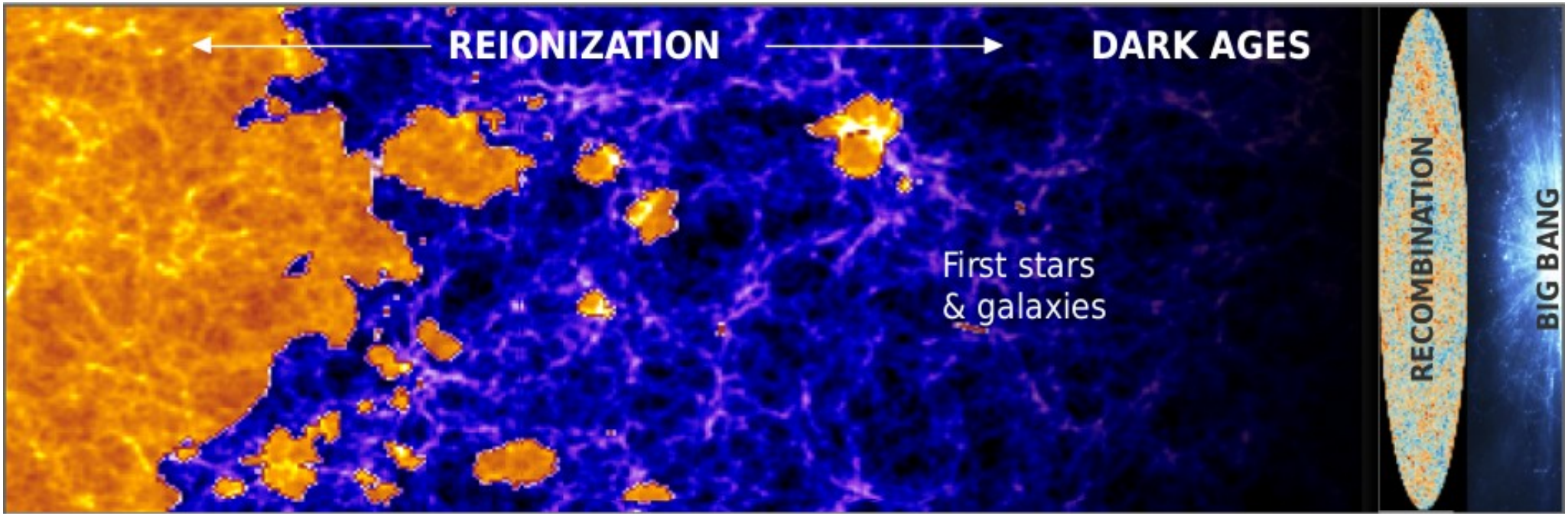

university of groningen
erc
DELPHI
Shedding light on the epoch of reionization with the 21cm signal
Anne Hutter
ASTRO 3D
ARC CENTRE OF EXCELLENCE FOR ALL SKY ASTROPHYSICS IN 3D
Catherine Watkinson, Jacob Seiler, Cathryn Trott, Pratika Dayal, Darren Croton, Manodeep Sinha,

The Epoch of Reionization

What is the reionization history, the evolution of $\langle \chi_{HI} \rangle$?

What are the sources of reionization and what is their escape fraction of ionizing photons into the IGM?



How does reionization affect galaxy formation & evolution?

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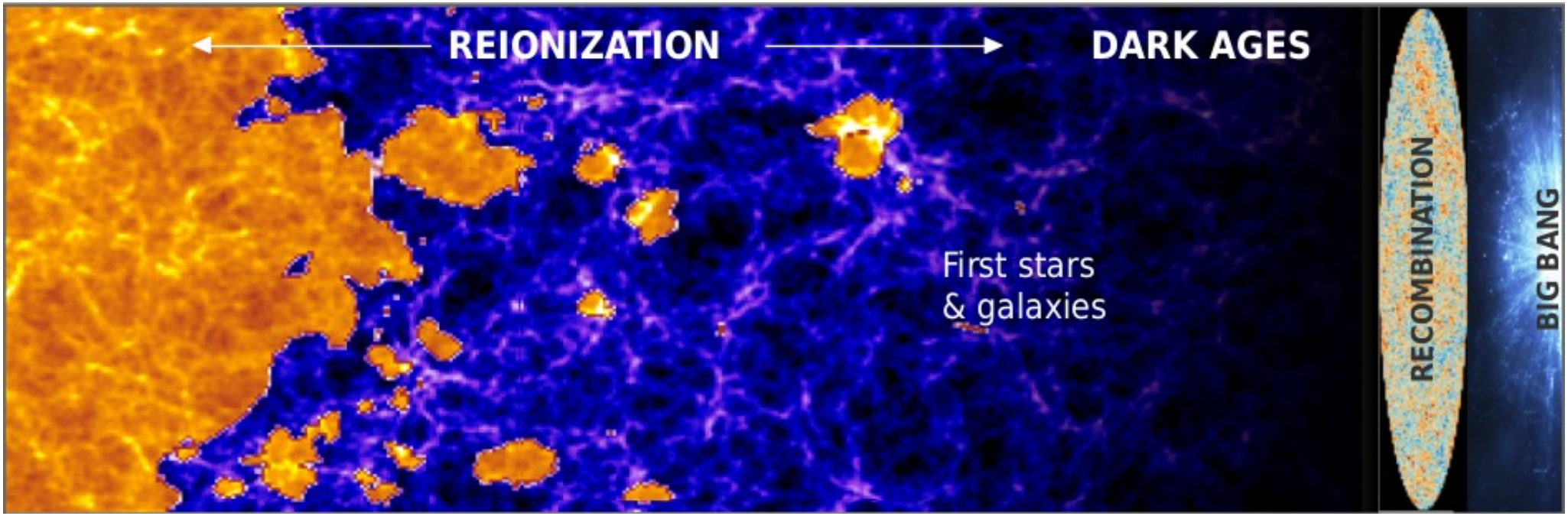

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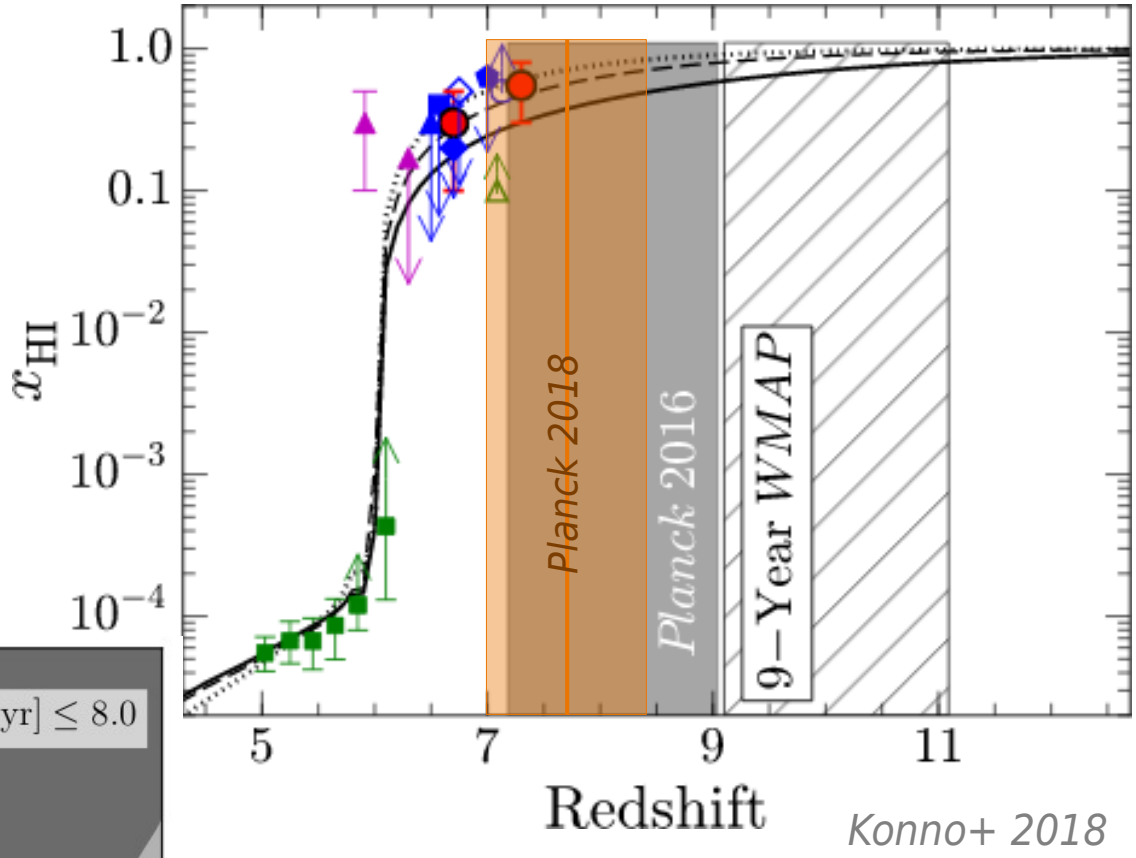
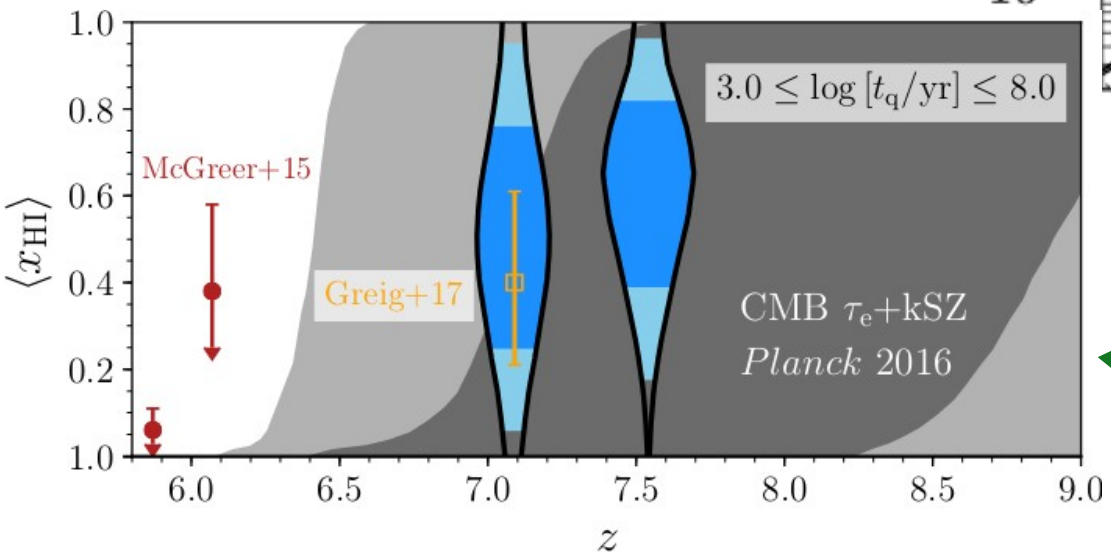
Observational constraints on reionization

- **Cosmic Microwave Background**
  optical depth τ = 0.054 ± 0.007
- **QSO absorption spectra**
- **Lyman-α emitter luminosity function & clustering**
- **GRB afterglow spectra**



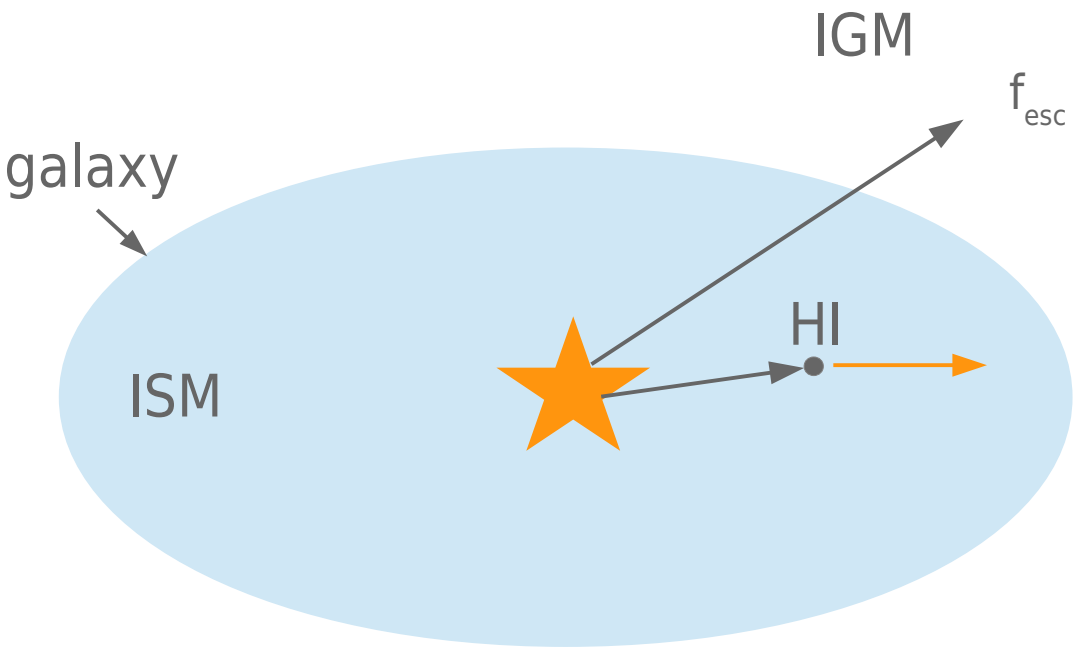
Konno+ 2018

Davies+ 2018



IGM damping wing in QSO absorption spectra during reionization

Lyman α emitters (LAEs) in the intergalactic medium



f_{esc} = escape fraction of ionizing photons (λ<912Å)

Lyman α photons emitted (recombination radiation)

ISM = interstellar medium
IGM = intergalactic medium

Hutter+ 2014

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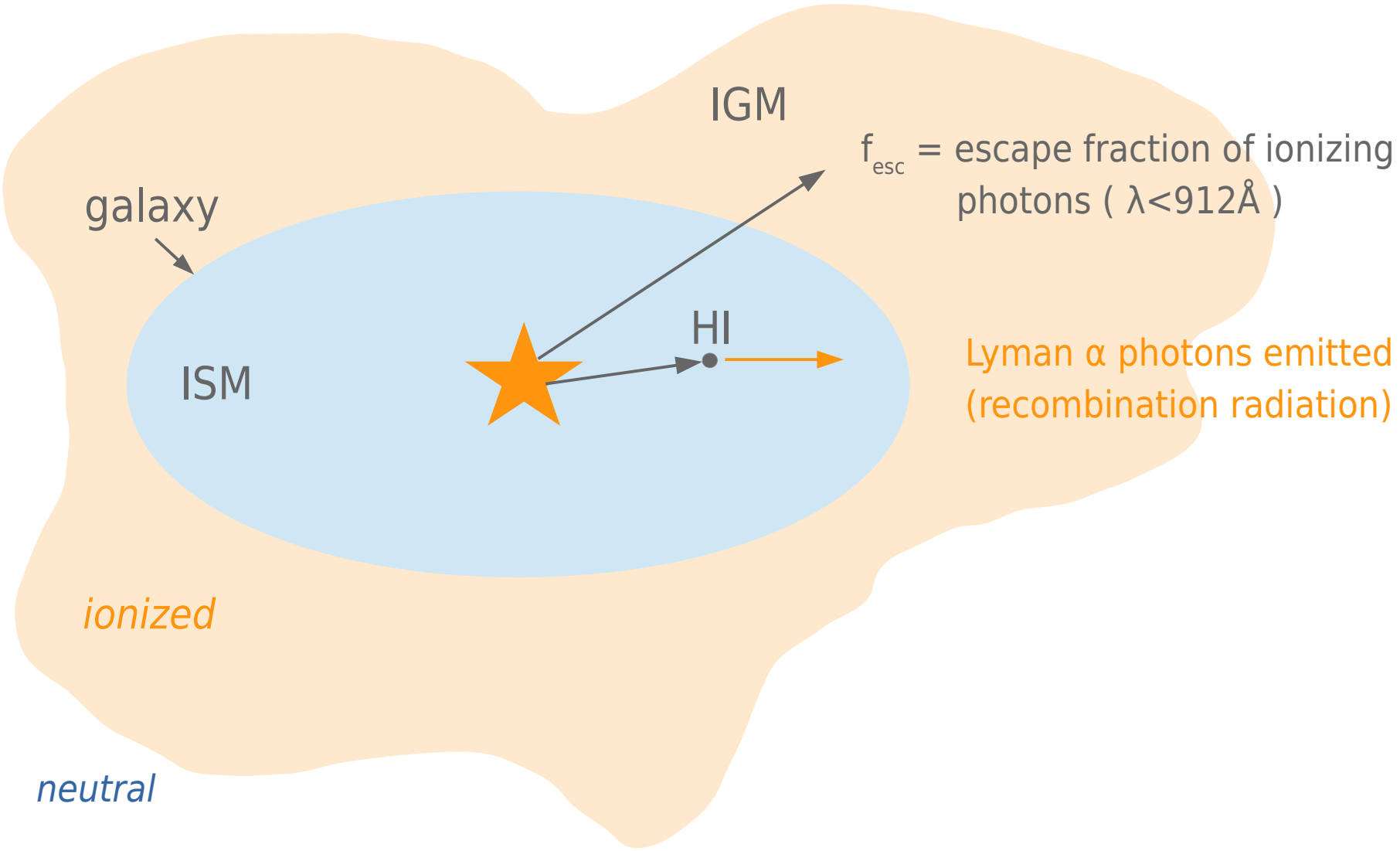

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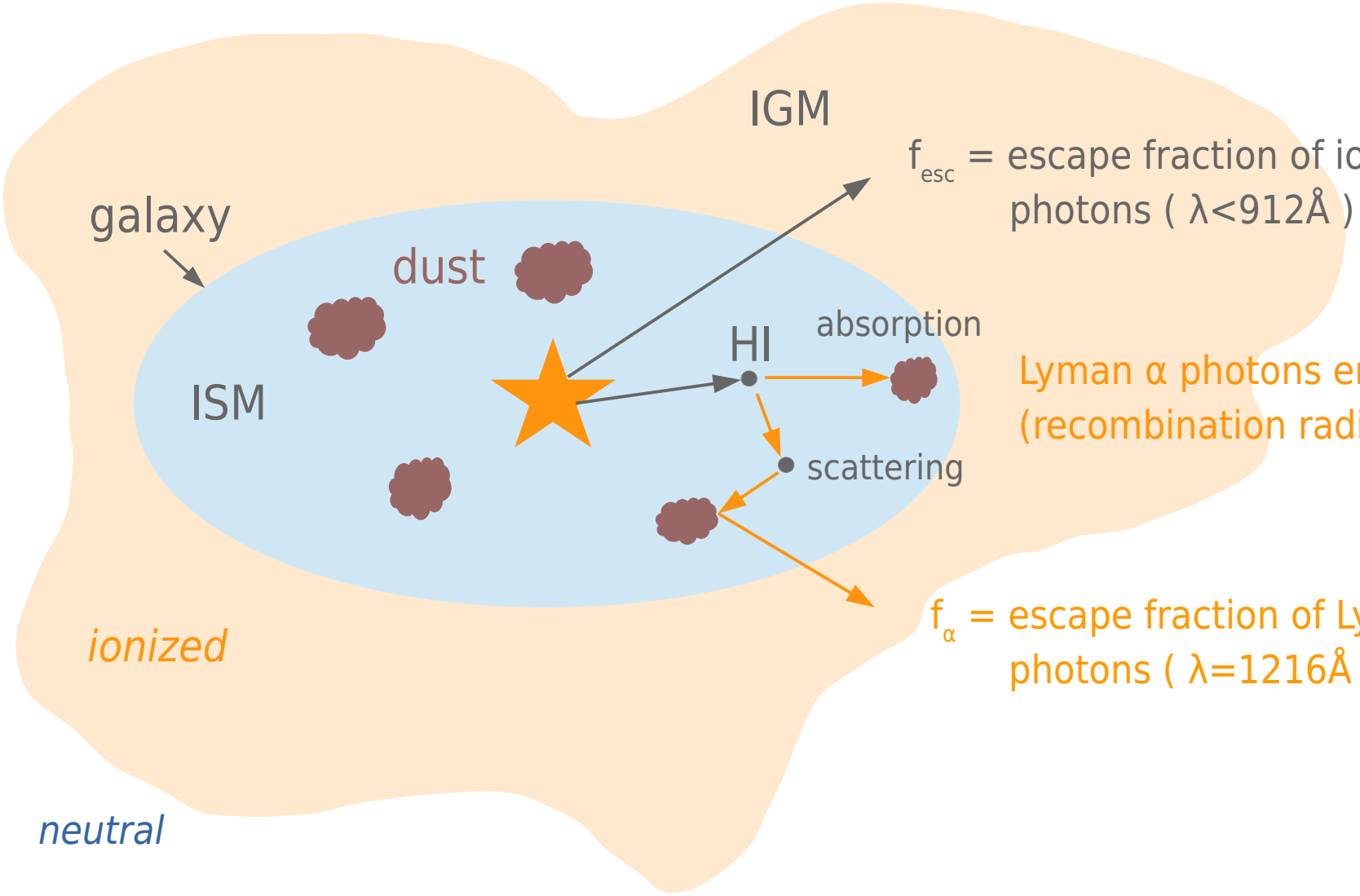

