# Latest (last?) constraints on the epoch of reionisation from Planck

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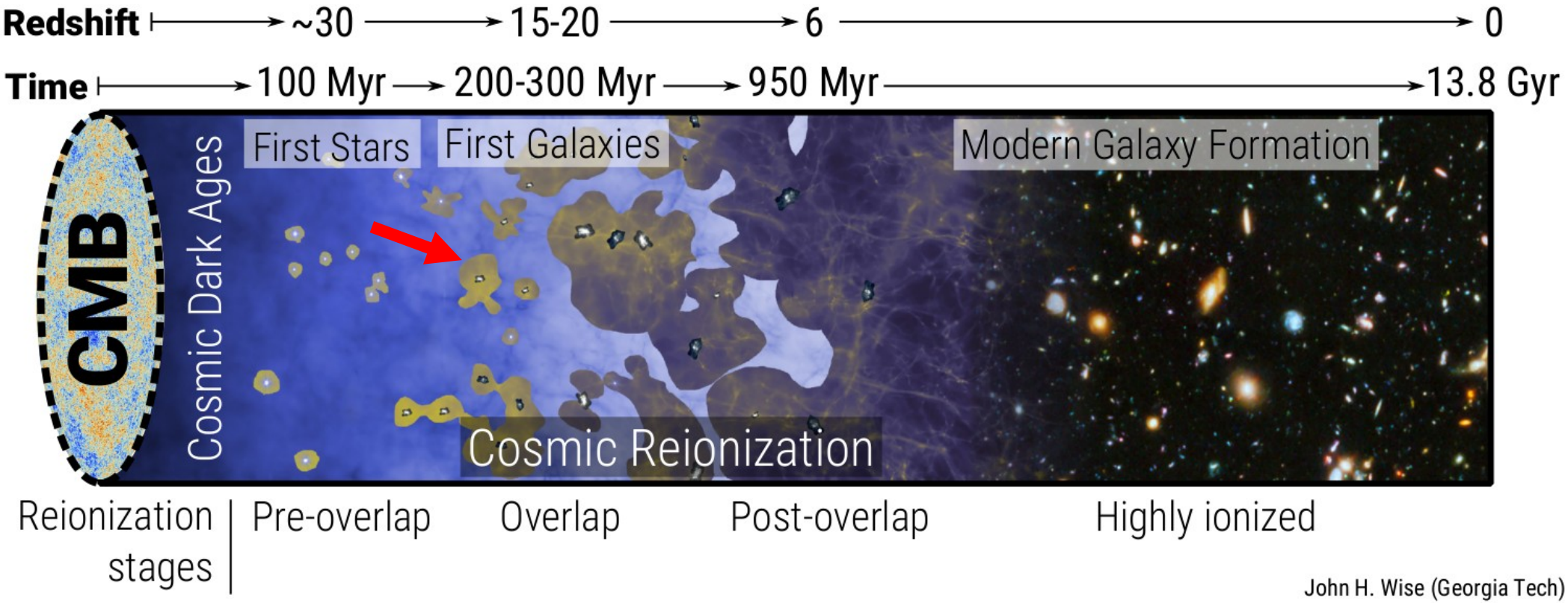
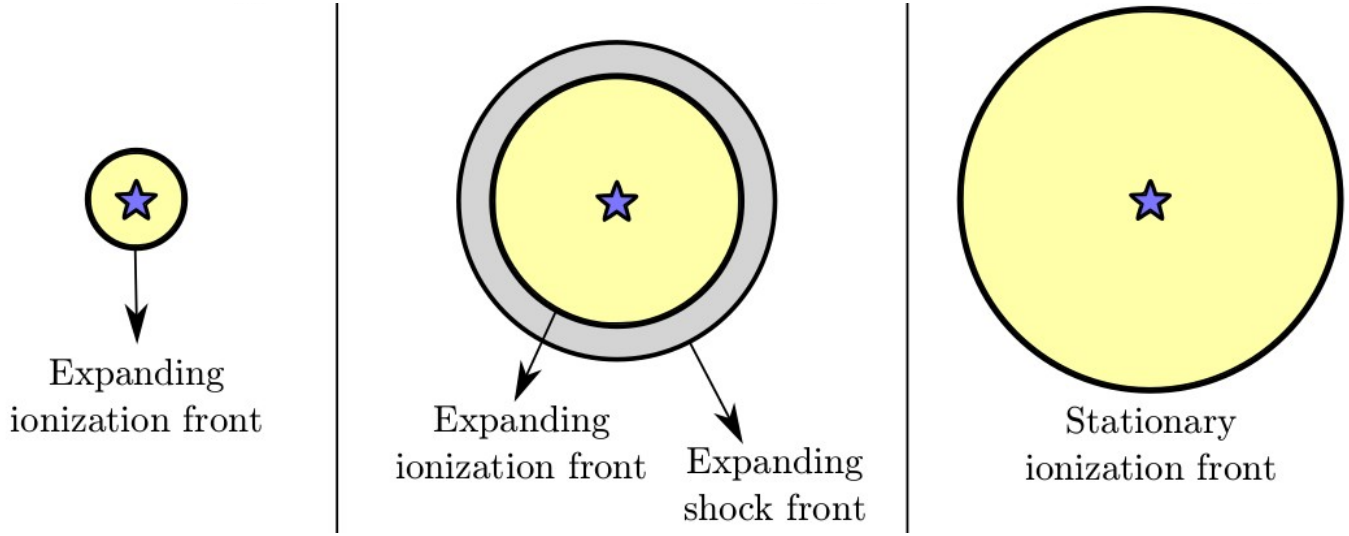
CMB France #6 @ IHP Paris, 18/12/2024

# The epoch of reionisation




John H. Wise (Georgia Tech)



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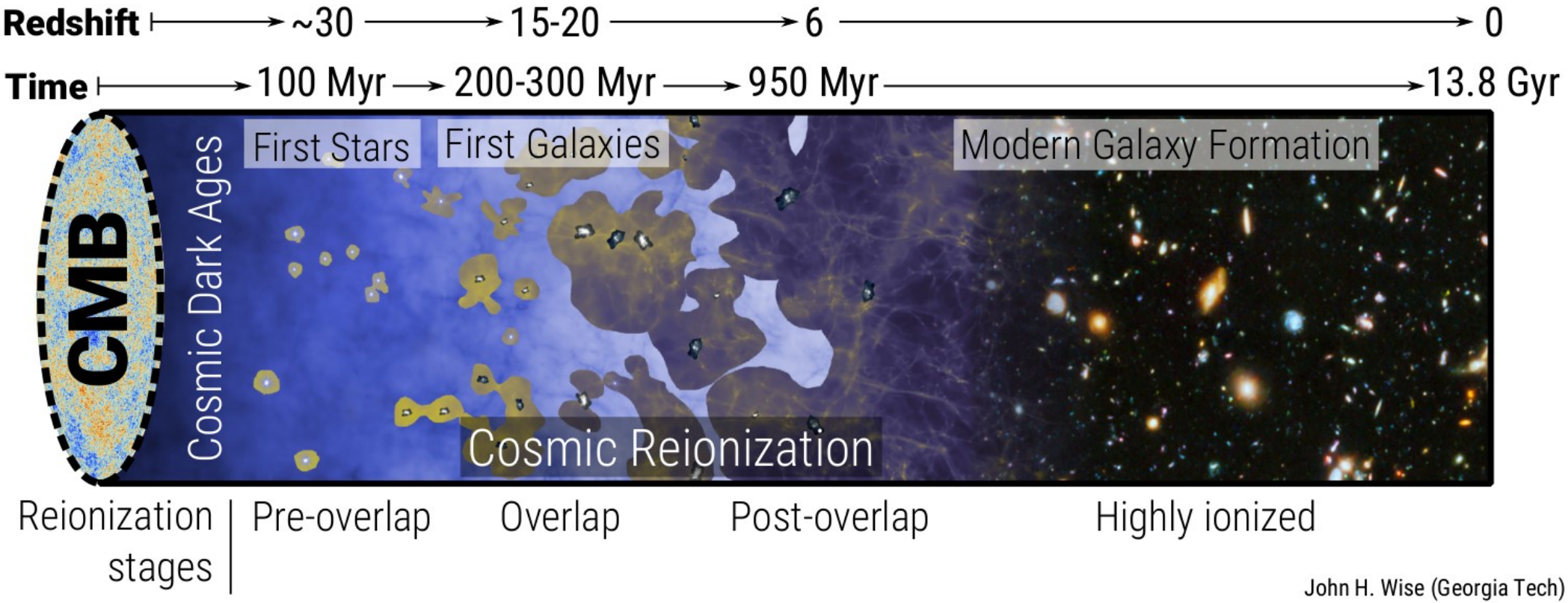
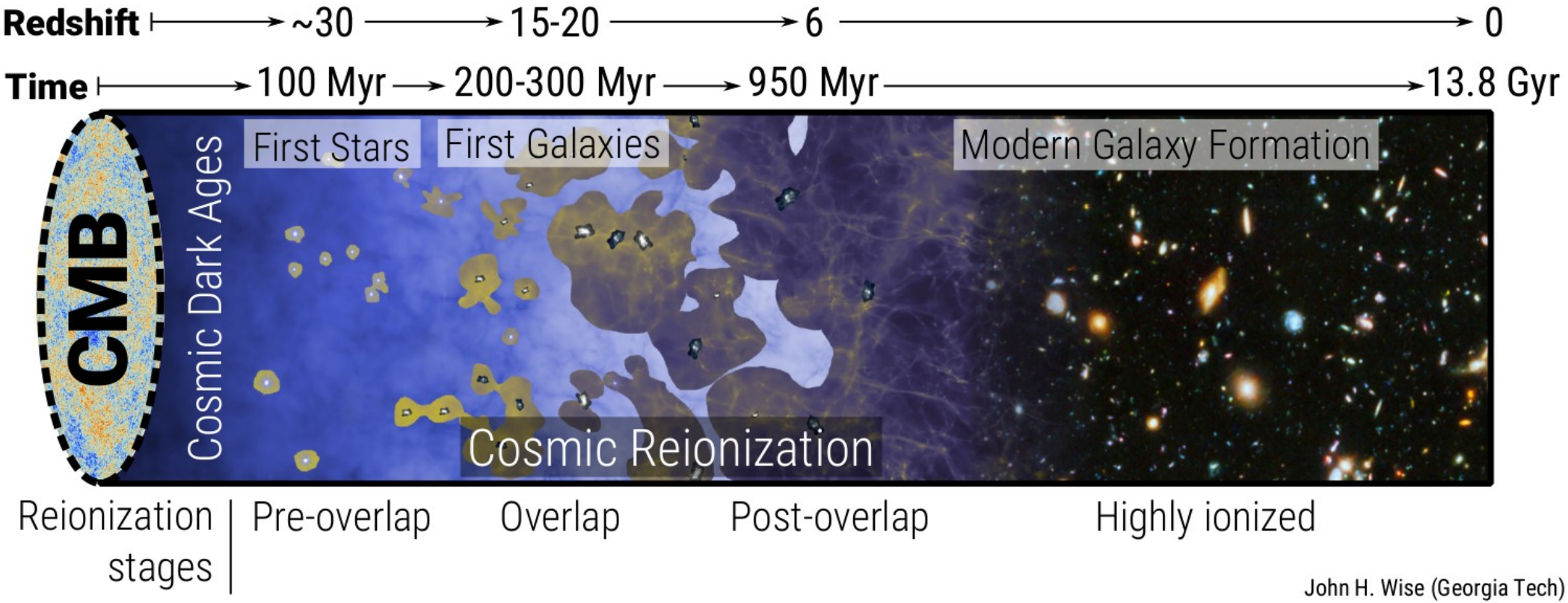



The transition from the neutral intergalactic medium (IGM = H + He) left after the Universe recombined at z~1100 to the fully ionised IGM observed today

# The epoch of reionisation

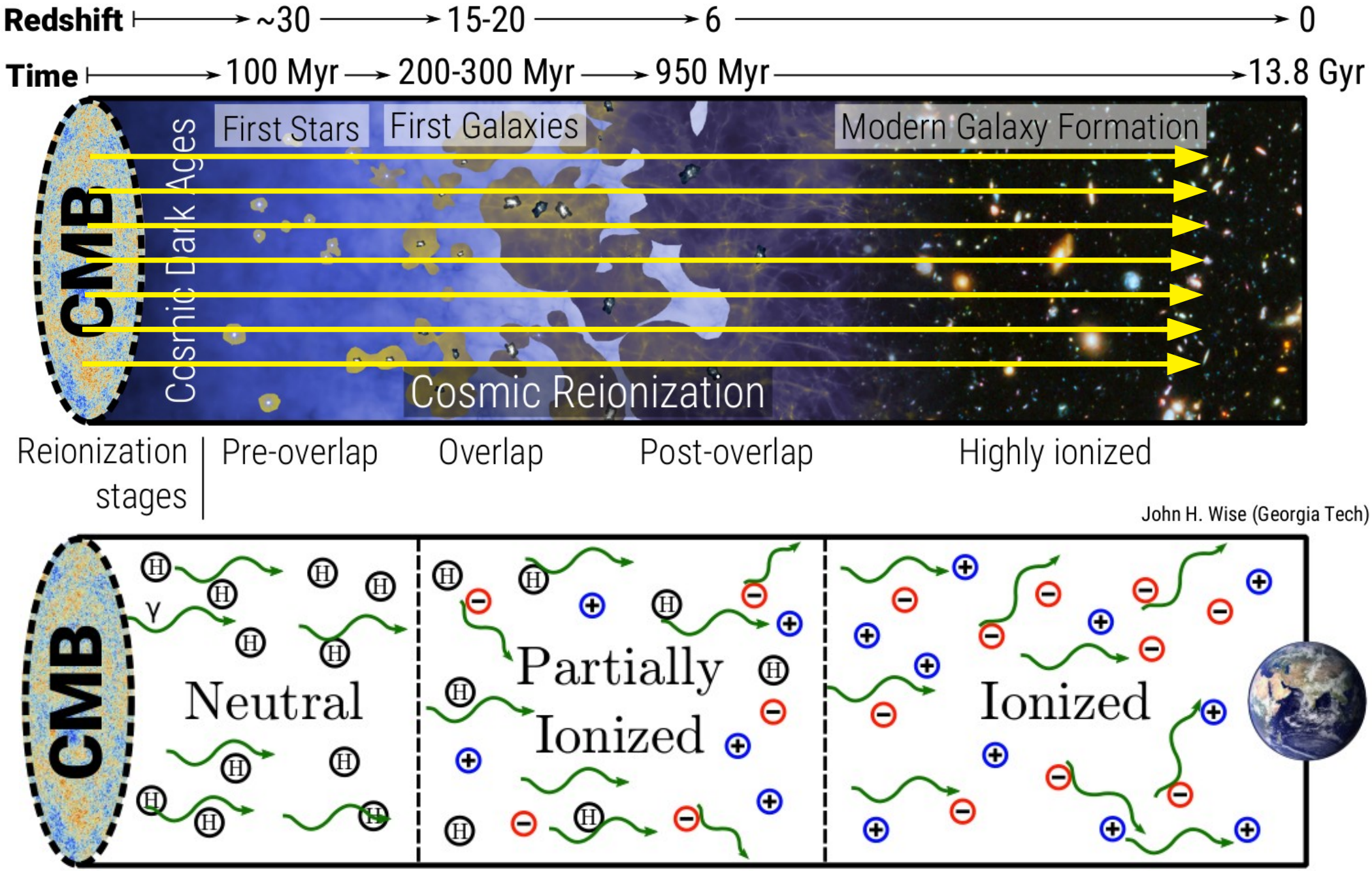



<u>Decades later, still many open questions:</u>

- WHEN: When did it happen? How long did it last?
- WHO: What were the sources responsible?
- HOW: How did it proceed? Was it gradual or sudden?

  What was its topology? Was it homogeneous or patchy?

