Lyman-alpha intensity mapping during the Epoch of Reionization

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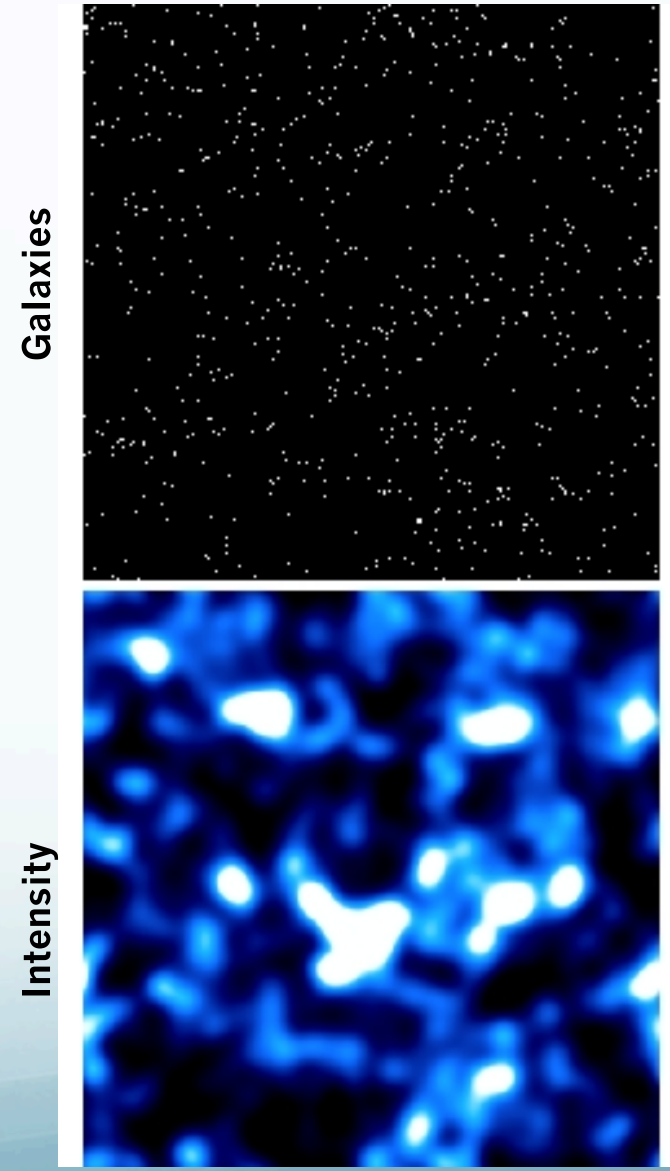
Marta Silva, Mario G. Santos, Yan Gong, Asantha Cooray (2012), arXiv:1205.1493

Intensity mapping?

- Make 3d maps during EoR
- Not resolving galaxies
- Measure intensity over many small frequency bands and over a large area of the sky (low angular resolution)
- Each band will map into an effective Lyα line redshift/position along line of sight
- If Lyα is only signal we're done after beating noise...
- Well, need to remove "foregrounds", e.g. everything else that falls into the band (coming from lower redshifts)
- Then make 3d boxes at "middle" redshift, get 3d power spectrum and you're done!



Sources of Lyα emission

- **Continuum** Ly-α emission from stars
  - Scattering of Ly-n photons in the IGM
- Hydrogen **Recombinations** (galaxies and IGM)
- HI **Collisional** excitations (galaxies and IGM)
- Gas cooling (gravitational collapse)

Powered by UV emission from stars

X-ray emission from Quasars?

Galaxies / IGM

- First assumption - use a two-medium model:
  - Galaxies
    - "Constant" temperature
    - "Constant" ionization fraction
    - "closed box"
  - IGM
    - Temperature increasing
    - Ionization fraction increasing
    - Should be ionized around galaxies…
  - UV escape fraction from galaxies → Reionization
  - Ly-α escape fraction (no scattering in IGM)
  - HI "glow" around galaxies?

Ly-α from Galaxies: Parameters

- Ionizing photon rate from stars - relate to Star Formation Rate:

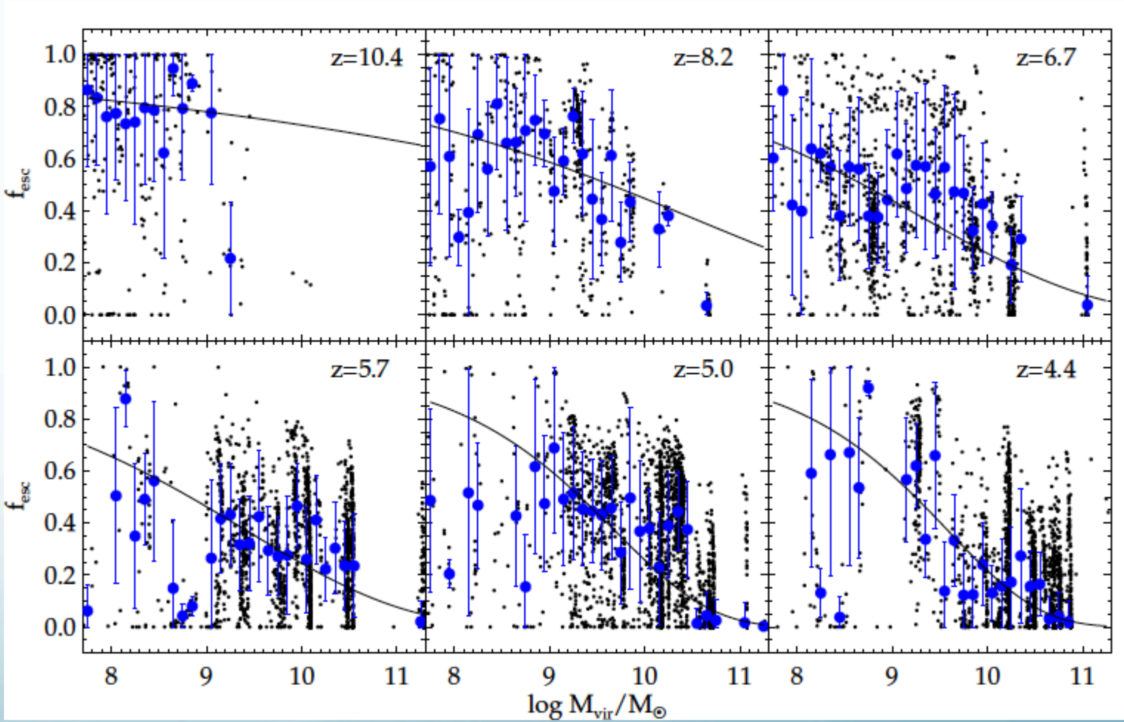
$$\dot{N}_{\rm ion} = Q_{\rm ion} \times {\rm SFR}$$

- Q_{ion} ~ 5.38×10^{60} UV photons/M$\odot$
- Salpeter IMF
- Ionizing Fluxes from Shaerer 2002
- (POP II, OB stars)
- 20% error?

- UV escape fraction:

$$f_{\rm esc}^{UV}(M,z) = \exp\left[-\alpha(z) M^{\beta(z)}\right]$$

- 20% uncertainty?



Razoumov & Sommer-Larsen (2010)

Ly-α from Galaxies: Parameters

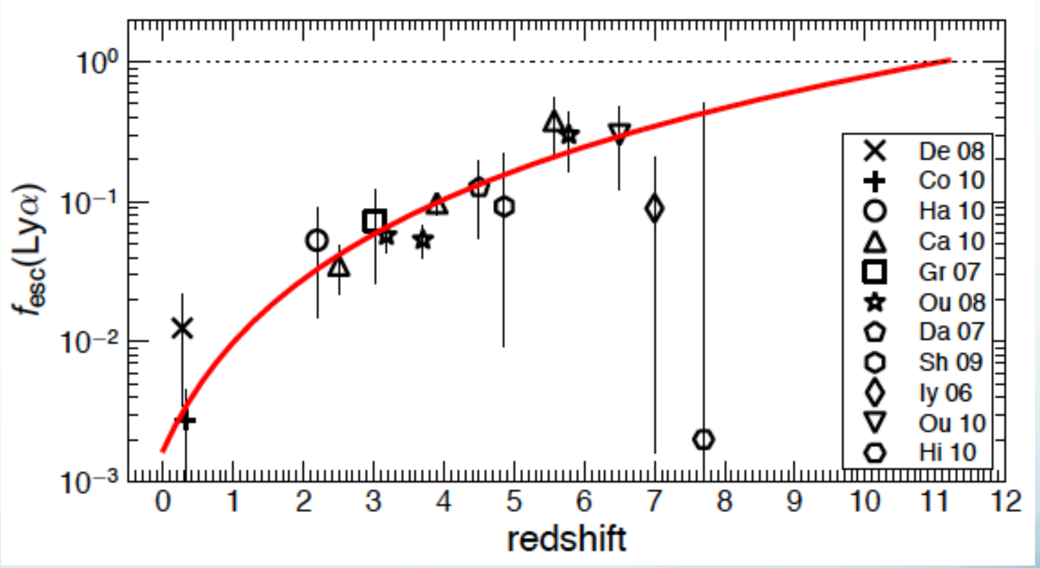
- Average number of Lyα photons per recombination:
  - f_{rec} ~ 0.66 (Gould & Weinberg, 1996)

    + 2-photon emission

- Lyα escape fraction (related to dust absorption)

$$f_{esc}^{\mathrm{Ly}\alpha}(z) = C_{\mathrm{dust}} \times 10^{-3}(1+z)^{\xi}$$

- Cdust ~ 3.34
- ξ ~ 2.57
- Mass dependence?



