Exploring the Epoch of Reionisation through its evolving topology

Emilie Thélie

Collaborating with D. Aubert, J. Hiegel, N. Gillet & P. Ocvirk

Thélie et al. (2022) ■ *Thélie et al. (accepted for publication in A&A, arxiv:2209.11608)* ■ *Hiegel, Thélie et al. (to be submitted to A&A)*

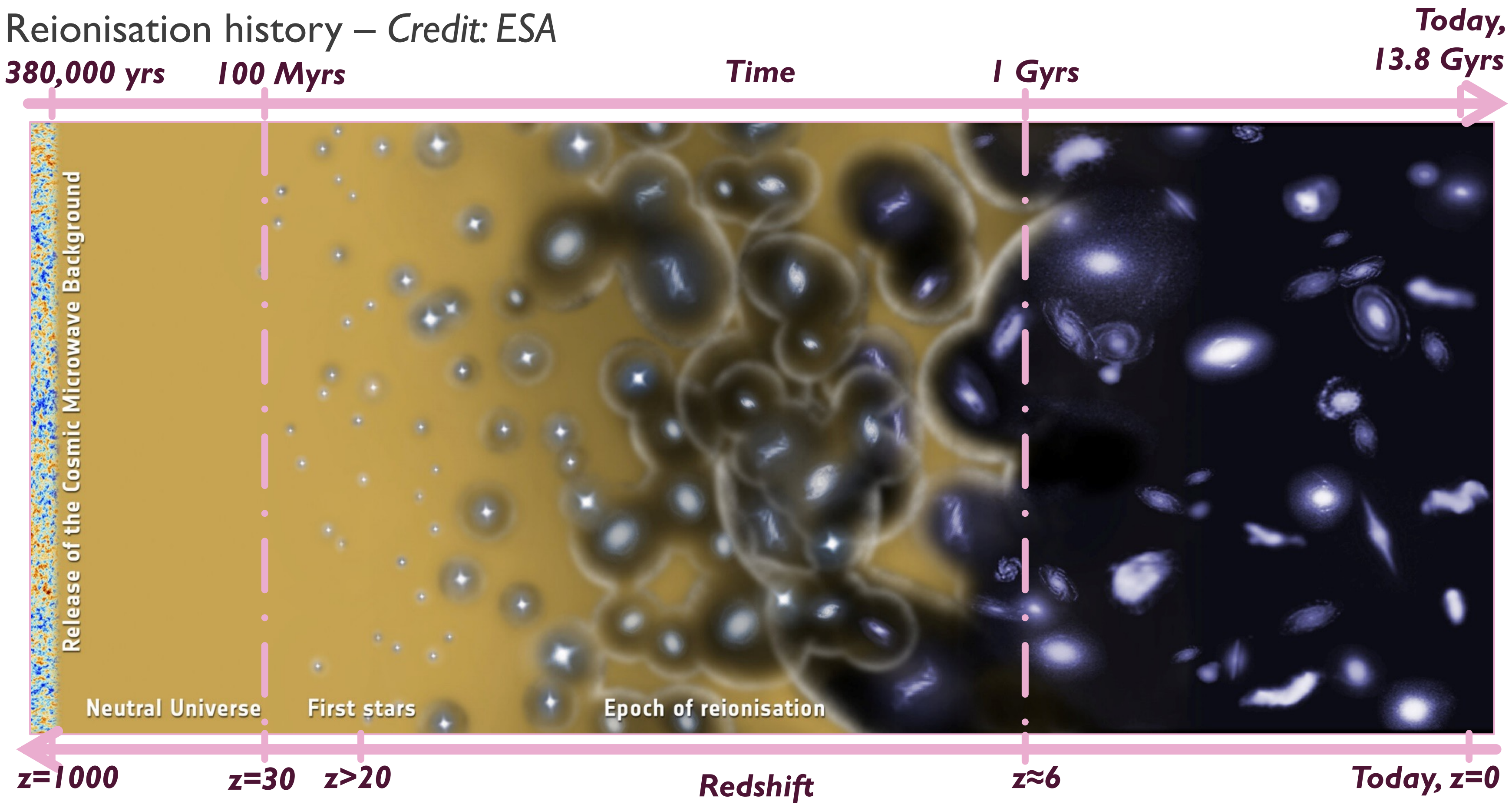
THE EPOCH OF REIONISATION & ITS OBSERVATIONS

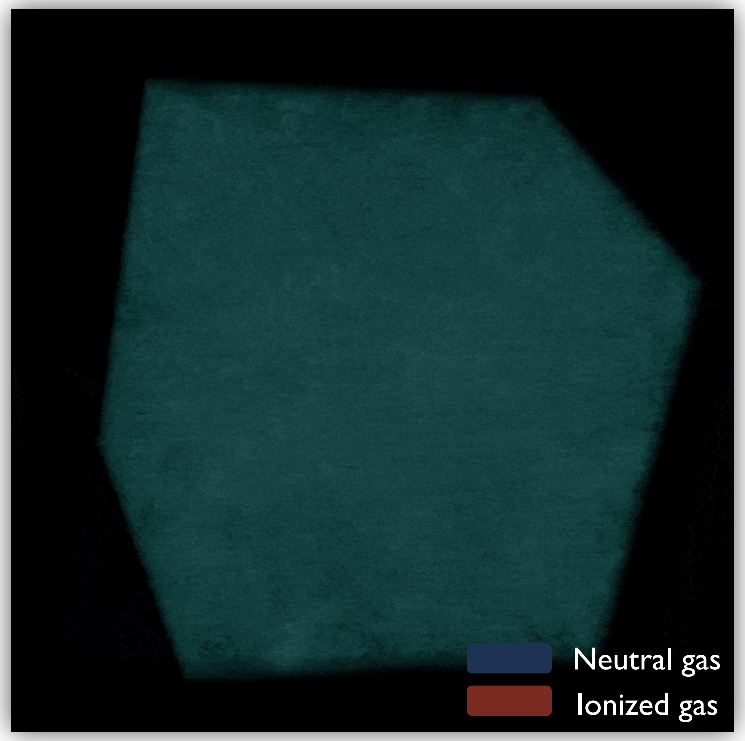
TOPOLOGY OF THE REIONISATION PROCESS

INTRODUCTION

The Epoch of Reionisation (EoR)

Reionisation history – *Credit: ESA*





Simulation with **1024^3 cells** and a volume of **128^3 Mpc^3/h**

Last big **transition** our Universe has known: **the gas goes from totally neutral to totally ionised**

INTRODUCTION

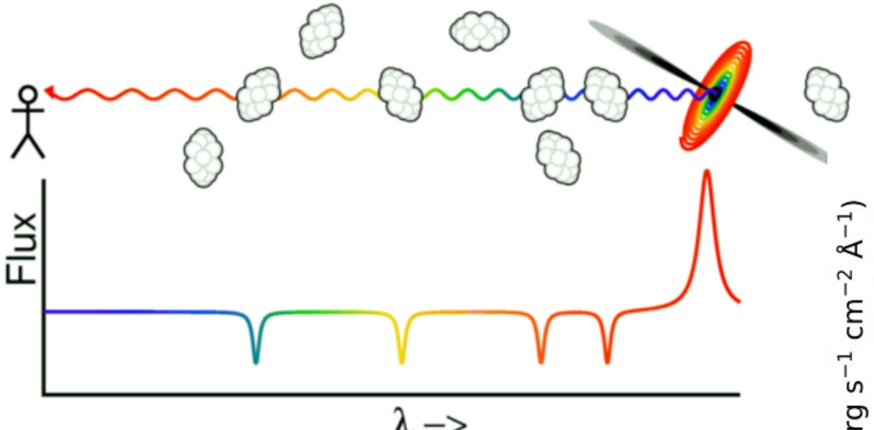
***Indirect** observations of the reionisation process*

Lyman α & Gunn-Peterson trough
Emission from distant quasars
= *distribution of hydrogen clouds along their line of sight*

CMB power spectrum
= *constraints on e.g. the optical depth τ*

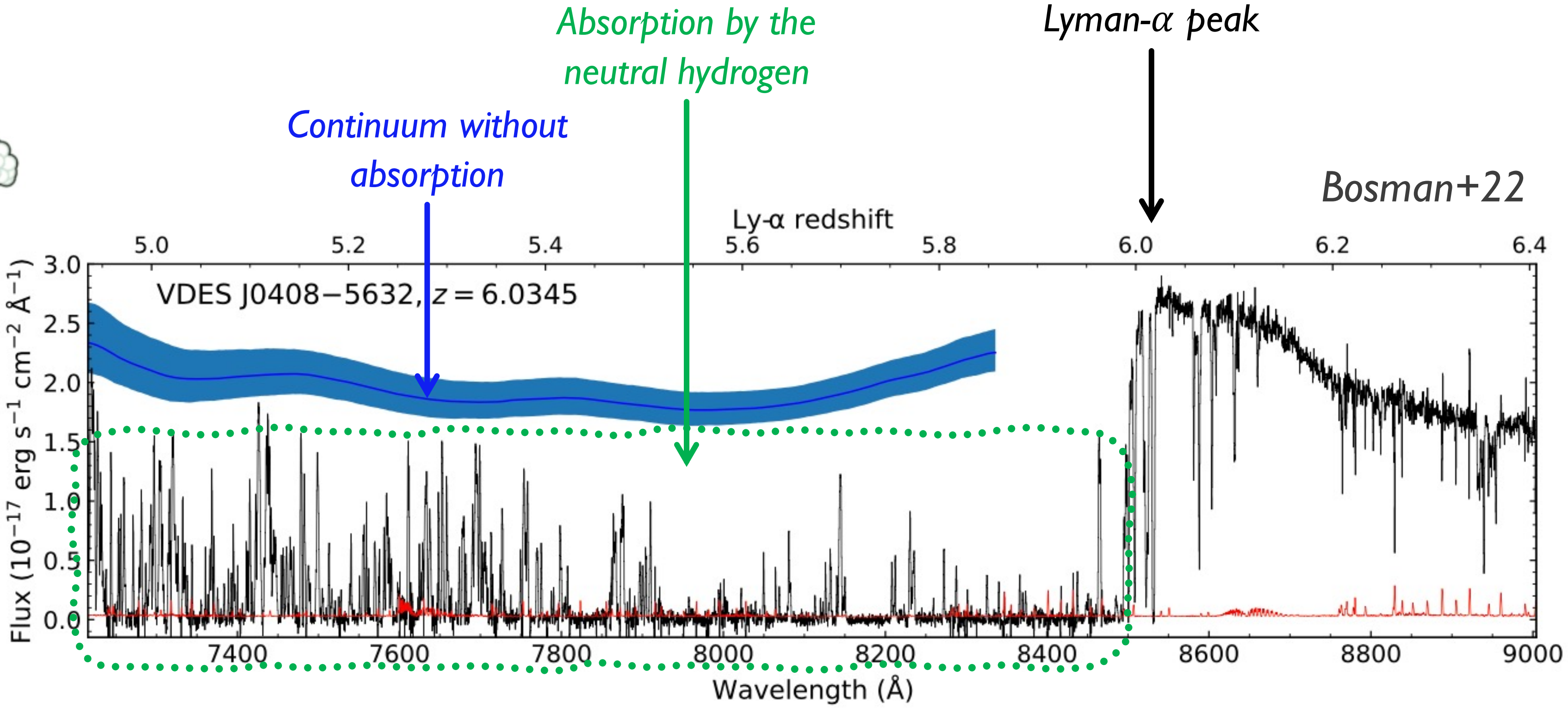
Deep surveys of distant galaxies ($z \lesssim 15$) with HST and JWST
= *galaxy properties distribution during the EoR*

Post-reionisation case



Credit: https://astro.ucla.edu/~wright/Lyman-alpha-forest.html

During reionisation case



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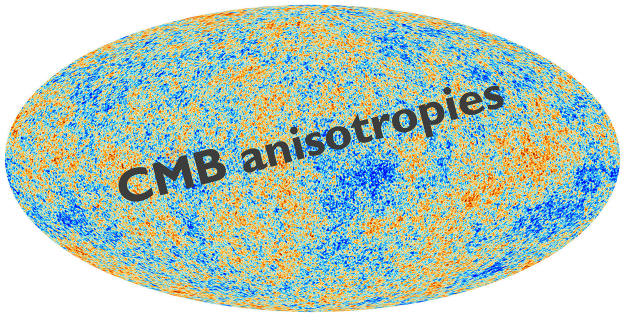
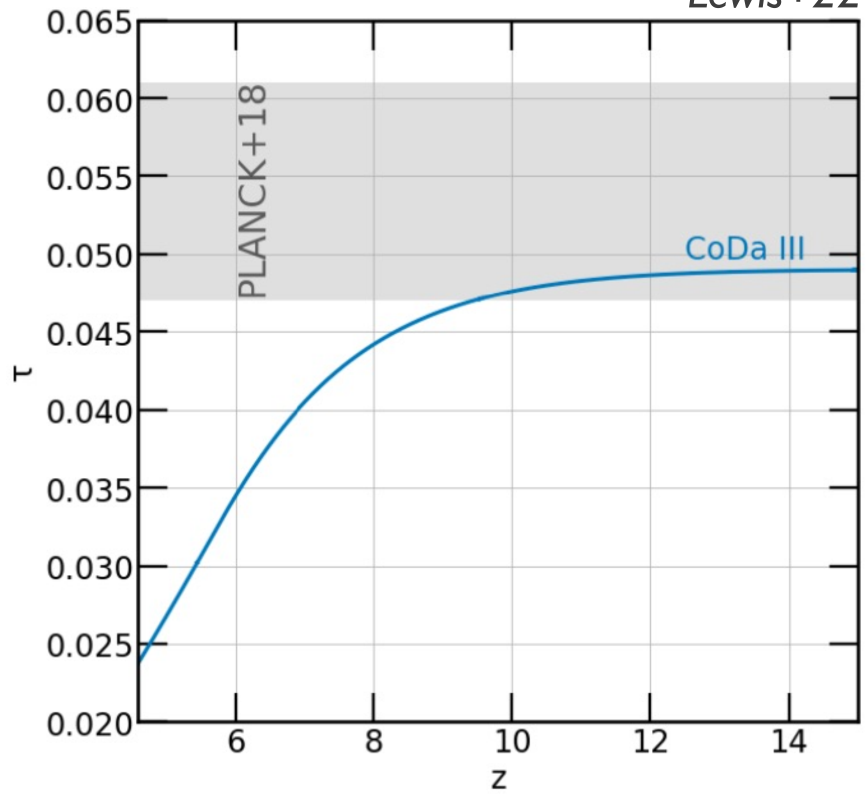


IGM contains a diffuse component of **ionised gas** (mainly HI) that scatters the photons of the CMB

Constraints on τ, which is a way to:

- **estimate the density** of the IGM.
- **probe the ionisation state** of the IGM.
- **constrain the mid-reionisation redshift** (Planck+18: $z_{\text{mid\_re}} = 7.68$).

Lewis+22



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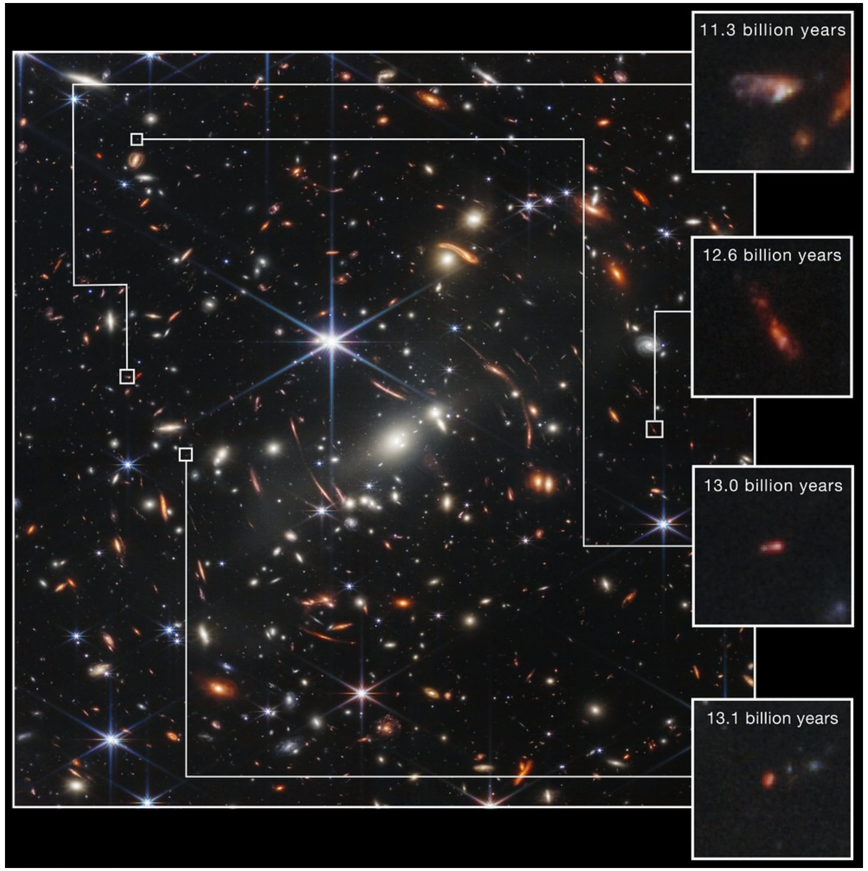
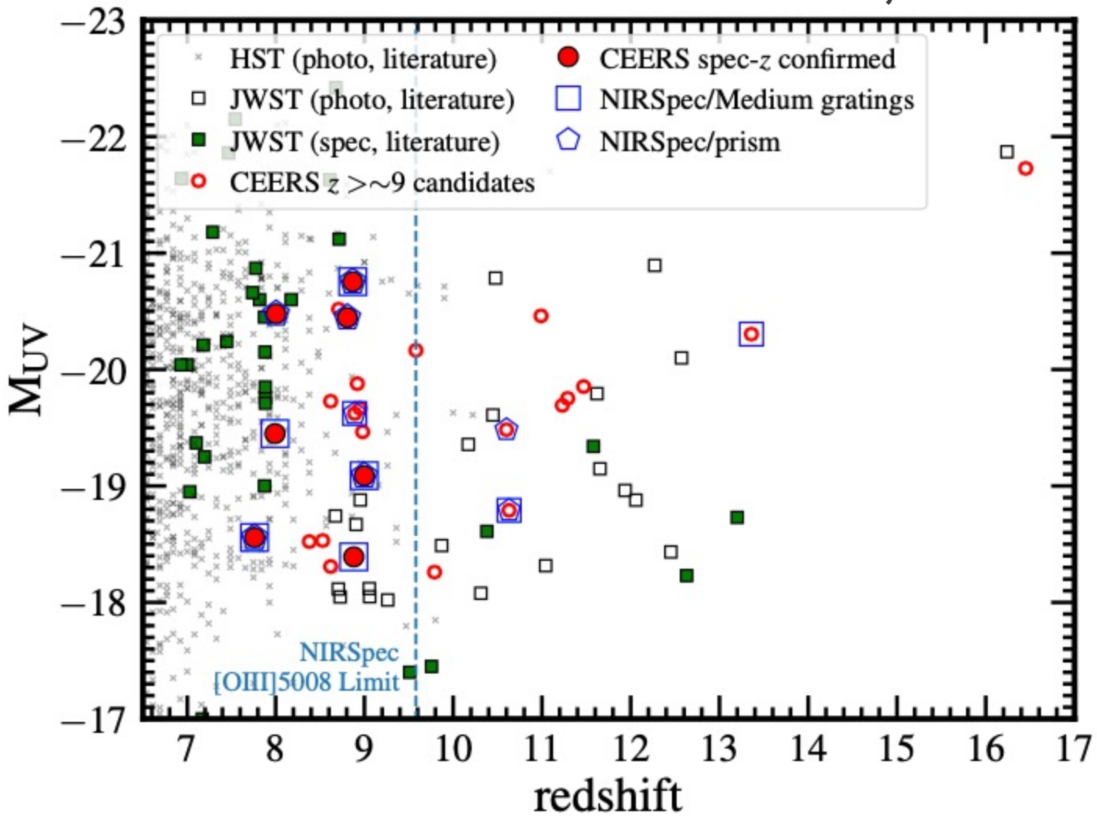


SMACS 0723 galaxy cluster
NIRCam Image, JWST
Credit: NASA

Fujimoto+23



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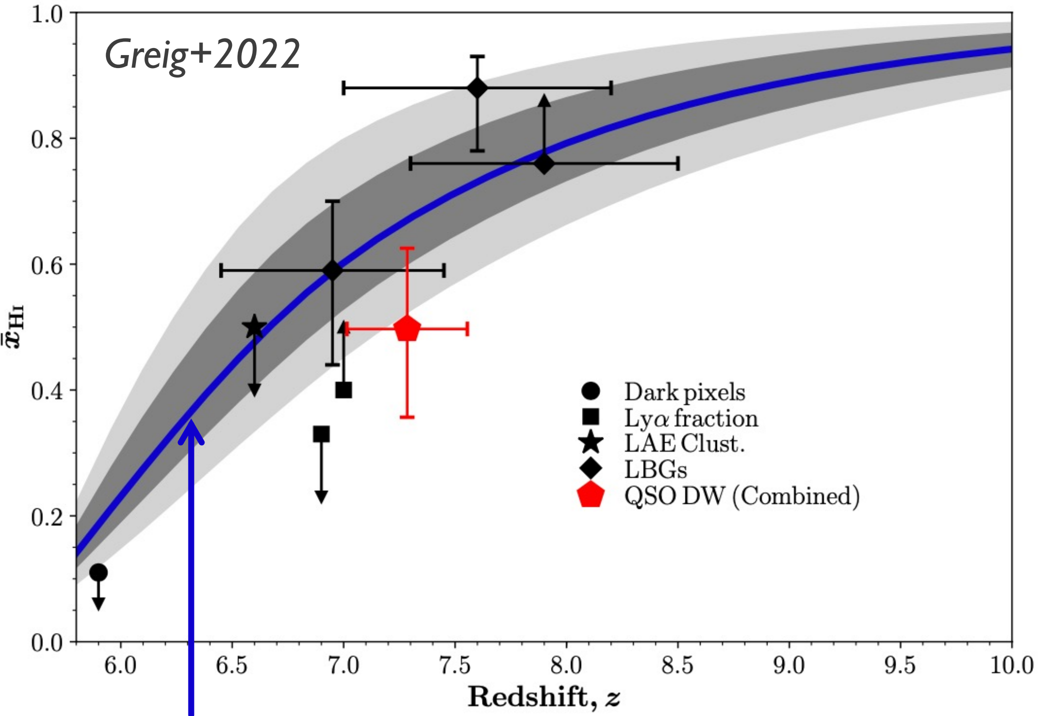
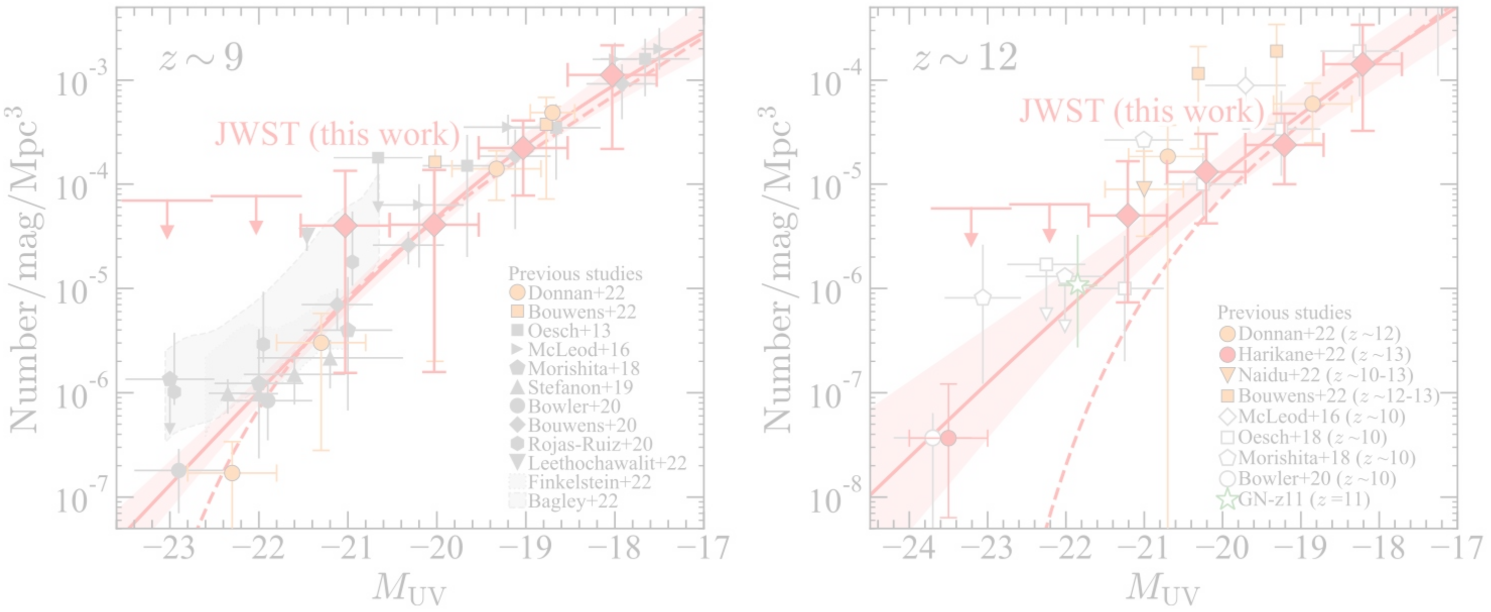
***Indirect** observations of the reionisation process: what do we learn?*

Reionisation history:
time evolution of the reionisation process

Luminosity functions of galaxies:
constraints on e.g. star formation rate (SFR) & galaxy parameters



Harikane+2023



Constraints from forward-modelling, including:

- *Large-scale Lyα forest opacity fluctuations*
- *CMB optical depth*
- *Fraction of dark pixels in the Lyα and Lyβ forests*
- *Observed UV luminosity functions at $z = 6 - 10$*

Example of astrophysical parameters that these studies allow to constrain: ionising photon production rate and efficiency, escape fraction, dust extinction

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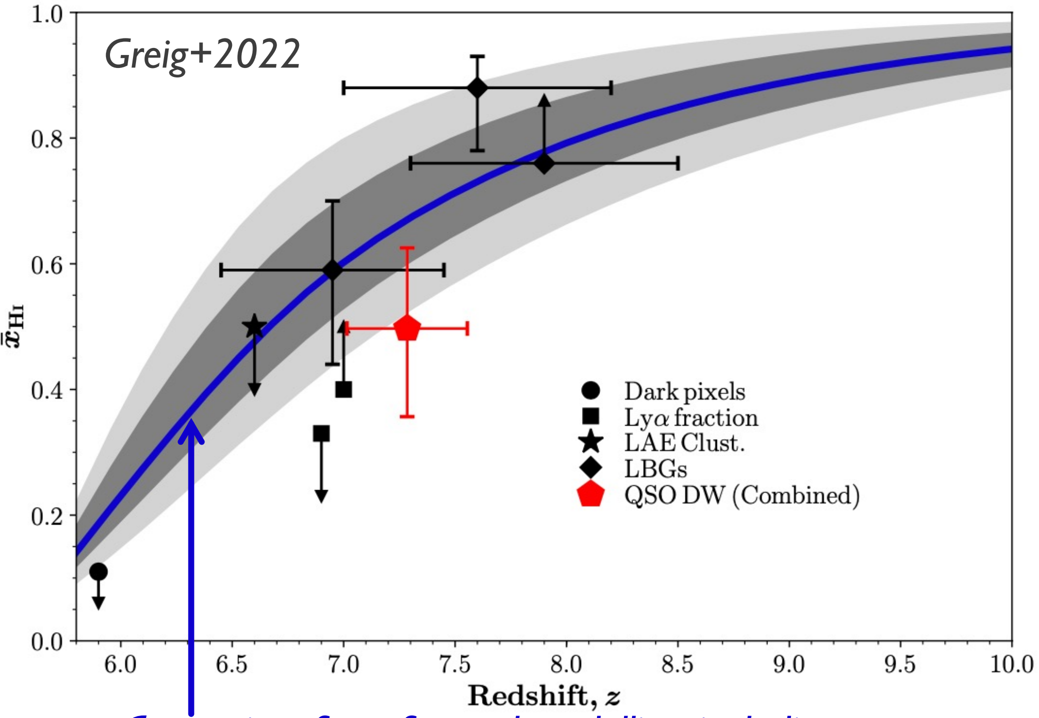

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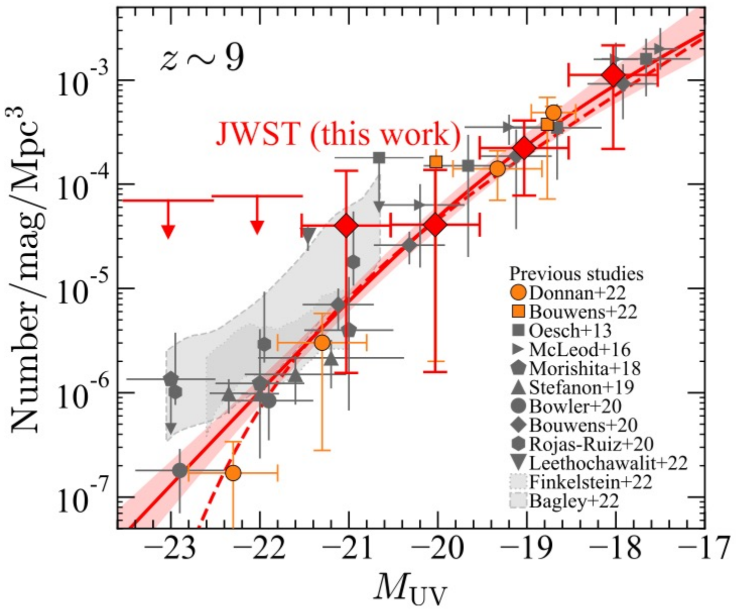

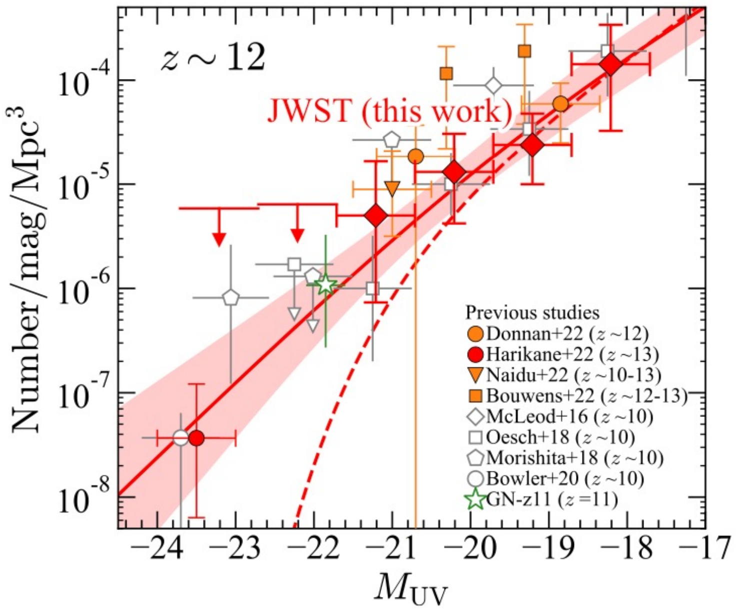

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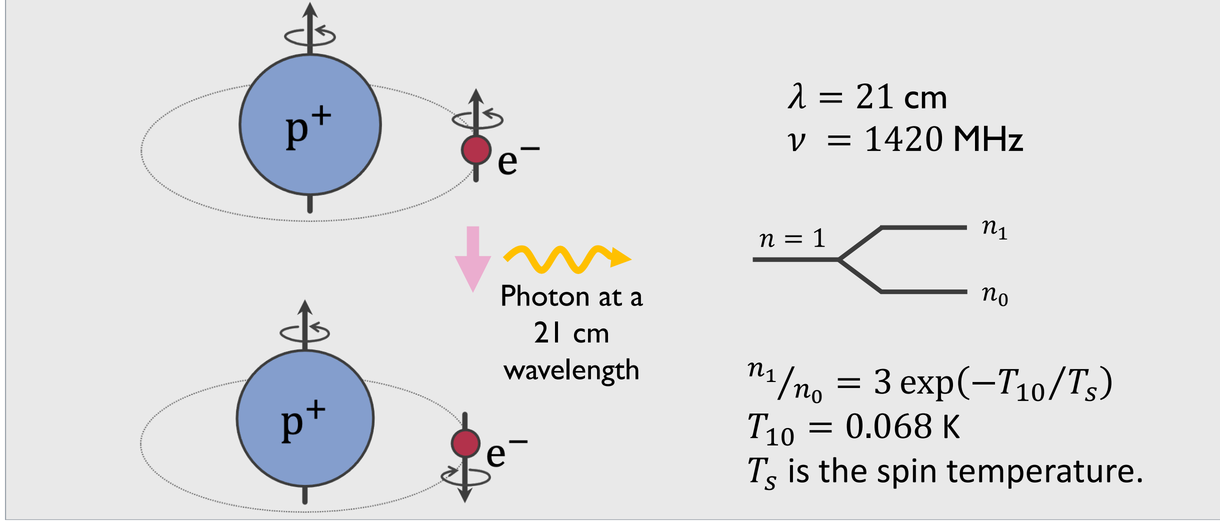
INTRODUCTION

