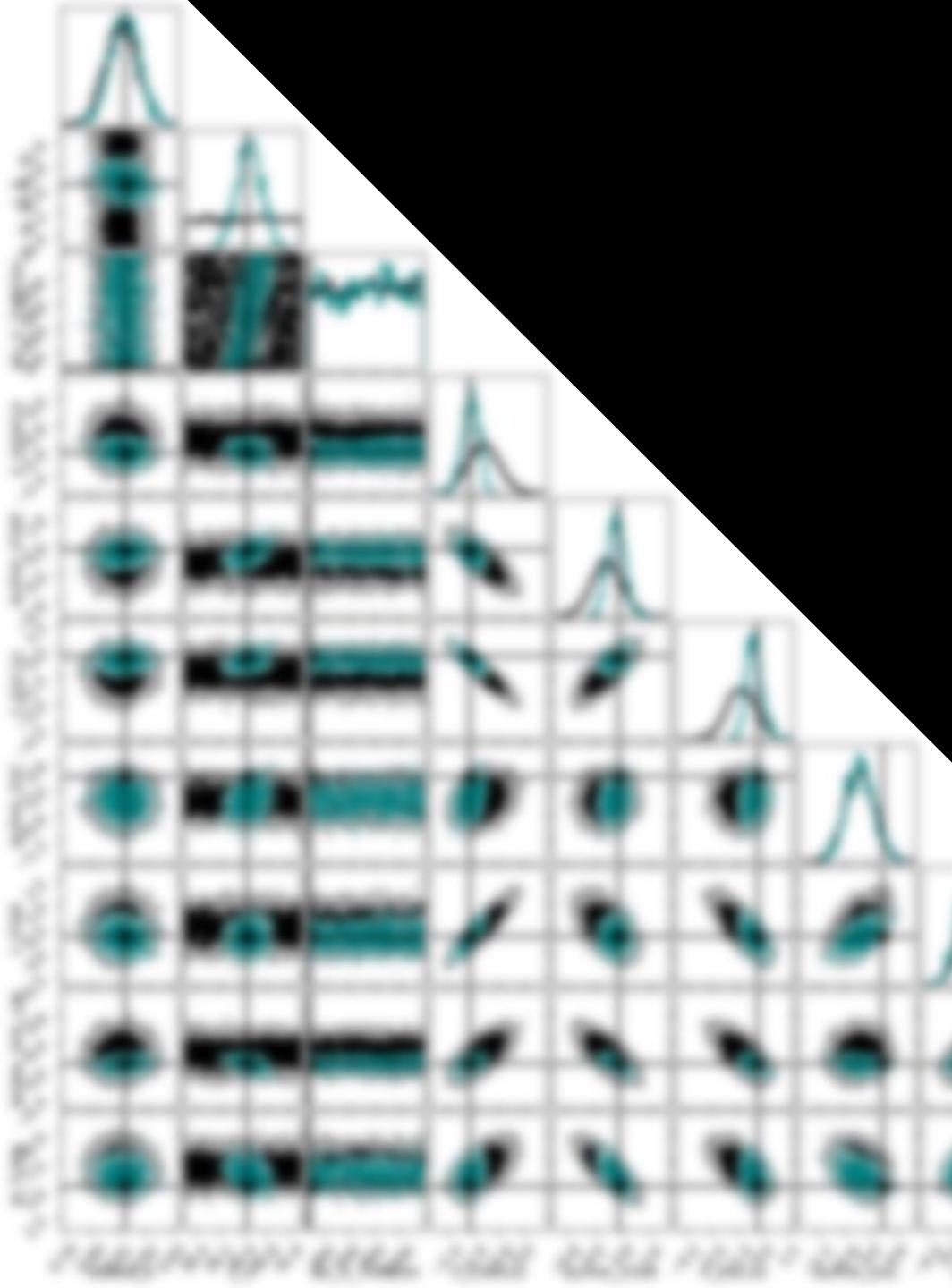
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