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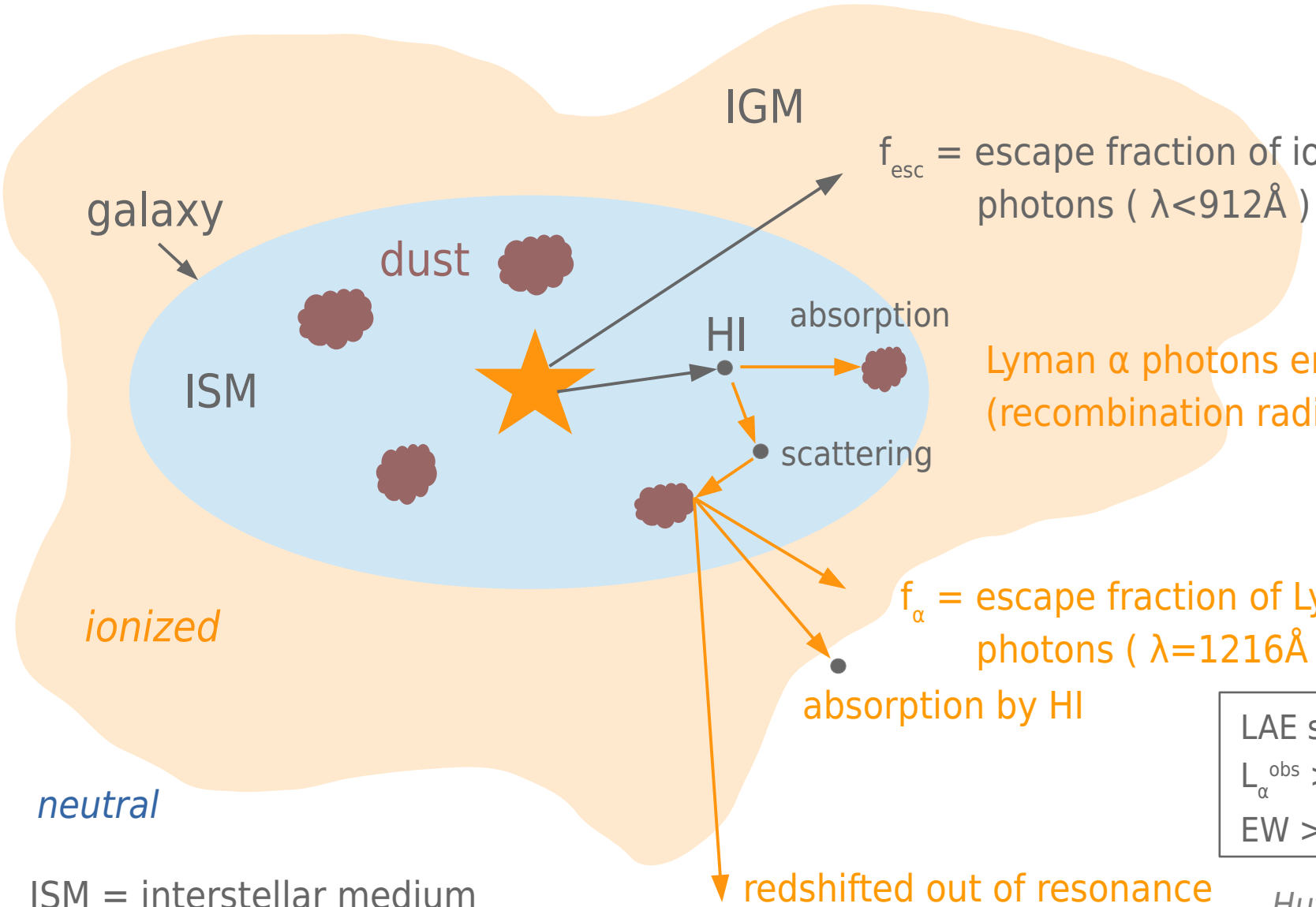

LAE selection criteria:
L_{α}^{obs} >10^{42} erg s^{-1}
EW > 20 Å

Hutter+ 2014

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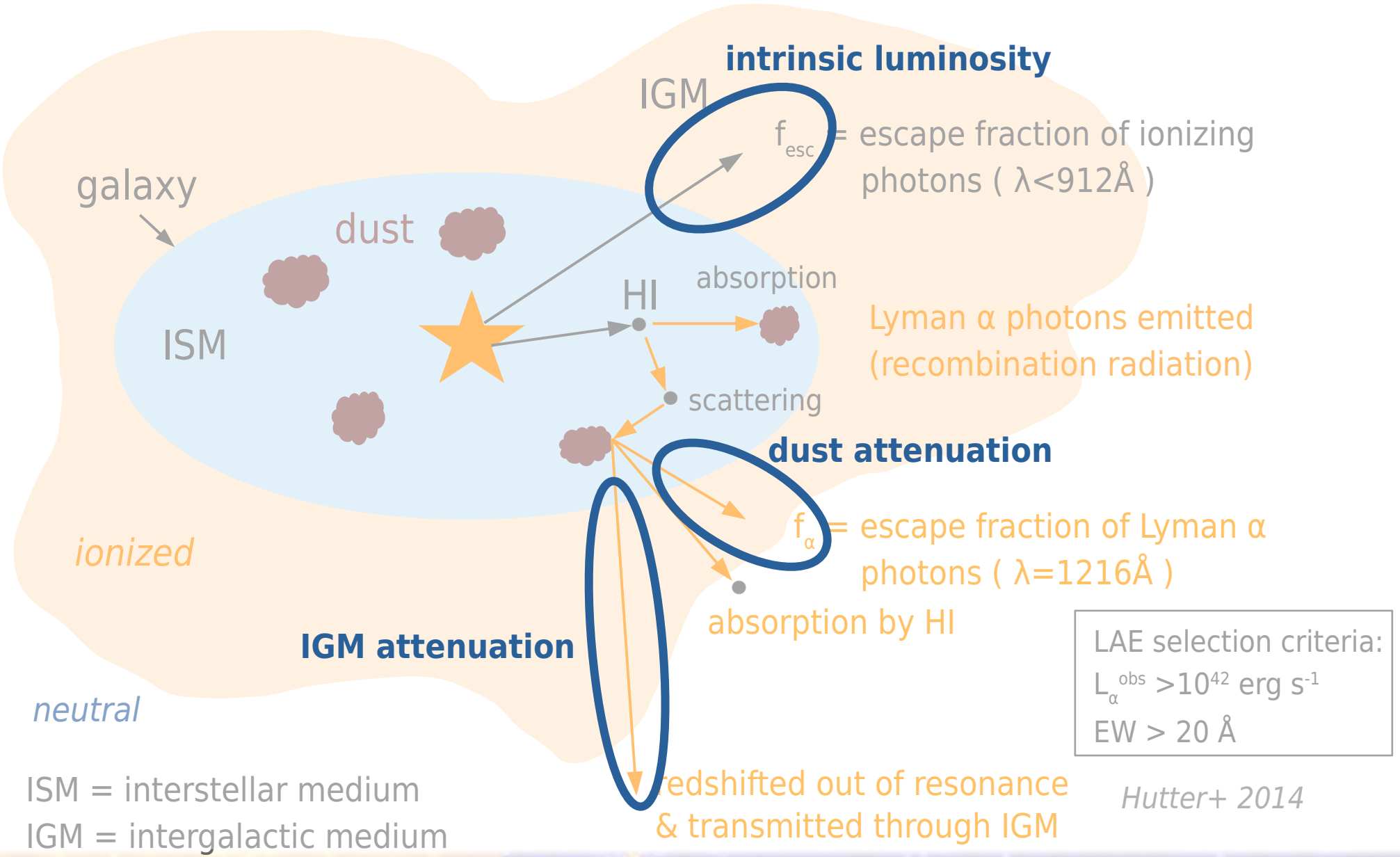

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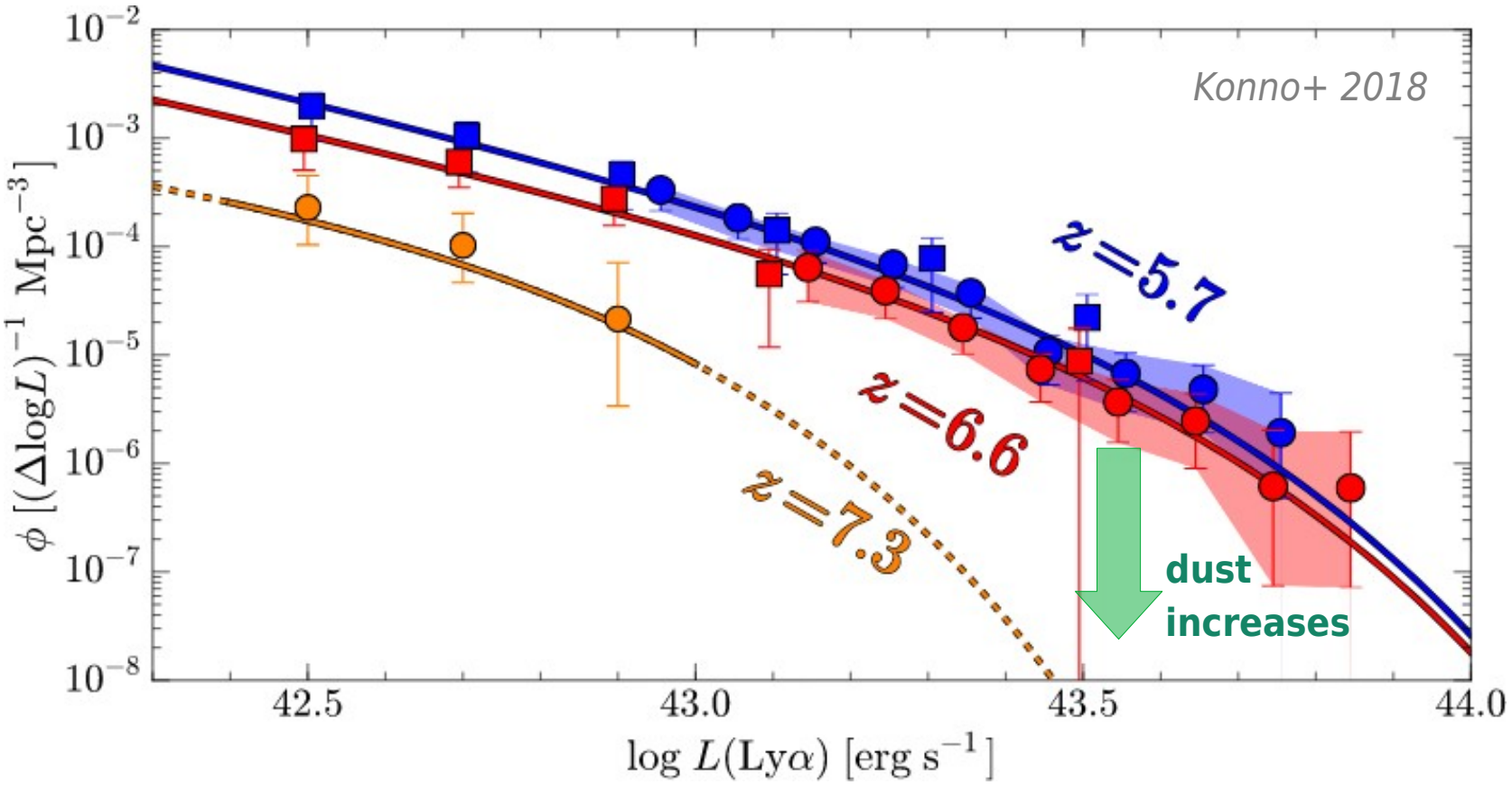
Lyman α emitters as probe of reionization



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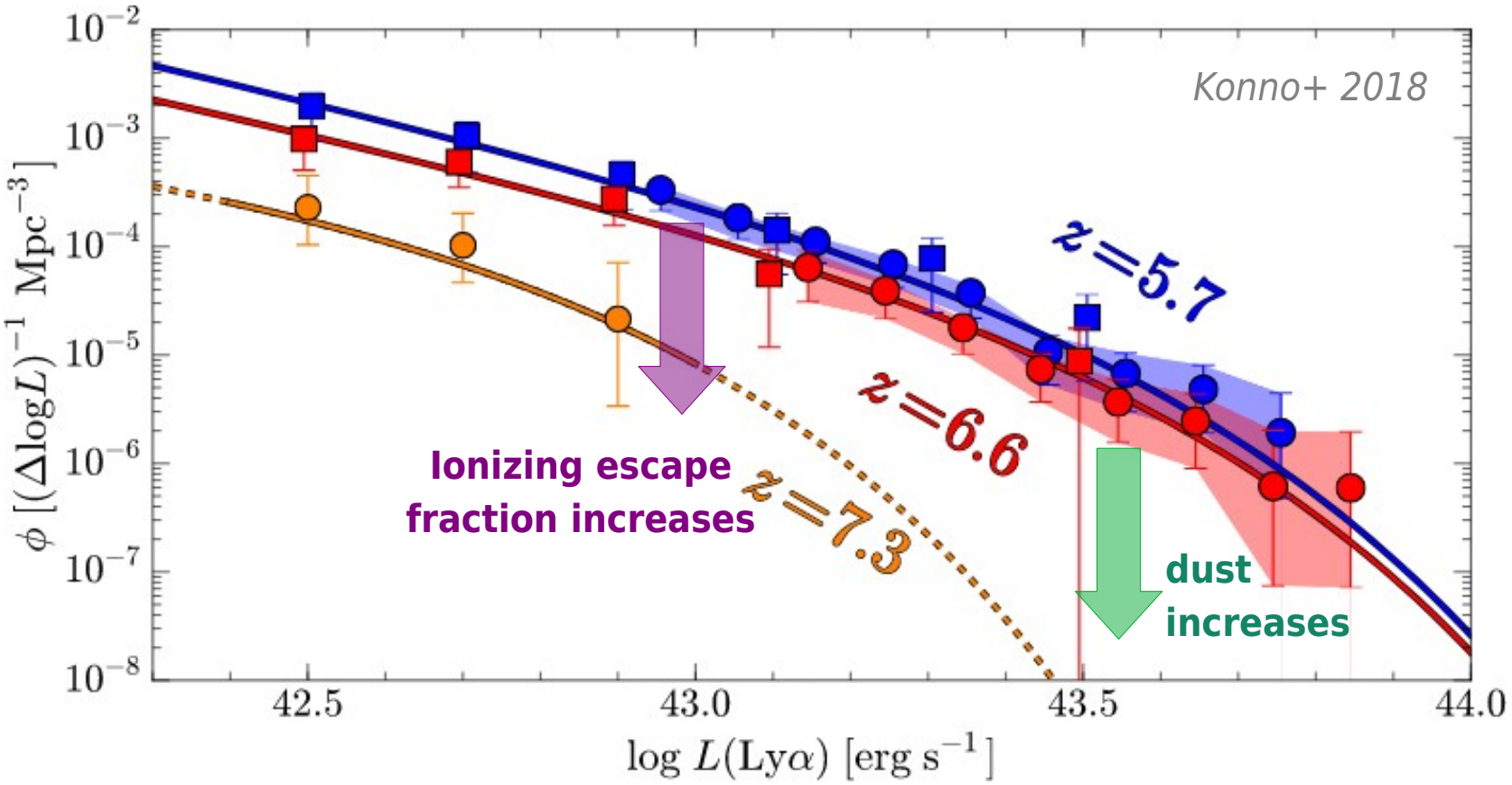

