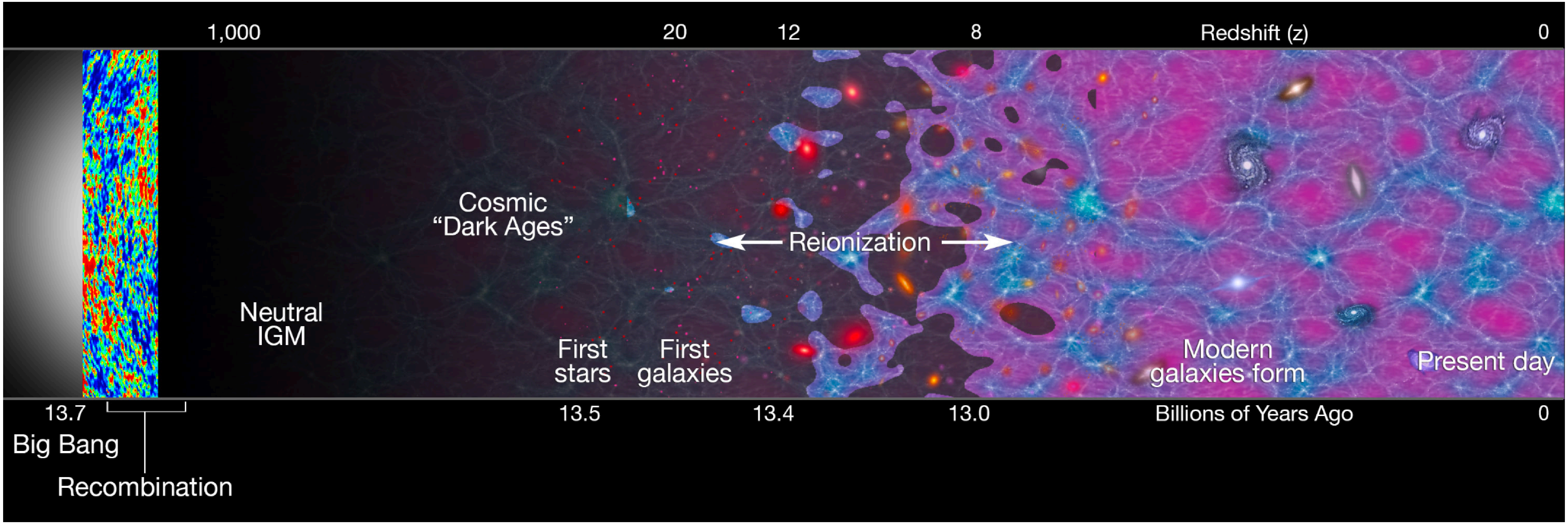
Cosmic Reionization: How Do We Simulate It?

Gnedin & Madau (2022)

Lena Einramhof

Reionization is the Last Phase Transition of the Universe

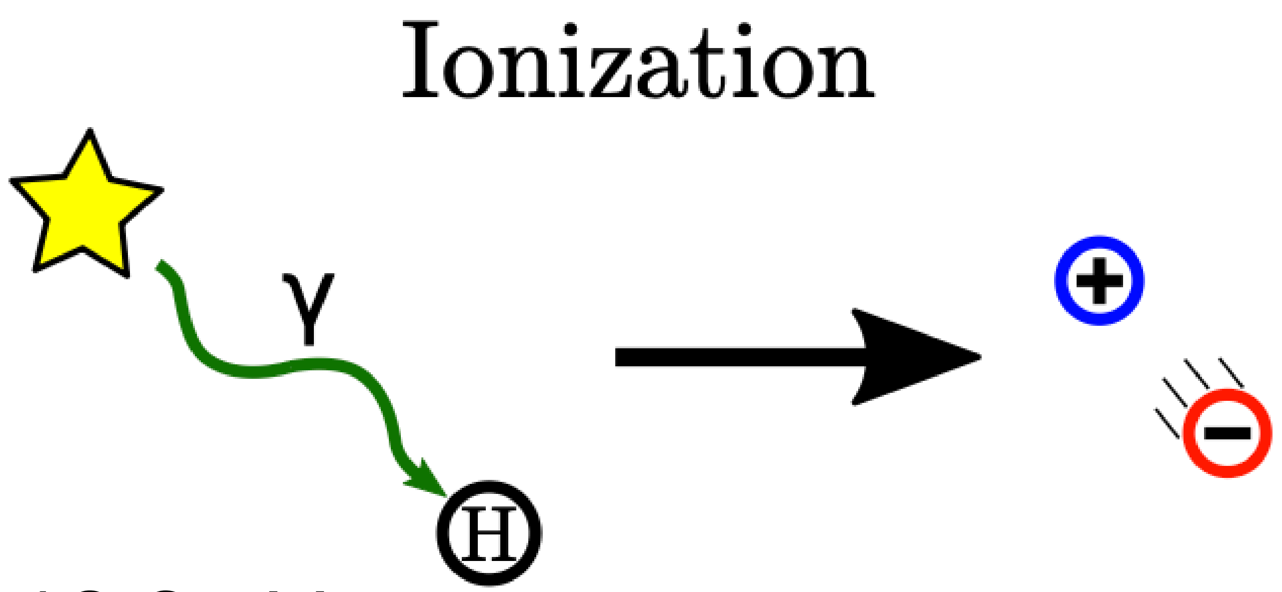


(Robertson et al., 2010)

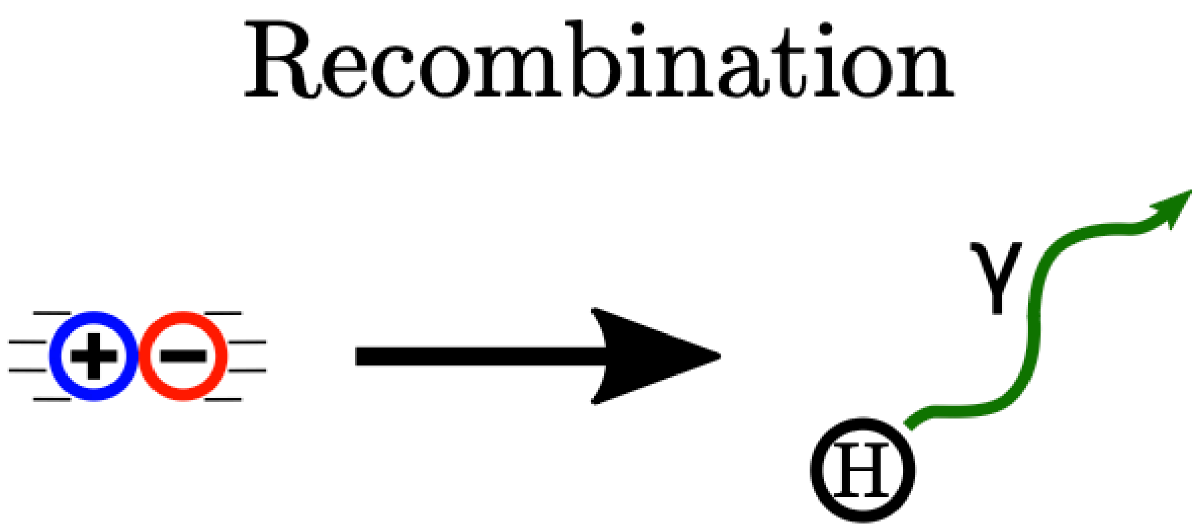
Transition from neutral to ionized IGM

Ionization & Recombination are the Key Processes in Driving Reionization

radiation escapes host halos → ionize and heat surrounding IGM



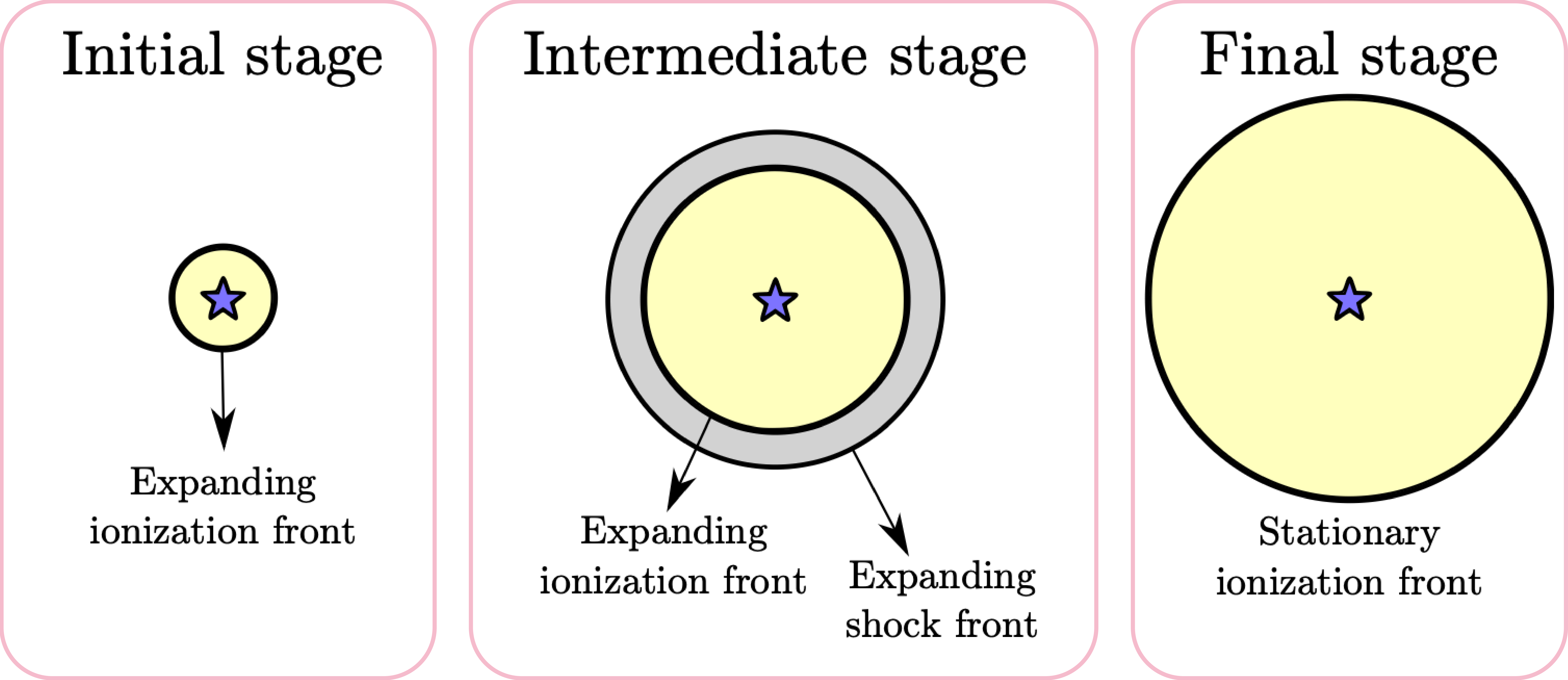
E > 13.6 eV



(Wise, 2019)