***Direct** observations of the reionisation process*

- Upcoming observations of the brightness temperature with the **21 cm signal**
  = distribution of neutral hydrogen gas at many frequencies
- 21 cm signal: $\delta T_b(z) \sim x_{HI}(z)(1+\delta_b(z))F(T)$



Ionisation state of the hydrogen gas

Excitation state of the hydrogen gas
→ depends on the contrast $T_s - T_{CMB}$

$$\delta T_b(z) \approx 27\, x_{HI}(z)\,(1+\delta_b(z))\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(1-\frac{T_{CMB}(z)}{T_s(z)}\right)\underbrace{\left(\frac{\Omega_b}{0.044}\frac{h}{0.7}\right)\left(\frac{\Omega_m}{0.27}\right)^{-\frac{1}{2}}}_{\text{Cosmology}}\ \mathrm{mK}$$

Density fluctuation of baryons

- *T_{CMB}: CMB temperature*
- *T_s: spin temperature → local excitation temperature of the two-spin states of the neutral hydrogen*

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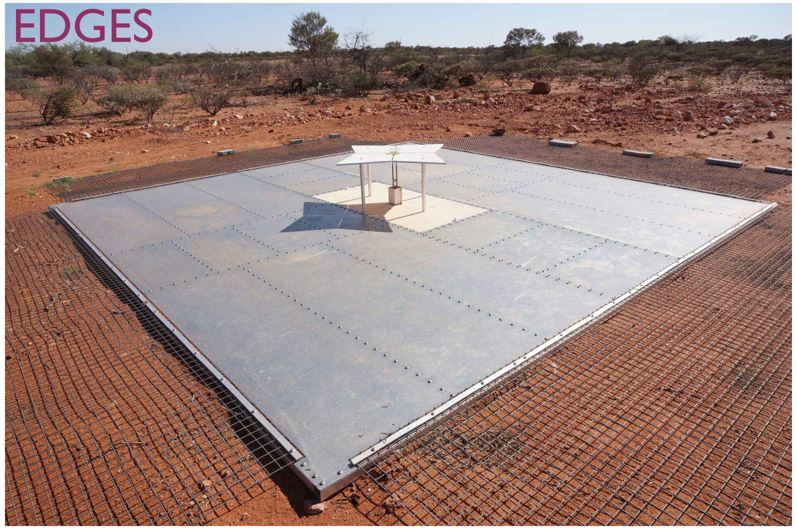
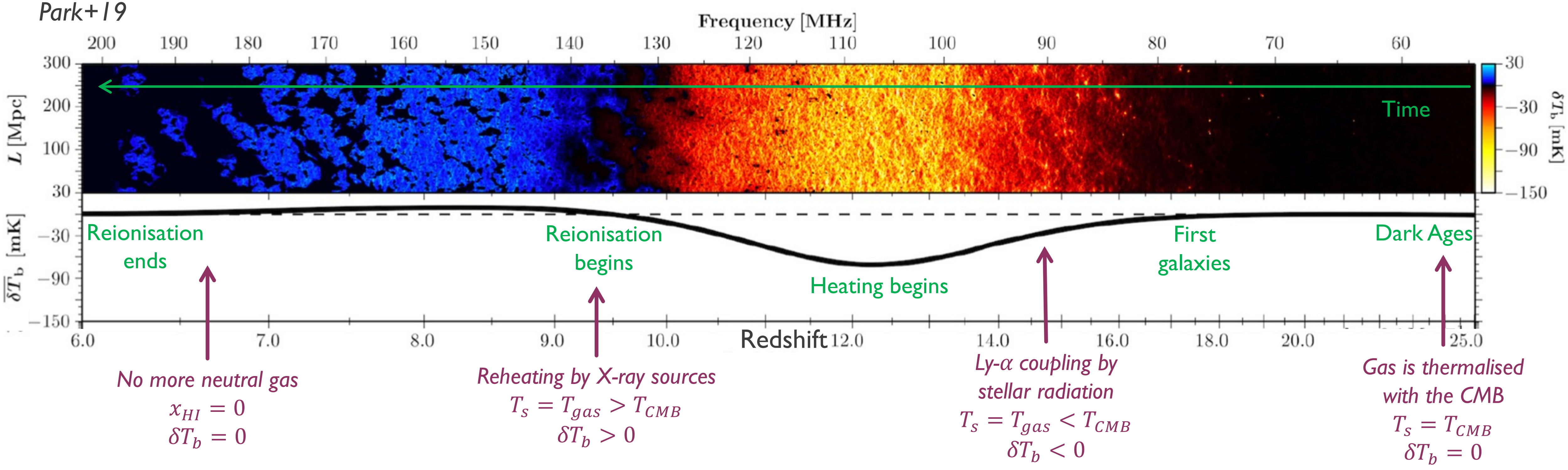


Park+19



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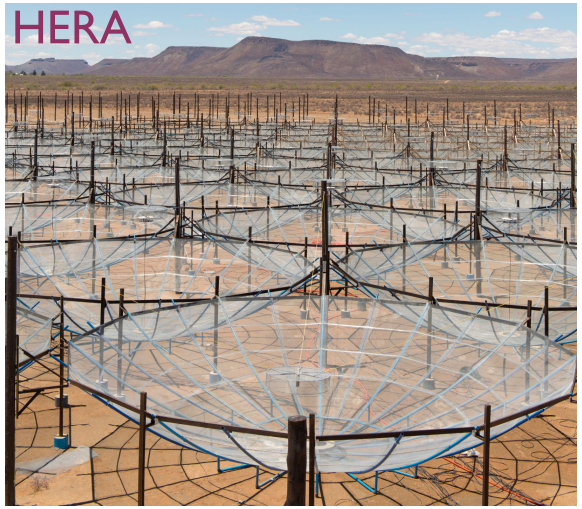
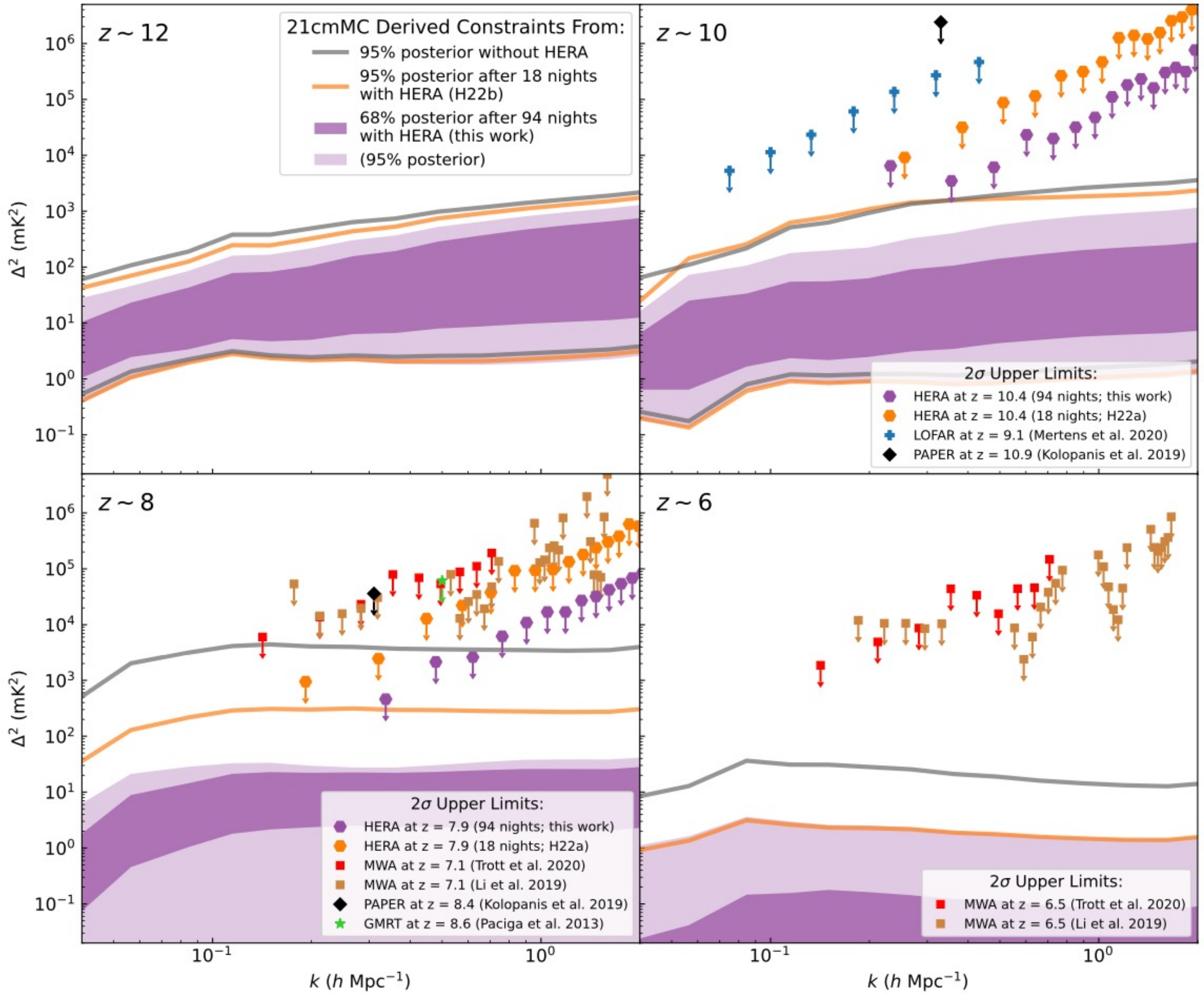


We have now **limits on the 21 cm power spectrum** *that will be useful to constrain on astrophysical parameters and the reionisation process.*

→ e.g. "IGM must have been heated above the adiabatic cooling", maybe by X-ray photons.

HERA collaboration. 2022b



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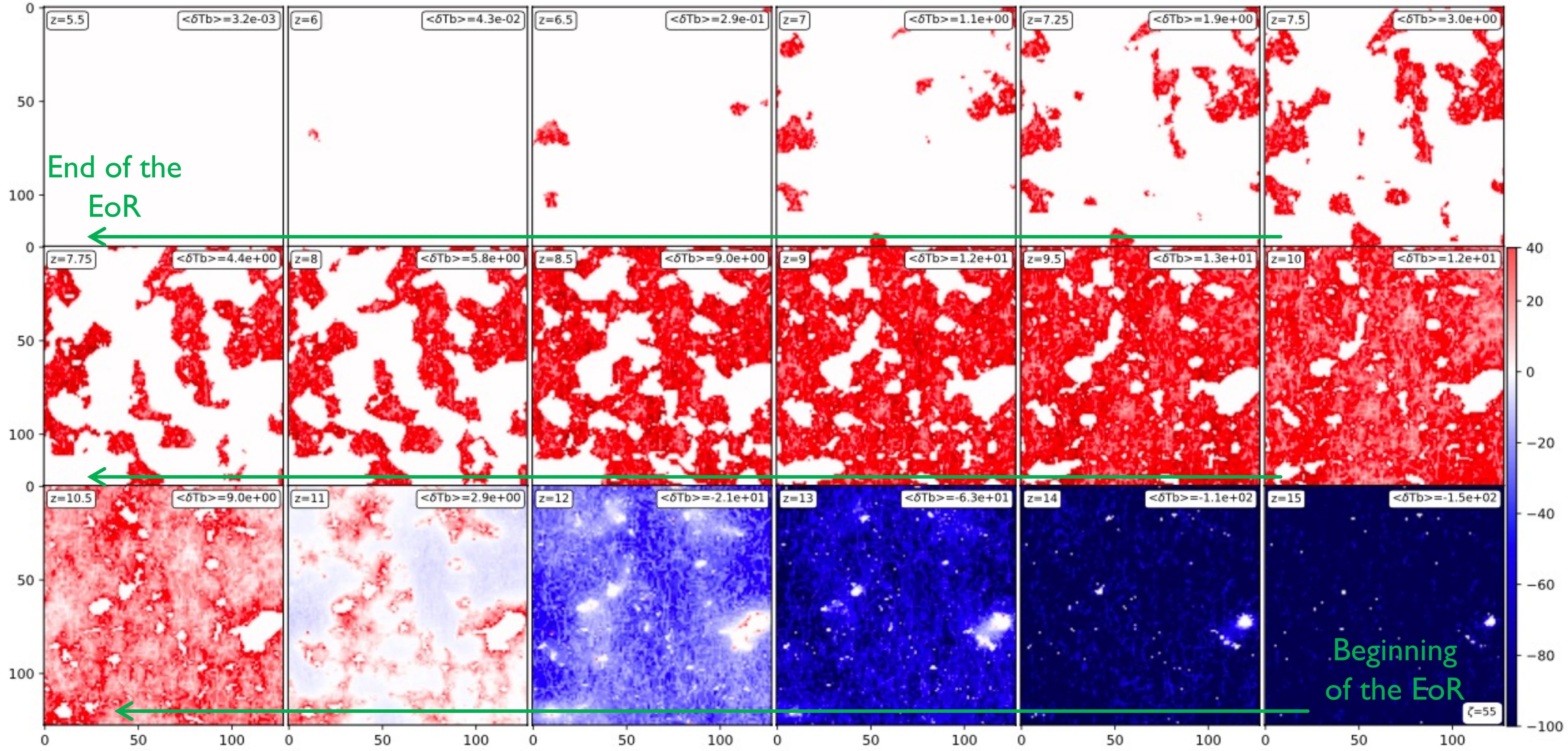
SKA-Low characteristics:

Redshifts range:
50 – 350 MHz $\sim z \in [6, 25]$

Field of view:
200 square degrees
(> 1 cGpc)

Resolution (see Giri+18):
- On the plane of the sky: $> \mathbf{7\ cMpc\ for\ } z > 6.5$
- In the frequency direction: $> \mathbf{1\ cMpc}$



2D images of the 21 cm signal at many frequencies: $\delta T_b(z)$
21cmFAST semi-analytical model
(256 cMpc/h)

Hiegel, Thélie+ (in prep.)

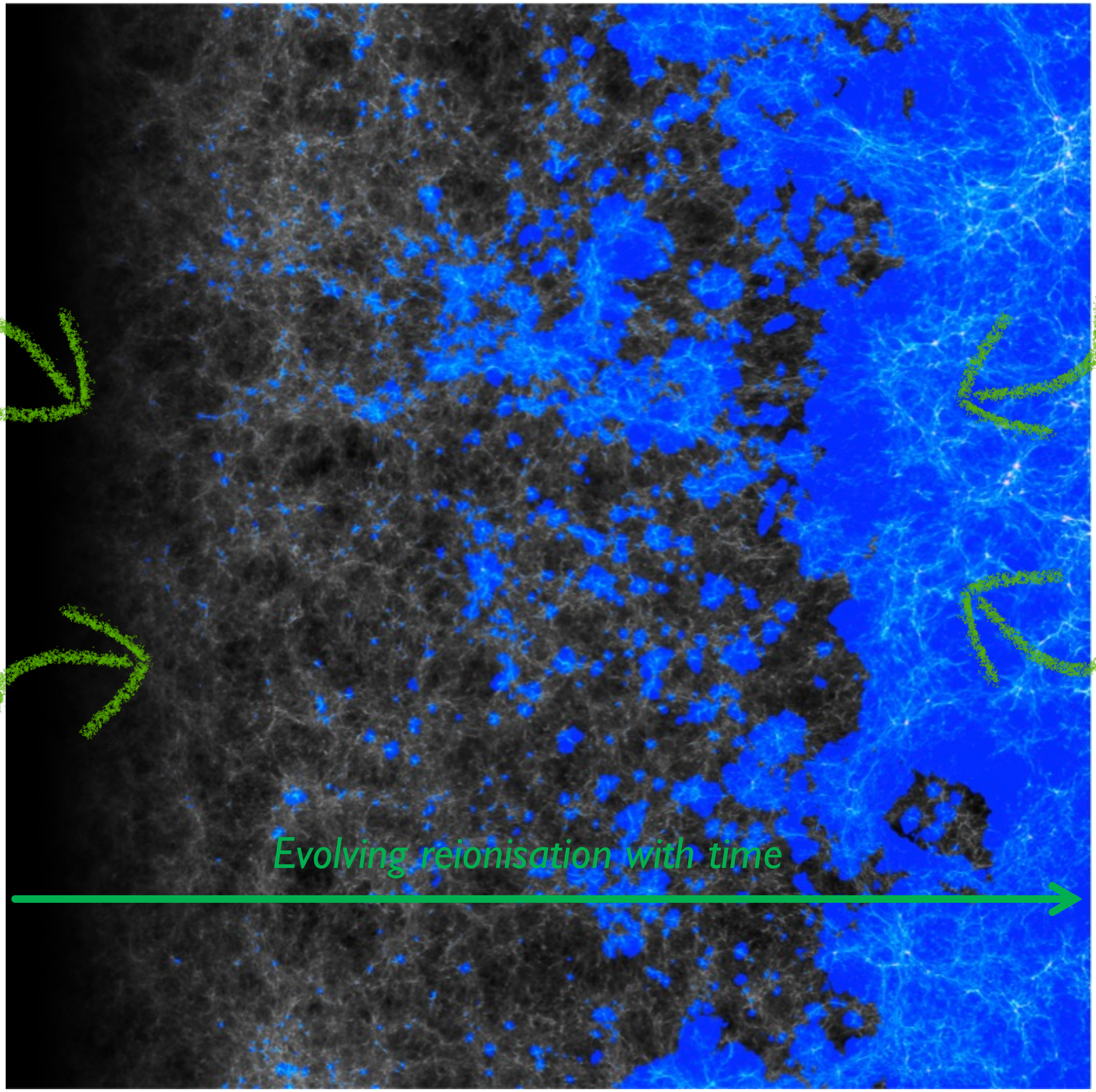
INTRODUCTION

The Epoch of Reionisation (EoR)

CoDa II (64 cMpc/h)
Ocvirk+20

Physical properties of individual sources
(e.g. luminosity, spectrum, f_{esc} fraction)

Properties of the source population
(e.g. number density, time evolution, spatial distribution)



Properties of the gas density field
(e.g. ionisation fraction)

Effects of the first generation of sources on the IGM
(through e.g. ionisation, photoheating, shock-heating, chemical enrichment)

THE EPOCH OF REIONISATION
& ITS OBSERVATIONS

TOPOLOGY OF MODELS OF THE REIONISATION PROCESS

INTRODUCTION

Modelling the Epoch of Reionisation

It is challenging!

High resolution
to model star formation

Large volume
to represent the cosmic density field

Radiative transfer
to take into account the radiation field

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Fully analytical models

→ Accessing the 21 cm **global signal & power spectrum**

- Barkana & Loeb 2005
- Pritchard & Furlanetto 2007
- Munoz 2023

Cosmological simulations

→ Implement **hydrodynamics + radiative transfer,** see e.g.:

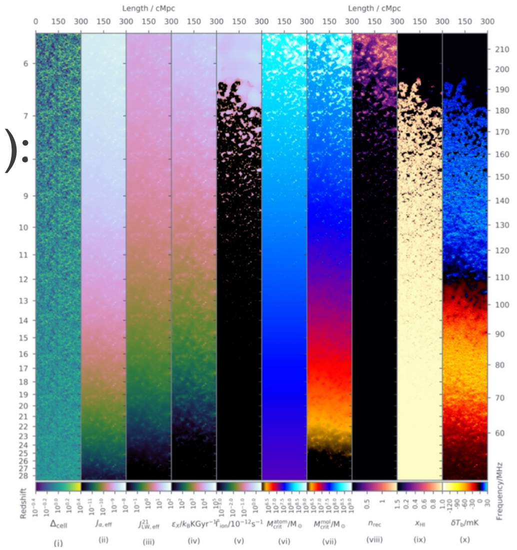
- RAMSES (Teyssier02)
- Gnedin14
- **EMMA** (Aubert+15)
- LICORICE (Semelin16)
- SCORCH (Doussot+20)
- THESAN project (Kannan+21)

Examples of **simulation suites based on RAMSES/ATON**:

- CoDa I, II & III (Ocvirk+16, Ocvirk+20, Lewis+22)
- SPHINX-MHD (Katz+21)
- Sherwood-Relics simulations (Puchwein+22)

Semi-analytical models

- **21cmFAST** (Mesinger+11): the most famous one, based on the excursion set formalism



- Furlanetto+04, Battaglia+13, Hutter18, …
- AMBER (Trac+22): through the calculation of the reionisation redshift field

How does the EoR happen?

Topological studies of x_{HII} or 21 cm maps to analyse:

- *Growth of structures*
- *Ionised/neutral bubbles geometry, distribution, organisation*
- *Percolation, evolution of the process*

A lot of existing methods within this field

Size of neutral and ionised bubbles…

… with diverse methods (e.g. FOF in Giri+19, spherical averages in Giri+18, …)

Spatial correlations…

… with 21 cm power spectra (e.g. Shimabukuro +22) and bispectra (e.g. Hutter+20)

Counts of 3D structures like peaks, tunnels and voids…

… with Betti numbers (e.g. Giri+20, Bianco+21)

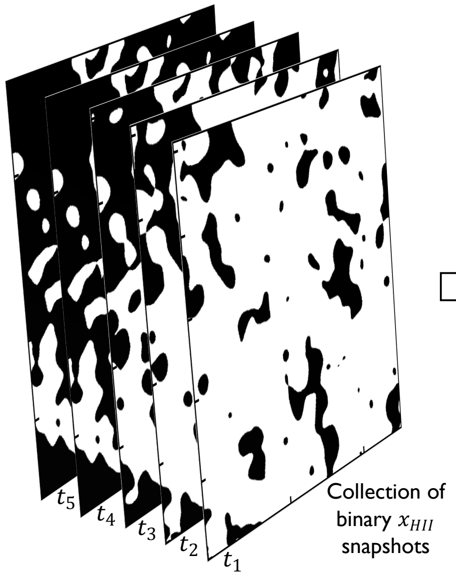
Geometry of bubbles and percolation…

- … with Minkowski functionals (e.g. Friedrich+11, Chen+19)
- … with the triangle correlation function (Gorce+19)

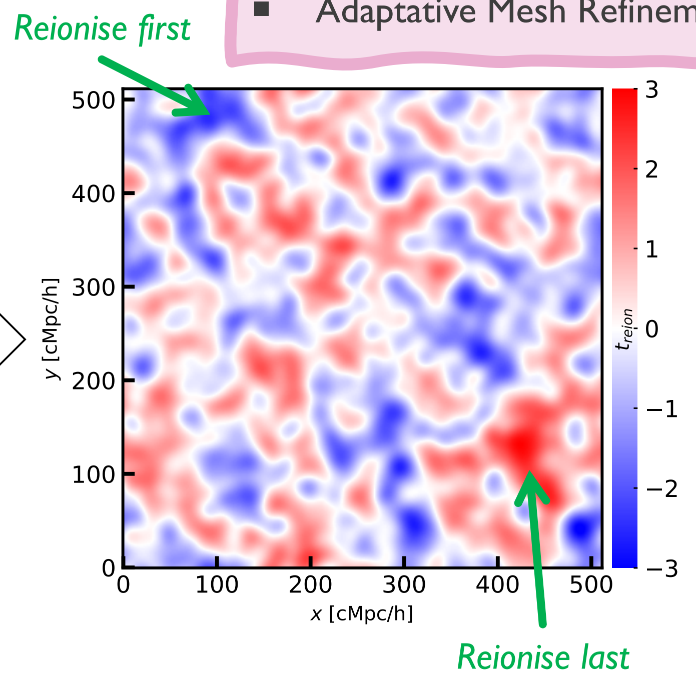
REIONISATION TIMES

Definition

EMMA cosmological simulation (512 cMpc/h):
- Hydrodynamics + radiative transfer
- Adaptative Mesh Refinement (AMR)



Thélie+ (arxiv:2209.11608)



Cell value = time at which the gas is reionised

Map of reionisation times:
- Local histories of reionisation of the gas
- Spatial and temporal information about the reionisation process

REIONISATION TIMES
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EMMA cosmological simulation (512 cMpc/h):
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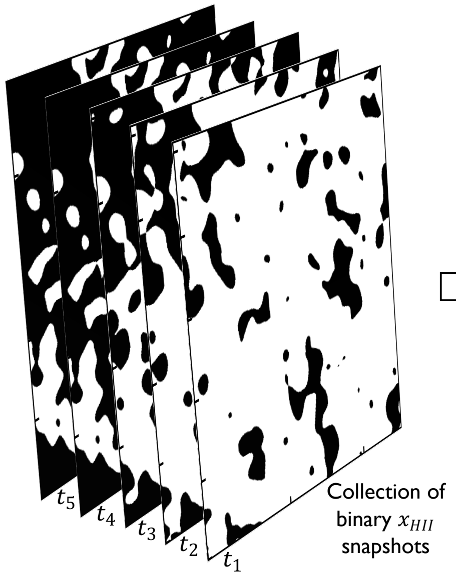
21cmFAST semi-analytical simulation (256 cMpc/h)



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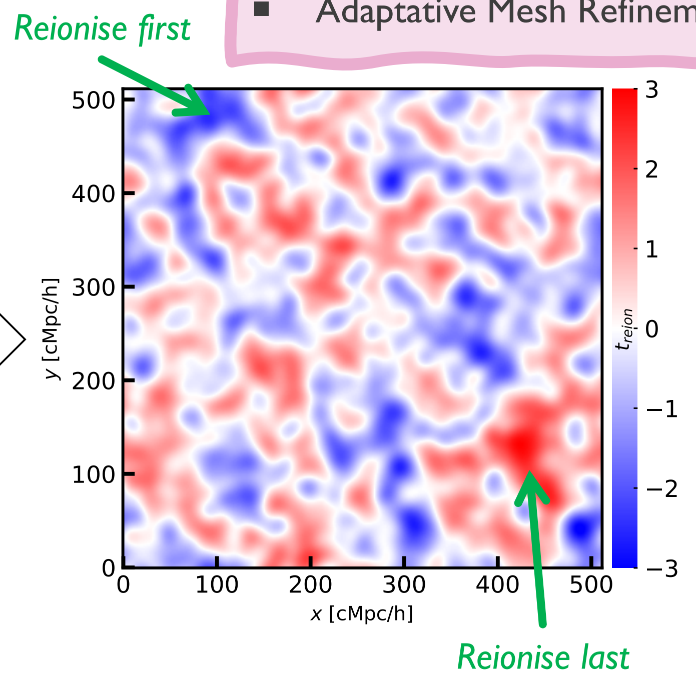

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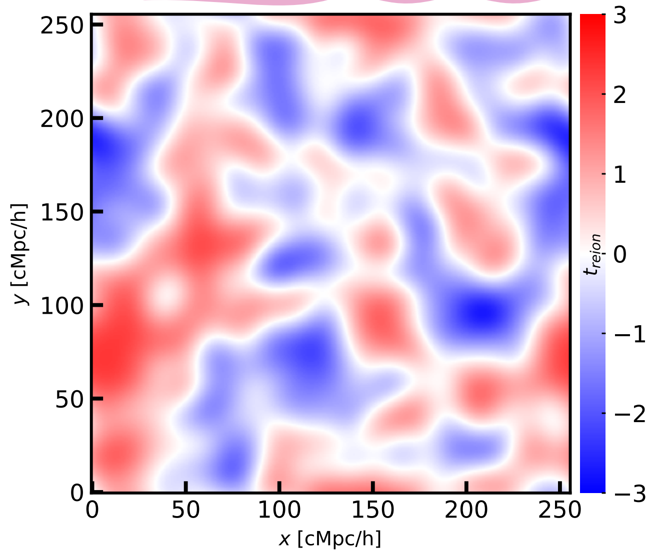

Map of reionisation times:
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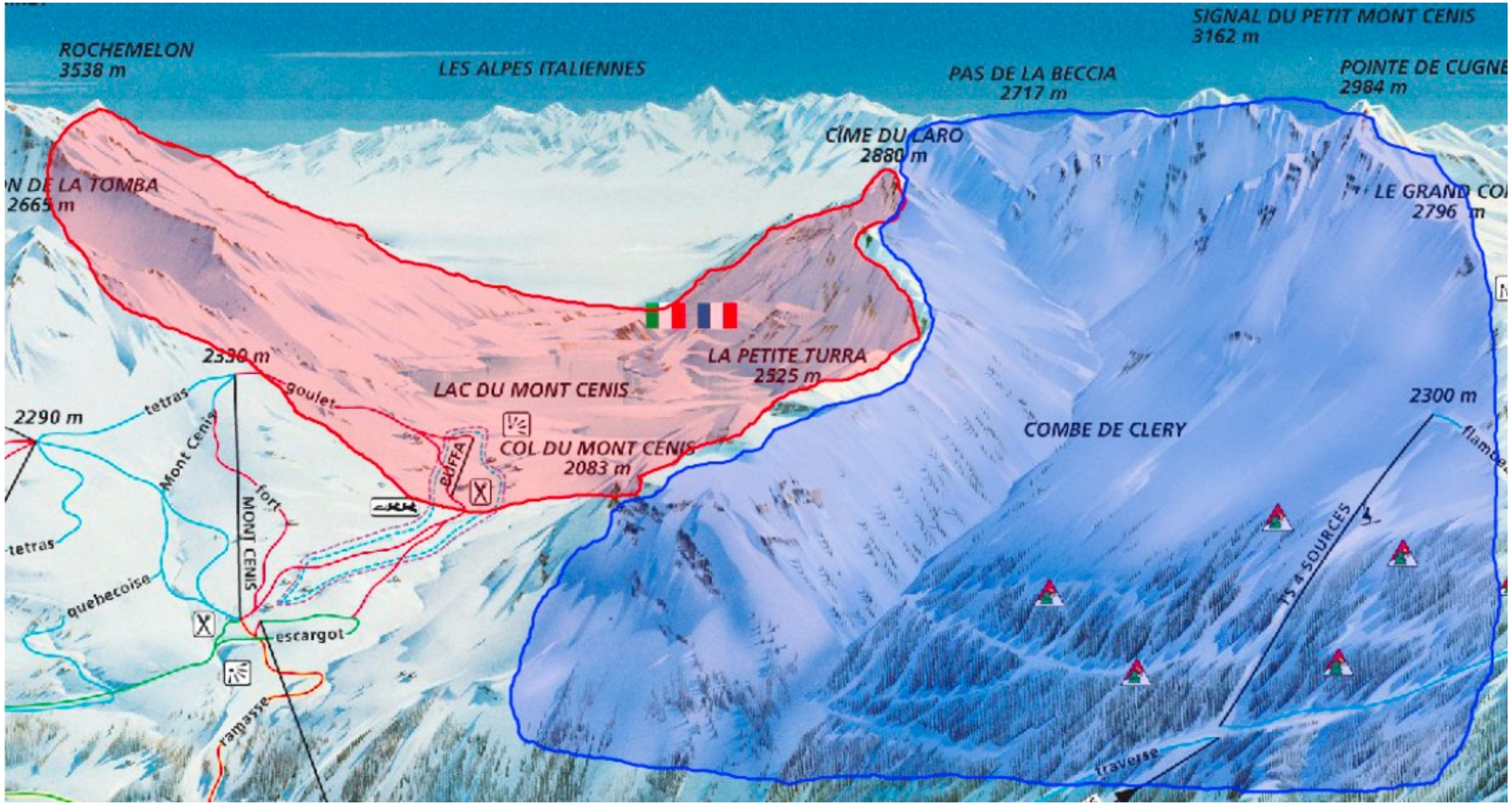
Reionisation simulations:
- **EMMA cosmological simulations** (Aubert+15) or **21cmFAST semi-analytical models** (Mesinger+11)
- Large scales: box size **>128 cMpc/h, 1 cMpc/h** resolution

REIONISATION TIMES

Topology as seen through a mountainous landscape

Credit: C. Gay thesis (2011)