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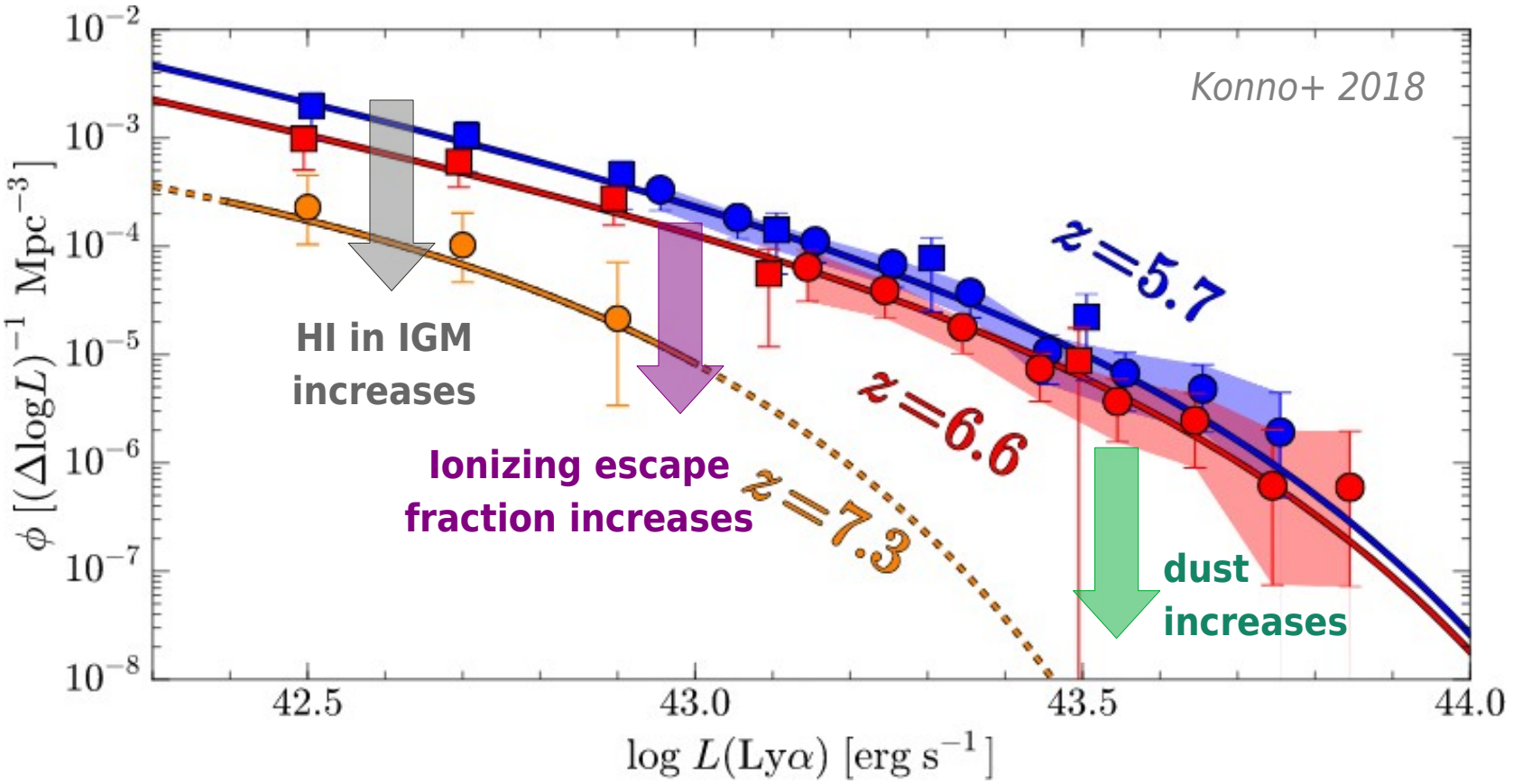
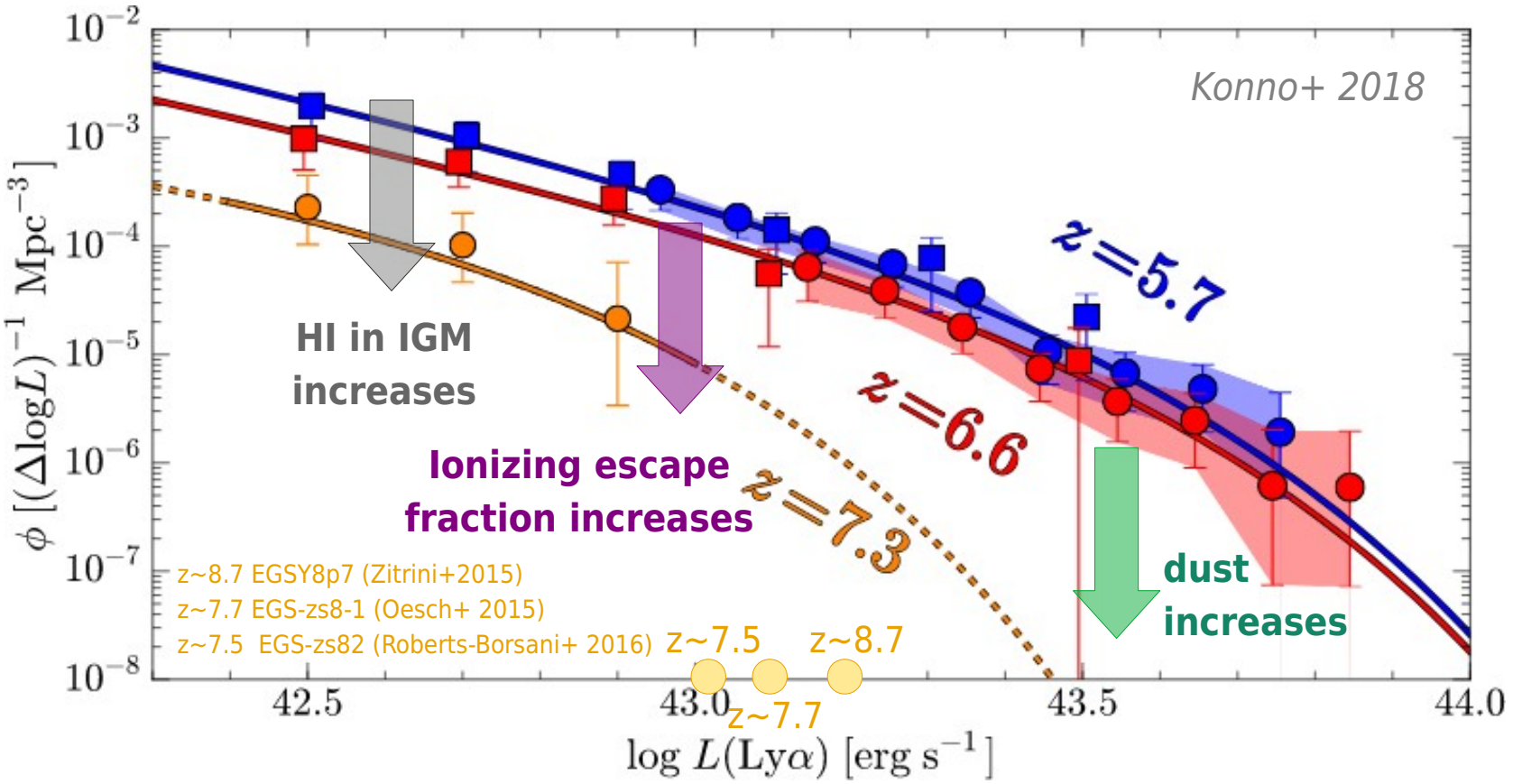


Degeneracy between the **ionizing escape fraction**, **dust attenuation** & **reionization** *(Hutter+ 2014)*

Lyman α emitters as probe of reionization



Degeneracy between the **ionizing escape fraction**,

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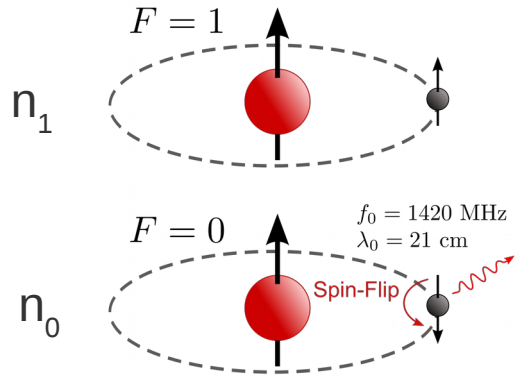
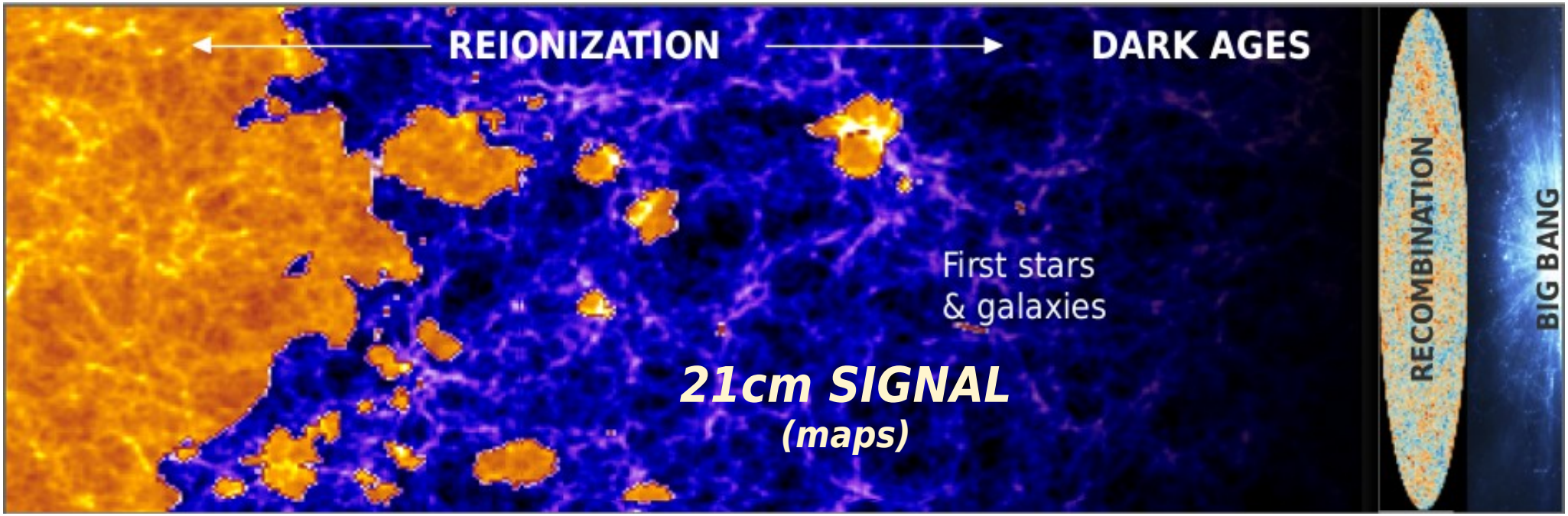
Ionization topology with the 21cm signal

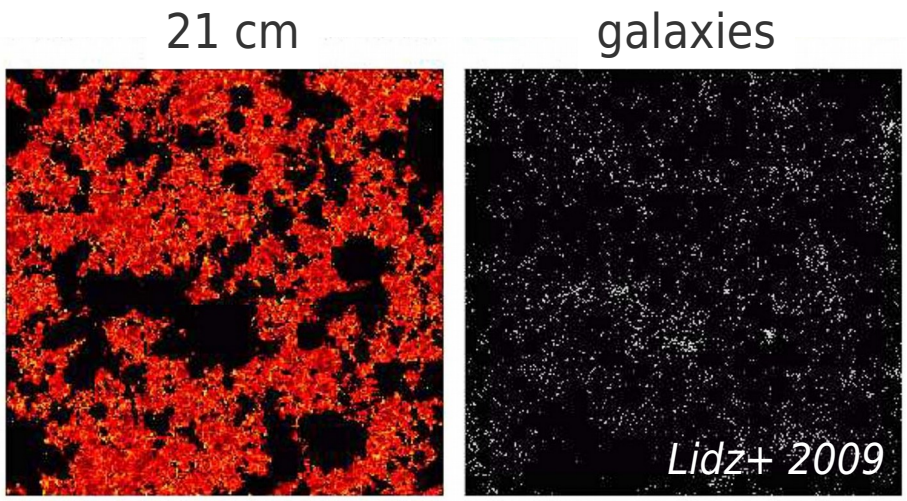


Distribution of atoms in states F=0 and F=1 is given by the **spin temperature T_s** & controls **intensity of the 21cm signal**



During the Epoch of Reionization the 21cm signal traces the **neutral hydrogen density.** Ionized regions appear as holes.

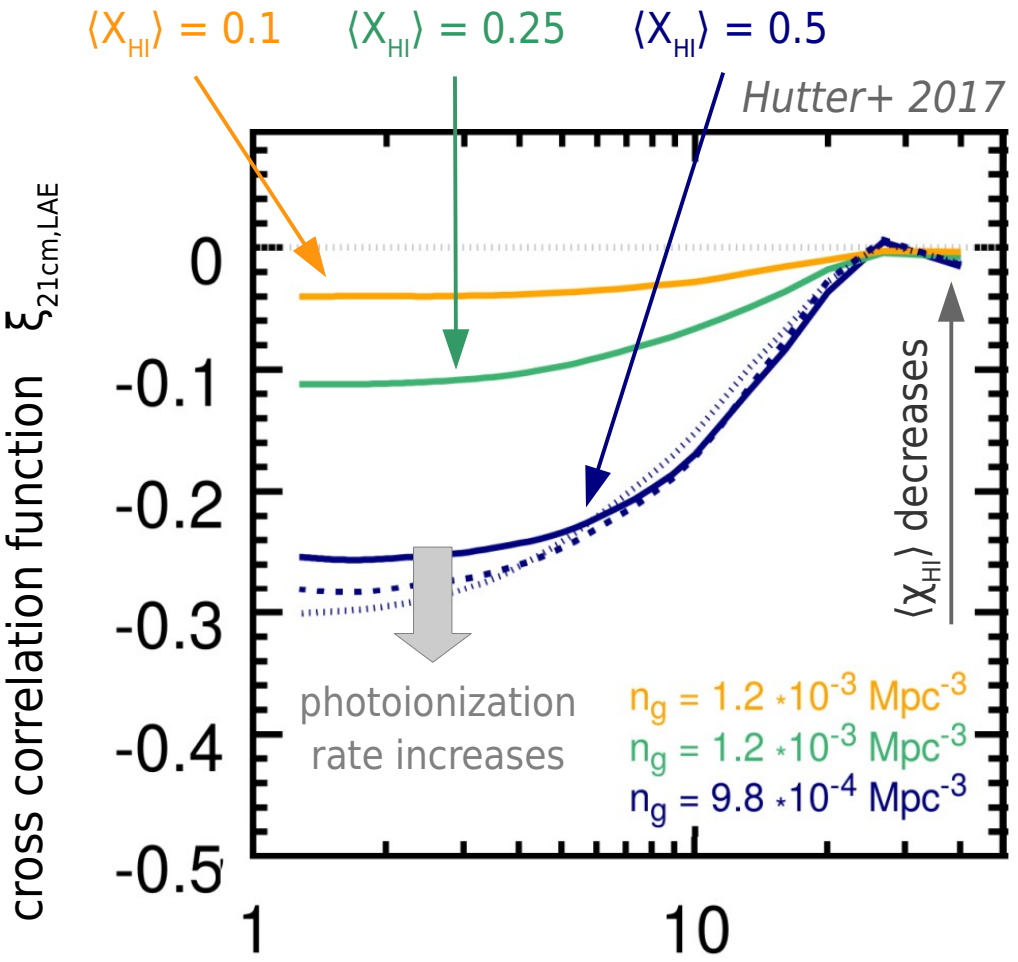
Constraining reionization with 21cm - LAE cross correlations



21cm-LAE cross correlations trace:

- IGM ionization state (amplitude)
- size of ionized regions around LAEs (turn over)

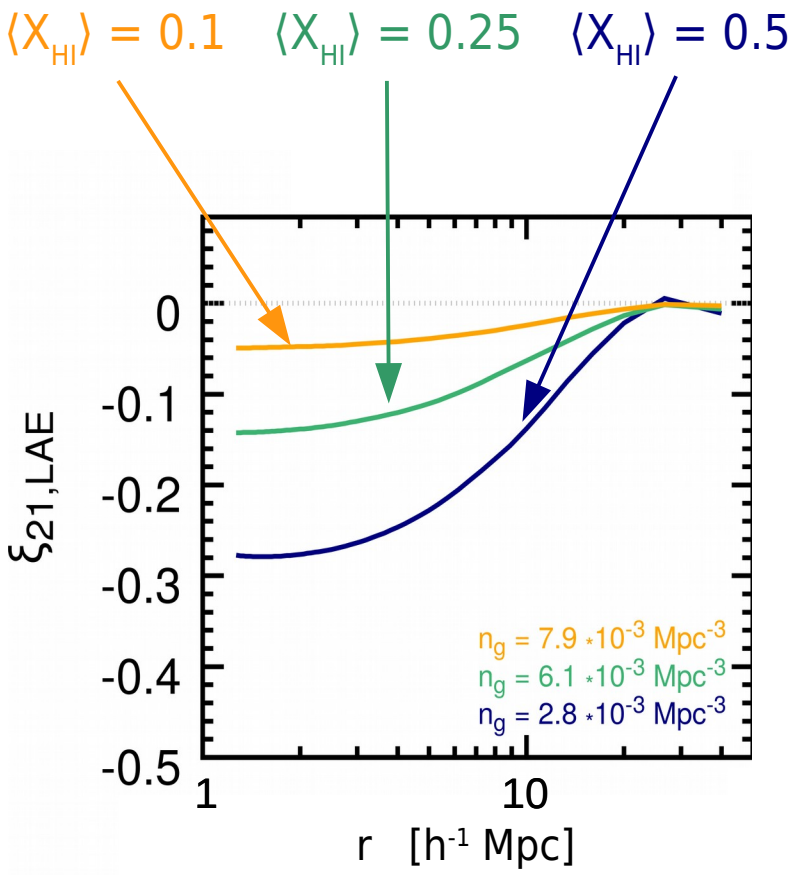
see also Vrbanec+2016, 2019, Sobacchi+ 2016, Heneka+2017, Kubota+2018



Hydro + RT 80h^{-1} Mpc box

Best survey parameters for detecting 21cm-LAE cross correlations with SKA

Hutter+ 2018



Survey volume ⟷ ***Survey luminosity limit***

decreases

decreases

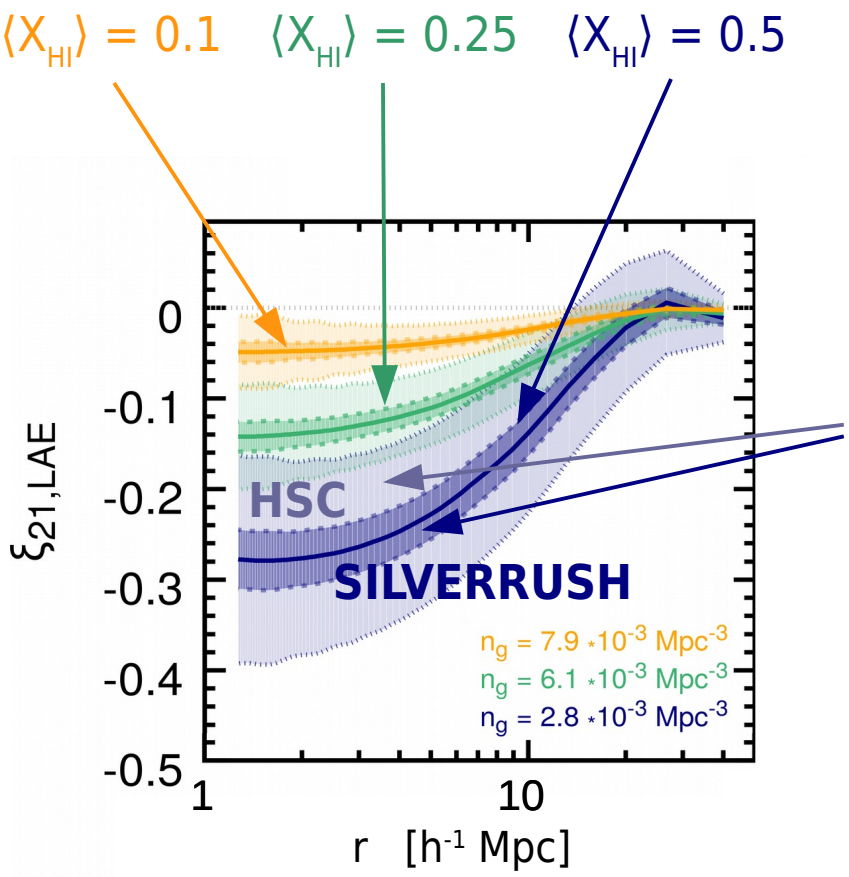
21cm sample variance | thermal noise | LAE sample variance | shot noise

$$\delta P^2_{21,LAE}(\boldsymbol{k}) = 2\ P^2_{21,LAE}(\boldsymbol{k}) + 2\ [P_{21}(\boldsymbol{k}) + \sigma^2_{21}(\boldsymbol{k})]\ [P_{LAE}(\boldsymbol{k}) + \sigma^2_{LAE}(\boldsymbol{k})]$$