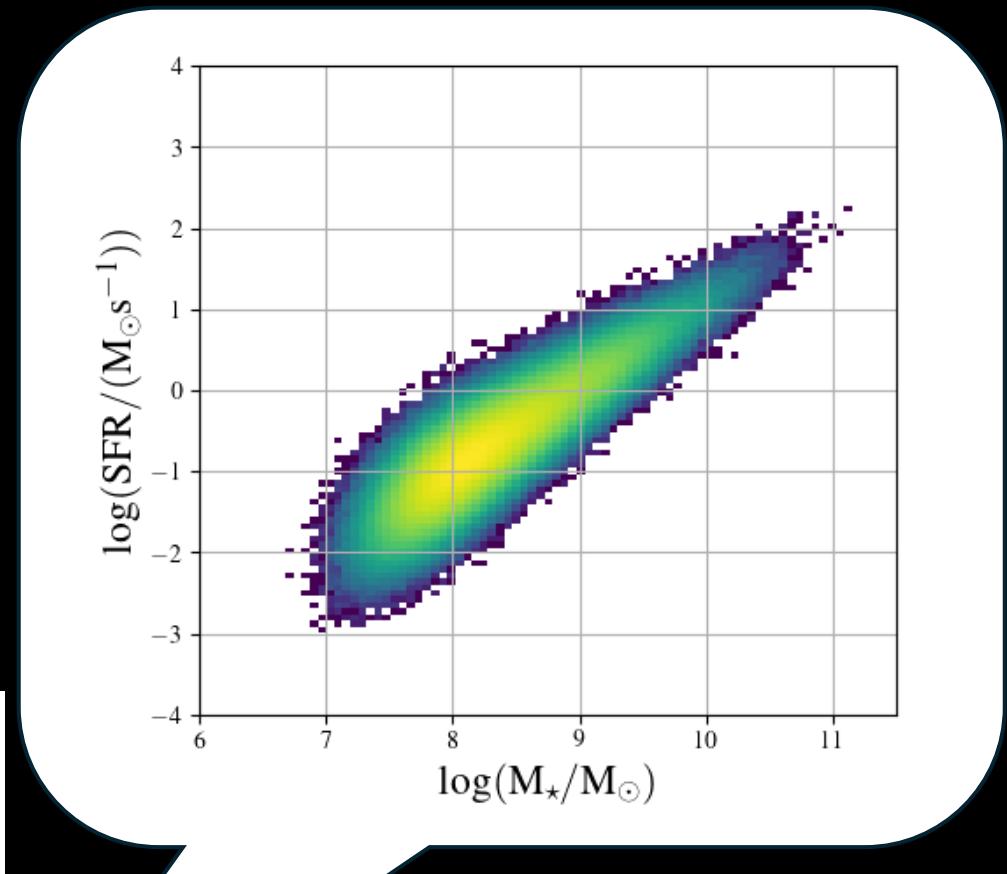
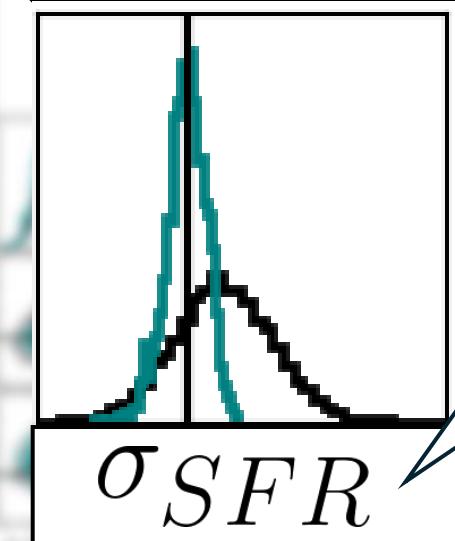
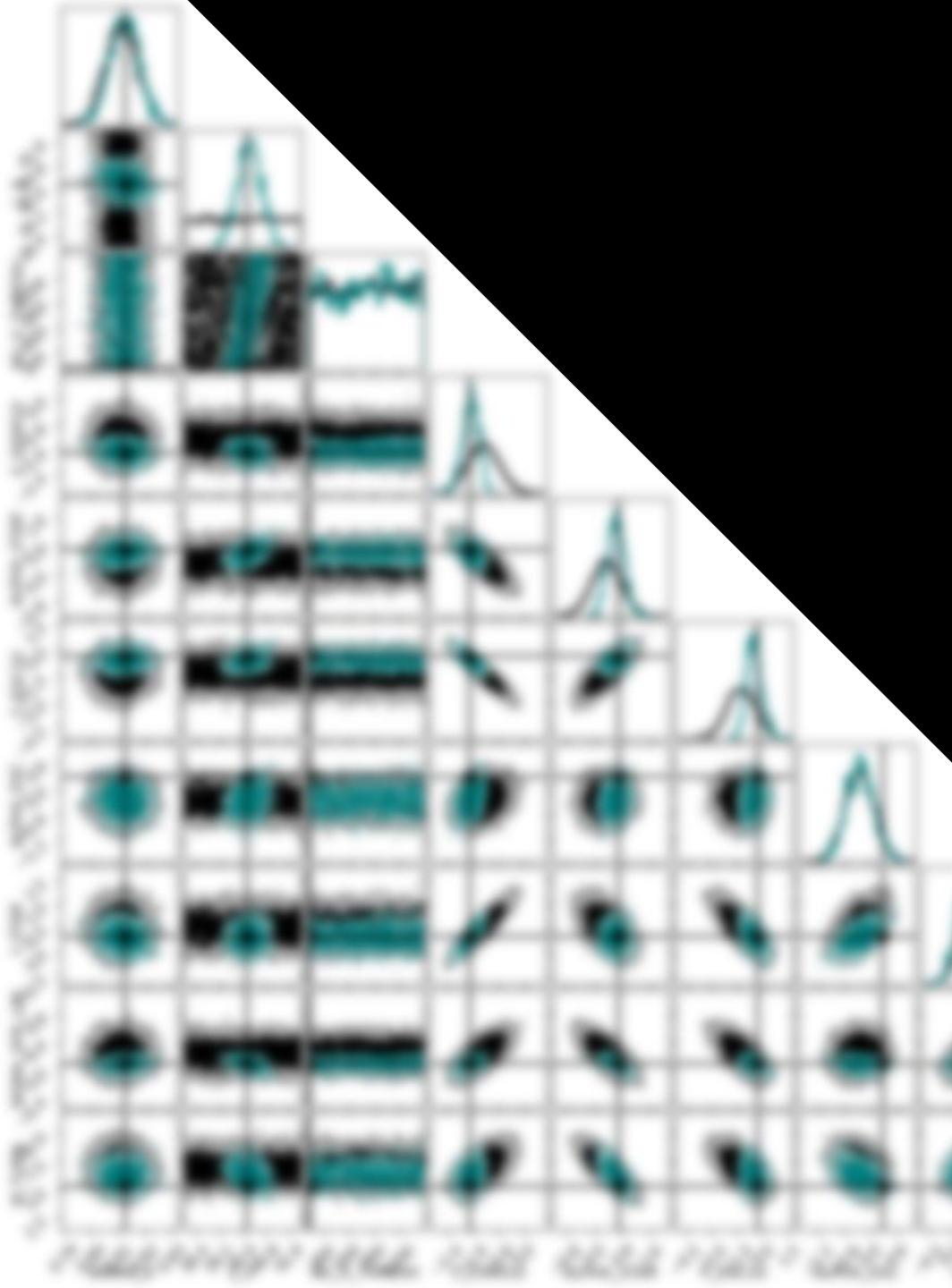
