Line Intensity Mapping targeting Astrophysics and Cosmology

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EXC Quantum Universe

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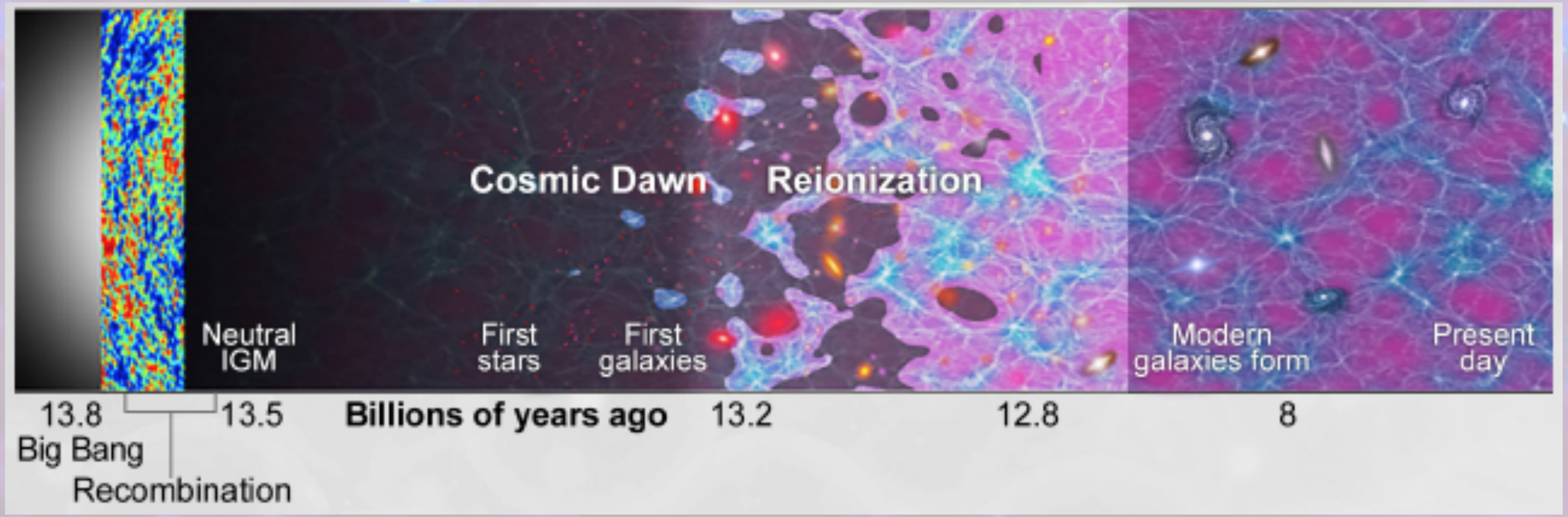
Partly based on: CH+ ApJ, 848 (2017), Heneka & Amendola JCAP10(2018)004, Liu+ JCAP05 (2020)
arXiv: 1611.09682, 1805.03629, 1910.02763, see also: 1805.11044, 1903.03144, 1903.03629, 1903.11744
Collaborators: Luca Amendola, Xue-Wen Liu, Asantha Cooray, Andrei Mesinger

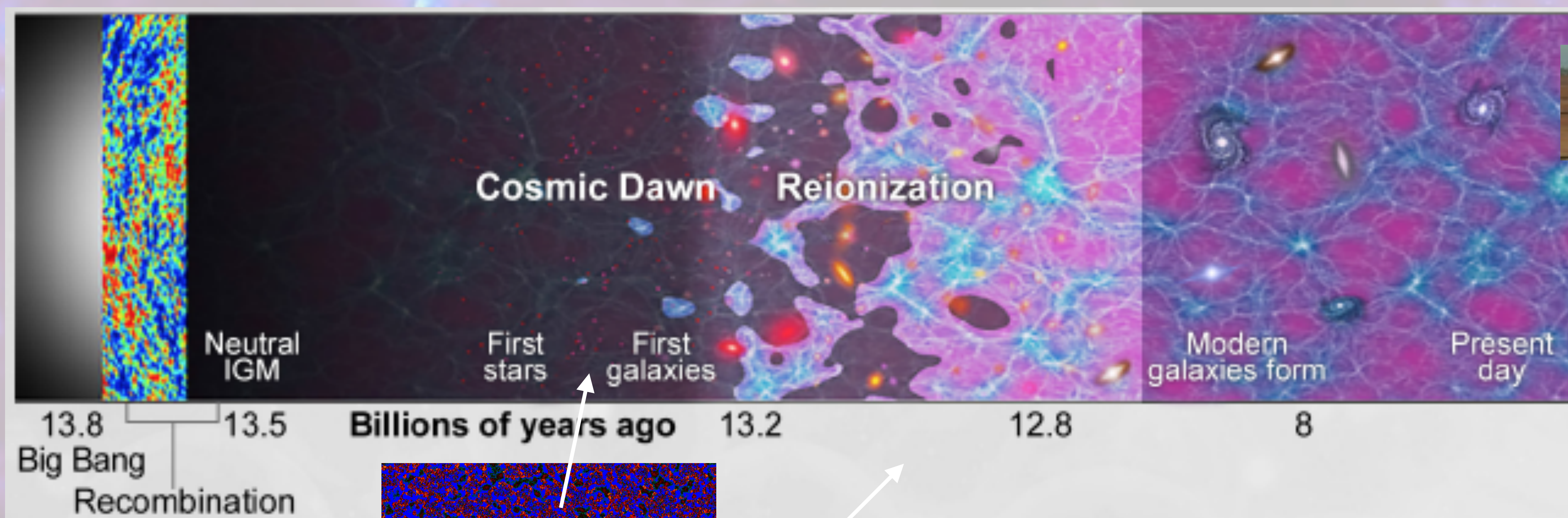
A brief history of time ..and the Universe

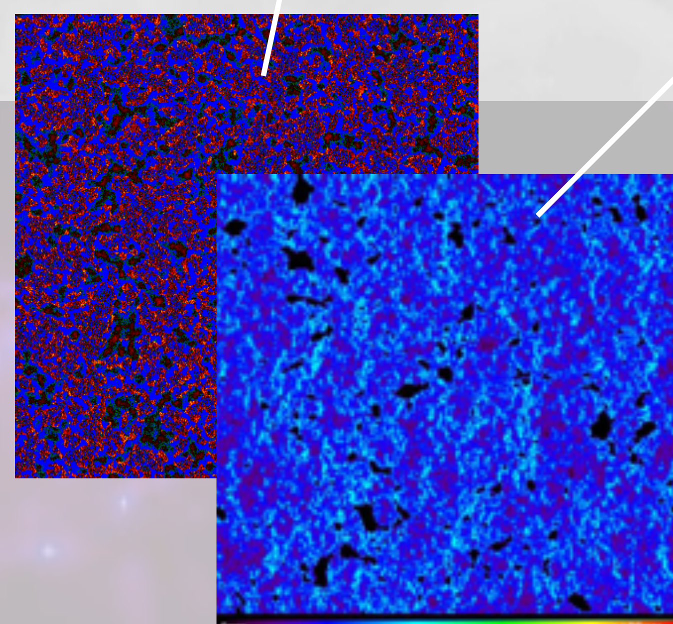


What astrophysics? Reionization model?
What cosmology? Structure growth?

A brief history of time ..and the Universe

Goal: Push measurements to tomography, up to high redshifts, for mapping of large number of modes and time evolution during structure formation





Create radio and near-IR spectroscopic legacy surveys

Why Intensity Mapping

What is the (large scale) structure of the Universe?

What are properties of radiating sources?

To find out, we can identify individual sources of emission.

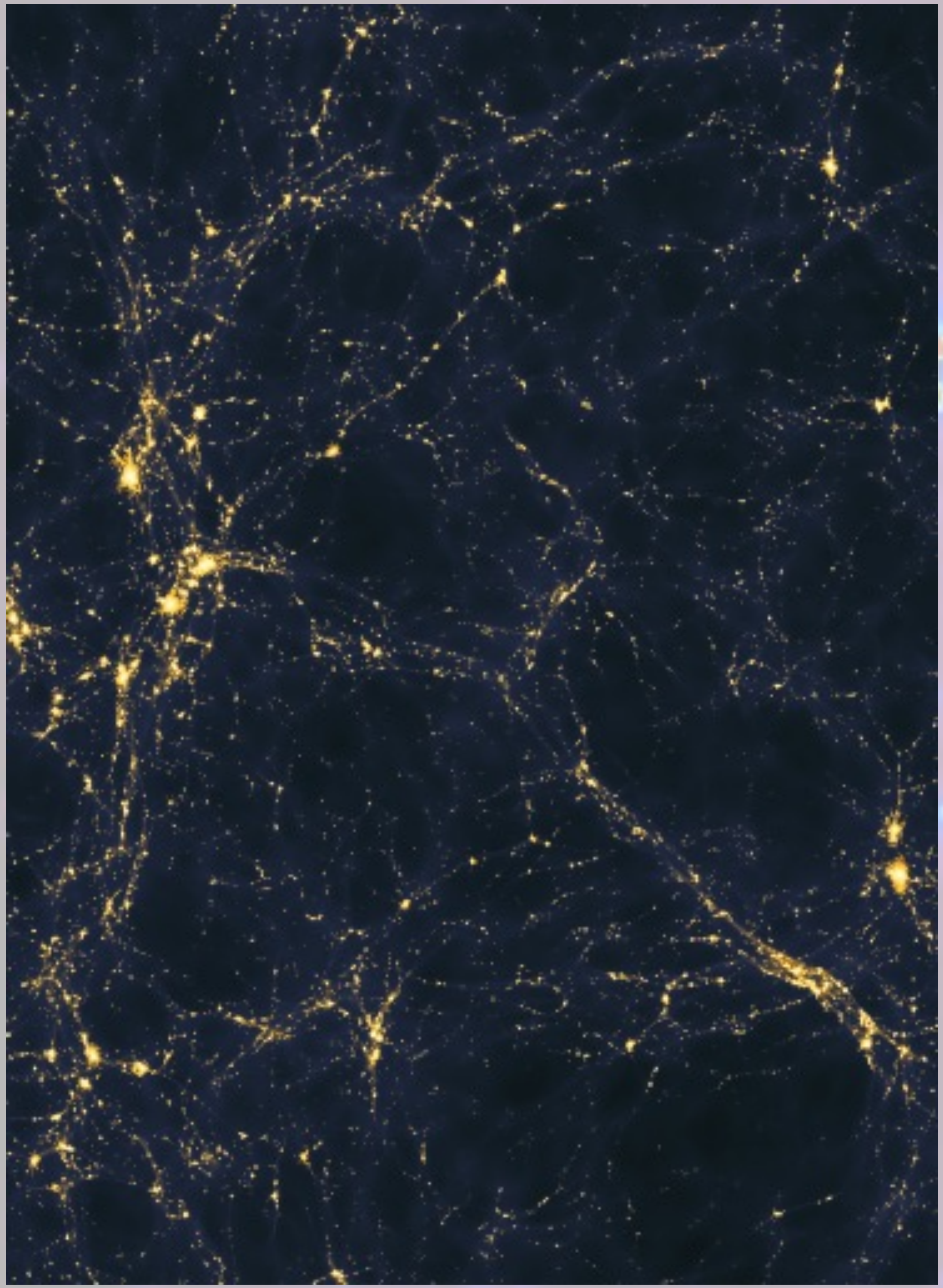


Image: Courtesy of Asantha Cooray

Why Intensity Mapping

What is the (large scale) structure of the Universe?

What are properties of radiating sources?

To find out, we can identify individual sources of emission.

OR

We can sum the emission in larger areas and measure fluctuations.

Example: Planck satellite for the CMB

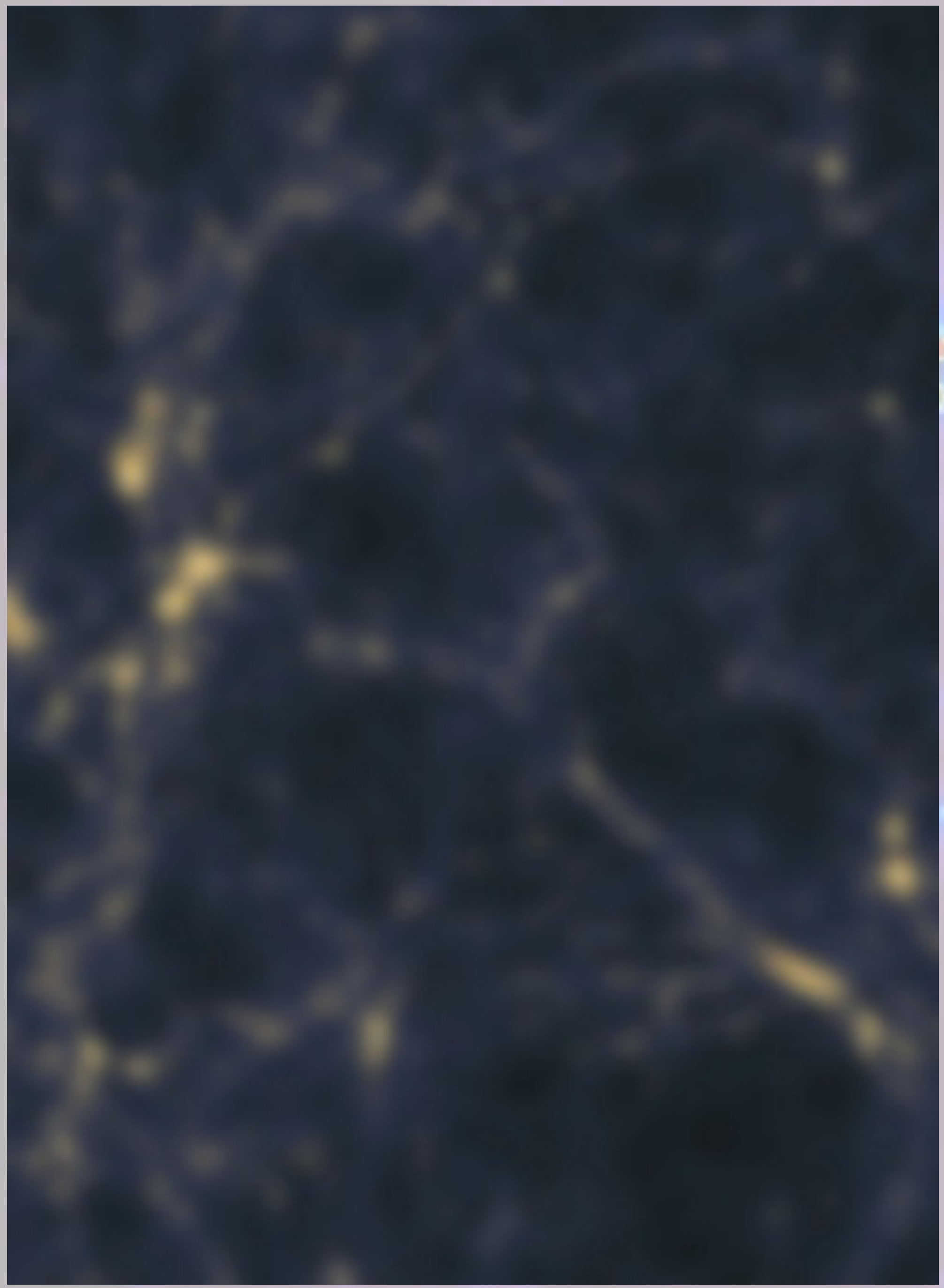
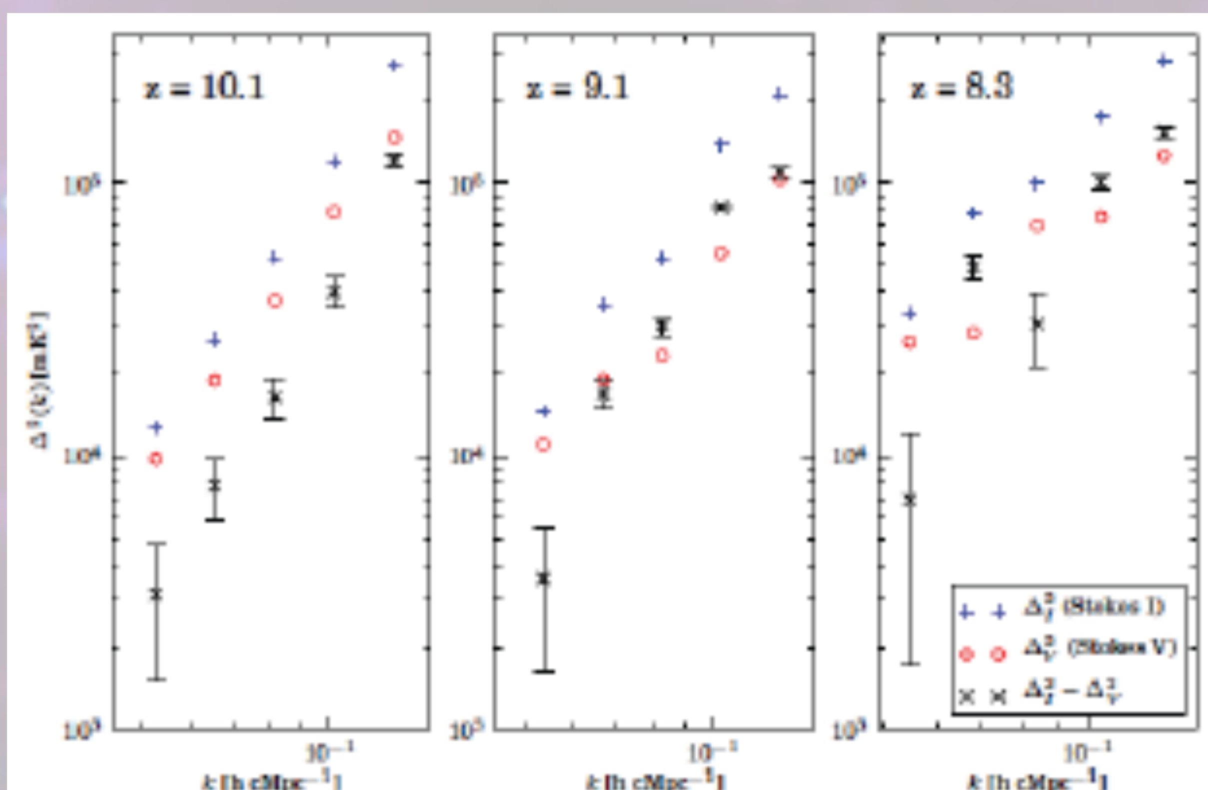


