Probing the First Stars with Upcoming Facilities

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NCRA • TIFR

Conference on
Shedding Light on the Dark Universe with Extremely Large Telescopes
ICTP, Trieste, Italy
4 July 2018

Plan of the talk

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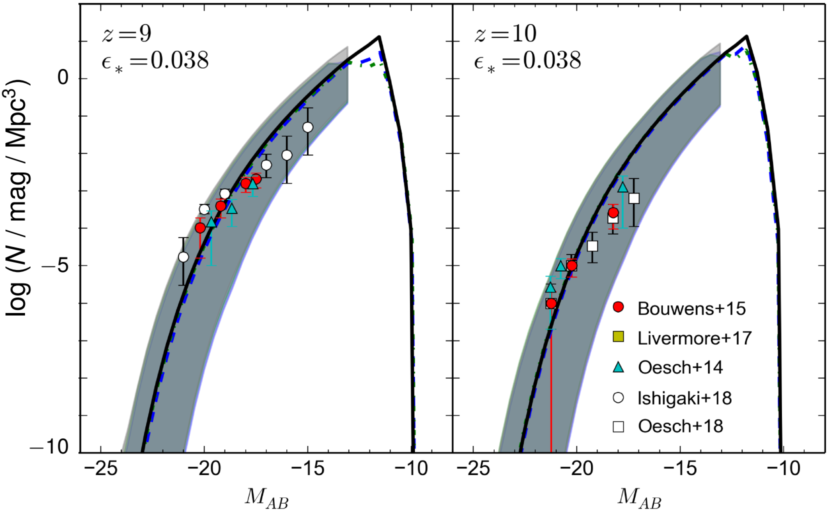
- Connection between the first stars and neutral hydrogen (HI): cosmic dawn and reionization
- Current constraints on reionization
- First detection of the cosmic dawn? (EDGES result)
- Upcoming probes of the 21 cm power spectrum and theoretical modelling

Search for the first stars



Mitra, **TRC** & Ratra (2018)

push to fainter luminosities with JWST (2021) and the ELTs

First stars and hydrogen

Big Bang

Universe expanding and cooling

Present day

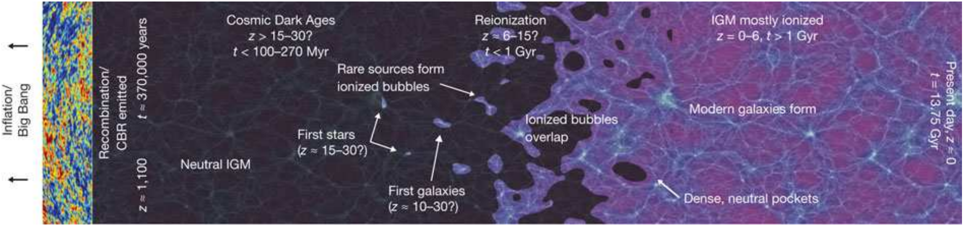
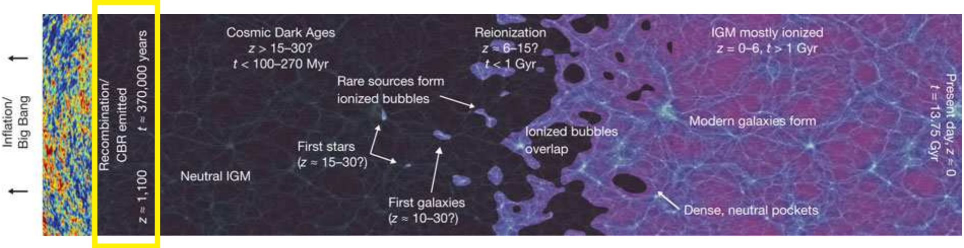


Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

First stars and hydrogen

Big Bang — Universe expanding and cooling — Present day



Last scattering epoch

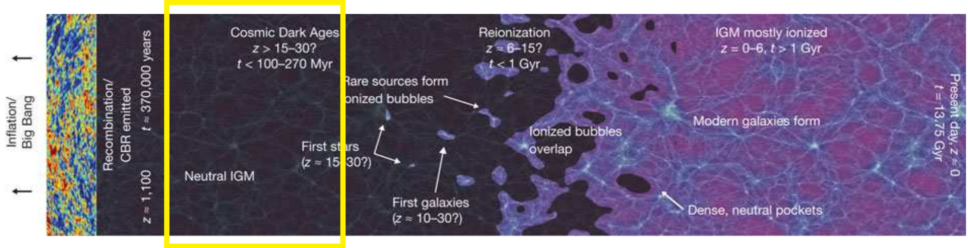
First hydrogen atoms form

Origin of the CMBR

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

First stars and hydrogen

Big Bang — Universe expanding and cooling → Present day



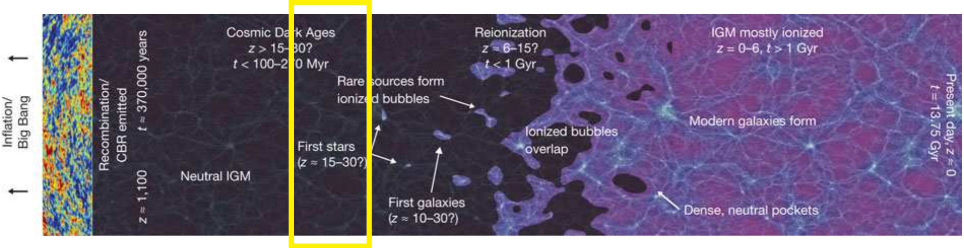
Dark ages

HI follows DM

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

First stars and hydrogen

Big Bang — Universe expanding and cooling → Present day



Cosmic dawn

First stars form

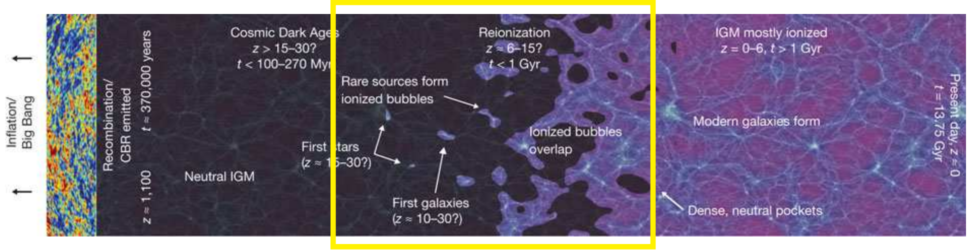
Lyα scattering

X-ray heating

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

First stars and hydrogen

Big Bang | Universe expanding and cooling | Present day



Reionization

HI $+\gamma \rightarrow$ HII

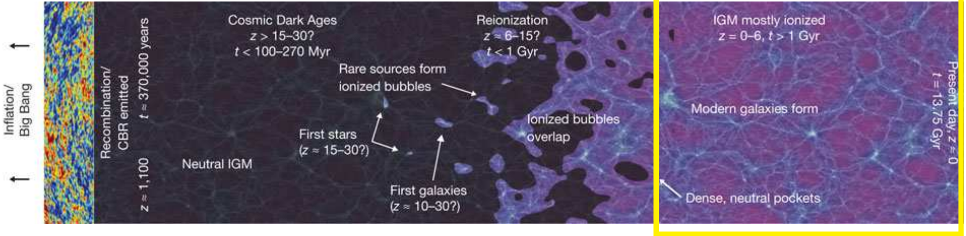
Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

First stars and hydrogen

Big Bang

Universe expanding and cooling

Present day



Post-reionization

Figure courtesy: http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html

First stars and hydrogen

Big Bang

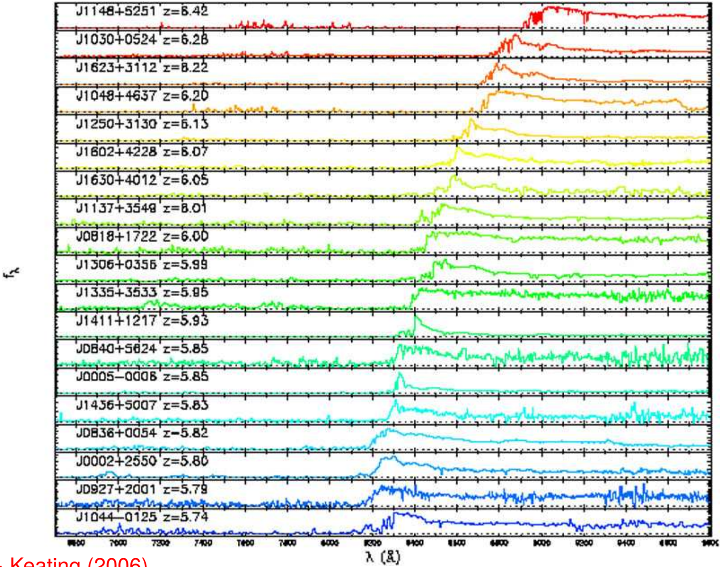
Universe expanding and cooling

Present day

“Final Frontier” of observational cosmology

Figure courtesy: `http://www.nature.com/nature/journal/v468/n7320/fig_tab/nature09527_F1.html`