# Reionisation & the CMB



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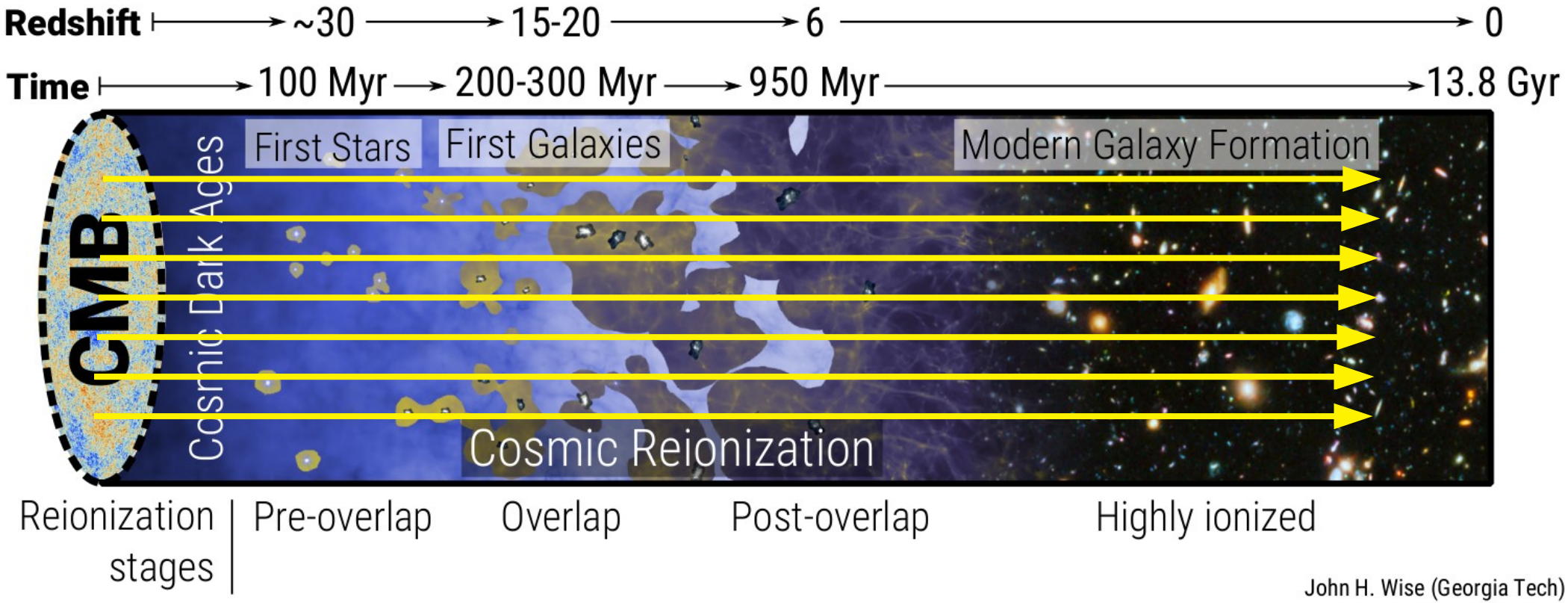


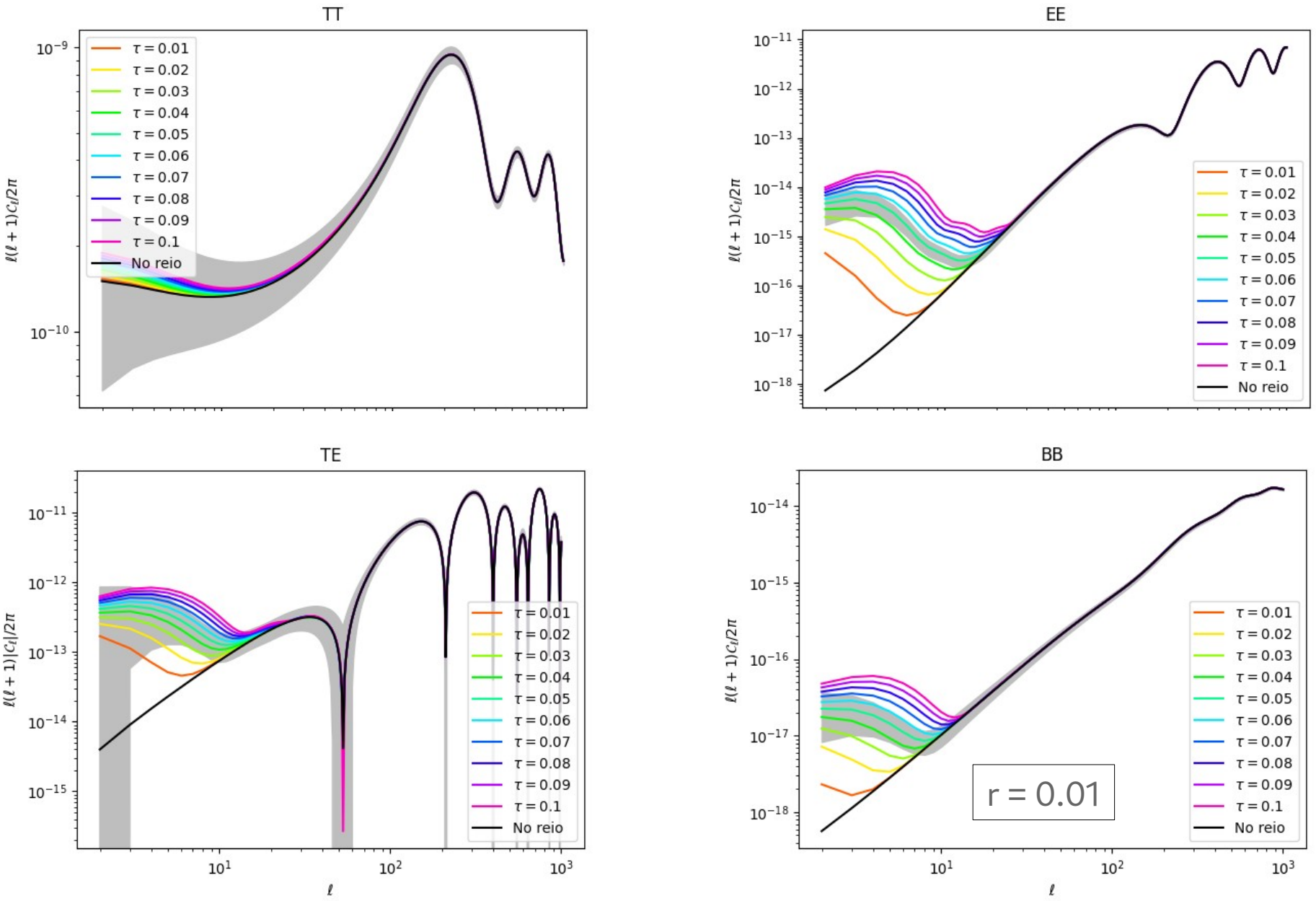

Density of free electrons

$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$

Probability for a CMB photon to be scattered = 1- exp(-τ)

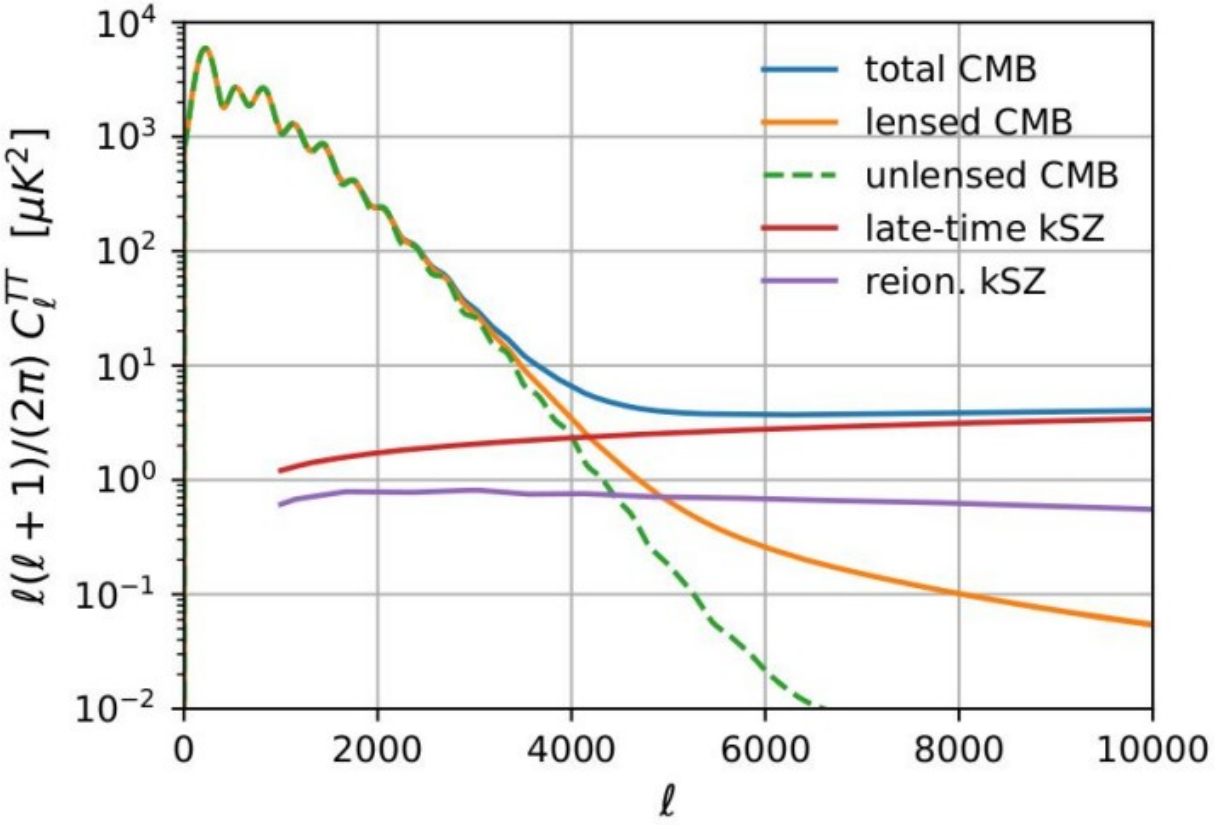
# Effects of reionisation on the CMB

Impact on all CMB angular power spectra:



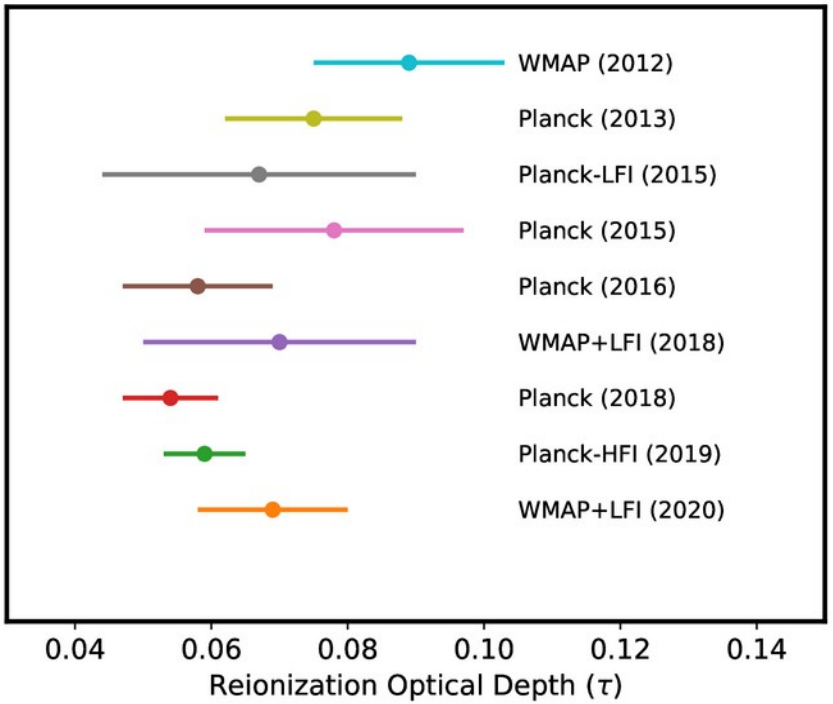
# Reionisation & the CMB

Kinetic Sunyaev-Zel'dovich (kSZ) effect

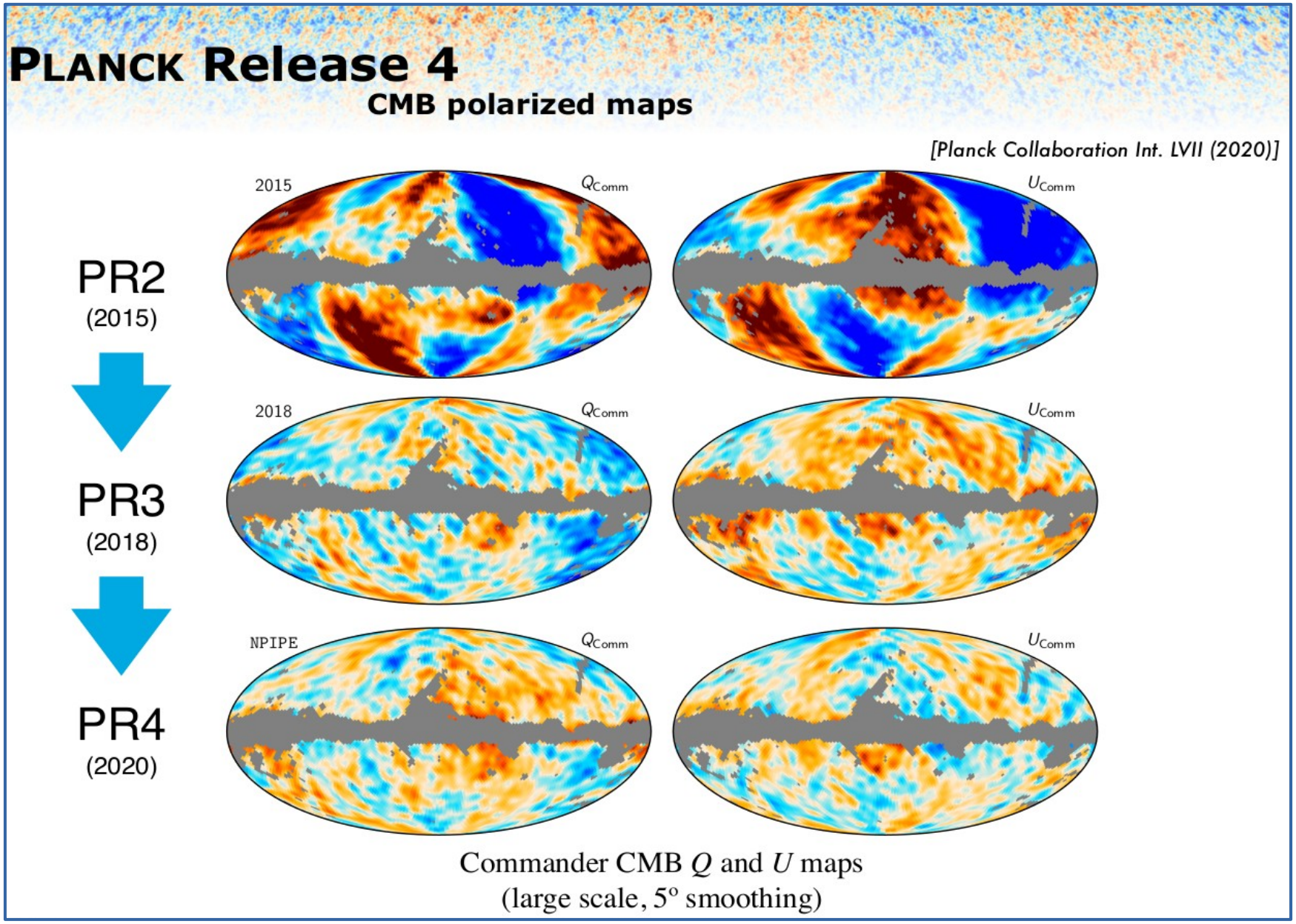


# Current reionisation constraints

$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$



# Revisiting large-scale CMB constraints




Courtesy of M. Tristram

# Why studying reionisation with large-scale CMB?

- Amplitude of matter fluctuations ($A_s/\sigma_8$) strongly degenerate with reionisation optical depth
- Neutrinos mass and hierarchy: impact of neutrinos hard to estimate without a good handle on the matter power spectrum
- Reionisation can potentially complicate the detection of inflationary signatures in the CMB

# Objectives

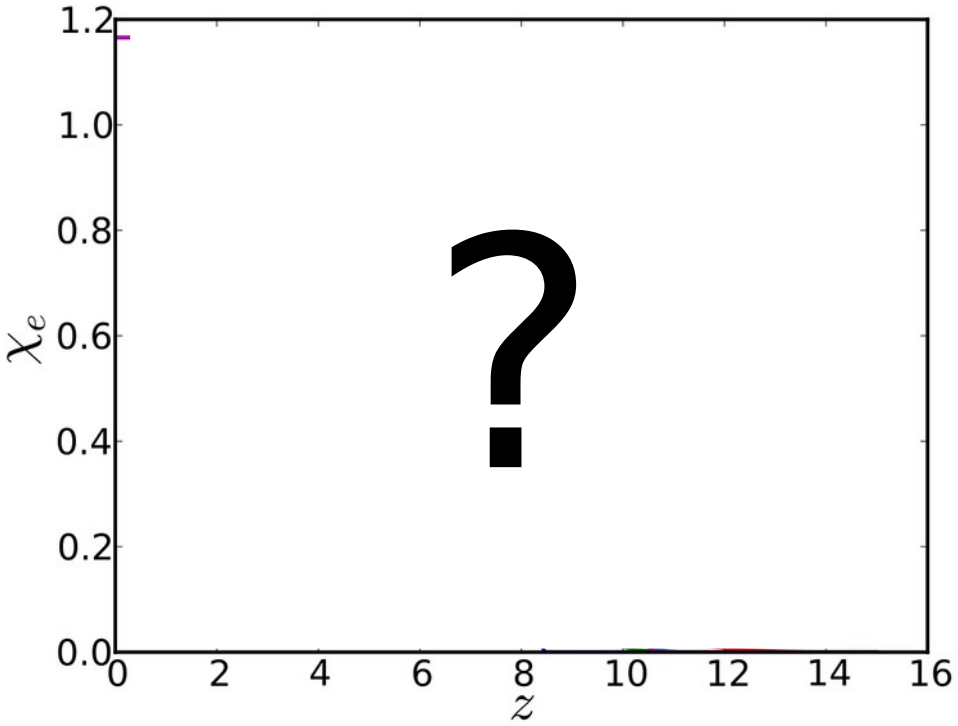
**<u>Ilić et al. in prep:</u> PR4 constraints on reionisation**

- Reassess in depth sensitivity of Planck on optical depth
- Explore constraints beyond instantaneous reionisation
- Determine the impact of the choice of model

# Modeling reionisation

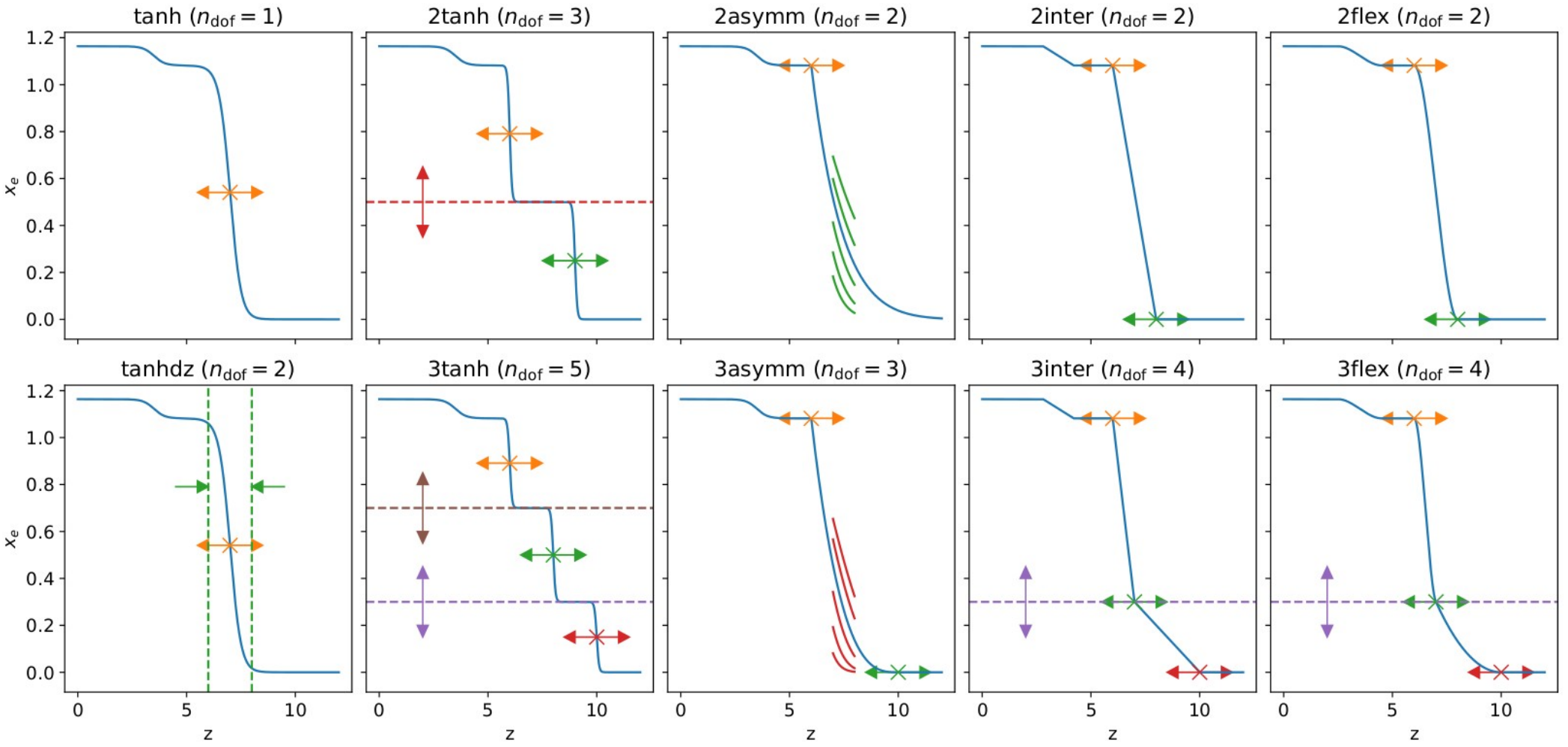
$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$

