The topology of Reionization times

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with

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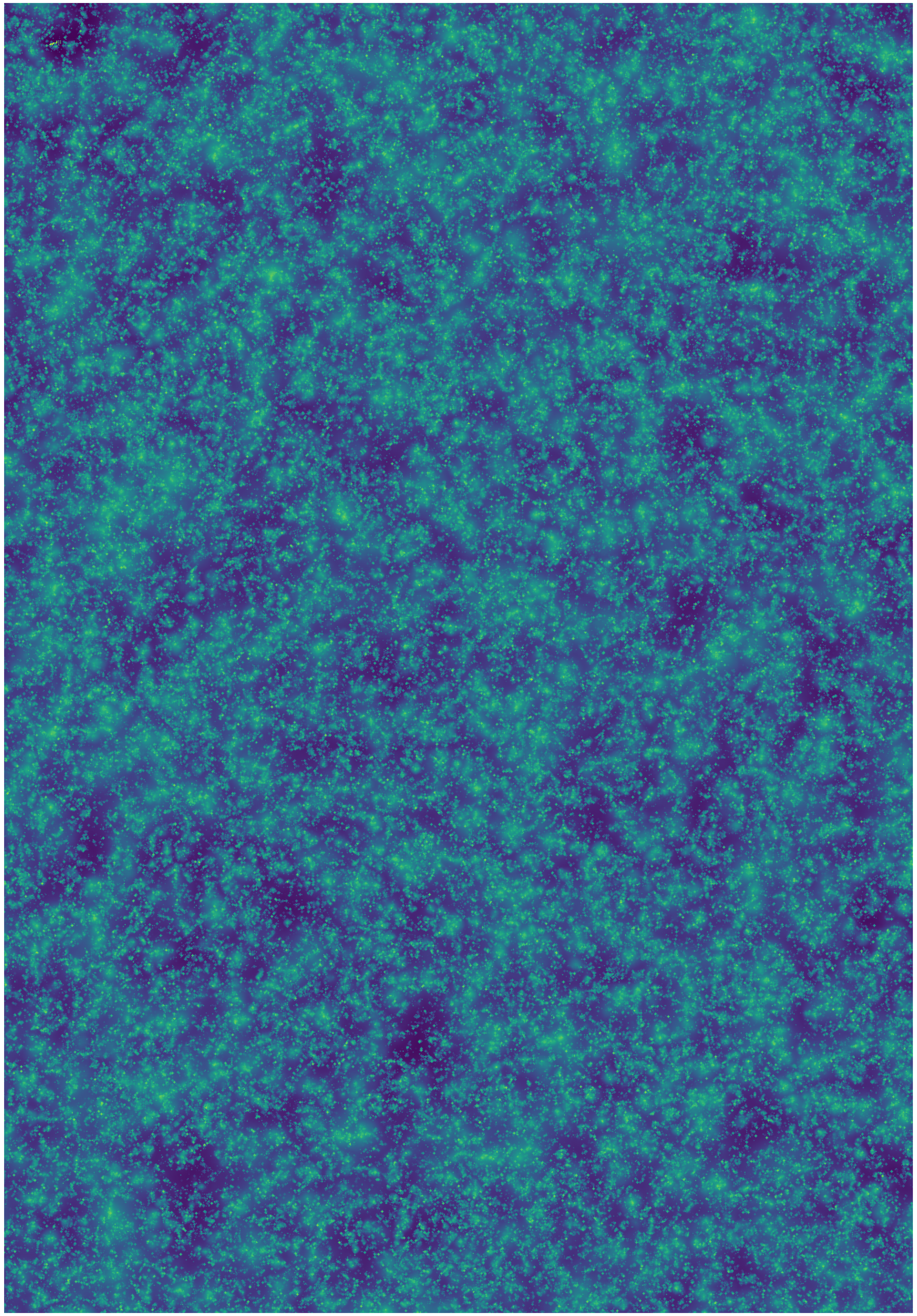
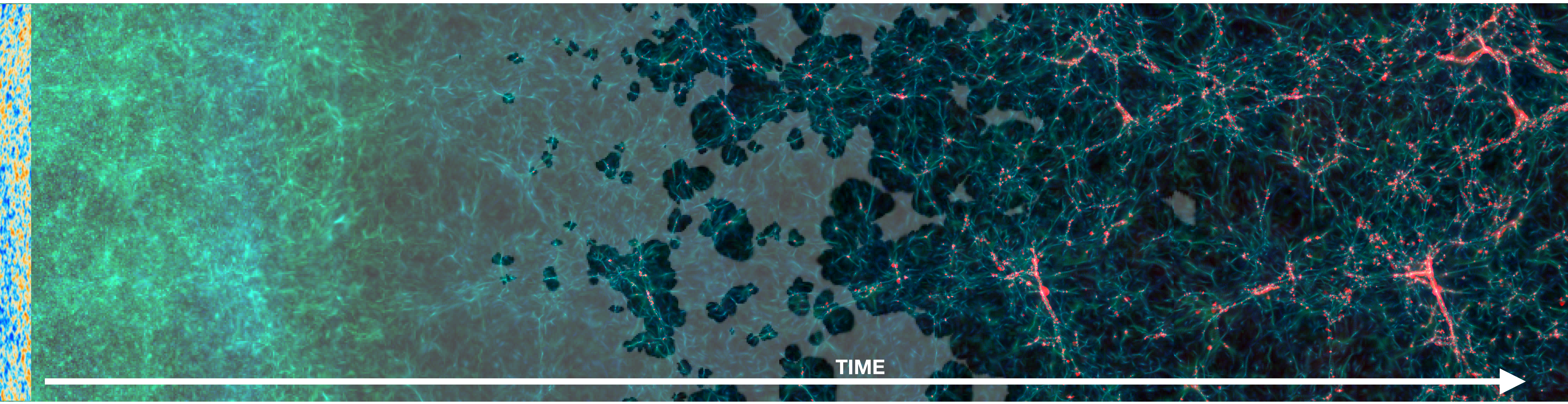