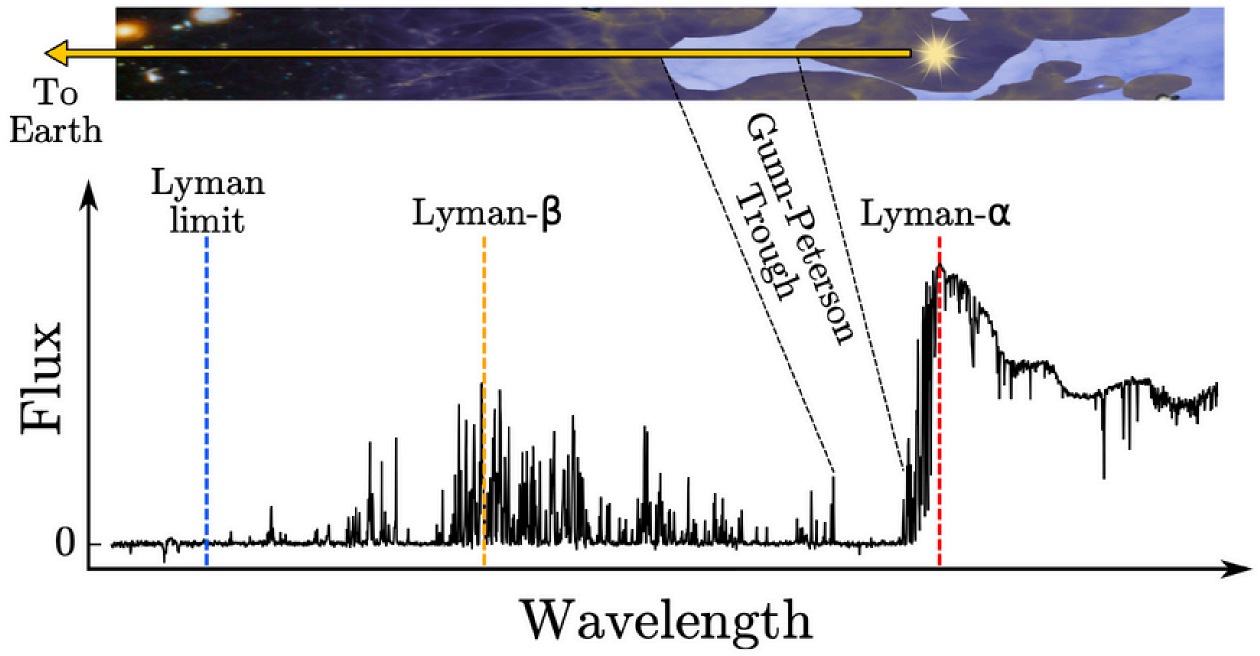
→ HII regions highly ionized

HII regions evolve over time

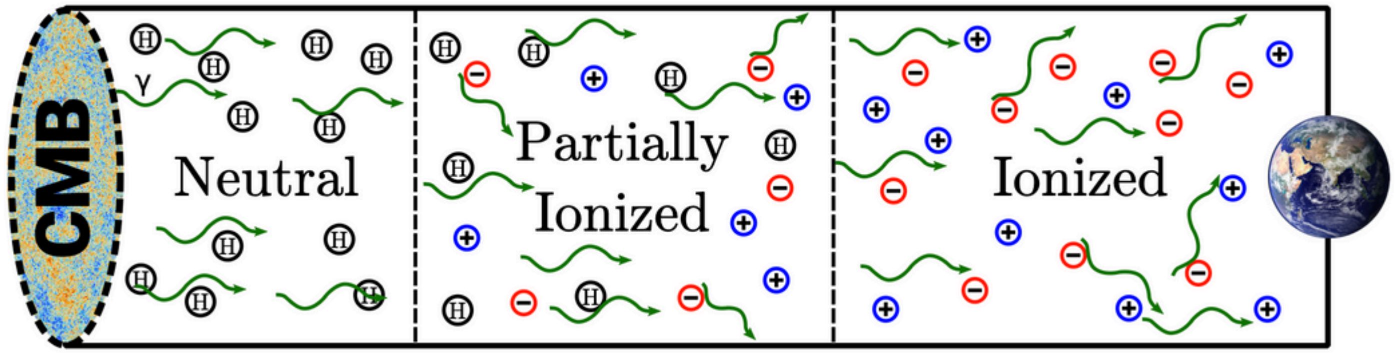


(Wise, 2019)

Observations constrain the ...



Wise (2019)



John H. Wise (Georgia Tech)

... end of reionization

QSO spectra

... neutral fraction

Lyman-alpha forest

... start of reionization

CMB

... morphology of the ionized regions

Neutral H (21 cm) absorption & emission

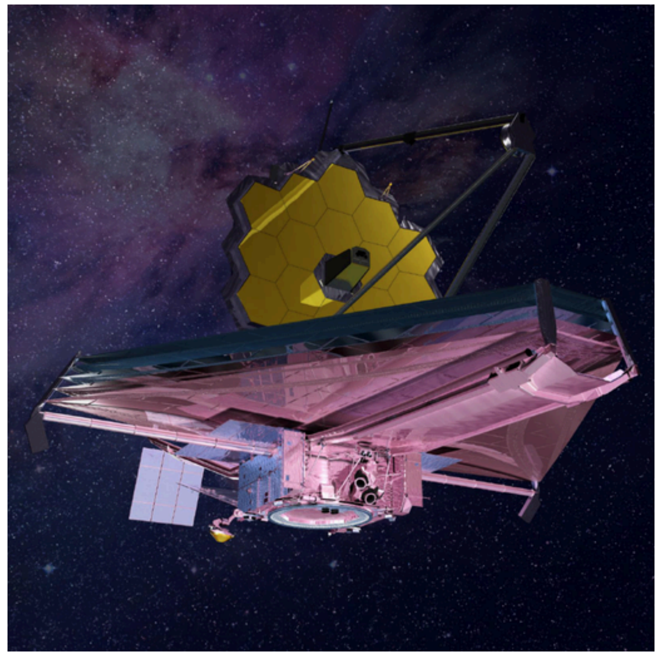
Why do we model reionization?

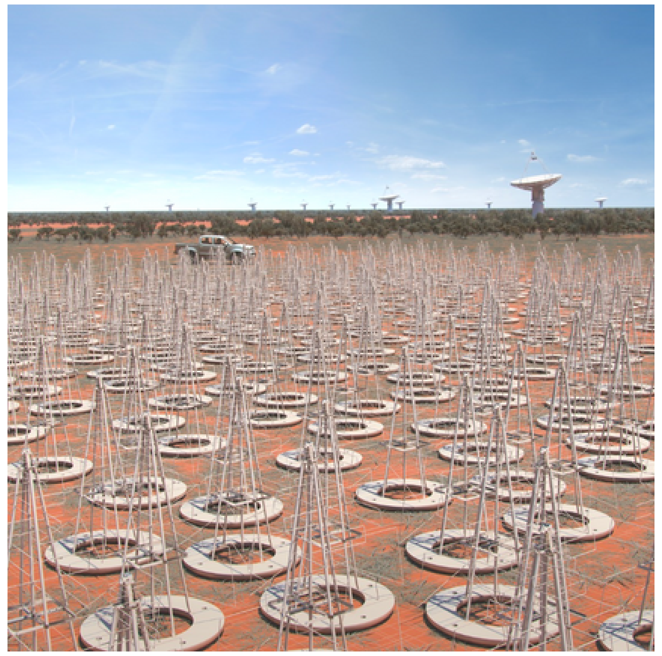
New observations

JWST

SKA

https://science.nasa.gov/wp-content/uploads/2024/05/jwst_artist_concept_0.png?w=1041





https://infrastructurepipeline.org/files/images/optimised/project_hero/files/images/project/square-kilometre-array-au-closeup-midres1-660e2856945e3579990669.jpg

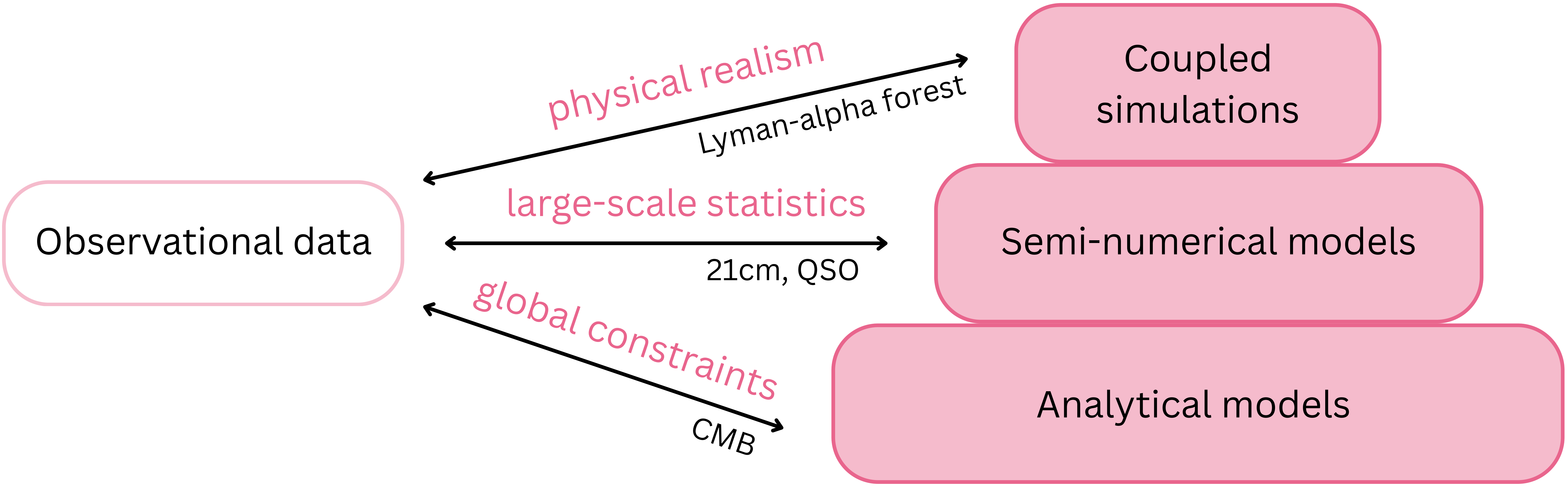
Multi-scale physics

Non-linear physics

No single observation isolates these effects → simulations

galaxies ⟶ photons ⟶ IGM state ⟶ observables

Why do we model reionization?



How is cosmic reionization modeled?

What physics must be modeled?

How do we treat radiative transfer numerically?

Modeling strategies

What physics must be modeled?

Physics sets the numerical requirements

Photoionization & Heating

Radiative Transfer

Clumpiness of the IGM

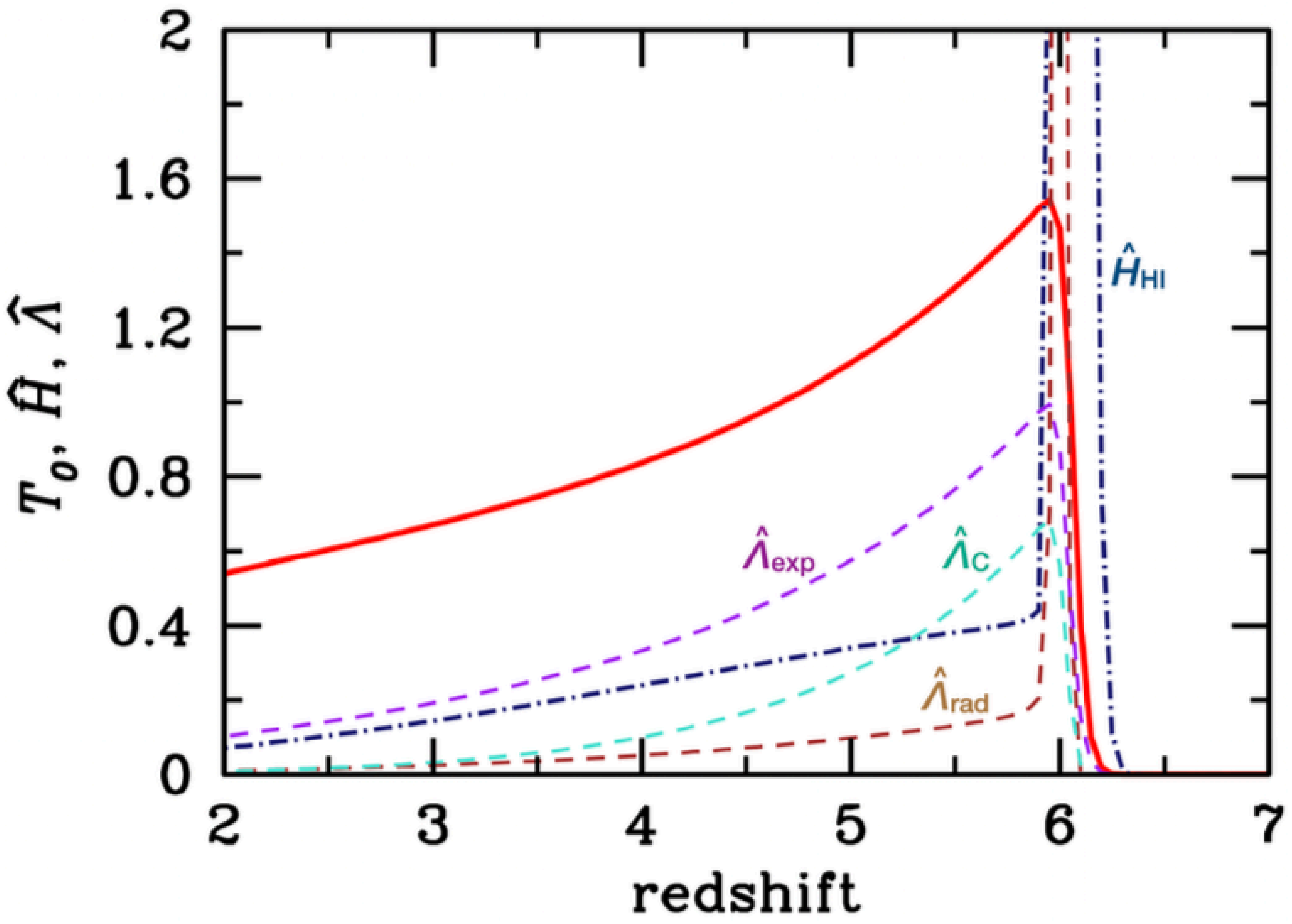
Photoionization Leads to Patchy Heating of the IGM

dT/dt = adiabatic cooling + change in internal energy per particle + net heat gain/loss from radiation processes

UV background → hydrogen photoheating
then: multiple cooling mechanisms

much more complex in reality!

