Detecting sources of reionization and cosmic dawn in 21-cm maps

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Sources of reionization and Cosmic dawn

- Galaxies (stars inside galaxies)
- QSOs
- Mini-QSOs, HMXBs, Pop III stars (X-ray sources)

21 cm signal

Differential Brightness temperature

$$\delta T_{\rm b}(\nu_{\rm obs}, \hat{\boldsymbol{n}}) \equiv \delta T_{\rm b}(\boldsymbol{x}) = 27\, x_{\rm H\,I}(z, \boldsymbol{x})[1 + \delta_{\rm B}(z, \boldsymbol{x})] \left(\frac{\Omega_{\rm B} h^2}{0.023}\right) \times \left(\frac{0.15}{\Omega_{\rm m} h^2} \frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\rm CMB}(z)}{T_{\rm S}(z, \boldsymbol{x})}\right] \,\mathrm{mK},$$

During reionization

$T_s >> T_{CMB}$

21 cm signal

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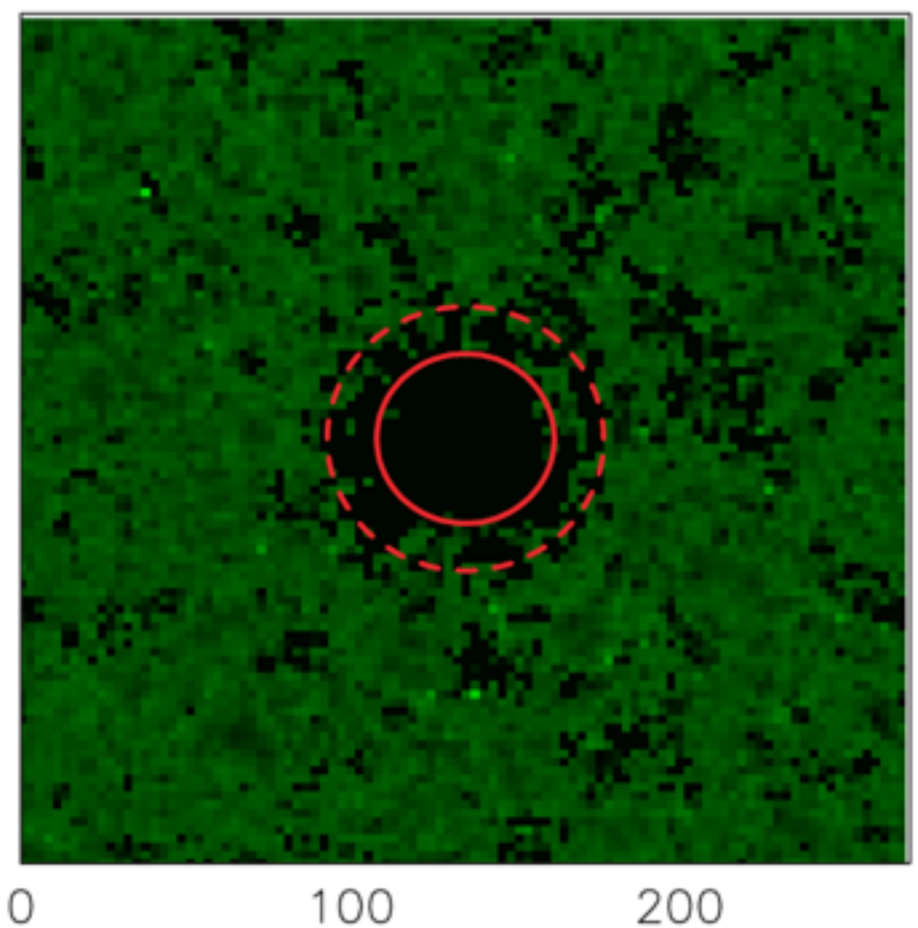
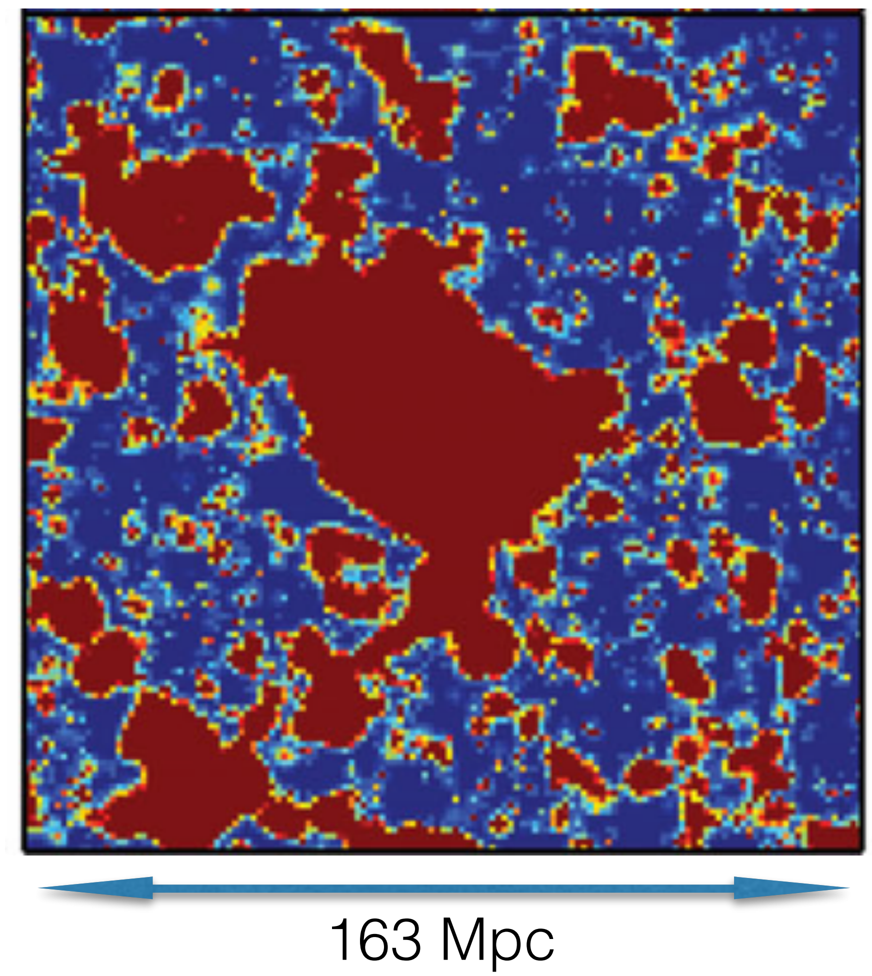
During reionization