Best survey parameters for detecting 21cm-LAE cross correlations with SKA

Hutter+ 2018

z = 6.6 Δz = 0.1
HSC: 1.8 deg²
SILVERRUSH: 21 deg²



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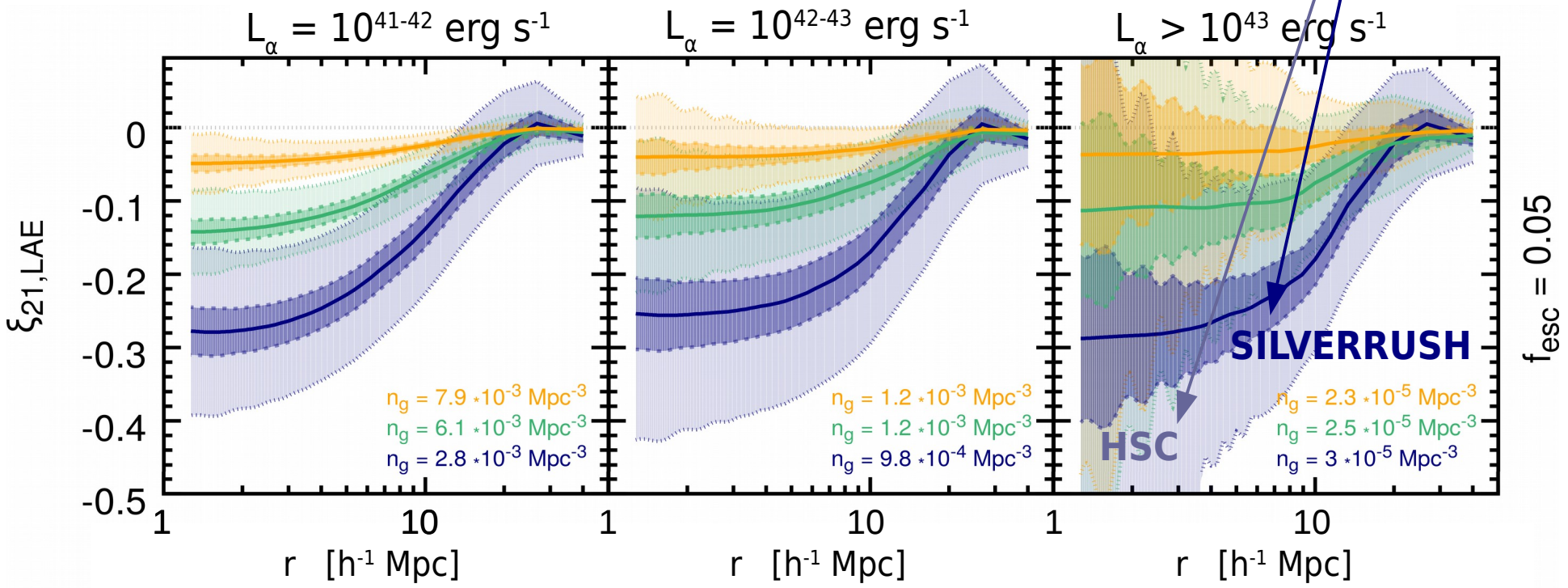

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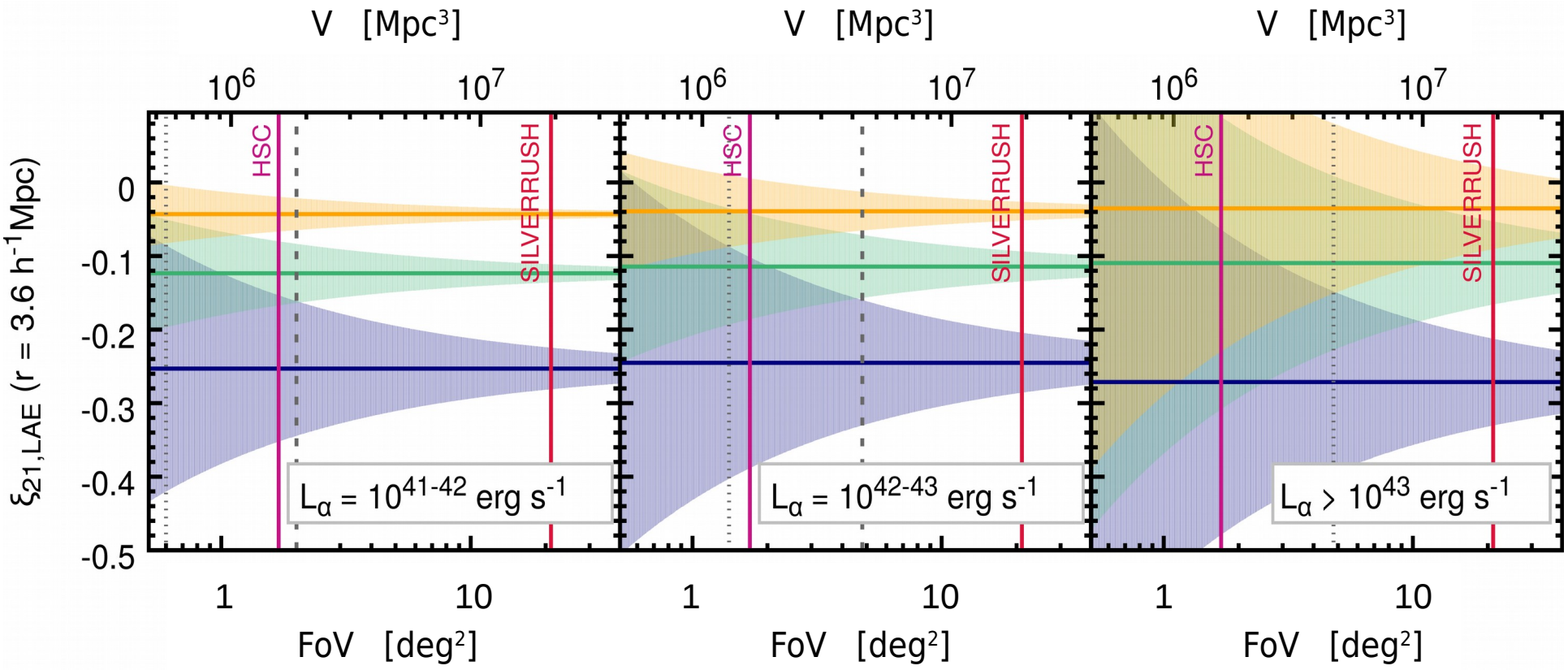
Hutter+ 2018, 2019



With current instruments shallow large FoV surveys are achievable

FoV > 20 deg² *and* ***L_α > 8x10⁴² erg s⁻¹***

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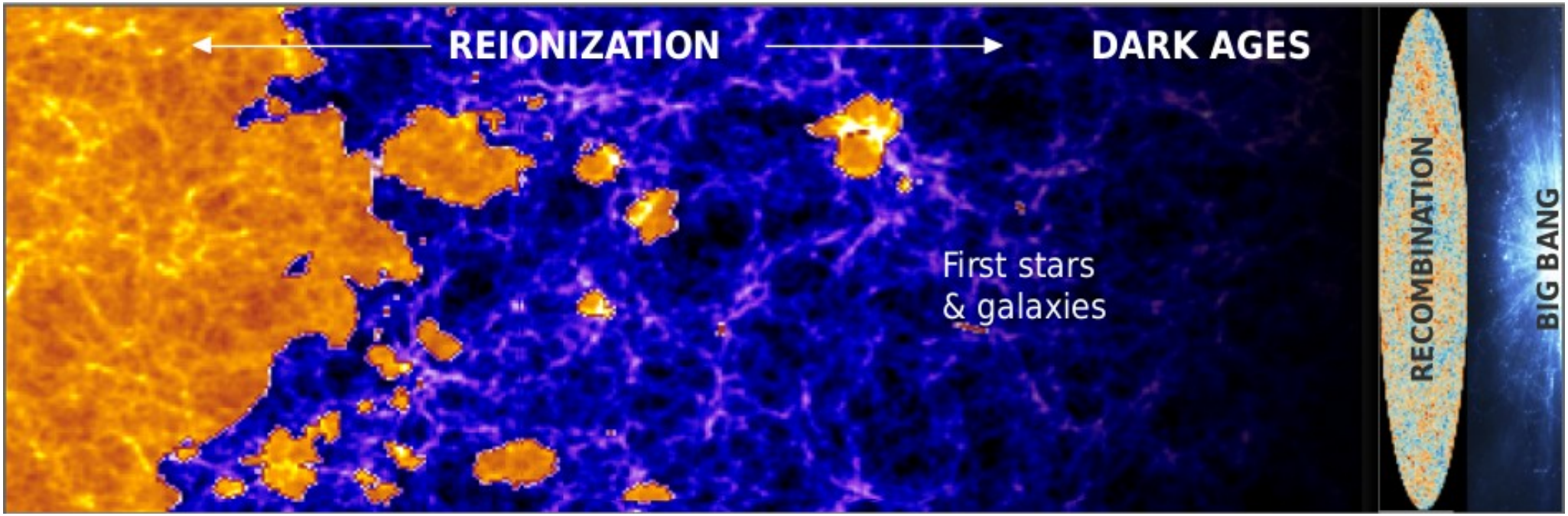

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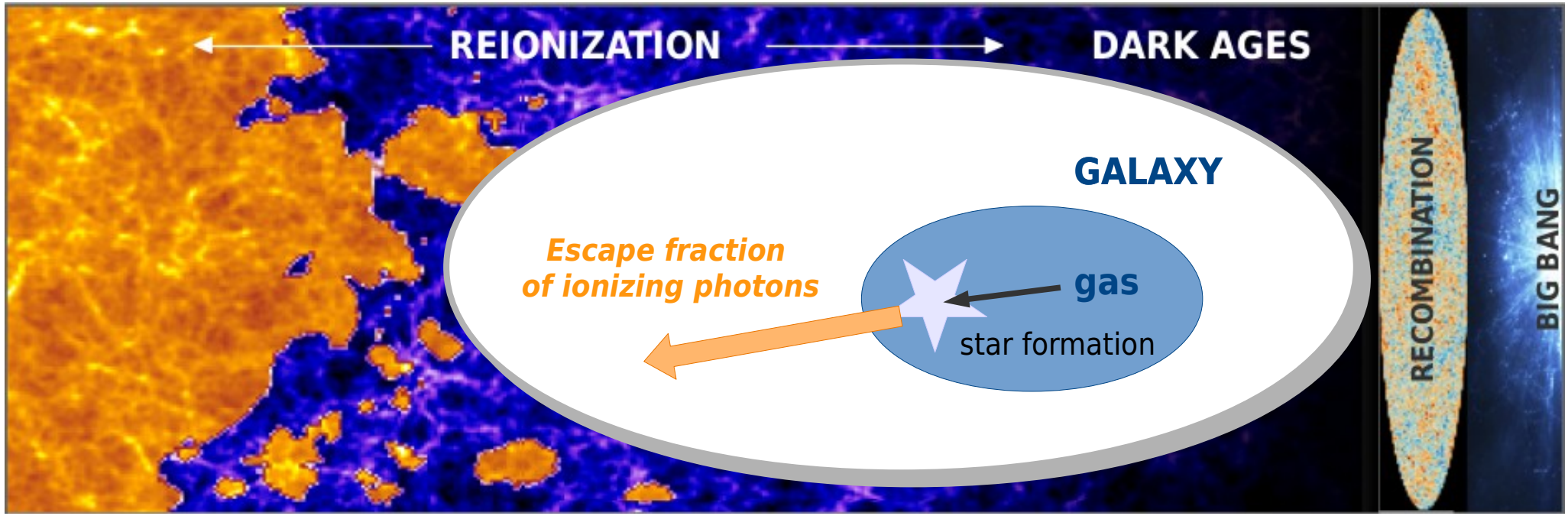

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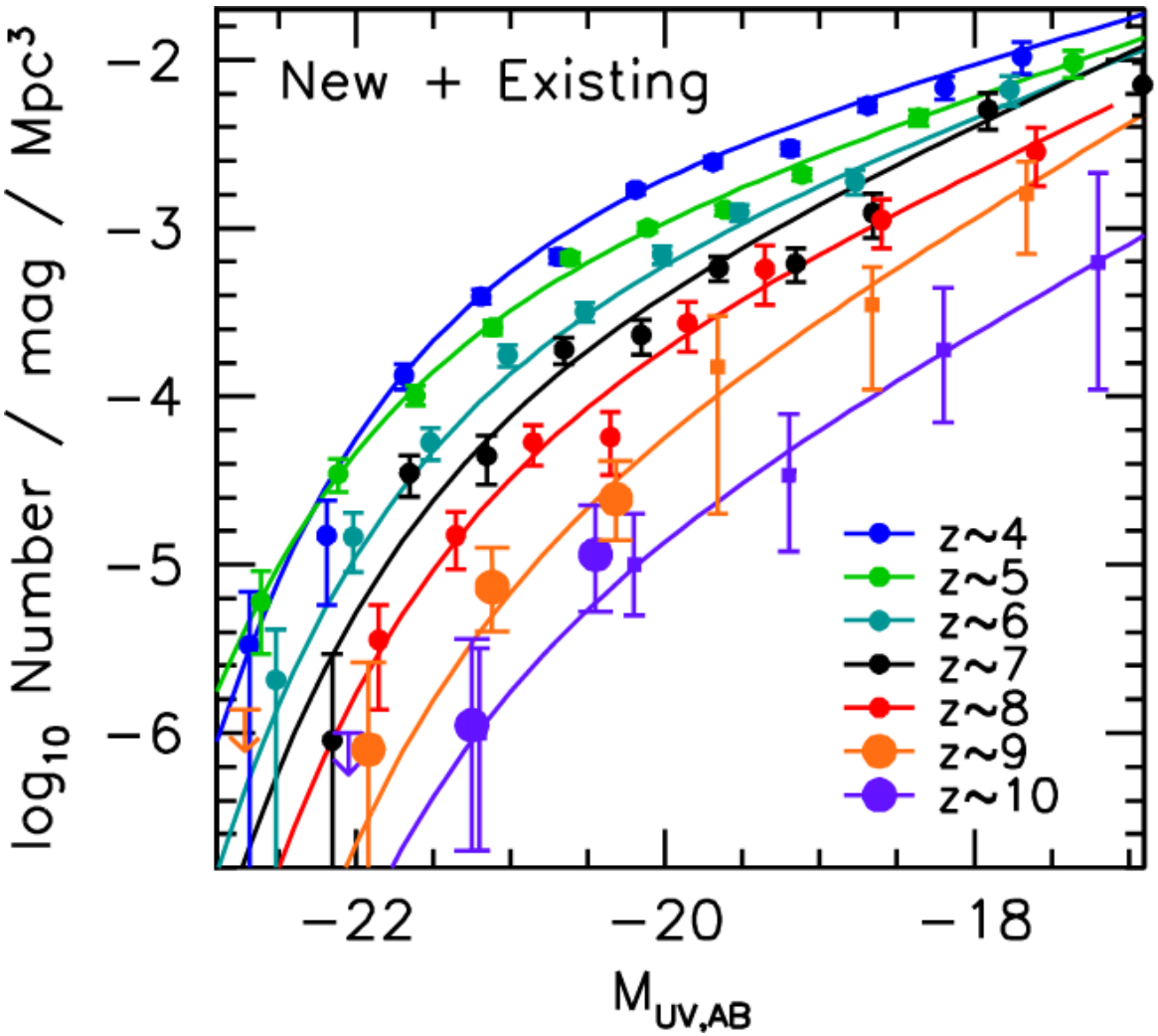
The sources of reionization

Star-forming galaxies can provide enough HI ionizing photons to reionize the Universe. *e.g. Finkelstein+ 2019, Robertson+2015, Mutch+ 2016, Seiler+ 2019*

Contribution from ***AGN*** is probably small.

e.g. Weigel+ 2015, Parsa+2017, Onoue+2017, Kulkarni+ 2019, Qin+ 2017, Yoshiki+ 2018, Trebitsch+ 2018, Mitra+ 2018

UV luminosity function *Bouwens+ 2019*



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The number of ionizing photons is given by

$$\dot{N}_{ion} = f_{esc}\ \xi_{ion}\ \rho_{UV}$$

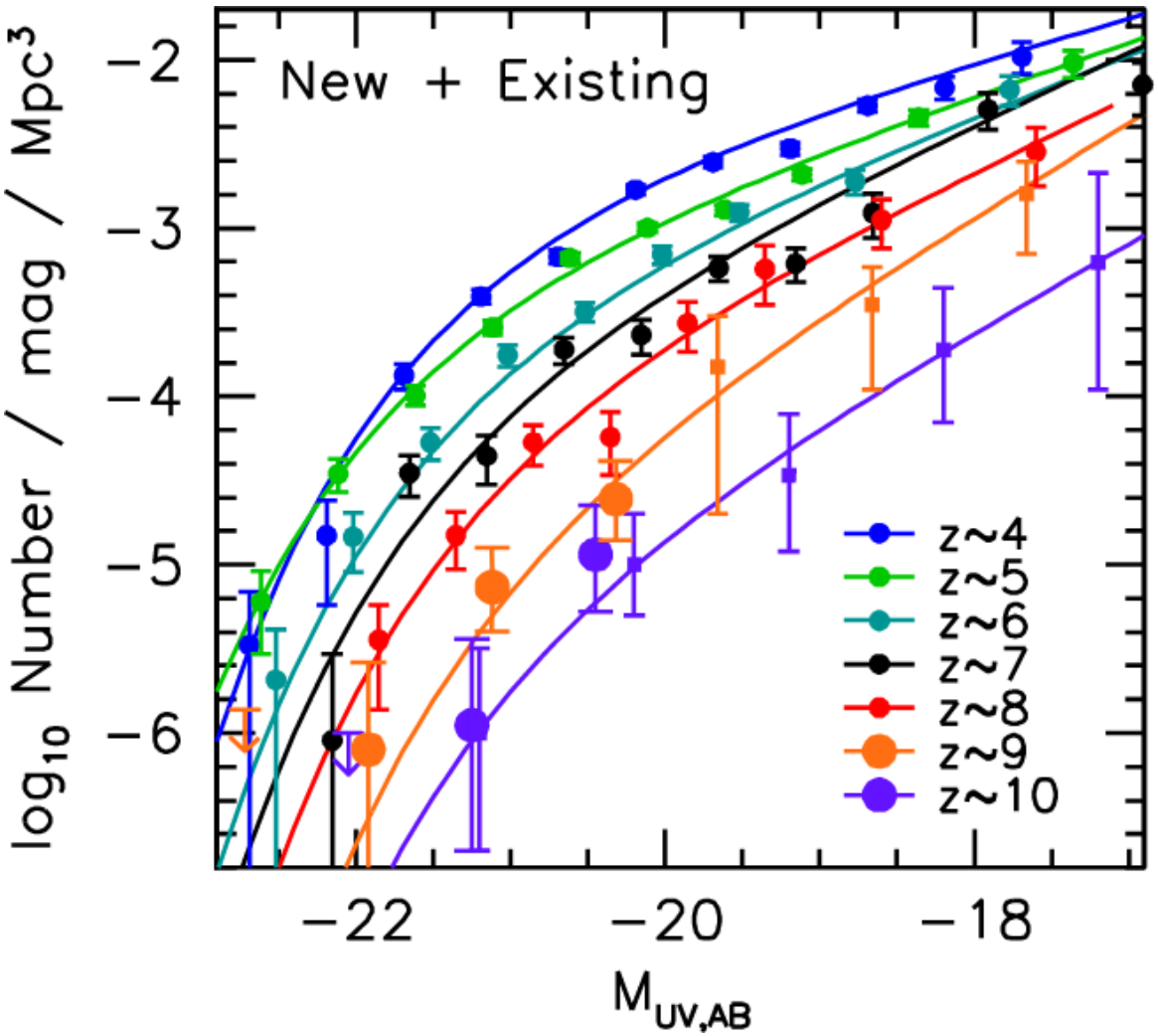
Escape fraction of LyC photons

LyC photon production efficiency

UV luminosity density of galaxies

?

