Reionization - III

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Cosmology - The Next Decade
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Topics to be covered

Concentrate on the physics of underlying structure of the IGM

- Observational constraints on reionization
- Theoretical models of reionization
- Future probes of reionization

References:

- Textbook: *Galaxy Formation and Evolution* by Houjun Mo, Frank van den Bosch & Simon White
- Review: *In the beginning: the first sources of light and the reionization of the universe* by Rennan Barkanaa & Abraham Loeb, Phys. Rept., 349, 125 (2001)
- Review: *Analytical Models of the Intergalactic Medium and Reionization* by T. Roy Choudhury, Current Science, 97, 841 (2009)

How to constrain reionization at $z \sim 7$?

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

An “ideal” experiment

- CMBR probes the “integrated” reionization history. Require a line transition so that observations can be done in different redshifts.

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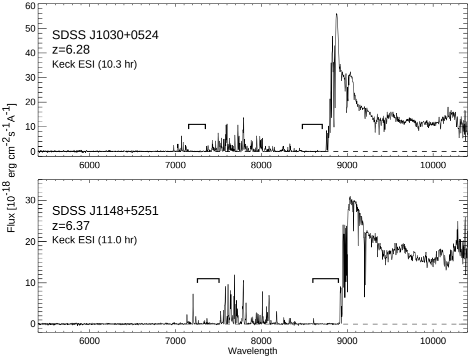
- Lyα is a line transition, but too “strong” $\Longrightarrow$ lines become saturated for $x_{\rm HI} \gtrsim 10^{-4}$ (i.e., $z > 6$).



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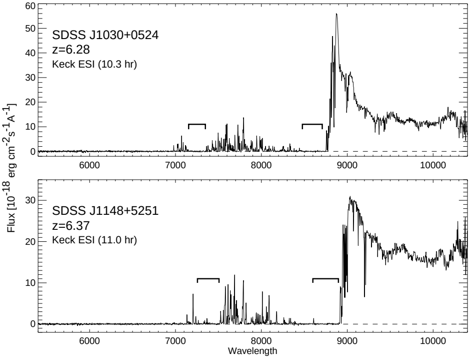
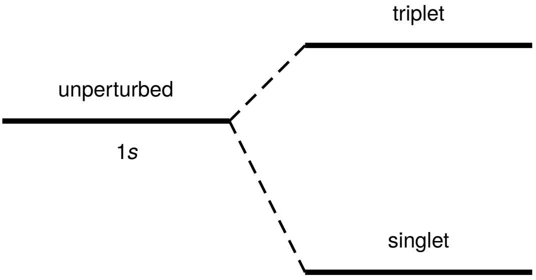


- Need a line transition which is “weak”

Future: 21 cm line

- Hydrogen 1s ground state split by the interaction between the electron spin and the nuclear spin.



$$|\uparrow\uparrow\rangle$$
$$\frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right]$$
$$|\downarrow\downarrow\rangle$$

$\nu = 1420$ MHz, $\lambda = 21$ cm

$$\frac{1}{\sqrt{2}}\left[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right]$$

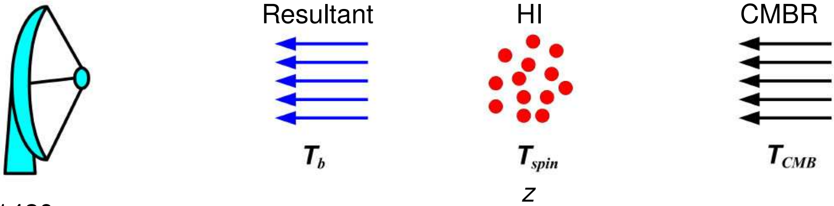
Line transition $\Longrightarrow$ a transition originating at z will be observed at a frequency $\nu_{\rm obs} = 1420/(1+z)$ MHz.

- It is a magnetic dipole transition, with transition probability $A_{21} = 2.85 \times 10^{-15}$ s^{-1} $\Longrightarrow$ an atom in the upper level is expected to make a downward transition once in 10^7 yr.
  For Lyα transition, the corresponding coefficient is $A_{21} \approx 6 \times 10^8$ s^{-1}.

How to observe the signal?