Hayes et al. (2011)

Ly-α from Galaxies

Hydrogen Recombinations:

$$\dot{N}_{\mathrm{Ly}\alpha} = f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} \times A_{He} f_{\mathrm{rec}} \times (1 - f_{\mathrm{esc}}^{\mathrm{UV}}) \times \dot{N}_{\mathrm{ion}}$$

$$\mathrm{L}_{\mathrm{rec}}^{\mathrm{Gal}} \sim 4.04 \times 10^8 \; [1 - f_{\mathrm{esc}}^{\mathrm{UV}}(M,z)] f_{\mathrm{esc}}^{\mathrm{Ly}\alpha}(z) \frac{SFR(M,z)}{\mathrm{M}_{\odot}\mathrm{yr}^{-1}} \mathrm{L}_{\odot}$$

Collisions - Heating/excitations:

$\langle E_\nu \rangle \sim 21.4\mathrm{eV}$

SED from Maraston (2005)
~ 1% for Lyα through excitations
(Gould & Weinberg '96)

$$\mathrm{L}_{\mathrm{exc}}^{\mathrm{Gal}} \sim 1.05 \times 10^8 \; [1 - f_{\mathrm{esc}}^{\mathrm{UV}}(M,z)] f_{\mathrm{esc}}^{\mathrm{Ly}\alpha}(z) \frac{SFR(M,z)}{\mathrm{M}_{\odot}\mathrm{yr}^{-1}} \mathrm{L}_{\odot}$$

Ly-α from Galaxies

Continuum emission:

Average number of photons – connect to UV emission/Reionization:

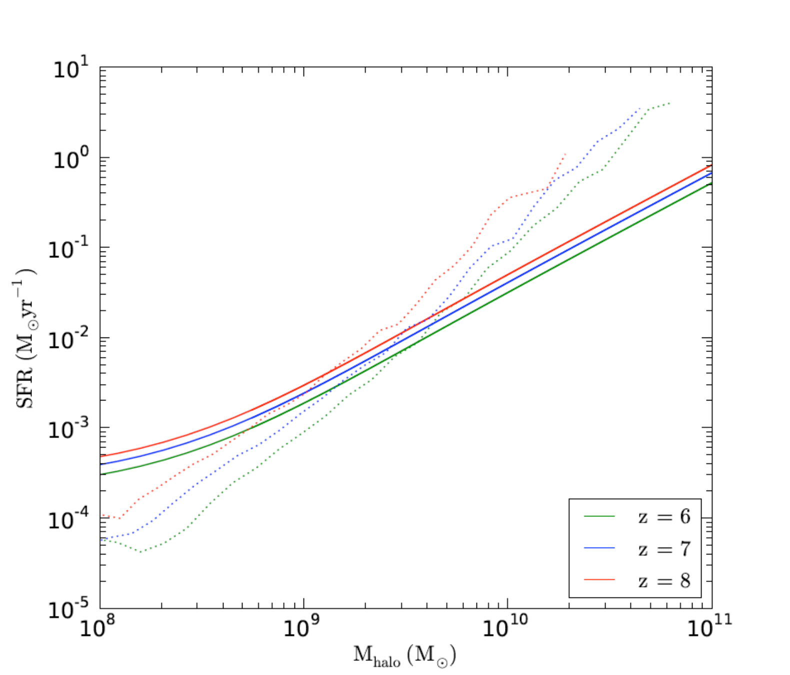
$Q_{\mathrm{Ly}\alpha} \sim 0.63\ Q_{\mathrm{ion}}$ (SED from OB stars)

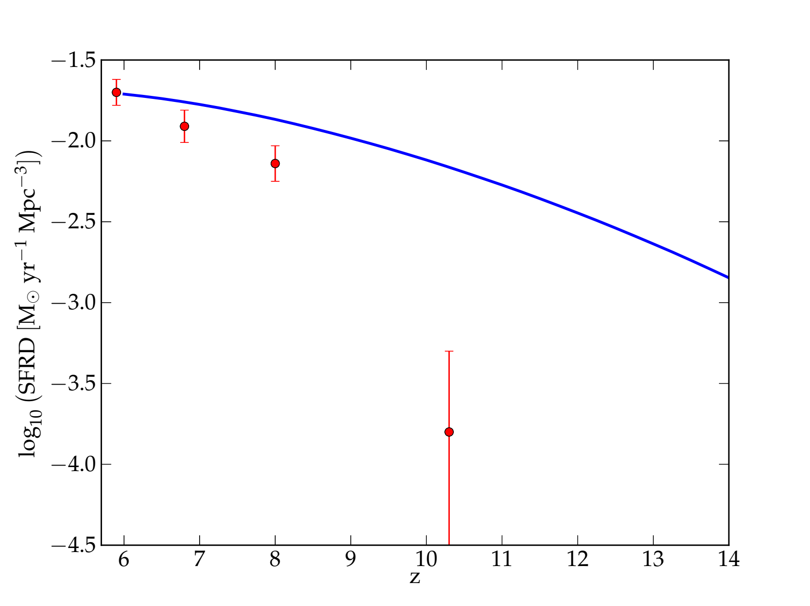
$$\mathrm{L}^{\mathrm{Gal}}_{\mathrm{cont}} \sim 4.63 \times 10^{8}\ f^{\mathrm{Ly}\alpha}_{\mathrm{esc}}(z)\frac{SFR(M,z)}{\mathrm{M}_{\odot}\mathrm{yr}^{-1}}\mathrm{L}_{\odot}$$

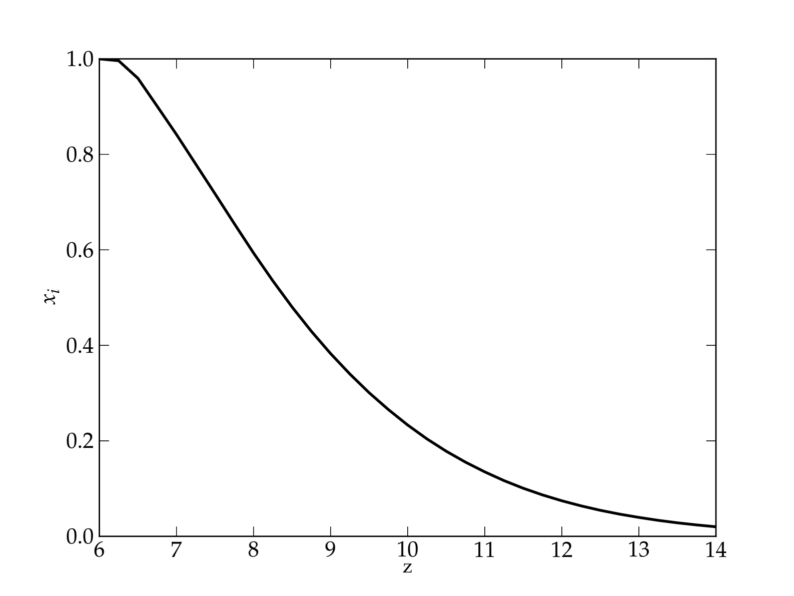
Cooling – gas collapse (negligible):

$$L^{\mathrm{Gal}}_{\mathrm{cool}}(M) \sim 44 f^{\mathrm{Ly}\alpha}_{\mathrm{esc}}\left(1+\frac{M}{10^{8}}\right)\left(1+\frac{M}{2\times 10^{10}}\right)^{2.1}\left(1+\frac{M}{3\times 10^{13}}\right)^{-3}\mathrm{L}_{\odot}$$