UV luminosity function *Bouwens+ 2019*



The escape fraction of ionizing photons into the IGM

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Escape fraction of LyC photons

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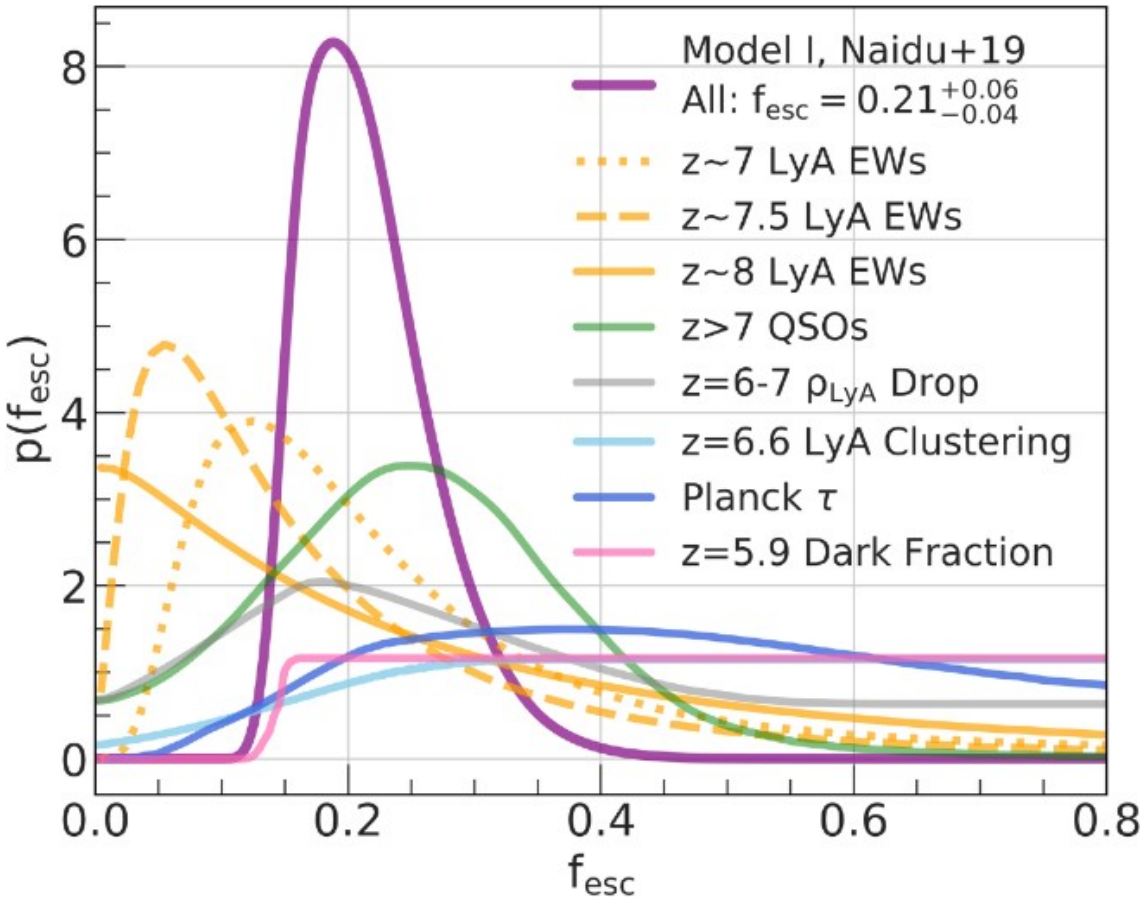
UV luminosity density of galaxies

ρ_{UV}: inferred from UV luminosity functions at z=4-10

ξ_{ion}: inferred from Hα emission line measurements at z~4-5

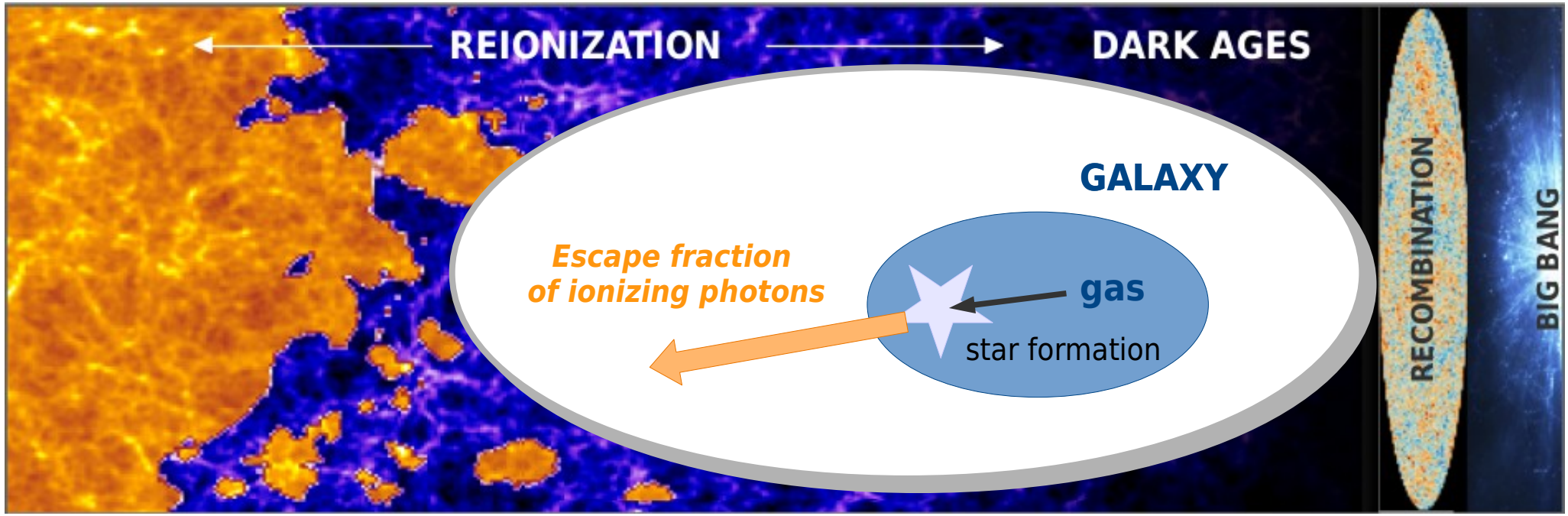
Naidu+ 2019



Bouwens+ 2016, Harikane+ 2018, Lam+ 2019, Naidu+ 2019

The ionizing escape fraction & the ionization topology

BUT: realistically the escape fraction of ionizing photons will depend on the physical processes and gas distributions in the galaxies



Paardekooper+ 2015, Kimm+ 2017, 2019, Trebitsch+ 2018, Seiler+ 2018

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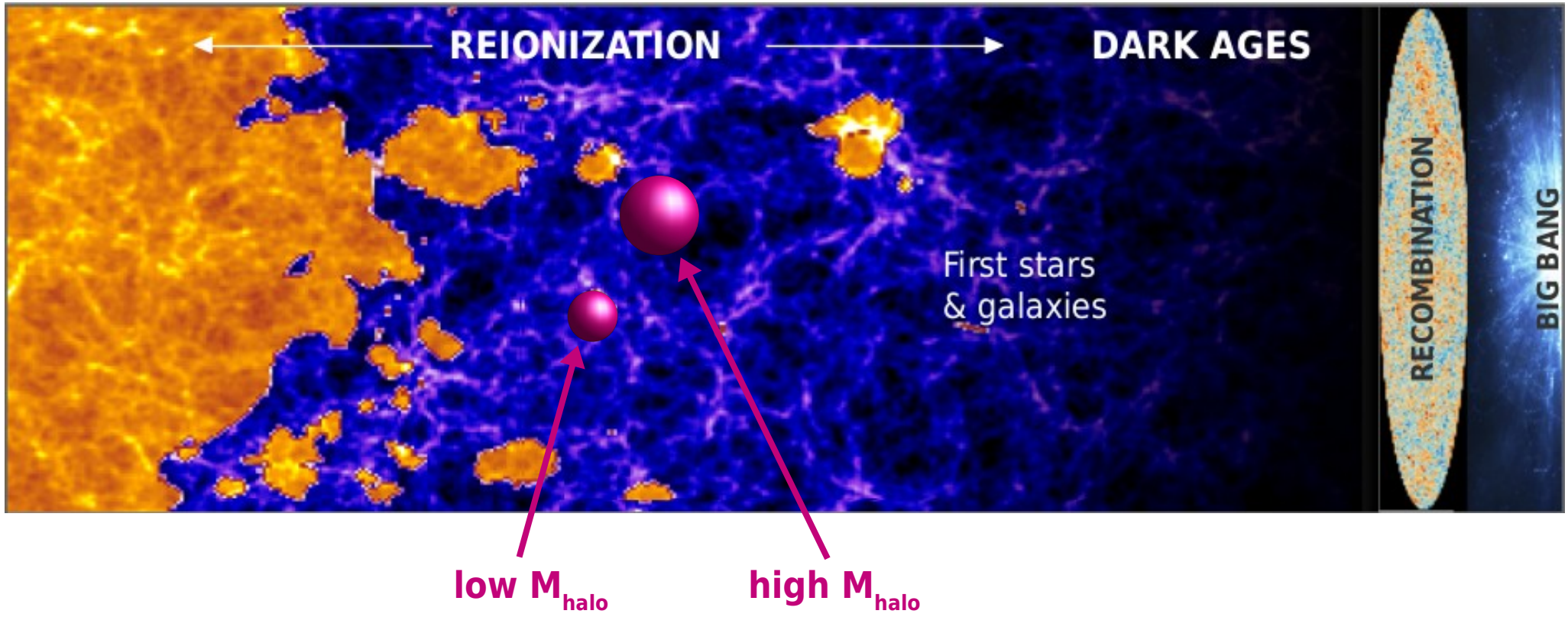

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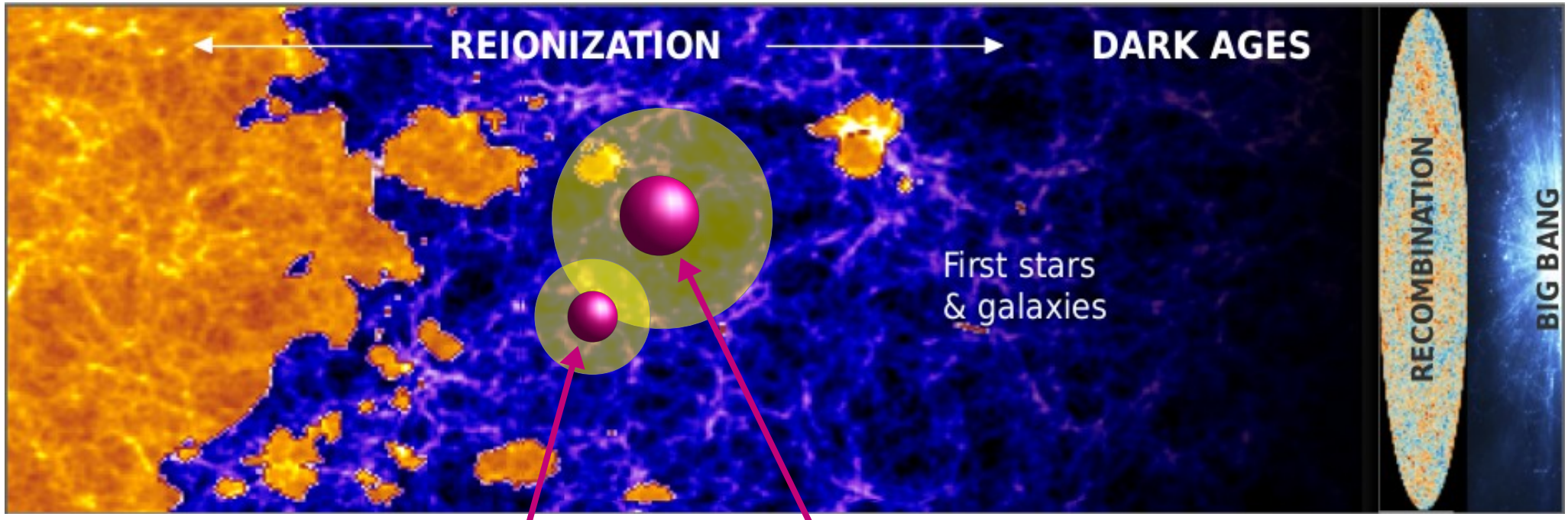

f_{esc} = constant

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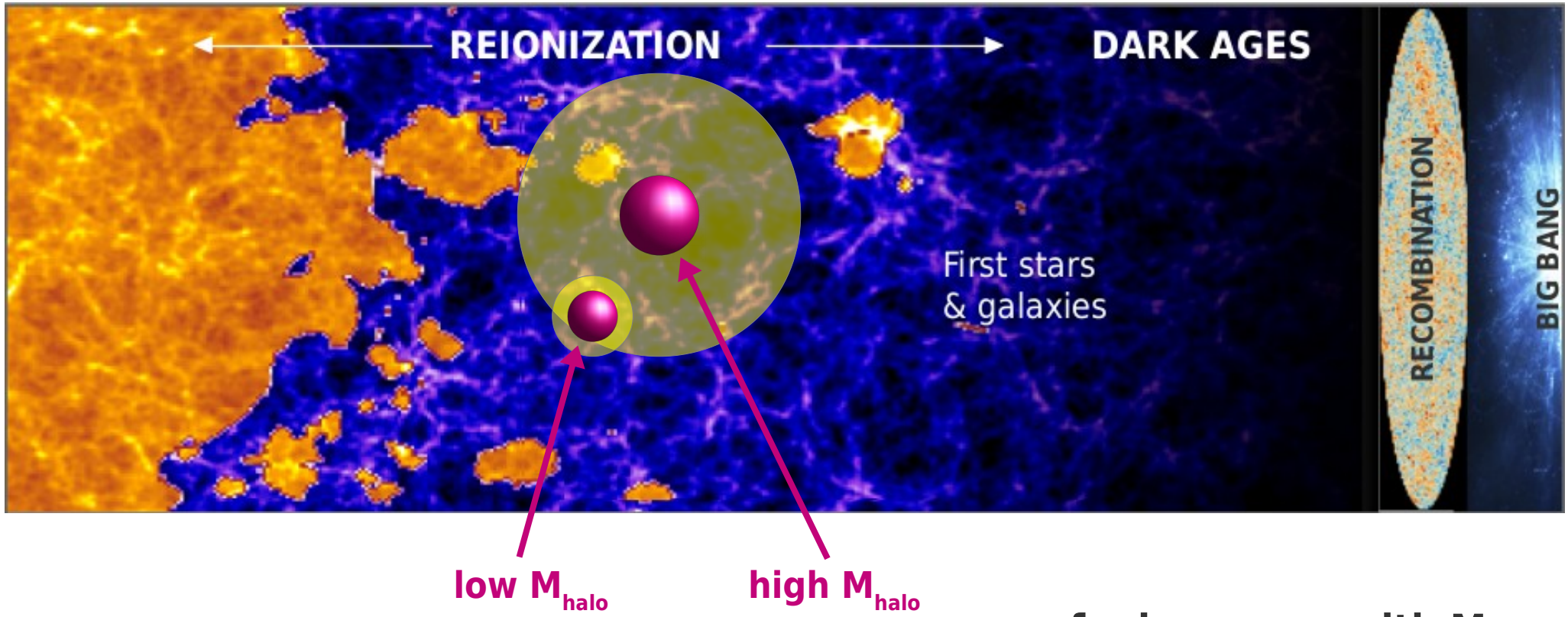

f_{esc} increases with M_{halo}

The ionizing escape fraction & the ionization topology

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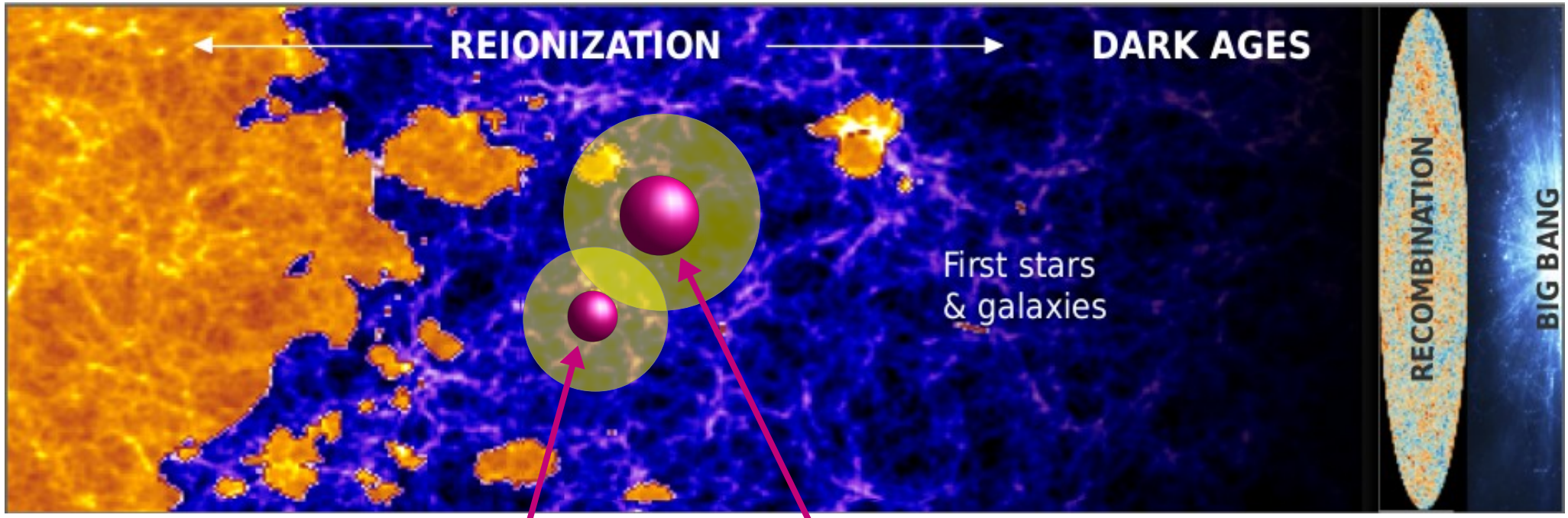

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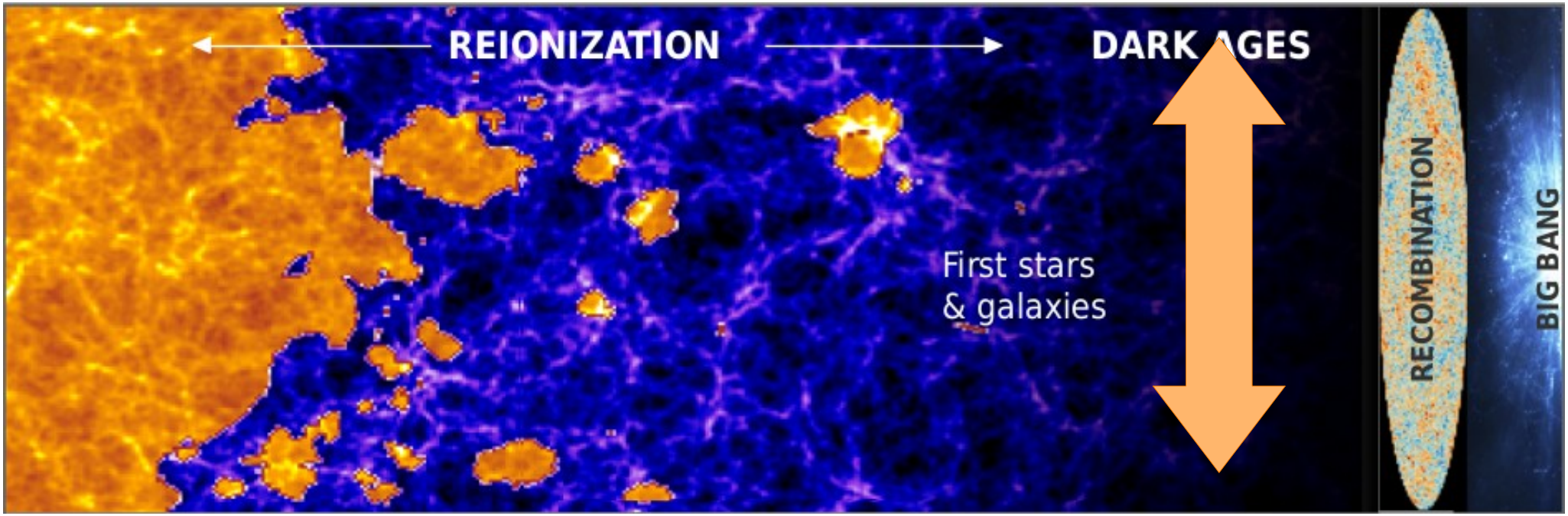
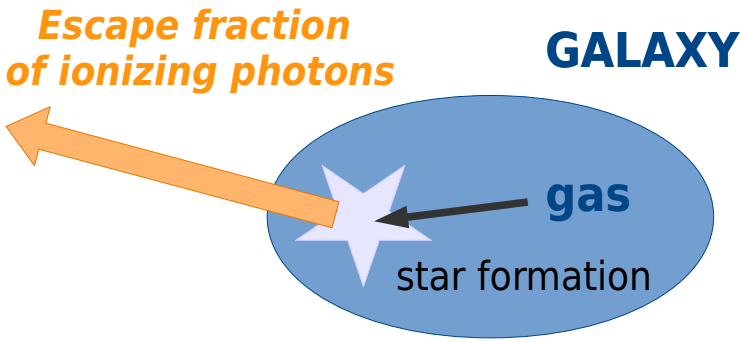


How does reionization affect galaxy formation & evolution?