$T_s >> T_{CMB}$

Ionized regions around bright QSOs



Using semi-numerical simulations
(Datta et al 2008)

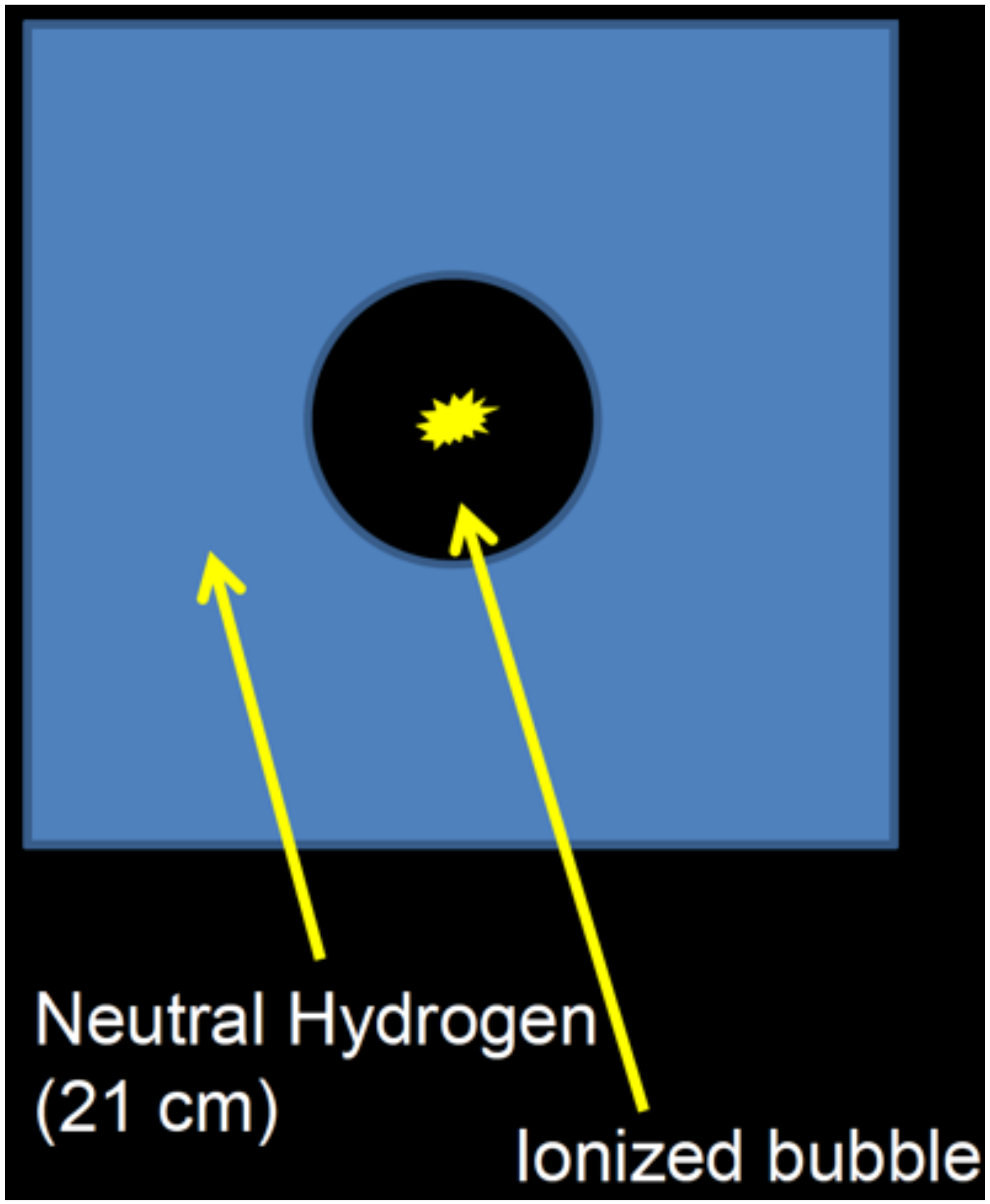


Radiative transfer (C2-Ray)
(Datta et al 2012)

