# Exploring the Epoch of Reionisation through its evolving topology

Emilie Thélie

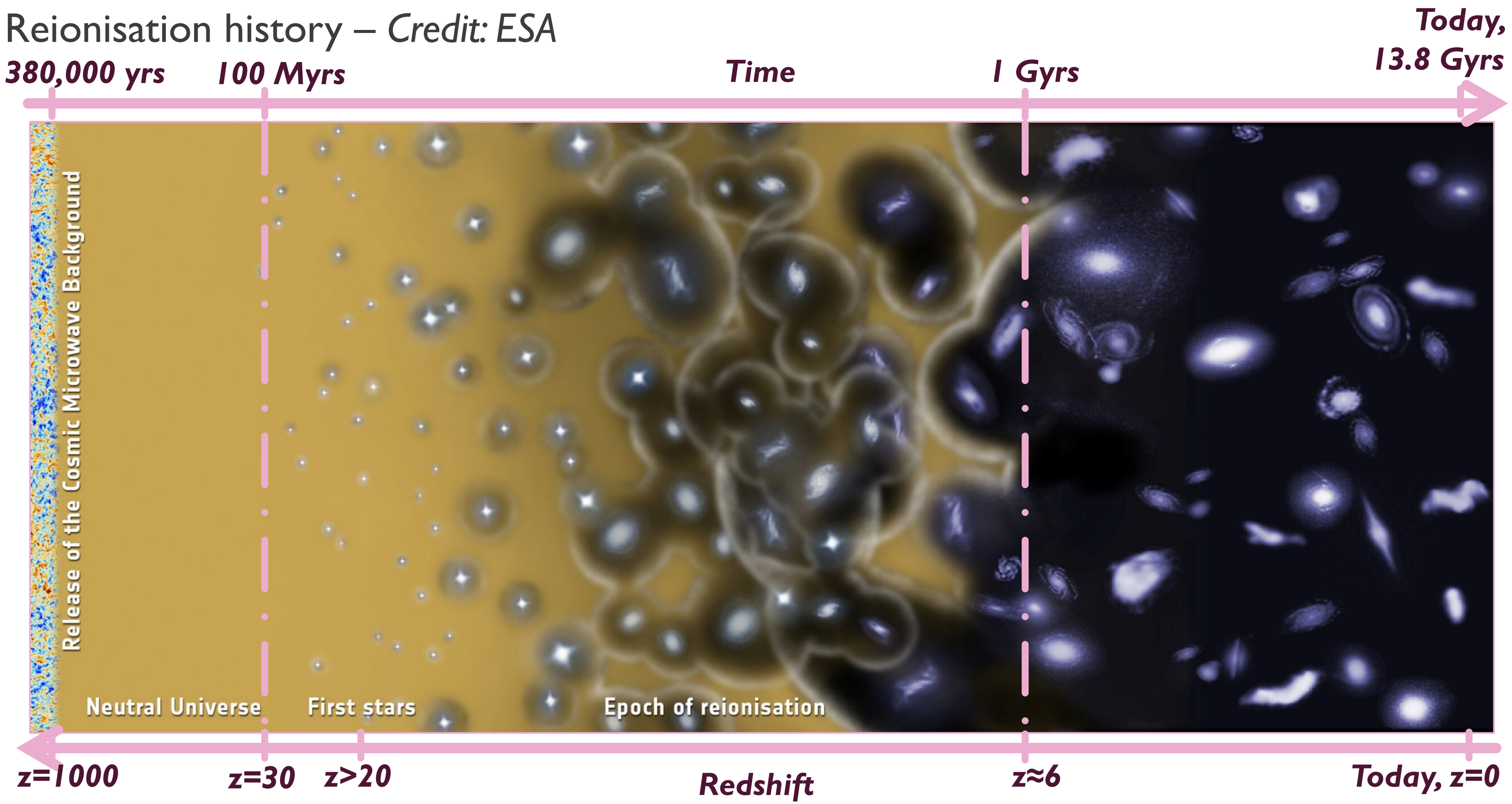
Collaborating with D. Aubert, J. Hiegel, N. Gillet & P. Ocvirk

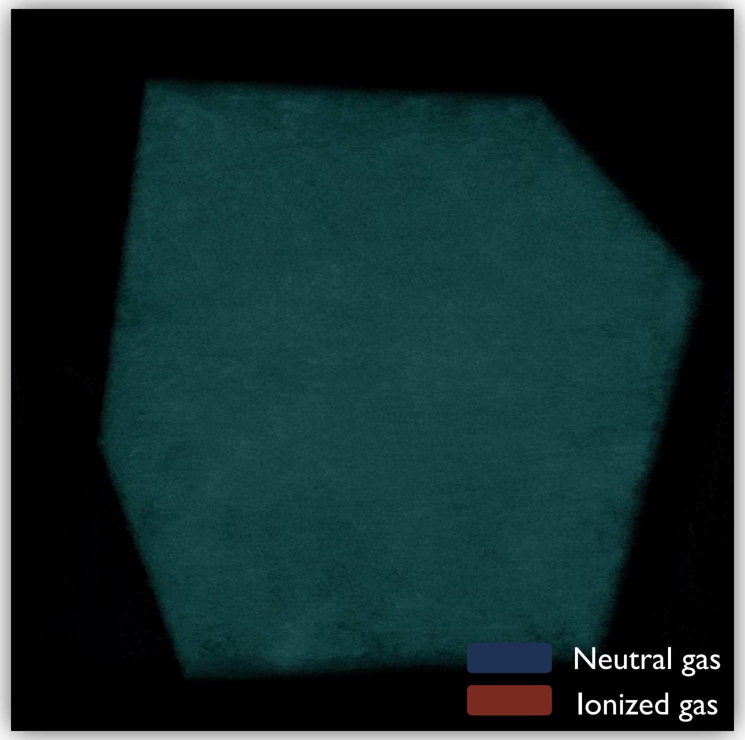
*Thélie et al. (2022)* ■ *Thélie et al. (arxiv:2209.11608)* ■ *Hiegel, Thélie et al. (to be submitted to A&A)*

# 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

*Observations of the Epoch of Reionisation:* ***indirect observations***

- Emission from distant quasars → Lyman $\alpha$ forest

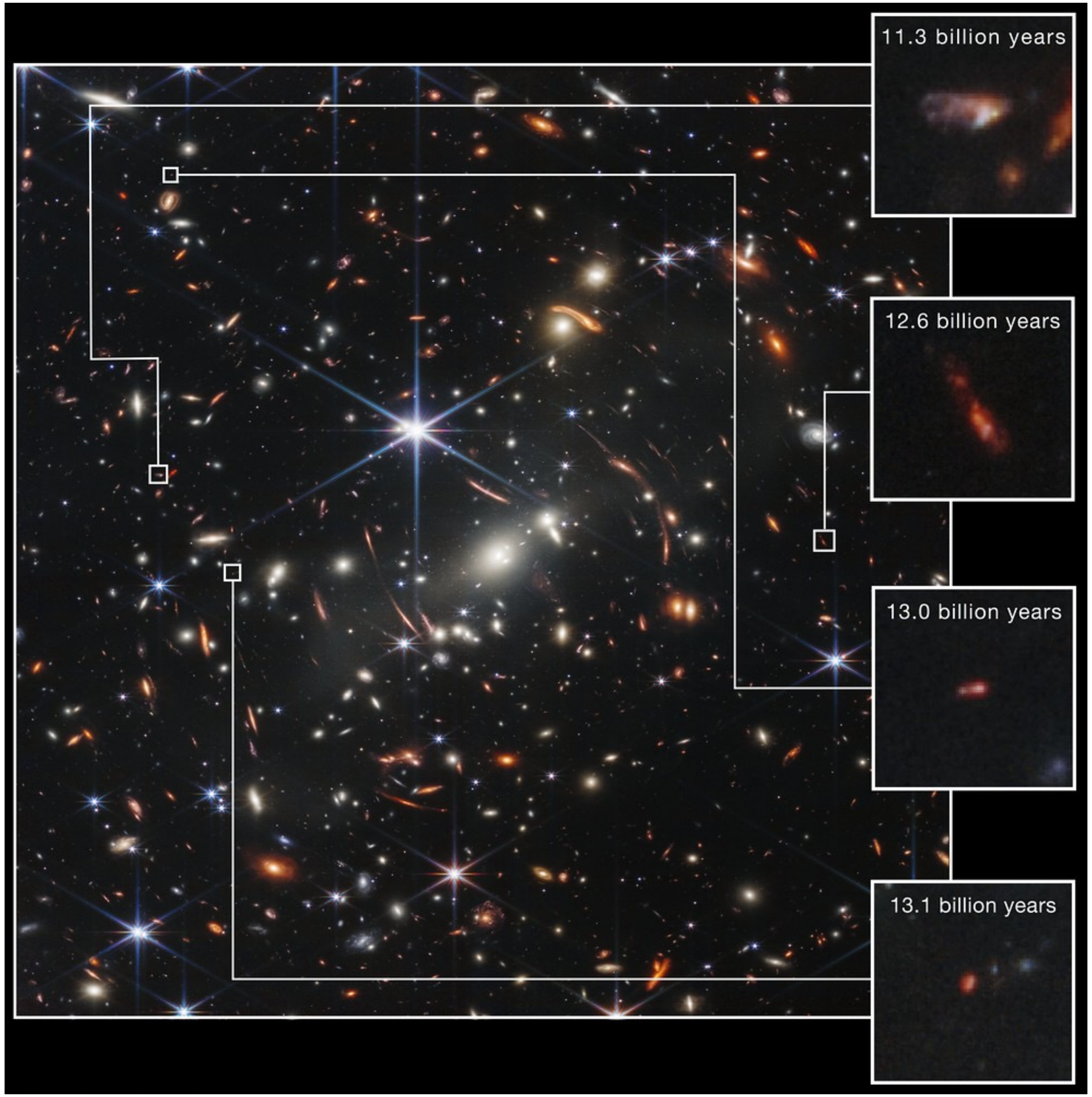
*= distribution of hydrogen clouds along their line of sight*

- HST, JWST : deep surveys of distant galaxies ($z \geq 11$)

*= galaxy distribution during the EoR*

- CMB power spectrum

*= constraints on e.g. the optical depth $\tau$*




SMACS 0723 galaxy cluster
NIRCam Image, JWST
*Credit: NASA*

# INTRODUCTION

*Observations of the Epoch of Reionisation:* ***direct observations***

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

# INTRODUCTION

## *Observations of the Epoch of Reionisation:* ***direct observations***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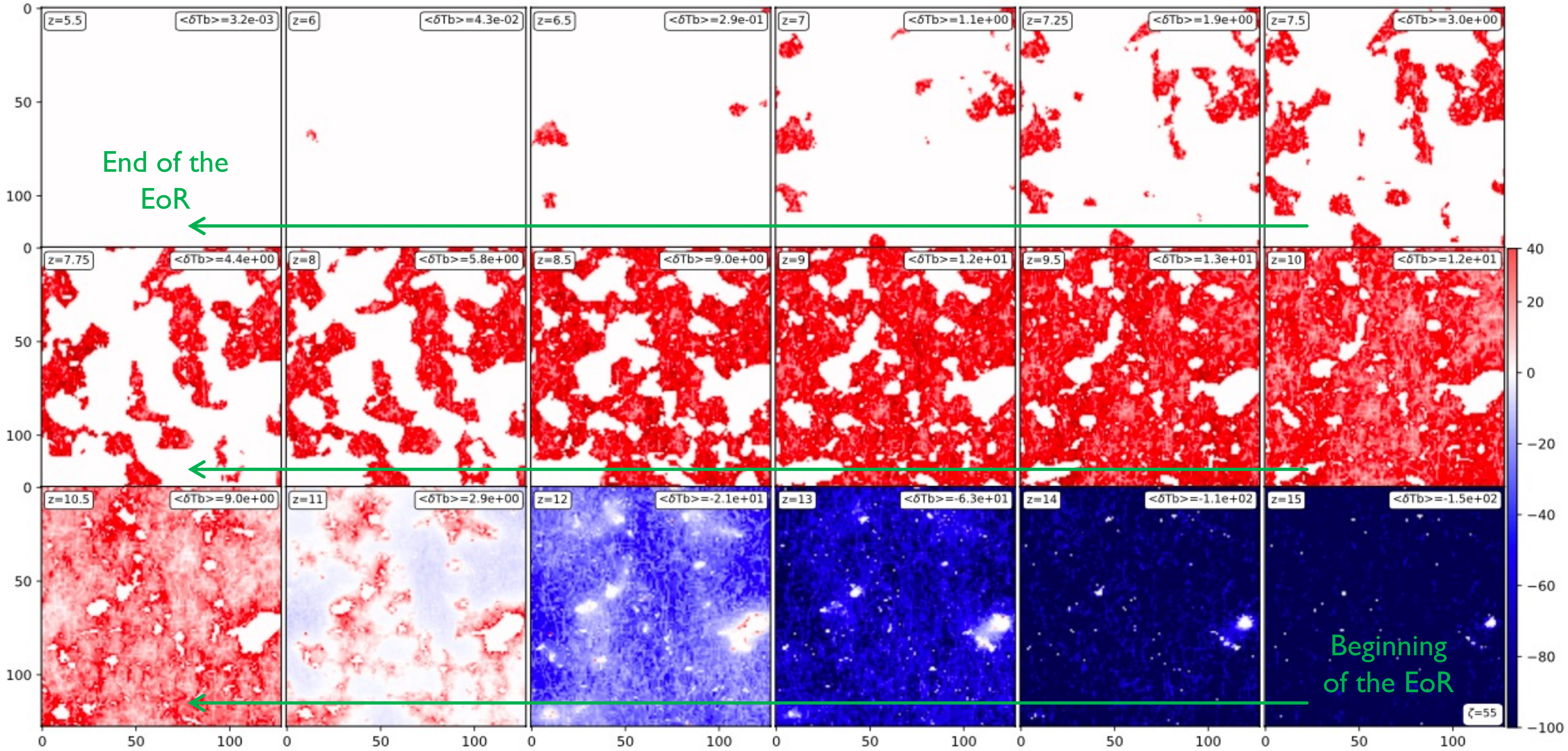


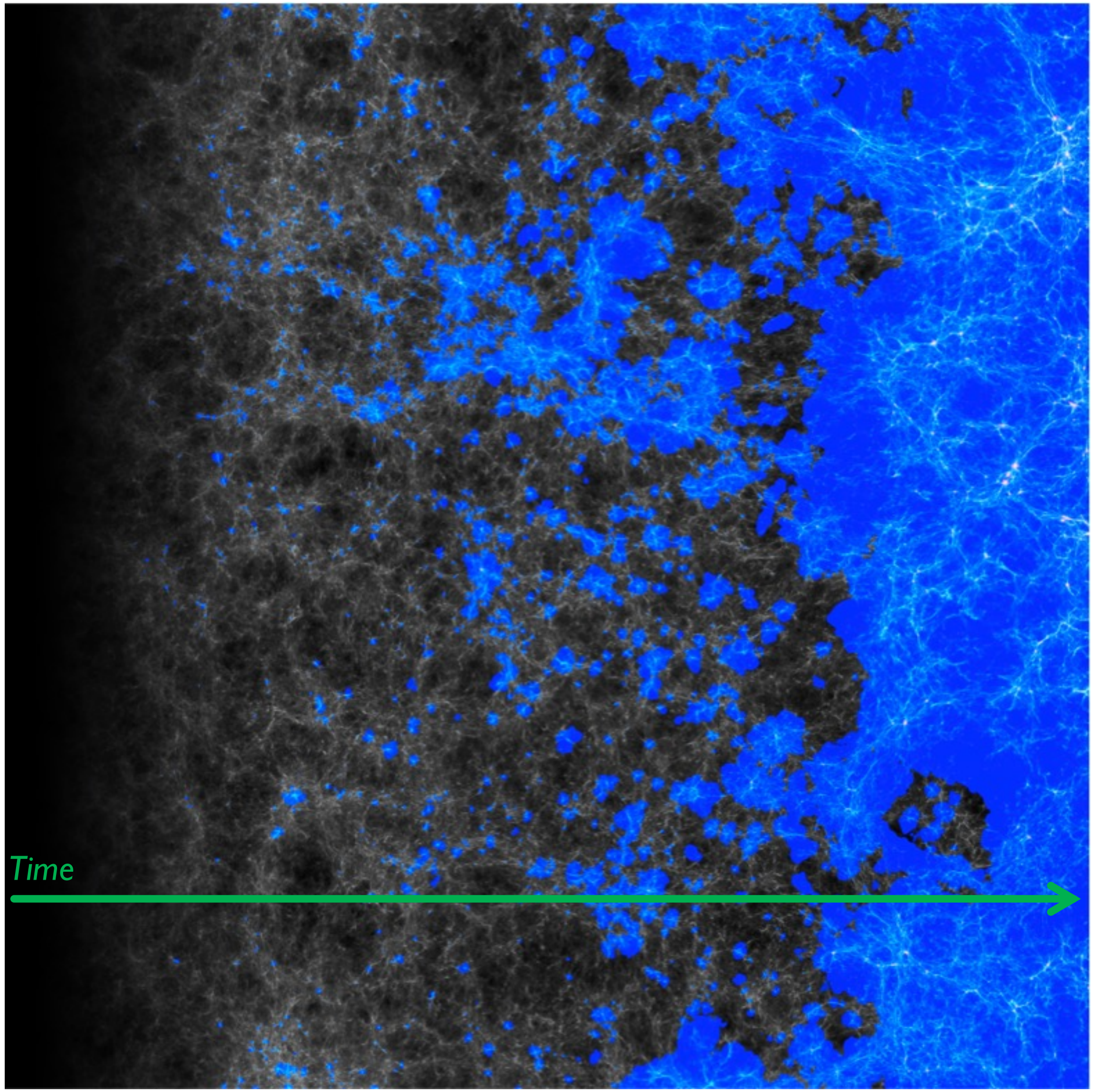

2D images of the 21 cm signal at many frequencies: $\delta T_b(z)$
21cmFAST semi-analytical model (256 cMpc/h)

*Hiegel, Thélie+ (in prep.)*

# INTRODUCTION

*Why studying the Epoch of Reionisation?*

CoDa II (64 cMpc/h)
*Credit: Ocvirk+20*




**1. Understanding past and present structures thanks to the EoR**

- Galaxy formation, evolution and properties
  *= constraints thanks to the EoR*
- Link cosmic web – EoR
  *= non-uniform distribution of matter at large scale*

**2. Understanding the evolution of the EoR**

- Timing of the EoR: beginning and end?
- Is reionisation uniform everywhere and for all the galaxies?
- Evolution of ionised and neutral bubbles

**How does the EoR happen?**

Topological studies 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, …)

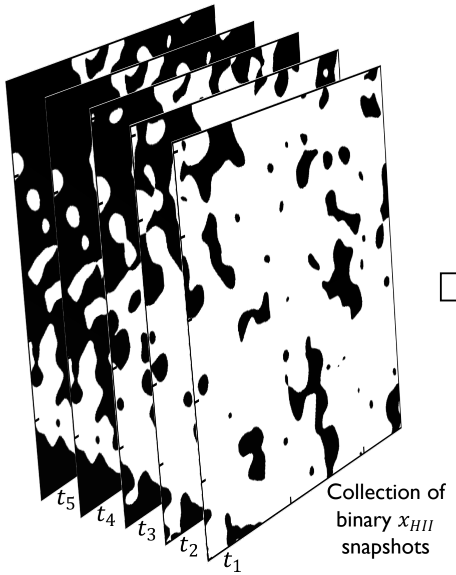
***Analyses of spatial structures…***
… with 21 cm power spectra (e.g. Gazagnes+21) and bispectra (e.g. Hutter+20)

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

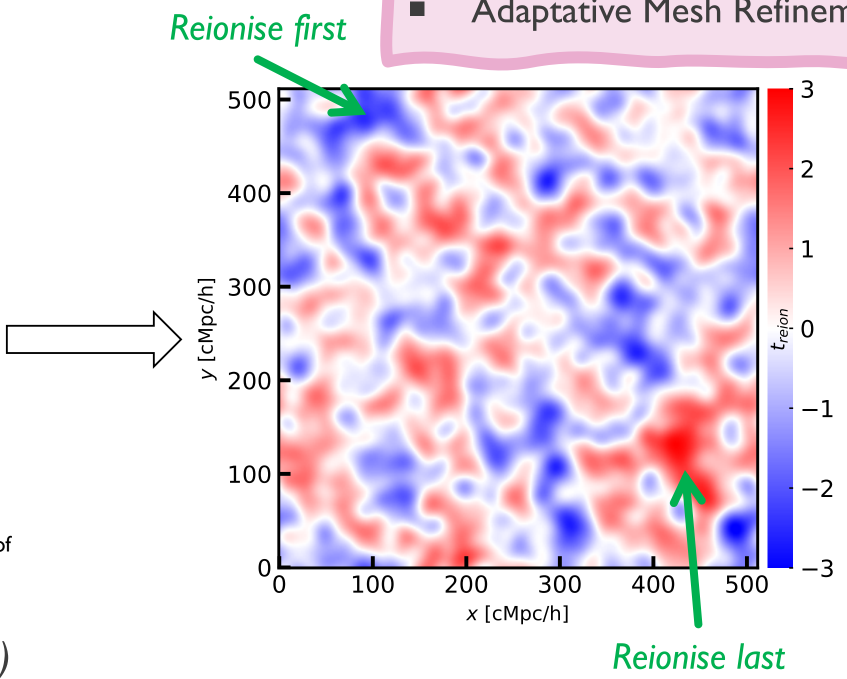
***Geometry of bubbles and percolation…***
- … with Minkowski functionals (e.g. Friedrich+11, Chen+19)
- … with the triangle correlation function (Gorce+19)

