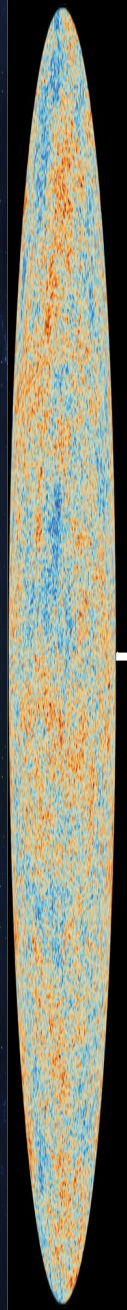


DAWN

Unravelling the cosmic reionisation puzzle: 21cm signal – galaxy synergies

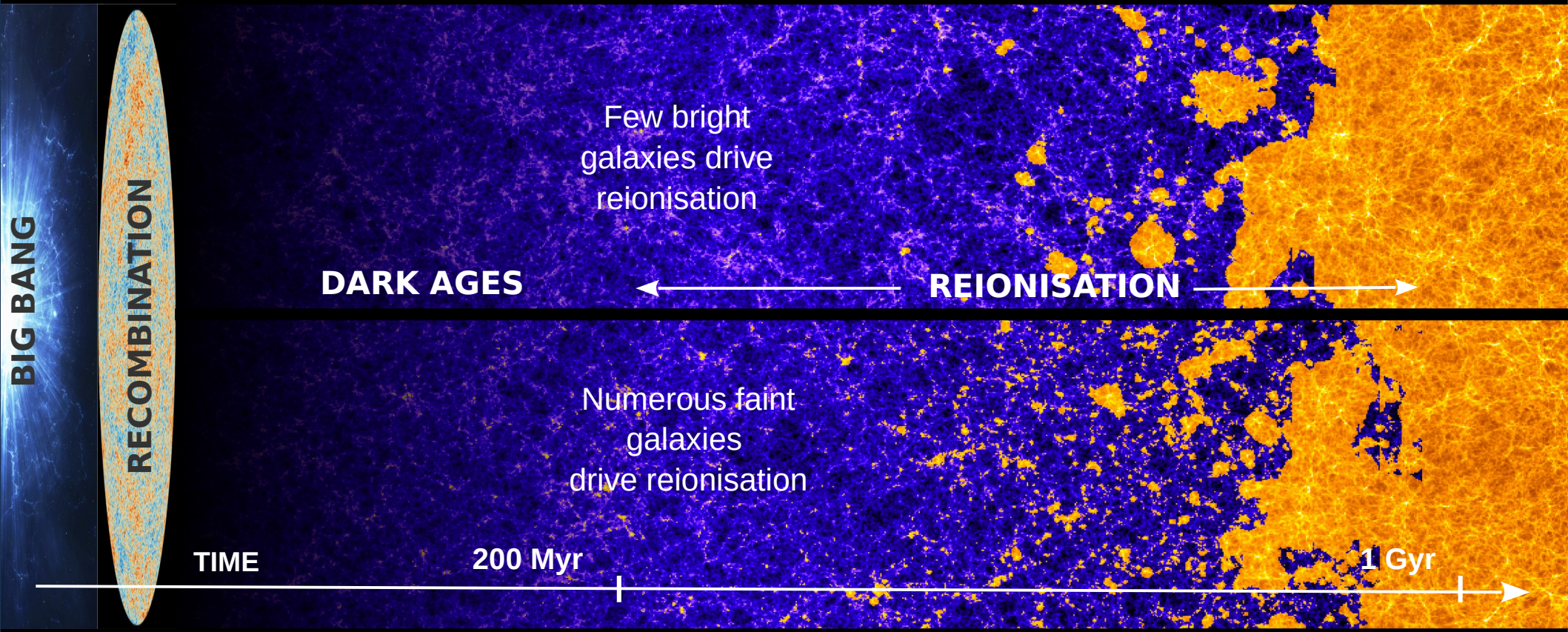
Anne Hutter

Cosmic Dawn Center, University of Copenhagen

Collaborators: Caroline Heneka, Astraeus Team (Pratika Dayal, Maxime Trebitsch, Stefan Gottlöber, Gustavo Yepes), Andrei Mesinger

UNIVERSITY OF COPENHAGEN

How did reionisation proceed?
How did the state of the intergalactic medium change?



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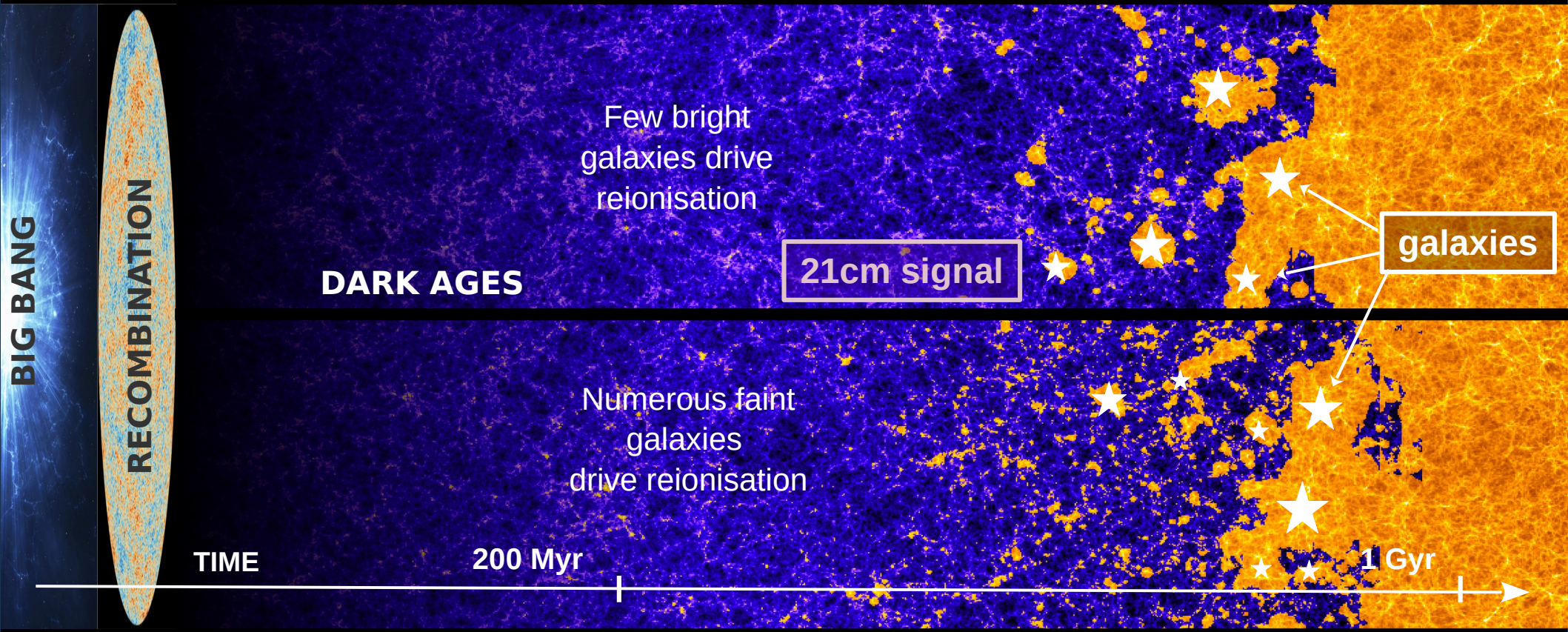
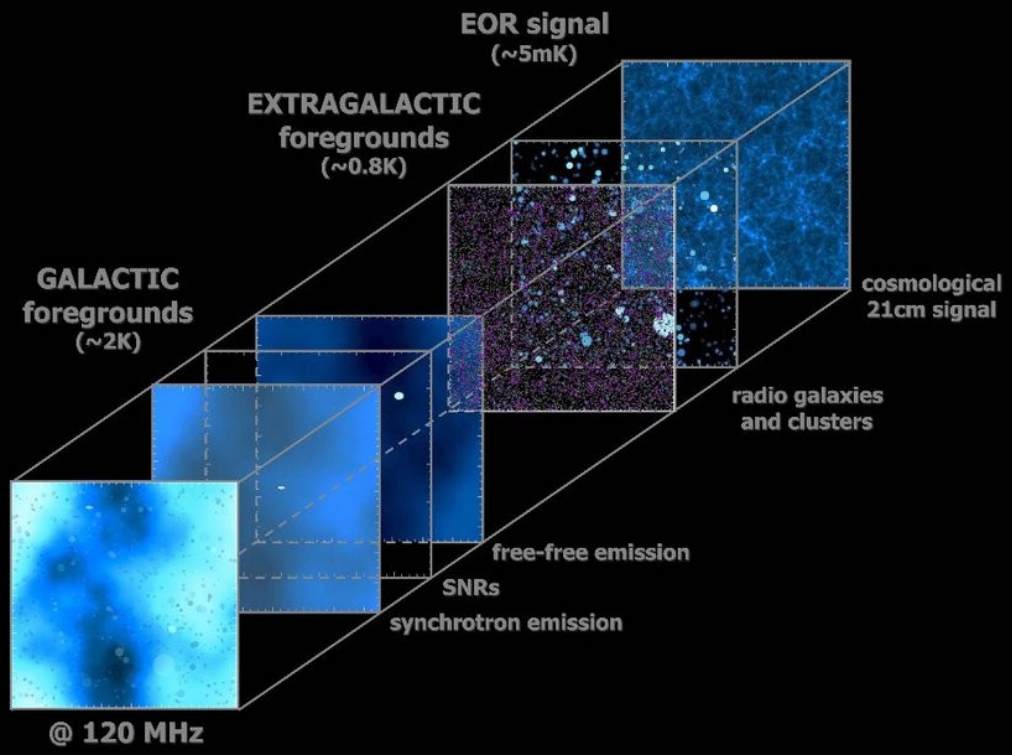


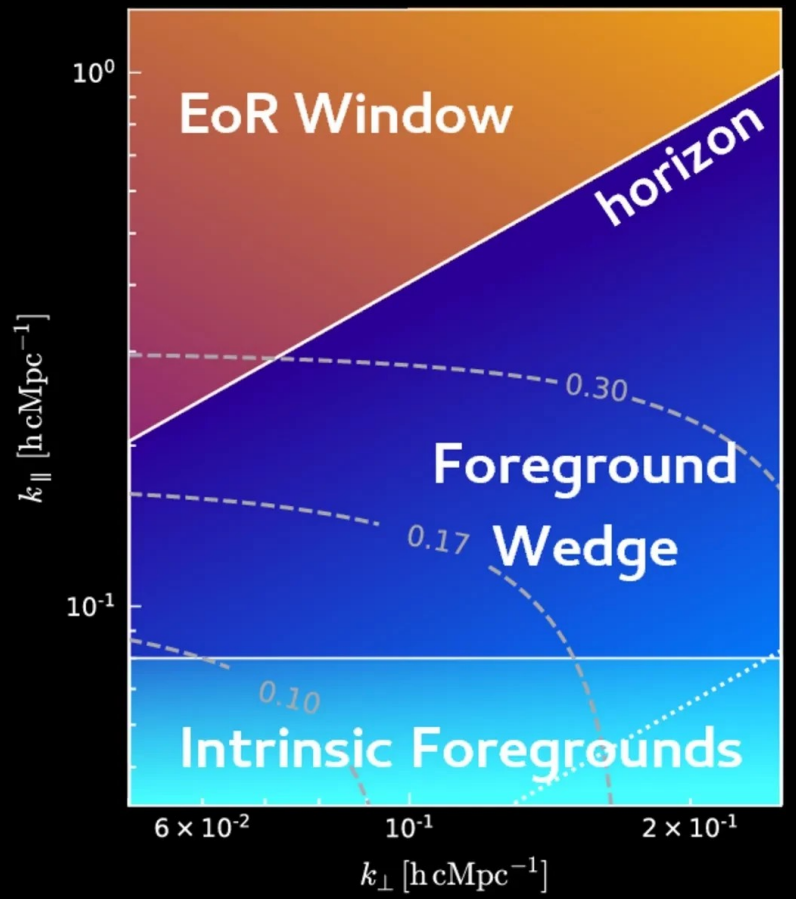
Why cross-correlating 21cm and galaxy surveys?



Credit: V. Jelic

Positions of high-z galaxies correlate with EoR 21cm signal but not with spectrally smooth foregrounds

Mertens+ 2018



What this talk will be about:

- How does the large-scale 21cm – galaxy cross correlation power evolve across cosmic time?
- What can we learn from the 21cm-galaxy cross correlation functions and cross power spectra during reionisation?
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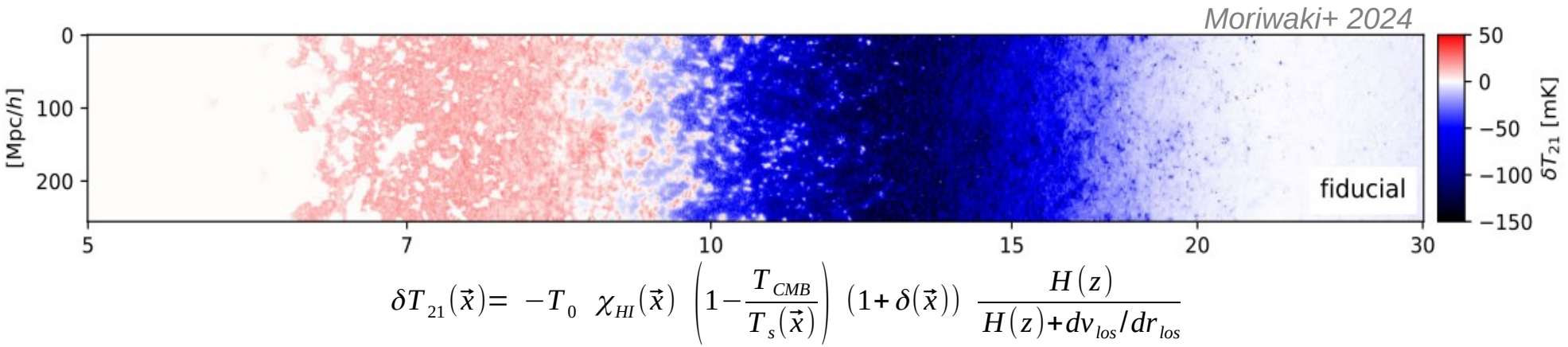
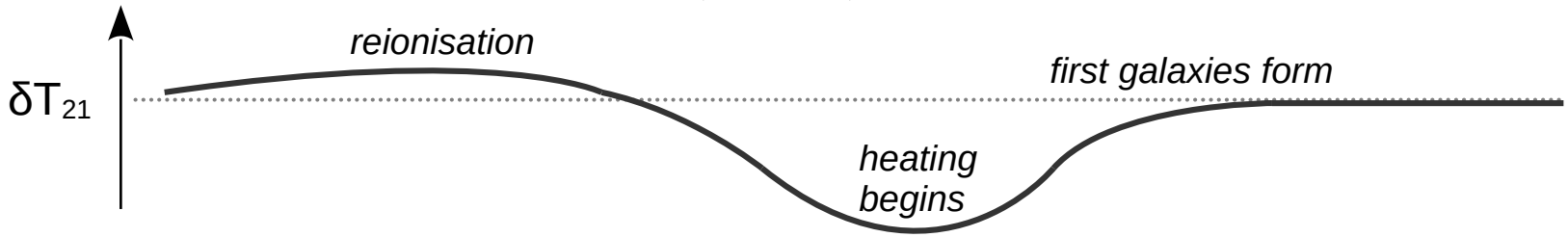
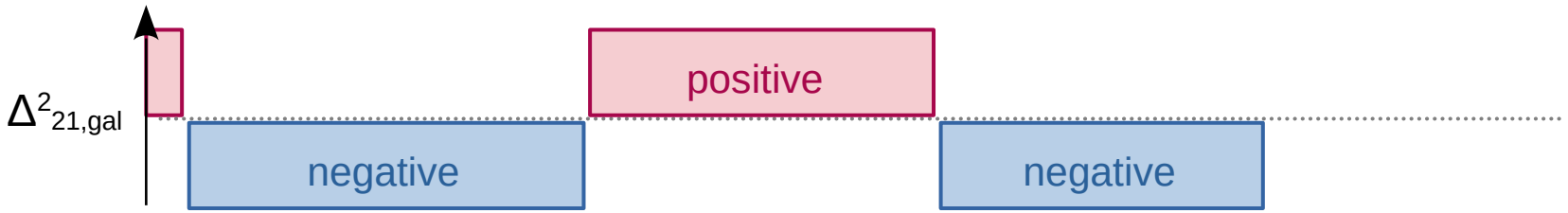
What cross correlation signal do we expect at different epochs?



$$\delta T_{21}(\vec{x}) = -T_0\ \chi_{HI}(\vec{x})\left(1-\frac{T_{CMB}}{T_s(\vec{x})}\right)(1+\delta(\vec{x}))\ \frac{H(z)}{H(z)+dv_{los}/dr_{los}}$$