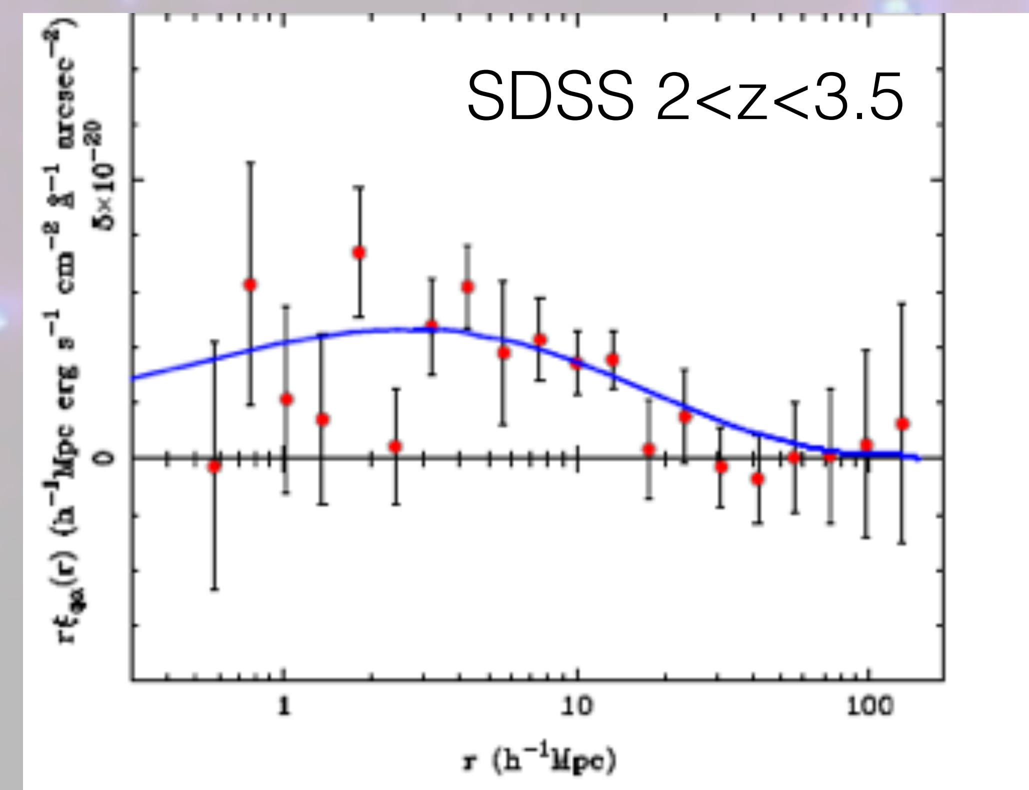
Image: Courtesy of Asantha Cooray

Is this measurable?

Power spectra
LOFAR 21cm
[Patil et al. 2017]

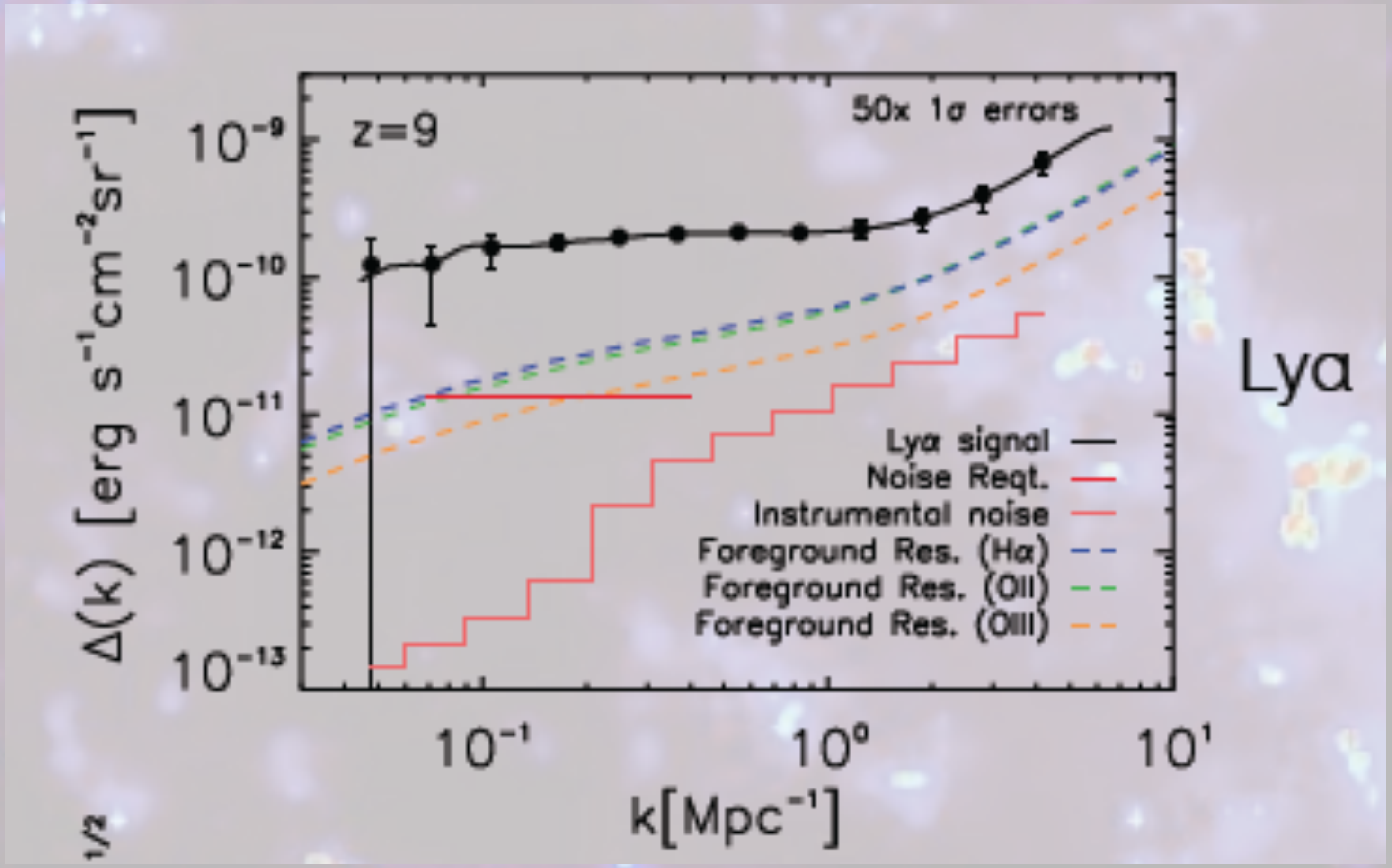


Cross-correlation
Lyα IM and quasars
[Croft et al. 2016]

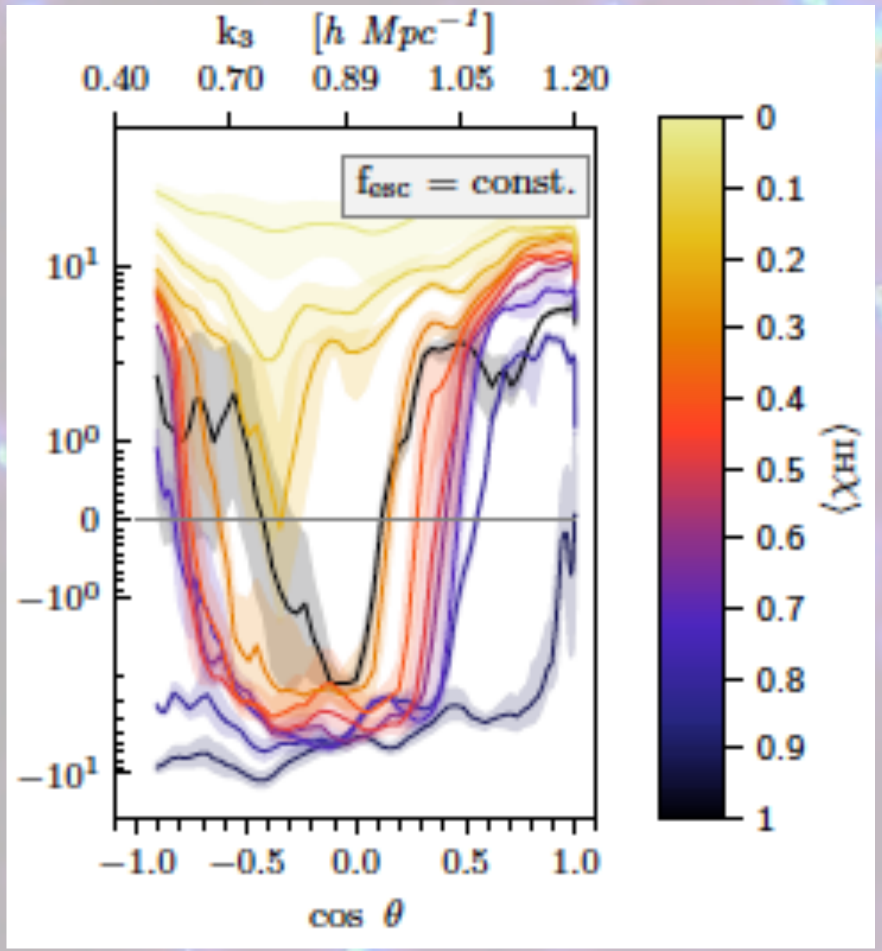


What is measurable?

Multi-line Tomography
SPHEREx, CDIM
[Cooray+, Heneka 2019]

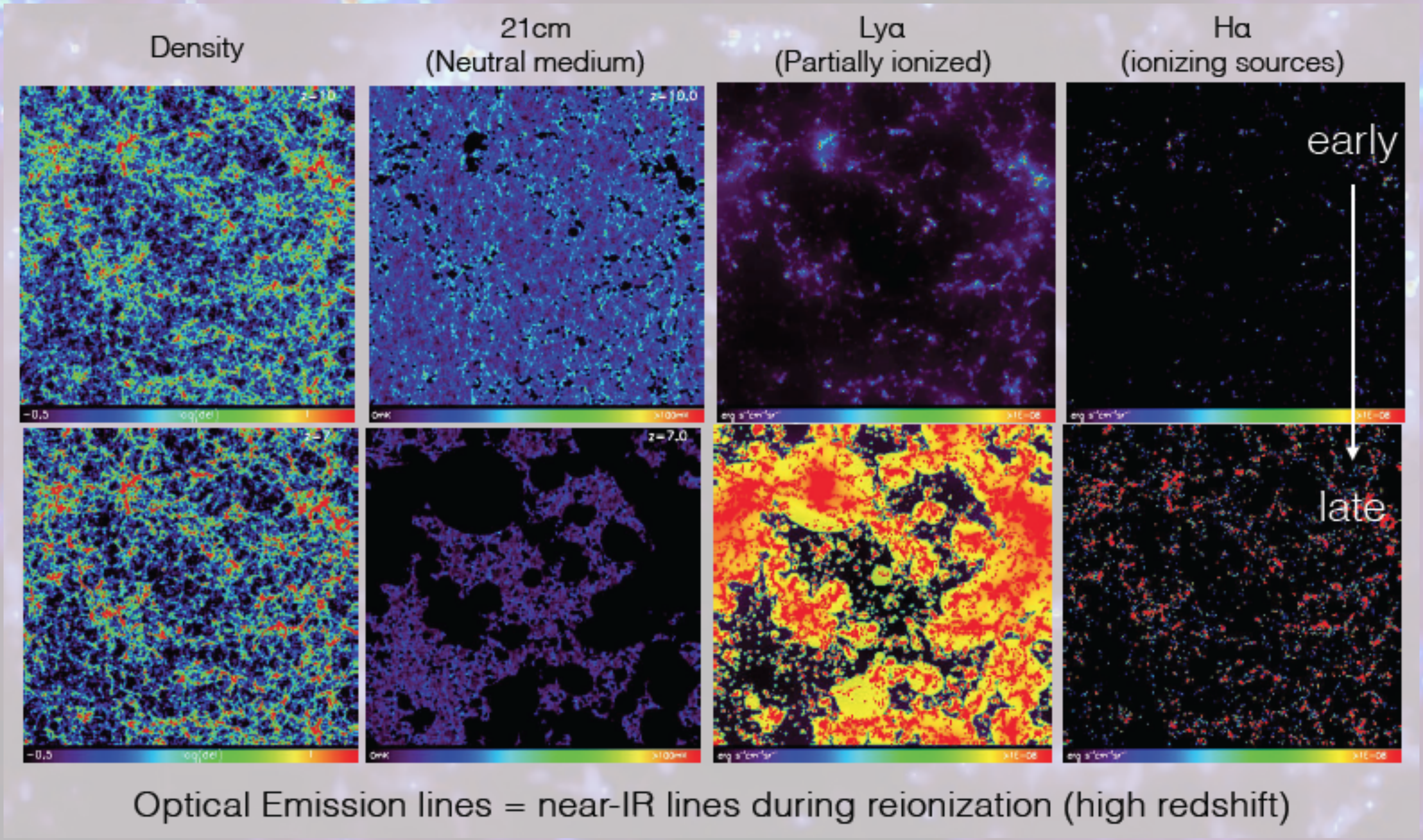


3pt / Bispectrum
[Hutter et al. 2019]



