Probing the IGM during Reionization with line cross-correlations

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based on: CH, Cooray, Feng, ApJ, 848 (2017), CH & Mesinger in prep.

Introduction

What astrophysics at play during Reionization?

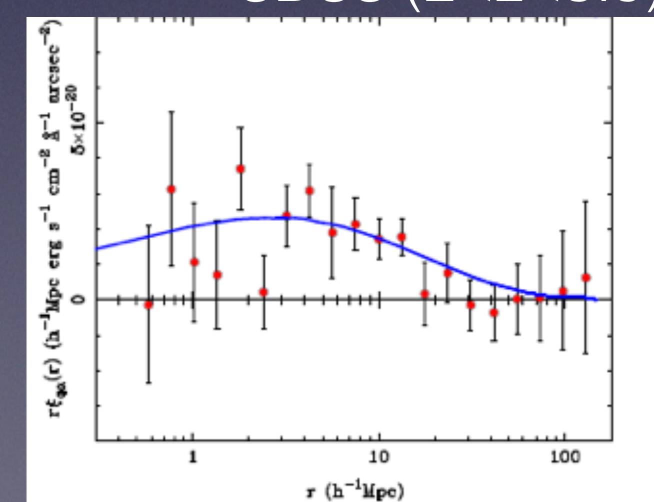
↓

Lines like Lyα, Hα, .. (galaxies) and 21cm complement each other:

What are properties of the cross-signal?
Is the cross-signal measurable?
Typical ionising sources during the EoR?

+CII intensity mapping: CONCERTO (Dumitru+18), CCAT-prime (Parshley+18)
+LOFAR 21cm upper limits (Patil+17)
+21cm-LAE cross-correlation (Sobacchi+16, Hutter+16, 18)
+Lyα intensity mapping during reionization (Silva+13, Heneka+17)
+Intensity mapping Hα, Lyα, OII, CO, .. at z<5 (Fonseca+16, Gong+17)

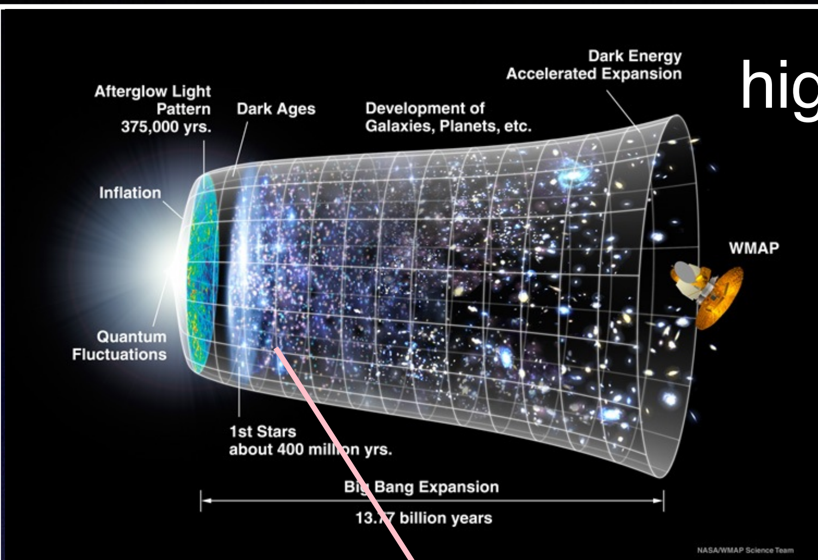
SDSS (2<z<3.5)



(Croft et al. 2015)

Reionization

high z: linear growth, simpler astrophysics(?)



$z \sim 6$

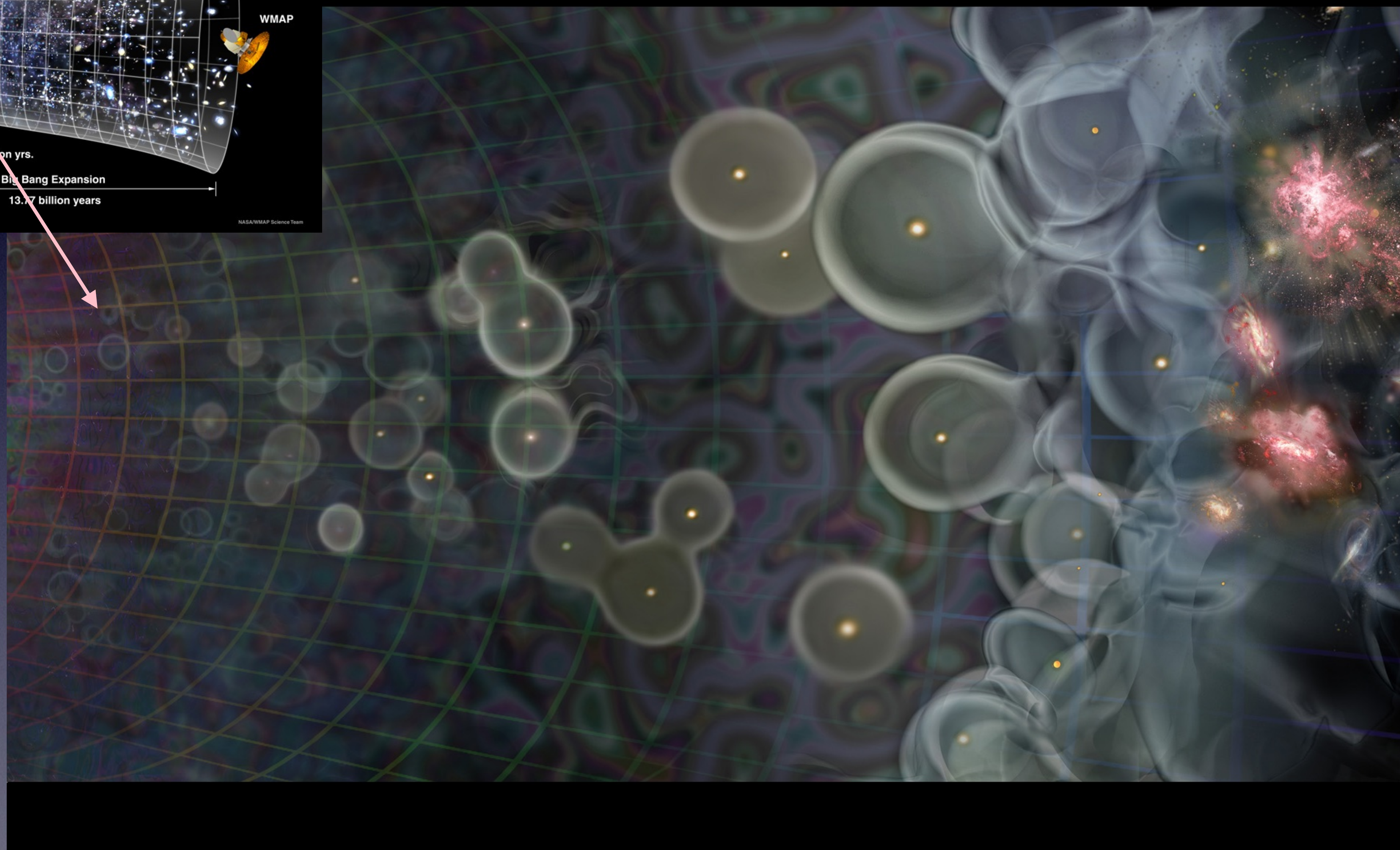


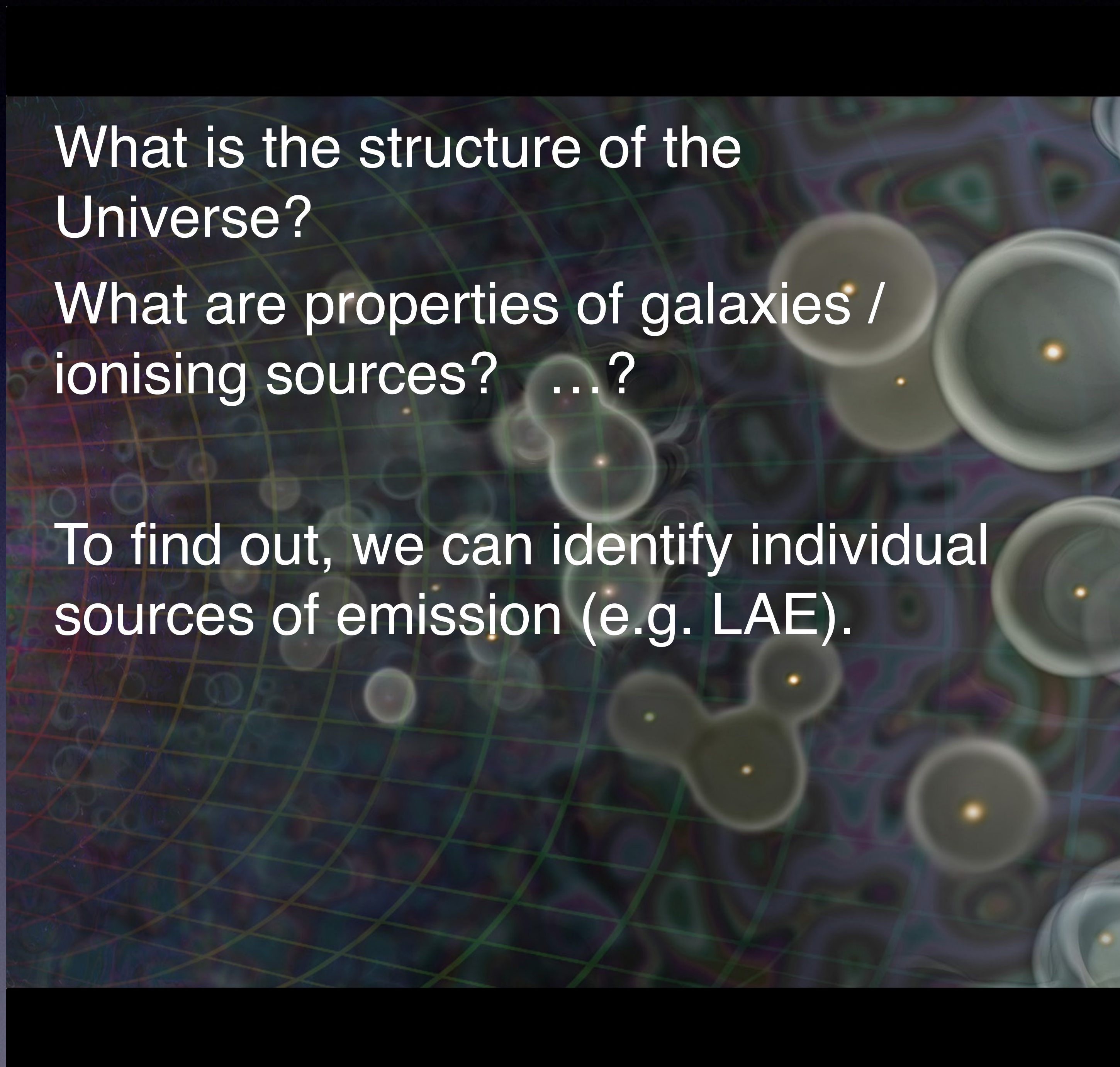
Image Credit: http://firstgalaxies.org/aspen_2016/

Introduction

What is the structure of the Universe?

What are properties of galaxies / ionising sources? …?

To find out, we can identify individual sources of emission (e.g. LAE).



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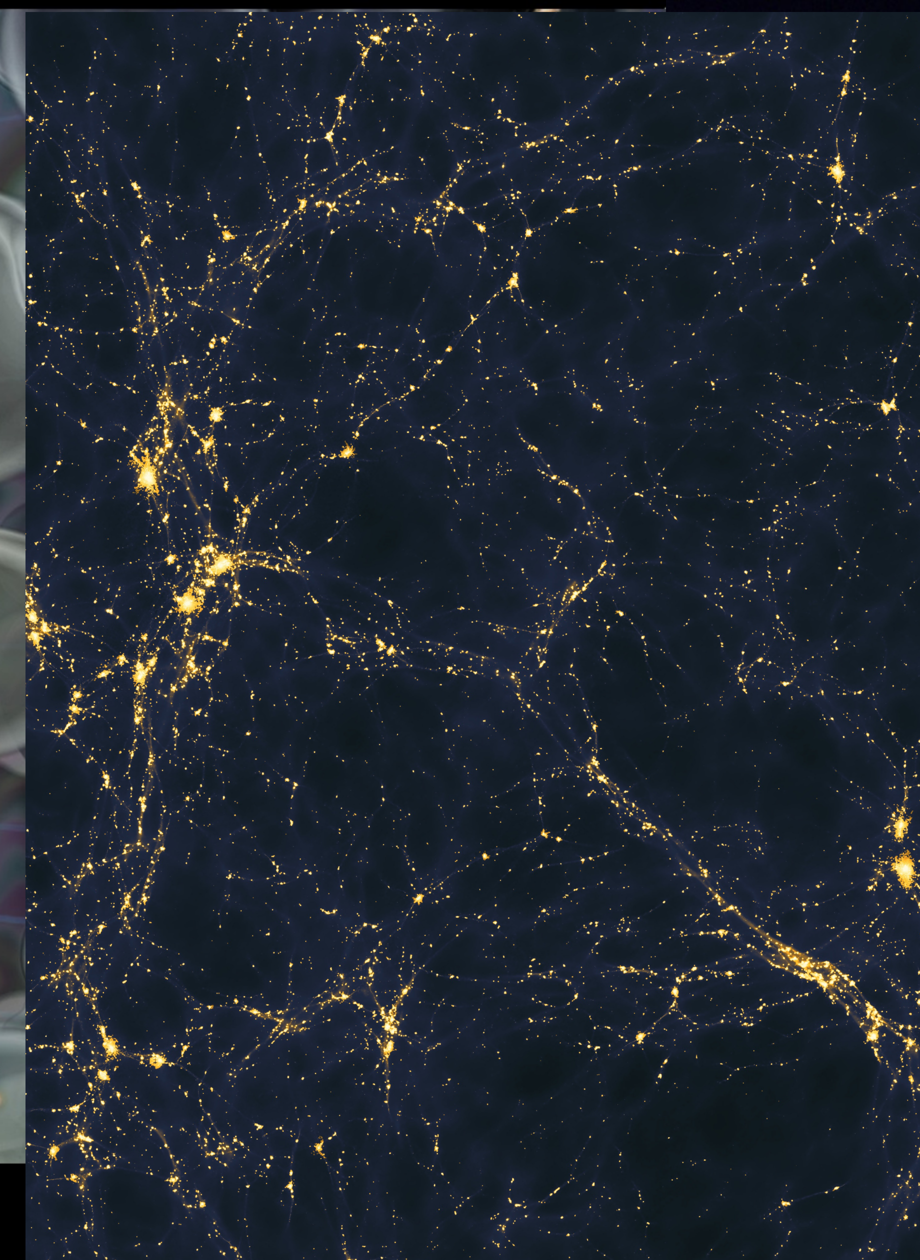


Image: Courtesy of Asantha Cooray

Introduction

What is the structure of the Universe?

What are properties of galaxies / ionising sources? … ?

To find out, we can identify individual sources of emission (e.g. LAE).

OR

We can sum all the emission in large areas and measure fluctuations (IM).

