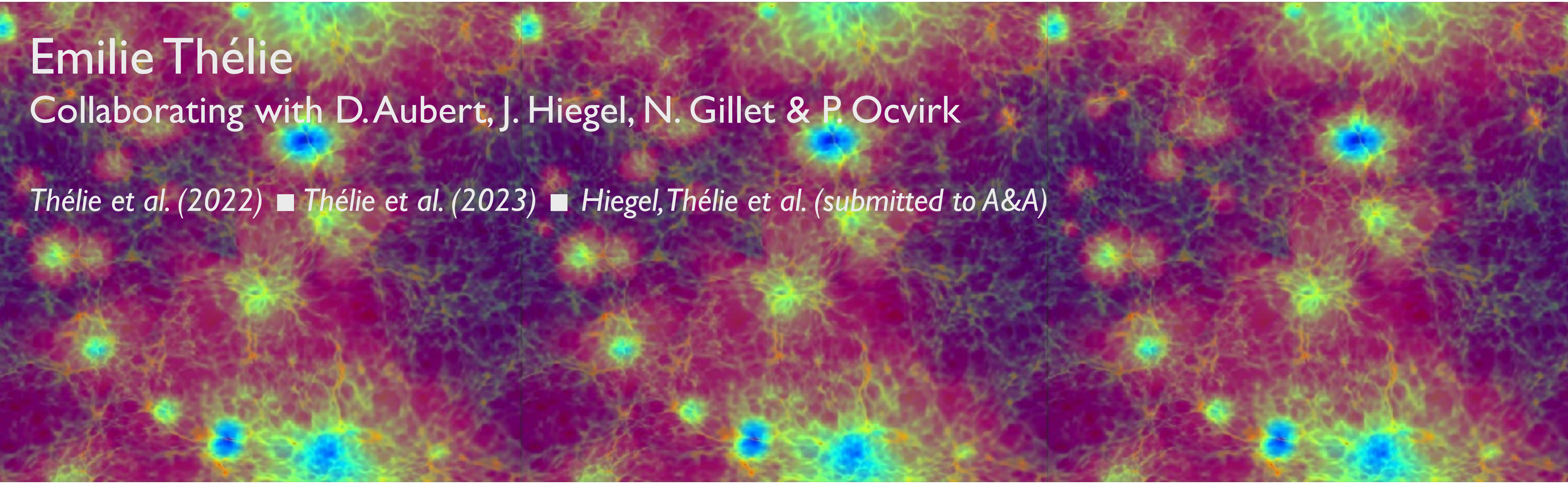
Exploring the Epoch of Reionisation through its evolving topology



Emilie Thélie

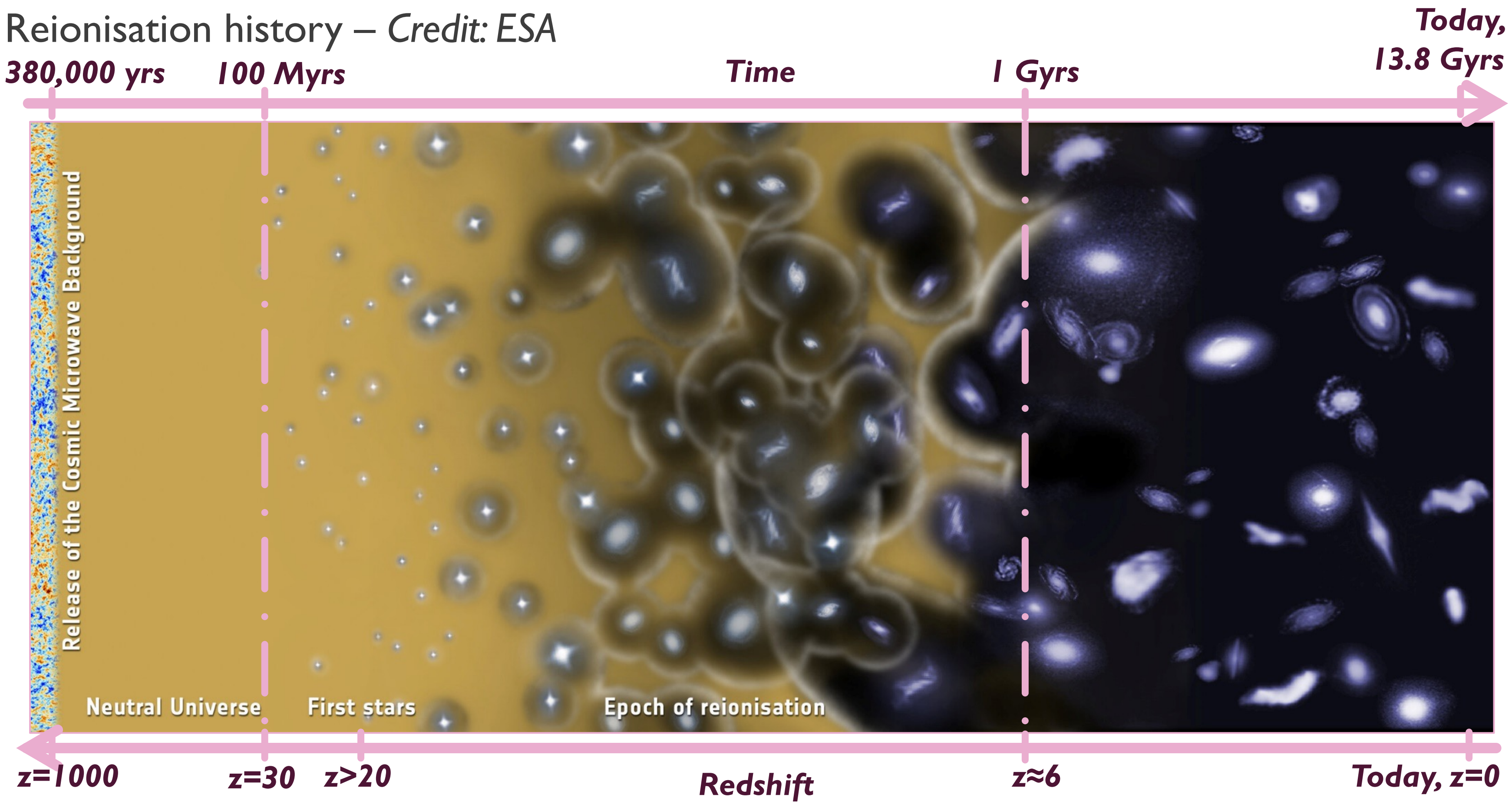
Collaborating with D. Aubert, J. Hiegel, N. Gillet & P. Ocvirk

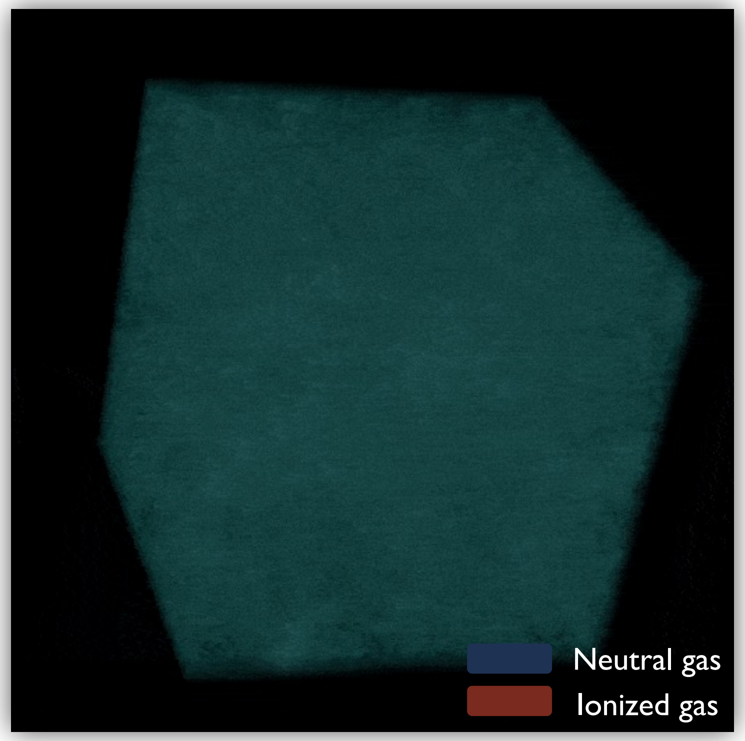
Thélie et al. (2022) ■ *Thélie et al. (2023)* ■ *Hiegel, Thélie et al. (submitted to A&A)*

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

Topology of the reionisation process

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…

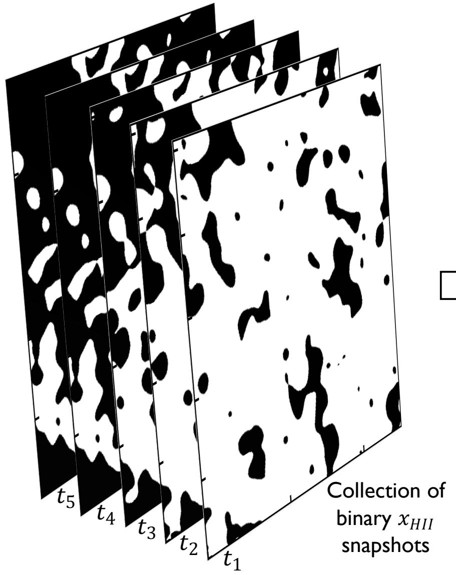
… with Betti numbers (e.g. Giri+20, Bianco+21)

Geometry of bubbles and percolation…

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

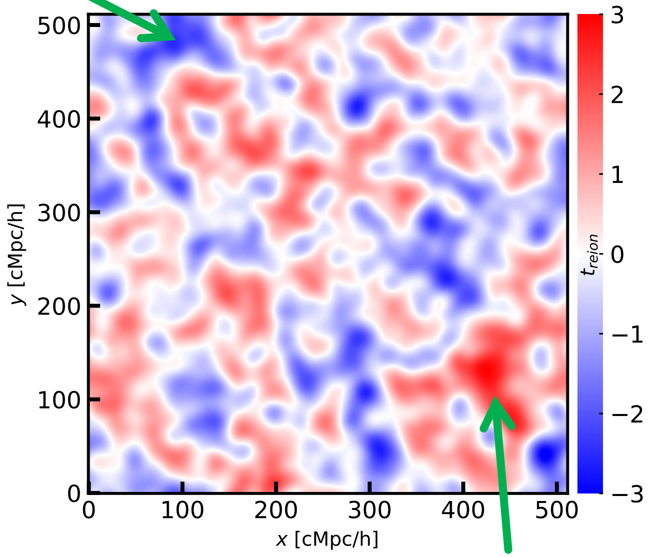
REIONISATION TIMES
Definition

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



Thélie et al. (2023)

Reionise first



Reionise last

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

Definition

EMMA cosmological simulation (512 cMpc/h):

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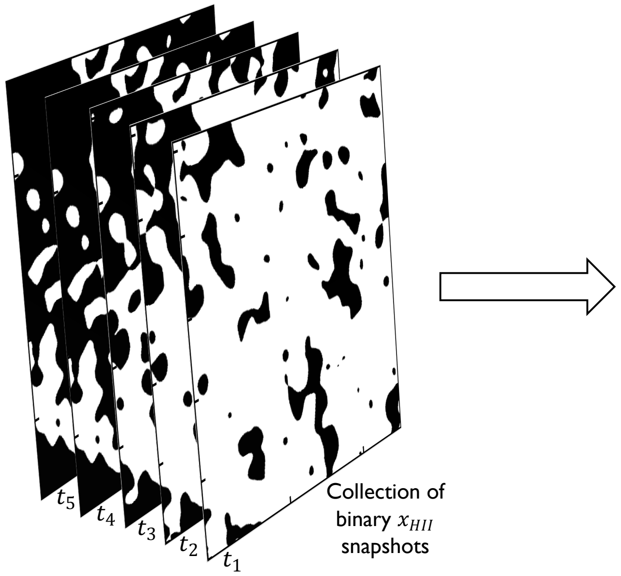
- Adaptative Mesh Refinement (AMR)

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



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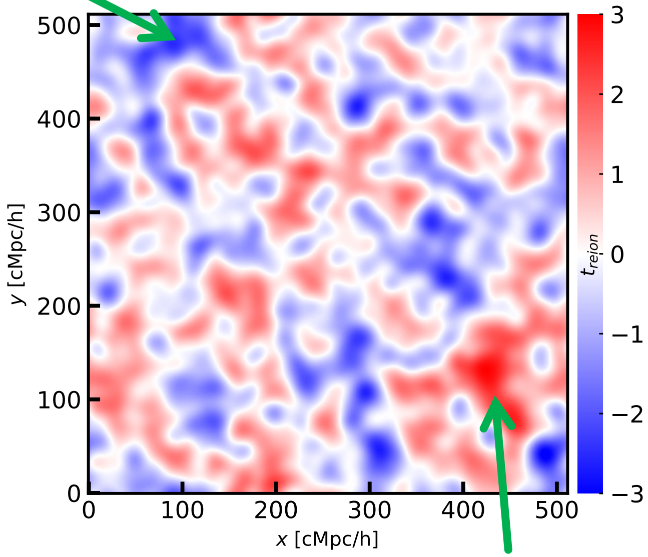

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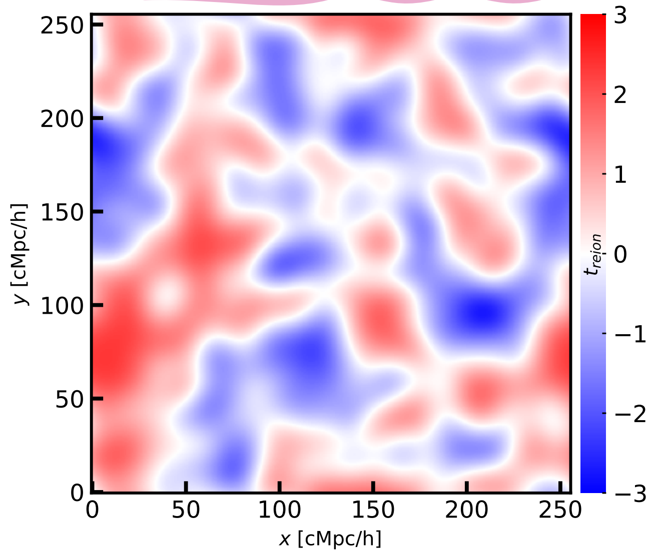


Map of reionisation times:

- Local histories of reionisation of the gas
- 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

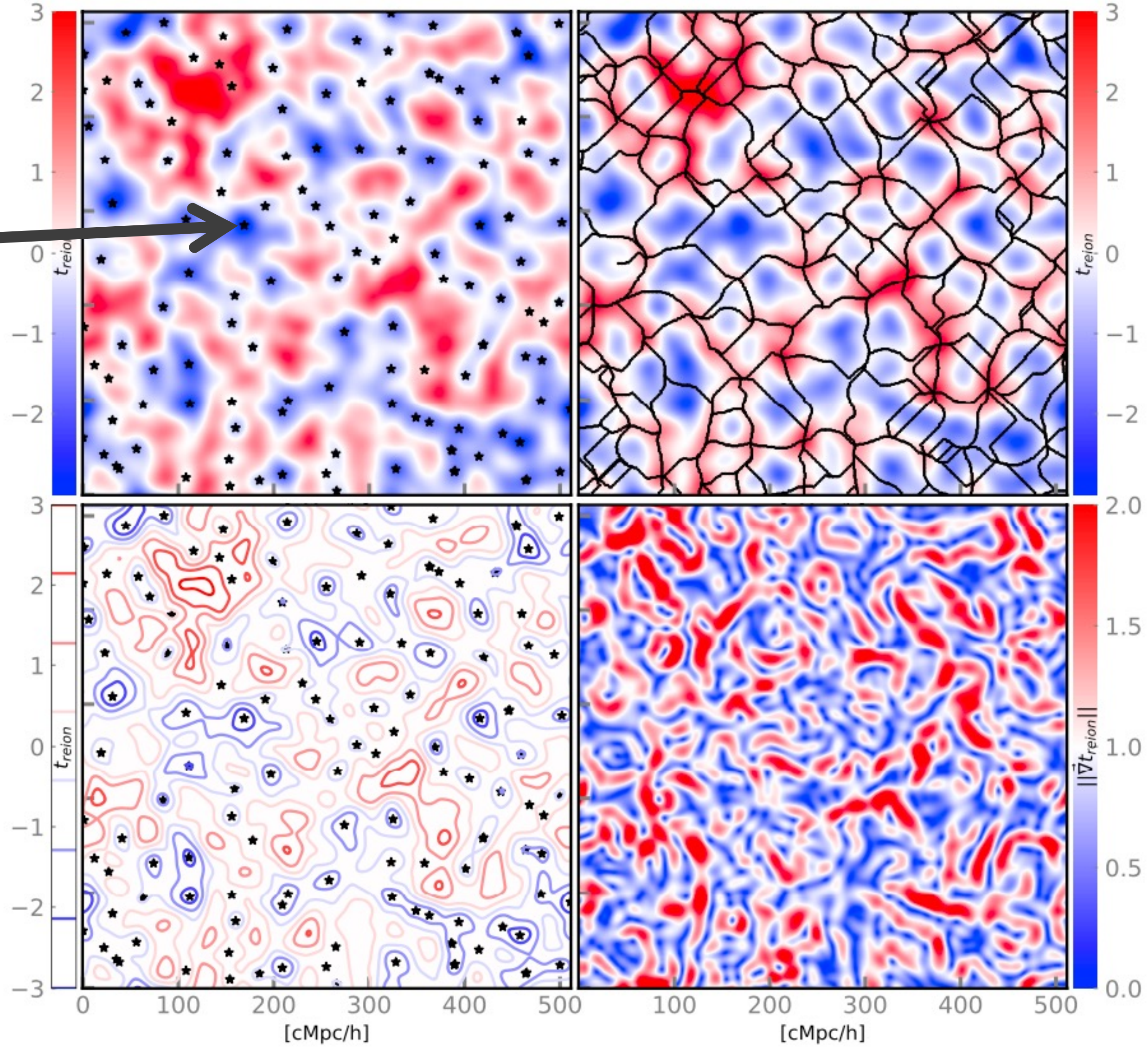
Evolving topology of the EoR

EMMA cosmological simulation maps (512 cMpc/h)

Thélie et al. (2023)

Minima:

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



REIONISATION TIMES

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Thélie et al. (2023)

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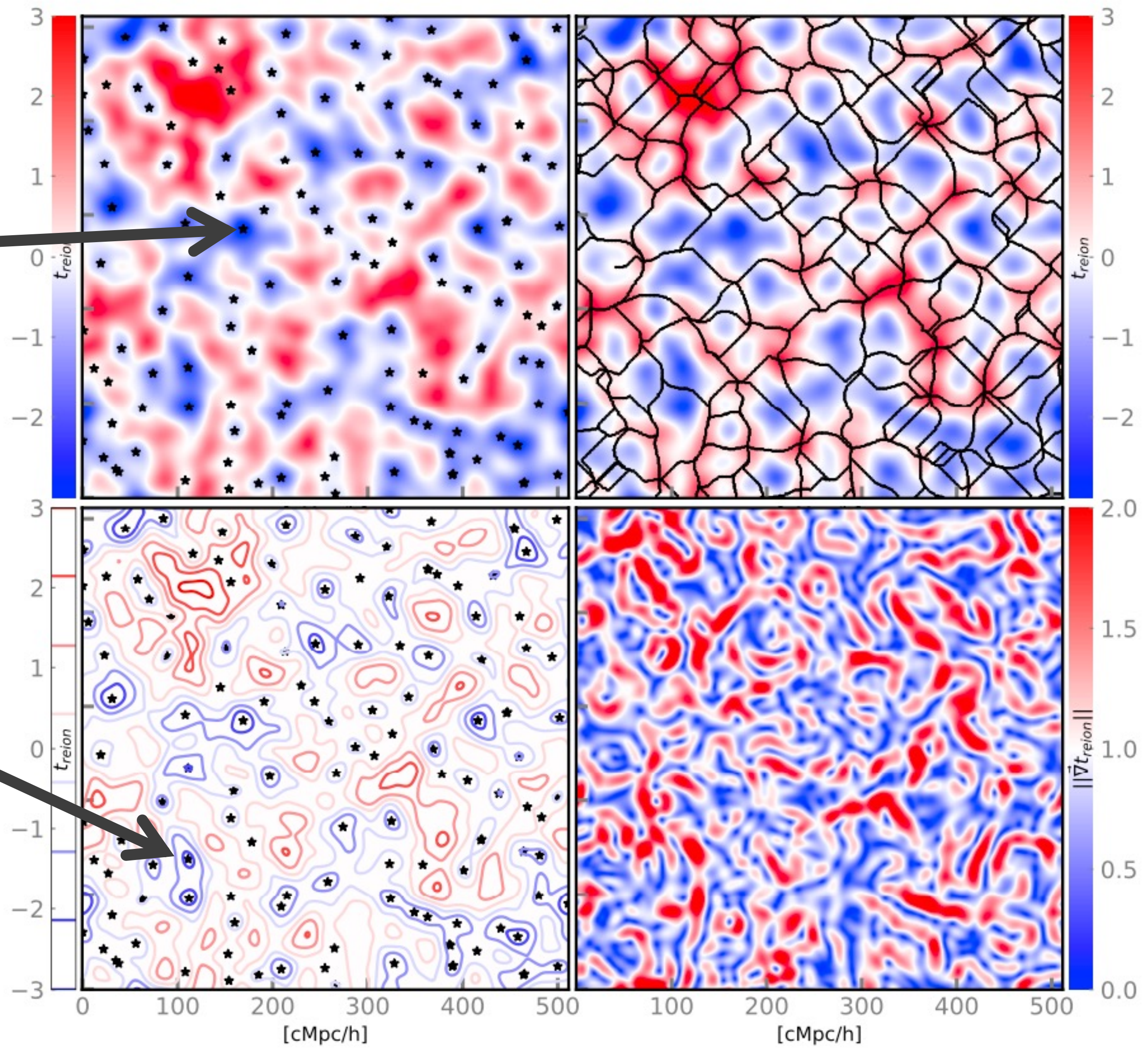
- *Regions reached by ionisation fronts at the same time*
- *Size evolution of bubbles*