→ Radiative transfer must be modeled explicitly



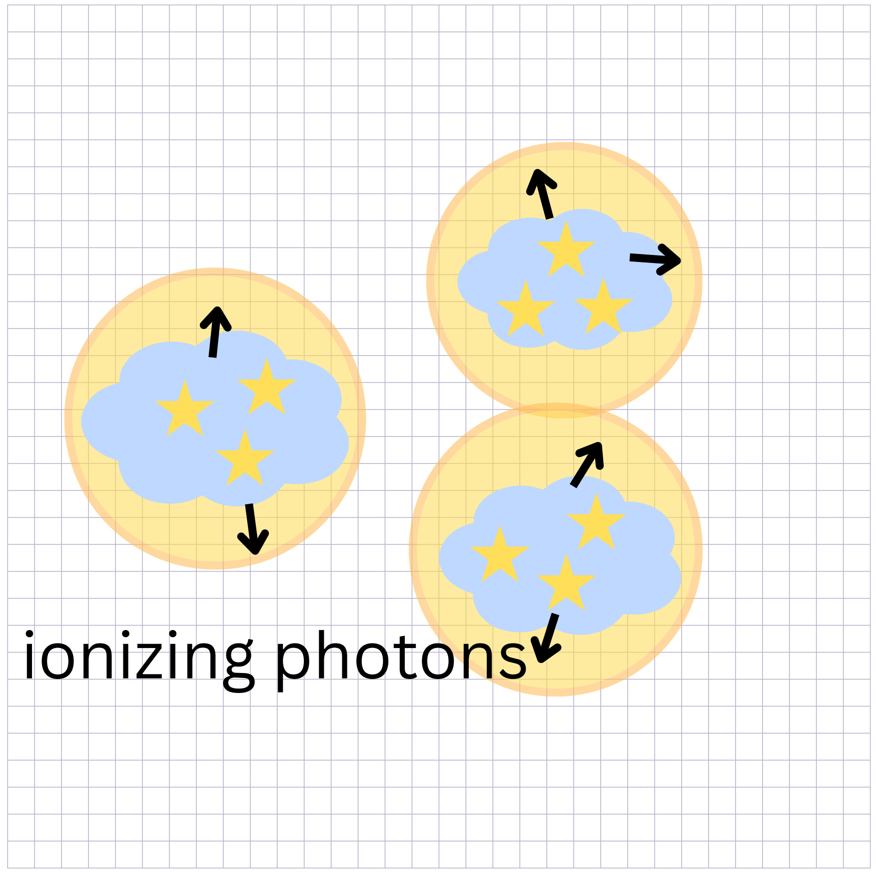
(Gnedin & Madau, 2022)

An Expanding Universe Leads to Non-local Radiation

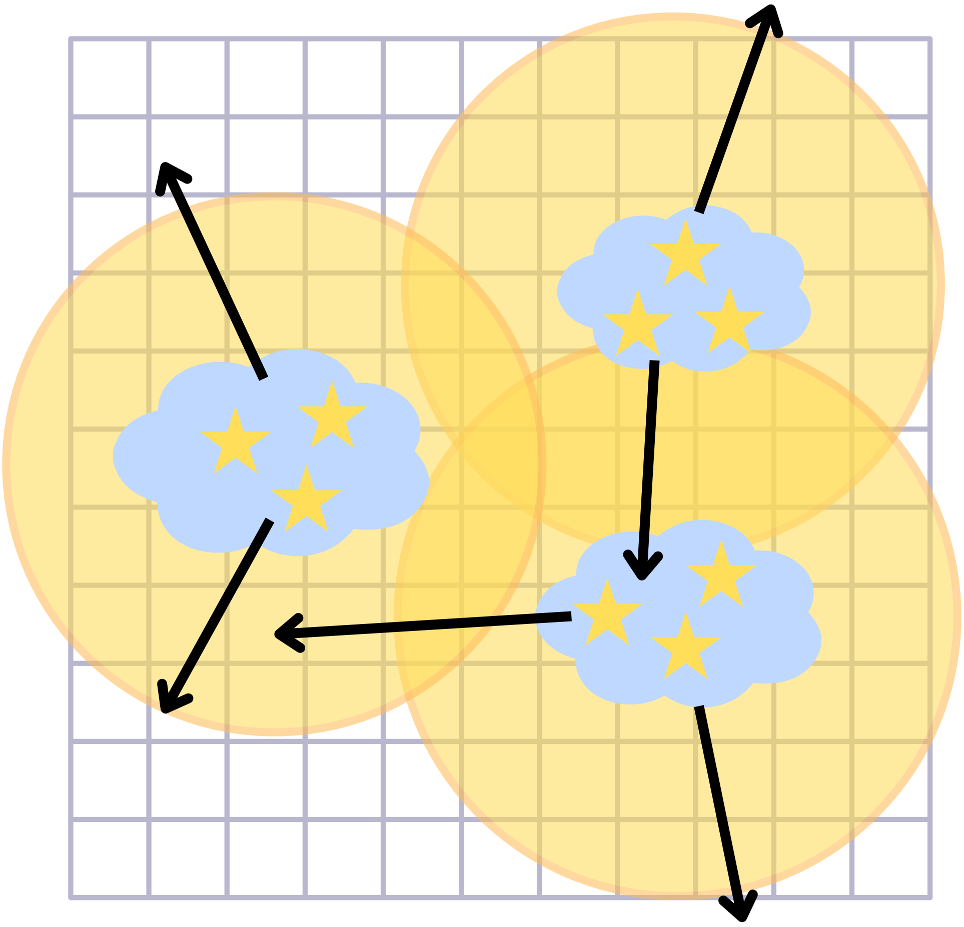
Cosmic expansion → longer mean free path, redshifting of photons, dilution of intensity