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

Figure from Zaroubi (2013)



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

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

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

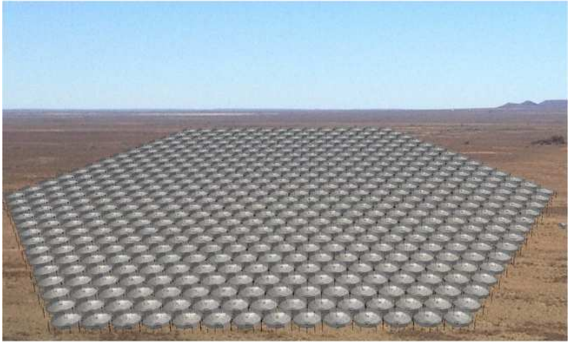
$$\propto \rho_{\mathrm{HI}} \text{ if } T_{\mathrm{spin}} \sim T_{\mathrm{gas}} \gg T_{\mathrm{CMB}}$$

Low frequency instruments

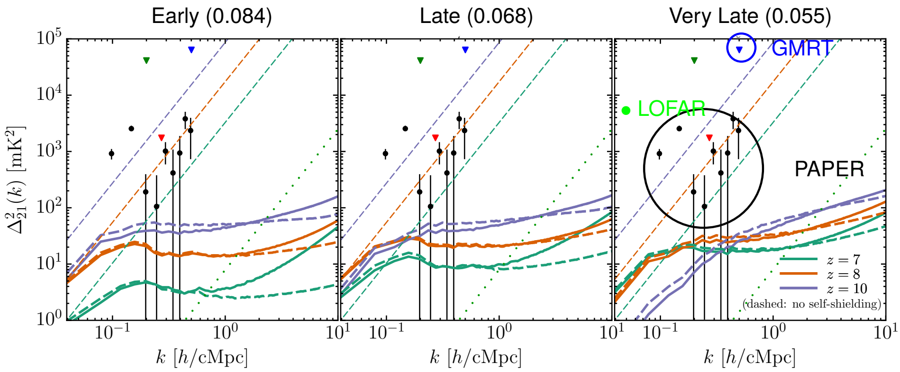
Future telescopes

SKA-LOW

HERA



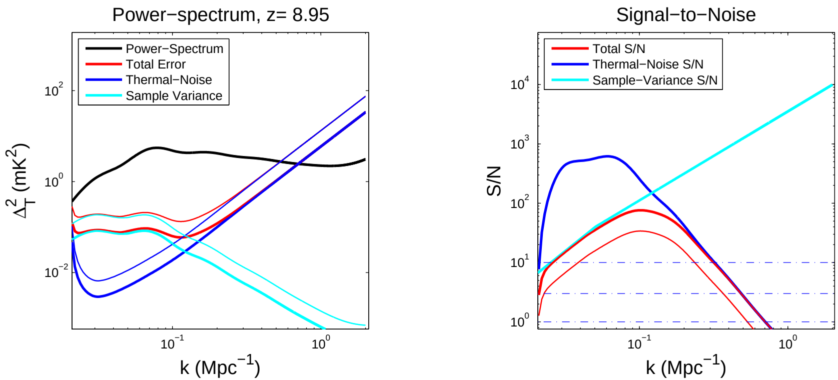
21 cm power spectra



$z = 7$
$z = 8$
$z = 10$

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

SKA1 sensitivity



Koopmans et al (2015)

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

Modelling the radiative transfer

- Radiative transfer is the most challenging part of theoretical reionization models
- Assume that locations of the sources (galaxies in dark matter haloes) and their luminosities are known. For simplicity, assume

$$n_\gamma(M_{\rm halo}) \propto N_{\rm ion}\, M_{\rm halo} \equiv \zeta\, M_{\rm halo}$$

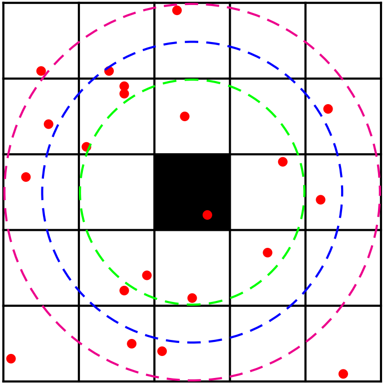
- 7-dimensional partial differential equation to determine the intensity $I_\nu(t, \mathbf{x}, \hat{\mathbf{n}})$ $\implies$ either inaccurate or inefficient

$$\frac{\partial I_\nu}{\partial t} + \frac{c}{a(t)} \hat{\mathbf{n}} \cdot \nabla_{\mathbf{x}} I_\nu - H(t)\nu \frac{\partial I_\nu}{\partial \nu} + 3H(t) I_\nu = -c\kappa_\nu I_\nu + \frac{c}{4\pi}\epsilon_\nu$$