Image Credit: http://firstgalaxies.org/aspen_2016/

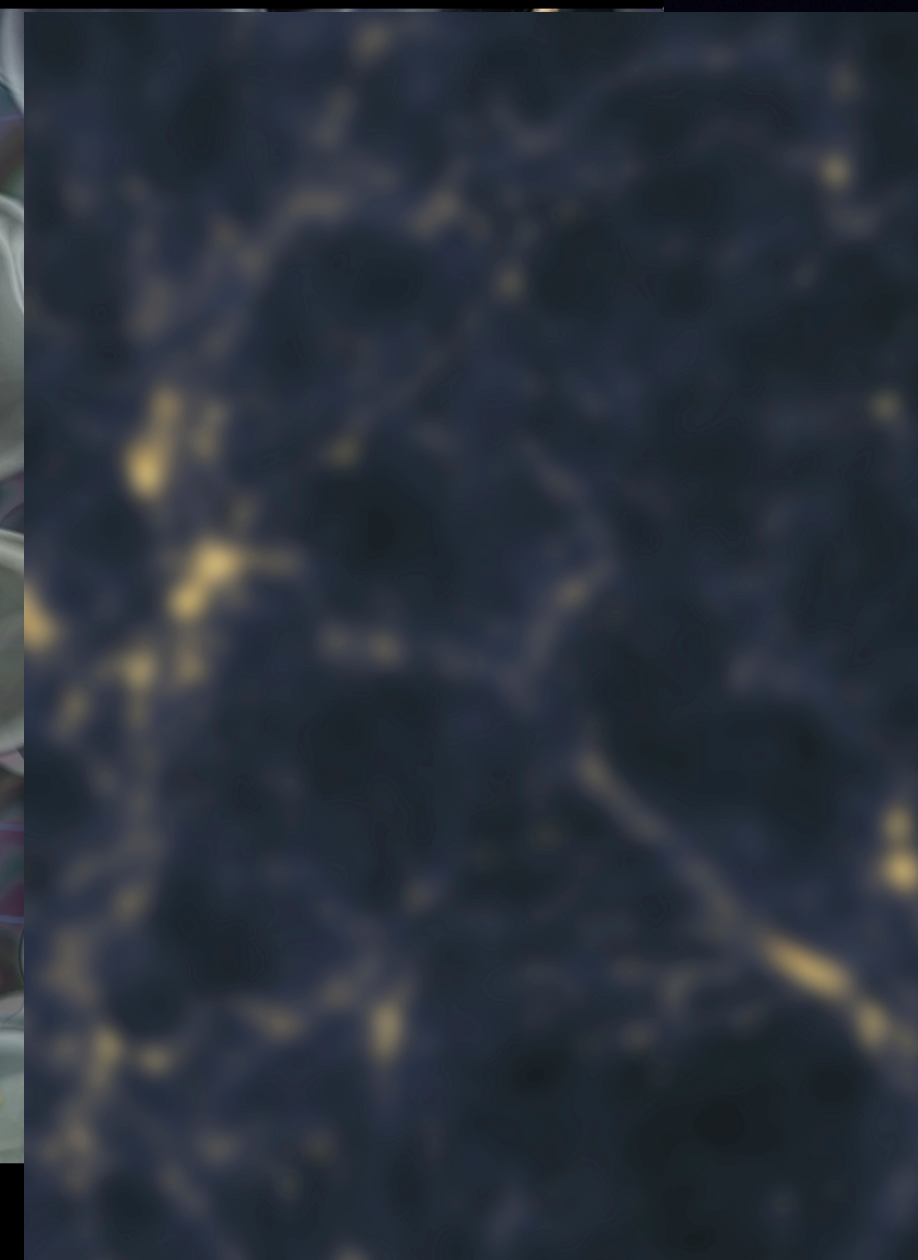


Image: Courtesy of Asantha Cooray

Cross-correlations: Line intensity mapping

Idea:

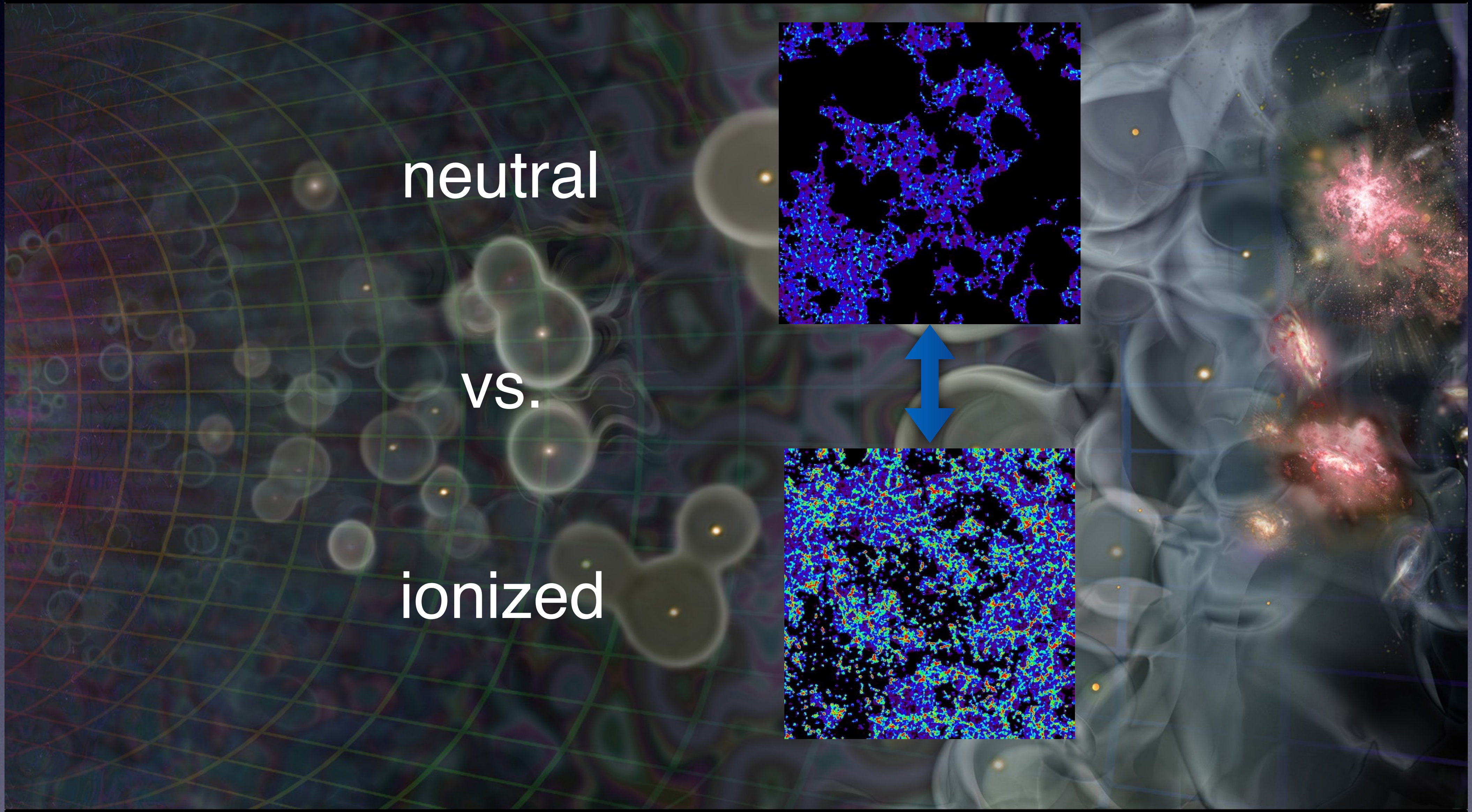
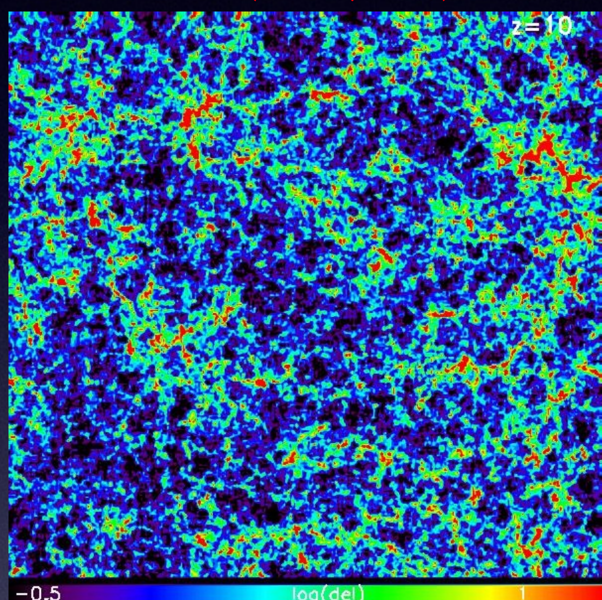


Image Credit: http://firstgalaxies.org/aspen_2016/

Simulations: neutral - 21 cm

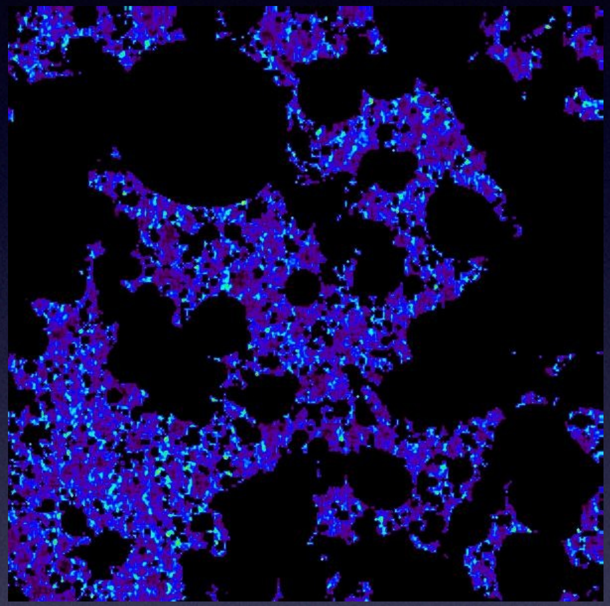
21cm FAST (DexM)
semi-numerical
[Mesinger et al.'10]

$\delta_{nl}, (\mathrm{d}v_r/\mathrm{d}r)$



density (+ velocity)
(Zel'dovich approximation)

ionization
x_{HI}
$f_{\rm coll}\left(\mathbf{x}, M, z\right) \geq \zeta^{-1}$
(filtering)



δT_b

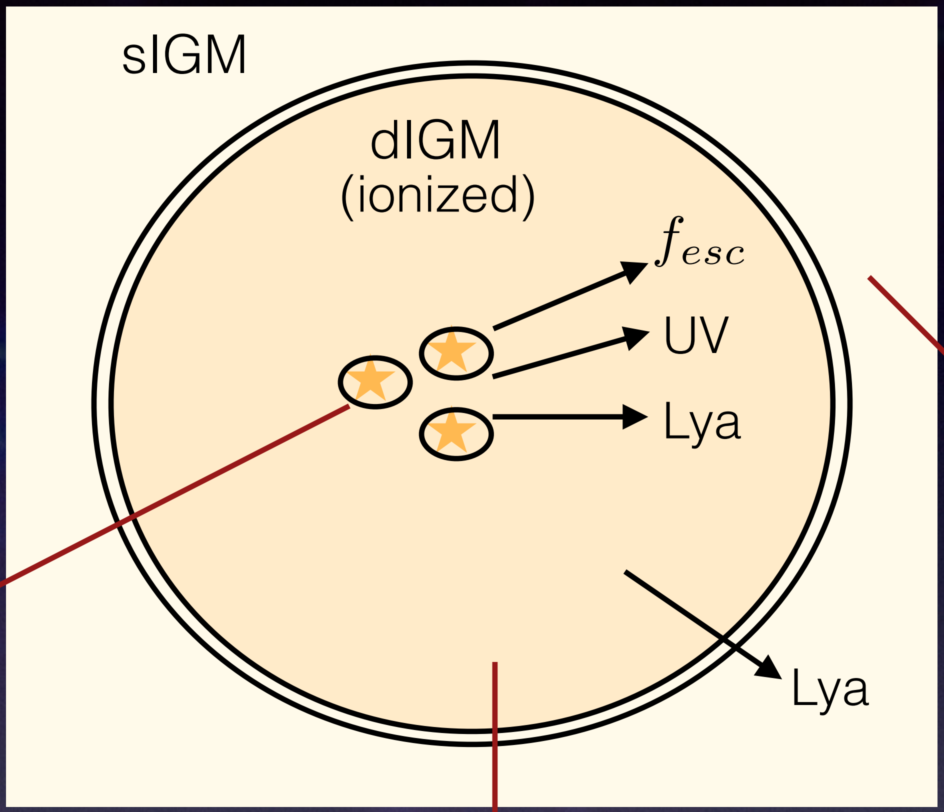
Offset 21-cm brightness temperature δT_b

$$\delta T_b\left(\nu\right) = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$

$$\propto x_{HI}\left(1+\delta_{nl}\right)\left(\frac{H}{\mathrm{d}v_r/\mathrm{d}r + H}\right)$$

Fiducial Cosmology: Planck

Simulations: Lyα fluctuations



Scattered IGM:

- Scattering Ly-n photons
- Excitations (UV/X-ray)

T_K, x_i

Galaxy contribution:

- Recombinations f_{rec}
- Excitations

$\propto$ SFR

[from Silva et al. 2013]

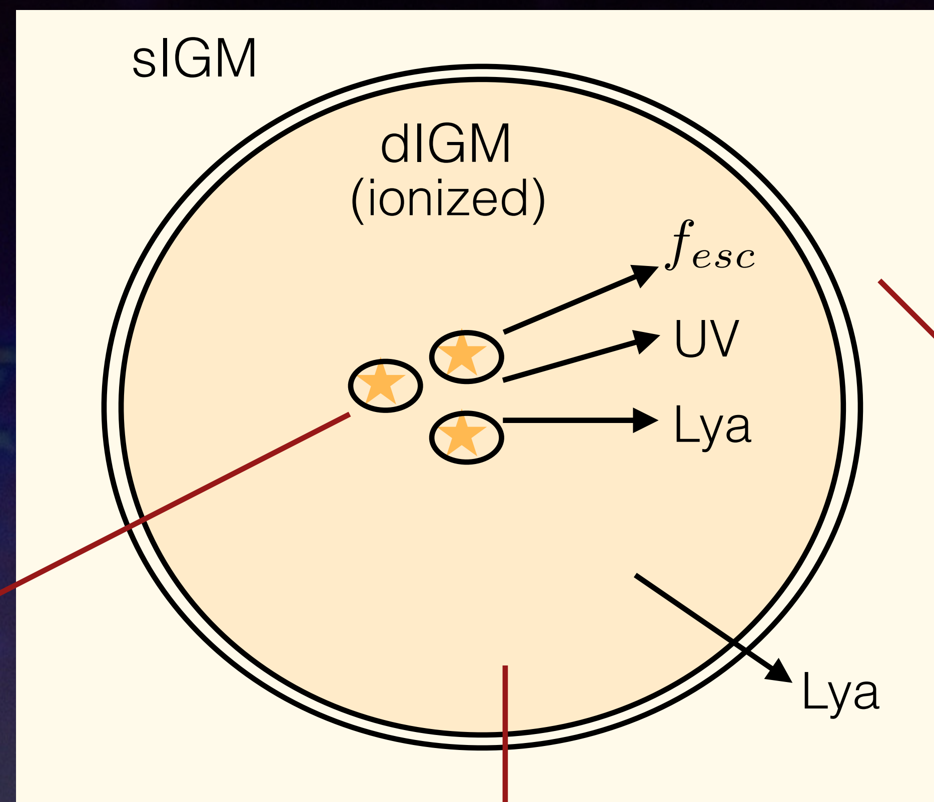
Diffuse IGM:

Recombination

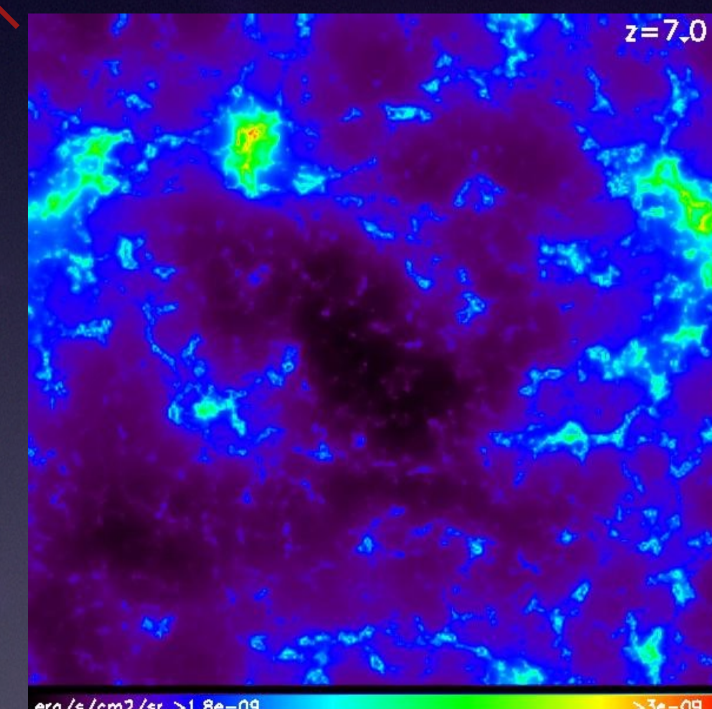
f_{esc} f_{rec}

Hα fluctuations :
Galactic + diffuse IGM

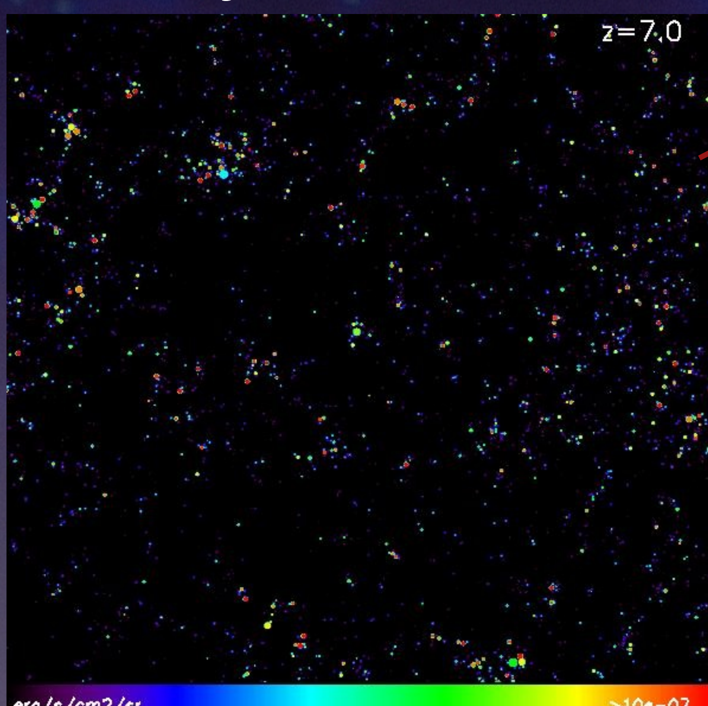
Simulations: Lyα fluctuations



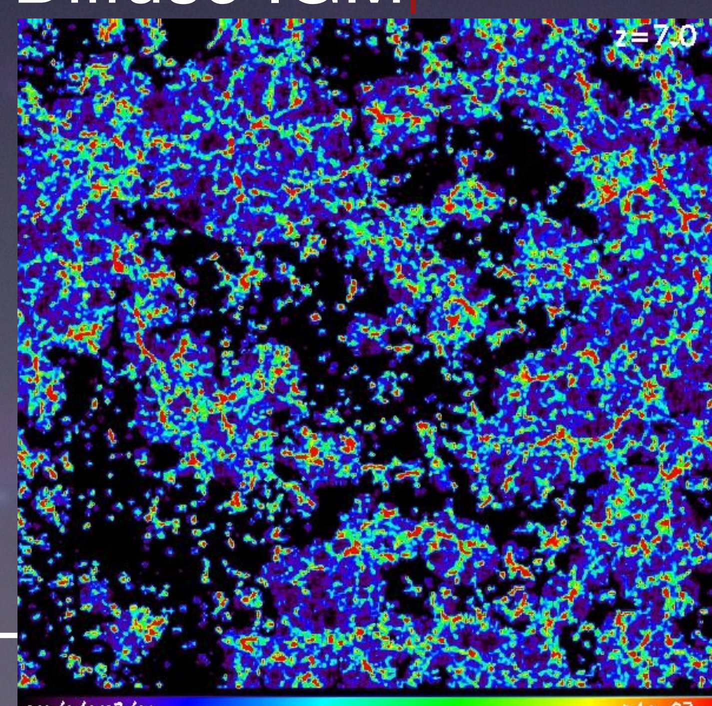
Scattered IGM



Galaxy contribution

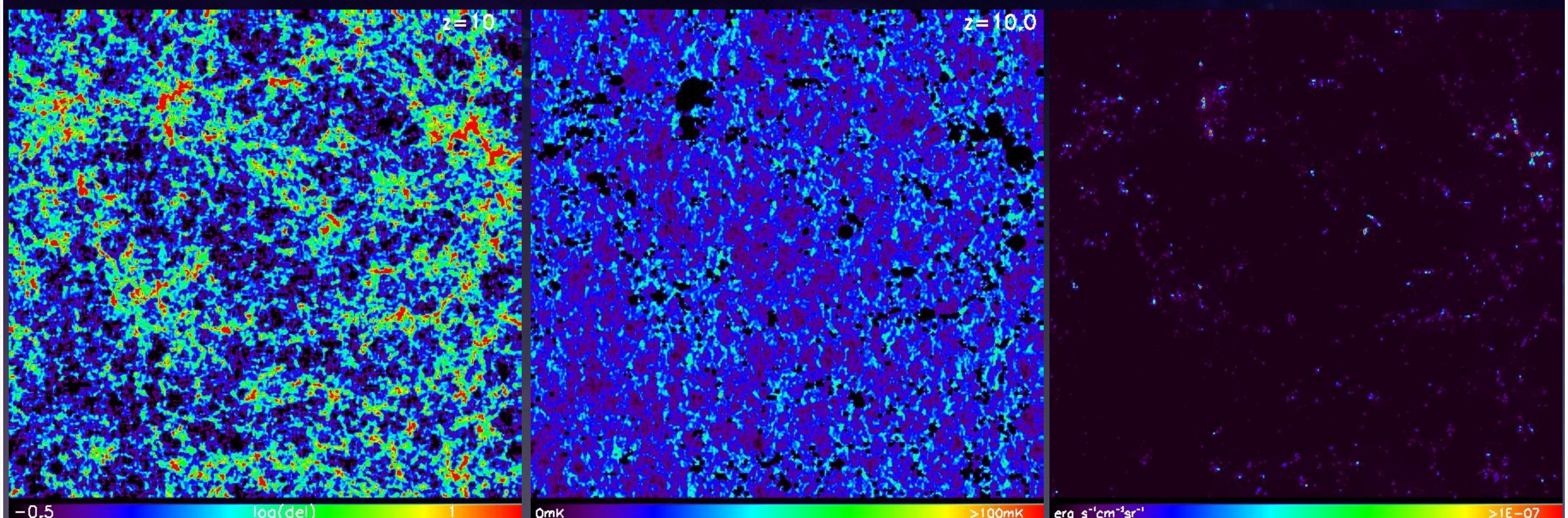


Diffuse IGM



Time evolution

density | 21 cm | Lyman-alpha

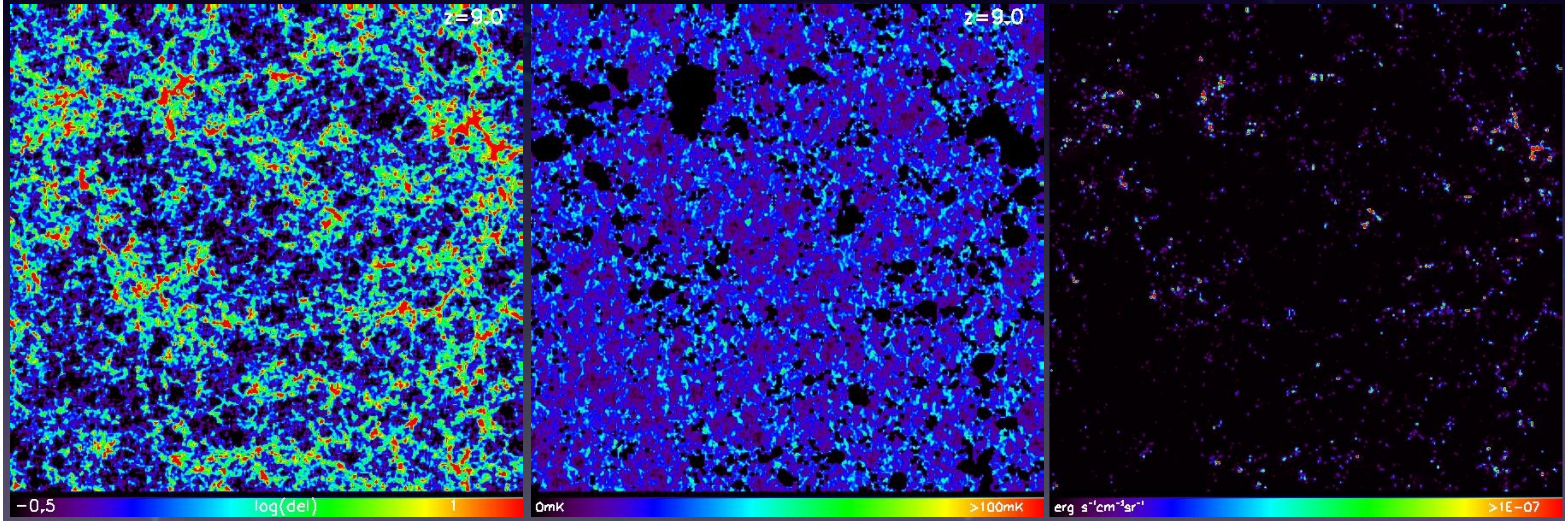


z=10

CH+ arXiv: 1611.09682

Time evolution

density | 21 cm | Lyman-alpha

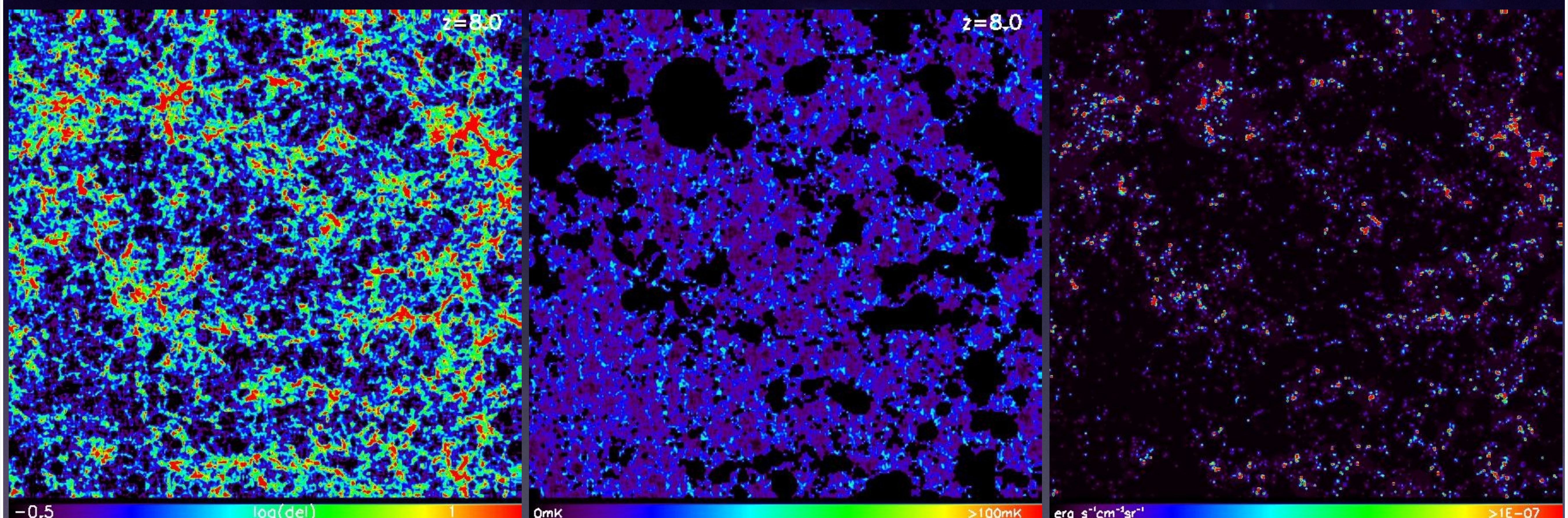


z=9

CH+ arXiv: 1611.09682

Time evolution

density | 21 cm | Lyman-alpha

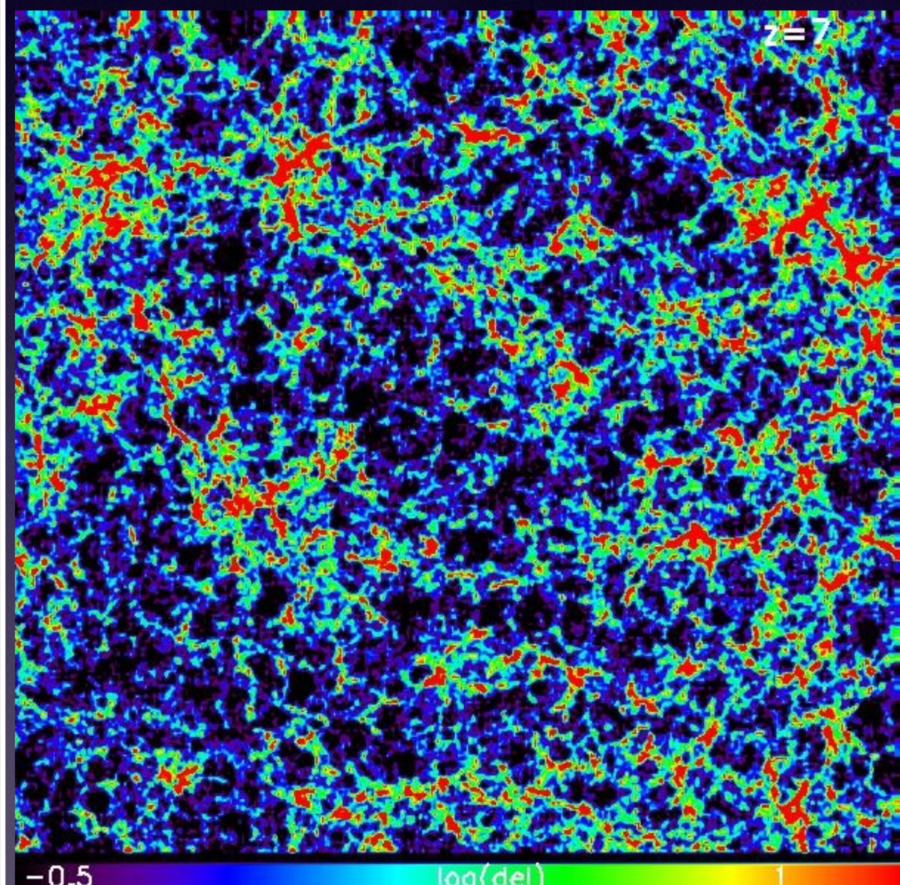


z=8