Free electron density




$\chi_e$ = ionisation fraction as a function of the redshift

# Modeling reionisation



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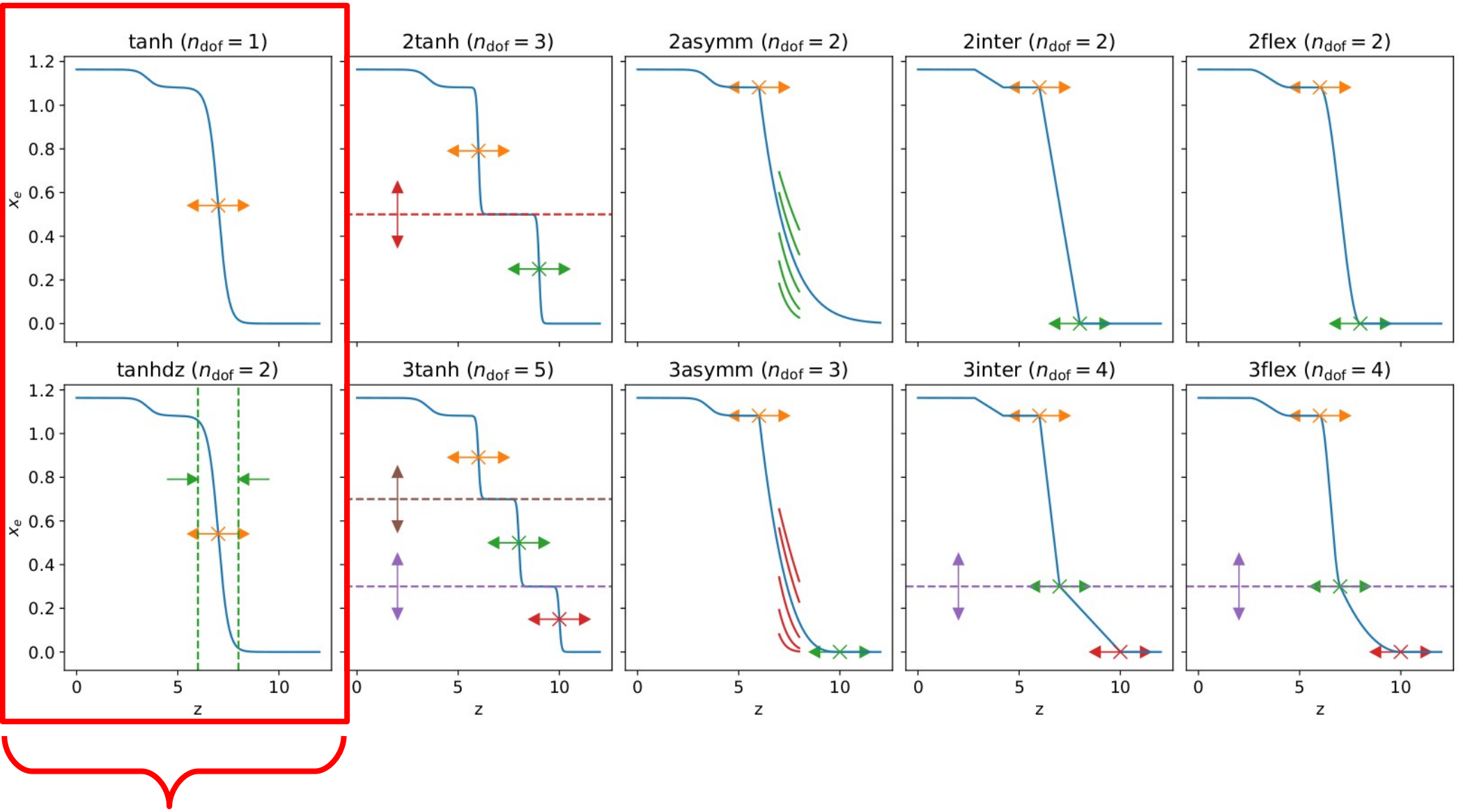
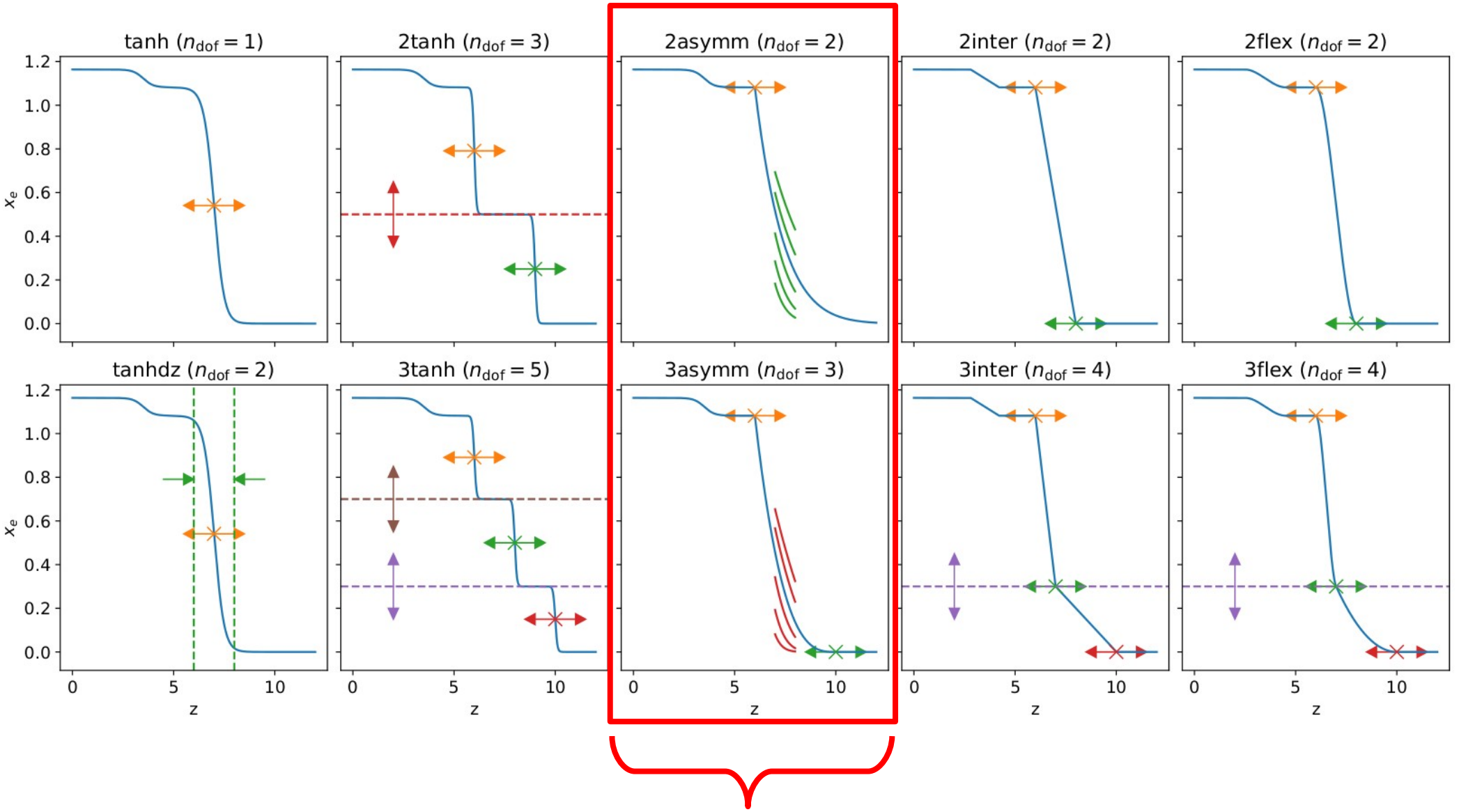



(Standard) symmetric models, tanh-based

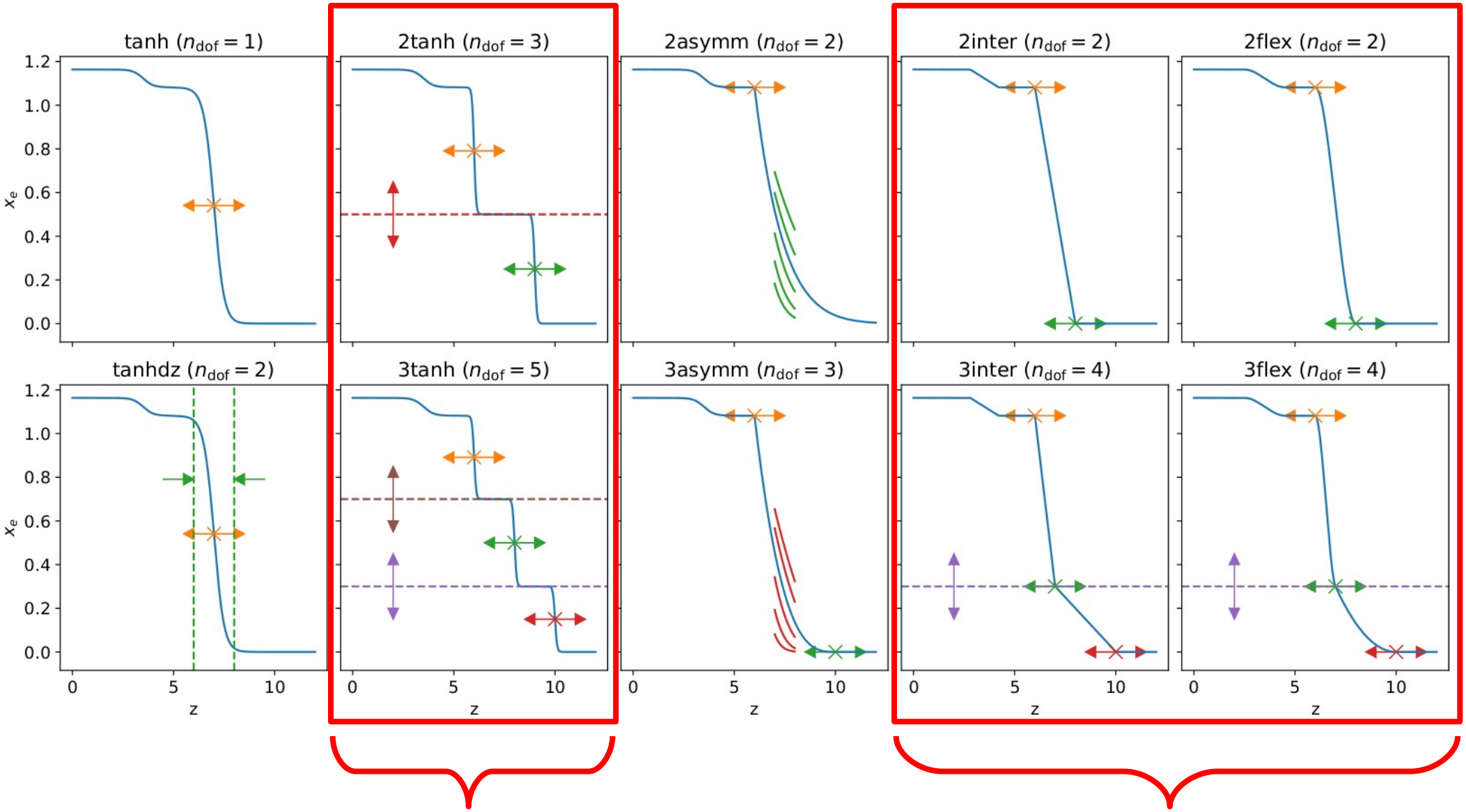
# Modeling reionisation




Asymmetric models, phenomenological,

emulating e.g. 2 populations of ionising sources

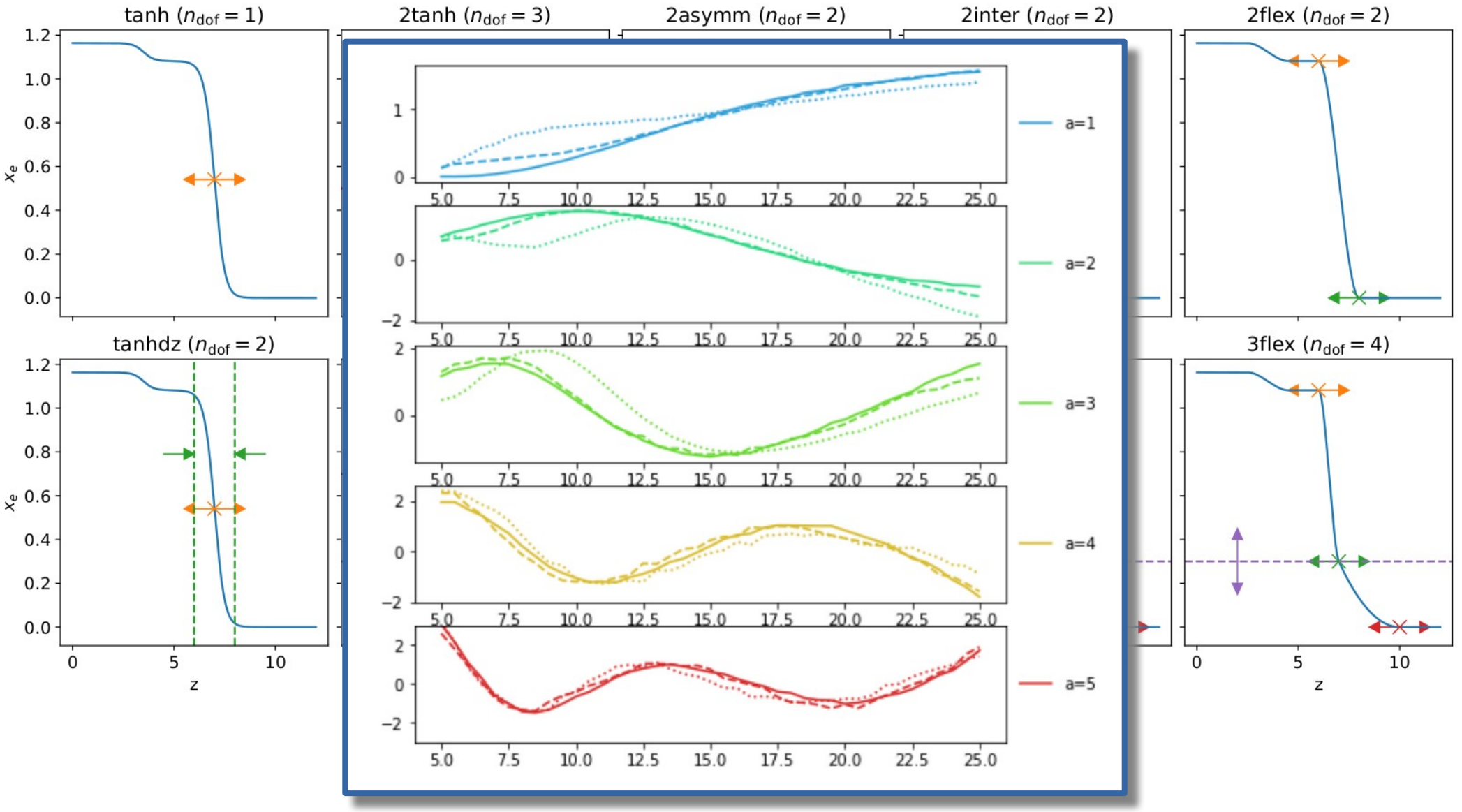
# Modeling reionisation




Model-independent approaches :