- Numerical simulations employ some approximate schemes (e.g., spherical symmetry, ray-tracing, Monte-Carlo sampling, ...)
- Alternatives: analytical or semi-numerical

Excursion set based semi-numerical models

naturally accounts for bubble overlap Furlanetto, Zaldarriaga & Hernquist (2004)



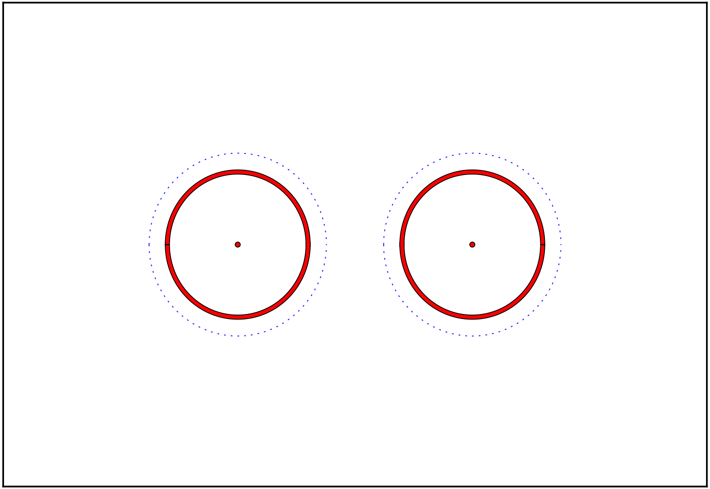
Assume that the density fields and haloes have been obtained from simulations

Smooth the fields in uniform grids

- Loop over all grid cells i:
  - Loop over all possible R:
    - is $n_\gamma(R) \geq n_H(R)$? which is equivalent to $\zeta f_{\rm coll}(R) \geq 1$?
    - if yes, then assign ionized fraction $x_i = 1$
  - If the condition is not satisfied for any R then assign $x_i = n_{\gamma,i}/n_{H,i} = \zeta\, f_{{\rm coll},i}$

A simple toy model

Two sources of equal strengths in a uniform medium, based on Zahn et al (2007)



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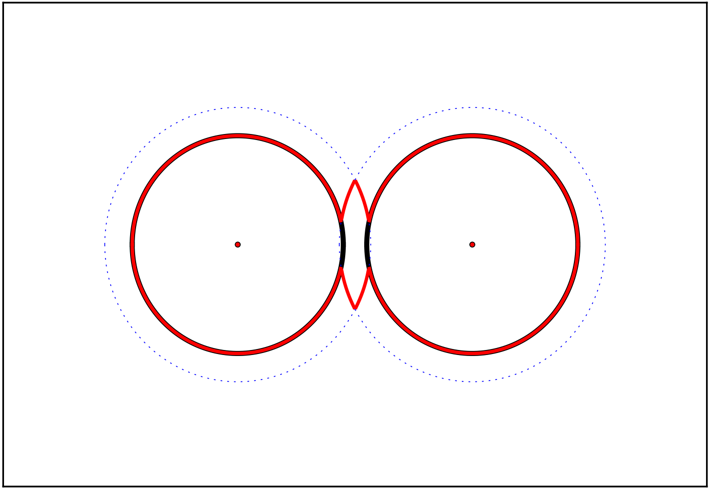