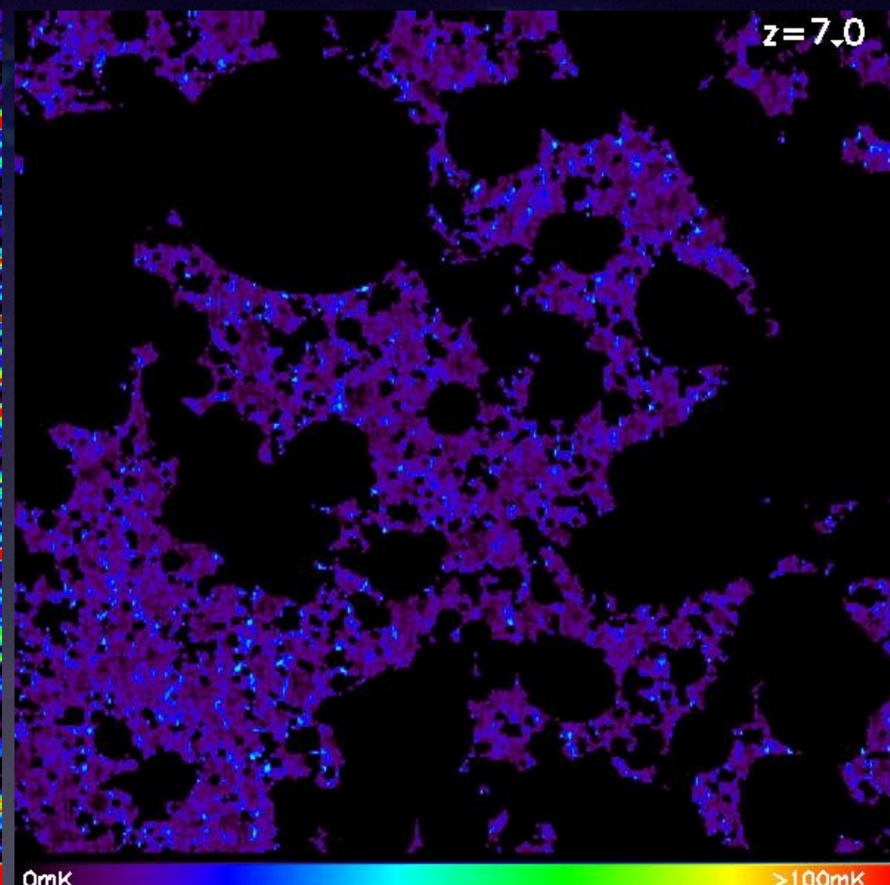
CH+ arXiv: 1611.09682

Time evolution

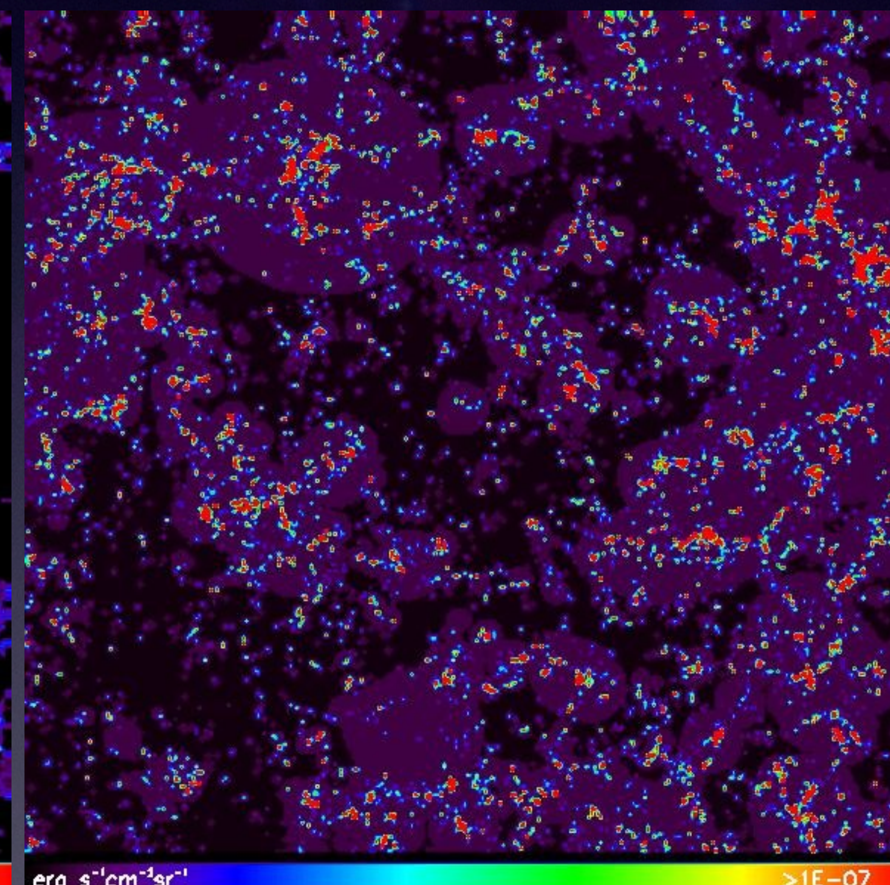
density



21 cm



Lyman-alpha

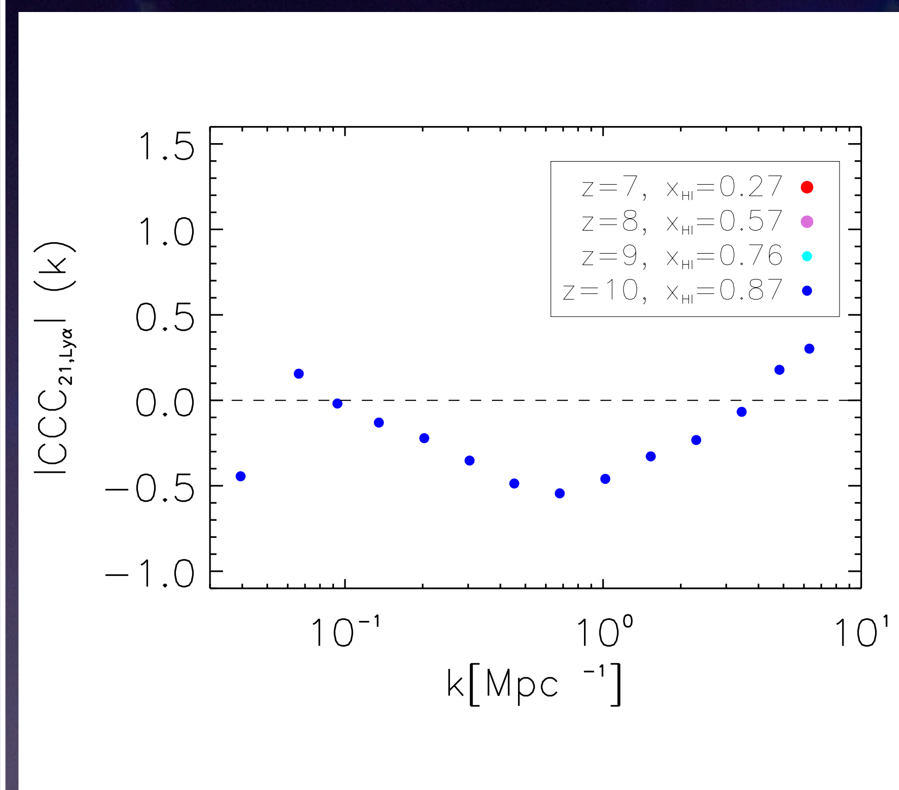


z=7

CH+ arXiv: 1611.09682

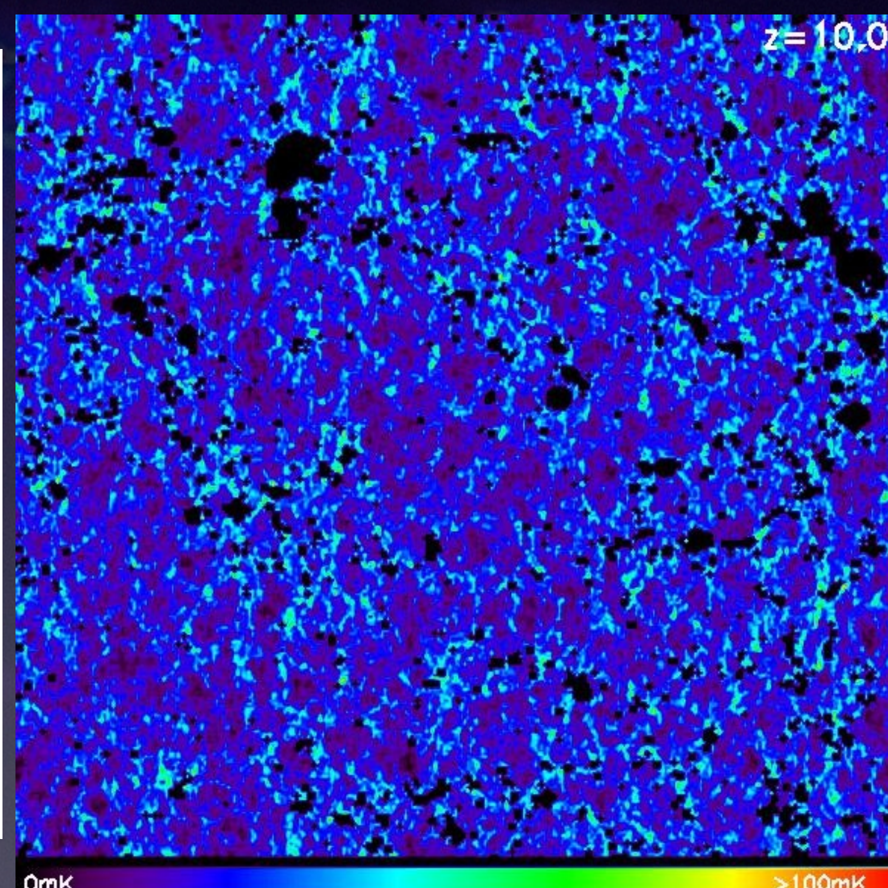
Time evolution

21-cm x Lyα

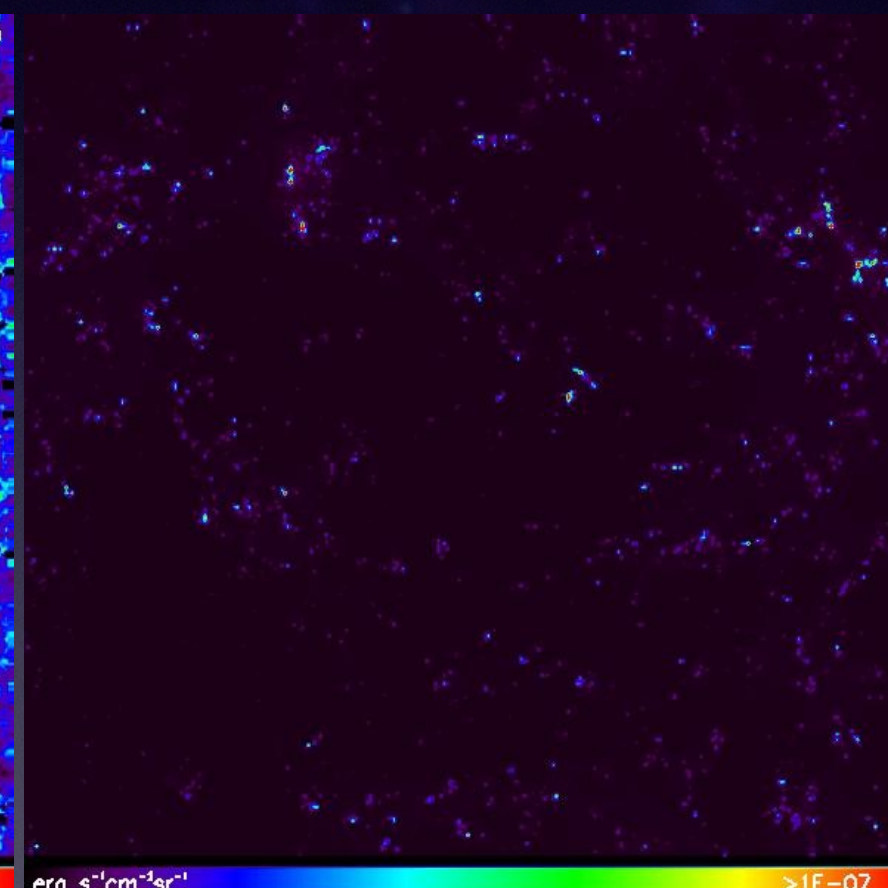


$$CCC_{I,J}(k) = \frac{\Delta_{I,J}(k)}{\sqrt{\Delta_I(k)\,\Delta_J(k)}}$$

21-cm



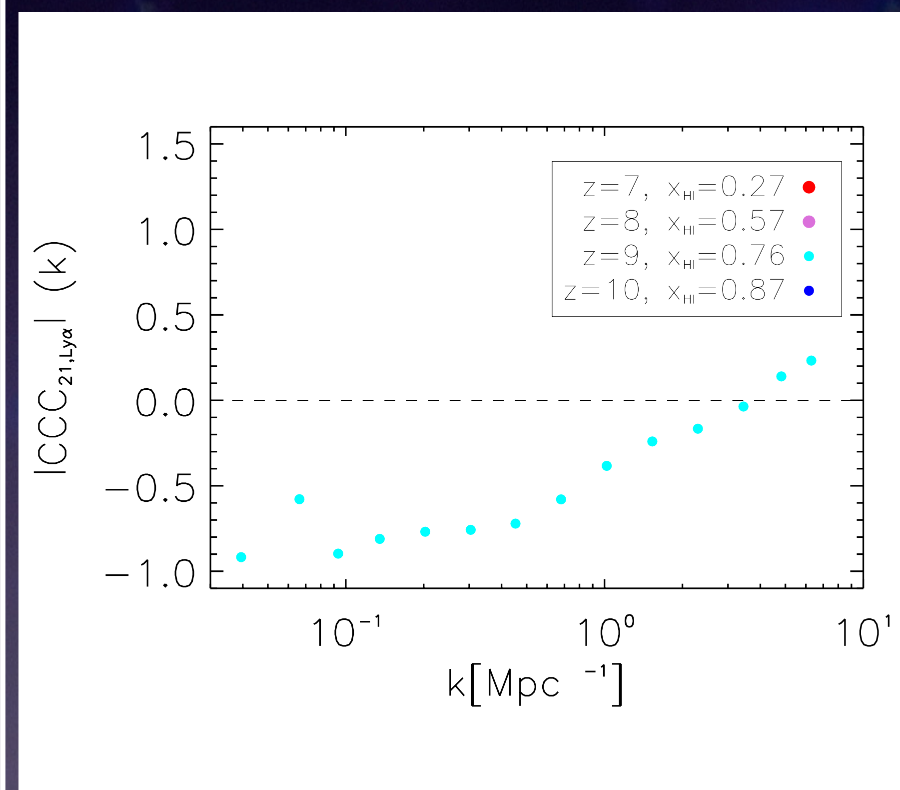
Lyα



Heneka, Cooray, Feng, ApJ, 848 (2017)

Time evolution

21-cm x Lyα



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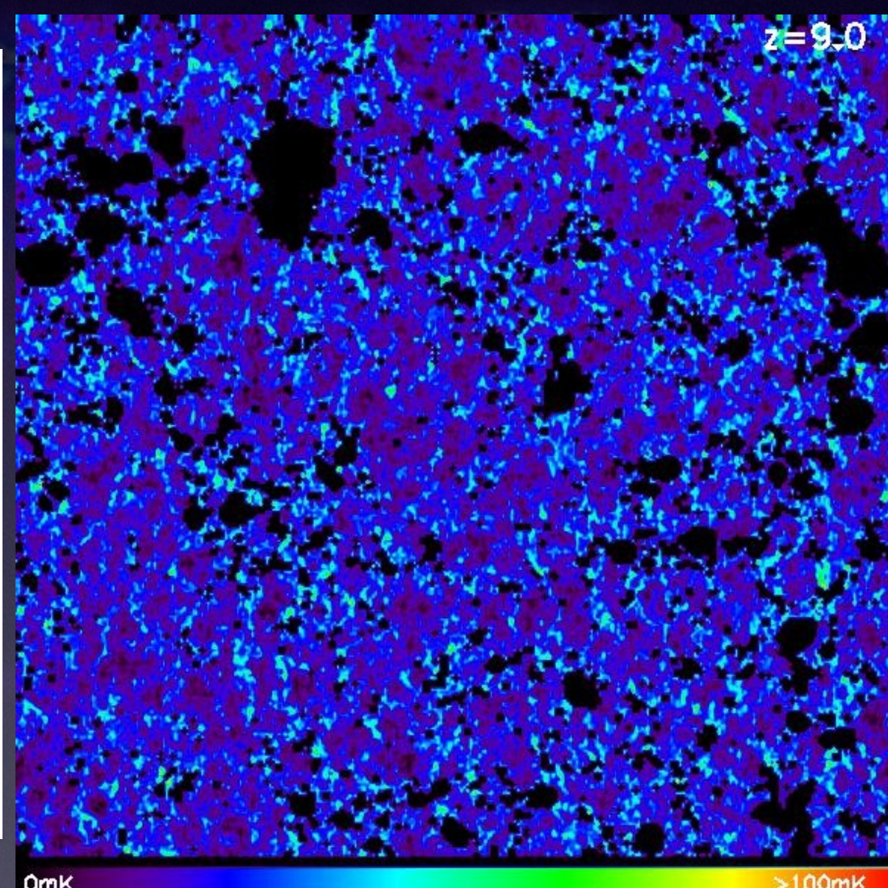
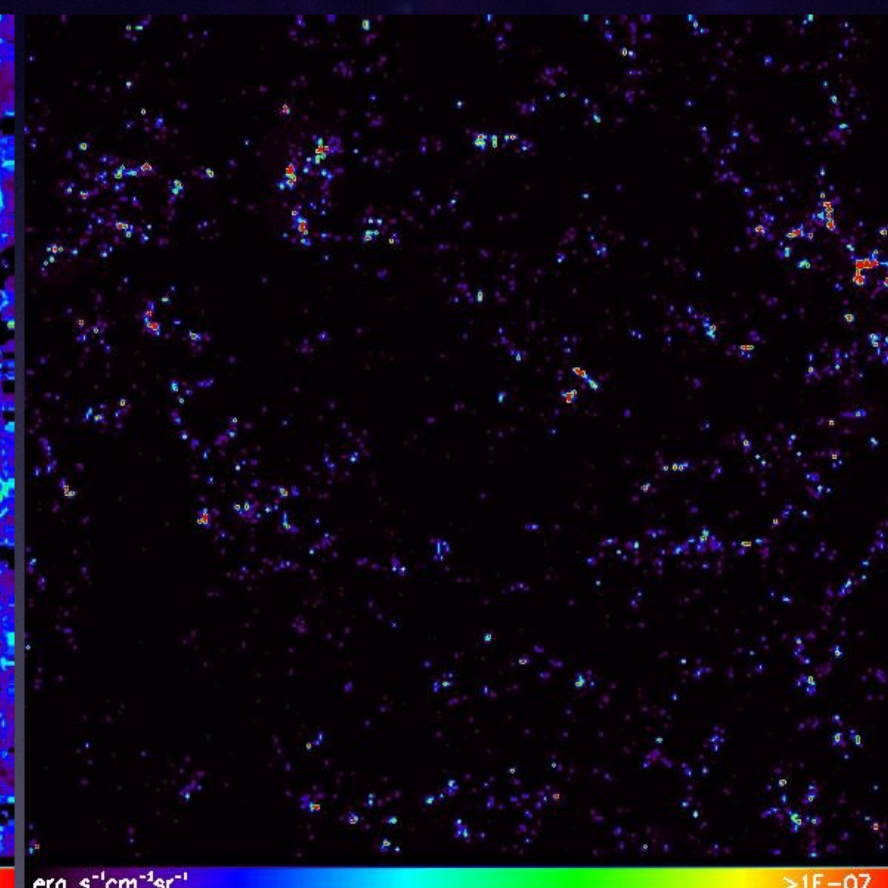
21-cm