Galaxies - SFR

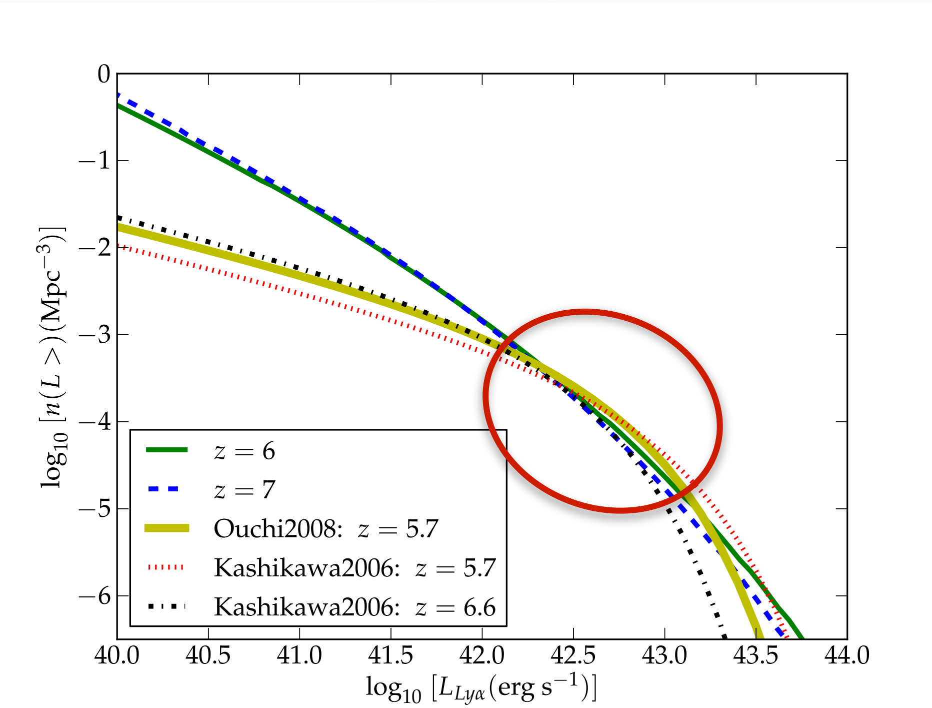


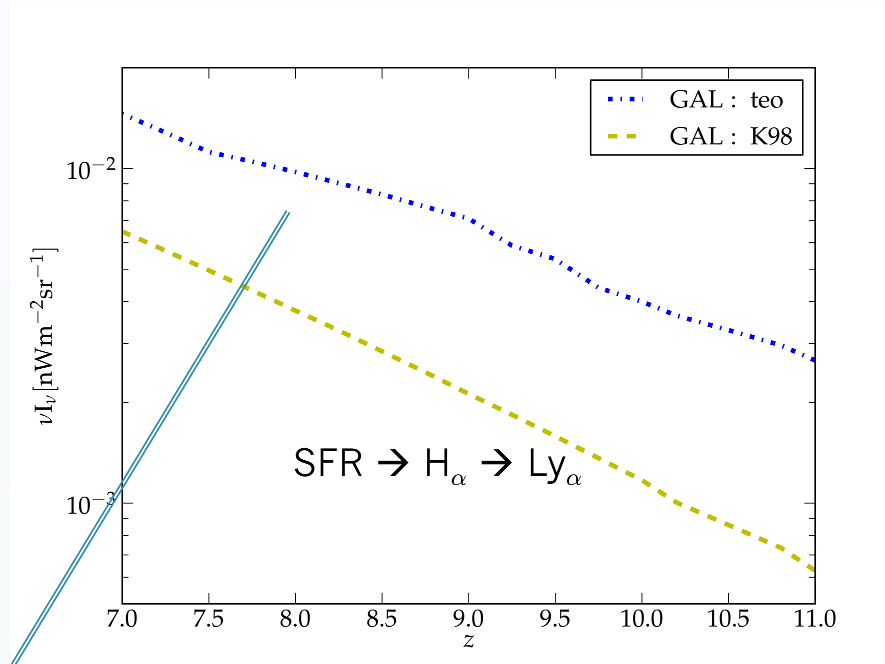




- **Top right:**
  - Solid lines - our model
  - Dotted lines - catalogue from Guo et al. (2011)
- **Top left:**
  - SFR density using our simulation (red – points from Bouwens et al. 2011)
- **Bottom:**
  - Obtained ionization fraction (x_i ~ 0.9 at z=7 and τ~ 0.07)

Intensity from Galaxies





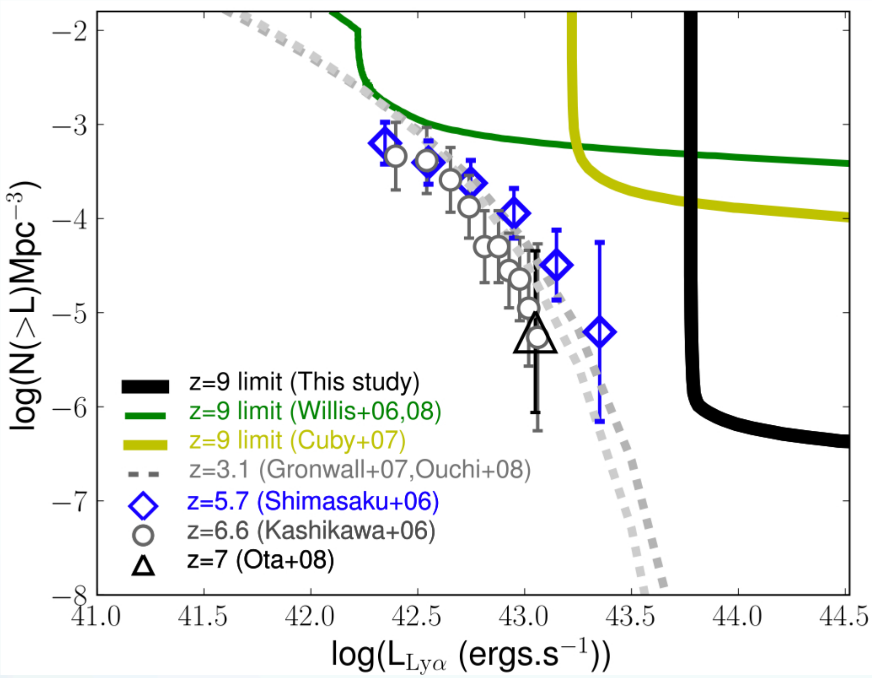
- Luminosity functions
  - Green/blue - with our SFR model
  - Yellow/black/red - "observations" with Schechter function fits

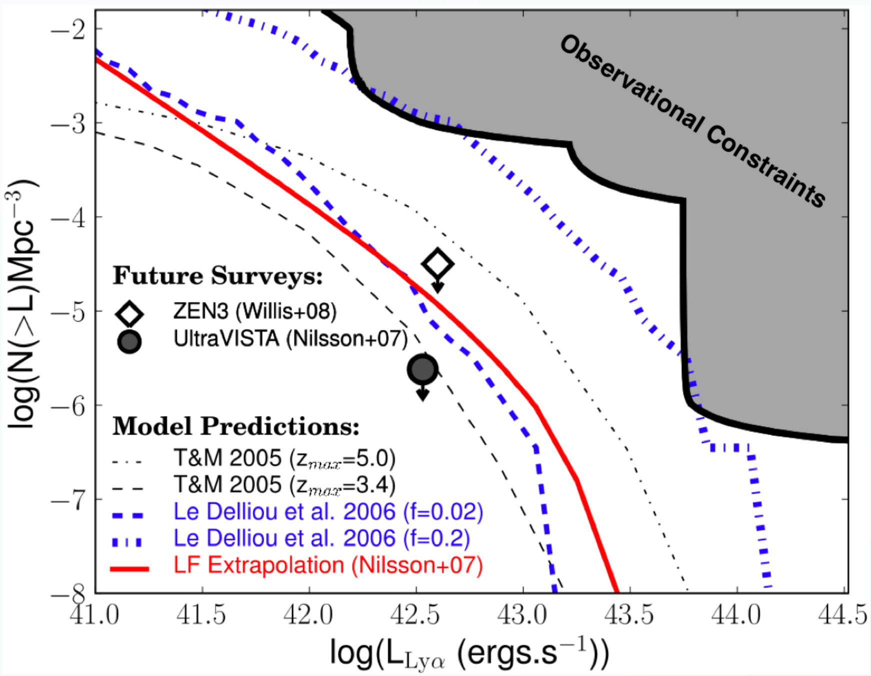
- Total Lyα intensity from galaxies
  - blue - analytical calculation using our luminosities
  - yellow - using the empirical relation from Jiang et al. (2011):

$$\mathrm{L}^{\mathrm{Gal}}_{\mathrm{K98}} \sim 2.9 \times 10^8 \frac{SFR(M,z)}{\mathrm{M_\odot yr^{-1}}} \mathrm{L_\odot}$$

$$\bar{I}_{\mathrm{Gal}}(z) = \int_{\mathrm{M_{min}}}^{\mathrm{M_{max}}} dM \frac{dn}{dM} \frac{L_{\mathrm{Gal}}(M,z)}{4\pi H(z)} \lambda_{\mathrm{Ly_\alpha}}$$

More Luminosity constraints...



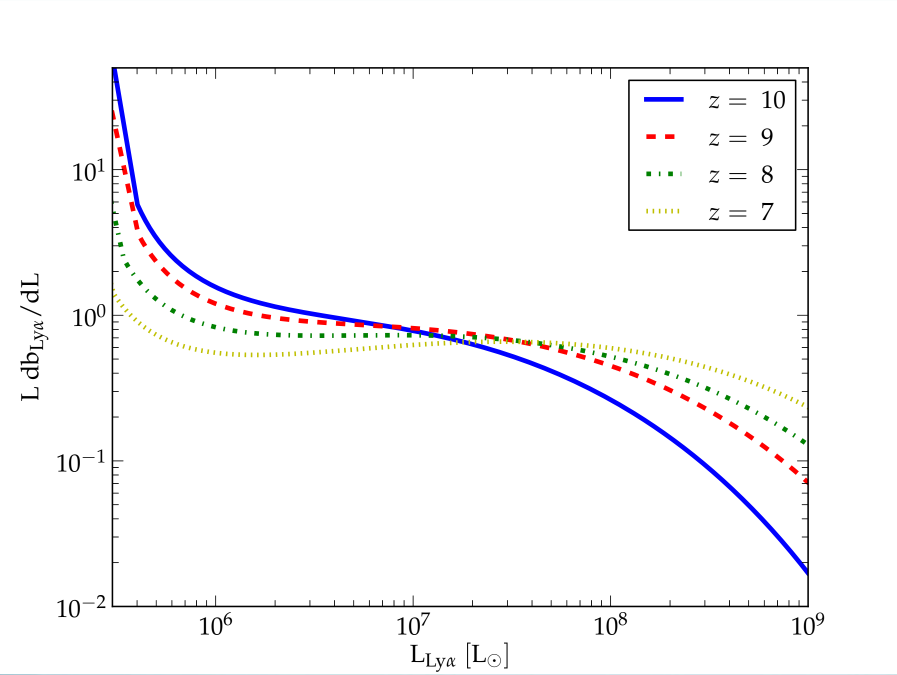


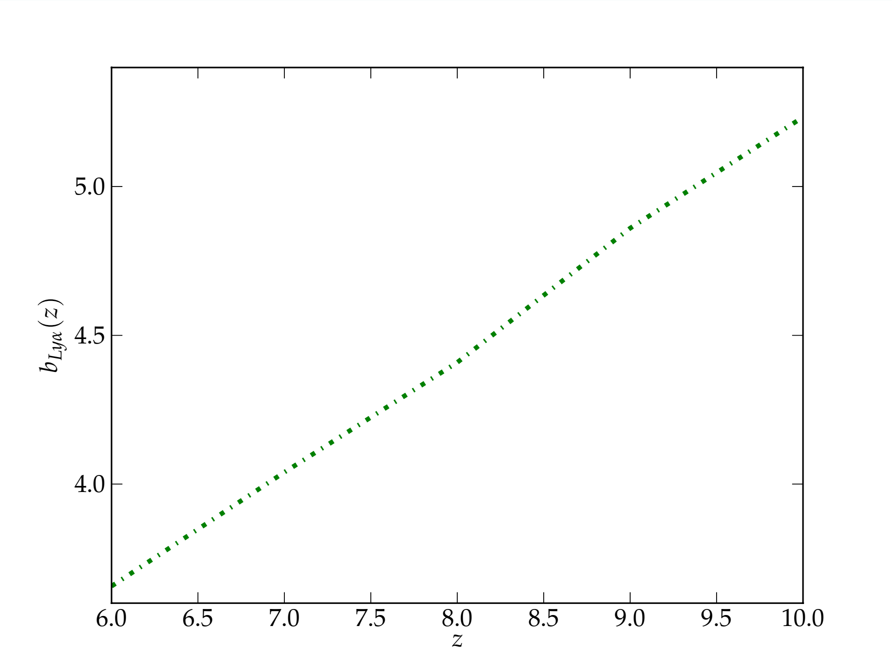
(from Sobral et al. 2009)