Altitude isocontours (IGN map)

- Mountainous landscape = **2D field** with the **altitude as the field value**

REIONISATION TIMES

Topology as seen through a mountainous landscape

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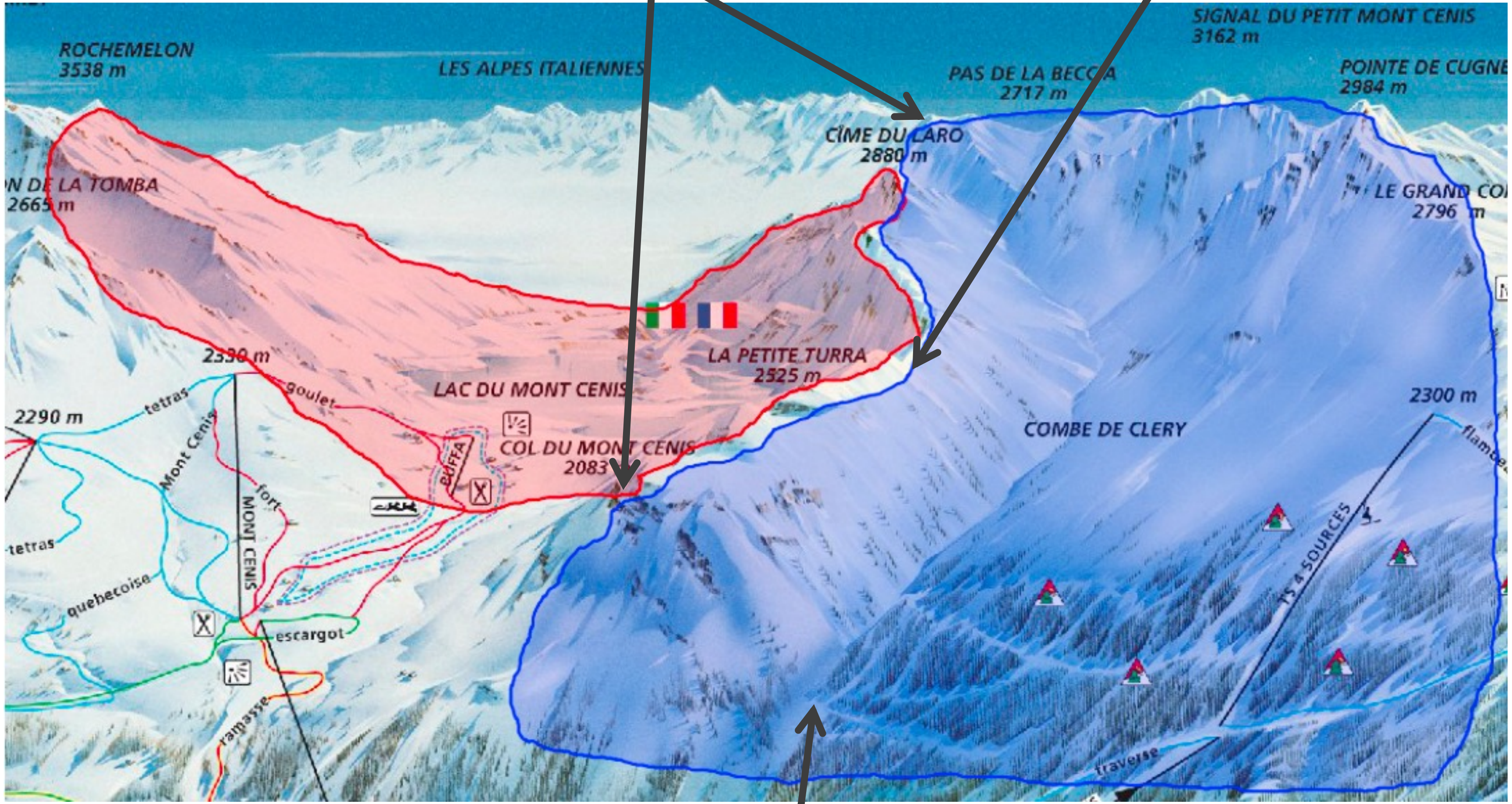
Peaks = *maxima*

Pass = *saddle point*



Valley hollow = *minimum*

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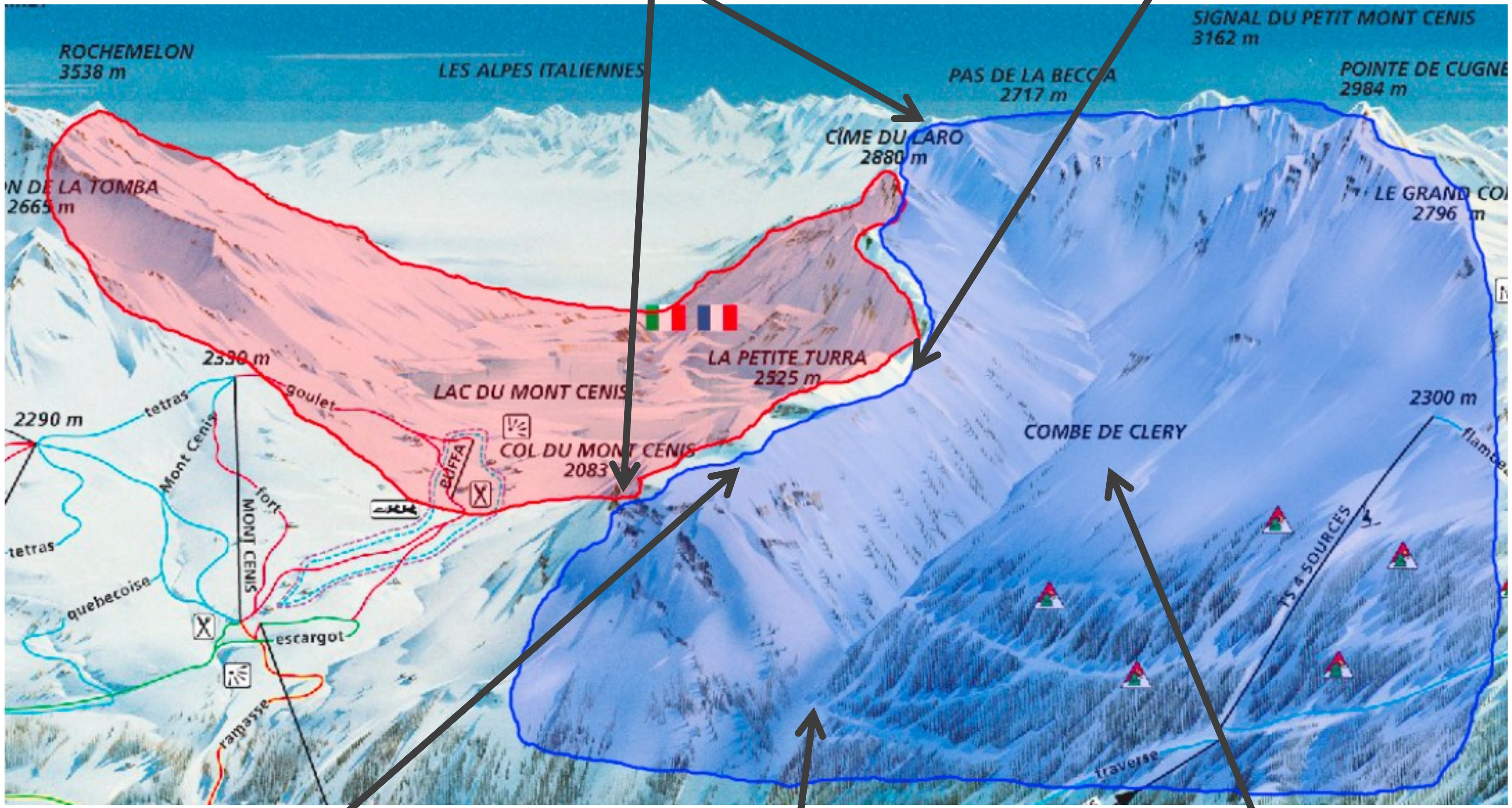


Ridge line = *skeleton filament*

Valley hollow = *minimum*

Valley = *void patch*

Altitude isocontours (IGN map)

- Mountainous landscape = **2D field** with the **altitude as the field value**
- Set of valleys = segmentation in **void patches**
- Set of ridge lines = **skeleton**

REIONISATION TIMES

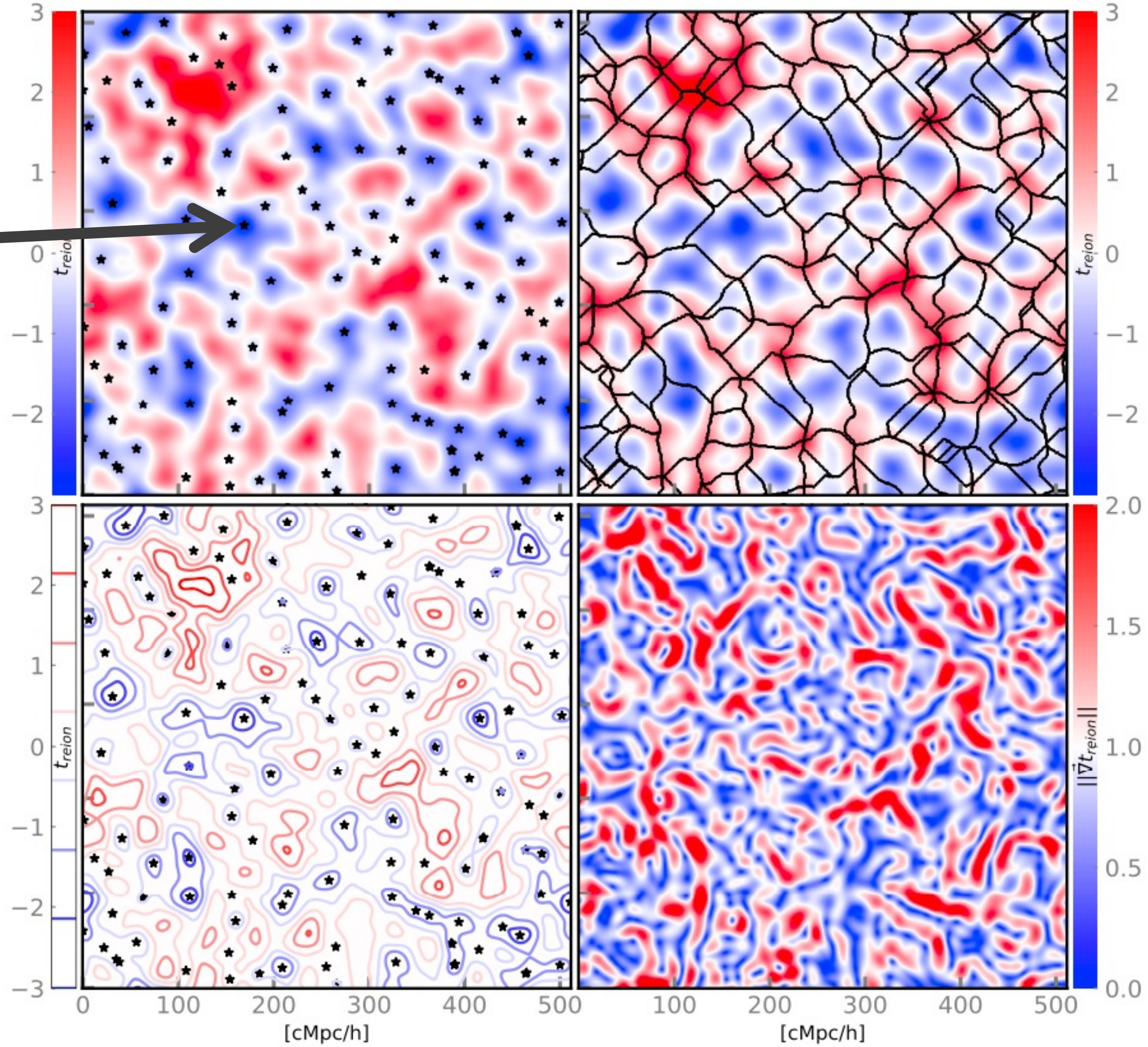
Evolving topology of the EoR

EMMA cosmological simulation maps (512 cMpc/h)

Thélie+ (arxiv:2209.11608)

Minima:

- *"Reionisation seeds": sources from which the ionisation fronts propagate*
- *First places to reionise*



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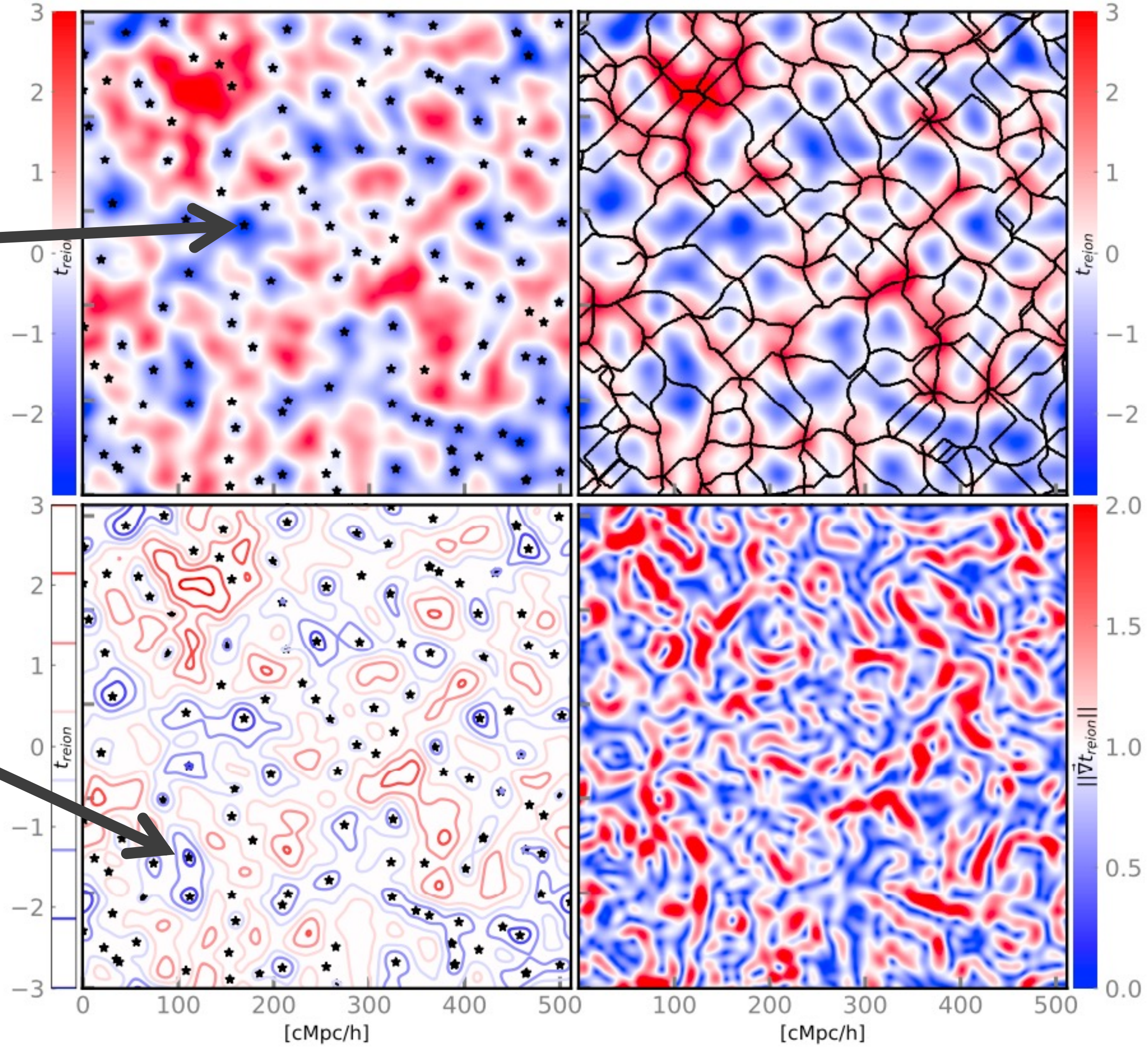

Isocontours:

- *Regions reached by ionisation fronts at the same time*
- *Size evolution of bubbles*

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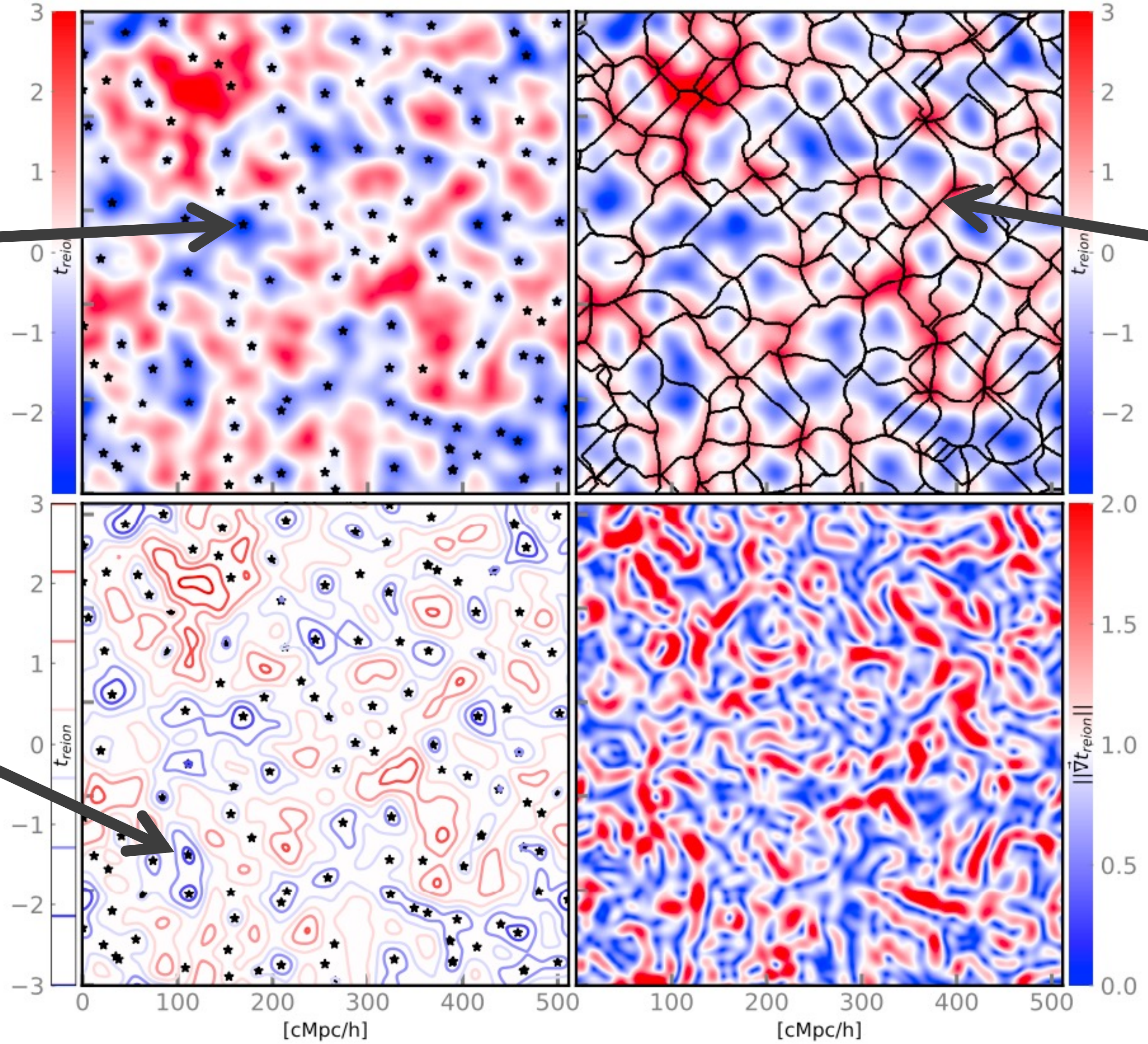

Reionisation patches:
- *Extension of the radiative influence of a source*

Patches edges = skeleton:
- *Percolation lines between ionisation fronts*

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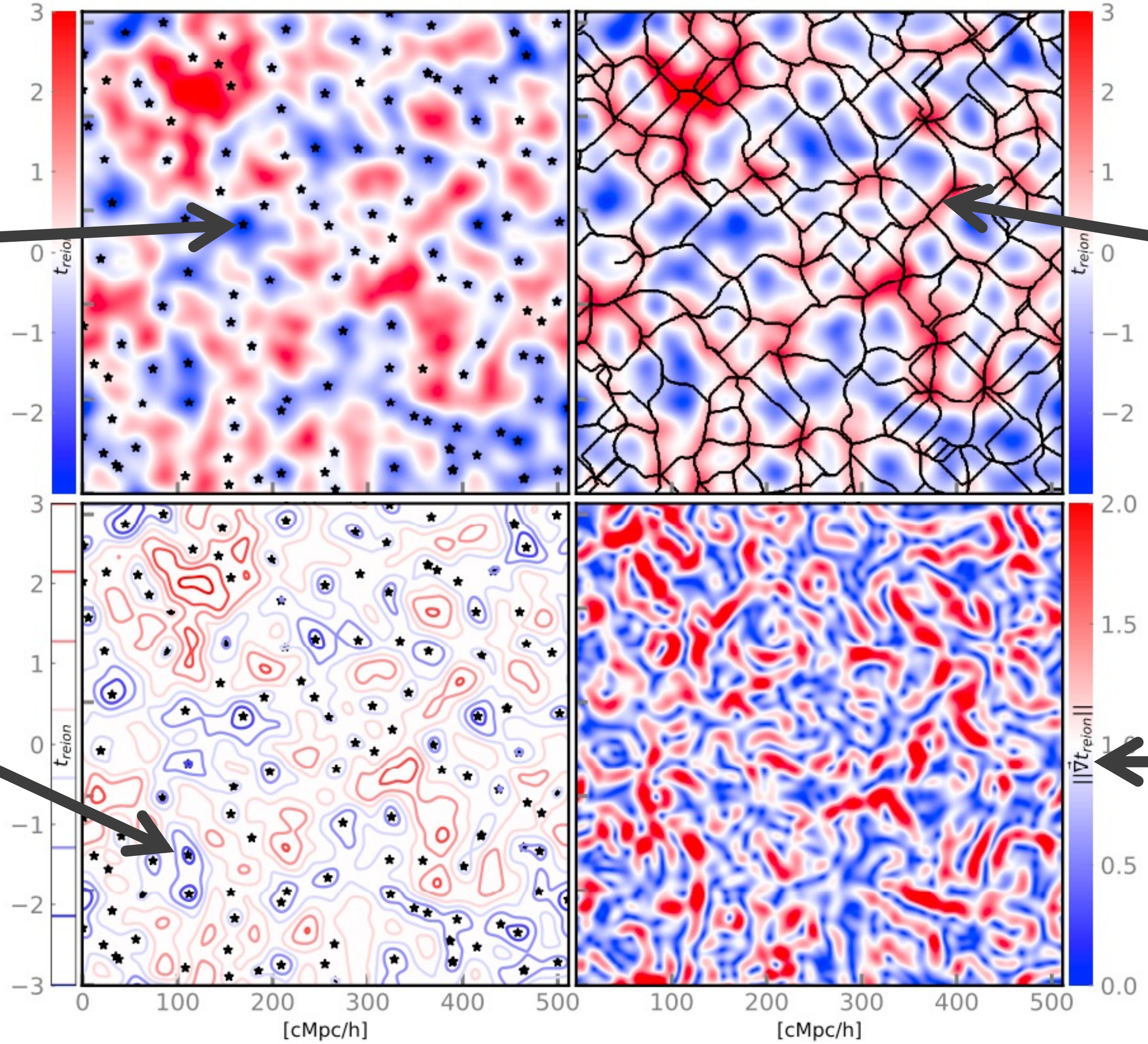

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Gradients:

- $\left\|\overrightarrow{\nabla t_{reion}}\right\| \sim \frac{\Delta t}{\Delta x} \sim v_{reion}{}^{-1}$
- *Inverse of the ionisation fronts speed*

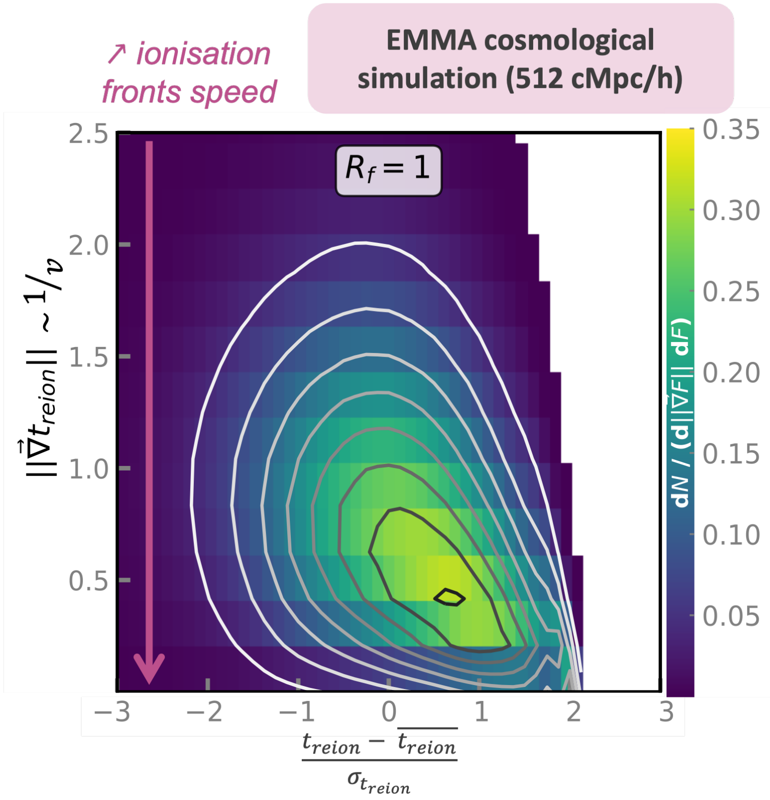
REIONISATION TIMES

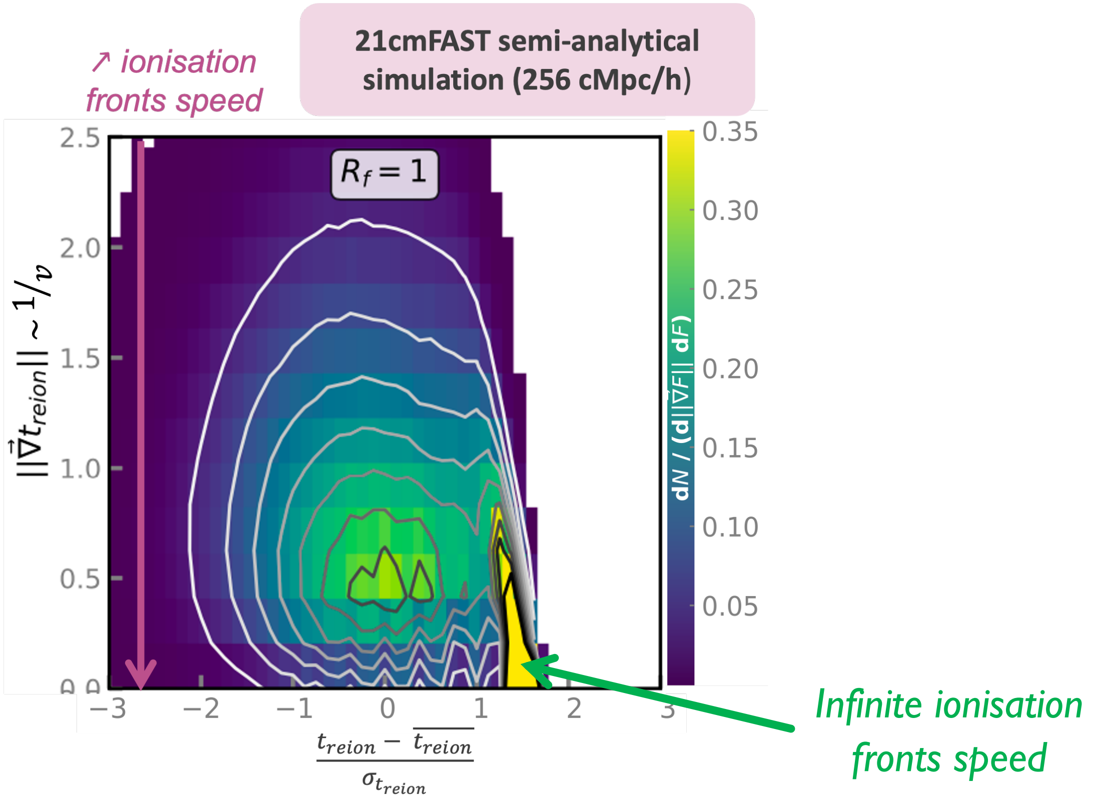
What can we do with it?

Analysing this map:

- Comparisons between **models of simulations**
- **Geometrical characterisation of models** of the EoR
- Comparison to the **gaussian random fields theory**
- Study of the **evolving topology of the reionisation process**

Thélie+ (arxiv:2209.11608)





A. REIONISATION TIMES RECONSTRUCTED FROM THE 21 CM SIGNAL

Hiegel, Thélie+ (to be submitted)

B. PROPAGATION OF IONISATION FRONTS AROUND MATTER FILAMENTS

Thélie+22 (A&A)

C. REIONISATION TIMES: TOPOLOGY AND GAUSSIAN RANDOM FIELD (GRF) THEORY

Thélie+ (accepted for publication in A&A, arXiv: 2209.11608)

A. 21 CM TO t_{reion}

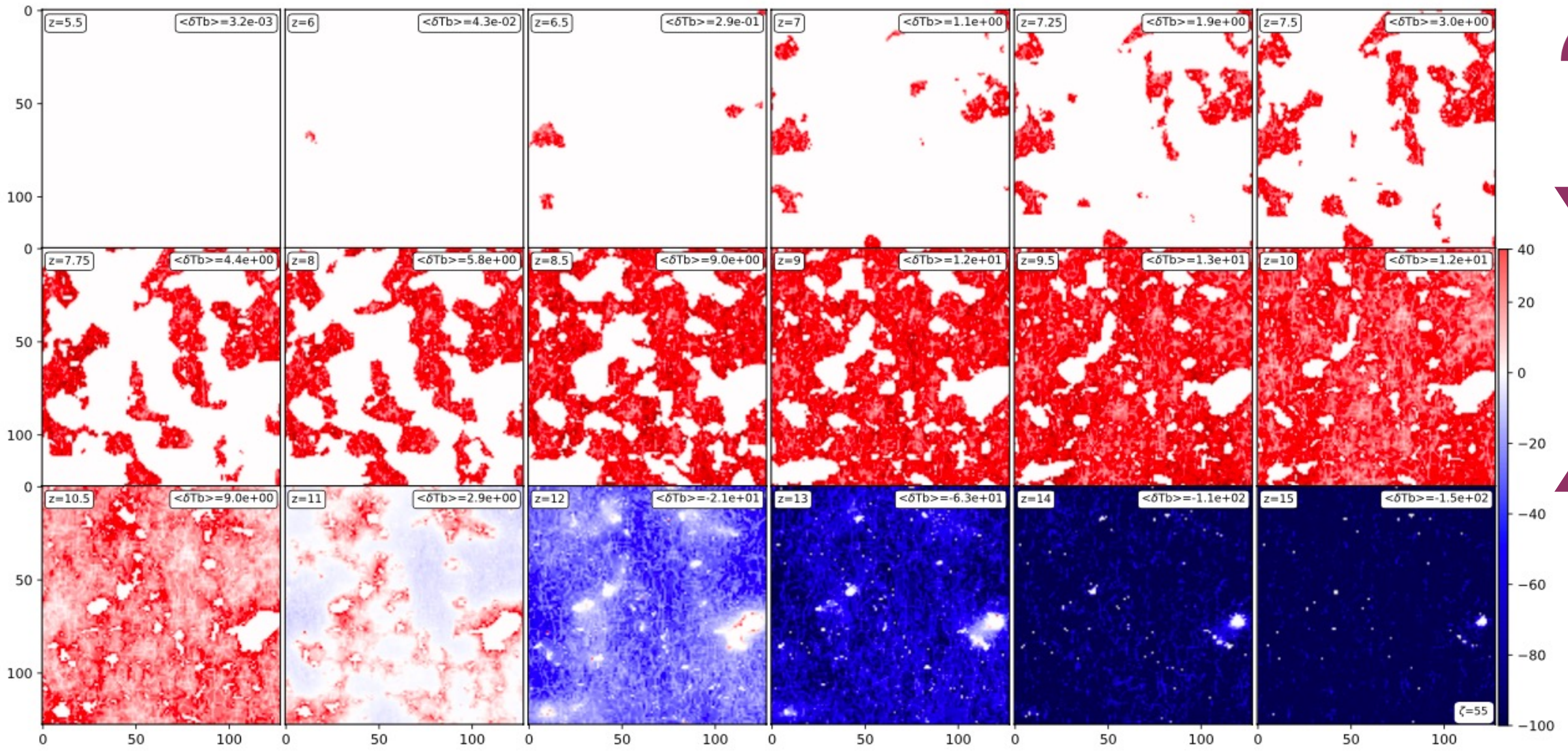
Reconstruction of reionisation times from 21 cm signal maps

Is it possible to reconstruct reionisation times maps from observations?