21cm-galaxy cross power spectrum



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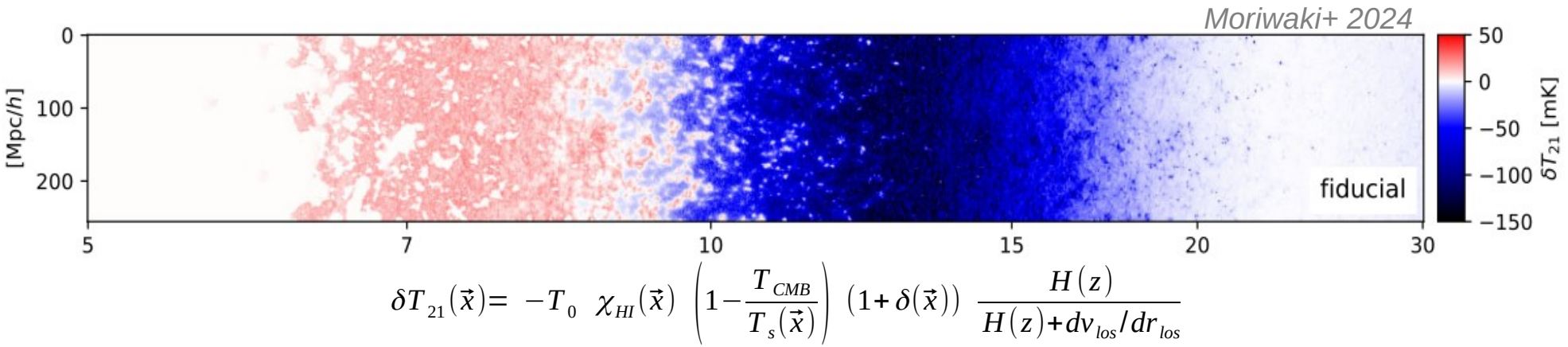

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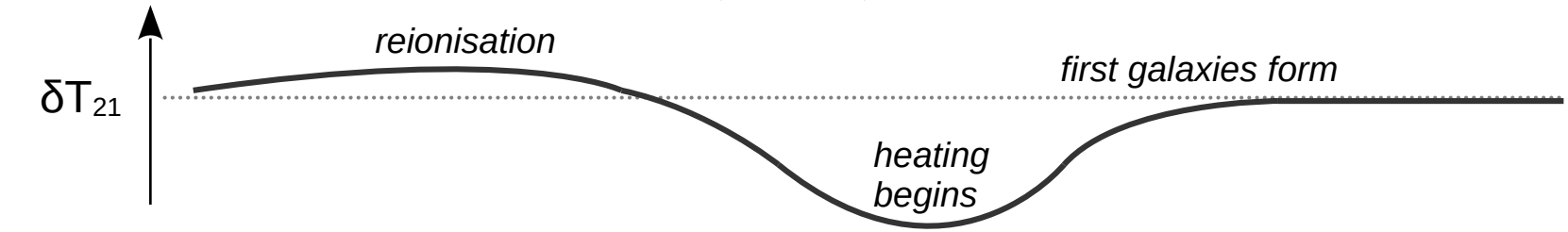
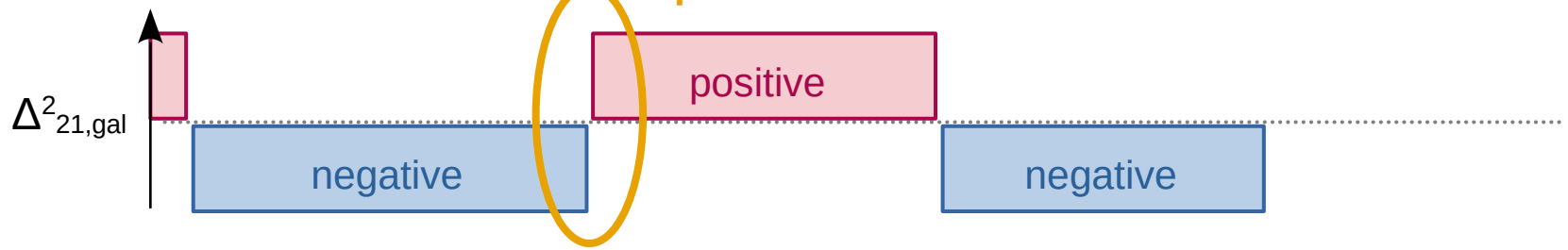


21cm-galaxy cross power spectrum

What does it depend on?



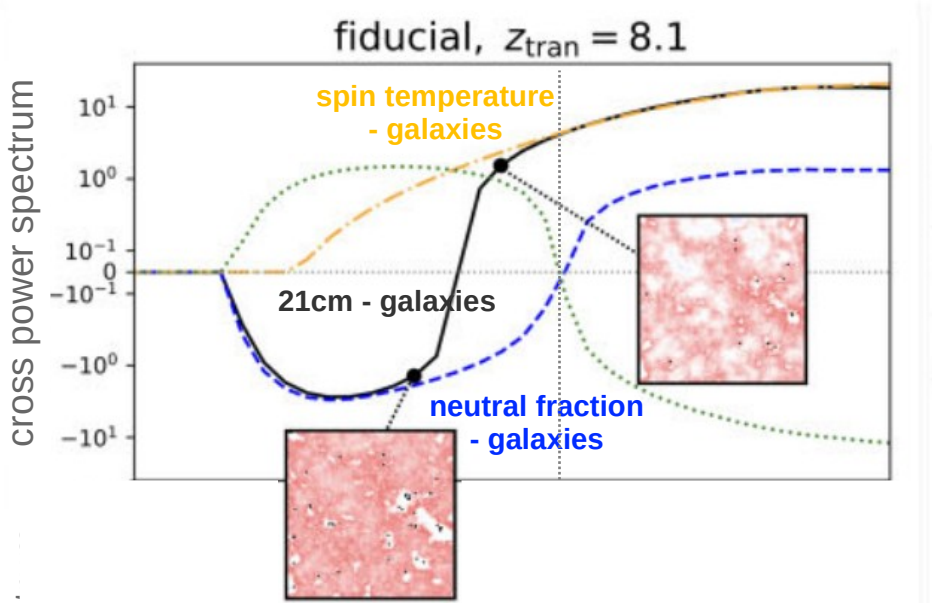
Neutral fraction and spin temperature fluctuations drive the 21cm-galaxy cross power spectrum

neutral fraction fluctuations

spin temperature fluctuations

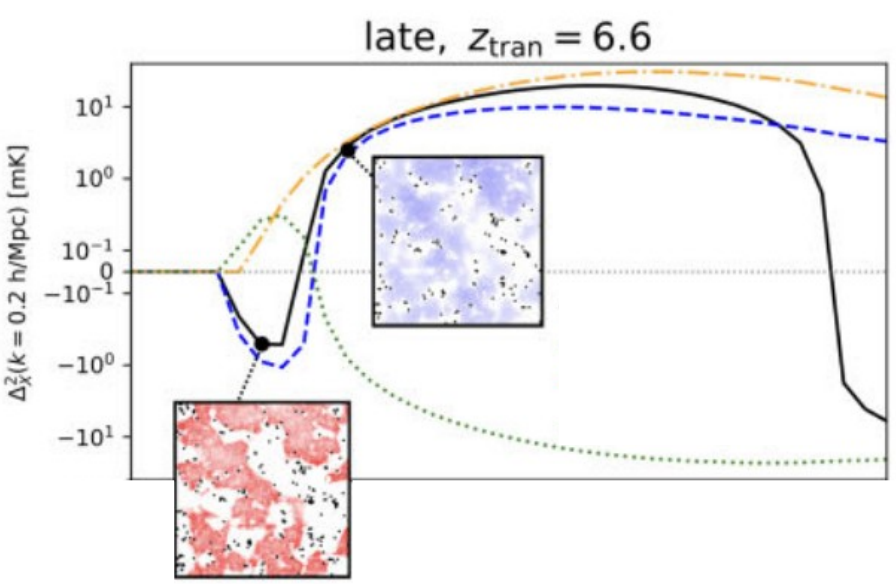
$$\delta T_{21}(\vec{x}) = -T_0\, \chi_{HI}(\vec{x}) \left(1 - \frac{T_{CMB}}{T_s(\vec{x})}\right) \times (1+\delta(\vec{x}))\, \frac{H(z)}{H(z)+dv_{los}/dr_{los}}$$

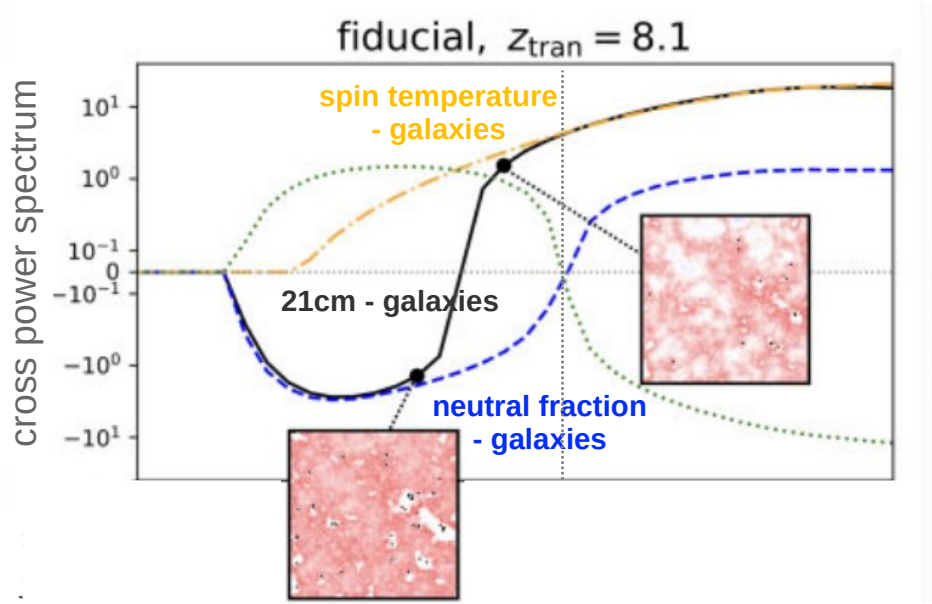
redshift density fluctuations



Moriwaki+ 2024

Sign change in 21cm-galaxy cross power traces end of heating!





neutral fraction fluctuations

spin temperature fluctuations

redshift density fluctuations

$$\delta T_{21}(\vec{x}) = -T_0\ \chi_{HI}(\vec{x})\left(1-\frac{T_{CMB}}{T_s(\vec{x})}\right) \times (1+\delta(\vec{x}))\ \frac{H(z)}{H(z)+dv_{los}/dr_{los}}$$

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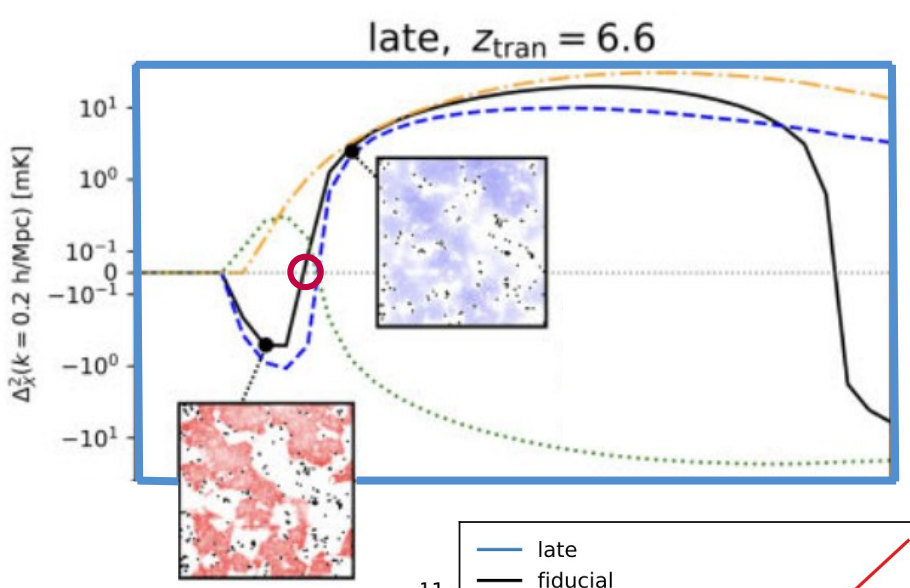

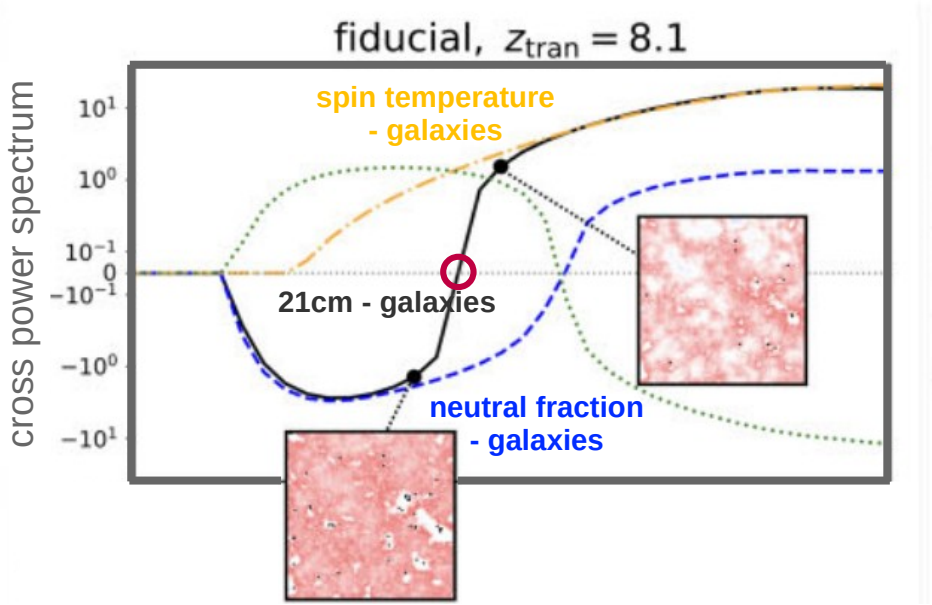

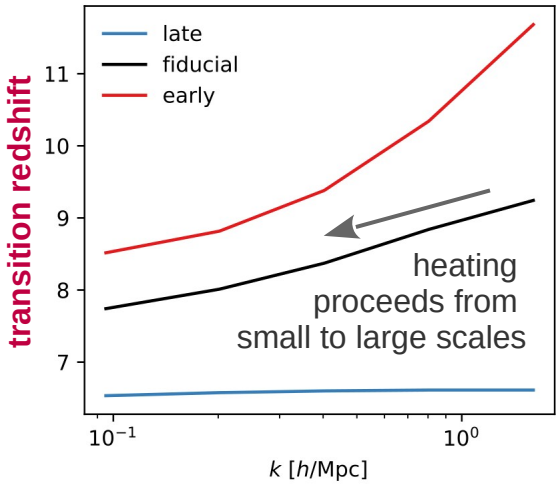

Moriwaki+ 2024

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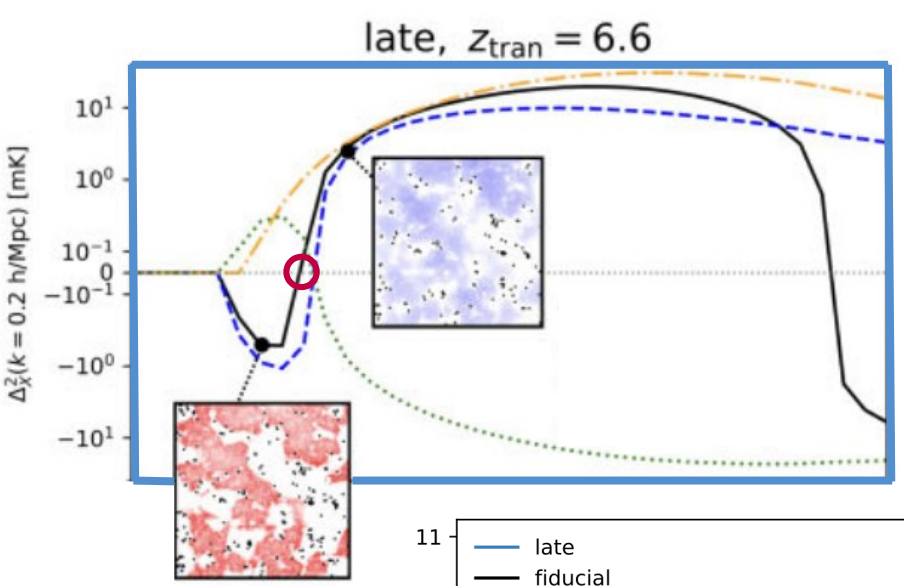
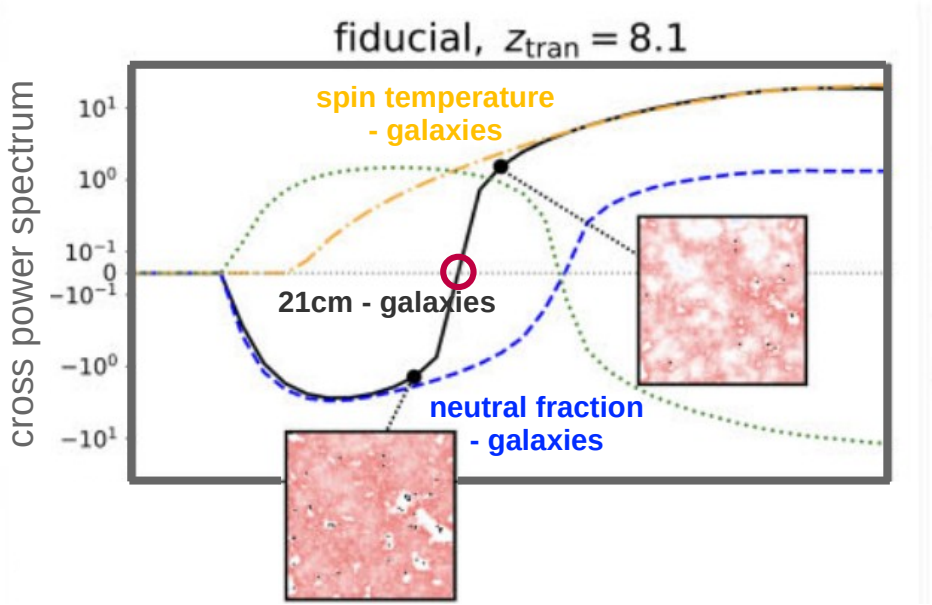
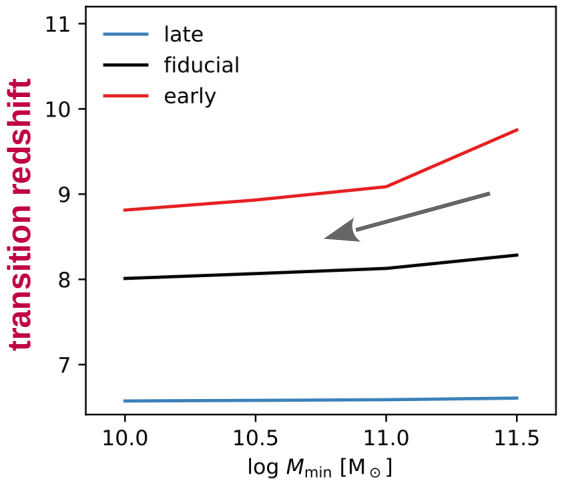