Lyα Power Spectrum from Galaxies

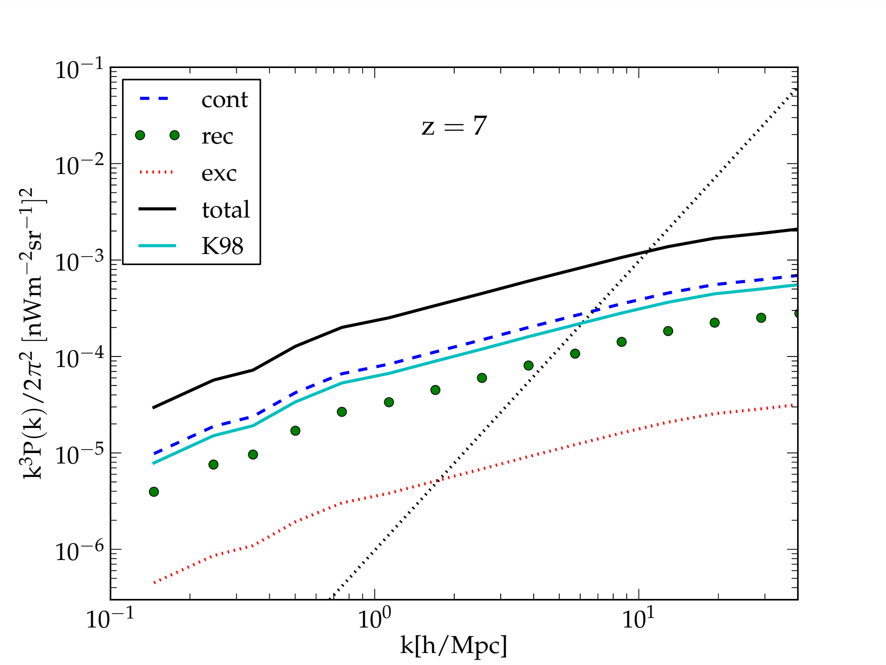
- Assume:

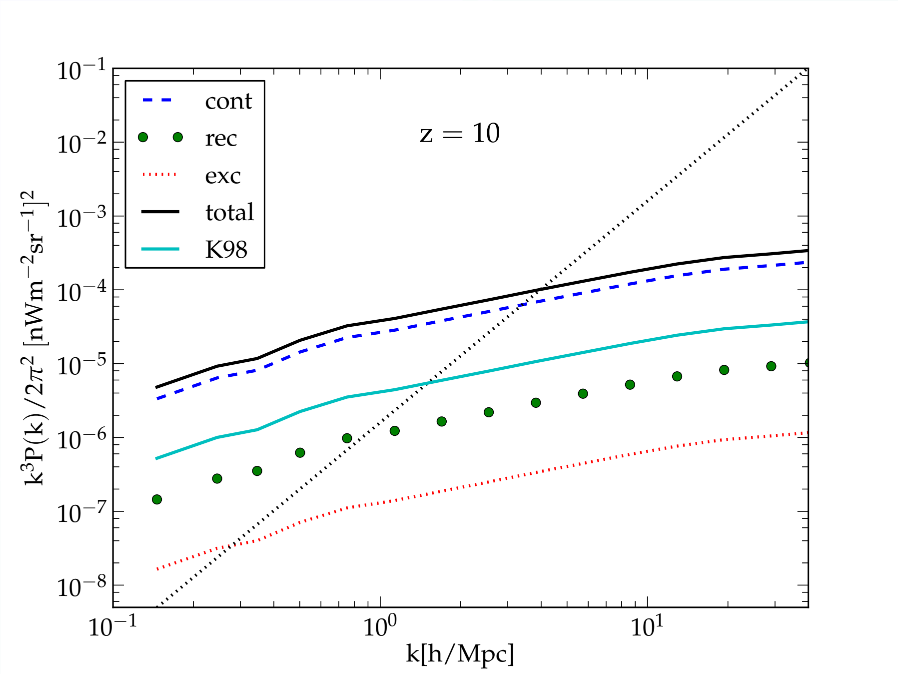
$$\delta I_{\rm GAL} = b_{\rm Ly\alpha} \bar{I}_{\rm GAL} \delta_{\rm m}(\mathbf{x}) \qquad b_{\rm Ly\alpha}(z) = \frac{\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} L_{\rm GAL}\, b(z, M)}{\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} L_{\rm GAL}}$$





Lyα Power Spectrum from Galaxies



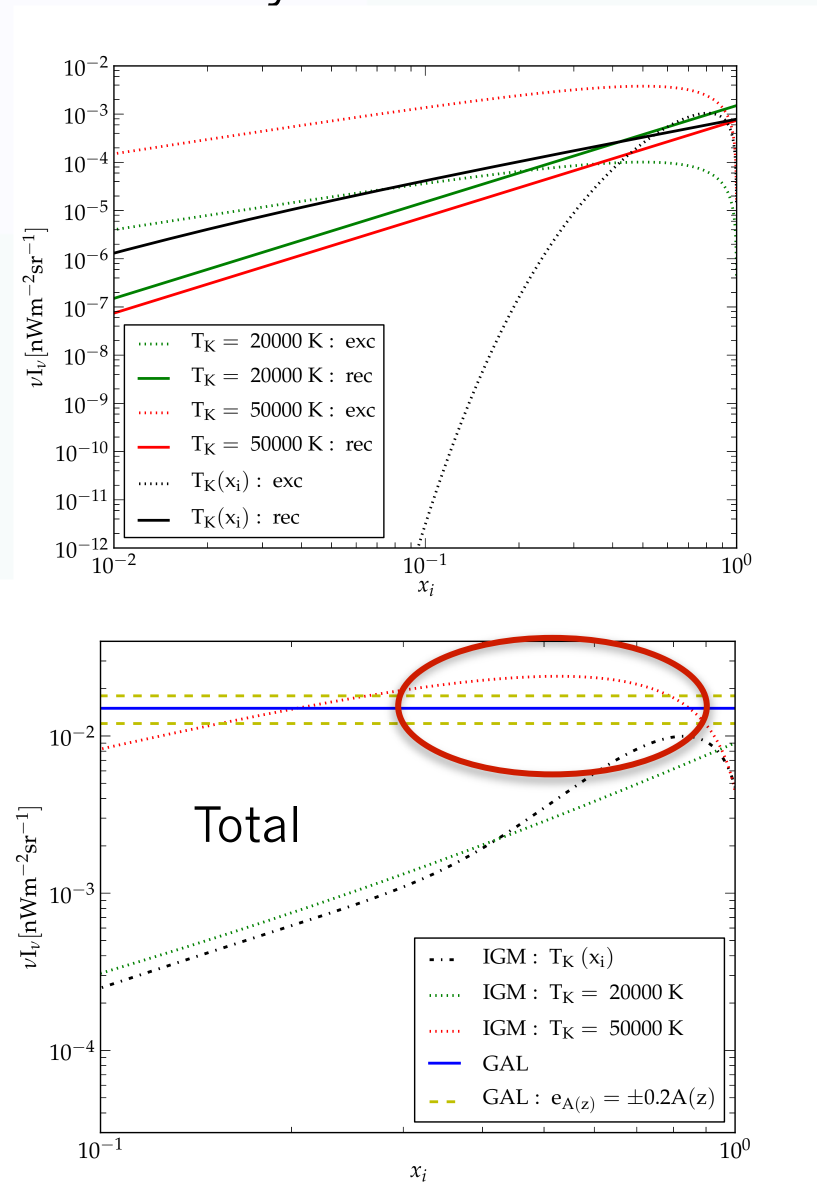


- Analytical calculation...
- “Continuum” emission from stars dominates
- At k ~ 1 Mpc^{-1} (R ~ 9 Mpc), rms ~ 0.03 $nWm^{-2}sr^{-1}$