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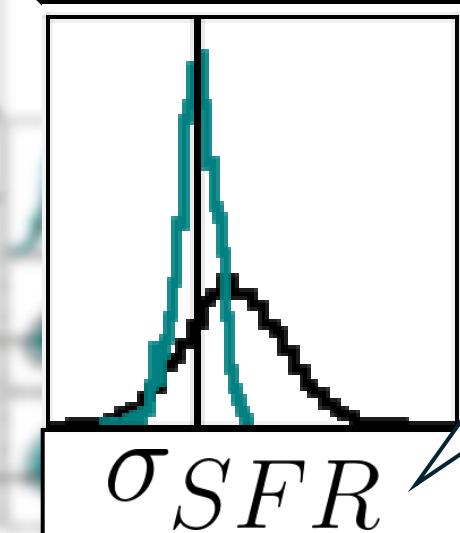
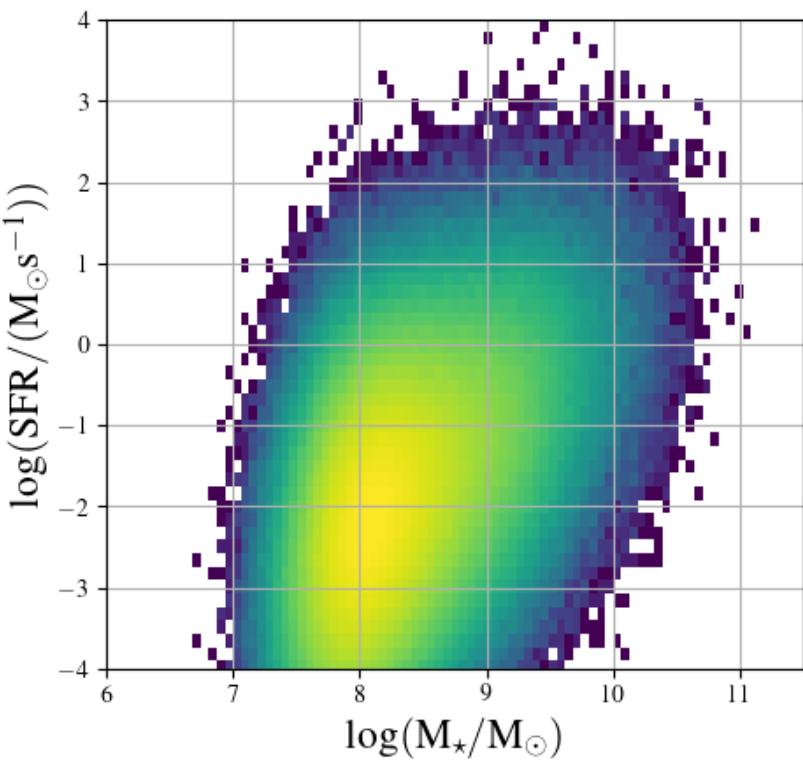
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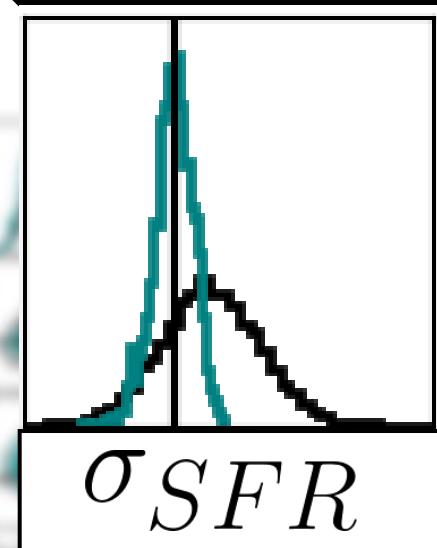