# REIONISATION TIMES
*Definition*

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




*Thélie+ (arxiv:2209.11608)*




**Map of reionisation times:**
- Cell value = time at which the gas is reionised
- Spatial and temporal information about the reionisation process

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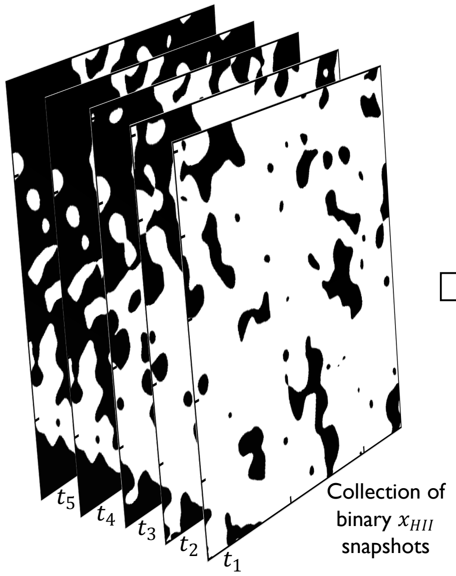
**21cmFAST semi-analytical simulation** (256 cMpc/h)

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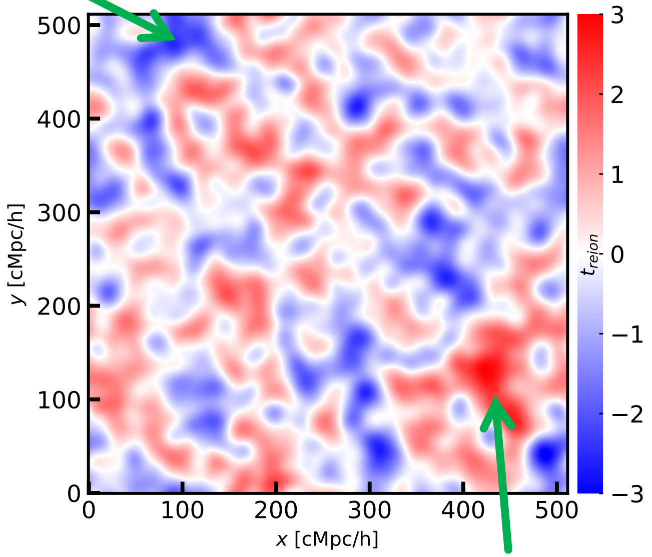
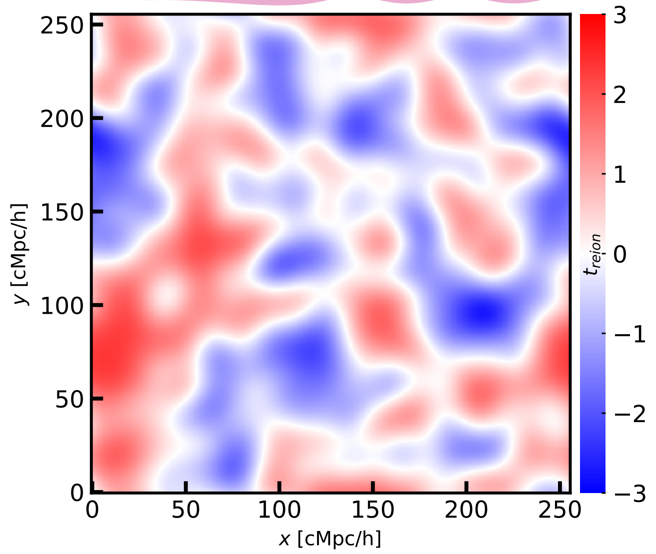
*Reionise first*




*Reionise last*




**Map of reionisation times:**
- Cell value = time at which the gas is reionised
- Spatial and temporal information about the reionisation process

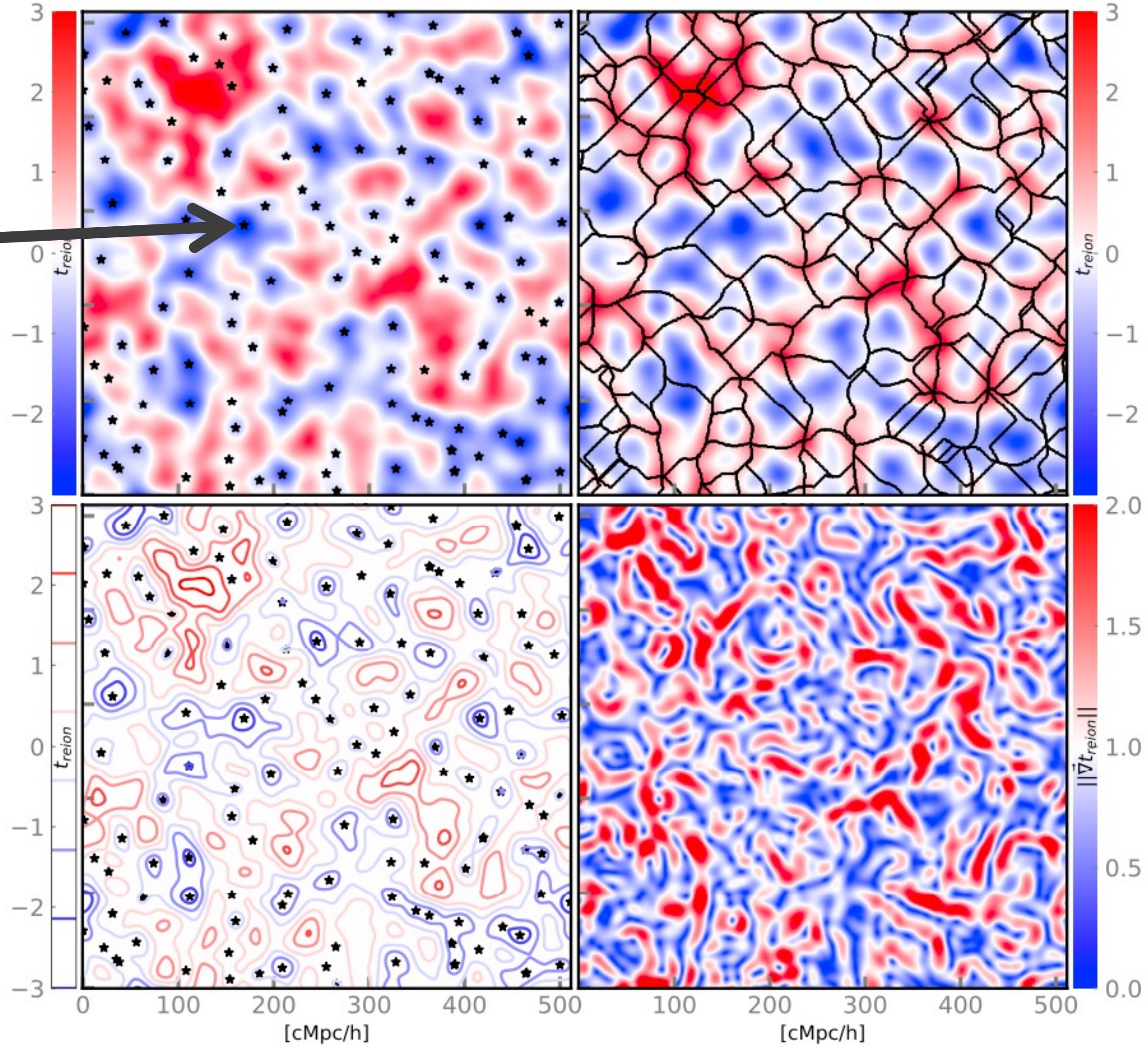
**Reionisation simulations:**
- **EMMA cosmological simulations** (Aubert+15) or **21cmFAST semi-analytical models** (Mesinger+11)
- Large scales: box size **>128 cMpc/h, 1 cMpc/h** resolution

# REIONISATION TIMES

*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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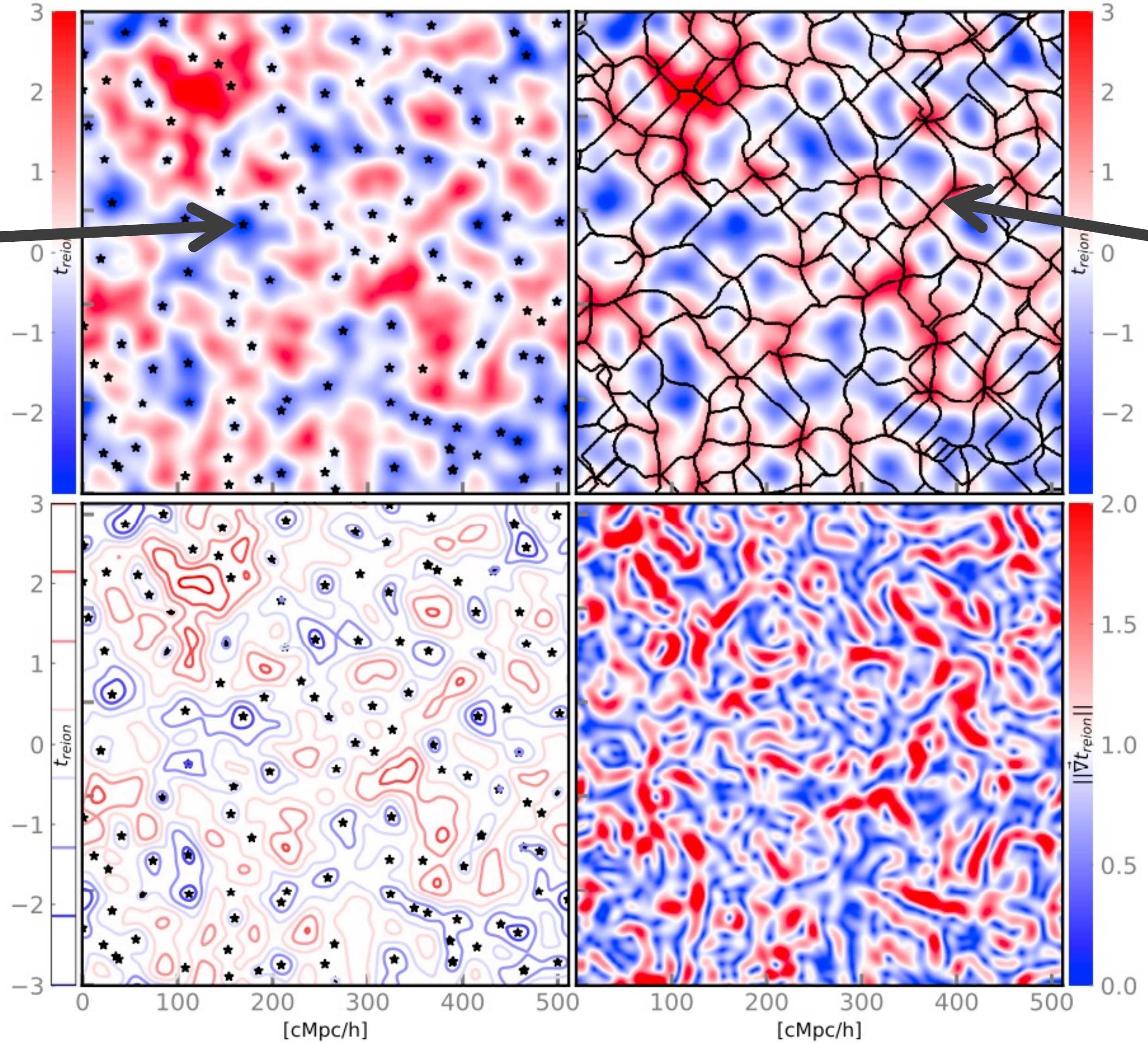


**Reionisation patches:**

- *Extension of the radiative influence of a source*

**Patches edges = skeleton:**

- *Percolation lines between ionisation fronts*

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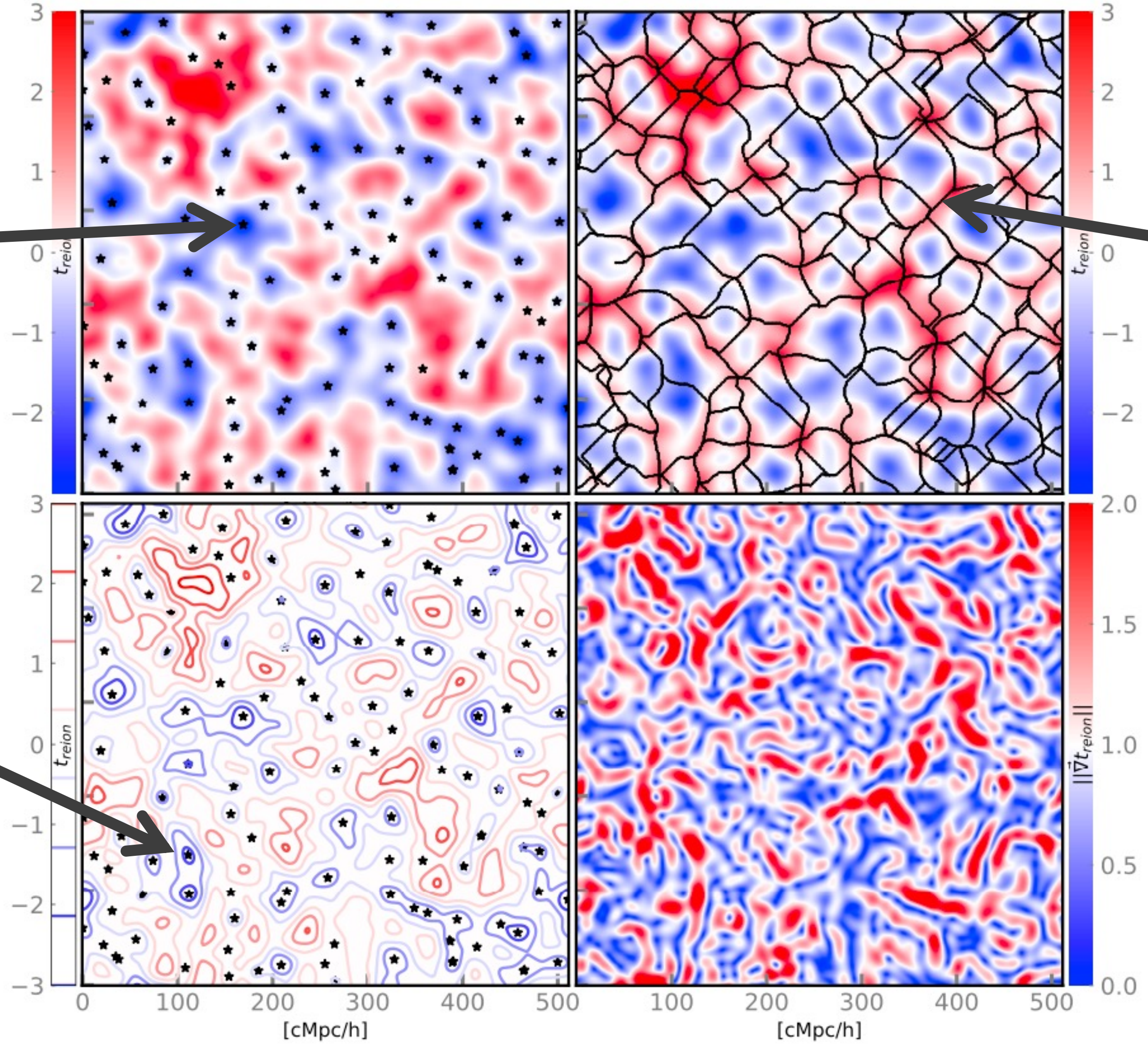
**Isocontours:**

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

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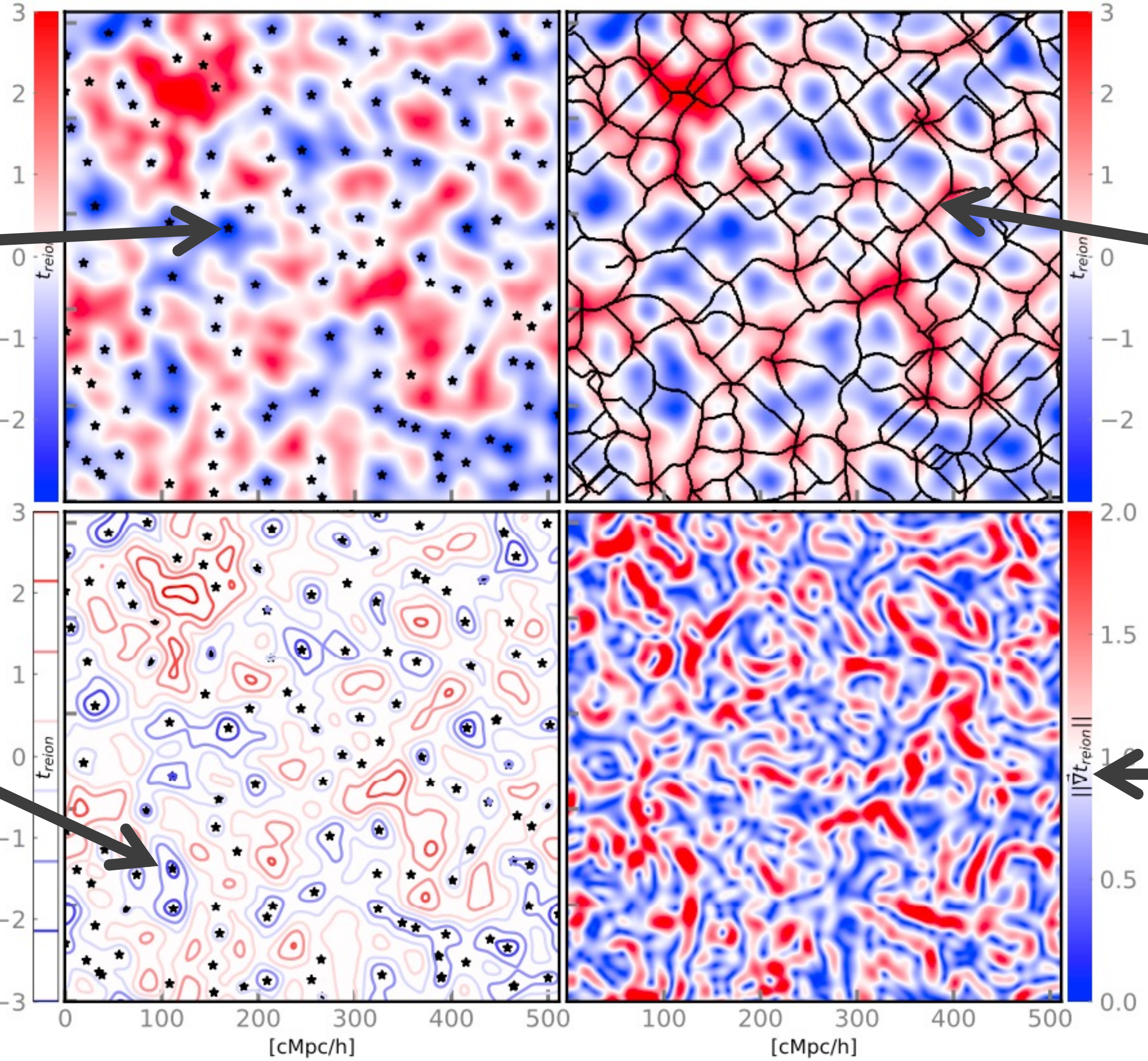


**Isocontours:**
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**Gradients:**
- $\left\|\overrightarrow{\nabla t_{reion}}\right\| \sim \frac{\Delta t}{\Delta x} \sim v_{reion}{}^{-1}$
- *Inverse of the ionisation fronts speed*