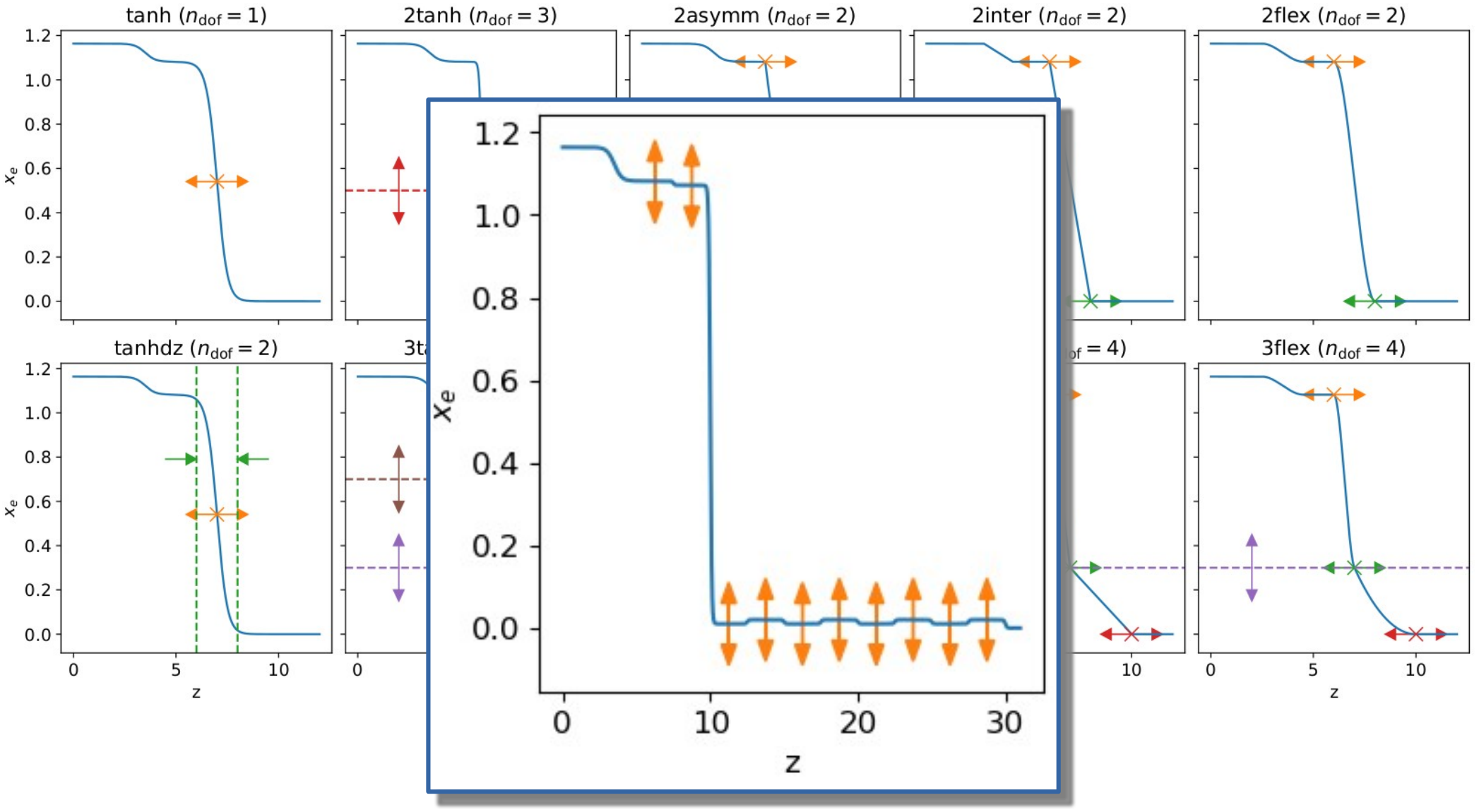
binned $x_e(z)$, interpolating polynomials (linear & PCHIP)

# Modeling reionisation




+ Principal Component Analysis

# Modeling reionisation




+ Reference 10 bins model

# Datasets & Methodology

**Data:**

**Planck Public Release 4, lollipop & hillipop**

- low-ell polarization data only
- low-ell & high-ell temperature and polarization data

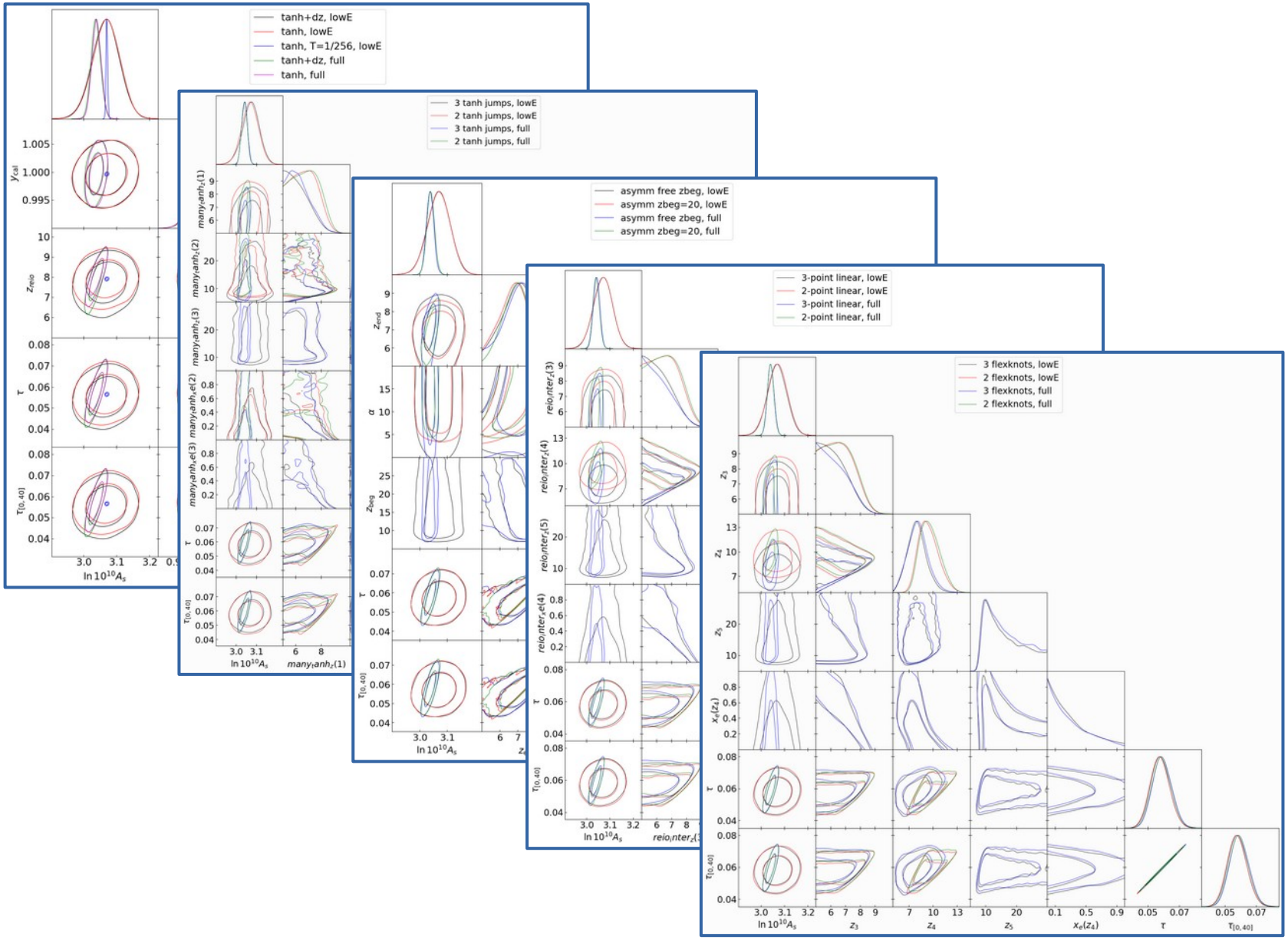
**Theory:**

**Custom version of Boltzmann code CLASS** (github.com/s-ilic/class_reio)

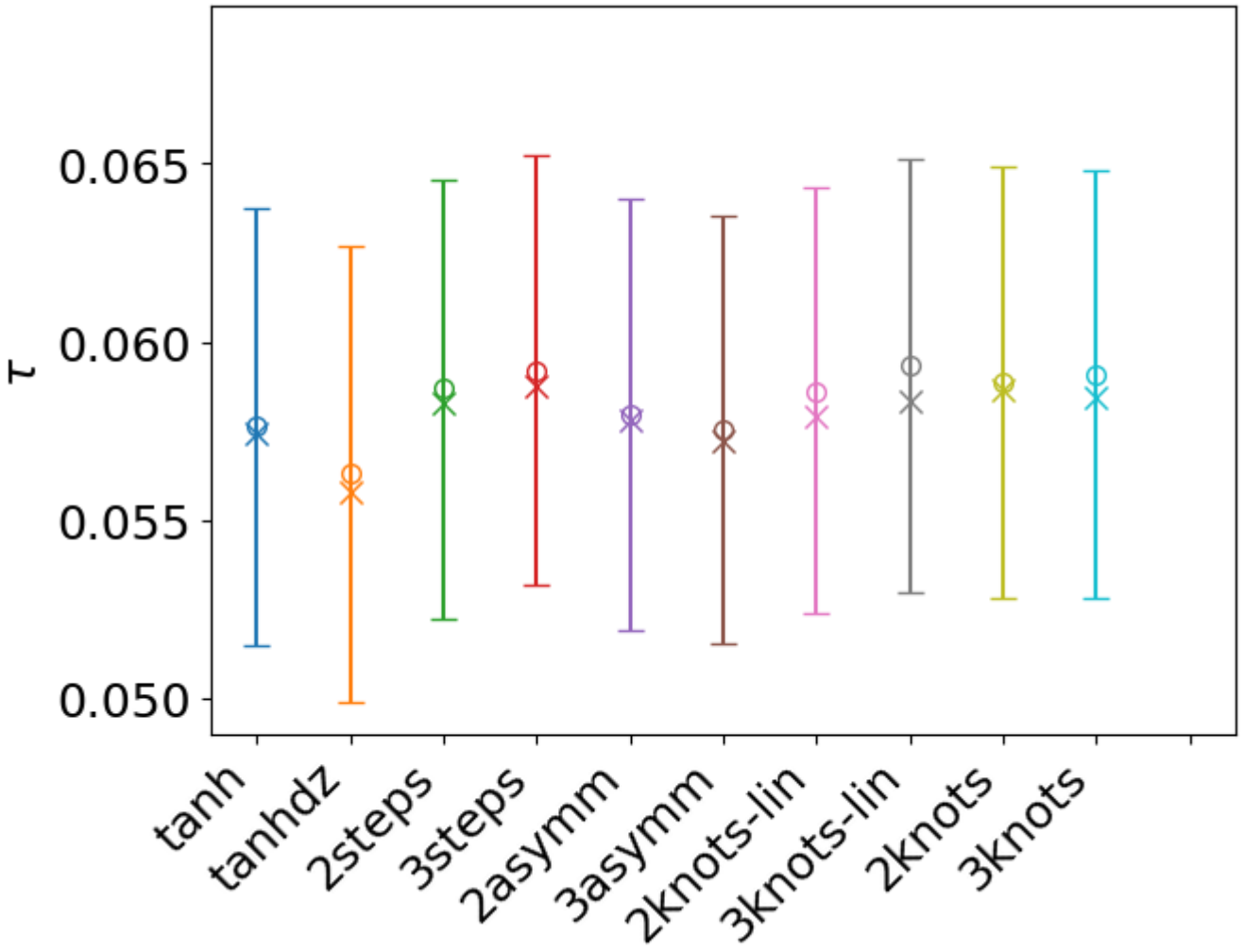
**Sampler/pipeline:**

**Ensemble sampling Markov Chains Monte Carlo via ECLAIR** (github.com/s-ilic/ECLAIR) (soon-to-be GPU compatible/accelerated)

# Constraints on reionisation parameters



# Constraints on τ



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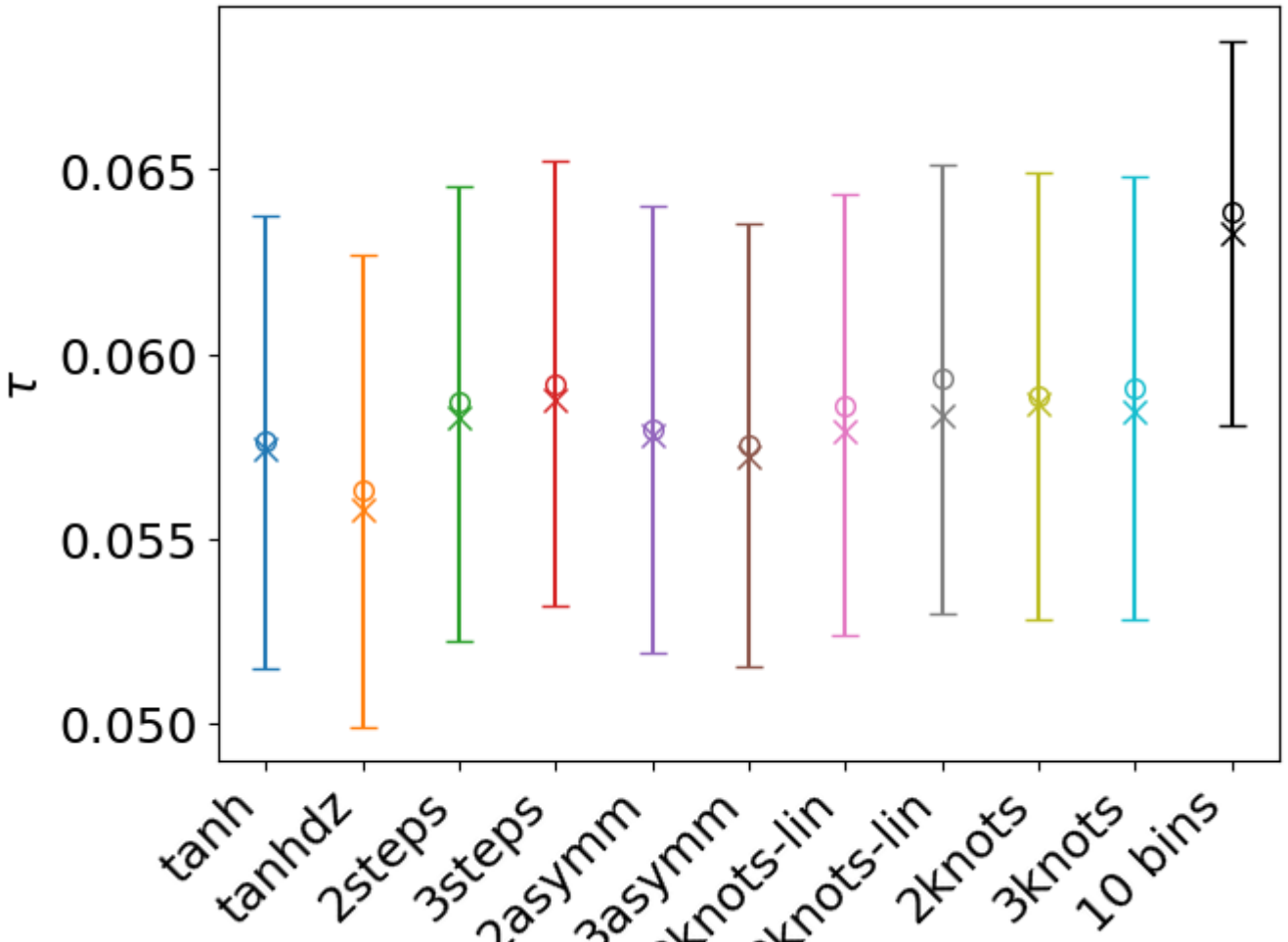
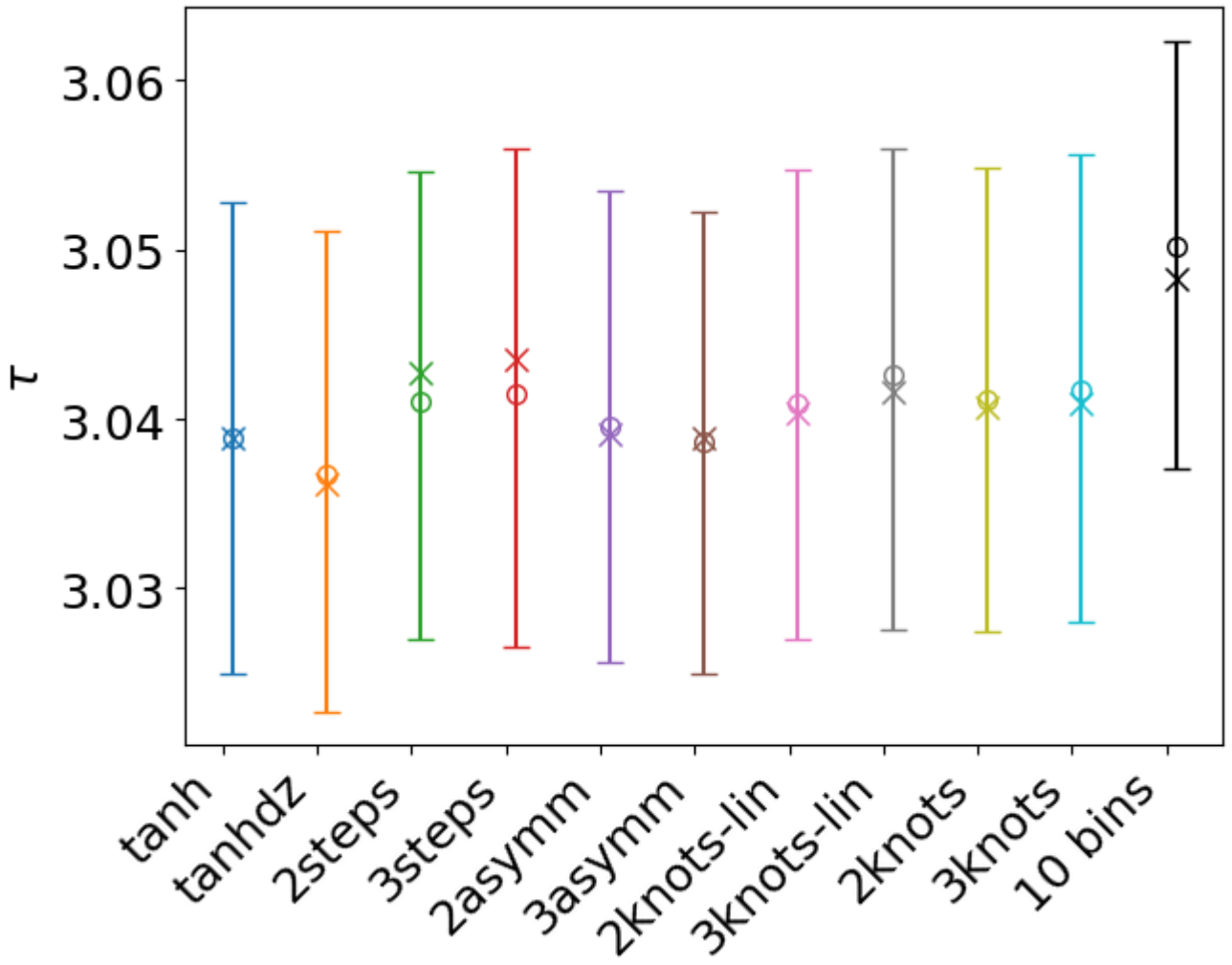