Cosmic Dawn & Reionization



CMB
z=1100
380 000 yrs

Cosmic Dawn
z ~ 30-15
t ~ 200 Myrs

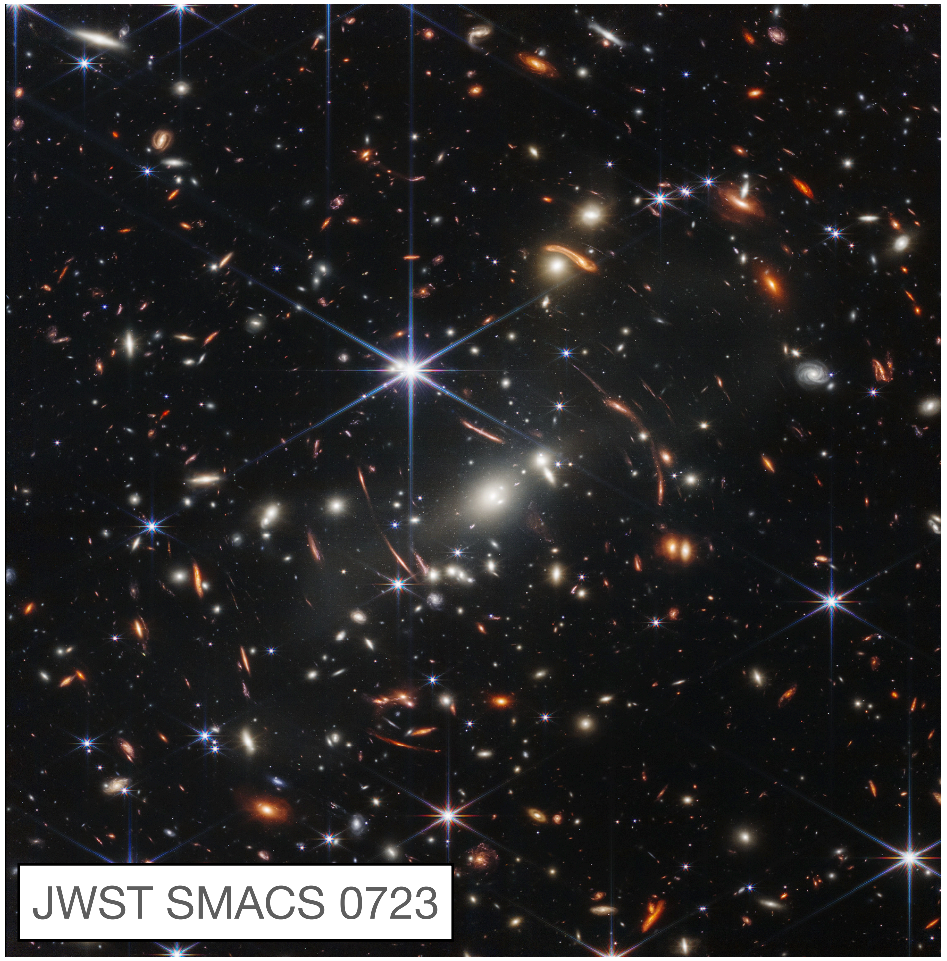
Reionization
z~15-5
t~ 800 Myrs

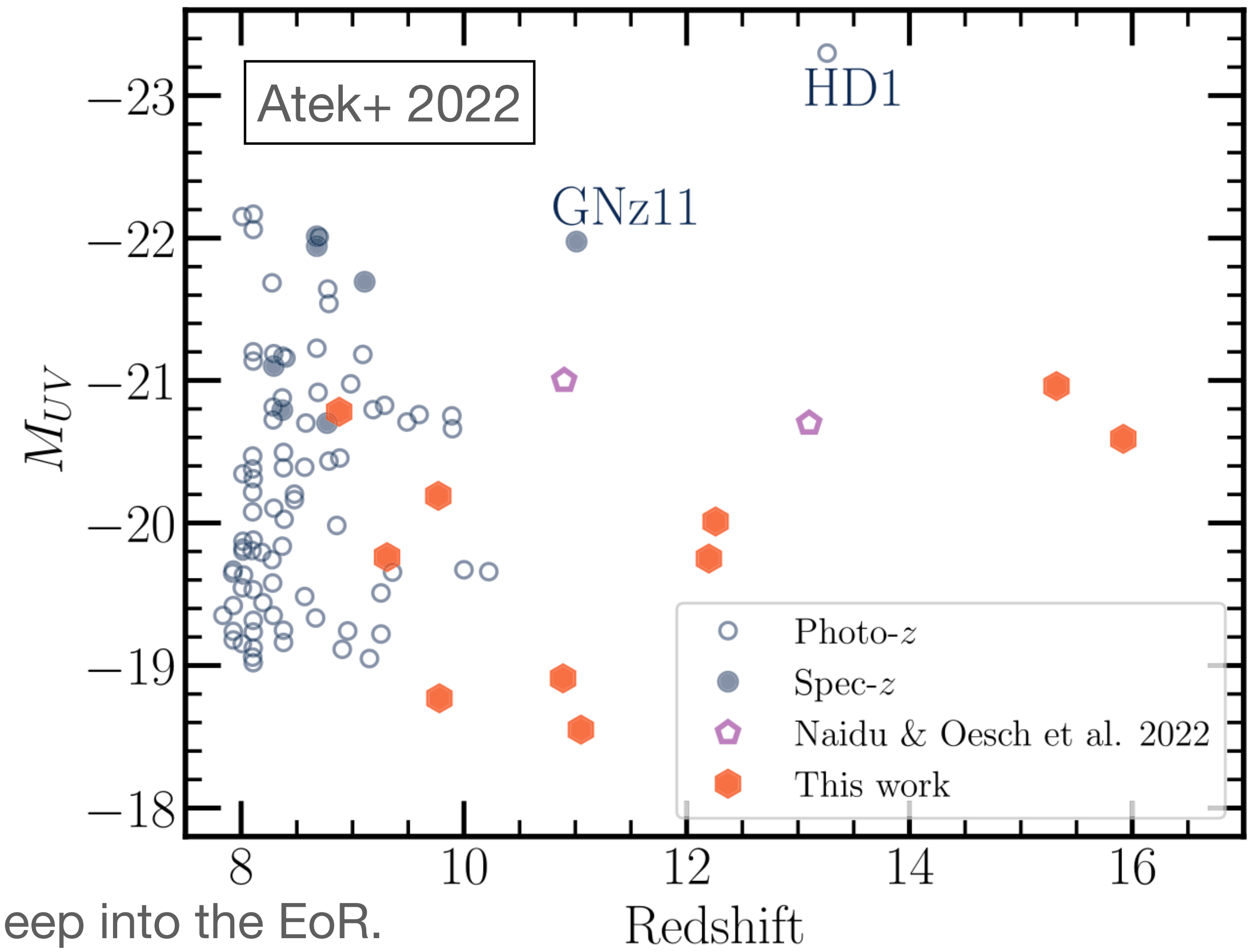
End of Reionization
z~5-6
t~1 Gyr

The Cosmic Dawn (CD) and the Epoch of Reionization (EoR) are driven by many facets of the buildup of large scale structures and sources (including the very first stars and AGNs). **About 1 Gyr after the Big-Bang**, hydrogen is fully reionized and we are left with a (fluctuating) UV background.

It is often characterized by the rise of a **network of ionised regions** (« bubbles »), created by the UV radiation of the first sources. This network is created the underlying distribution of sources. Conversely, the sources and the IGM can be influenced by the Reionization (heating, ionisation, stellar content and formation).

Looking indirectly and directly at the Reionization





With JWST, galaxies can be observed deep into the EoR.
It's the beginning of **the « flood** » (© Nick Gnedin).

Future probes of the EoR includes for exemple **intensity mapping** experiments (SphereX [2024], Concerto [CII, Ongoing, end of survey mid 2023]) ,or future X-Ray satellites (Athena ?). They also include **21cm experiments** such as HERA or SKA [2027, for the low frequency array]

It **complements classic probes** of the EoR, such as e.g. the evolving Lyman-Alpha Forest/GP throughs at z>5, or the constraints on τ from the CMB.

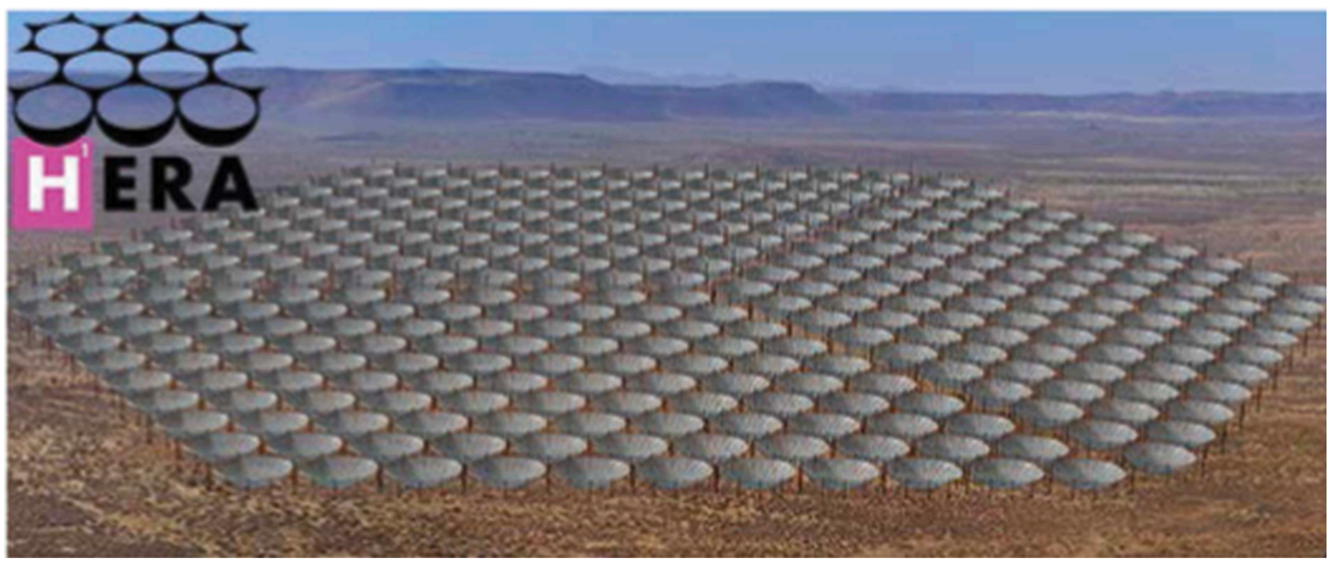
21 cm signal from Cosmic HI

Cosmic Hydrogen in the IGM will produce a radio signal at 21 cm/1420 MHz + redshift, to be seen e.g. with SKA-Low between 50 MHz and 250 MHz.

This signal depends on the history of

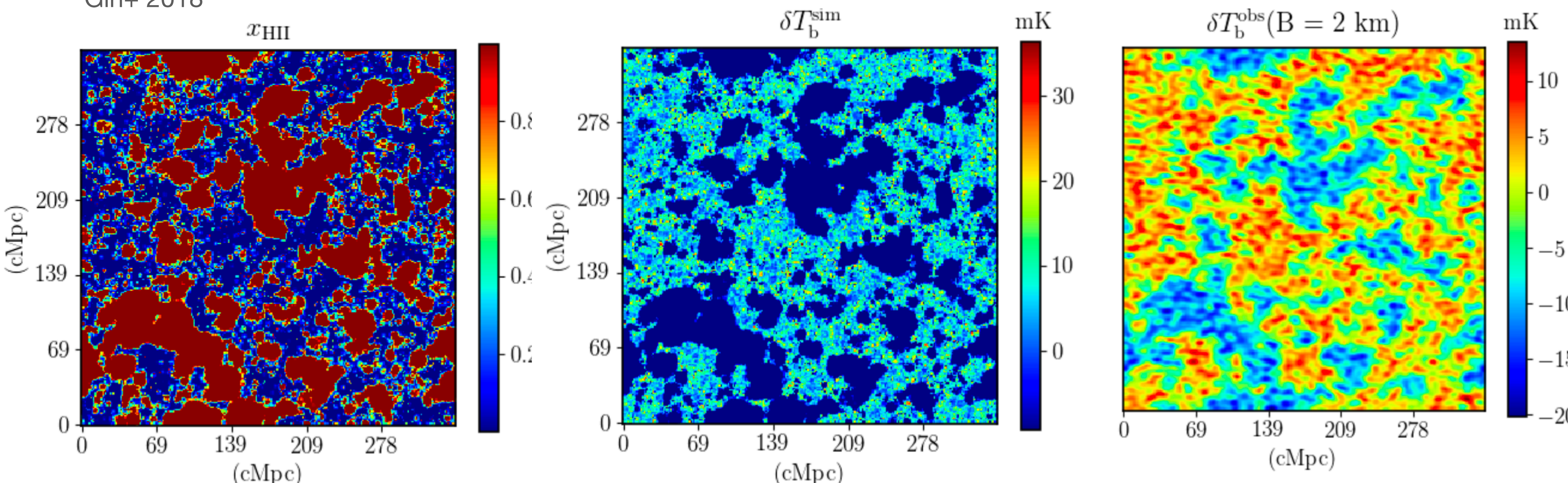
- the ionization state,
- the local baryon density, velocity and temperature
- cosmology.
- the radiation field (LyA, Radio background, X-rays,…)

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{dv_r/dr+H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$



21cm maps

Giri+ 2018



[SKA 1000h , z=7, xHI ~0.5, 180 MHz, $\Delta\theta = 2.87$ arcmin, $\Delta x \sim 7$ cMpc]

Note : it's a difficult task. Because of :

- Radio-frequency interference
- Ionosphere
- Galactic/Extragalactic Foregrounds : $\sim 10^5 \times$ signal.

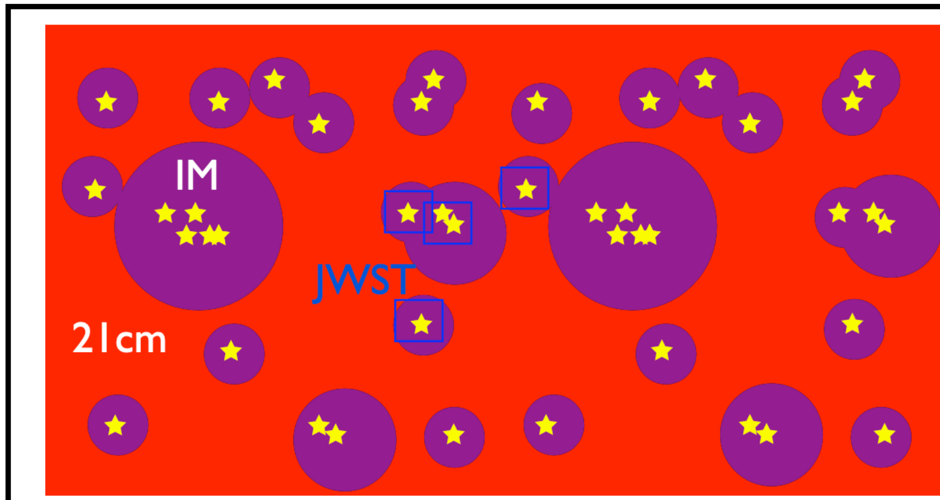


Figure 12. Cartoon of the role intensity mapping would play in understanding galaxy formation. Deep galaxy surveys with HST and JWST image the properties of individual galaxies in small fields (blue boxes). 21 cm tomography (red filled region) provides a "negative space" view of the Universe by determining the properties of the neutral gas surrounding groups of galaxies. Intensity mapping (purple filled regions) fills in the gaps providing information about the collective properties of groups of galaxies. Together the three would give a complete view of the early generation of galaxies in the infant universe.