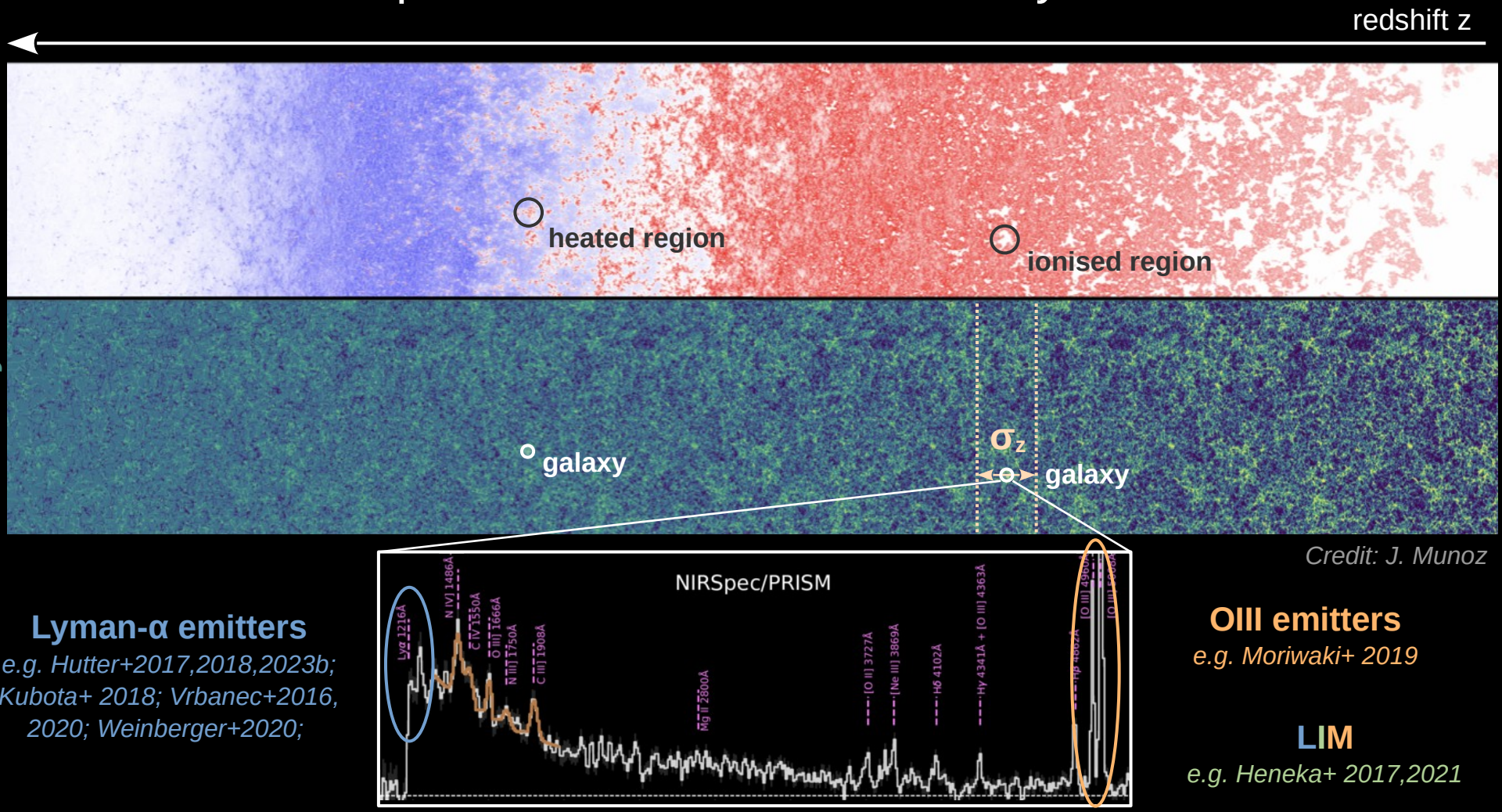


Transition redshift is not very sensitive to the chosen galaxy sample!

Similar to 21cm bispectrum sign change discussed in Kamran+ 2021

Moriwaki+ 2024

Emission line selected galaxies or intensity mapping provide best redshift accuracy



Credit: J. Munoz

Lyman-α emitters

e.g. Hutter+2017,2018,2023b; Kubota+ 2018; Vrbanec+2016, 2020; Weinberger+2020;

OIII emitters

e.g. Moriwaki+ 2019

LIM

e.g. Heneka+ 2017,2021

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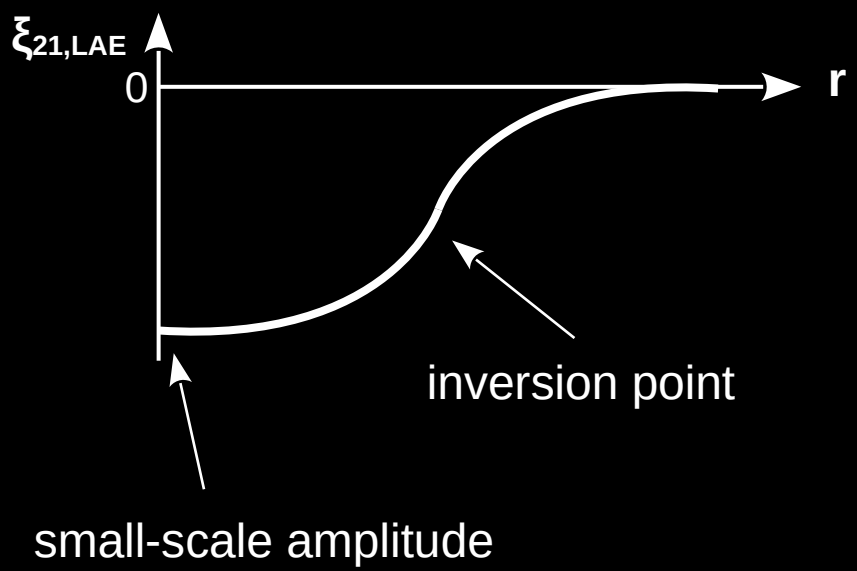
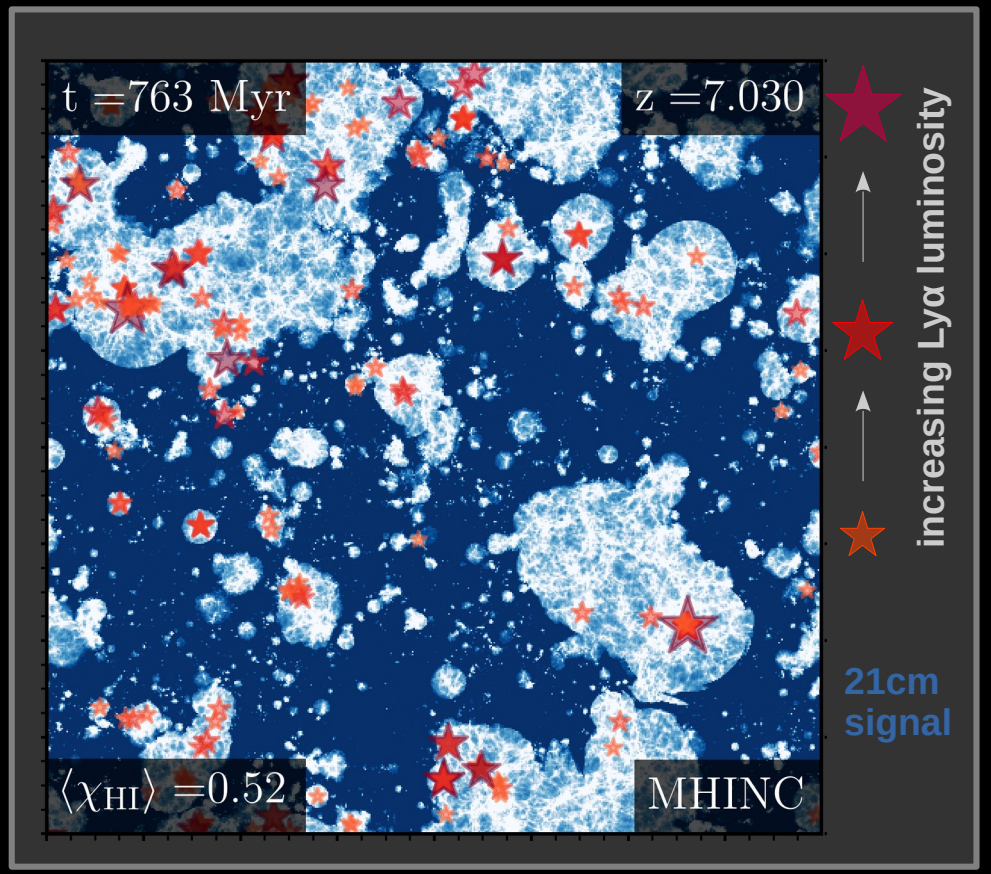
21cm – LAE cross correlation function: characteristics

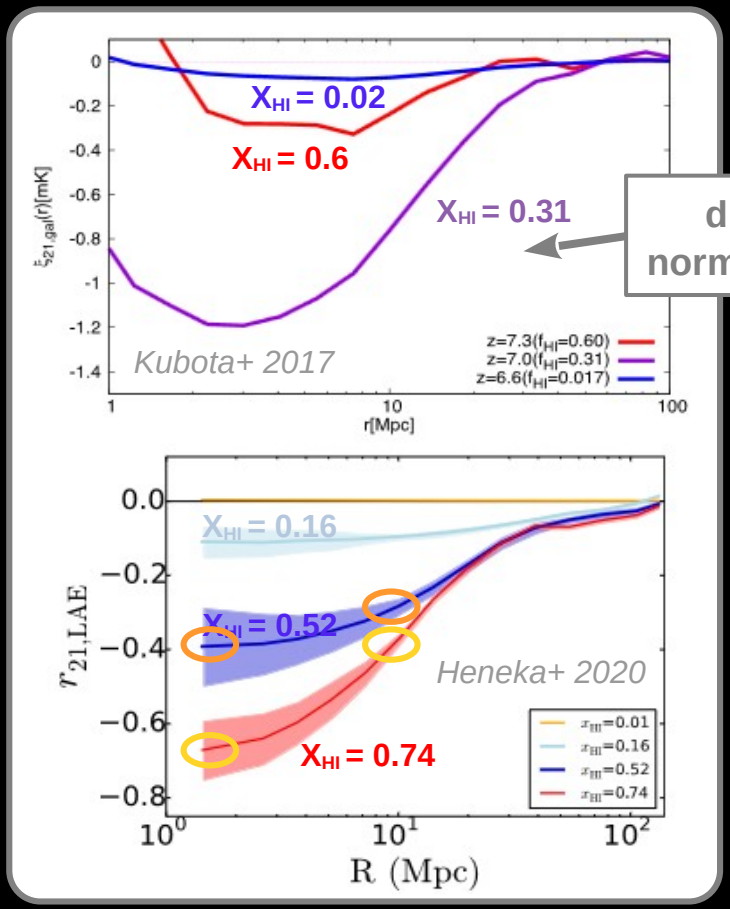




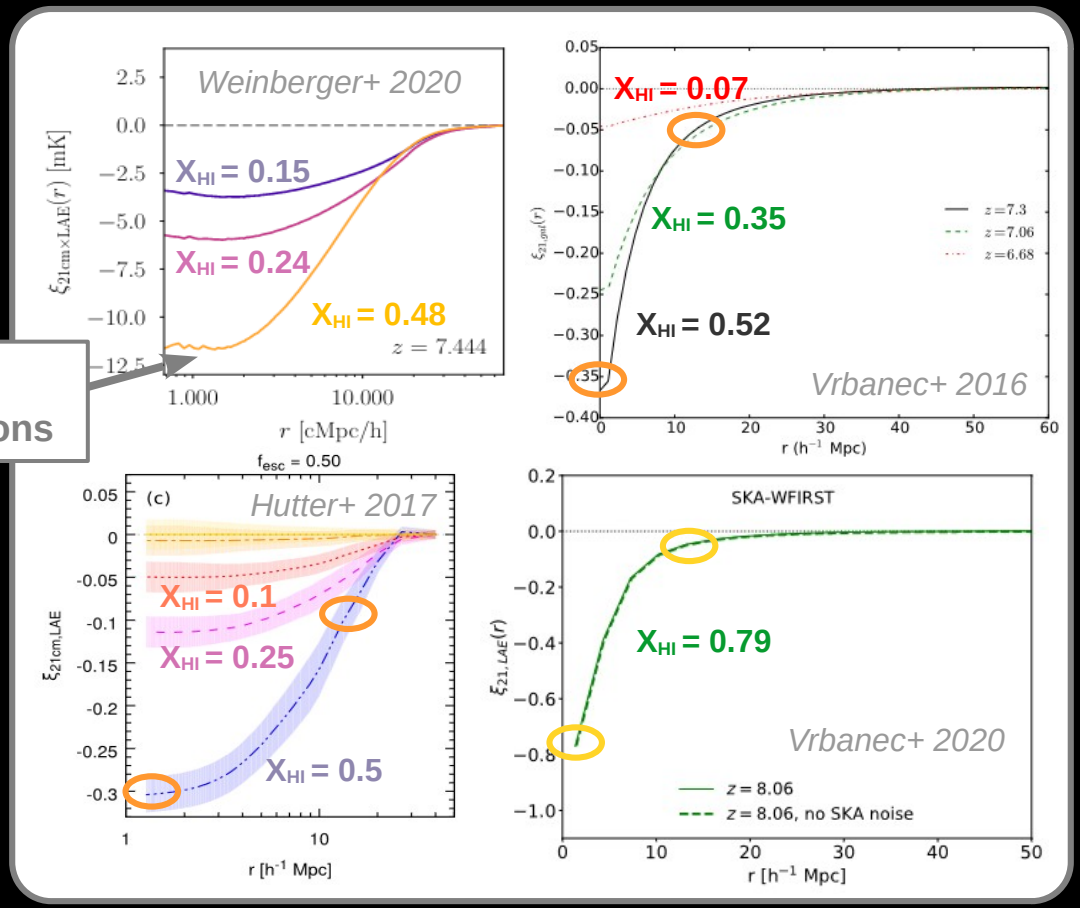
Hutter, Heneka+ 2023

Simulation results during the EoR: 21cm – LAE cross correlations

21cm-LAE cross correlation functions from different models/simulations differ.