# 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**

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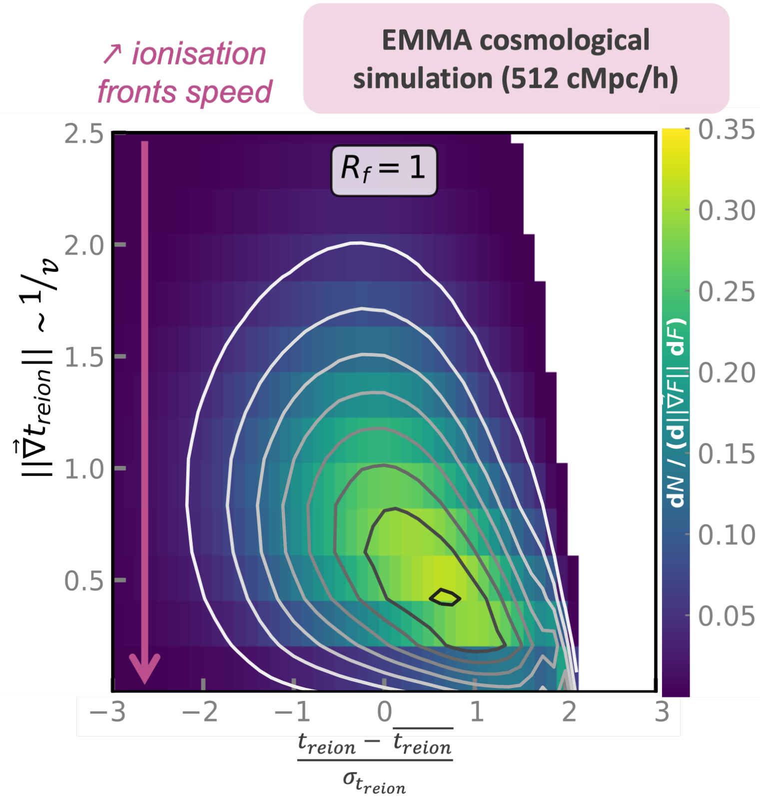


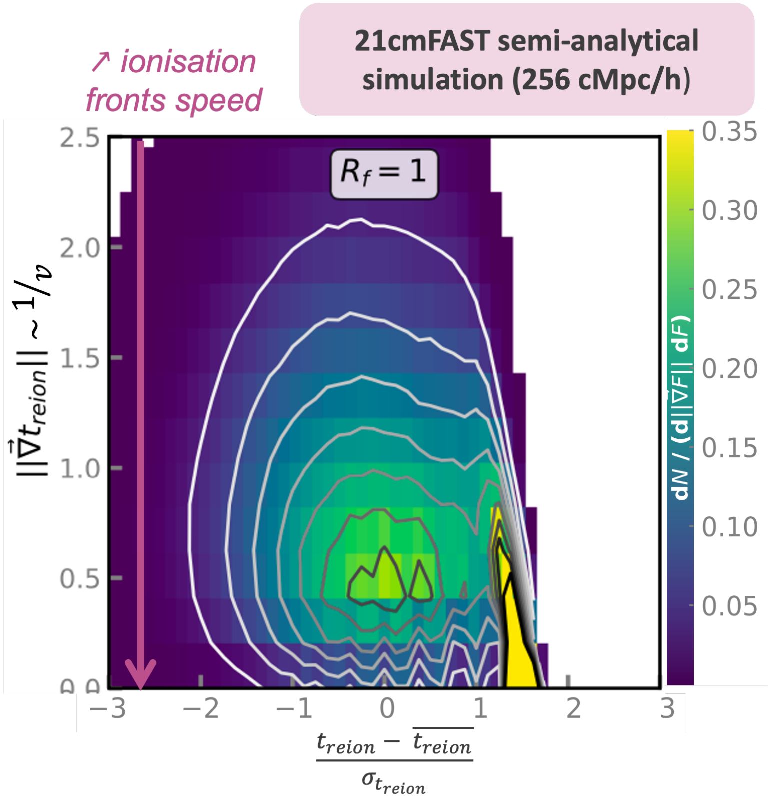

## A. REIONISATION TIMES RECONSTRUCTED FROM THE 21 CM SIGNAL

*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

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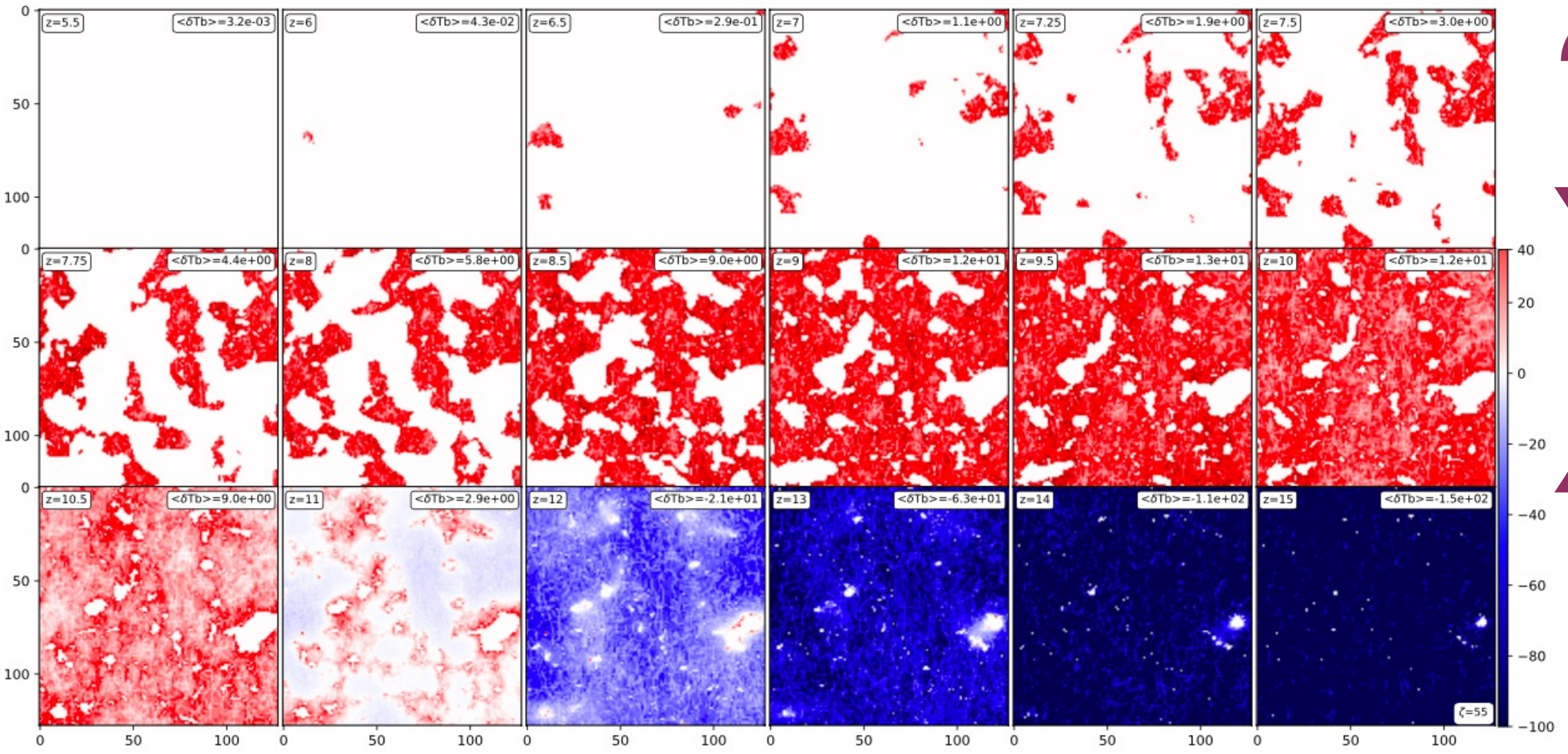
# A. 21 CM TO $t_{reion}$

*Reconstruction of reionisation times from 21 cm signal maps*

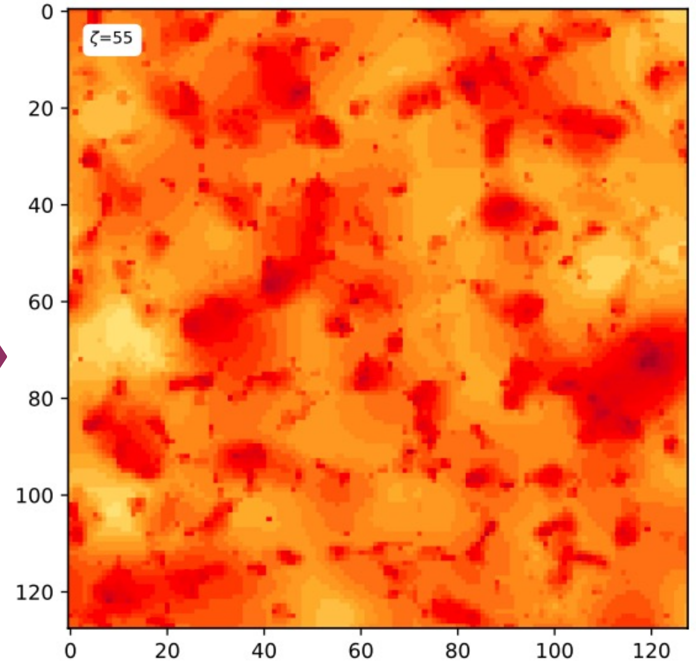
**Is it possible to reconstruct reionisation times maps from observations?**

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: $\delta T_b(z)$



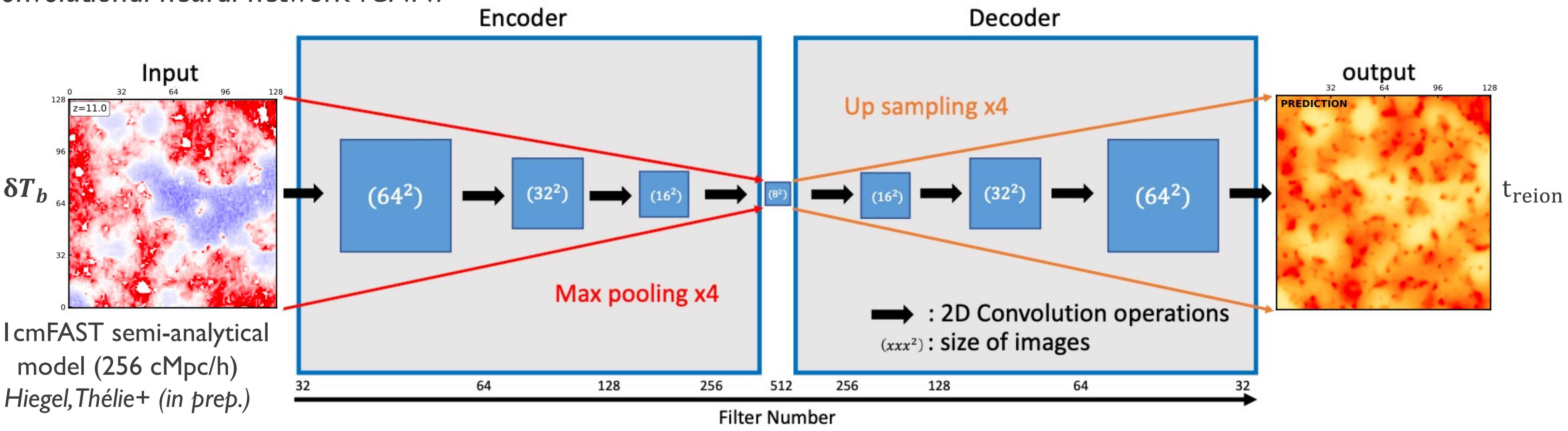

$t_{reion}$




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*
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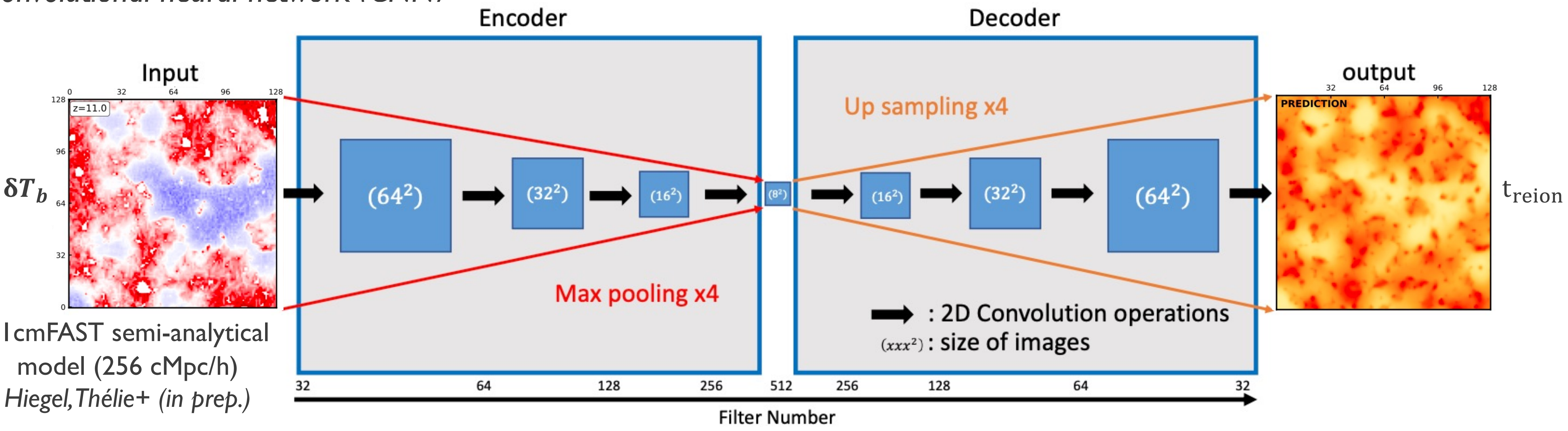


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## SIMULATIONS

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

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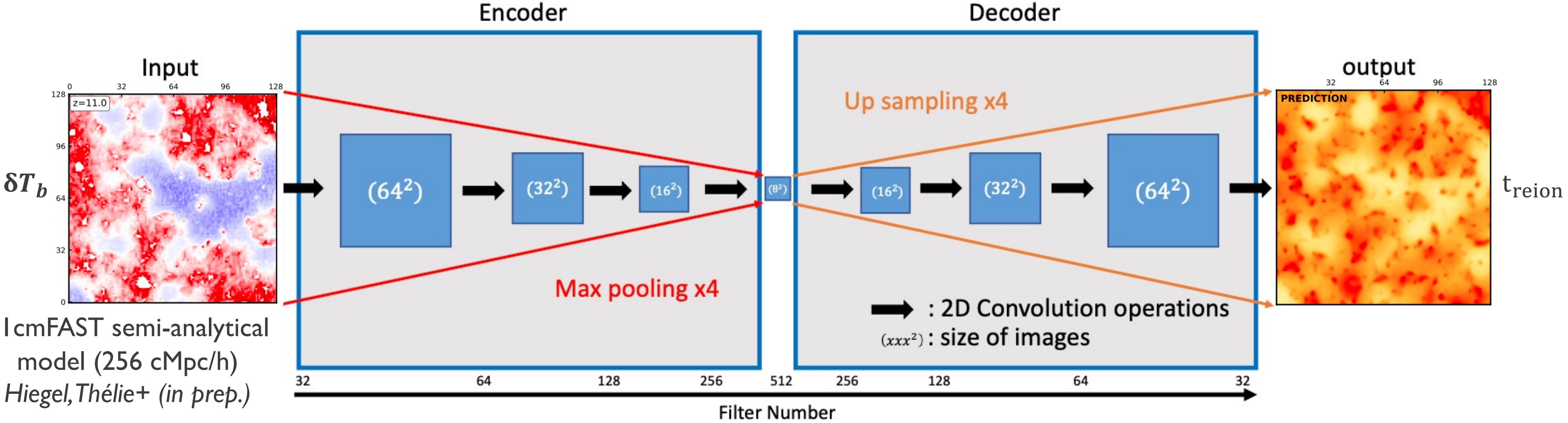


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## LEARNING

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

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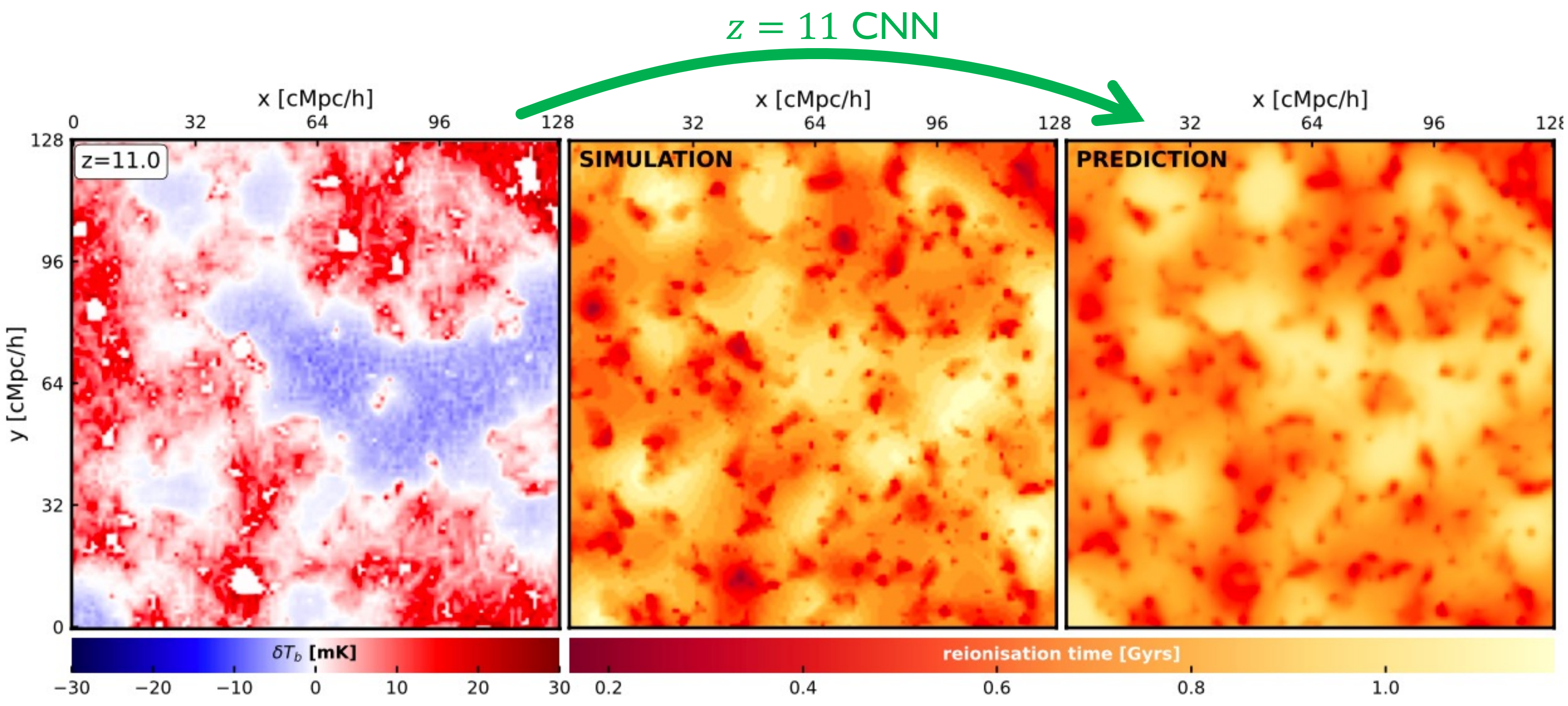
*Reconstruction of reionisation times from 21 cm signal maps*

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- Example with $z_{obs} = 11$: less small structures but visually really close

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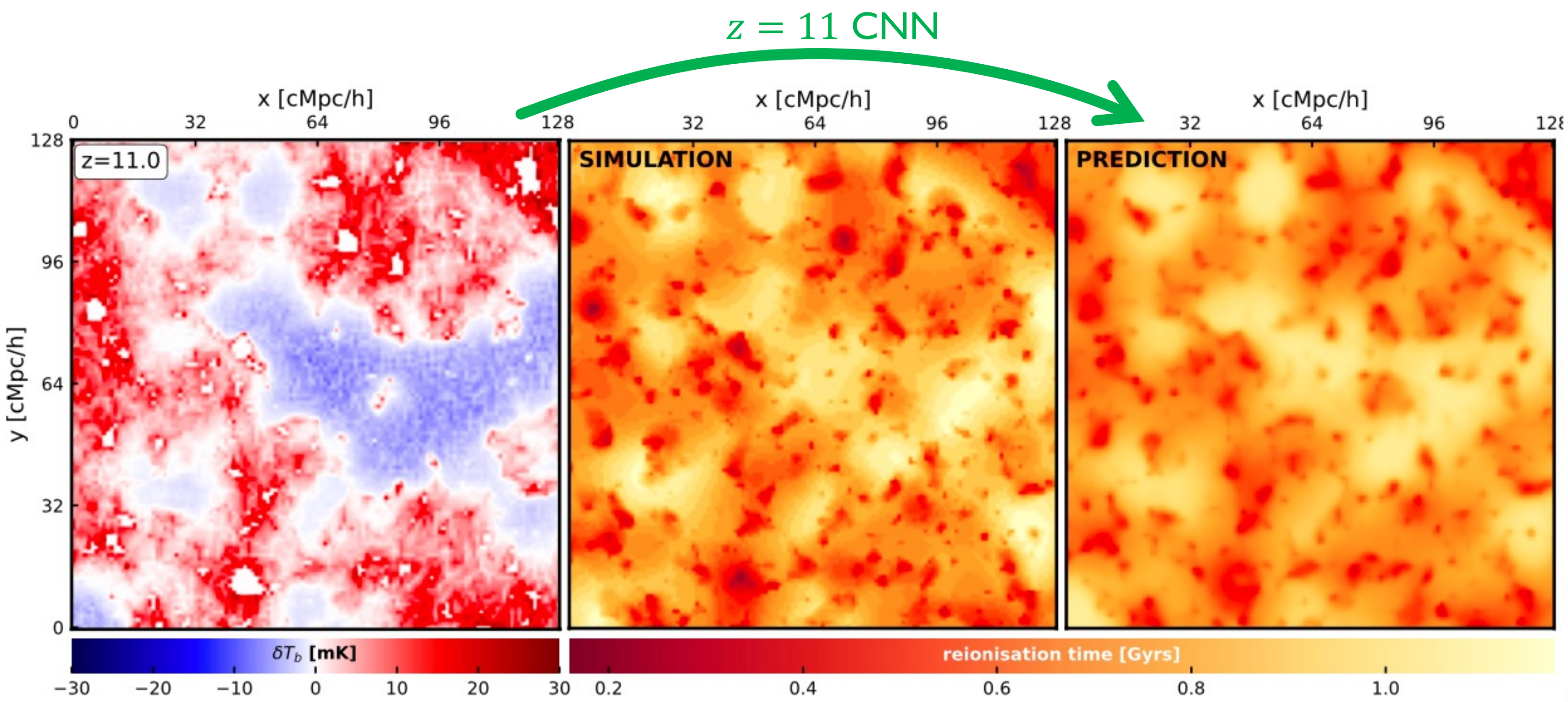