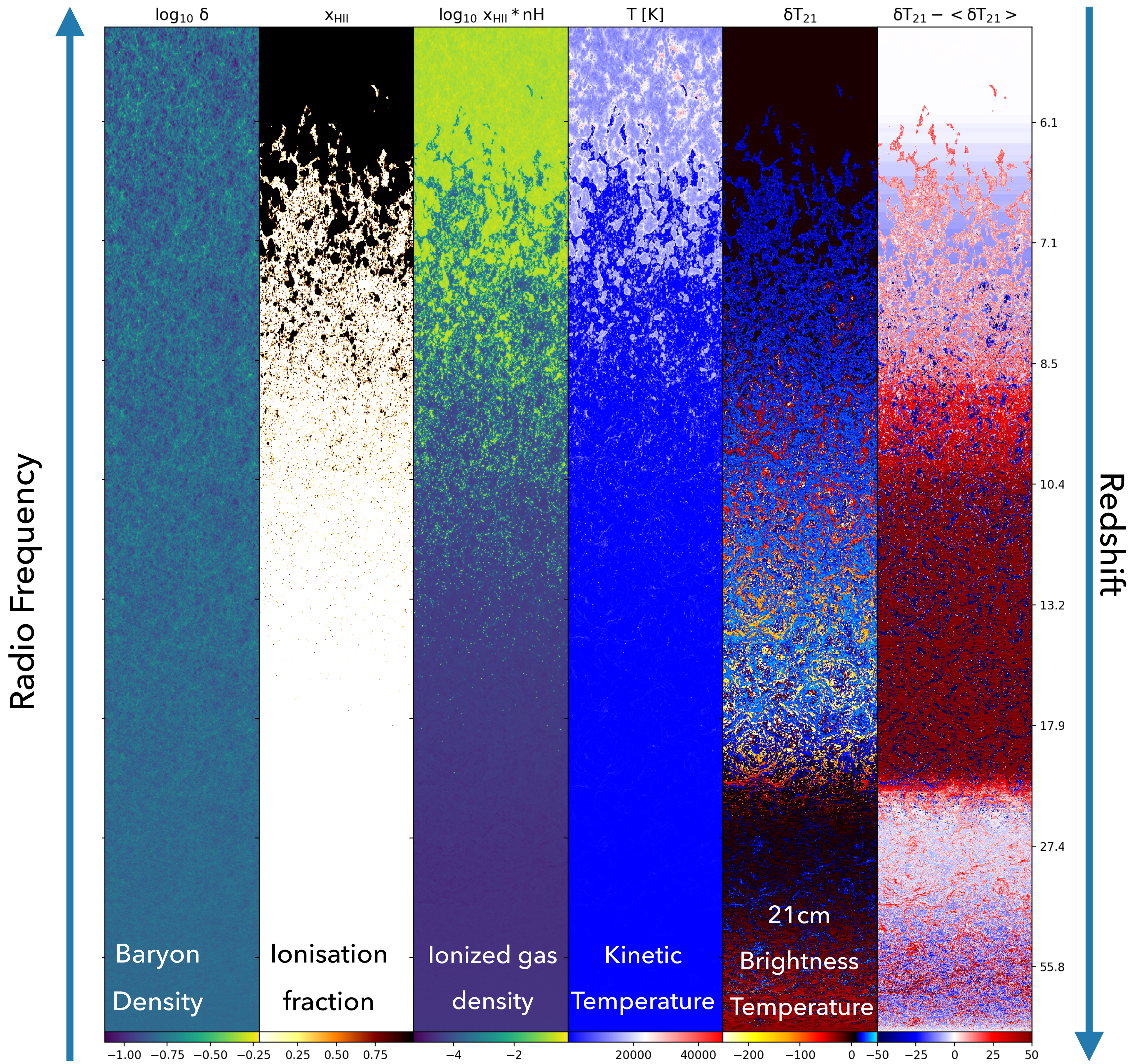
Pritchard & Loeb 2012

Light-Cones

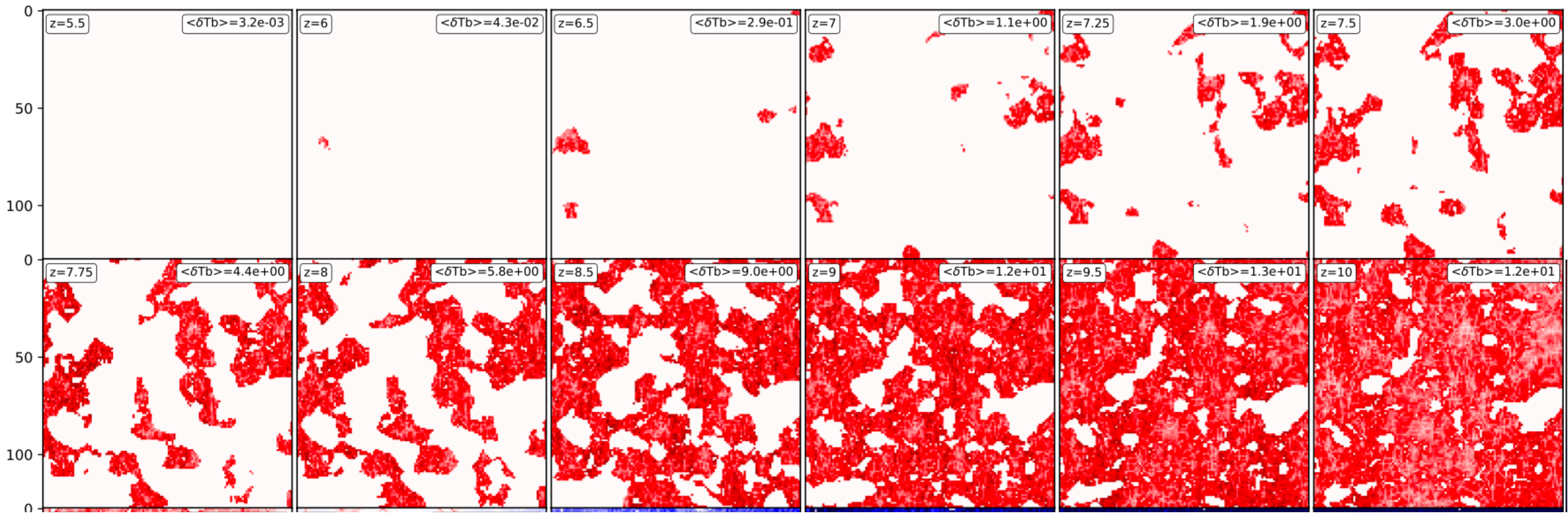
Frequency « scans » will provide the time evolution of the 21cm signal production, giving access to the **chronology of the percolation process** and of the underlying physics and objects.

x_{ion} maps or 21cm maps can be investigated **using concepts inspired from topology (e.g. Betti numbers)** [e.g. recently Elbers & Van de Weygaerts 2022, Giri & Mellema 2021].

They are used to classify the evolving features (bubbles, tunnel, islands, etc.) of the reionization… **but they don't really study the evolution itself.**



How to track this evolution ?



21cmFast semi-analytical model

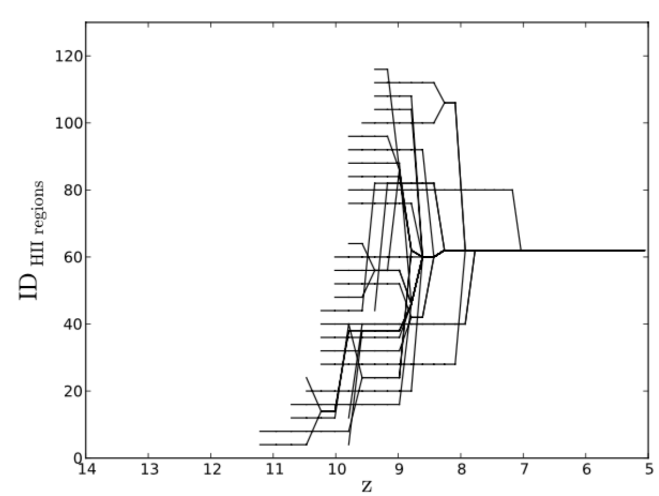


Fig. 1. Illustration of the merger tree of HII regions. Each black line represents an ID evolution with the redshift for a distinct HII region. For clarity, we represent here only the ID evolution for 30 regions.

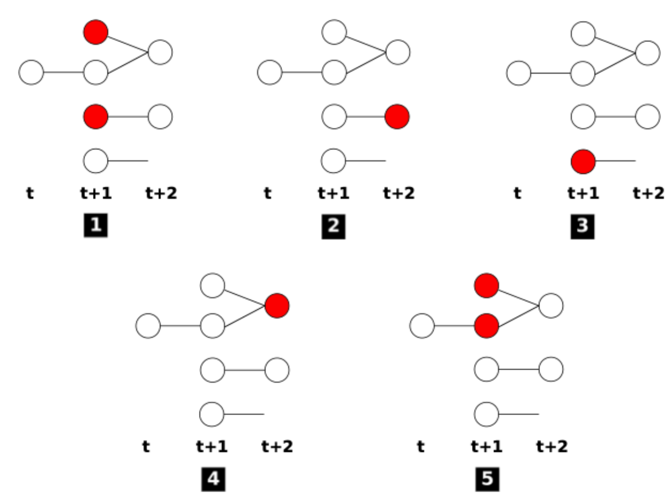
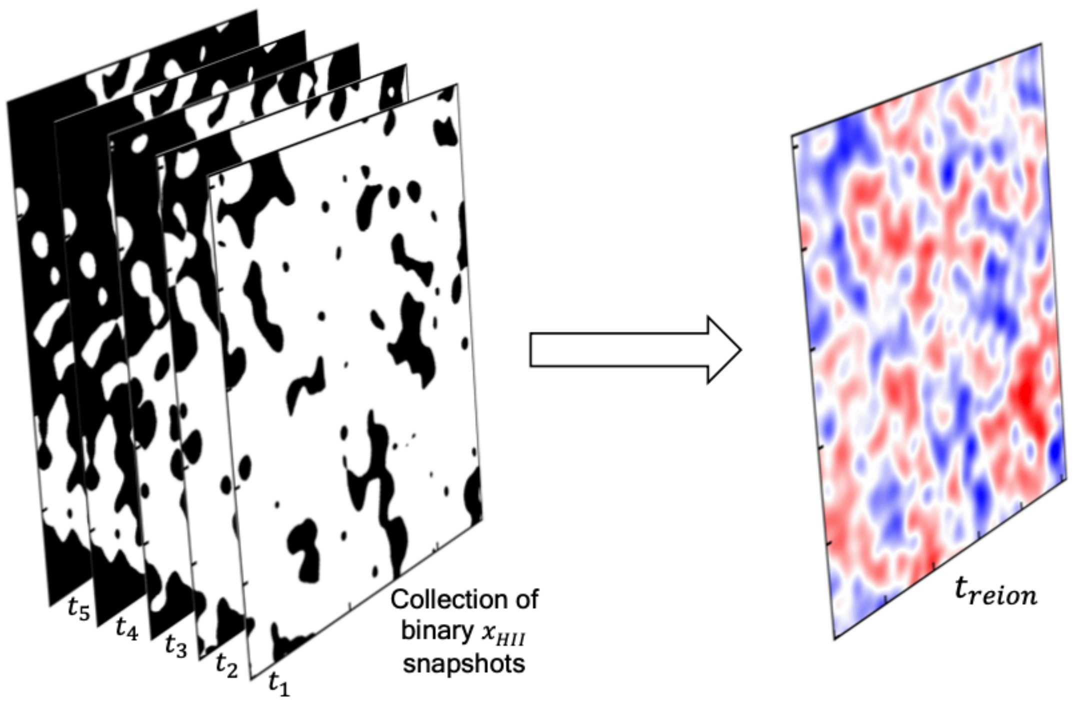


Fig. 2. Illustration of the properties that we can follow with the merger tree. In each diagram, red items symbolize the kinds of properties that we follow. 1: The number of new HII regions between two snapshots; 2: the number of growing ionized regions; 3: the number of HII regions that recombine; 4: the number of HII regions resulting from mergers and, 5: the number of parents involved for an HII region resulting from mergers.