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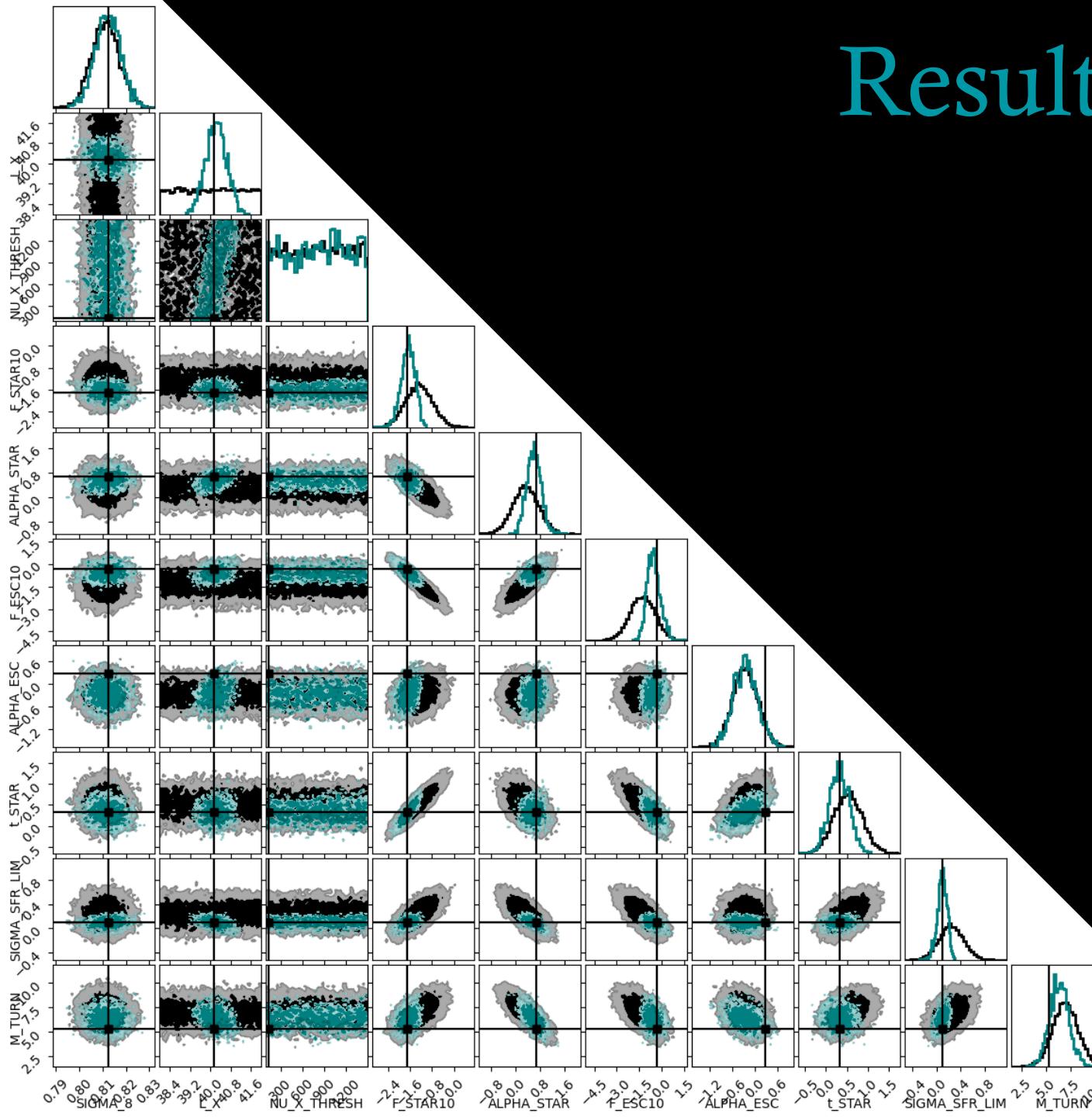
Results