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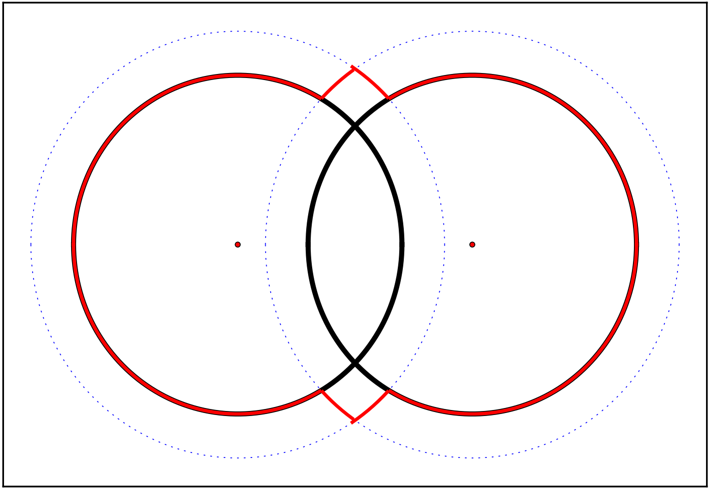
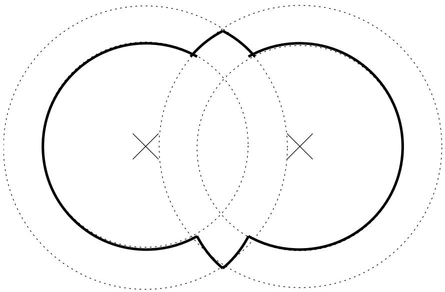
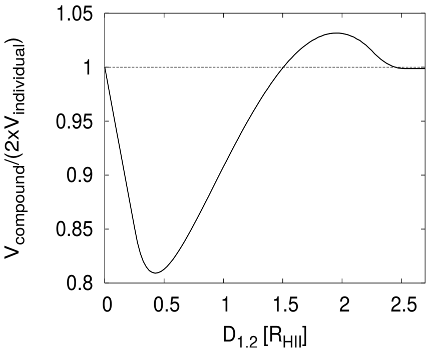


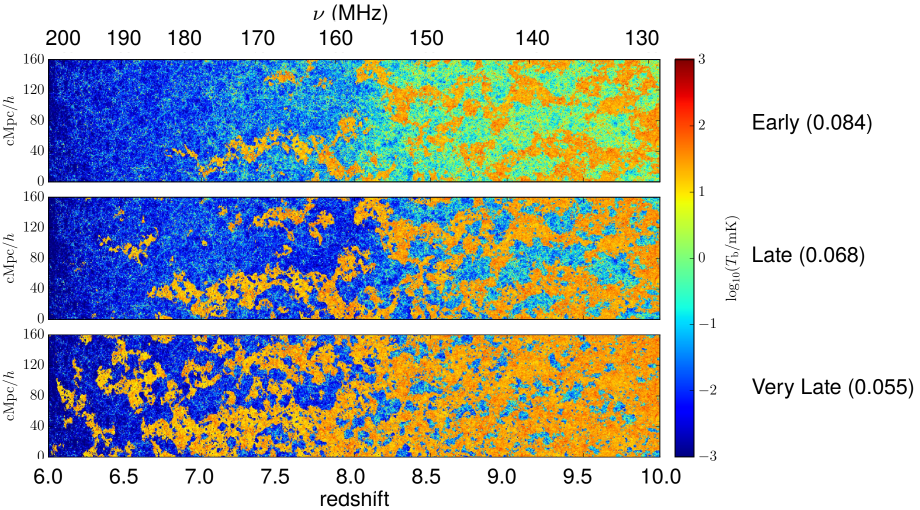
Photon non-conservation





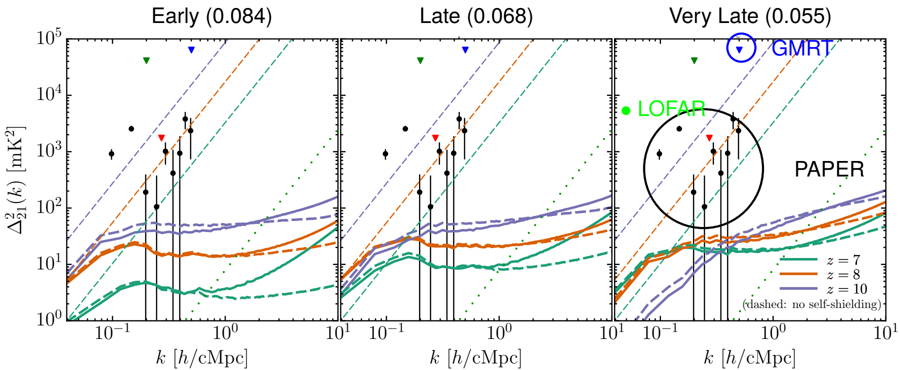
Zahn et al (2007)