# Constraints on $A_s$



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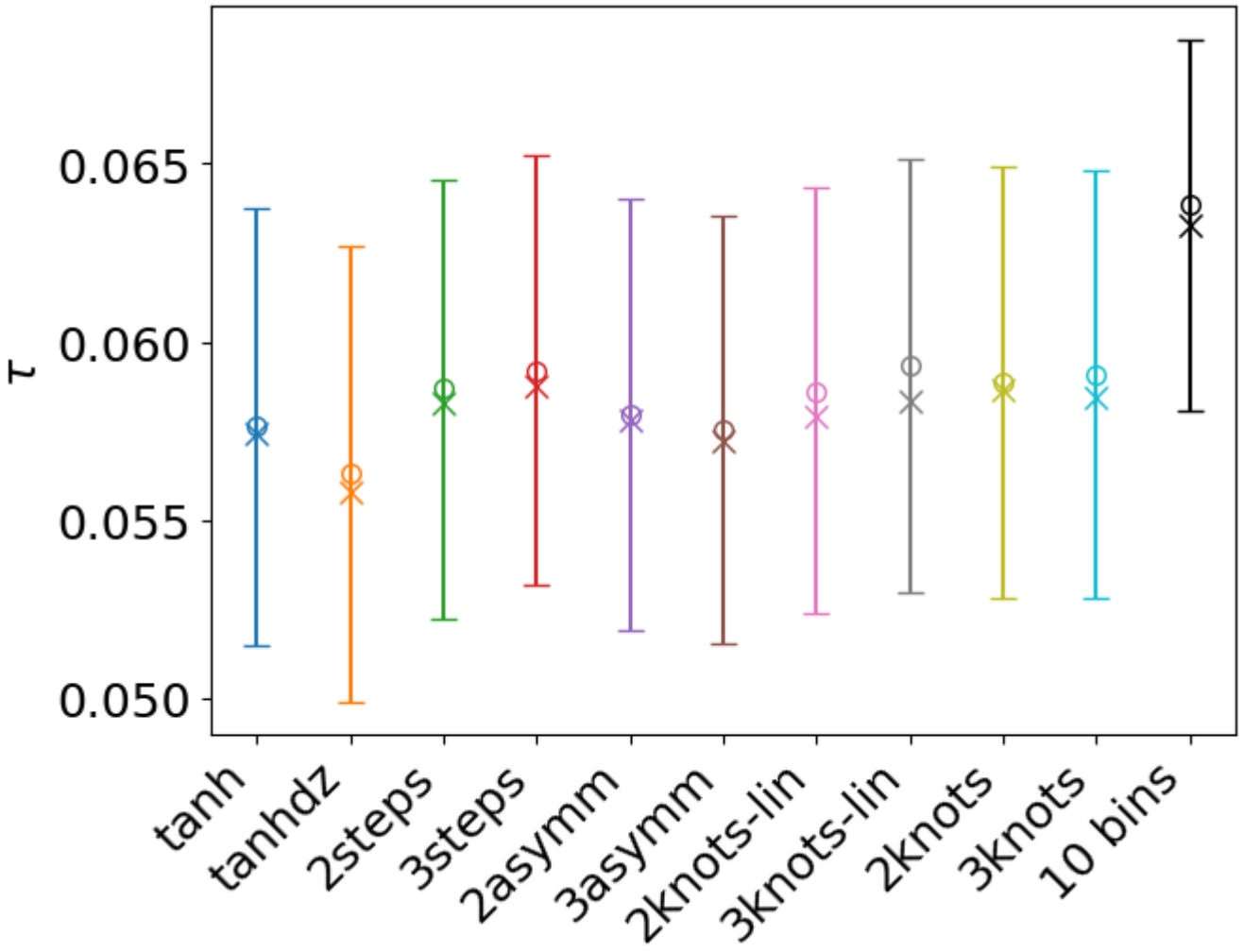
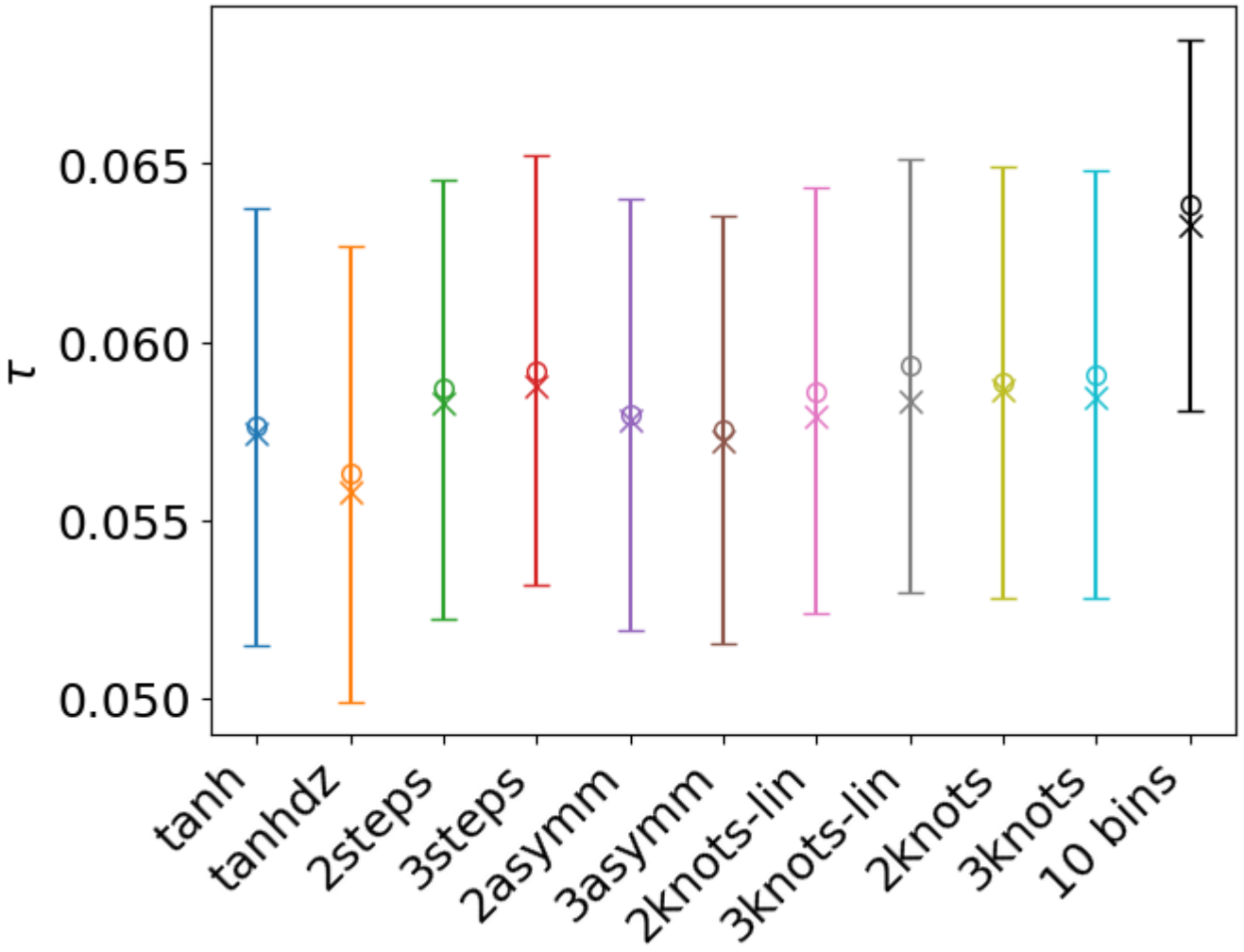
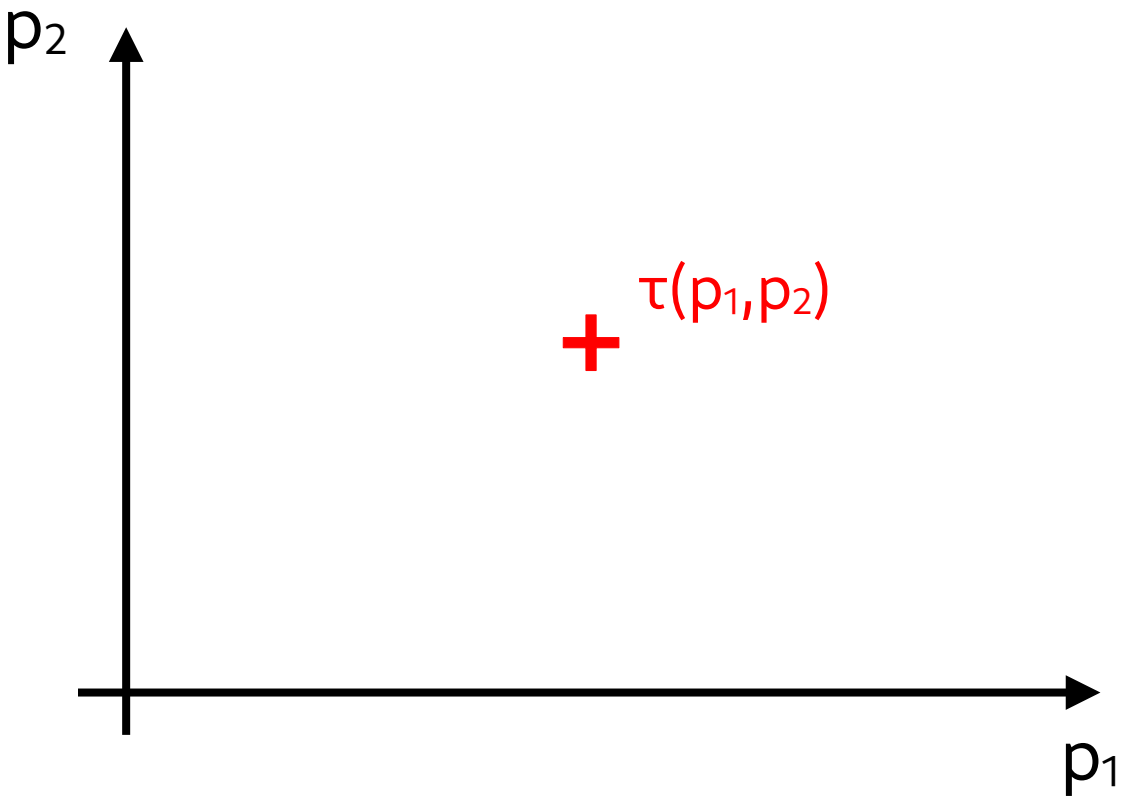


# Constraints on τ

## Effects of an implicit prior on τ



# Influence of model choice on τ prior




2-parameter
reionisation model

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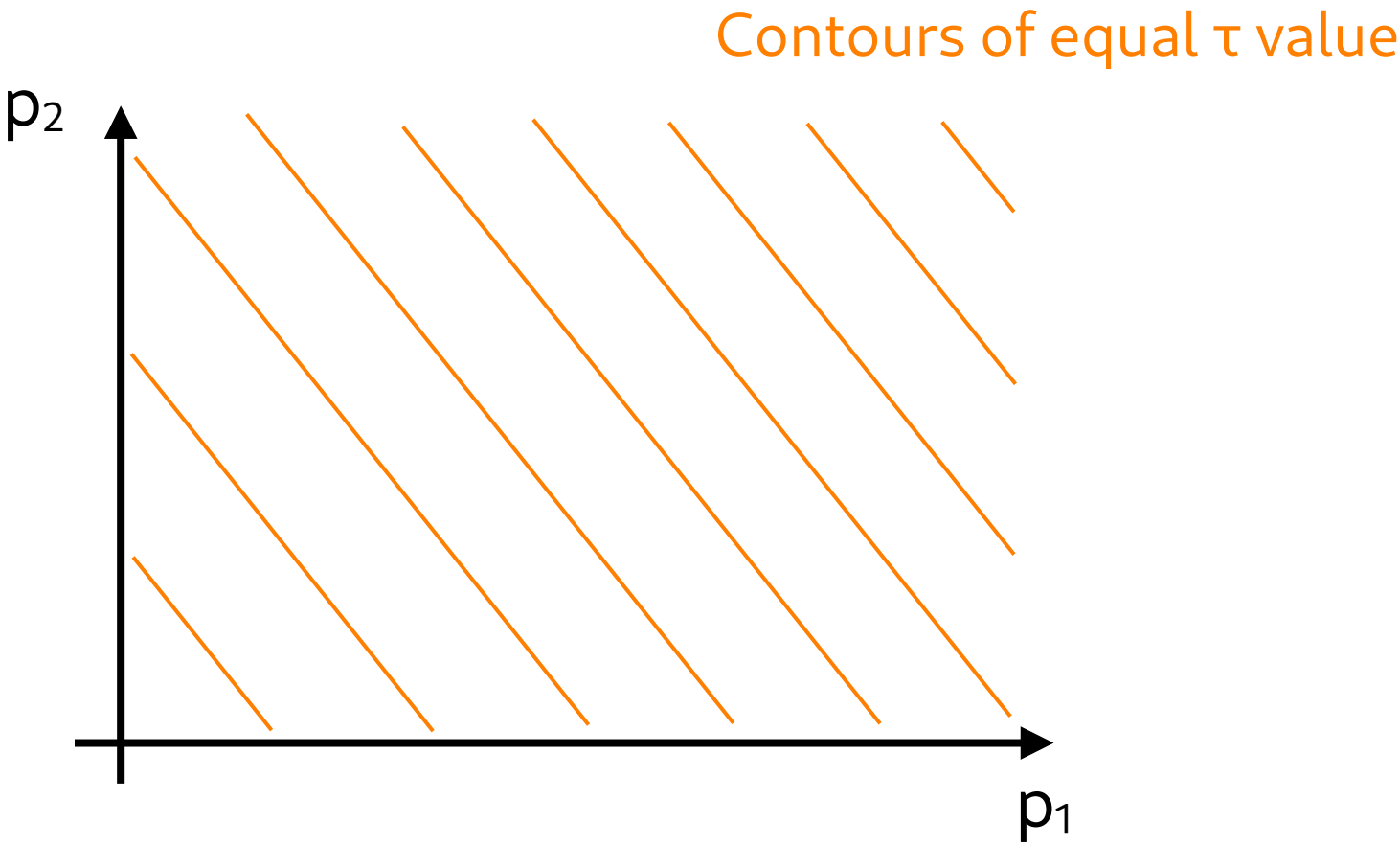

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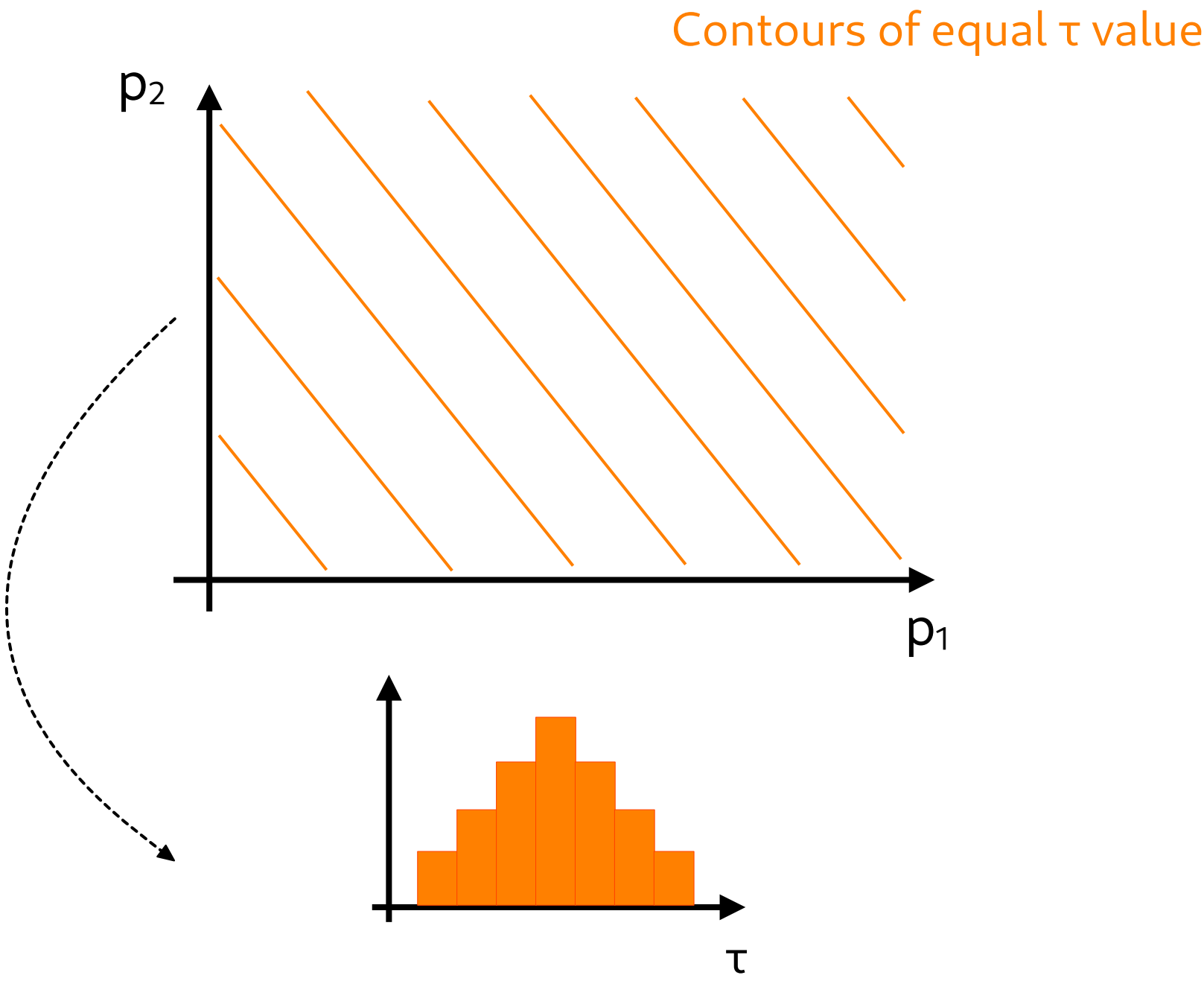