$$\delta T_b(\boldsymbol{x}) = 27 \, x_{\rm H\,I} \text{ mK}$$

Noise~40 mK (4 arc mins, LOFAR) 1000 hrs

21 cm signal around sources



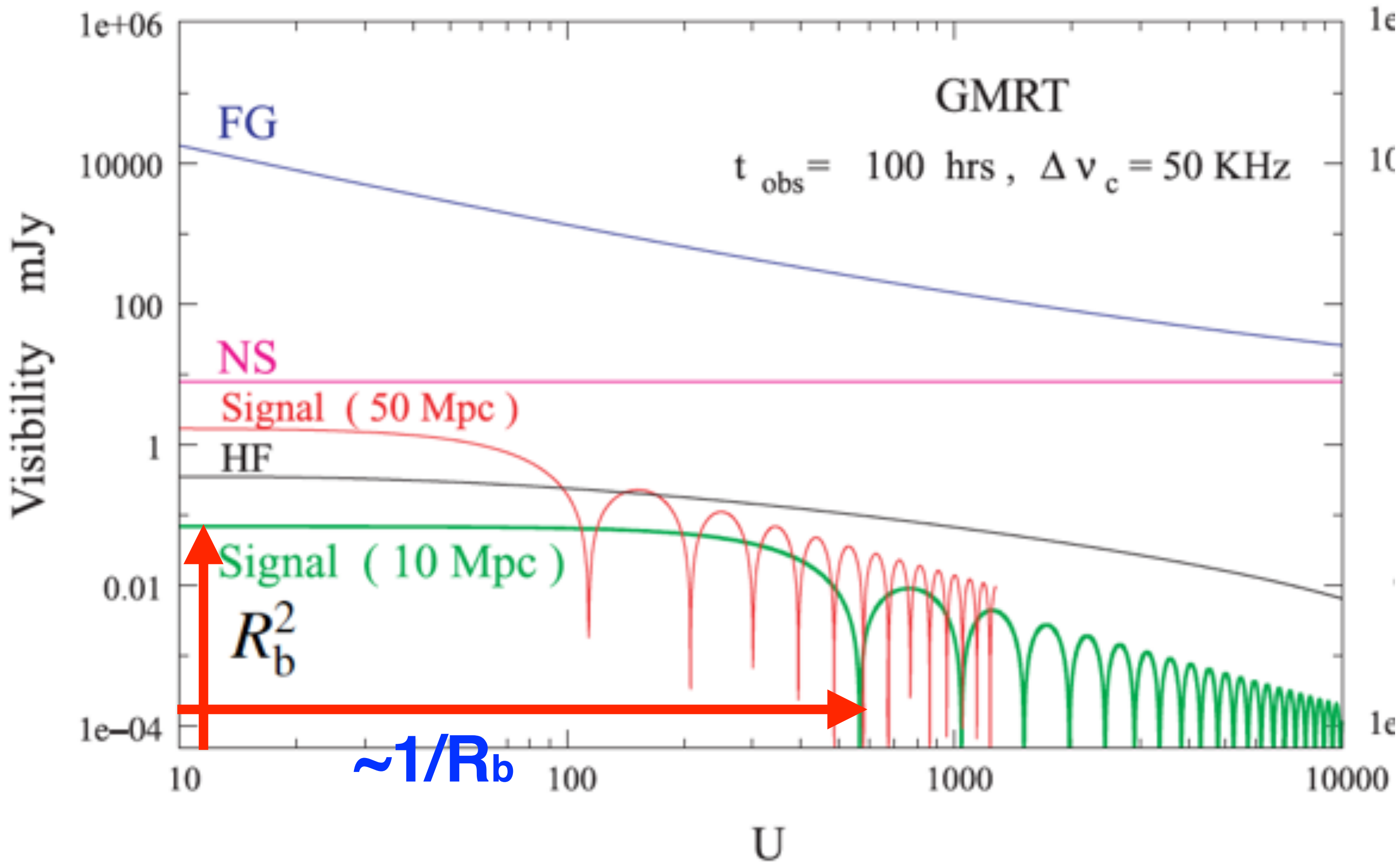
Visibility is related to sky sp. intensity