21 cm maps



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

21 cm power spectra



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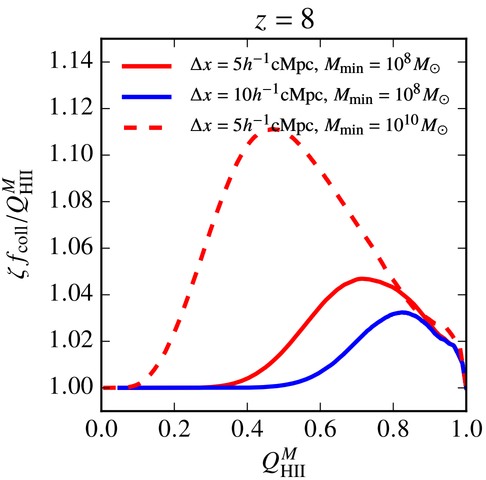
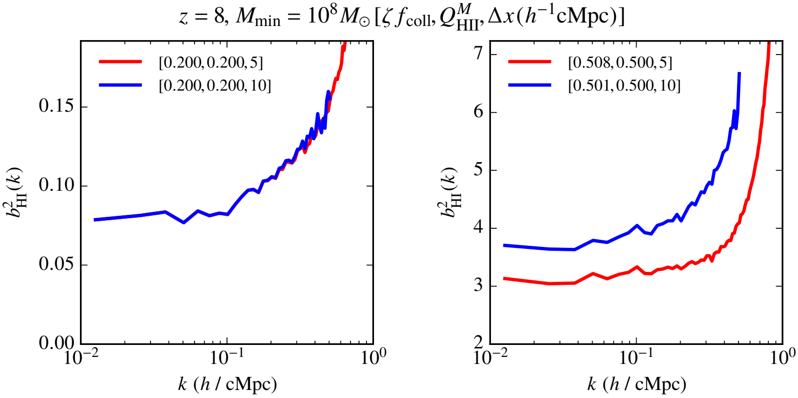
Amount of photon non-conservation



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

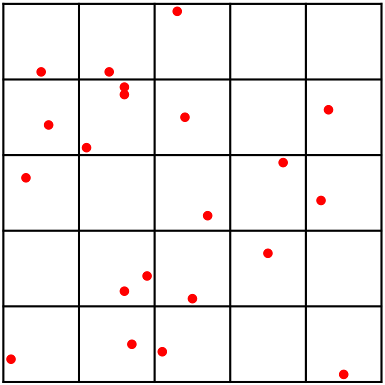


TRC & Paranjape (2018)

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

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

Photon-conserving model



Photon-conserving model

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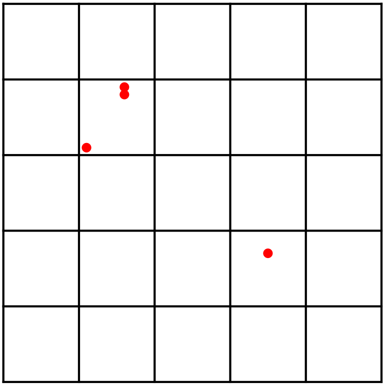

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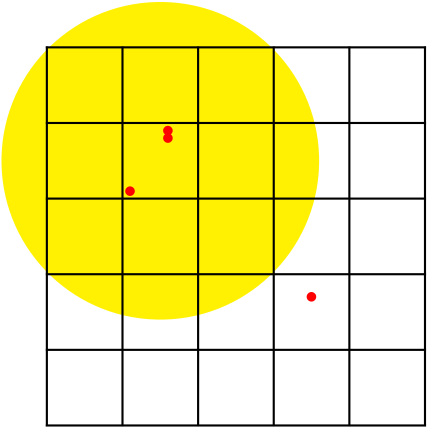