How do you track an evolving geometry, a percolation process, in a « satisfying » way ?

For example, in Chardin+12, we developped a strategy that relies on merger trees and FOF identification of ionized bubbles.
Time consuming and not very intuitive.

Reionization times map

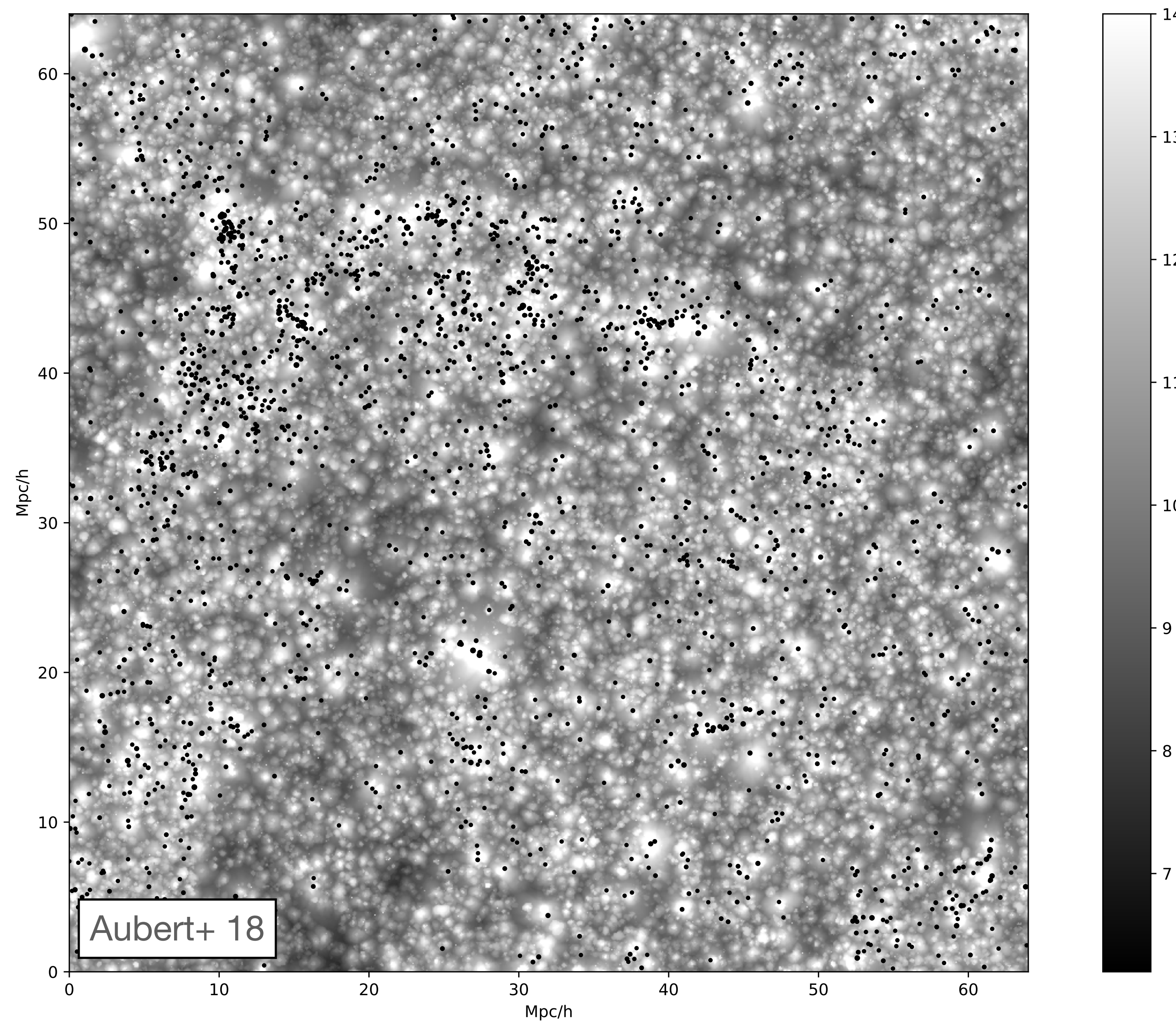


Each pixel is assigned the time at which it reionizes (defined as the first time it crosses the 50% ionisation threshold).

Instead of having a collection of fields at different times,
time is the field itself $t_{\text{reion}}(\vec{r})$

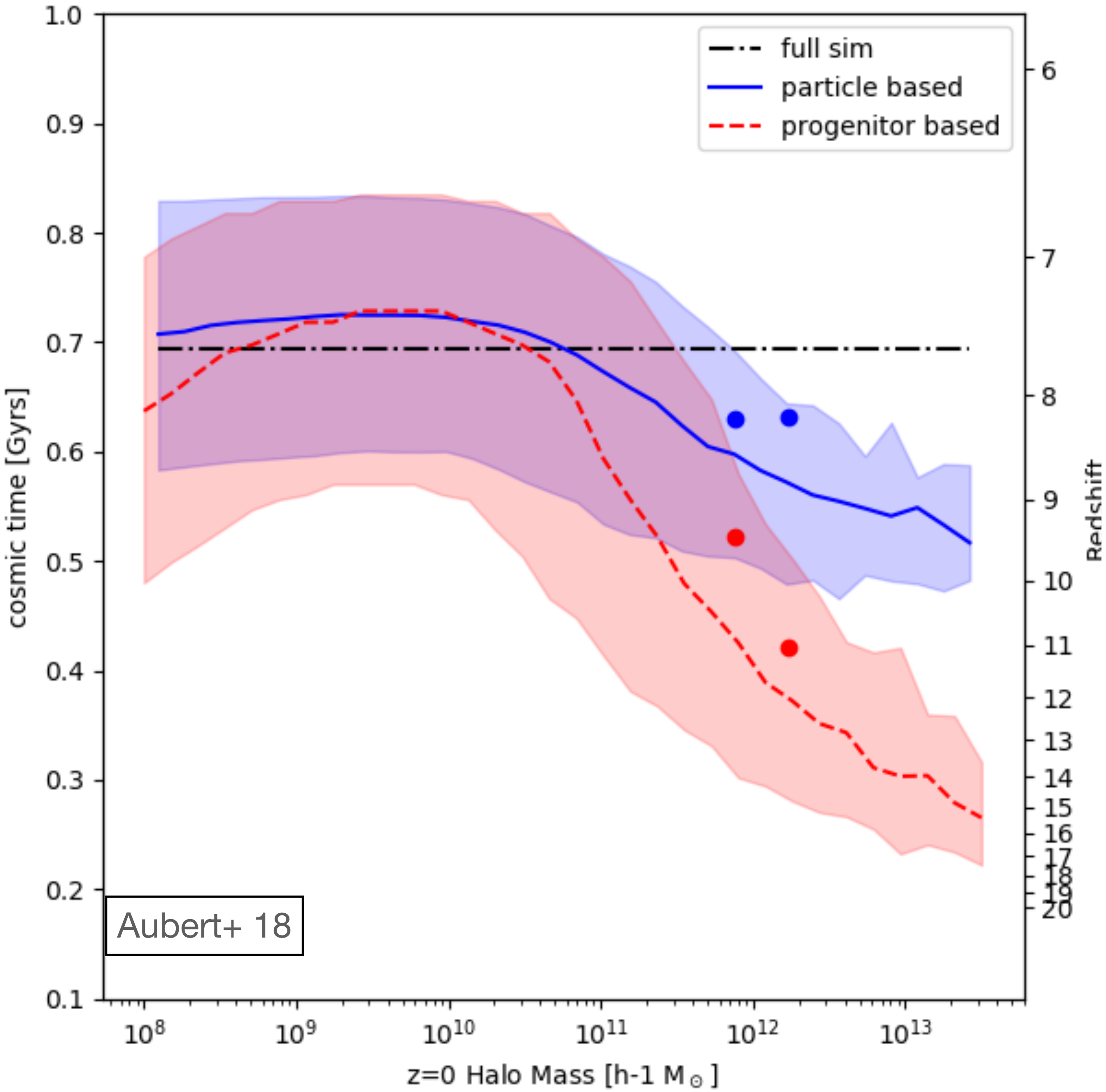
Reionization times (or redshift) maps « compress » the information on the evolution.

Used in e.g. Trac et al. 2008; Battaglia et al. 2013; Aubert et al. 2018; Zhu et al. 2019; Sorce et al. 2022 …