Quasar absorption spectra at $z \gtrsim 6$



Fan, Carilli & Keating (2006)

$$F_{\rm obs} = F_{\rm cont}\ {\rm e}^{-\tau_{\rm GP}}, \quad \tau_{\rm GP} \sim \left(\frac{x_{\rm HI}}{10^{-5}}\right)$$

Thomson scattering $\tau_{\rm el}$ from CMBR

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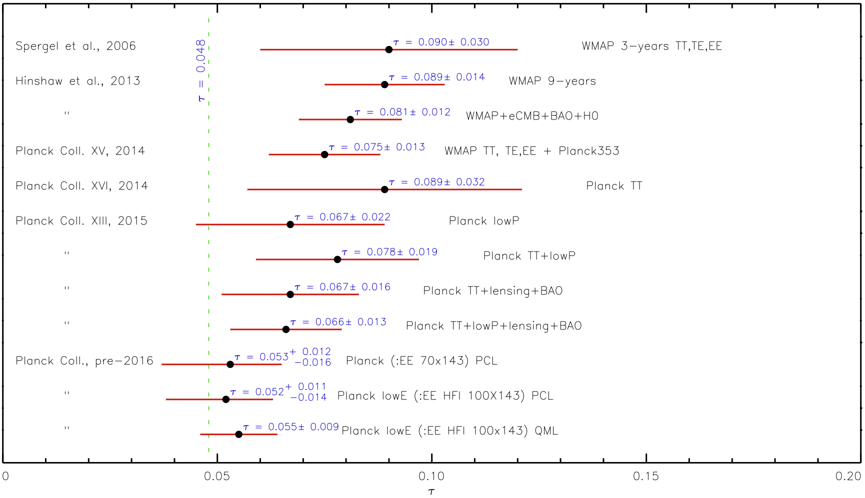
$$\tau_{\rm el} = \sigma_T c \int_0^{z[t]} {\rm d}t\, n_e\, (1+z)^3$$

Planck Collaboration (2016)



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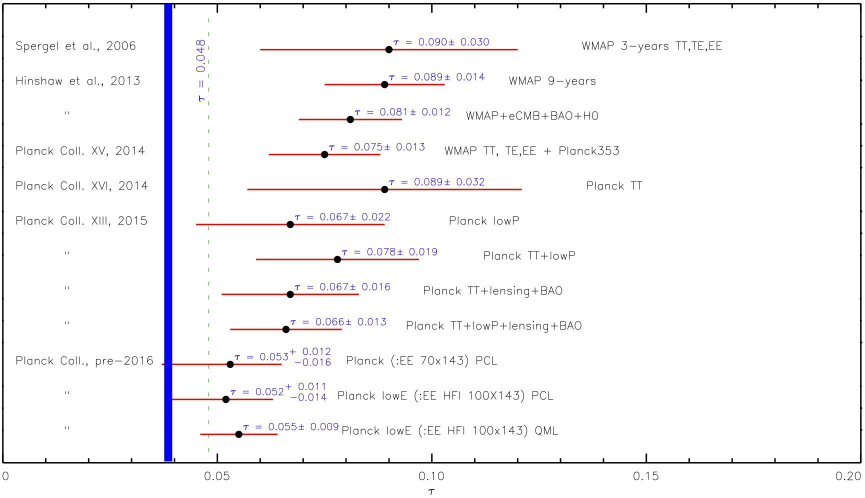


Analytical models

- Reionization mainly by galaxies
- Photon production rate:

$$\dot{n}_\gamma = \zeta \left(\frac{\Omega_b}{\Omega_m}\right) \frac{\mathrm{d}f_{\rm coll}}{\mathrm{d}t}$$

Number of ionizing photons in the IGM per baryons

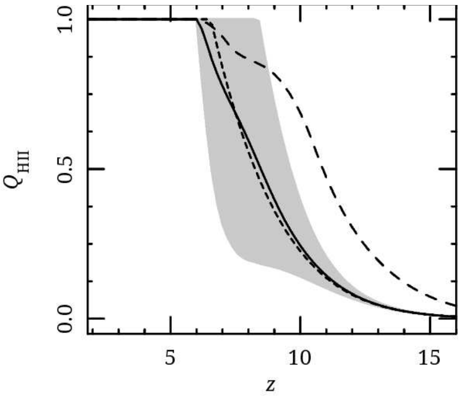
Collapse rate of dark matter haloes

$$\zeta = f_{\rm esc}\, \epsilon_* \times \text{ number of photons per baryons in stars}$$