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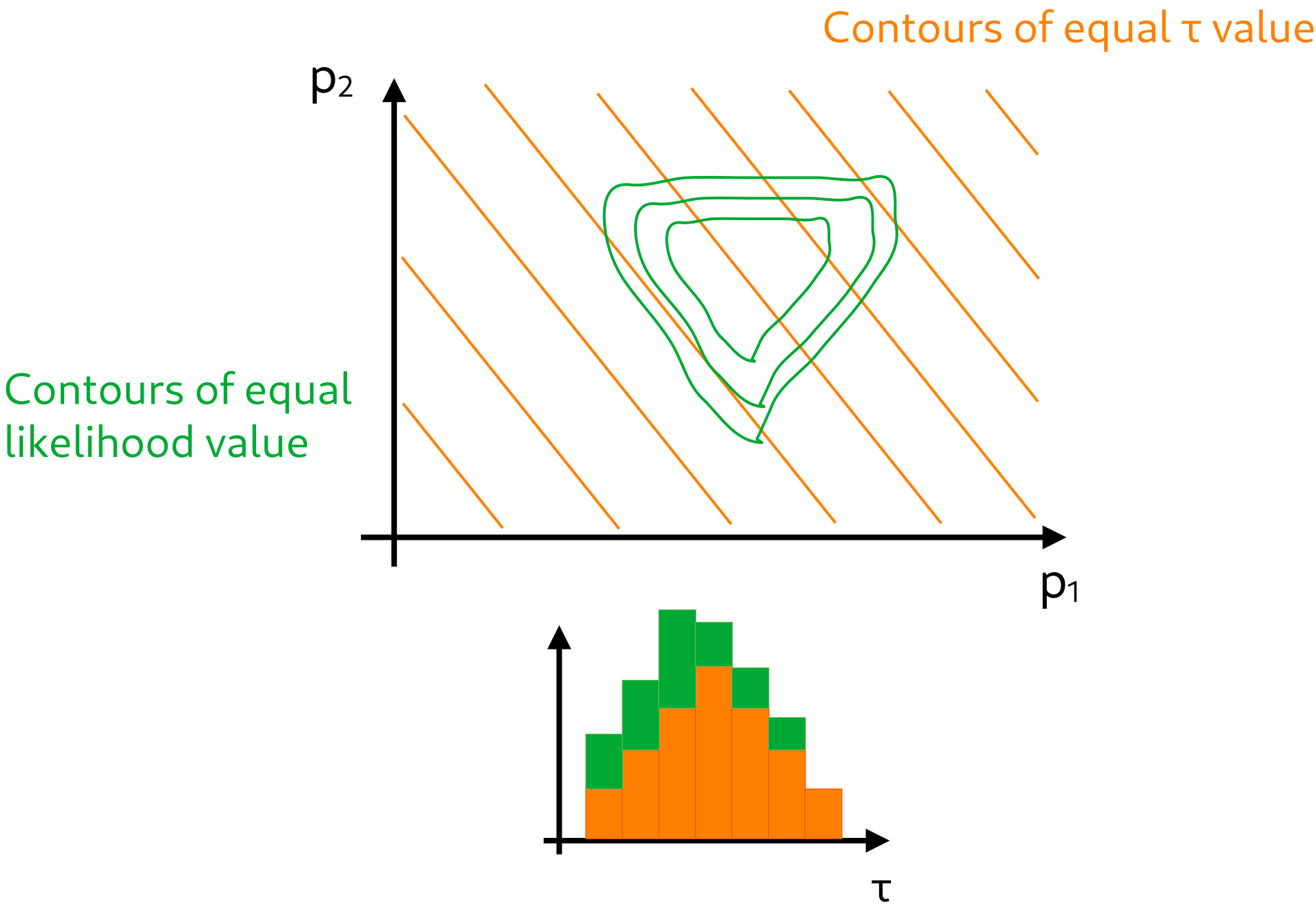
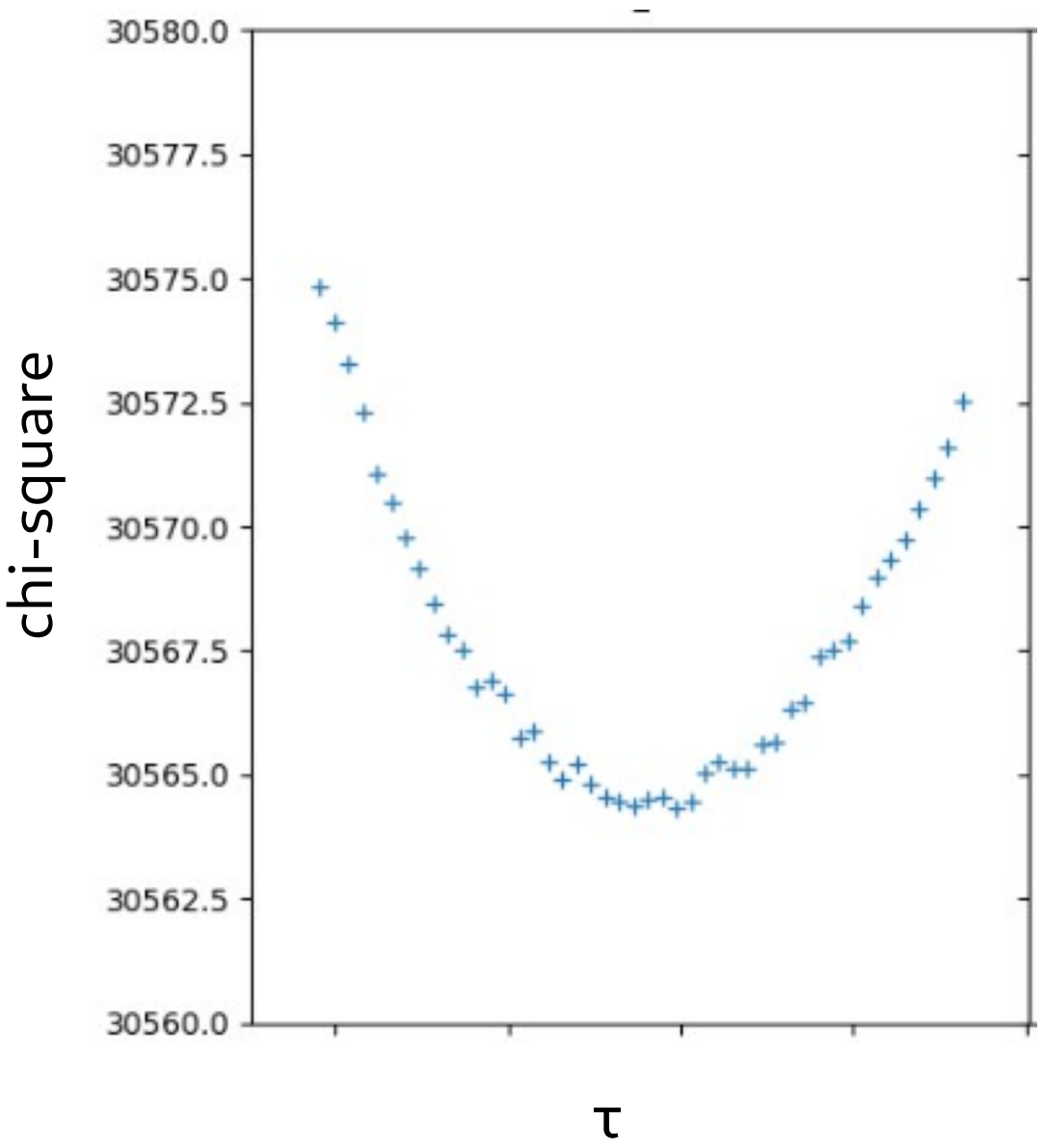


# Profile likelihood method




Given a fixed grid of τ values, find for each of them the best possible model by minimizing the chi-square across all other free parameters

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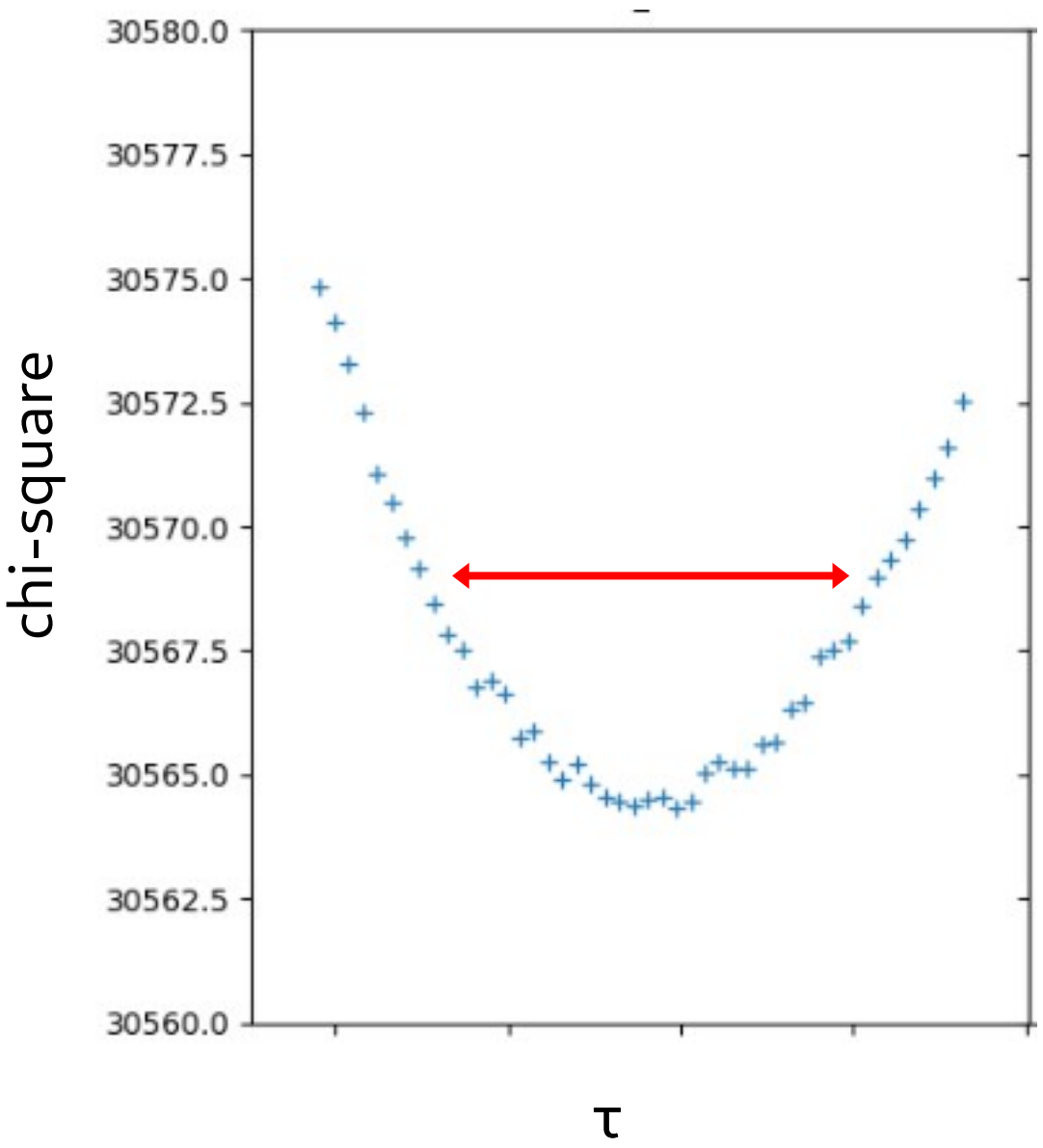


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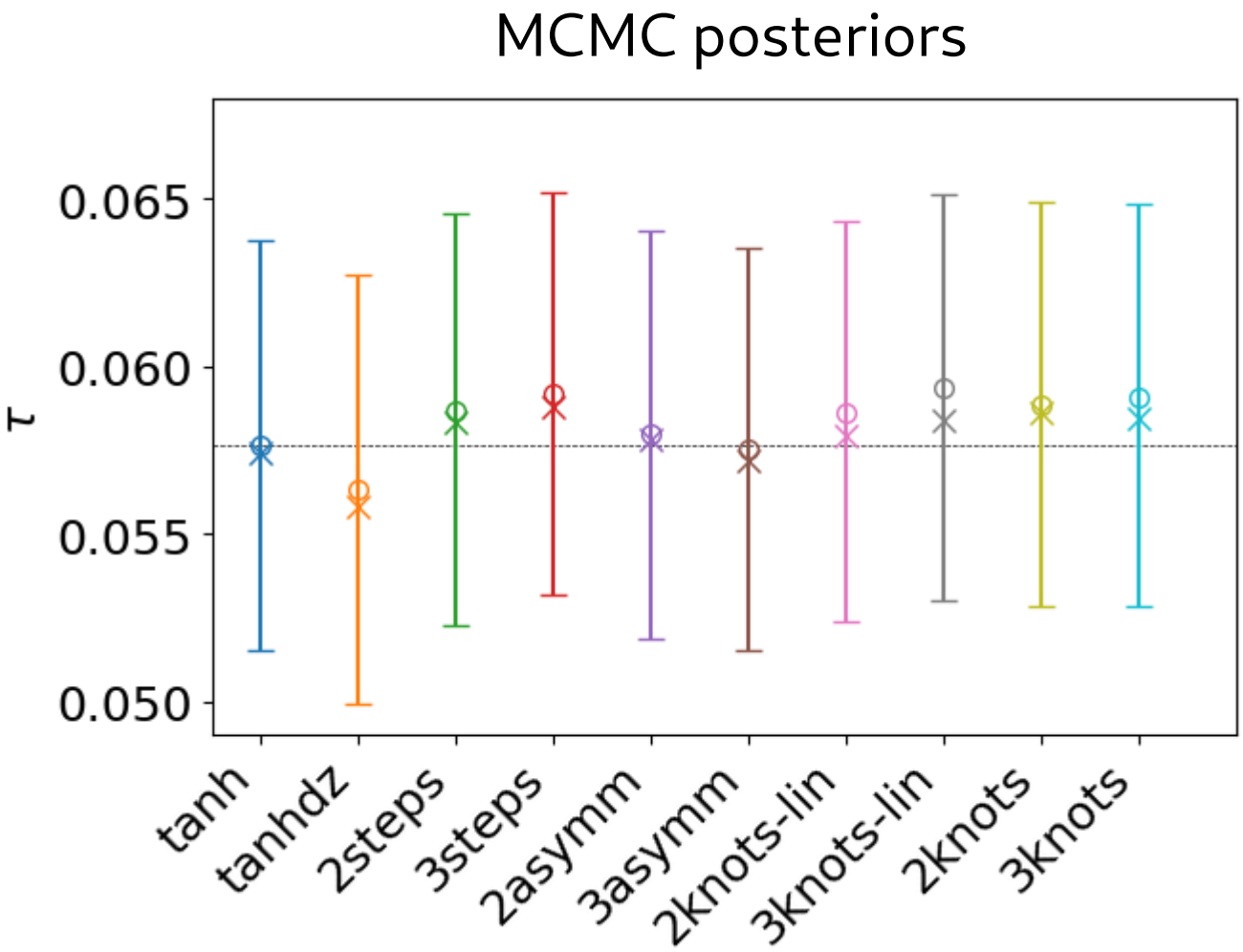
# Comparison of approaches on τ constraints



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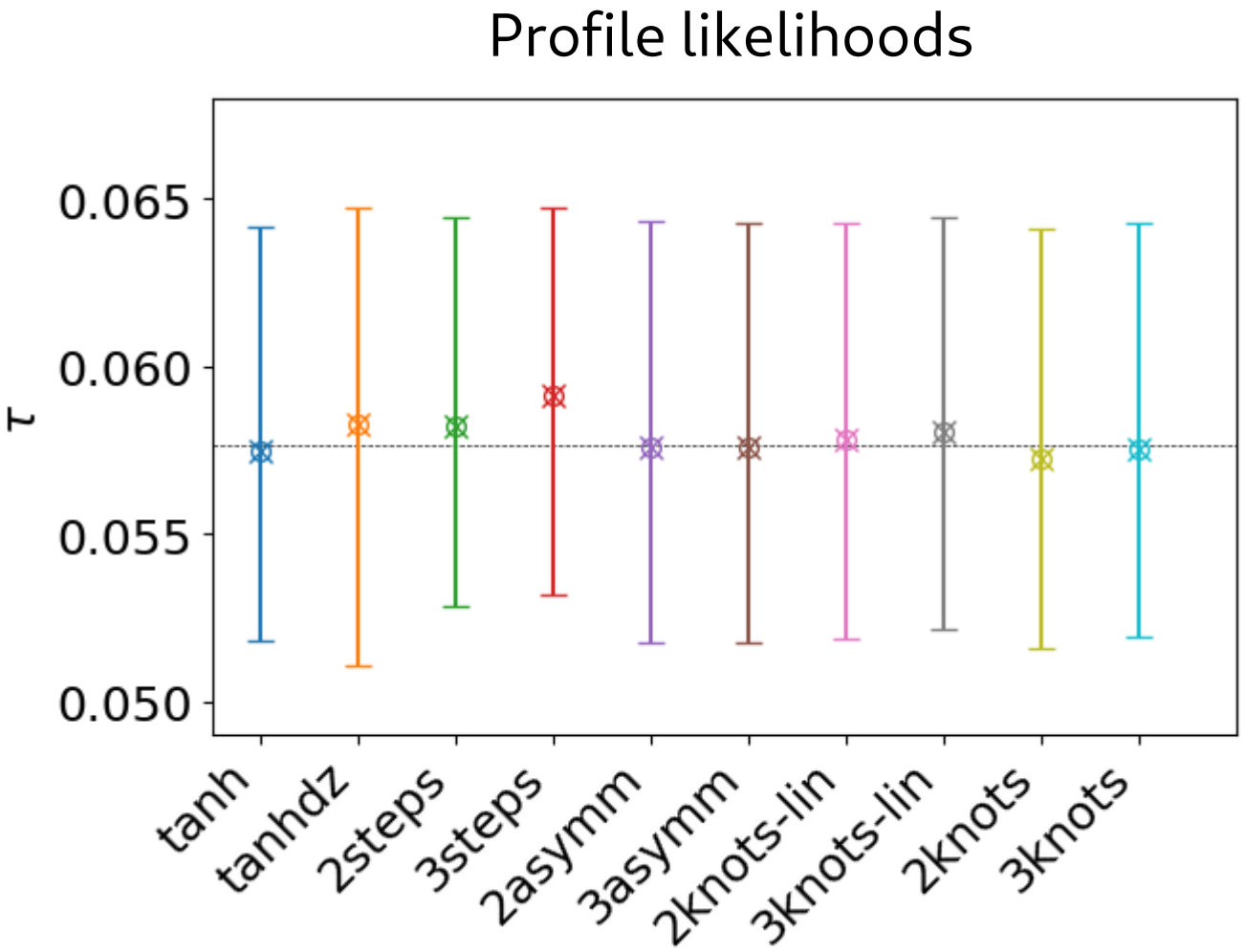
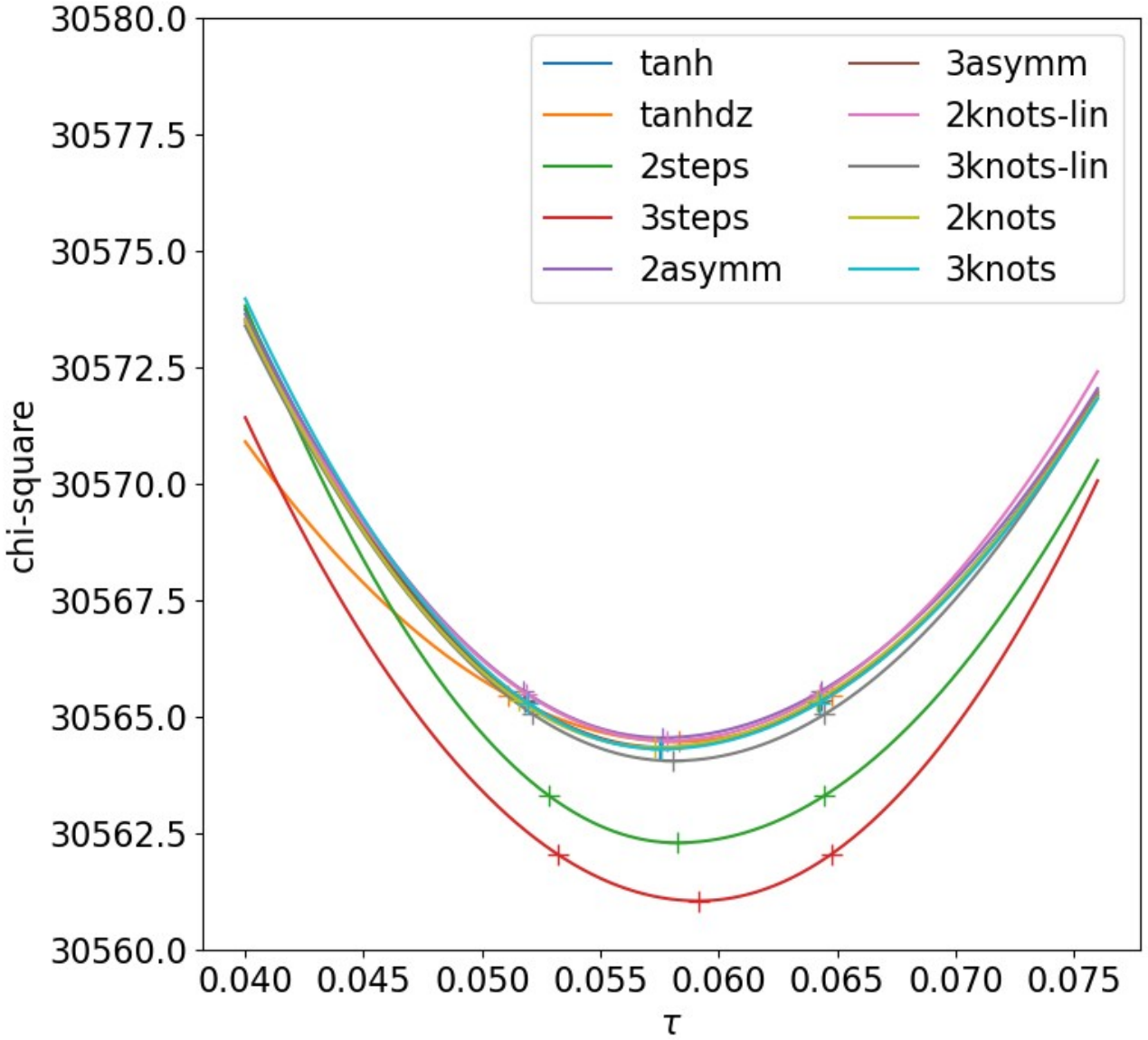