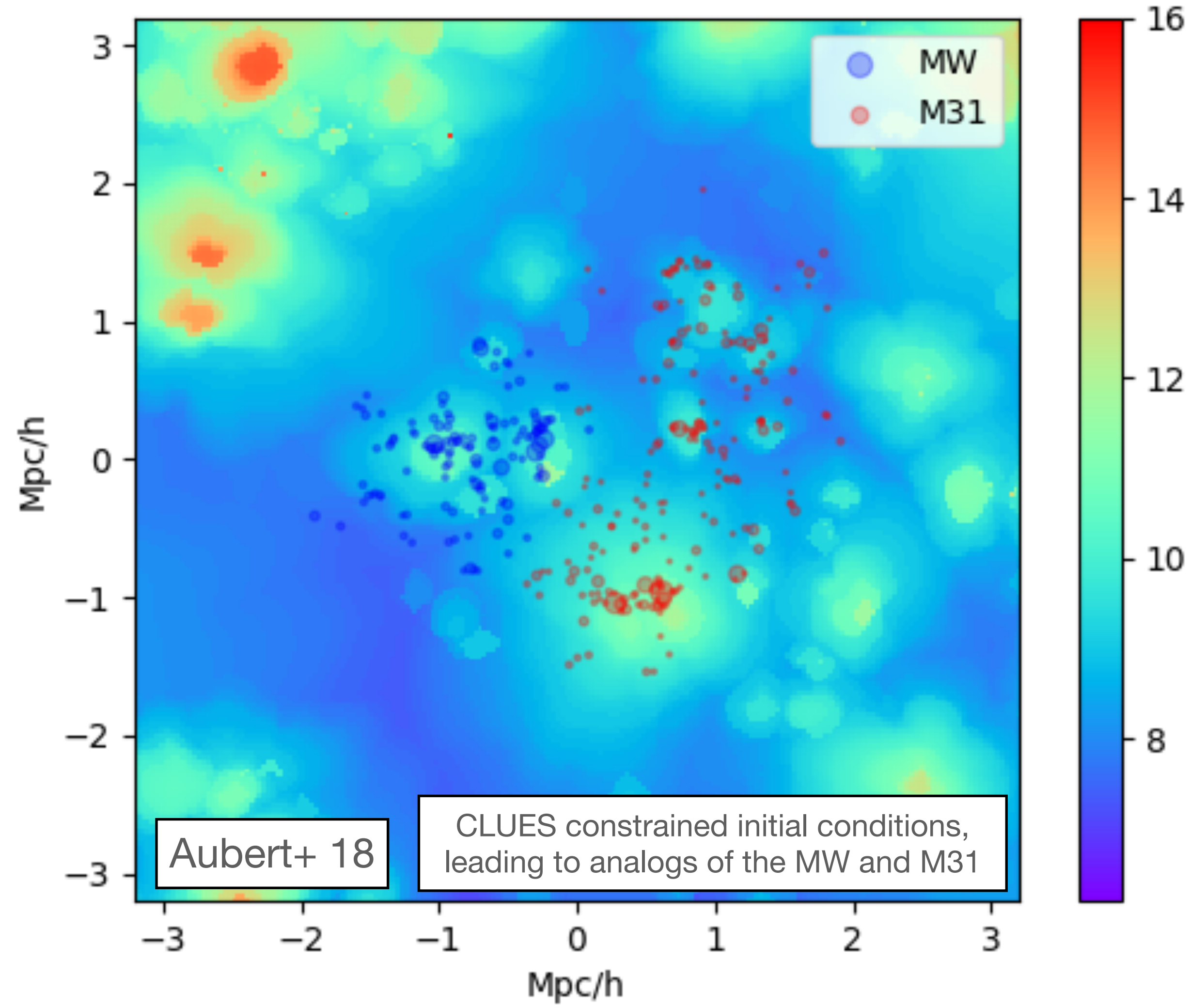


Reionization redshifts maps (CoDaI- AMR EMMA simulation) superimposed with the z=6 halo populations of a Gadet simulation that shares the same initial conditions.

Local reionization times



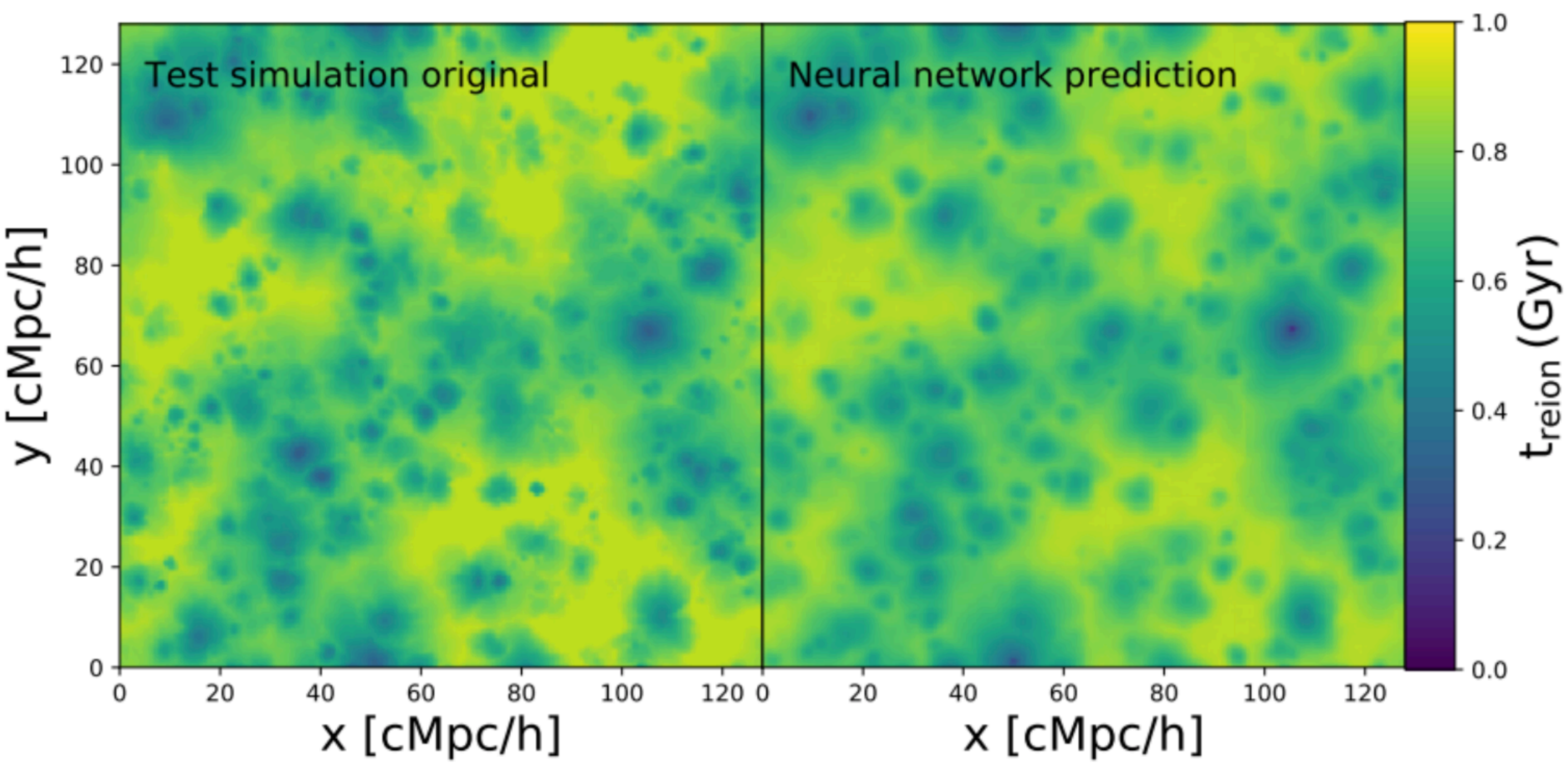
By tracking haloes or particles back in time in the reionization time map, we can reconstruct e.g. the reionization times of z=0 haloes.



Or measure the ‘reach’ of a reionization source (e.g. in the Local Group), using the patches of the reionization times.

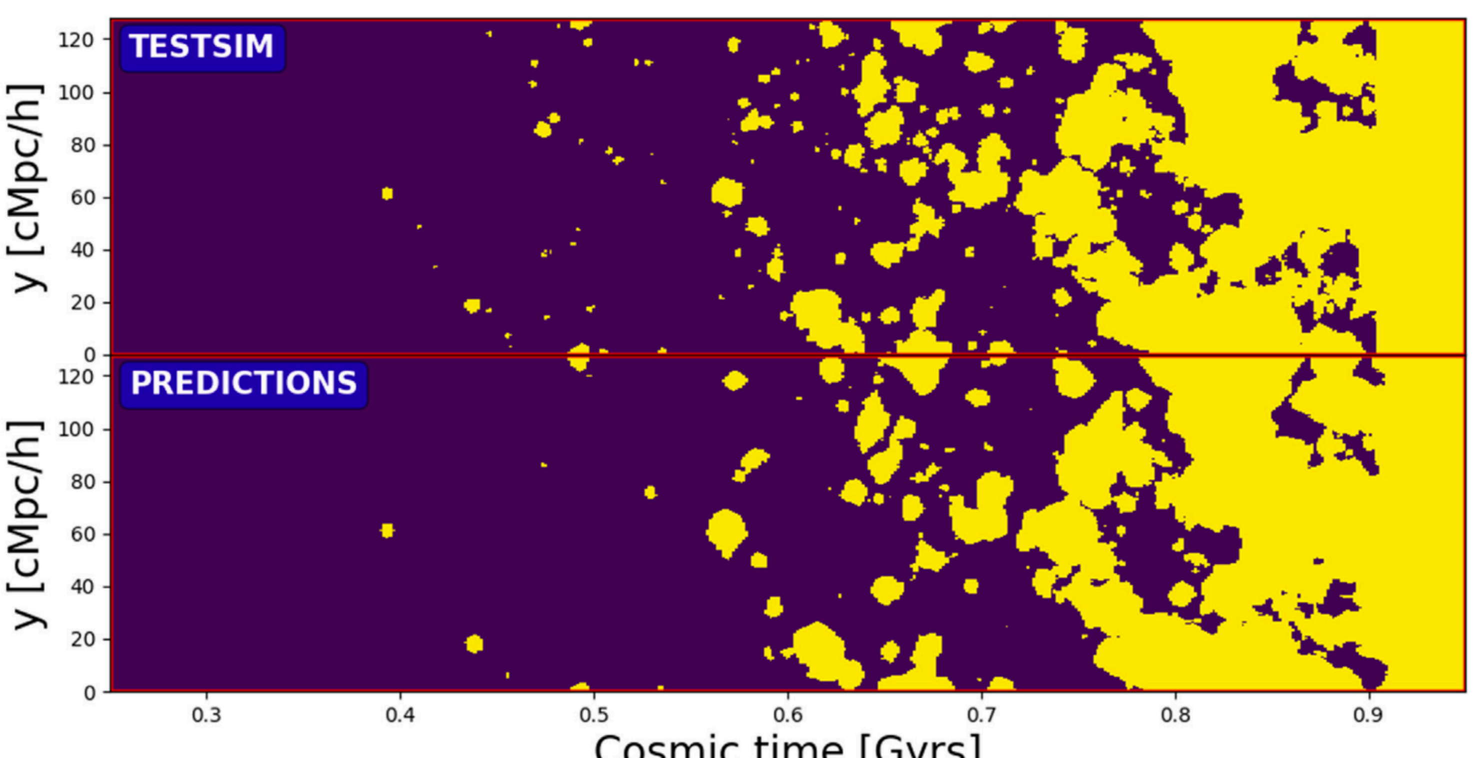
To some extent, the star formation history of low mass galaxies or their distribution can hint of their local reionization histories (see e.g. Ocvirk+ 2011, 2020).

Reionization times maps reconstruction from density and source distributions.