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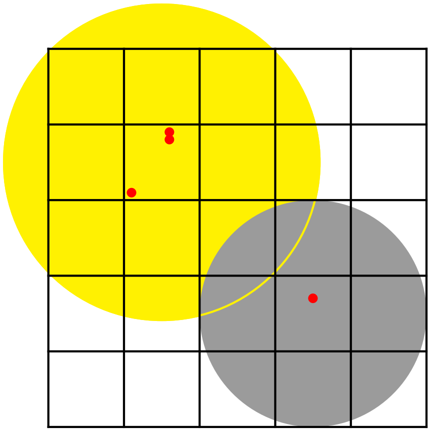

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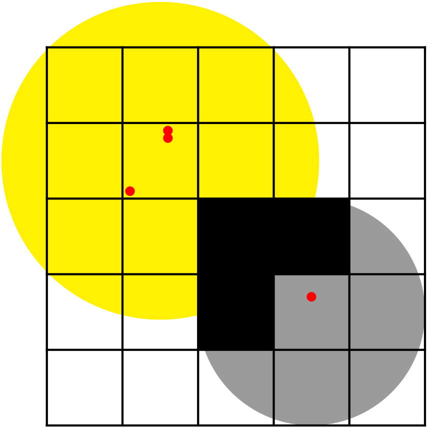

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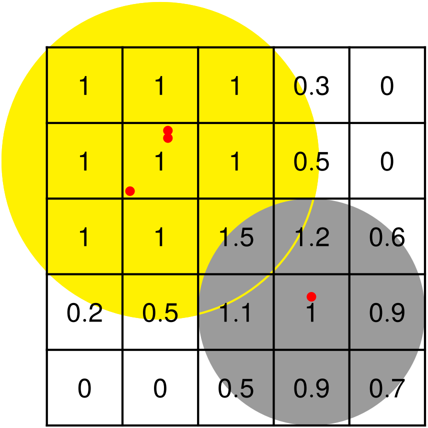

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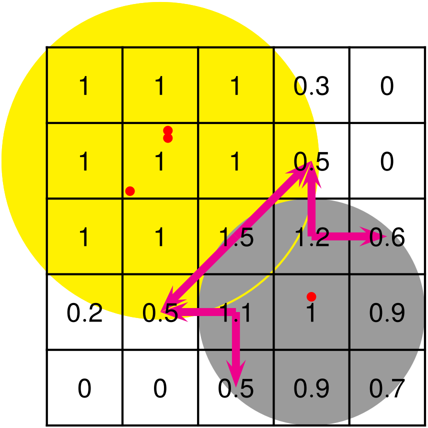

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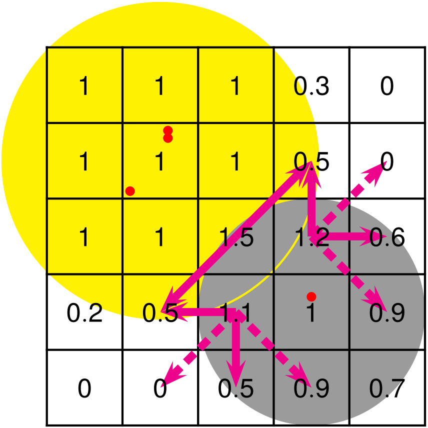
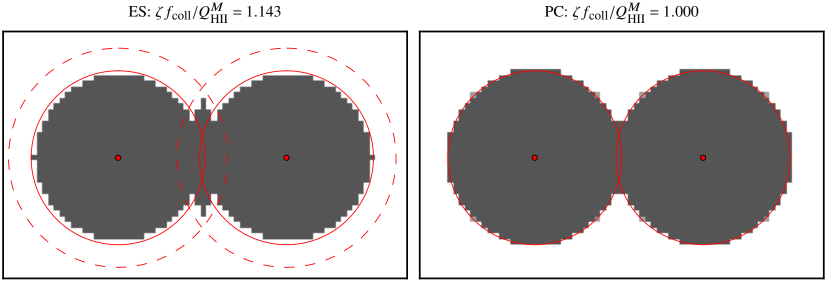
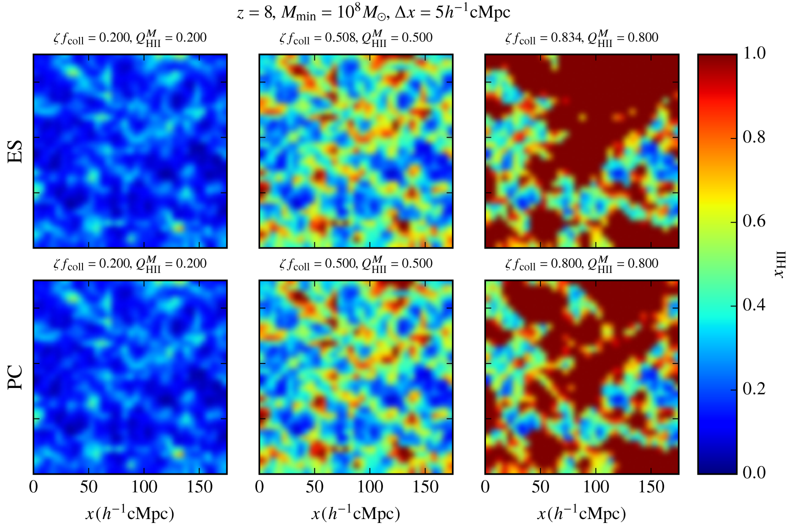