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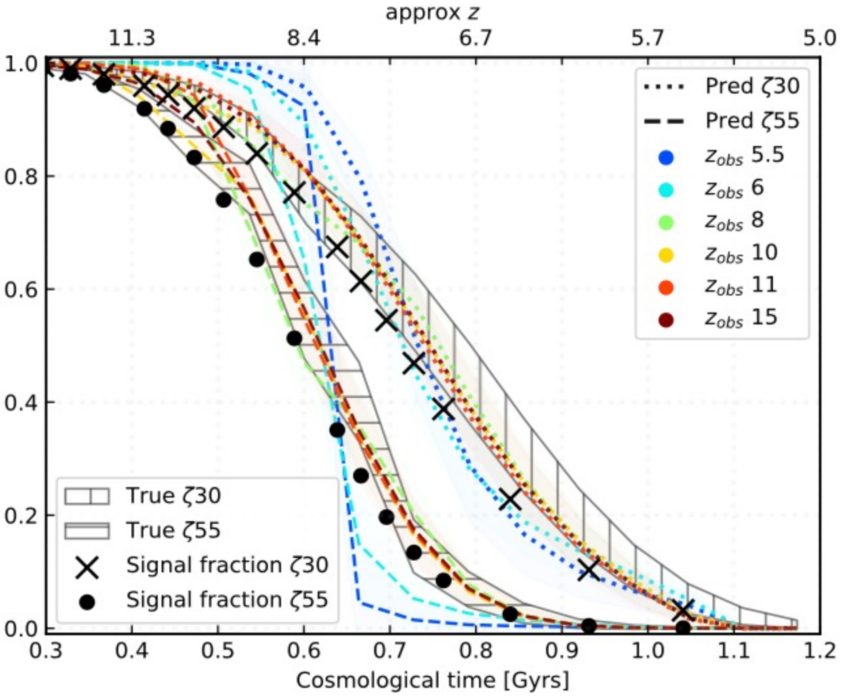
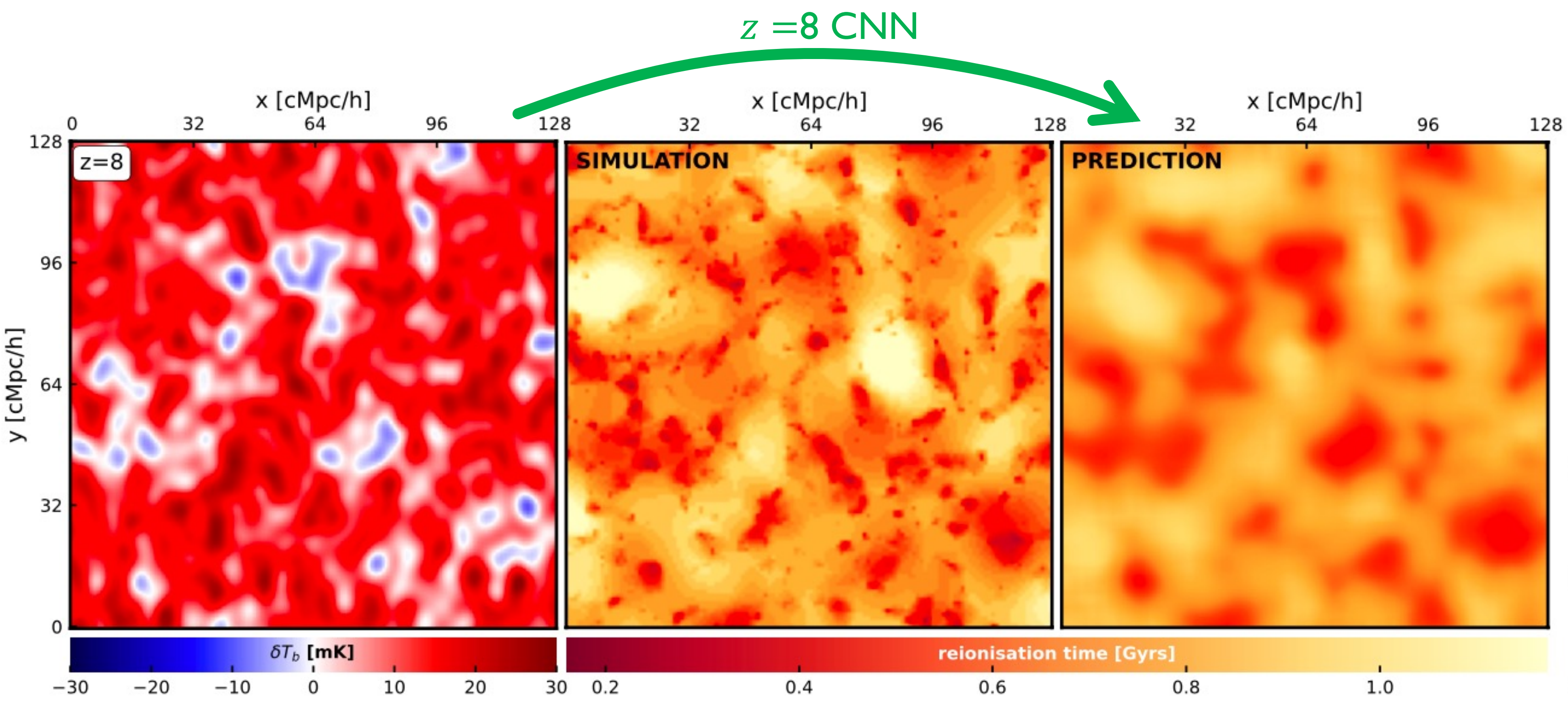
Volume fraction of neutral gas




- Example with $z_{obs} = 11$: less small structures but visually really close
- 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*




**Noise characteristics** (Tool21cm, Giri+20)

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

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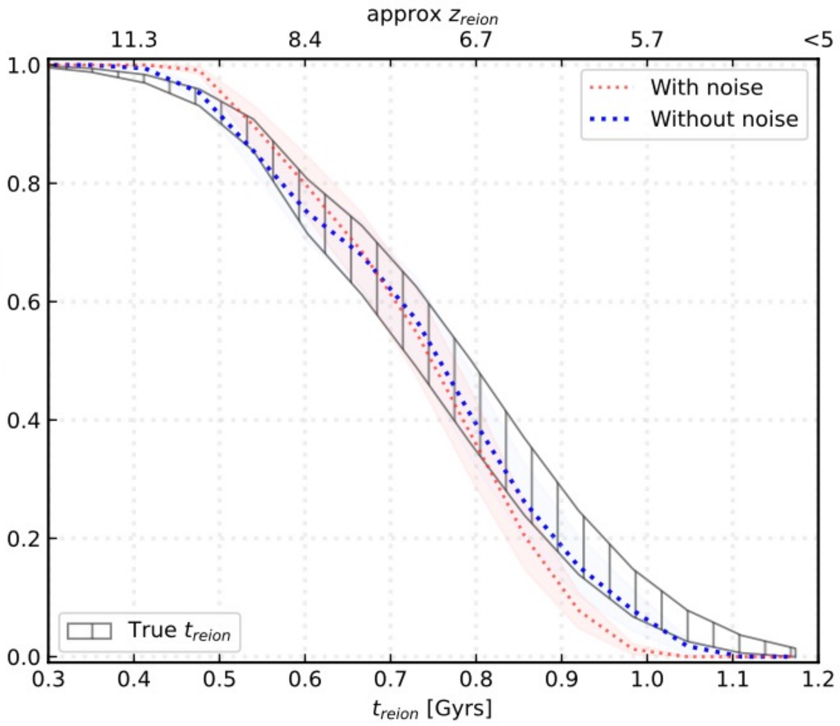


WORK IN PROGRESS

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

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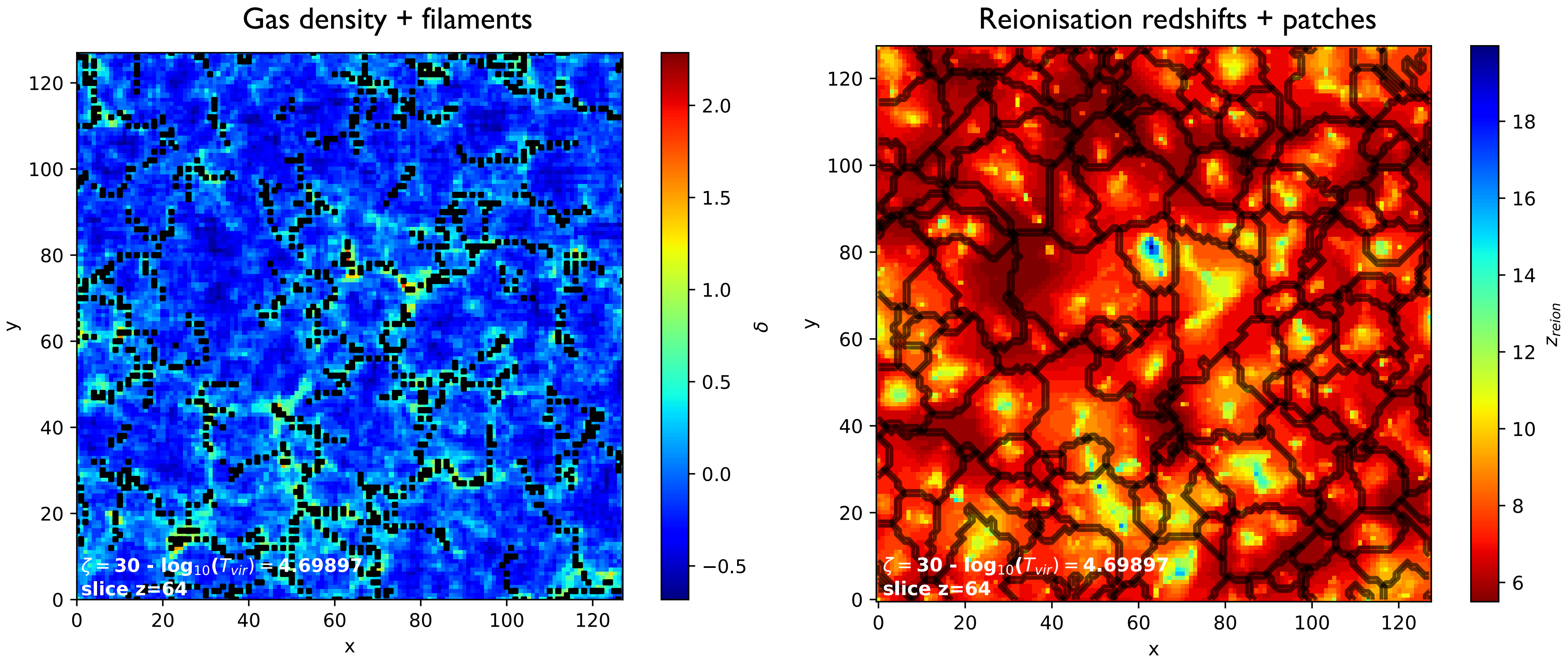
# B. REIONISATION PATCHES

*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)**

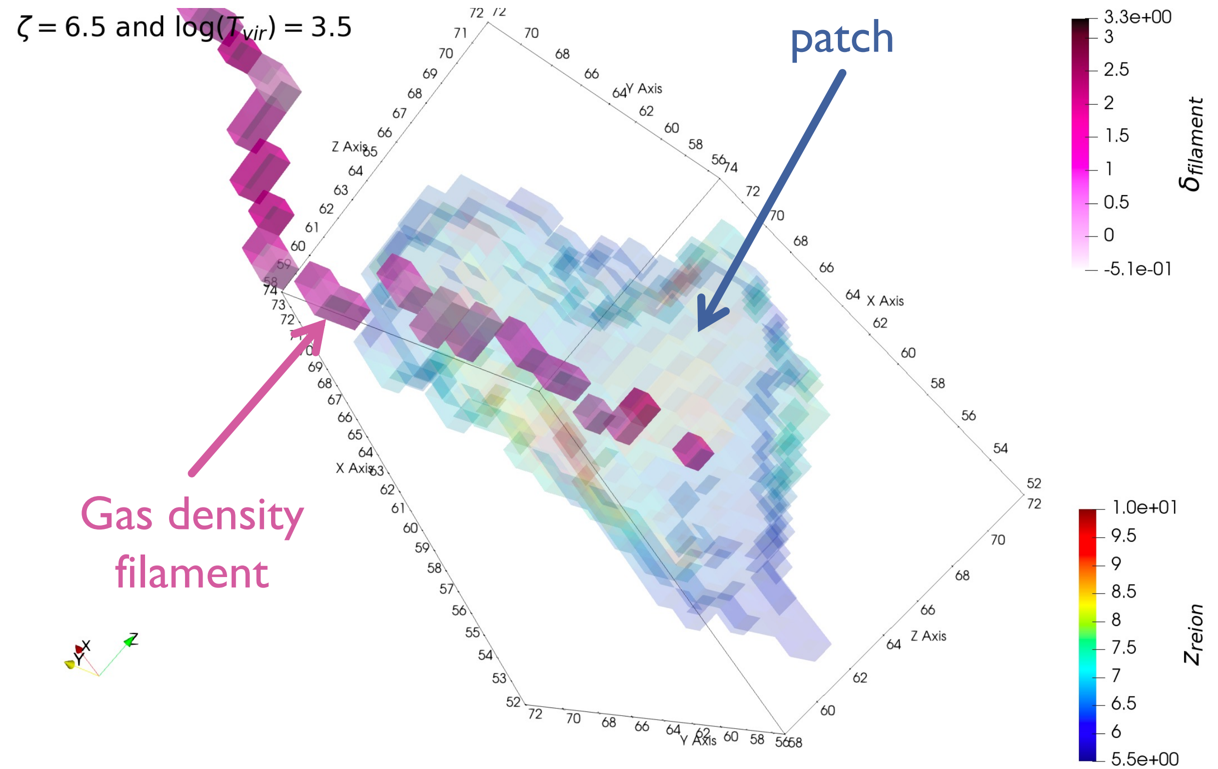
*Thélie+ (2022)*

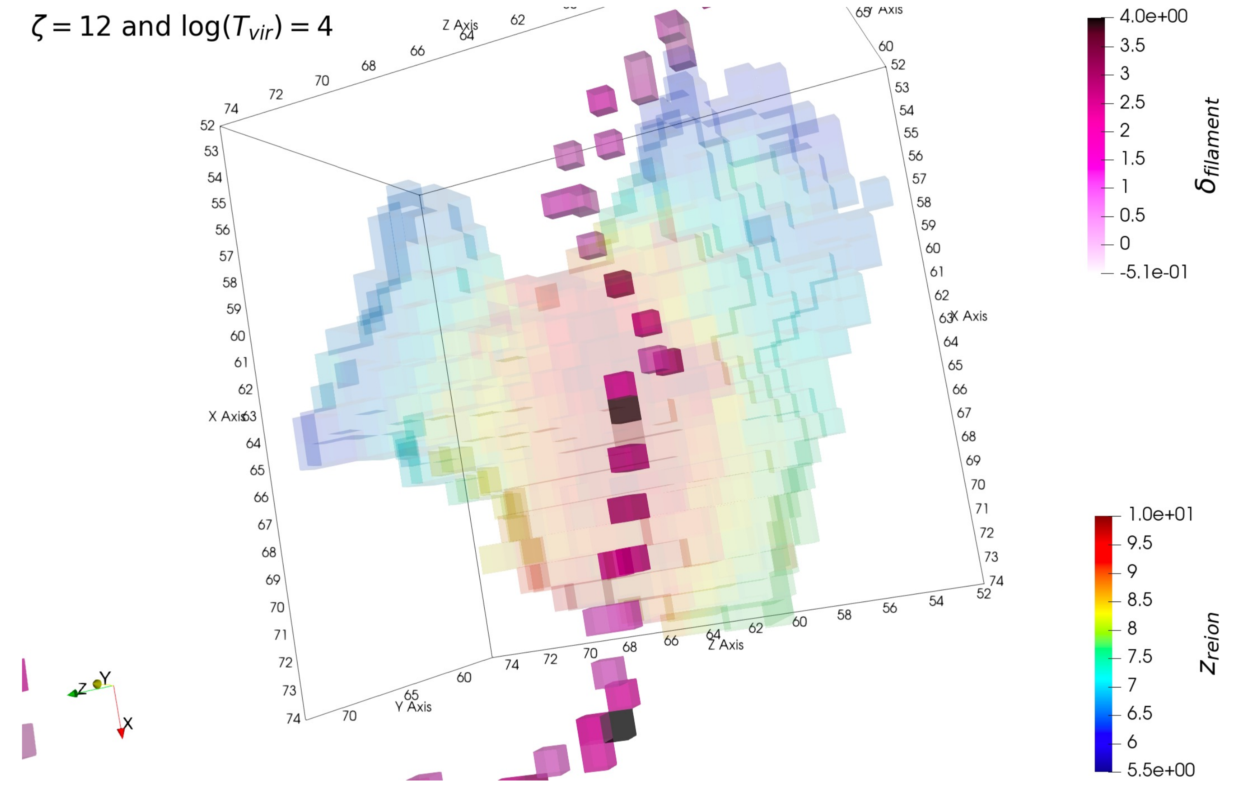
**$z_{reion}$**

- 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

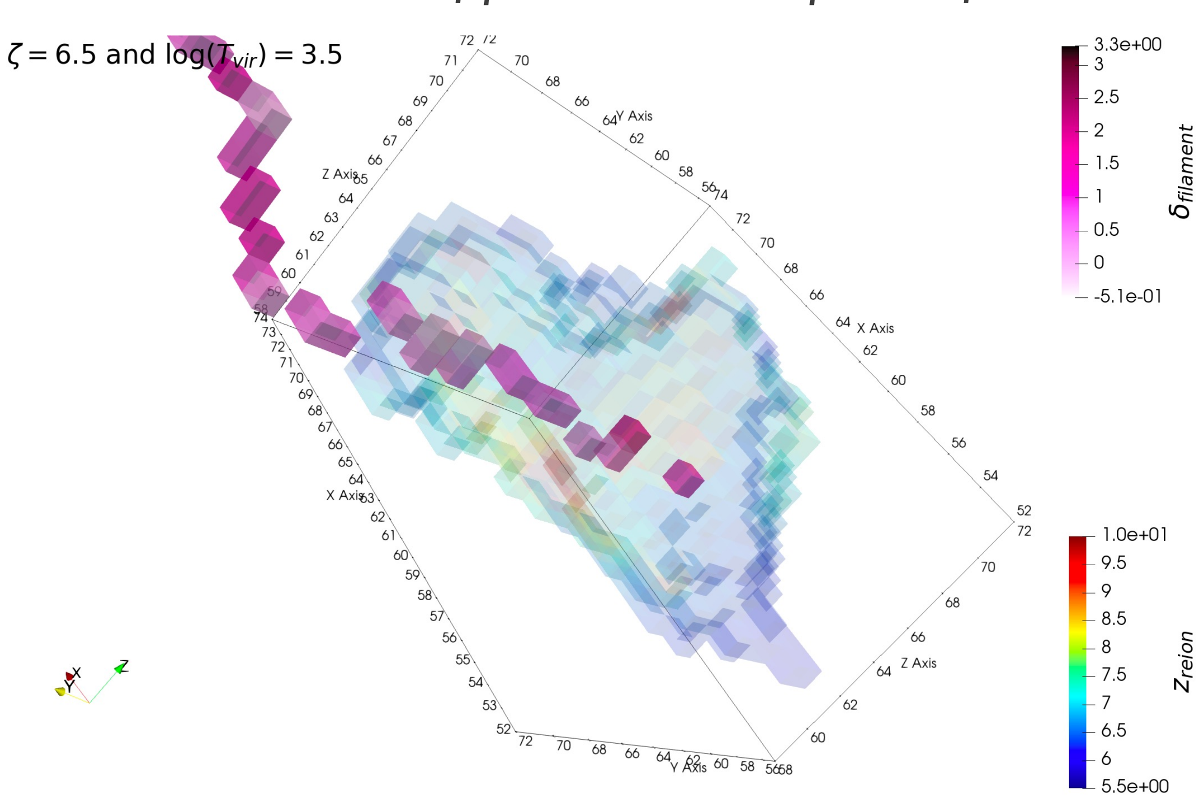
*= radiations follow the matter filament*