short λ_{mfp} → local, source–sink coupled

Early times



Late times

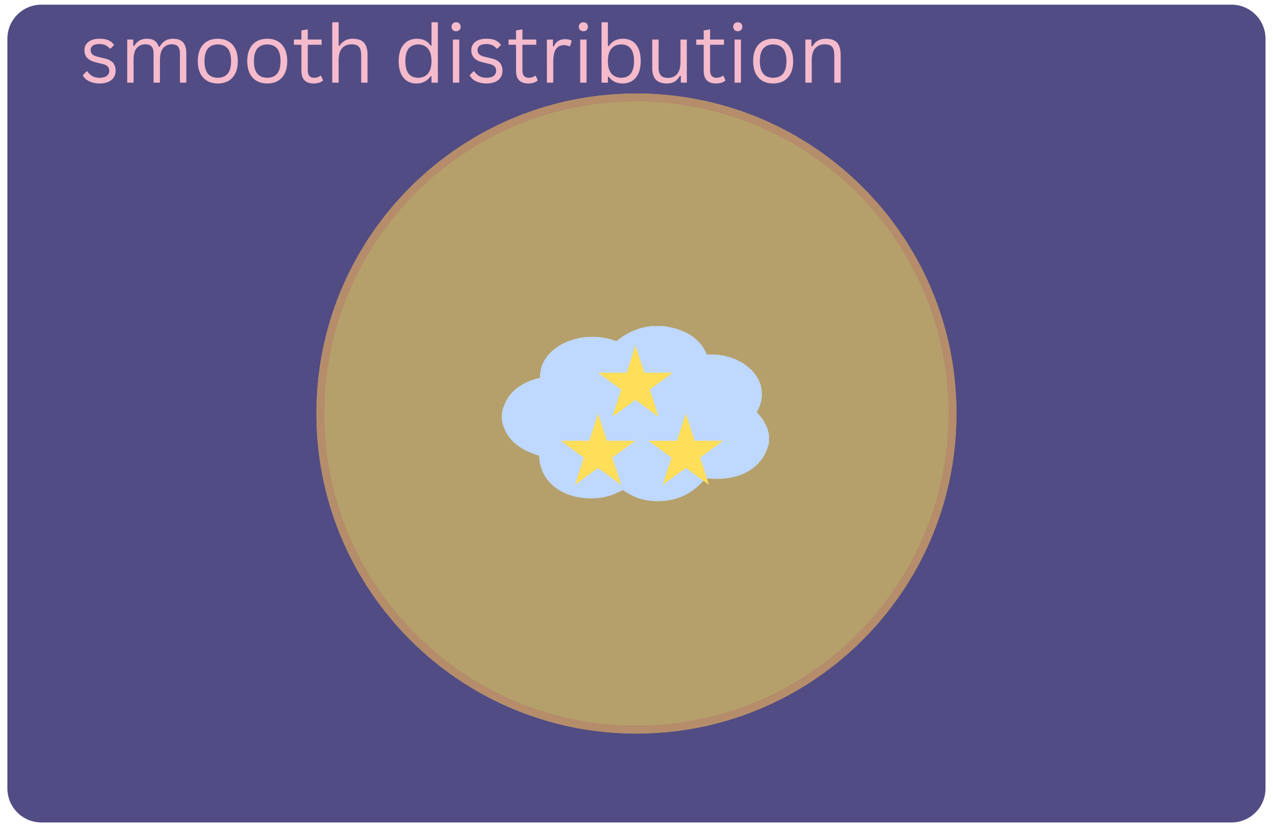


long λ_{mfp} → global, non-local UV background

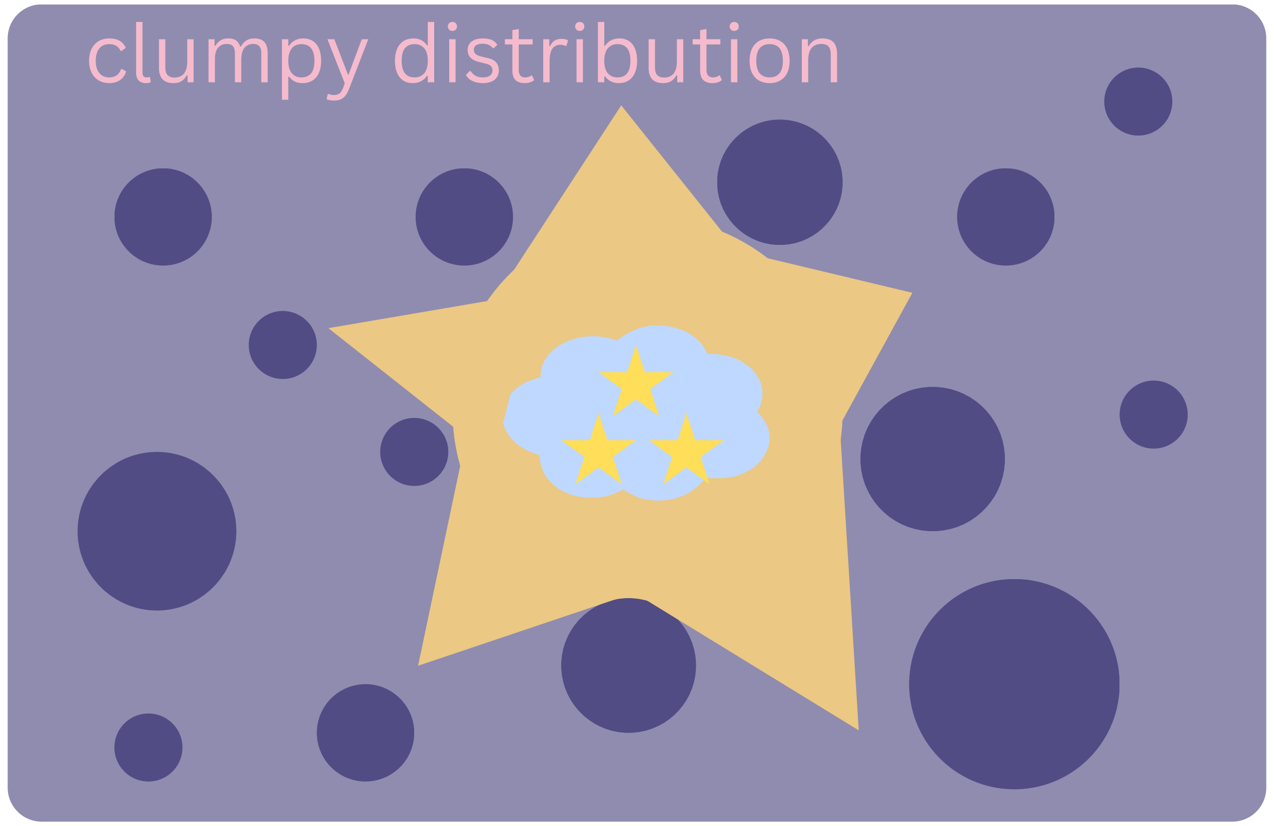
→ Radiative transfer must be modeled explicitly

Clumpiness of the IGM Leads to Anisotropic Photon Propagation

Nonlinear evolution of density fluctuations → IGM highly inhomogeneous



Spherical ionization front



Enhanced recombinations in dense regions

Non-spherical ionization fronts

Direction-dependent $\lambda_{\rm mfp}$

→ Radiative transfer must be modeled explicitly

How do we treat radiative transfer numerically?

The physics of radiation transport
strongly constrains how reionization can be simulated

What Makes Radiative Transfer Difficult?	Ray Tracing vs Moment Methods	Reduced Speed of Light Approximation

What makes radiative transfer difficult?

2D angular coordinates

time

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\mathbf{n}}{a}\cdot\frac{\partial I_\nu}{\partial \mathbf{x}} - \frac{H(t)}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + S_\nu$$

3D position

frequency

What makes radiative transfer difficult?

$$I_\nu = I_\nu(\mathbf{x}, \mathbf{n}, \nu, t)$$

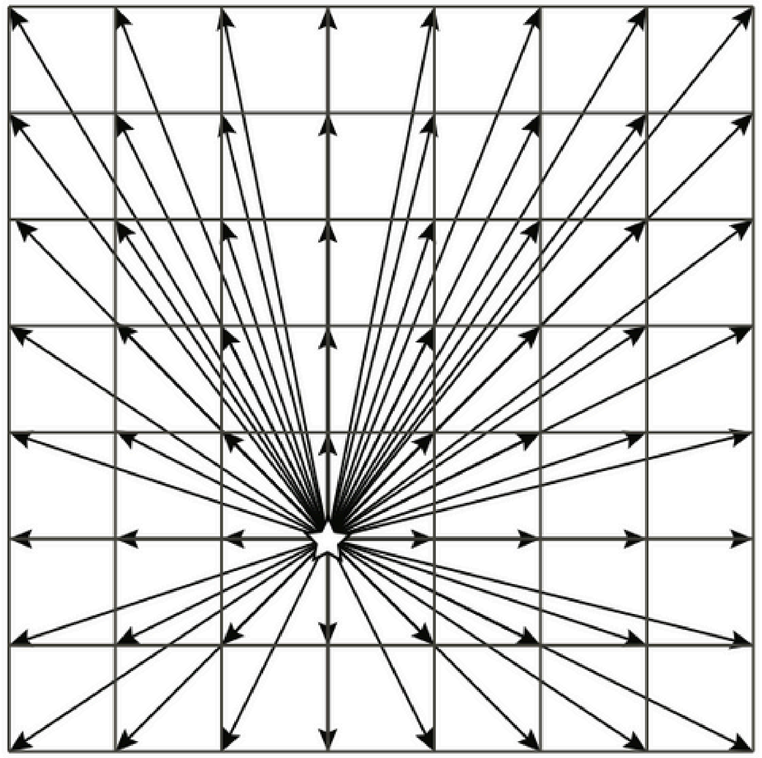
3 + 2 + 1 + 1 = 7 parameters

→ need approximation/computational optimization

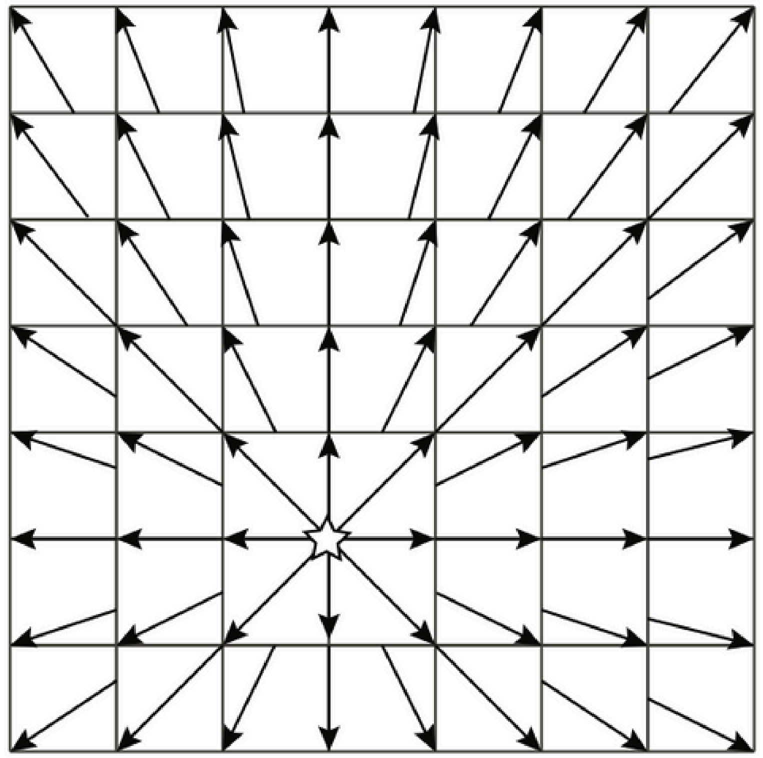
Ray Tracing

spatial

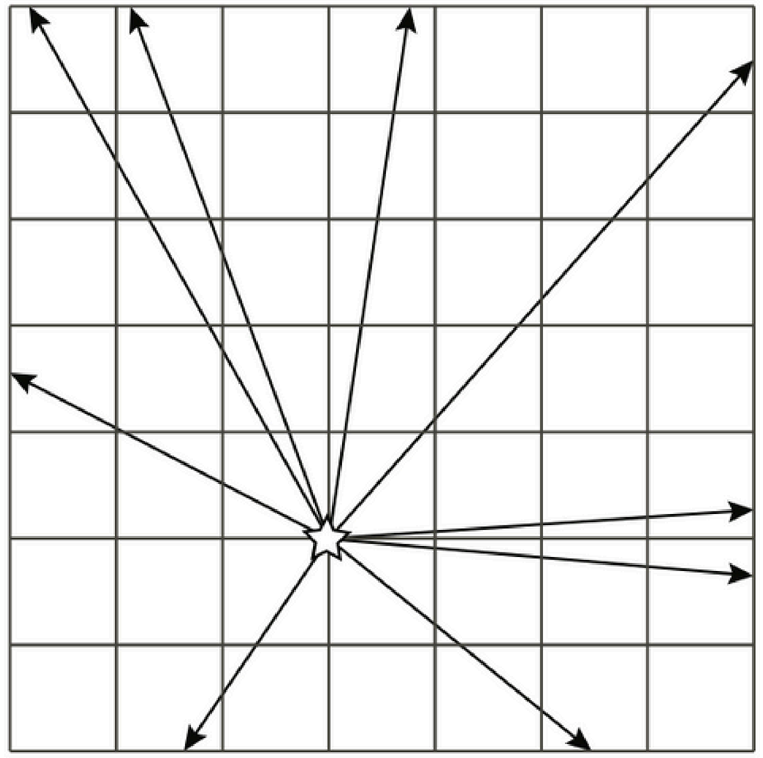
solve radiative transfer along a one dimensional ray



Long characteristics method



Short characteristics method



Monte Carlo ray tracing

(Partl, 2011)

→ accurate ionization fronts
BUT computationally expensive

Moments Methods

spatial

J_ν mean intensity
How many photons are here?

F^i_ν radiation flux vector
Which way are they flowing?

P^{ij}_ν radiation pressure tensor
How isotropic is the field?

replaces the full angularly-resolved radiation field with a few averaged quantities

→ computationally cheaper
BUT approximates how radiation propagates

Reduced Speed of Light Approximation

time

1 hydrodynamic time step

1000 radiative transfer time steps

→ computationally expensive!

Ionization fronts move << c

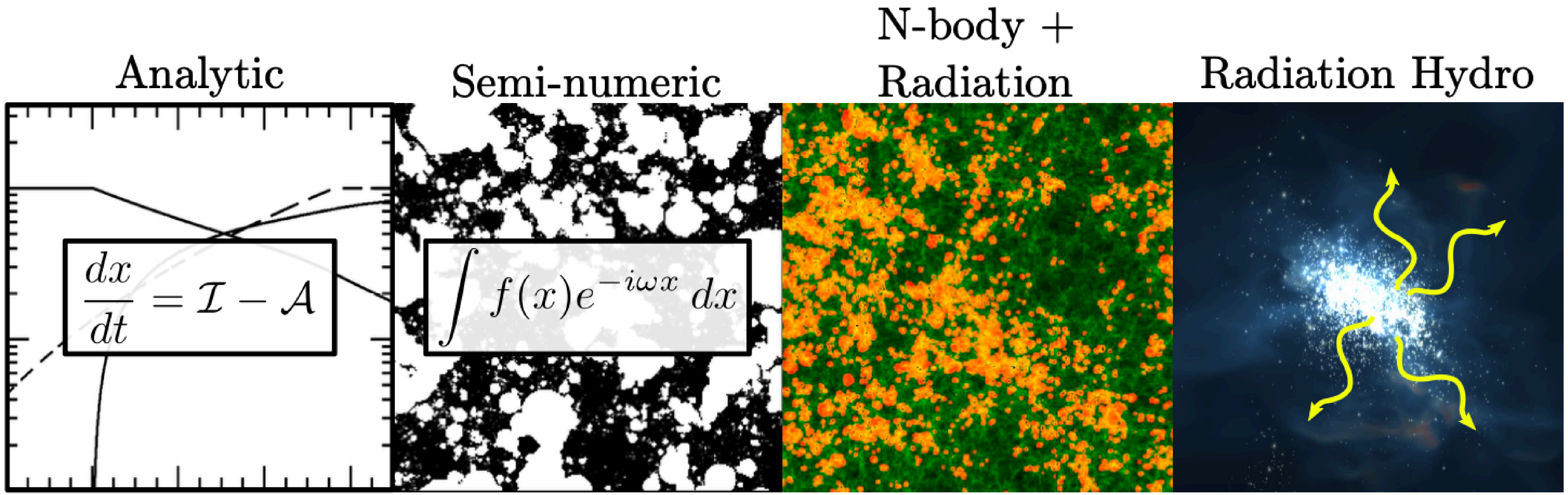
$$\boxed{c \rightarrow \hat{c} \ll c}$$

Where it breaks:

- RSL delays distant background photons
- UV background builds up too slowly
- Photon conservation violated in low-flux regions

→ much faster
BUT problems not fully solved yet & needs to be used carefully

Modeling Strategies



(Wise, 2019)