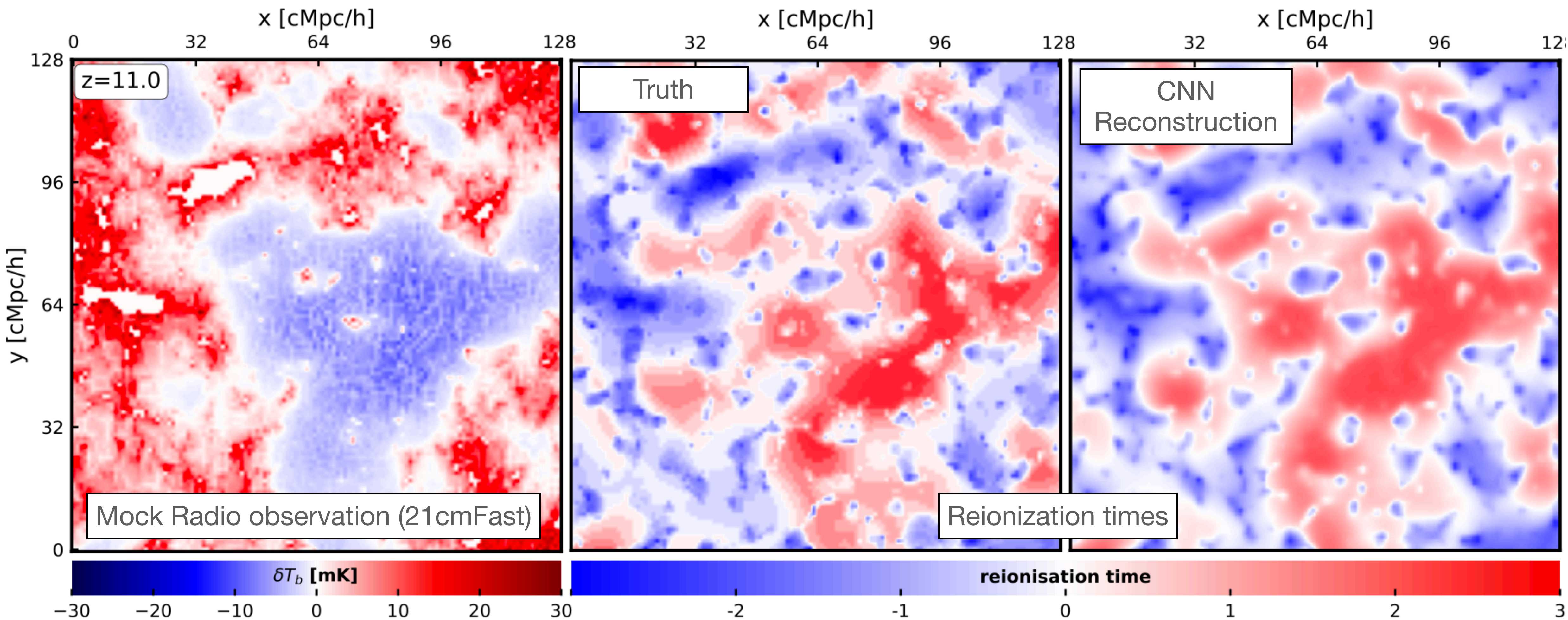
Using U-Net Convolutional Neural Networks, we found that $t_{\rm reion}(\vec{r})$ can be reconstructed from the spatial distribution of the z=6 gas density and sources, with some loss on small scales.

From $t_{\rm reion}$ *isocontours,* light cones of ionized regions can be reconstructed.



Chardin+ 2019

CNN-Reconstruction of reionization times from 21cm (WIP)



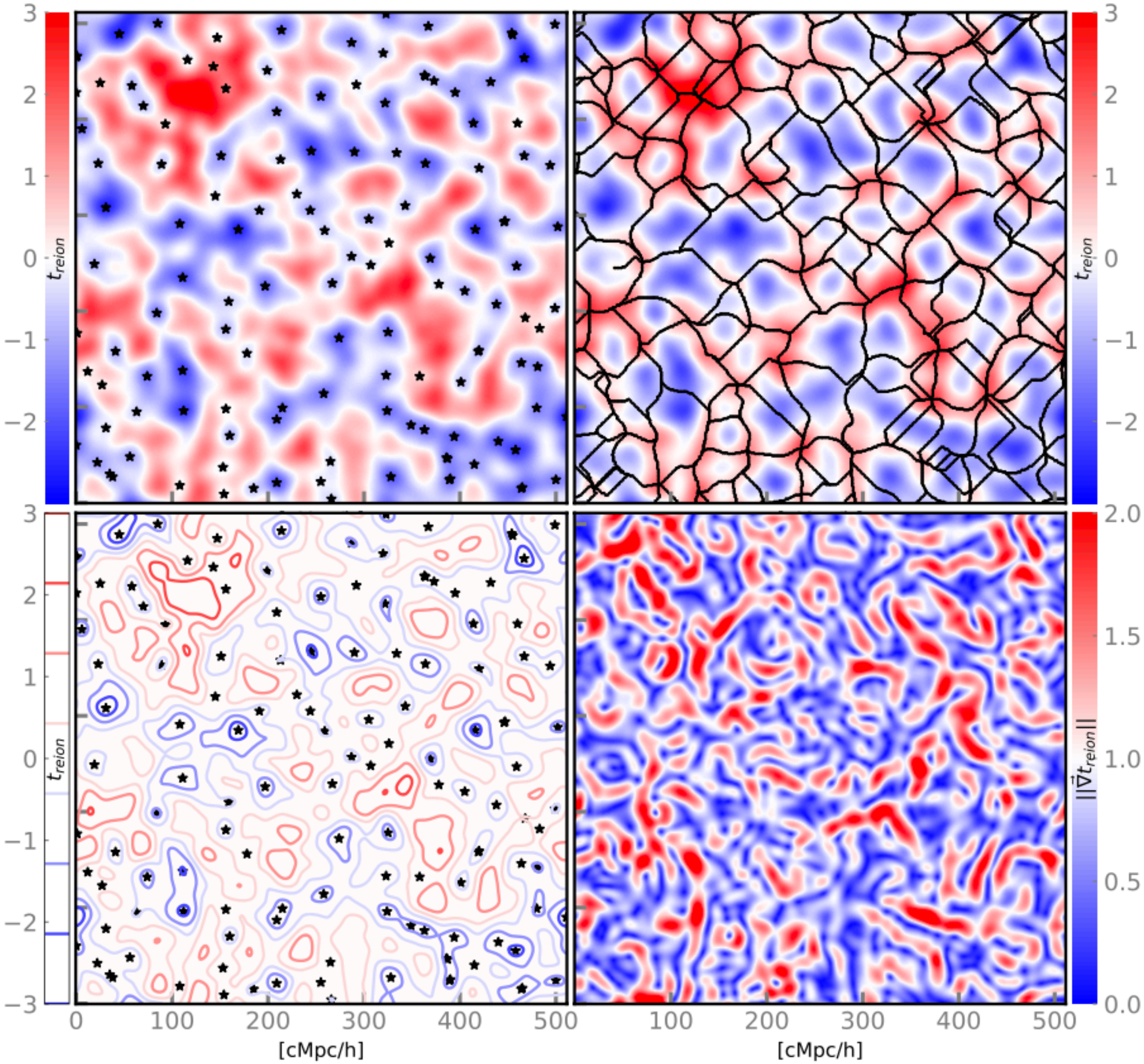
Hiegel+., in prep., Thélie+, submitted

Likewise, it seems that reionization times can be reconstructed directly from (perfect) 21cm observations, using the same kind of CNN, again with some loss at small scales. A lot of things remain to be tested, but it implies that the information is here.

Two interesting things :

- it means that an observation of the state of matter at a single redshift can be used to **reconstruct its evolution in the past and extrapolate its future evolution.**
- it means that we have access to a **time evolution in the transverse plane of the sky** and it can complement or be cross-checked with the usual investigations along the line of sight.

Topology of reionization times



$t_{\rm reion}$ contains a lot of informations about the evolution of ionized regions.

- the $t_{\rm reion}$ *minima* are the location of the first sources/seeds of radiation
- the $t_{\rm reion}$ *patches* show the extent of the radiative ‘reach’ of theses sources
- the $t_{\rm reion}$ *isocontours* encode the evolution of the bubbles with time
- the $t_{\rm reion}$ *skeleton* trace the percolation lines of the ionization fronts
- the $t_{\rm reion}$ *gradients* ($\sim \Delta t/\Delta x$) approximate the fronts propagation speed
- the $t_{\rm reion}$ *filling factor* is Q_{HII}, the ionized gas filling factor

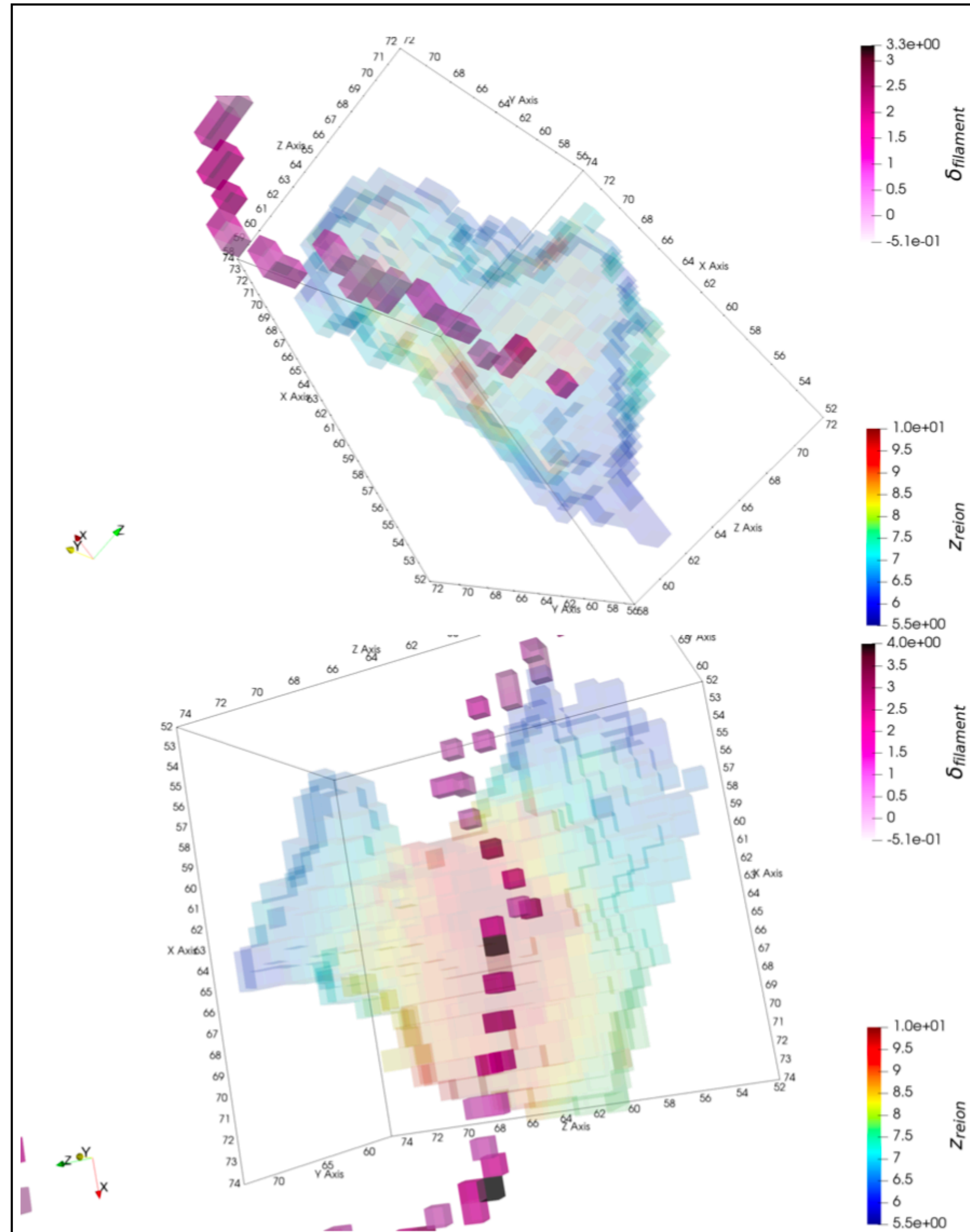
All the concepts in *italics* are ‘well’ defined and provide reproducible and quantitative ways to obtain an overview of the ionization evolution.