Results

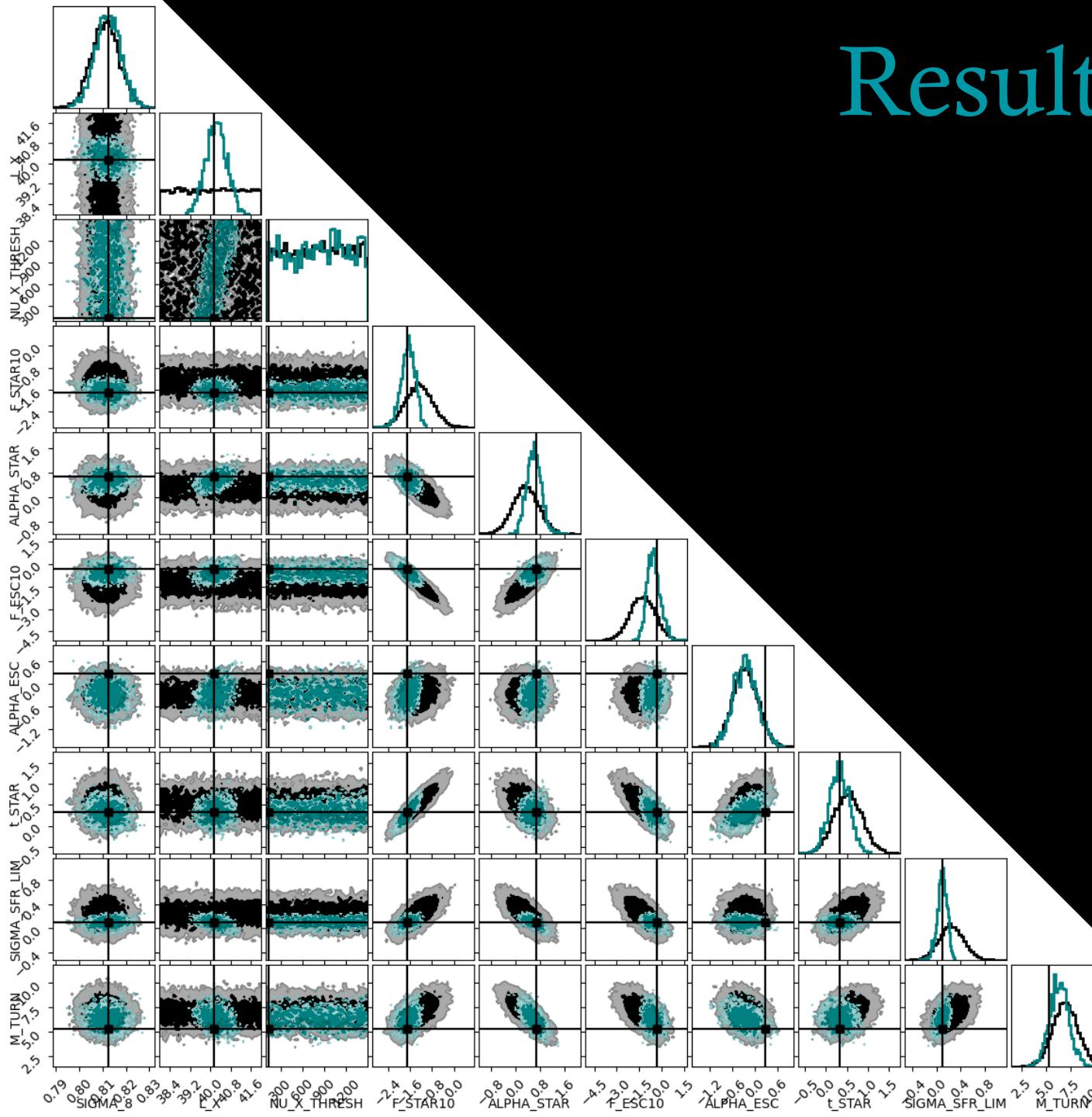


Results



Results

consistent
over multiple mocks



Key-takeaways...



Key-takeaways...

- We need a **multi-tracer** approach
take advantage of the **complimentary information**

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Use

21cmFASTv4

Key-takeaways...

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Use

21cmFASTv4

Stay tuned

21cmDATABASE