What is the ionization topology, the evolution of the sizes and location of the ionized regions?

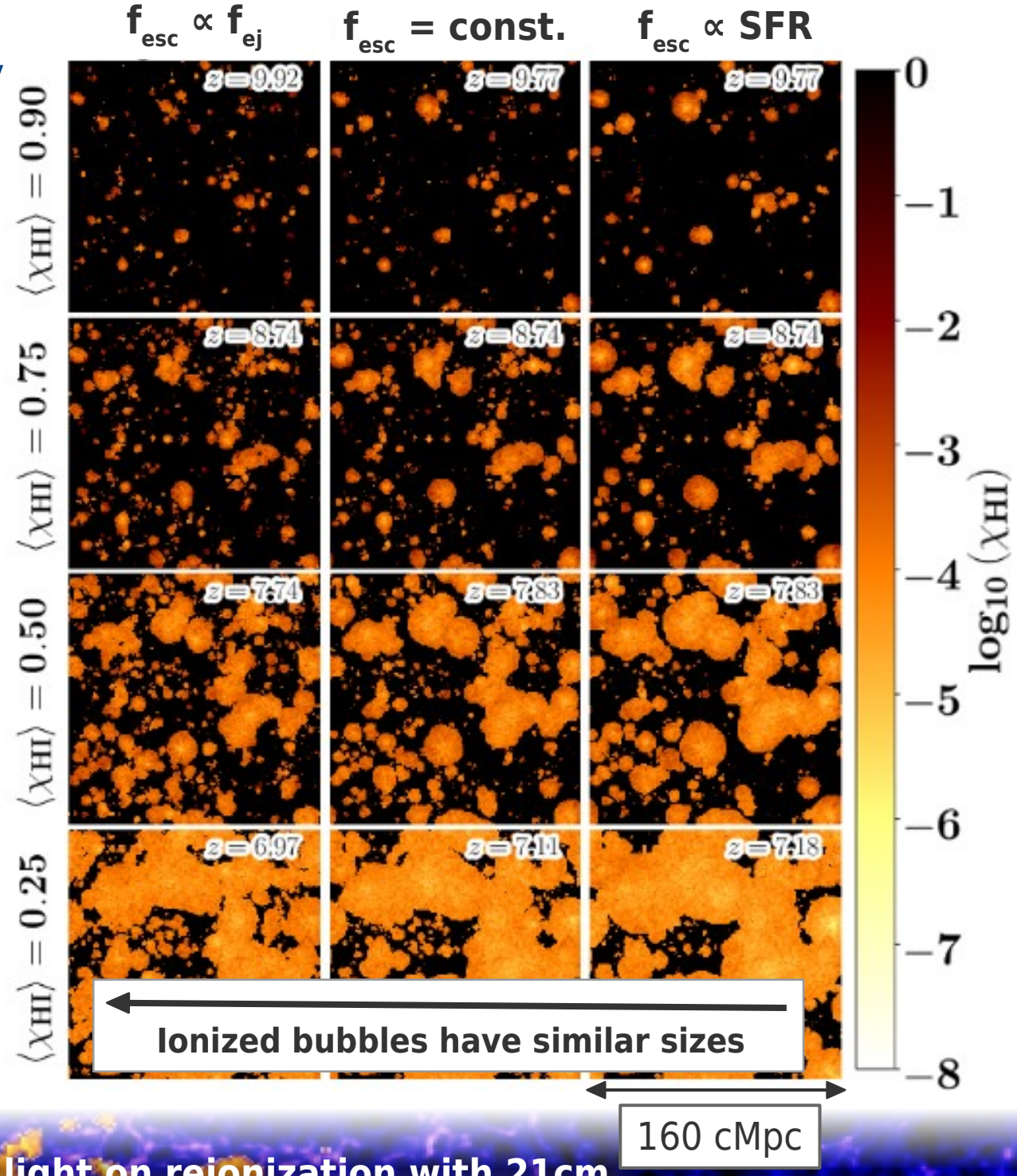
The ionization topology

- f_{esc} increases with SFR ($\uparrow$ with M_h)
- f_{esc} is constant.
- f_{esc} increases with the ejected gas fractions ($\downarrow$ with M_h)

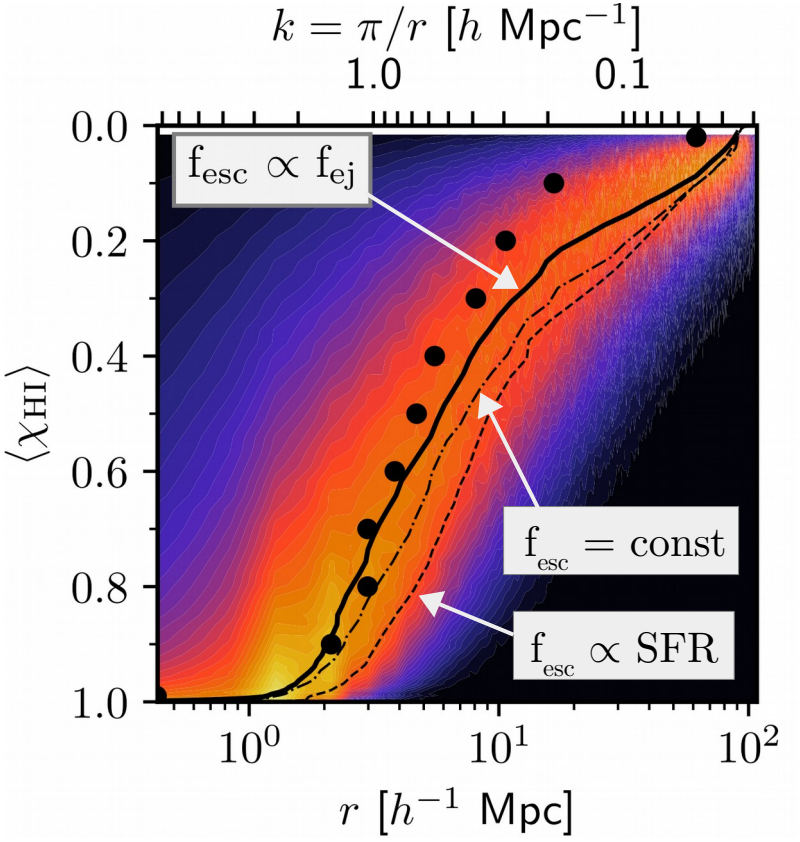


RSAGE: semi-numerical model of galaxy evolution & reionization

Seiler, Hutter+ 2019

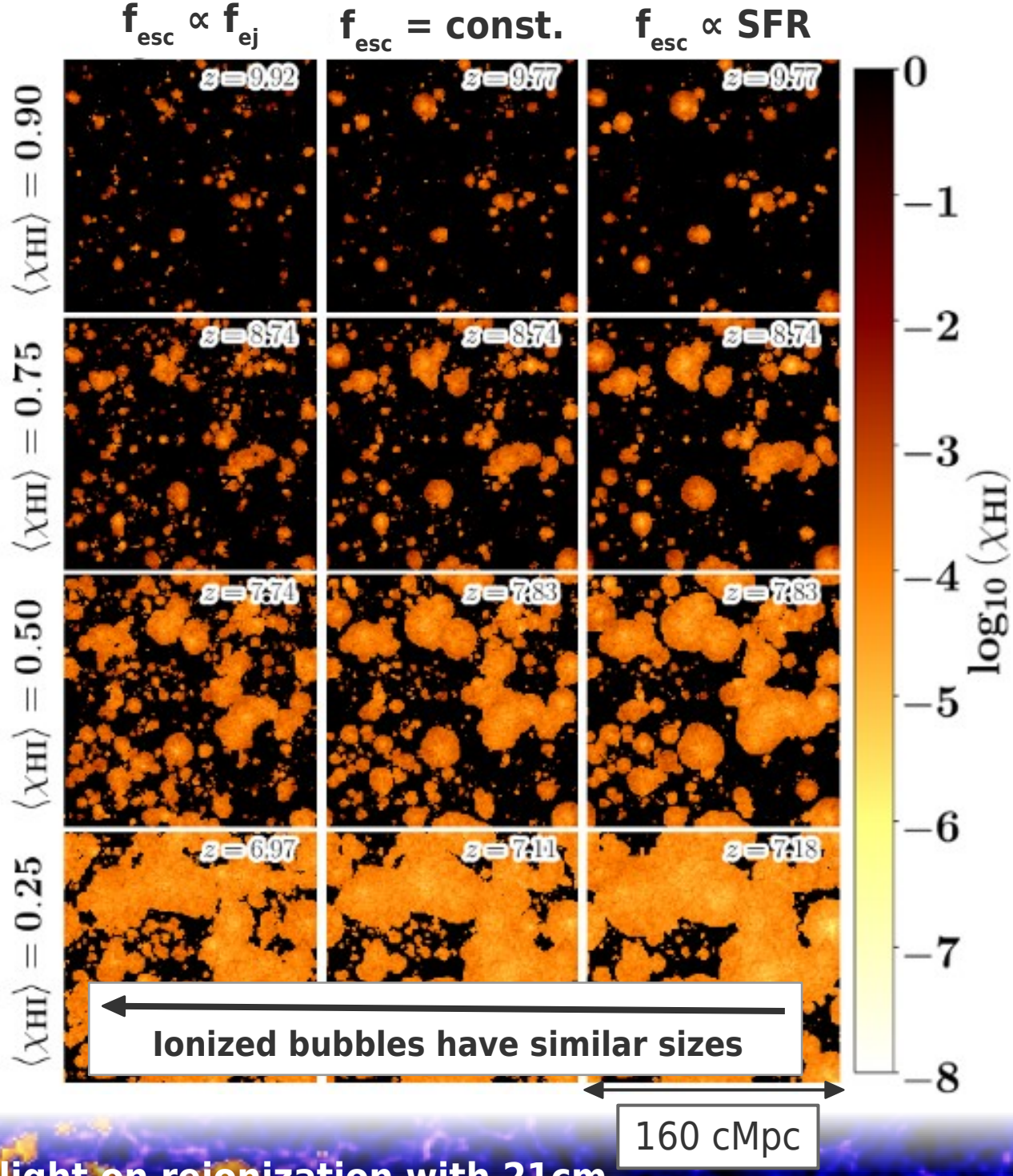


The ionization topology



Ionized regions become larger from $f_{esc} \propto f_{ej}$ to $f_{esc} \propto$ SFR

Hutter+ 2019, arXiv 1907.04342



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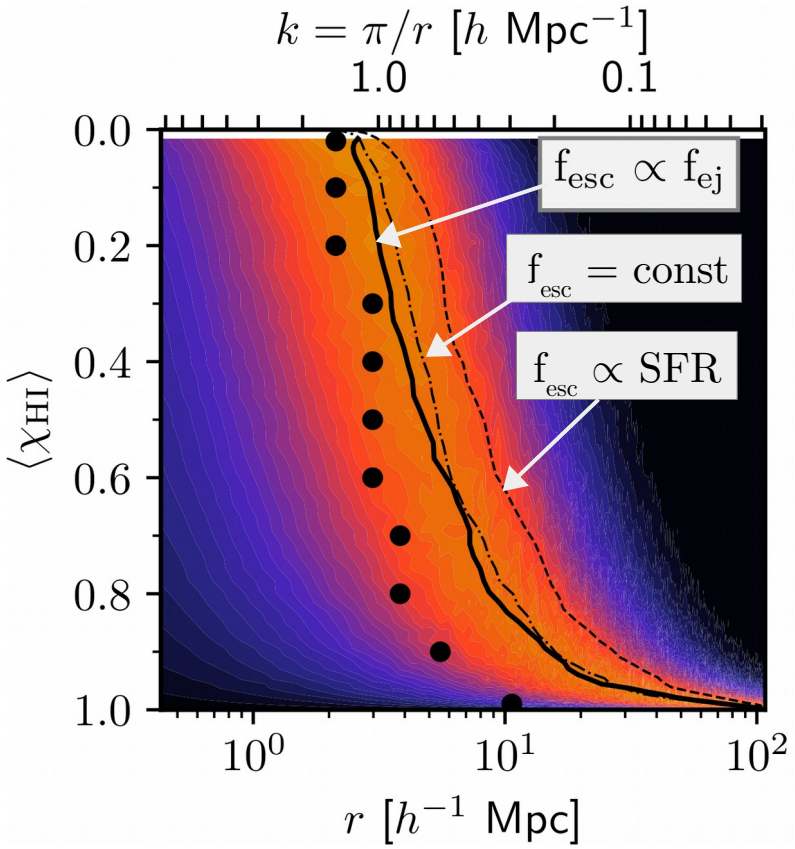
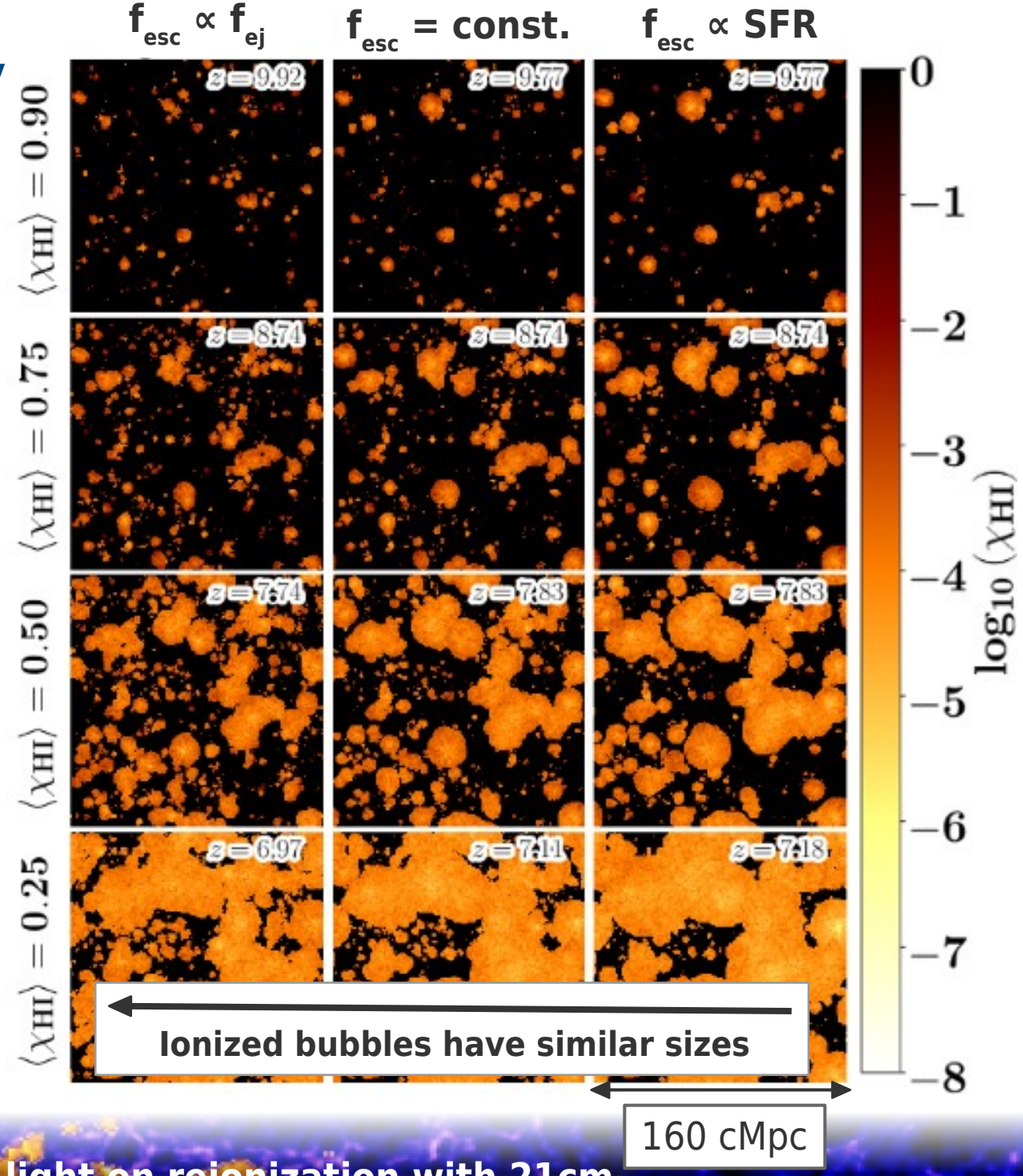


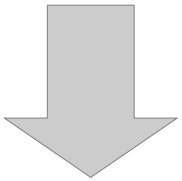
Neutral regions become also larger from $f_{esc} \propto f_{ej}$ to $f_{esc} \propto$ SFR

Hutter+ 2019, arXiv 1907.04342

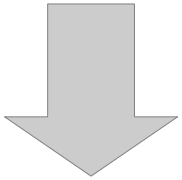


More information with higher-order statistics?

The 21cm signal from reionization is non-Gaussian.



The 21cm power spectrum only traces the Gaussian part.