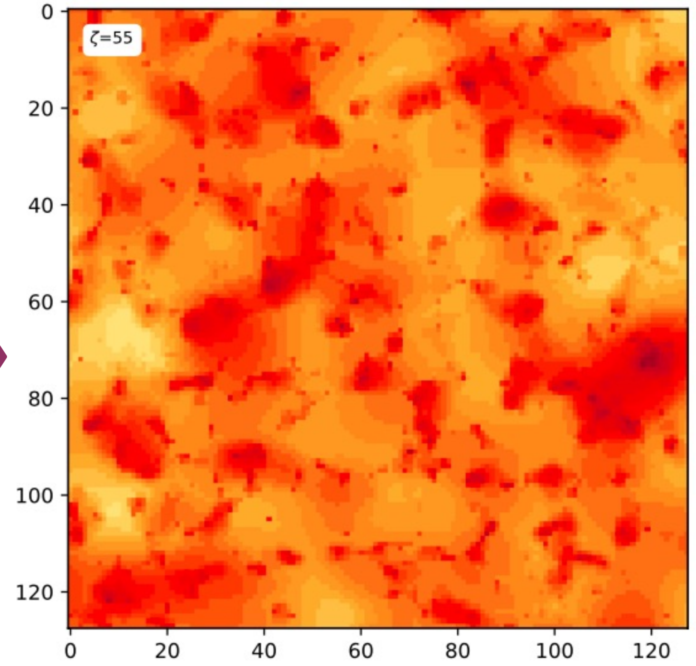
Future observations with SKA :

- *2D maps on the plane of the sky…*
- *… of neutral gas distribution during the EoR…*
- *… at many observational redshifts*

2D images of the 21 cm signal at many frequencies: $\delta T_b(z)$



t_{reion}

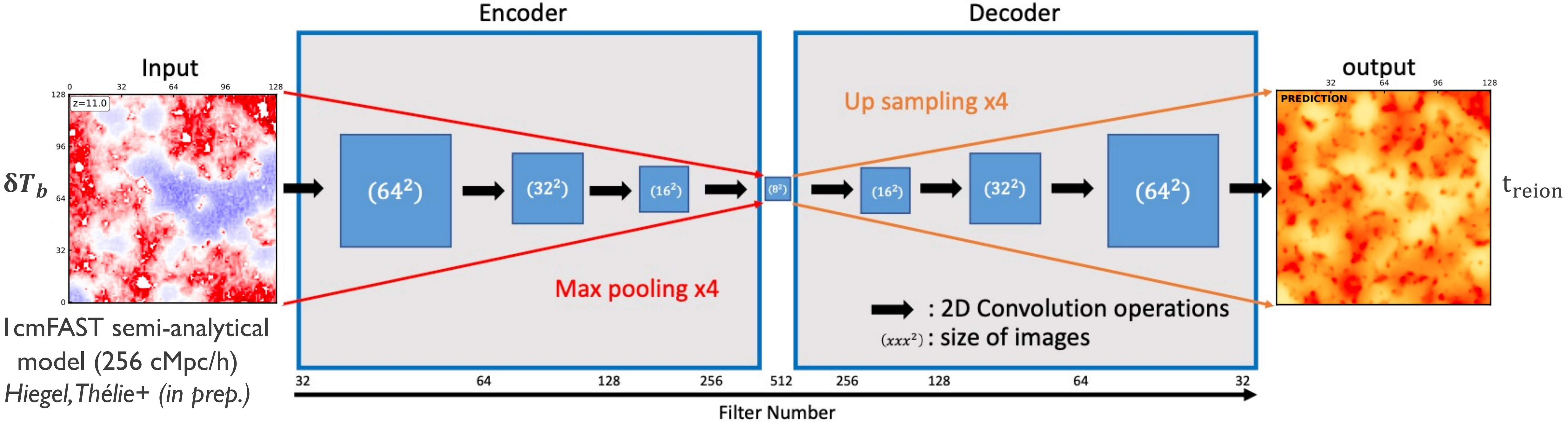


21cmFAST semi-analytical model (256 cMpc/h)

Hiegel, Thélie+ (in prep.)

A. 21 CM TO t_{reion}

Convolutional neural network (CNN)



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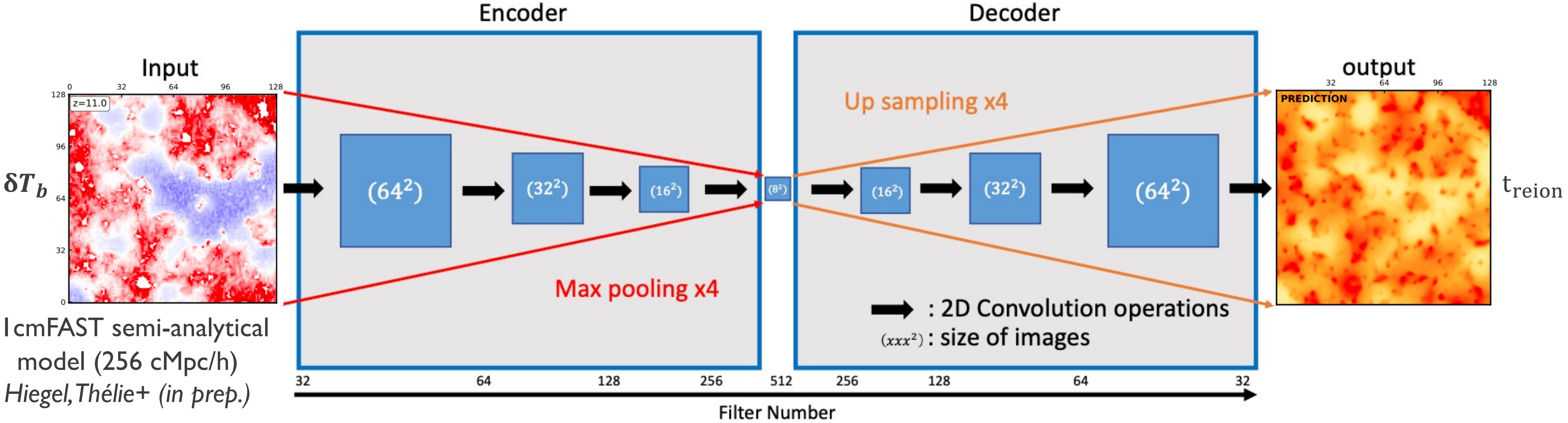
CNN

- Developed with Tensorflow and Keras
- U-net: 2 parts with the same number of images and filters
  - *Encoder = convolve and reduce dimension*
  - *Decoder = deconvolve and increase back to original dimension*

A. 21 CM TO t_{reion}

Convolutional neural network (CNN)



21cmFAST semi-analytical model (256 cMpc/h)
Hiegel, Thélie+ (in prep.)

CNN

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SIMULATIONS

- 50 21cmFAST semi-analytical simulations (256 cMpc/h)
- 2 models of reionisation with varying ionisation emissivity of galaxies $\zeta \in \{\mathbf{30}, 55\}$

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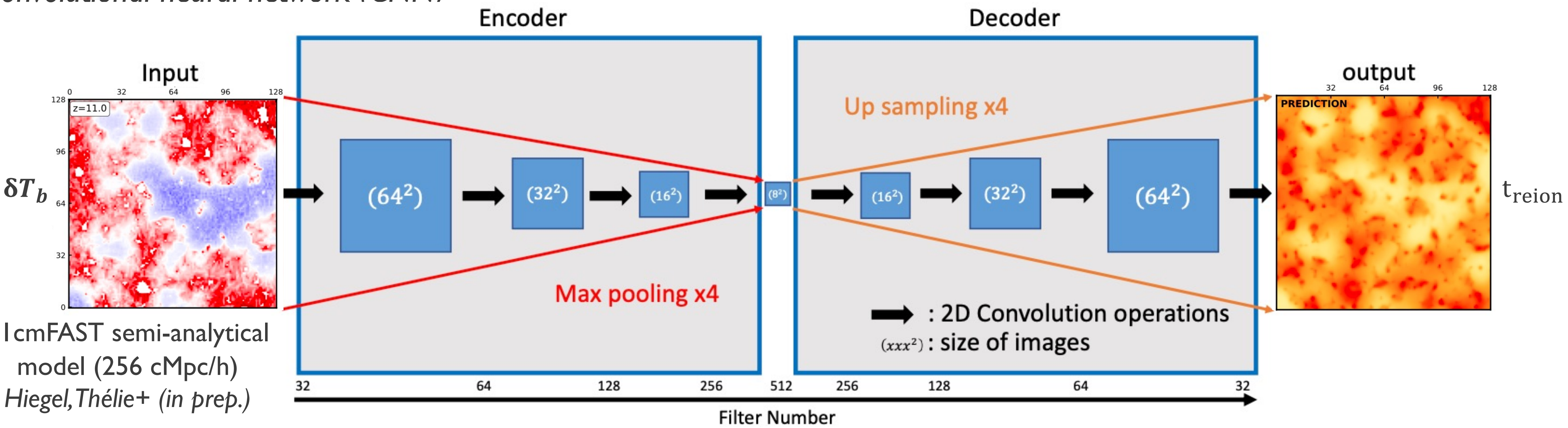

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SIMULATIONS

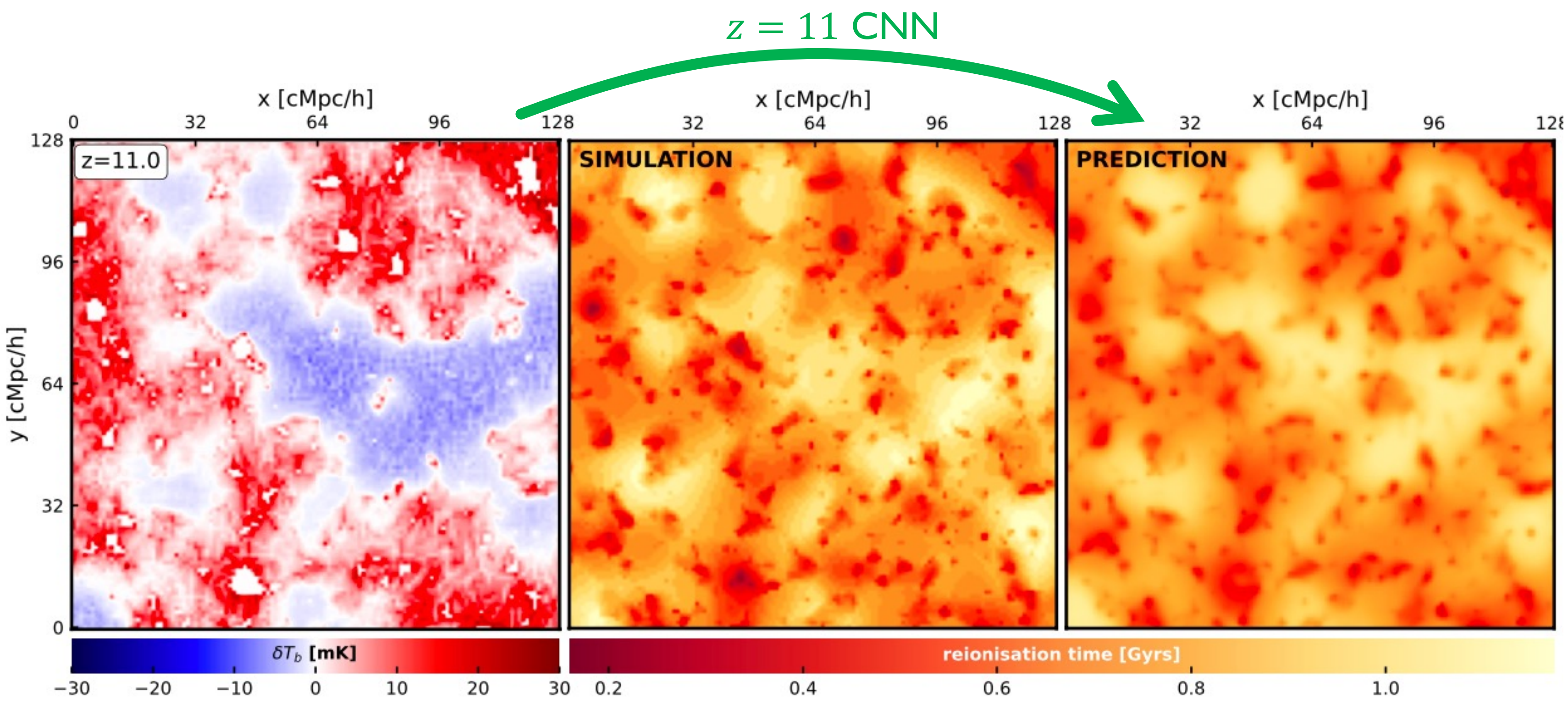
- 50 21cmFAST semi-analytical simulations (256 cMpc/h)
- 2 models of reionisation with varying ionisation emissivity of galaxies $\zeta \in \{\mathbf{30}, 55\}$

LEARNING

- One prediction per observational redshift
- 35,000 images:
  - *90% for the training set*
  - *10% for the test set*

A. 21 CM TO t_{reion}

Reconstruction of reionisation times from 21 cm signal maps



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- Example with $z_{obs} = 11$: less small structures but really close to the true map

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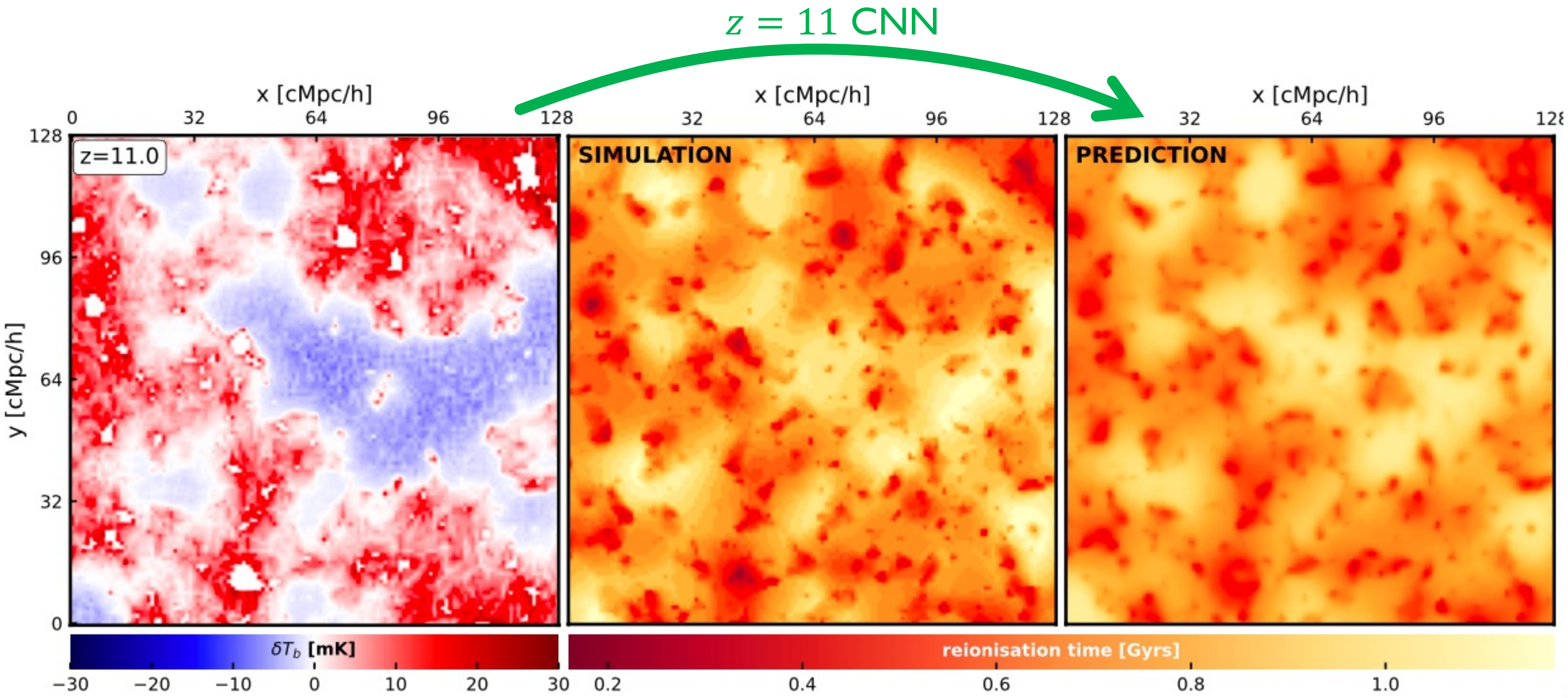

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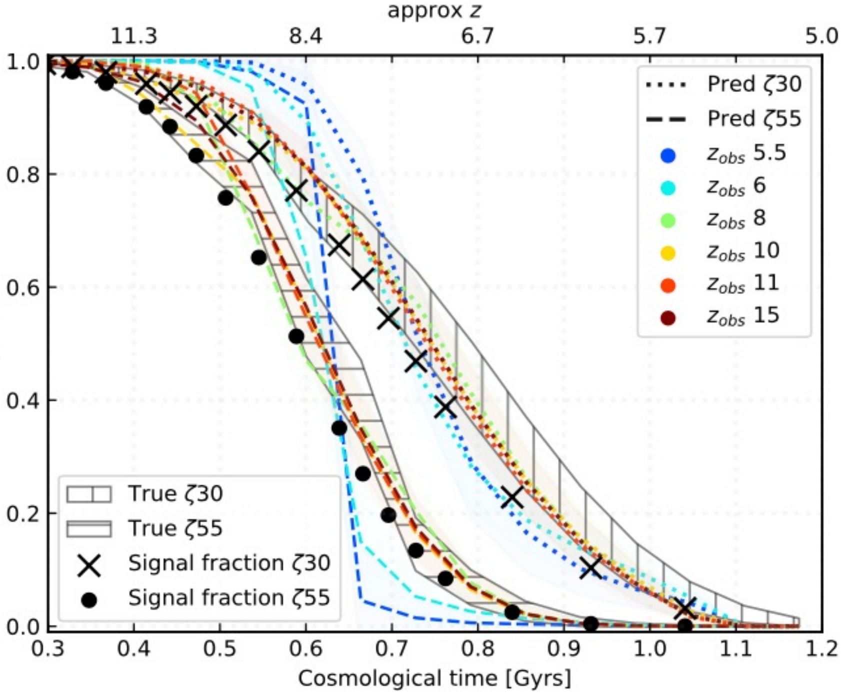
Hiegel, Thélie+ (in prep.)

Volume fraction of neutral gas

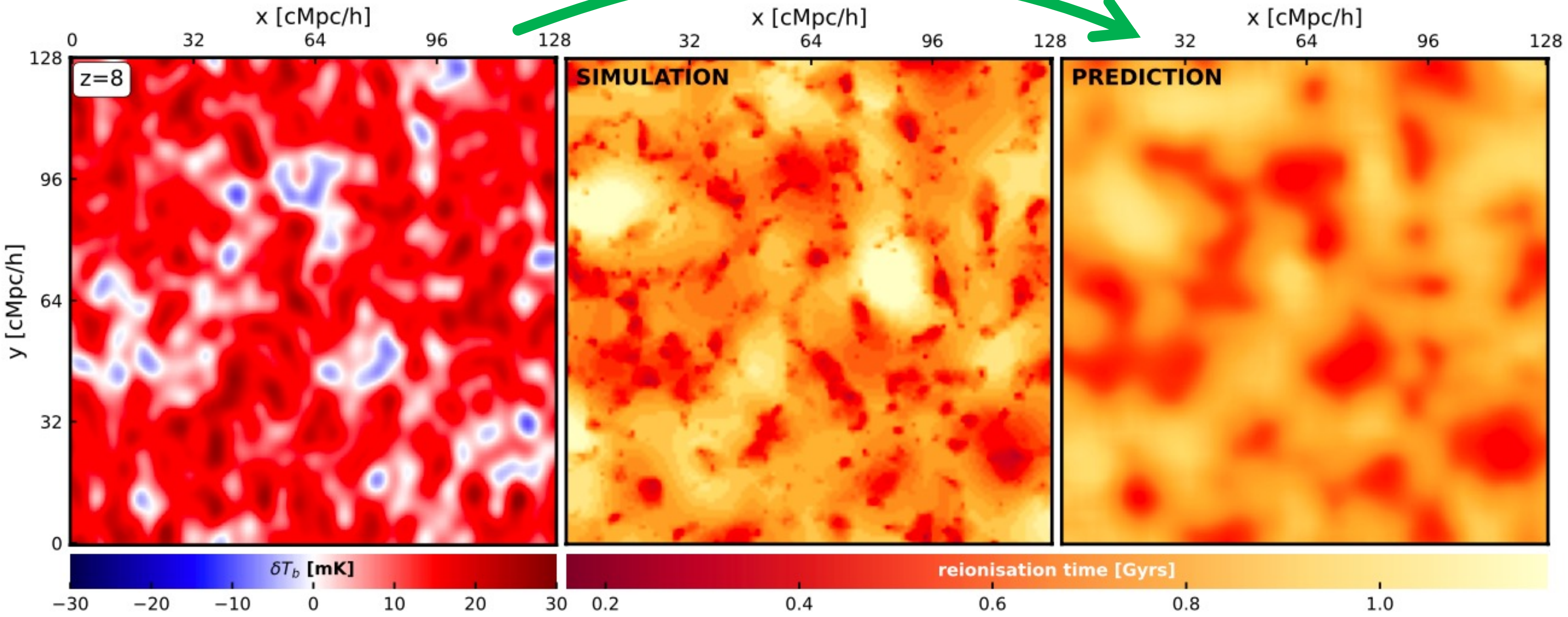


- Example with $z_{obs} = 11$: less small structures but really close to the true map
- Access to the **entire** reionisation history with a **unique** observational redshift: *reconstruction of the past and extrapolation of the future*

A. 21 CM TO t_{reion}

Reconstruction of reionisation times from 21 cm signal maps including instrumental noise

z =8 CNN



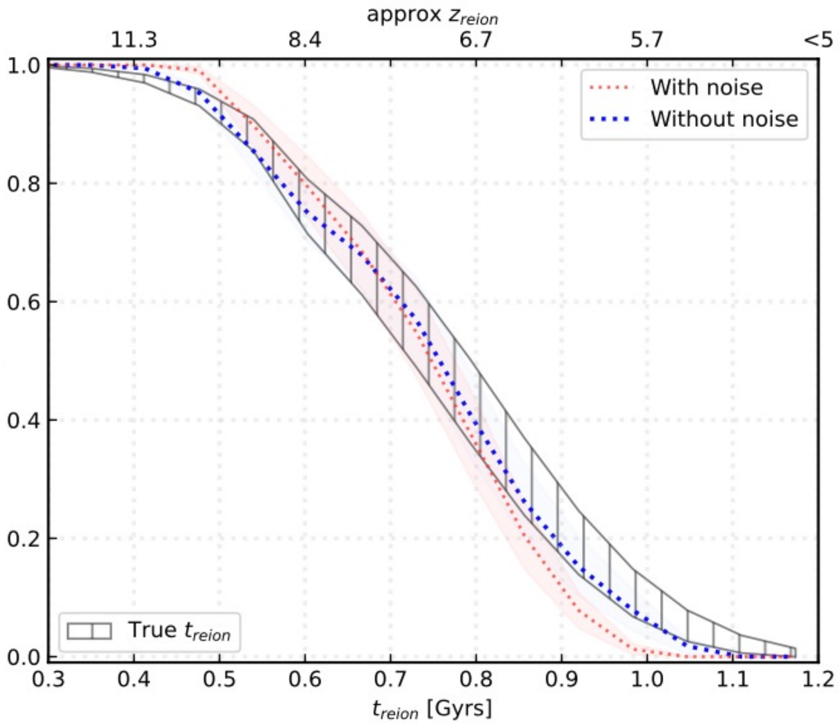
Noise characteristics (Tool21cm, Giri+20)

- Daily scan: 6h
- Integration time: 10s
- Number of observations hours: 1000h
- Maximum baseline: 2 km

21cmFAST semi-analytical model (256 cMpc/h)

Hiegel, Thélie+ (in prep.)

Volume fraction of neutral gas



WORK IN PROGRESS

- Example with $z_{obs} = 8$: reconstructed maps even more smoothed
- But statistics not that far away from reconstructions without noise

A. REIONISATION TIMES RECONSTRUCTED FROM THE 21 CM SIGNAL

Hiegel, Thélie+ (to be submitted)

B. PROPAGATION OF IONISATION FRONTS AROUND MATTER FILAMENTS

Thélie+22 (A&A)

C. REIONISATION TIMES: TOPOLOGY AND GAUSSIAN RANDOM FIELD (GRF) THEORY

Thélie+ (accepted for publication in A&A, arXiv: 2209.11608)

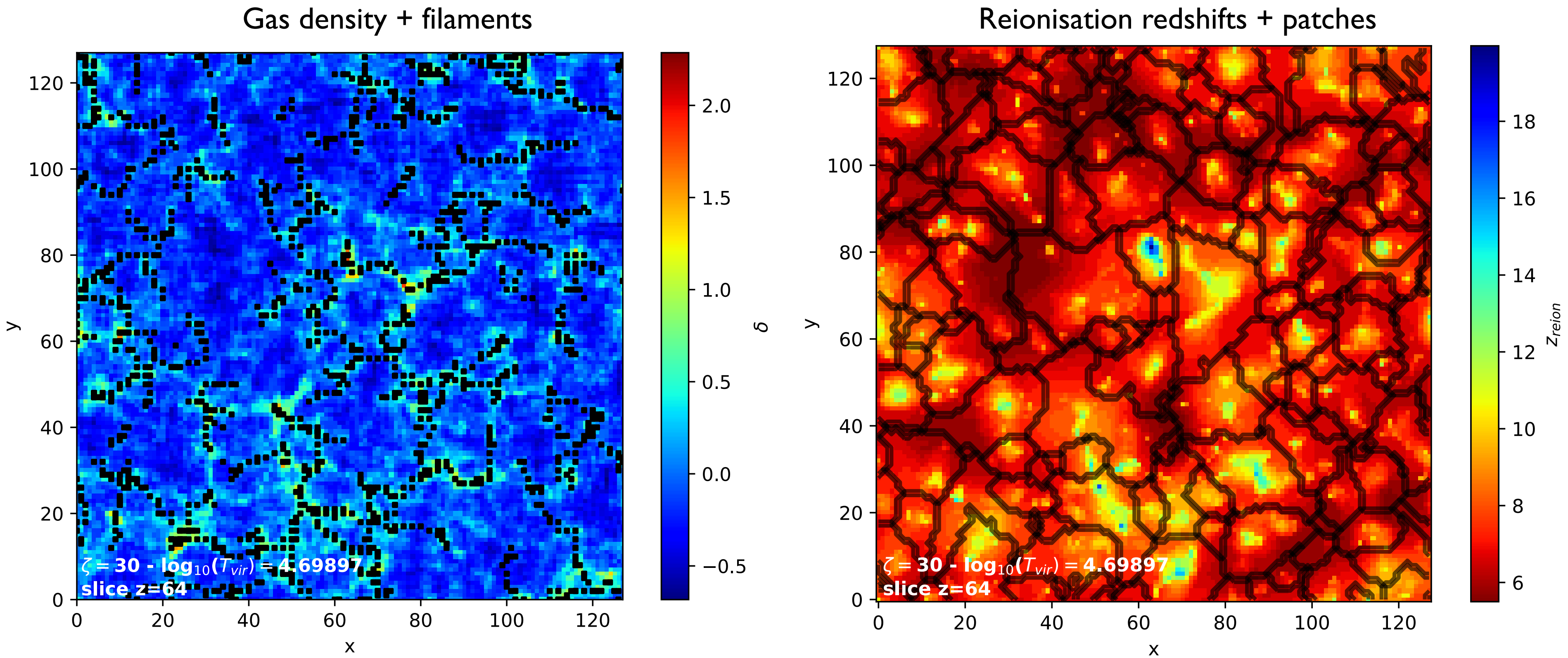
B. REIONISATION PATCHES

Propagation of ionisations fronts in 21cmFAST maps

How does the radiation from reionisation sources propagate?