REIONISATION TIMES

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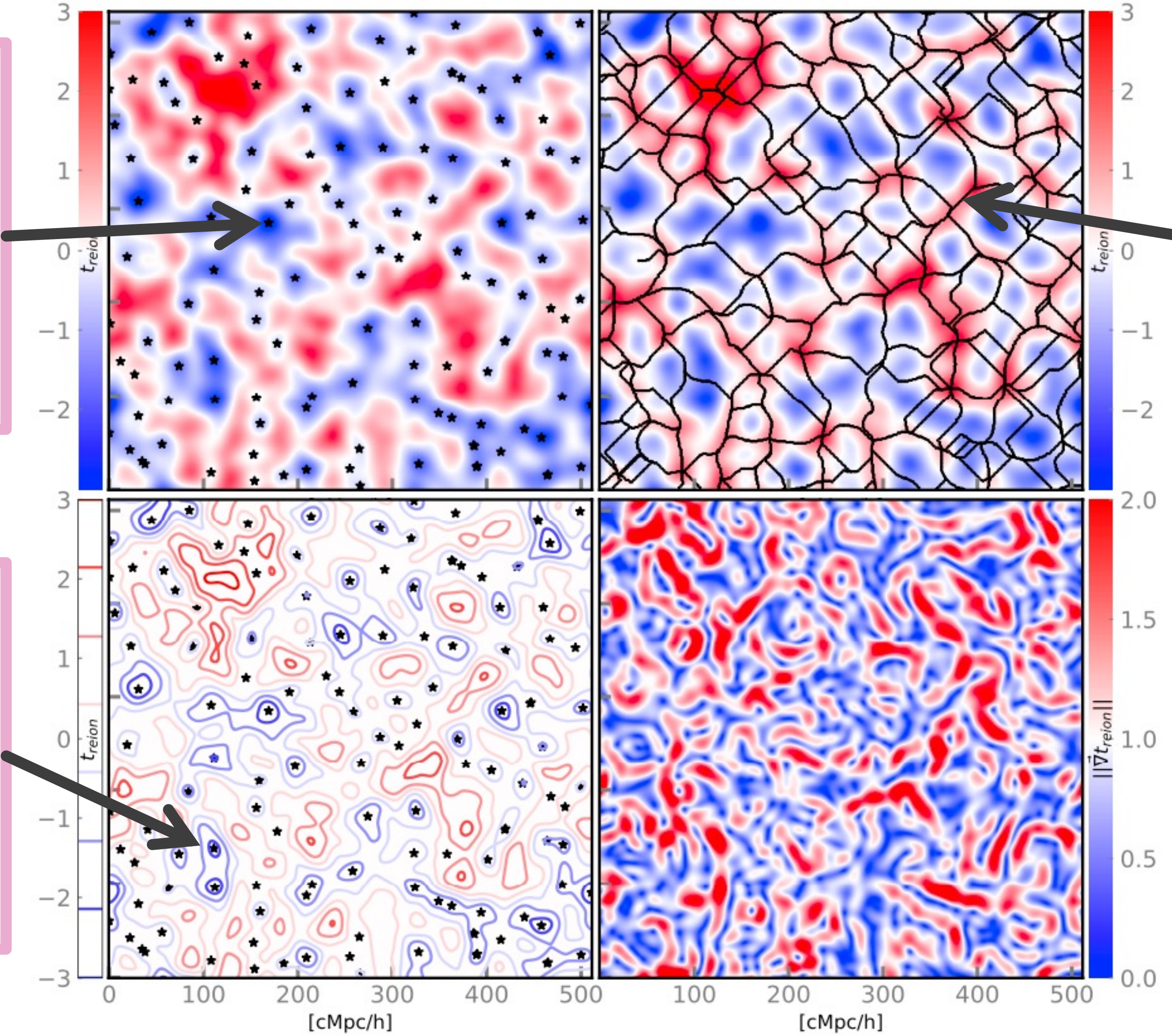

Reionisation patches:
- *Extension of the radiative influence of a source*

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

Isocontours:
- *Regions reached by ionisation fronts at the same time*
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REIONISATION TIMES

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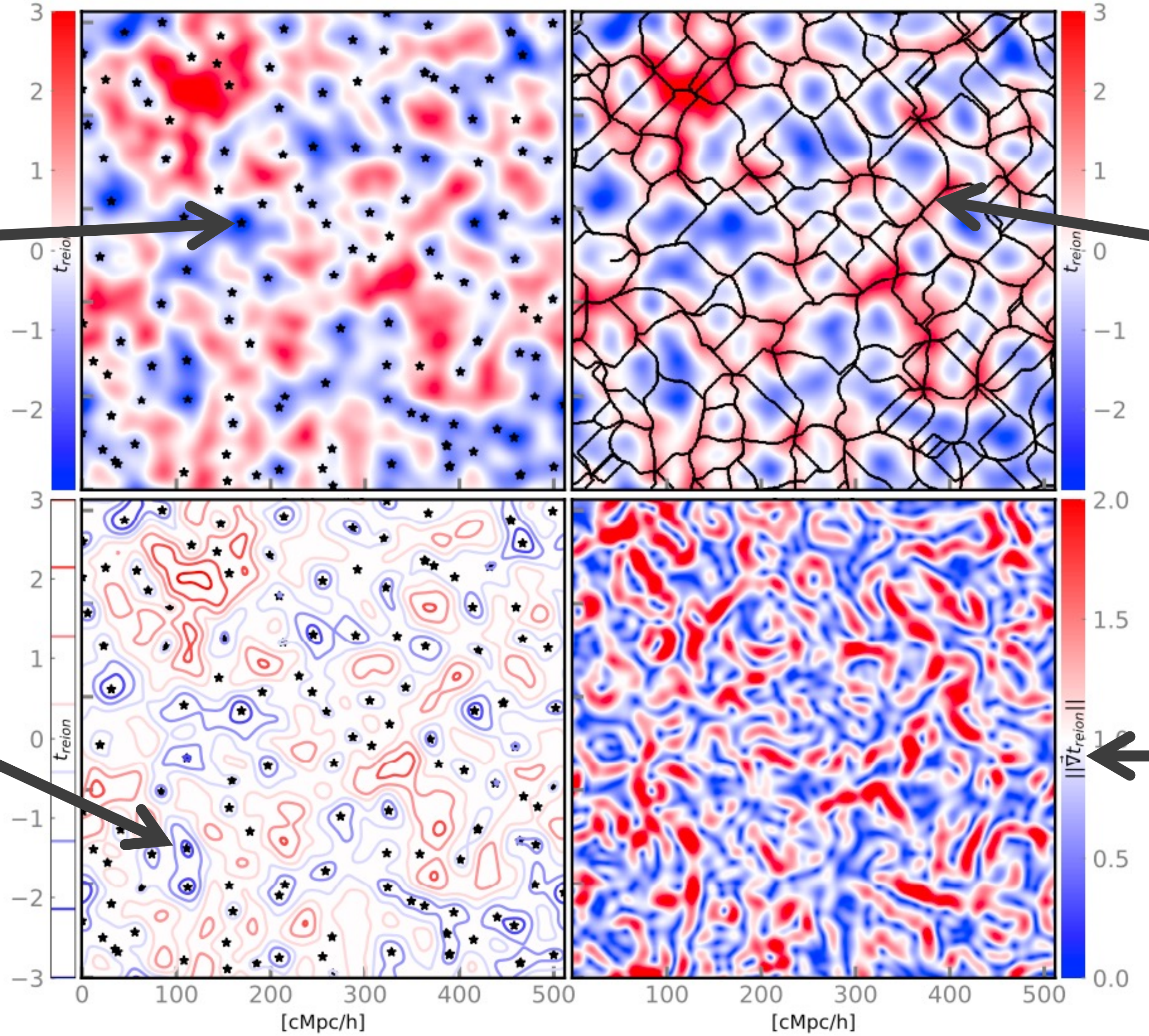


Reionisation patches:
- *Extension of the radiative influence of a source*

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

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

21 CM MAPS → TREION

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

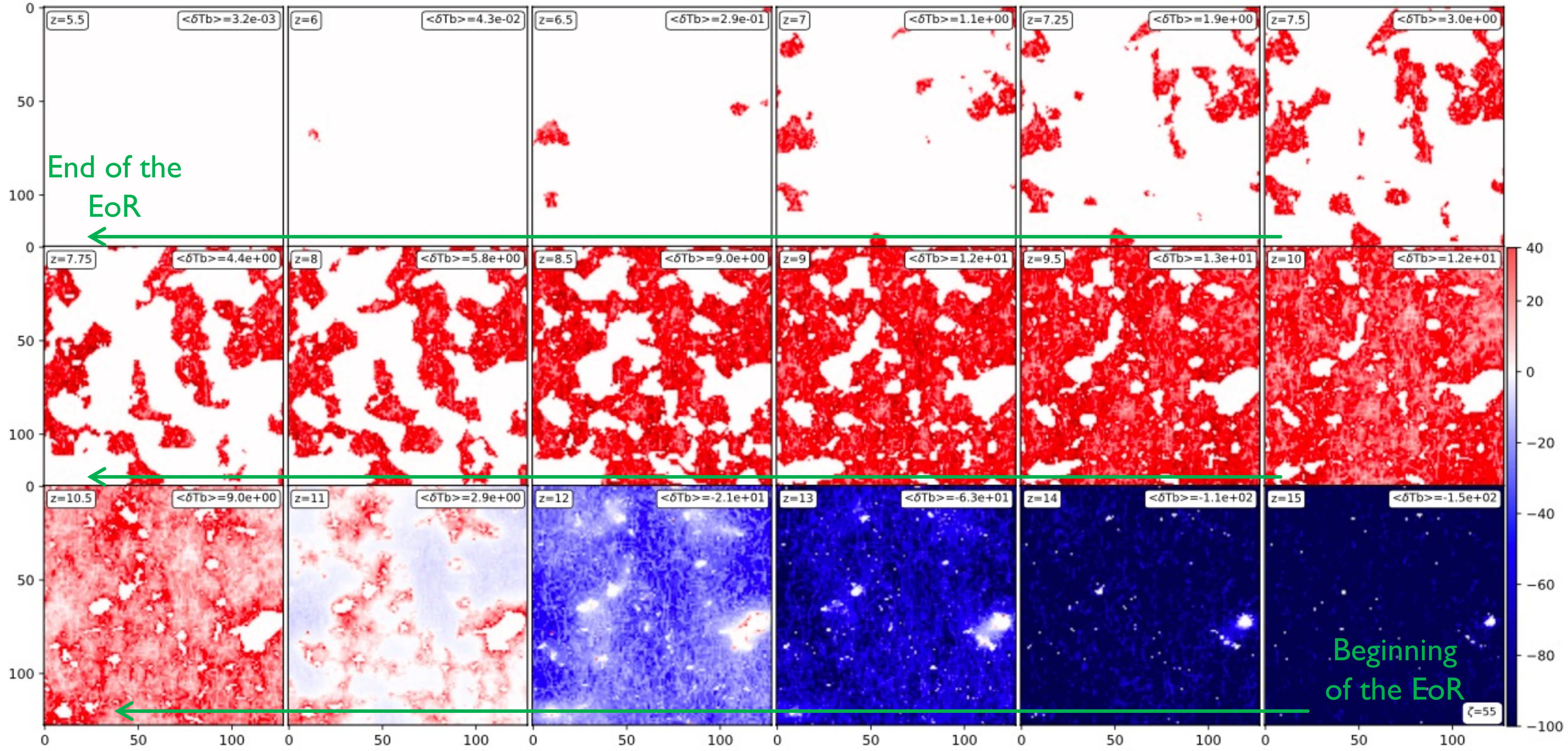
- Upcoming observations of the brightness temperature with the **21 cm signal**
  = distribution of neutral hydrogen gas at many frequencies
- 21 cm signal: $\delta T_b(z) \sim x_{HI}(z)(1+\delta_b(z))F(T)$

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: $>$ **7 cMpc for** $z > 6.5$
- In the frequency direction: $>$ **1 cMpc**

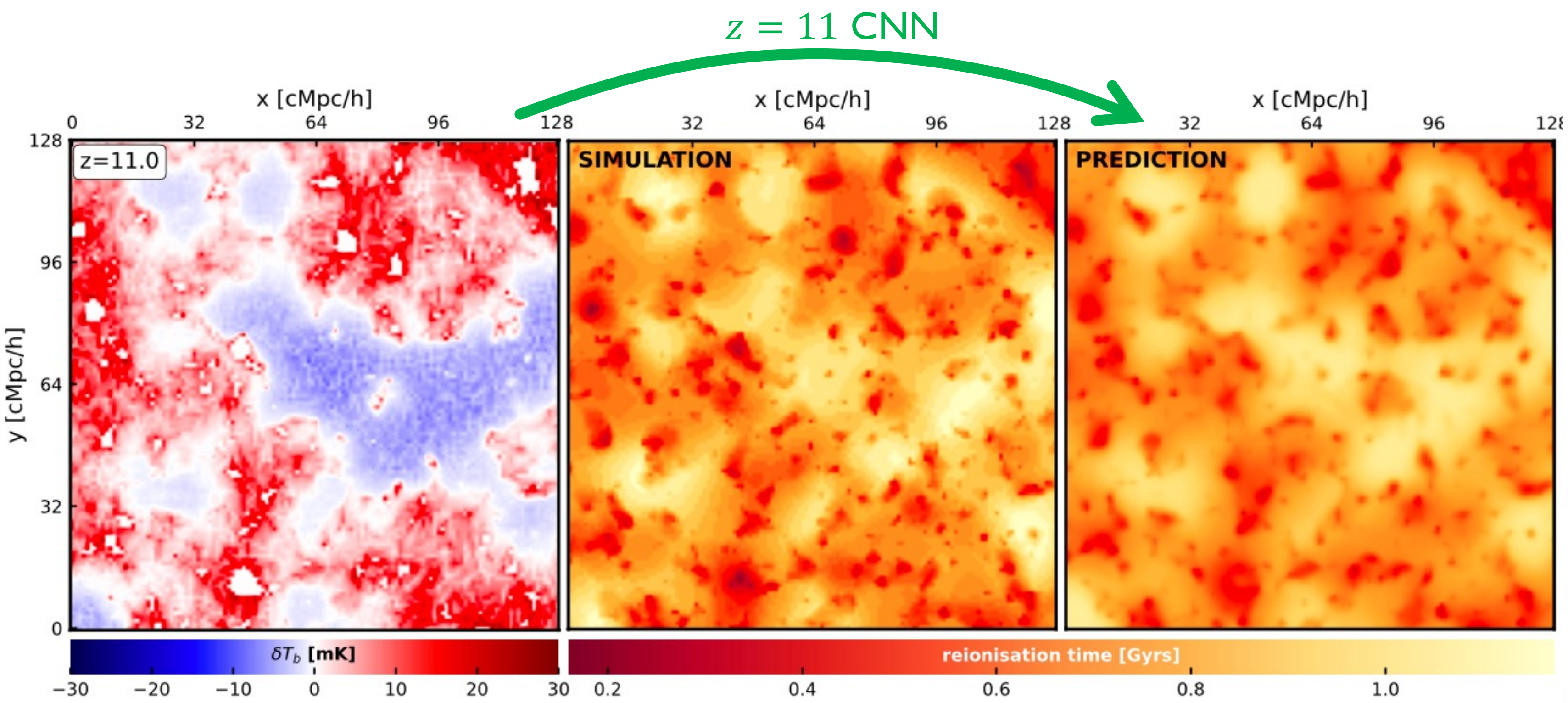


2D images of the 21 cm signal at many frequencies: $\delta T_b(z)$
21cmFAST semi-analytical model (256 cMpc/h)

Hiegel, Thélie+ (submitted to A&A)

21 CM MAPS → TREION

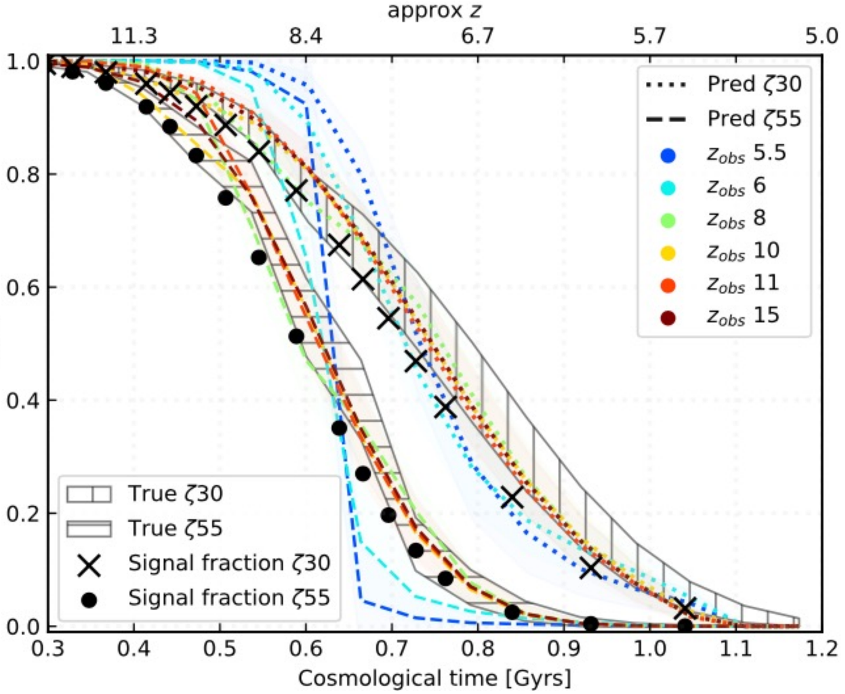
Results



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

Hiegel, Thélie+ (submitted to A&A)

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. PROPAGATION OF IONISATION FRONTS AROUND MATTER FILAMENTS

Thélie+22 (A&A)

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

Thélie+23 (A&A)

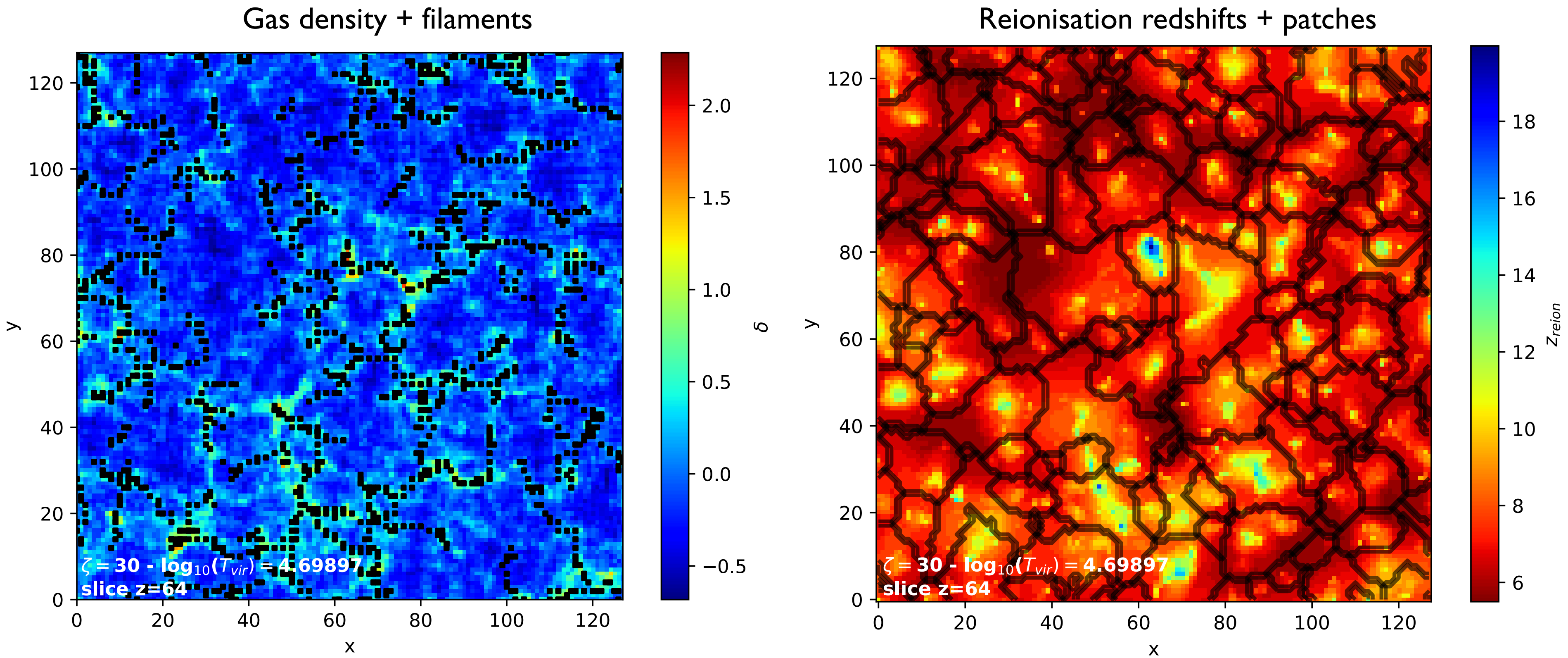
B. REIONISATION PATCHES

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)