Results for the toy model

Two sources of equal strengths in a uniform medium

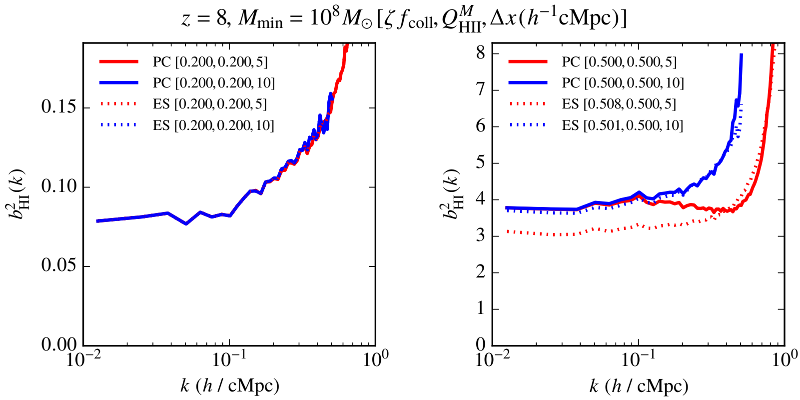


Photon-conserving maps



TRC & Paranjape (2018)

Power spectrum converges



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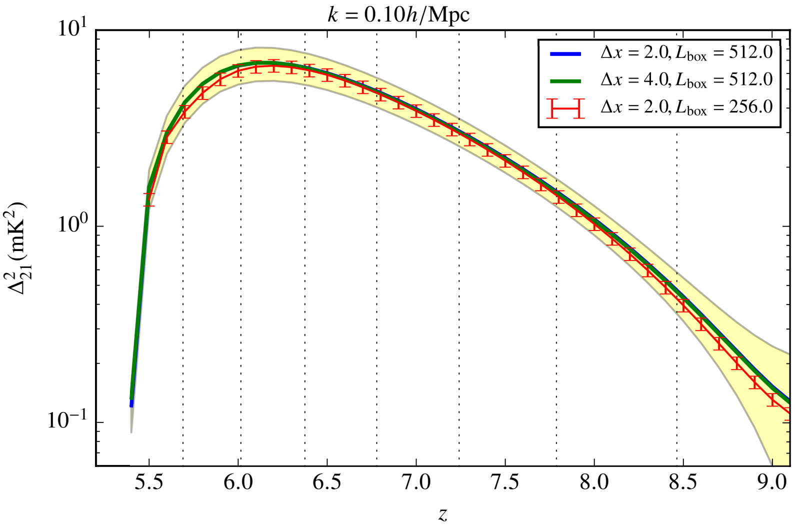
Redshift evolution



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- The photon-conserving model runs $\sim 2 - 4$ seconds in one processor (again assuming the density and halo fields are given)
- Can be adapted for exploration of the the astrophysical parameters (e.g., $x_{\rm HI}$, $M_{\rm min}$)

Looking ahead

- Currently working on generating the halo catalogue efficiently

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- Comparison with full radiative transfer simulations
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- Additional physical effects to be incorporated:
  (i) line of sight effects (light-cone),
  (ii) recombinations,
  (iii) maps based on reionization history