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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Inferring galaxy properties from forward models of the first billion years

Andrei Mesinger (SNS)

Spoke 3 General Meeting, Elba 5-9 / 05, 2024

SCUOLA NORMALE SUPERIORE
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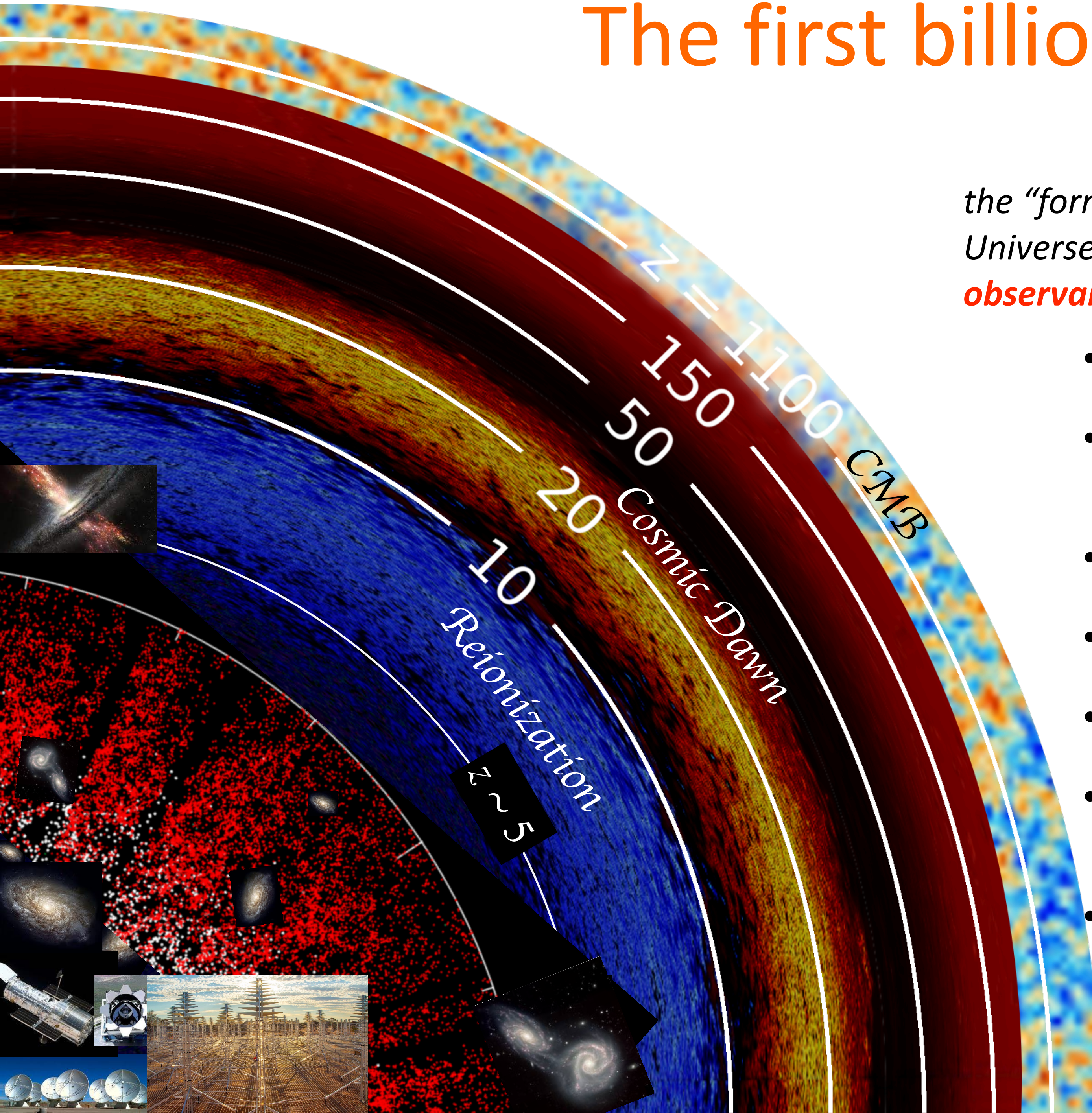
The first billion years

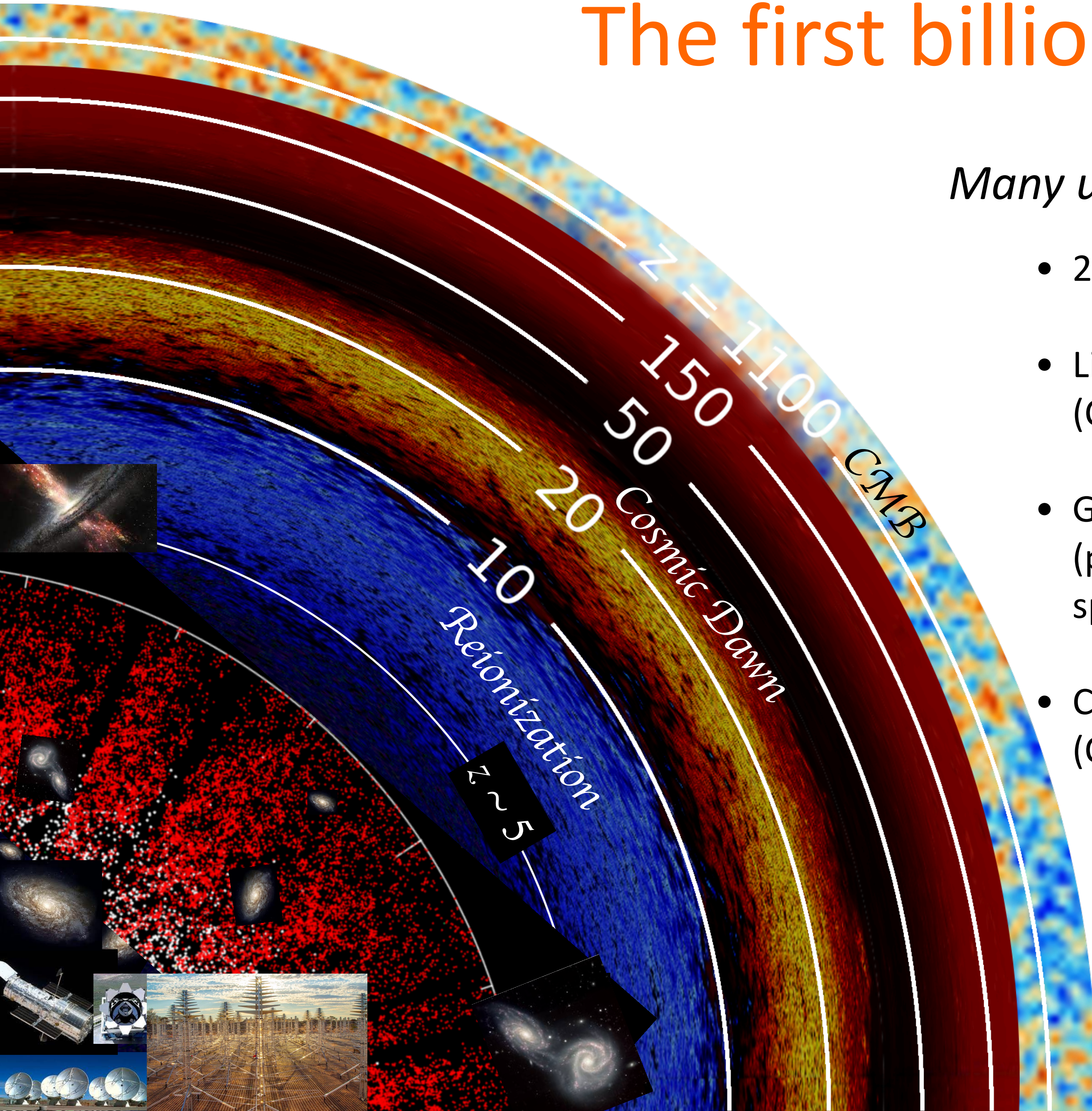


the "formative childhood" of the Universe, yet the ***majority of the observable volume***

- When and how did the first galaxies form?
- How did they impact each other and their surroundings?
- What are the dominant feedback mechanisms?
- Can we learn about Dark Matter properties?
- How does the Hubble parameter evolve?
- What are the properties of the first stars and black holes?
- etc….