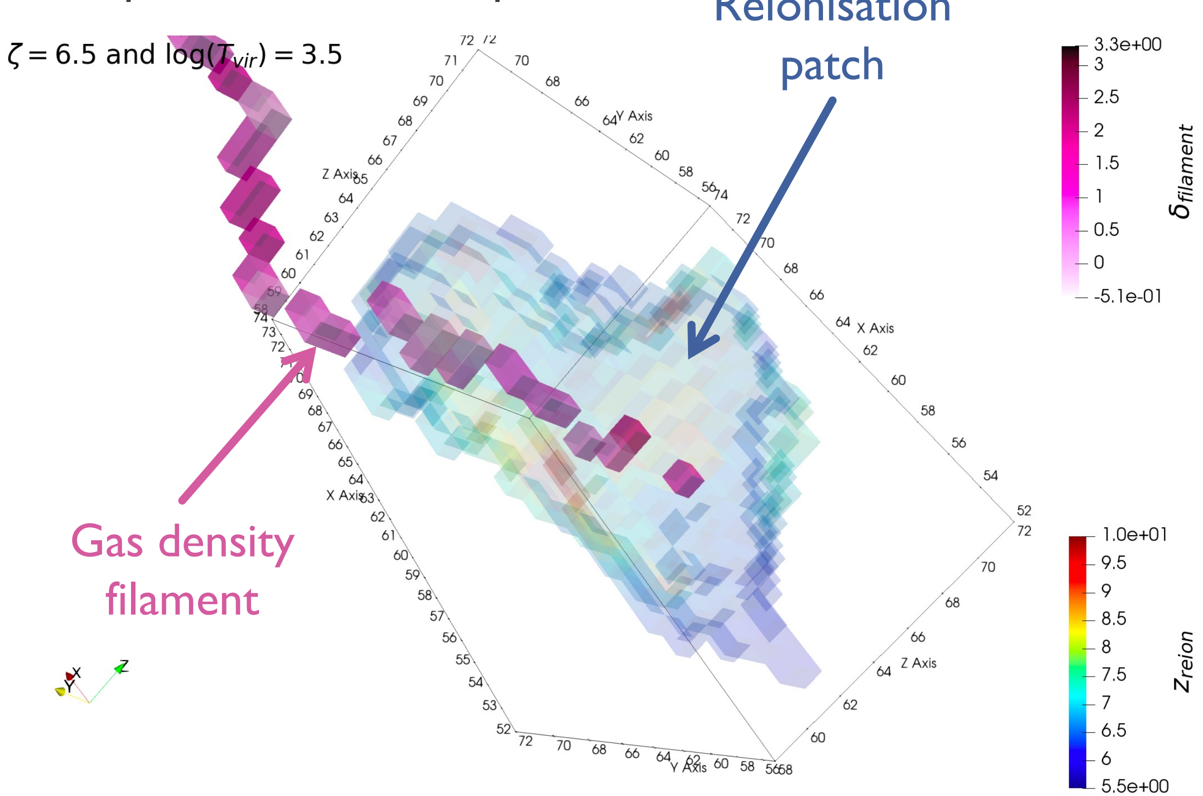
Thélie et al. (2022)

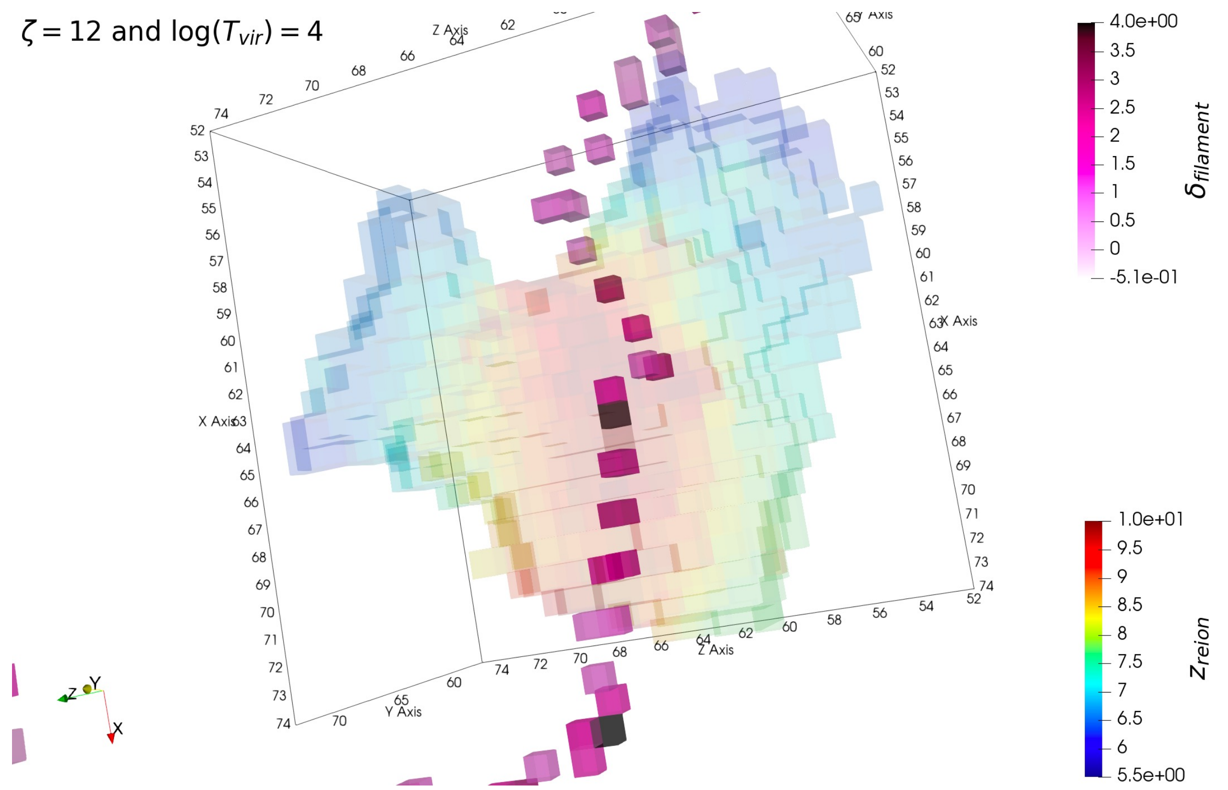
z_{reion}

- 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 et al. (2022)

Reionisation patch aligned with the filament

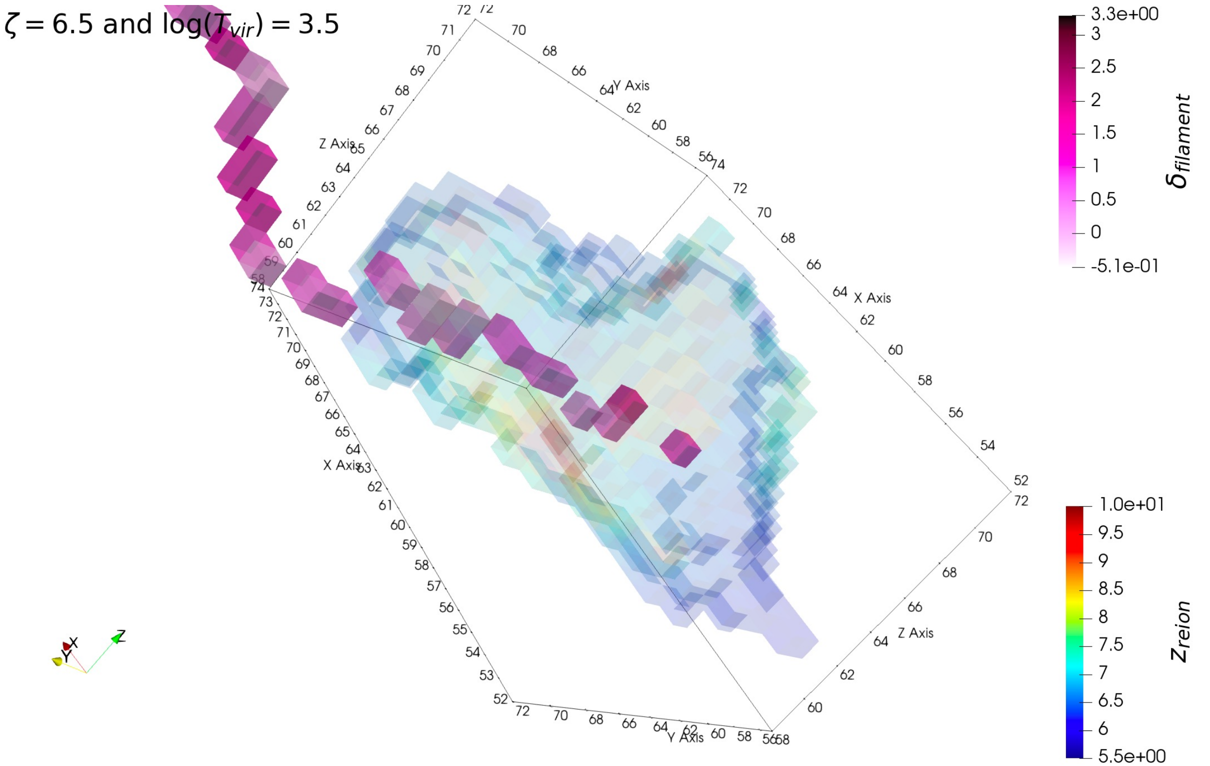
= radiations follow the matter filament

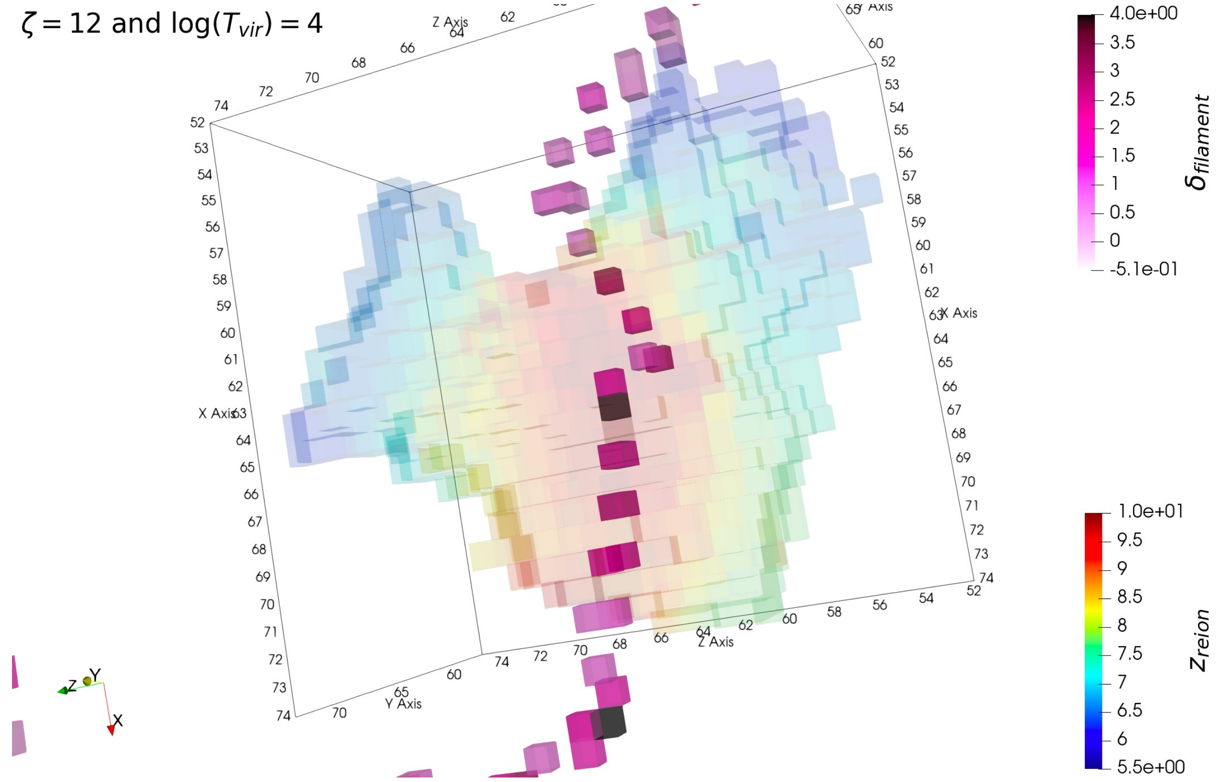
Reionisation patch in a butterfly shape

= radiations follow the path of least resistance

B. REIONISATION PATCHES

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





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

Thélie et al. (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. PROPAGATION OF IONISATION FRONTS AROUND MATTER FILAMENTS

Thélie+22 (A&A)

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

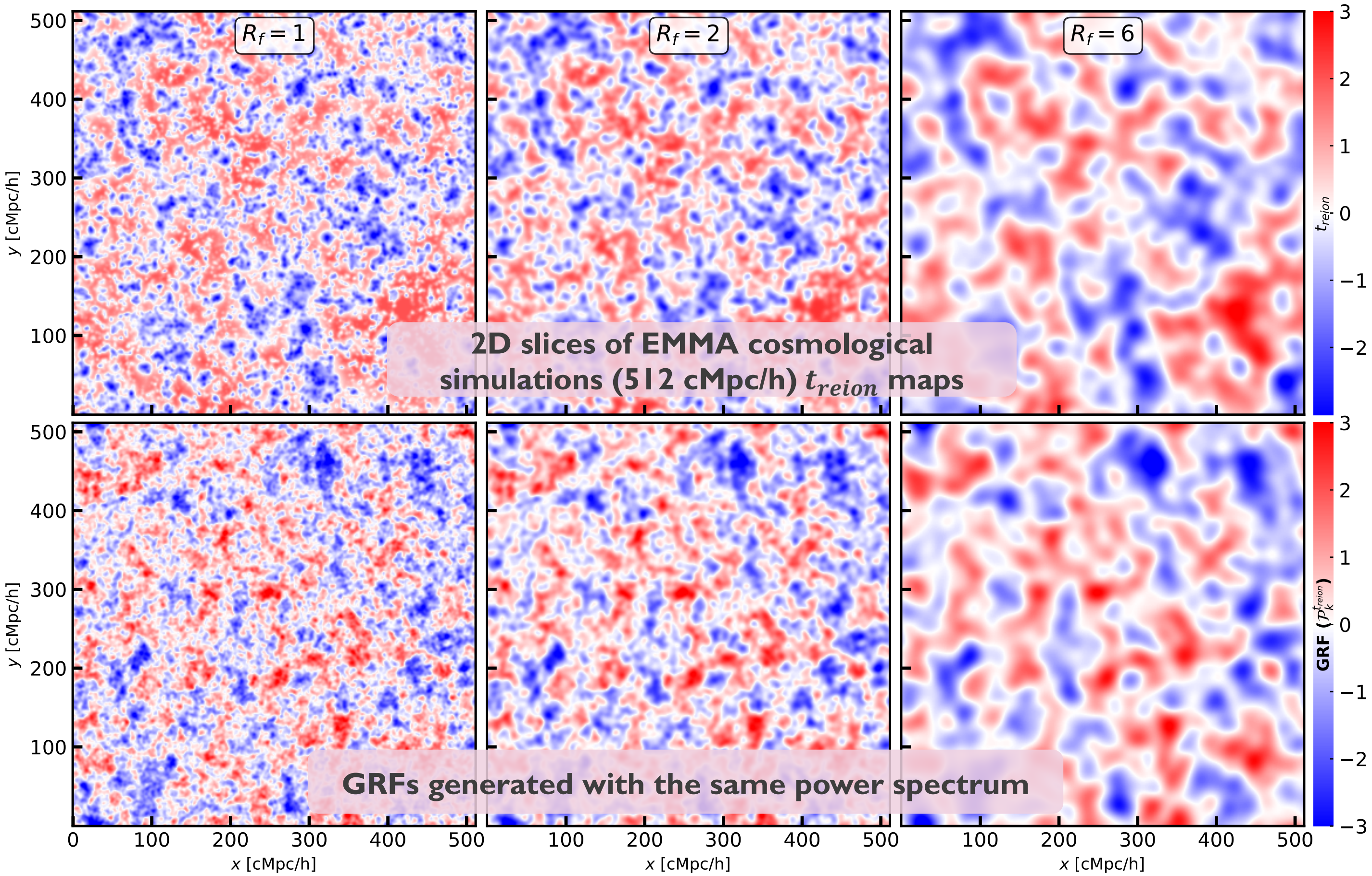
Thélie+23 (A&A)

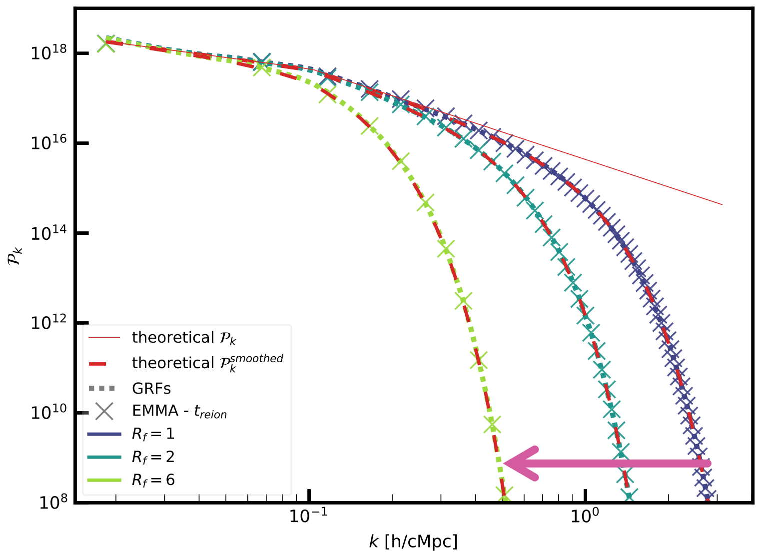
C. TOPOLOGY AND GRF THEORY

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*





↗ smoothing kernel size

Thélie et al. (2023)

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)

For a Gaussian random field:

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

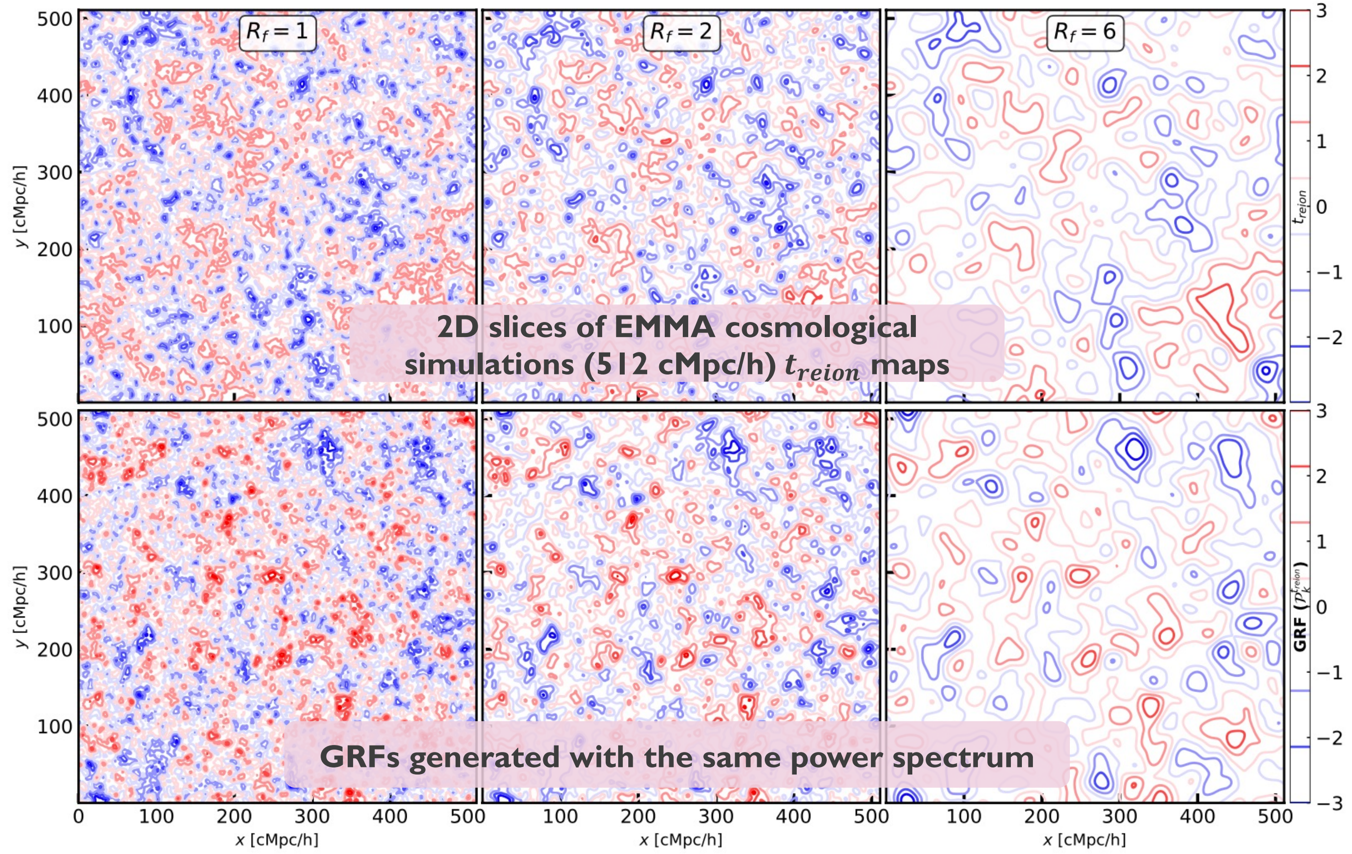
PDF of field values at its minima
= reionisation seed counts