- Study the evolution of globally-averaged ionized mass fraction.
- Supplemented by temperature and species evolution equations
- Predict observables, e.g., $\tau_{\rm el}$ (or C_ℓ), photoionization rate (or mean transmitted flux), …

TRC & Ferrara (2005, 2006)

Data constrained models

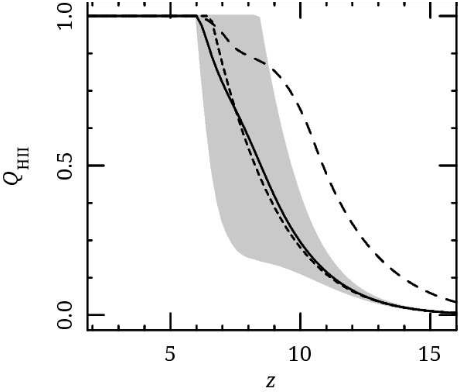


Mitra, **TRC** & Ferrara (2015)

Constraints based on

- Planck15 data on τ_{el}
- quasar absorption line measurements at $z \lesssim 6$ (either Γ_{HI} or $\langle \tau_{eff} \rangle$)
- prior on x_{HI} at $z \sim 5.5 - 6$ based on "dark pixel" fraction
  McGreer, Mesinger & D'Odorico (2015)

Data constrained models



Mitra, **TRC** & Ferrara (2015)

- reionization starts at $z \sim 12 - 15$
- 50% ionized at $z \sim 6 - 10$
- large uncertainties at $7 \lesssim z \lesssim 10$

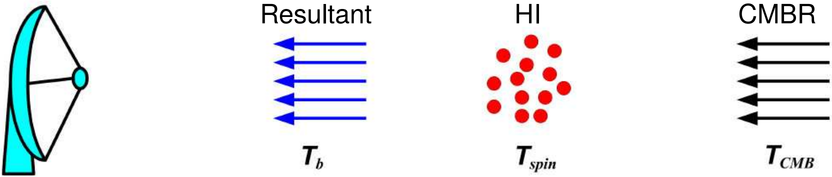
Other probes of reionization

- Galaxy luminosity function: uncertain escape fraction
- Quasar absorption spectra (damping wings/near zones): only a few quasars known till date
- IGM temperature: requires detailed modelling
- Lyman-α emitters (number density and clustering): systematics, model dependent constraints

Future: the 21 cm signal

$$\frac{n_2}{n_1} = 3\,\mathrm{e}^{-T_{\rm spin}/T_{21}}$$

Figure from Zaroubi (2013)



z

$$\nu = \frac{1420}{1+z}\ \text{MHz}$$

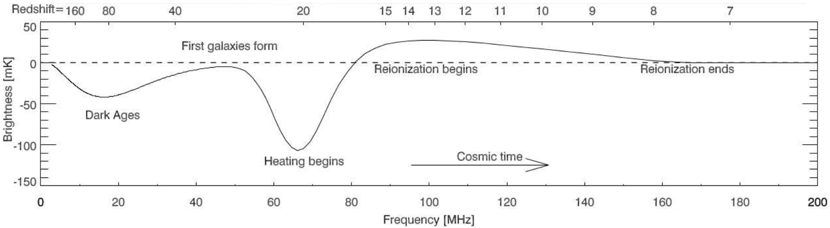
$$\nu = 1420\ \text{MHz}$$

The signal: $\delta I_\nu \propto \rho_{\rm HI}\left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right)$

Global 21 cm signature

$$\delta T_b \propto \frac{T_s - T_{\rm CMB}(z)}{T_s} \rho_{\rm HI}$$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



Pritchard & Loeb (2012)

Global 21 cm signature

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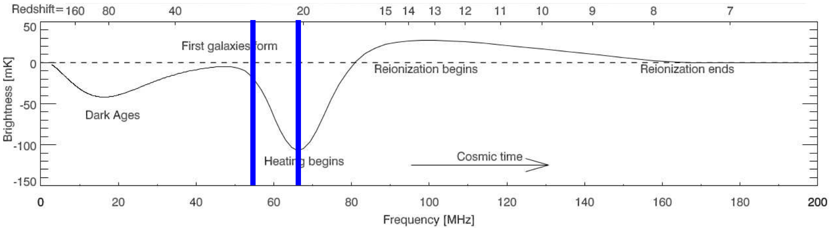