Analysis of the **topology of reionisation redshifts** with **DisPerSE** (Sousbie+11):

- ***Radiative influence of reionisation sources on their environment****: orientation of reionisation patches with respect to the matter filaments*
- *Geometry of reionisation patches, percolation*



Maps from a 21cmFAST semi-analytical model (128 cMpc/h)

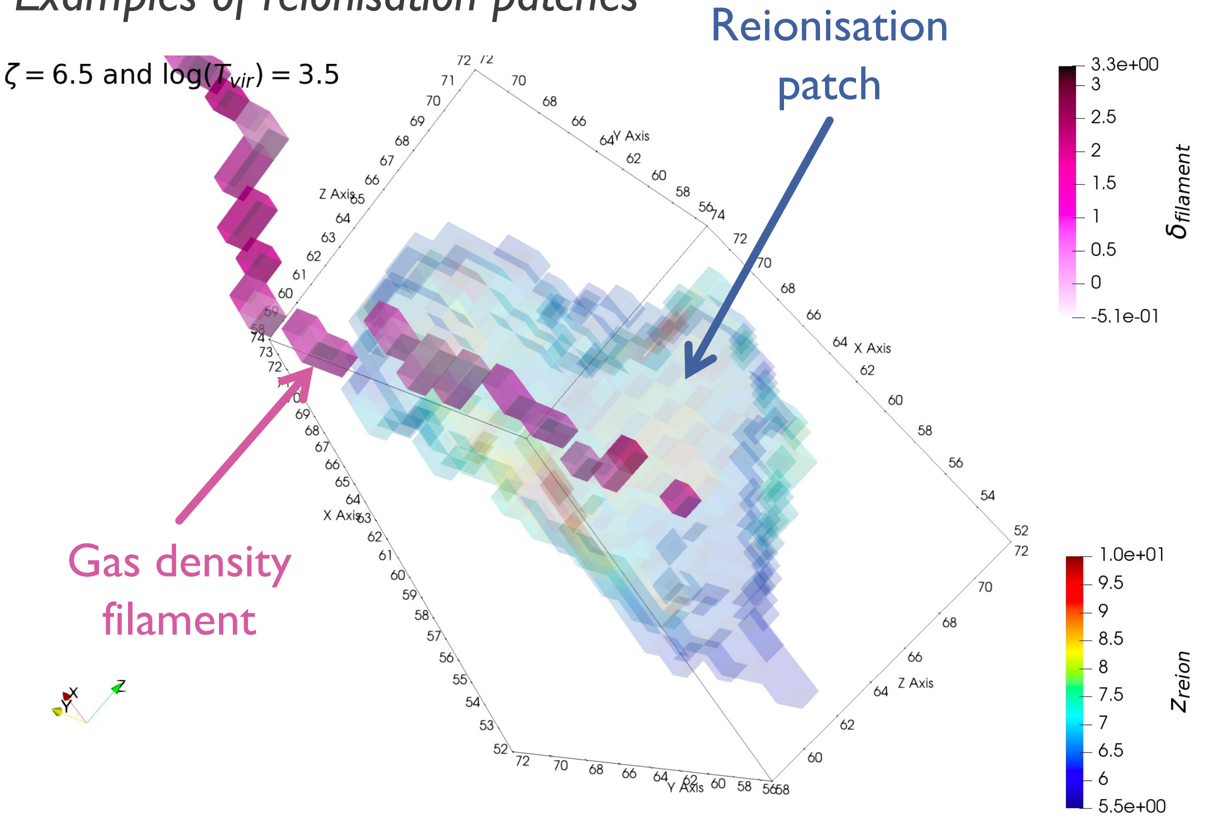
Thélie+ (2022)

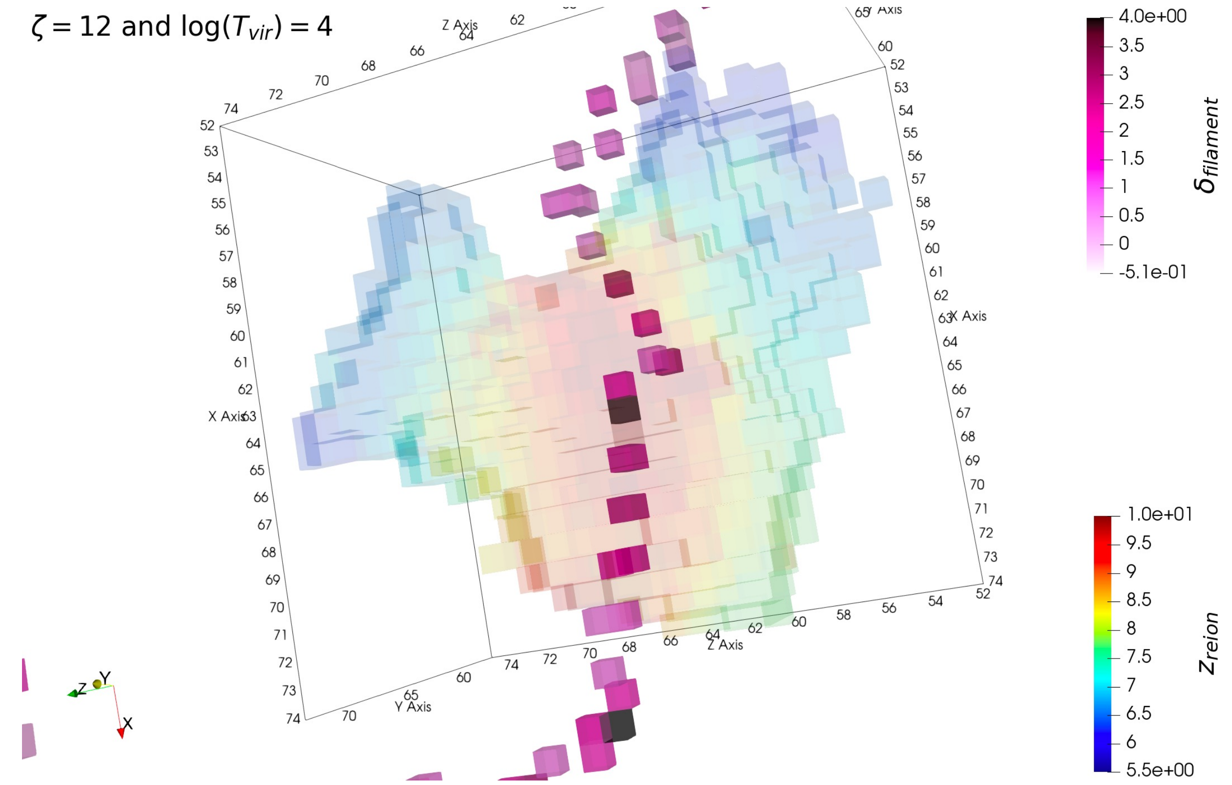
z_{reion}

- Maxima = *first places to reionise*
- *Propagation of ionisation fronts* along gradient lines
- Reionisation patches = *extension of radiative influence of the sources*

B. REIONISATION PATCHES

Examples of reionisation patches





From a 21cmFAST semi-analytical model (128 cMpc/h)
Thélie+ (2022)

Reionisation patch aligned with the filament
= *radiations follow the matter filament*

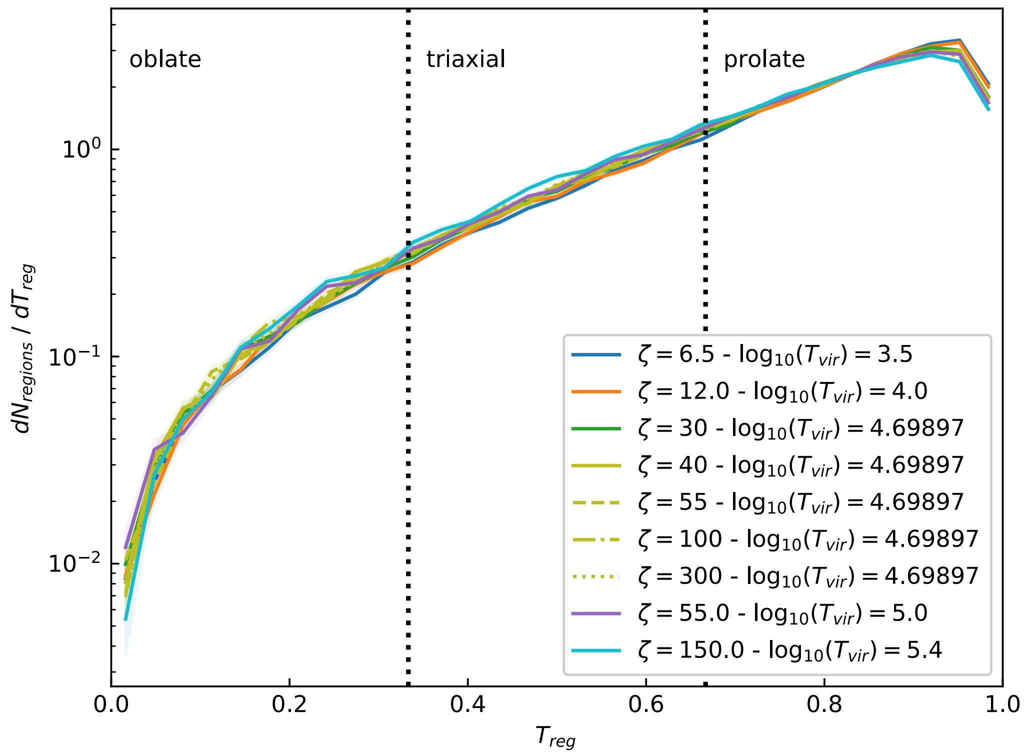
Reionisation patch in a butterfly shape
= *radiations follow the path of least resistance*

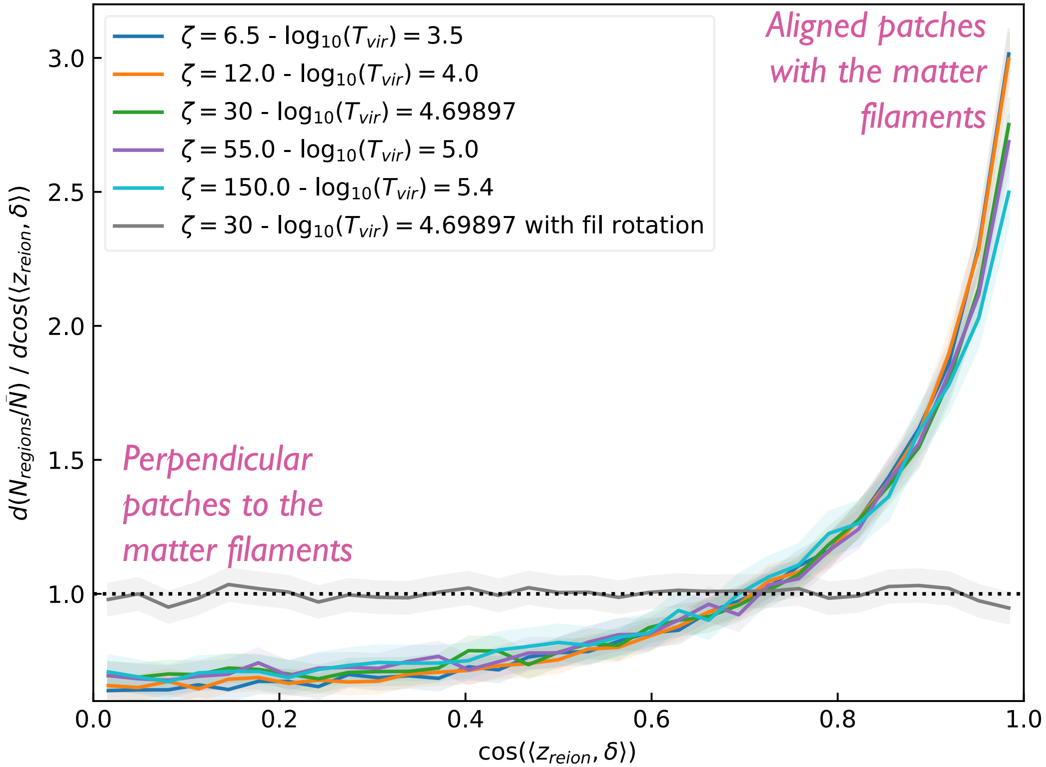
B. REIONISATION PATCHES

***Results**: orientation of patches with respect to filaments*

Reionisation patches shape

- Triaxiality parameter: $T = \frac{\lambda_3^2 - \lambda_2^2}{\lambda_3^2 - \lambda_1^2}$
- Majority of prolate patches



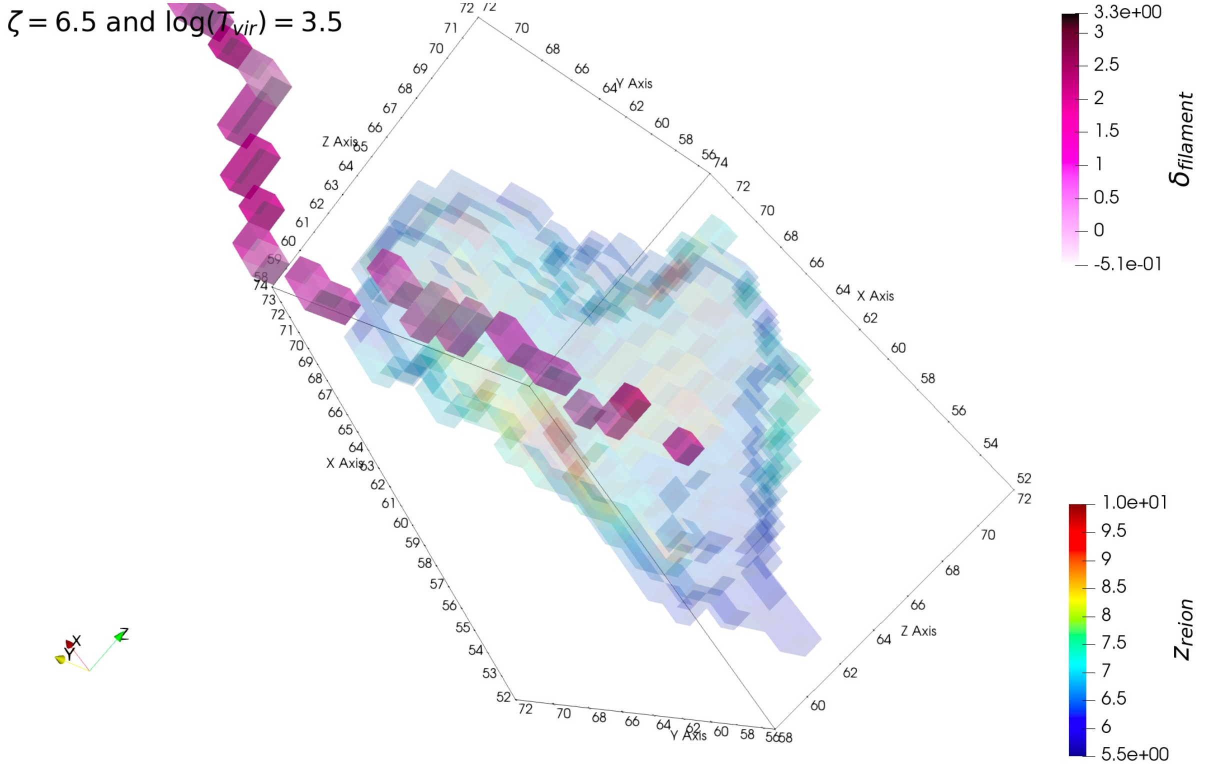


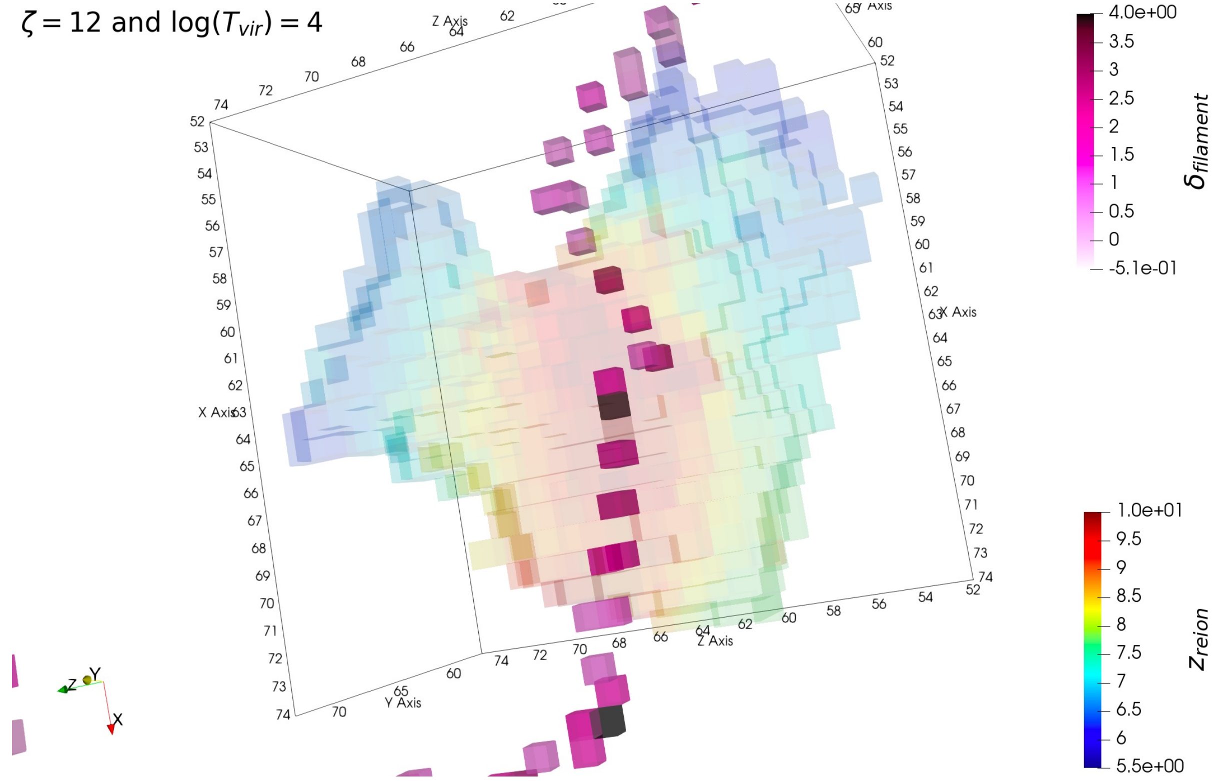
Orientation of reionisation patches with respect to matter filaments

- Majority of aligned patches to the matter filaments

B. REIONISATION PATCHES

***Results**: orientation of patches with respect to filaments*





From a 21cmFAST semi-analytical model (128 cMpc/h)

Thélie+ (2022)

DOMINANT CASE (47%)

Prolate-aligned patch

= beaded sources along the matter filament
(that supposedly have same properties of emissivity, age…)

UNDER-REPRESENTED CASE (2%)

"Butterfly" patch

= isolated and/or strong emitter driving reionisation

A. REIONISATION TIMES RECONSTRUCTED FROM THE 21 CM SIGNAL

Hiegel, Thélie+ (to be submitted)

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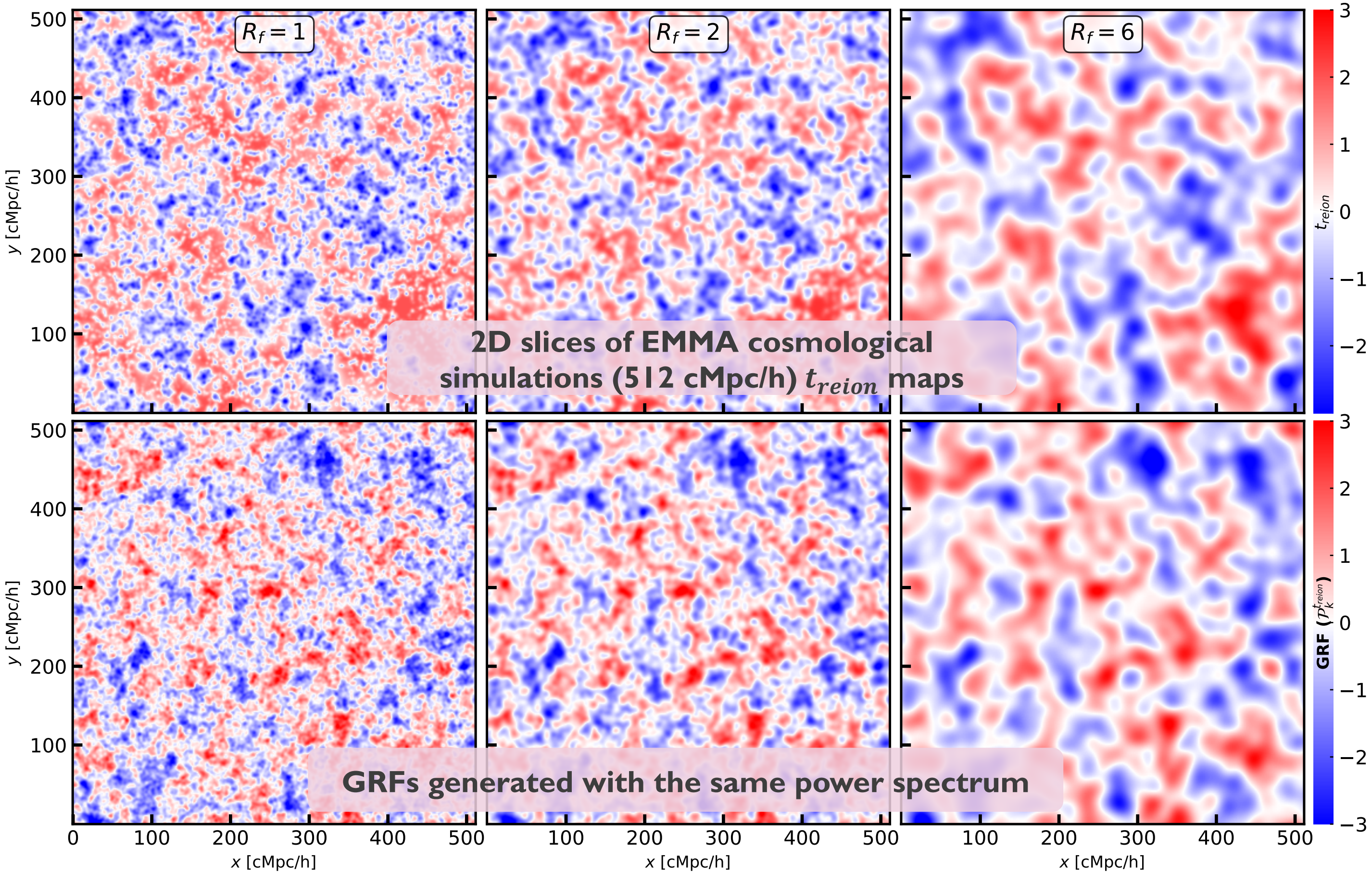
C. TOPOLOGY AND GRF THEORY

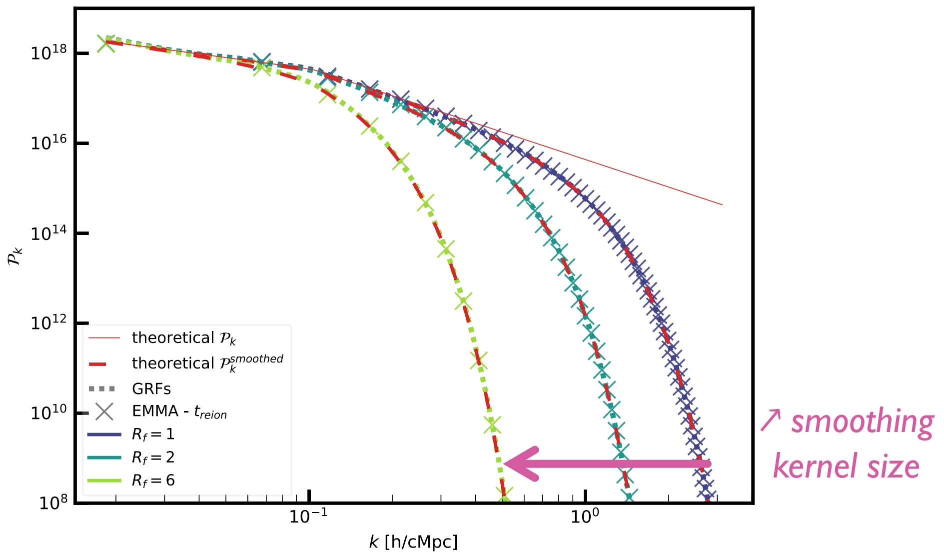
Characterisation of the evolving topology of the EoR

How to characterise the evolution of reionisation?

By using topological statistics that are…

- *… measurable in reionisation times maps,*
- *… predictable with GRF theory,*
- *… and entirely defined with the power spectrum of the gaussian field*





Thélie+ (arxiv:2209.11608)

6 data sets

- 100 EMMA maps of $t_{reion}(x, y)$
- 100 GRFs
- 3 different smoothings

C. TOPOLOGY AND GRF THEORY

Gaussian random fields theory *(Rice+44, Longuet-Higgins+57, Bardeen+86, Gay+12)*

Normalised gaussian field and its derivatives

Probability distribution functions (joint PDFs of the field/its derivatives)

Analytical predictions of statistics

Filling factor
= reionisation history

Filling factor of the gradient field norm
= ionisation fronts speed

Isocontour length
= evolution of the neutral/ionised bubbles size

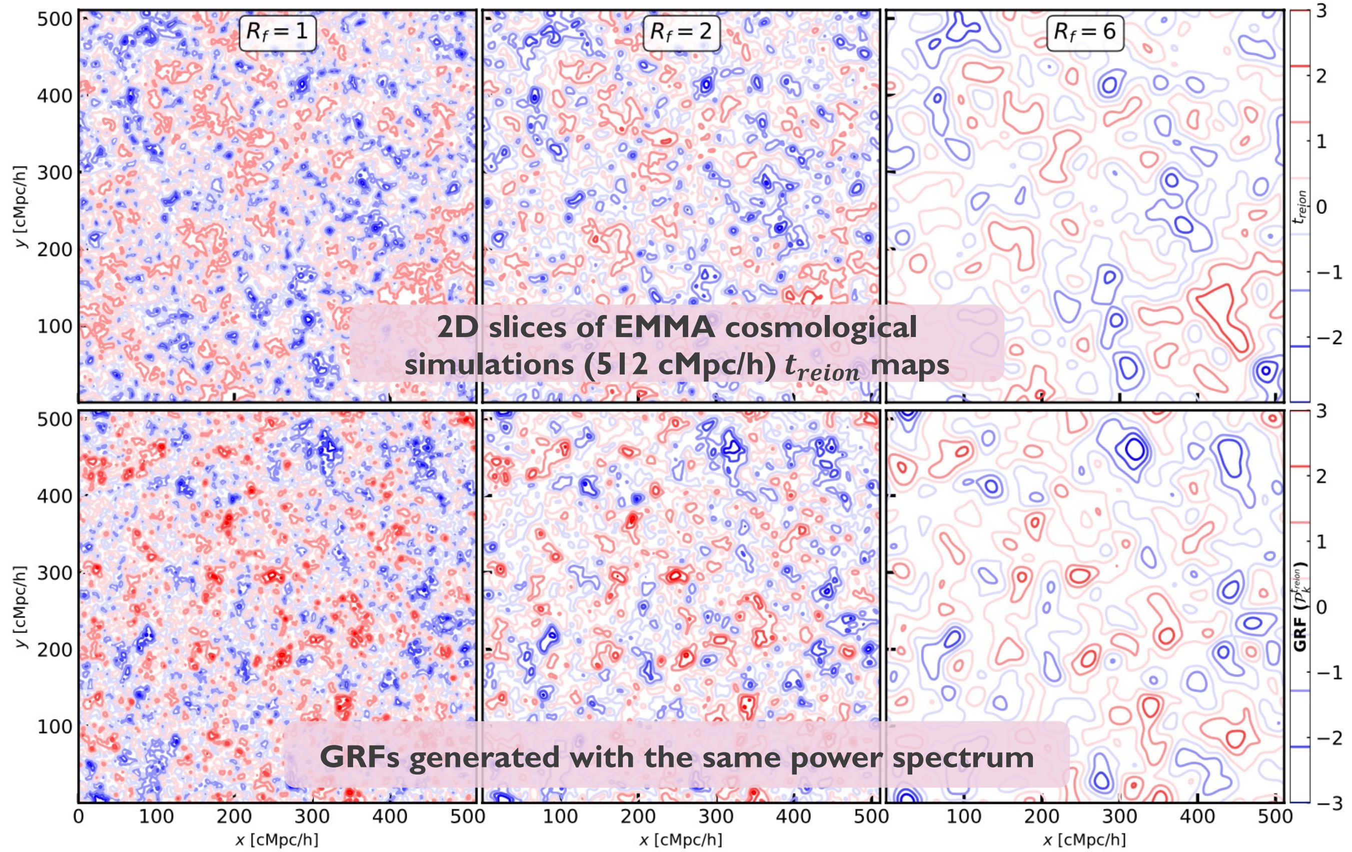
PDF of field values at its minima
= reionisation seed counts

Skeleton length
= places of percolation of the ionisation fronts

C. TOPOLOGY AND GRF THEORY

Simulation measurements & GRFs predictions

- Isocontours = regions reached by ionisation fronts at the same time
  → follow the size evolution of ionised/neutral bubbles
- **EMMA measurements close to gaussian predictions**



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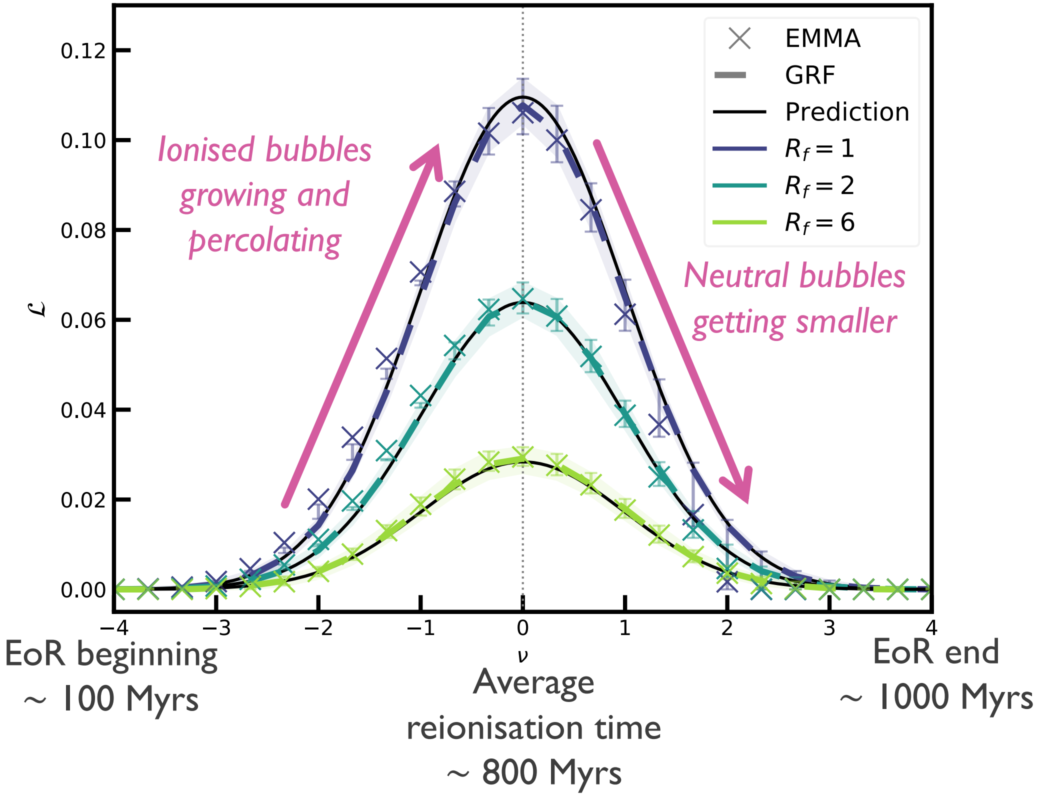

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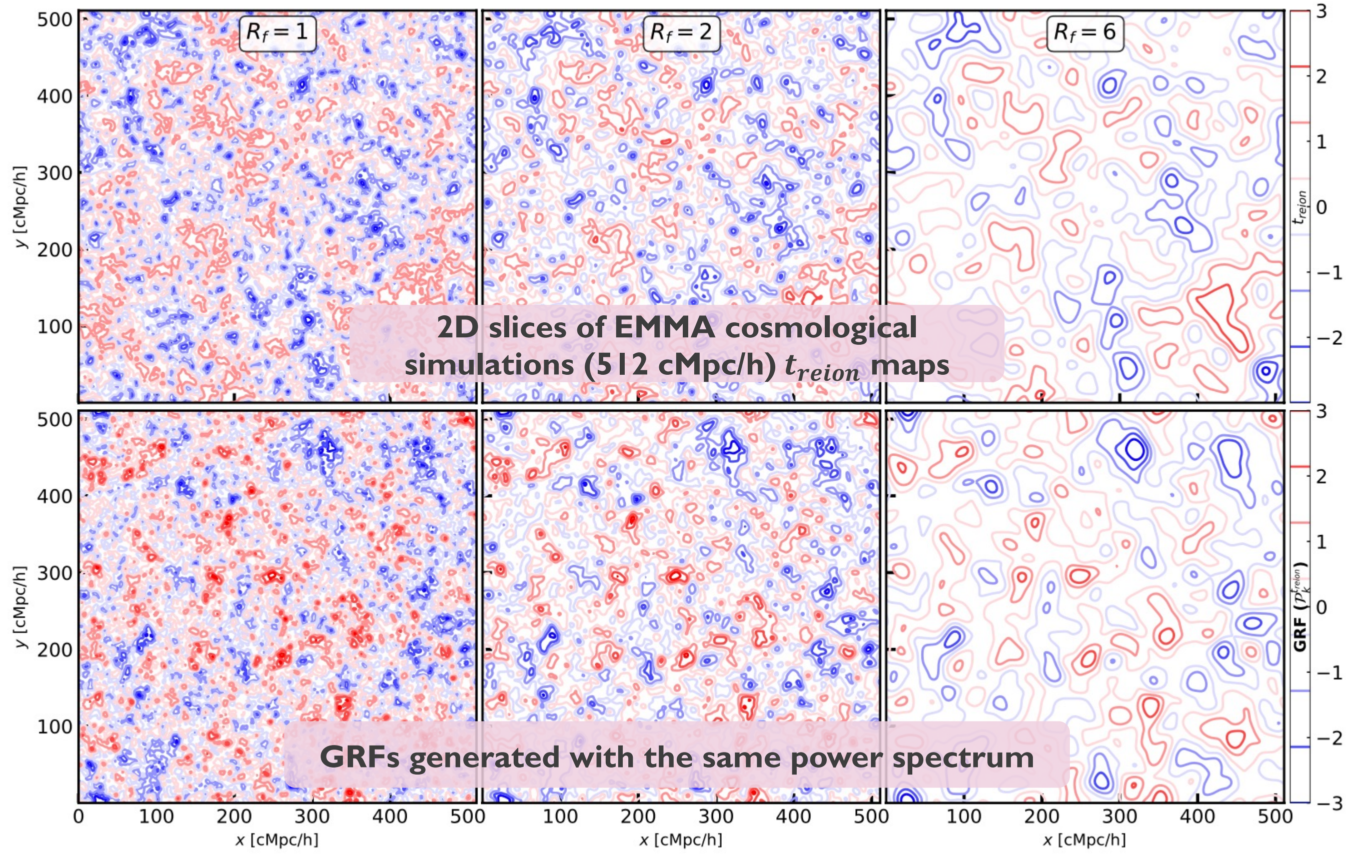