# Comparison of goodness-of-fit



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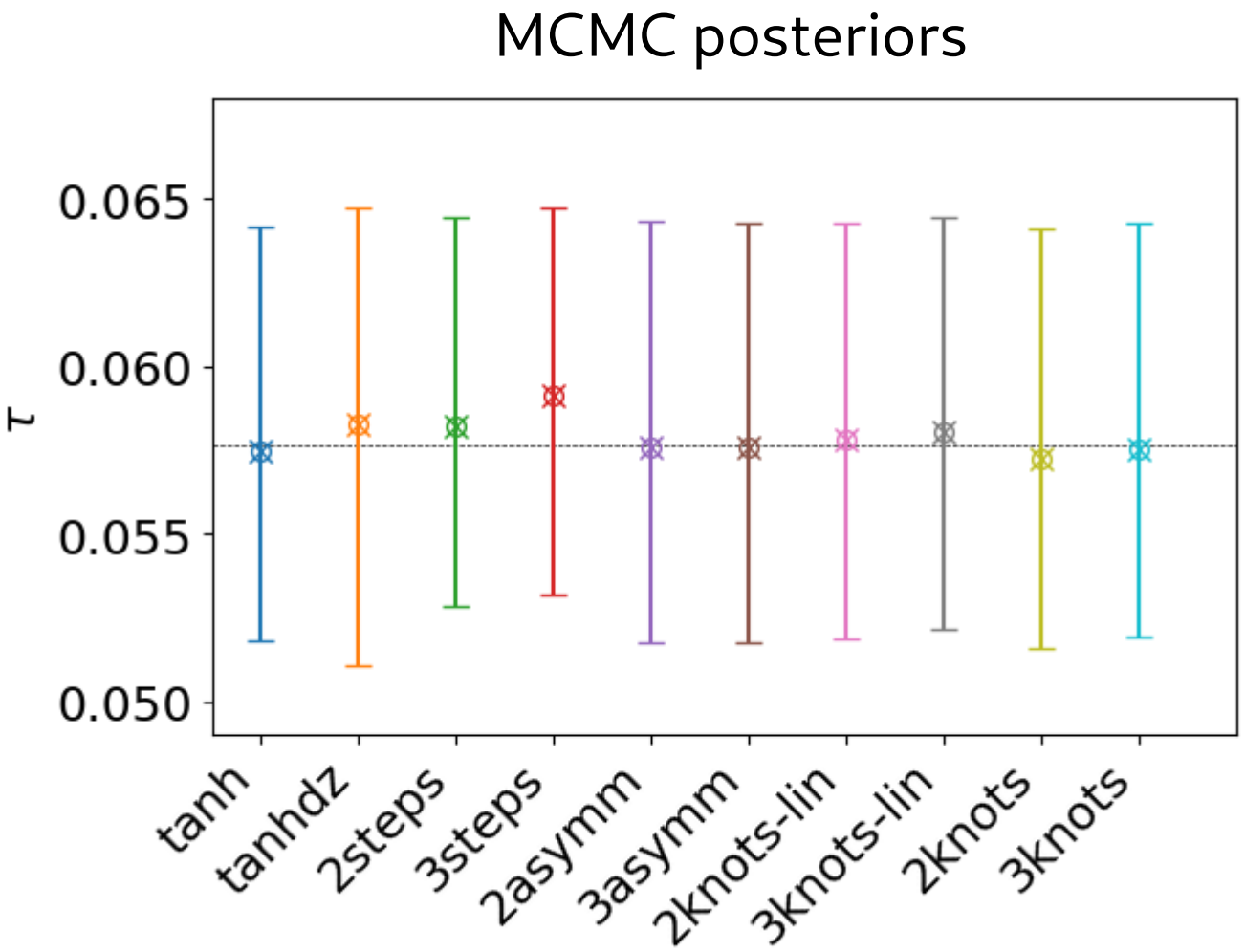
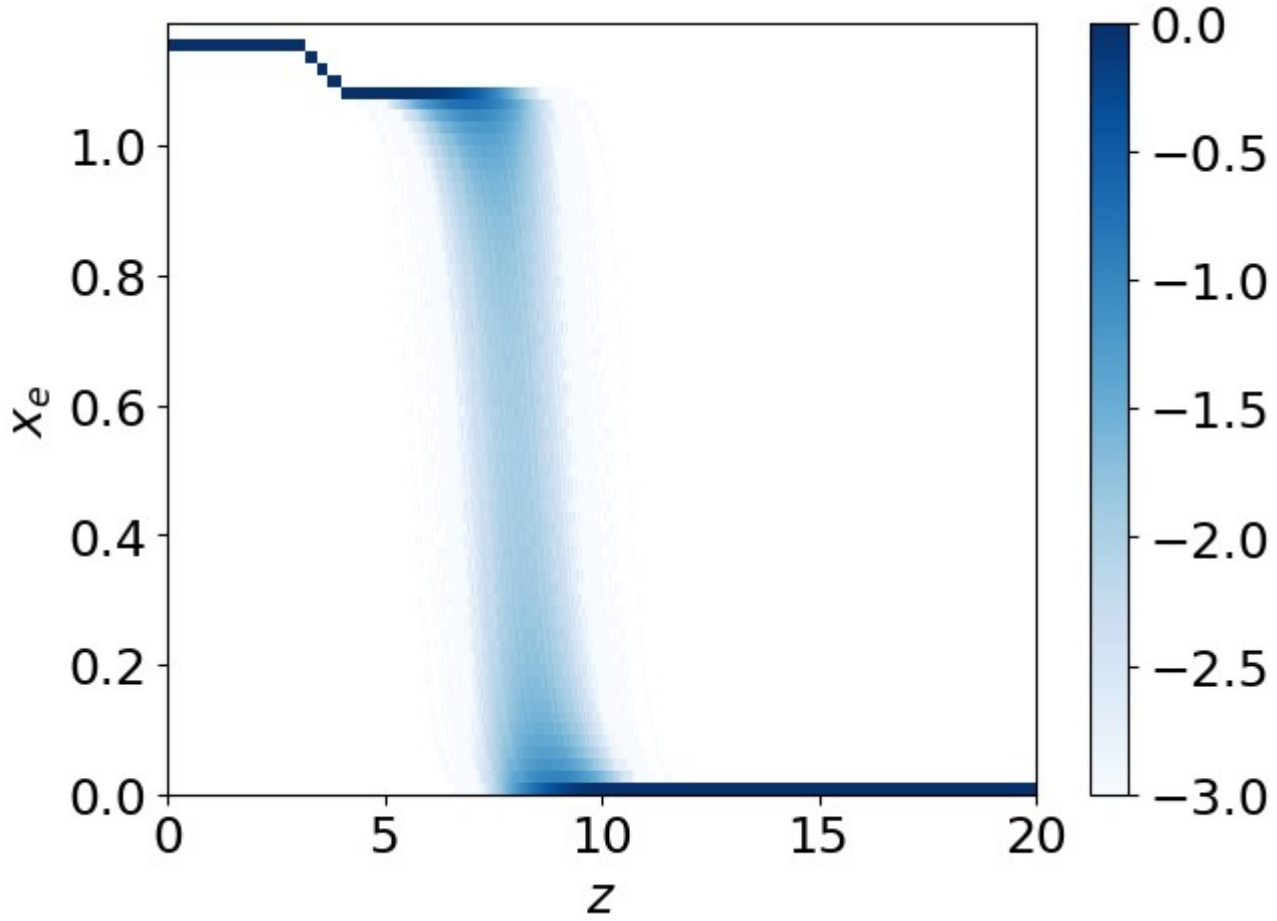


# Constraints on $x_e(z)$



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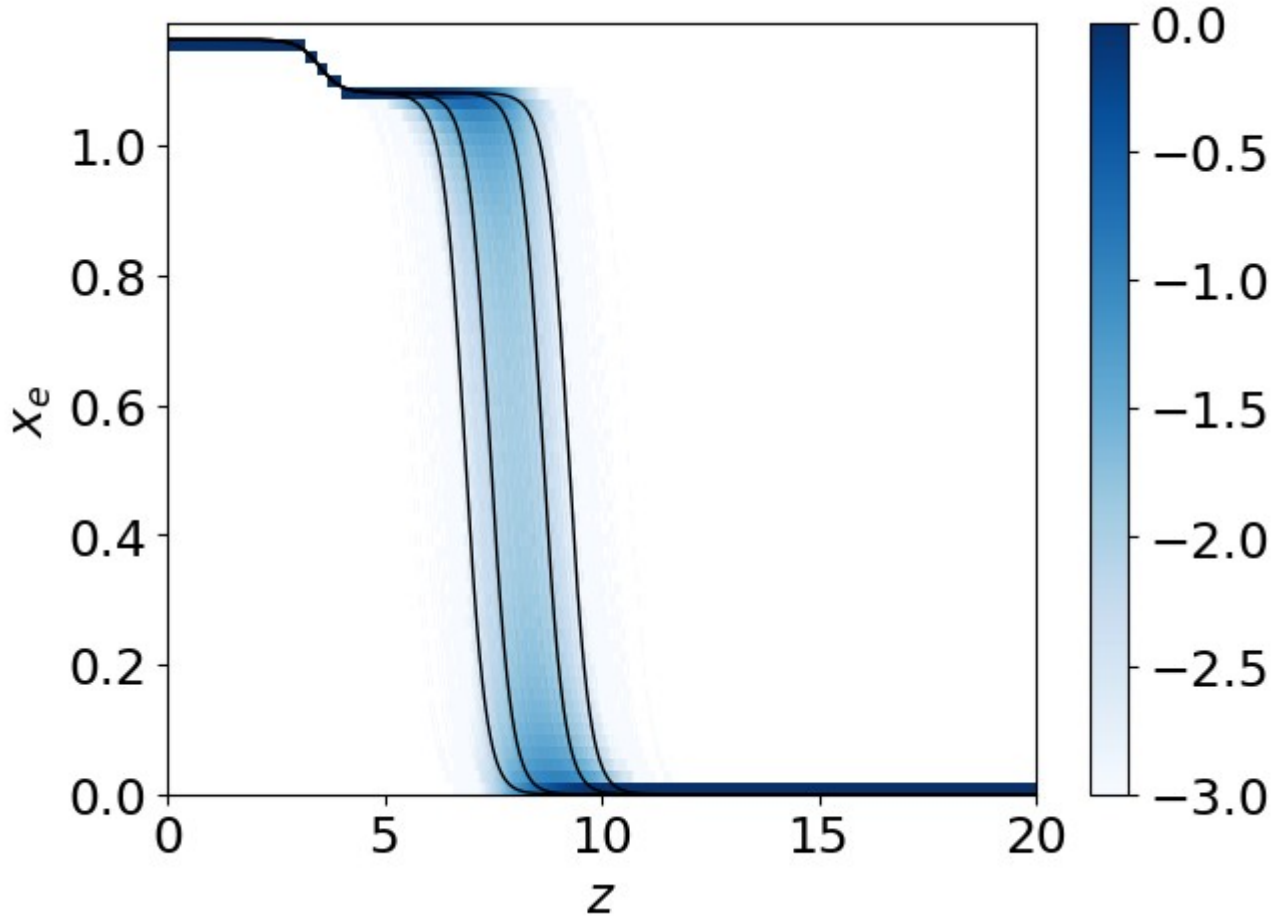