Lyα



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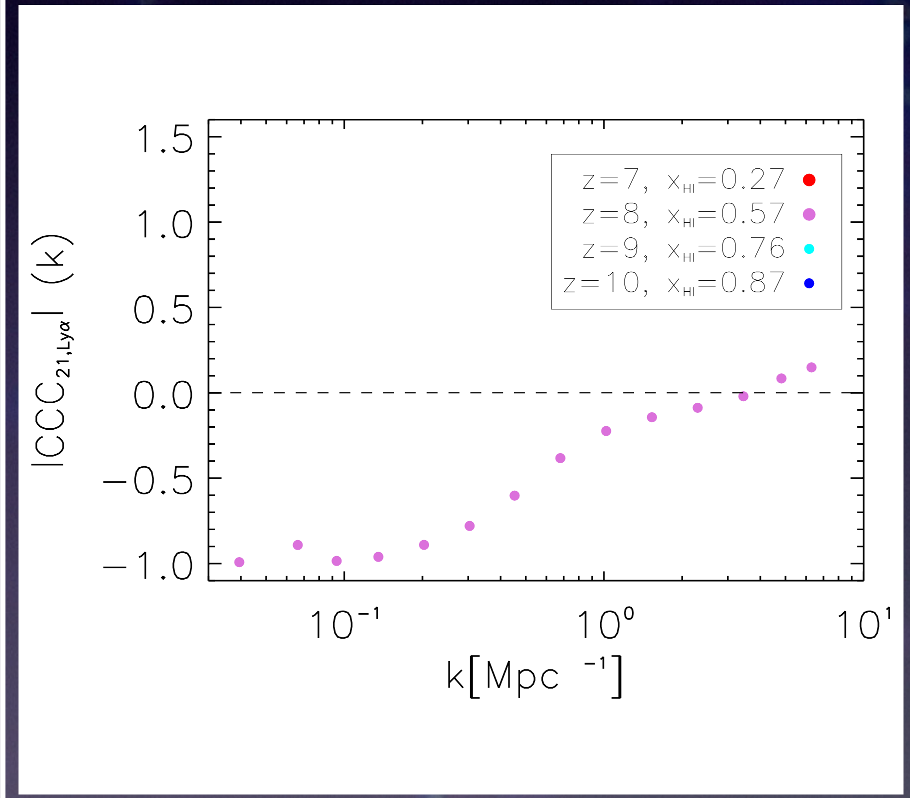
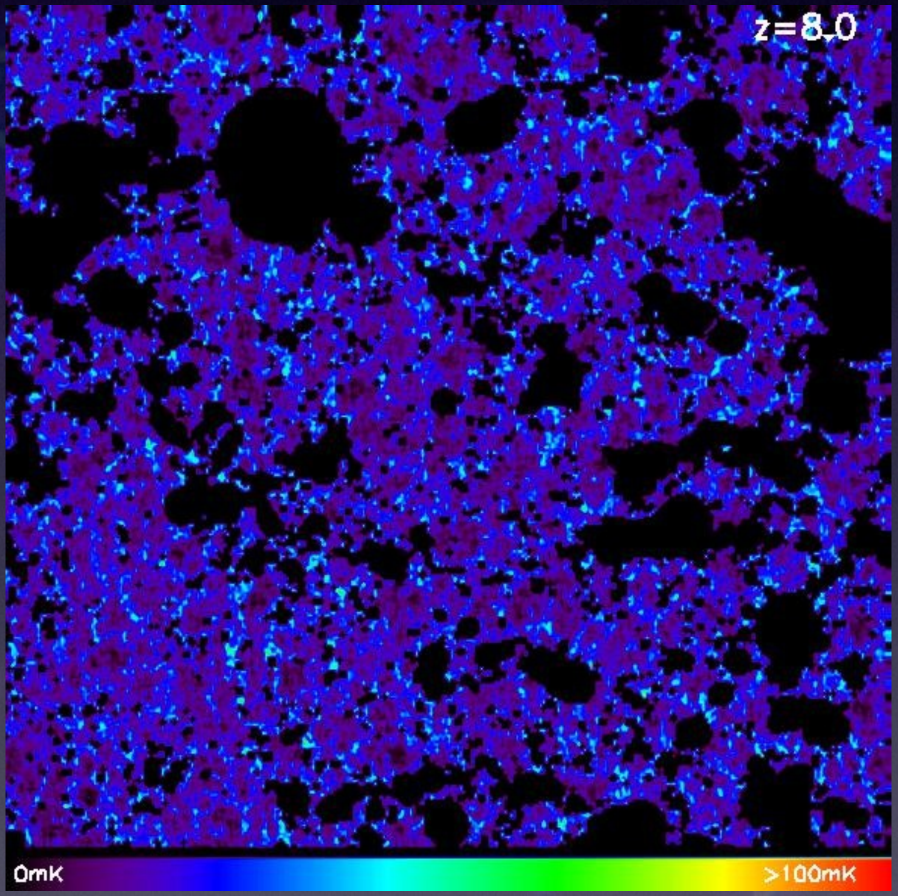
Time evolution

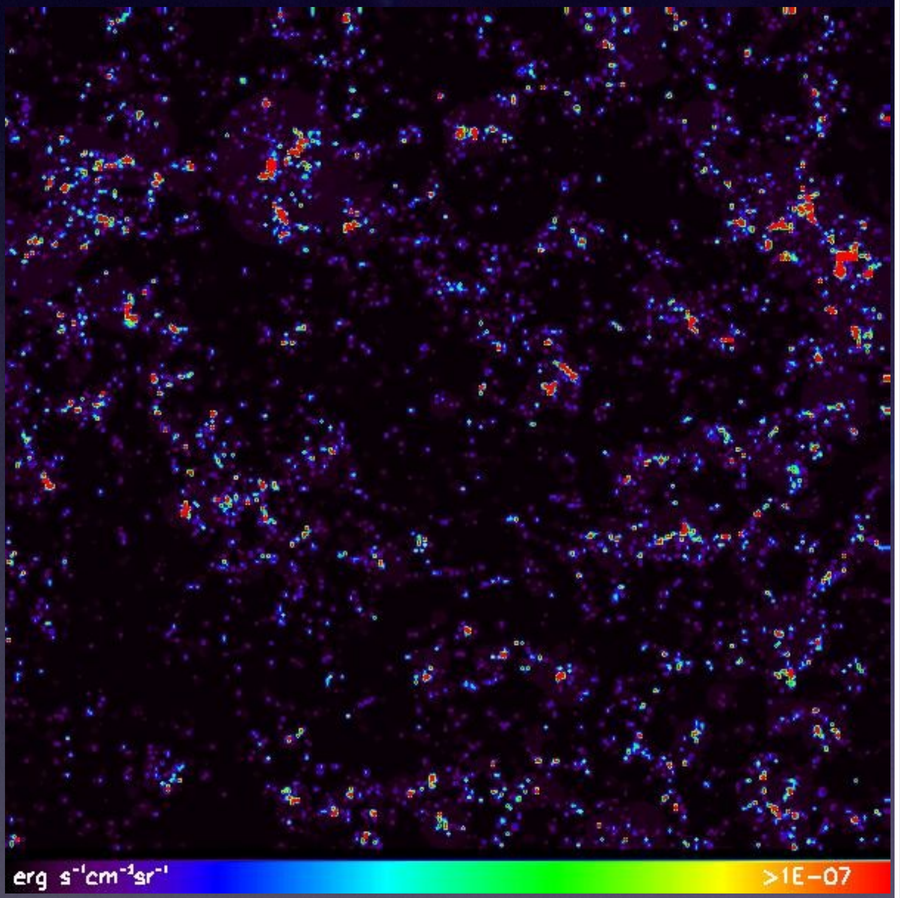
21-cm x Lyα

21-cm

Lyα





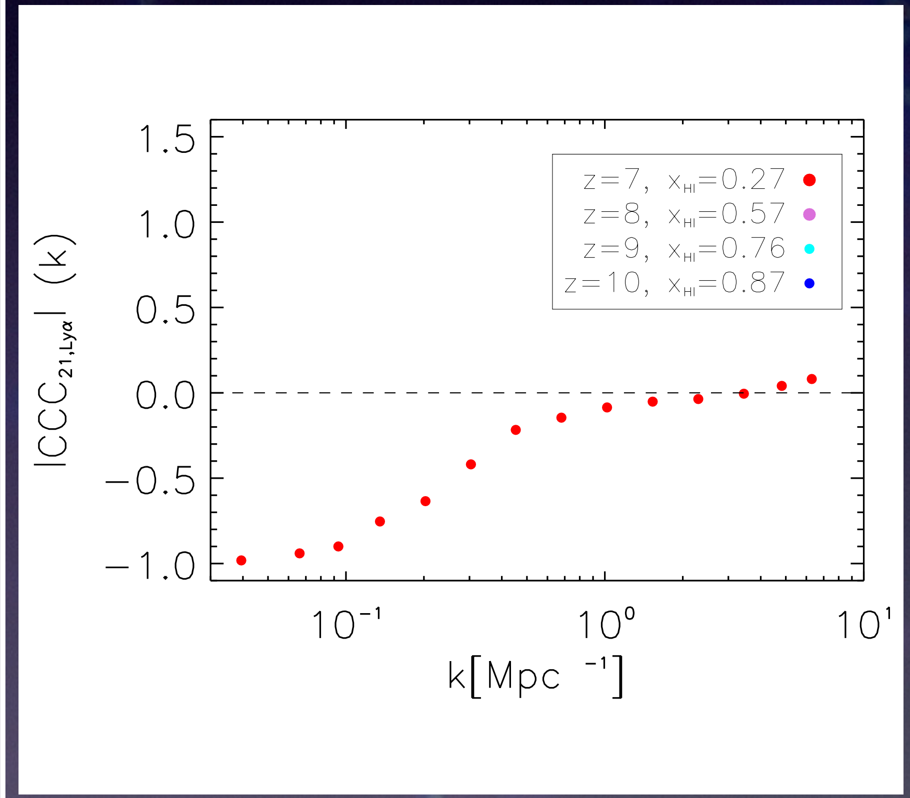


$$CCC_{I,J}(k) = \frac{\Delta_{I,J}(k)}{\sqrt{\Delta_I(k)\,\Delta_J(k)}}$$

Heneka, Cooray, Feng, ApJ, 848 (2017)

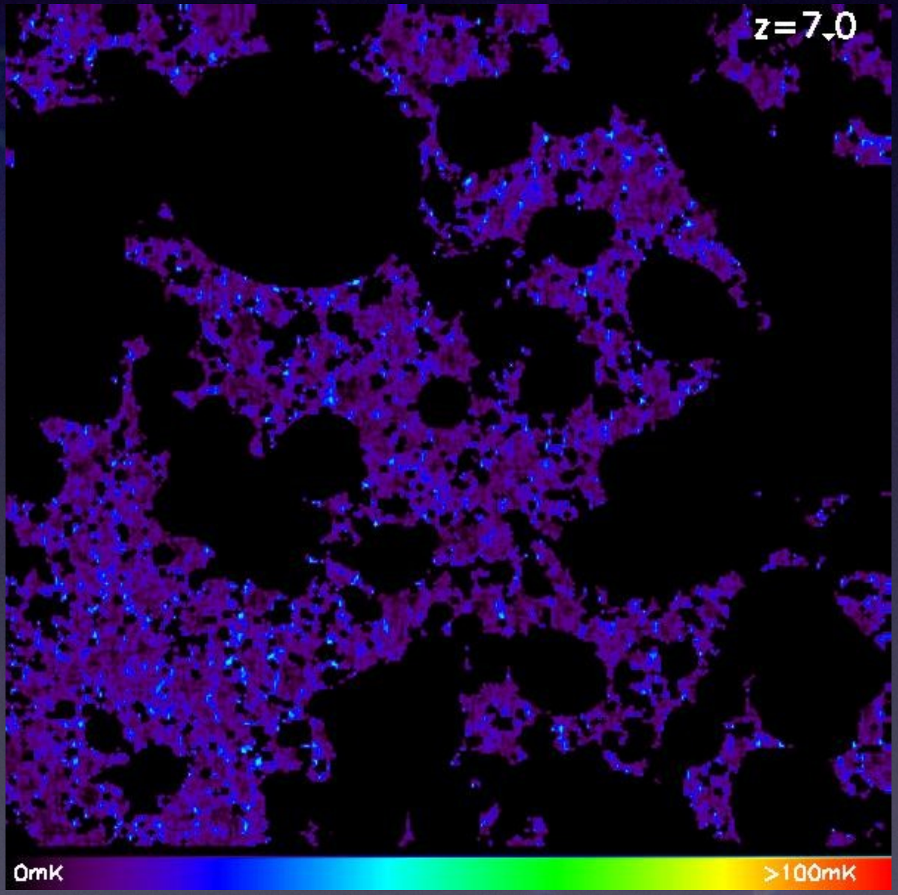
Time evolution

21-cm x Lya

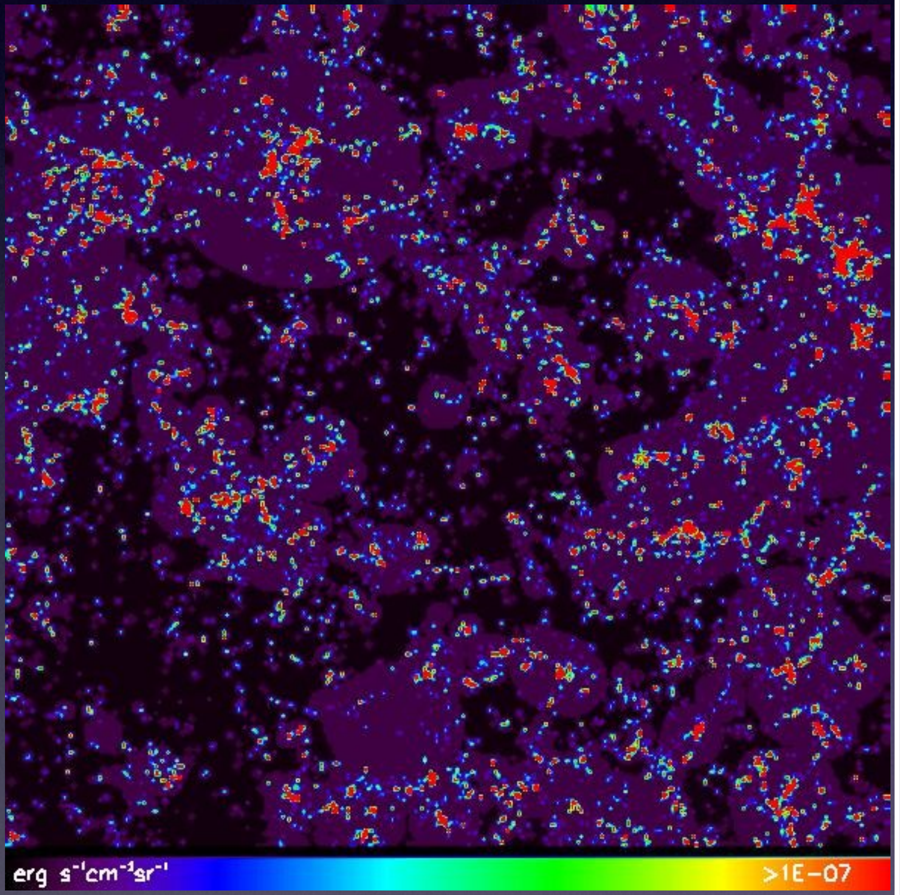


$$CCC_{I,J}(k) = \frac{\Delta_{I,J}(k)}{\sqrt{\Delta_I(k)\,\Delta_J(k)}}$$

21-cm

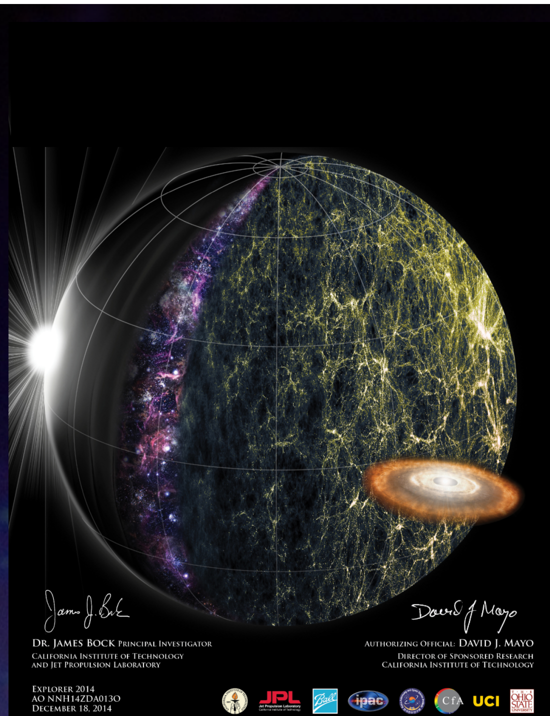


Lya



Heneka, Cooray, Feng, ApJ, 848 (2017)

Is this measurable? - The future



Cosmic Dawn Intensity Mapper (CDIM)
<u>Spectro-imaging of the Universe</u>

- Legacy applications with 21-cm background
- Ideal wavelength coverage and high sensitivity to detect the EoR integrated galaxy intensity signal
- Multiple bands enable correlation tests sensitive to redshift history

Resolving Power and Wavelength Coverage :
λ= 0.75 - 7.5 μm
R = 300
pixel size 1”
survey size 300° (30°)

Also: SPHEREx
NASA Small Explorer
<u>All-sky near-IR spectral survey</u>

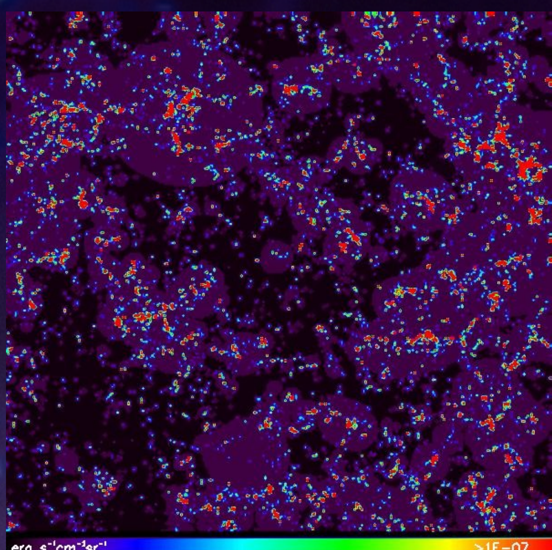
λ= 0.75-4.1 μm; R=41.5
λ= 4.1-4.8 μm; R=150