adapted from C. Chiang

The first billion years



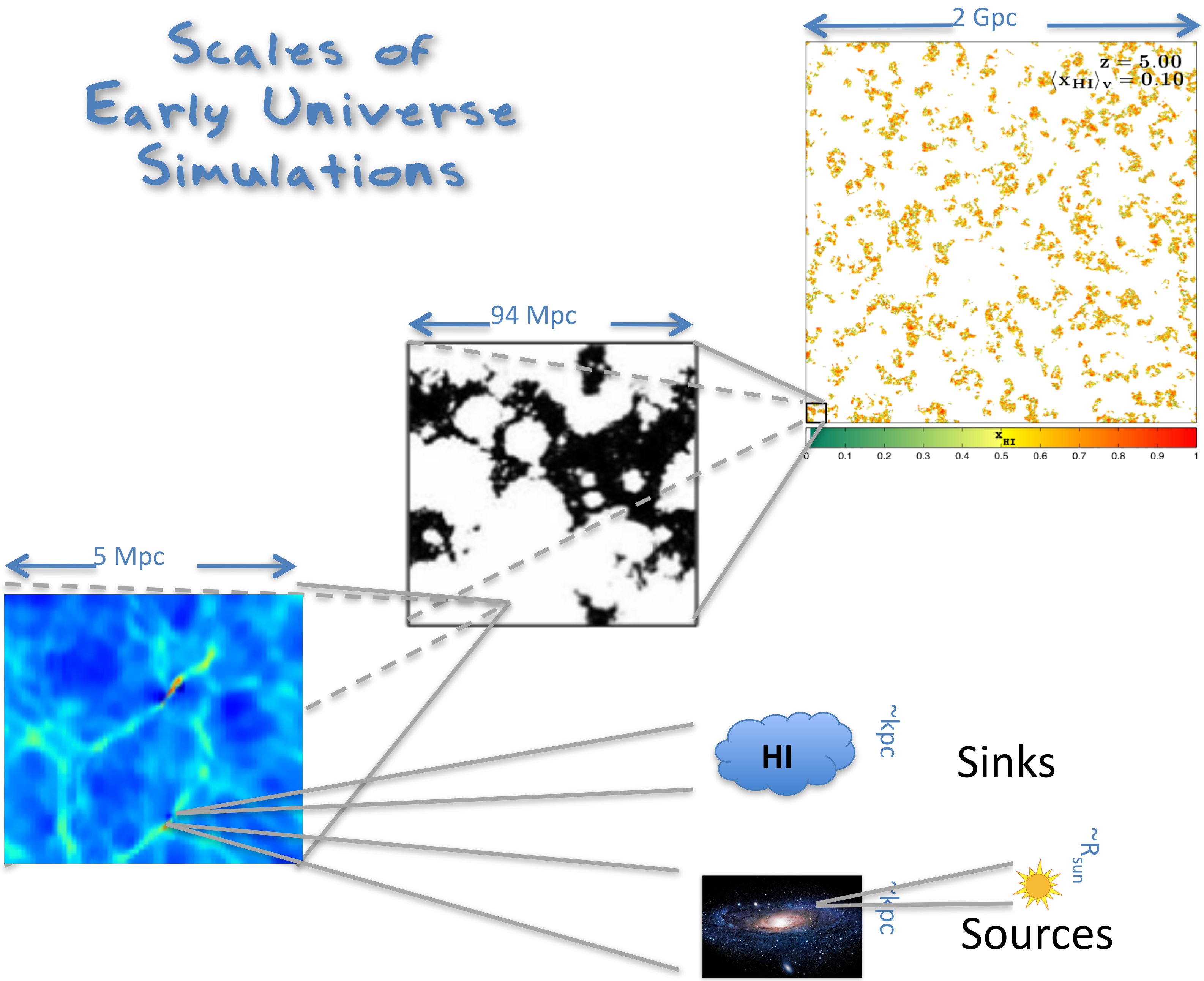
Many upcoming probes:

- 21-cm IGM tomography
- Line intensity mapping (CII, C+, OIII, Lya)
- Galaxy surveys (photometric, grism, spectroscopy)
- Cosmic backgrounds (CMB, XRB, NIR)

adapted from C. Chiang

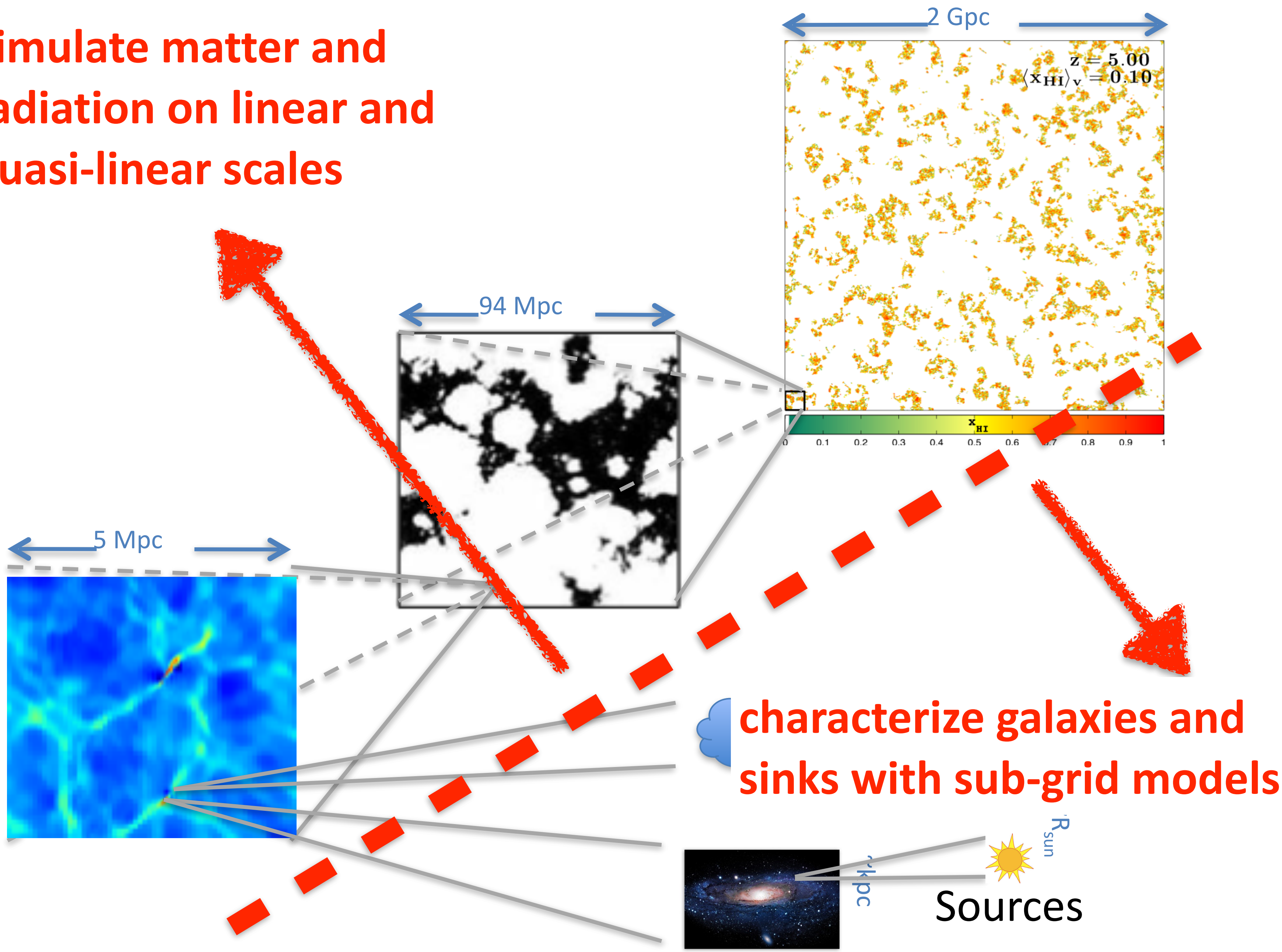
Simulating the Universe

Scales of Early Universe Simulations



Simulating the Universe

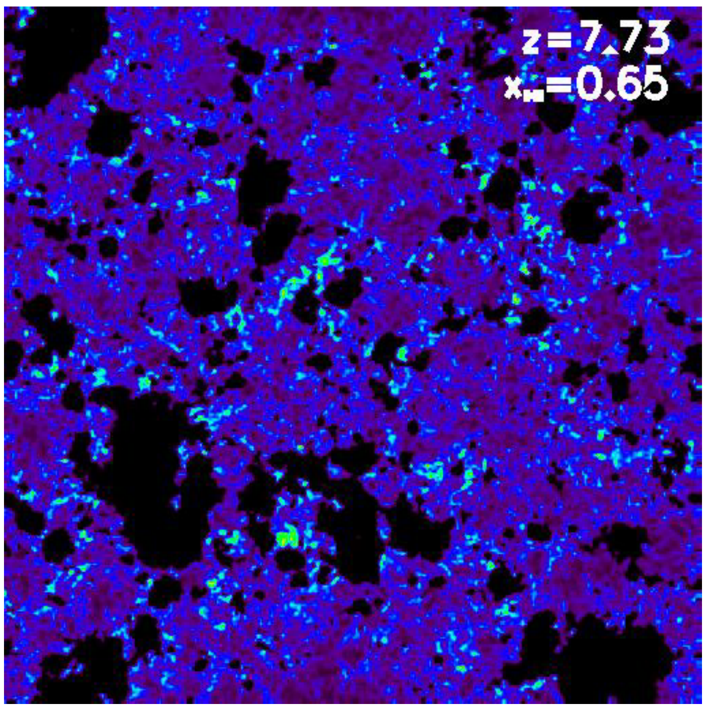
Simulate matter and radiation on linear and quasi-linear scales



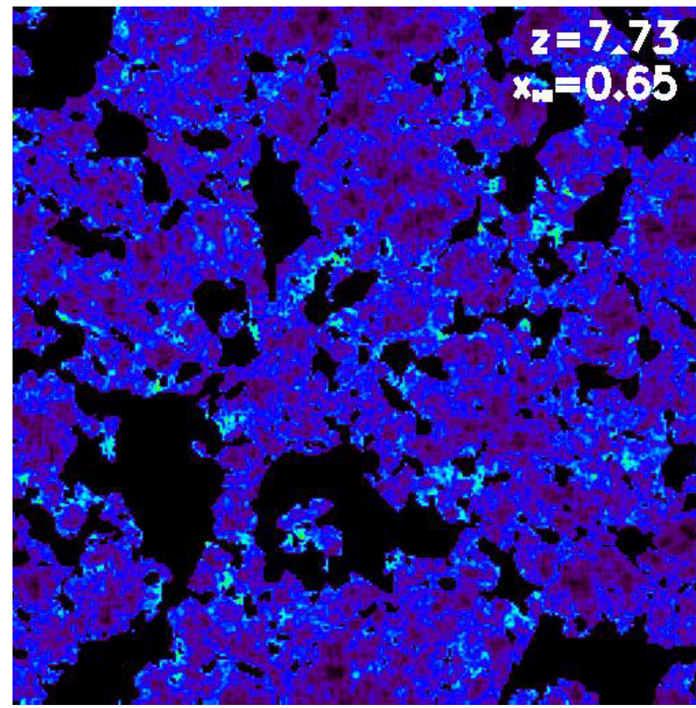
characterize galaxies and sinks with sub-grid models