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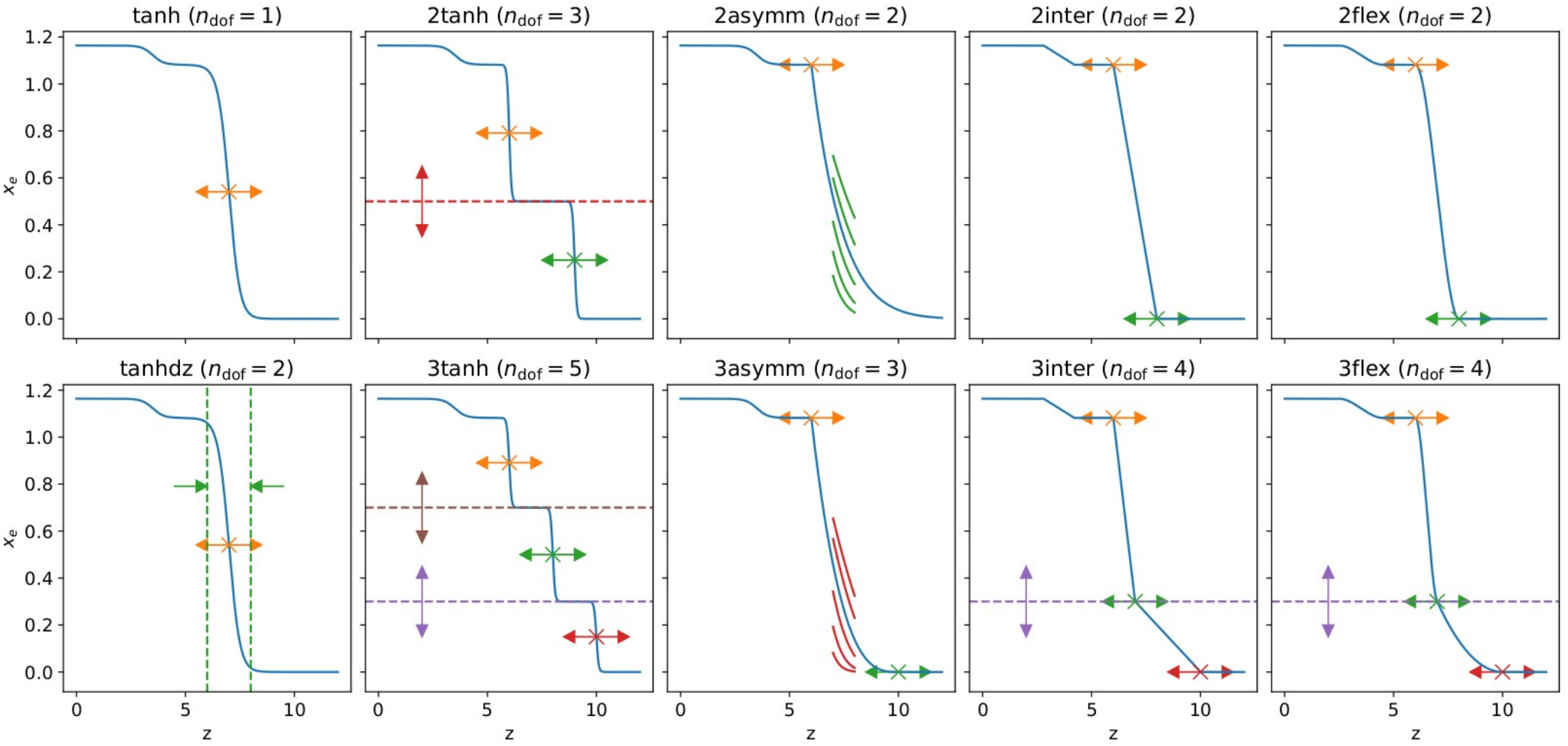
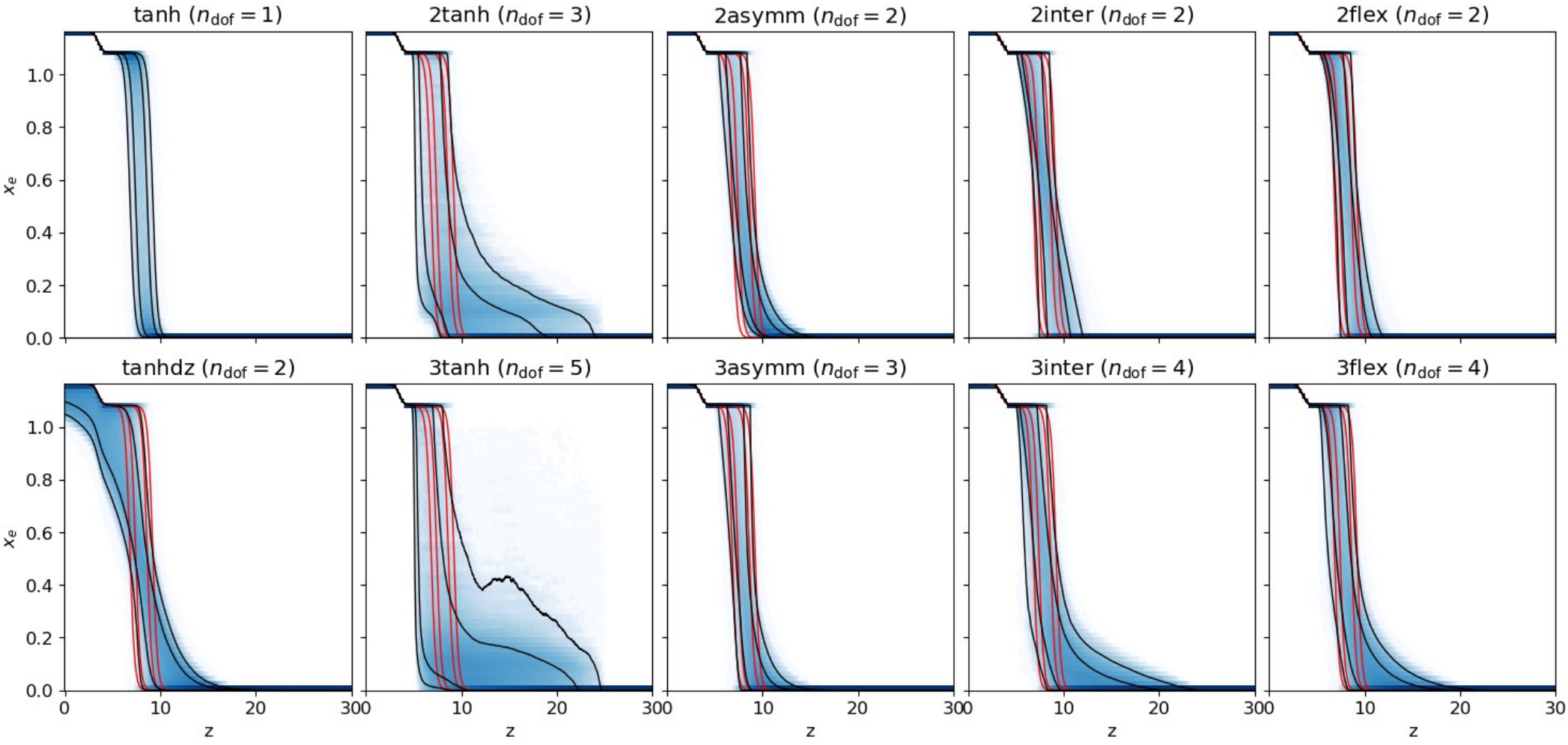
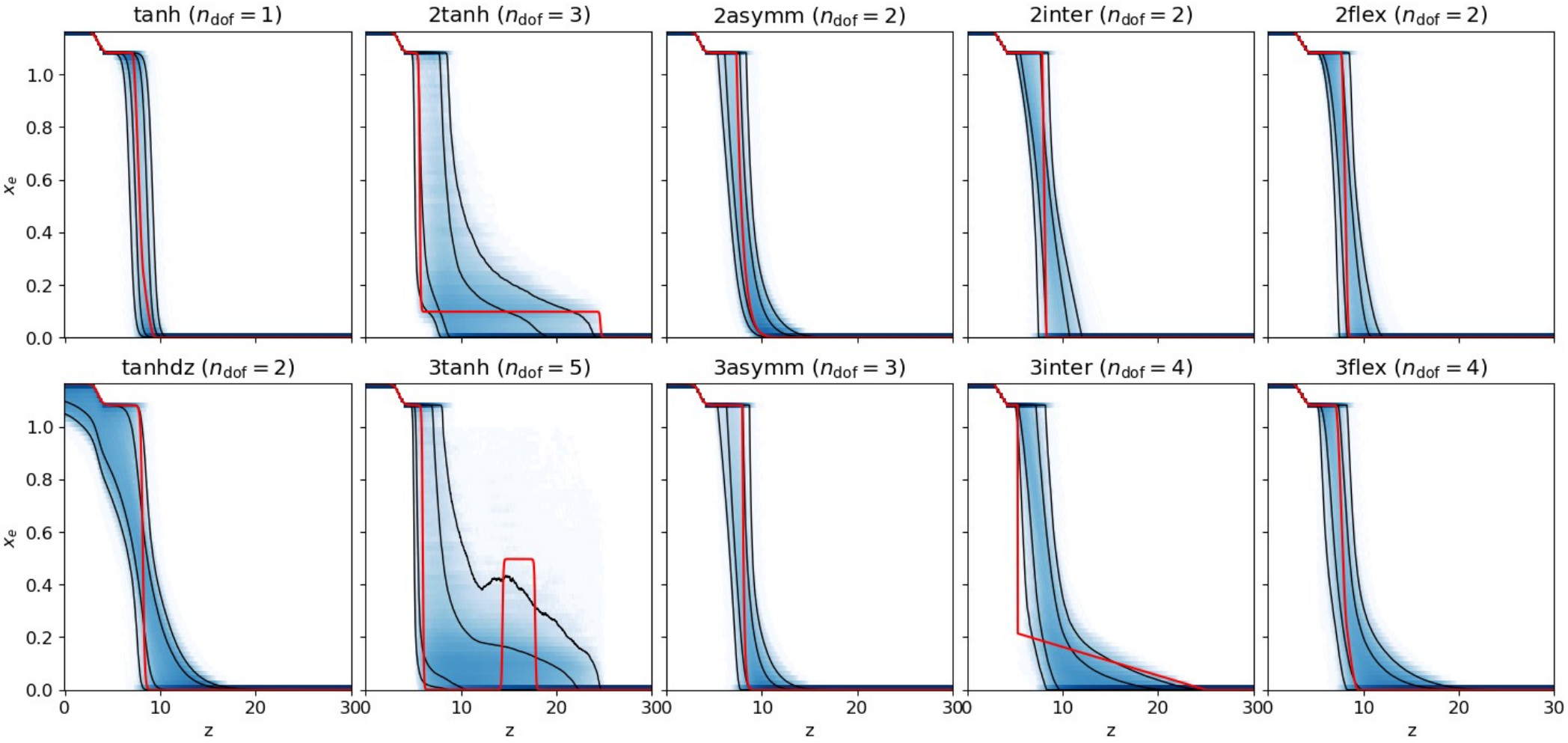


# Constraints on $x_e(z)$ : 68/95% limits



# Constraints on $x_e(z)$ : best fits



# Final words and perspectives

- Finishing touches to be applied to Ilić et al. (steps models, 10 bins, and PCA)

- Some future perspectives:

  - Interplay with neutrinos constraints/models

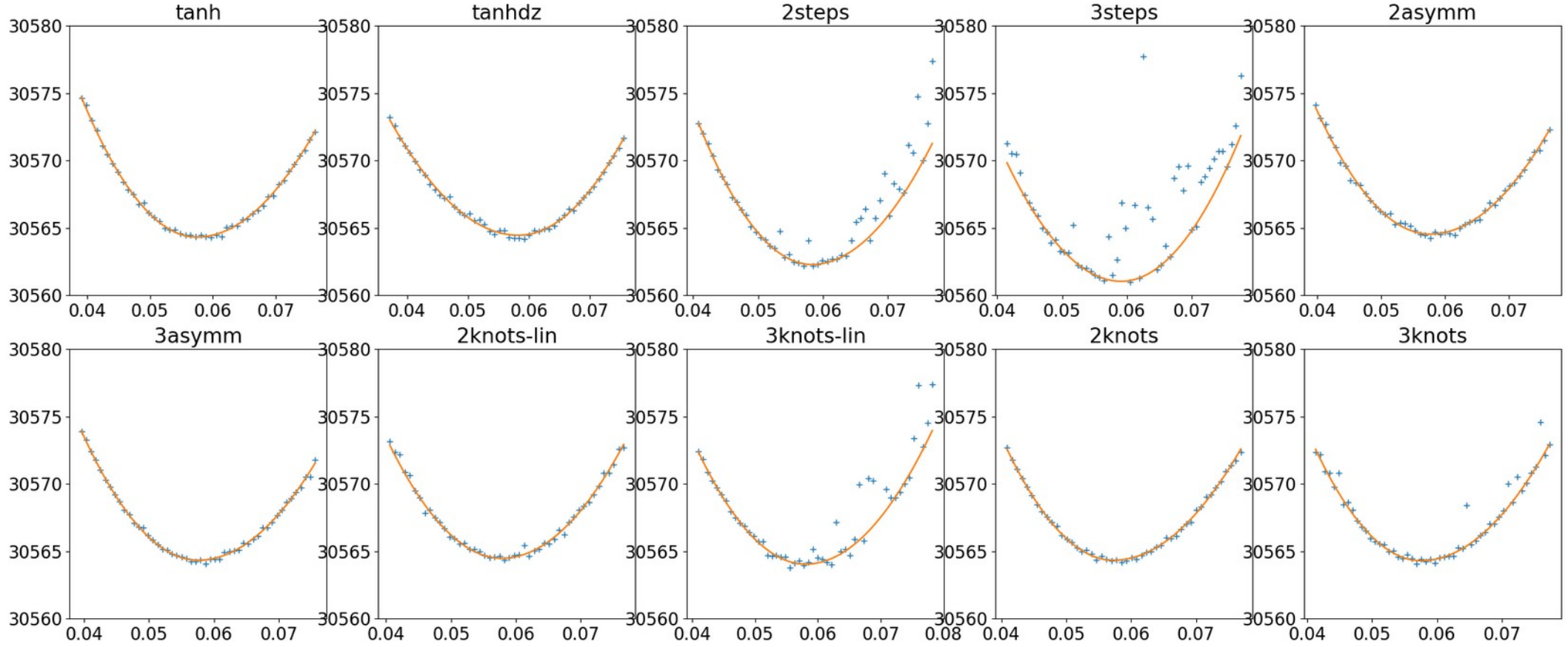
  - Combination with external datasets:
    - → ground-based CMB e.g SPT & ACT
    - → background measurements e.g. BAO
    - → LSS measurements
    - → astrophysical measurements

Stay tuned !

# The end

Thank you very much
for your attention!

# Profile likelihoods



# Constraints on τ(z, 30)

$$\tau = \int_0^{\eta_0} a n_e \sigma_T d\eta$$

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z

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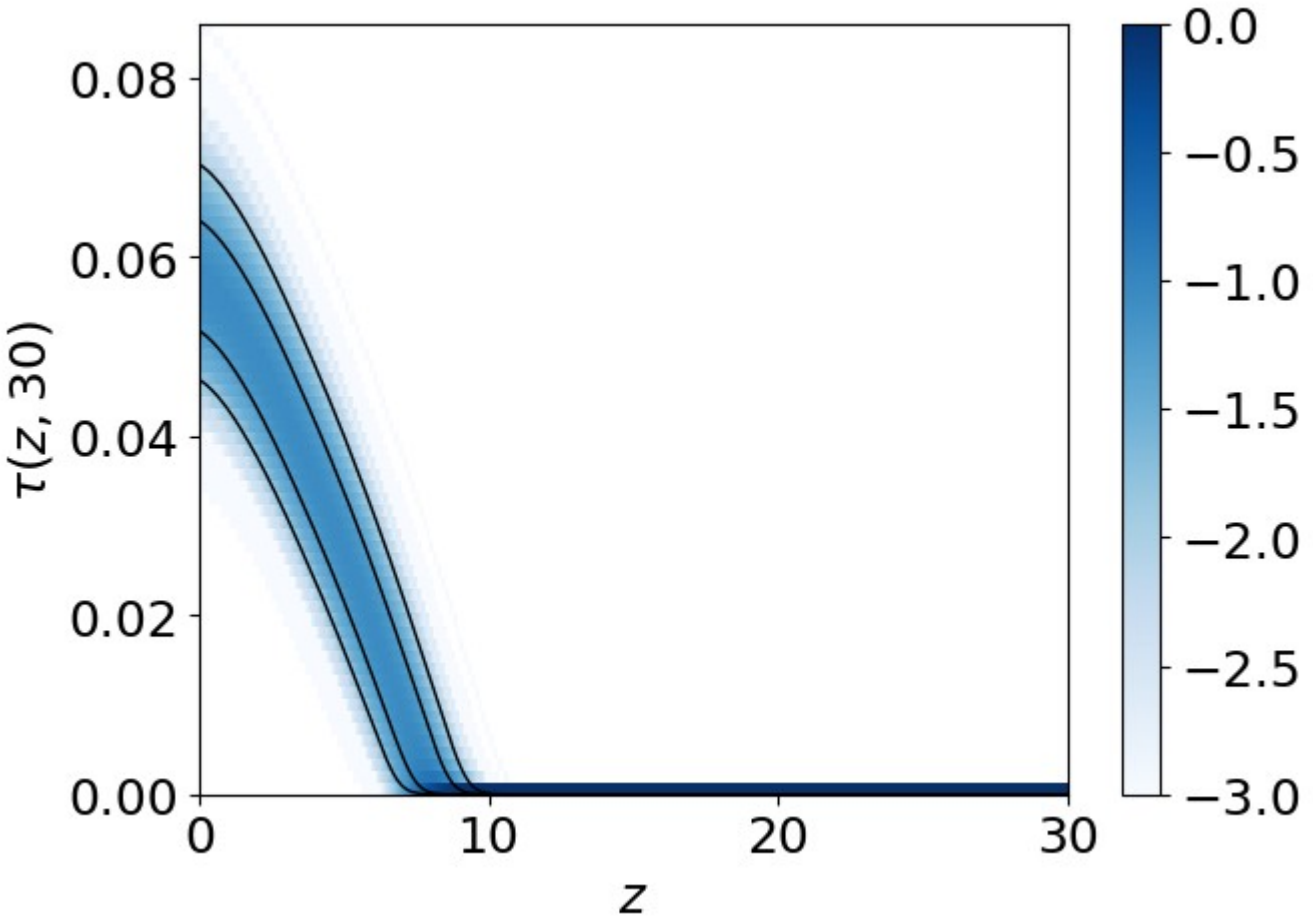

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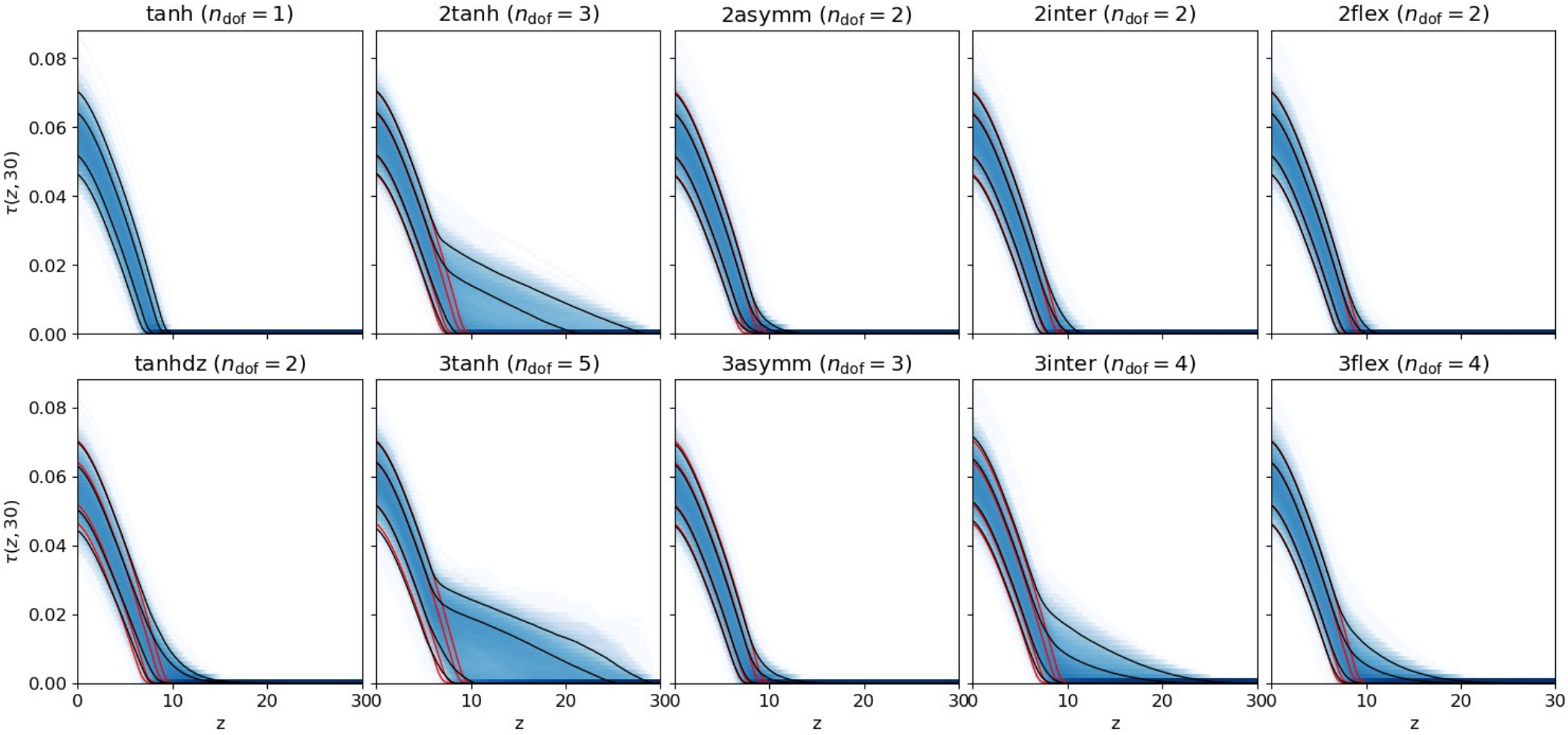

# V) Further observations

- QSO spectra
- Lyman-alpha forests
- IGM temperature measurements
- ...
- Neutral hydrogen (21cm) absorption/emission