different normalisations

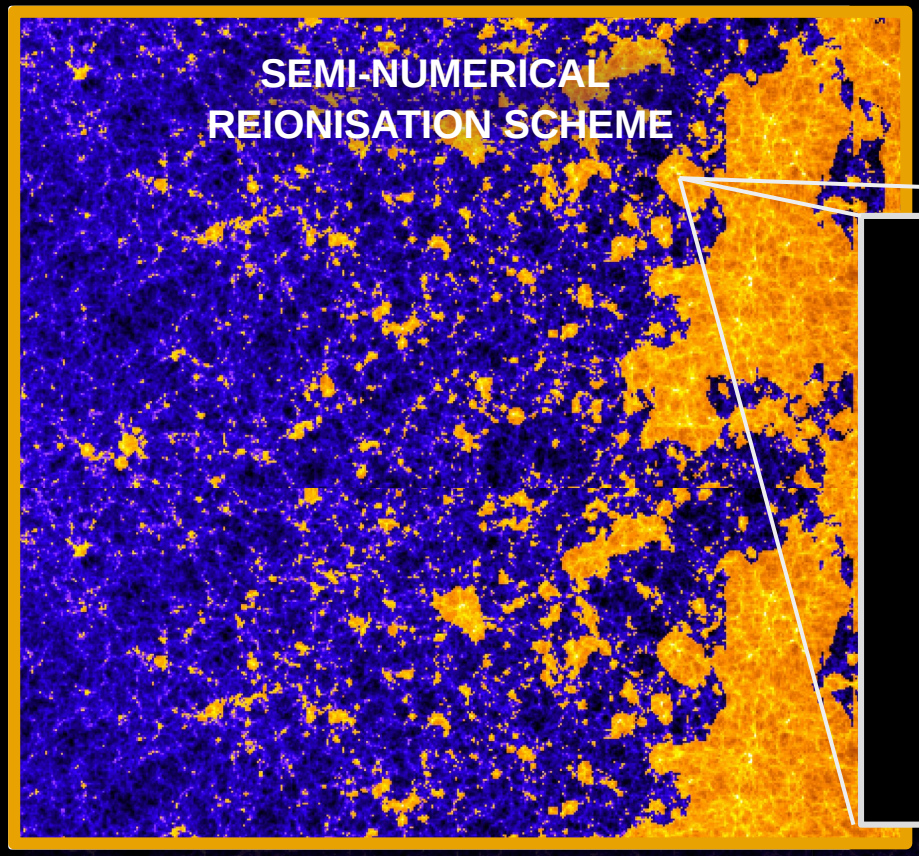


Overall shape agrees BUT amplitudes differ

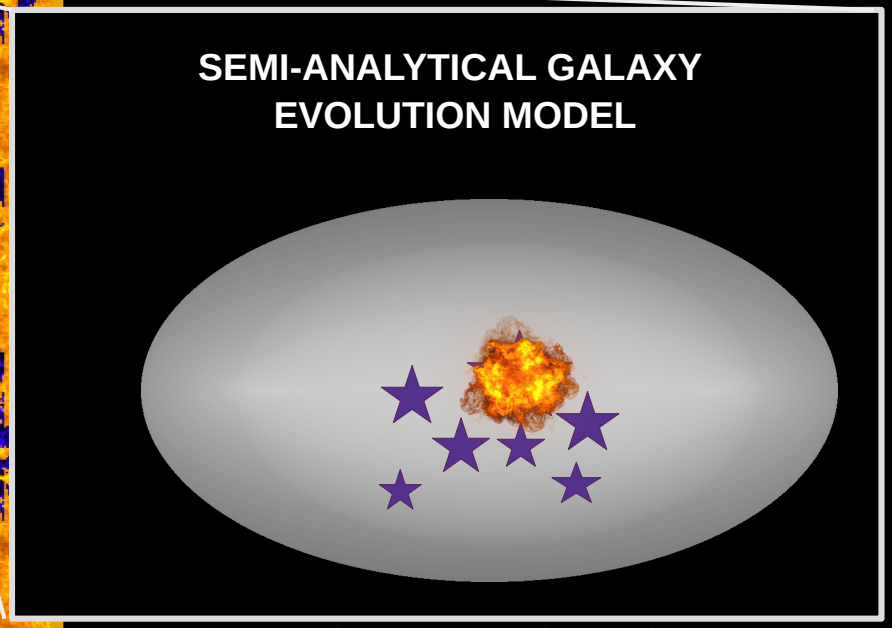
WHY? What would we expect?

normalisation, box size, physics (ionisation, LAE identification)?

Astraeus – a fast framework for simulating the evolution of the first galaxies and the intergalactic medium

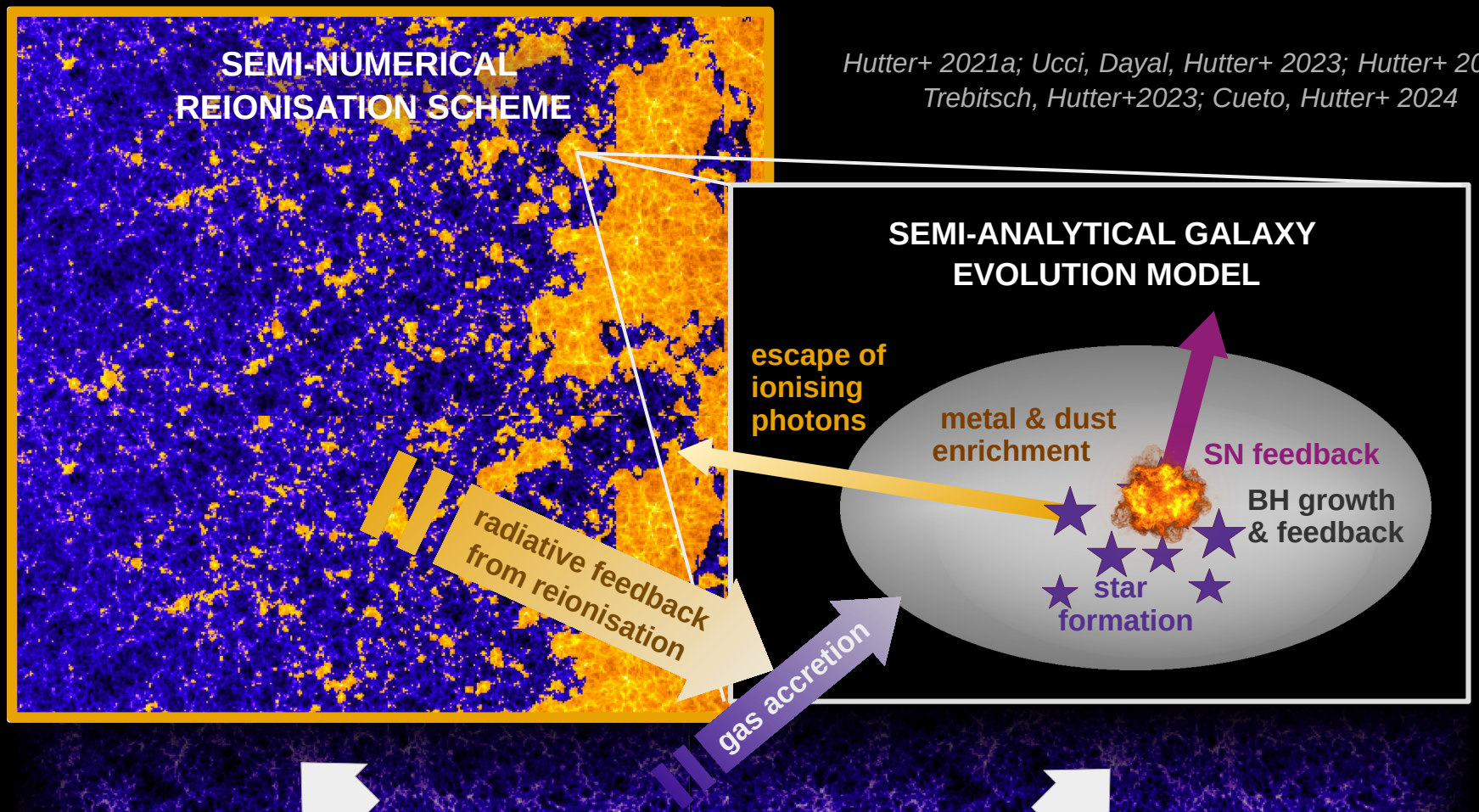


Hutter+ 2021a; Ucci, Dayal, Hutter+ 2023; Hutter+ 2023a; Trebitsch, Hutter+2023; Cueto, Hutter+ 2024



DARK MATTER ONLY N-BODY SIMULATION

Astraeus – a fast framework for simulating the evolution of the first galaxies and the intergalactic medium

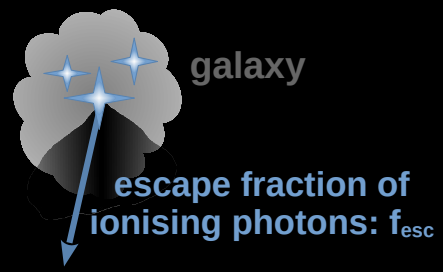


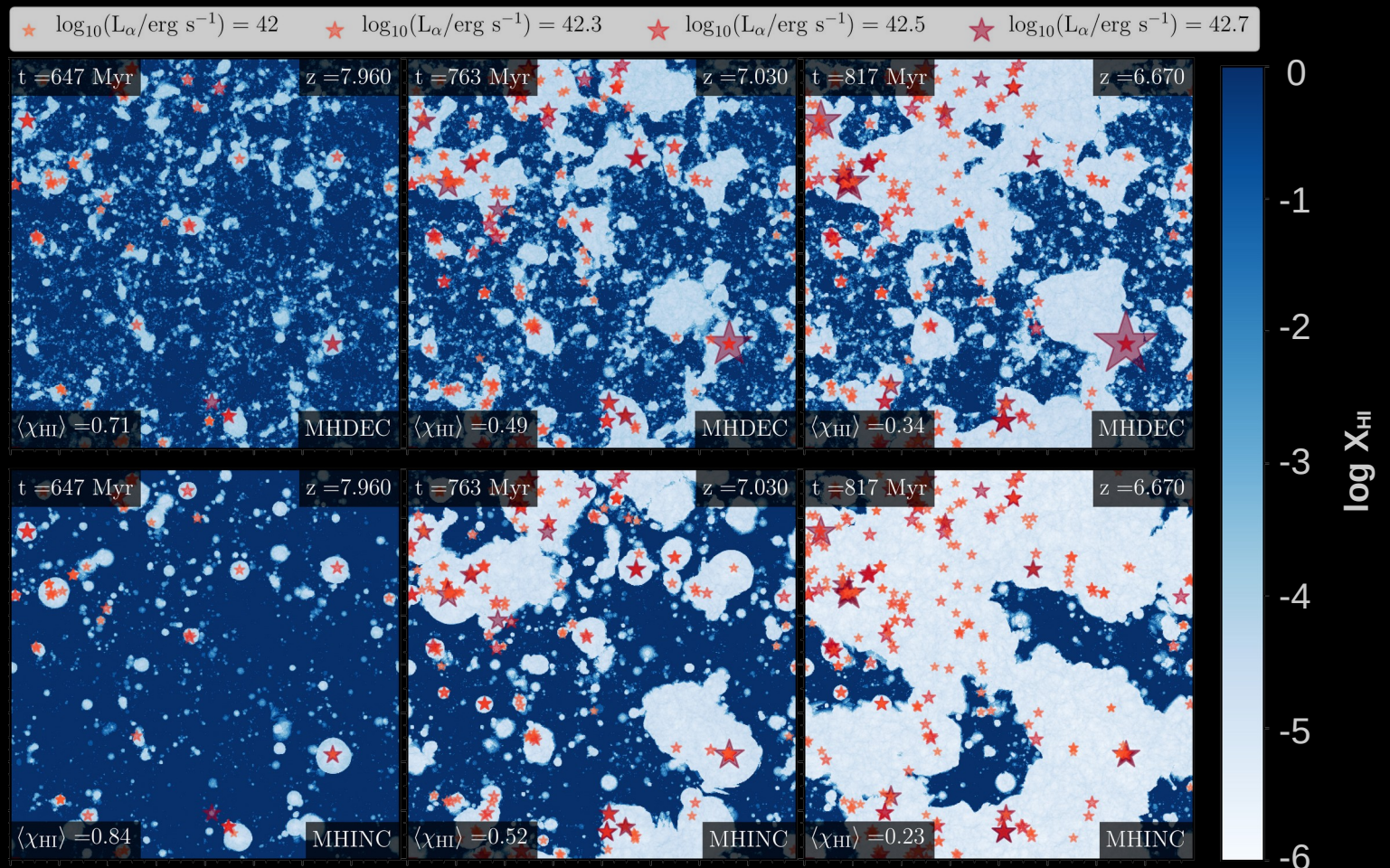
Hutter+ 2021a; Ucci, Dayal, Hutter+ 2023; Hutter+ 2023a; Trebitsch, Hutter+2023; Cueto, Hutter+ 2024

Two reionisation scenarios differing in their ionisation morphology

f_{esc} decreases with halo mass
MHDEC

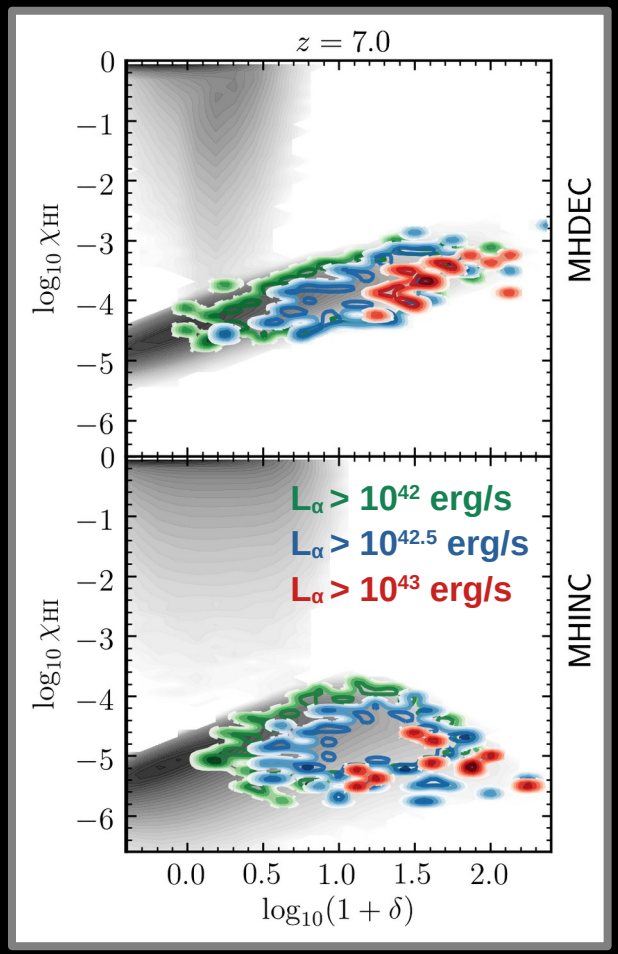
f_{esc} increases with halo mass
MHINC





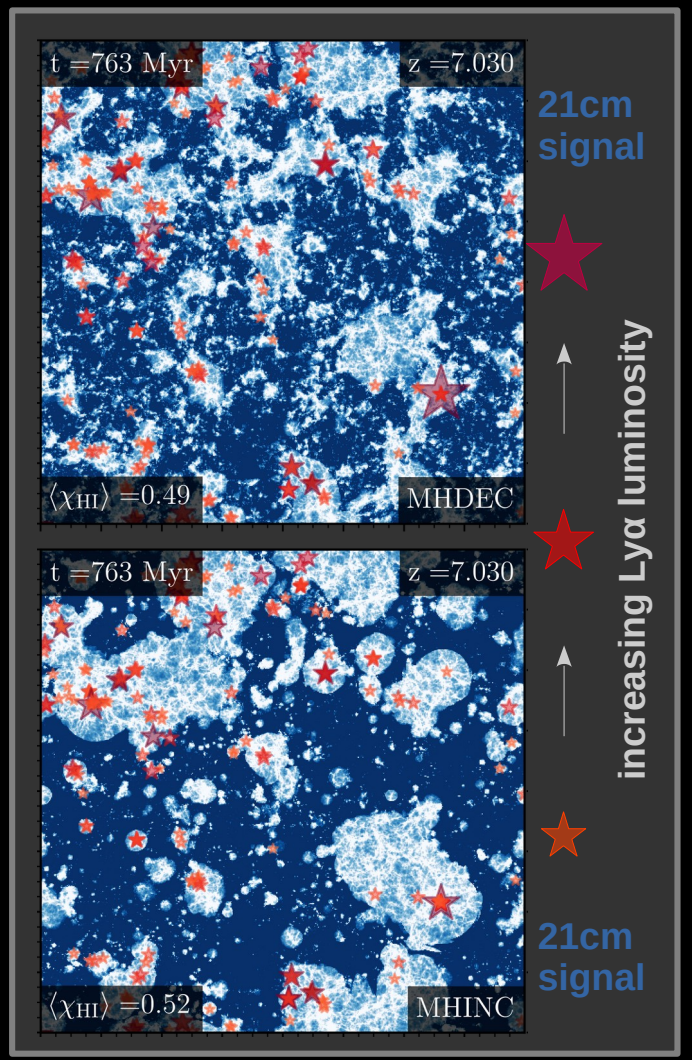
Hutter+ 2023a

Where are Lyman-α emitters located in the IGM?