Simulator

21cmFAST (AM+2007, 2011) — public, efficient semi-numerical 3D simulation code generating IGM **density** (with 2LPT), **temperature, halo** and associated **radiation** fields (with a combination of excursion-set and lightcone integration).



hydro+RT (Trac+2009):
~10^7 core hours



21cmFAST:
~0.1 core hours

Simulator

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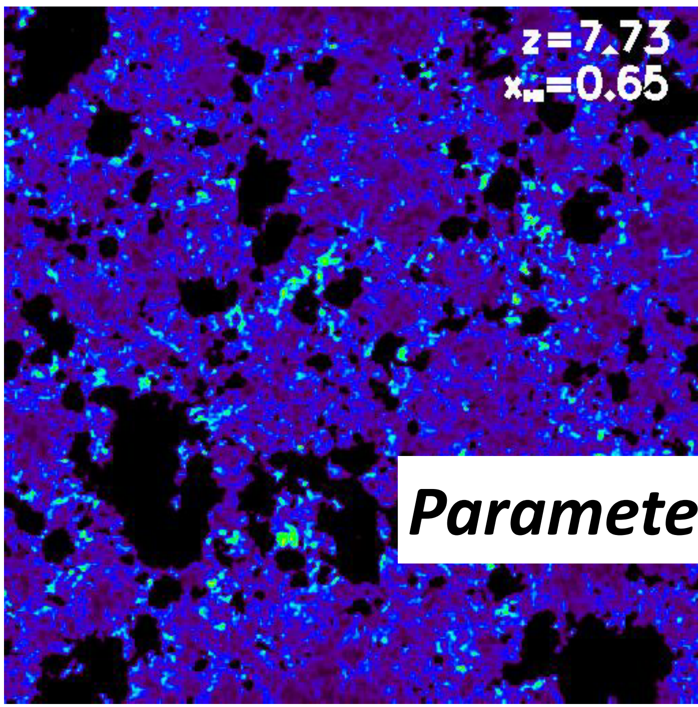
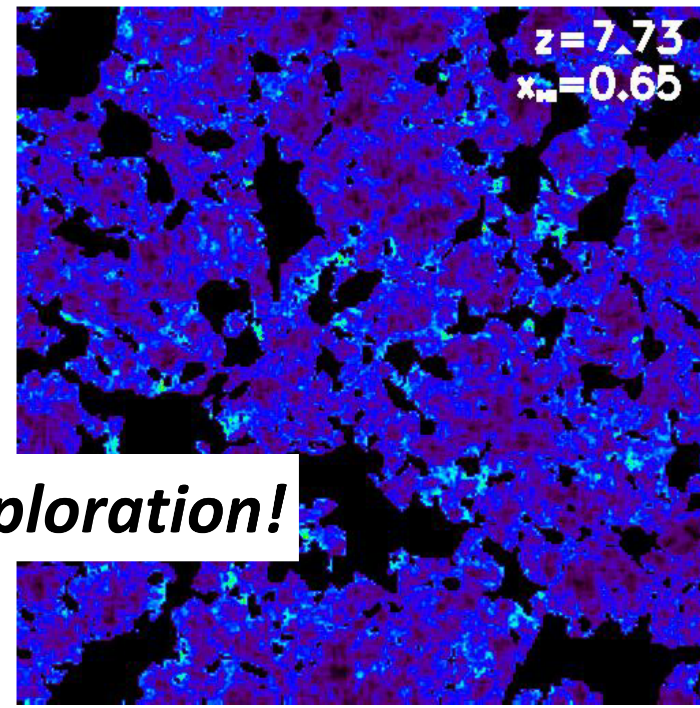




Parameter space exploration!

hydro+RT (Trac+2009):
~10^7 core hours

21cmFAST:
~0.1 core hours

Global brand

***21cmFAST** is being used by researchers in over **29 countries** studying a broad range of early Universe topics*

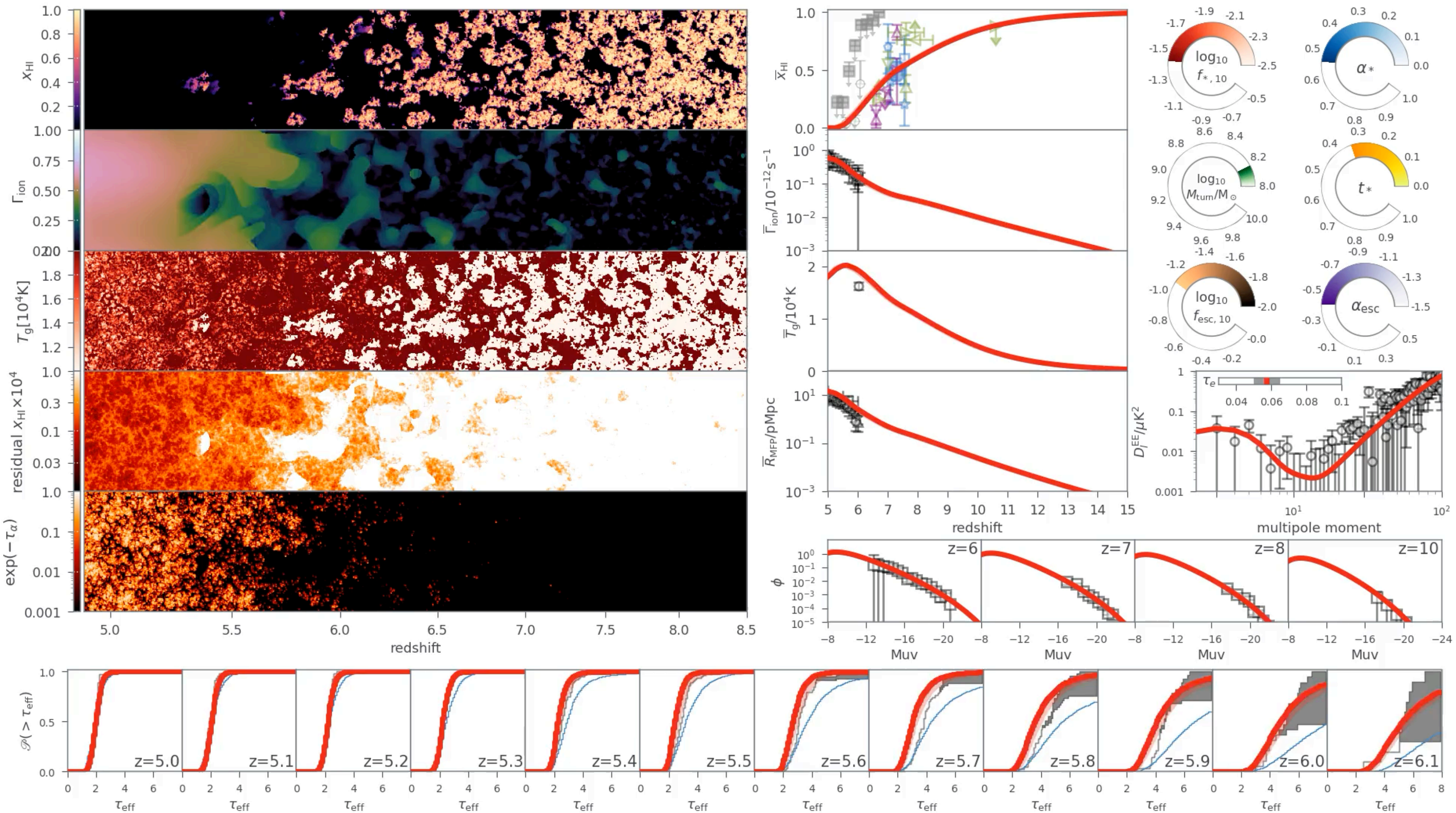
Forward modeling

Sample ***Initial Seed, Cosmology, Galaxy properties*** and create multi-wavelength lightcone

Repeat ~**1M** times to make a **database**

Systematics / ***Noise*** / ***Instrument effects*** can be added in post processing