Realism
Computational Cost & Effort

Ease of parameter studies
Cosmological volume possible

Analytical Models

Reionization = balance between ionizing photons and recombinations

Reionization equation:

universe-average ionized fraction

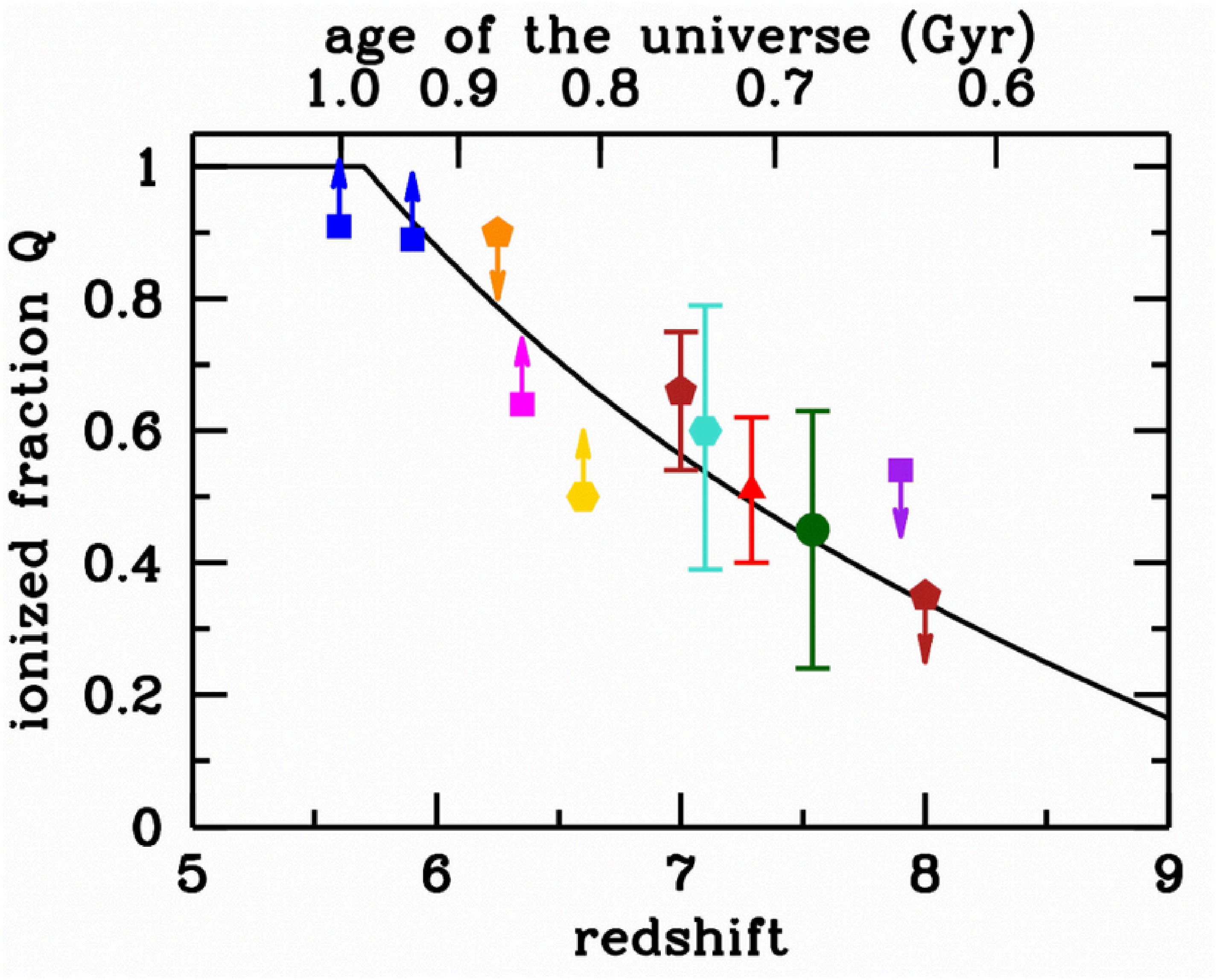
$$\frac{dQ}{dt} = \frac{\dot{n}_{\rm ion}}{n_{\rm H,0}} - \frac{Q}{\bar{t}_{\rm rec}}$$

how fast the IGM recombines

how fast galaxies ionize the Universe

Analytical Models

Reionization = balance between ionizing photons and recombinations



(Gnedin & Madau, 2022)

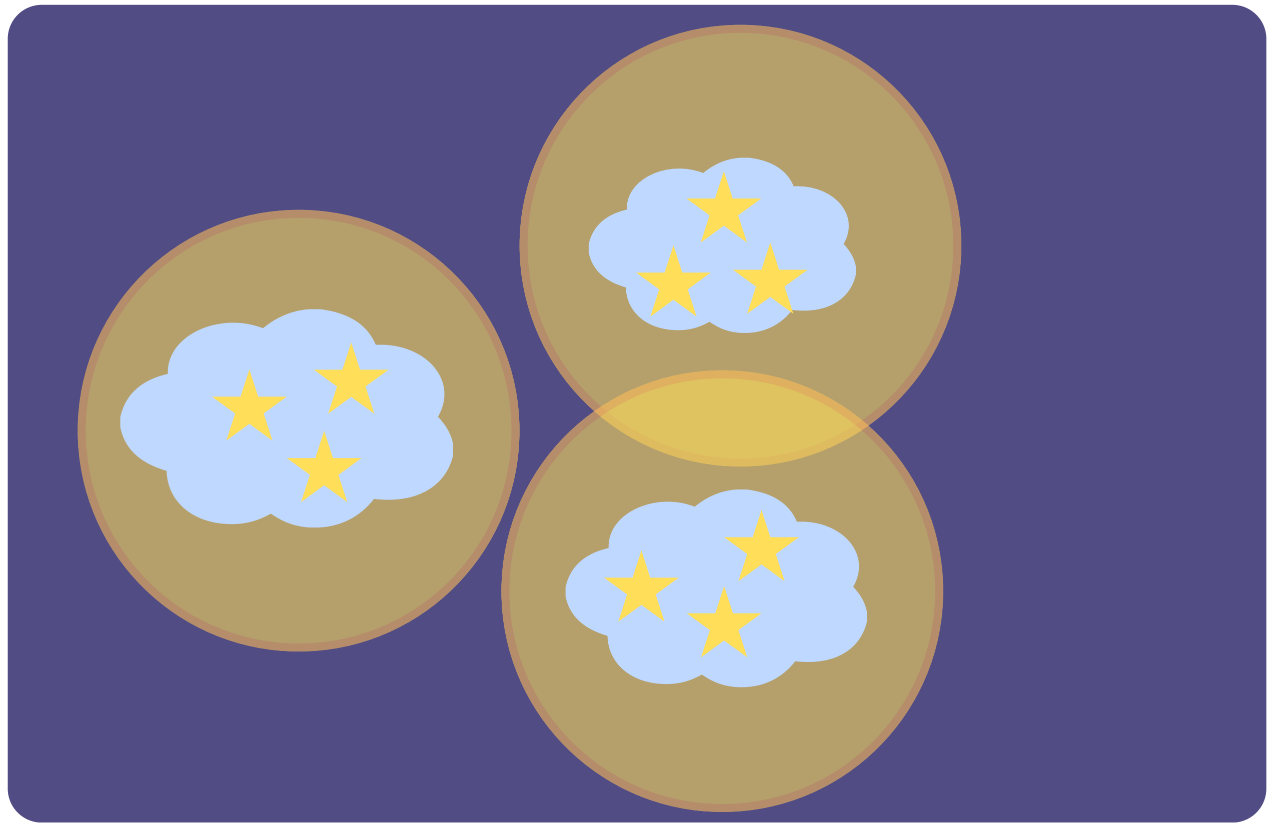
Assumptions:

- photons ionize locally
- radiation field is spatially averaged
- recombination rate summarized by a clumping factor
- source–sink correlations ignored

→ fails for morphology, patchiness & early stages

Analytical Models + Spatial Information

Inside-out (Excursion set-based models)



- overdense regions collapse first
- form galaxies → ionize dense surroundings

Outside-in (PDF-based models)

- underdense regions easier to ionize
- dense self-shielded clumps consume photons through recombination

→ two stages of same "inside-out-back-in" process: early ionization driven by source location (inside-out), late by gas density (outside-in)

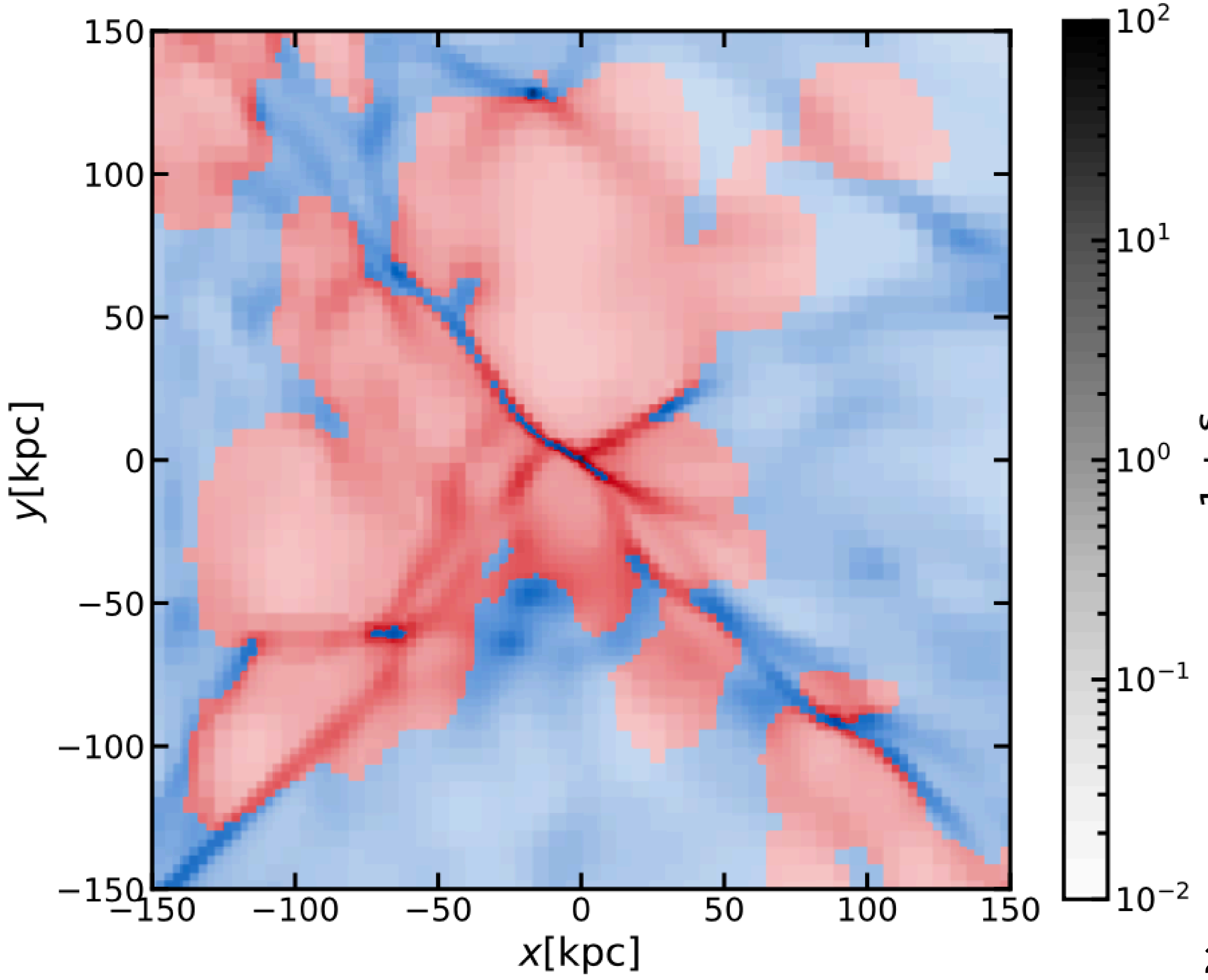
Analytical Models

Excursion Set Models

ionized bubble around massive galaxy from CROC simulation at z=9

neutral gas ionized gas

→ filaments remain neutral long after nearby voids are ionized



(Gnedin & Madau, 2022)