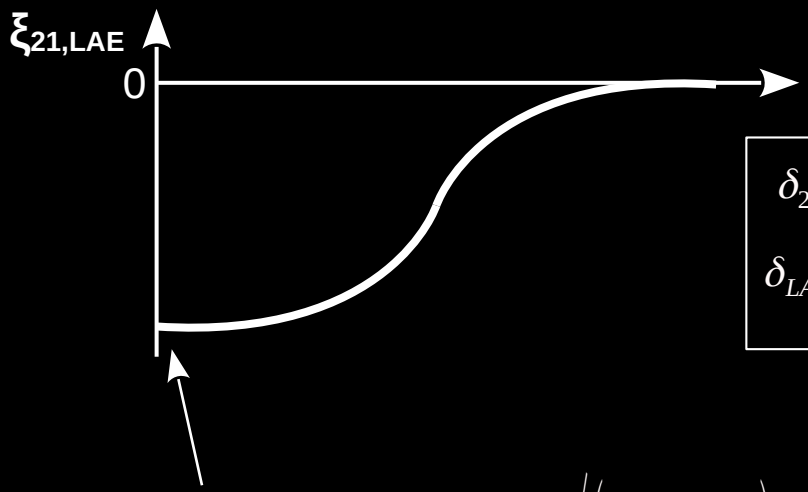
LAEs are located in the most ionised overdense regions

no 21cm signal



Hutter+ 2023a,b

21cm – LAE cross correlation functions: small-scale amplitude



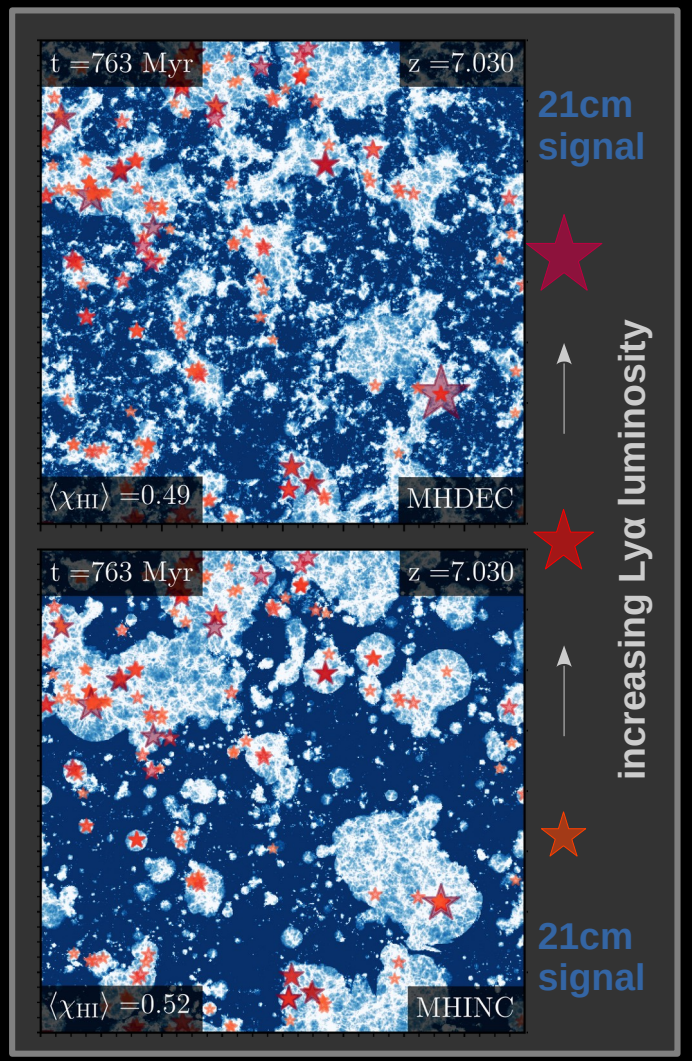
$$\delta_{21}(x) = \delta T_b(x)/T_0$$

$$\delta_{LAE}(x) = \frac{n_{LAE}(x)}{\langle n_{LAE}\rangle} - 1$$

$$\xi_{21,LAE}(r\approx 0) \approx -\langle \chi_{HI}\rangle \left\langle \left(1-\frac{T_{CMB}}{T_s}\right)(1+\delta)\right\rangle_{HI}$$

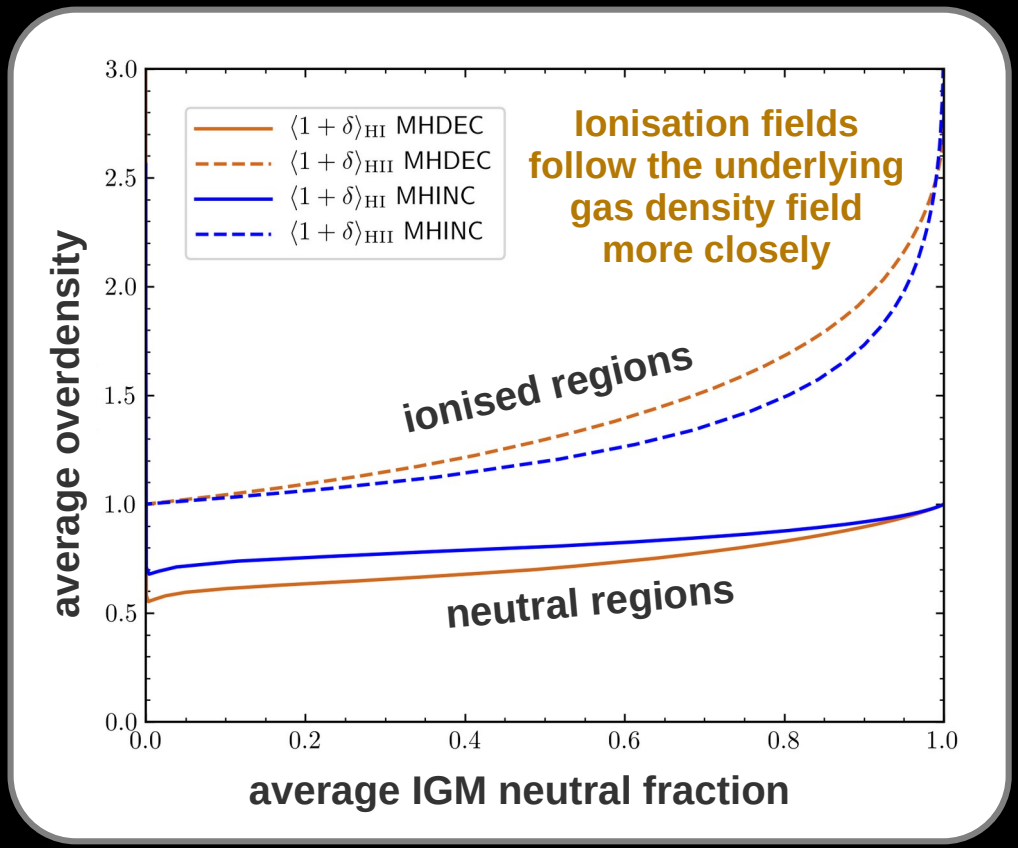
During reionisation:

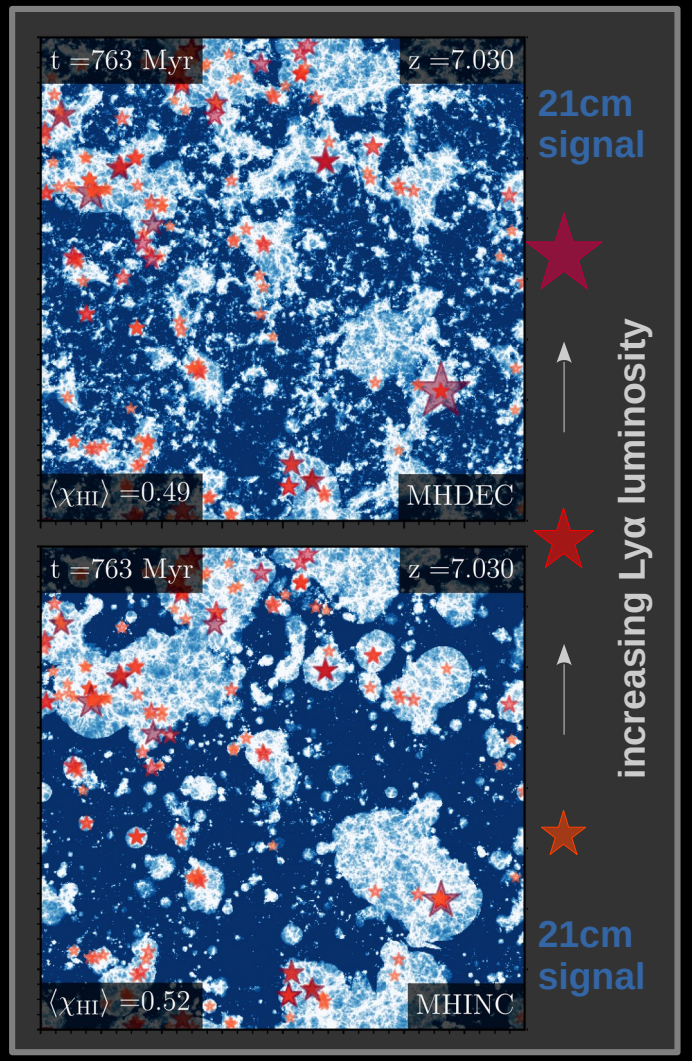
$$\xi_{21,LAE}(r\approx 0) \approx -\langle \chi_{HI}\rangle \langle 1+\delta\rangle_{HI}$$



Hutter, Heneka+ 2023

21cm – LAE cross correlation function: small-scale amplitude traces ionisation morphology!

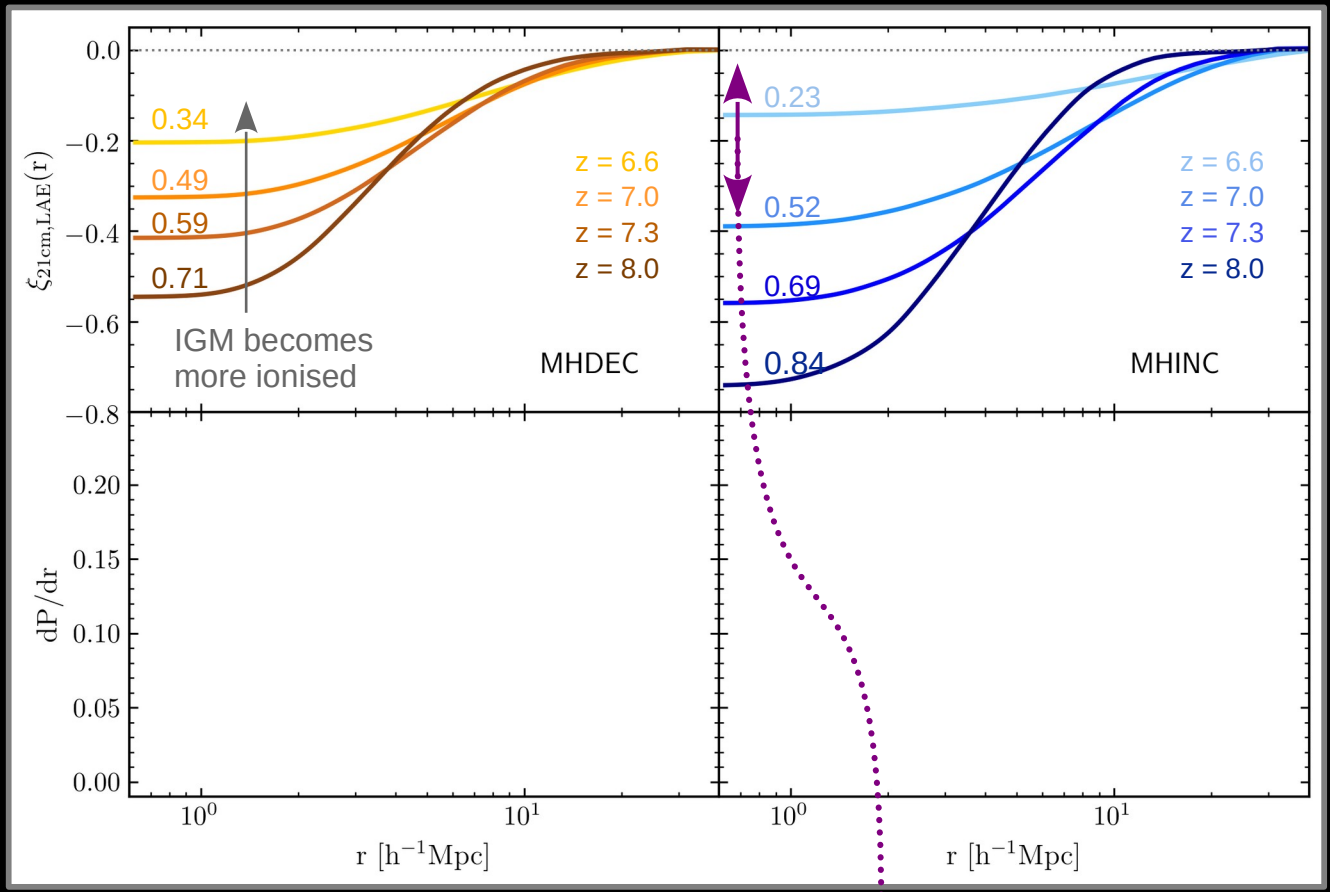




Hutter, Heneka+ 2023

21cm – LAE cross correlations are sensitive to ionisation morphology!

21cm-LAE cross correlation function



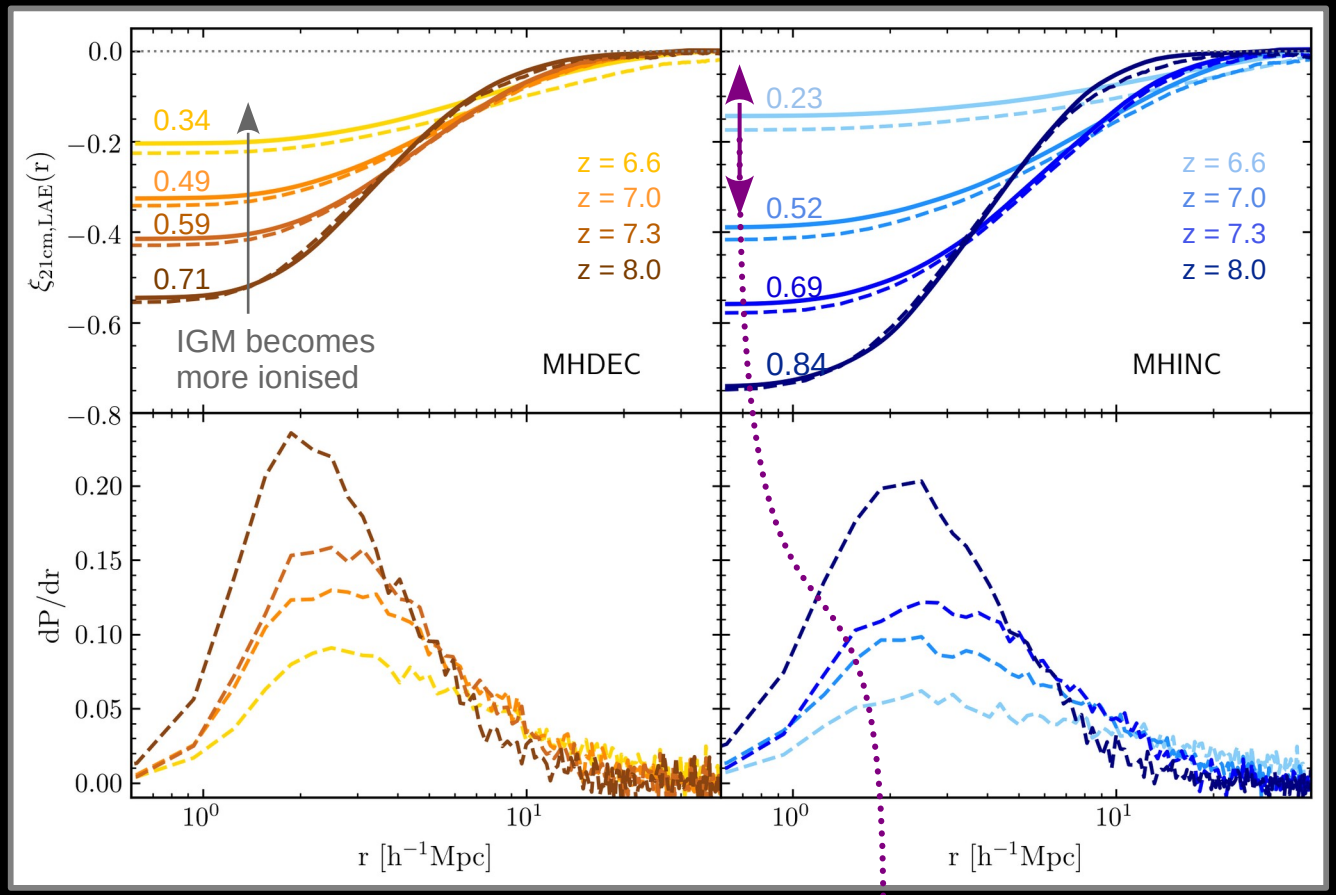
Hutter, Heneka+ 2023b

Analytical limit: $\xi_{21,LAE}(r \approx 0) \approx -\langle \chi_{HI} \rangle \langle 1+\delta \rangle_{HI}$

21cm – LAE cross correlations are sensitive to ionisation morphology!