=> Model comparison

Reionization Patches and Density Filaments

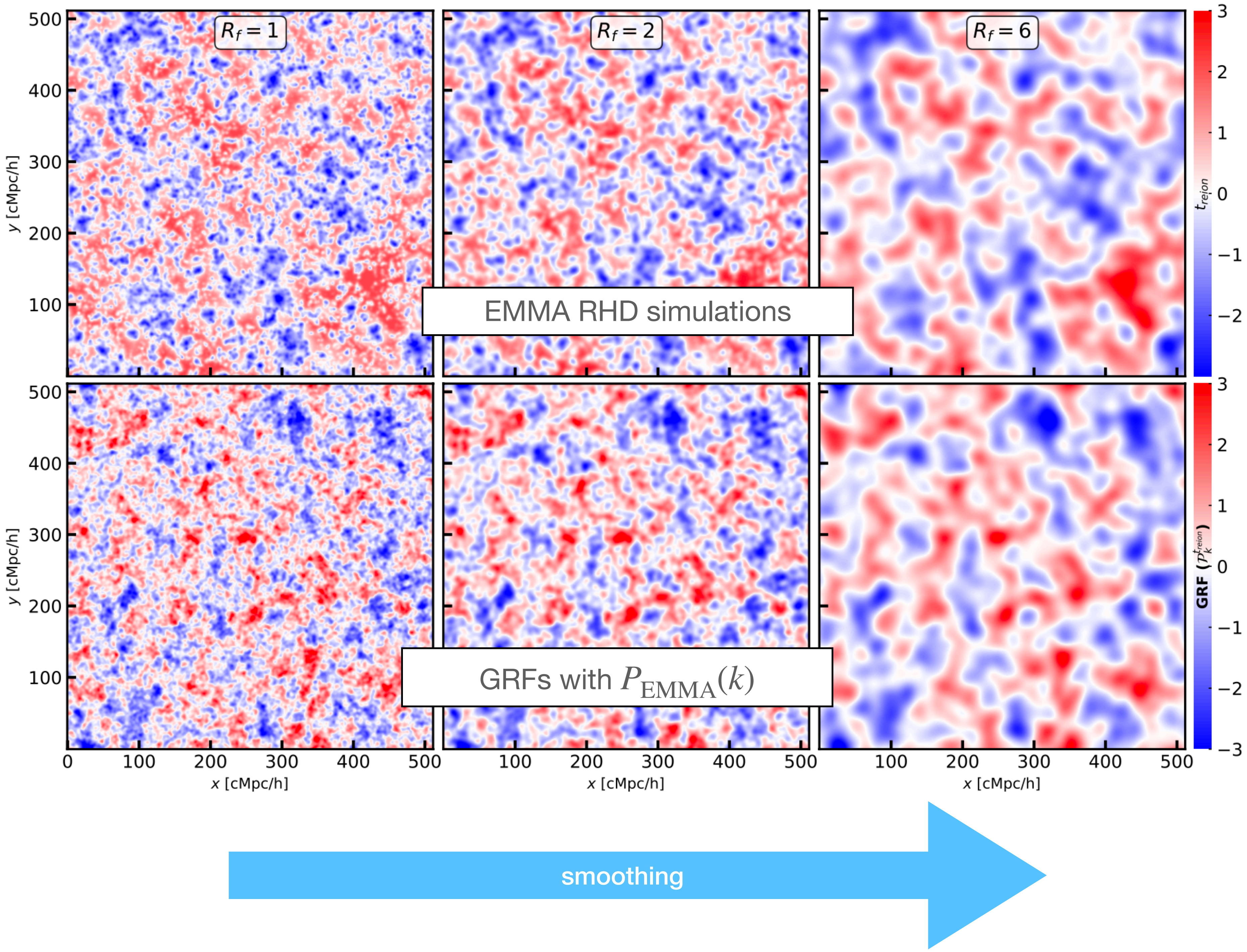
For example, we measured the alignement the gas filaments and reionization patches in RHD (EMMA) and semi-analytical models (21cmFast).

At our (1cMpc) resolution, most configurations (50%) are aligned, whereas « butterflies » are less frequent (only a few percent, corresponding to powerful and isolated sources).



Thélie+ 2022

Gaussian Random field predictions

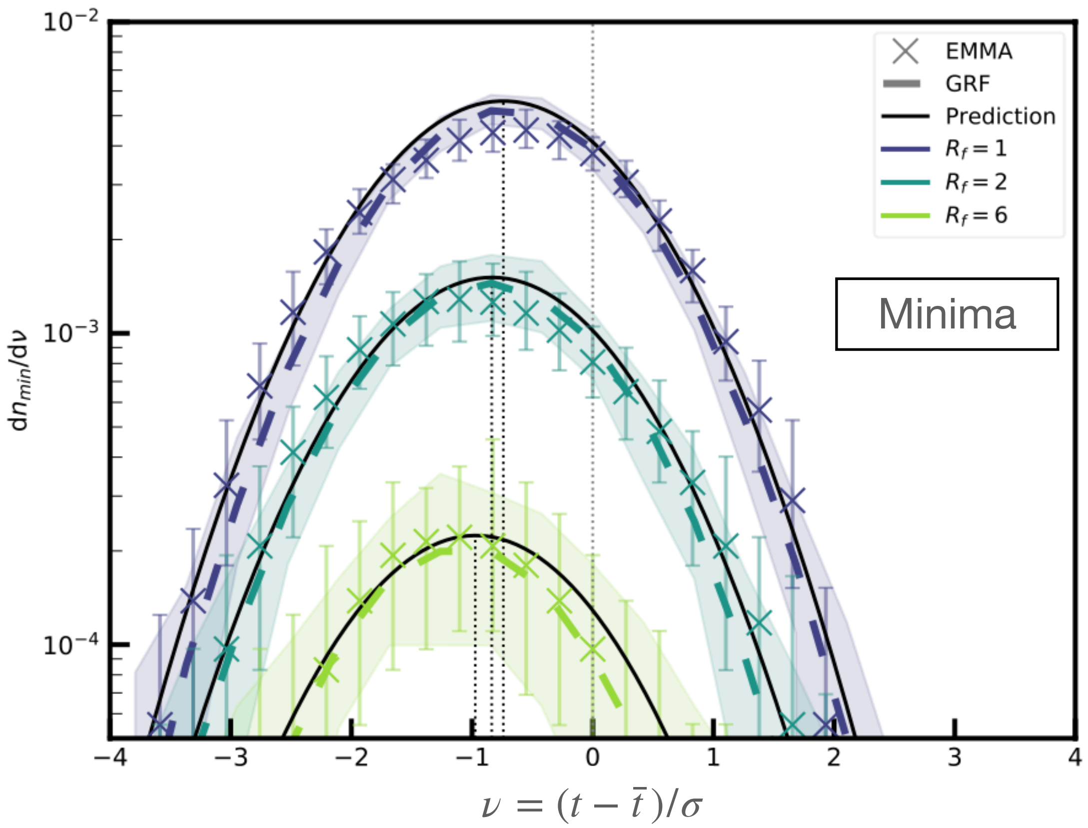


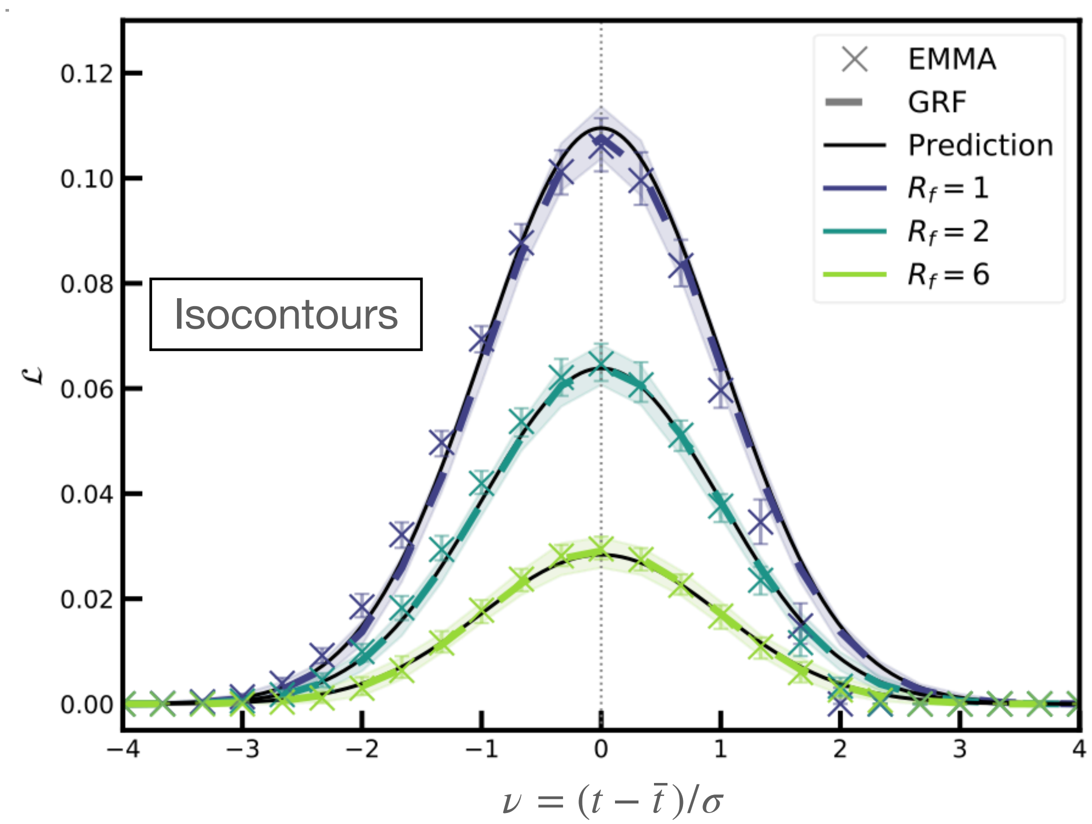
All the previous concepts can actually be predicted for gaussian random fields.