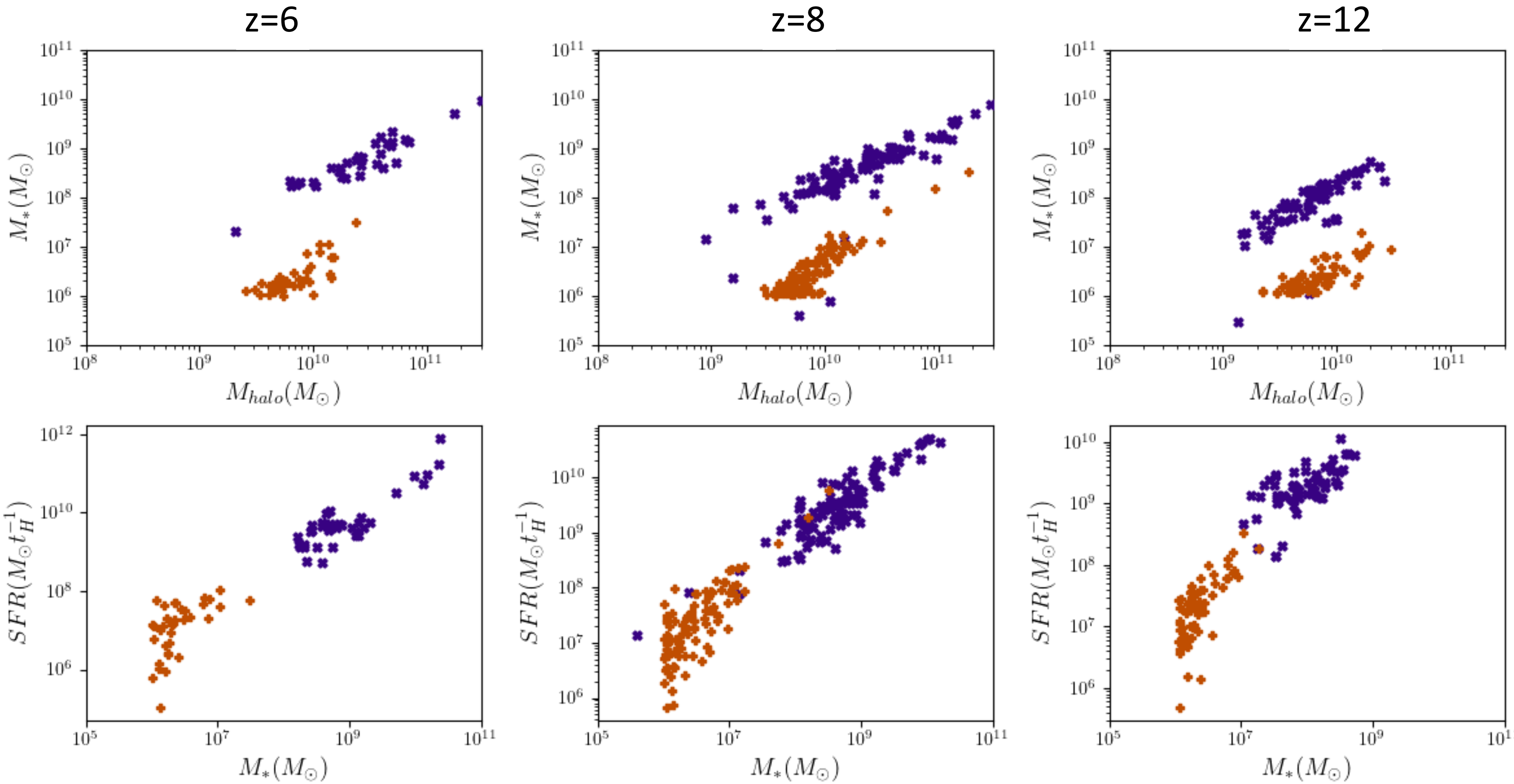
Qin, AM+ in prep



Forward modeling

Wait, what are ***Galaxy properties?***

Relate galaxies to DM halos with semi-empirical scaling relations: a *"universal language"*

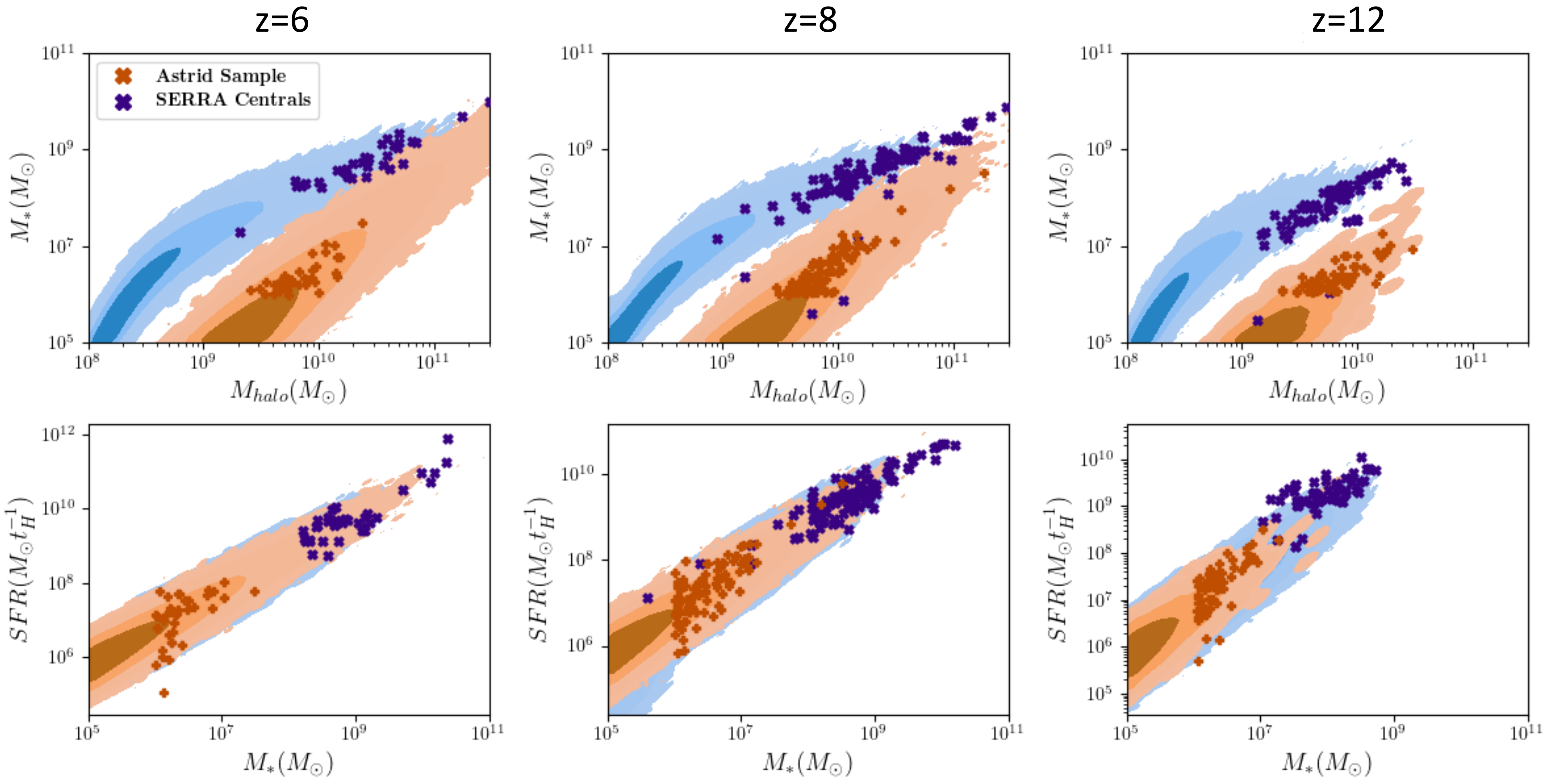


SERRA; Pallottini+2022

ASTRID; Ni+2022

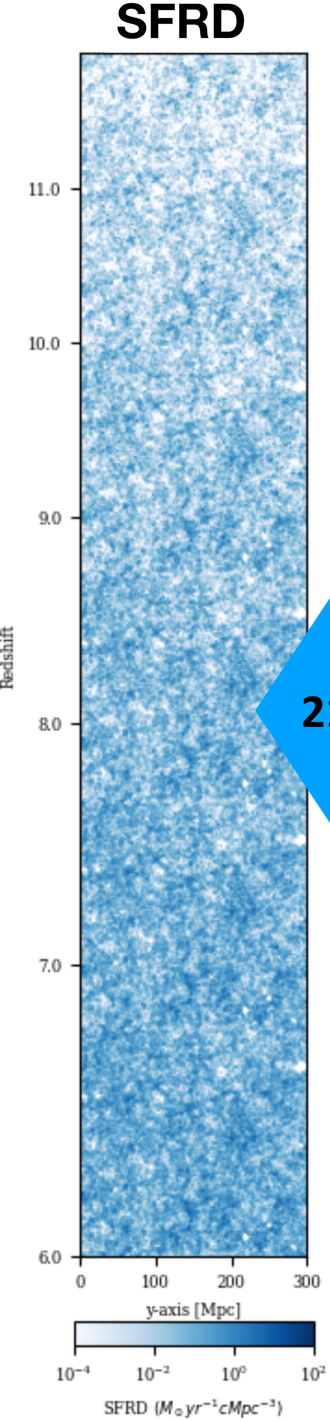
Davies, AM+ in prep

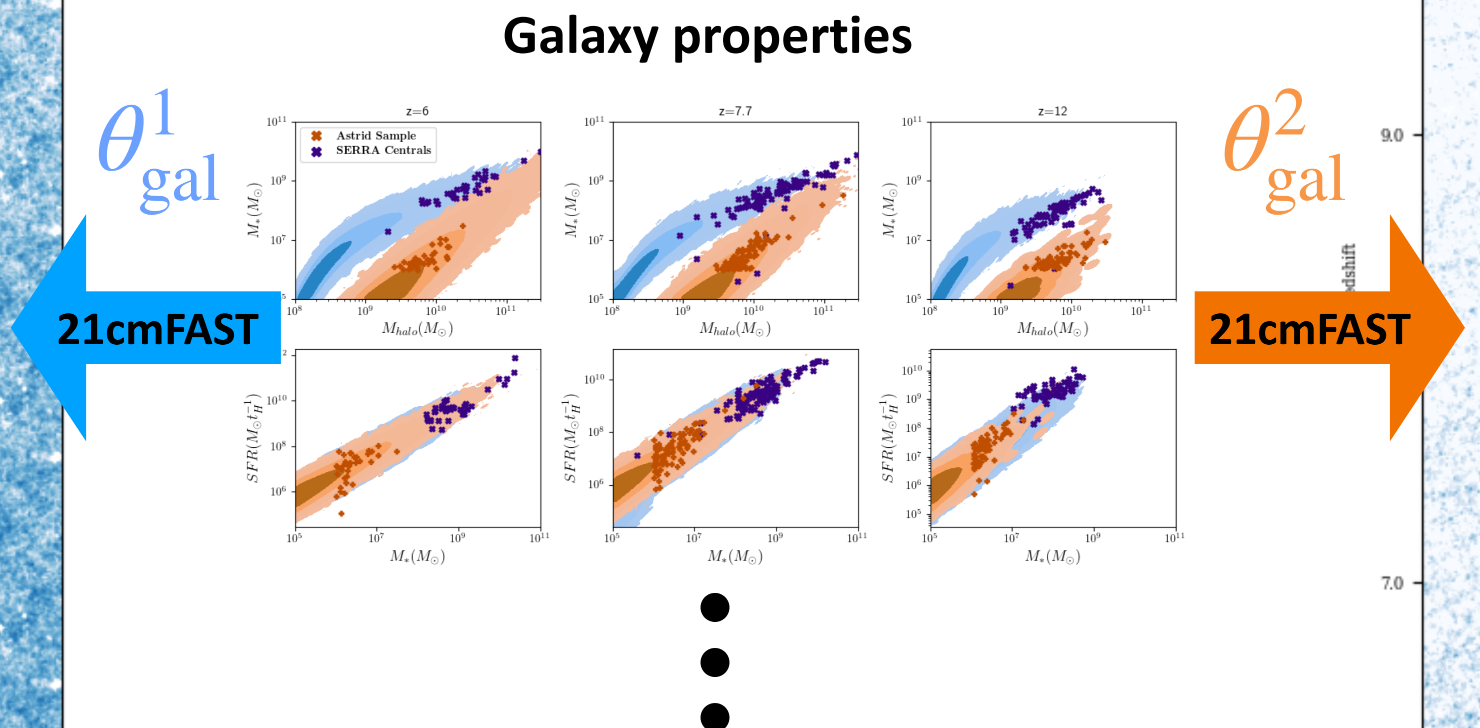
Relate galaxies to DM halos with semi-empirical scaling relations: a *"universal language"*