Lyα IGM intensity

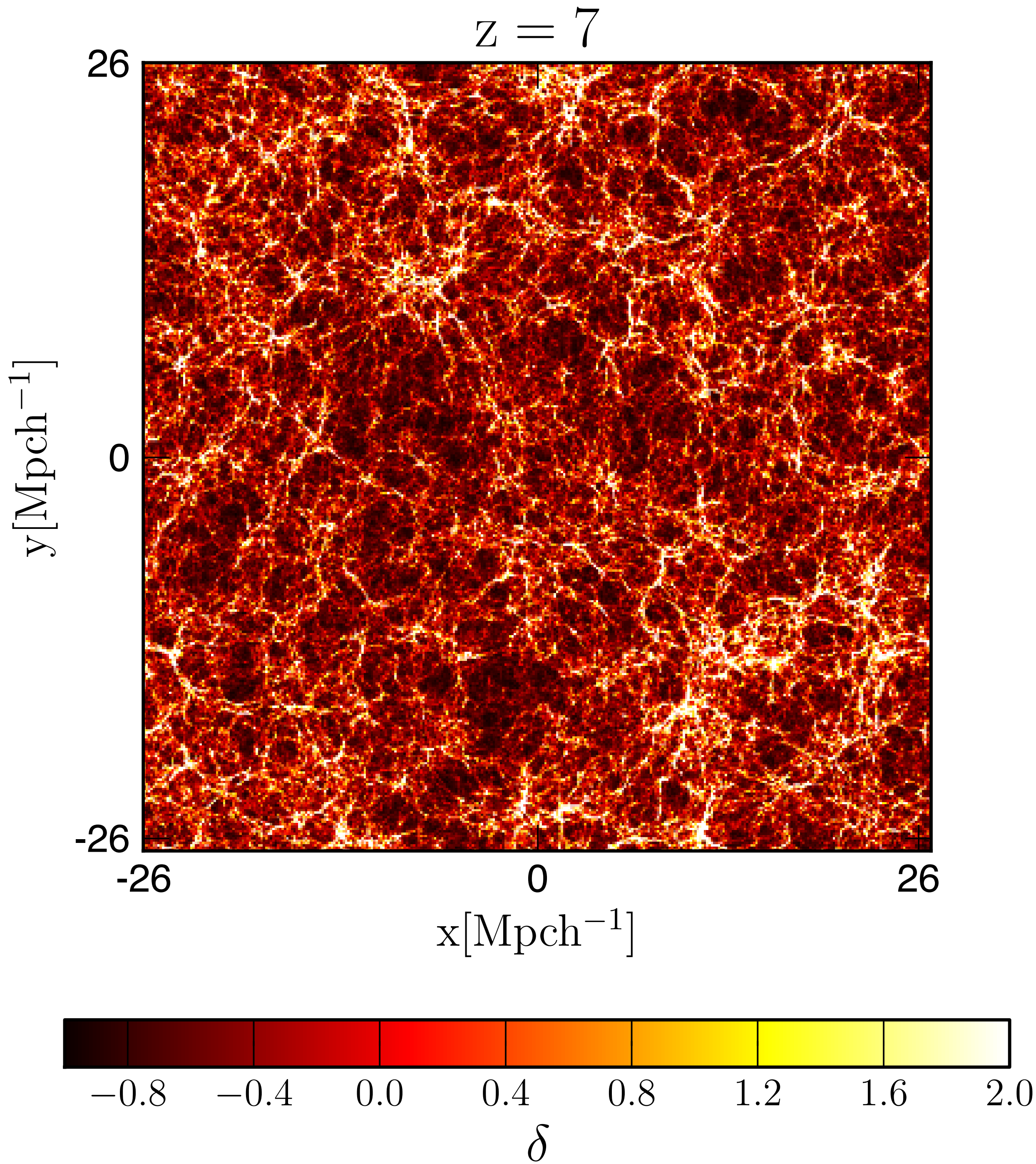
- Processes:
  - Recombinations
  - Radiative cooling
  - Ly-n scattering
- Depends on:
  - Ionization fraction
  - Gas temperature
  - matter density
- Need to connect to UV photons that escape galaxy and SFR
- **Need simulations!**

Analytical calculations

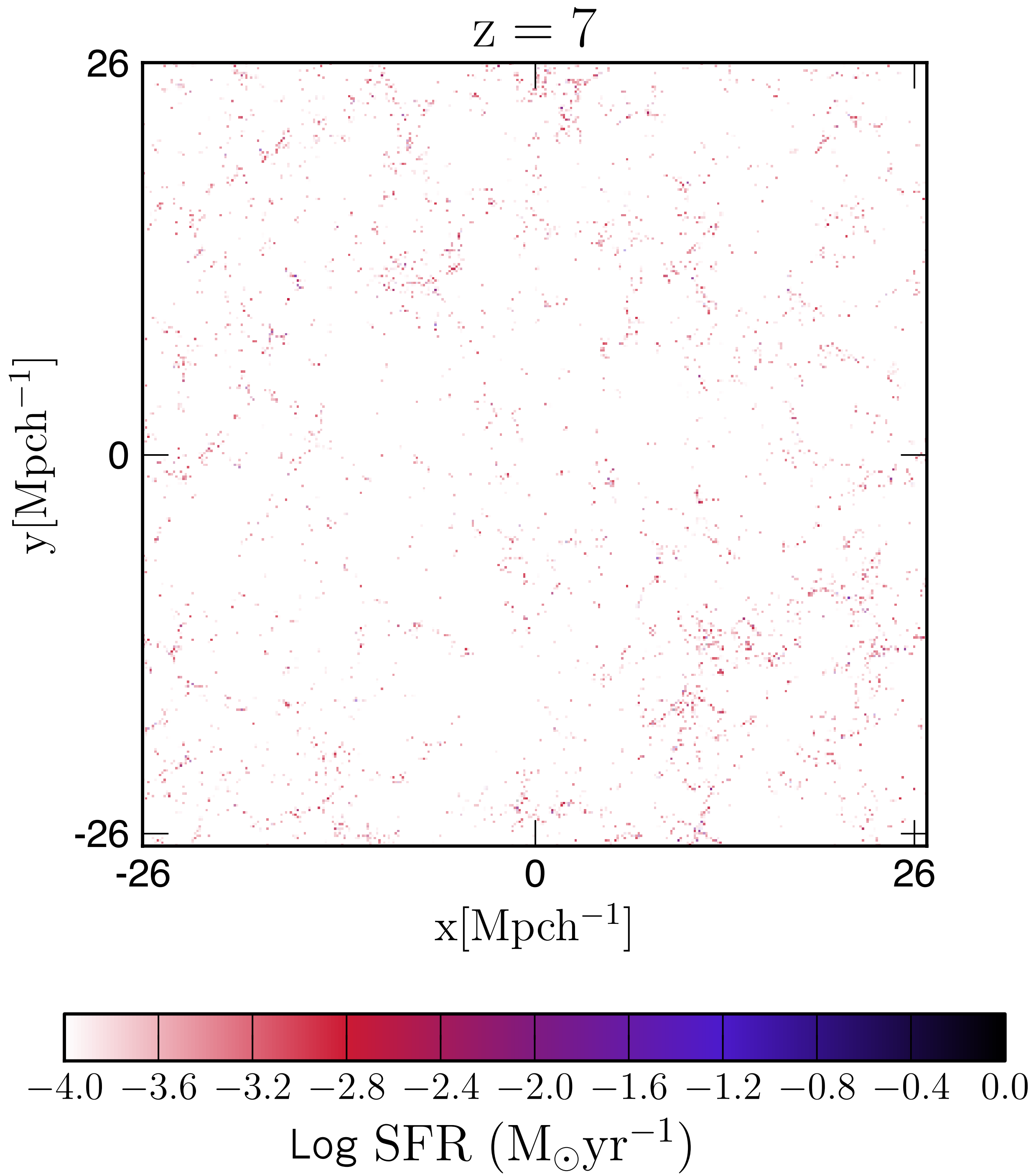


"Semi-numerical" simulation

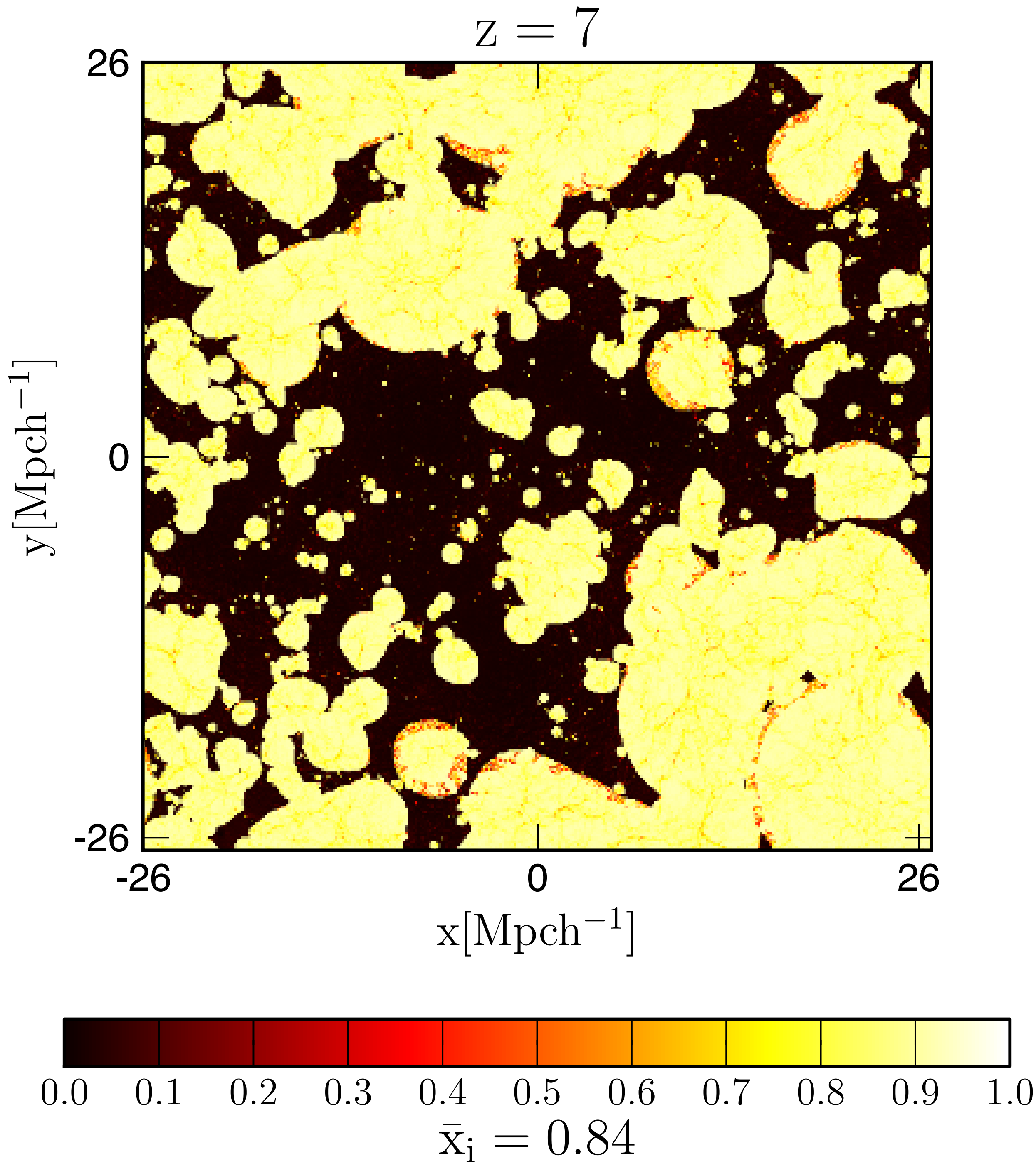
- Modified version of SimFast21 (Santos et al. 2010, www.simfast21.org)
- Start with density field