Semi-Numerical Models

21cmFAST

Generate ionization fields using analytic prescriptions based on density & collapsed fraction

Density field

evolved with Zel'dovich approximation

→

Analytic collapsed fraction

Excursion set theory

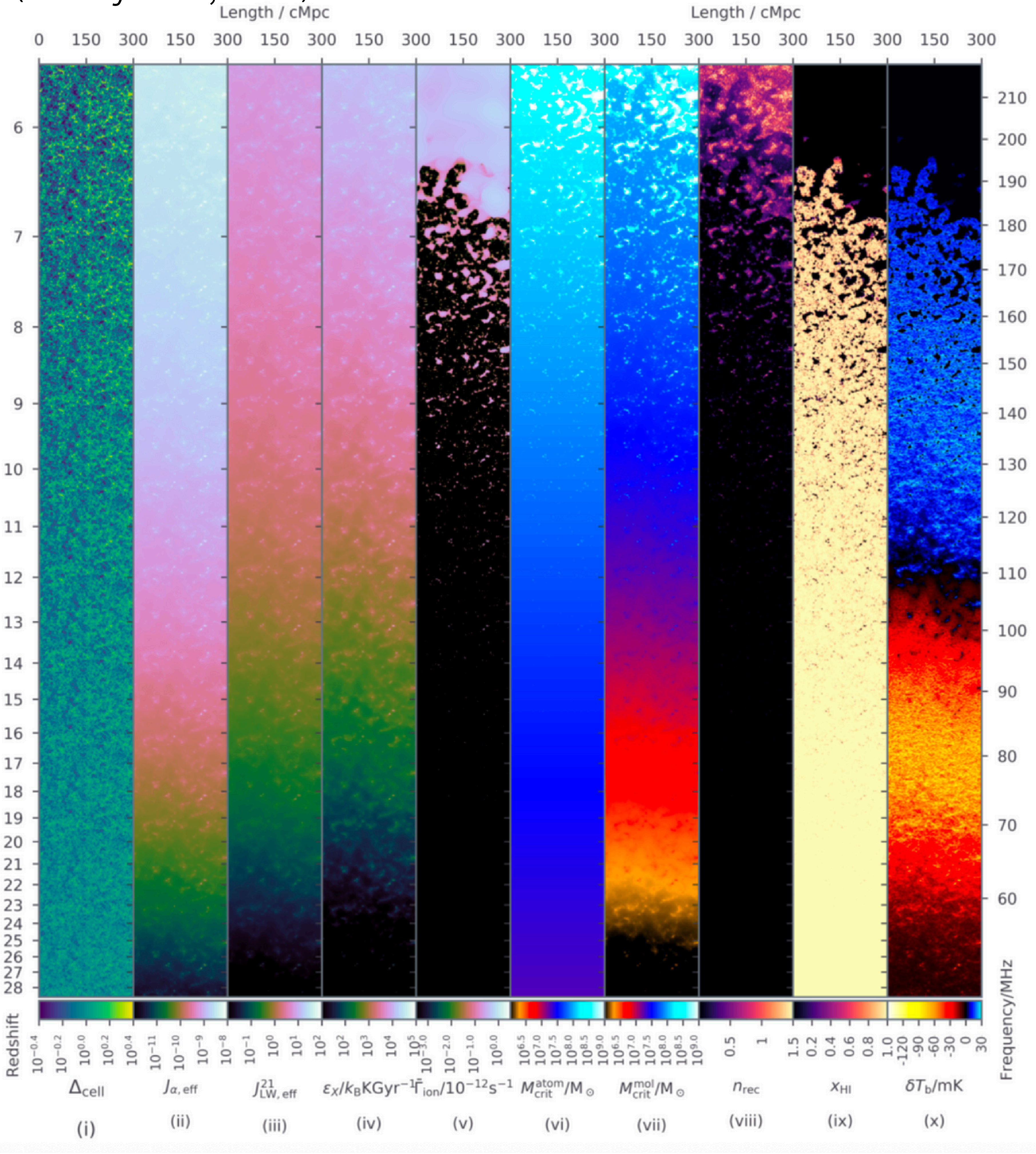
→

Distribution of ionized gas

large-scale maps

→ extremely fast

(Murray et al., 2020)



Semi-Numerical Models

21cmFAST

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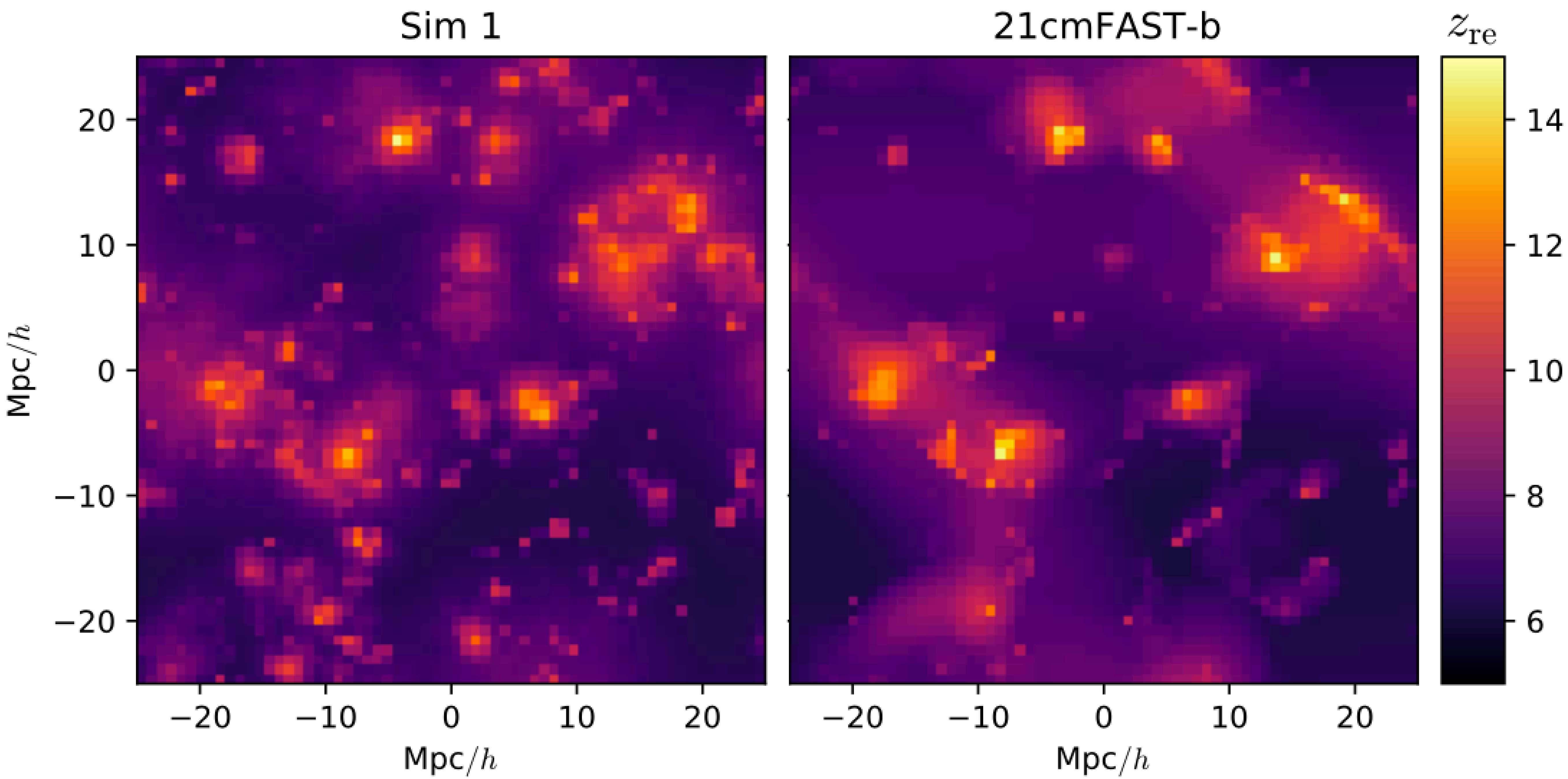


(Trac et al., 2022)

Dark-Matter-Only Simulation + Semi-Analytical Model

ASTRAEUS

DM N-body simulation → baryonic physics assigned through analytic prescriptions

DM N-body simulation

DM halo evolution

→

Semi-analytical galaxy evolution model (DELPHI)

computes ionizing photon production

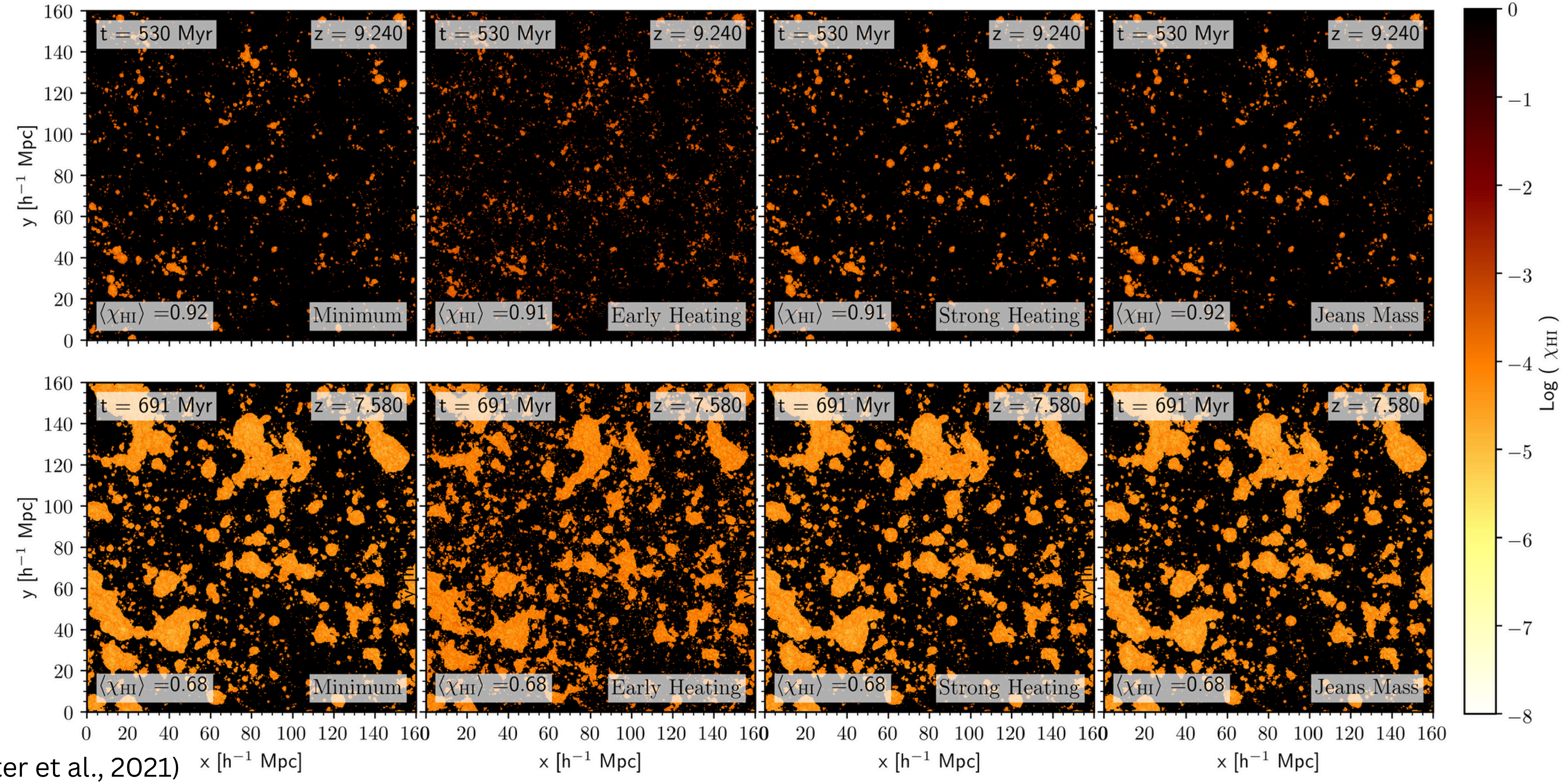
→

Semi-numerical reionization code (CIFOG)