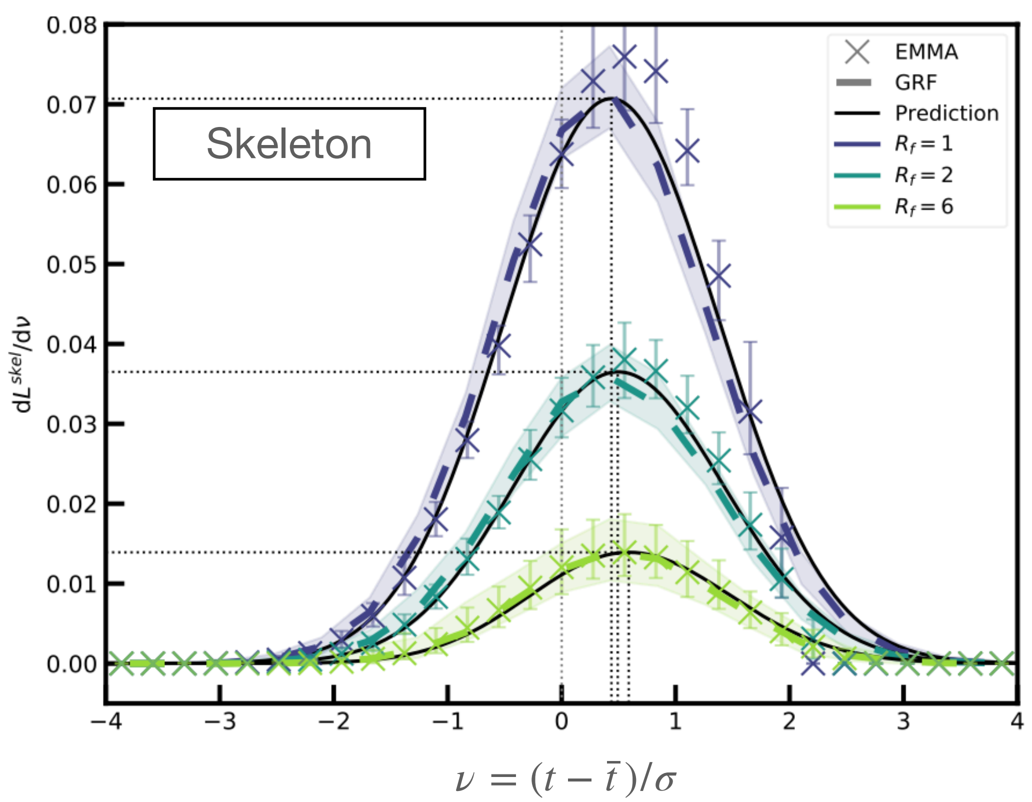
$x_{\rm ion}$ and 21cm maps are known to be highly non-gaussians.

But $t_{\rm reion}$ might be close to a GRF, especially when smoothed to SKA-like resolutions

Gaussian Random field predictions for t_{reion}



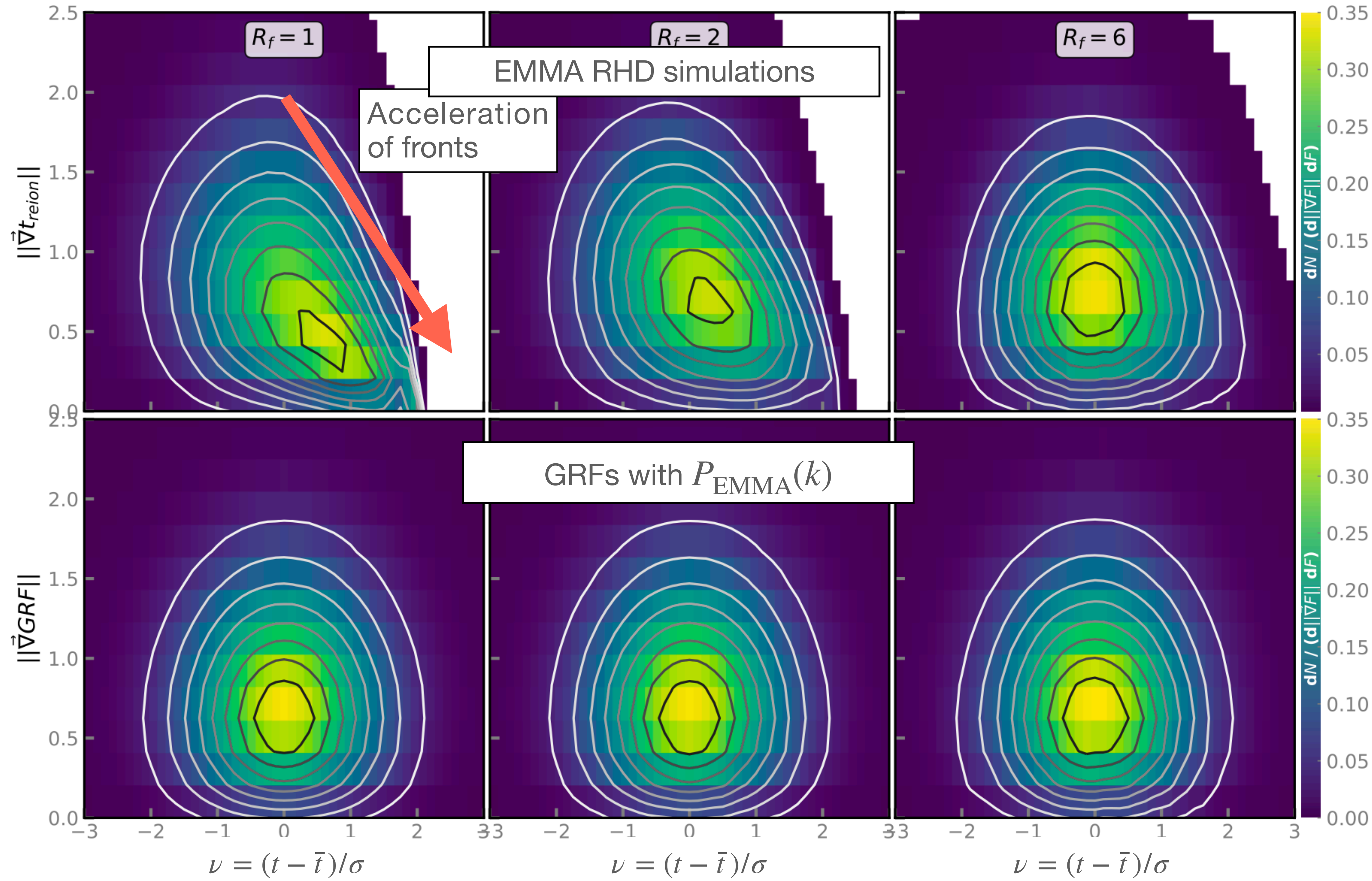




Knowing the power spectrum of t_{reion} we can make comparisons against GRFs realisations and GRFs theoretical predictions (following Pogosyan et al. 2009a,b; Pichon et al. 2010; Gay et al. 2012; Cadiou et al. 2020).

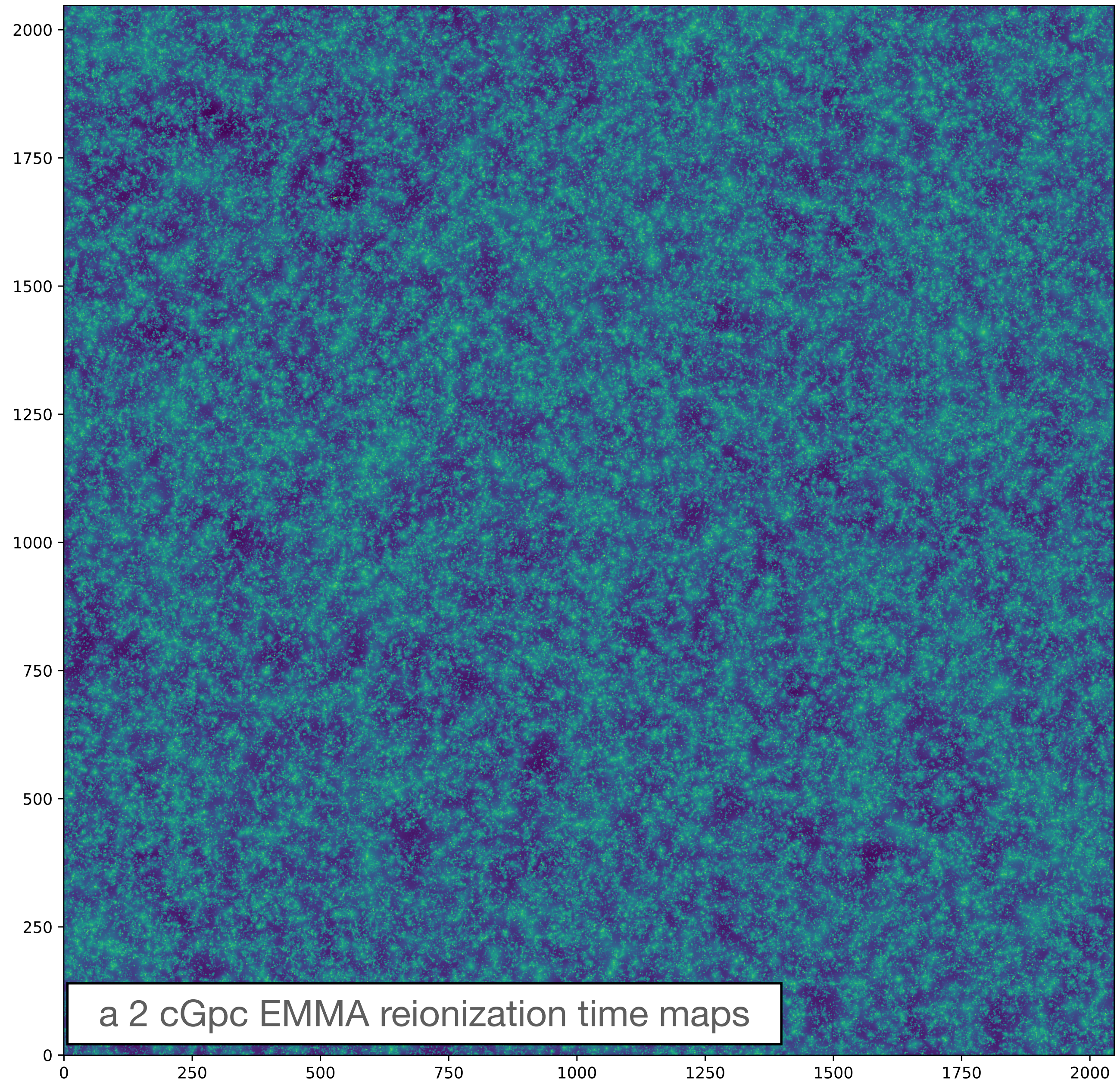
The t_{reion} value distribution of minima, isocontours length and skeleton length, show that we are not far-off a GRF.

Non-Gaussianities



A primordial source of non-gaussianities seem to be the **acceleration of fronts** close to the percolation at the end of reionization. It can be mitigated when the field is smoothed. The non-gaussian departure seems less severe at early times.

To Conclude



The reionization of the inter-galactic medium provides a mean to probe the cosmic web at large z, in almost a dual way.

Data is coming, especially in the radio range with instruments such as SKA or HERA

The $t_{\mathrm{reion}}(\vec{r})$ field could in principle be extracted from such observations and is easily obtained from models.

It contains a great deal of information about the timing of ionized regions expansion, in the transvere plane of the sky.

This information is contained in a 'time web' and can be extracted from well-defined geometrical concepts. In addition, it doesn't seem so far off being a GRF, at least on the largest (10+ cMpc) scales.

Now we would like to explore :

- the non-gaussianities,
- the connection between the cosmic web and the time web
- the possibility of model generation in the GRF approximation,
- how sensitive is the $t_{\mathrm{reion}}(\vec{r})$ topology to the underlying model