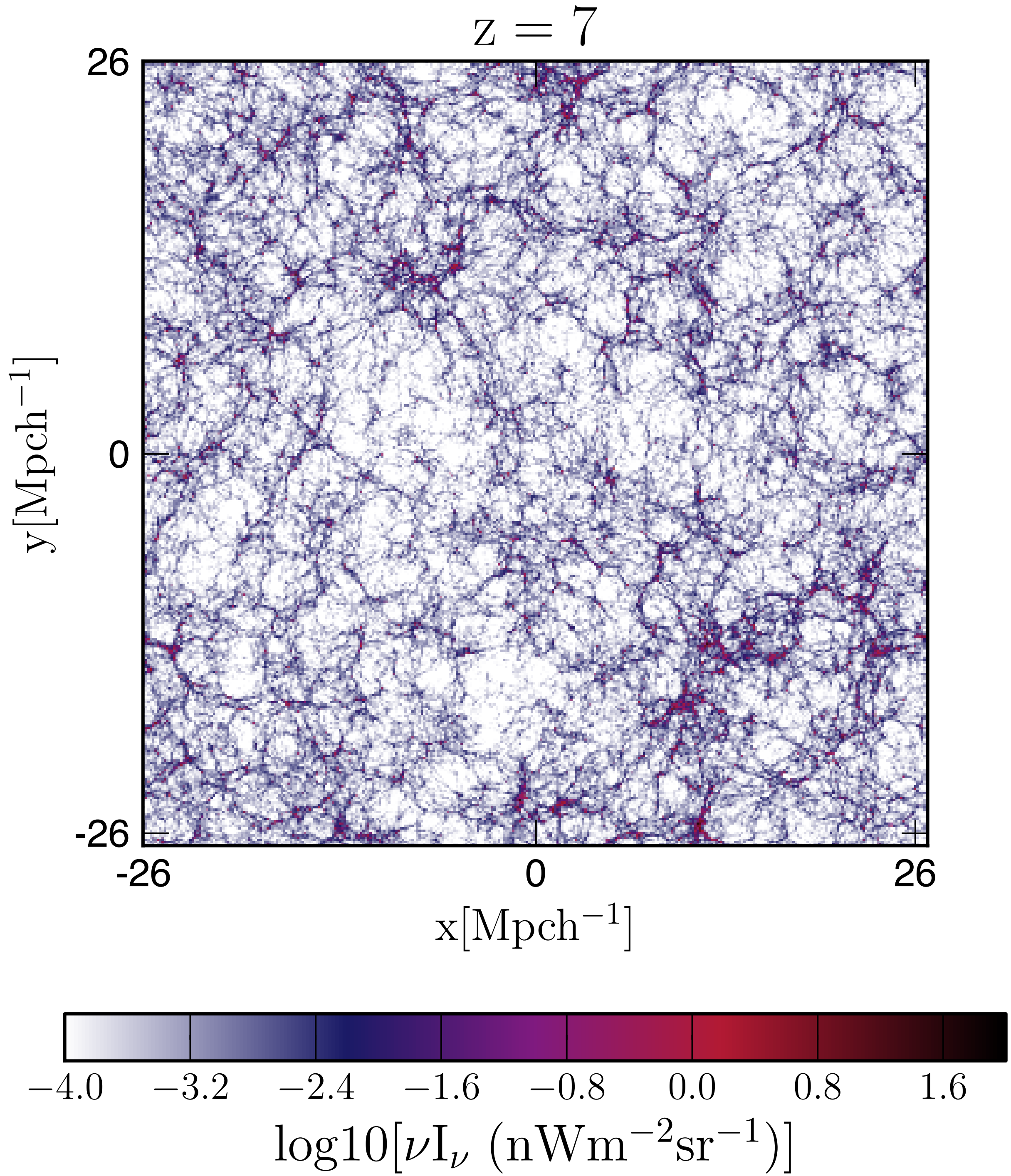
- Get halos (Sheth & Tormen)
- Minimum – 10^8 $M_\odot$
- Relate to SFR using previous model



- Relate emission for UV, X-ray and Lyn photons to SFR
  - Assume POP II type stars
- Integrate temperature:
  - X-ray heating (IGM), see Santos et al. 2008/2010
  - Photoionization heating (HII bubbles)
  - Adiabatic cooling (no other cooling sources)
- At same time generate HII bubbles in a given region using condition:
  - $N_{ion} \geq N_{HI}+N_{HeI}$ (with "excursion-set" algorithm", e.g. Furlanetto et al. 2006)
  - Use f_{esc}!
  - Take into account Recombinations (using temperature, $n_{\_HII}$)
  - Add back recombined HI to bubble

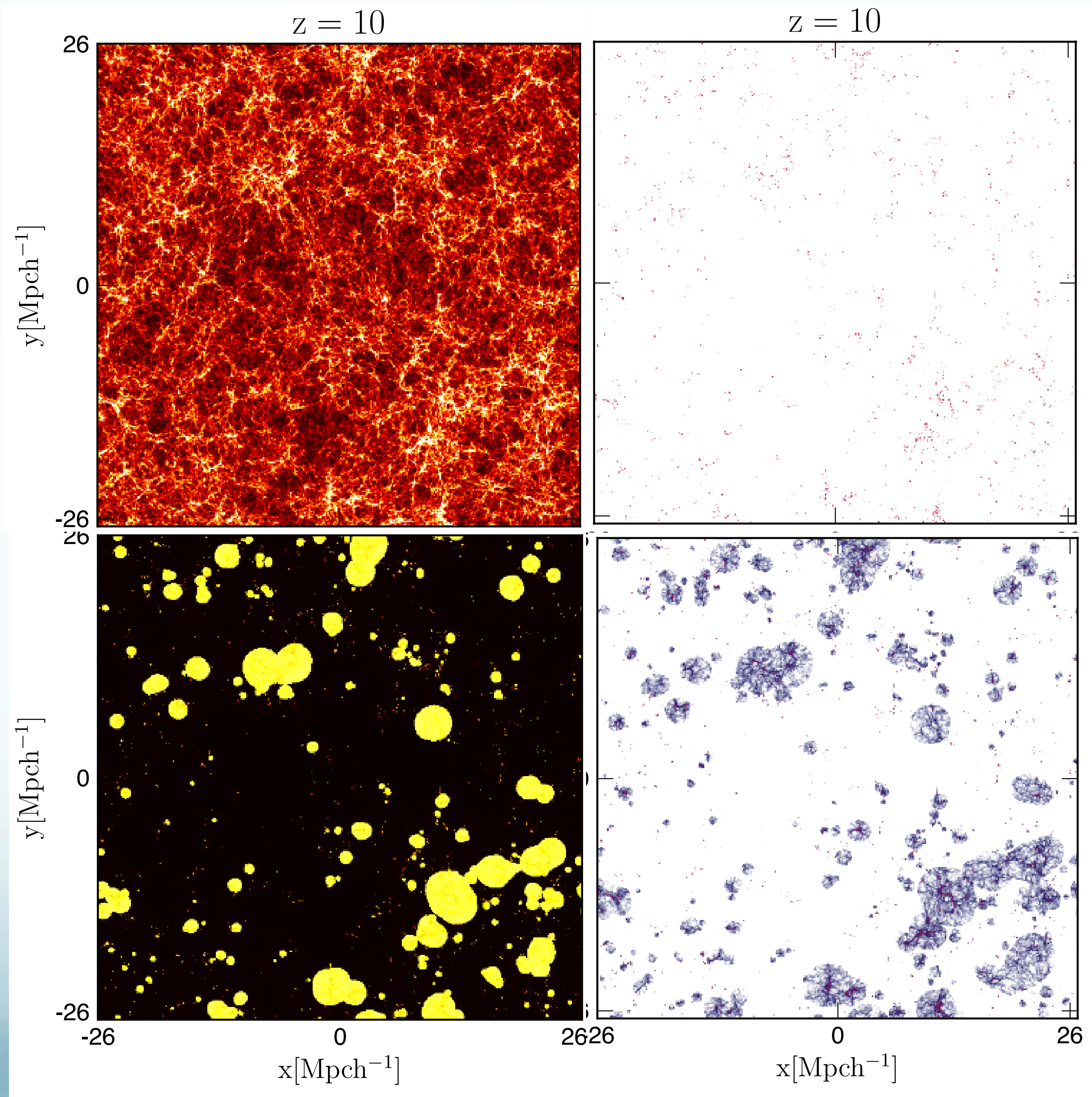


- Use same prescription to relate Lyα emission from Galaxies to SFR
- Calculate IGM Lyα luminosity density from recombinations and excitations/heating (direct excitations negligible)
- Calculate luminosity density from scattering of Lyn photons in the IGM



Lyα at z=10

- Note: Ionized bubbles contribute to IGM because they are not 100% ionized – main contribution in IGM from excitations through heating