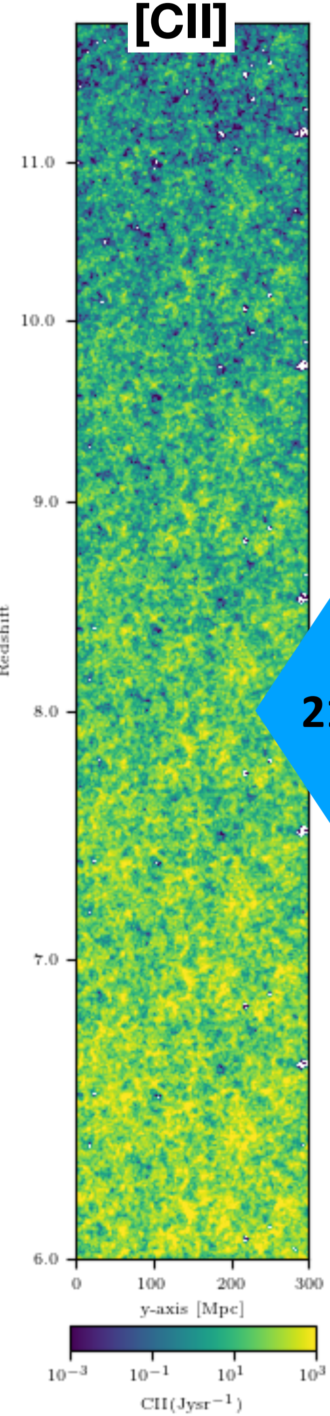
Davies, AM+ in prep

Forward-modeling the first billion years





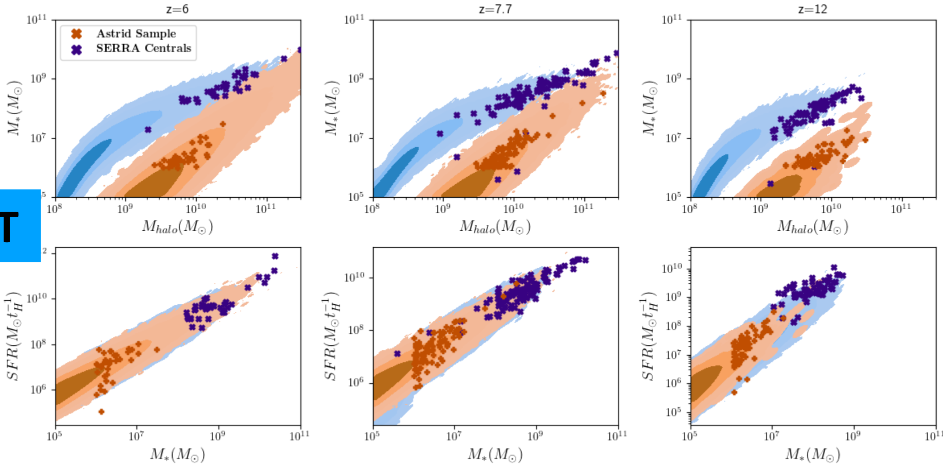
Forward-modeling the first billion years