Summary paper: Cooray *et al.* 2016

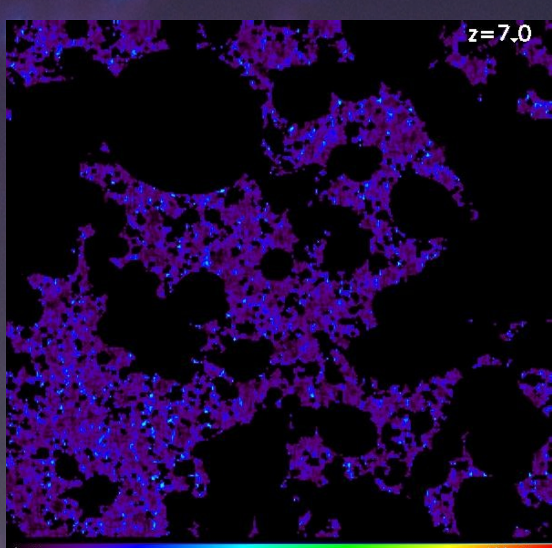
Intensity mapping

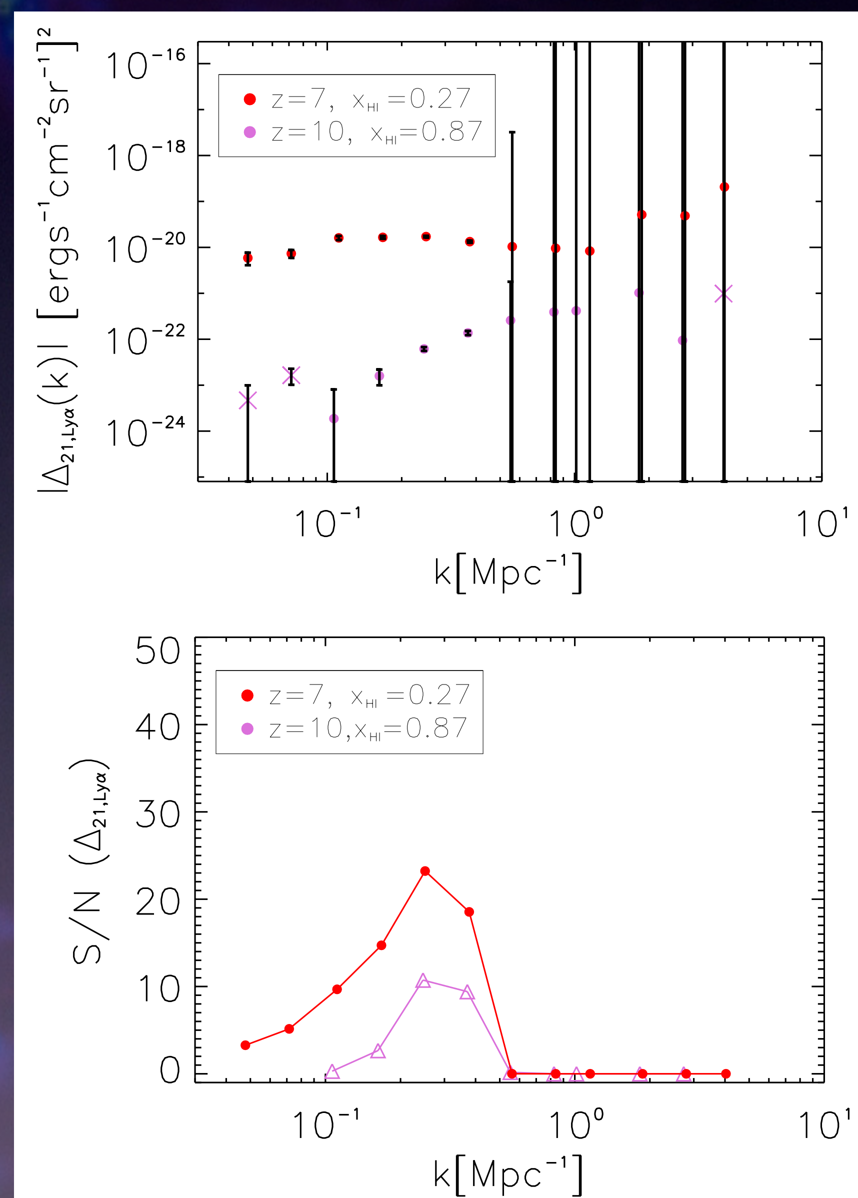
Lyα X 21cm (SKA)

+foreground wedge
+Lyα damping



X





(a) Lyα intensity maps ideal for cross-correlation with 21cm

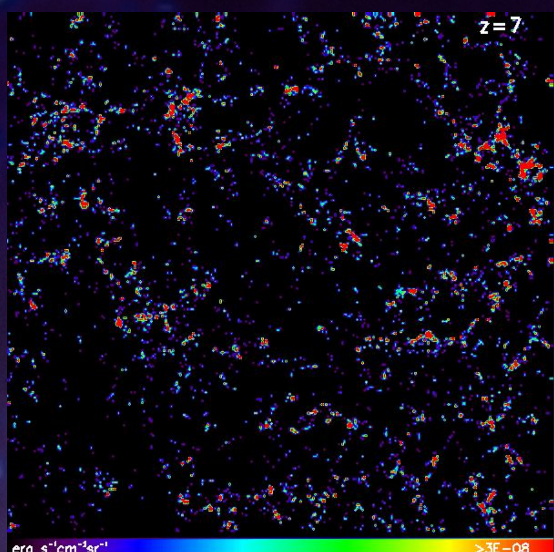
(b) Correlation neg. at small k, pos. at large k

(c) Statistical measure of reionized regions

$$\Delta_{I,J} \propto \langle \delta_I \delta_J^* \rangle_k$$

Intensity mapping

Hα X 21cm (SKA)



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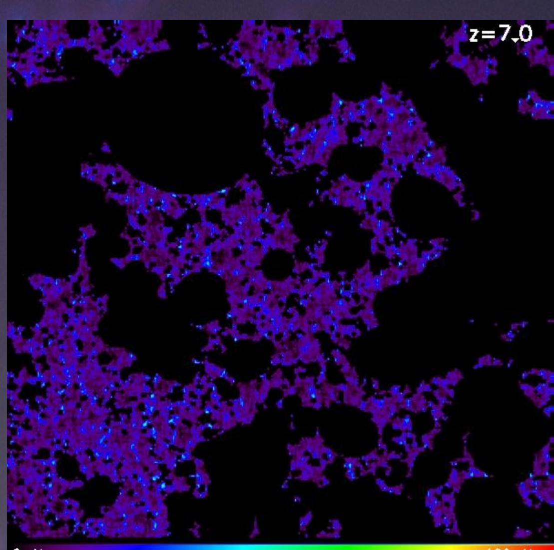
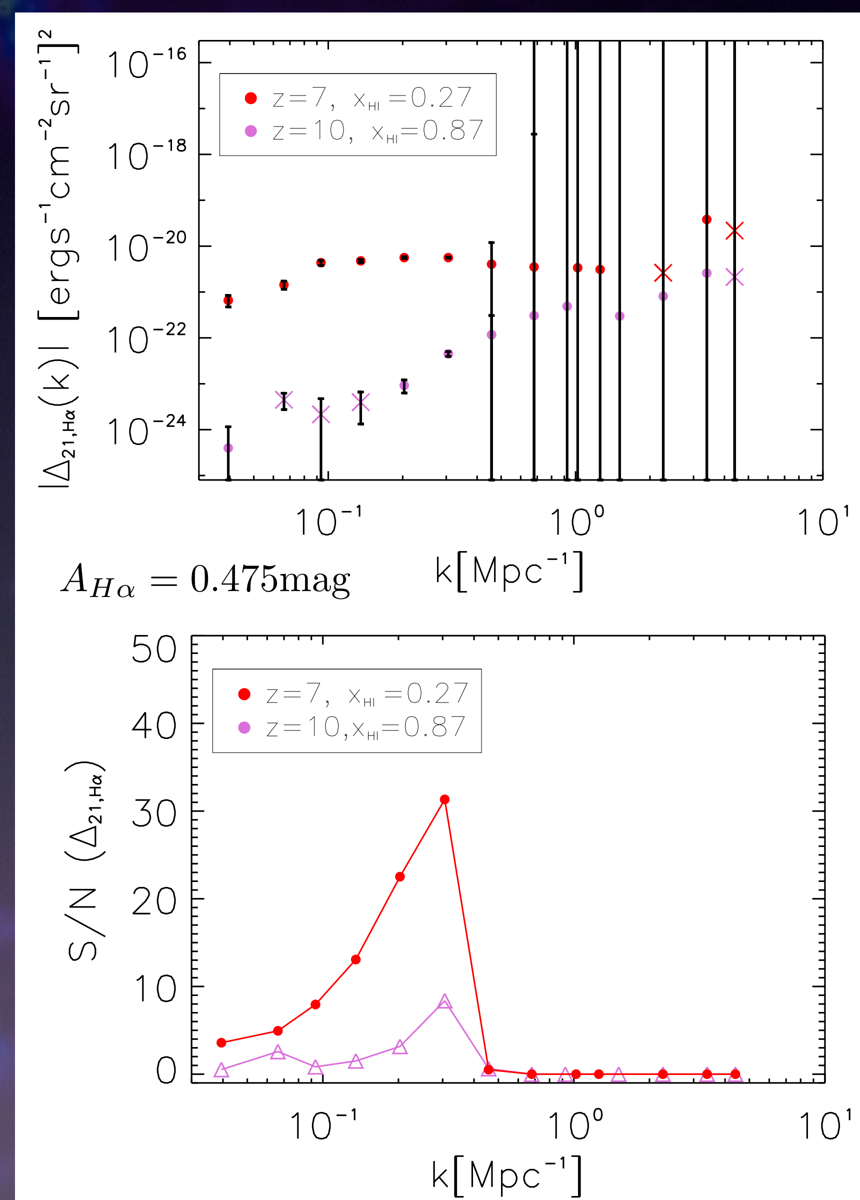




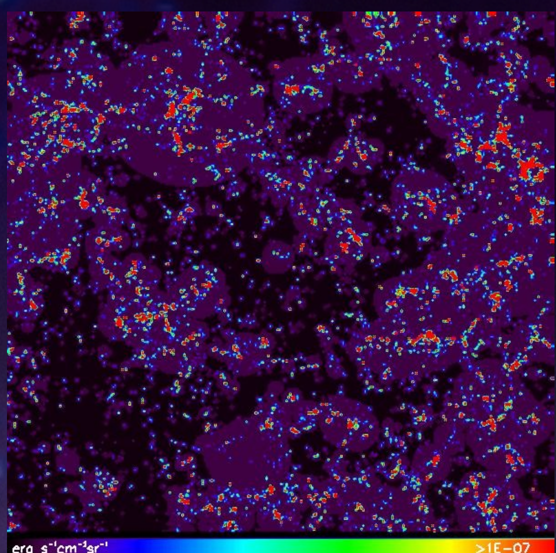
(a) Also suitable for cross-correlation with 21cm

(b) Correlation neg. at small k, pos. at large k

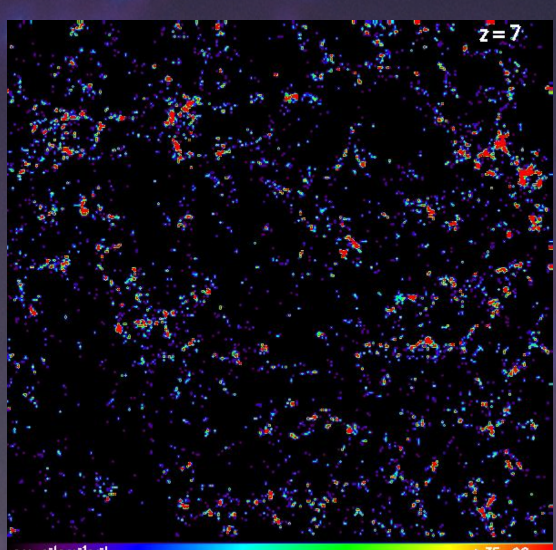
(c) Single out dust (globally)?

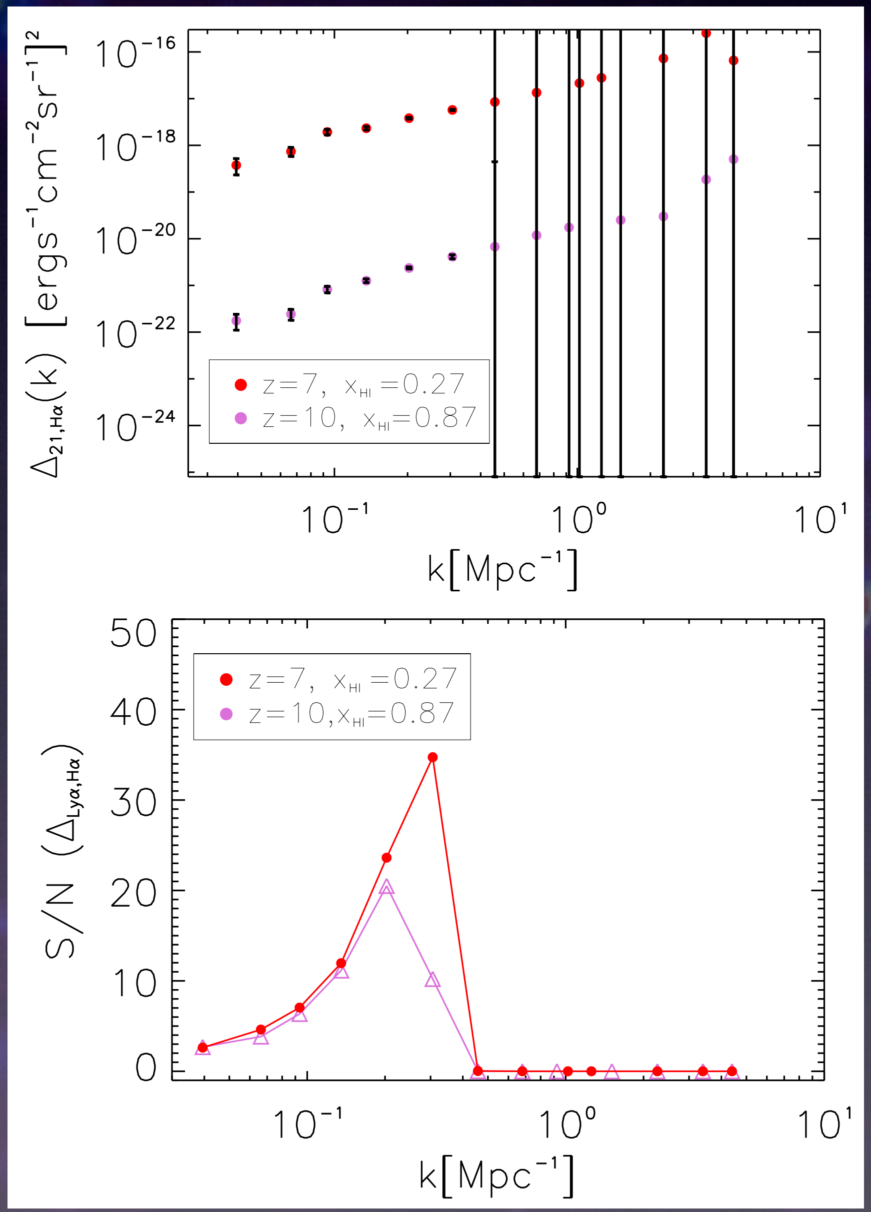
Intensity mapping

Lyα X Hα



X





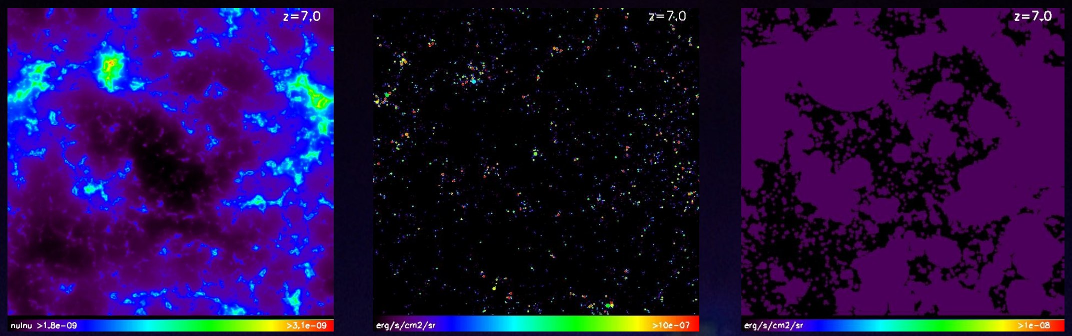
(a) Different tracers for overdensities / galaxies