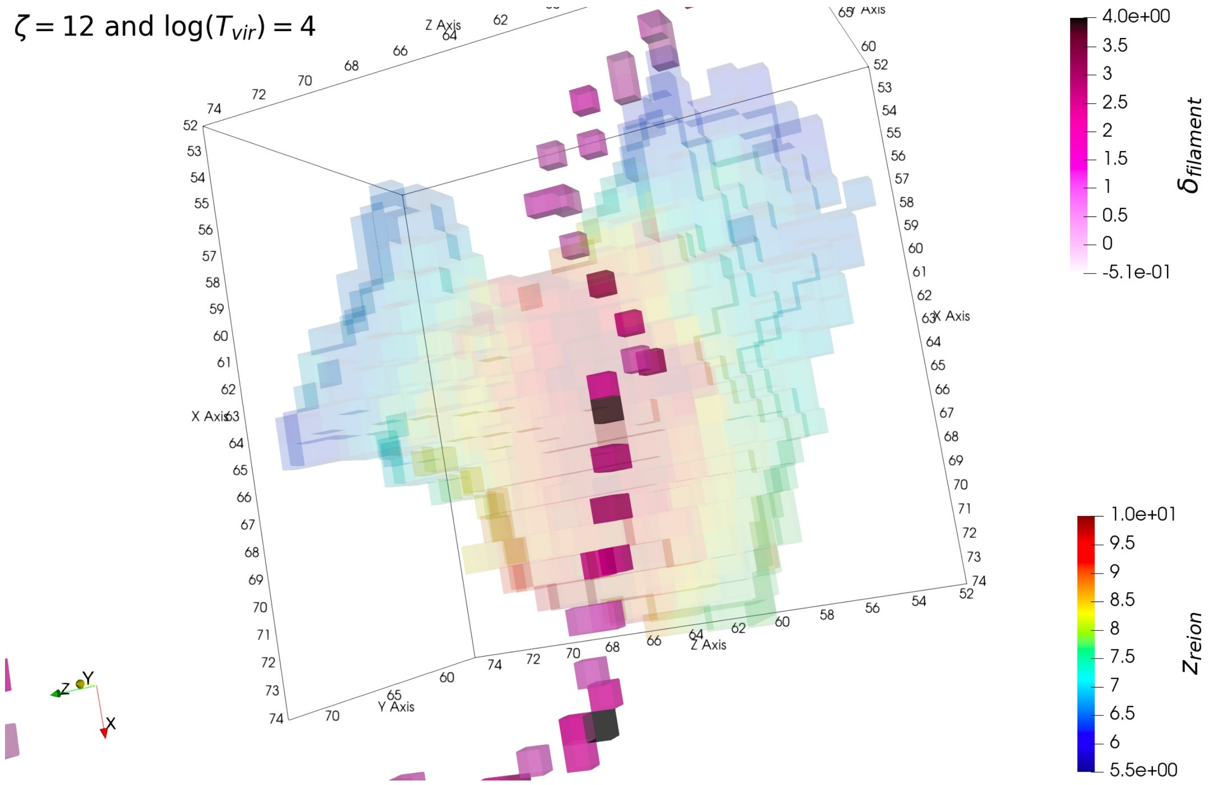
Reionisation patch in a butterfly shape

*= radiations follow the path of least resistance*

# B. REIONISATION PATCHES

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

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*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*

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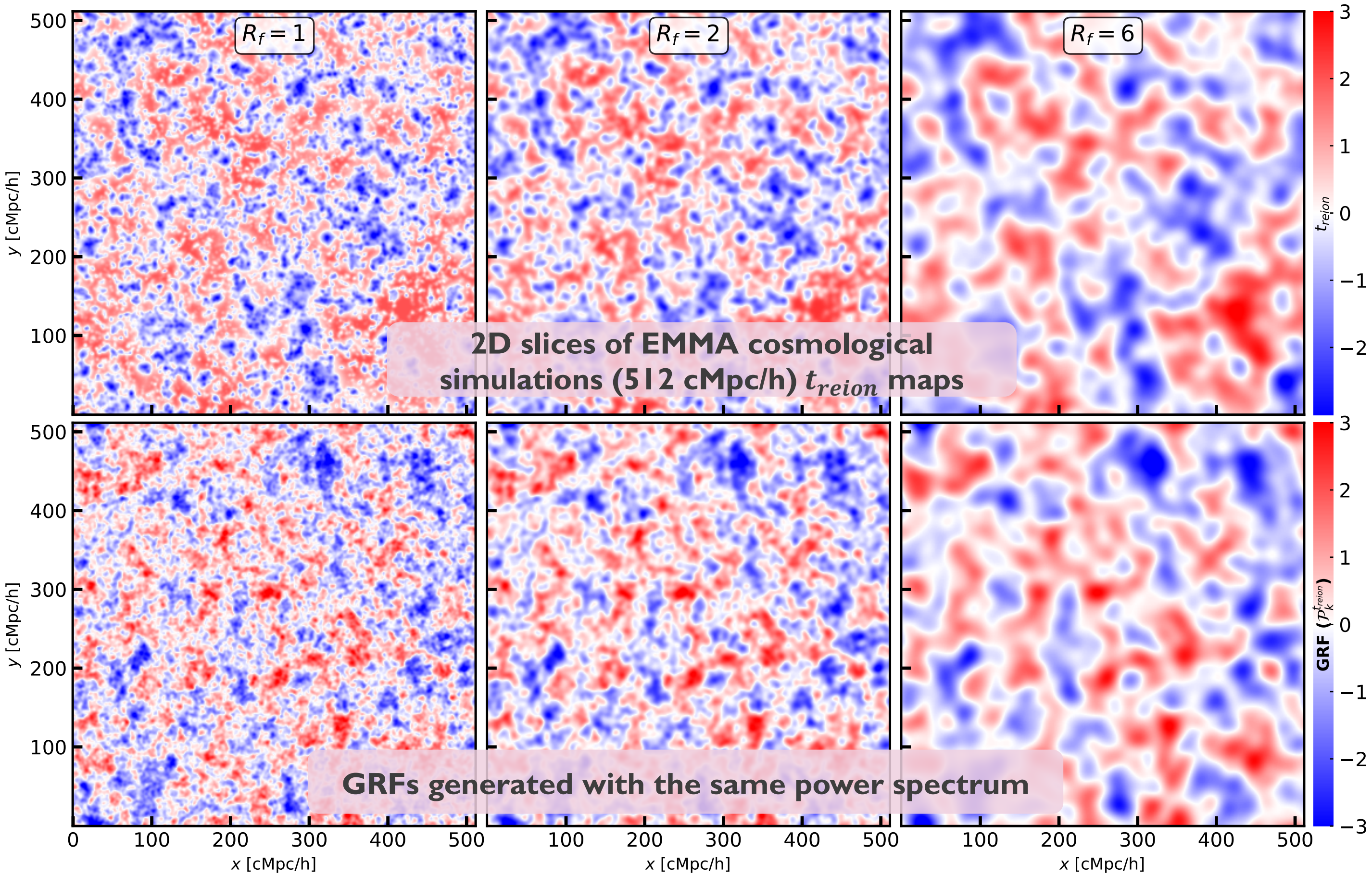
# C. TOPOLOGY AND GRF THEORY

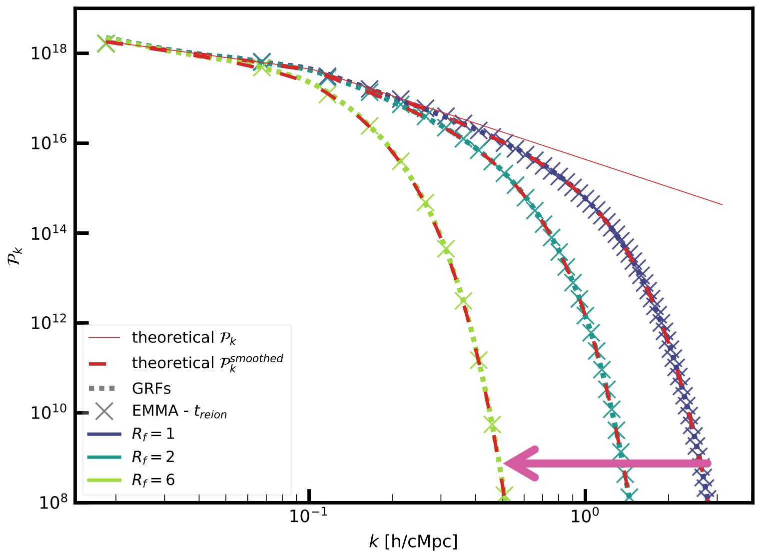
*Characterisation of the evolving topology of the EoR*

**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+ (submitted to A&A)*

**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***

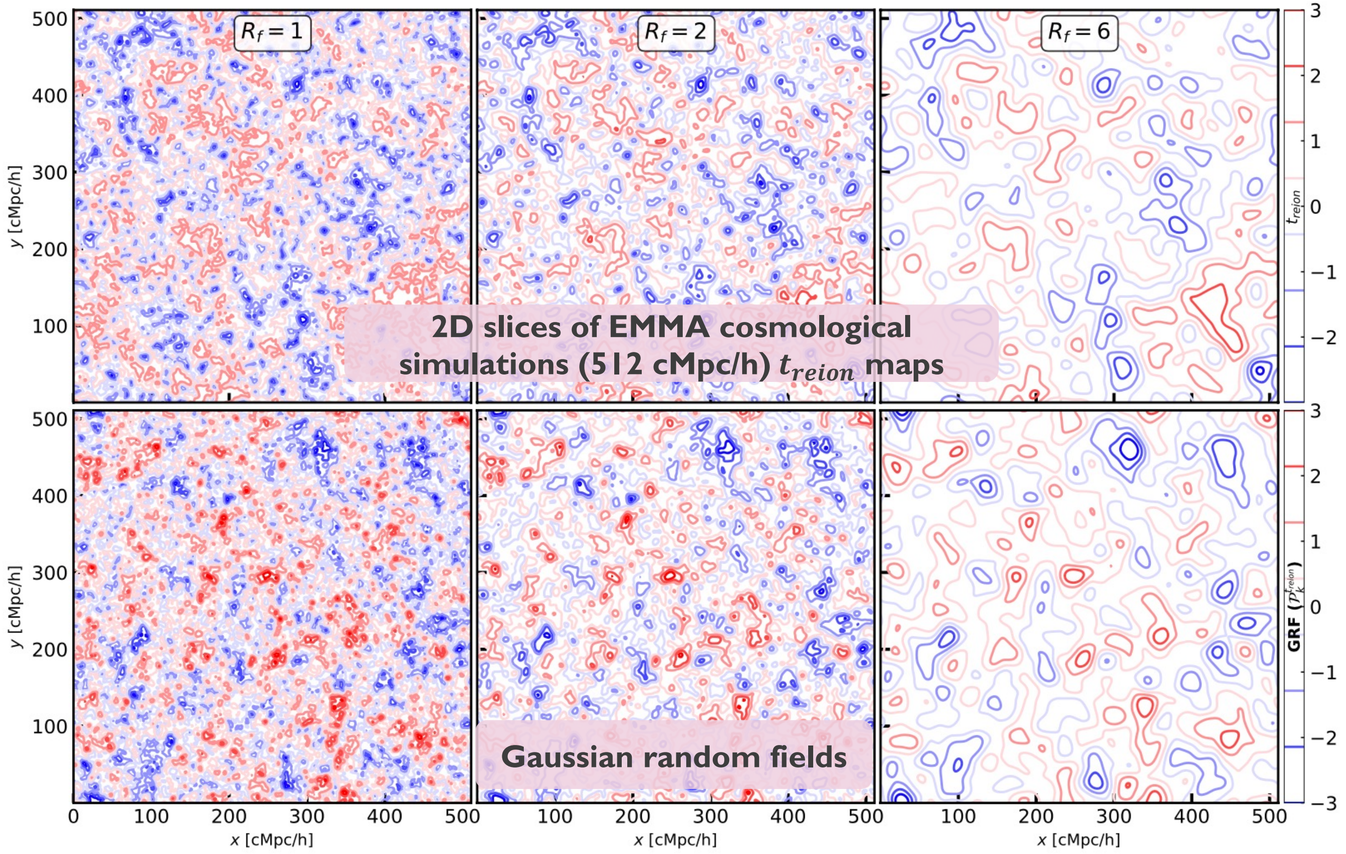
PDF of field values at its minima
*= reionisation seed counts*

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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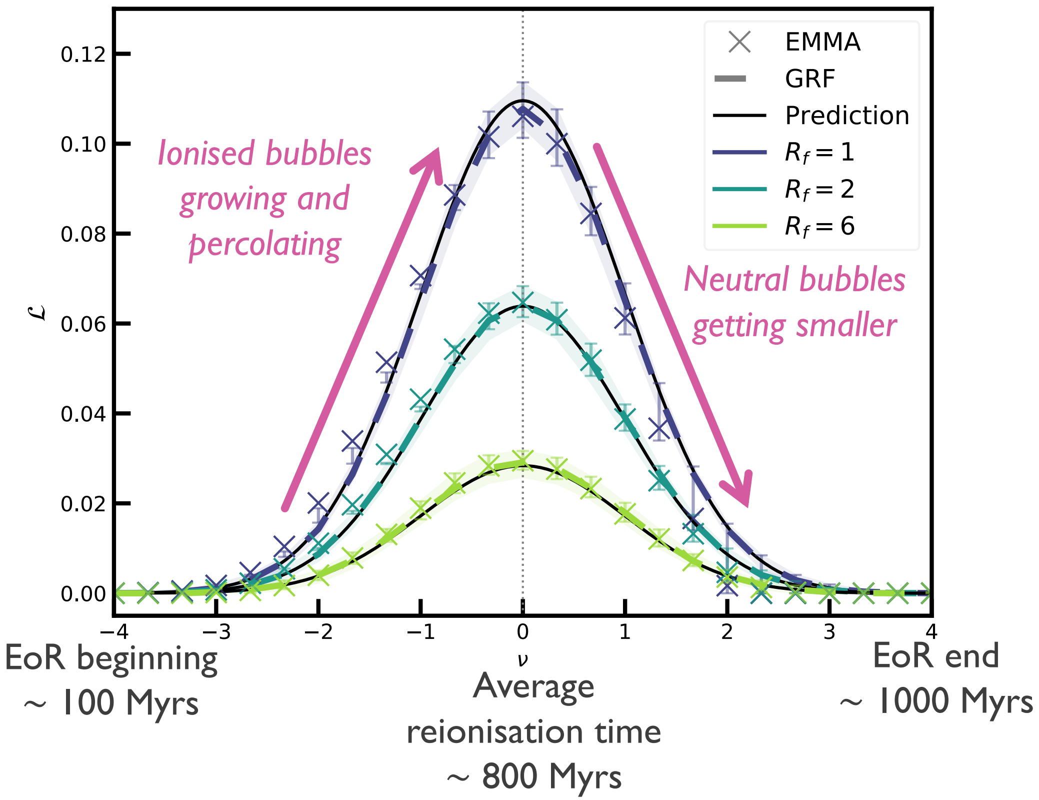
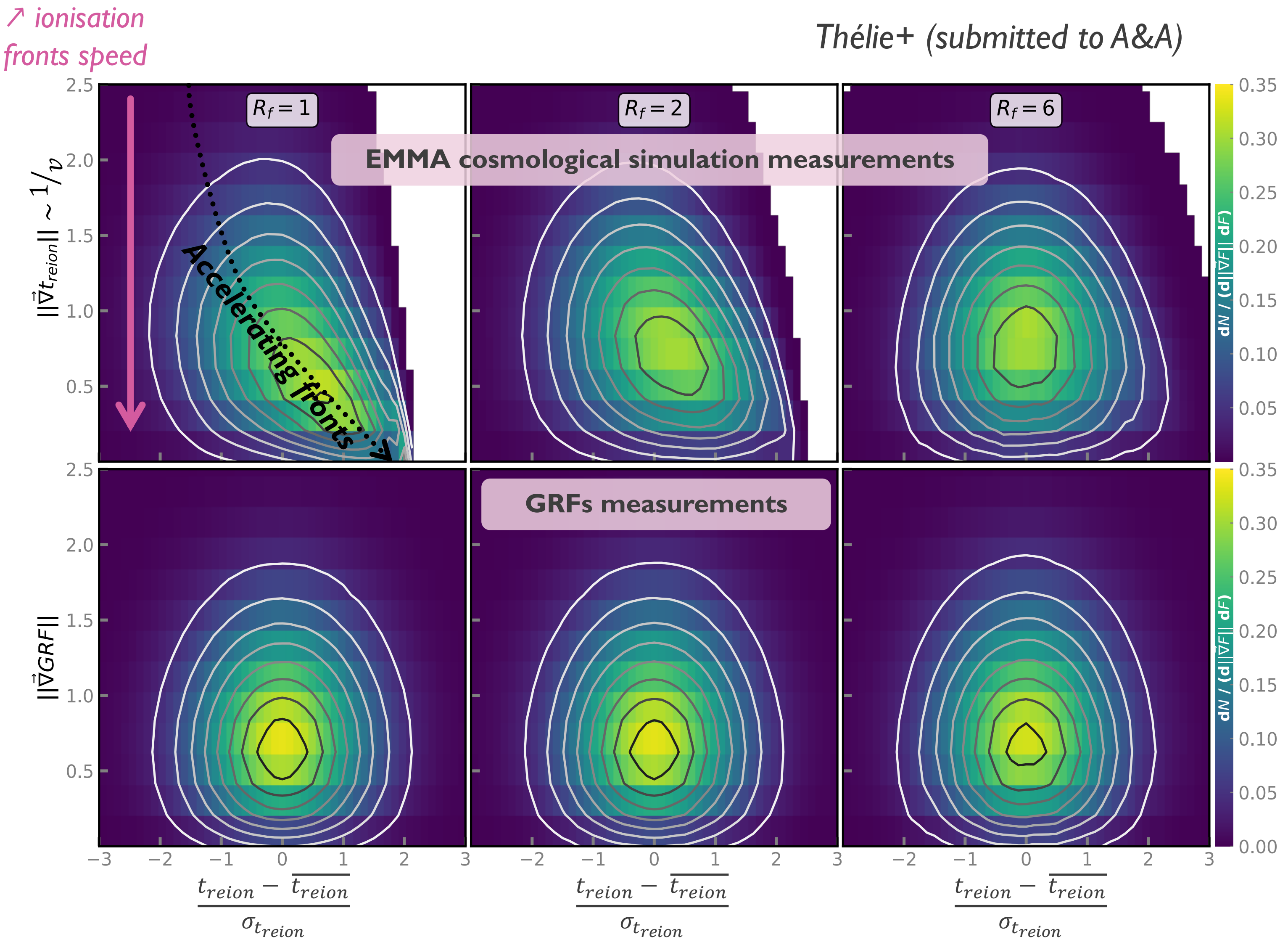


# C. TOPOLOGY AND GRF THEORY

*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*



# 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

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- *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

**How does the EoR happen?**

Topological studies to analyse:

- *Growth of structures*
- *Ionised/neutral bubbles geometry, distribution, organisation*
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- Geometrical characterisation of different EoR model
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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