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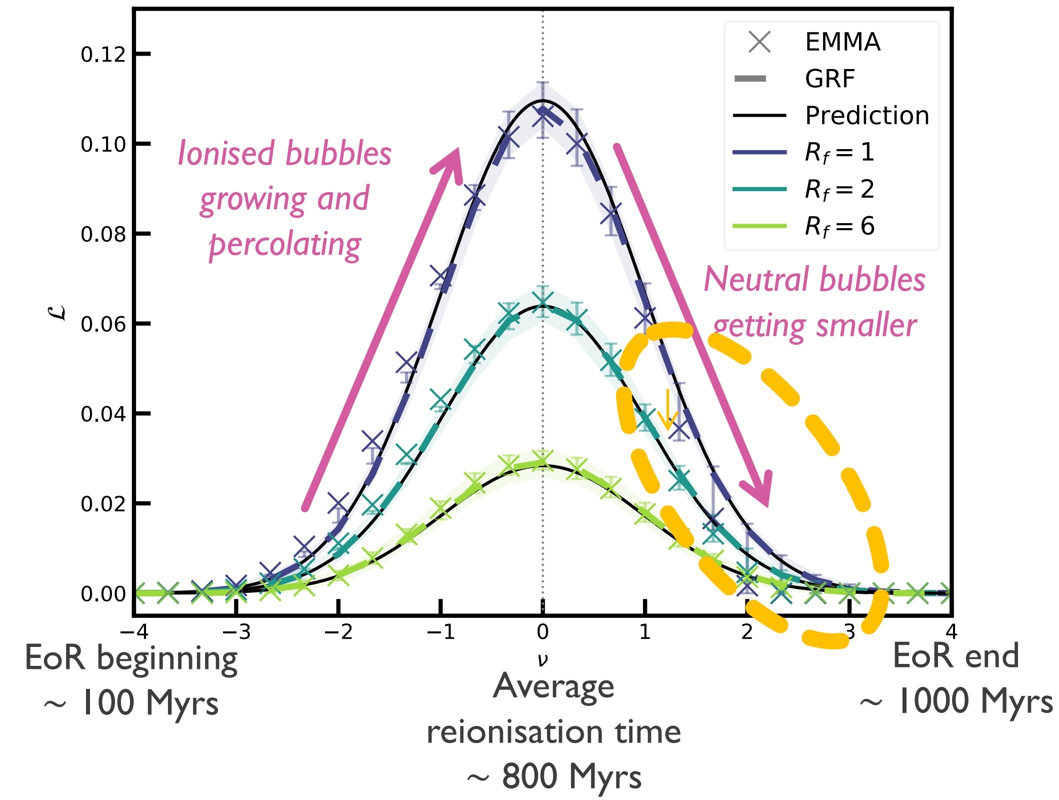
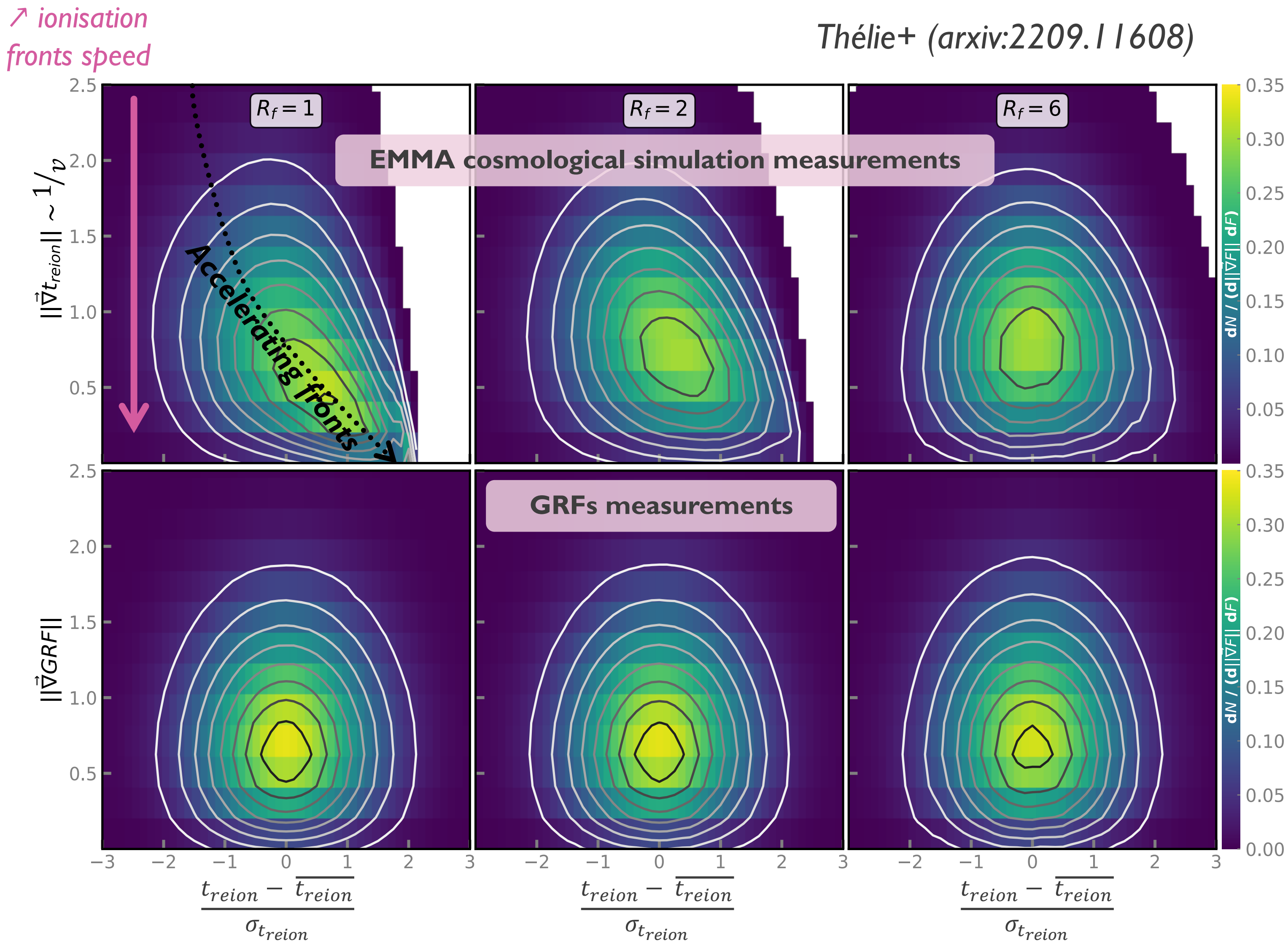


C. TOPOLOGY AND GRF THEORY

Simulation measurements & GRFs predictions

- **EMMA measurements close to gaussian predictions**
- **When $R_f \nearrow$:** EMMA measurements more symmetric
- $R_f \in \{1, 2\}$ **:** asymmetry (non-gaussianity)
  - *Slow reionisation before it accelerates*
  - *Acceleration of ionisation fronts at the end of the EoR*

Thélie+ (arxiv:2209.11608)



CONCLUSIONS & PERSPECTIVES

How does the EoR happen?

Topological studies to analyse:

- *Growth of structures*
- *Ionised/neutral bubbles geometry, distribution, organisation*
- *Percolation, evolution of the process*

Reionisation times

- Geometrical characterisation of different EoR model
- Comparisons of cosmological and semi-analytical simulations

A. 21 CM → t_{reion}

- Good reconstruction of reionisation times map, even if they are a little bit smoothed (with and without noise)
- Best reconstructions with observed redshifts $8 < z < 12$

B. Reionisation patches

- Beaded sources along the matter filaments
- Minority of butterflies (isolated sources or strong emitters)

C. Reionisation times: topology and GRFs theory

- Diverse statistics on the evolution of the reionisation process…
- … that are analytically computable t_{reion}

CONCLUSIONS & PERSPECTIVES

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A. 21 CM → t_{reion}
- Good reconstruction of reionisation times map, even if they are a little bit smoothed (with and without noise)
- Best reconstructions with observed redshifts $8 < z < 12$

- Improving the neural network to reconstruct well the small scales
- Topological analyses of the CNN reconstructions t_{reion} maps

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C. Reionisation times: topology and GRFs theory
- Diverse statistics on the evolution of the reionisation process…
- … that are analytically computable t_{reion}

- Take into account the asymmetries in the GRFs predictions (e.g. with Gram-Charlier expansion)
- Same study but with larger or more resolved simulations (e.g. with Dyablo)
- Inference of the power spectrum parameters from topological measurements

Thank you for your attention!

INTRODUCTION

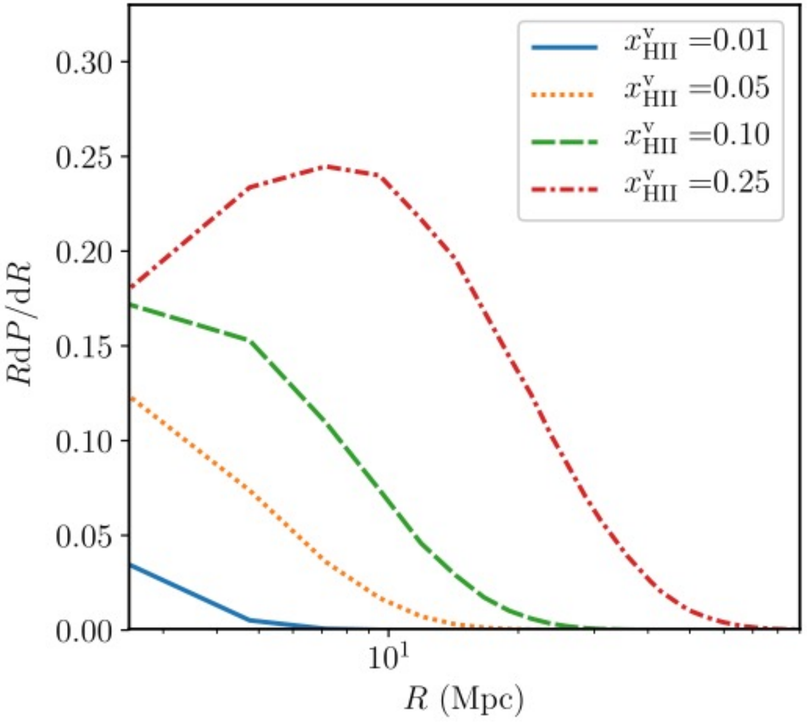
Topology of the reionisation process

Size of neutral and ionised bubbles
… with diverse methods (e.g. mean free path in Giri+19, spherical averages in Giri+18)

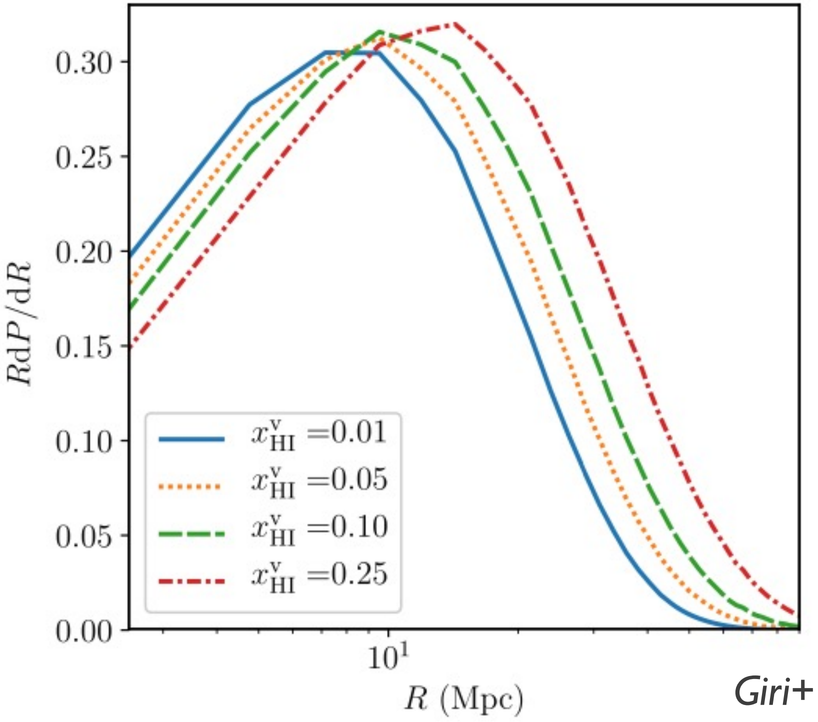
Analyses of spatial structures
… with 21 cm power spectra (e.g. Gazagnes+21) and bispectra (e.g. Hutter+20)

Counts of 3D structures like peaks, tunnels and voids
… with Betti numbers and Euler characterstic (e.g. Giri+20, Bianco+21)

Ionised bubble size distribution (BSD)



Neutral island size distribution (ISD)



Giri+19

- BSD → early phases of the EoR
  ISD → late phases of the EoR
- BSD/ISD are **different depending on the way to measure it**: they give different information on the size properties of bubbles.

INTRODUCTION

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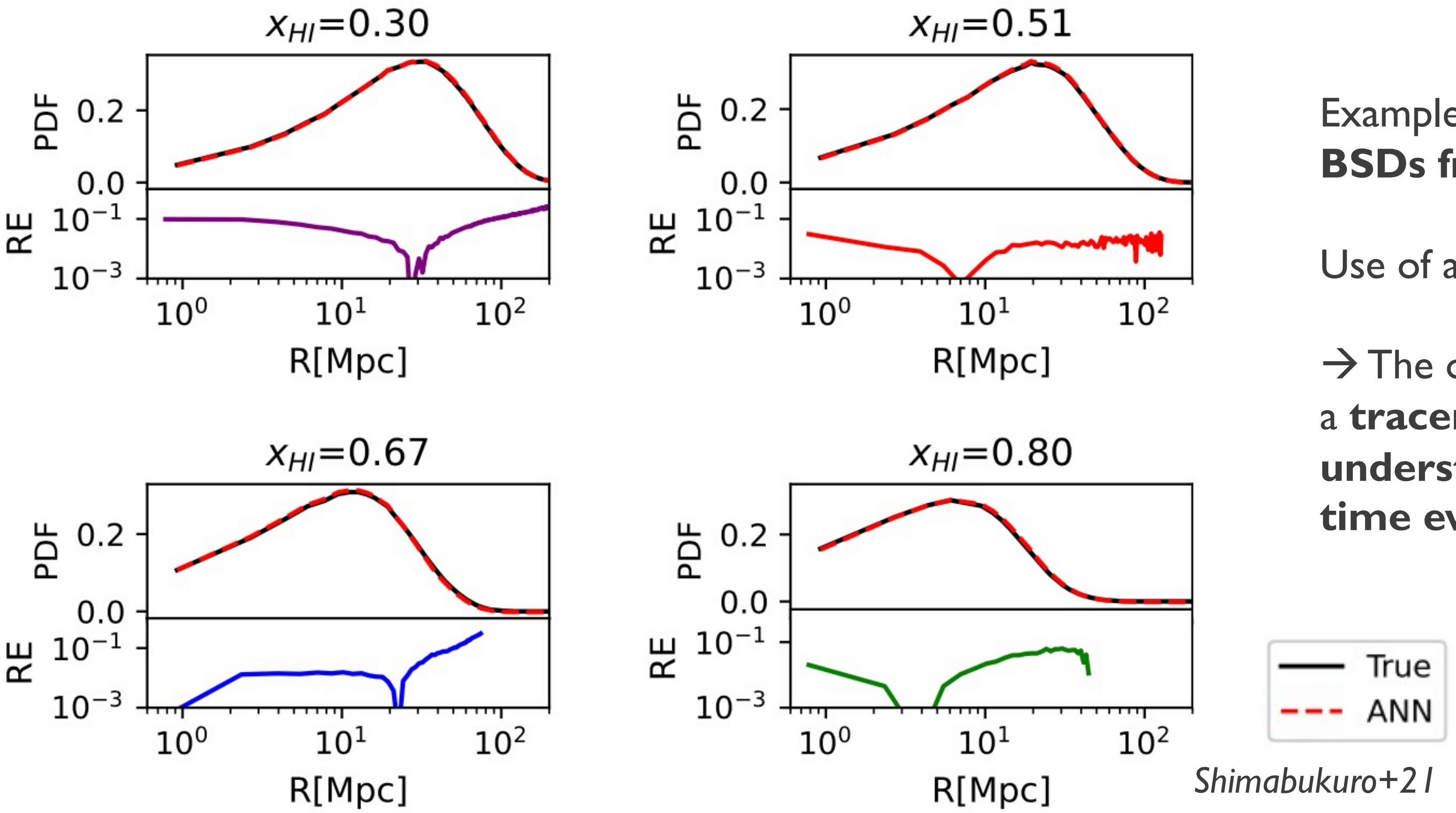

Shimabukuro+21

Example of (model dependent) **predictions of BSDs from the 21 cm power spectrum**.

Use of an **artificial neural network** (ANN).

→ The observed 21 cm power spectrum will be a **tracer of the BSD**, which will help us to **understand the bubble geometry and its time evolution**.

INTRODUCTION

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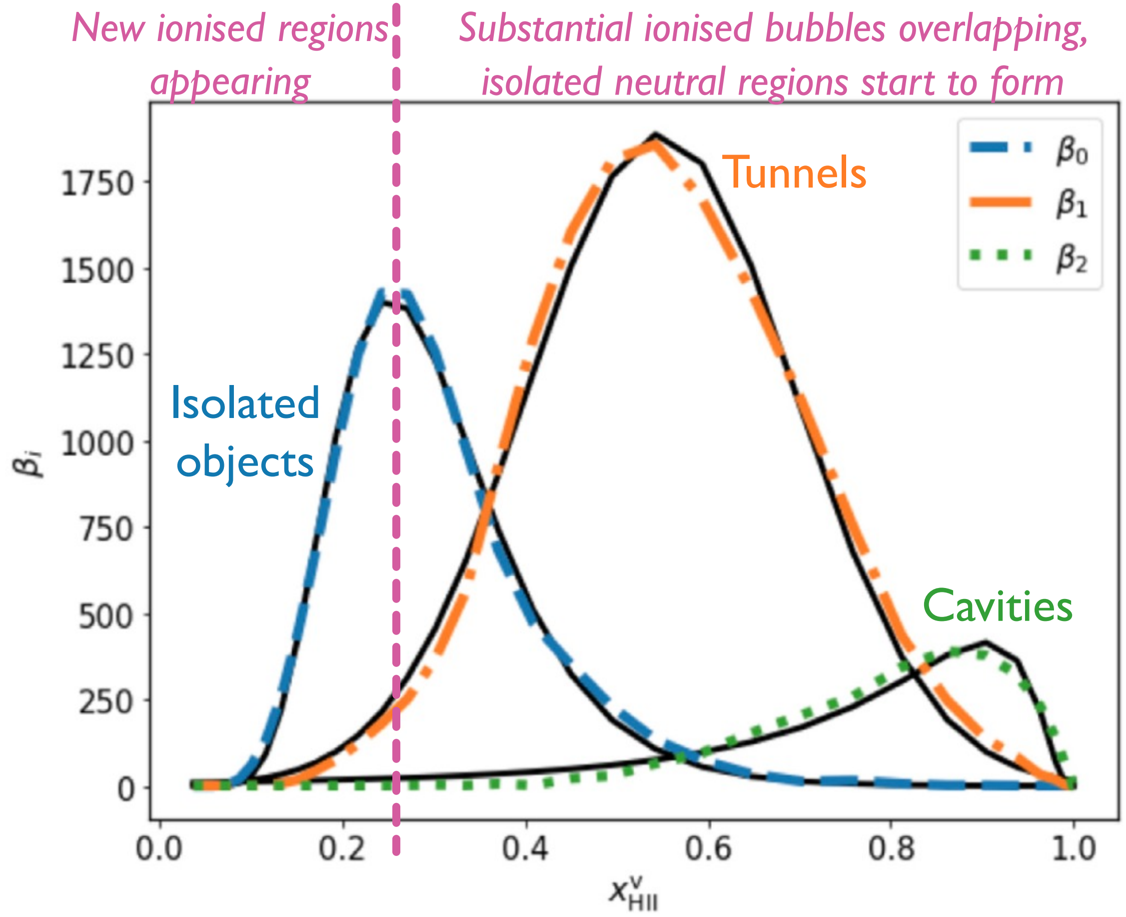


Giri+21

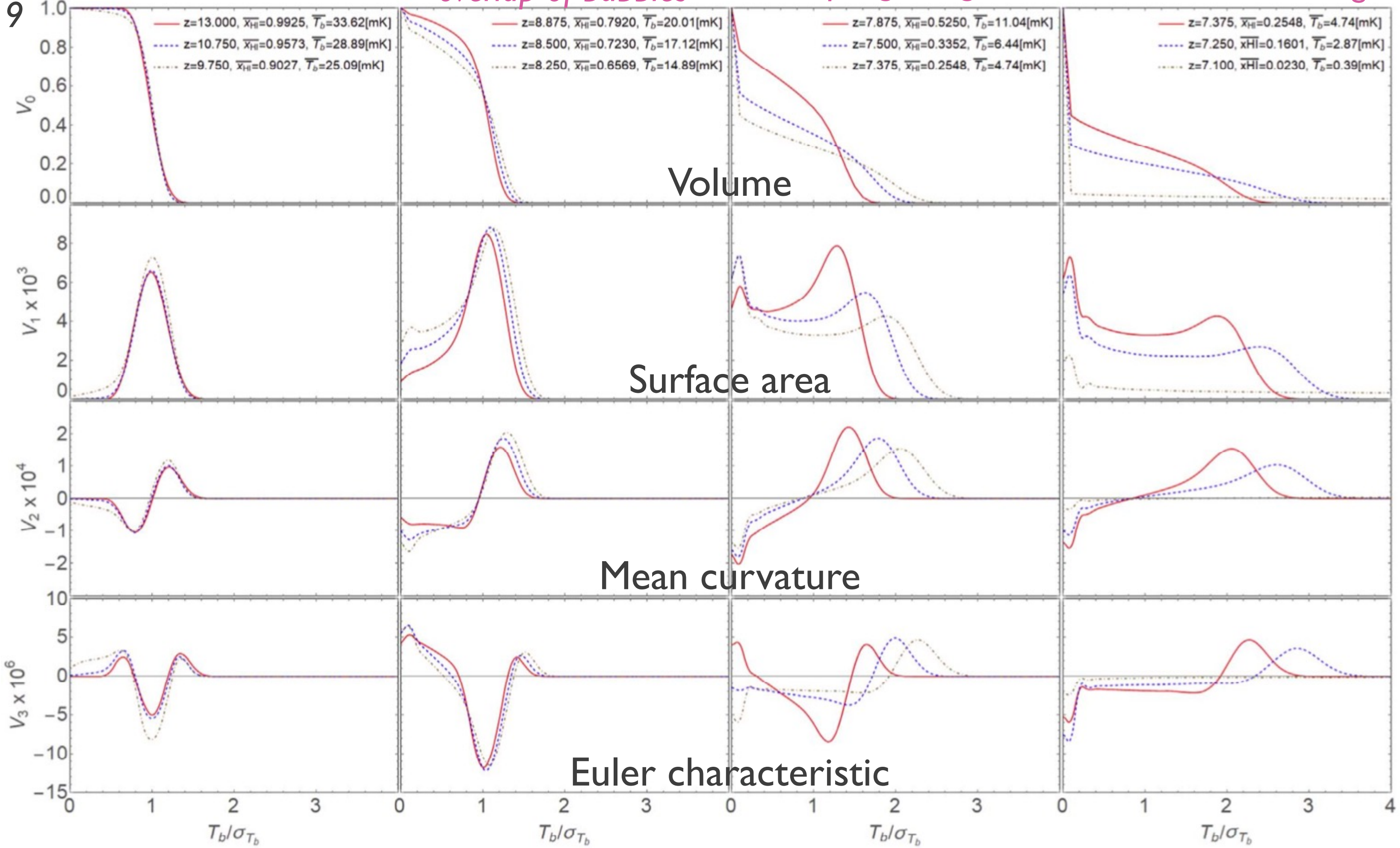
- β_k = rank of the k_{th} homology group → number of connected components, 1D holes, 2D cavities…
- They trace the **evolution of the HII regions topology**.
- They can be parametrized as a function of $x_{H_{II}}$ (Giri+19).
- They are more informative than the Euler characteristic $\chi = \beta_0 - \beta_1 + \beta_2$.

INTRODUCTION

Topology of the reionisation process

Ionised bubbles stage | *Ionised fibres stage + percolation and overlap of bubbles* | *Sponge stage* | *Neutral fibres stage + neutral islands stage*

Chen+19



Geometry of bubbles and percolation…

- … with Minkowski functionals (e.g. Friedrich+11, Chen+19)
- … with the triangle correlation function (Gorce+19)

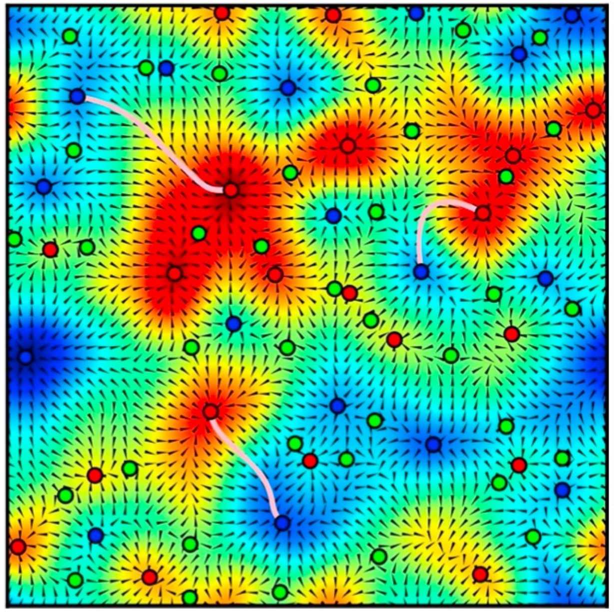
- Minkowski functionals are measurements of **topological features** (e.g. volume…) **of regions exceeding a given threshold**.
- With them, we can **follow the time evolution of the EoR**, through **different phases**.

INTRODUCTION

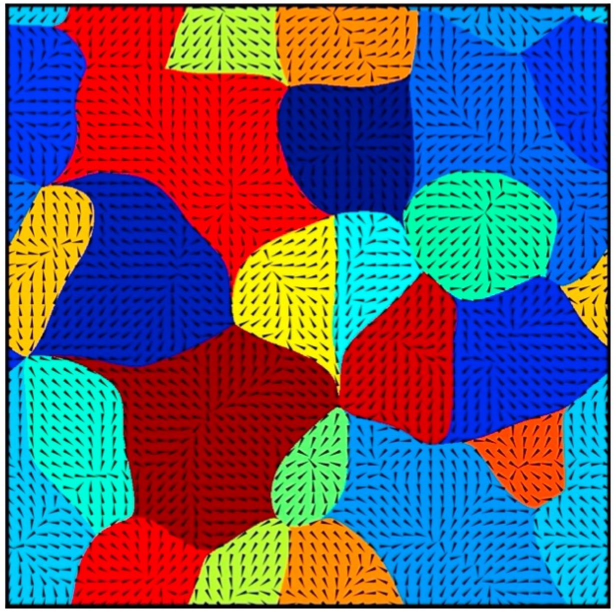
Topology of the reionisation process with DisPerSE

Discrete Persistent Structure Extractor (Sousbie+11)

- Morse theory and persistent homology
- Extracts topological features from a field thanks to a mathematical approach

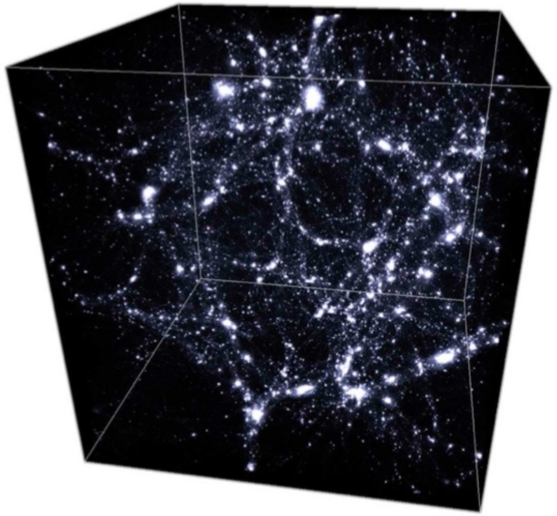


2D field
with its gradients and critical points

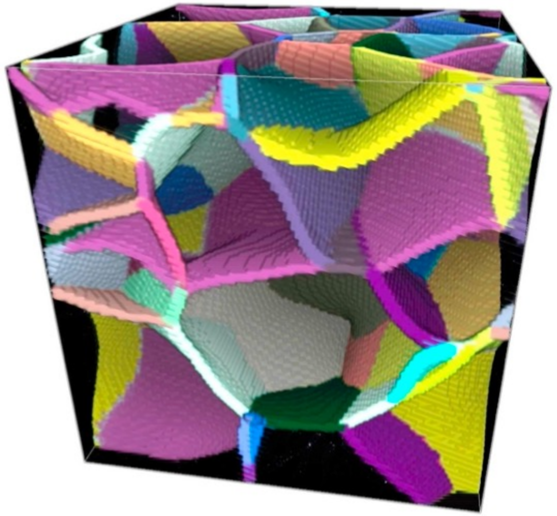


Maxima patches

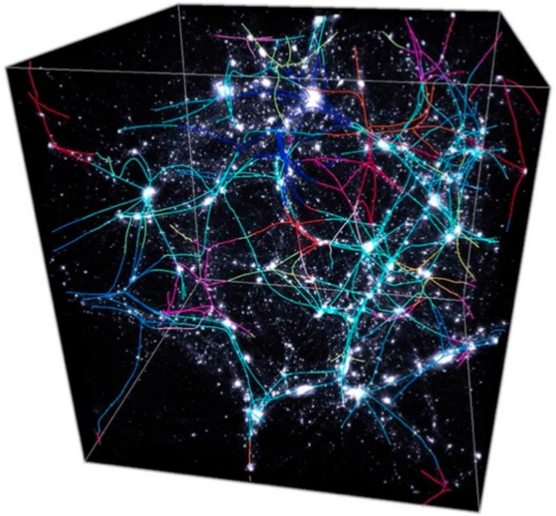
Dark matter density



Voids



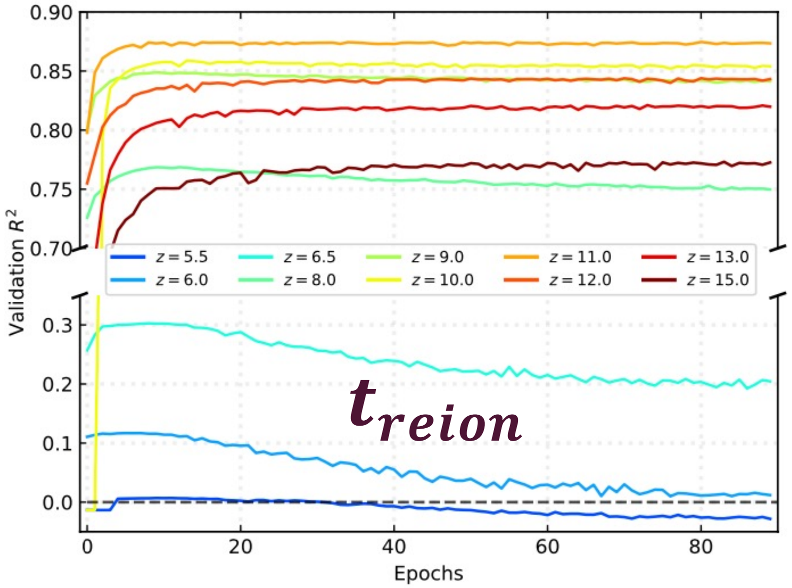
Walls

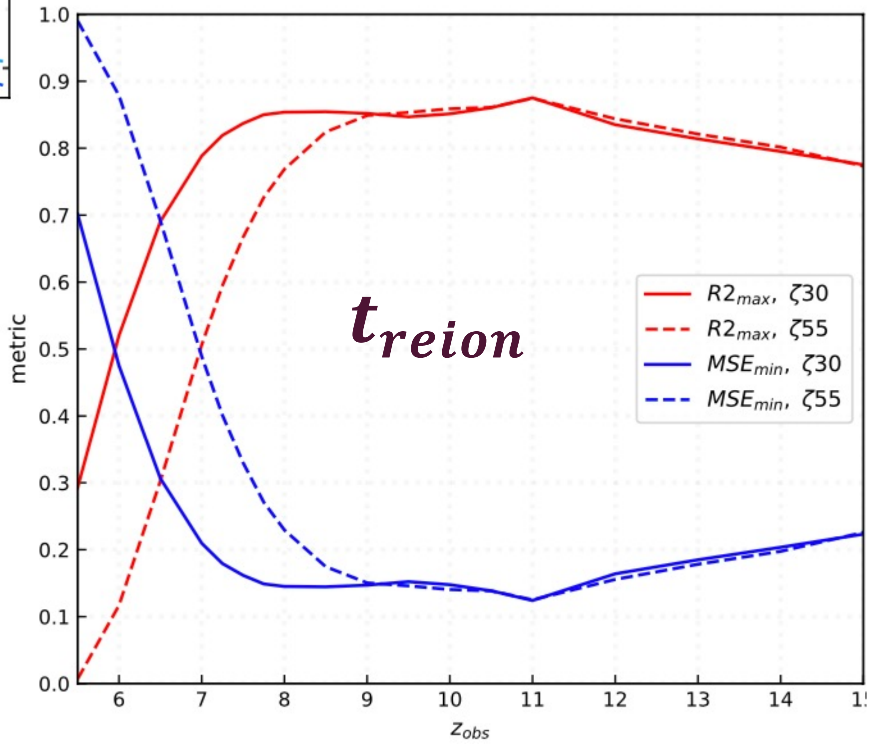


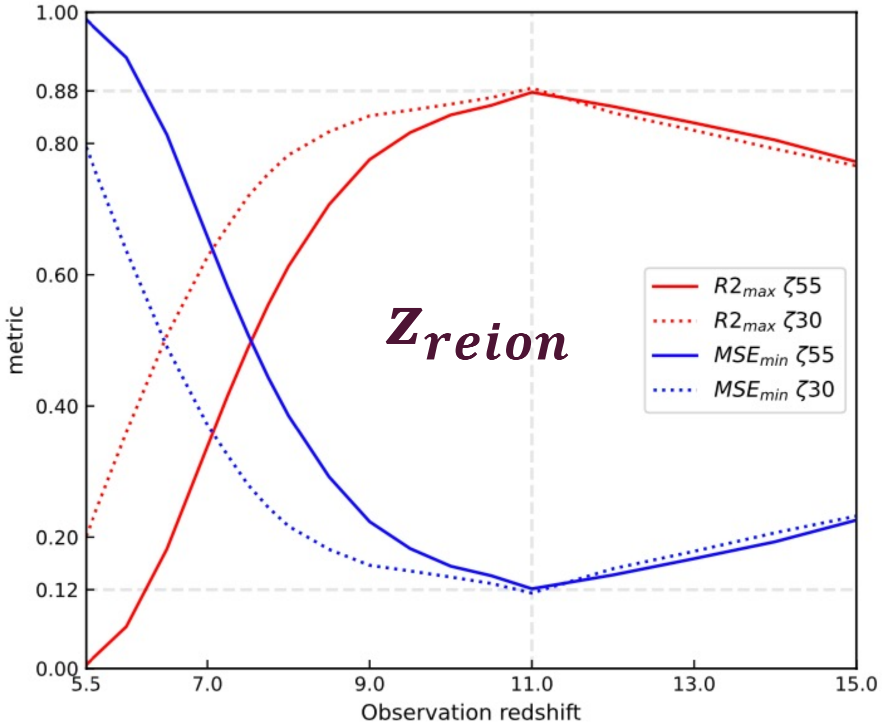
Filaments

A. 21 CM → t_{reion}

Monitoring performances of the CNN







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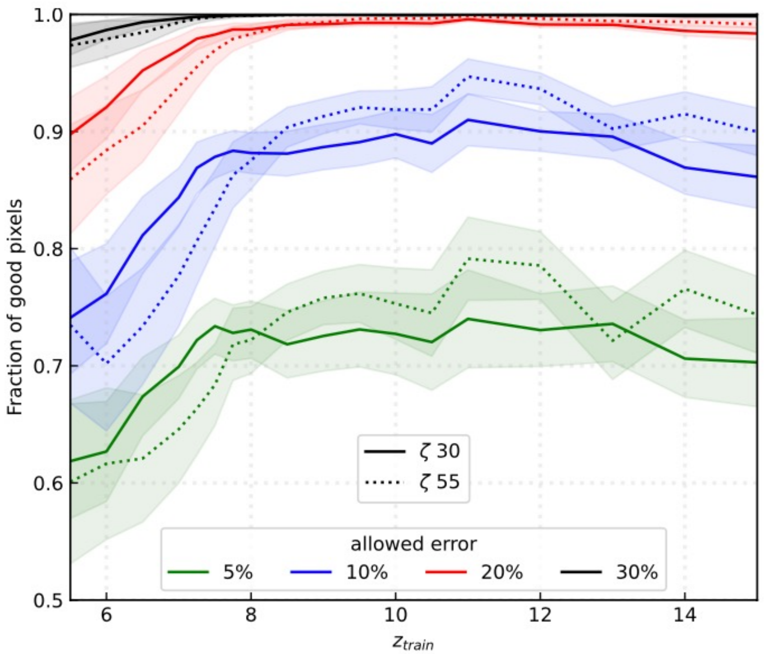