$$V(\boldsymbol{U}, \nu) = \int \mathrm{d}^2\theta \, A(\boldsymbol{\theta}) I_\nu(\boldsymbol{\theta}) \mathrm{e}^{2\pi \mathrm{i} \boldsymbol{\theta} \cdot \boldsymbol{U}}$$

For spherical ionized bubble visibility can be written as

$$S_{\mathrm{centre}}(\boldsymbol{U}, \nu) = -\pi \bar{I}_\nu x_{\mathrm{H\,I}} \theta_\nu^2 \left[\frac{2 J_1(2\pi U \theta_\nu)}{2\pi U \theta_\nu} \right] \Theta \left(1 - \frac{|\nu - \nu_c|}{\Delta \nu_b} \right)$$

Components of observed visibility



Matched filter formalism

Estimator

$$\hat{E} = \left[\sum_{a,b} S_f^*(\boldsymbol{U}_a, \nu_b)\hat{V}(\boldsymbol{U}_a, \nu_b)\right] \bigg/ \left(\sum_{a,b} 1\right)$$

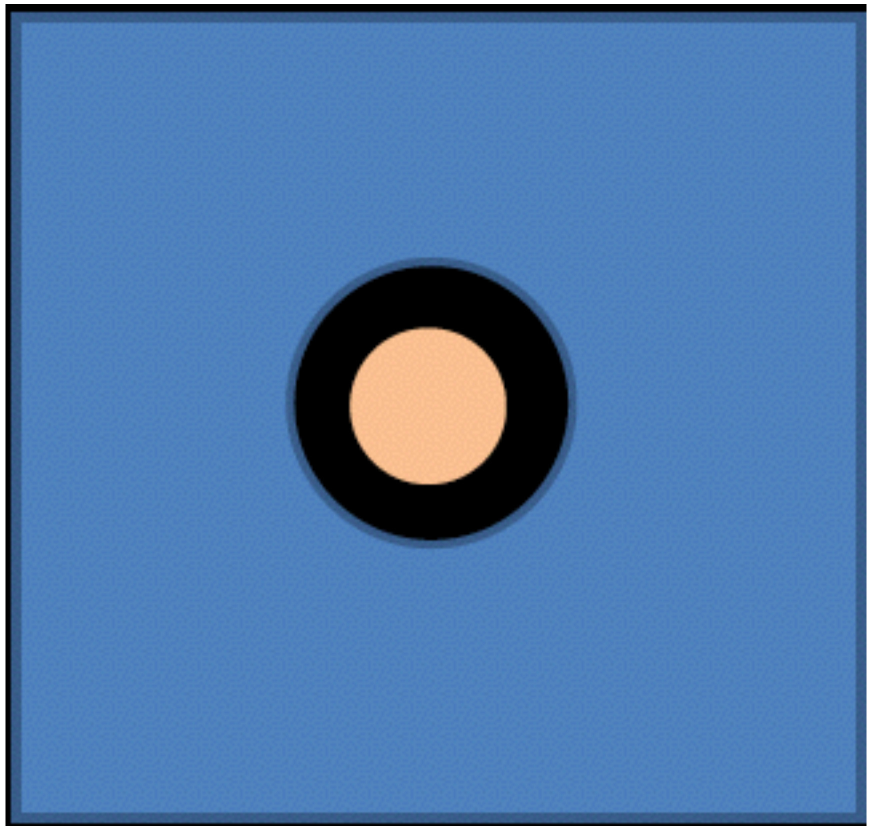
Variance

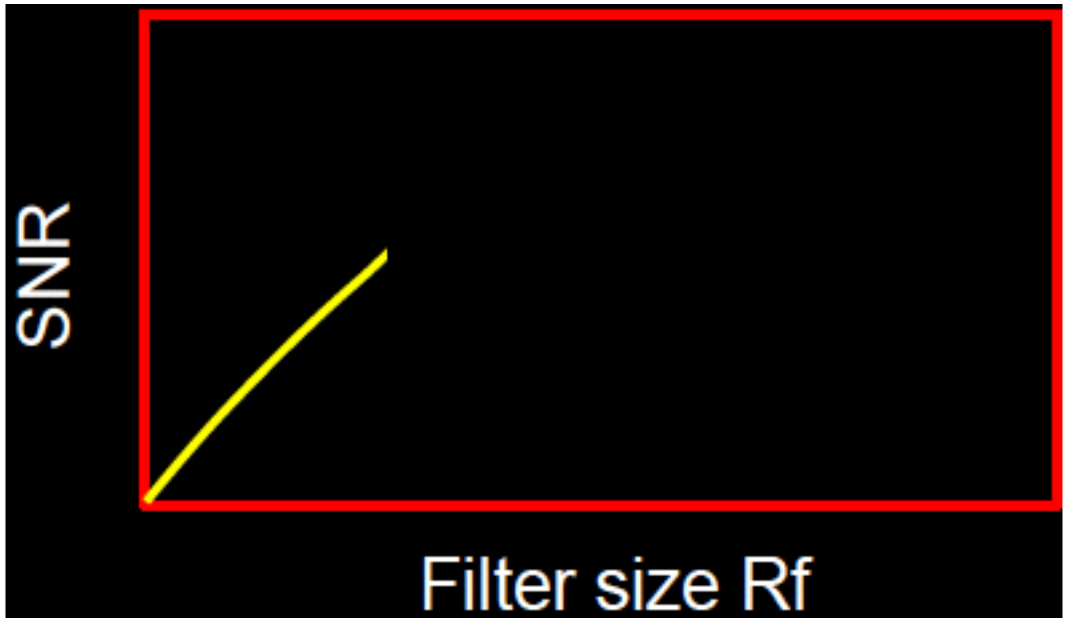
$$\langle(\Delta\hat{E})^2\rangle_{\rm NS} = \sigma^2 \int \mathrm{d}^2U \int \mathrm{d}\nu\, \rho_N(\boldsymbol{U}, \nu)\, |S_f(\boldsymbol{U}, \nu)|^2$$

Filter

$$S_{\rm f}(\boldsymbol{U}, \nu) = \left(\frac{\lambda_{\rm c}}{\lambda}\right)^2 \Big[S(\boldsymbol{U}, \nu) - \frac{\Theta(1 - 2\mid \nu - \nu_{\rm c} \mid /B')}{B'} \int_{\nu_{\rm c}-B'/2}^{\nu_{\rm c}+B'/2} S(\boldsymbol{U}, \nu')\, \mathrm{d}\nu'\Big]$$