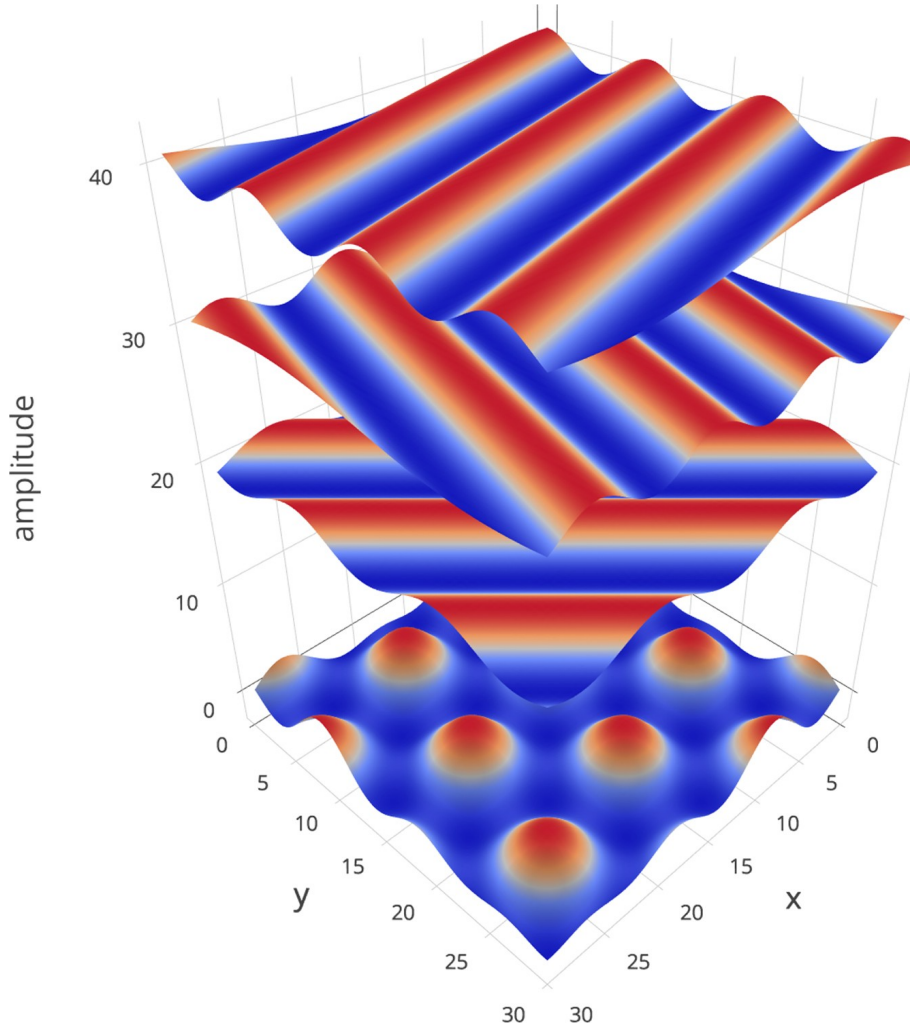
Analyzing non-Gaussianities with the 21cm BISPECTRUM during reionization

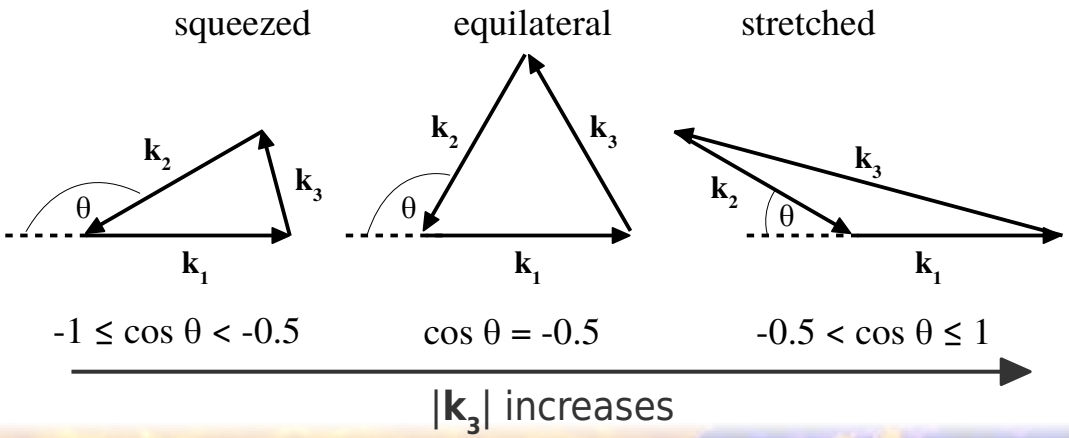
21cm bispectra tracing ionization topology?

Bispectrum is the Fourier transform of the 3-point correlation function:

$$(2\pi)^3 \; B(\vec{k}_1,\vec{k}_2,\vec{k}_3) \; \underbrace{\delta_D(\vec{k}_1+\vec{k}_2+\vec{k}_3)}_{\text{contributes only when } \vec{k}_1+\vec{k}_2+\vec{k}_3=0} = \langle \Delta(\vec{k}_1) \; \Delta(\vec{k}_2) \; \Delta(\vec{k}_3) \; \rangle$$

Watkinson+2017

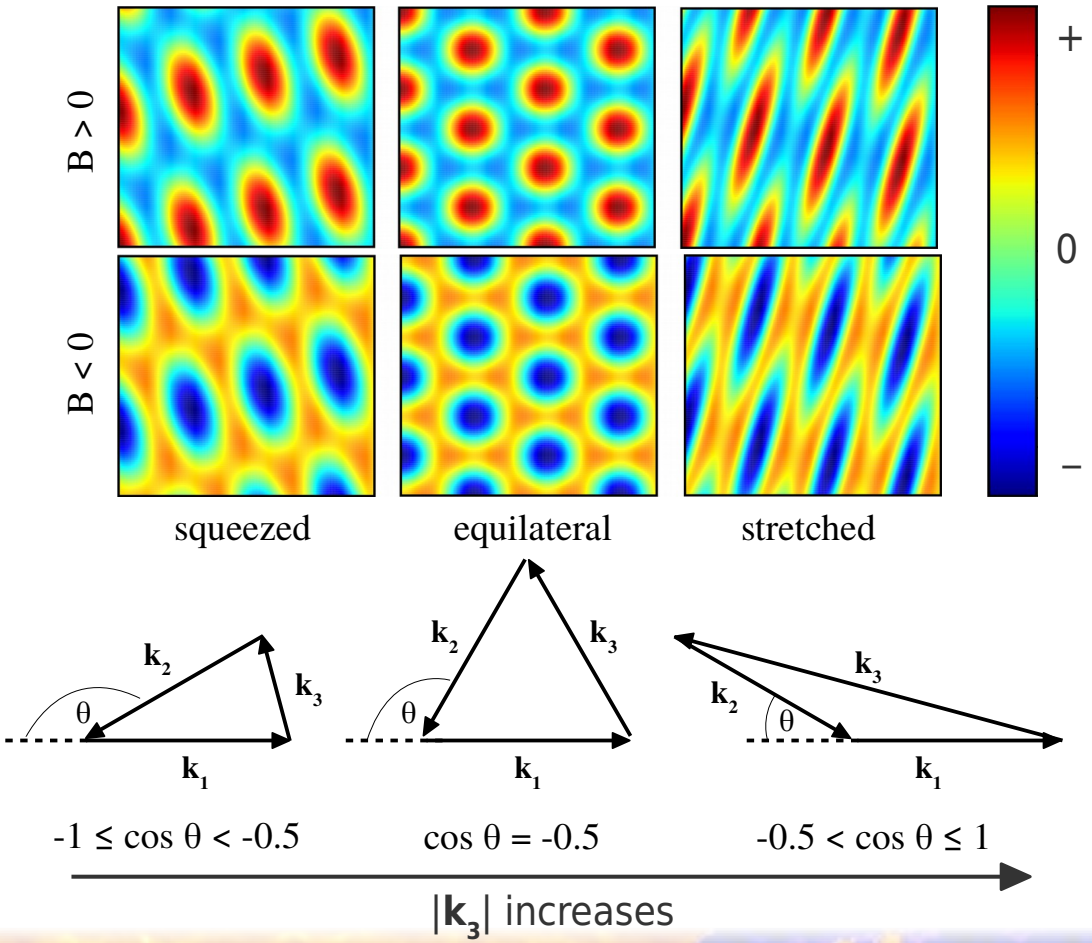




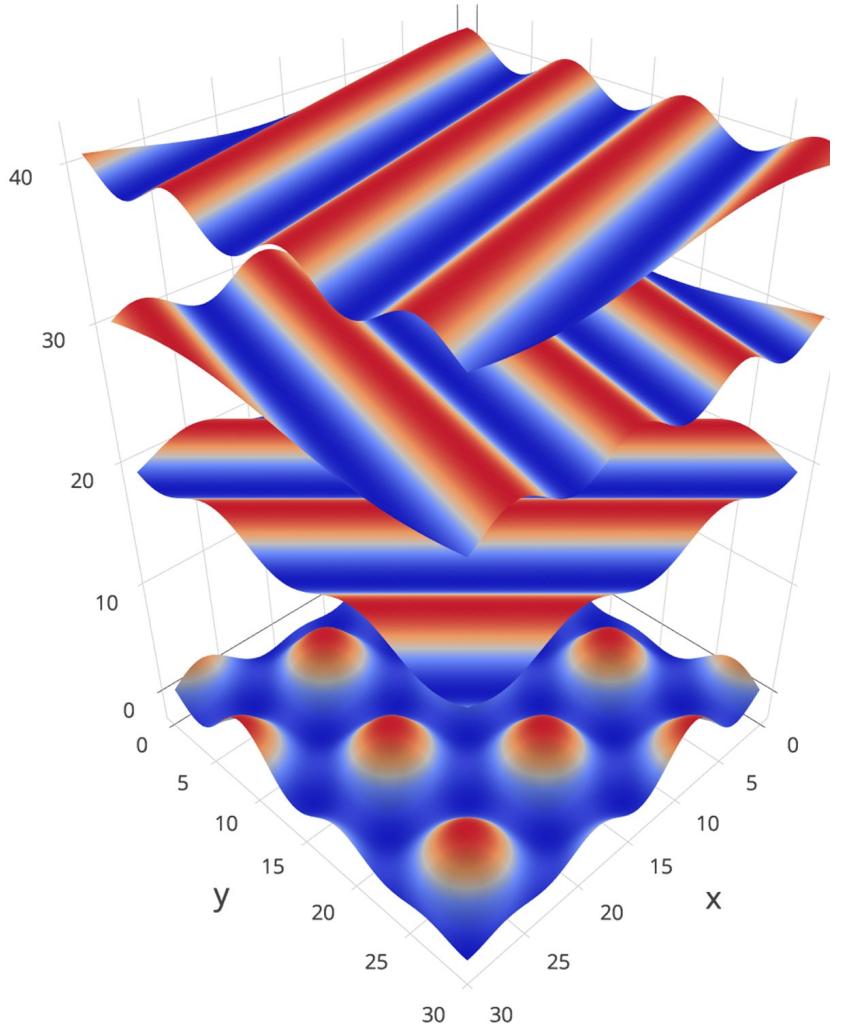
21cm bispectra tracing ionization topology?

Bispectrum is the Fourier transform of the 3-point correlation function:

$$(2\pi)^3 \; B(\vec{k}_1,\vec{k}_2,\vec{k}_3) \; \underbrace{\delta_D(\vec{k}_1+\vec{k}_2+\vec{k}_3)}_{\text{contributes only when } \vec{k}_1+\vec{k}_2+\vec{k}_3=0} = \langle \Delta(\vec{k}_1) \; \Delta(\vec{k}_2) \; \Delta(\vec{k}_3) \; \rangle$$



Watkinson+2017



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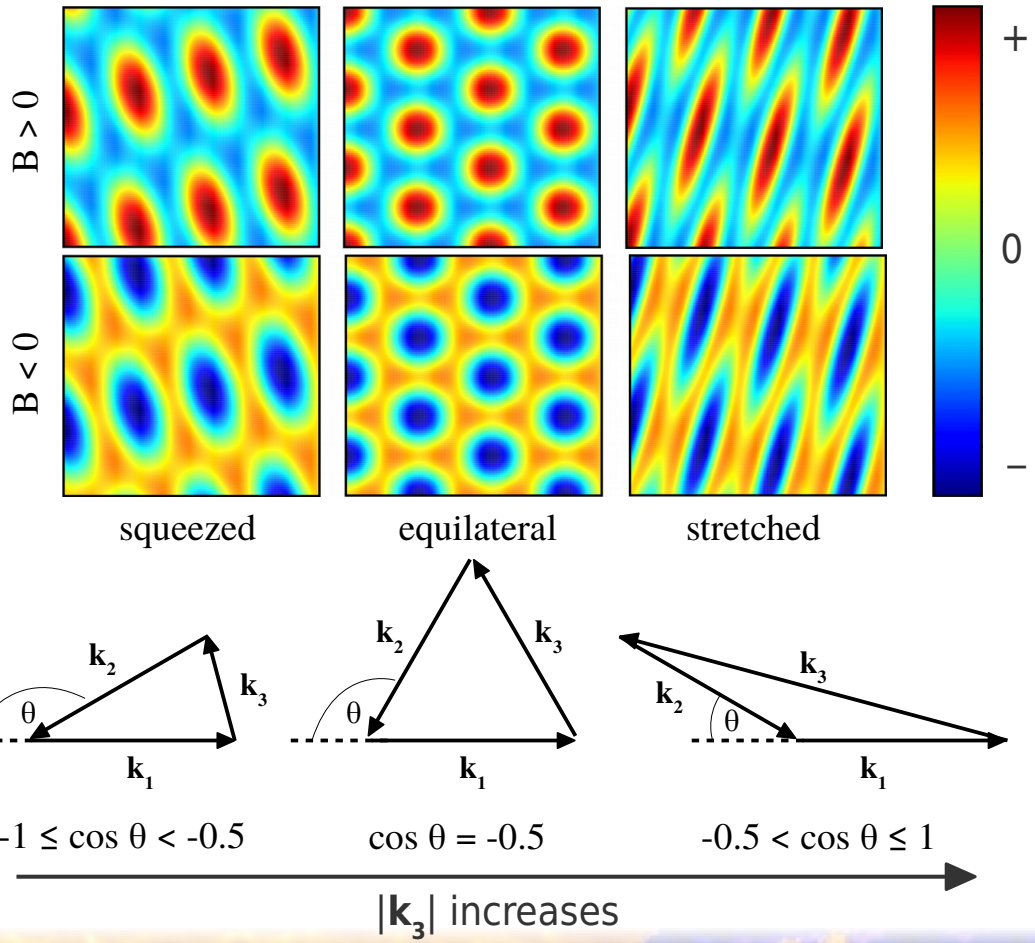
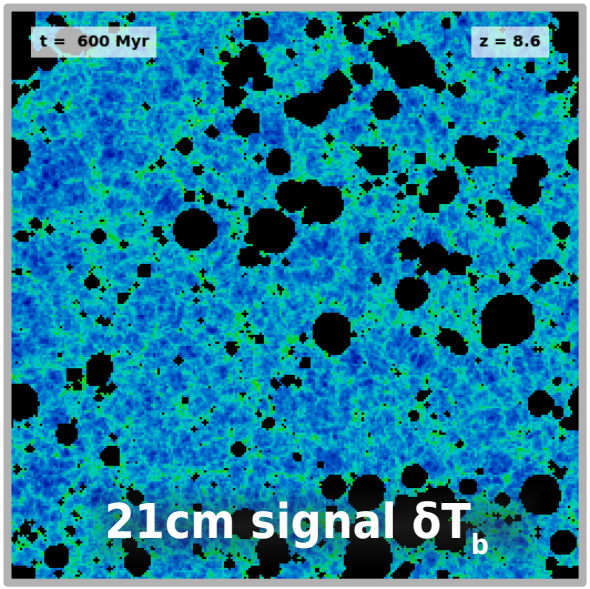
$$\Delta(\vec{k}) = FT[\delta T_b(\vec{x})]$$

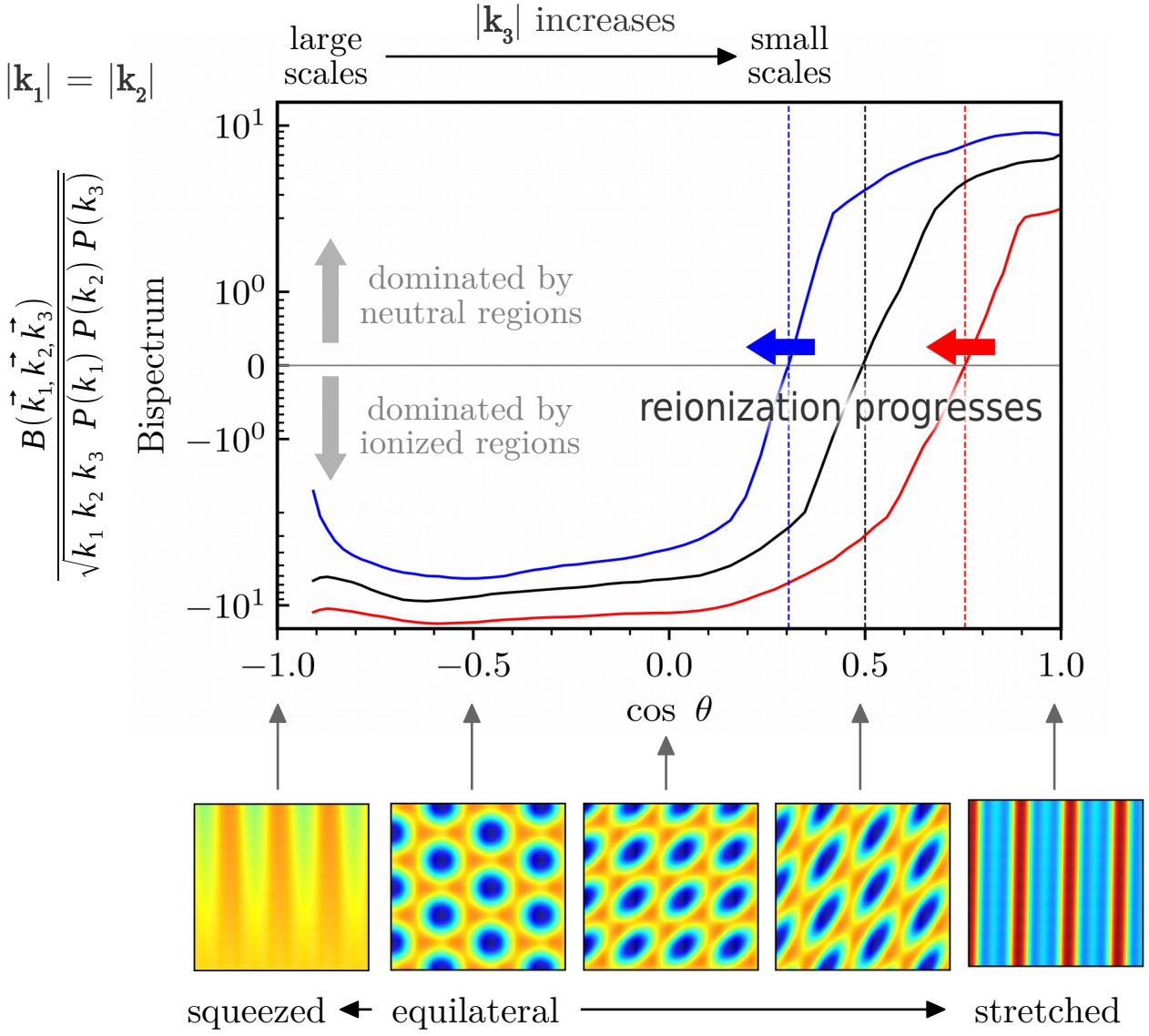




B > 0 : concentrated over-densities
neutral regions

B < 0 : concentrated under-densities
ionized regions

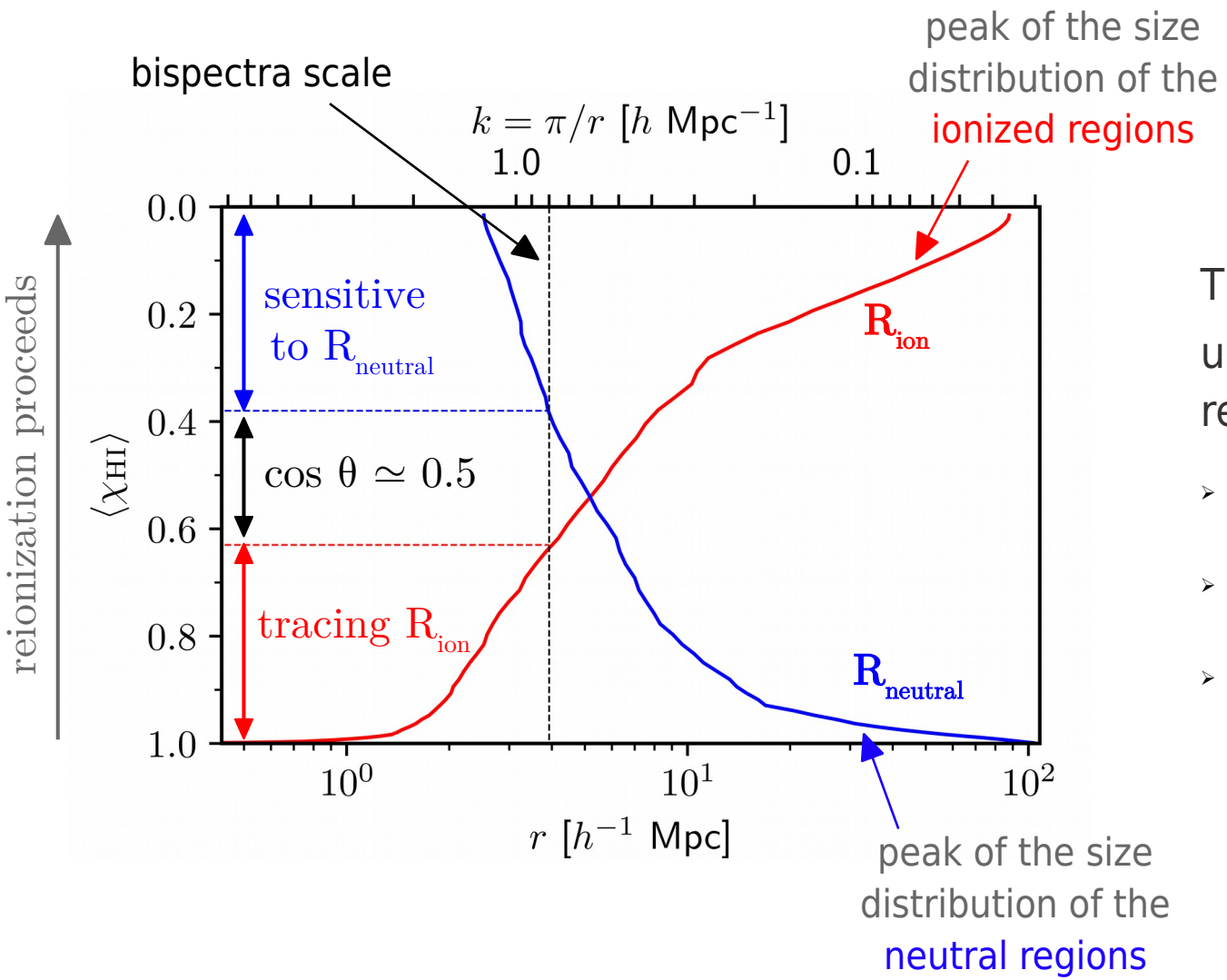
21cm bispectra tracing ionization topology?



see also Majumdar+ 2018

Hutter+ 2019, arXiv 1907.04342

21cm bispectra tracing ionization topology?

