X-ray heating during the Cosmic Dawn

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The Cosmic Dawn

- **the Cosmic Dawn:** the heating of the IGM by the first sources before reionization is significantly underway

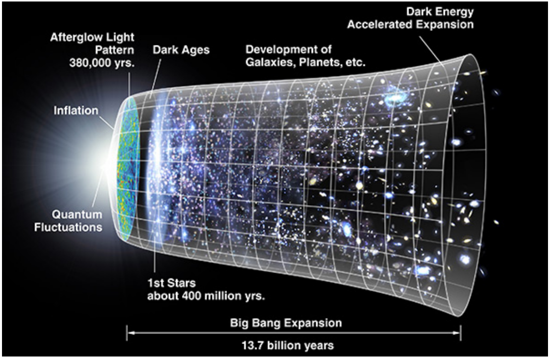


Figure 1 : Image from NASA/WMAP Science Team

The 21-cm signal and SKA

- 21-cm photons redshift from the EoR ($z \approx 25 - 10$) redshift to **50 - 130 MHz**.
- **SKA1-Low: 50 - 350 MHz**
- Unlike previous telescopes SKA-Low will be capable of **detecting the Cosmic Dawn**

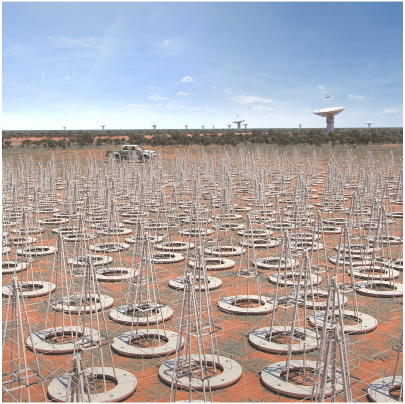


Image from SKA: http://www.skatelescope.org/australia/

The Differential Brightness Temperature

- The observable quantity is the **differential brightness temperature**:

$$\delta T_b = \frac{T_{\mathrm{S}} - T_{\mathrm{CMB}}}{T_{\mathrm{S}}} \frac{(1 - e^{-\tau})}{1 + z}$$

- T_{S} **coupled** to the temperature of the CMB:

$$T_{\mathrm{S}} = \frac{T_{\mathrm{CMB}} + y_{\alpha} T_{\mathrm{c}} + y_{\mathrm{c}} T_{\mathrm{K}}}{1 + y_{\alpha} + y_{\mathrm{c}}}$$

- If we assume that Ly-α saturation has been reached: $\mathbf{T_S = T_K}$

- However if a uniform Ly-α background has not been built up: $\mathbf{T_S = (T_{CMB} + y_{\alpha} T_K)/(1 + y_{\alpha})}$

Radiative Feedback

Stellar sources:

- emit photons with **short** mean free paths

  ↓

- photons only **heat** and **ionize** gas **locally**

  ↓

- **DO NOT** impact the cold neutral IGM

X-ray sources:

- emit photons with **long** mean free paths

  ↓

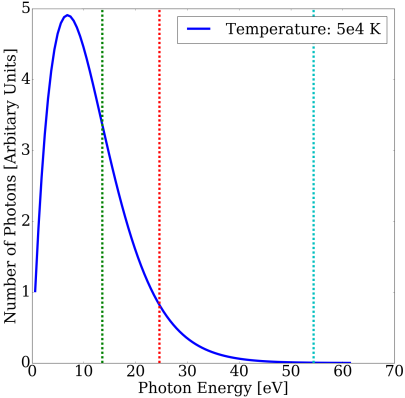
- photons **penetrate** and **heat**/ionise the neutral IGM

  ↓

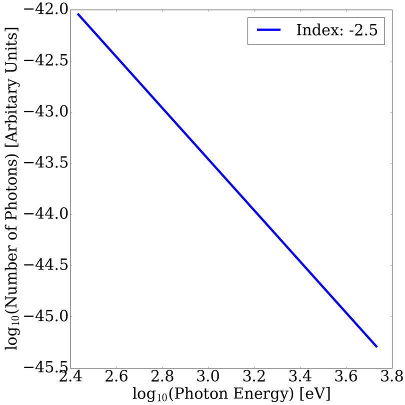
- **DO** impact the cold neutral IGM, particularly temperature