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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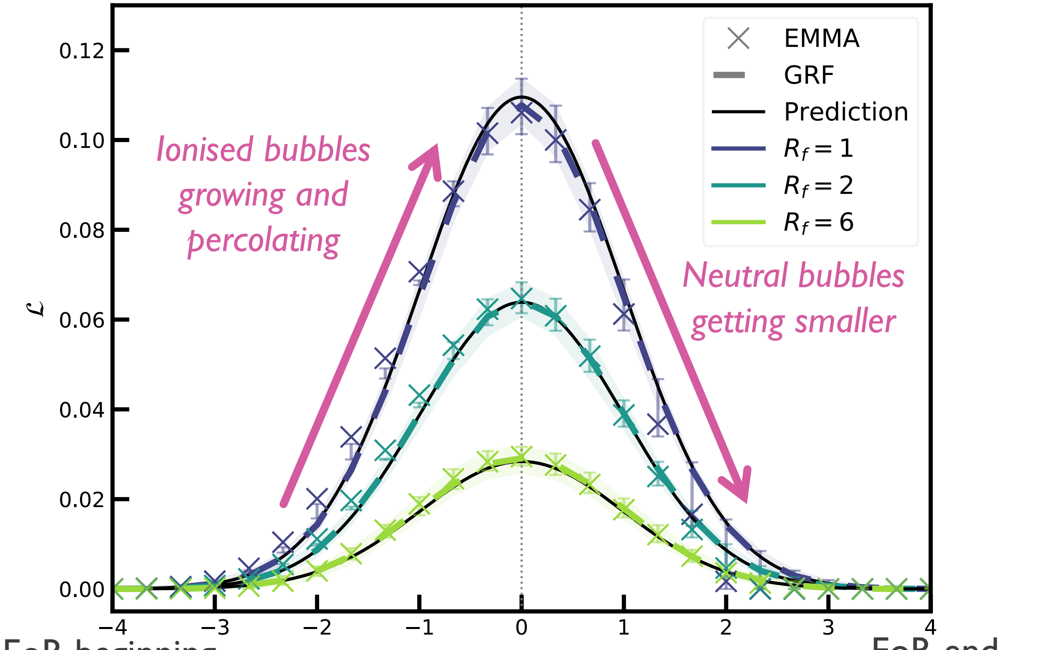

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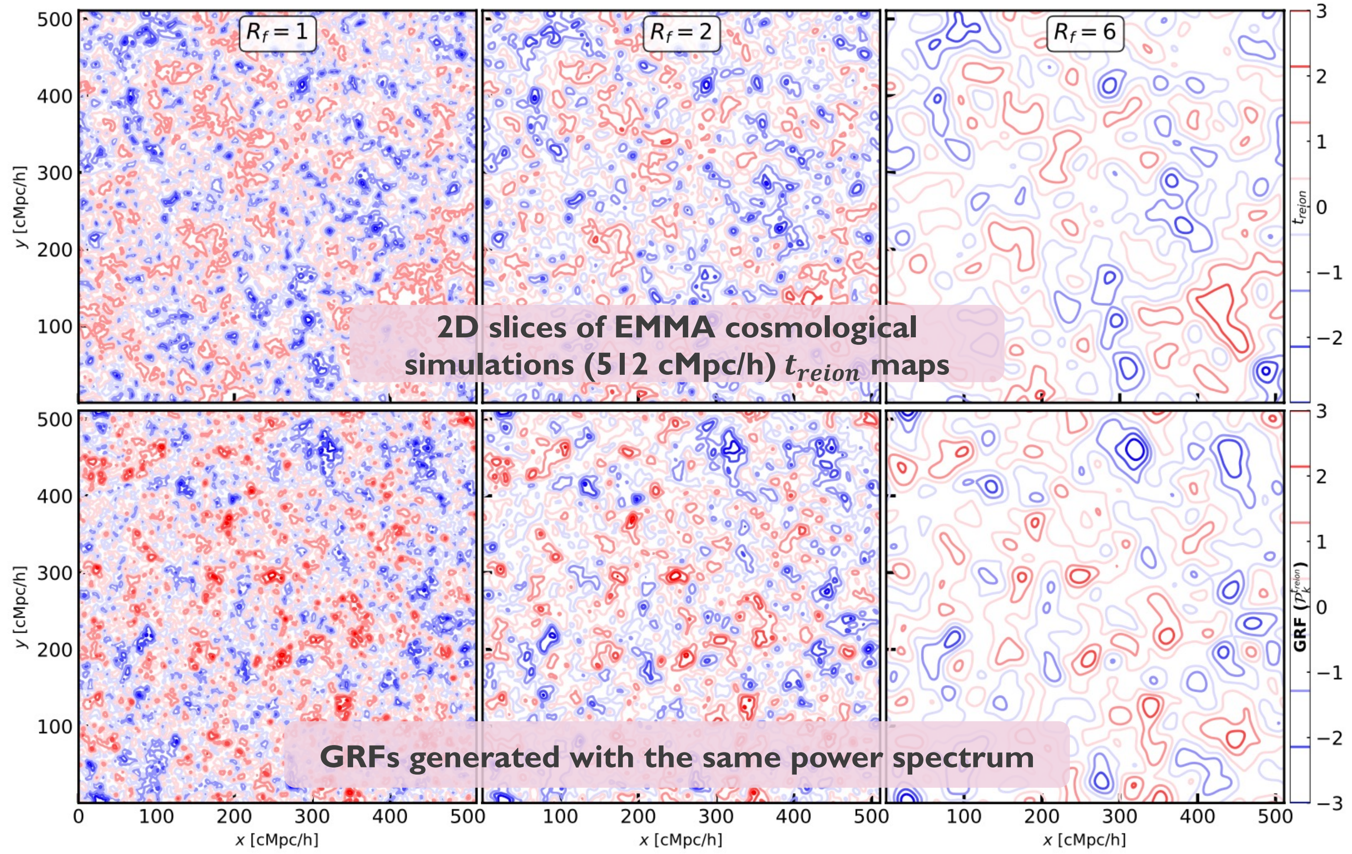
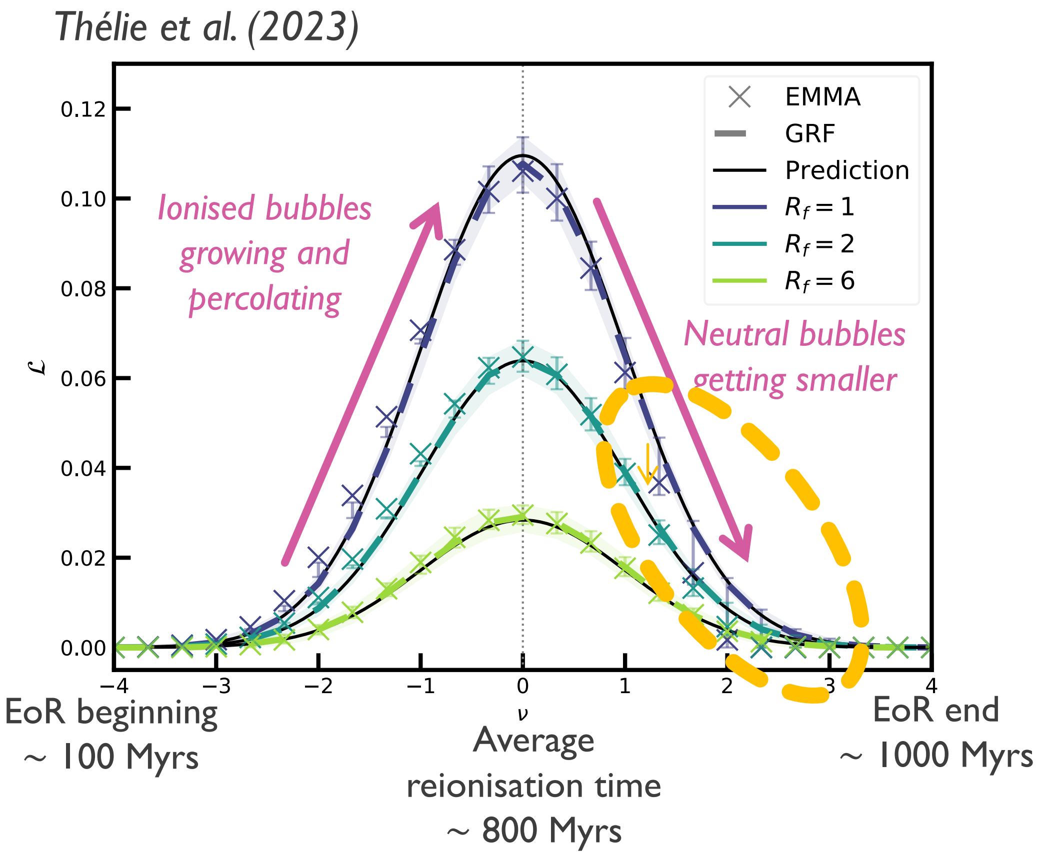
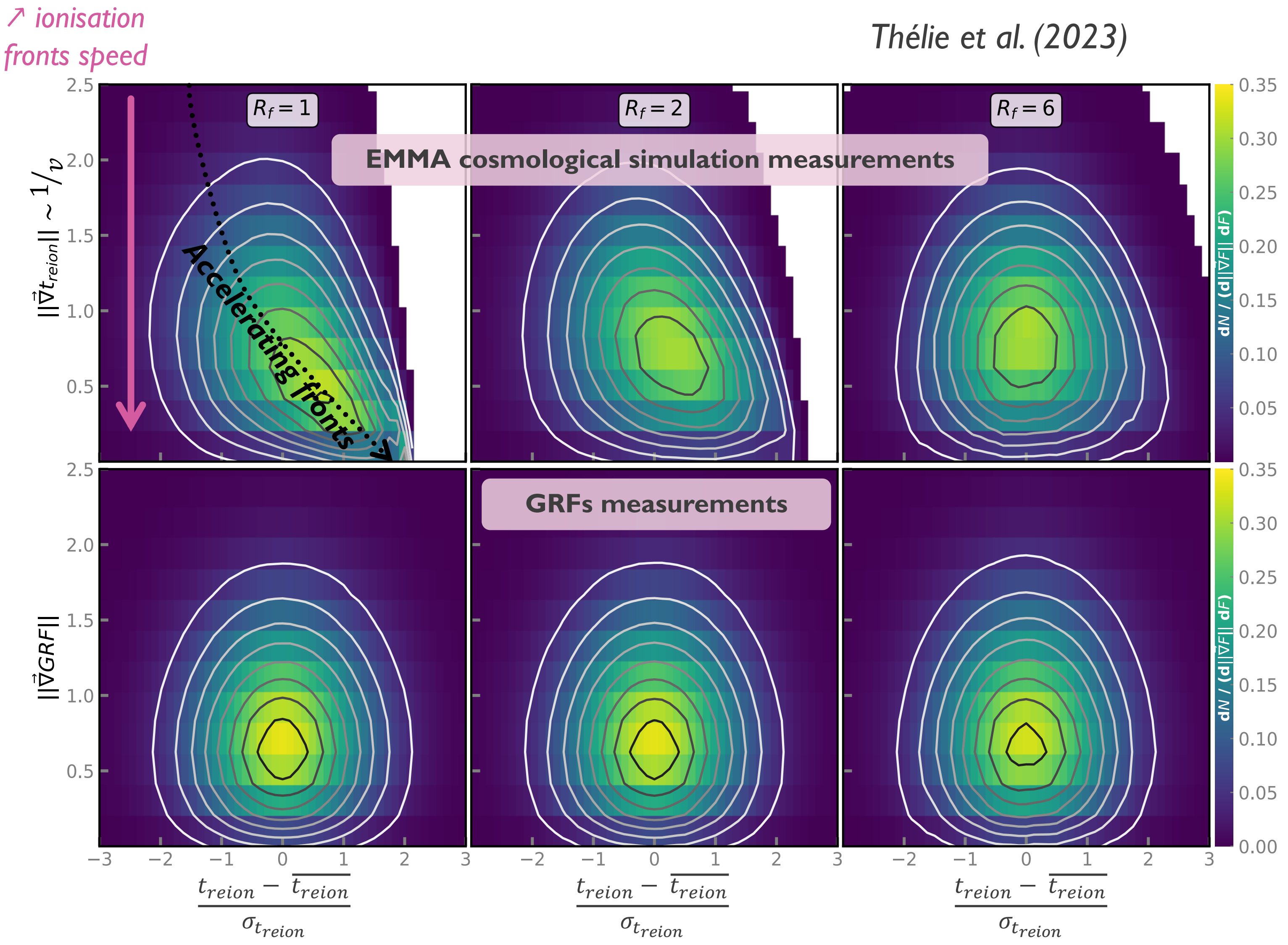




C. TOPOLOGY AND GRF THEORY

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

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

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!

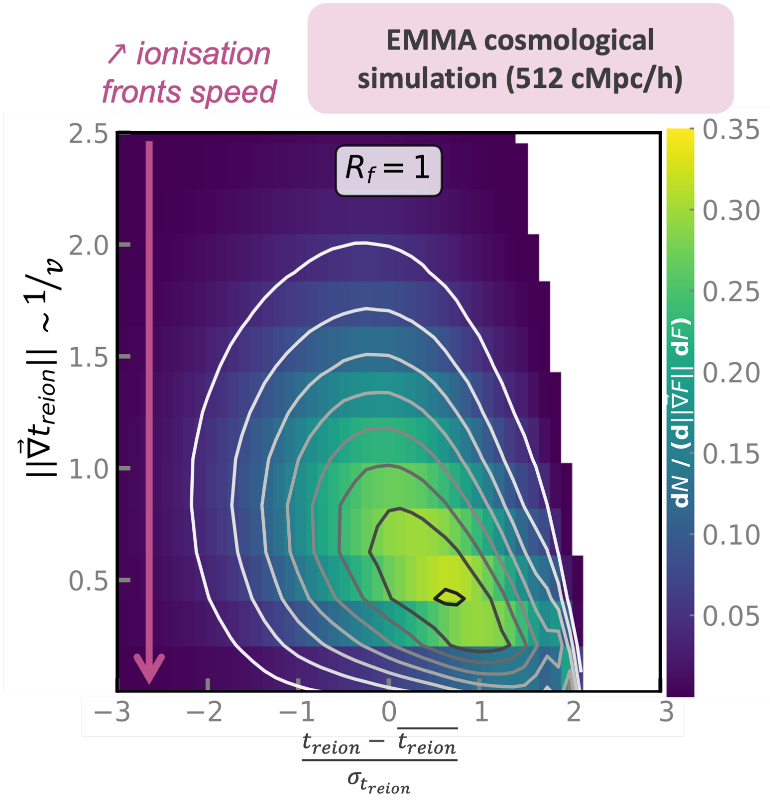
REIONISATION TIMES

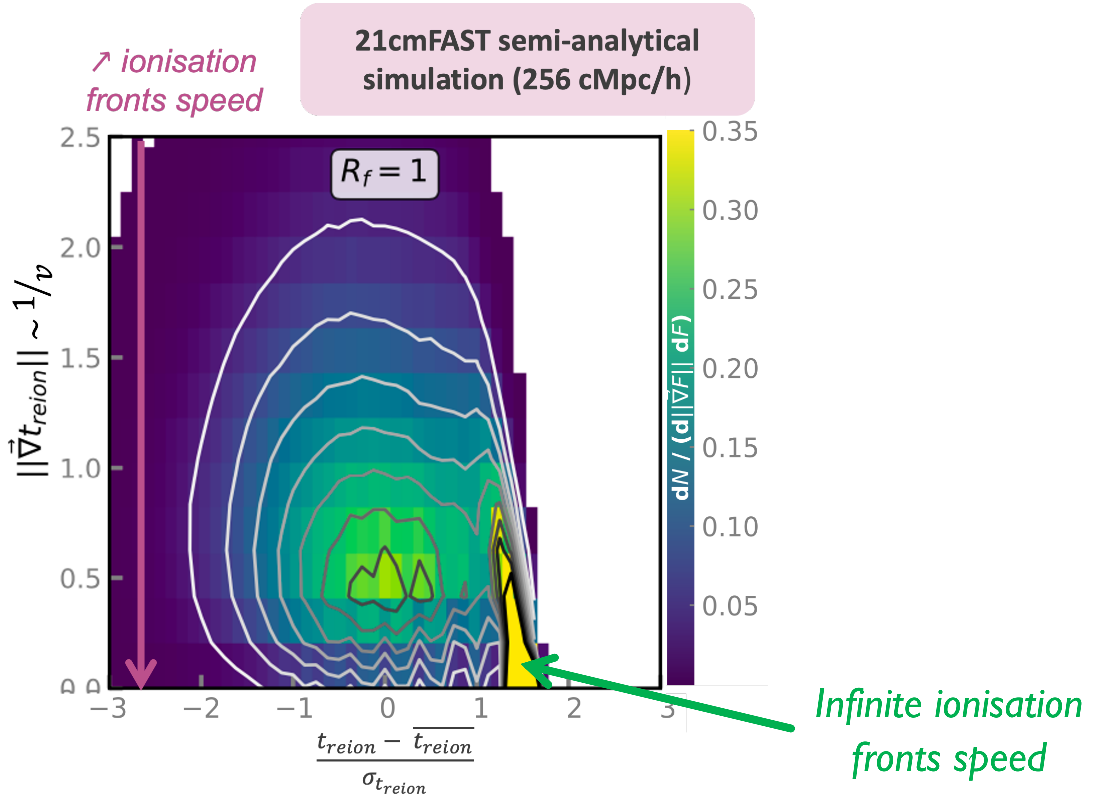
What can we do with it?

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 et al. (2023)



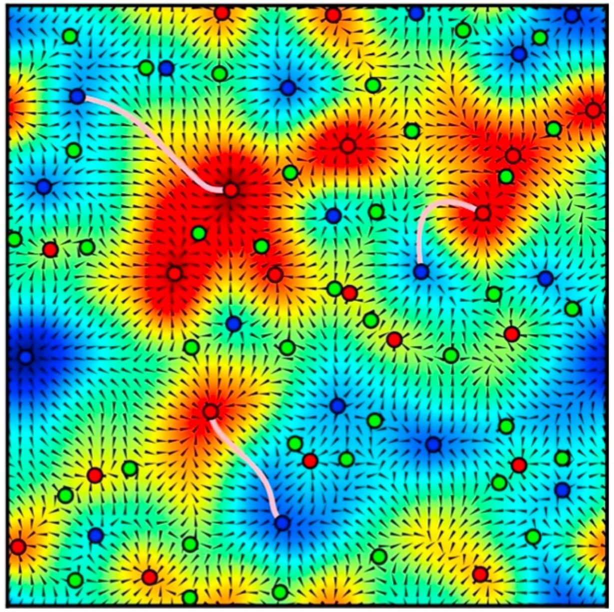


INTRODUCTION

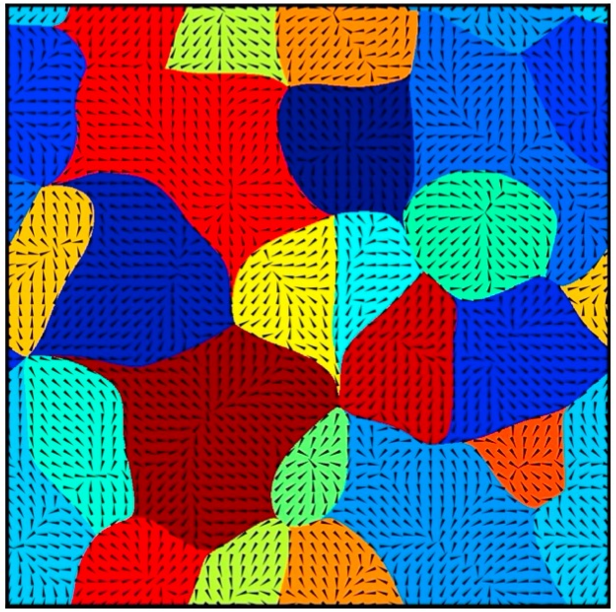
Topology of the reionisation process with DisPerSE

Discrete Persistent Structure Extractor (Sousbie+11)

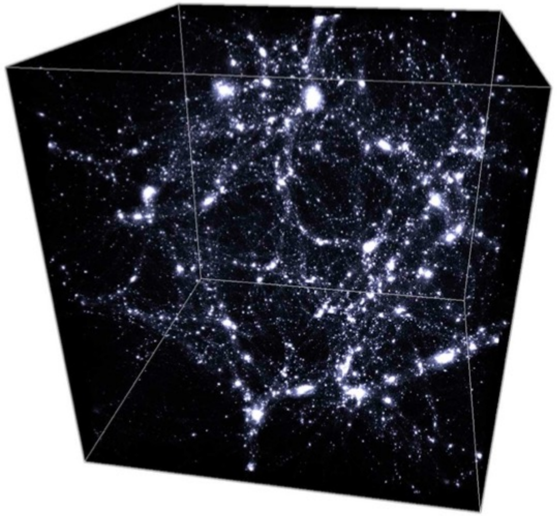
- Morse theory and persistent homology
- Extracts topological features from a field thanks to a mathematical approach



2D field
with its gradients and critical points

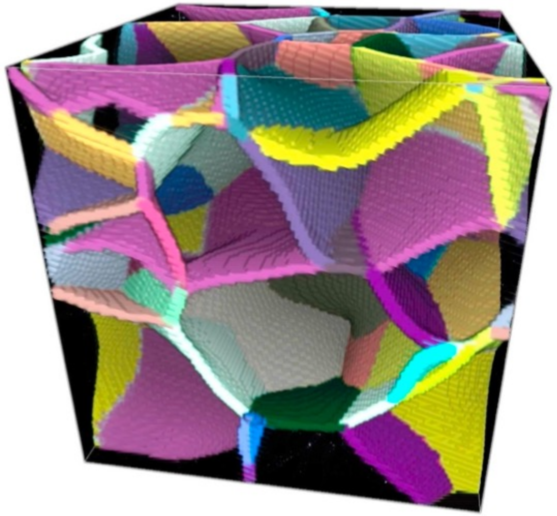


Maxima patches

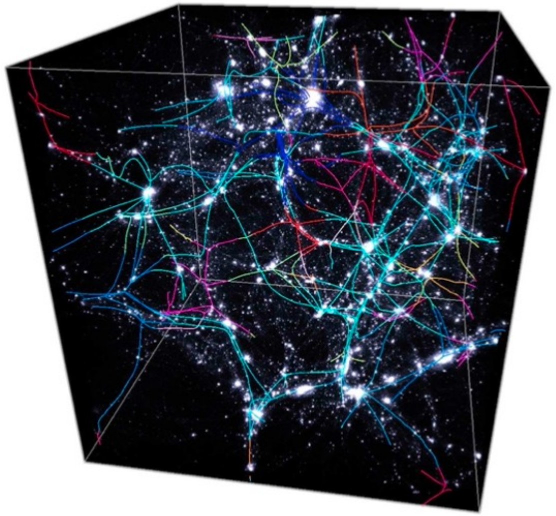


Dark matter density

Voids



Walls

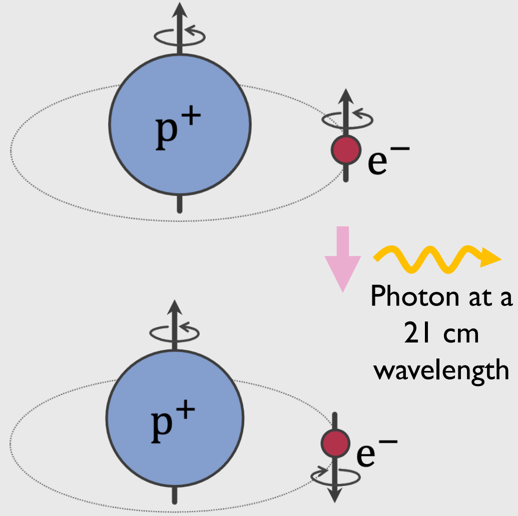


Filaments

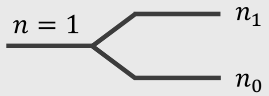
21 CM MAPS → TREION

***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: $\delta T_b(z) \sim x_{HI}(z)(1+\delta_b(z))F(T)$



$\lambda = 21$ cm
$\nu = 1420$ MHz



$n_1/n_0 = 3\exp(-T_{10}/T_s)$
$T_{10} = 0.068$ K
T_s is the spin temperature.