Intensity

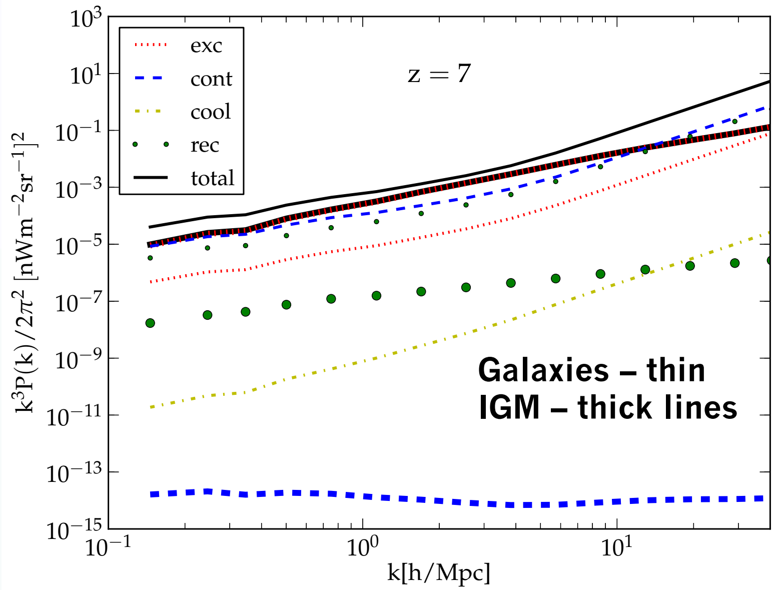
3d Power Spectrum

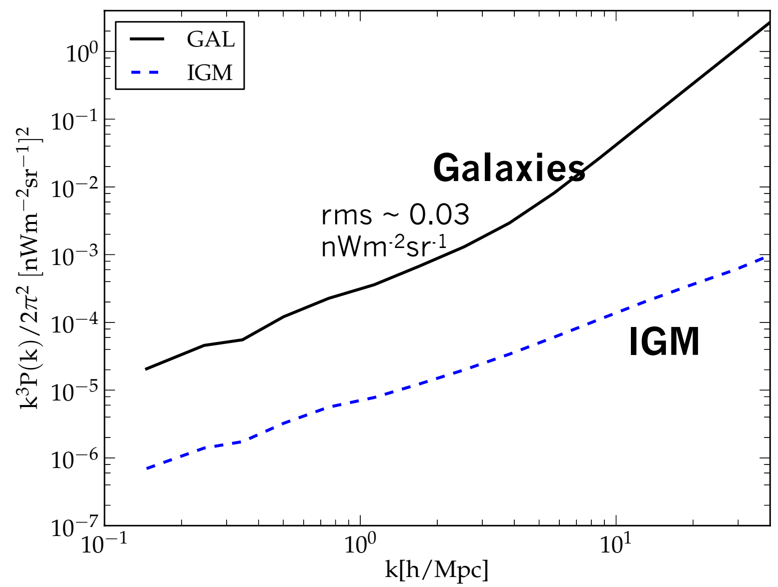
- Galaxies

Source of emission in [$nWm^{-2}sr^{-1}$]	νI_ν(z=7)	νI_ν(z=8)	νI_ν(z=10)
Recombinations	3.9×10^{-3}	2.3×10^{-3}	5.7×10^{-4}
Excitations	1.4×10^{-3}	8.0×10^{-4}	2.0×10^{-4}
Cooling	5.7×10^{-6}	3.0×10^{-6}	9.5×10^{-7}
Continuum	7.3×10^{-3}	5.7×10^{-3}	2.9×10^{-3}
Total	1.3×10^{-2}	8.8×10^{-3}	3.7×10^{-3}

- IGM

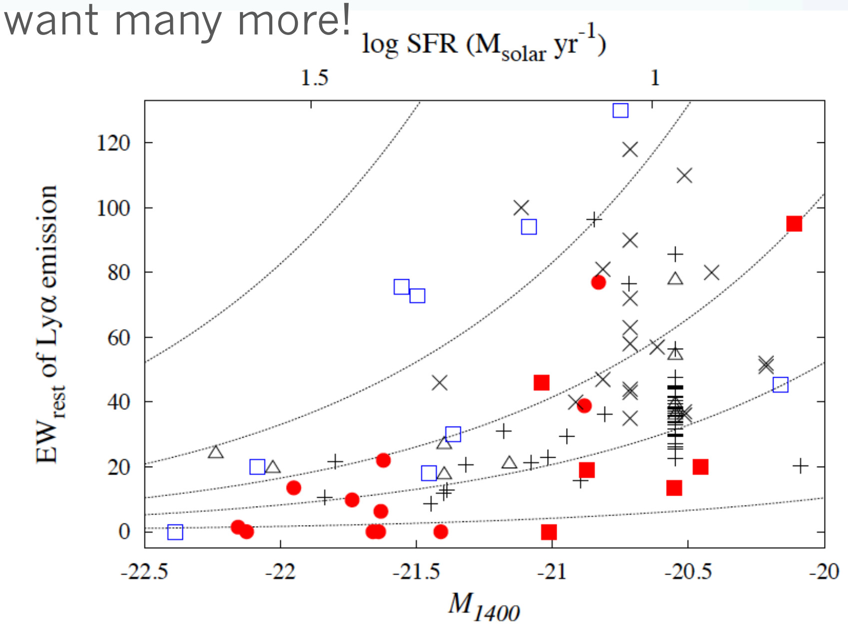
Source of emission in [$nWm^{-2}sr^{-1}$]	νI_ν(z=7)	νI_ν(z=8)	νI_ν(z=10)
Recombinations	8.0×10^{-4}	5.5×10^{-4}	2.4×10^{-4}
Excitations	5.2×10^{-3}	1.9×10^{-3}	2.3×10^{-4}
Continuum	1.2×10^{-7}	6.5×10^{-7}	2.1×10^{-6}
Total	6.0×10^{-3}	2.5×10^{-3}	4.7×10^{-4}





Experimental issues...

- Observations ~ 1 μm (z ~ 7)
- During the EoR we want to probe
  - 3d modes: k ~ 0.05 Mpc^{-1} to 10 Mpc^{-1}
  - Spatial scales: r ~ 0.5 Mpc to 125 Mpc
  - Angular scales: θ ~ 10'' to 1 deg (l ~ 150 to 6.5×10^4)
  - Band: $\delta\lambda$ ~ 2A to 450A (dz ~ 0.0016 to 0.37 - careful with cosmological evolution...)
  - Note: 450A for "one" redshift observation – want many more!
  - But Lyα line width will "wash out" fluctuations along line of sight, so maybe no point to go below **$\delta\lambda$ ~ 30A?** (**k < 0.7 Mpc^{-1} along line of sight**)

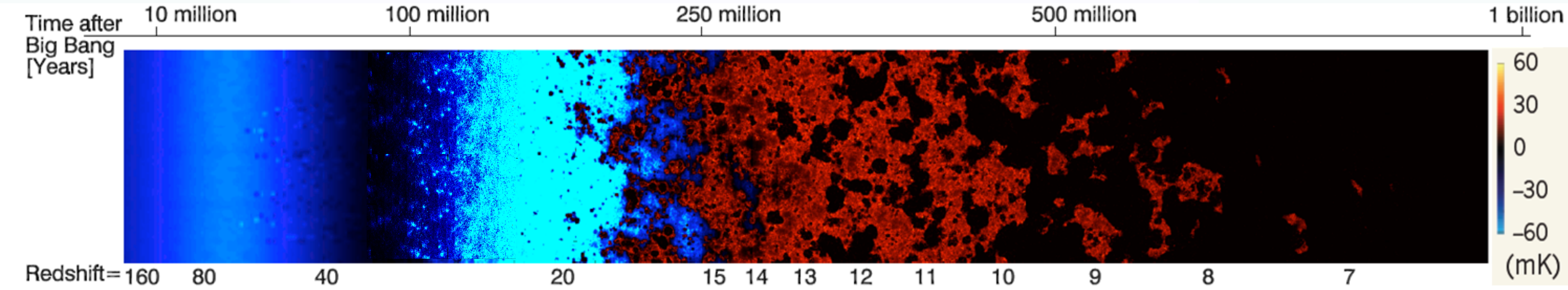


Ly\alpha widths
(Ando et al. 2006)

Experimental issues...

- Noise dominated by photon count from sky glow (earth observations) or Zodiacal light (space observations)
- Foregrounds: continuum emission and other lines (H_α?) from low-z galaxies
- Need many continuous slices/bands to fit-out the smooth foregrounds
- Also correlate with other low-z surveys to check contamination

Don’t forget other lines!