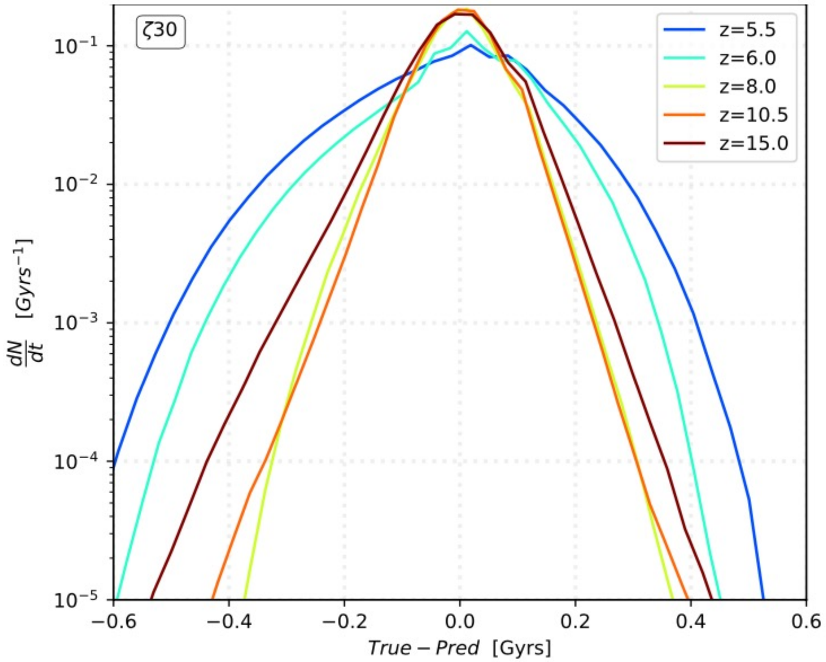

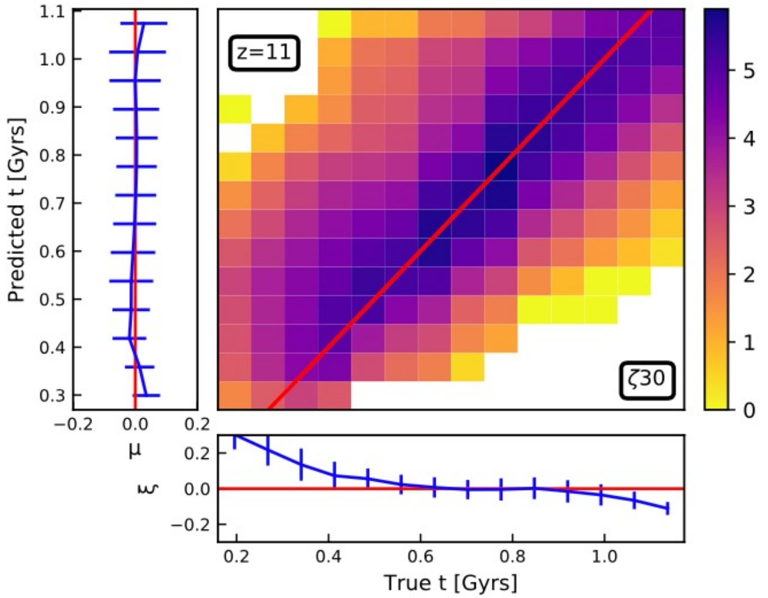

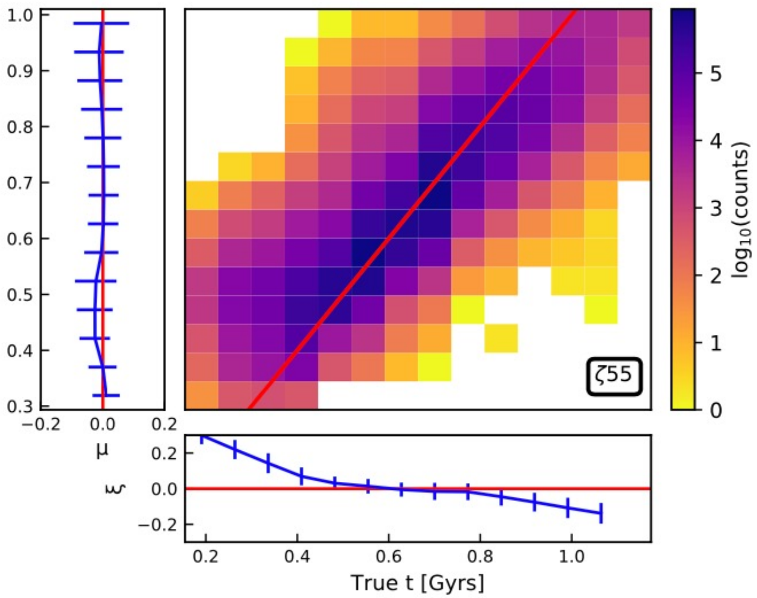

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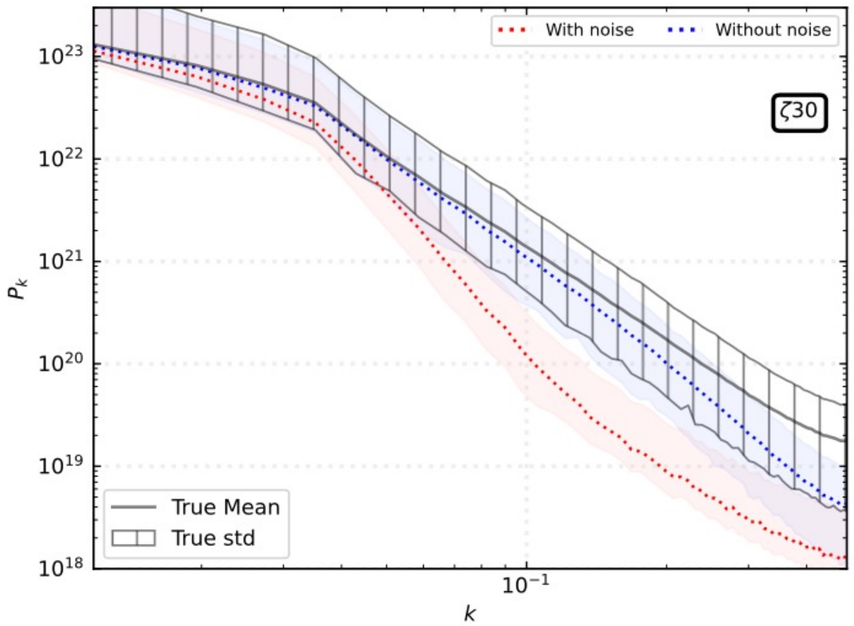
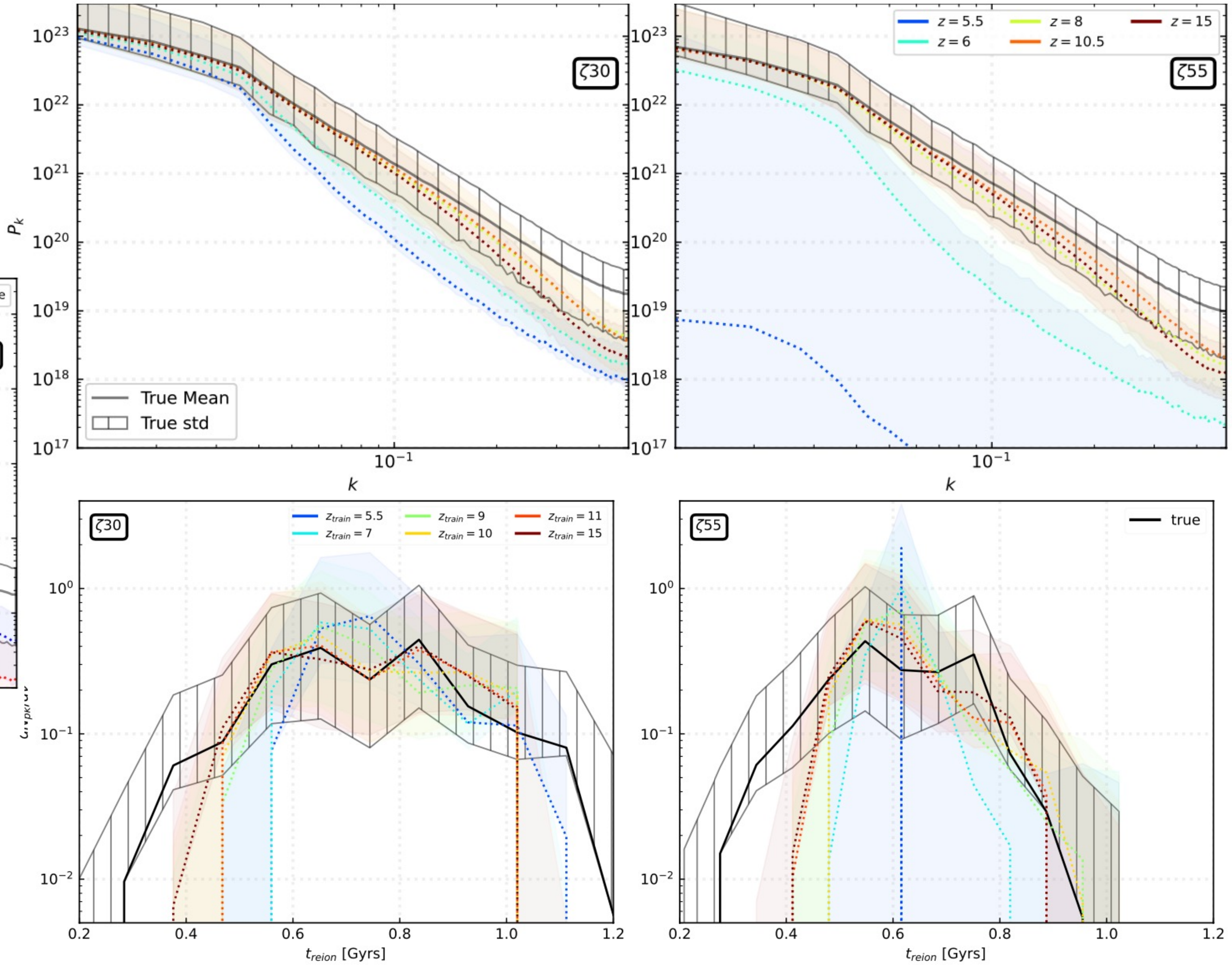




B. PATCHS DE REIONISATION

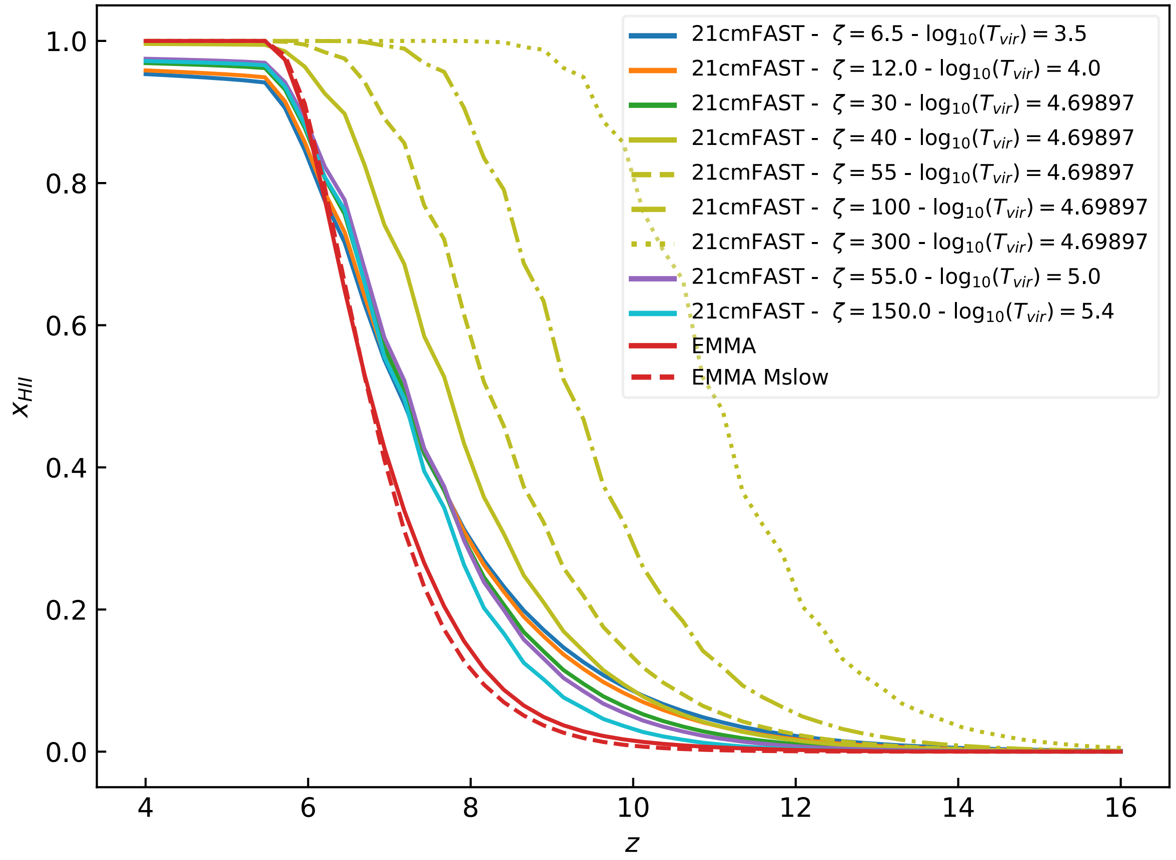
Simulations

21cmFAST semi-analytical simulations (128^3 cellules - 128^3 cMpc³/h³ ; Mesinger+11) :

- ζ : galaxies ionising efficiency
- $T_{vir} \sim M_{min}^3$: minimal virial temperature so that a halo start to form stars

EMMA cosmological simulations (512^3 cellules - 512^3 cMpc³/h³ ; Aubert+15, Gillet+21) :

- Mass resolution for the stellar particle ($10^7 M_\odot$ for the Mslow one and $10^8 M_\odot$ for the other)



B. REIONISATION PATCHES

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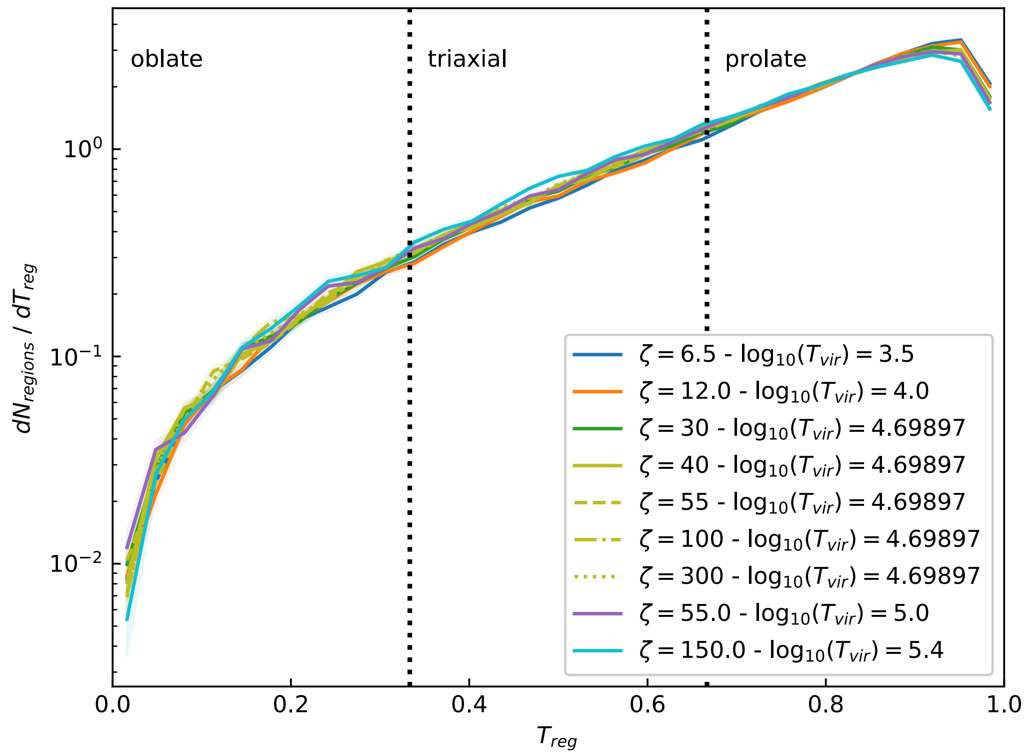
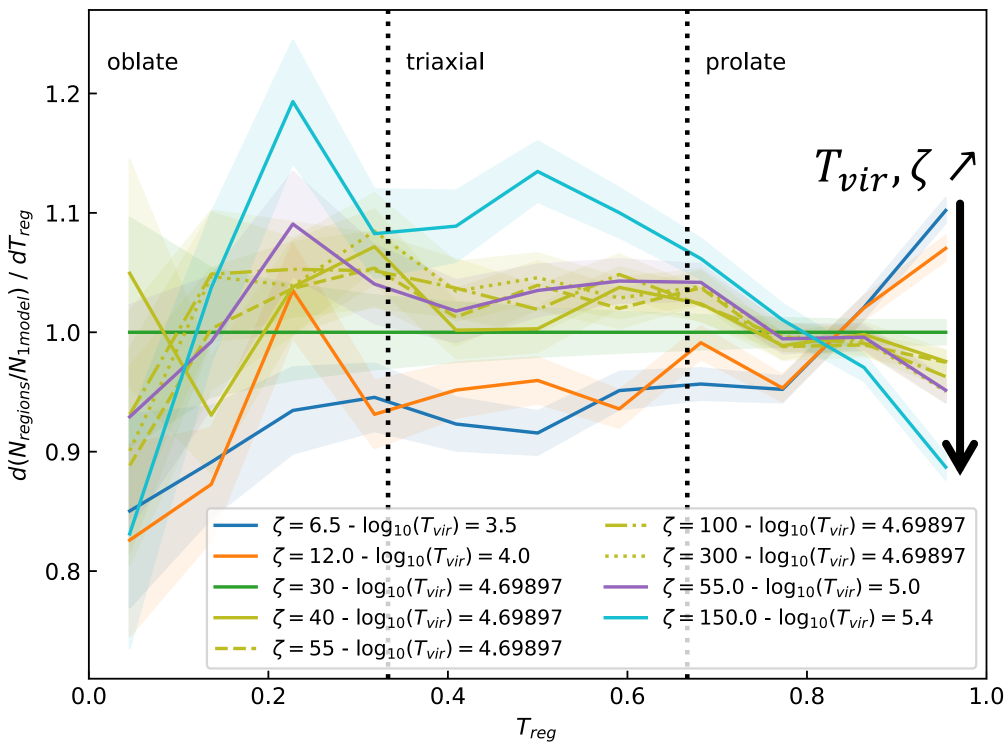
- Triaxiality parameter: $T = \dfrac{\lambda_3^2 - \lambda_2^2}{\lambda_3^2 - \lambda_1^2}$
- Majority of prolate patches
- Less prolate patches for halos that are stronger emitter and more massive

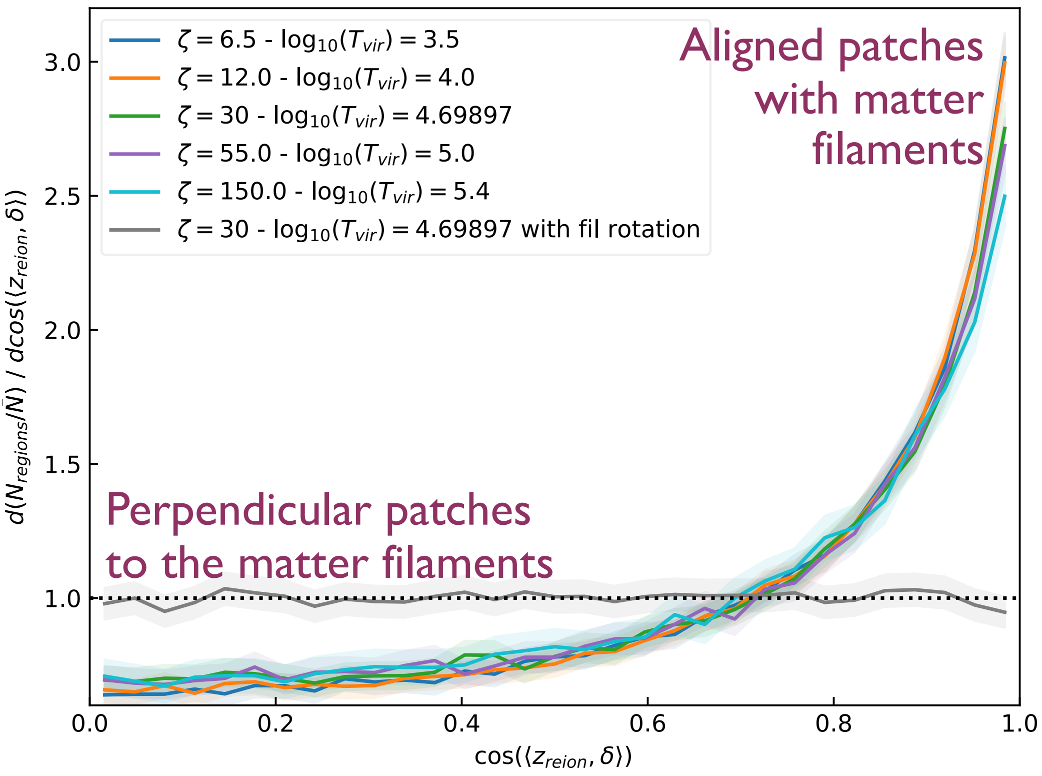


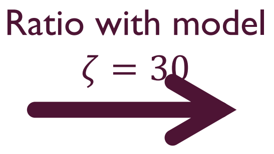
Ratio with model $\zeta = 30$

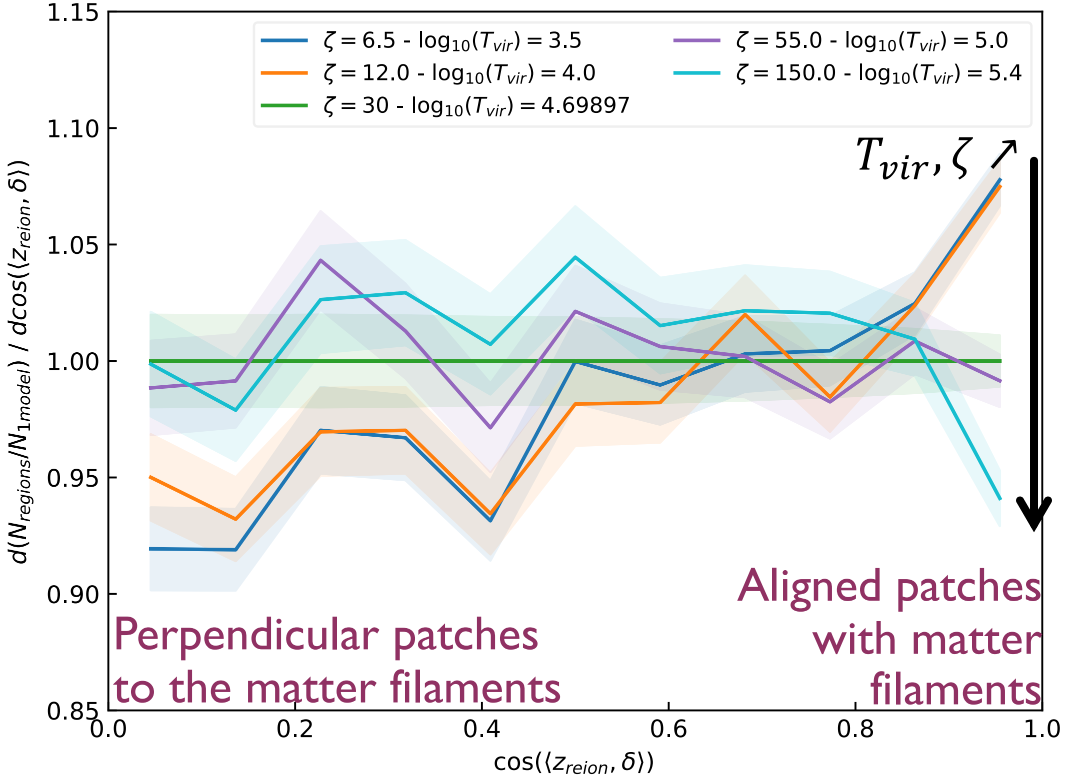


B. REIONISATION PATCHES

Orientation of patches with respect to the matter filaments



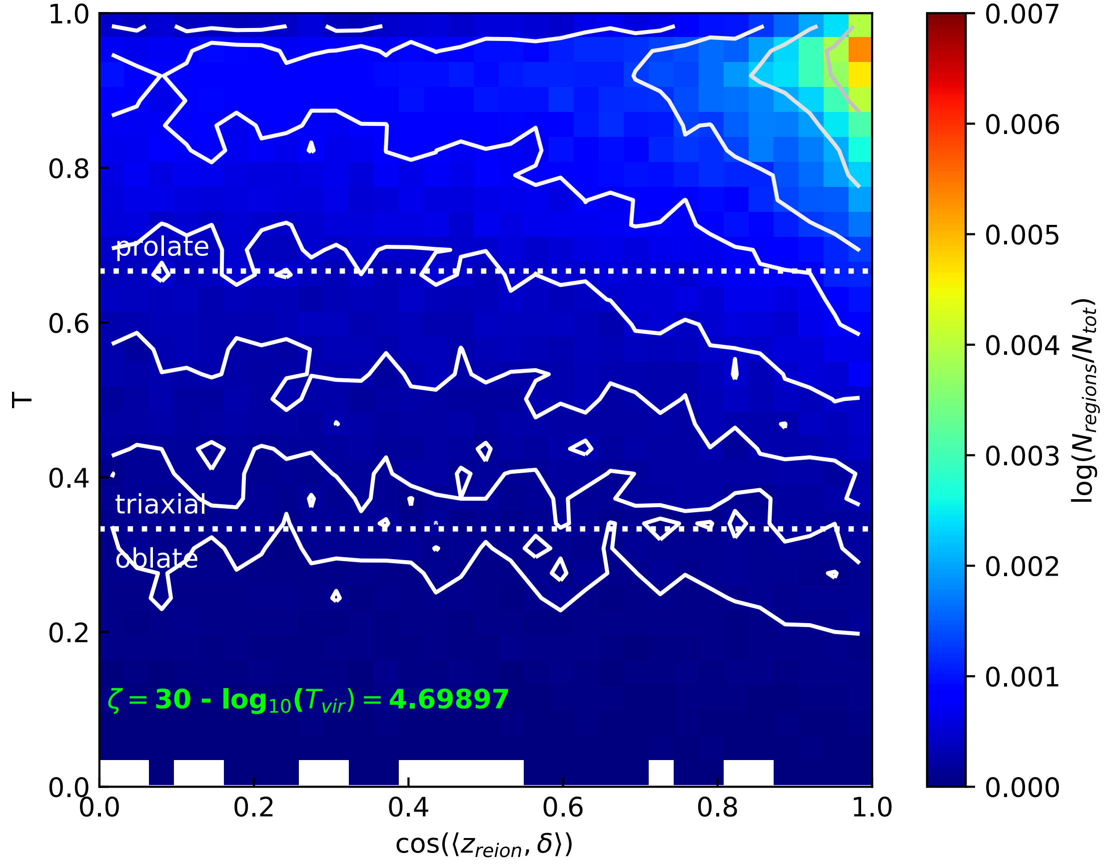




- Majority of aligned patches to the matter filaments
- Less aligned patches for halos that are stronger emitter and more massive