Stellar Sources

- form in **dark matter halos** with luminosity **proportional** to mass
- halos greater than the **Jeans mass** for 10^4K gas are un-suppressible
- spectra are **black body** with temperature corresponding to O & B stellar spectra
- Sources live for **11.5 Myrs** (Iliev et al 2006)



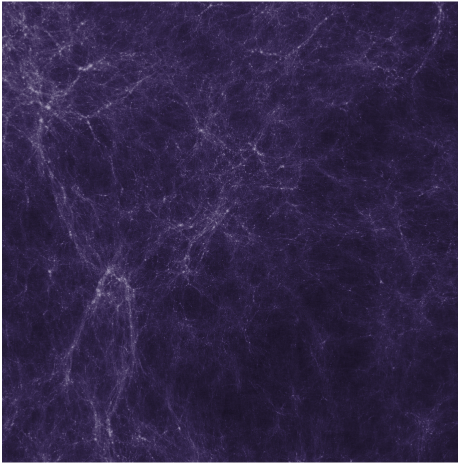
X-ray Sources(1): HMXBs



- modelled as sources with a **power law spectrum** with an index of **-1.5**
- assumed to **trace** the stellar population
- luminosity **proportional** to the mass of the halo with a different efficiency

N-body simulation: CubeP^{3}M

- **boxsize 244Mpc/h**: large enough to capture reionization patchiness (Iliev et al 2013)
- **64 billion particles**: reliable halo identification to $\mathbf{10^9\ M_\odot}$
- smaller halos added using a **subgrid model** (Ahn et al 2015)
- From **PRACE4LOFAR** (all simulations will be made available)



Radiative transfer Simulations: C^2-Ray

Sources and density gridded onto a **250^3 mesh** for RT

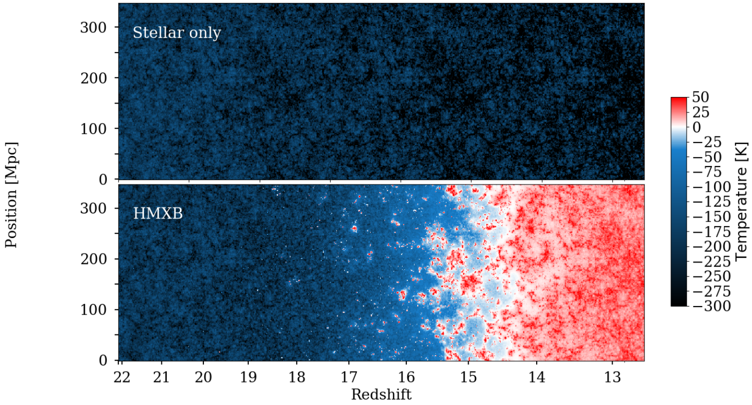
Cconservative, **C**causal, **Ray**-tracing method (Mellema et al. 2006). Updated in Friedrich et al. 2012 to include:

- **multi Frequency** ionization and heating
- the effects of the three species of **Helium**
- **secondary** Ionisations

has been tested extensively (Iliev et al 2006; Iliev et al 2009; Friedrich et al. 2012)