21cm-LAE cross correlation function

size distribution of ionised regions around LAEs



Hutter, Heneka+ 2023b

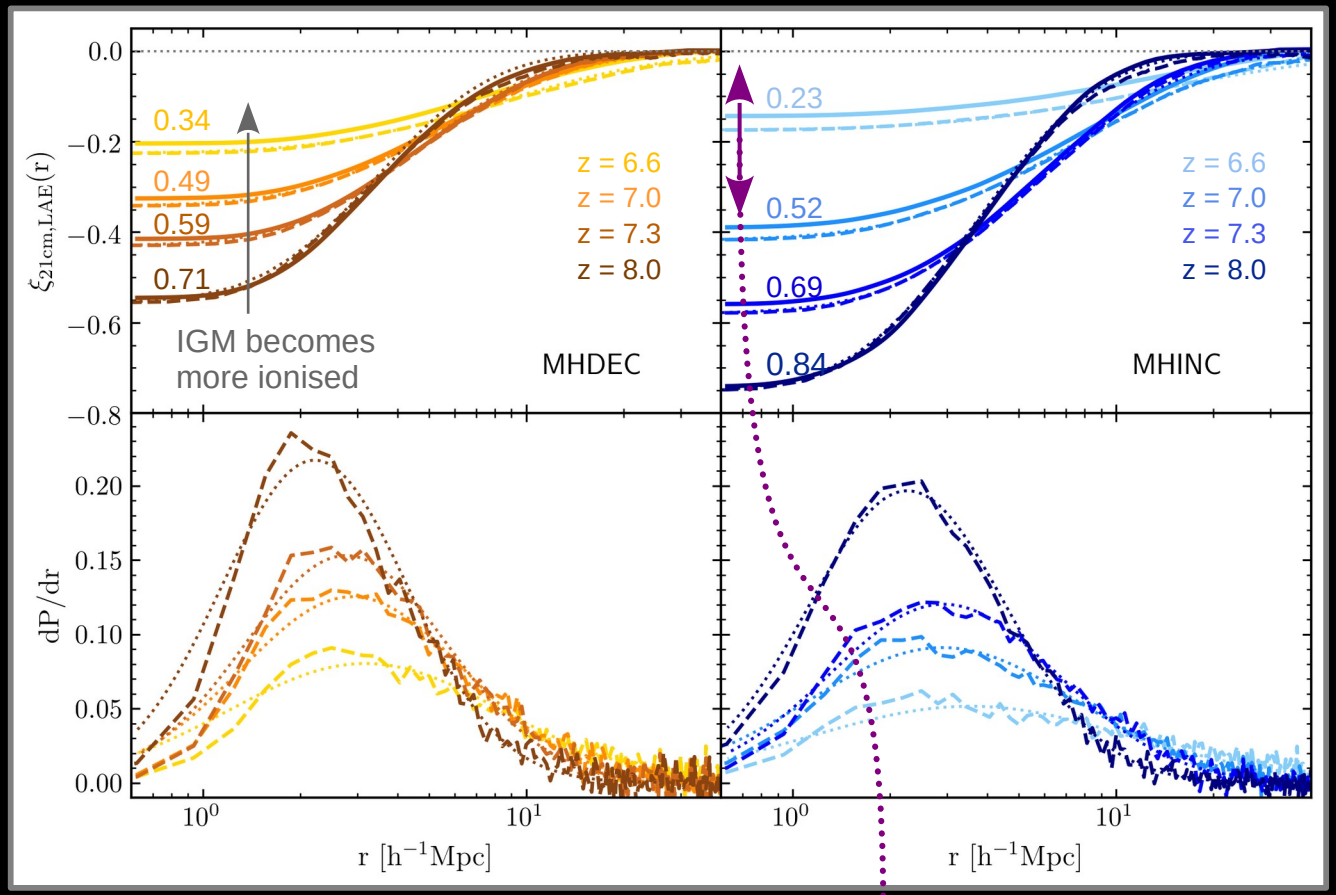
Cumulative distribution function of size of ionised regions around LAEs

Analytical fitting function: $\xi_{21,LAE}(r) \approx -\langle \chi_{HI} \rangle \langle 1+\delta \rangle_{HI} \left[1 - \langle \chi_{HI} \rangle CDF(r) \right]$

21cm – LAE cross correlations are sensitive to ionisation morphology!

21cm-LAE cross correlation function

size distribution of ionised regions around LAEs



Hutter, Heneka+ 2023b

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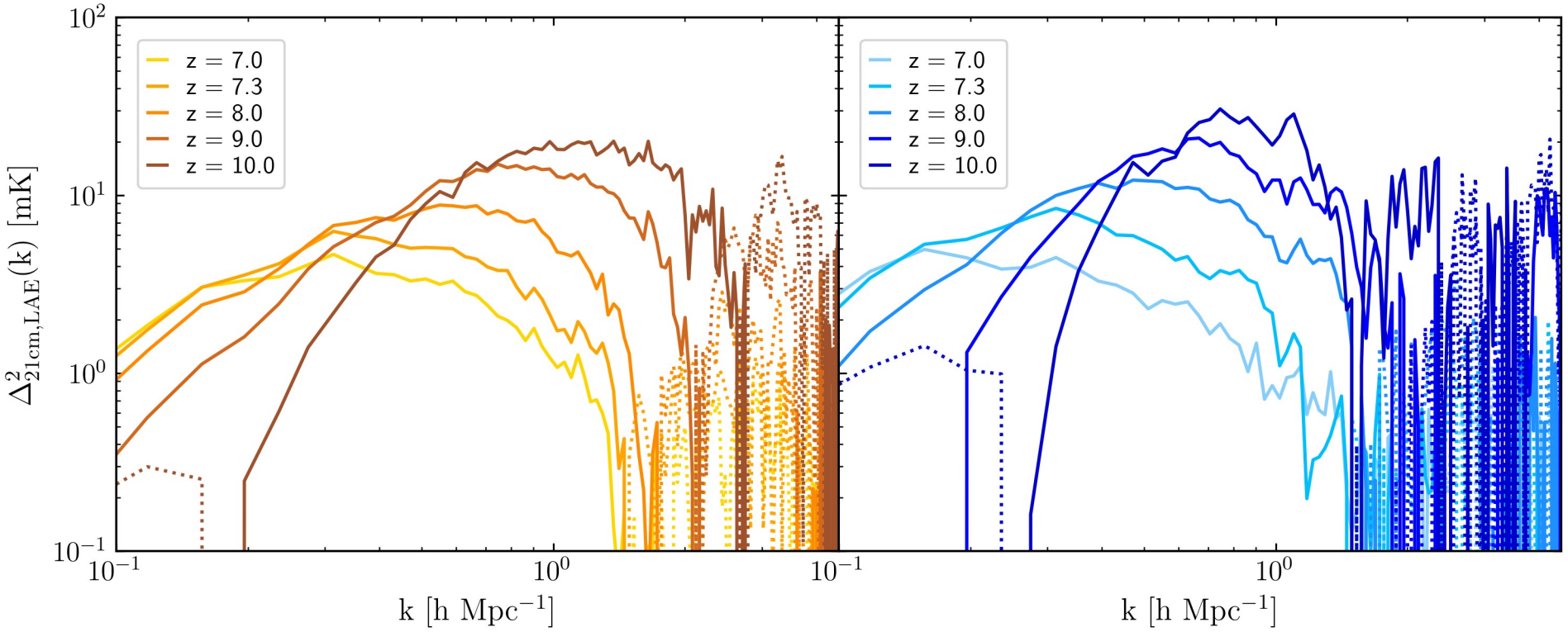
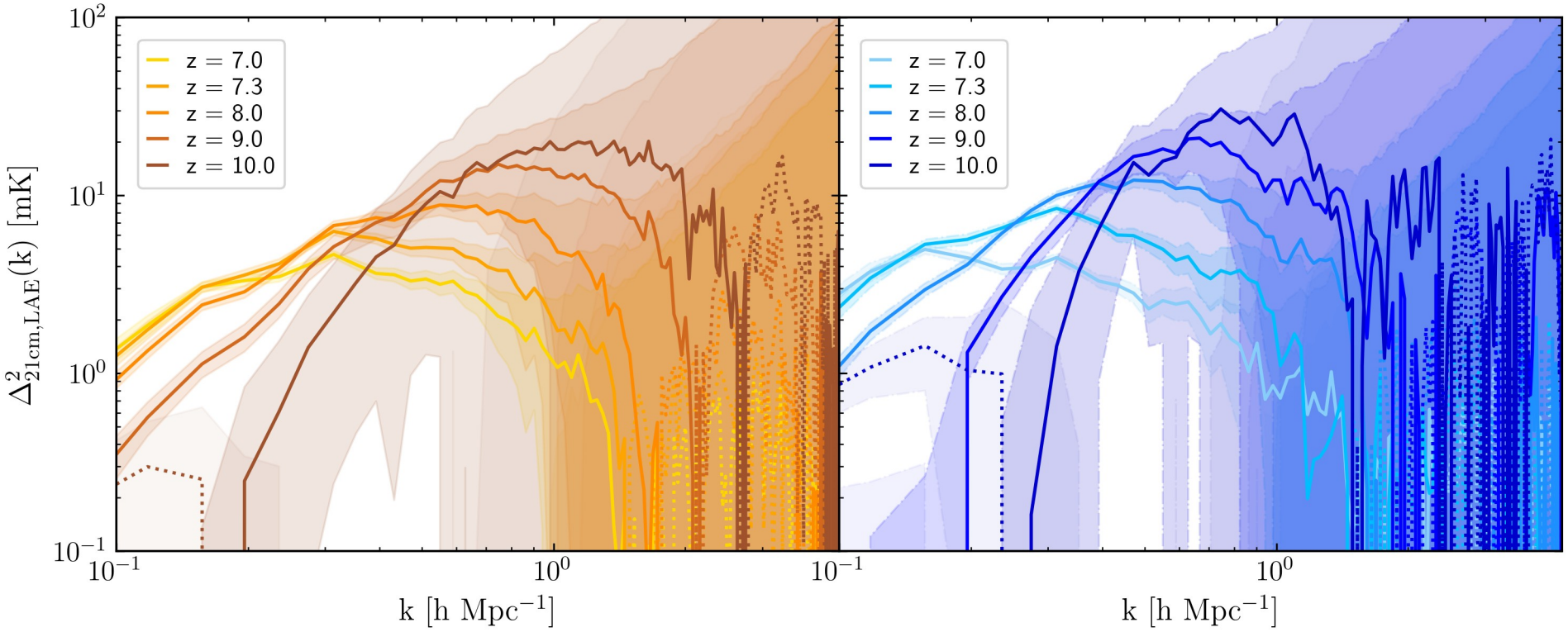
21cm – LAE cross power spectra sensitive to ionisation morphology!



A higher (negative) cross power amplitude implies an overall higher HI density

Sign change in cross power corresponds to the typical size of ionised regions.

Ionisation morphology distinguishable by measuring 21cm – LAE cross power spectra?



21cm: SKA1-LOW (baselines < 10km)

LAEs: Subaru Prime Focus Spectrograph *(σ_z=0.0007)*

Survey area: FoV = 25 deg^2

Survey depth: $L_\alpha > 10^{42}$ erg/s

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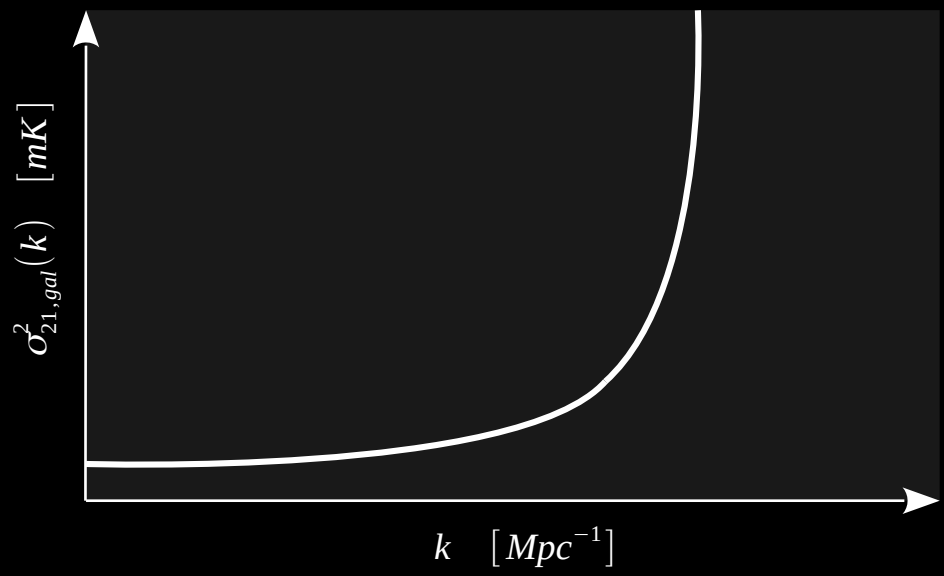
Observational uncertainties for 21cm-galaxy cross correlations

$$\sigma^2_{21,gal}(k,\mu) = \frac{1}{2}\left[P^2_{21,gal}(k,\mu) + \left(\overbrace{P_{21}(k,\mu)}^{\text{sample variance}} + \overbrace{P^{noise}_{21}(k,\mu)}^{\text{thermal noise}}\right)\left(\overbrace{P_{gal}(k,\mu)}^{\text{sample variance}} + \overbrace{P^{noise}_{gal}(k,\mu)}^{\text{shot noise}}\right)\right]$$

$$\frac{1}{\sigma^2_{21,gal}(k)} = \sum_{\mu} N_k \frac{1}{\sigma^2_{21,gal}(k,\mu)}$$

$$N_k = \frac{k^2\,\Delta k\,\Delta\mu\,V_{surv}}{(2\pi)^2}$$



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$$\propto n_{gal}^{-1} \exp\left(k_{par}\frac{c\,\sigma_z}{H(z)}\right)$$

increase survey depth

$$\frac{1}{\sigma^2_{21,gal}(k)} = \sum_\mu N_k \frac{1}{\sigma^2_{21,gal}(k,\mu)}$$

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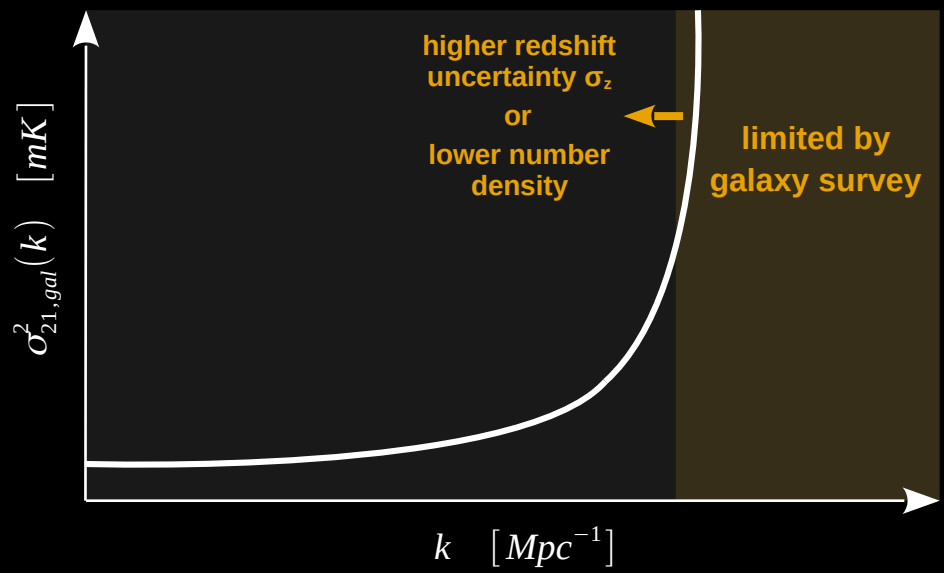
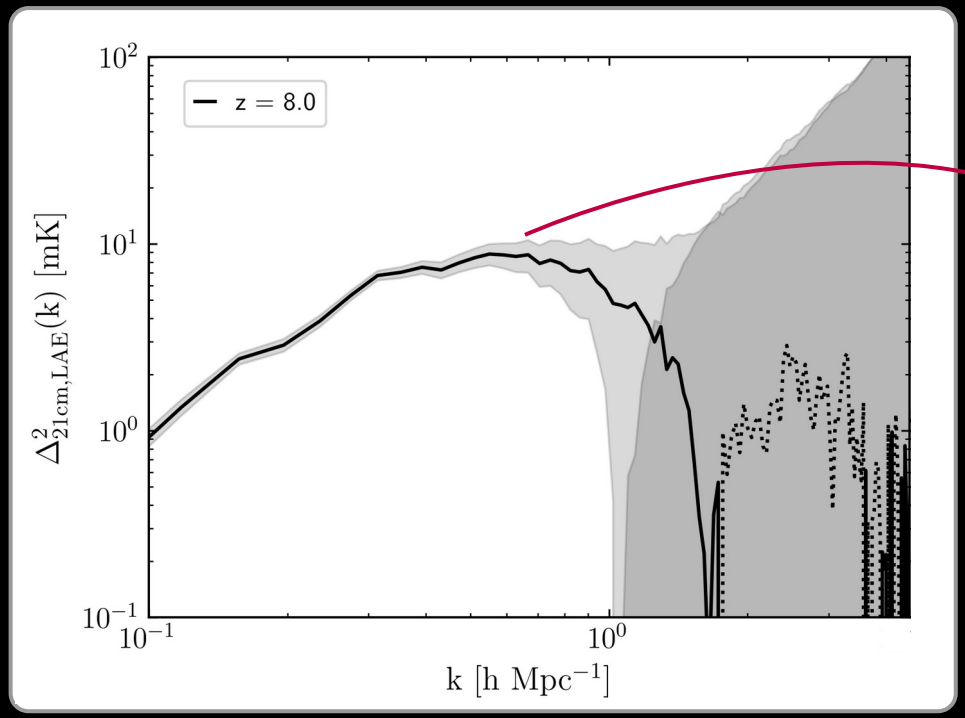
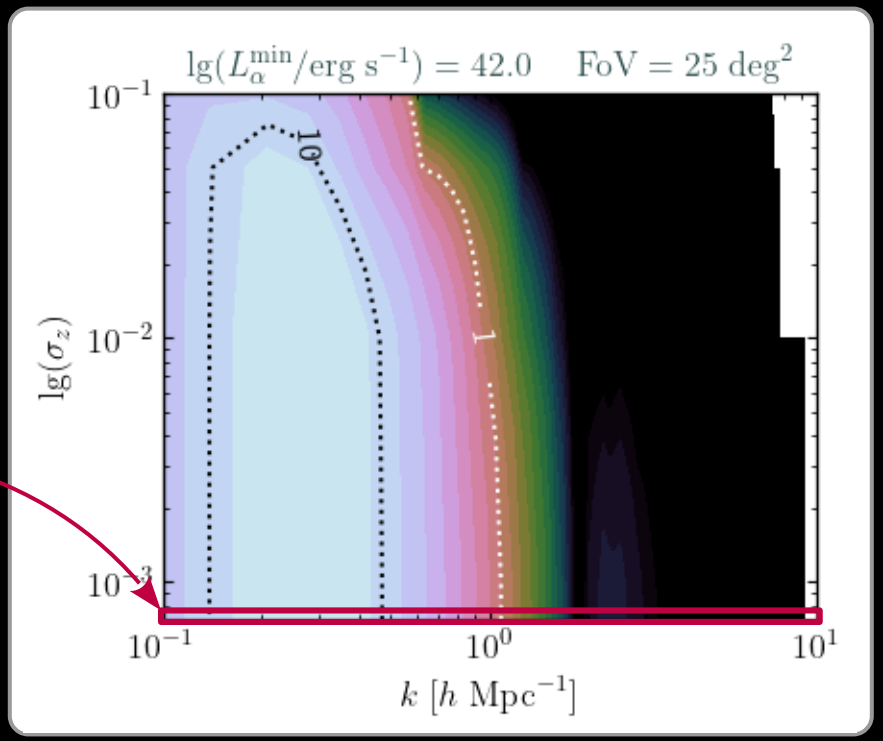