Ionisation state of the hydrogen gas

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

$$\delta T_{\rm b}(z) \approx 27\, x_{HI}(z)\,(1+\delta_{\rm b}(z)) \left(\frac{1+z}{10}\right)^{\frac{1}{2}} \left(1 - \frac{T_{\rm CMB}(z)}{T_{\rm s}(z)}\right) \left(\frac{\Omega_{\rm b}}{0.044}\frac{h}{0.7}\right) \left(\frac{\Omega_{\rm m}}{0.27}\right)^{-\frac{1}{2}} \text{mK}$$

Density fluctuation of baryons

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

Cosmology

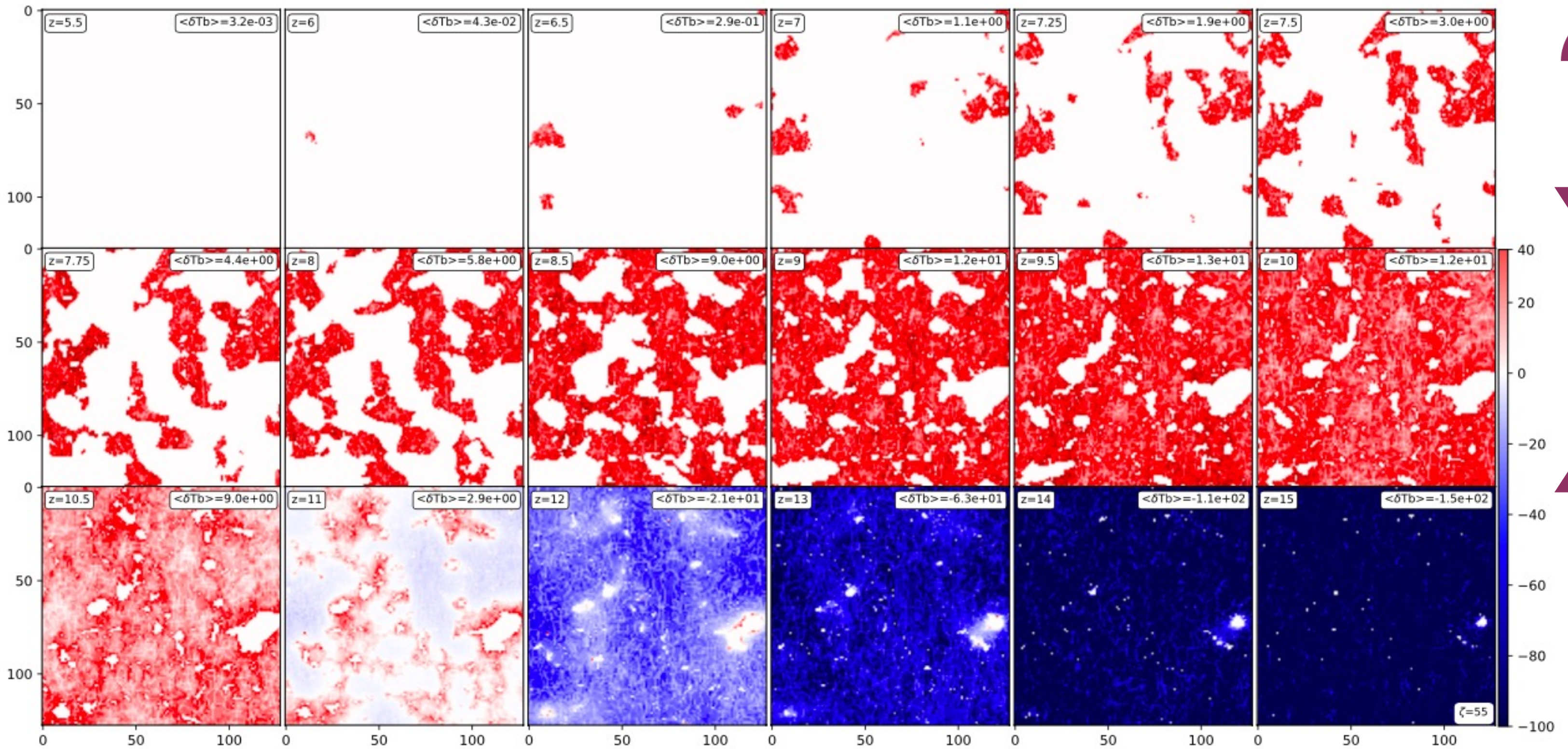
A. 21 CM TO t_{reion}

Reconstruction of reionisation times from 21 cm signal maps

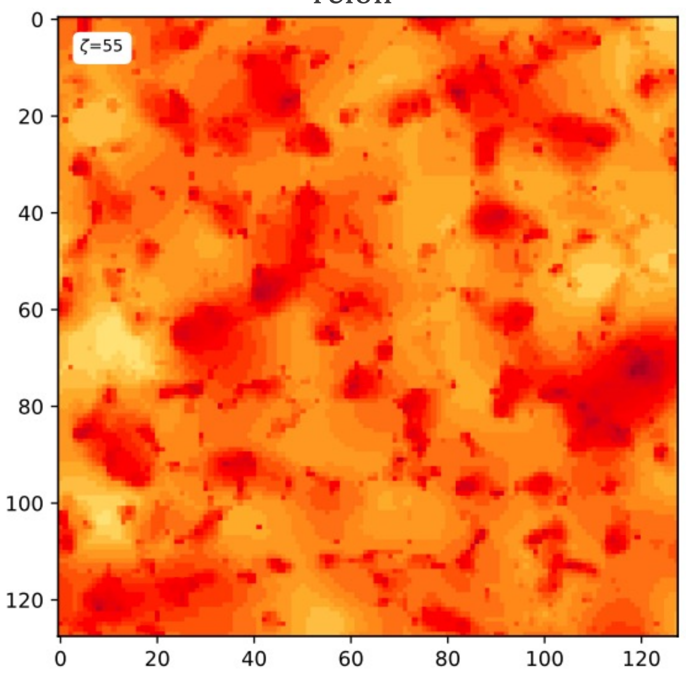
Is it possible to reconstruct reionisation times maps from observations?

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}

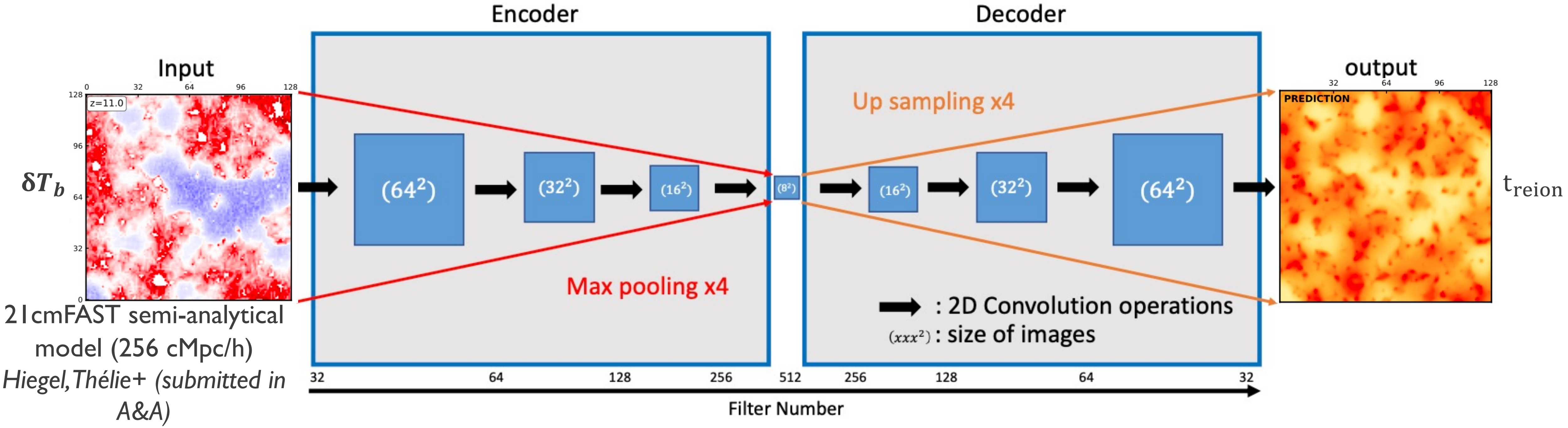


21cmFAST semi-analytical model (256 cMpc/h)

Hiegel, Thélie+ (submitted in A&A)

A. 21 CM TO t_{reion}

Convolutional neural network (CNN)



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

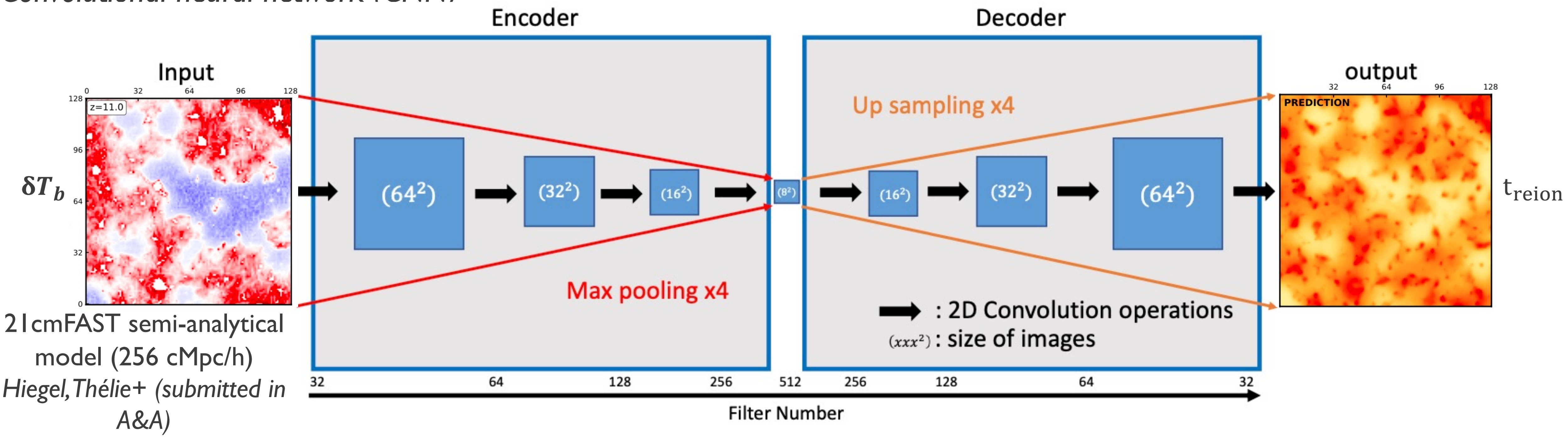
Hiegel, Thélie+ (submitted in A&A)

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)

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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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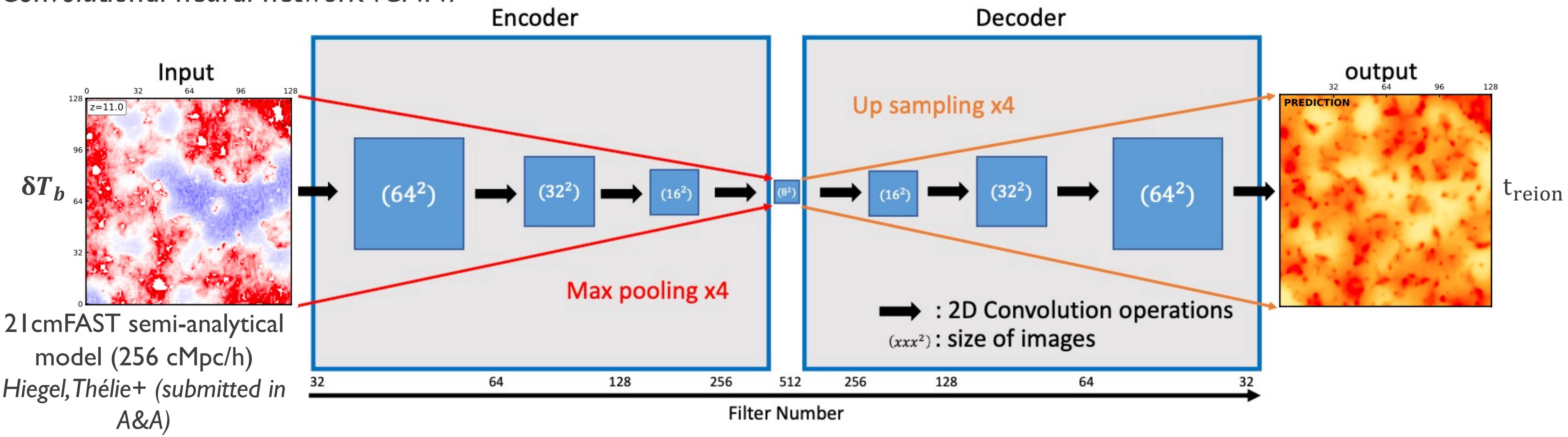

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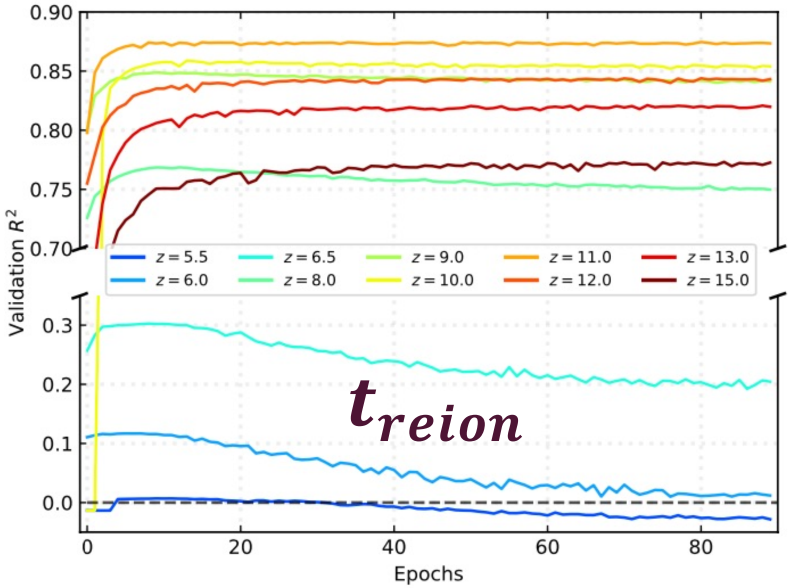
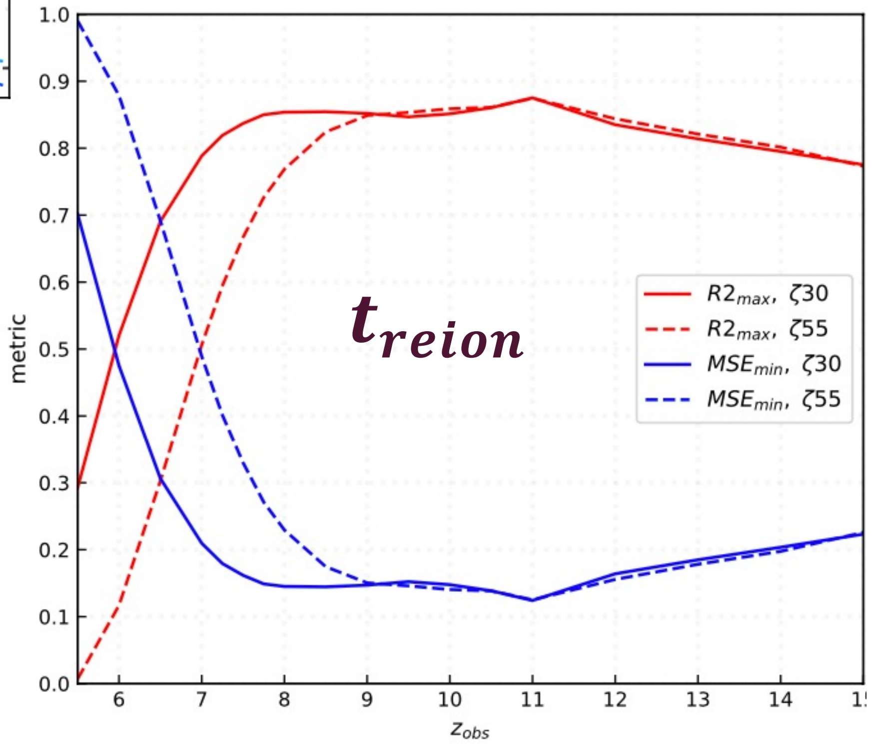
LEARNING

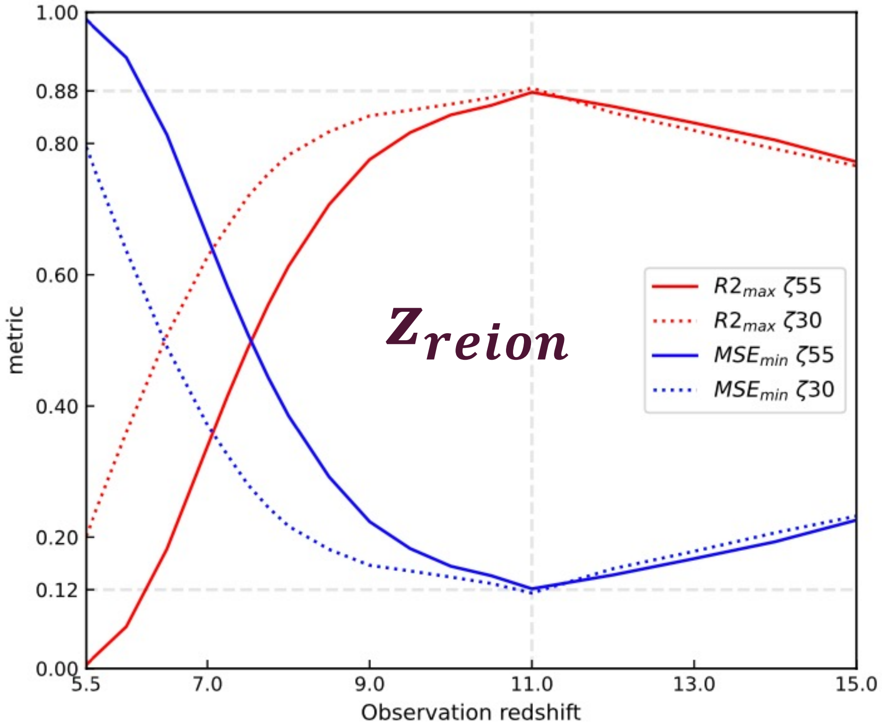
- One prediction per observational redshift
- 35,000 images:
  - *90% for the training set*
  - *10% for the test set*

A. 21 CM → t_{reion}

Monitoring performances of the CNN







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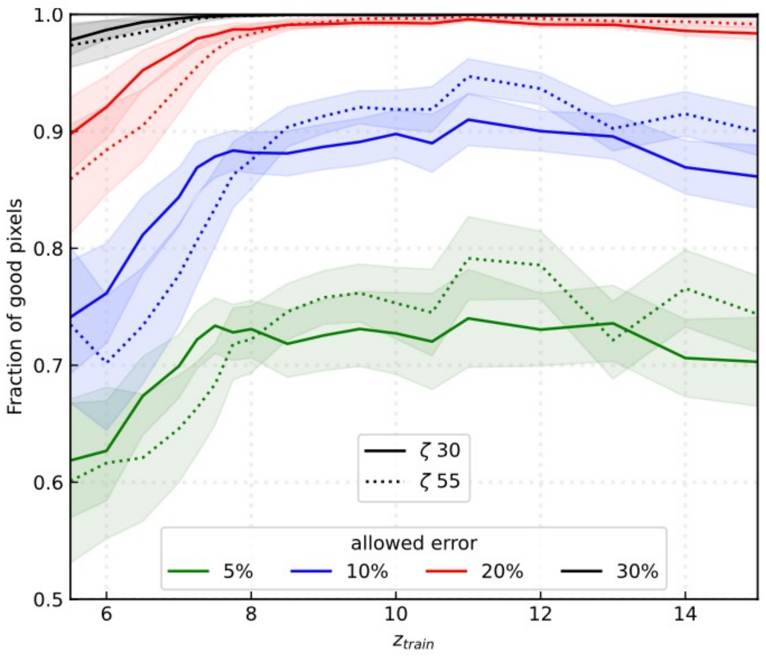