$\theta^1_{\rm gal}$

21cmFAST

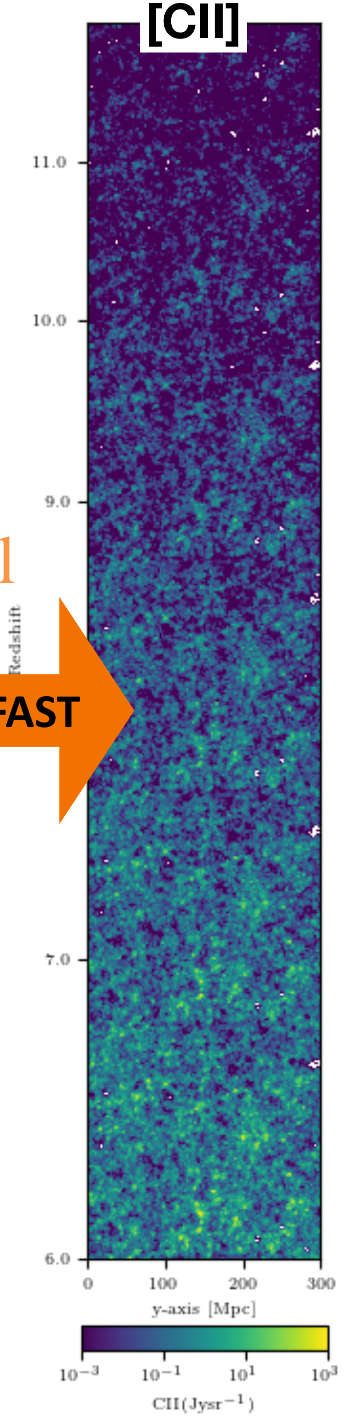
Galaxy properties



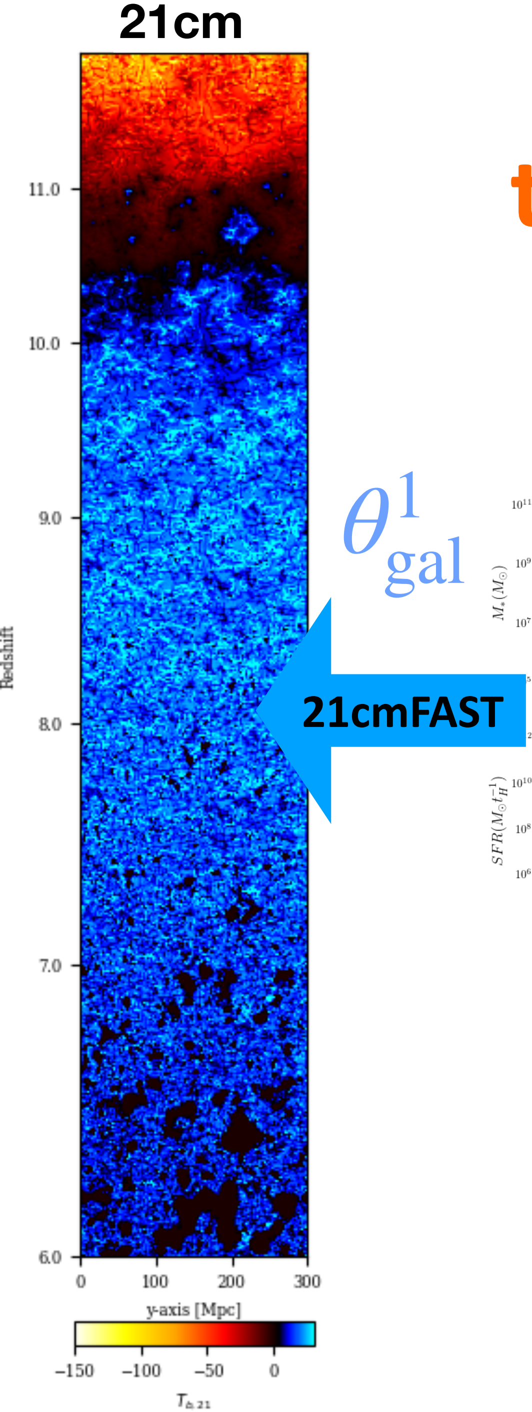
• • •

$\theta^2_{\rm gal}$

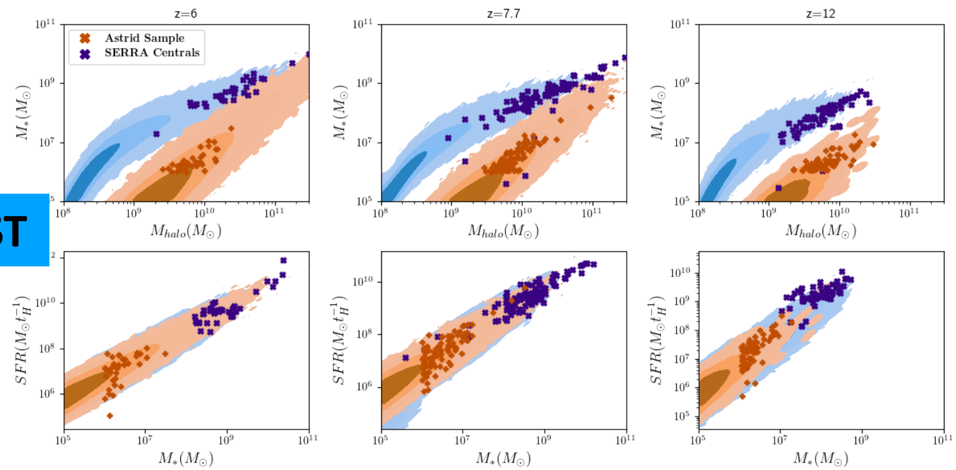
21cmFAST

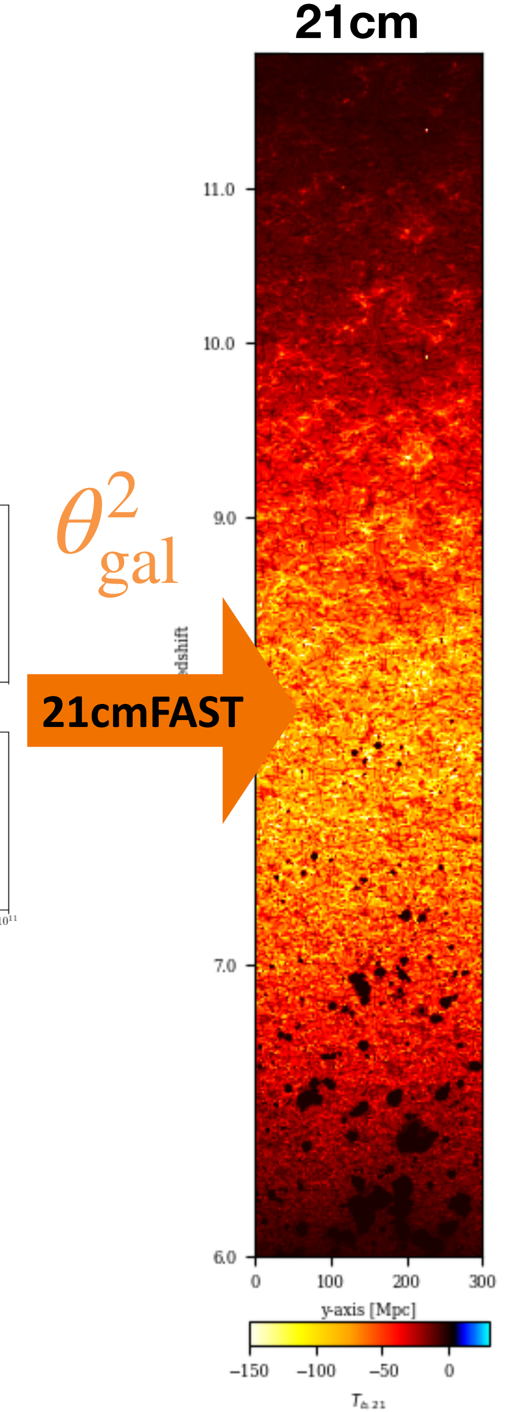


Forward-modeling the first billion years



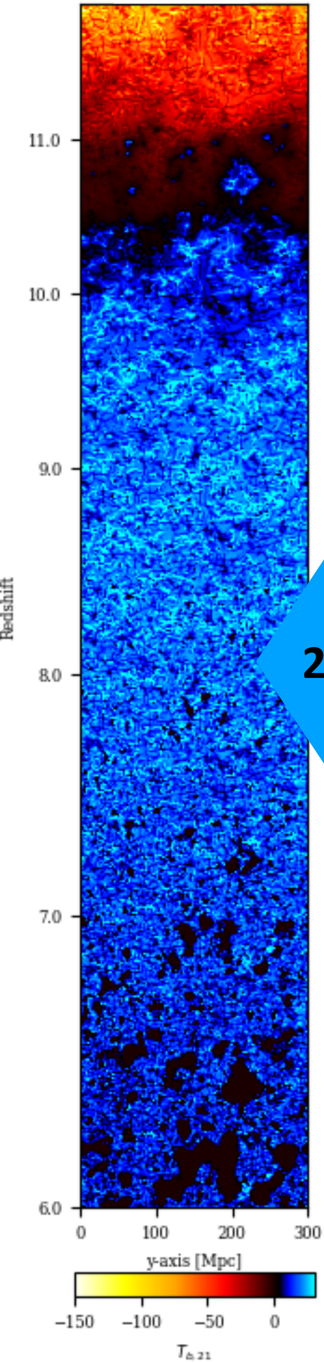
Galaxy properties





Forward-modeling the first billion years

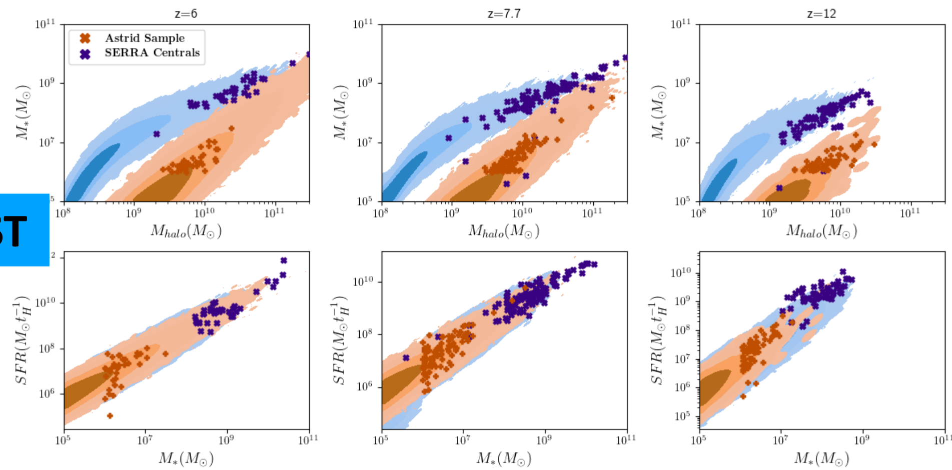
21cm



$\theta^1_{\rm gal}$

21cmFAST

Galaxy properties

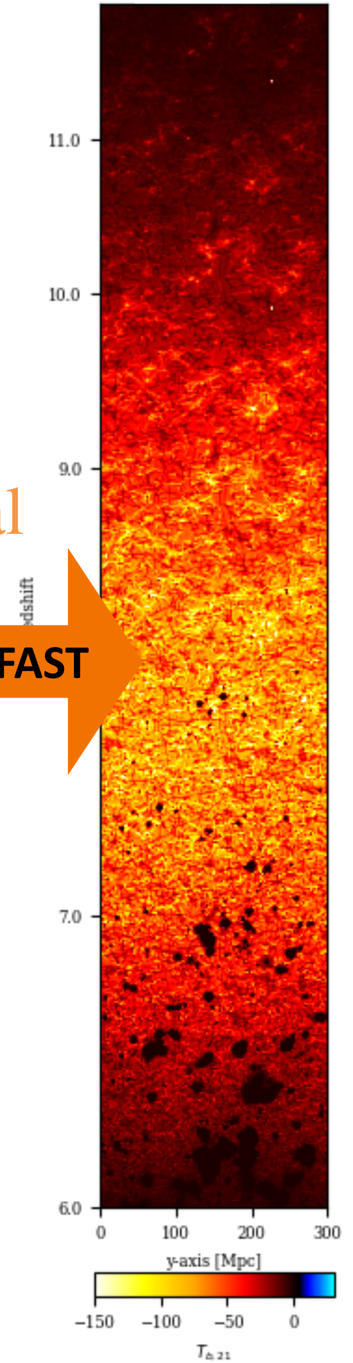


⋮

$\theta^2_{\rm gal}$

21cmFAST

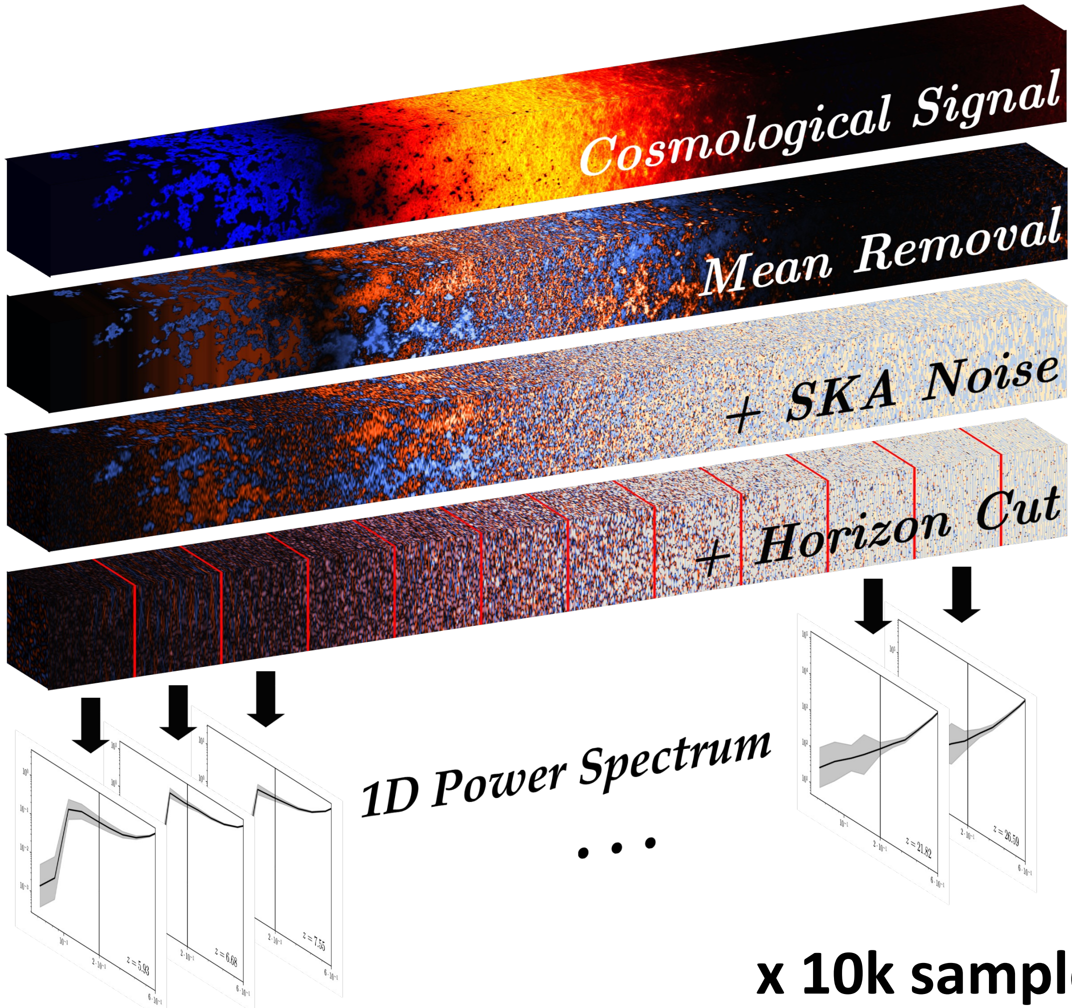
21cm



All of this takes ~ 1 core hour!