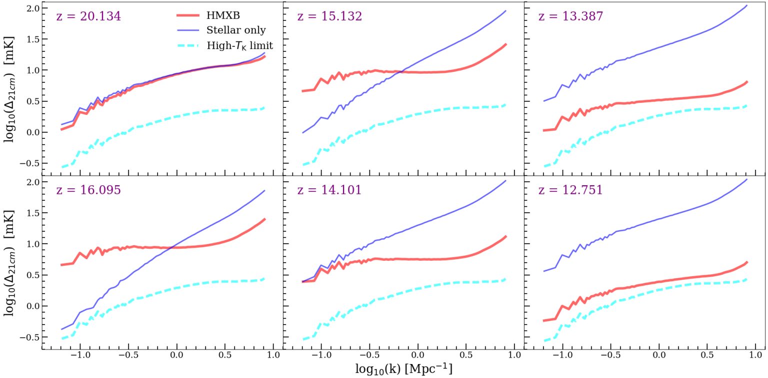
δT_b lightcone

- X-ray simulation **fully transitions** into emission, stellar does not



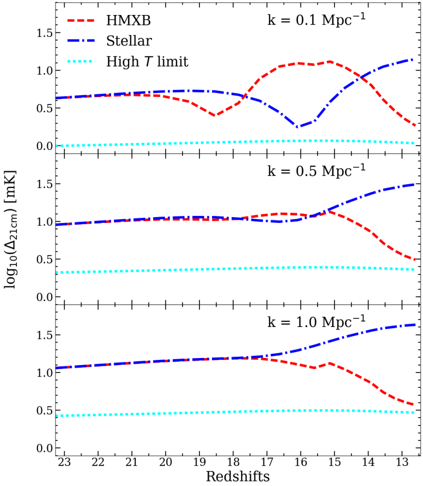
21-cm δT_b 3D Power Spectra

- initially **large** scales **boosted** by X-rays
- later all scales have **less power** in X-ray case than in stellar only case

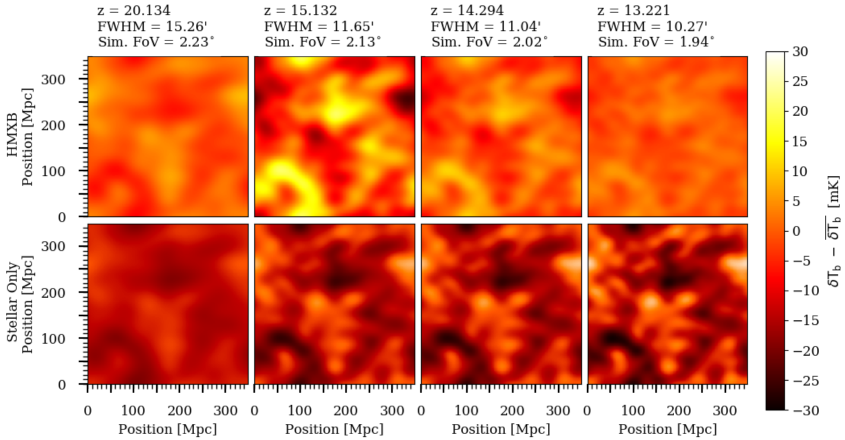


Evolution of Individual K-modes

- X-ray heating results in a **peak** at $z \approx 15.5$
- peak is most pronounced on **large scales**
- X-ray and stellar only cases are different on **all scales**
- neither case is close to the **High-T limit**, but the X-ray case starts to **approach** it

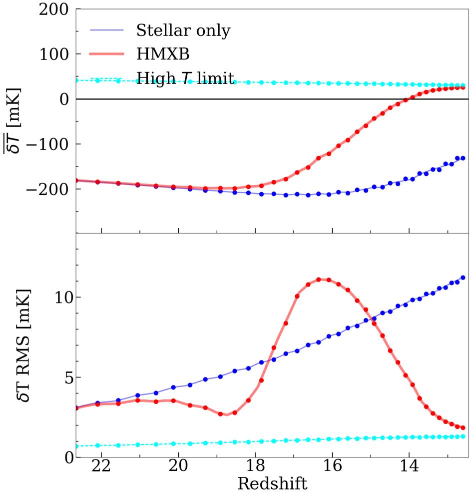


Maps at SKA resolution



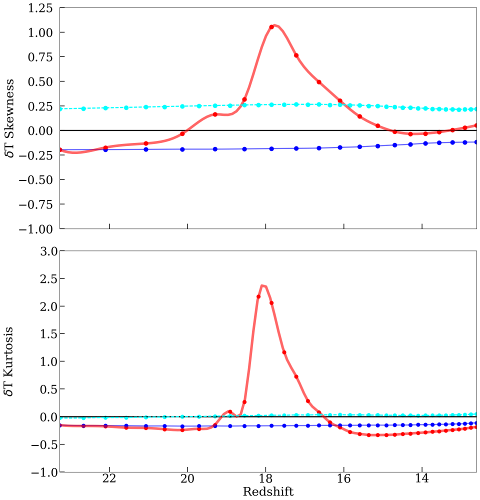
Mean δT_b and RMS

- $\delta \bar{T}_b$ **higher** in X-ray case than stellar only case
- these value **greater** than the **expected noise**: 10 mK per resolution element for 1000 hrs (Koopmans et al. 2015)