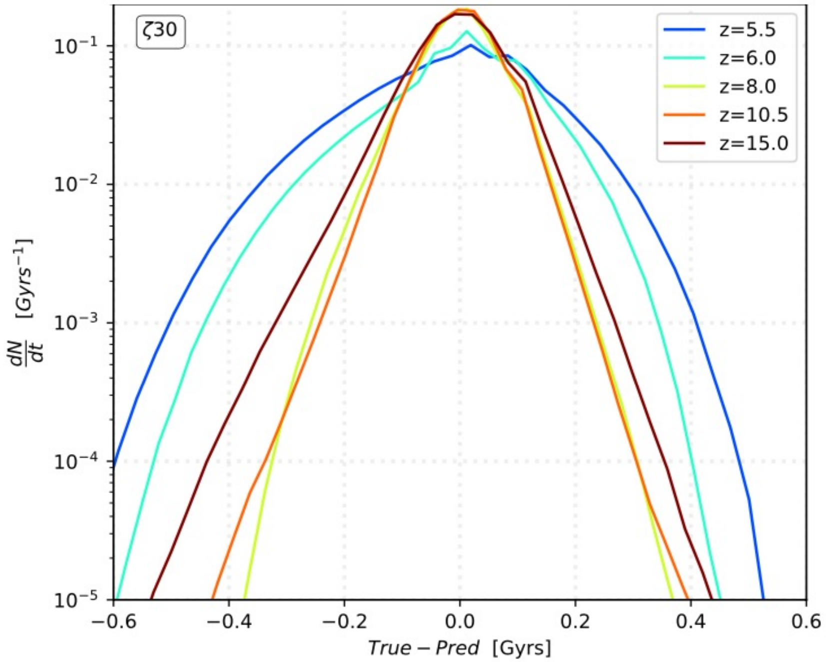

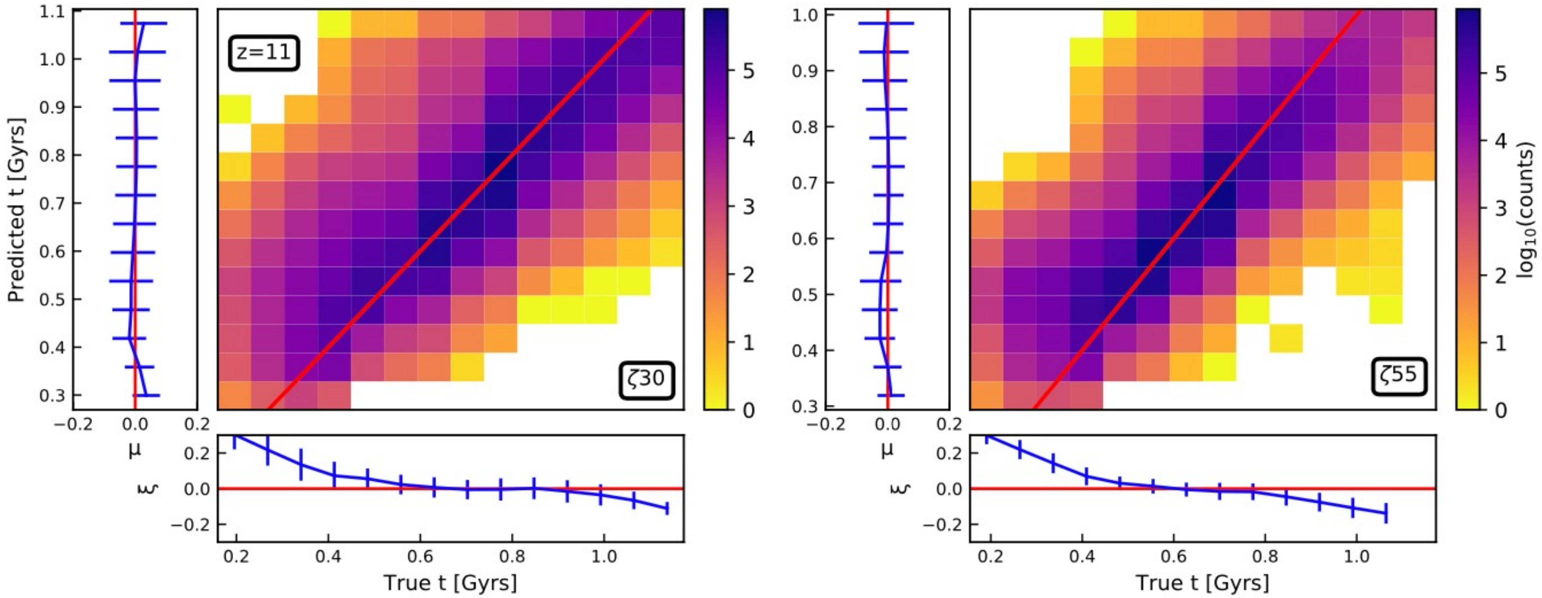

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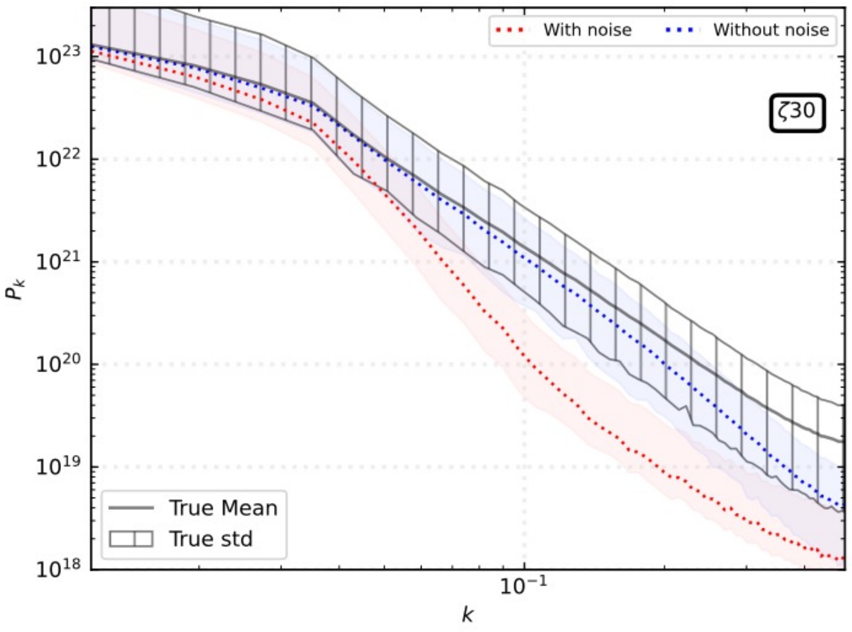
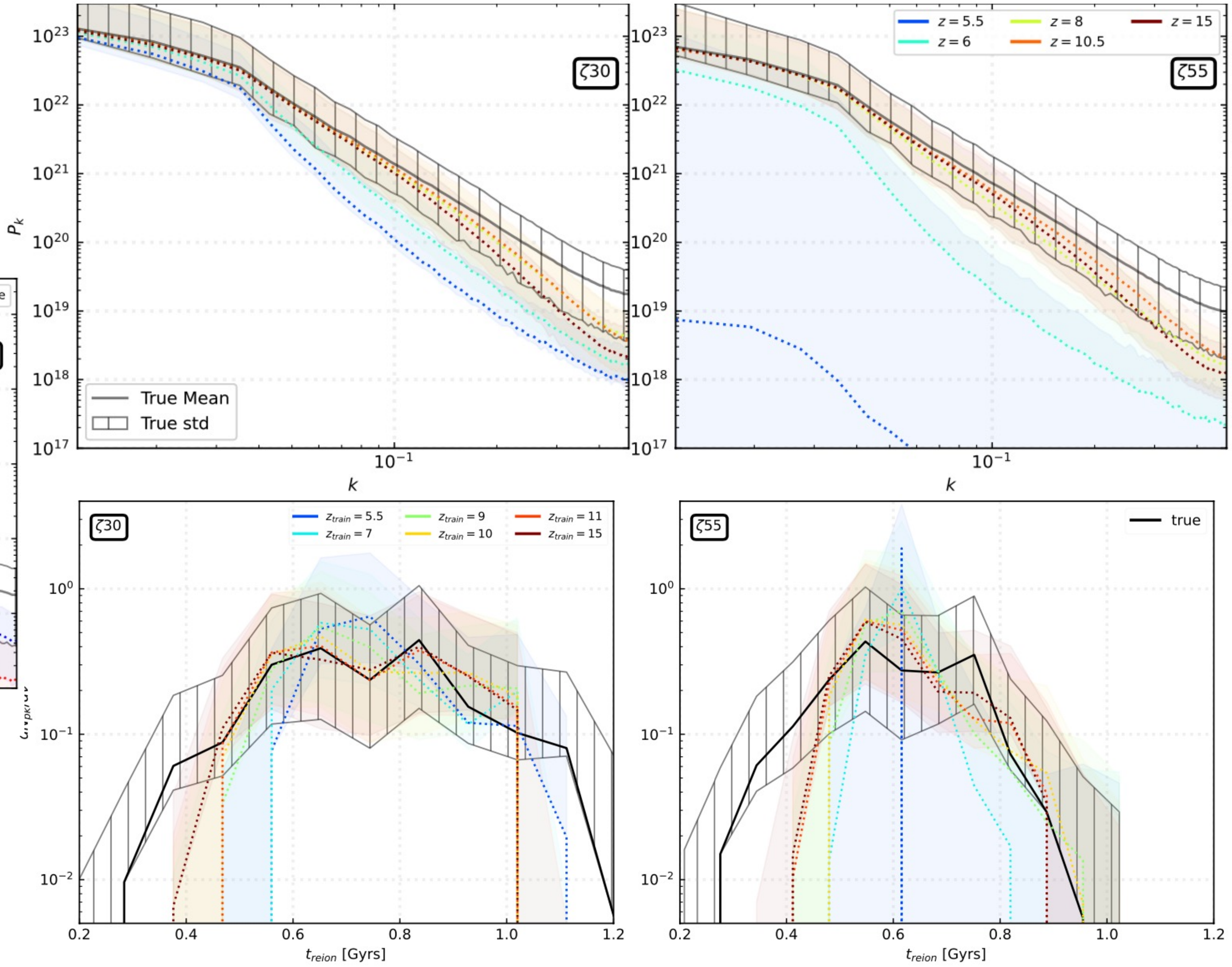
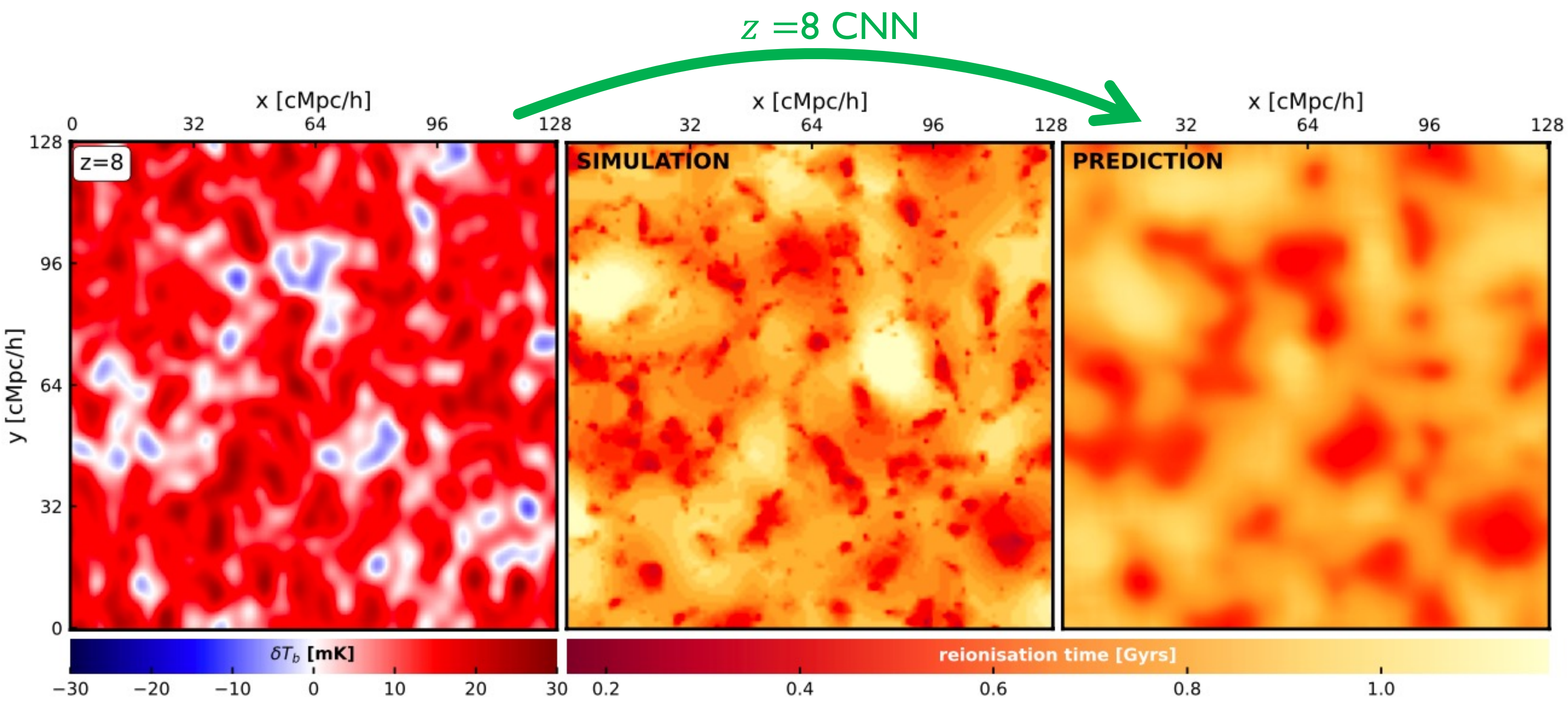




A. 21 CM TO t_{reion}

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

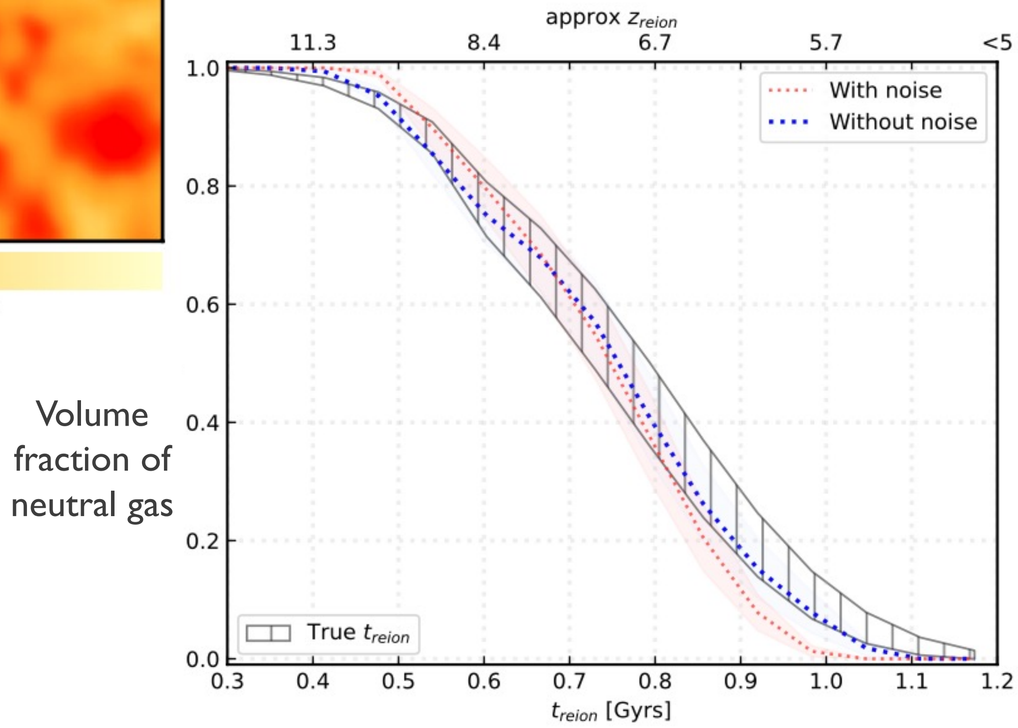


Noise characteristics (Tool21cm, Giri+20)

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

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

Hiegel, Thélie+ (submitted in A&A)



WORK IN PROGRESS

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

B. PATCHS DE REIONISATION

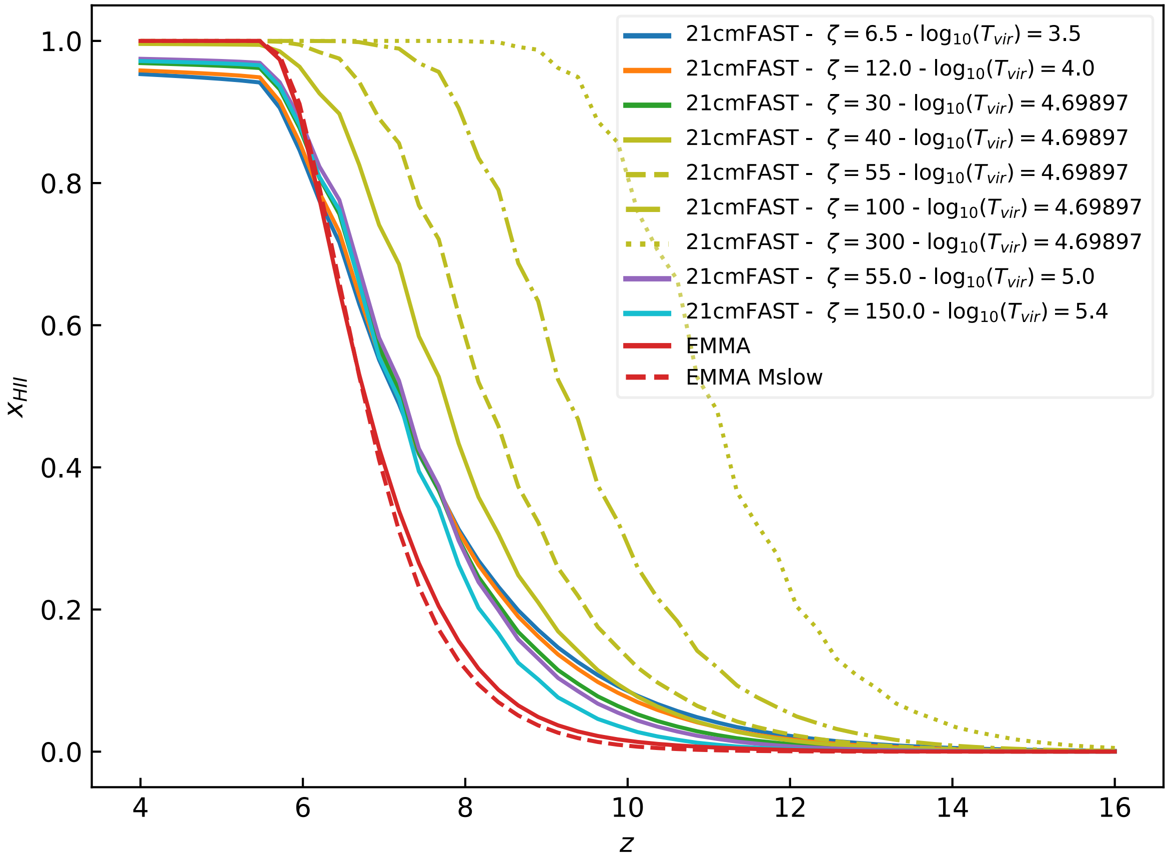
Simulations

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) :

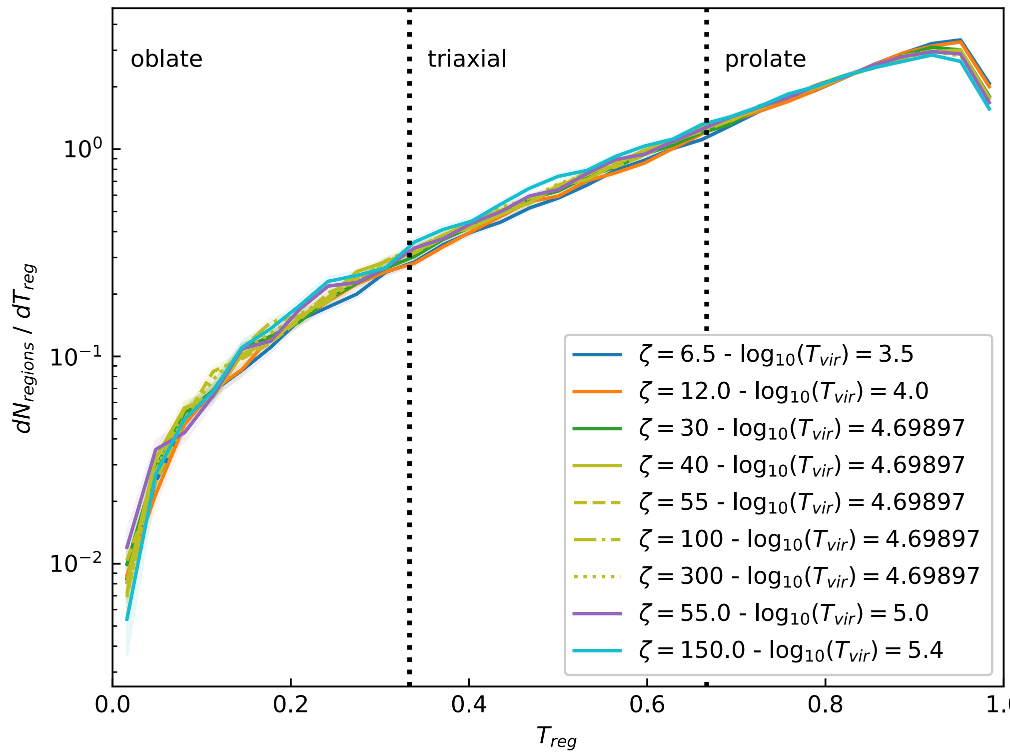
- Mass resolution for the stellar particle ($10^7 M_\odot$ for the Mslow one and $10^8 M_\odot$ for the other)