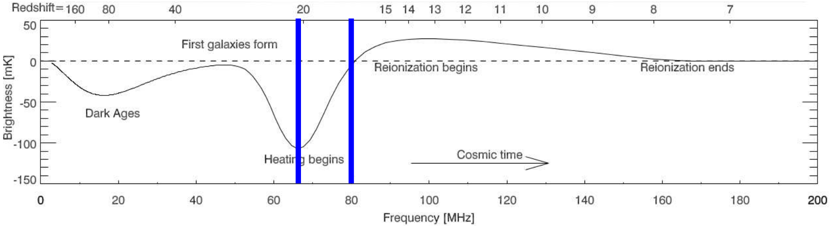
Pritchard & Loeb (2012)

$z_* \gtrsim z \gtrsim z_\alpha$: star formation starts, leading to Lyα coupling.
Then $T_S \sim T_K < T_{\rm CMB}(z)$. Absorption signal.

Global 21 cm signature

$$\delta T_b \propto \frac{T_s - T_{\rm CMB}(z)}{T_s} \rho_{\rm HI}$$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



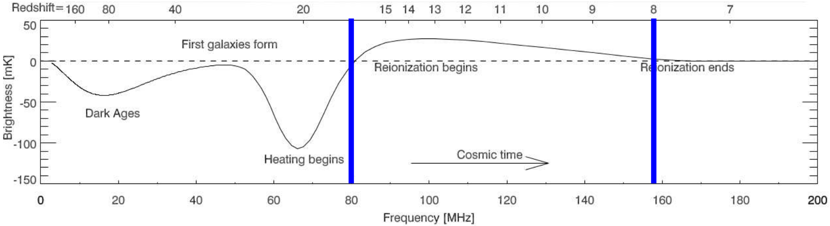
Pritchard & Loeb (2012)

$z_\alpha \gtrsim z \gtrsim z_h$: heating becomes significant, though still $T_S \sim T_K < T_{\rm CMB}(z)$. Eventually $T_K = T_{\rm CMB}(z)$ at $z = z_h$.

Global 21 cm signature

$$\delta T_b \propto \frac{T_s - T_{\rm CMB}(z)}{T_s}\rho_{\rm HI}$$

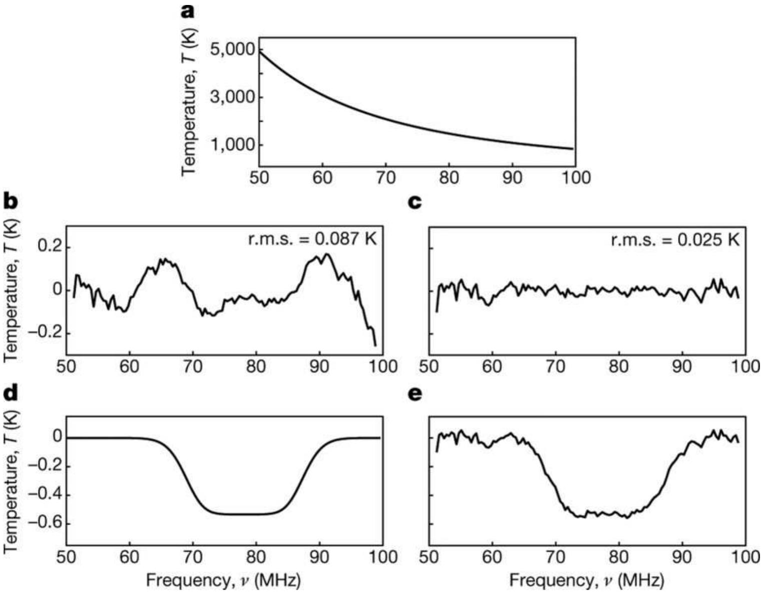
$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



Pritchard & Loeb (2012)

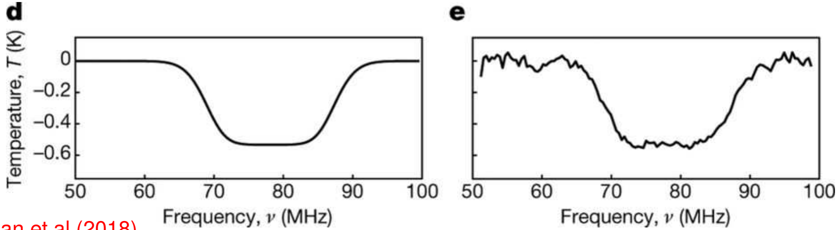
$z_h \gtrsim z \gtrsim z_r$: photoheating dominates, giving $T_S \sim T_K \sim 10^4$ K $\gg T_{\rm CMB}(z)$. Signal in emission. Also $[T_S - T_{\rm CMB}(z)]/T_S \approx 1 \implies \delta T_b \propto x_{\rm HI}$. Signal directly probes neutral hydrogen density field.