**B. Reionisation patches**

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

**C. Reionisation times: topology and GRFs theory**

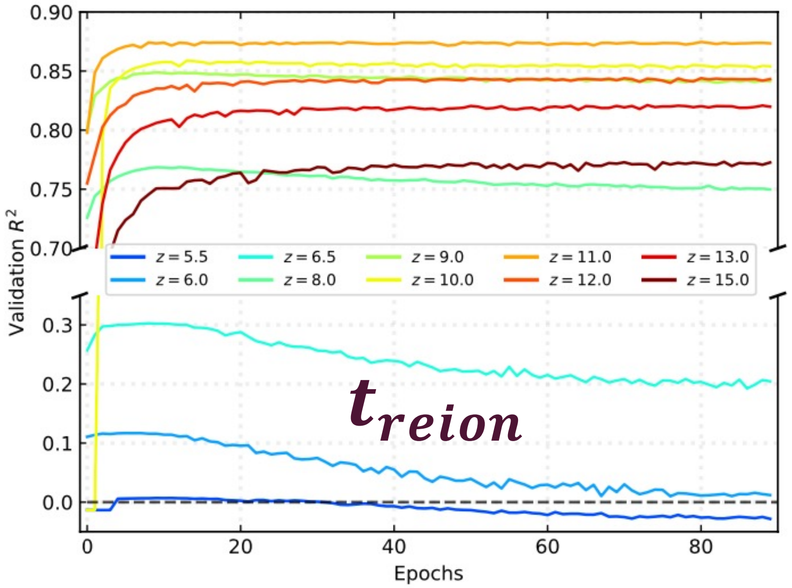
- Diverse statistics on the evolution of the reionisation process…
- … that are analytically computable $t_{reion}$

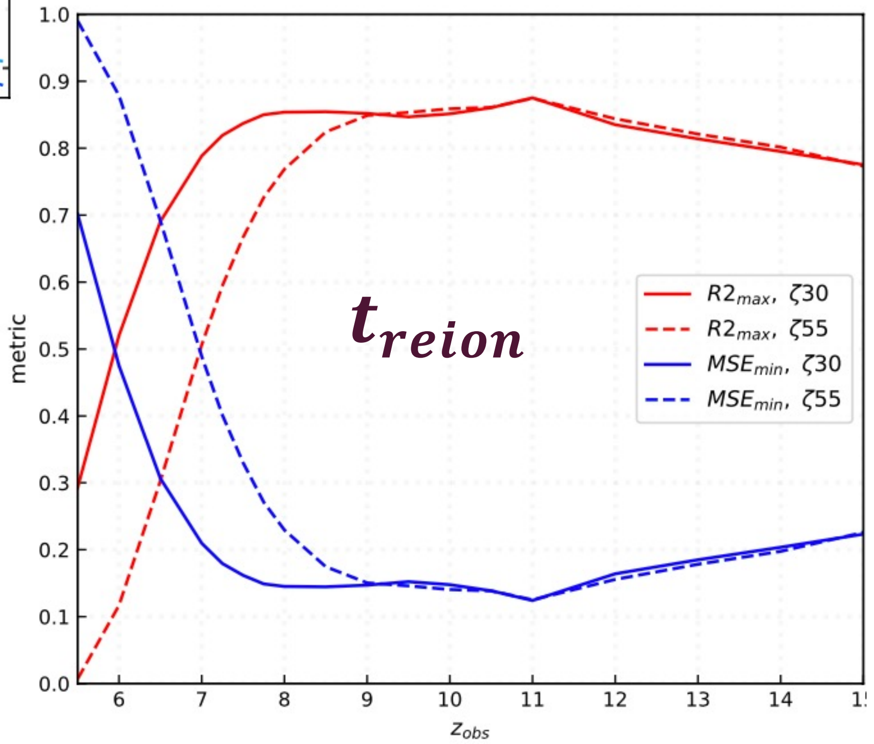
- Take into account the asymmetries in the GRFs predictions (e.g. with Gram-Charlier expansion)
- Same study but with larger or more resolved simulations (e.g. with Dyablo)
- Inference of the power spectrum parameters from topological measurements

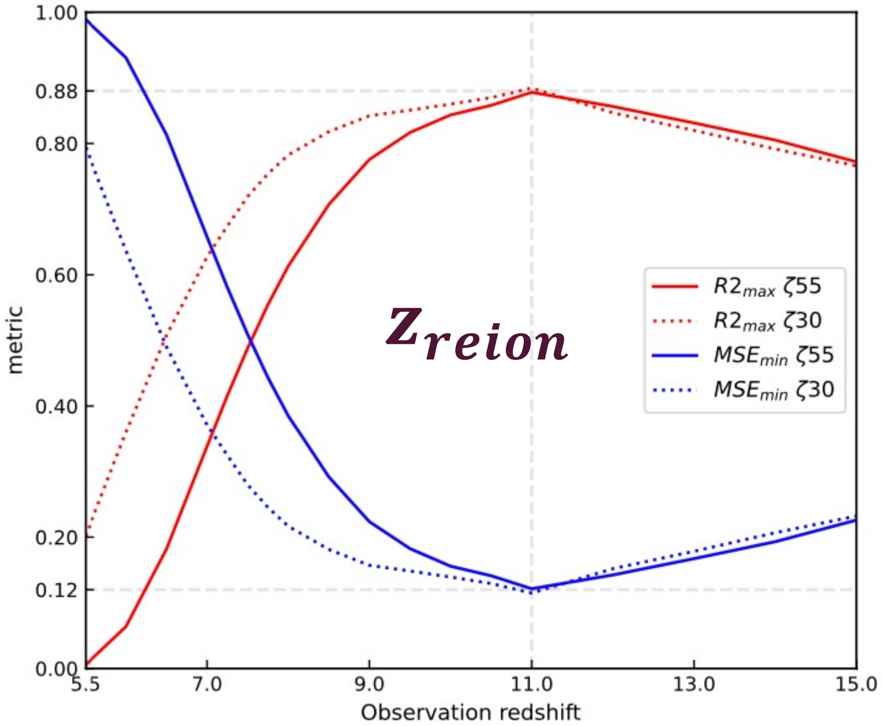
Thank you for your attention!

# A. 21 CM → $t_{reion}$

*Monitoring performances of the CNN*



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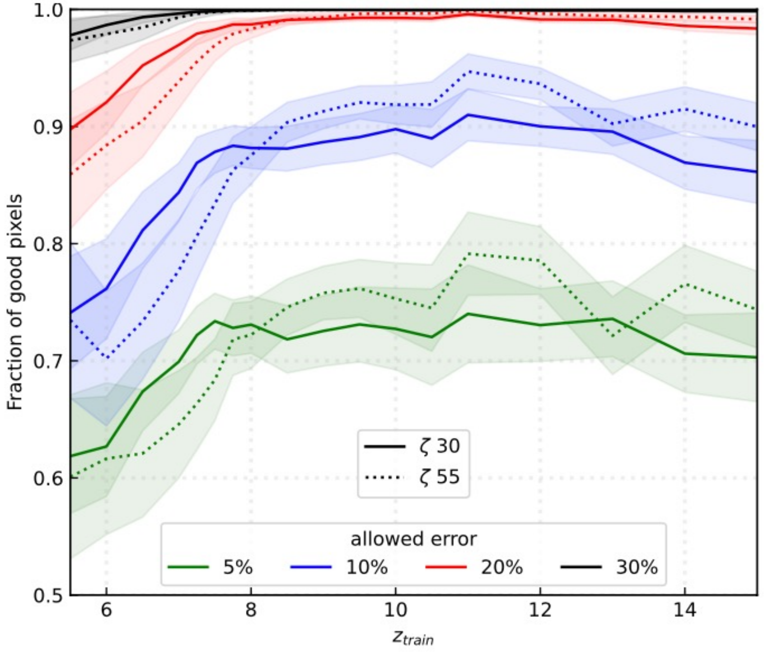


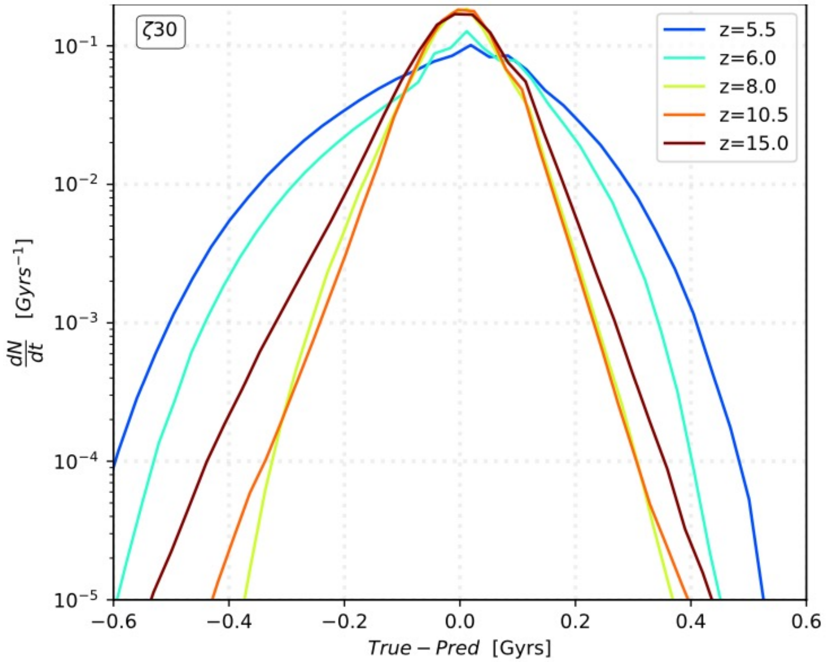


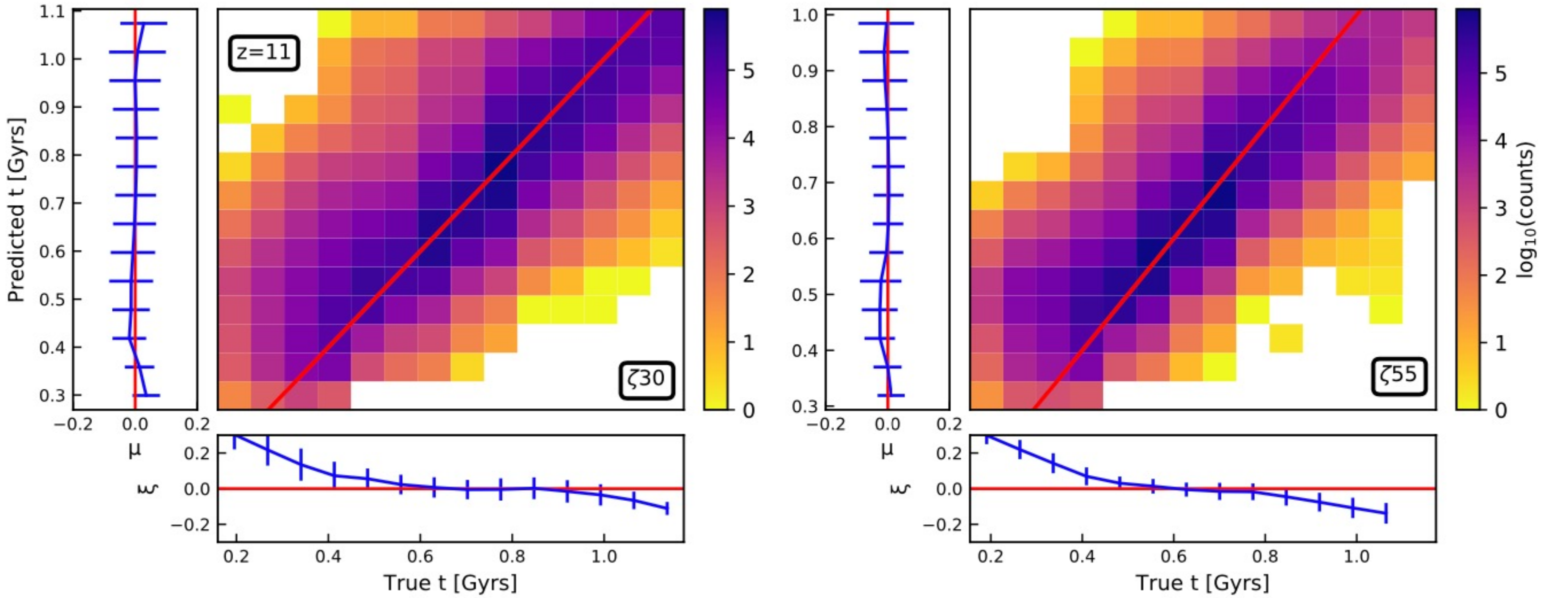

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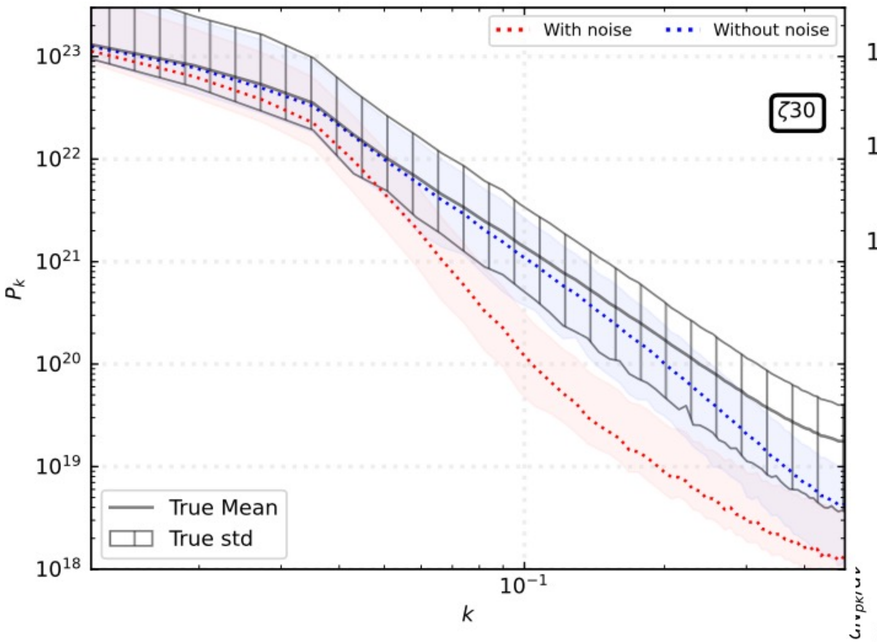
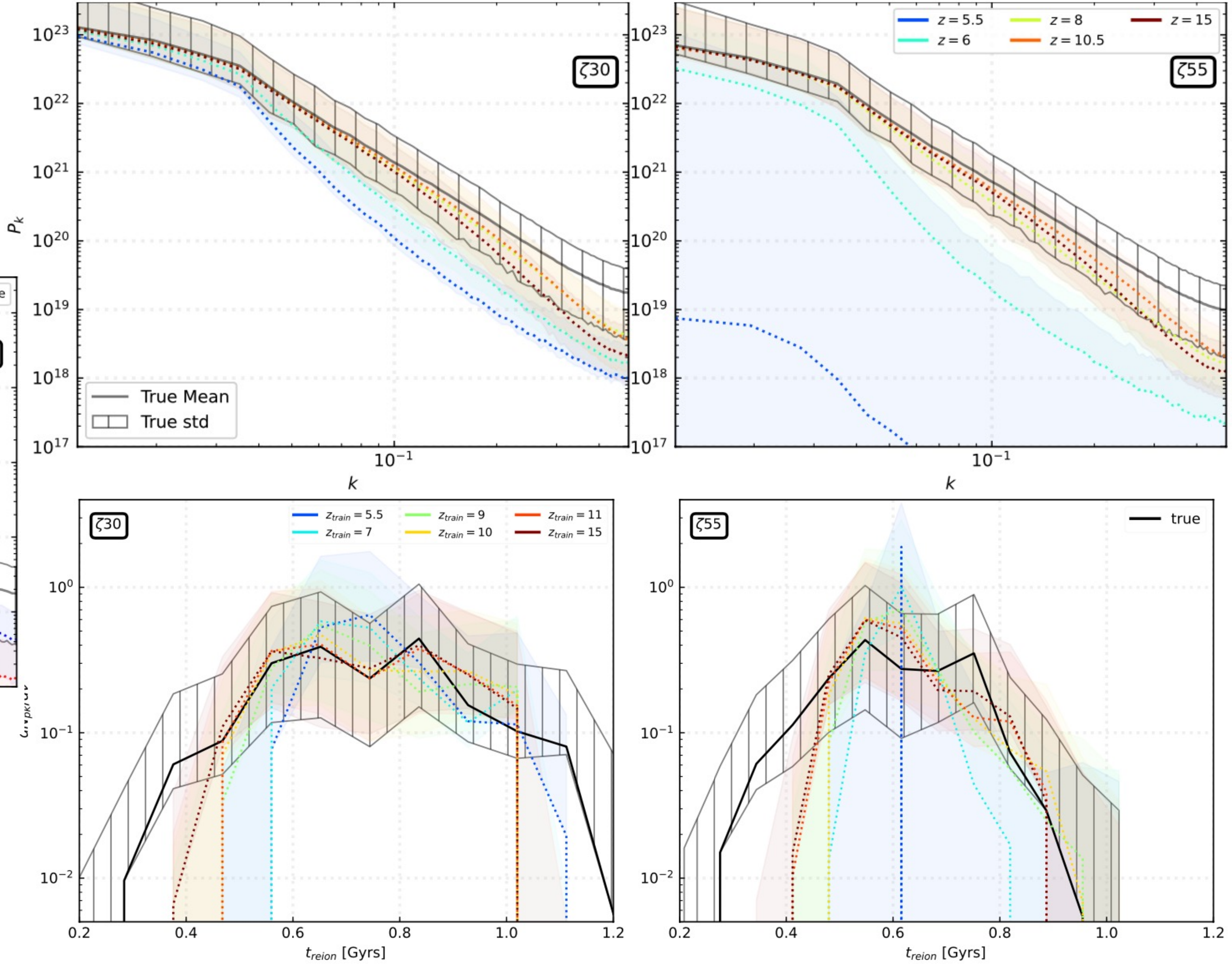


# B. PATCHS DE REIONISATION

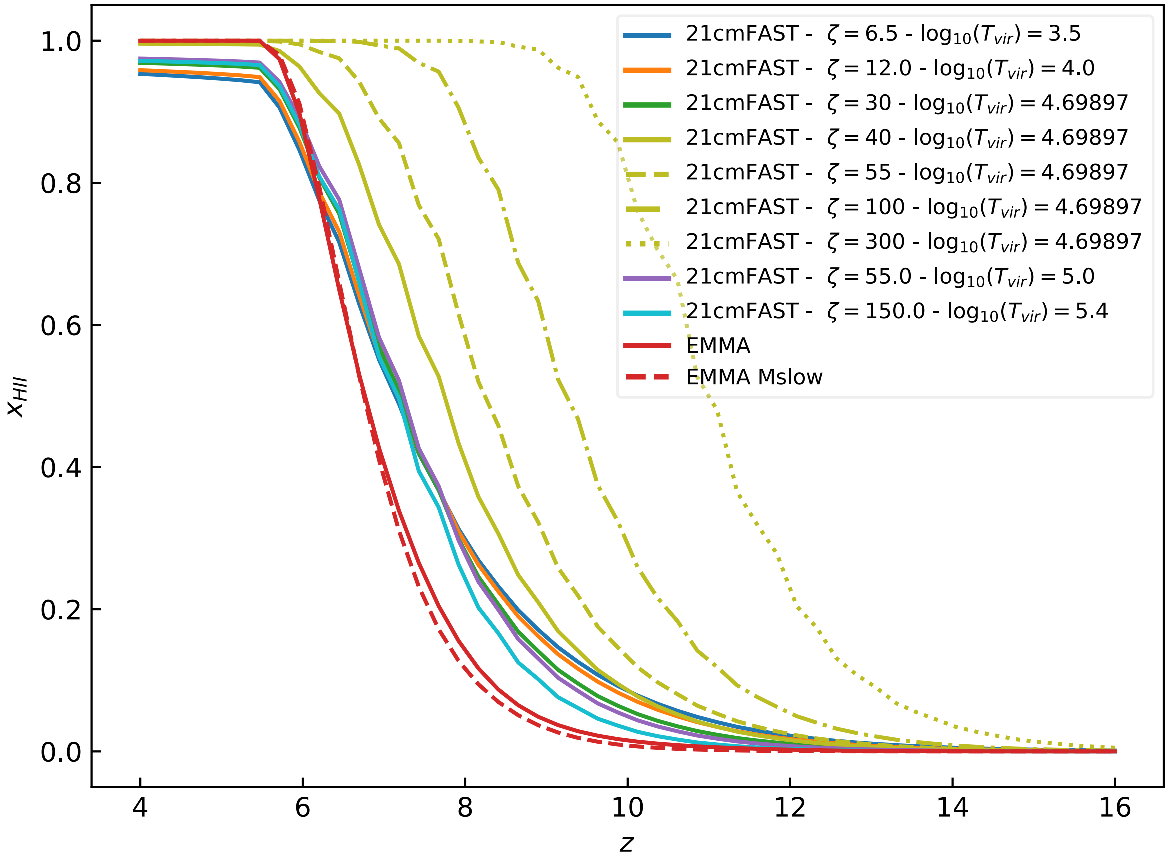
*Simulations*

**21cmFAST semi-analytical simulations ($128^3$ cellules - $128^3$ cMpc$^3$/h$^3$ ; 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 - $512^3$ cMpc$^3$/h$^3$ ;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)