Multi-Line Intensity Mapping

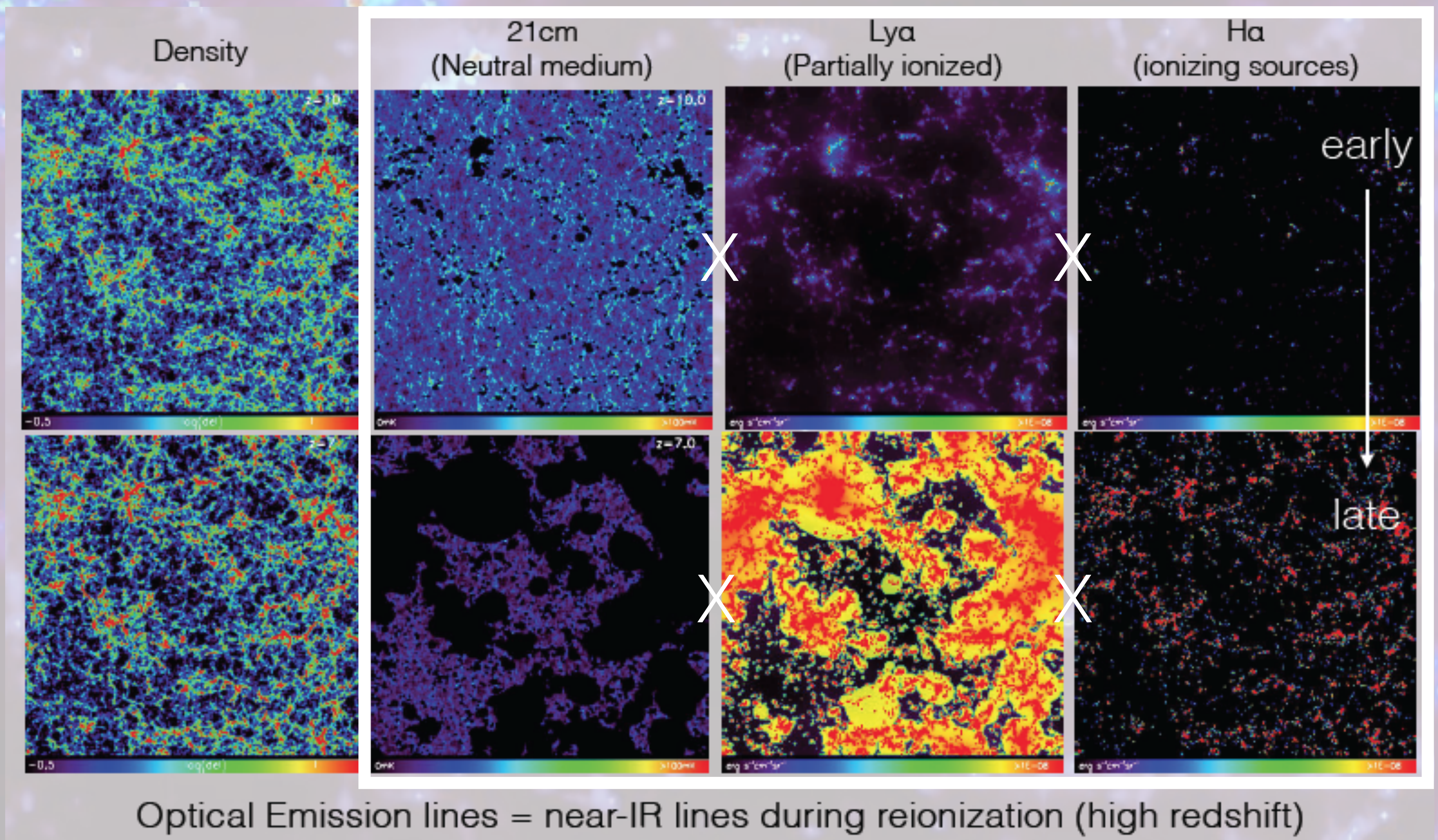
Gain complementary information on **LSS**, IGM, sources:



[CDIM Science Report, Cooray+, Heneka 2019]

Intensity Mapping - for Astrophysics

Gain complementary information on **LSS**, IGM, sources: auto and cross-signals

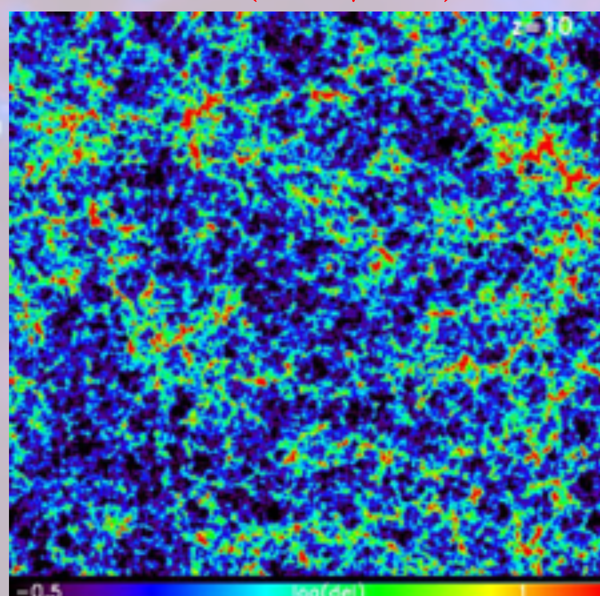


[CDIM Science Report, Cooray+, Heneka 2019]

Simulations: neutral - 21 cm

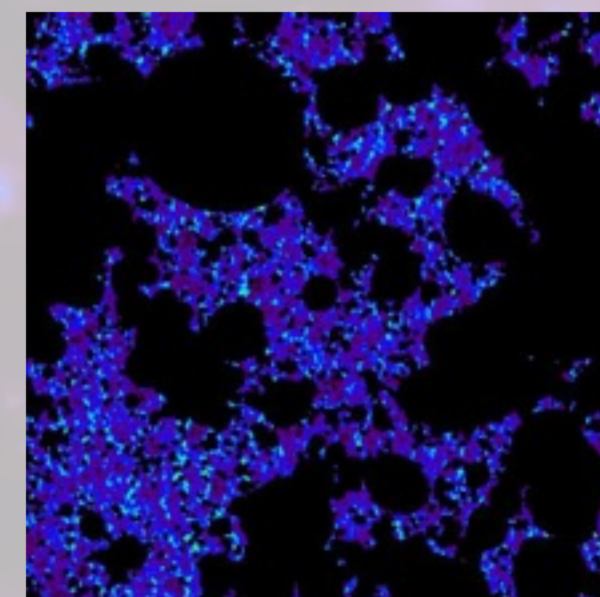
21cm FAST / DexM
semi-numerical simulations
[Mesinger et al.'10]

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



density (+ velocity)
(Zel'dovich approximation)

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



δT_{b}

Offset 21-cm brightness temperature:

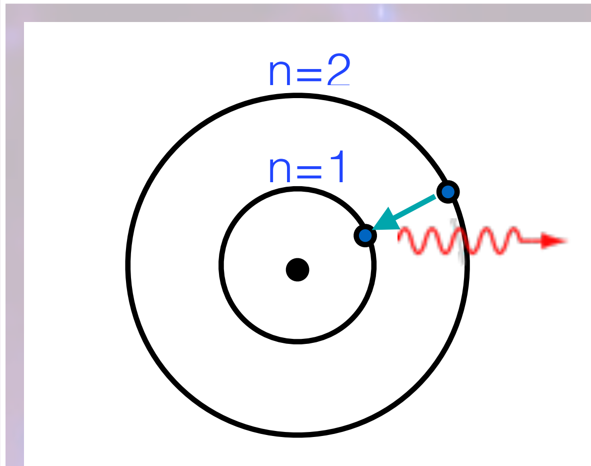
$$\delta T_b\left(\nu\right) = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$

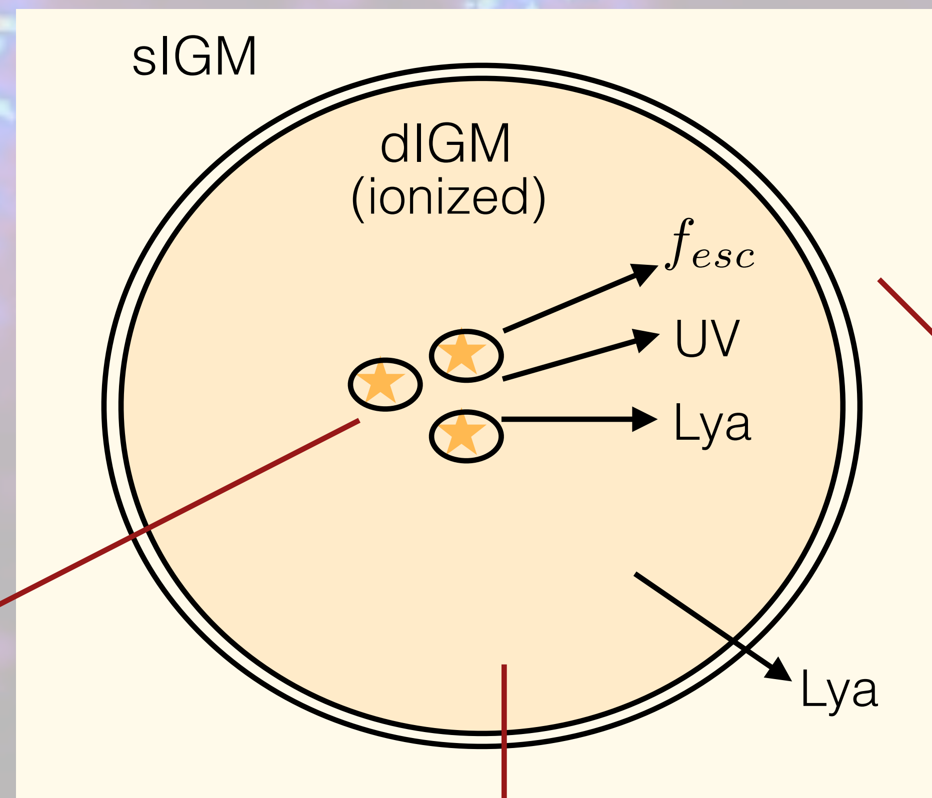
$$\propto x_{HI}\left(1+\delta_{nl}\right)\left(\frac{H}{\mathrm{d}v_r/\mathrm{d}r + H}\right)$$

Post-heating approximation:
$T_{\mathrm{s}} \gg T_\gamma$

Fiducial Cosmology: Planck

Simulations: (partially ionised) - Lyα





Scattered IGM:

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

Galaxy contribution:

- Recombinations f_{rec}
- Excitations

$\propto$ **SFR**

[see also Silva et al. 2013]

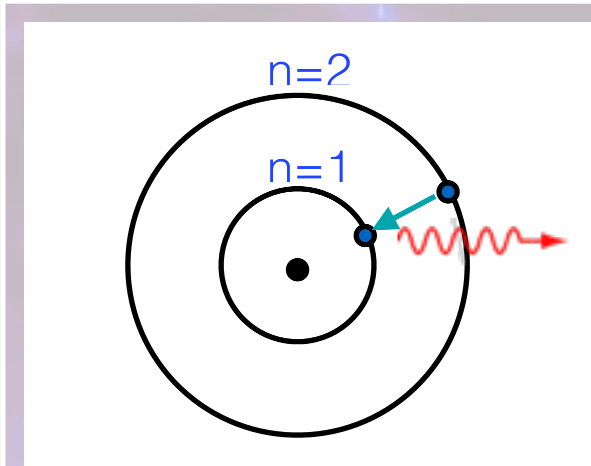
$T_{\mathrm{K}}, x_{\mathrm{i}}$

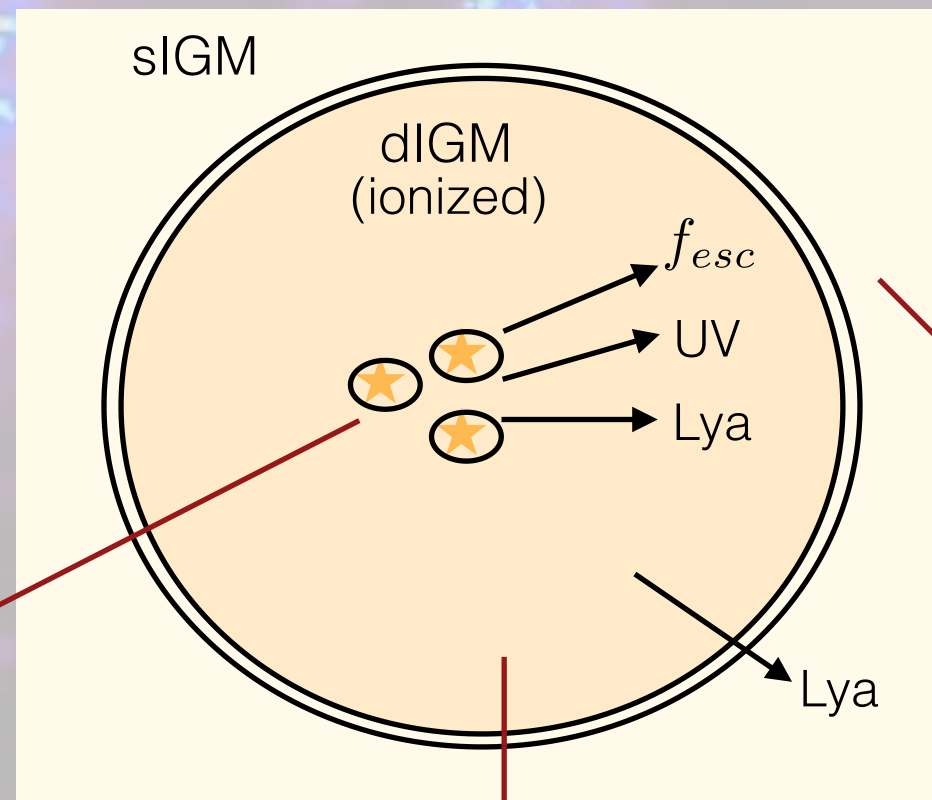
Diffuse IGM:

Recombination

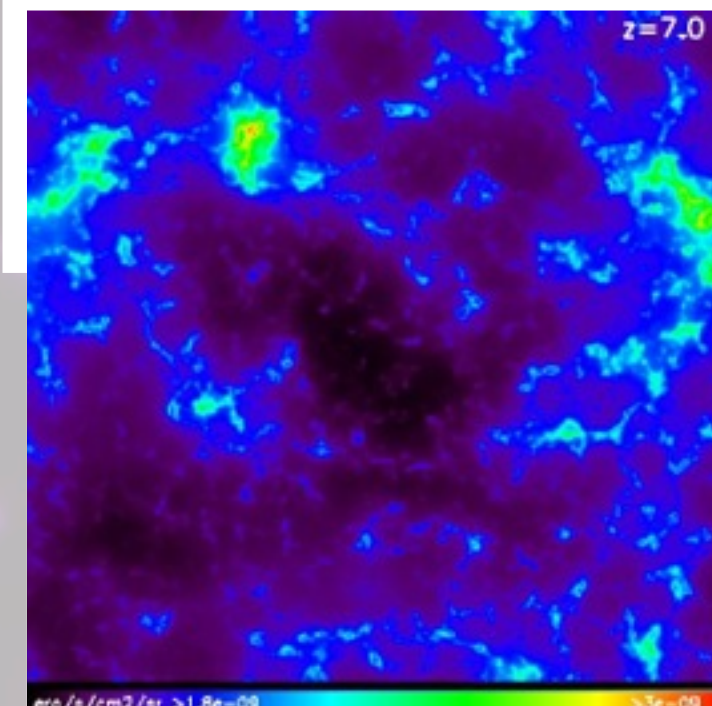
f_{esc} f_{rec}

Simulations: (partially ionised) - Lyα

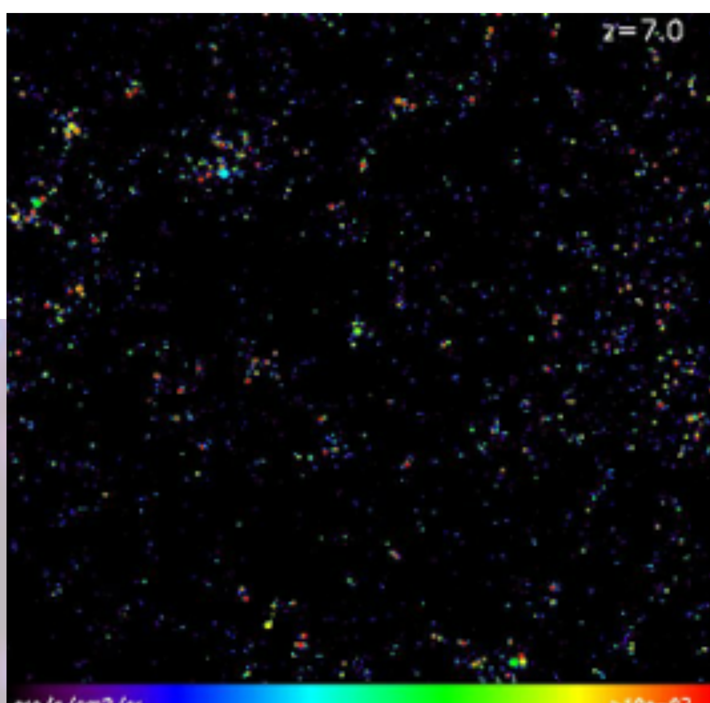




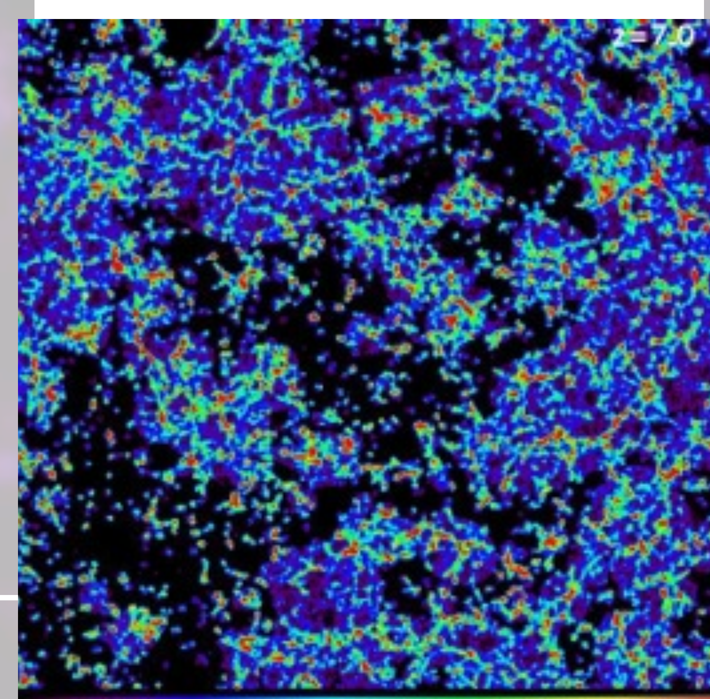
Scattered IGM:



Galaxy contribution:



Diffuse IGM:

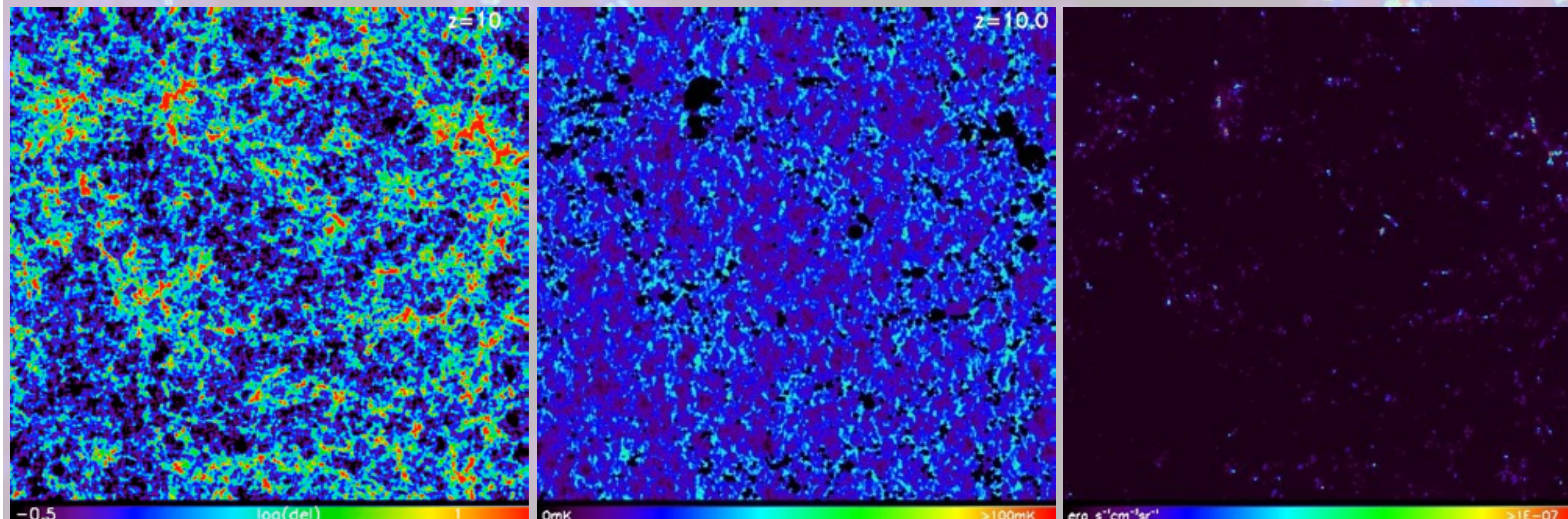


Example: 21cm x Lyα

density

21-cm

Lyα



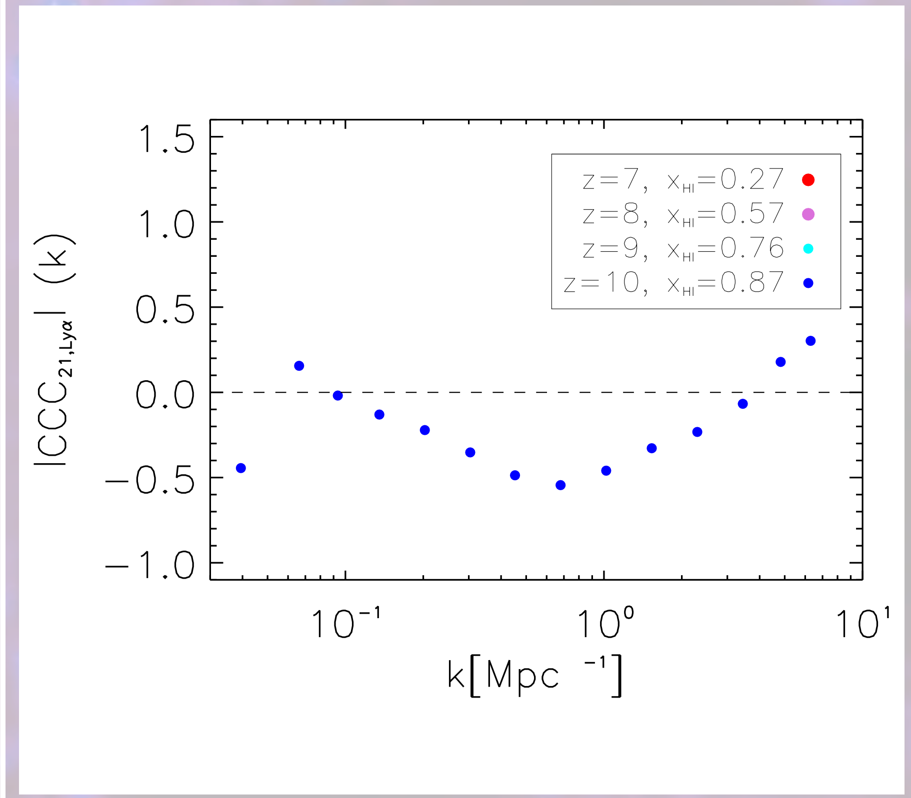
Heneka, Cooray, Feng, ApJ, 848 (2017)

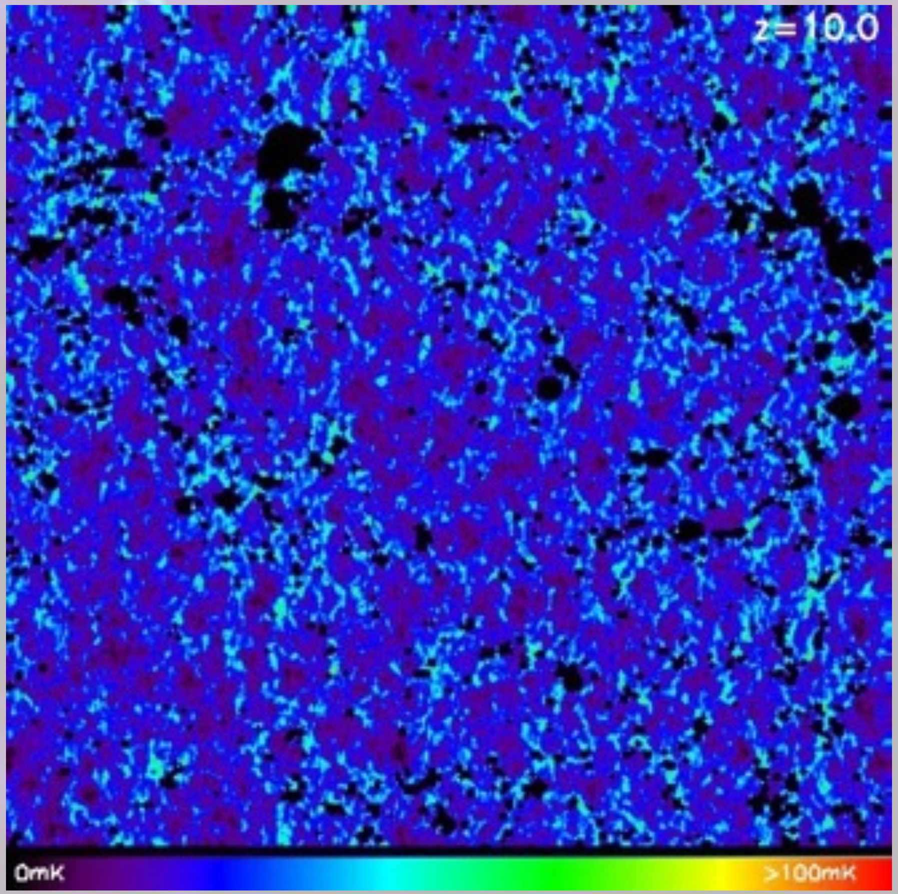
Example: 21cm x Lyα

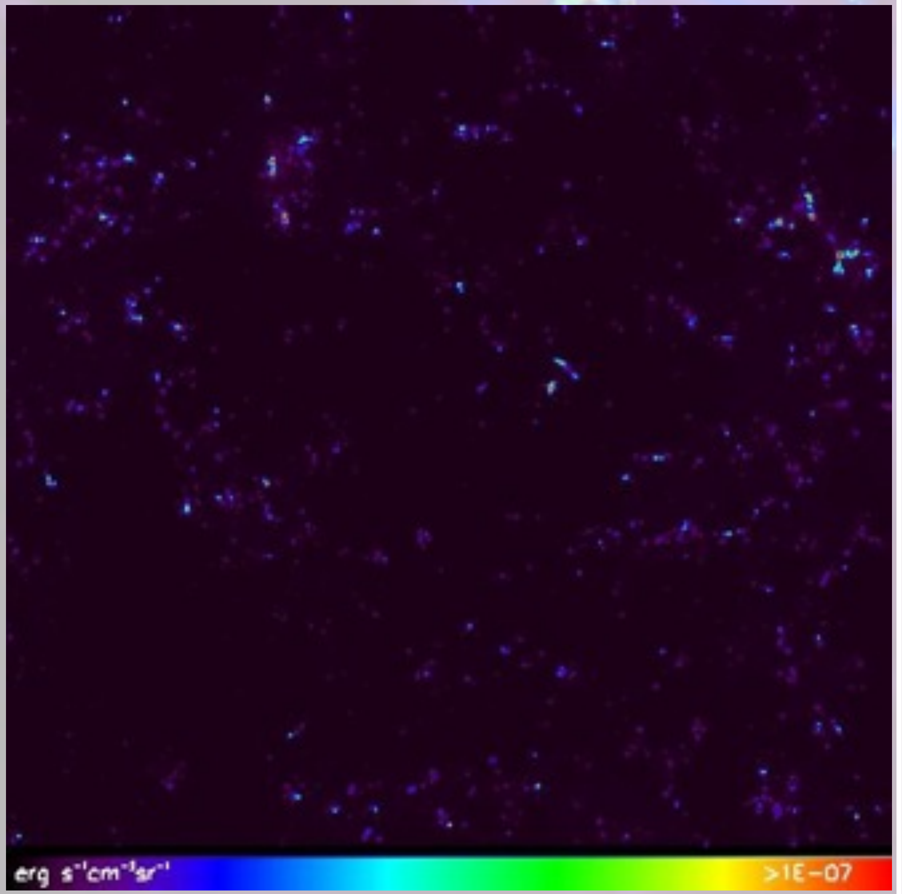
21-cm x Lyα

21-cm

Lyα





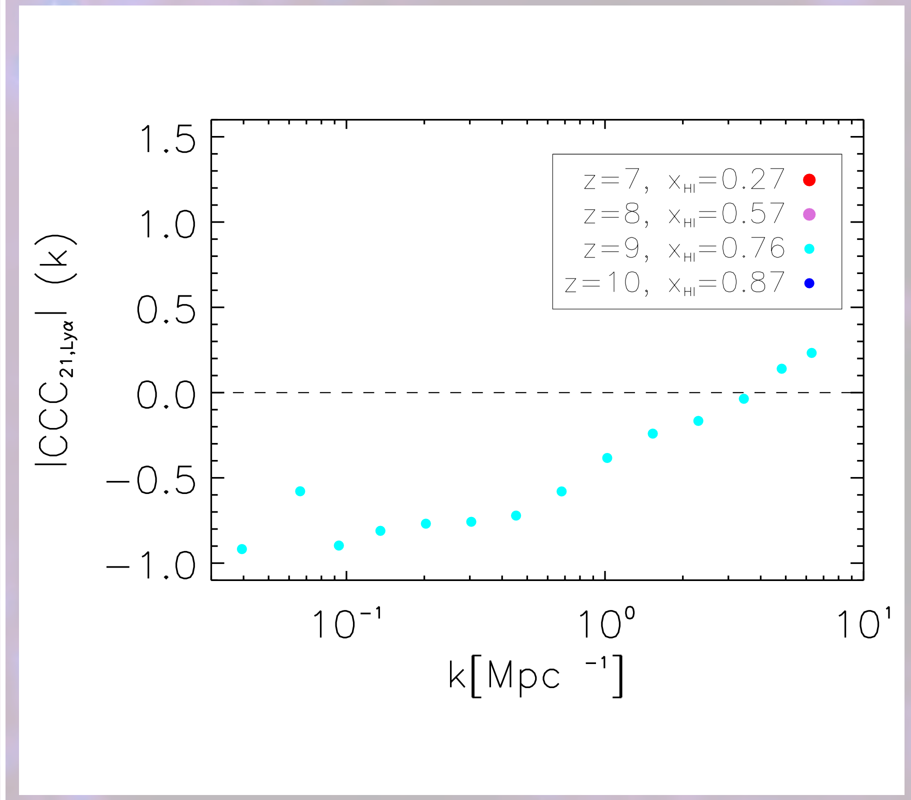


$$CCC_{I,J}(k) = \frac{\Delta_{I,J}(k)}{\sqrt{\Delta_I(k)\,\Delta_J(k)}}$$

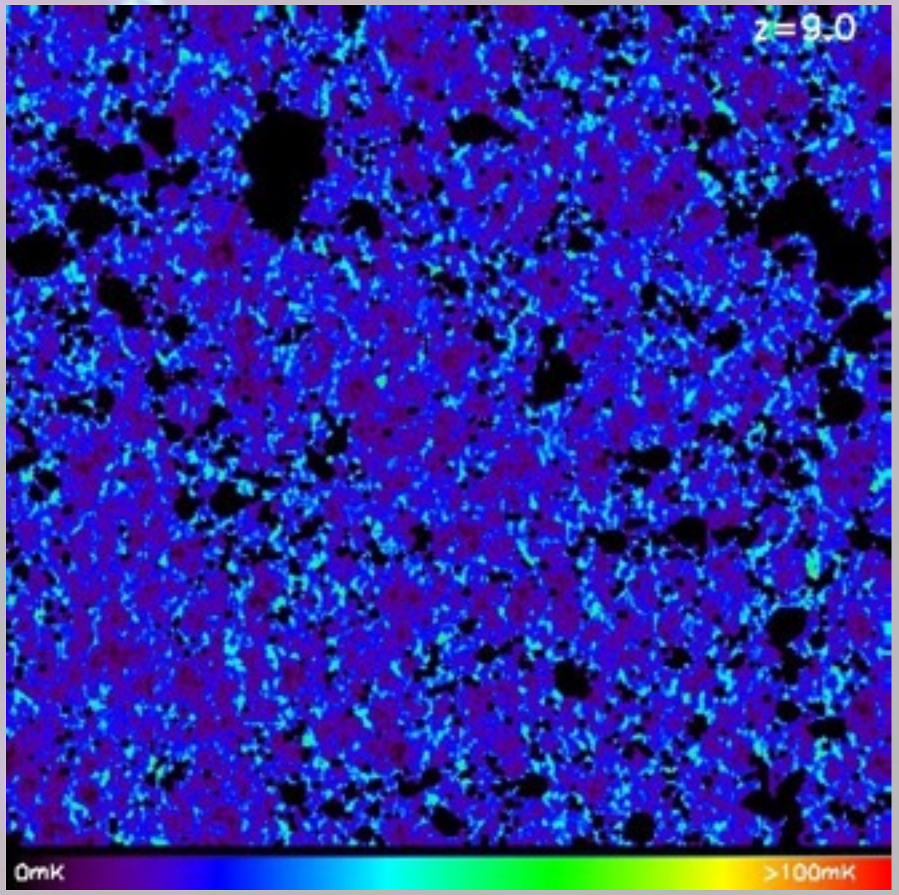
Heneka, Cooray, Feng, ApJ, 848 (2017)