Recent detection of the global 21 cm signal

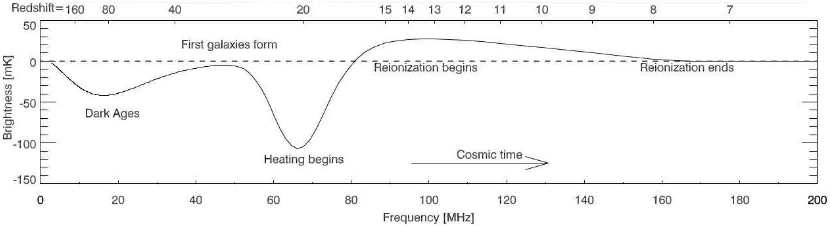


Bowman et al (2018)

Consistent with standard calculations?



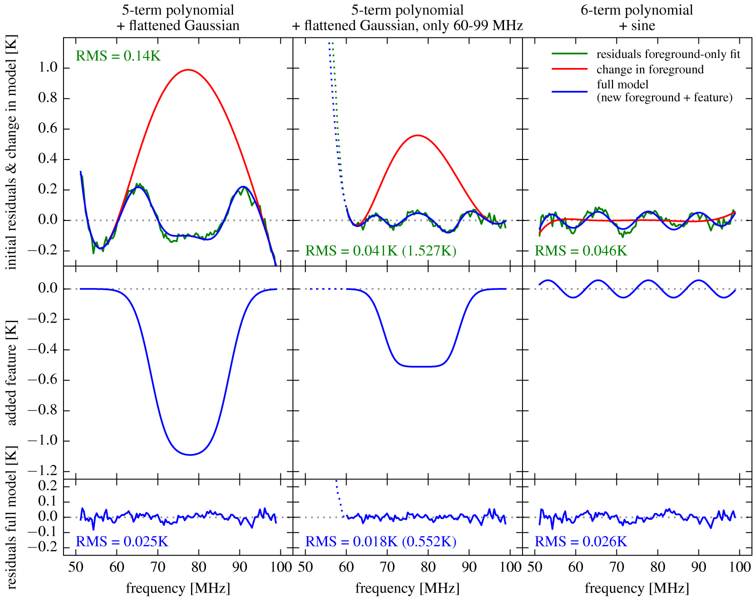
Bowman et al (2018)



Pritchard & Loeb (2012)

$$\delta T_b = 0.023\ \mathrm{K}\ x_{\mathrm{HI}} \left(\frac{T_s - T_{\mathrm{CMB}}(z)}{T_s} \right)$$

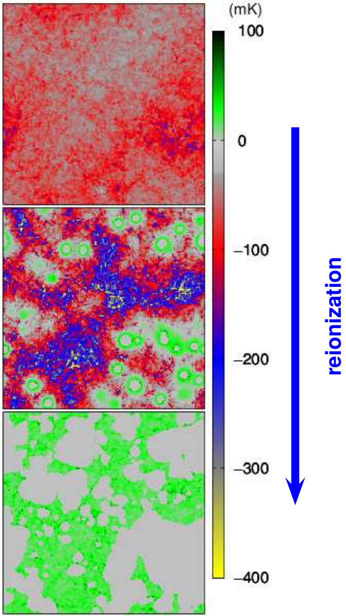
Systematics?



Hills et al (2018)

21 cm fluctuations

Ghara, **TRC** & Datta (2014)



$z \sim 15$ ($\nu \sim 90$ MHz), $x_{\rm HII} \sim 10^{-3}$

$z \sim 12$ ($\nu \sim 110$ MHz), $x_{\rm HII} \sim 0.02$

$z \sim 8$ ($\nu \sim 160$ MHz), $x_{\rm HII} \sim 0.56$

Low frequency instruments

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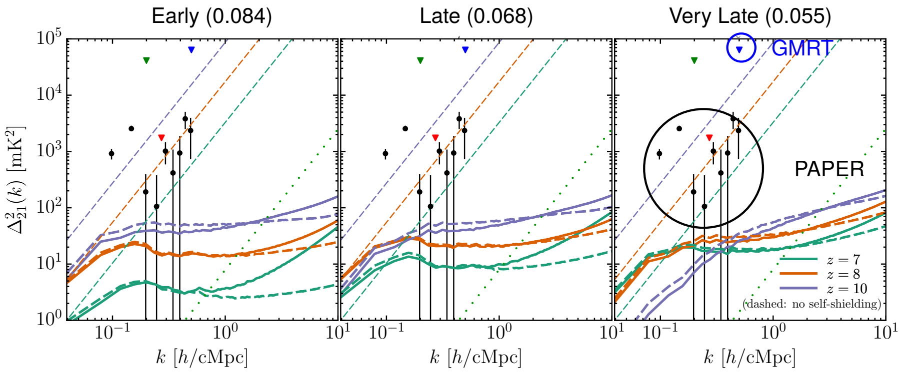
21 cm power spectra