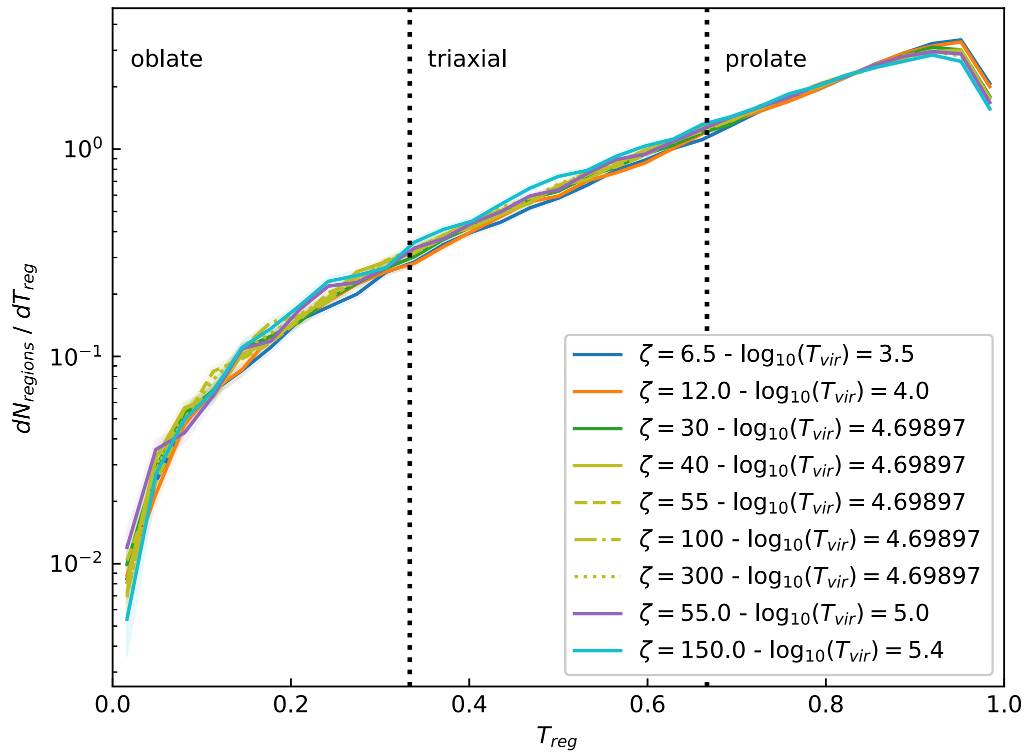


# B. REIONISATION PATCHES

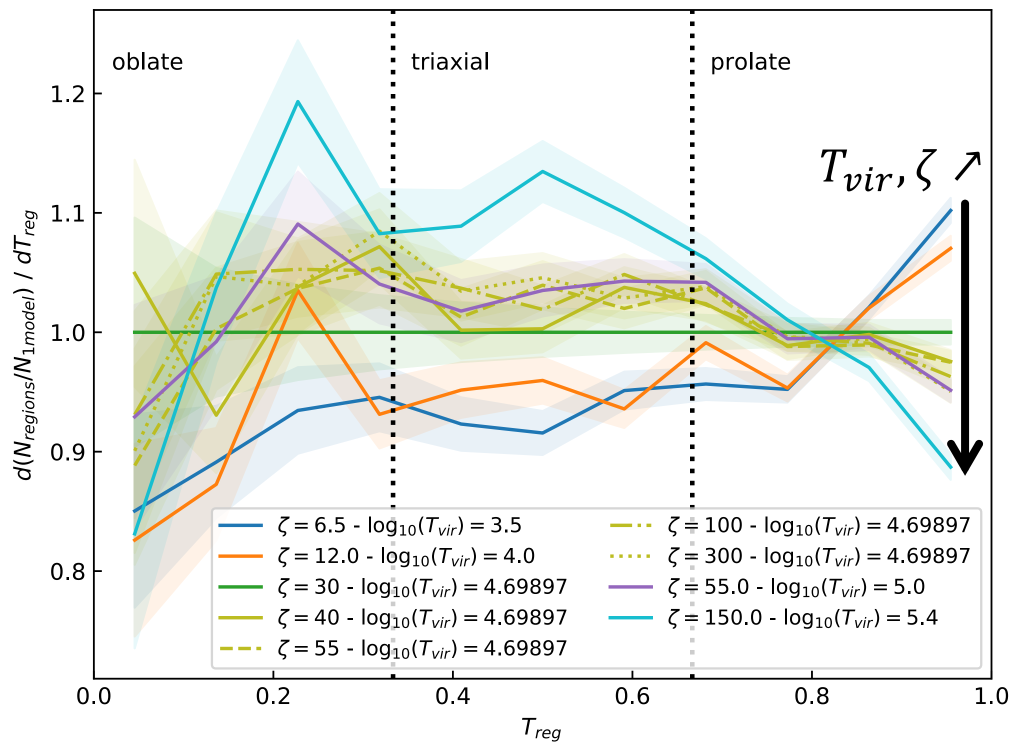
*Patches shape*



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

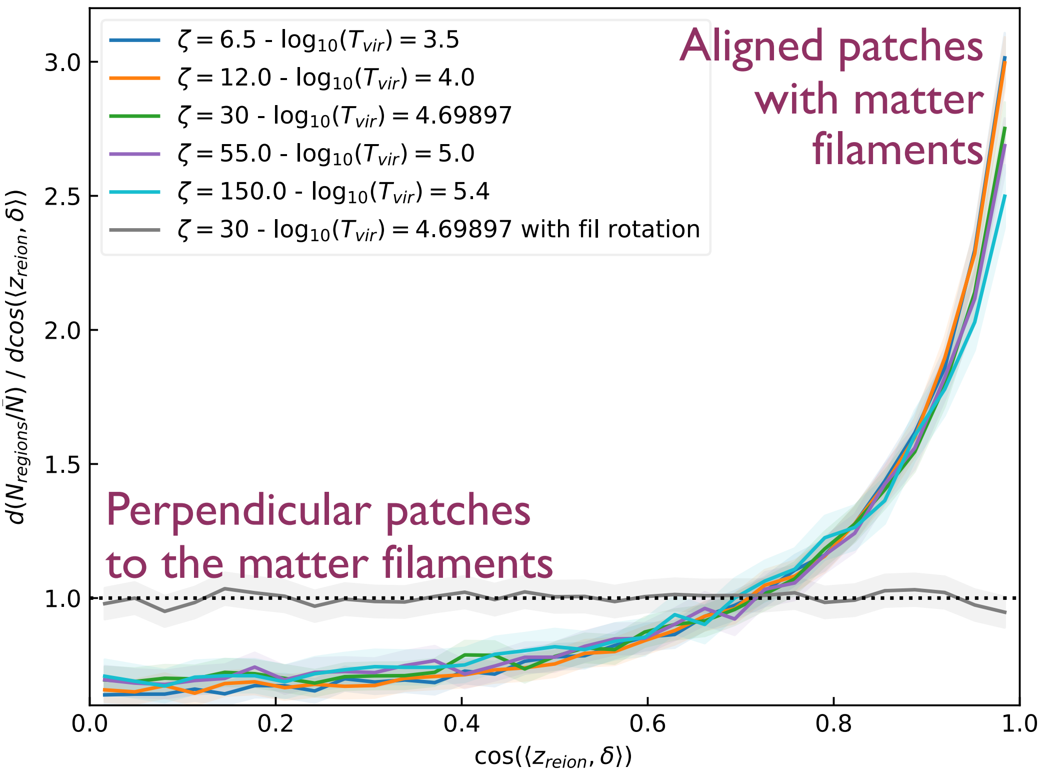



Ratio with model
$\zeta = 30$

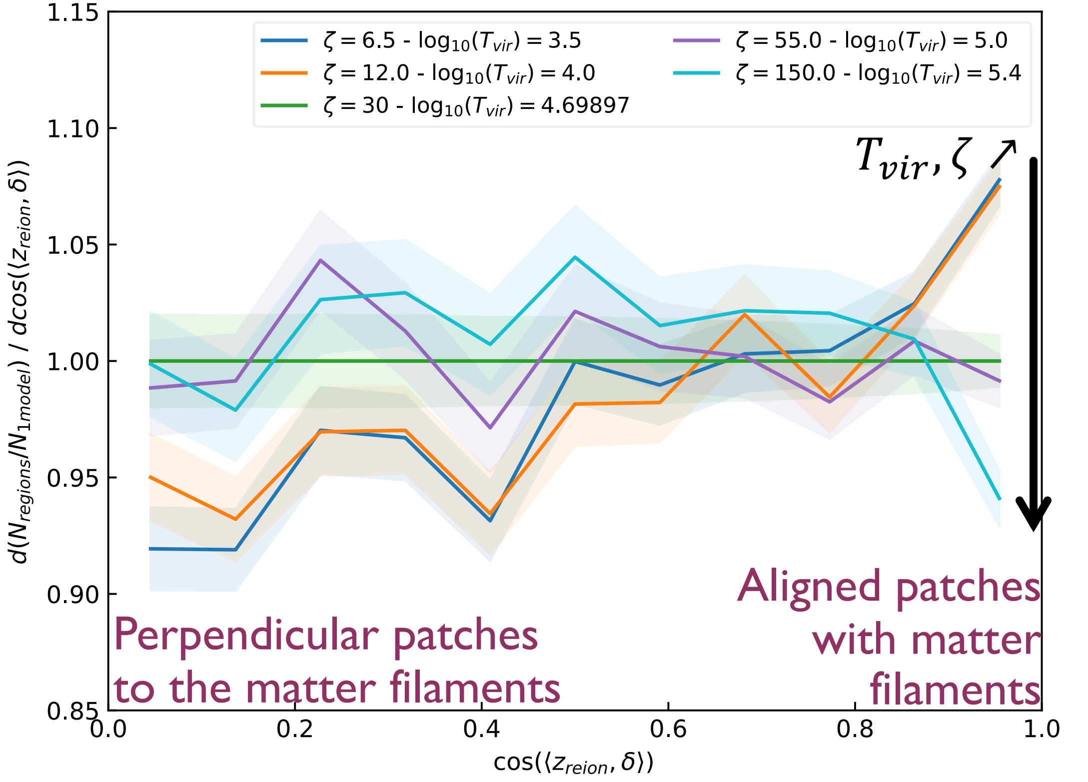


# B. REIONISATION PATCHES

*Orientation of patches with respect to the matter filaments*



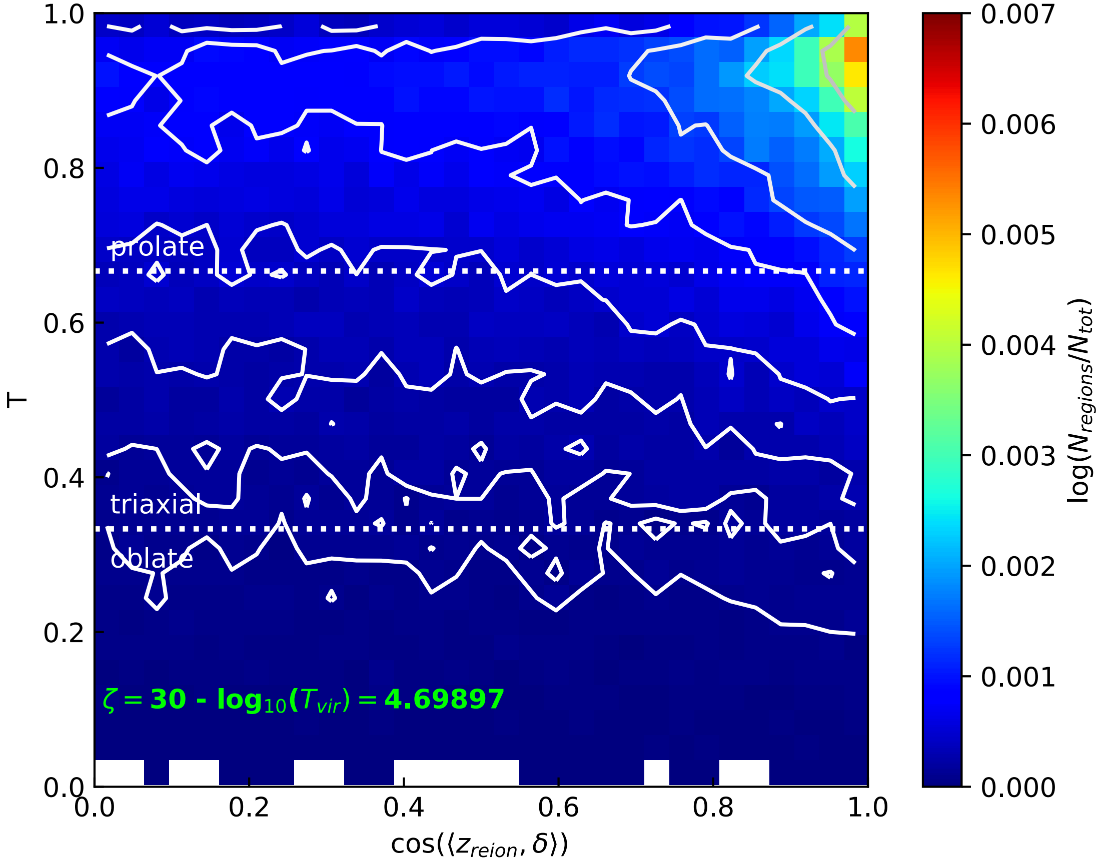

Ratio with model $\zeta = 30$




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

# B. REIONISATION PATCHES

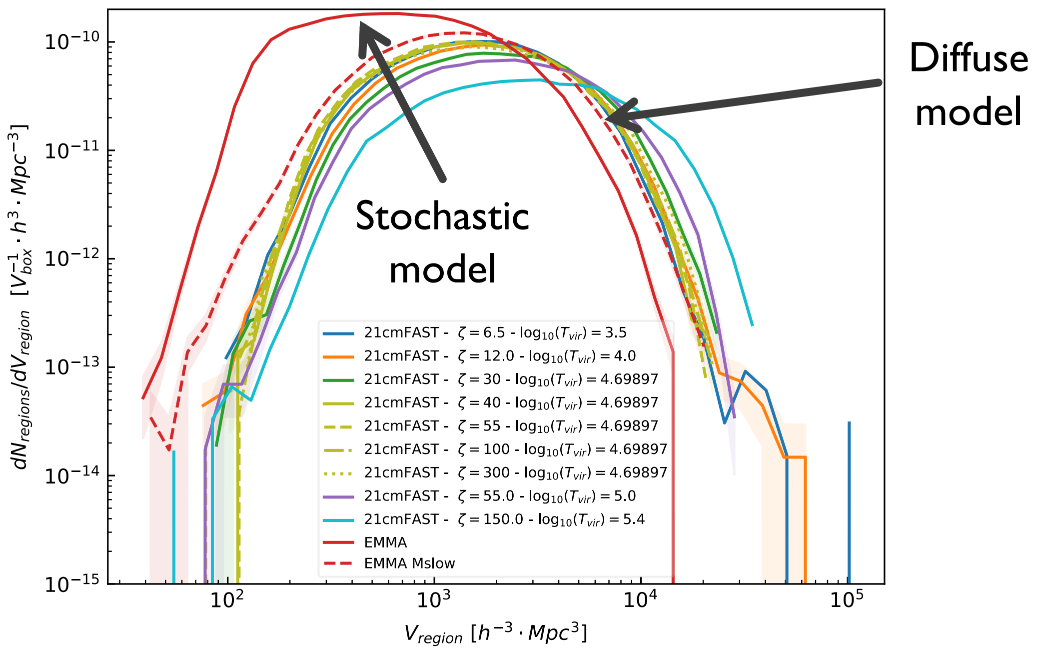
*Shape vs. orientation of patches with respect to the matter filaments*

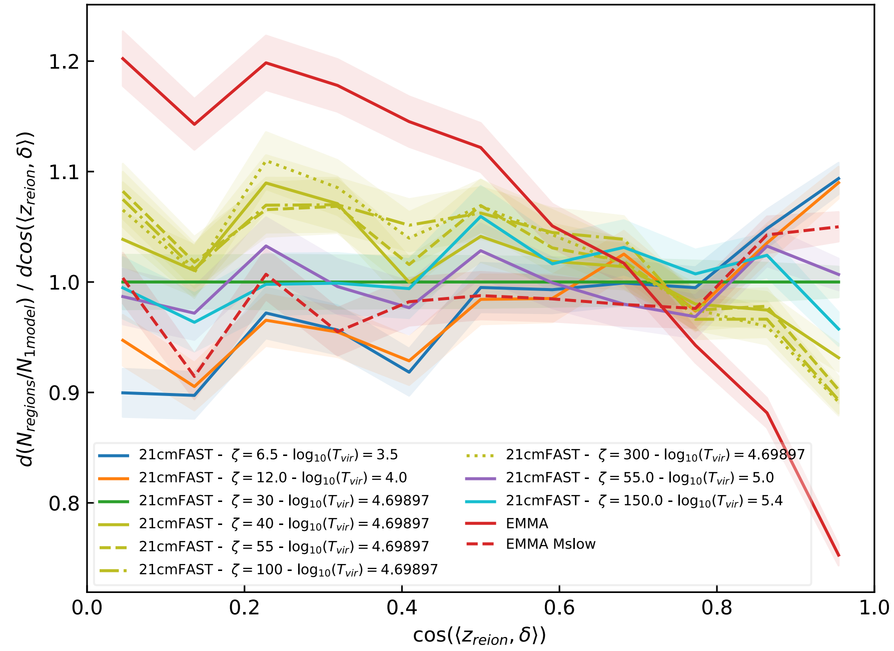


*Thélie+22*

# B. PATCHS DE REIONISATION

*Comparaison avec EMMA, une simulation cosmologique*



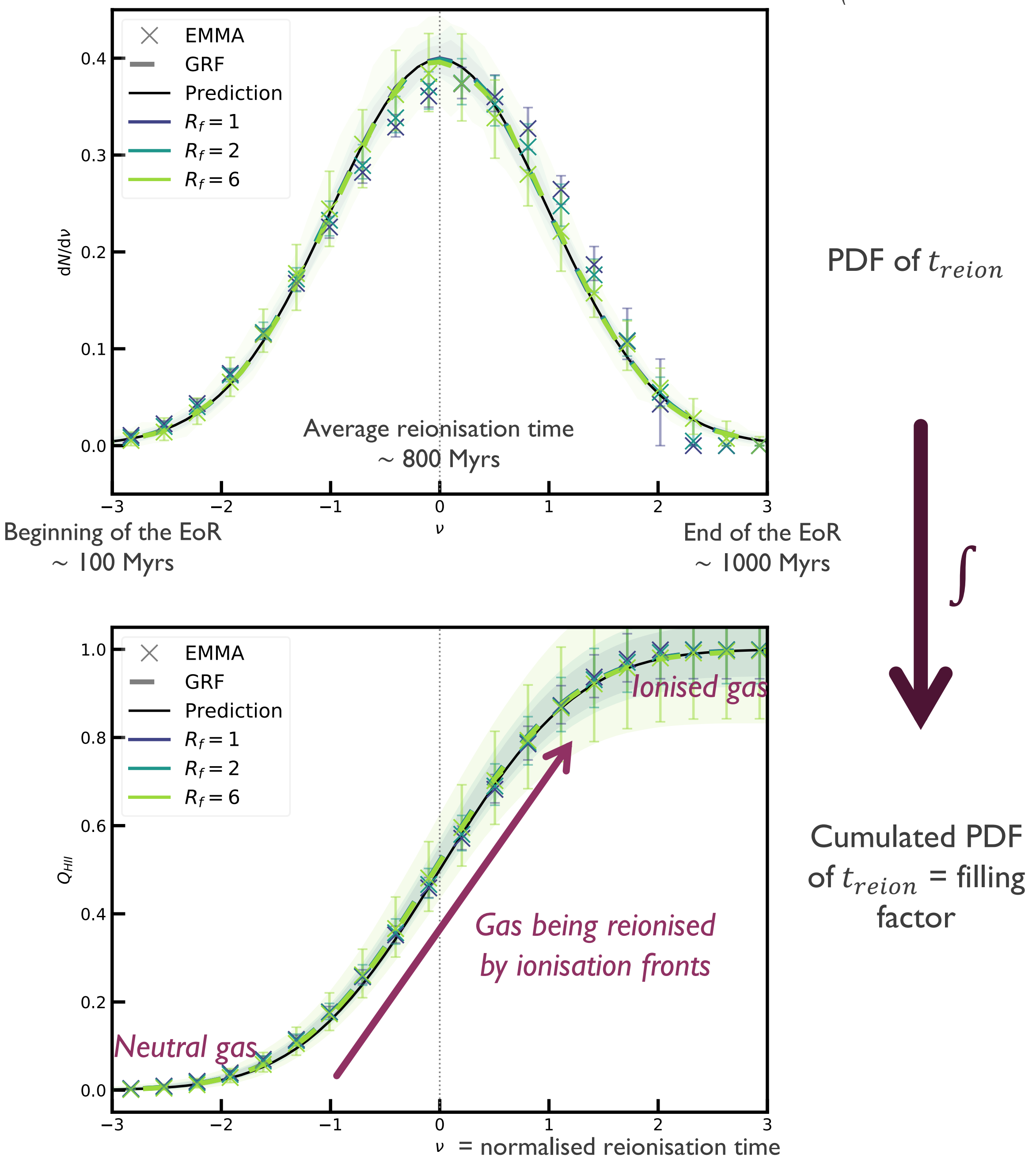

- Same conclusions for both type of simulations
- BUT EMMA can also produce models with rather different topologies (for the same $x_{HII}(z)$)