B. REIONISATION PATCHES

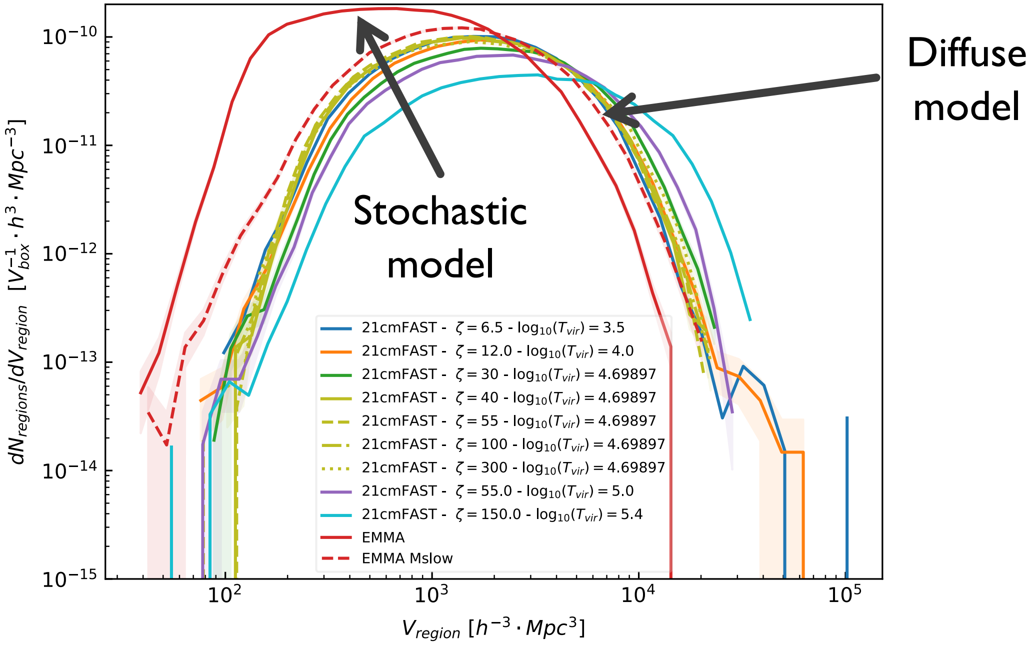
Shape vs. orientation of patches with respect to the matter filaments



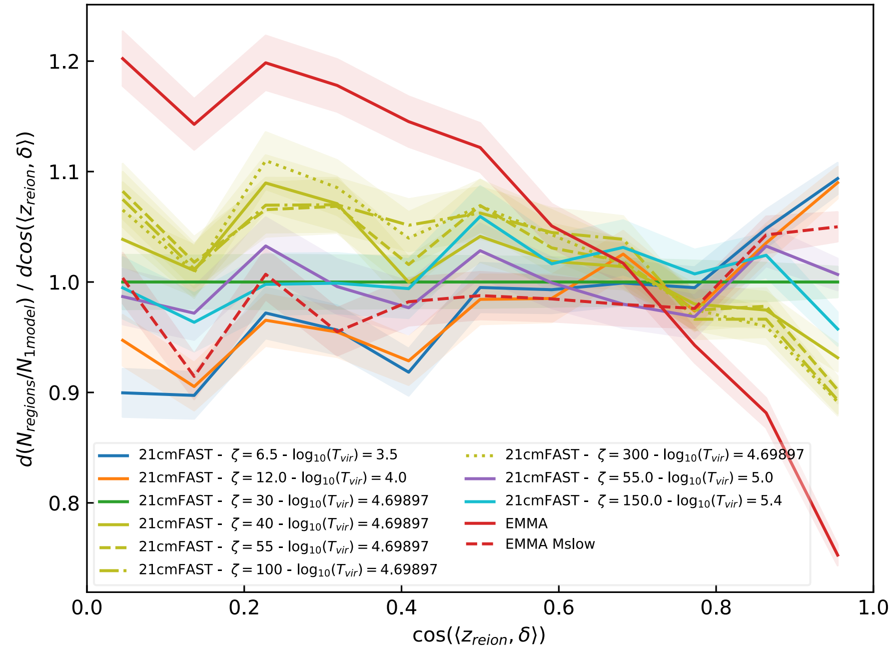
Thélie+22

B. PATCHS DE REIONISATION

Comparaison avec EMMA, une simulation cosmologique



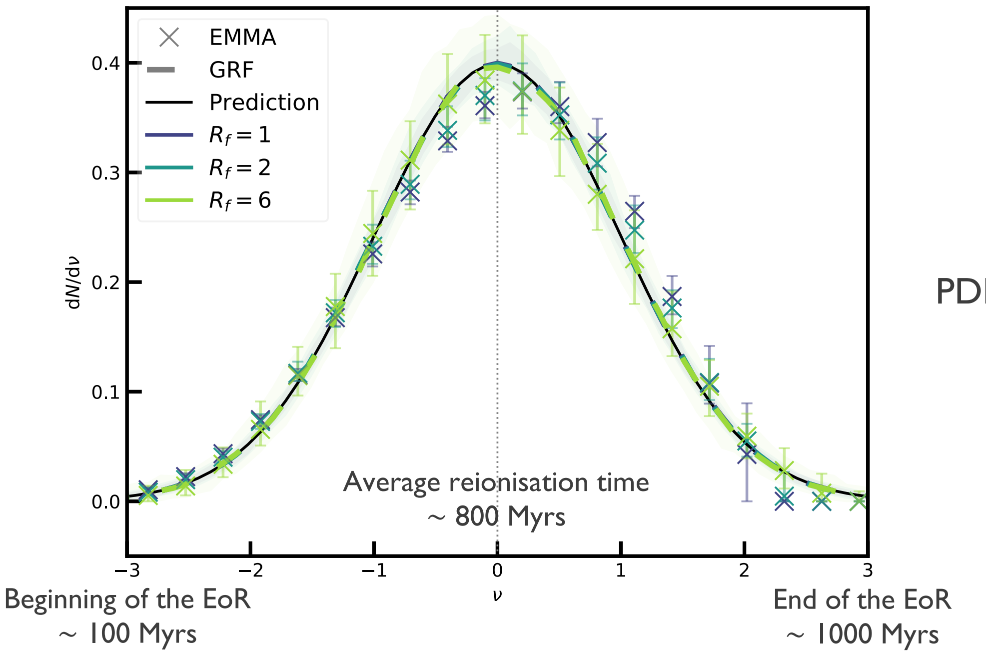
- Same conclusions for both type of simulations
- BUT EMMA can also produce models with rather different topologies (for the same $x_{HII}(z)$)



C. TOPOLOGY AND GRF THEORY

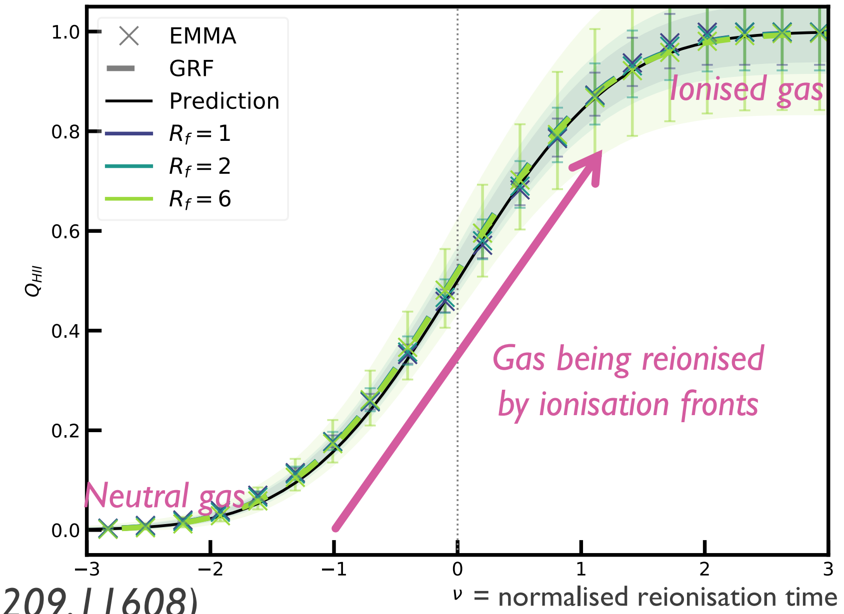
Simulation measurements & GRFs predictions

- PDF of reionisation times = counts the number of cells that have reionised as a function of time
- CDF of reionisation time → reionisation history
- **EMMA measurements close to gaussian predictions**



PDF of t_{reion}

$\int$



Cumulated PDF of t_{reion} = filling factor

Thélie+ (arxiv:2209.11608)

C. TOPOLOGY AND GRF THEORY

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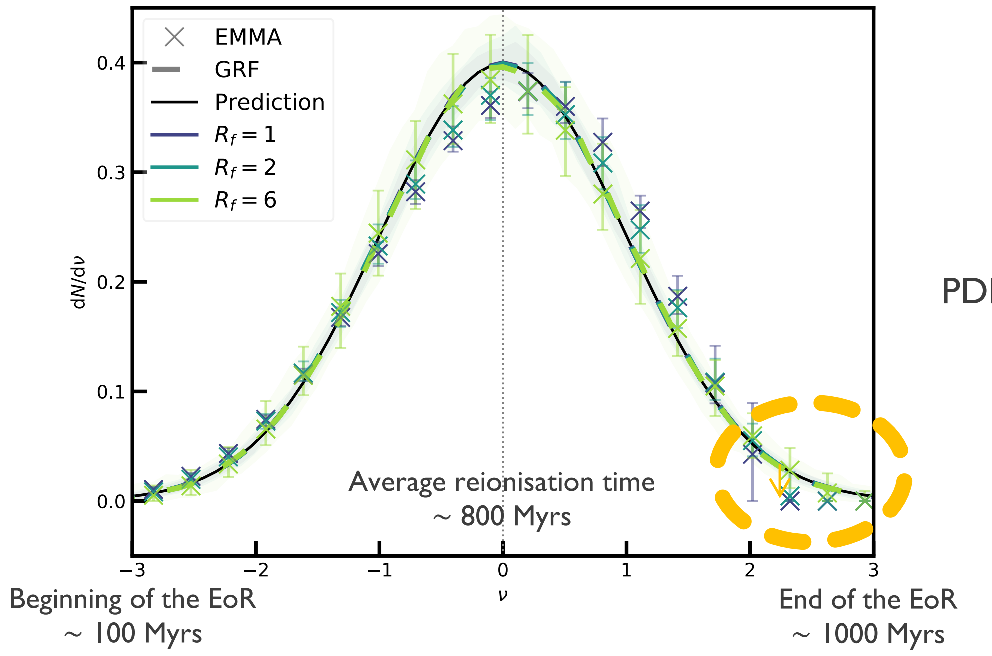
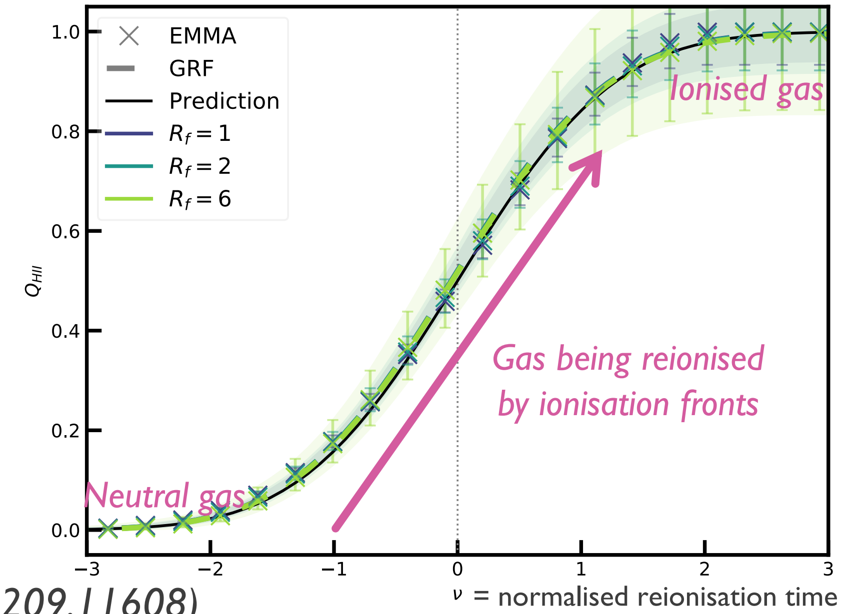


PDF of t_{reion}

$\int$

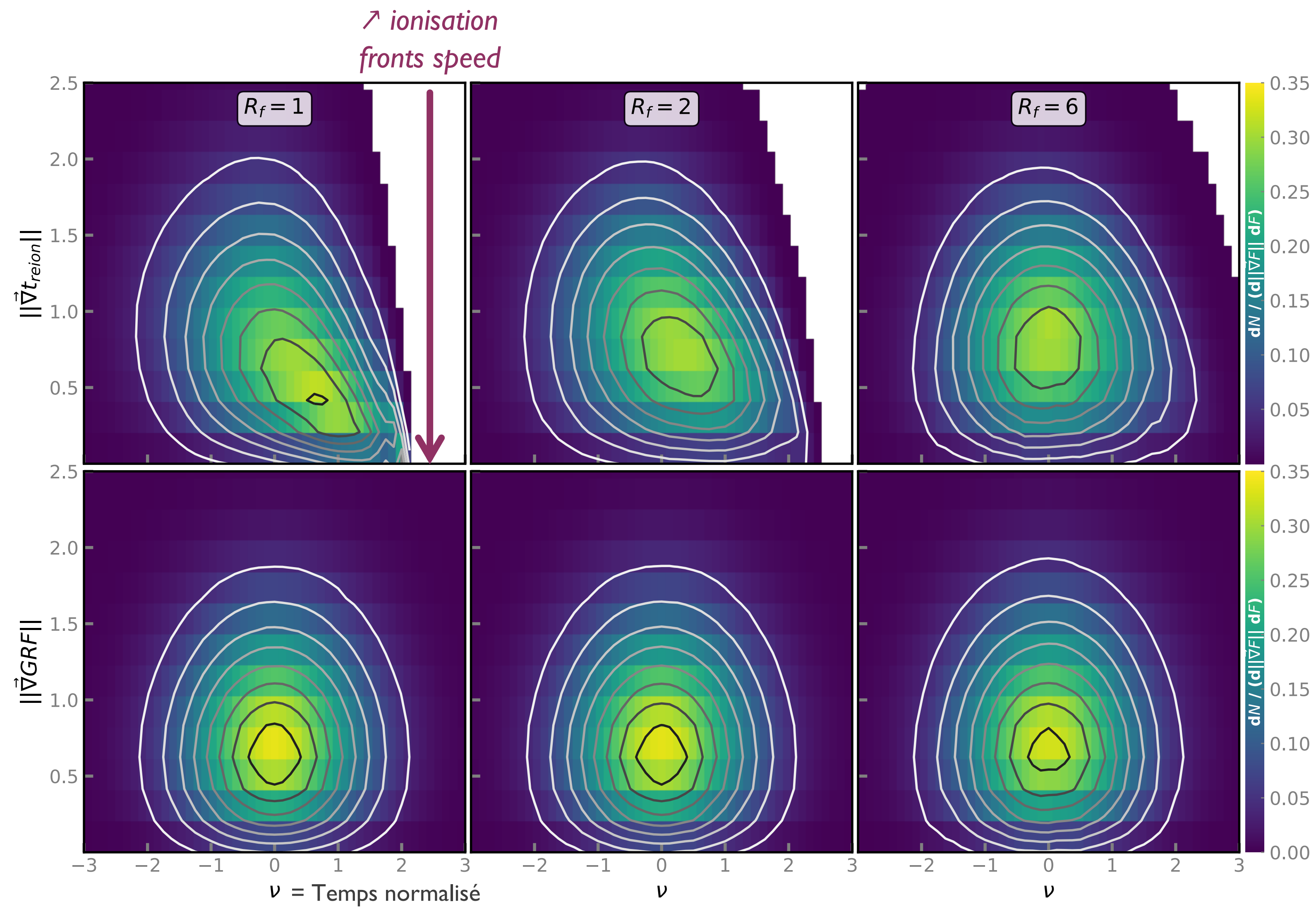


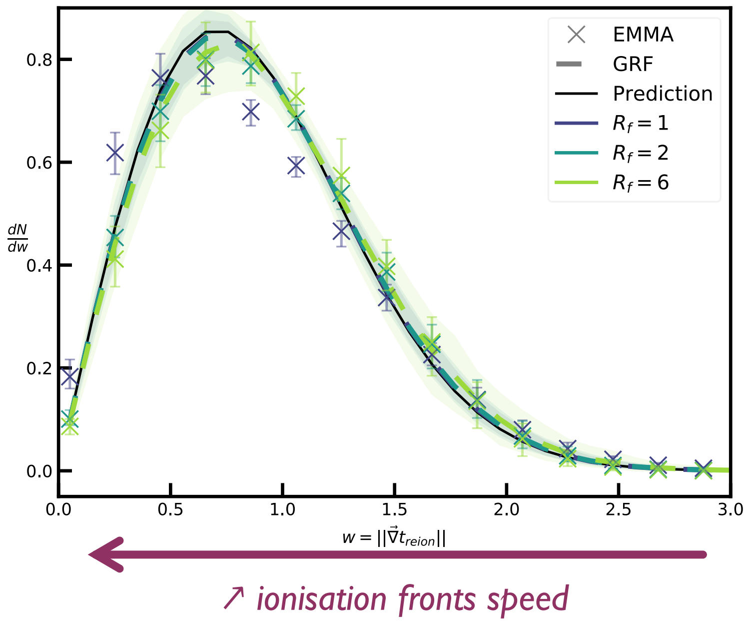
Cumulated PDF of t_{reion} = filling factor

Thélie+ (arxiv:2209.11608)

C. TOPOLOGY AND GRF THEORY

PDF of the gradients field norm: ionisation fronts speed

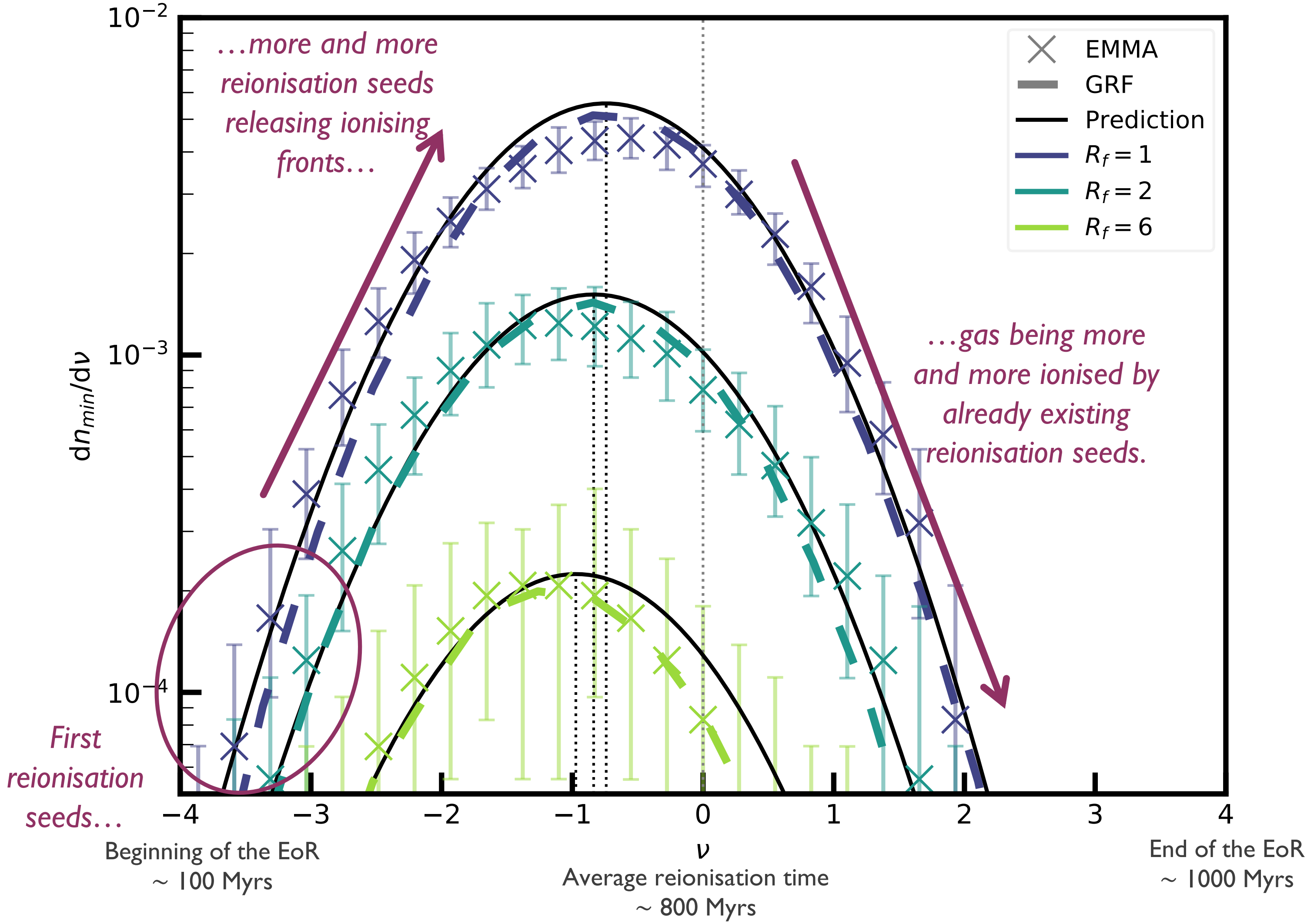




- $\boldsymbol{R_f}$ ↗ **:** EMMA measurements more symmetric
- $\boldsymbol{R_f \in \{1, 2\}}$ **:** imprints of non-gaussianity in the form of an asymmetry
  = *acceleration of the ionisation fronts at the end of the EoR*

C. TOPOLOGY AND GRF THEORY

PDF of the field value at its minima: reionisation seed counts

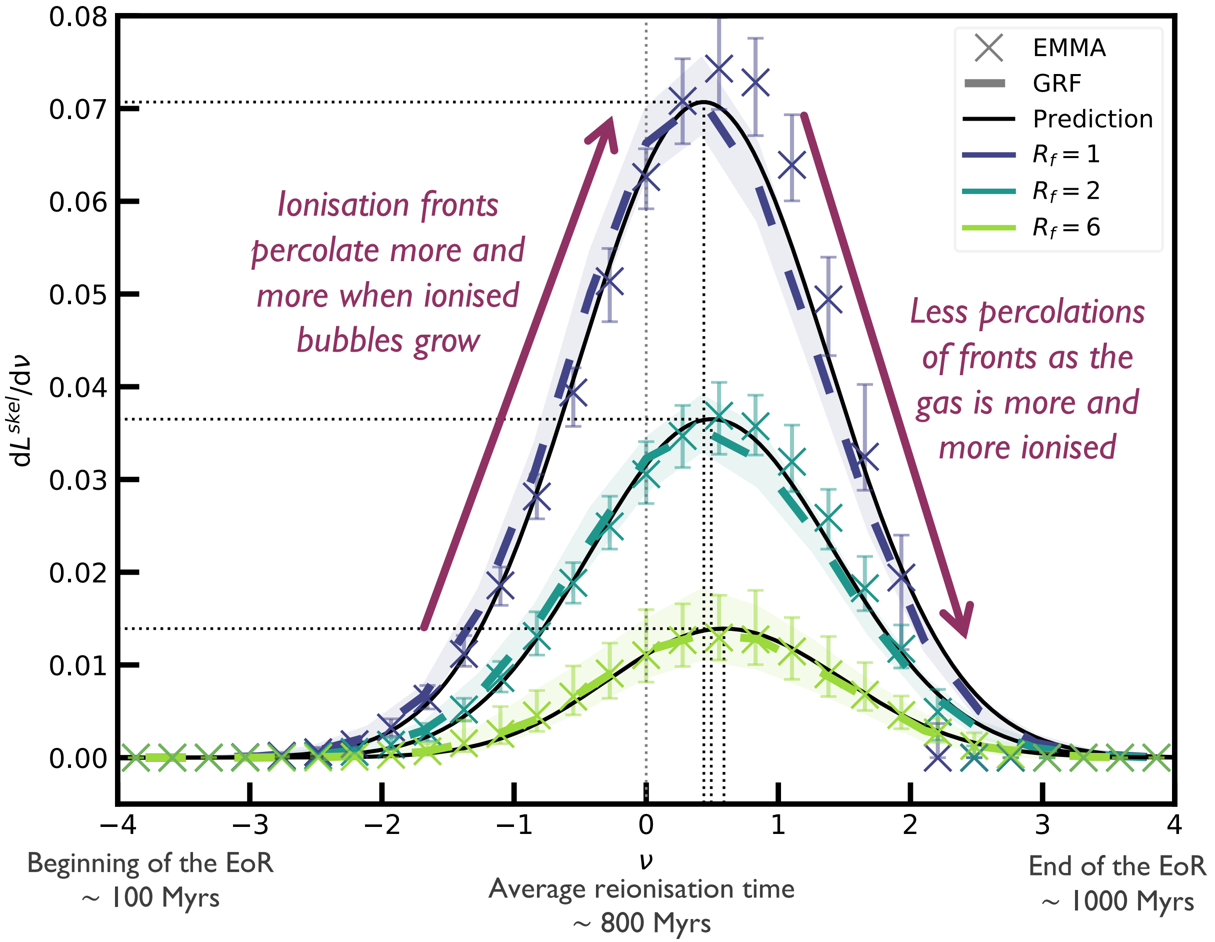


C. TOPOLOGY AND GRF THEORY

Skeleton length: places where the ionisation fronts percolate

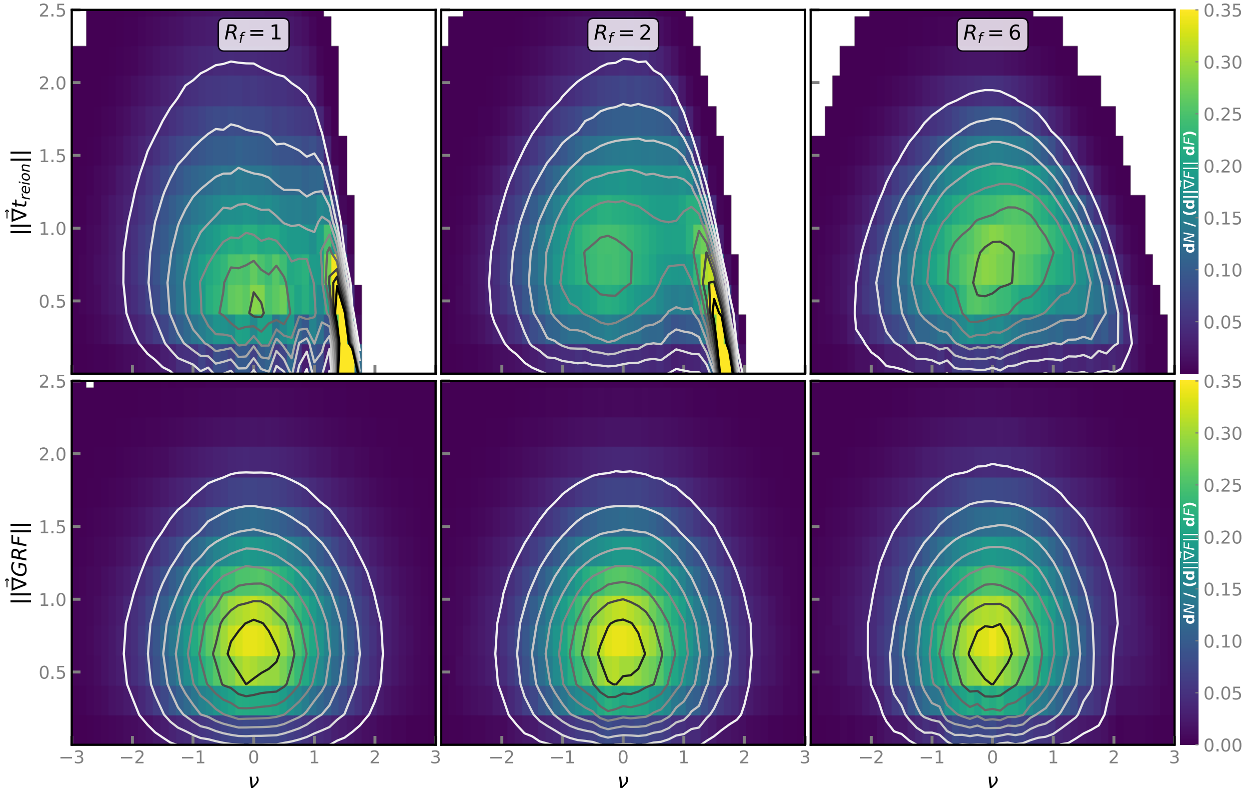
$$L^{\mathrm{tot}} = \left(\frac{1}{8} + \frac{\sqrt{2}}{4\pi}\right)\frac{1}{R_*}$$

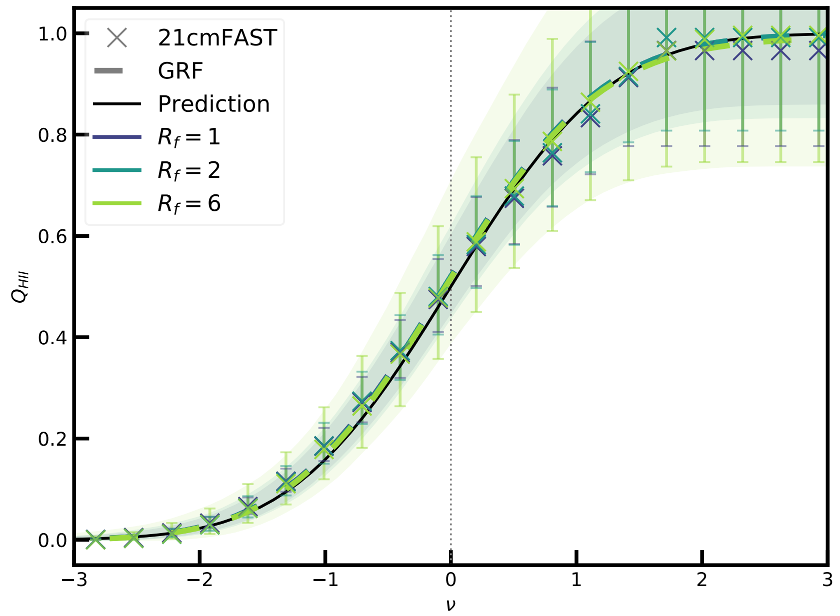
- "Stiff" approximation + global (measurements) or local (GRFs) calculations → predictions under-estimating the skeleton length: **measurements have to be renormalised**
- $R_f \nearrow$: EMMA measurements more symmetric
- $R_f \in \{1, 2\}$: asymmetry
  = *acceleration of ionisation fronts at the end of the EoR*

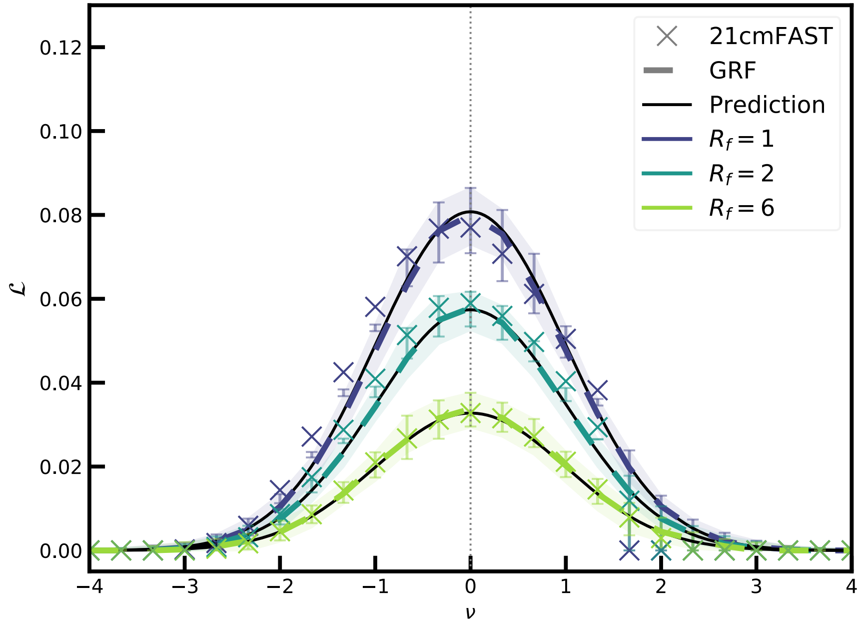


C. TOPOLOGY AND GRF THEORY

Comparisons with 21cmFAST







- Same behaviour as the EMMA measurements globally
- $\boldsymbol{R_f} \nearrow$ **:** 21cmFAST measurements more symmetric
- $\boldsymbol{R_f \in \{1, 2, 6\}}$ **:** asymmetry because of the absence of modelisation of radiation propagation within 21cmFAST