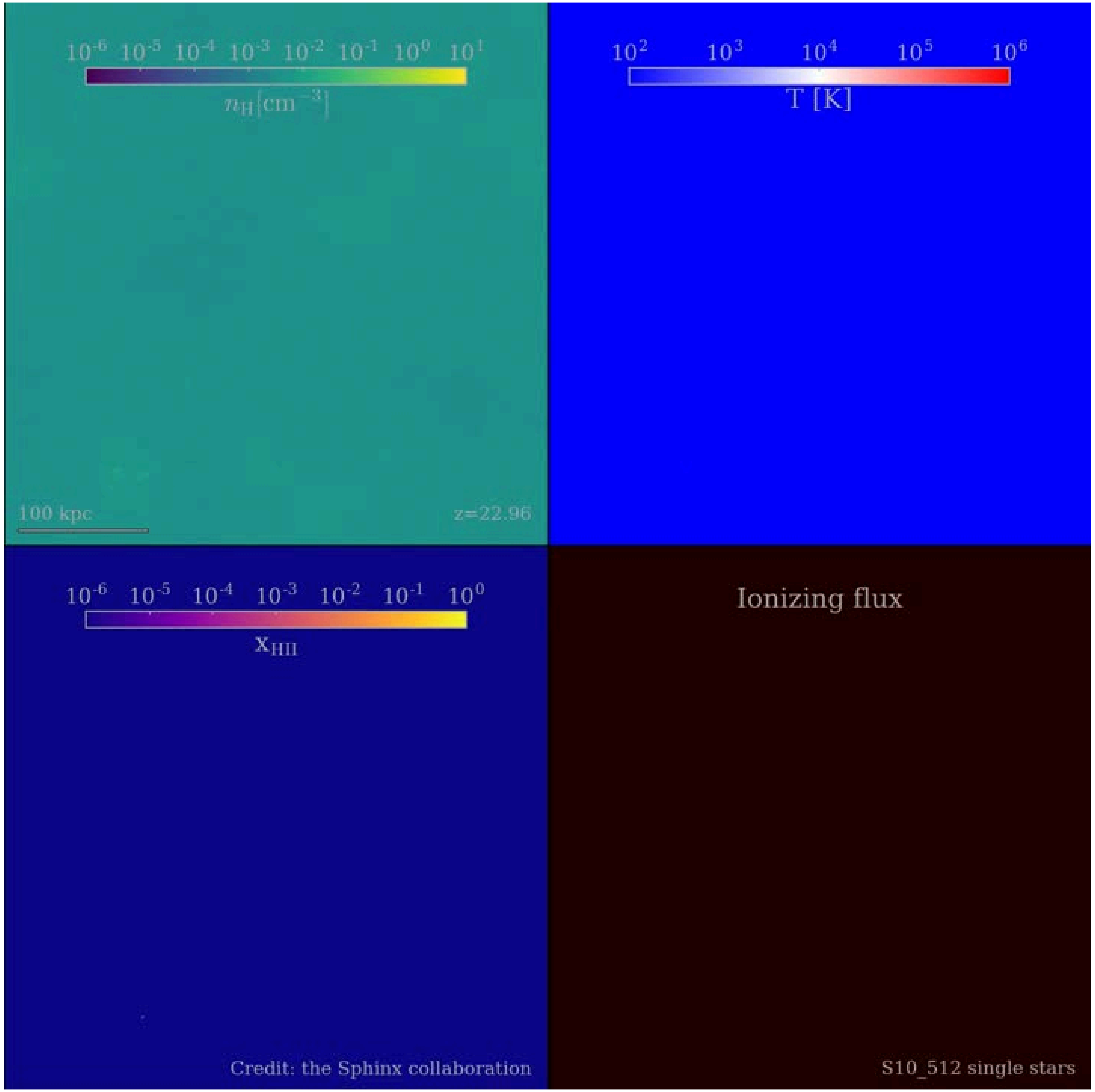
computes ionized hydrogen maps

Dark-Matter-Only Simulation + Semi-Analytical Model

ASTRAEUS



(Hutter et al., 2021)



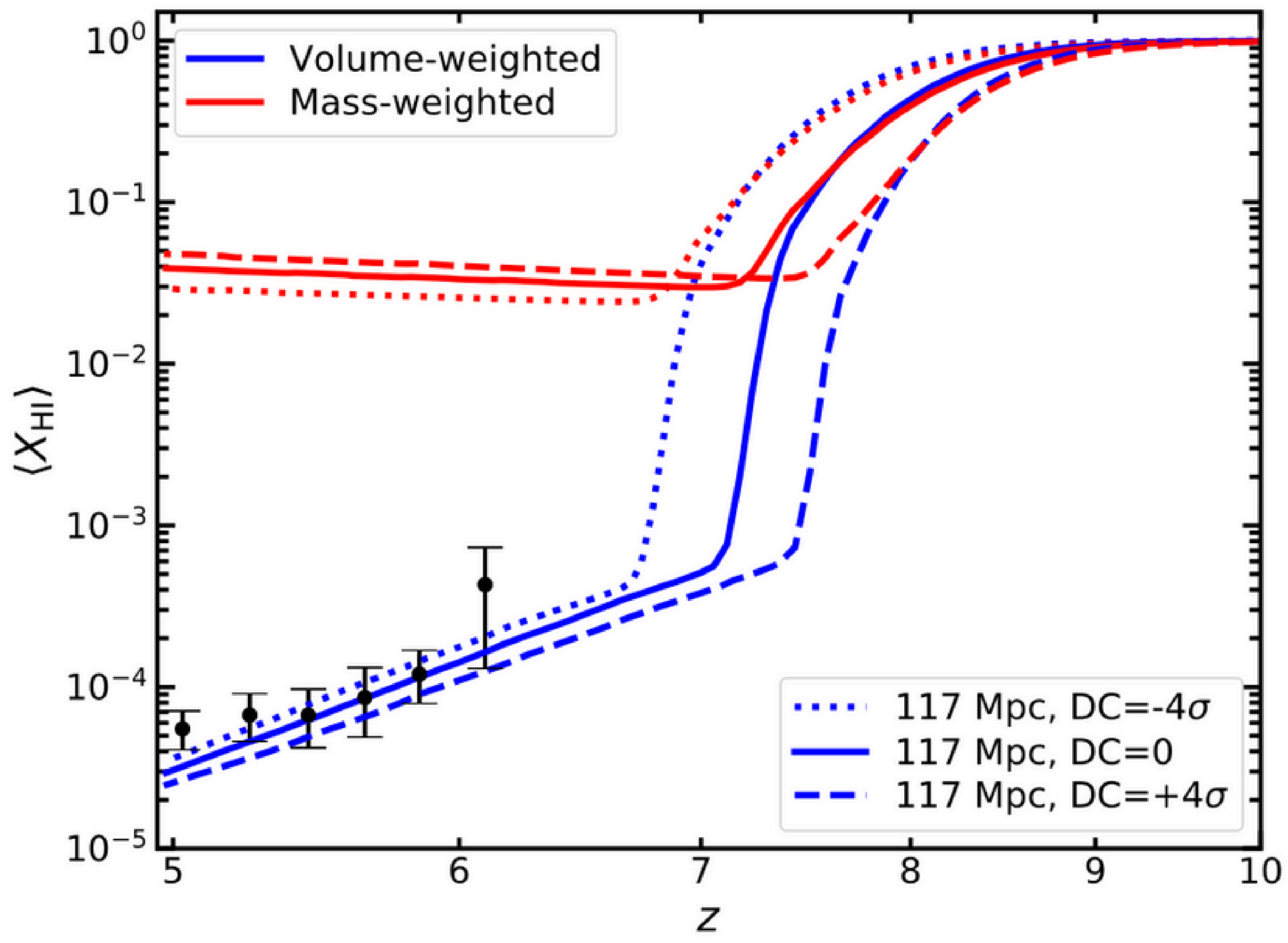
https://sphinx.univ-lyon1.fr/animations/