$z = 7$

$z = 8$

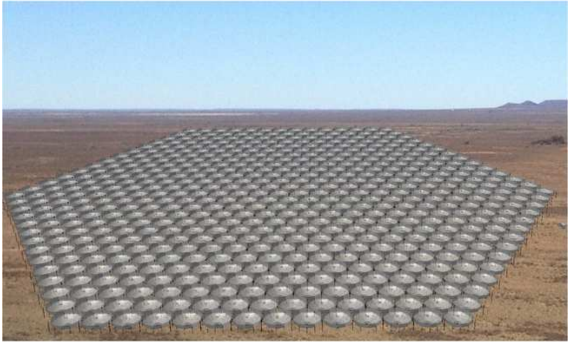
$z = 10$

Kulkarni, **TRC**, Puchwein & Haehnelt (2016)

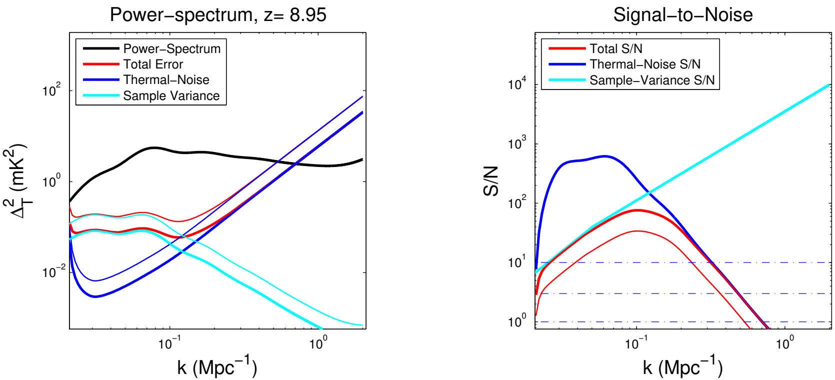
Future telescopes

SKA-LOW

HERA



SKA1 sensitivity



Koopmans et al (2015)

Errors on $P(k) \lesssim 10\%$ (1000 hours of integration)

Semi-numerical calculations

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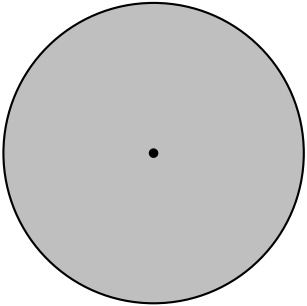
Excursion set based method (accounts for bubble overlap)



Self-ionization condition:
$n_\gamma(R) \geq n_H(R) \implies \zeta f_{\rm coll}(R) \geq 1$

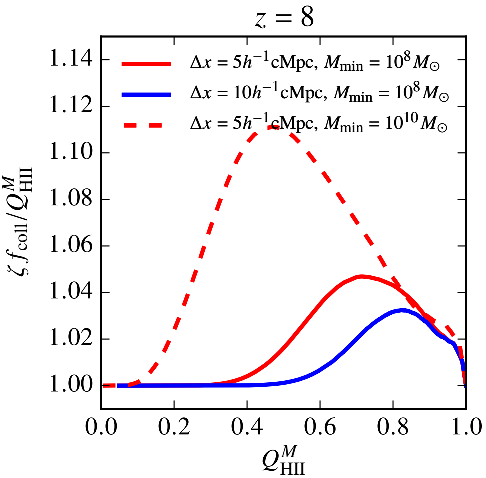
Very similar to the halo formation problem

Furlanetto, Zaldarriaga & Hernquist (2004)

Photon conservation issues

Paranjape, **TRC** & Padmanabhan (2016)