Simulation Based Inference (SBI)

Inference using SBI: *if including all main sources of stochasticity, each forward model is a sample from the joint distribution of model & data. The* ***likelihood*** *can just be fit with NDEs.*



No need for an analytic likelihood!!!

difficult to write down for non-Gaussian and correlated observations

x 10k samples

Prelogovic & AM (2023)

Objectives

1. Construct a ~**1M sample, public database of IGM and galaxy lightcones** spanning the first billion years (Cosmic Dawn and Epoch of Reionization)

2. Using bespoke telescope models (e.g. SKA-low, ROMAN grism, ELT, Subaru) to construct **mock observations**

3. Apply simulation-based inference on multi-wavelength data to **infer the properties of galaxies and cosmology**

Why a KSP?

- It will require significant computational and storage resources! **Submitted KSP request on March 4th**

- It will be **of interest to the broader Italian community**: intermediate data products, such as the matter density field in extended cosmologies or the star formation rate density lightcone, can be **post-processed to create many different observables**, even after the reionization

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Foreground Mitigation Strategy: The cross-correlation between 21cm signal and [CII] intensity mapping

Yilong Zhang (张艺泷) - SNS

Spoke 3 General Meeting, Elba 5-9 / 05, 2024

Introduction

- 21cm signal:

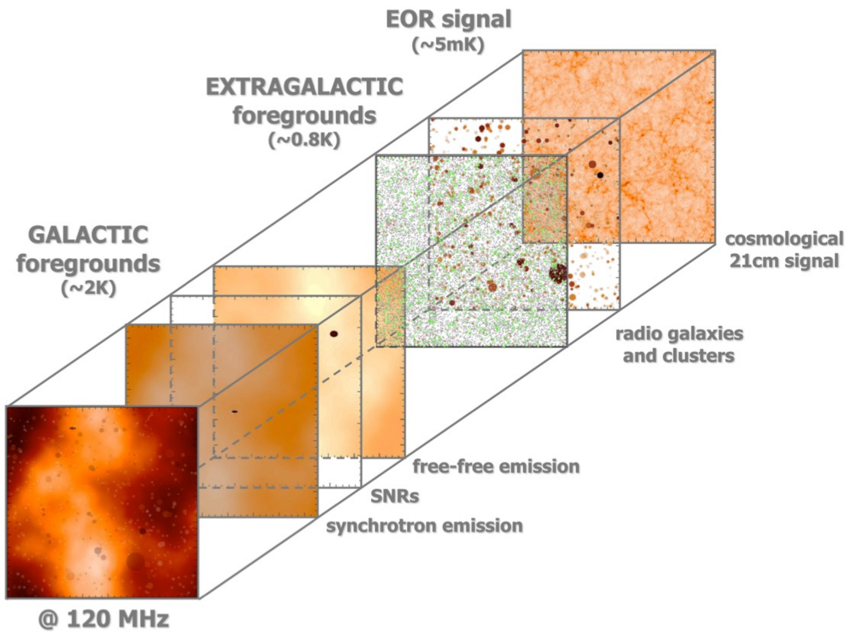
Spin-flip transition of neutral hydrogen in the intergalactic medium (IGM) during the epoch of reionization (EoR).

- Science Prospects:

- Reionization and ionizing properties of IGM;
- The evolution of galaxies during EoR;
- Structure formation and dark matter distribution.

-Technique Challenge:

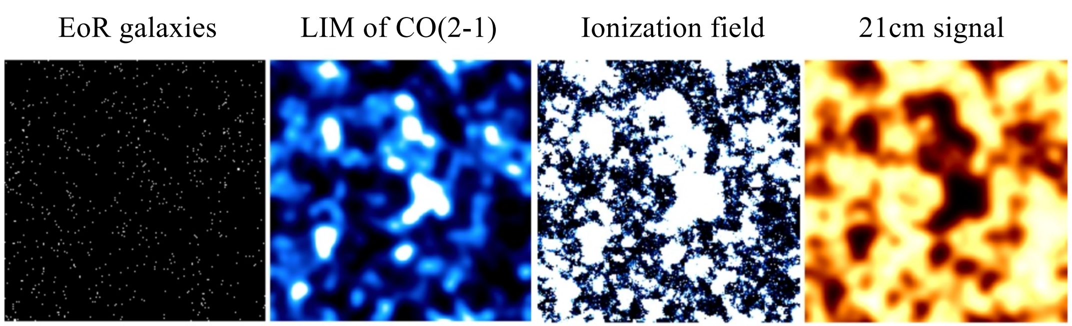
The amplitude of the foreground contaminations (mainly synchrotron radiation) is several orders of magnitude above the cosmological signal.



The various simulated Galactic and extragalactic contaminants of the redshifted 21 cm radiation from the EoR. (V. Jelić, 2008)

Methodology: Cross-correlation Technique

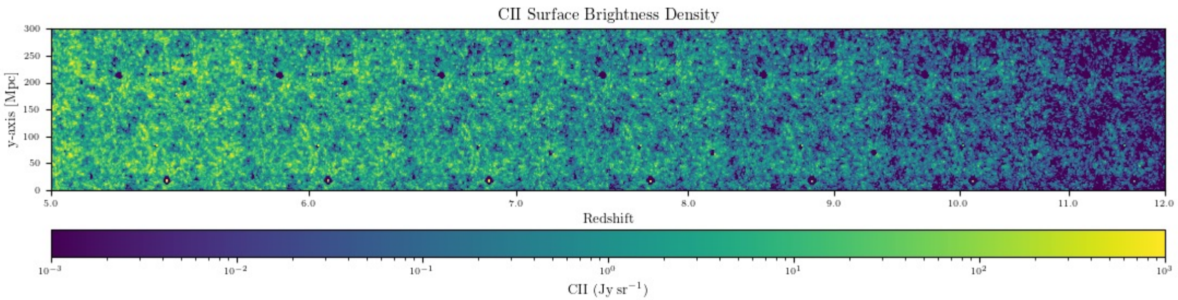
- **Cross-correlating with Line-Intensity Mapping Surveys**
- **[CII] line: fine-structure line emitted by the interstellar medium (ISM) of star-forming galaxies (expected to be one of the brightest line emissions among all metal lines)**
- **Scientific Rationale:**
  - The foreground of 21cm and [CII] fields should be uncorrelated.
  - The 21cm and [CII] fields are anti-correlated on large scales during early EoR.
- **21cm-[CII] cross-correlation:**
  - Mitigate foreground contamination;
  - Verify the detection of 21cm signal;
  - Provide extra information for EoR.

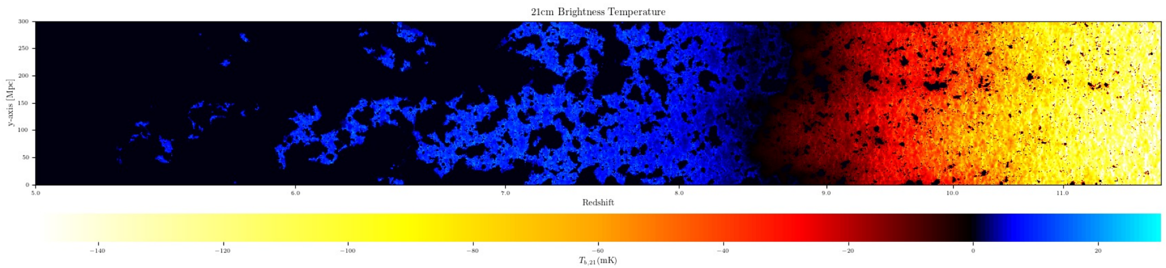


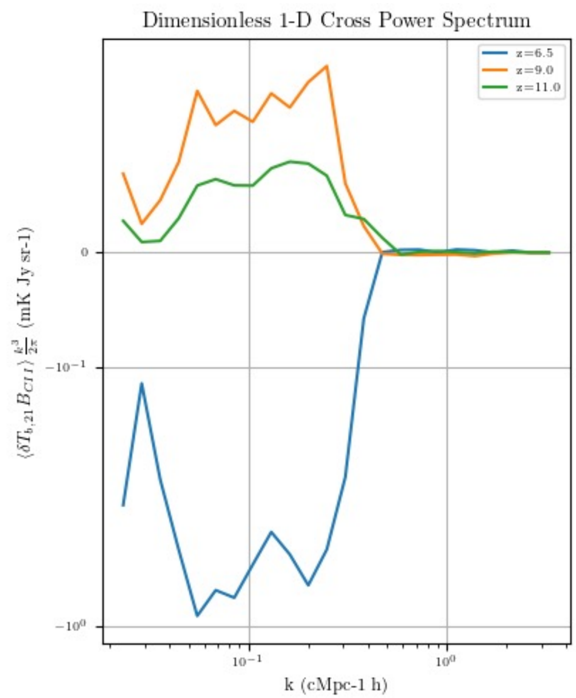
21cm simulation of the EoR and intensity mapping simulations in other lines.
(E. D. Kovetz, et al. 2017)

Implementation and Expected Results

- Calculate the 21cm-[CII] cross-correlation signal.
- Optimize the observation strategy to maximize the SNR.