Observational uncertainties for 21cm-galaxy cross correlations

21cm: SKA1-LOW (baselines < 10km)
LAEs: Subaru Prime Focus Spectrograph *(σ_z=0.0007)*

Survey depth: $L_\alpha > 10^{42}$ erg/s
Survey area: FoV = 25 deg^2





see also LaPlante+ 2023 (HERA-Roman);
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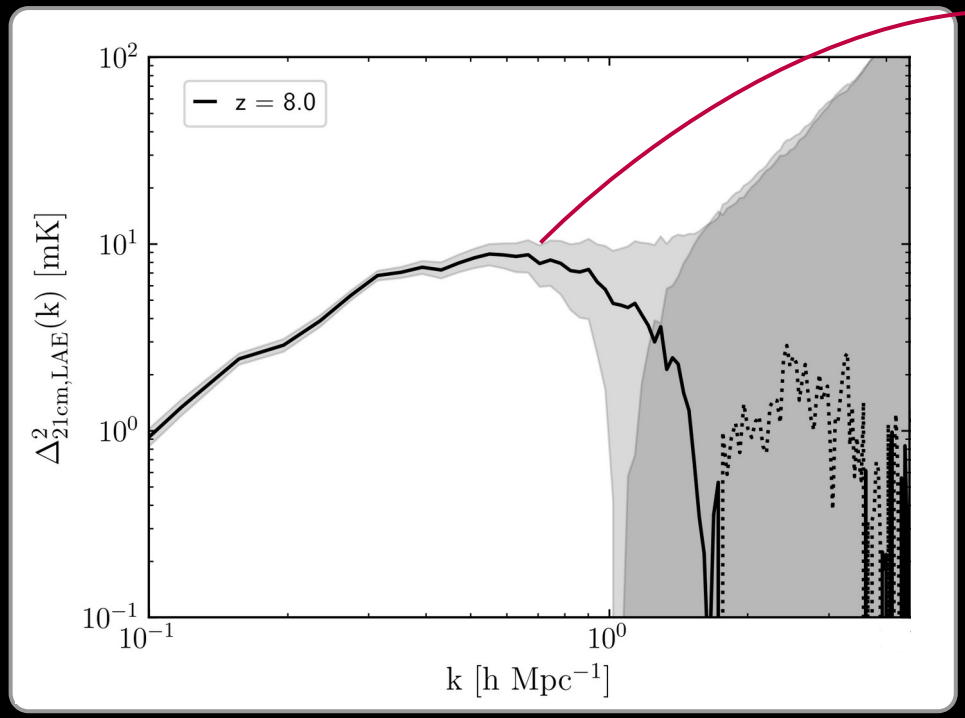

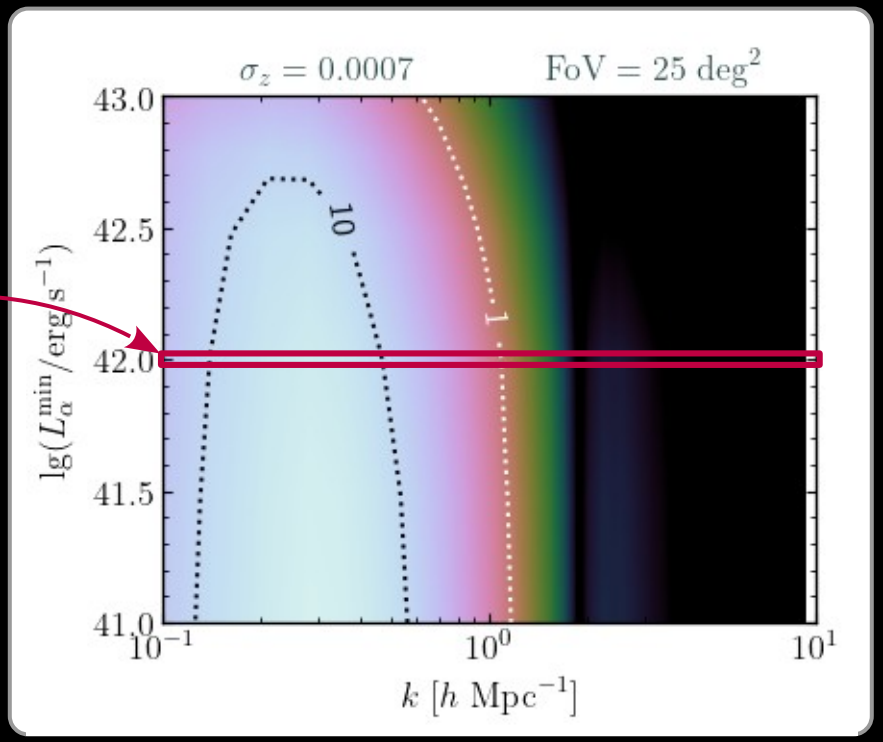

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Observational uncertainties for 21cm-galaxy cross correlations

$$\sigma^2_{21,gal}(k,\mu) = \frac{1}{2}\left[P^2_{21,gal}(k,\mu) + \left(\overbrace{P_{21}(k,\mu)}^{\text{sample variance}} + \overbrace{P^{noise}_{21}(k,\mu)}^{\text{thermal noise}}\right)\left(\overbrace{P_{gal}(k,\mu)}^{\text{sample variance}} + \overbrace{P^{noise}_{gal}(k,\mu)}^{\text{shot noise}}\right)\right]$$

$$\propto \frac{1}{t_{obs}\; n_b(k_{perp})}$$

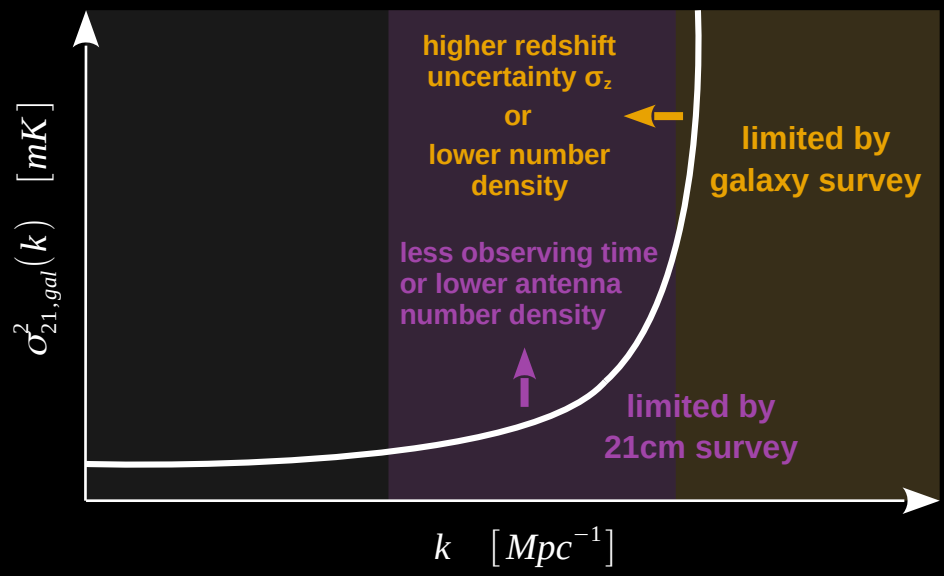
increase observing time or number density of antennas

$$\propto n_{gal}^{-1} \exp\left(k_{par}\frac{c\,\sigma_z}{H(z)}\right)$$

increase survey depth

$$\frac{1}{\sigma^2_{21,gal}(k)} = \sum_\mu N_k \frac{1}{\sigma^2_{21,gal}(k,\mu)}$$

$$N_k = \frac{k^2\,\Delta k\,\Delta\mu\,V_{surv}}{(2\pi)^2}$$



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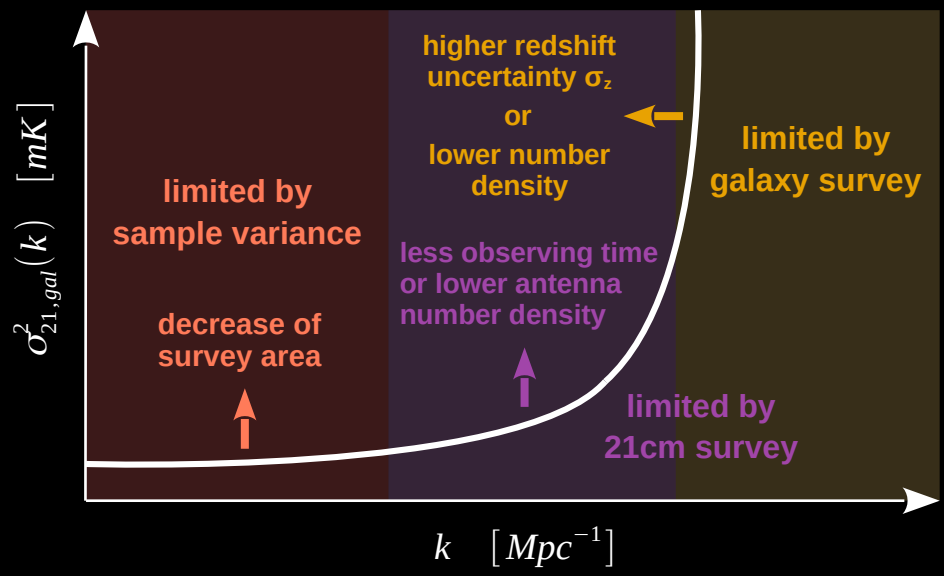
increase of survey area



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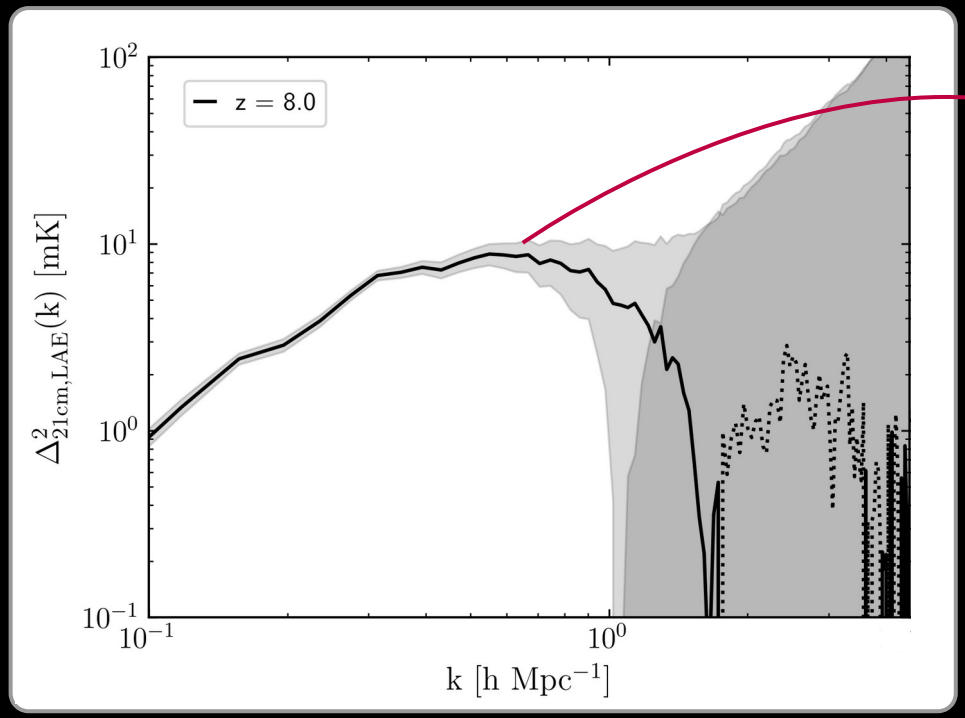

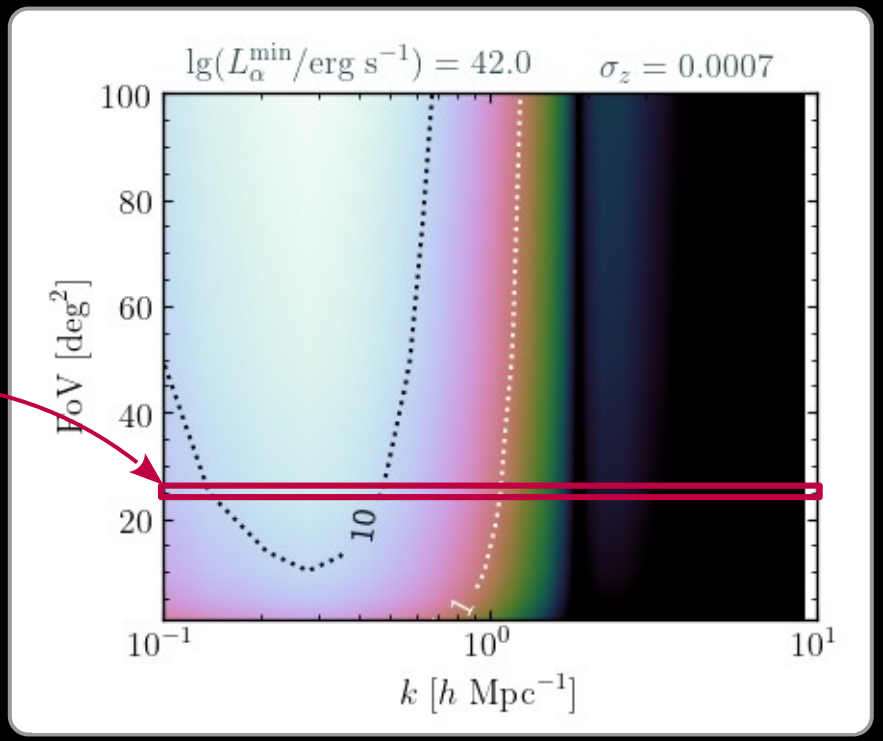

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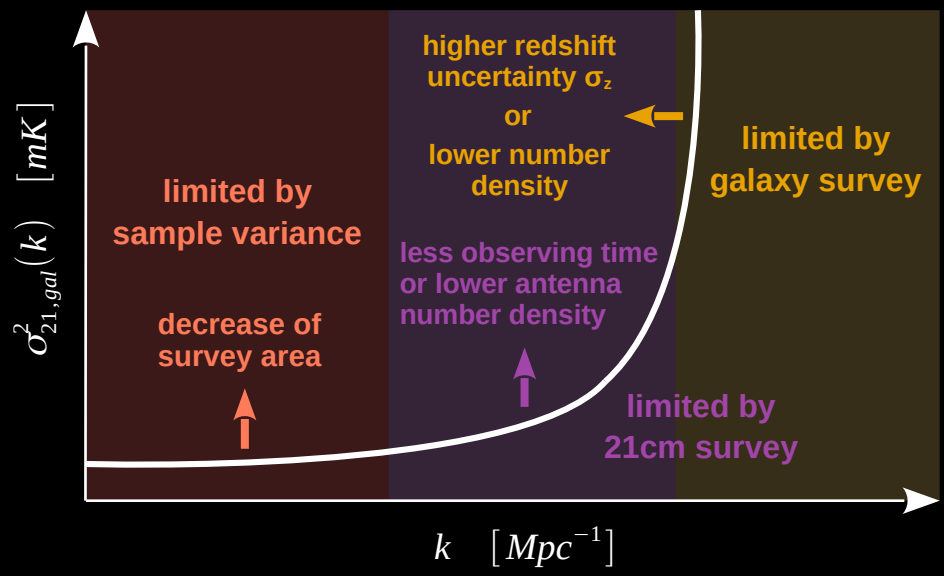
increase of survey area