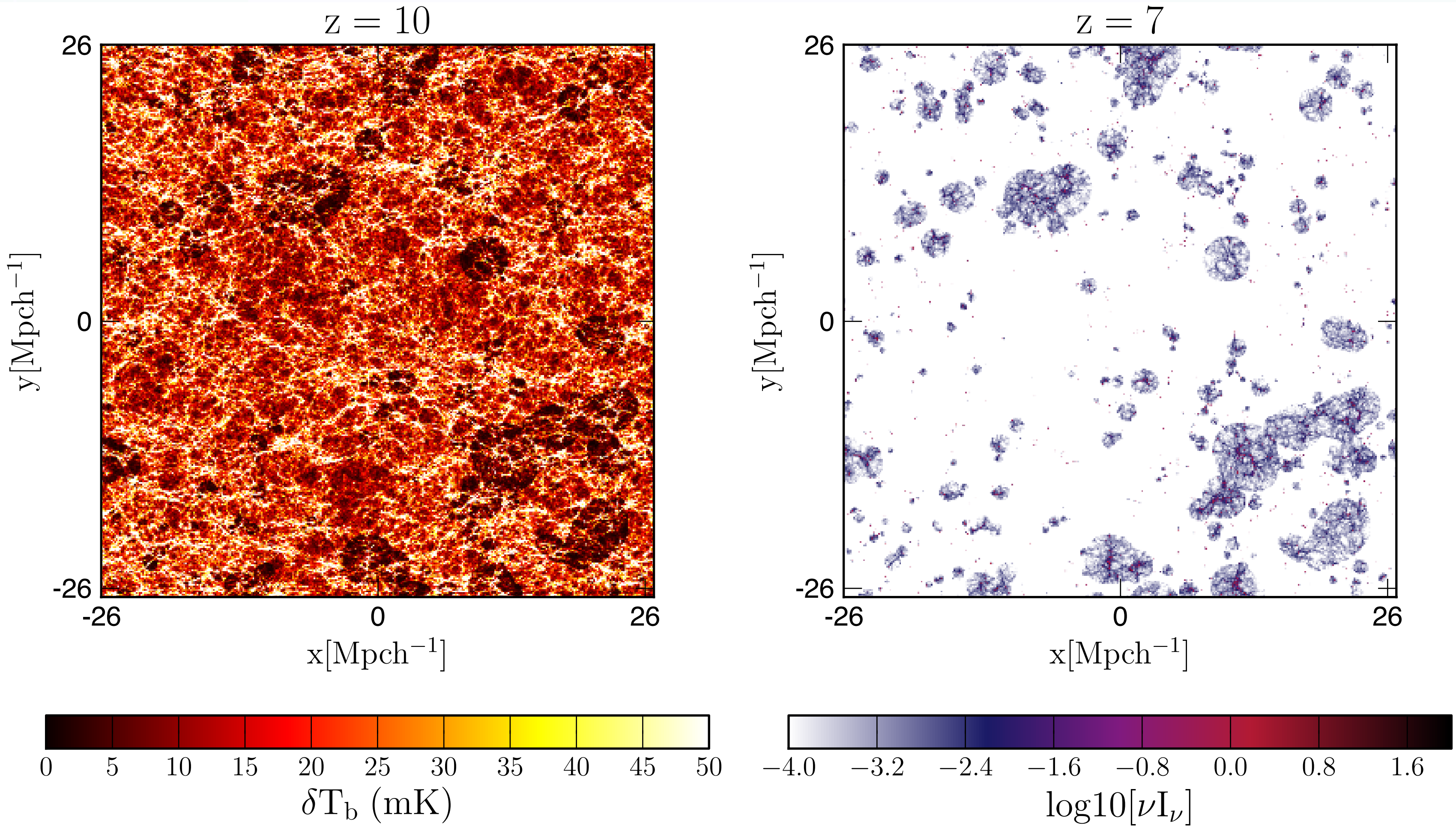


See Santos et al. 2008/2010 (simfast21.org)

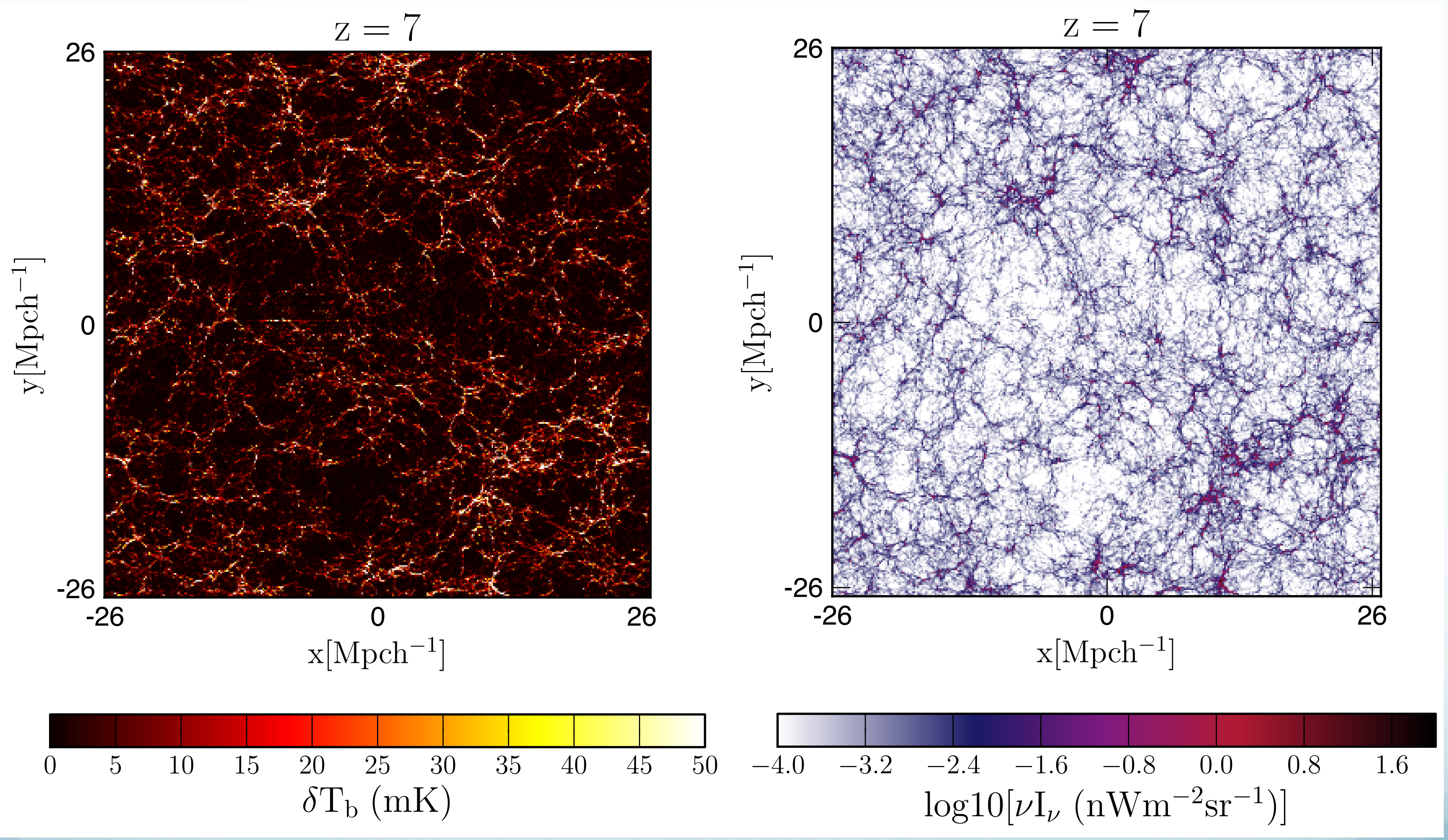
- 21cm intensity evolution with redshift
  - Sensitive to:
    - IGM Gas density
    - IGM temperature
    - ionization fraction
    - Star formation rate
    - Lyman- α flux

See also:
- CO (Gong et al. 2011)
- CII (Gong et al. 2011)

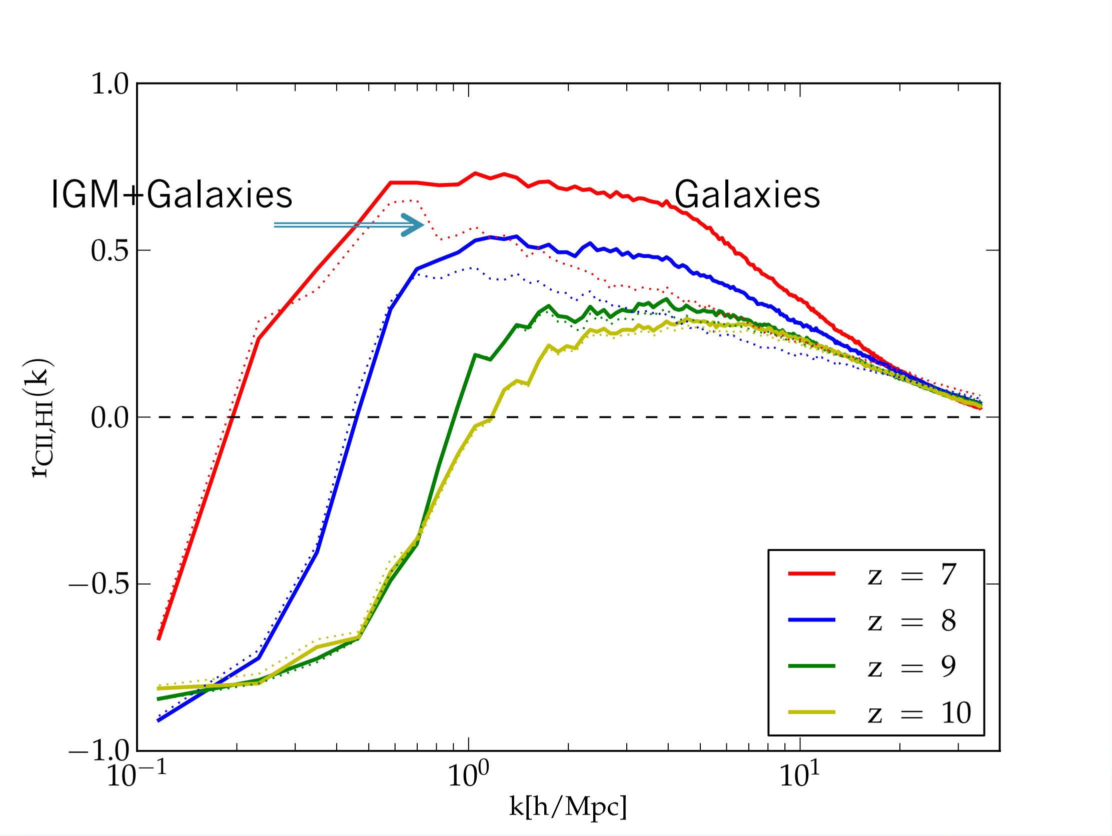
21cm/Lyα maps at z=10



21cm/Lyα maps at z=7



21cm/Lyα cross-correlation



- Cross-correlation coefficient (dashed – total, solid – galaxies only)
- Transition from negative to positive related to typical bubble size (increases from z=10 to z=7)

Conclusions

- We considered emission from both Galaxies and IGM
- Signal from Galaxies dominate over IGM with 1.3×10^{-2} $nWm^{-2}sr^{-1}$ at z=7 and 3.7×10^{-3} $nWm^{-2}sr^{-1}$ at z=10
- 3d power spectrum – rms ~ 0.03 $nWm^{-2}sr^{-1}$
- Cross-correlation with 21 cm signal can help with foregrounds and provide information about the ionization process
- Lyα intensity mapping can provide a tomographic picture of the EoR but… probably need to go to space