Example: 21cm x Lyα

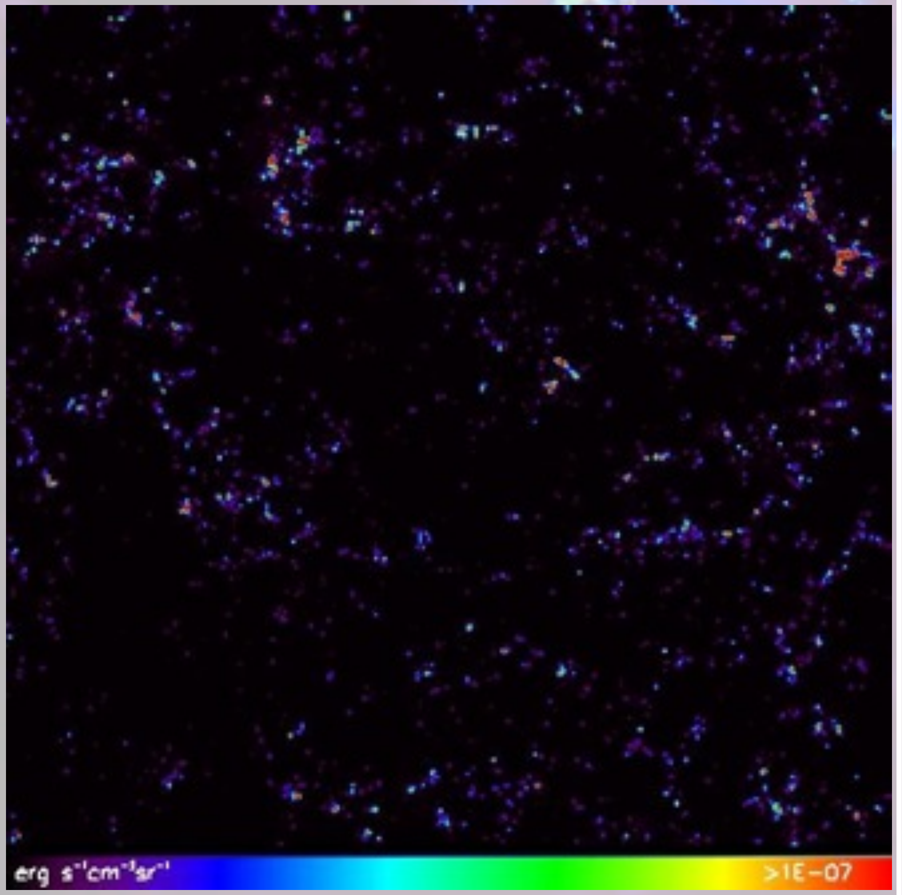
21-cm x Lyα



21-cm



Lyα



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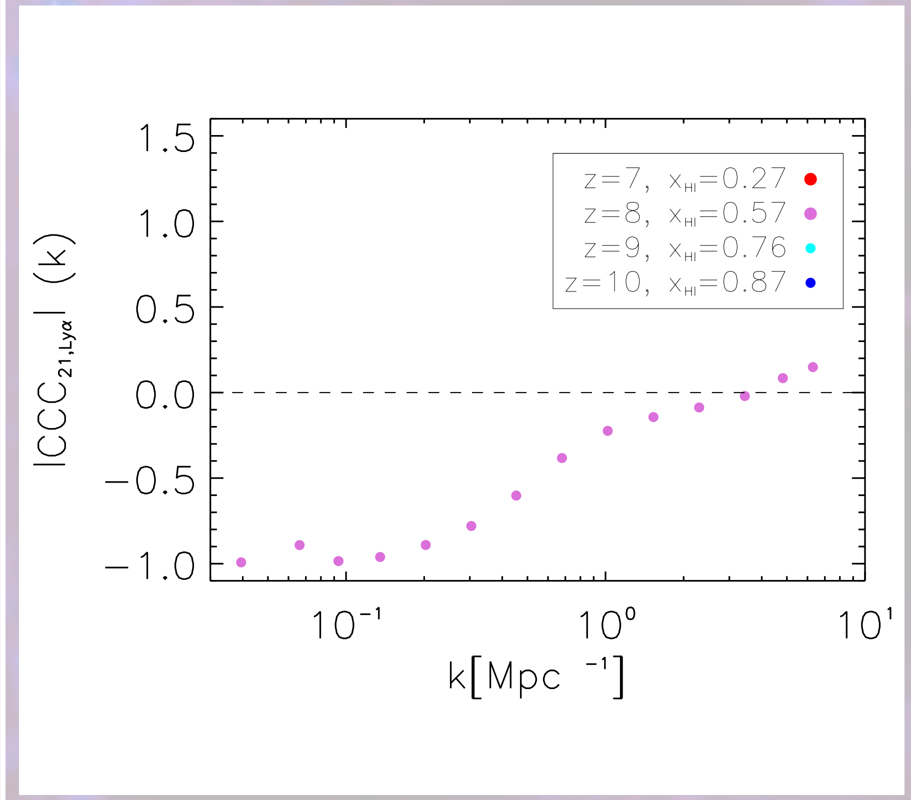
Heneka, Cooray, Feng, ApJ, 848 (2017)

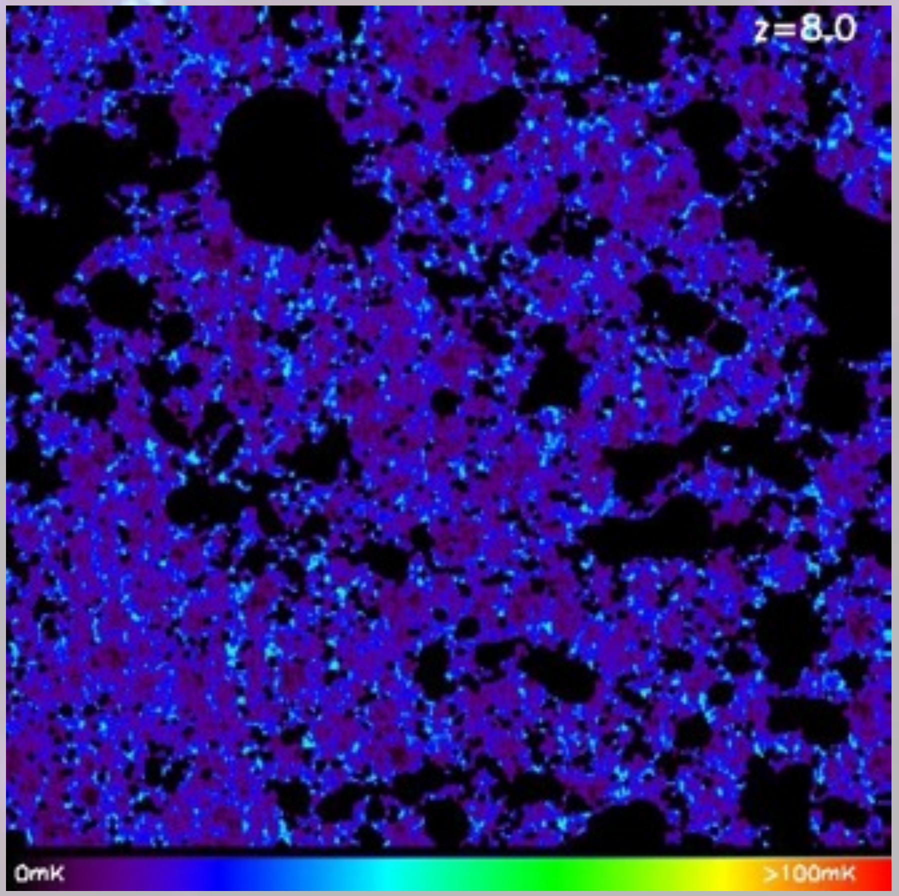
Example: 21cm x Lyα

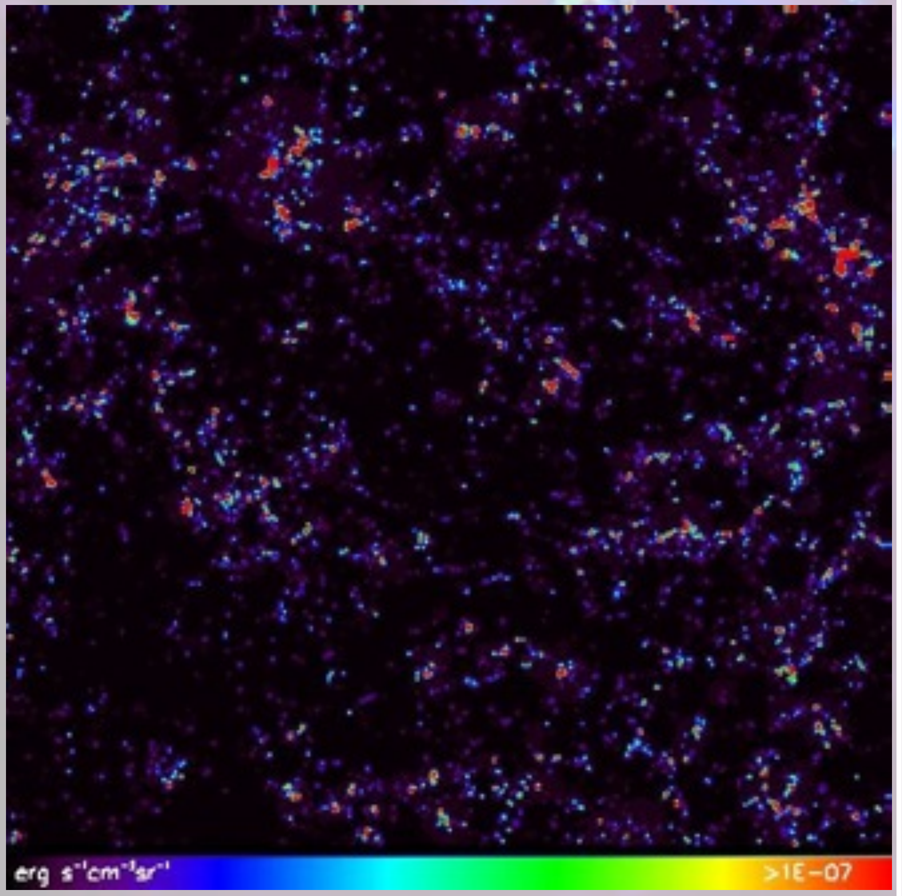
21-cm x Lya

21-cm

Lya





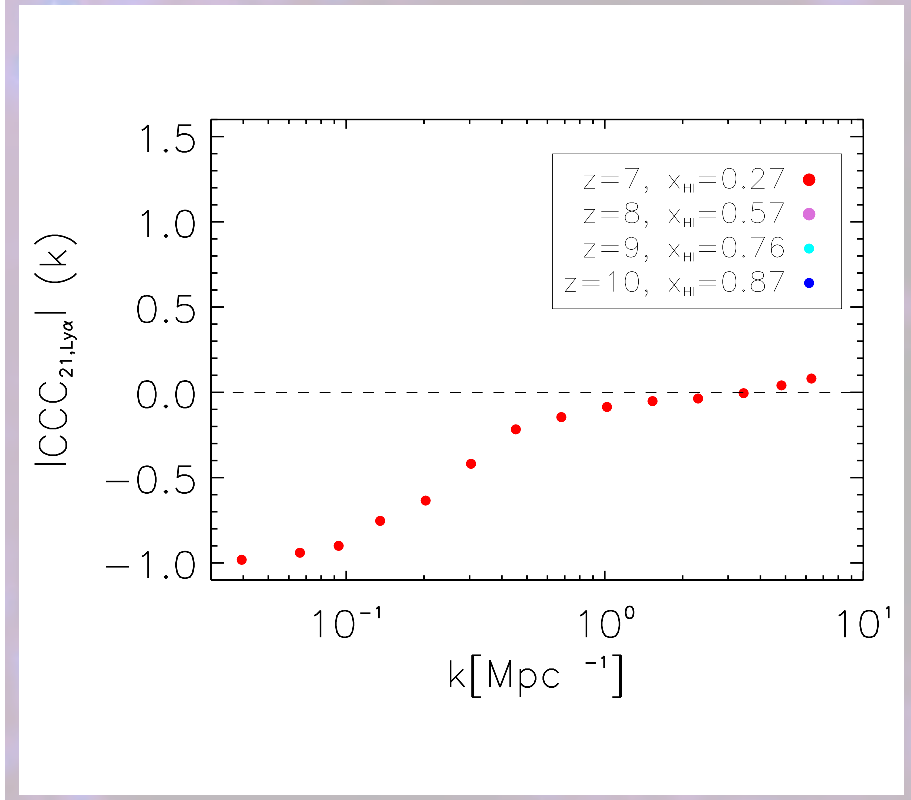


$$CCC_{I,J}\left(k\right) = \frac{\Delta_{I,J}\left(k\right)}{\sqrt{\Delta_I\left(k\right)\Delta_J\left(k\right)}}$$

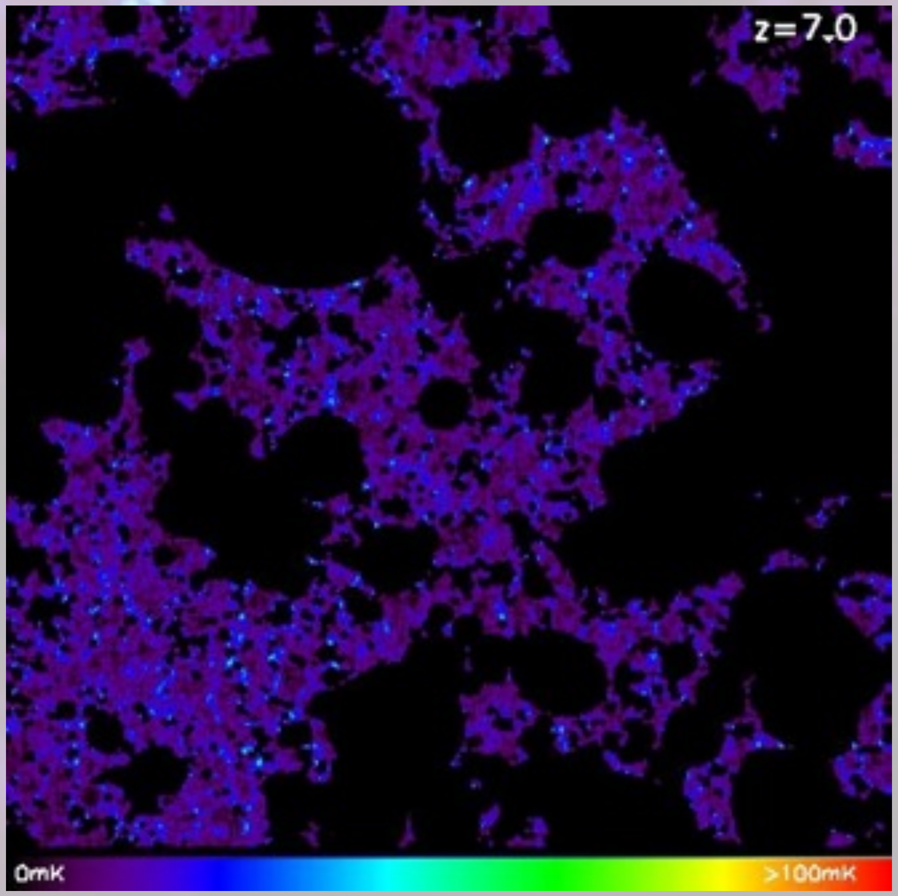
Heneka, Cooray, Feng, ApJ, 848 (2017)