(b) As expected: positive correlation on all scales

(c) Distinguish e.g. IGM contribution for Lya

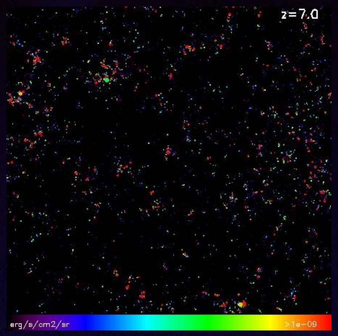
Other lines: Hα

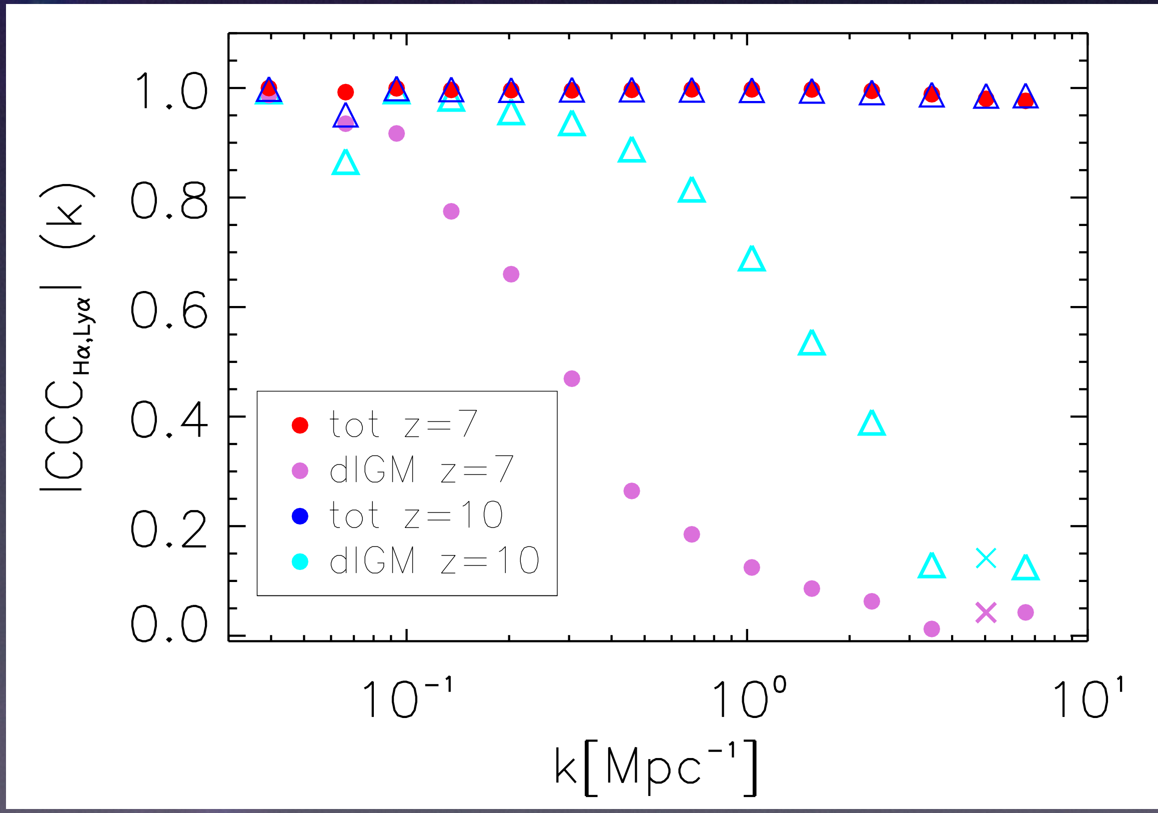
Lya



X

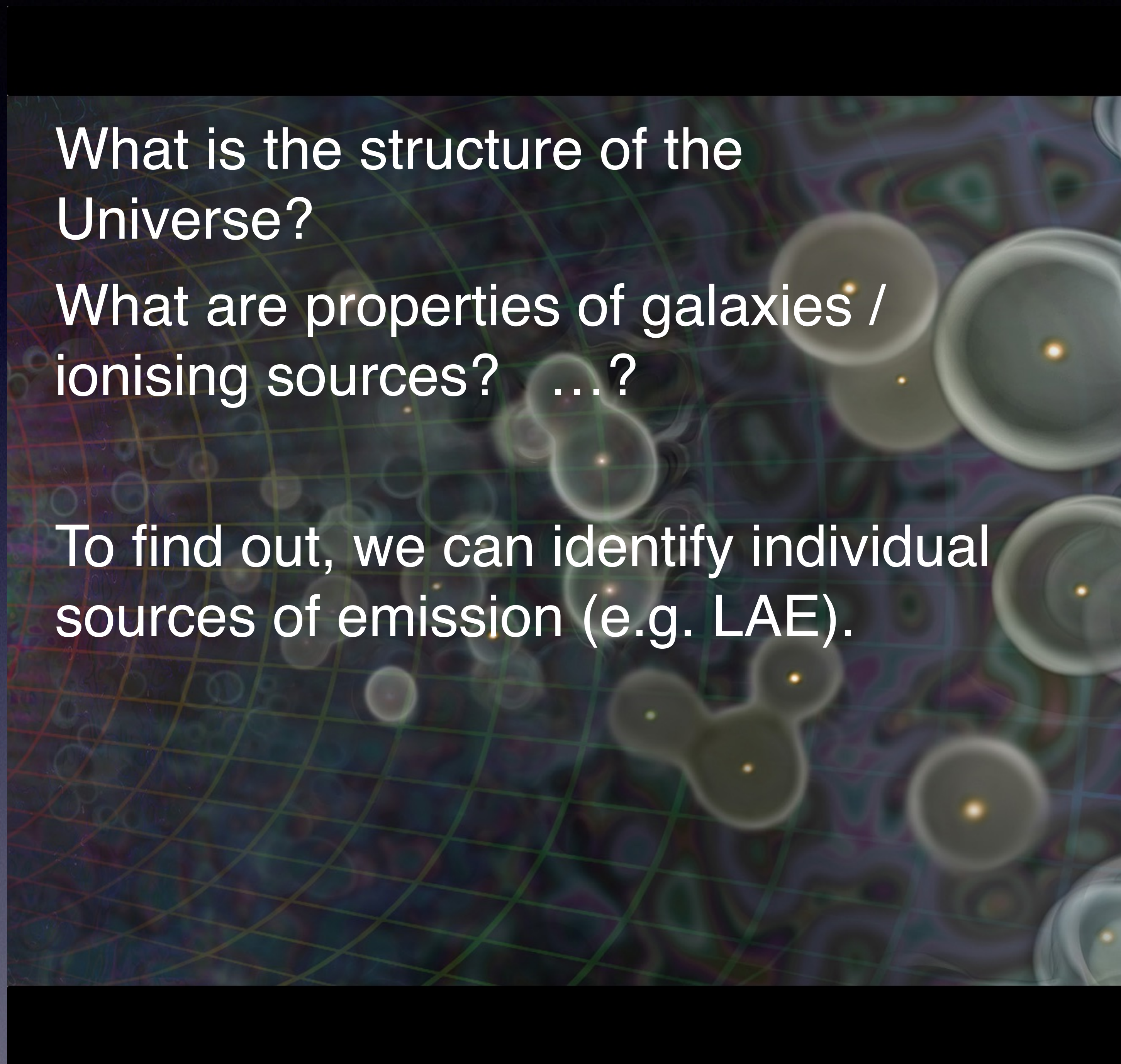
Hα





CH+ ApJ, 848 (2017)

Back to: Introduction



What is the structure of the Universe?

What are properties of galaxies / ionising sources? …?

To find out, we can identify individual sources of emission (e.g. LAE).

Image Credit: http://firstgalaxies.org/aspen_2016/

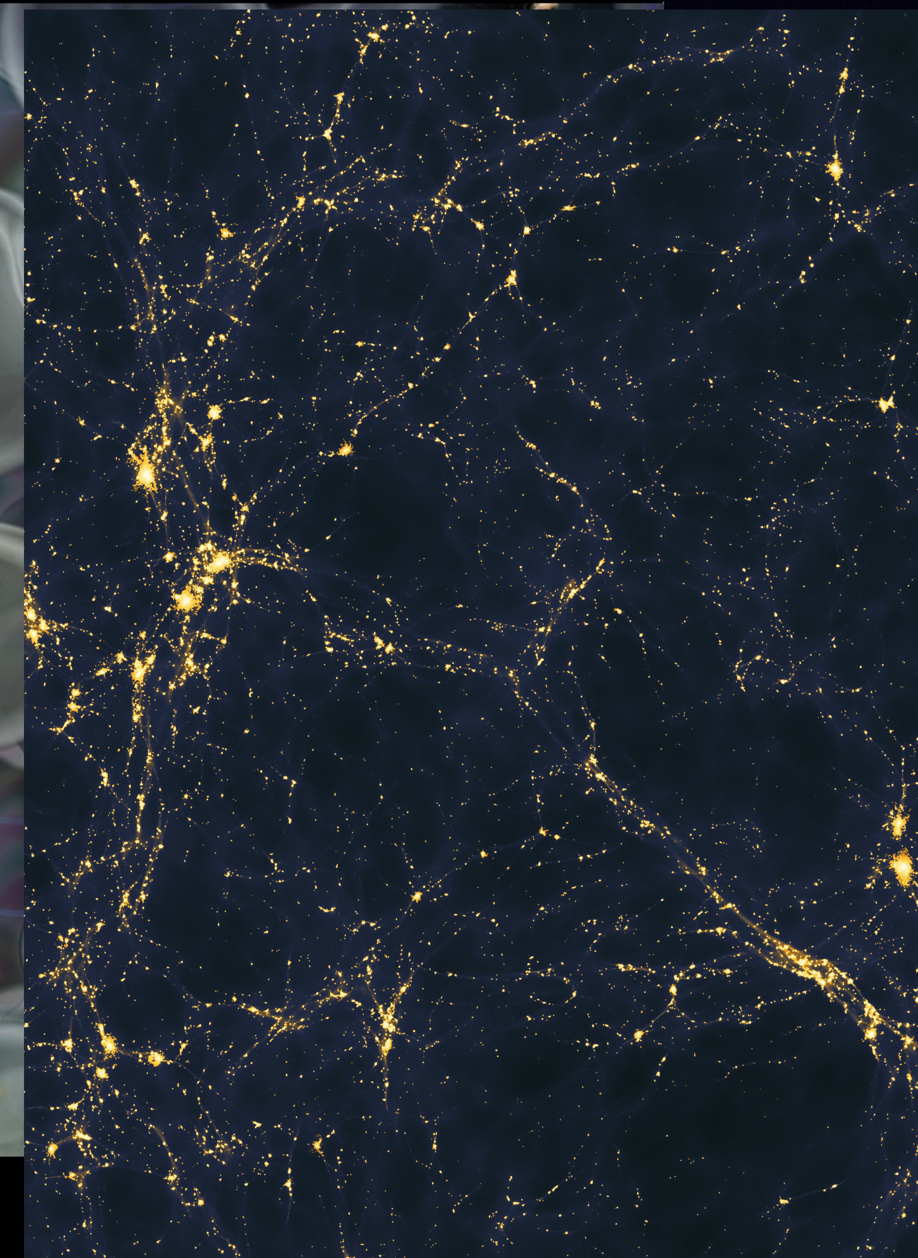
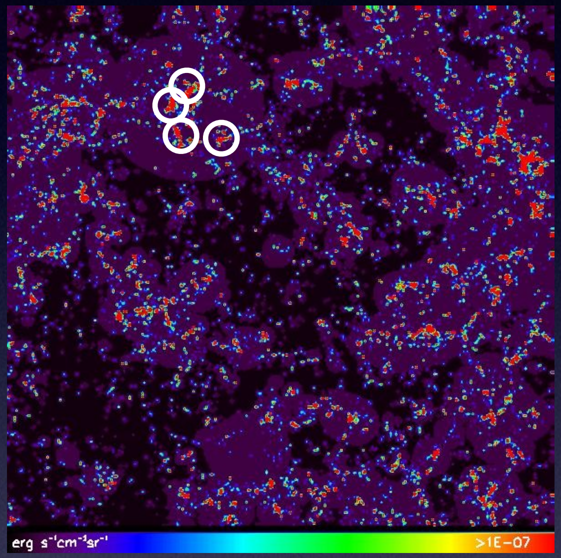


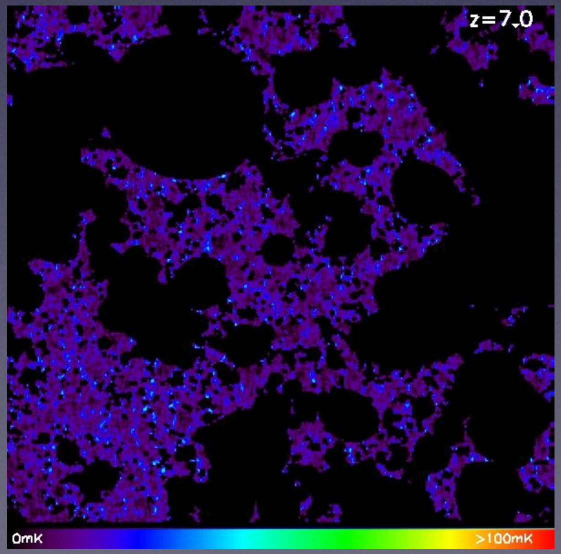
Image: Courtesy of Asantha Cooray

Intensity mapping

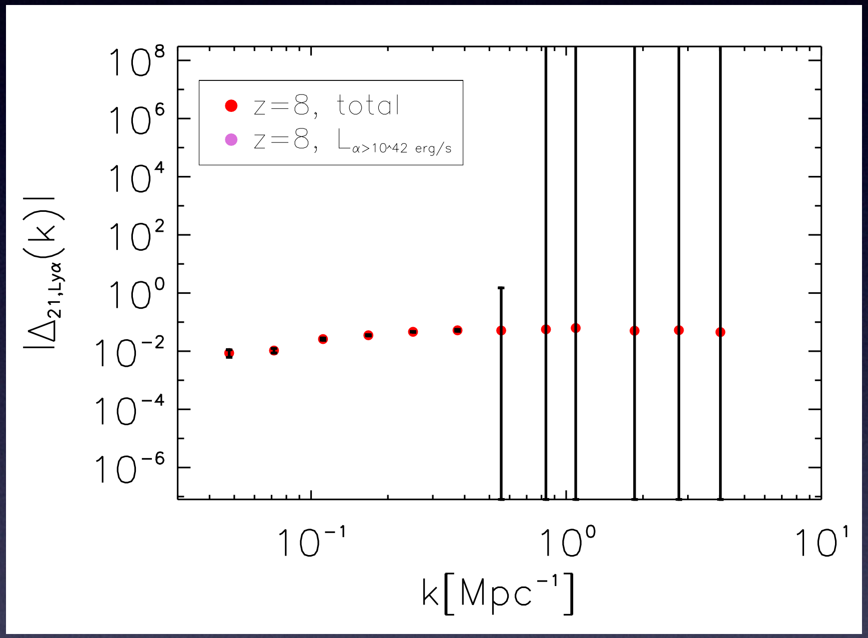
$L_\alpha > 10^{42}\,\mathrm{erg/s}$



X



'LAE' X 21cm (SKA)