21cm survey
large survey area

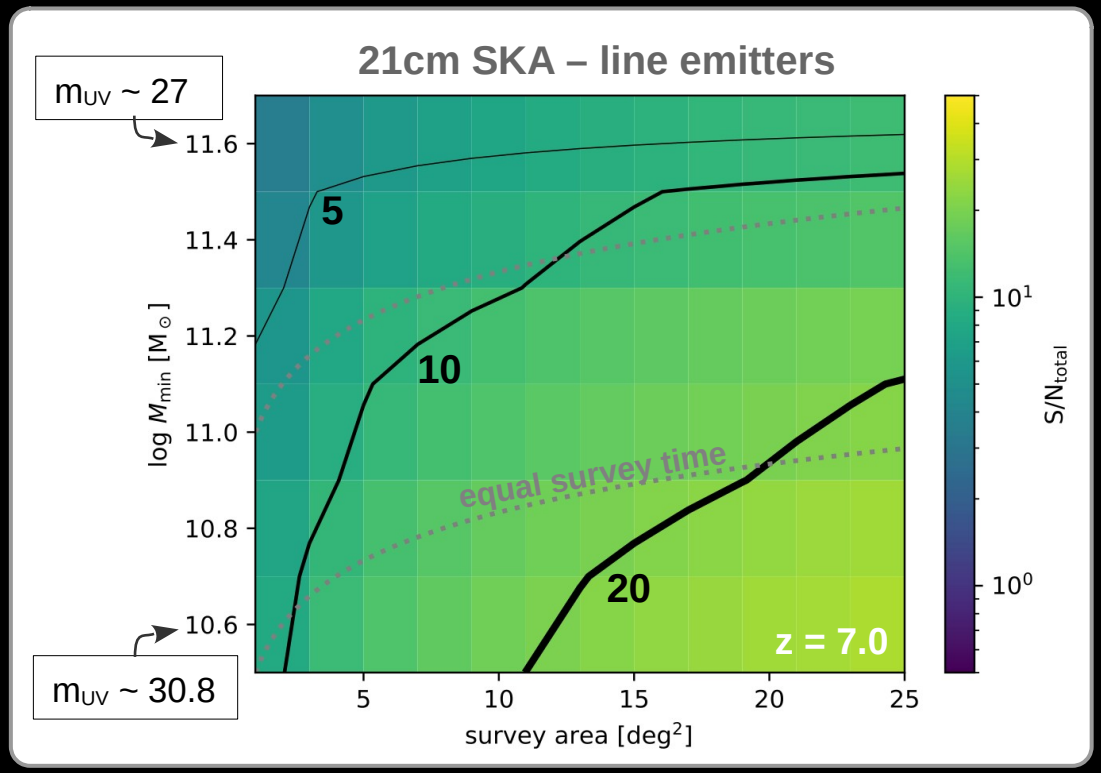
galaxy survey
large survey depth



21cm – galaxy cross correlation uncertainties forecasts

$$S/N = \sum_k \frac{\sigma^2_{21,gal}(k)}{P^2_{21,gal}(k)}$$

Moriwaki+ 2024



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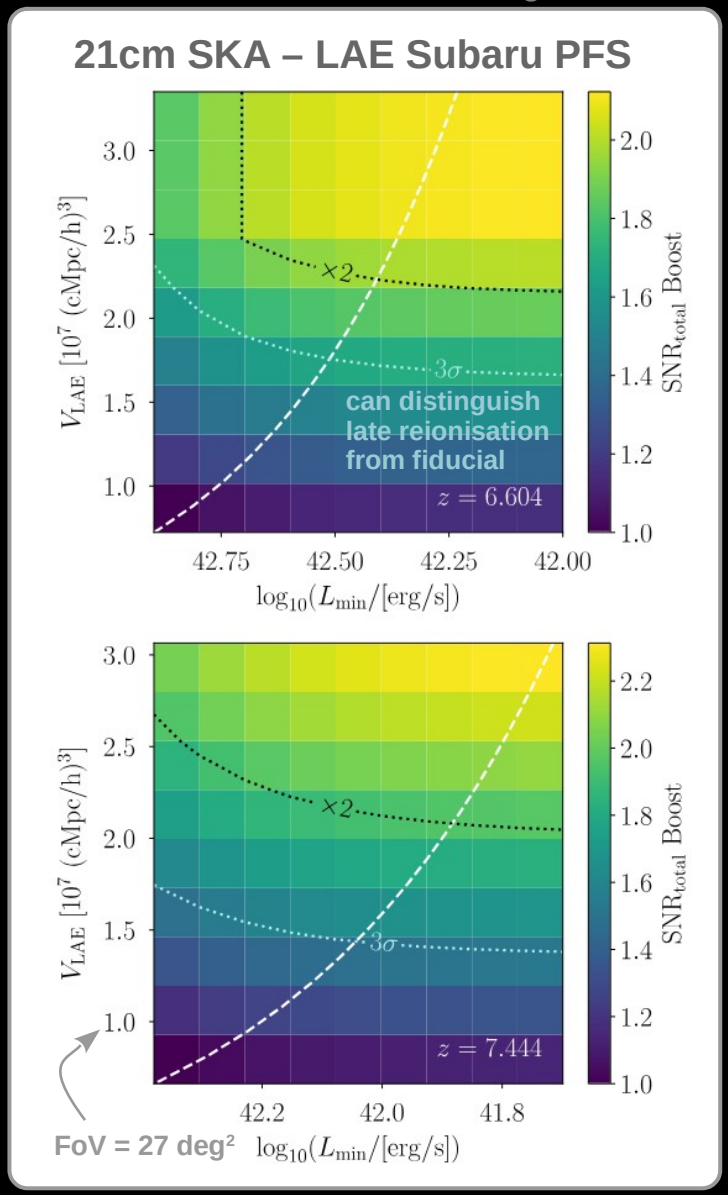
Weinberger+ 2020



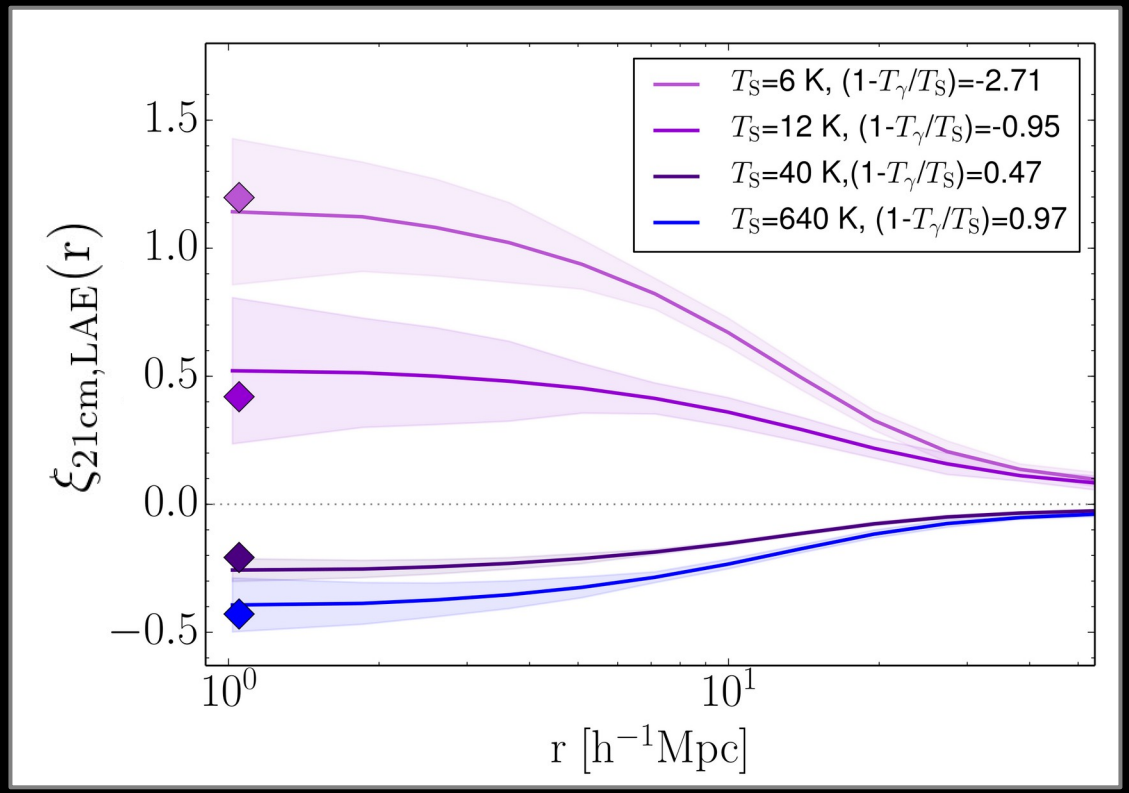
Conclusions

- **How does the large-scale 21cm – galaxy cross correlation power evolve across cosmic time?**
  - Cross power changes sign three times: onset of X-ray heating, end of X-ray heating, end of reionisation
  - Second sign change tracks when IGM is heated

- **What can we learn from the 21cm-galaxy cross correlation functions and cross power spectra during reionisation?**
  - Ionisation history and morphology:
    - Real-space small-scale amplitude traces overall IGM HI density
    - Inversion (cross correlation fuction) or sign change (cross power spectrum) trace typical size of ionised regions around galaxies

- **What type of 21cm and galaxy surveys would we need?**
  - Balance between large survey area (21cm driven uncertainties) and large survey depths (galaxy driven uncertainties): area timewise cheaper than depth

21cm – LAE cross correlations trace the 21cm profile around LAEs



EOS simulations with 21cmFAST

$(1.6\ \mathrm{Gpc})^3$ with 1024^3 cells

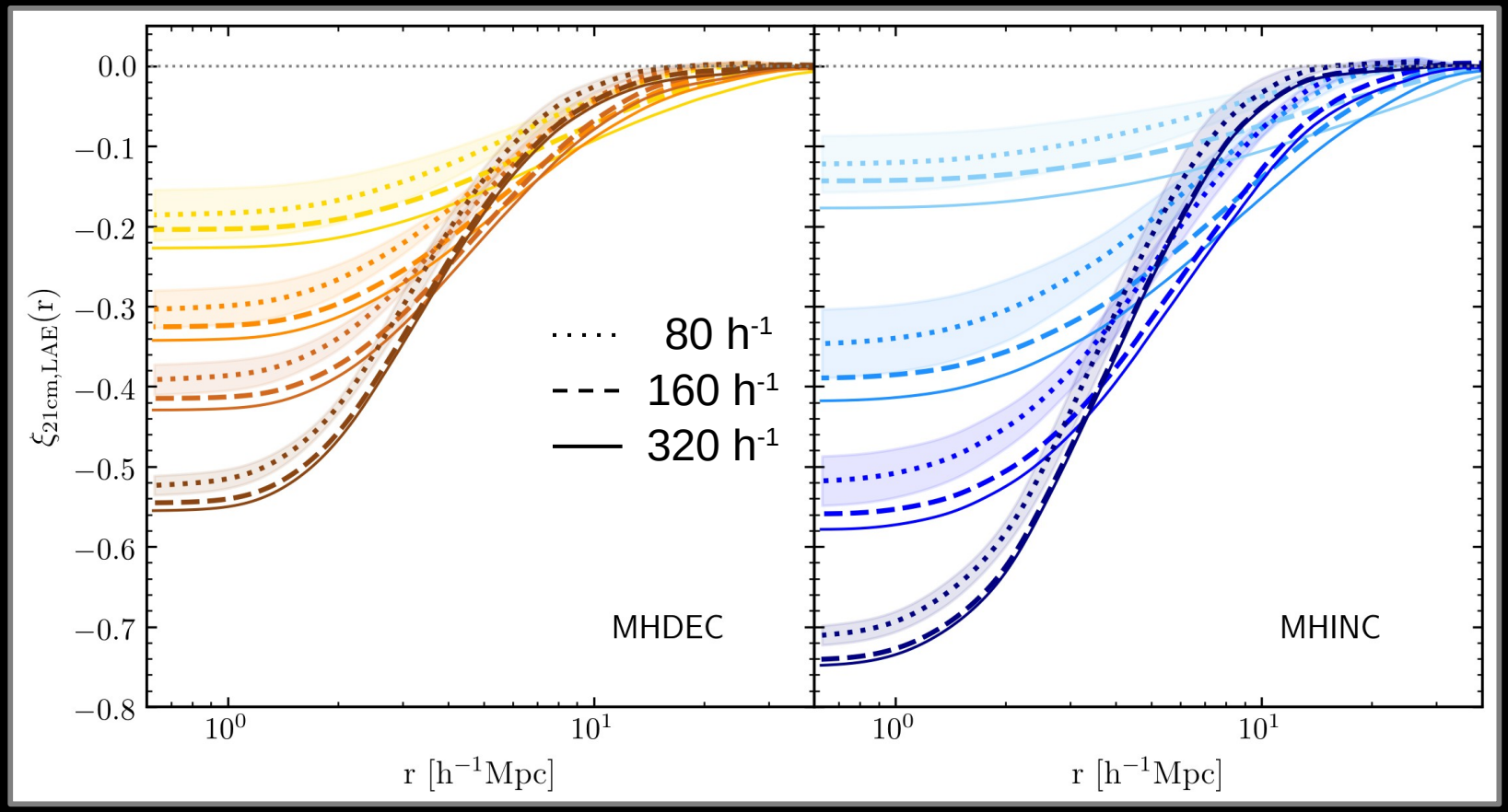
Mesinger+ 2016

LargeHII scenario:

only halos with $T_{vir} > 2 \times 10^5$ K are sources

Hutter, Heneka+ 2023

Too small boxes underestimate 21cm – LAE cross correlation amplitudes due to missing large-scale power



Simulation volumes of larger than ~(250 cMpc)^3 needed.

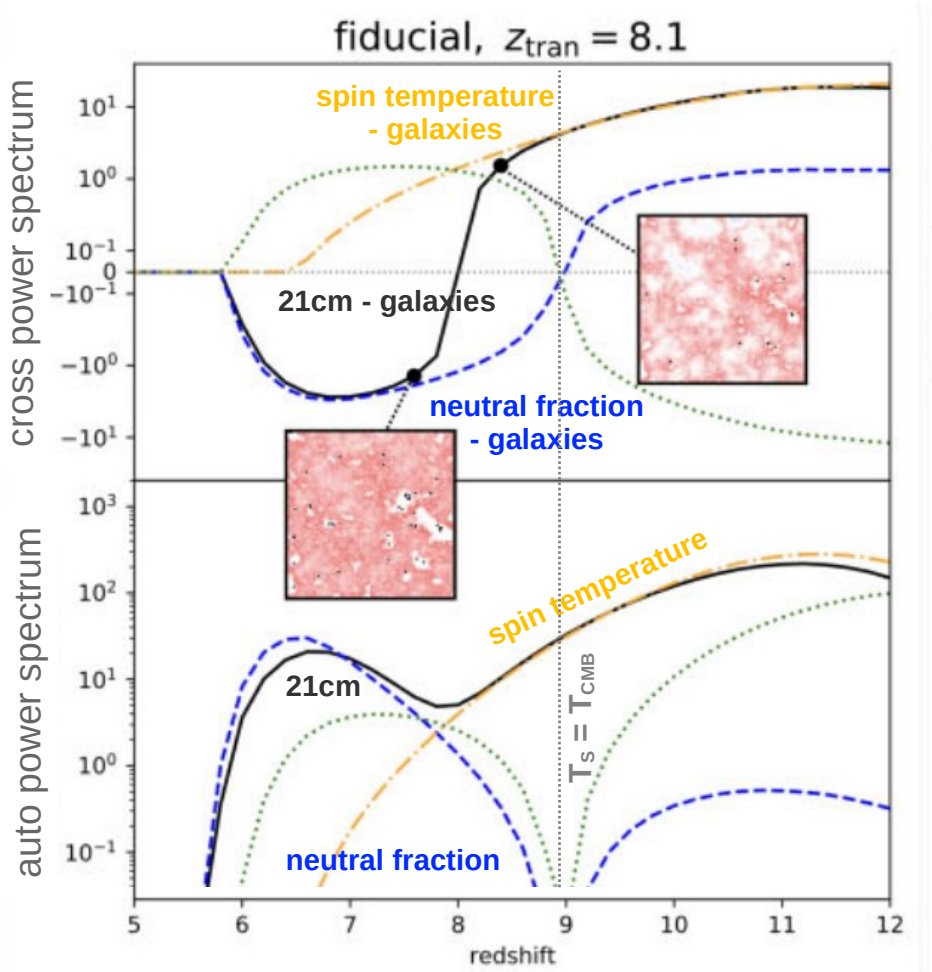
Neutral fraction and spin temperature fluctuations drive the 21cm-galaxy cross power spectrum

neutral fraction fluctuations

spin temperature fluctuations

$$\delta T_{21}(\vec{x}) = -T_0\, \chi_{HI}(\vec{x}) \left(1 - \frac{T_{CMB}}{T_s(\vec{x})}\right) \times (1+\delta(\vec{x}))\, \frac{H(z)}{H(z)+dv_{los}/dr_{los}}$$

redshift density fluctuations



Moriwaki+ 2024