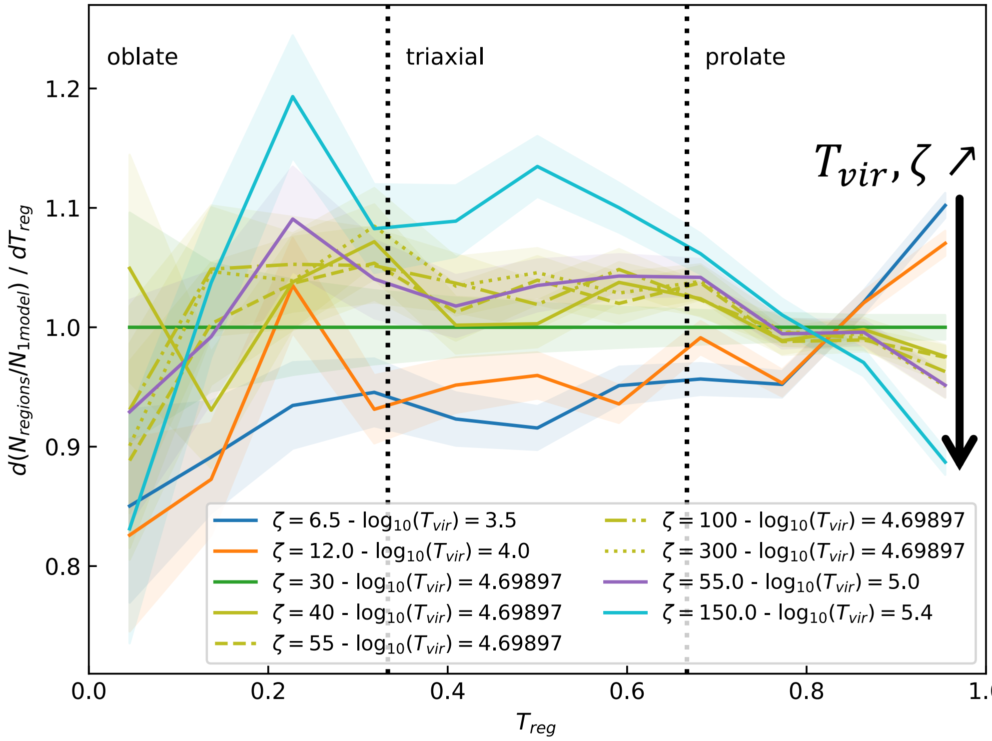
B. REIONISATION PATCHES

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

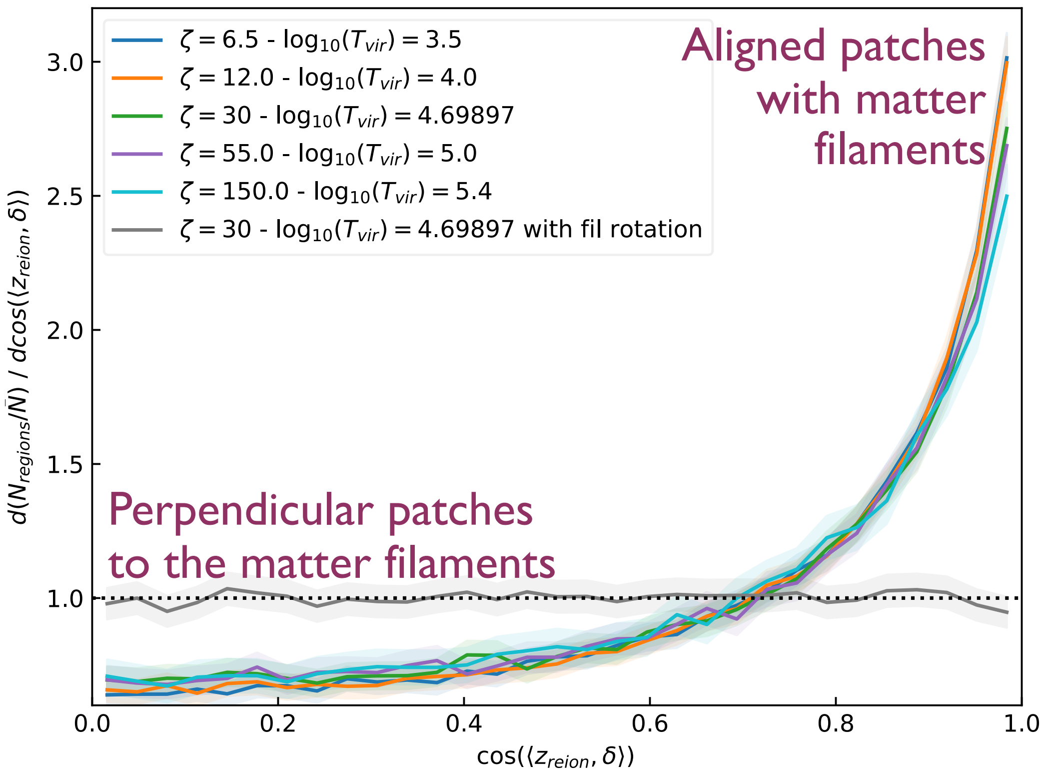


Ratio with model $\zeta = 30$

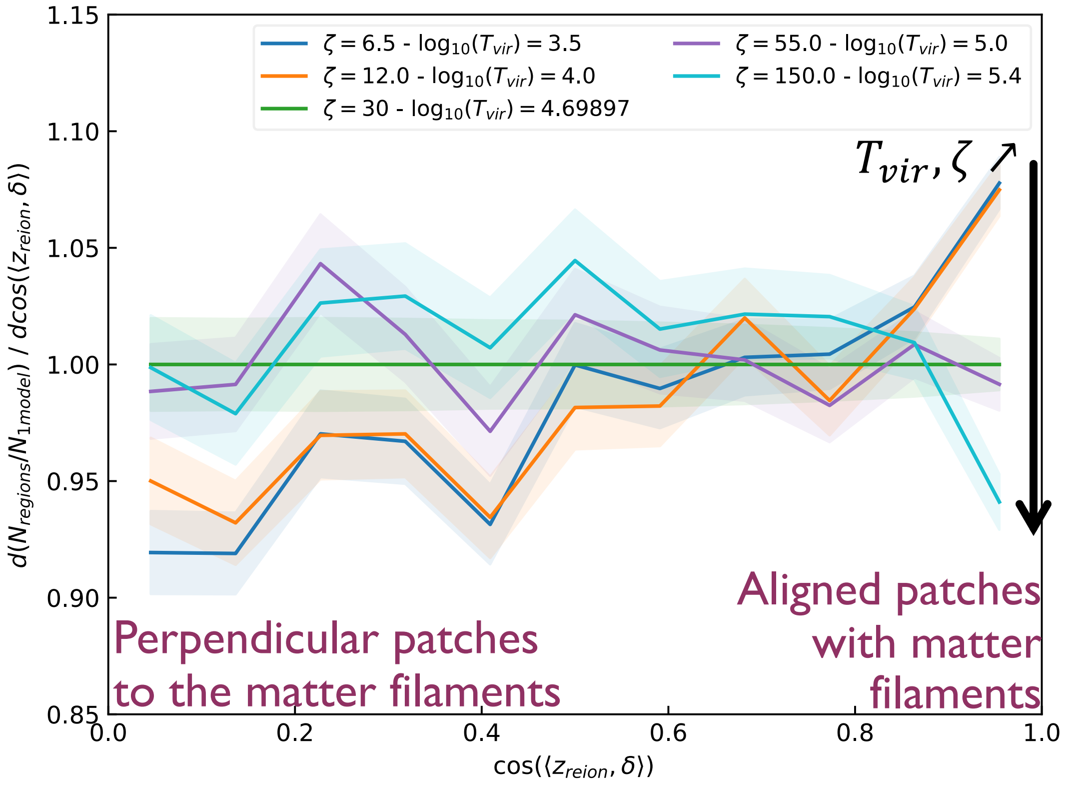


B. REIONISATION PATCHES

Orientation of patches with respect to the matter filaments



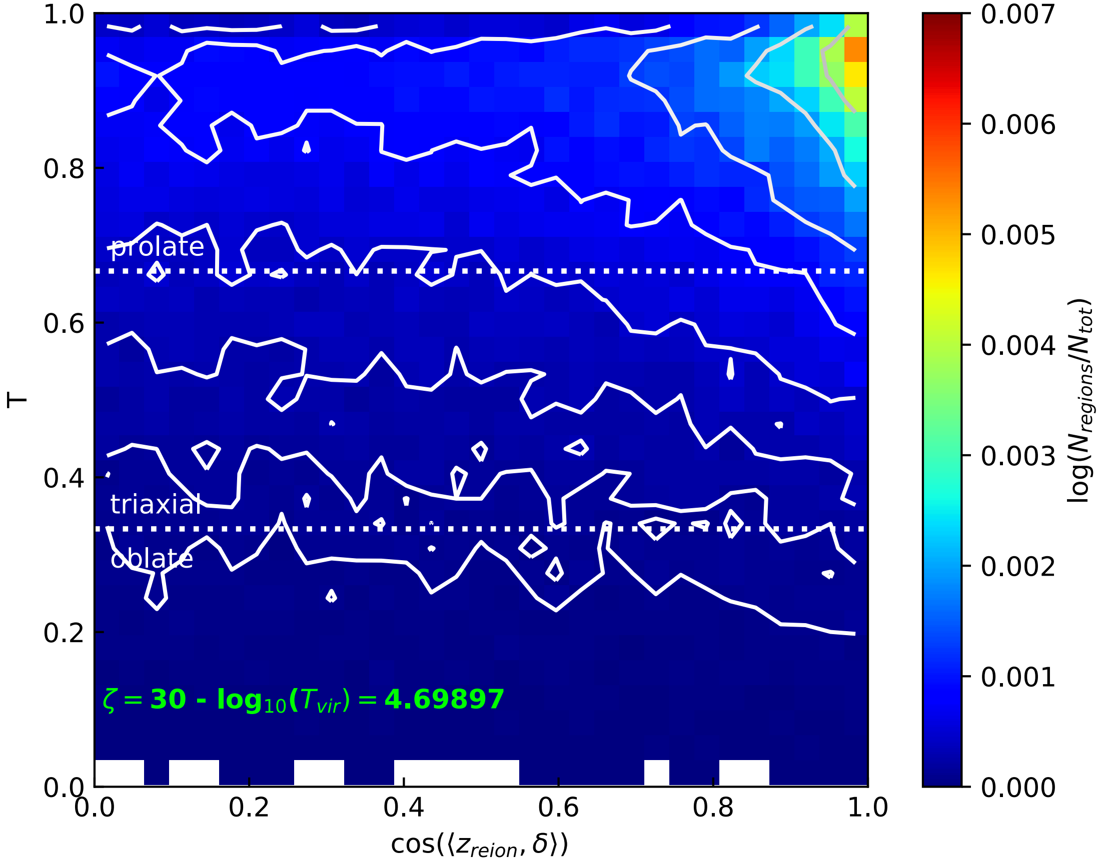
Ratio with model $\zeta = 30$



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

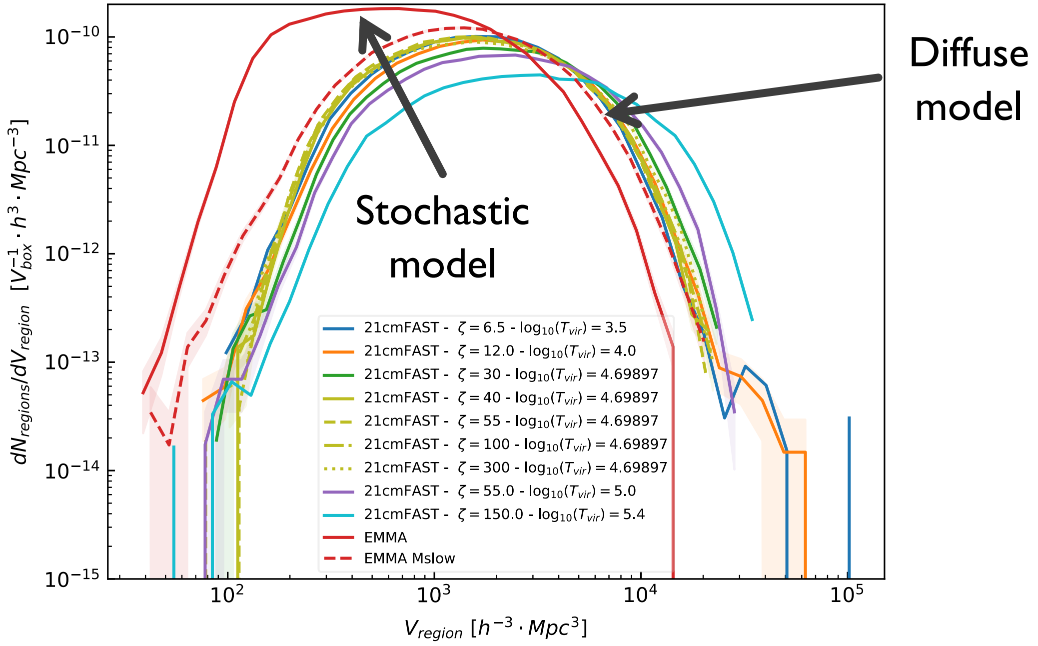
B. REIONISATION PATCHES

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

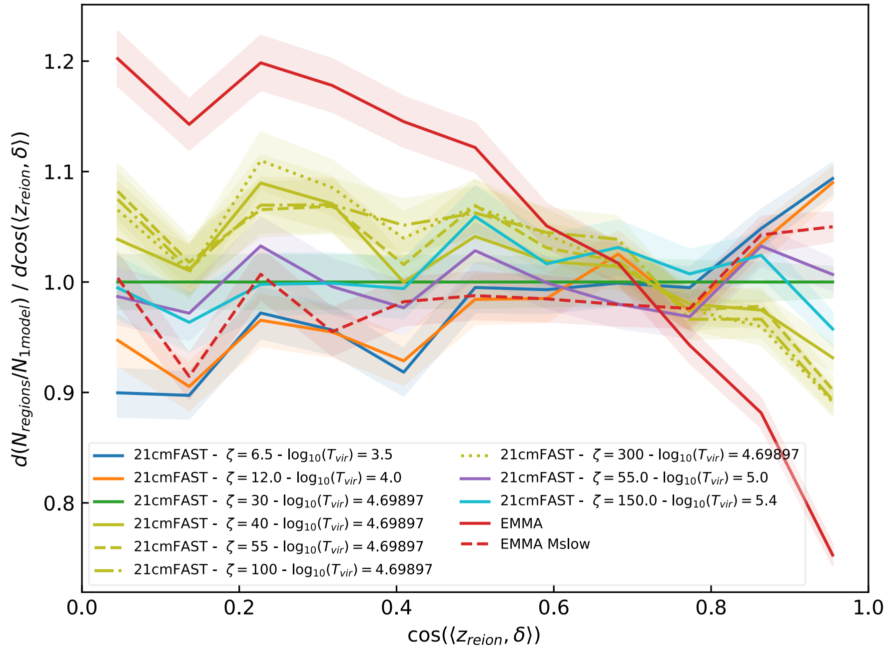


B. PATCHS DE REIONISATION

Comparaison avec EMMA, une simulation cosmologique



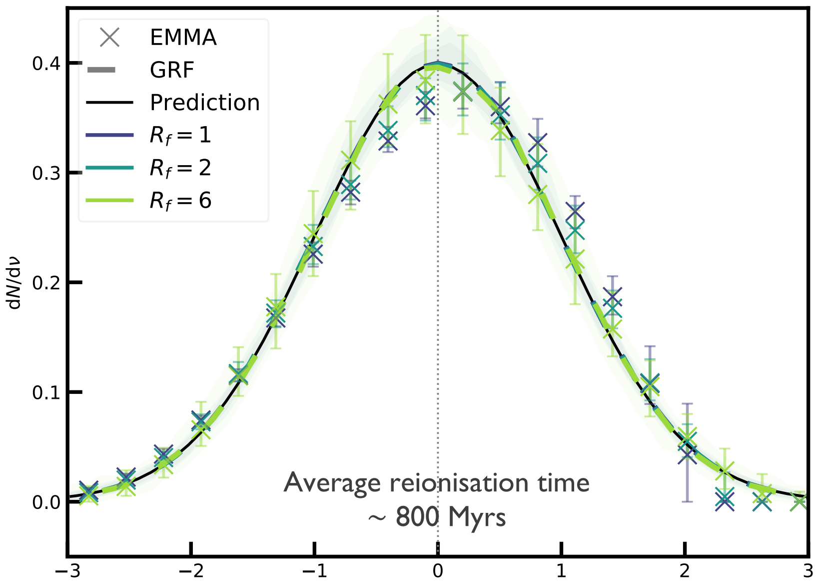
- Same conclusions for both type of simulations
- BUT EMMA can also produce models with rather different topologies (for the same $x_{HII}(z)$)



C. TOPOLOGY AND GRF THEORY

Simulation measurements & GRFs predictions

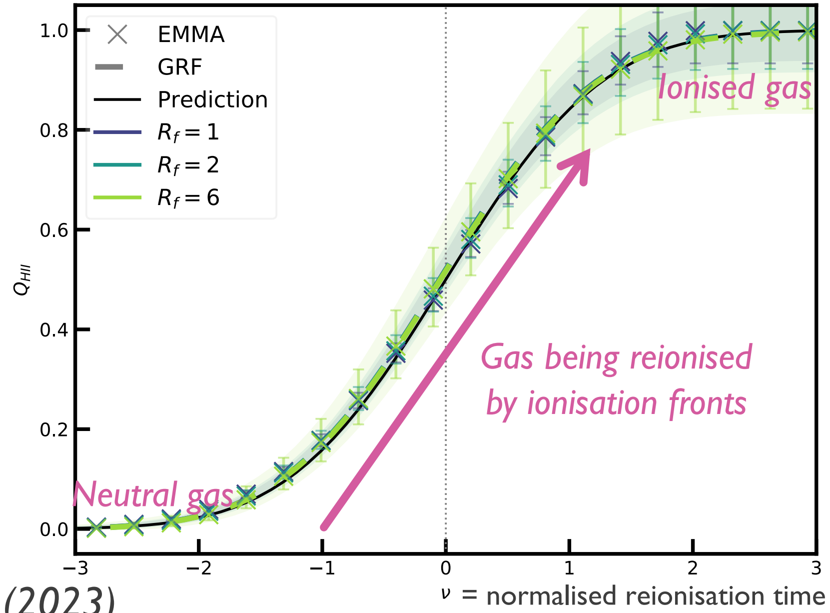
- PDF of reionisation times = counts the number of cells that have reionised as a function of time
- CDF of reionisation time → reionisation history
- **EMMA measurements close to gaussian predictions**



Beginning of the EoR
~ 100 Myrs

End of the EoR
~ 1000 Myrs

PDF of t_{reion}



Cumulated PDF of t_{reion} = filling factor

Thélie et al. (2023)