Intensity mapping

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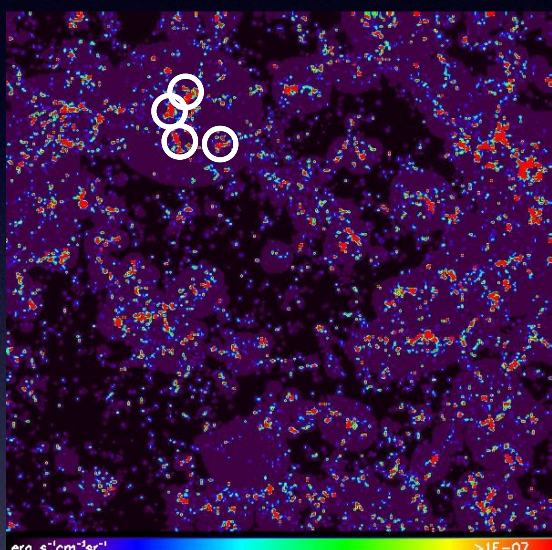
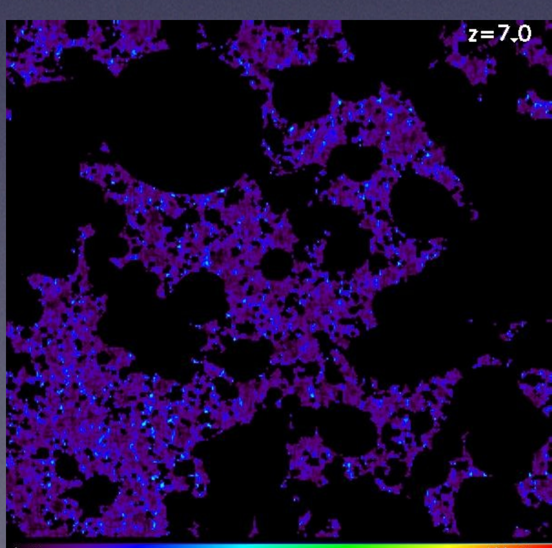
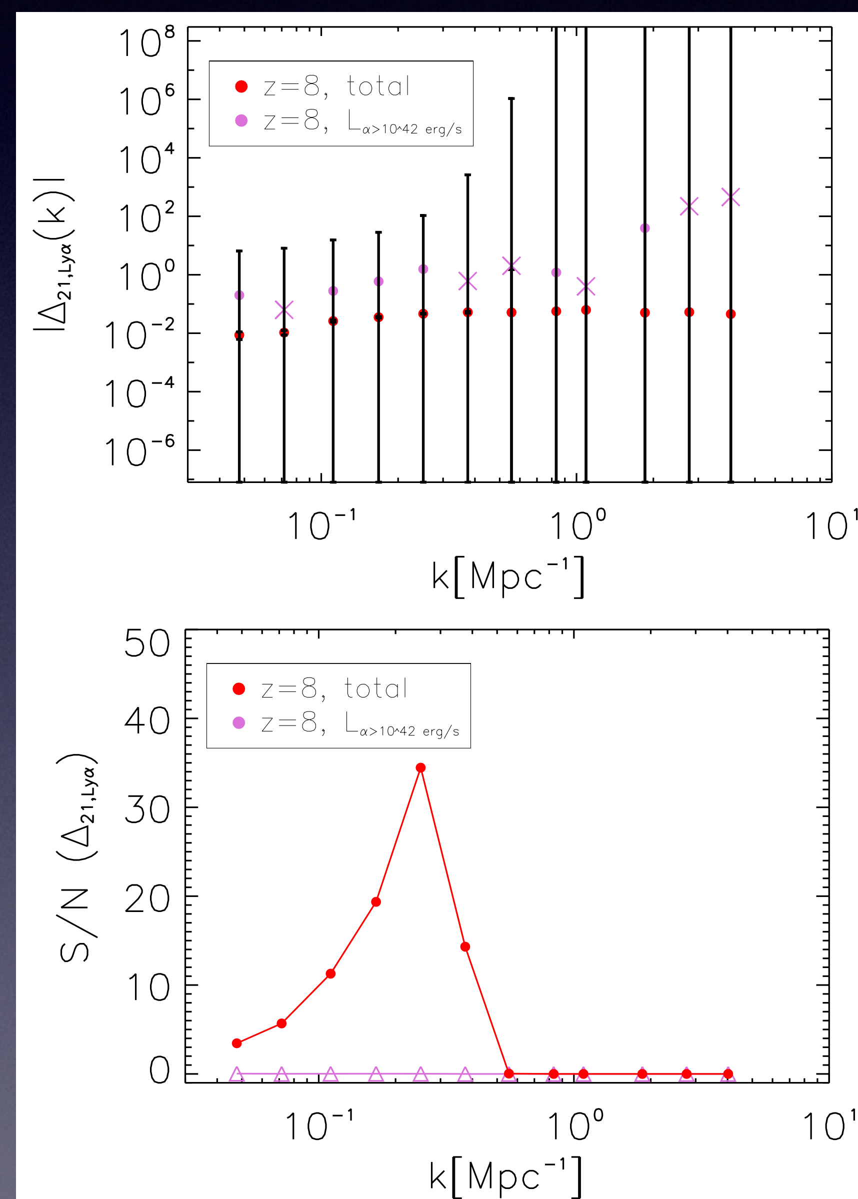


X

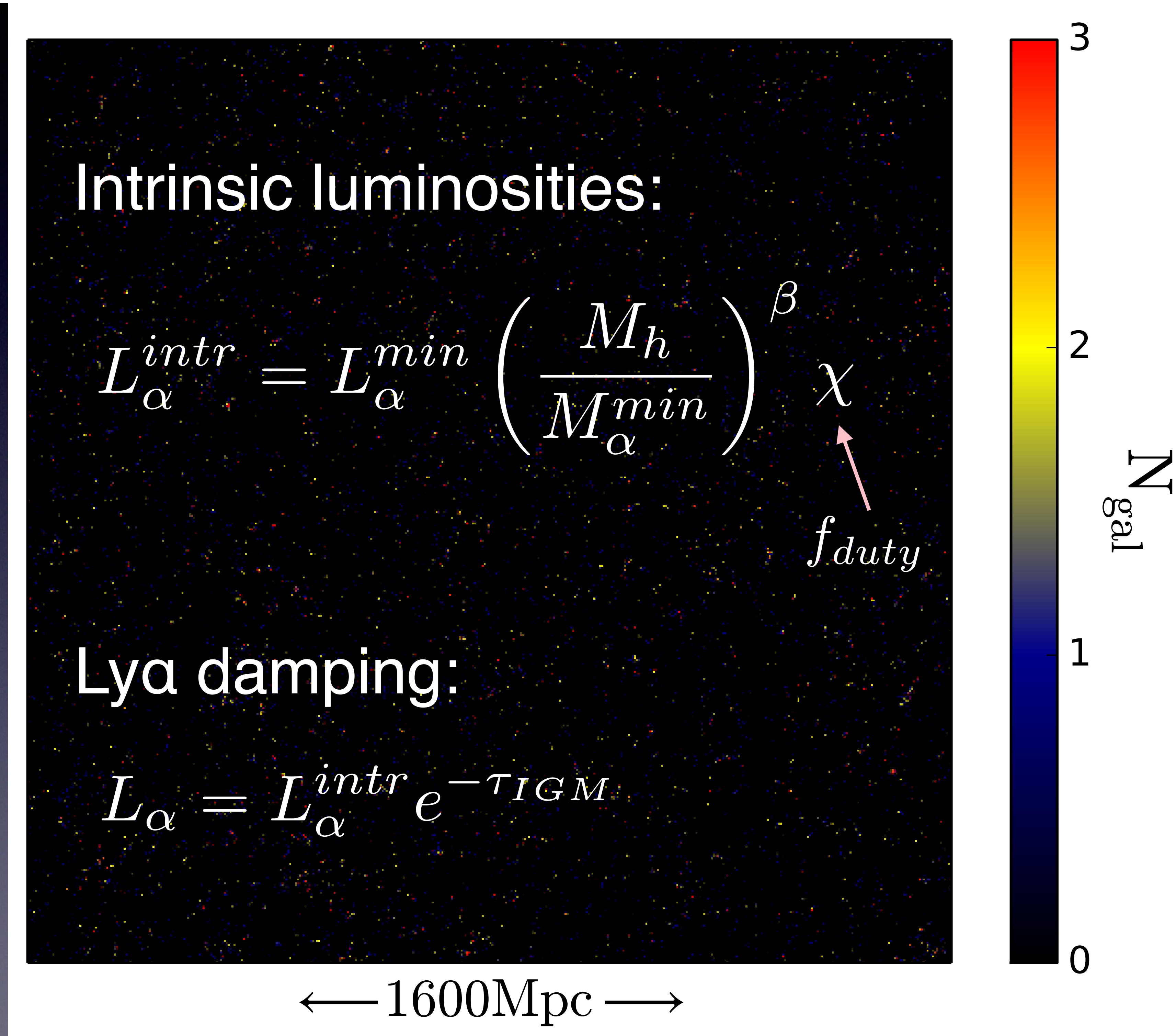


‘LAE’ X 21cm (SKA)



not detectable for
$L_\alpha > 10^{42}\,\mathrm{erg/s}$

Simulations: LAE at z=6.6



Intrinsic luminosities:

$$L_\alpha^{intr} = L_\alpha^{min} \left(\frac{M_h}{M_\alpha^{min}} \right)^\beta \chi$$

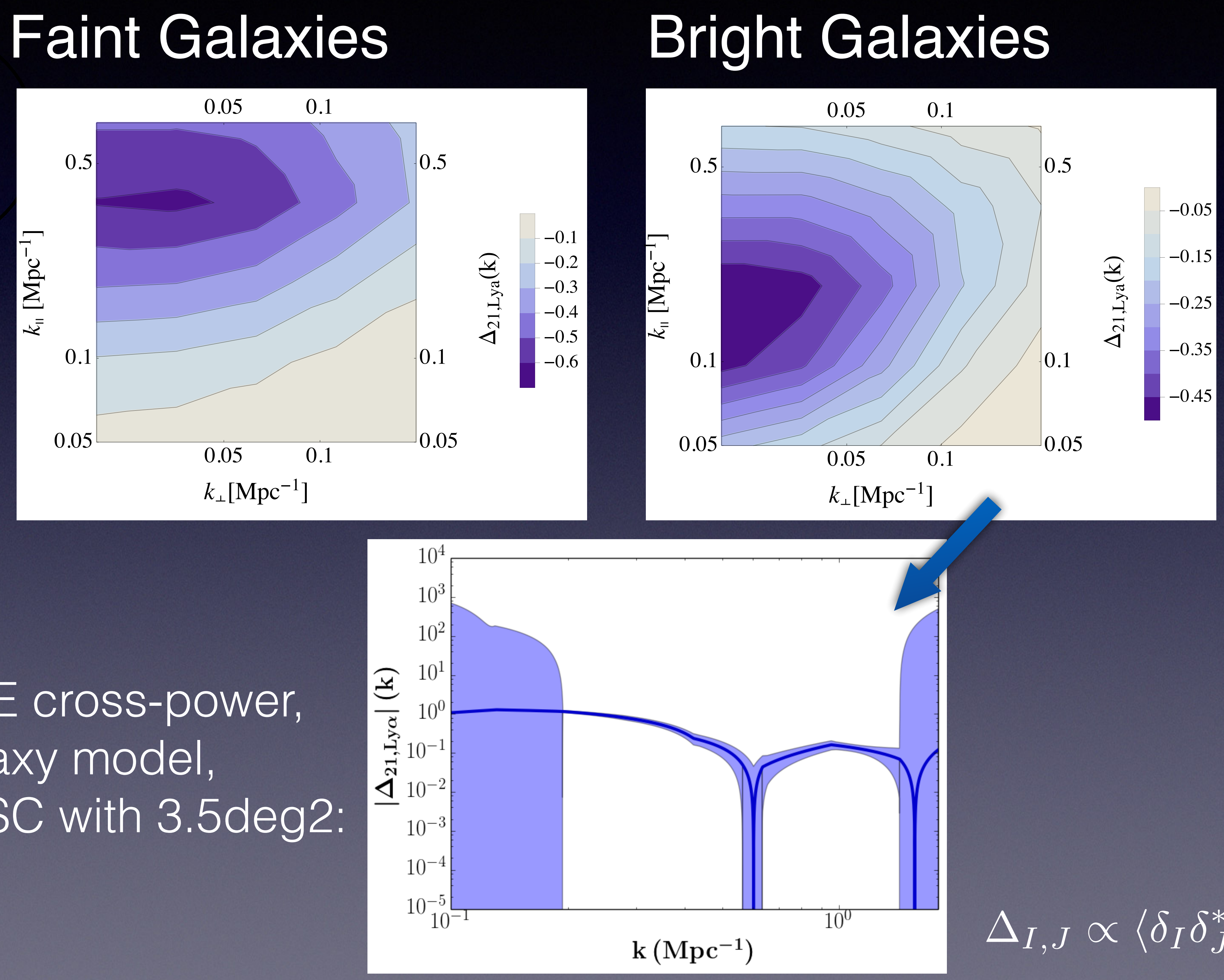
f_{duty}

Lyα damping:

$$L_\alpha = L_\alpha^{intr} e^{-\tau_{IGM}}$$

see: Sobacchi, Mesinger, Greig ‘16

21-cm - LAE cross-correlation



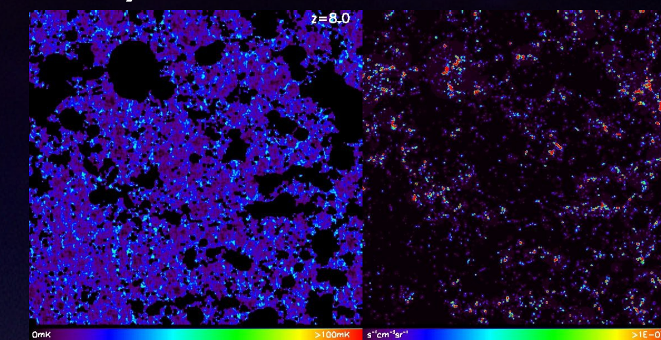
21-cm-LAE cross-power, bright galaxy model, Subaru HSC with 3.5deg2:

$$\Delta_{I,J} \propto \langle \delta_I \delta_J^* \rangle_k$$

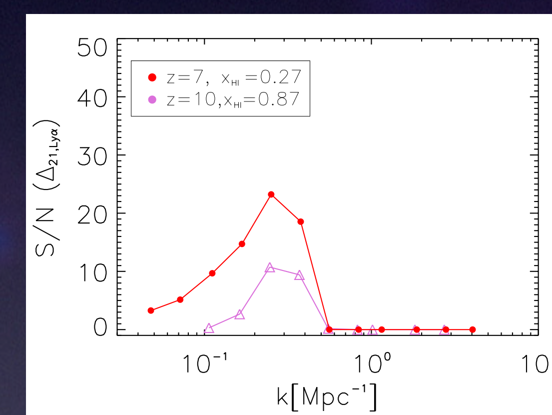
Heneka & Mesinger 2018 in prep.

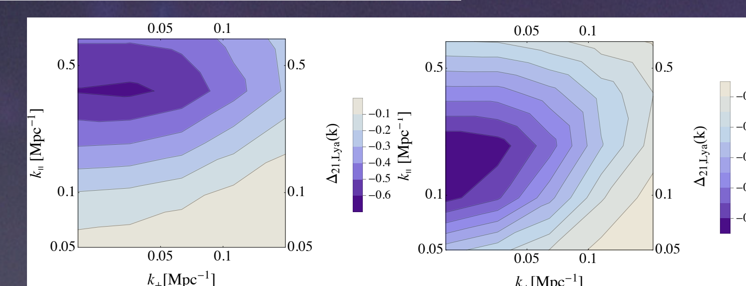
Conclusion

Synergy of 21-cm, Lyα and Hα signal (IM and LAE)



- Expected to be less prone to systematics
- Signal is measurable
- Determine structure of the IGM
- Distinguish sources driving reionization





What else to learn? Other lines?

Forecast for upcoming and ongoing experiments

E.g. luminosity functions measured with IM as input for galaxy formation

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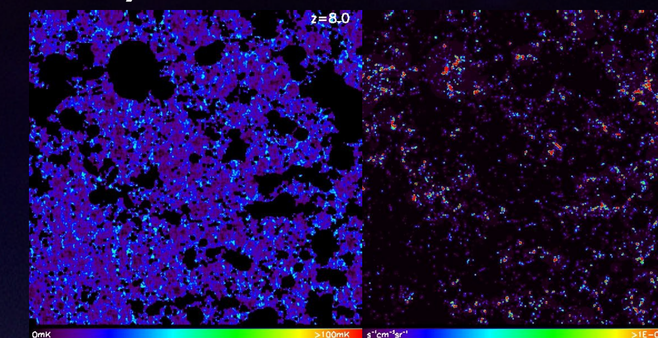
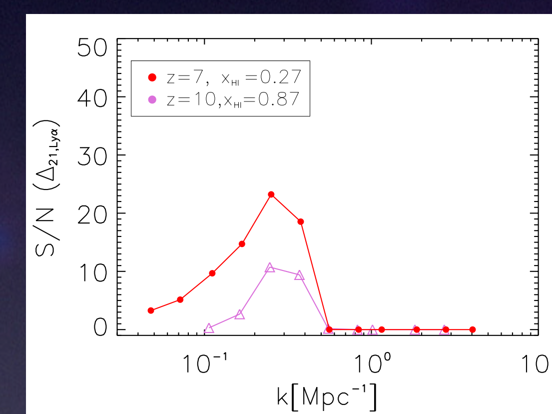
Conclusion

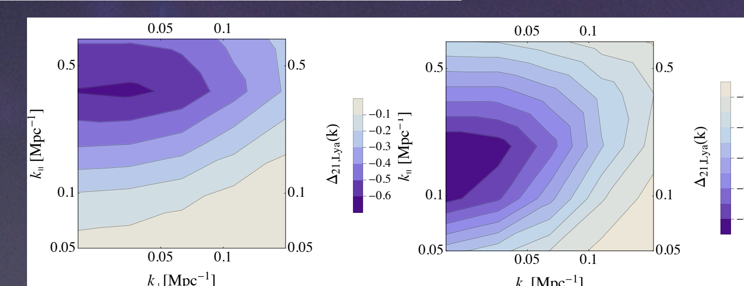
Thank you!

Synergy of 21-cm, Lyα and Hα signal (IM and LAE)



- Expected to be less prone to systematics
- Signal is measurable
- Determine structure of the IGM
- Distinguish sources driving reionization





What else to learn? Other lines?

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