# C. TOPOLOGY AND GRF THEORY

*Filling factor: PDF et reoinisation history*

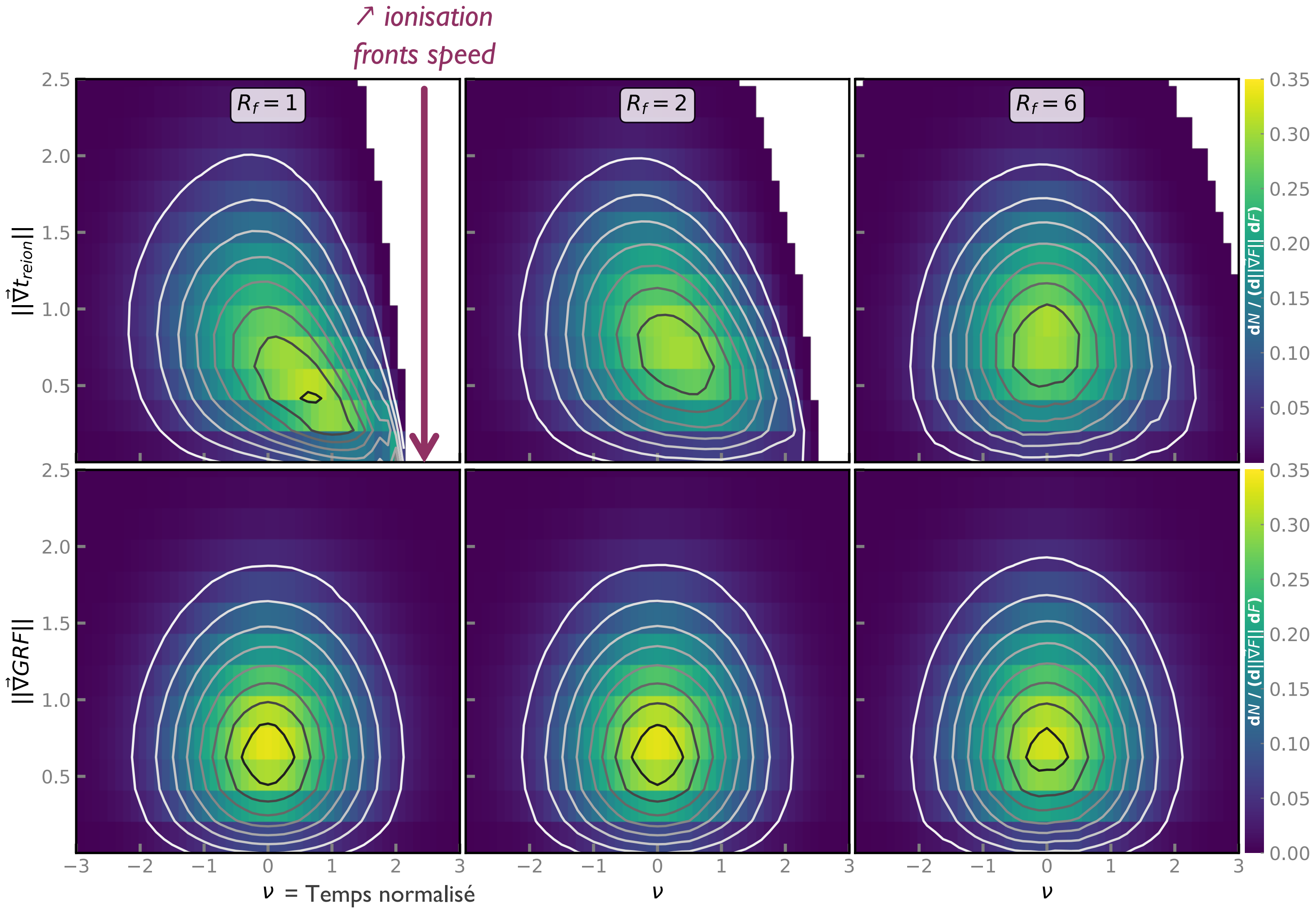
- $R_f \nearrow$ : EMMA measurements more symmetric
- $R_f \in \{1, 2\}$ : imprints of non-gaussianity in the form of an asymmetry

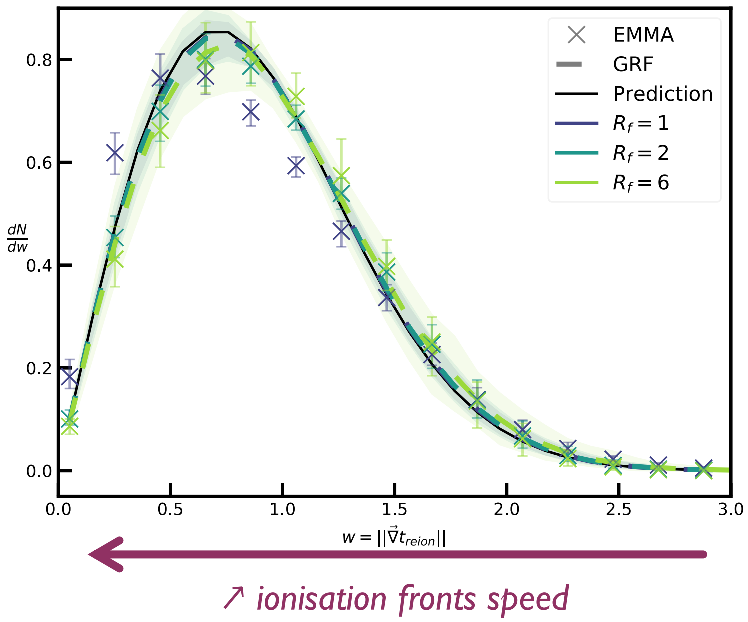
  *= slow reionisation before it is accelerated*



# C. TOPOLOGY AND GRF THEORY

*PDF of the gradients field norm: ionisation fronts speed*

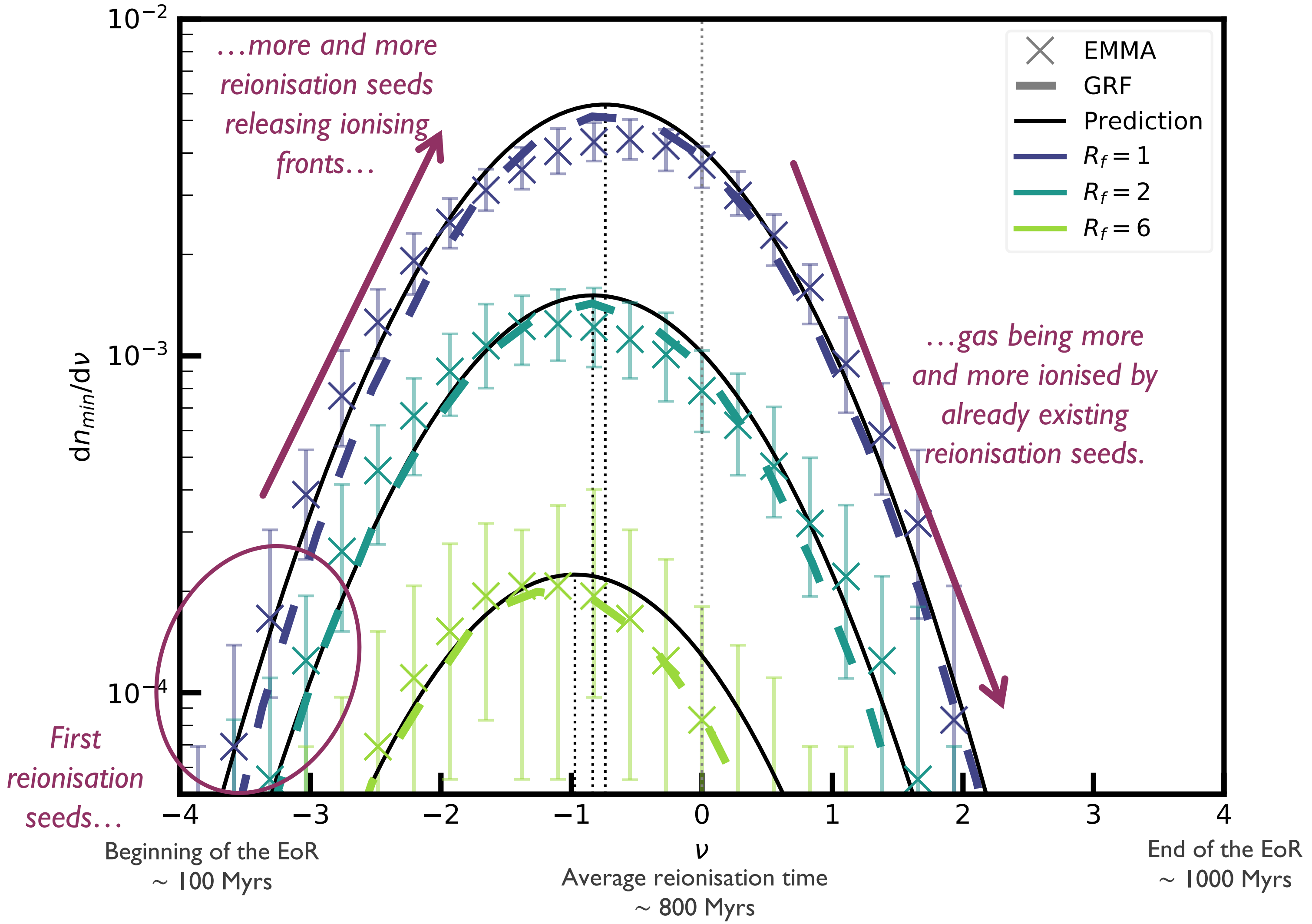



- $\boldsymbol{R_f}$ ↗ **:** EMMA measurements more symmetric
- $\boldsymbol{R_f \in \{1, 2\}}$ **:** imprints of non-gaussianity in the form of an asymmetry
  = *acceleration of the ionisation fronts at the end of the EoR*

# C. TOPOLOGY AND GRF THEORY

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

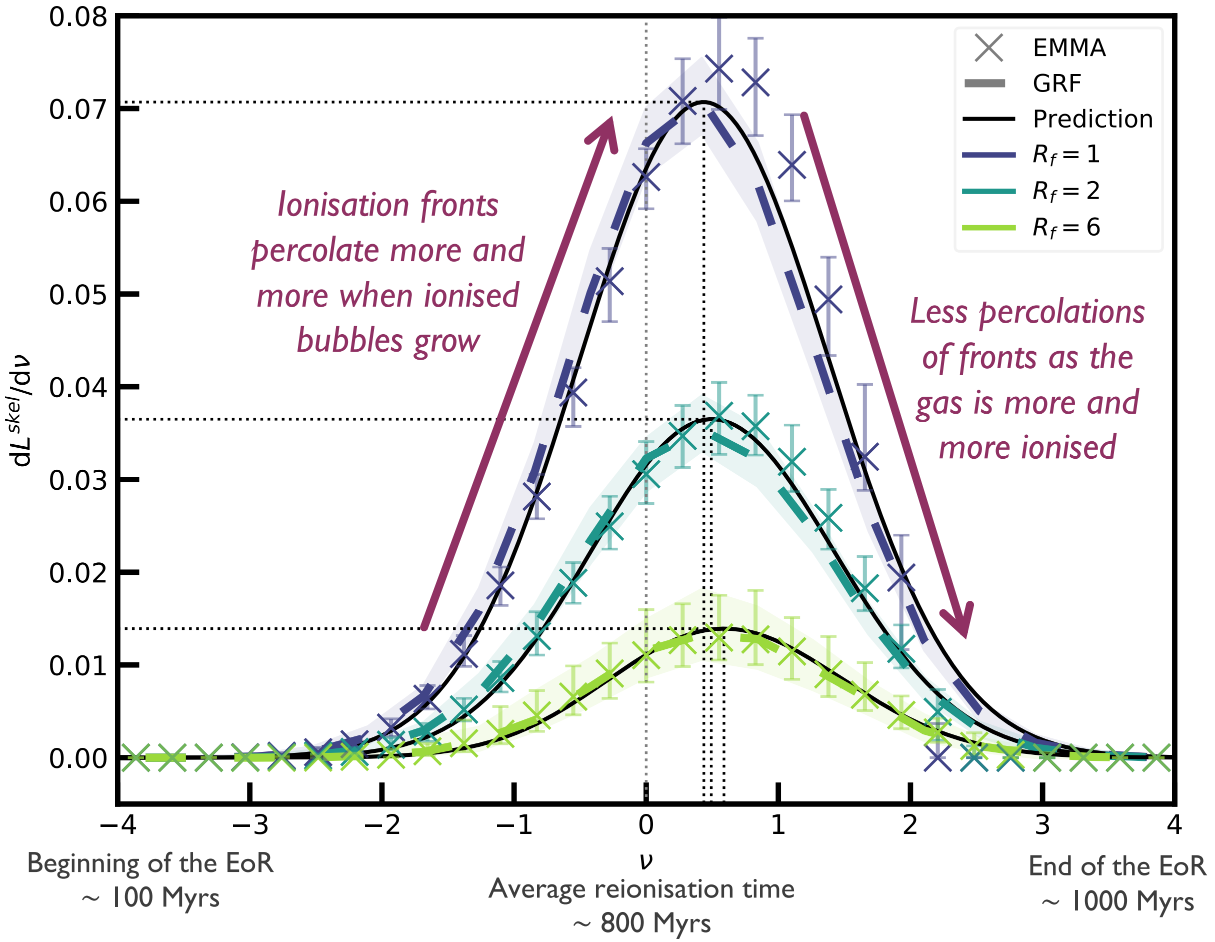


# C. TOPOLOGY AND GRF THEORY

*Skeleton length: places where the ionisation fronts percolate*

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

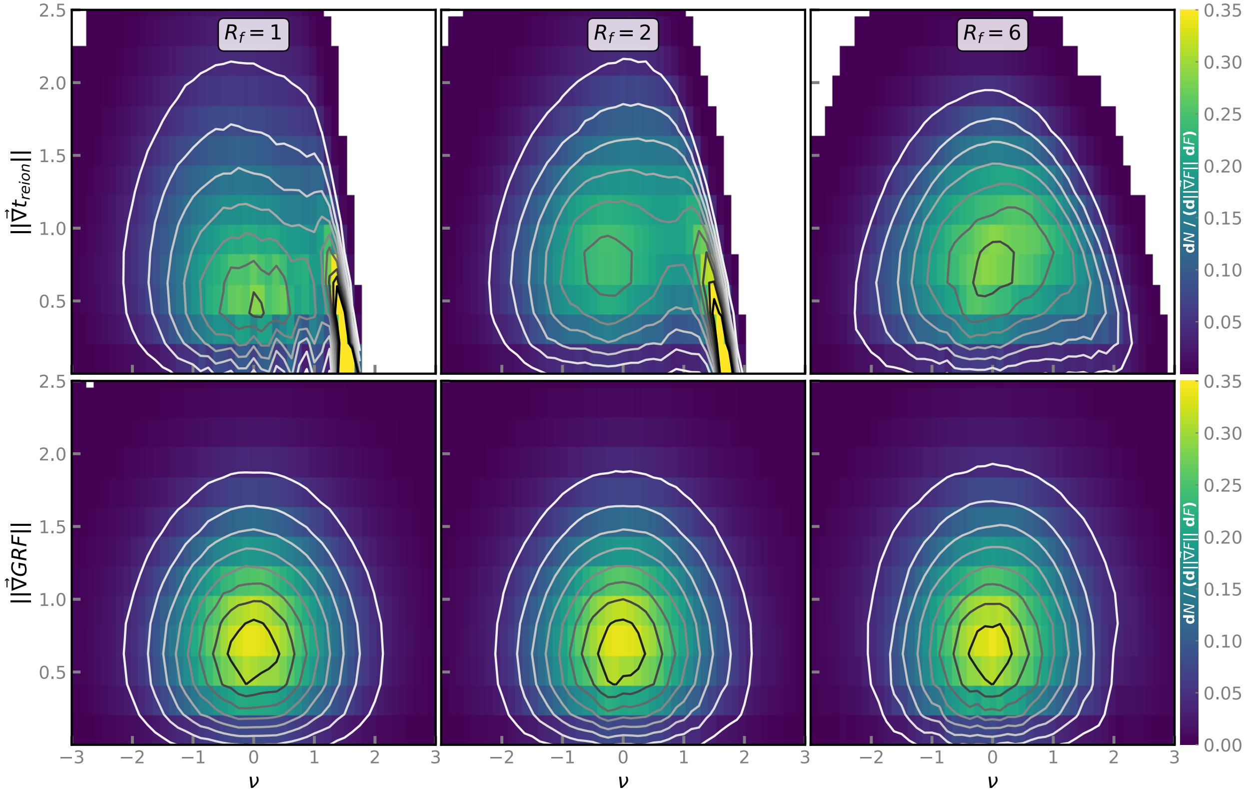
- "Stiff" approximation + global (measurements) or local (GRFs) calculations → predictions under-estimating the skeleton length: **measurements have to be renormalised**
- $R_f \nearrow$ : EMMA measurements more symmetric
- $R_f \in \{1, 2\}$ : asymmetry
  = *acceleration of ionisation fronts at the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

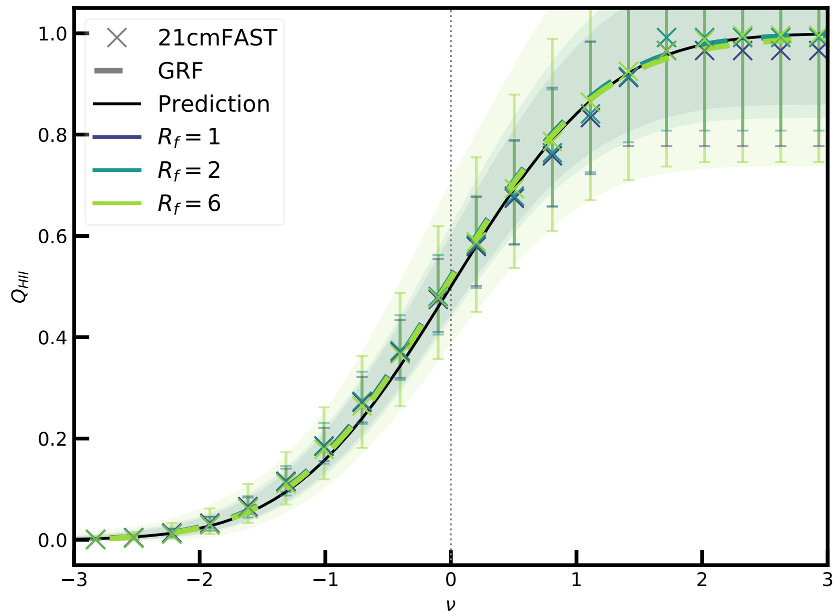


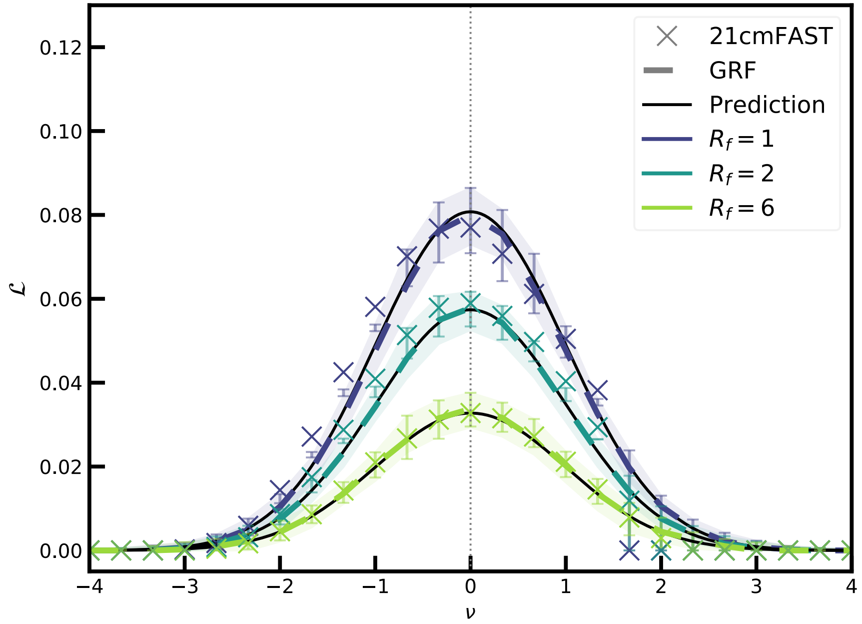
# C. TOPOLOGY AND GRF THEORY



## *Comparisons with 21cmFAST*




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