Skewness and Kurtosis

- High temperature limit & stellar only case **dominated** by density fluctuations
- X-ray heating introduces **significant non-Gaussianity**

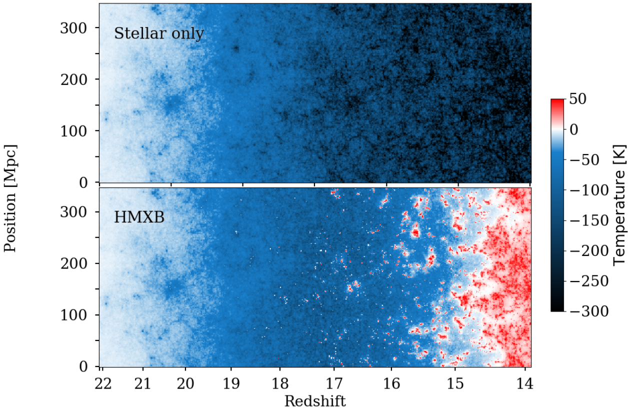


Lightcones with Inhomogeneous Ly-α background

- Ly-α flux is calculated $\mathbf{1/R^2}$ profile
- We assume Ly-α radiation does **not** impact the astrophysical processes being simulated. Therefore can be applied as a post processing step
- Calculation assumes the escape fraction of the ionizing photons to be **10 per cent** and the escape fraction of Ly-α photons to be **100 per cent**
- These results are **preliminary**

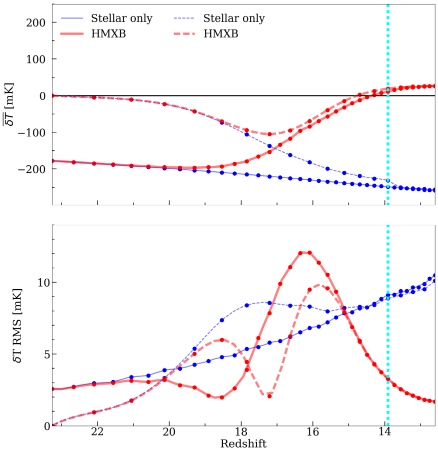
Lightcones with Inhomogeneous Ly-α background

- Ly- α flux variations also introduce fluctuations into the signal



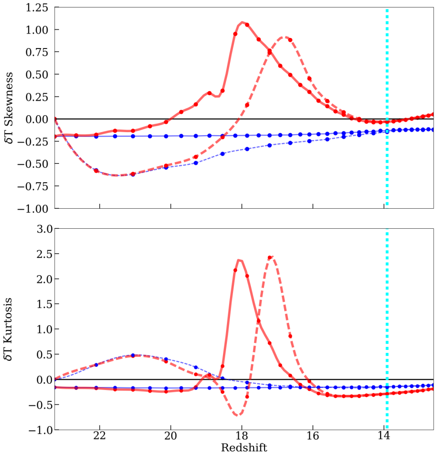
Statistics with inhomogeneous Ly-α background

- Ly-α coupling has an impact in the **early stages** of the Cosmic Dawn
- An **additional RMS peak** is introduced the the inclusion of Ly-α flux variations



Statistics with inhomogeneous Ly-α background

- An additional trough is introduced to the Skewness
- An second peak is introduced to the Kurtosis
- The heating driven peak in the Skewness and the Kurtosis occurs slightly later



Conclusions

- X-rays lead to a **clear difference** in the 21-cm produced at SKA1-low resolution
- Maps suggest **direct imaging may be possible**
- RMS fluctuations from X-ray case are **above** SKA1-Low estimated noise
- Fluctuations in the Ly-α photon density introduce **additional fluctuations**

Thanks for Listening!