Amount of photon non-conservation

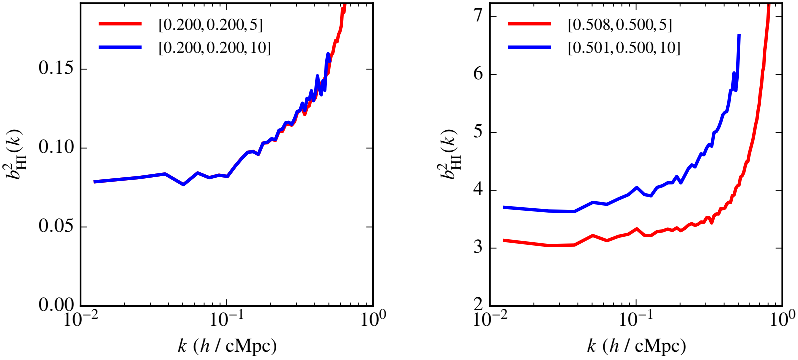


TRC & Paranjape (2018)

$$\text{ratio} = \frac{n_\gamma}{n_{\rm HII}\,(1 + \bar{N}_{\rm rec})} \neq 1\text{, depends on the resolution!}$$

Resolution-dependent power spectrum

$z = 8,\ M_{\min} = 10^8 M_\odot\ [\zeta f_{\rm coll}, Q^M_{\rm HII}, \Delta x (h^{-1}{\rm cMpc})]$



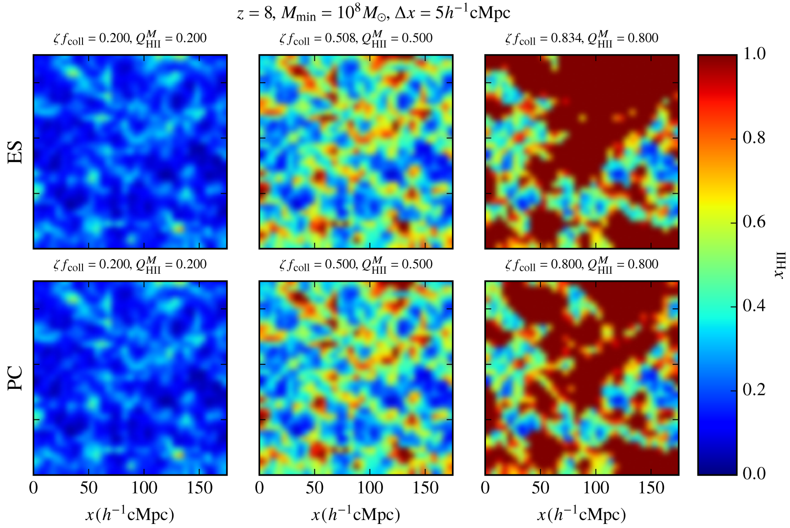
TRC & Paranjape (2018)

$$b^2_{\rm HI}(k) = \frac{P_{\rm HI}(k)}{P_{\rm DM}(k)}$$

photon non-conservation leads to non-converging power spectrum!

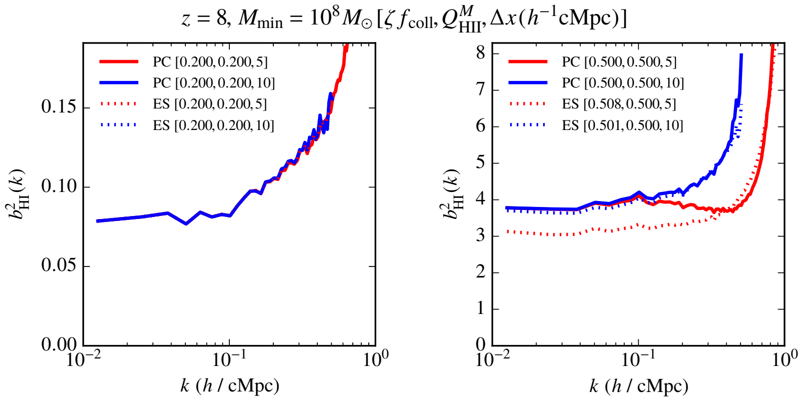
Photon-conserving model

- Find ionized bubbles around each “source”.
- Distribute excess photons in bubble overlaps to nearby regions.



TRC & Paranjape (2018)

Power spectrum converges



TRC & Paranjape (2018)

$$b^2_{\rm HI}(k) = \frac{P_{\rm HI}(k)}{P_{\rm DM}(k)}$$

Summary

- First stars can be probed through their effect on HI.
- 21 cm experiments would open a new window to study the first stars, looking forward to the next generation of radio telescopes, e.g., SKA1!
- Need more accurate (and efficient) theoretical models to interpret the SKA1 data.

Summary

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- First stars can be probed through their effect on HI.
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Thank you