Example: 21cm x Lyα

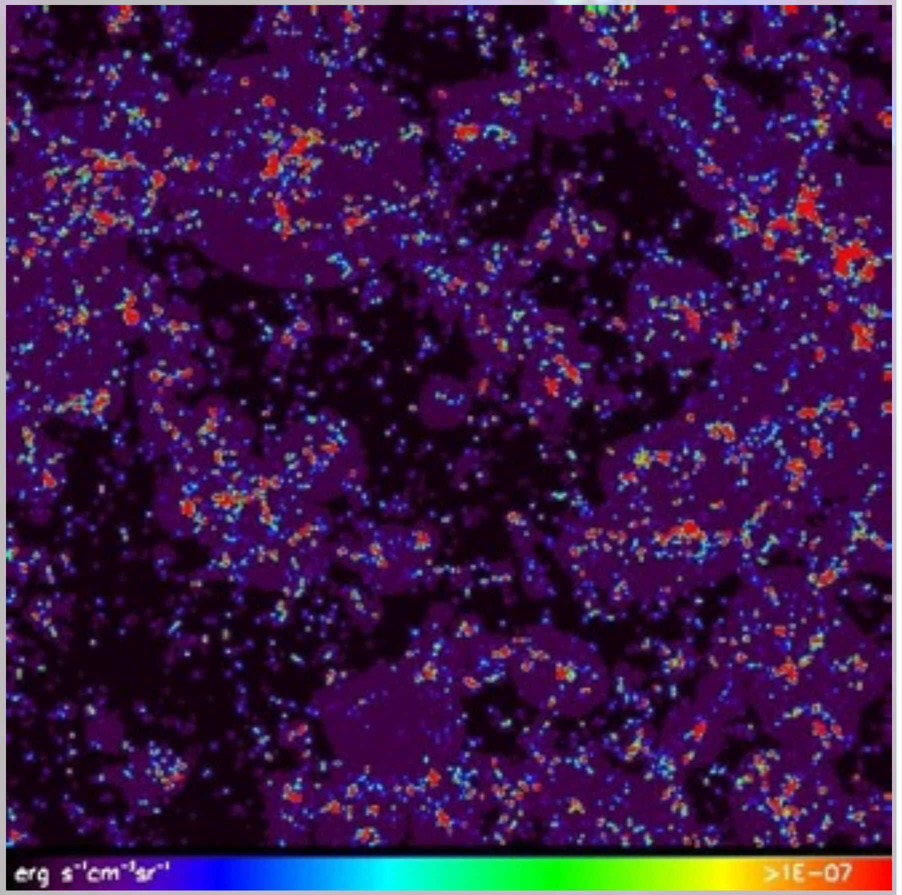
21-cm x Lyα



21-cm



Lyα

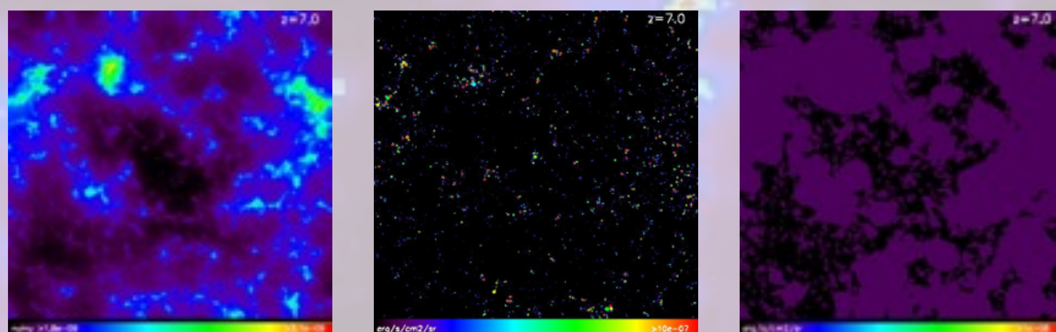


- Follow reionisation progress, growth of ionised regions
- Parameter dependencies, e.g. escape fraction and SFR

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

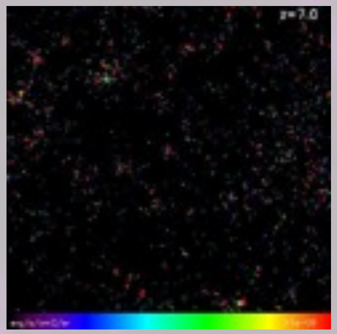
Example: Lyα x Hα

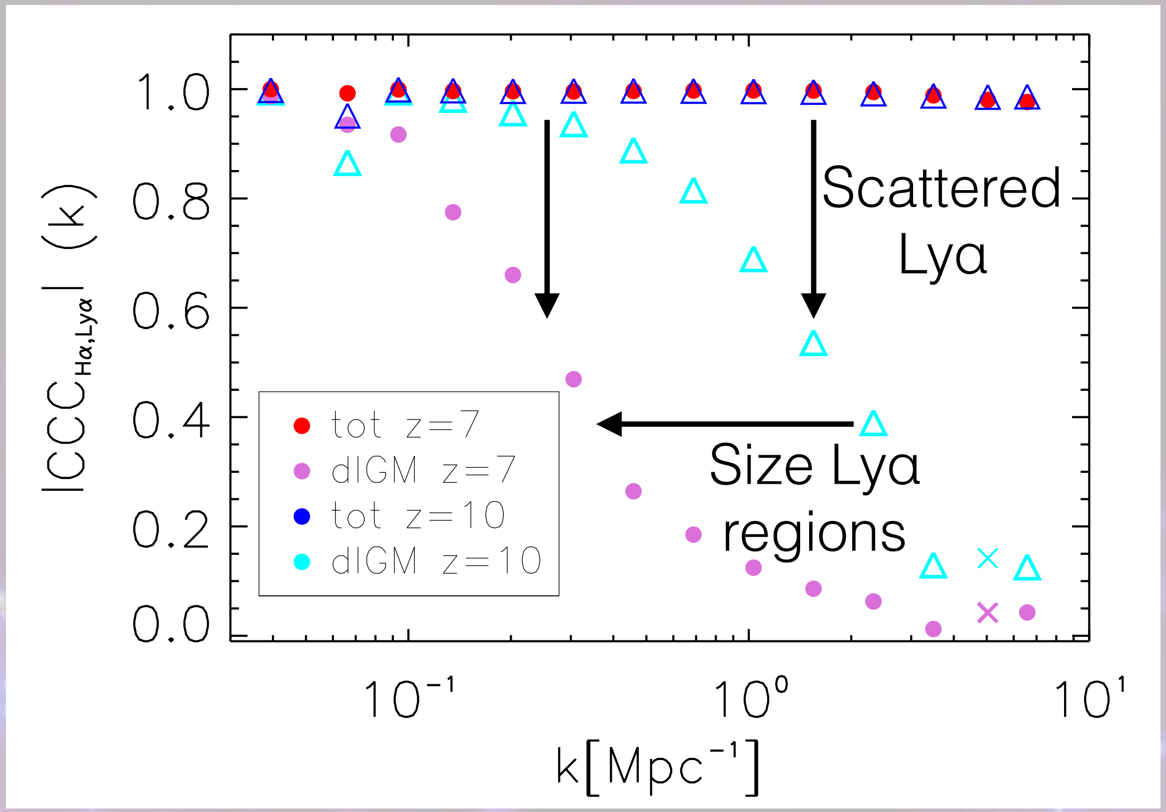
Lyα



X

Hα



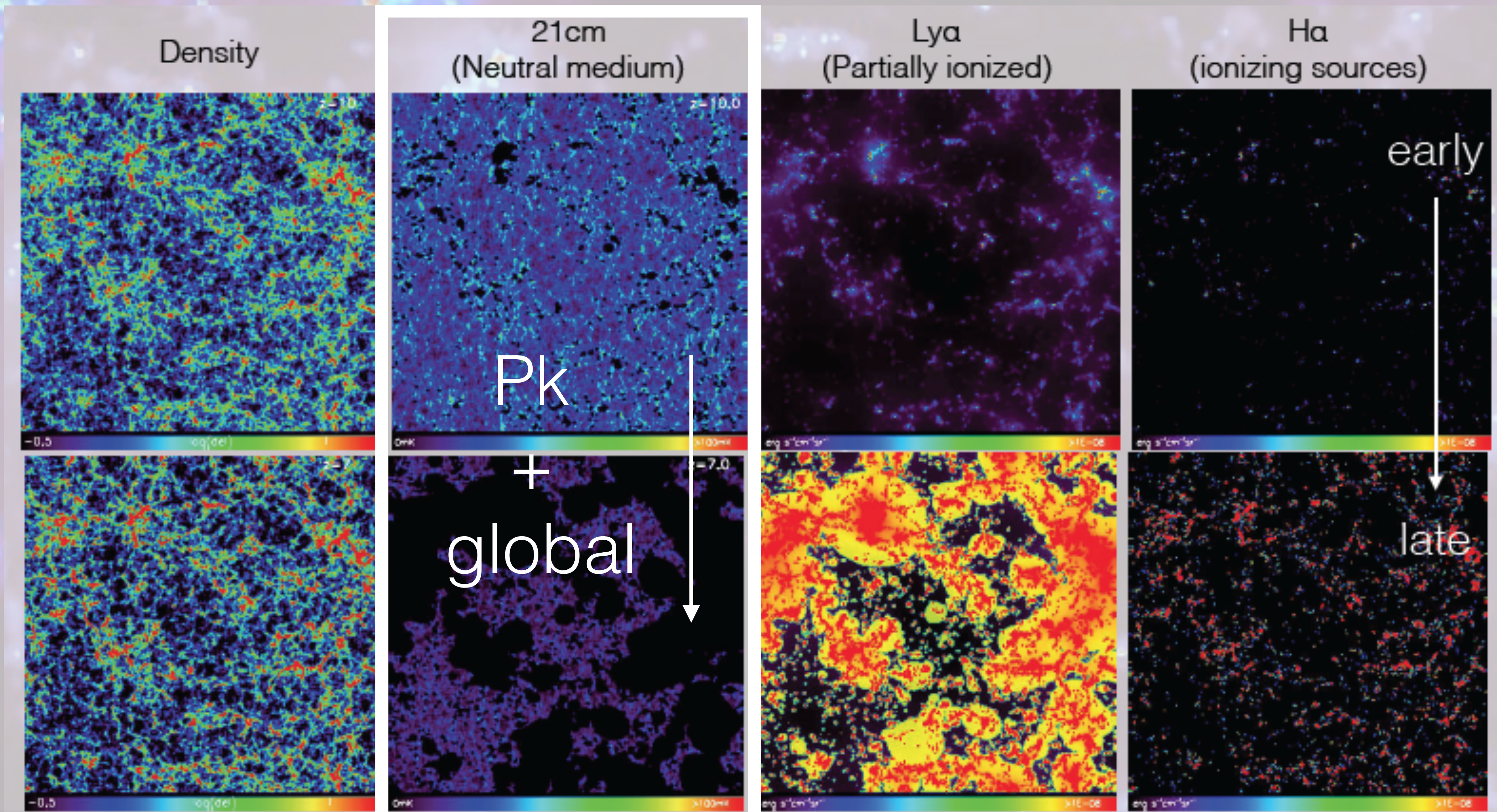


- How much Lya gets scattered
- How far (mean free path)

CH+ ApJ, 848 (2017)

Multi-Line Intensity Mapping

Gain complementary information on **LSS**, IGM, sources:



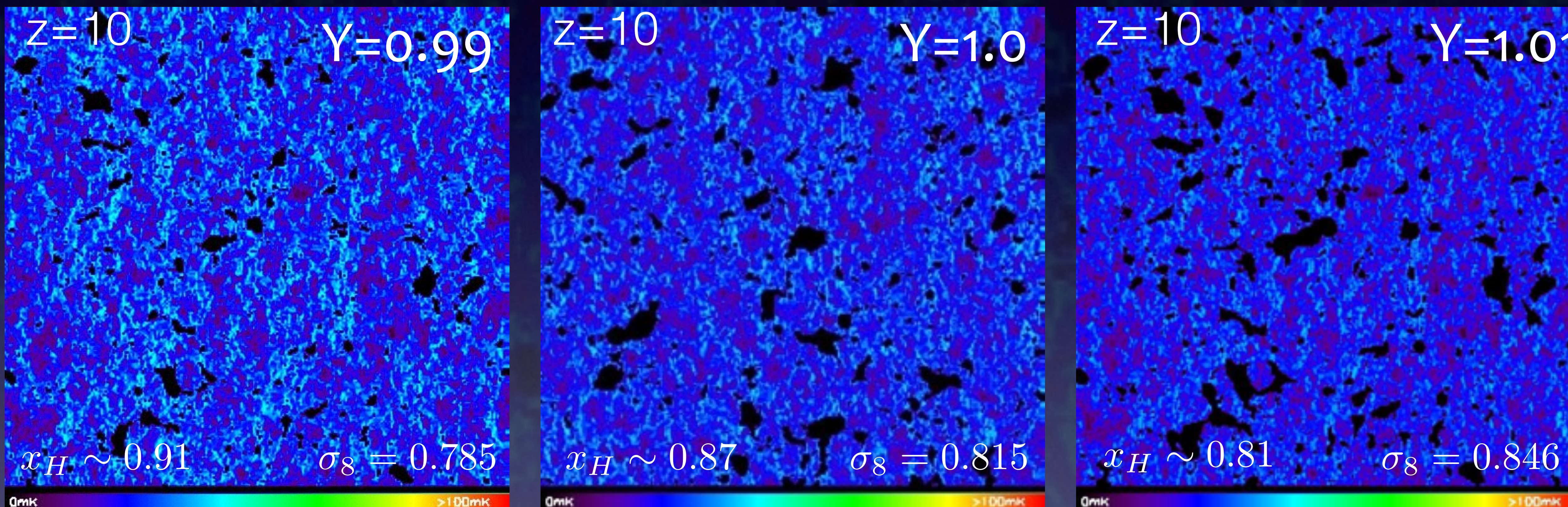
Optical Emission lines = near-IR lines during reionization (high redshift)

[CDIM Science Report, Cooray+, Heneka 2019]

Beyond GR: What to learn from 21cm P(k)

Starting with a general modification to GR: Y ~ effective G, $\alpha = \delta'_{in}/\delta_{in}$

GR: $Y = 1 \quad \alpha = 1$



Offset 21-cm brightness temperature:

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

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

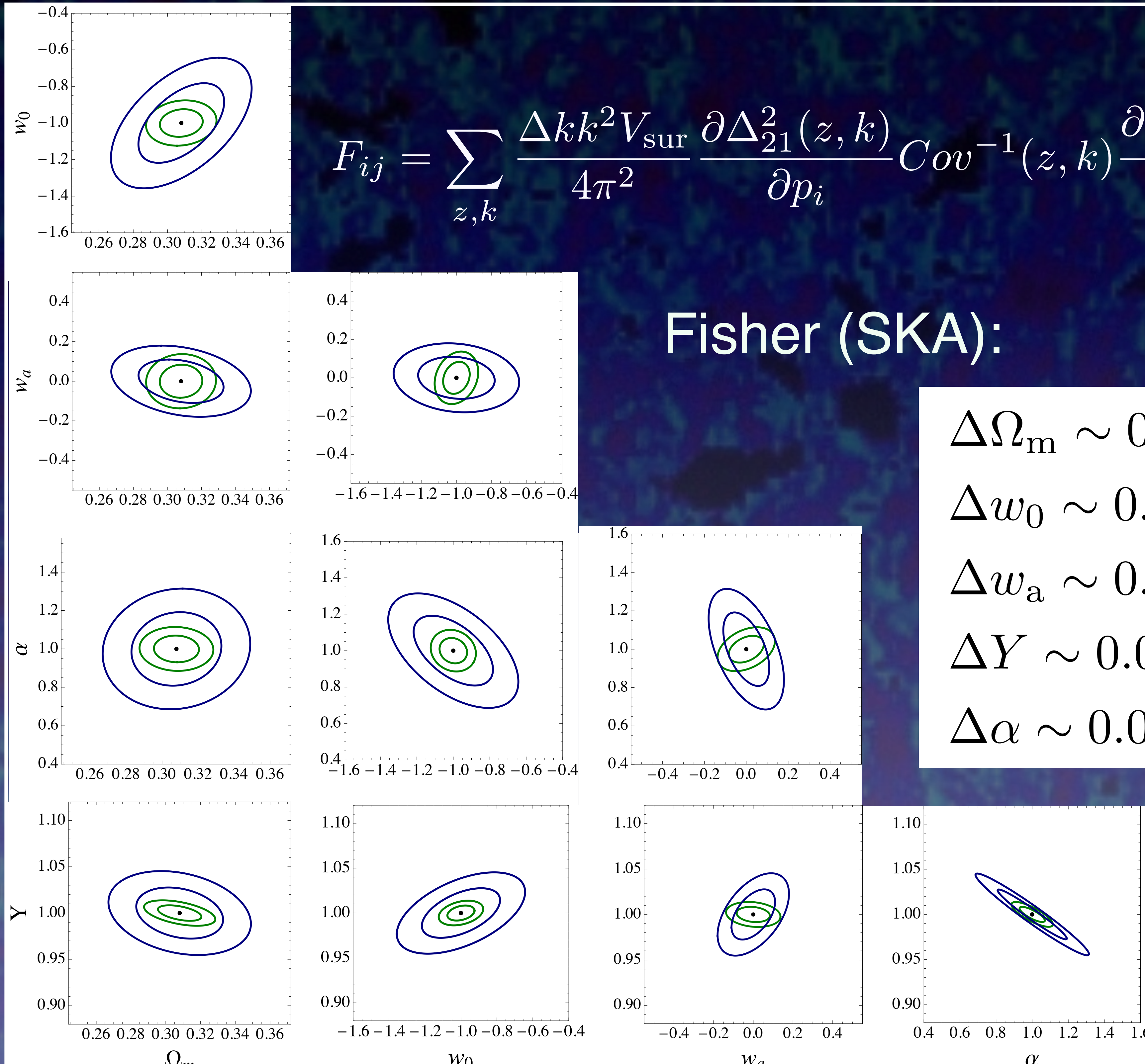
Growth evolution:

$$\delta''_m + \left(2 + \frac{E'}{E}\right)\delta'_m = \frac{3}{2}\frac{\delta_m}{a^3 E^2}\Omega_{m,0} Y$$

with IC: $\alpha = \delta'_{in}/\delta_{in}$

C. Heneka & L. Amendola, 2018

Beyond GR: What to learn from 21cm P(k)



+ foreground removal

$$F_{ij} = \sum_{z,k} \frac{\Delta k k^2 V_{\rm sur}}{4\pi^2} \frac{\partial \Delta^2_{21}(z,k)}{\partial p_i} Cov^{-1}(z,k) \frac{\partial \Delta^2_{21,l}(z,k)}{\partial p_j}$$

$$k_\parallel \le \frac{d_c E(z) \theta_0}{d_H (1+z)} k_\perp$$

Fisher (SKA):

$\Delta\Omega_{\rm m} \sim 0.008$ (0.016)

$\Delta w_0 \sim 0.05$ (0.144)

$\Delta w_{\rm a} \sim 0.16$ (0.072)

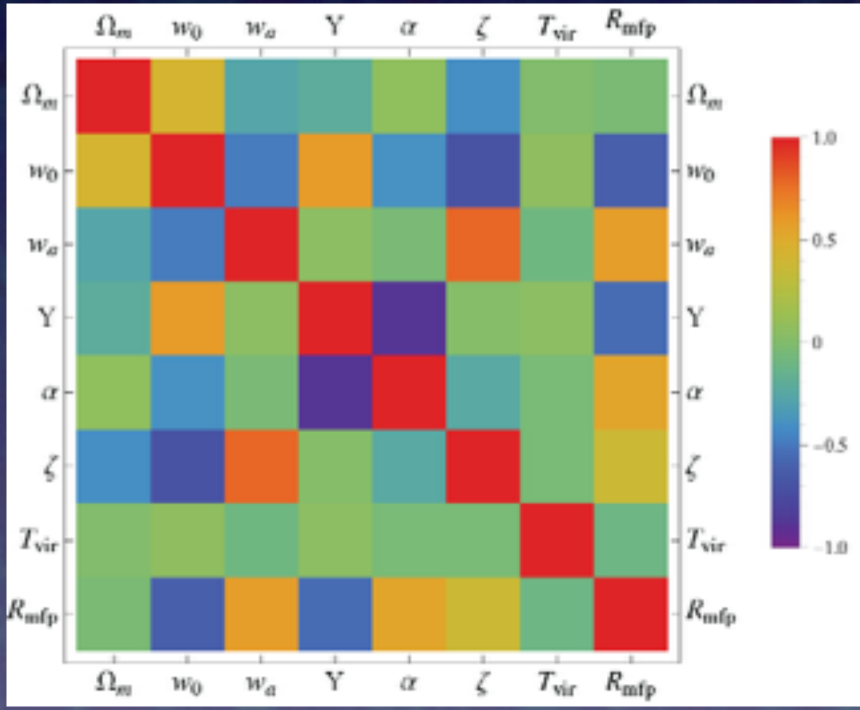
$\Delta Y \sim 0.006$ (0.018)

$\Delta\alpha \sim 0.06$ (0.126)

[For 5 z-bins z=6-10]

Beyond GR: What to learn from 21cm P(k)

$$P_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$



For cosmological parameters only:

$\Delta Y \sim 0.006$

$\Delta\alpha \sim 0.06$

'the optimist'

Plus reionization parameters:

$\Delta Y \sim 0.013$

$\Delta\alpha \sim 0.119$

+ order % errors
on other parameters

Tomography is key!

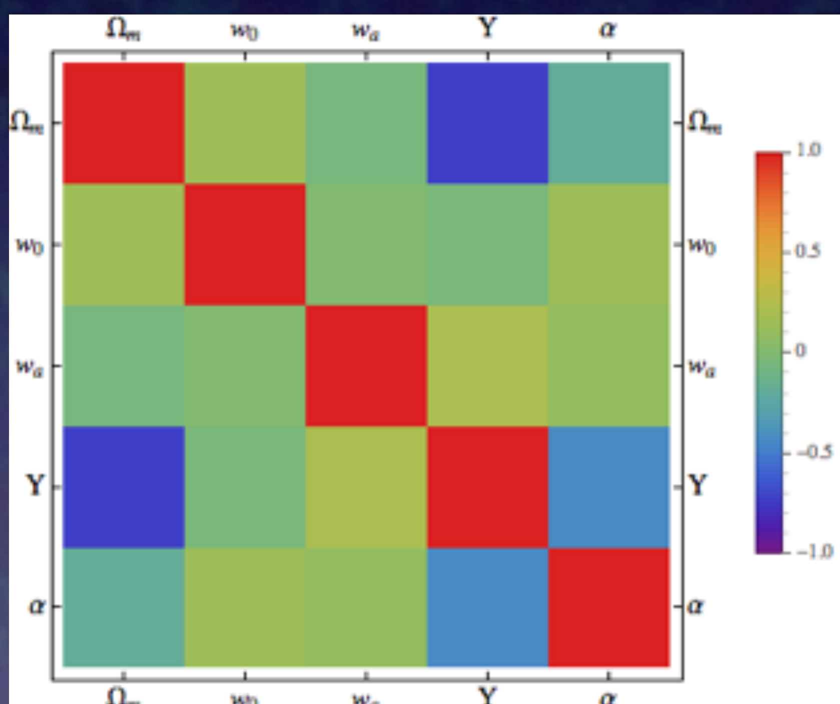
Beyond GR: What to learn from 21cm P(k)

From cosmological parameters only:

$\Delta Y \sim 0.006$

$\Delta\alpha \sim 0.06$

$$P_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$



Cut non-linear scales

$\Delta Y \sim 0.12$

$\Delta\alpha \sim 0.88$

Shot-noise cut

$\Delta Y \sim 0.04$

$\Delta\alpha \sim 0.34$

Important to model (mildly) non-linear scales!

Beyond GR: What to learn from 21cm P(k) + global signal

Choose a coupled quintessence setup:

Q ~ coupling to DM

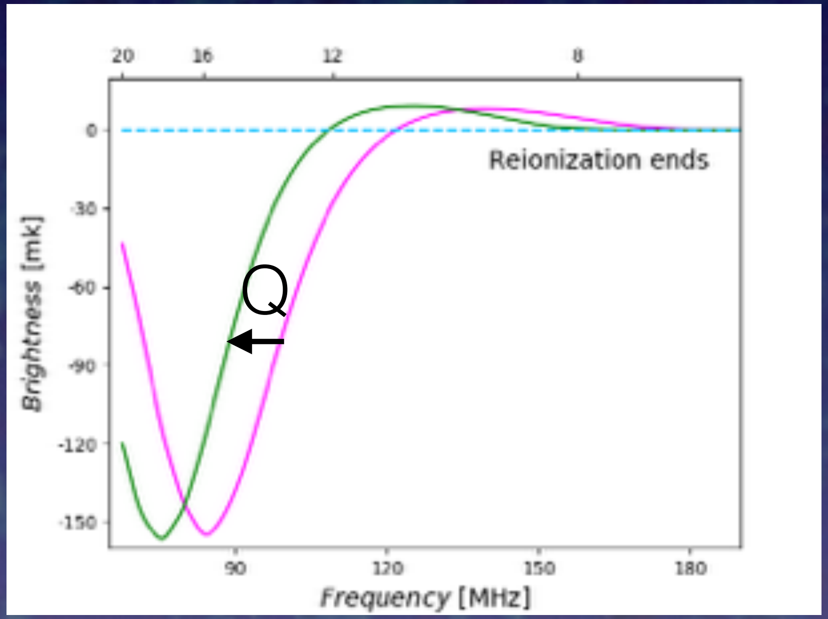
$$\nabla_\mu T^\mu_{\nu(\phi)} = -I_{\rm int}$$

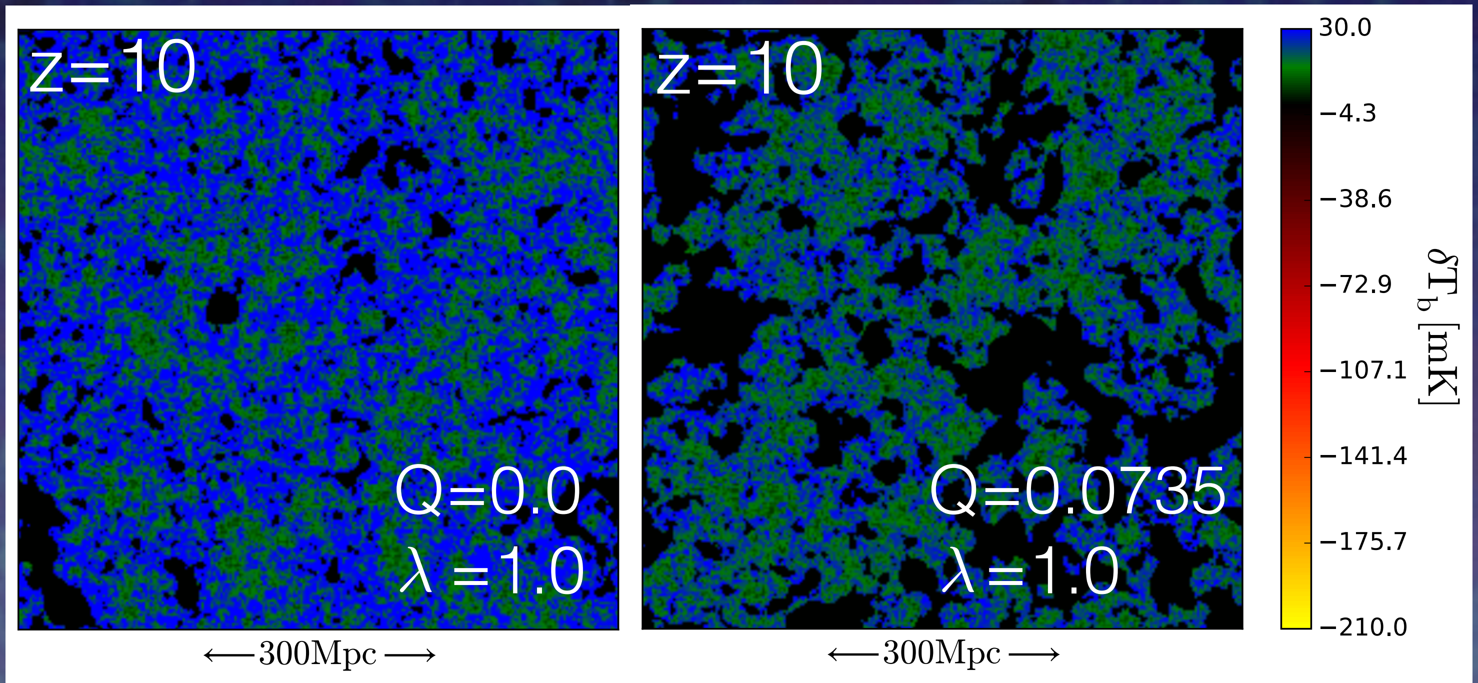
$$\nabla_\mu T^\mu_{\nu(\rm dm)} = +I_{\rm int}$$

$$I_{\rm int} = Q T_{\rm dm} \nabla_\nu \phi$$

λ ~exp. potential

$$V(\phi) = V_0 e^{-\lambda\phi}$$





[Normalized to same growth at CMB]

Fisher forecast for
1) fiducial global experiment
2) power spectra (SKA)

Liu, Heneka, Amendola, 2020

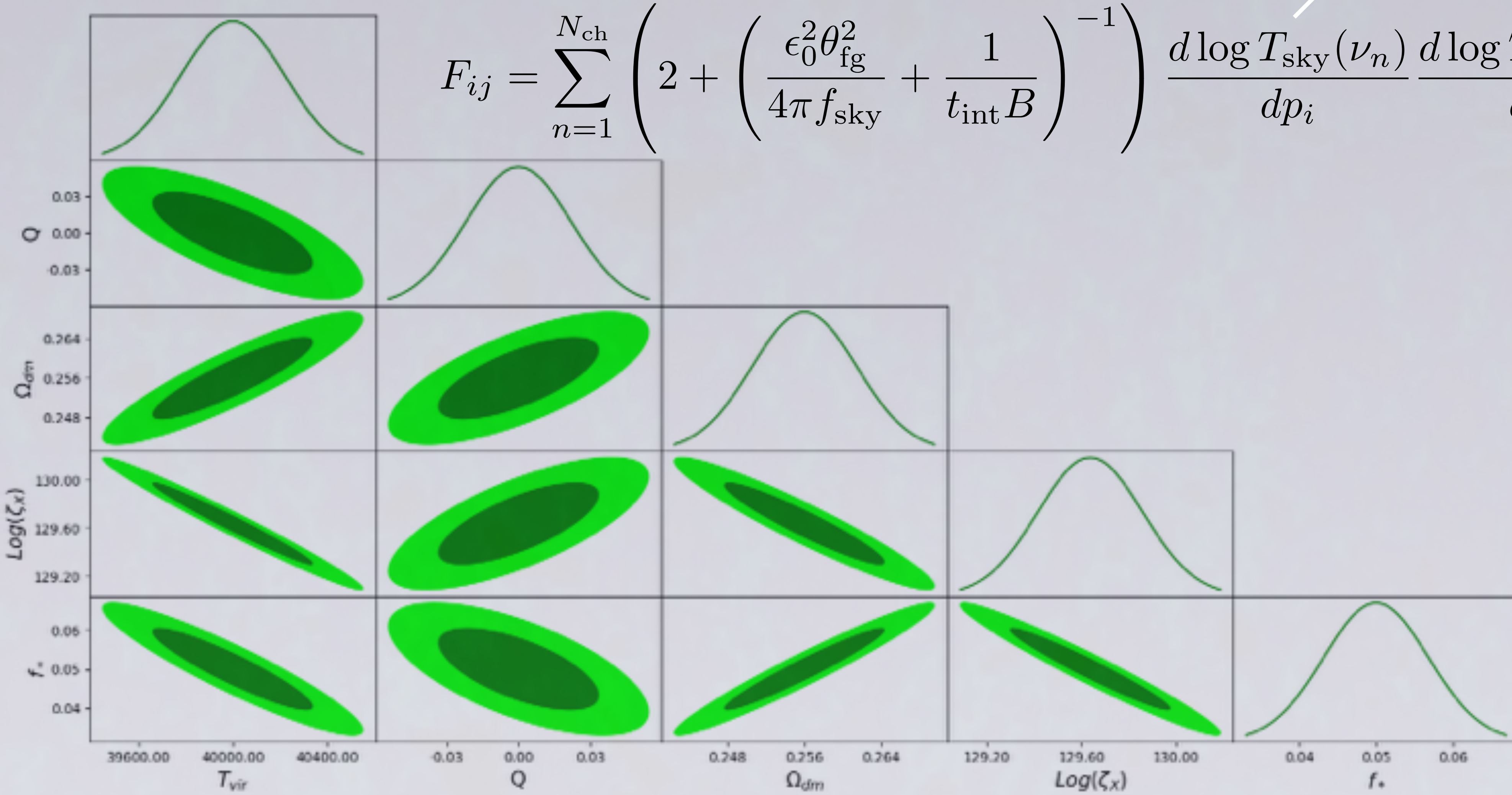
Beyond GR: What to learn from 21cm P(k) + global signal