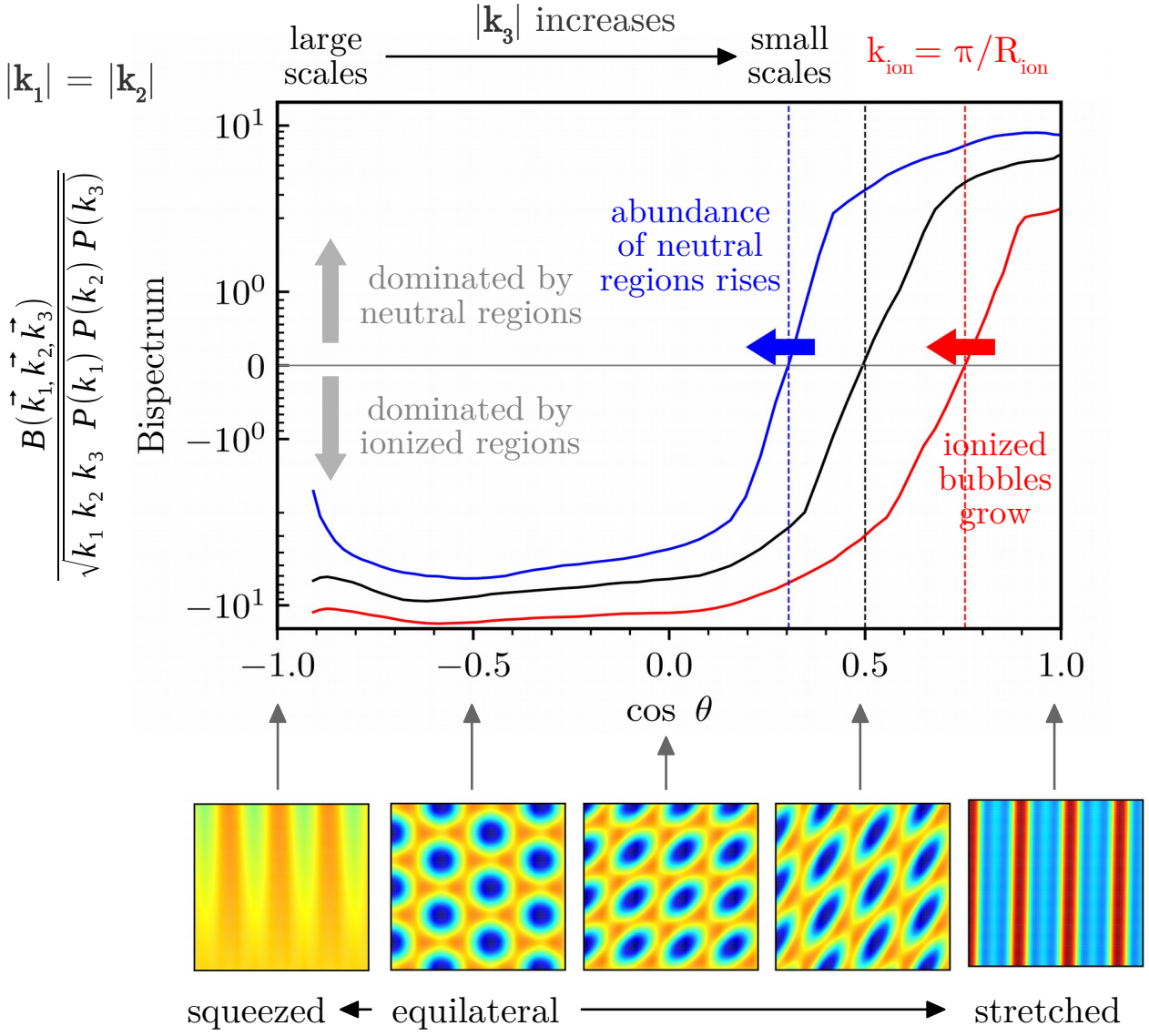


The χ_{HI} (21cm) bispectrum undergoes 3 regimes during reionization:

- $R > R_{ion}$ & $R < R_{neutral}$
- $R < R_{ion}$ & $R < R_{neutral}$
- $R < R_{ion}$ & $R > R_{neutral}$

Hutter+ 2019, arXiv 1907.04342

21cm bispectra tracing ionization topology?



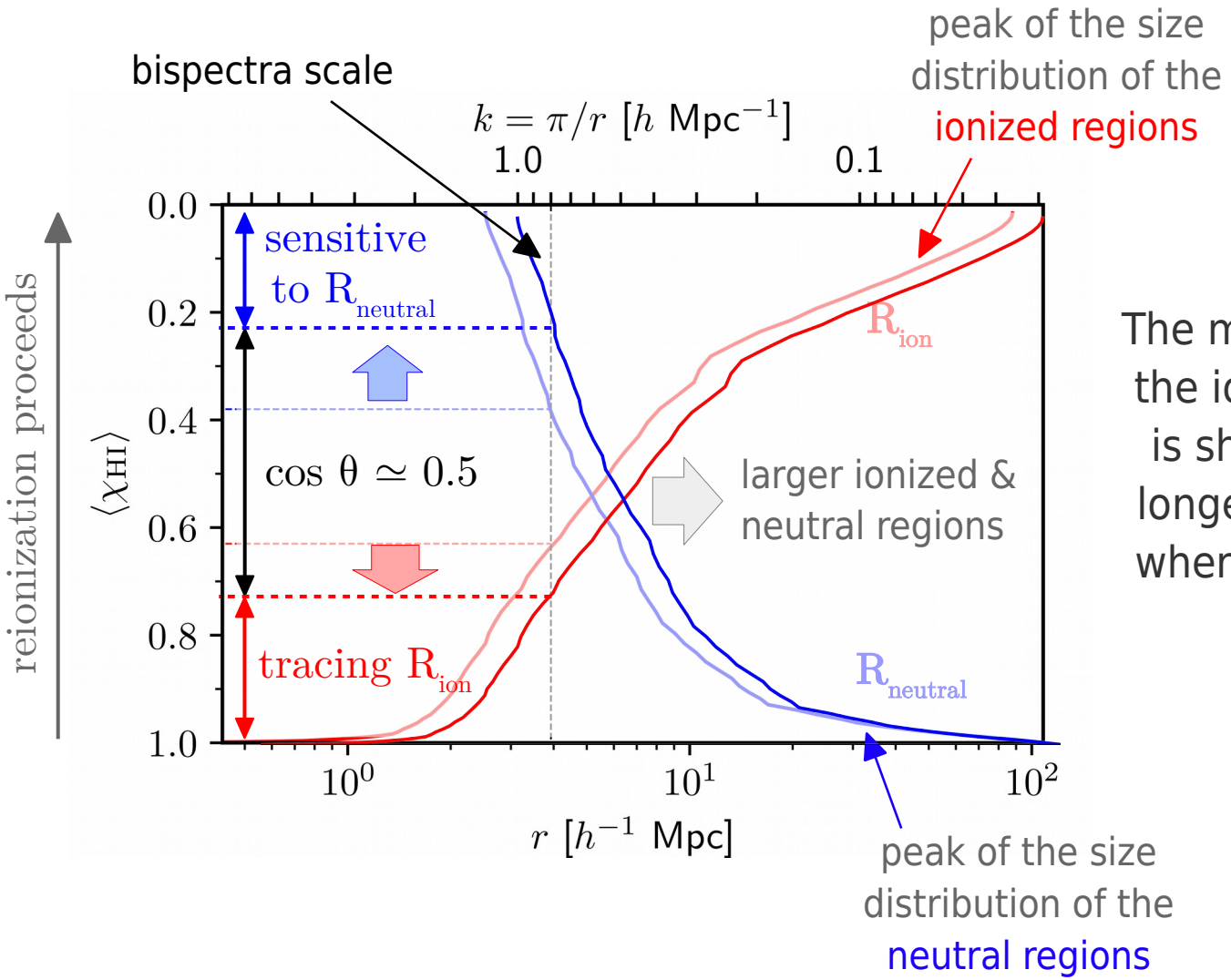
see also Majumdar+ 2018

The χ_{HI} (21cm) bispectrum

- traces the typical ionized bubble size at the early stages of reionization.
- is sensitive to the abundance of neutral regions near the end of reionization.

Hutter+ 2019, arXiv 1907.04342

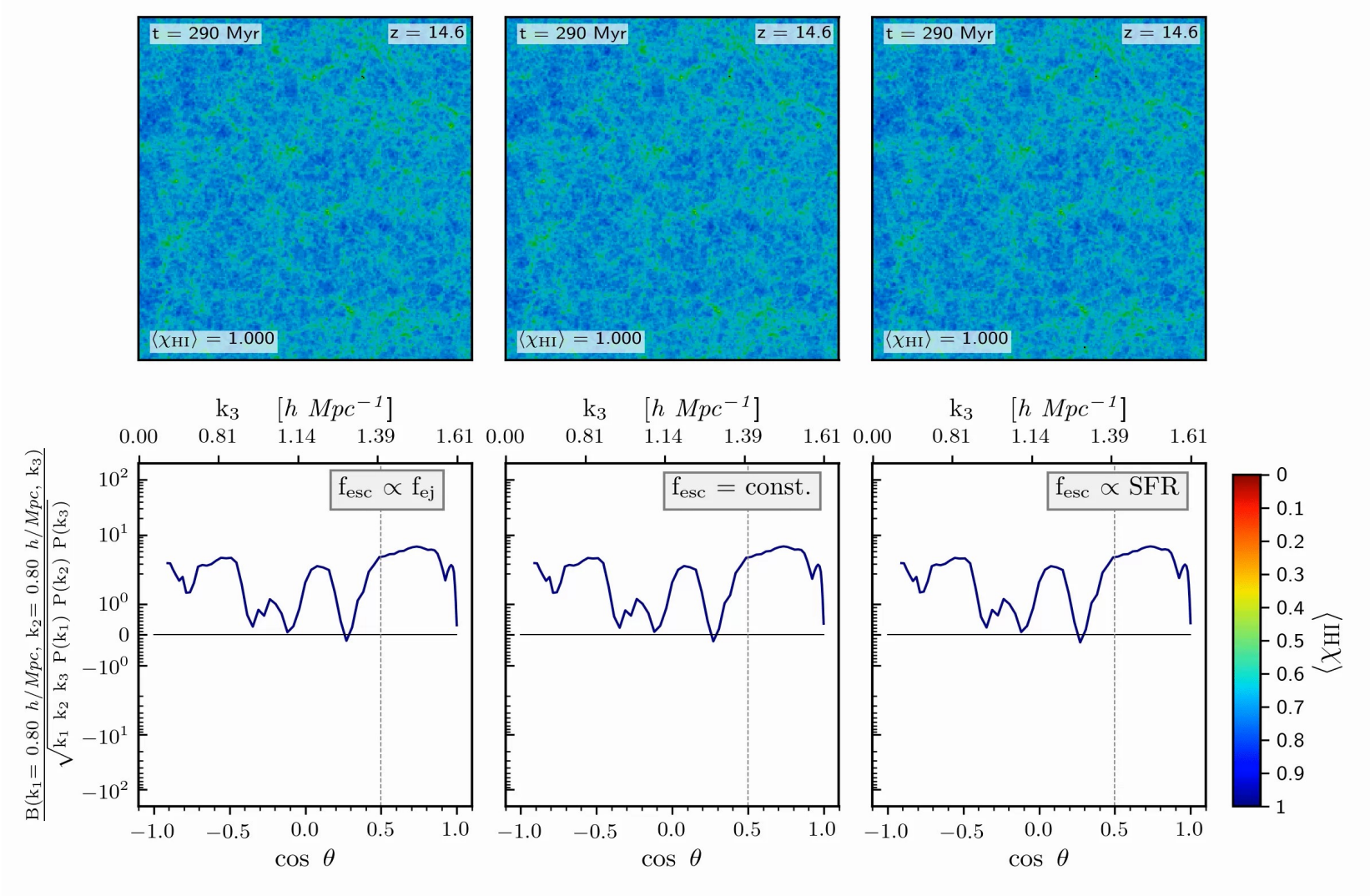
21cm bispectra tracing ionization topology!



The more the size distribution of the ionized and neutral regions is shifted to larger scales, the longer it remains in the regime where the bispectrum switches signs at cosθ ≃ 0.5

Hutter+ 2019, arXiv 1907.04342

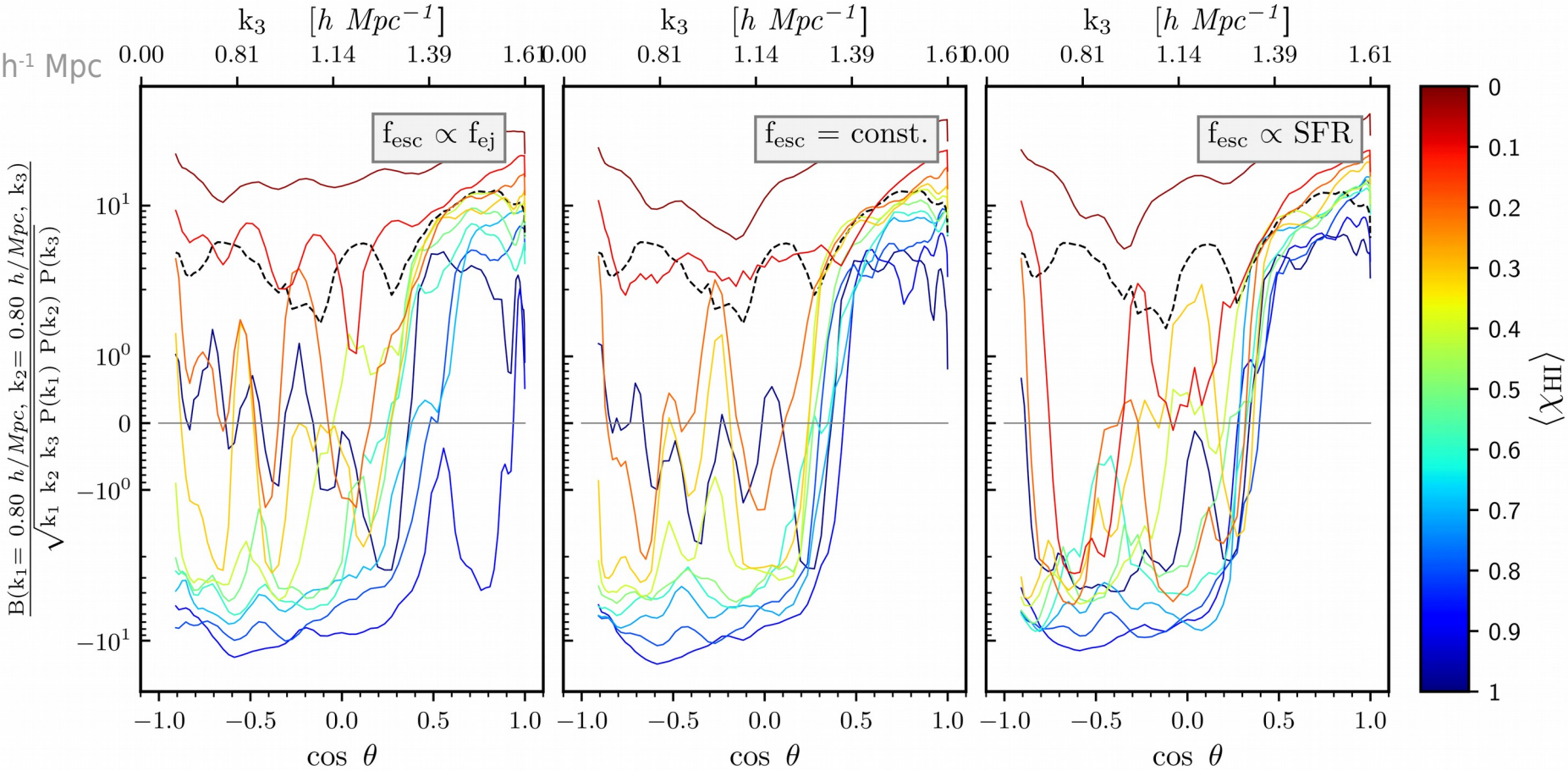
21cm bispectra tracing ionization topology!



21cm bispectra tracing ionization topology!

typical size of the ionized regions becomes larger

π/k = 4h^{-1} Mpc



The 21cm bispectrum during reionization traces the ionization topology and differs for different ionizing escape fraction models.

Hutter+ 2019, arXiv 1907.04342

Conclusions

21cm – LAE CROSS CORRELATIONS:

- Synergising 21cm observations with the underlying galaxy populations (specially LAEs given their precise redshifts) will allow us to put *constraints on reionization* and the *typical ionized bubble size* around the respective galaxy population.

GALACTIC PROPERTIES & TOPOLOGY OF REIONIZATION:

- Measuring the *difference between the small- and large-scale 21cm power spectrum* can be used to constrain the trend of the *ionizing escape fraction with galactic properties*. A negative slope is a strong indicator for a biased distribution of the ionizing emissivity.
- The *21cm bispectrum* provides a valuable tracer of the *ionization topology* with the change of sign tracking the *typical size of the ionized regions* during the earlier stages of reionization.