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Radiative Transfer Simulations of Galaxies & AGN in the Early Universe

Saksham Chandna, Supervisor: Simona Gallerani

Scuola Normale Superiore

Spoke 3 General Meeting, Elba 5-9 / 05, 2024

Scientific Motivation

Observations of $z \sim 6$ quasars have shown that these bright sources are powered by rapidly accreting super massive black holes (SMBHs, $M_{BH} \sim 10^8 - 10^{10} M_{sun}$).

The existence of such early SMBHs is a puzzle for current theoretical models that are striving to understand how these gigantic BHs have formed and what is their impact on the host galaxy properties.

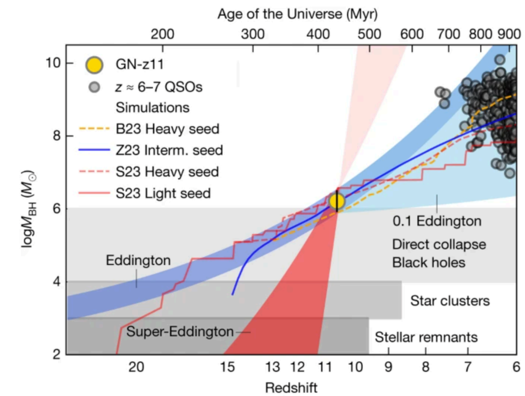
Studying massive black holes of $\sim 10^6 - 10^7 M_{sun}$ at higher redshift is essential in order to take a step forward in this field.

Recent James Web Space Telescope (JWST) data have revealed the presence of $\sim 10^6 - 10^7 M_{sun}$ black holes at $z \sim 8 - 11$. These objects may represent the progenitors of the SMBHs powering $z \sim 6$ quasars.

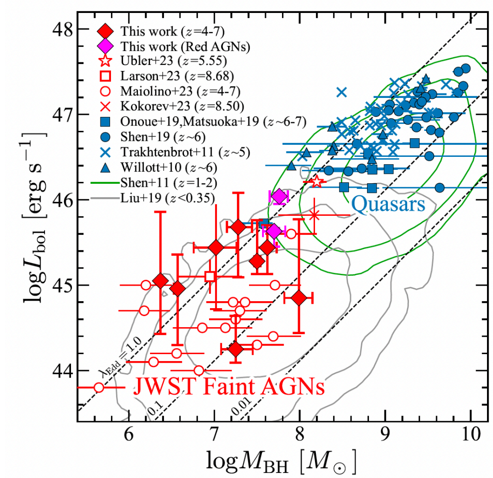
GOALS

To provide a theoretical support to these observations

To predict the observational signatures (detectable with ALMA and JWST) of SMBHs and their progenitors



Maiolino et. al (2024)



Harikane et. al (2023)

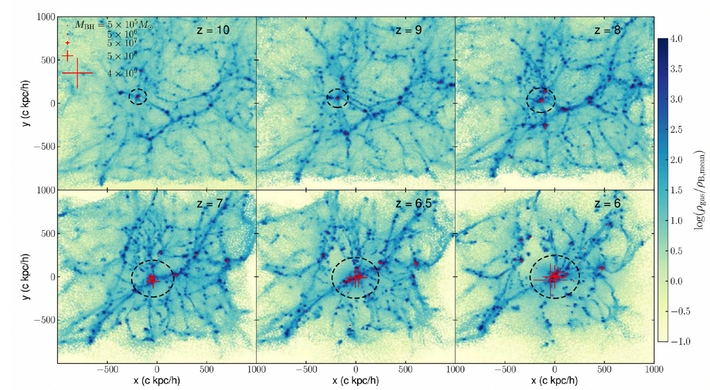
Methodology

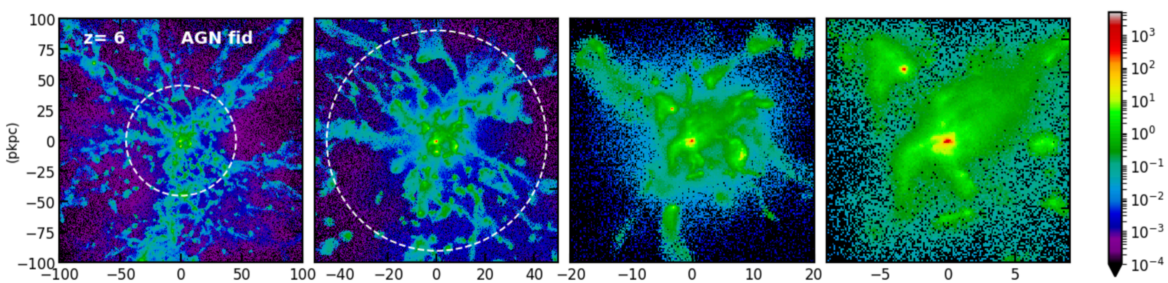
- We will exploit cosmological simulations already available to our group, that are based on a modified version of the SPH `GADGET-3` code (Barai et al. 2018; Valentini et al. 2021).

- These simulations have been already post-processed with radiative transfer (RT) calculations by using the publicly available `SKIRT 8` code that solves the *continuum* RT problem in a dusty medium (Di Mascia et al. 2021 a/b).

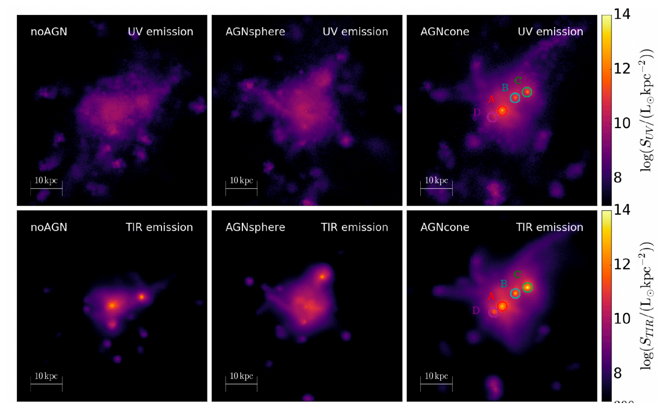
- We will exploit the new `SKIRT 9` version that solves the *line* radiative transfer problem.

Barai et. al (2018)



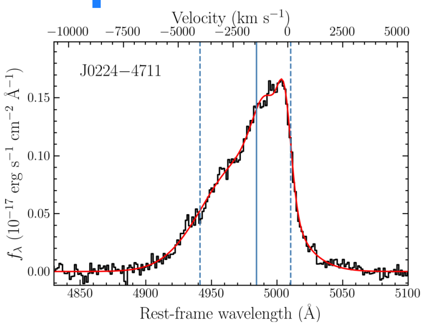


Valentini et. al (2021)

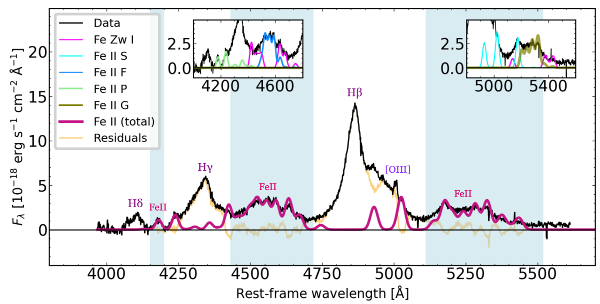


Di Mascia et al. (2021a/b)

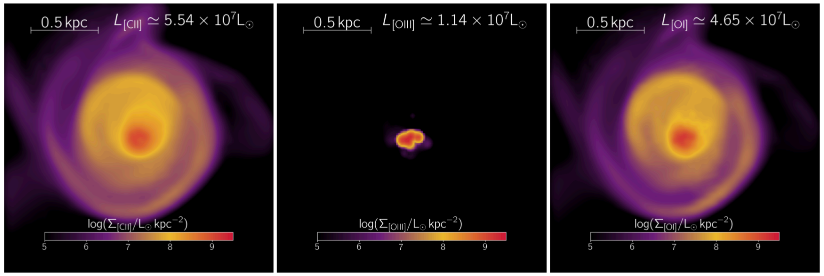
Expected Results: far infrared and nebular emission synthetic data



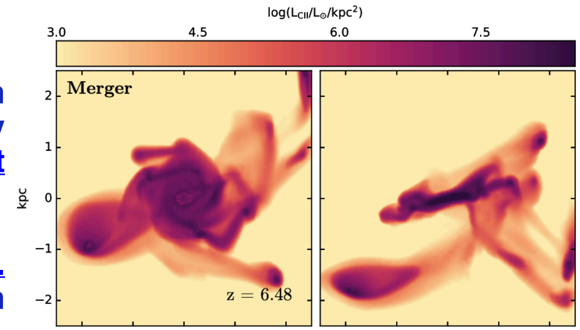
Yang et al. (2023)

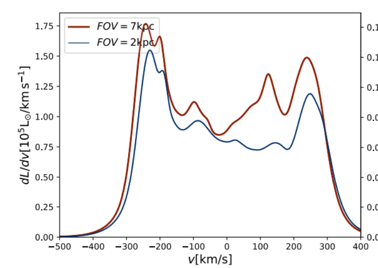


Loiacono et al. (2024)



Pallottini et al. (2022)





Kohandel et al. (2019)

- We will compute far infrared and nebular continuum and line emissions, similarly to what have been already done in our group (Pallottini et al. 2017a/b; Pallottini et al. 2022).
- We will produce synthetic data cubes (Kohandel et al. 2019) that will be suitable for a proper comparison between simulations and ALMA/JWST data.
- This theoretical framework will provide insightful information about the properties of galaxies and AGN in the early Universe.