C. TOPOLOGY AND GRF THEORY

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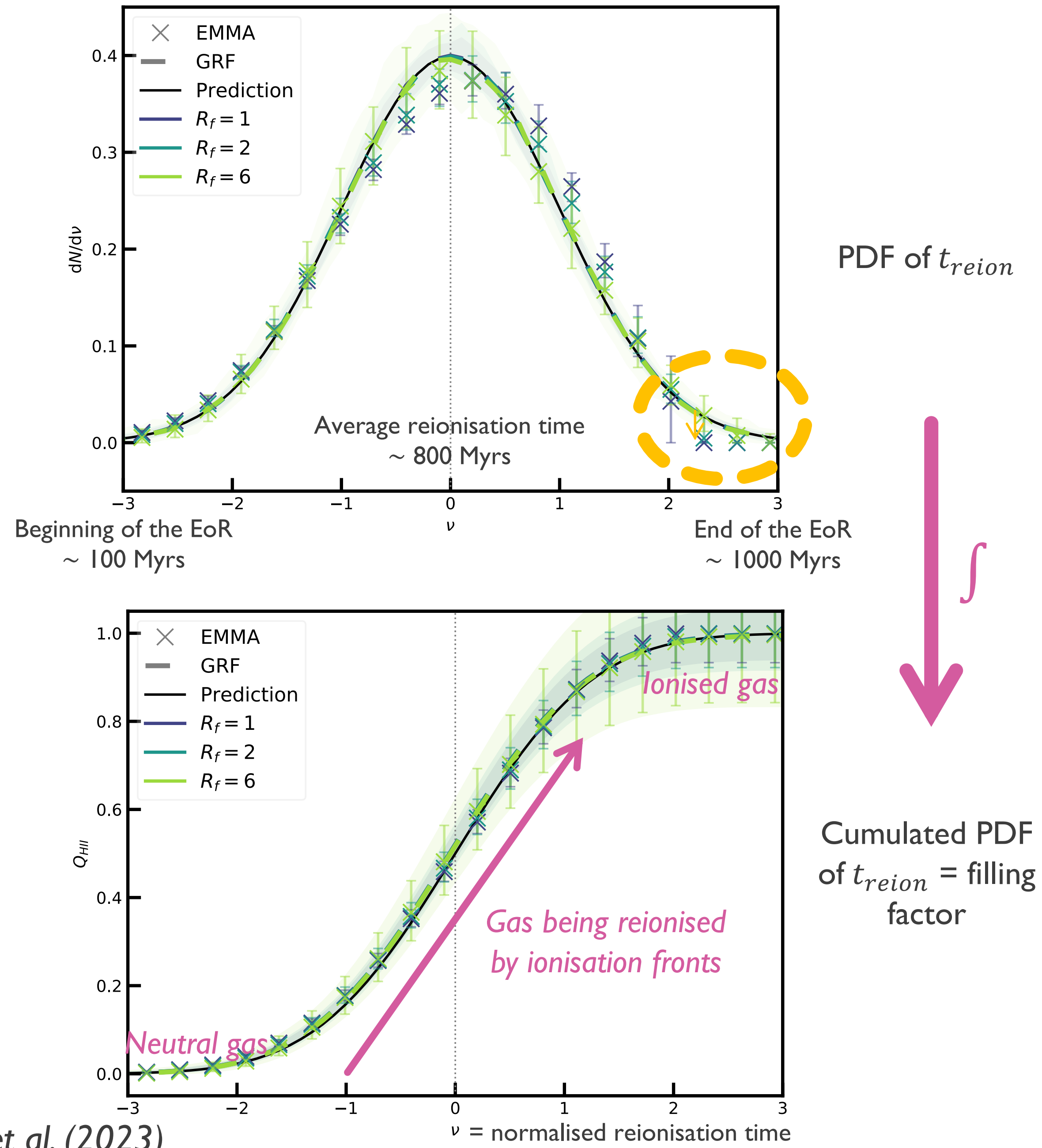
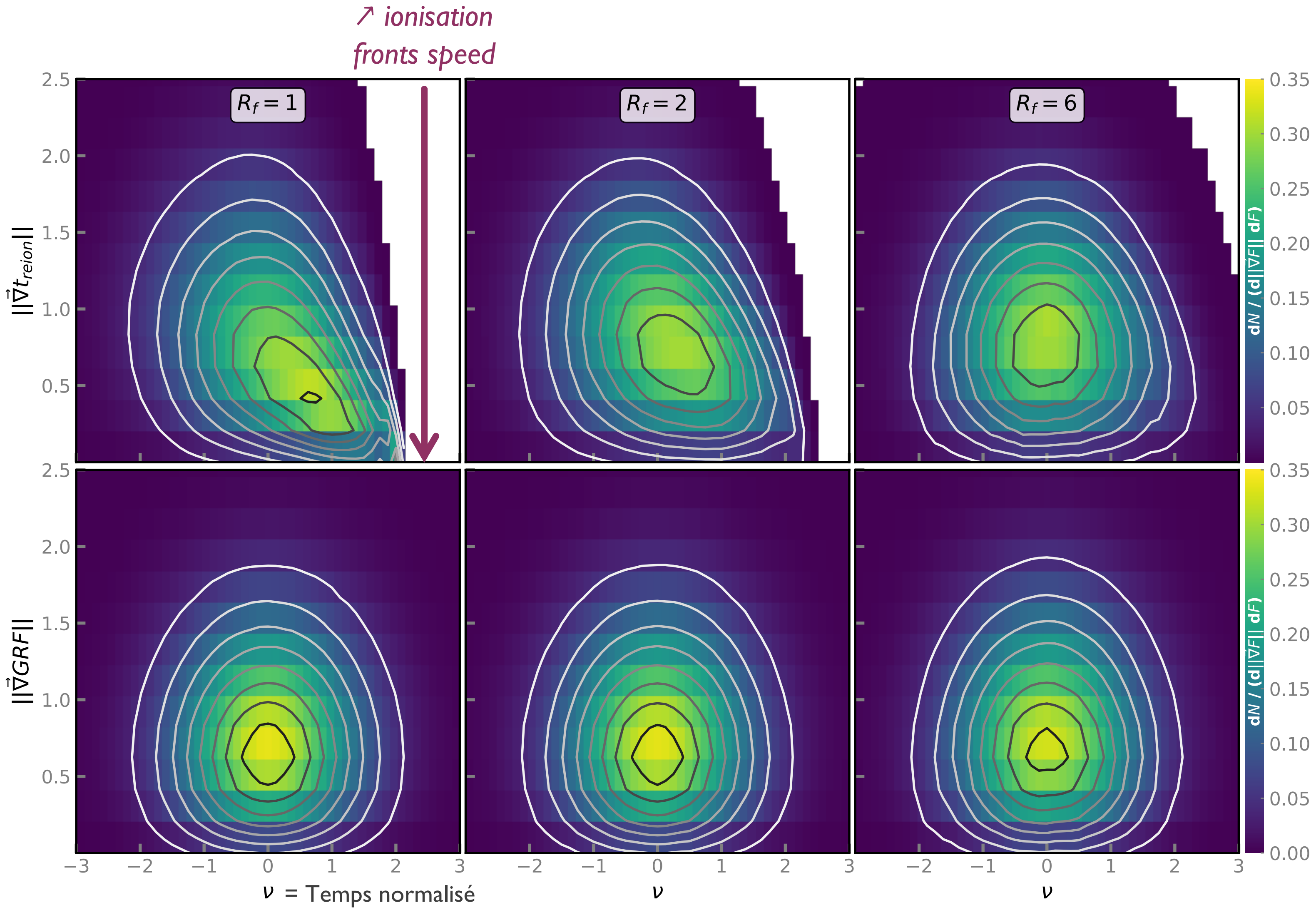
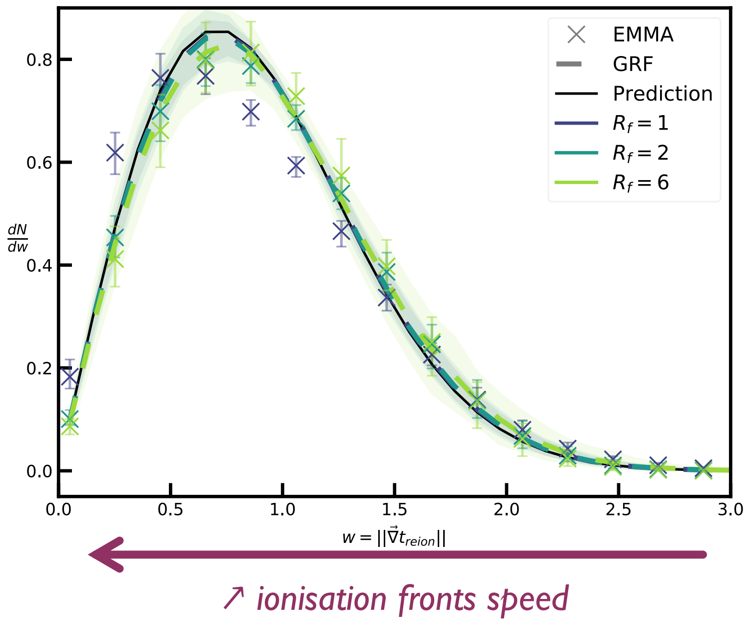


Thélie et al. (2023)

C. TOPOLOGY AND GRF THEORY

PDF of the gradients field norm: ionisation fronts speed

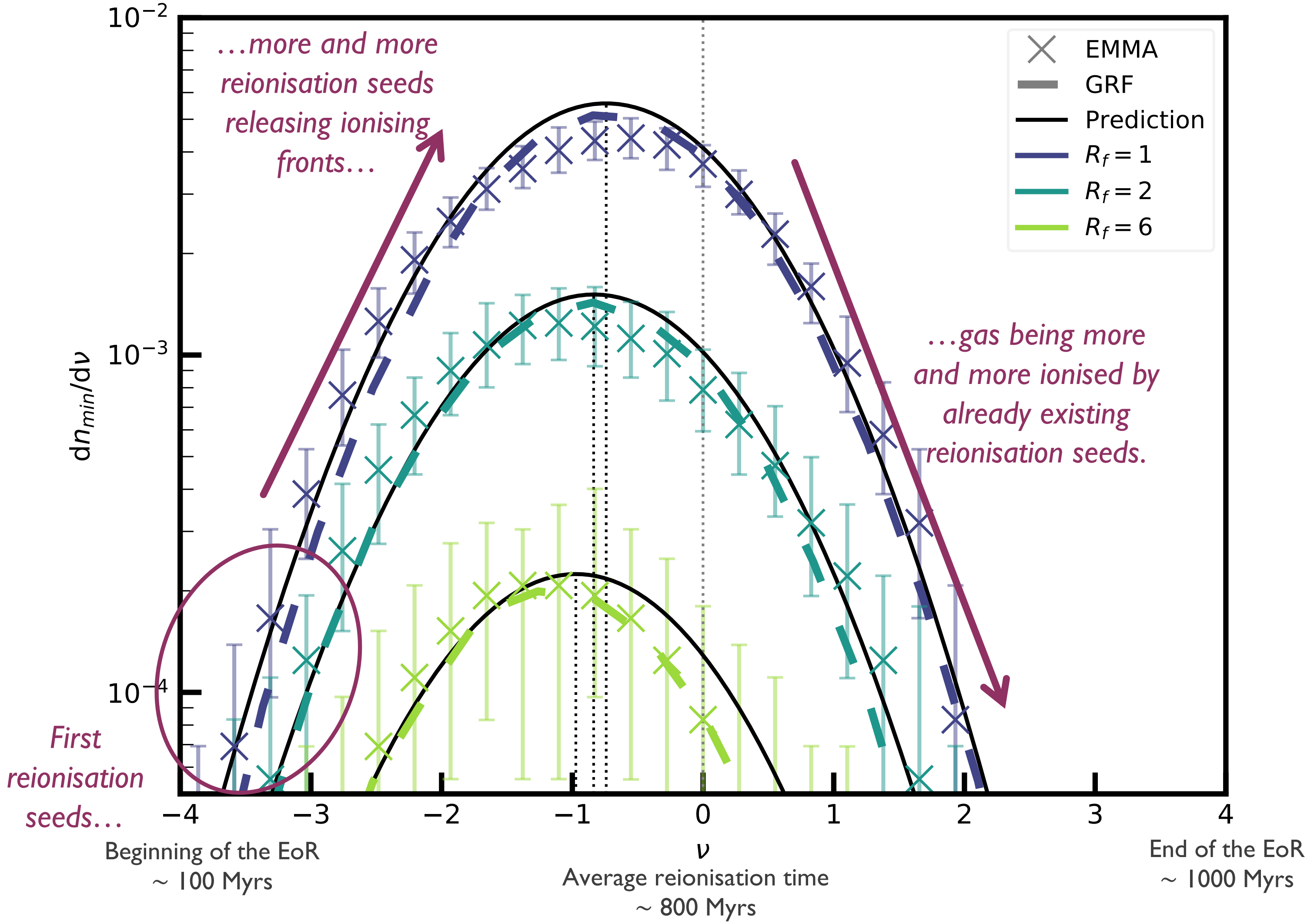




- R_f ↗ **:** EMMA measurements more symmetric
- $R_f \in \{1, 2\}$ **:** imprints of non-gaussianity in the form of an asymmetry
  = *acceleration of the ionisation fronts at the end of the EoR*

C. TOPOLOGY AND GRF THEORY

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

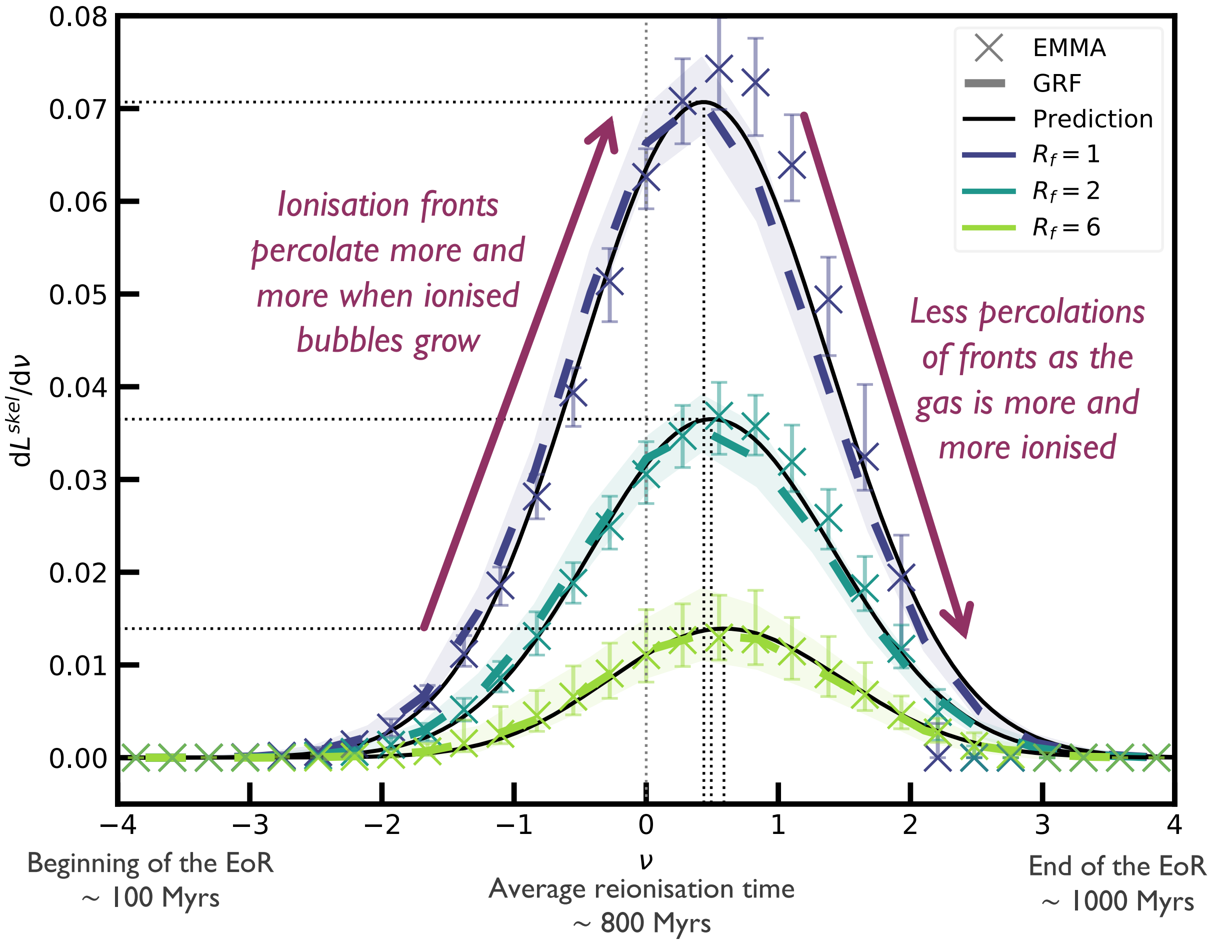


C. TOPOLOGY AND GRF THEORY

Skeleton length: places where the ionisation fronts percolate

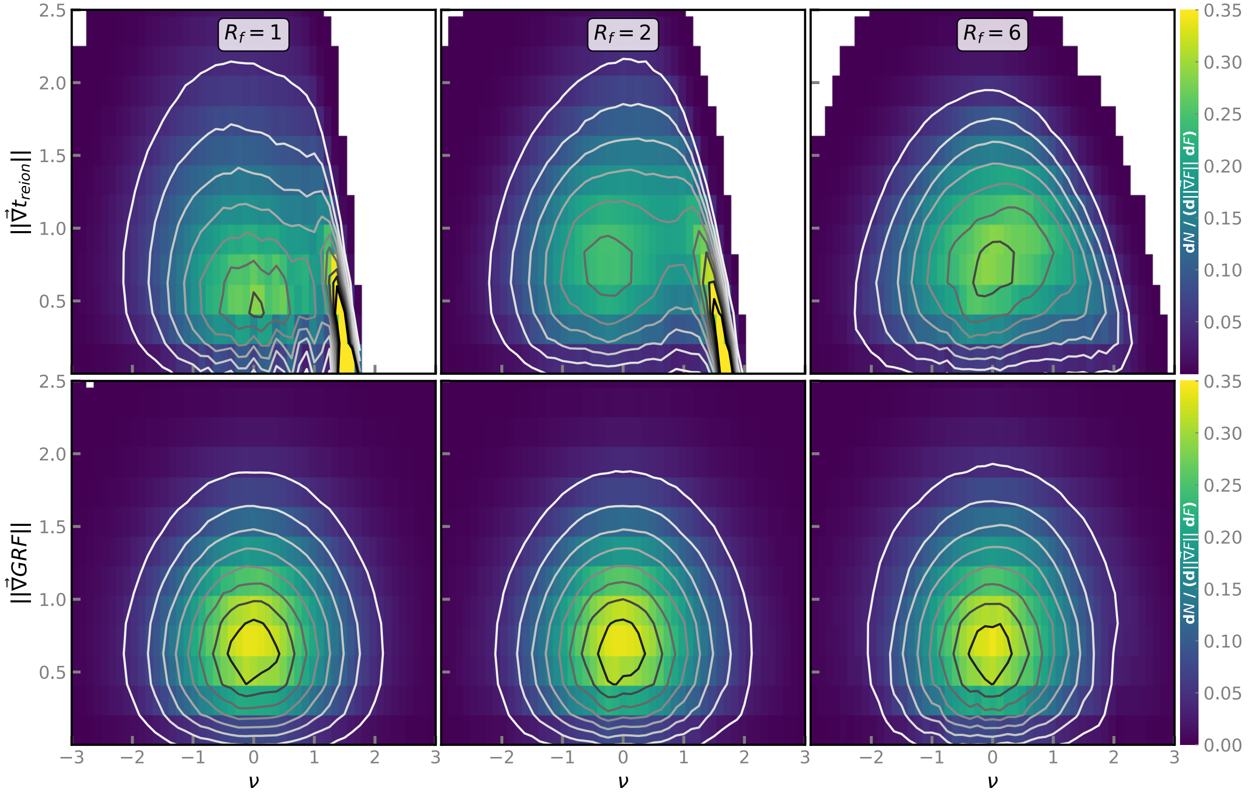
$$L^{\rm tot} = \left(\frac{1}{8} + \frac{\sqrt{2}}{4\pi}\right)\frac{1}{R_*}$$

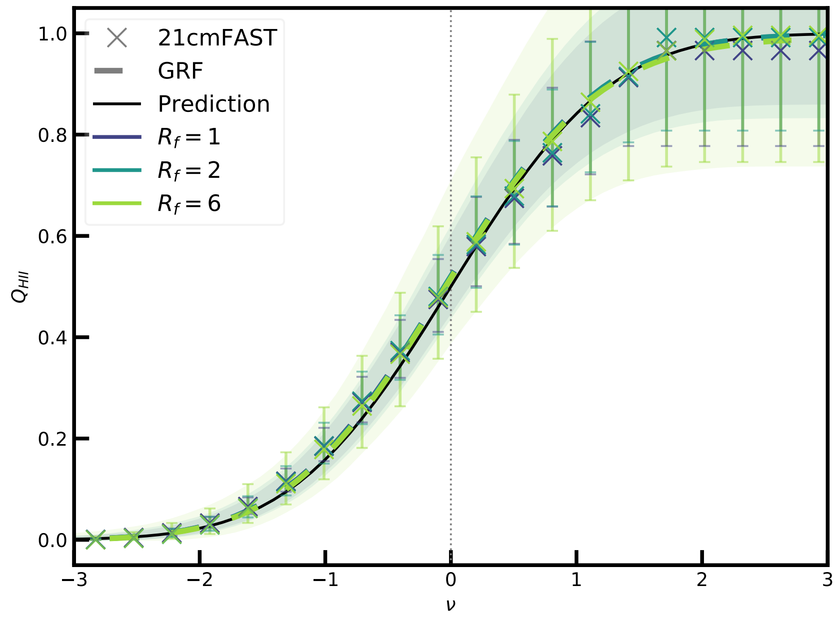
- "Stiff" approximation + global (measurements) or local (GRFs) calculations → predictions underestimating the skeleton length: **measurements have to be renormalised**
- $R_f \nearrow$: EMMA measurements more symmetric
- $R_f \in \{1, 2\}$: asymmetry
  = *acceleration of ionisation fronts at the end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

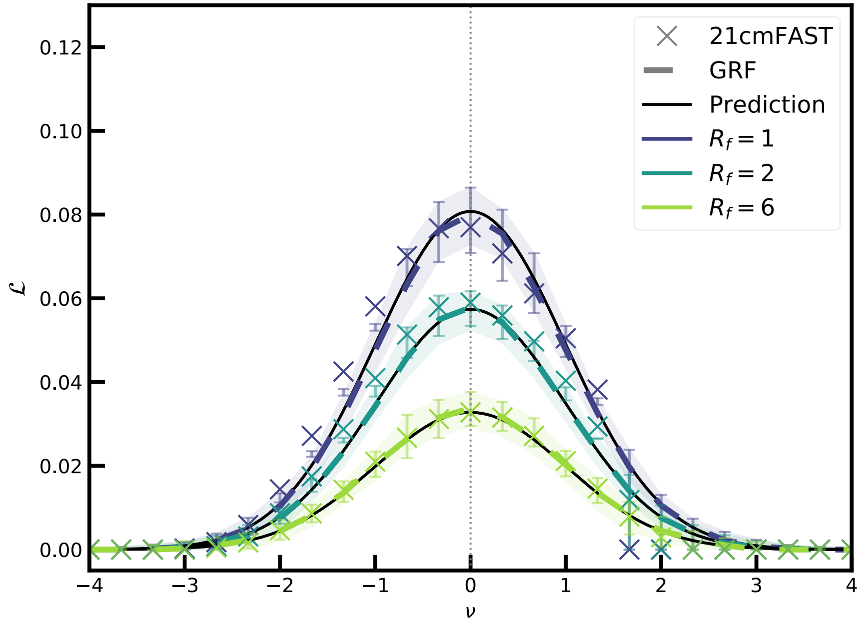


C. TOPOLOGY AND GRF THEORY

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