Fisher forecast for
1) fiducial global experiment

1) global

$$T_{\rm sky}(\nu) = T_{\rm fg}(\nu) + T_{\rm b}(\nu)$$

$$F_{ij} = \sum_{n=1}^{N_{\rm ch}} \left(2 + \left(\frac{\epsilon_0^2 \theta_{\rm fg}^2}{4\pi f_{\rm sky}} + \frac{1}{t_{\rm int} B} \right)^{-1} \right) \frac{d \log T_{\rm sky}(\nu_n)}{dp_i} \frac{d \log T_{\rm sky}(\nu_n)}{dp_j}$$



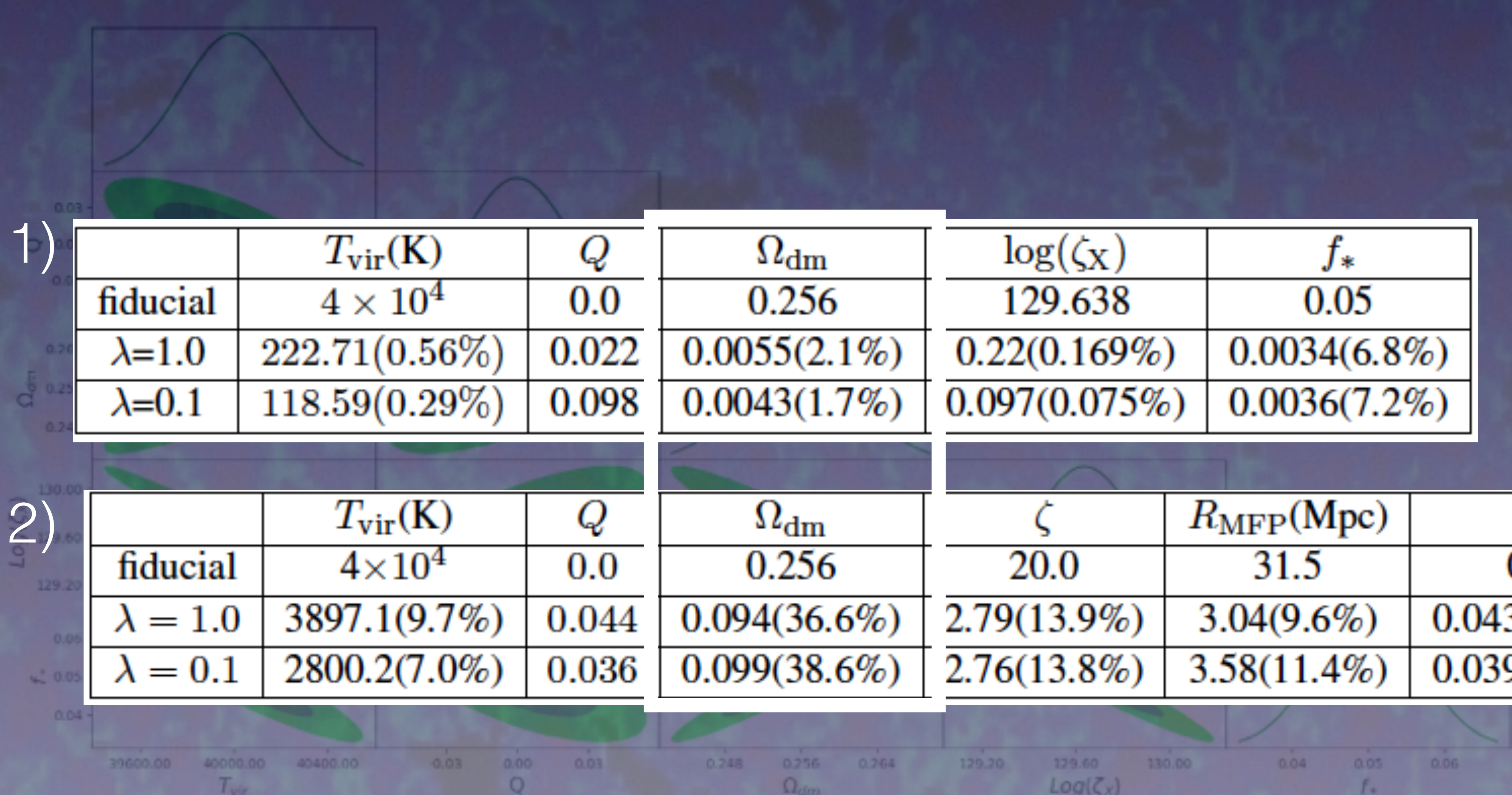
[For 6 z-bins z=15-20]

Beyond GR: What to learn from 21cm P(k) + global signal

Fisher forecast for
1) fiducial global experiment
2) power spectra (SKA)

Main take away →

- global signal improves constraints $\Omega_{\rm dm}$



1)

	$T_{\rm vir}$(K)	Q	$\Omega_{\rm dm}$	$\log(\zeta_X)$	f_*
fiducial	4×10^4	0.0	0.256	129.638	0.05
λ=1.0	222.71(0.56%)	0.022	0.0055(2.1%)	0.22(0.169%)	0.0034(6.8%)
λ=0.1	118.59(0.29%)	0.098	0.0043(1.7%)	0.097(0.075%)	0.0036(7.2%)

2)

	$T_{\rm vir}$(K)	Q	$\Omega_{\rm dm}$	ζ	$R_{\rm MFP}$(Mpc)	f_*
fiducial	4×10^4	0.0	0.256	20.0	31.5	0.05
$\lambda = 1.0$	3897.1(9.7%)	0.044	0.094(36.6%)	2.79(13.9%)	3.04(9.6%)	0.043(85.9%)
$\lambda = 0.1$	2800.2(7.0%)	0.036	0.099(38.6%)	2.76(13.8%)	3.58(11.4%)	0.039(77.9%)

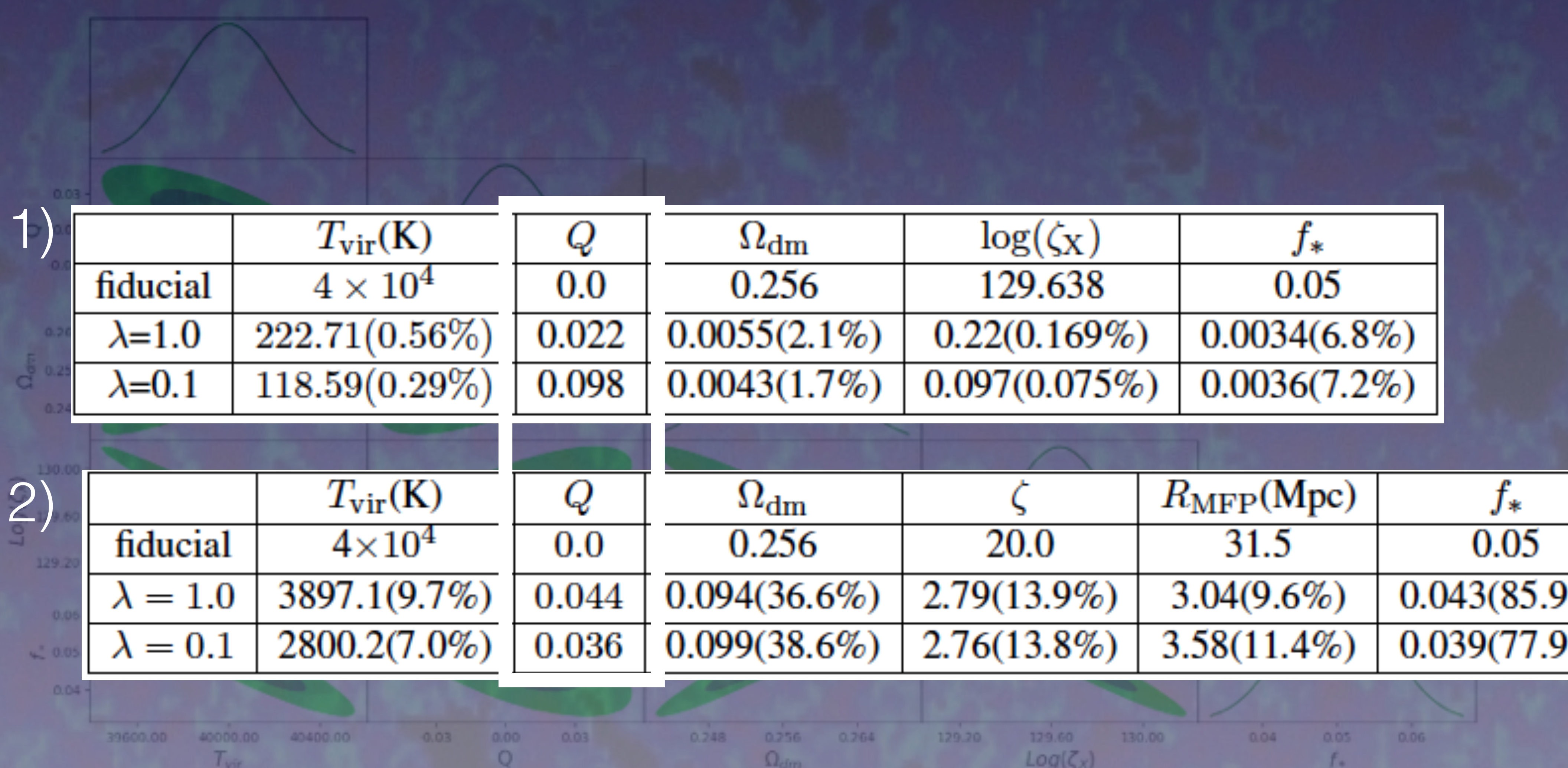
Liu, Heneka, Amendola, 2020

Beyond GR: What to learn from 21cm P(k) + global signal

Fisher forecast for
1) fiducial global experiment
2) power spectra (SKA)

Main take away $\longrightarrow$

- global signal improves constraints $\Omega_{\rm dm}$
- similar constraints on Q
- (mildly) dependent on λ



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2)

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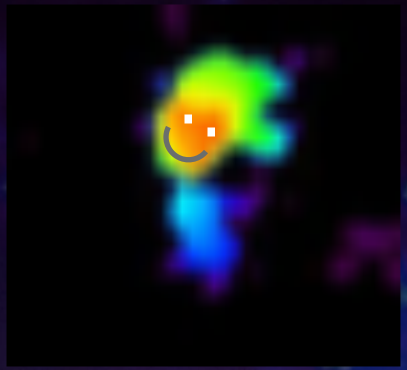
fiducial	4×10^4	0.0	0.256	20.0	31.5	0.05
$\lambda = 1.0$	3897.1(9.7%)	0.044	0.094(36.6%)	2.79(13.9%)	3.04(9.6%)	0.043(85.9%)
$\lambda = 0.1$	2800.2(7.0%)	0.036	0.099(38.6%)	2.76(13.8%)	3.58(11.4%)	0.039(77.9%)

Liu, Heneka, Amendola, 2020

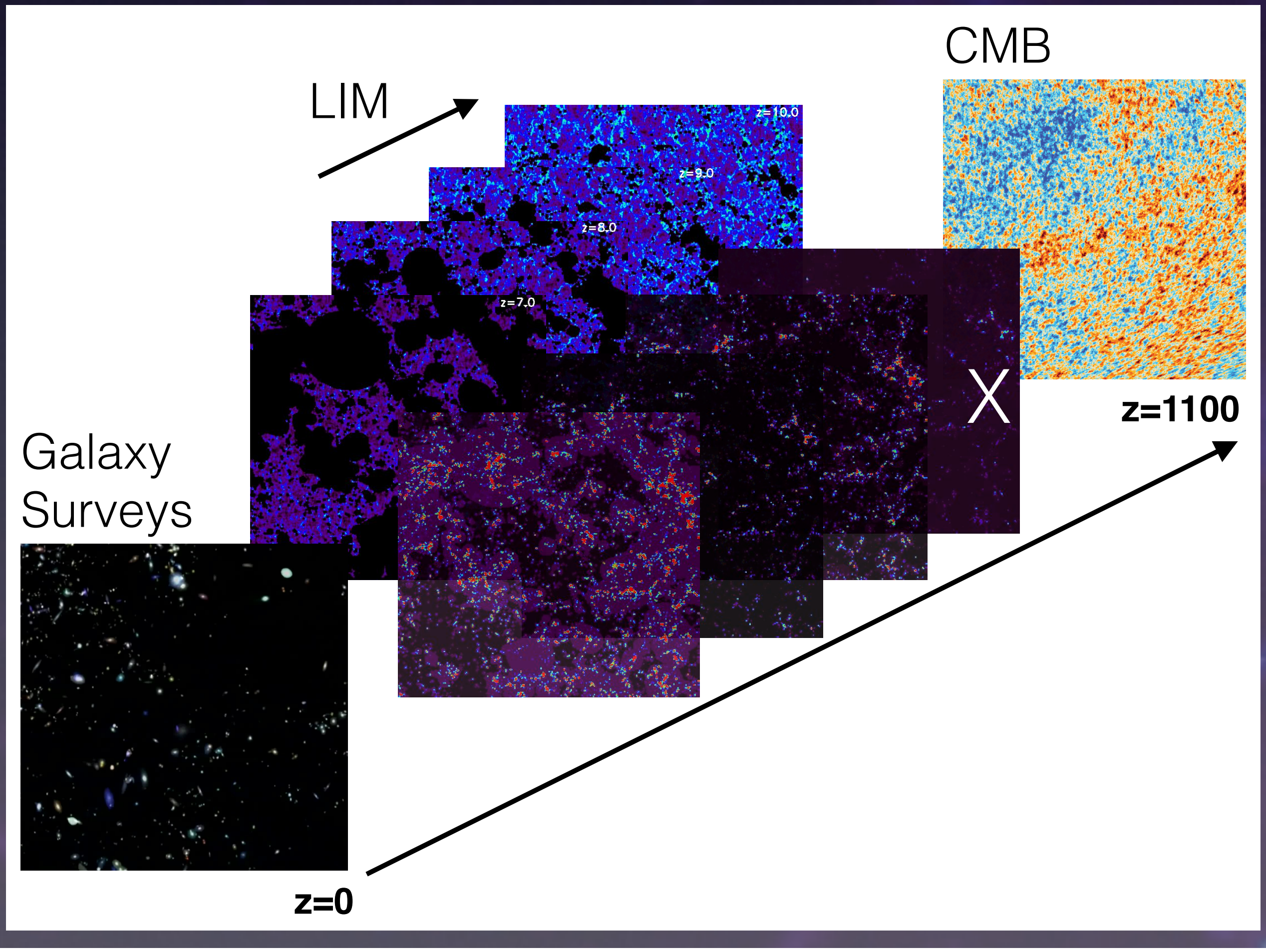
Intensity Mapping for Astro and Cosmo

- Avenue to probe cosmology and astrophysics

  %-precision even for extended models within reach
- Tomography is key
- Also large scale structure needs the non-linear



Thank you!



Ongoing & Upcoming:

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