Fully Coupled Radiation-Hydrodynamics

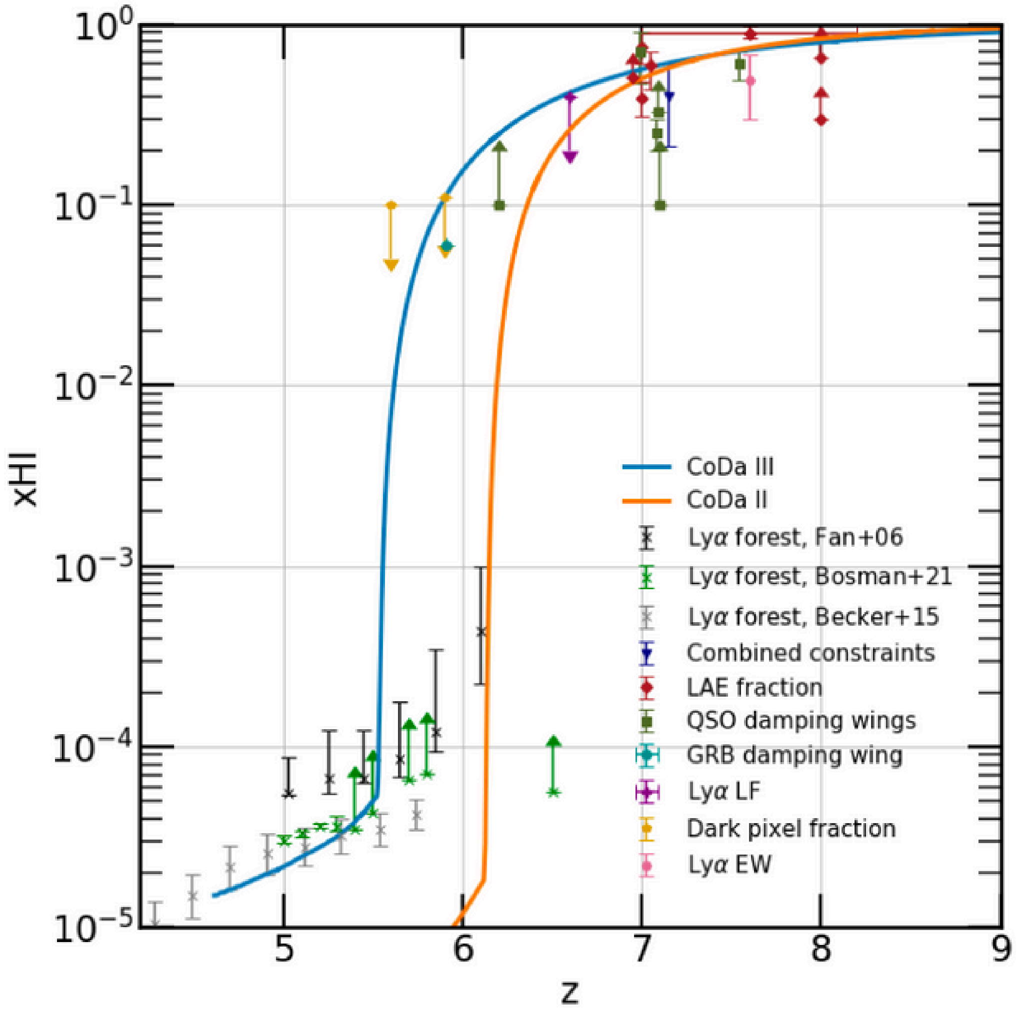
Solve

- DM dynamics
- gas dynamics
- radiative transfer
- source formation & feedback

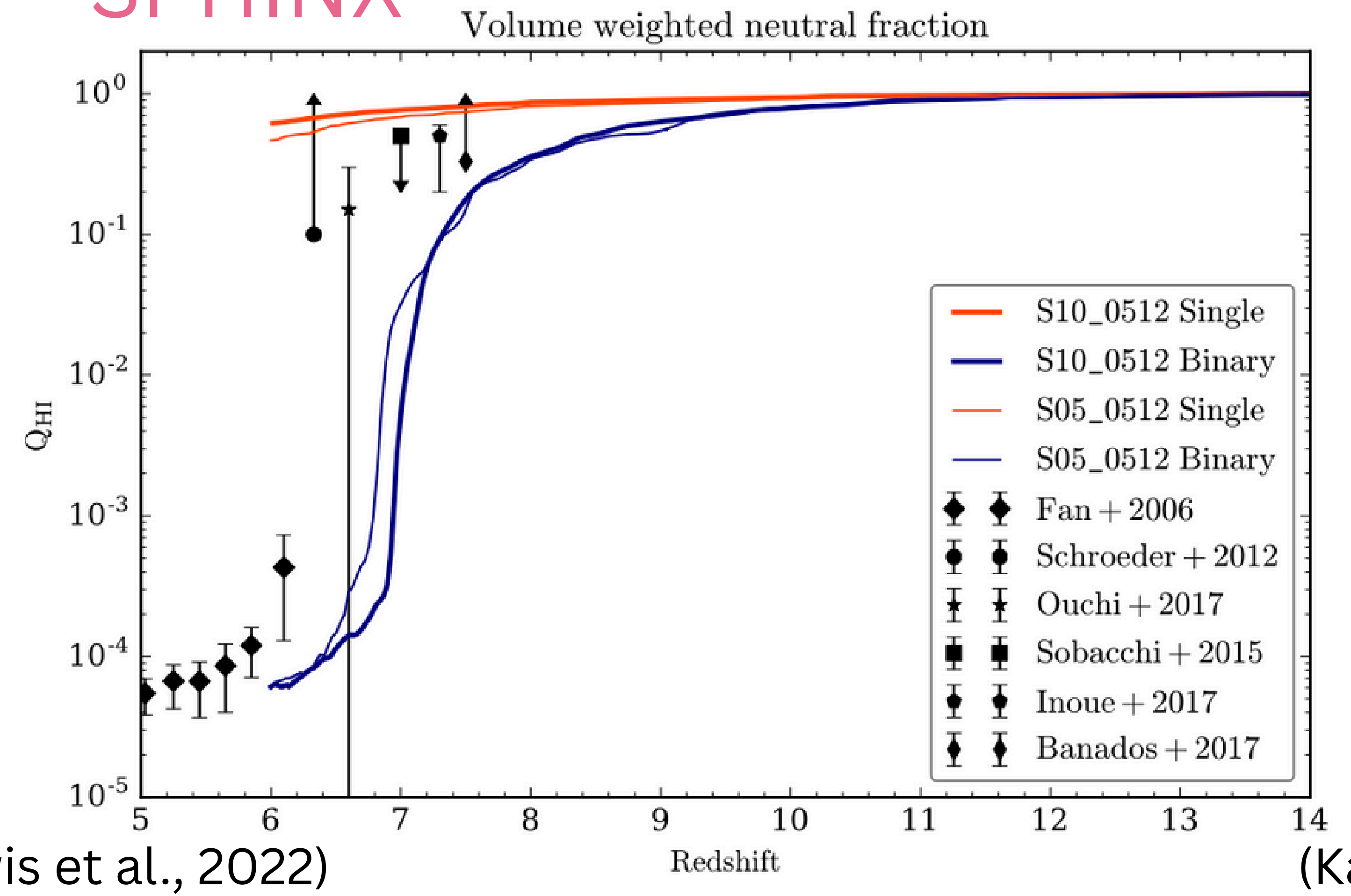
CROC



(Rosdahl et al., 2018) CoDa

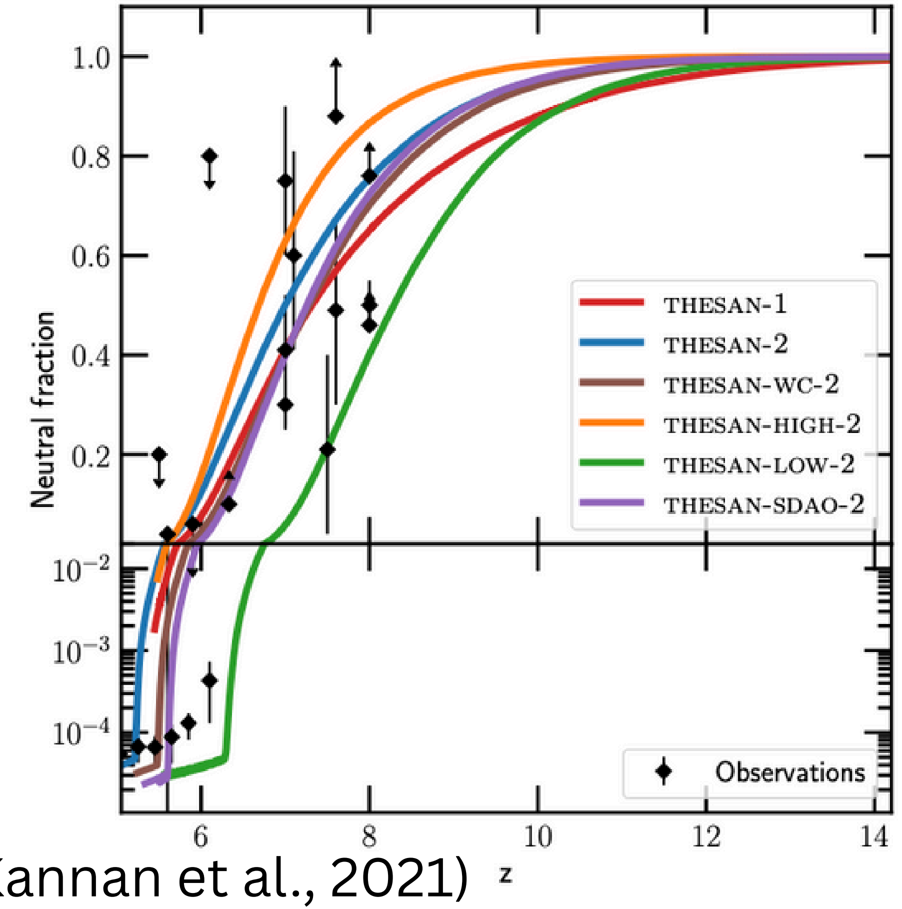


SPHINX



(Lewis et al., 2022)

Thesan



(Kannan et al., 2021)

Fully Coupled Radiation-Hydrodynamics

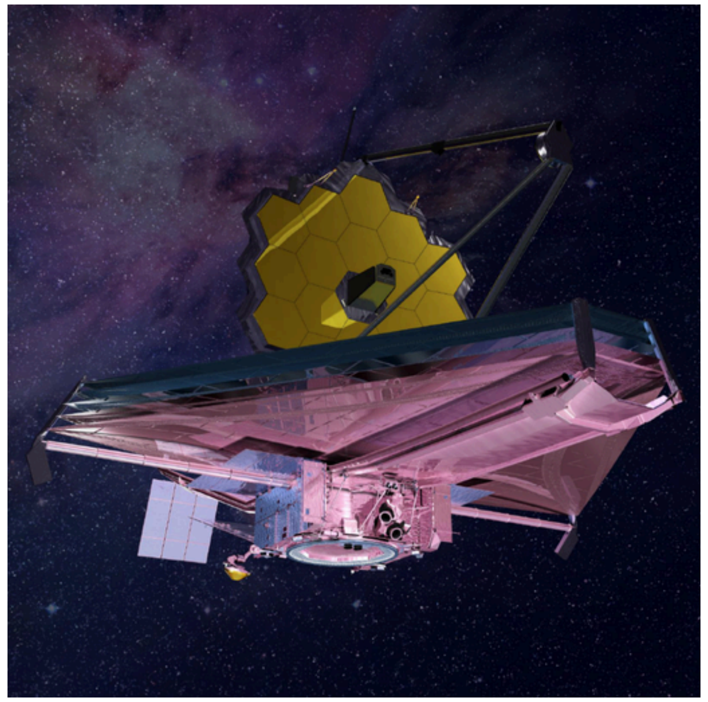
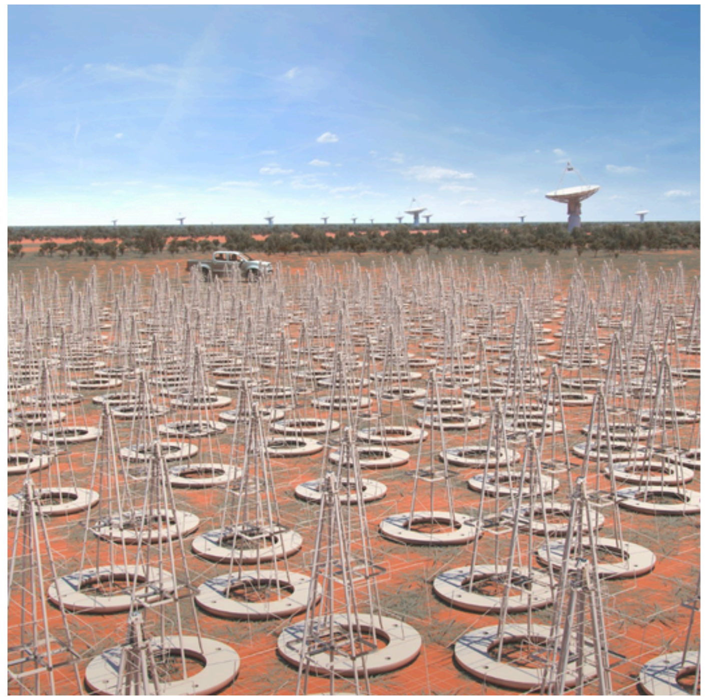
struggle to predict observations at the required precision
→ future simulations

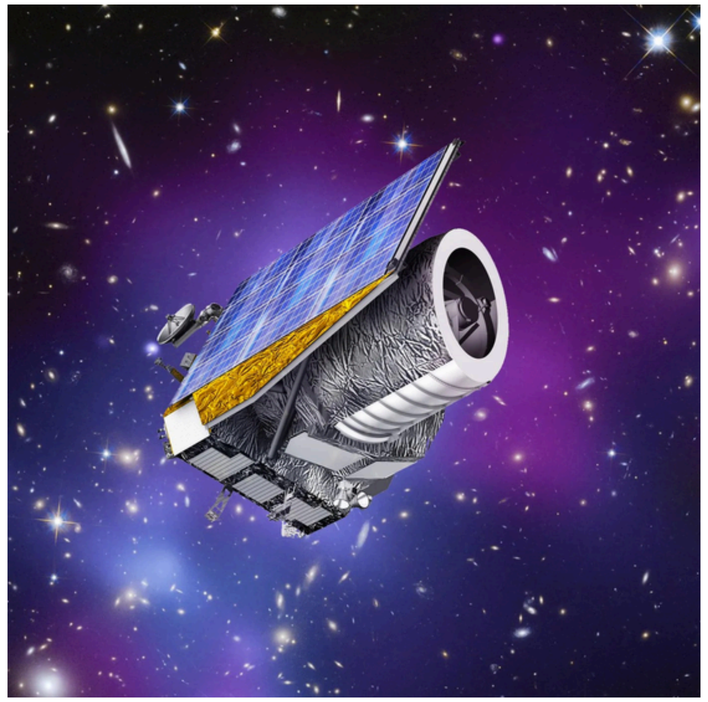
Outlook

https://infrastructurepipeline.org/files/images/optimised/project_hero/files/images/project/square-kilometre-array-au-closeup-midres1-660e2856945e3579990669.jpg

https://science.nasa.gov/wp-content/uploads/2024/05/jwst_artist_concept_0.png?w=1041

DESI, HSC, ELT, ALMA, HERA, SKA, JWST, Euclid



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https://science.nasa.gov/wp-content/uploads/2023/06/euclid20170509-full-jpeg.webp

1) First sources of radiation and heating & interactions with environment

2) Progression of cosmic reionization process & impact on observations

3) Thermal history of cosmic gas

4) Physics that influence small-scale properties of the cosmic web

Take-home points

Clumpy gas, patchy ionization and anisotropic photon propagation make reionization inherently complex

Explicit radiative transfer is essential to capture how ionizing photons propagate and are absorbed

Larger, higher-resolution simulations with improved radiative transfer are needed to interpret new observations

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