Matched filter method





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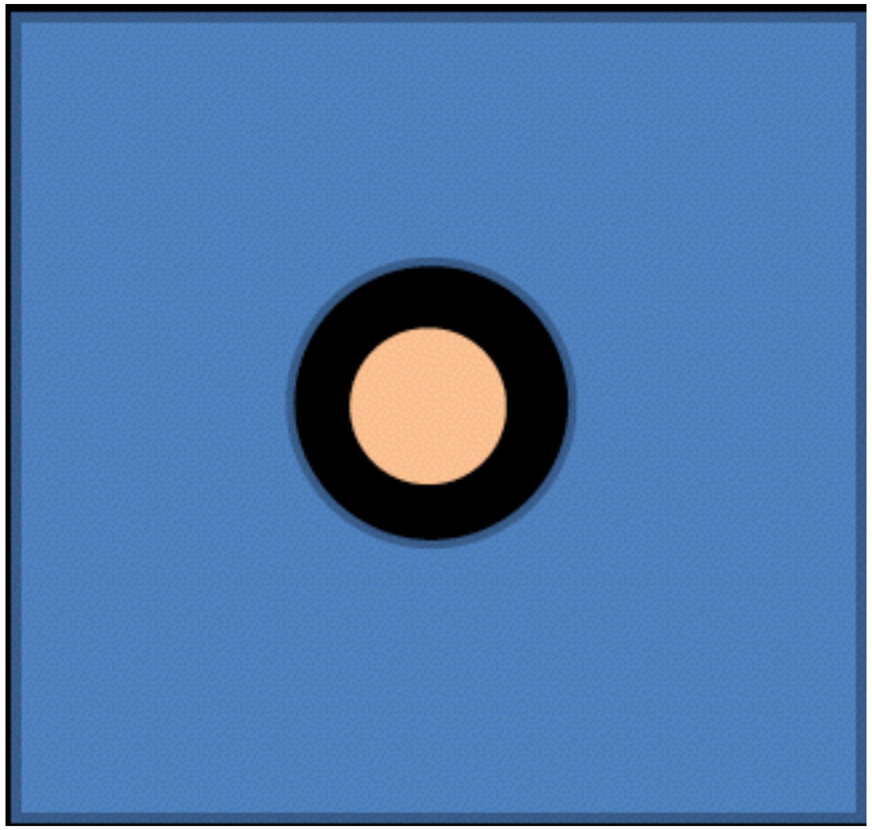
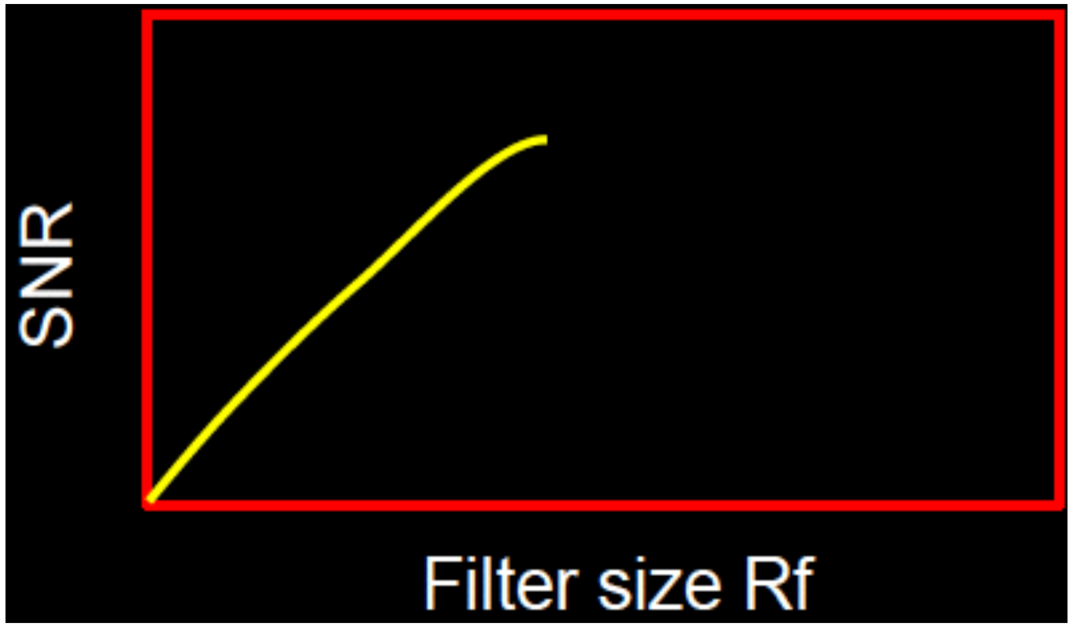
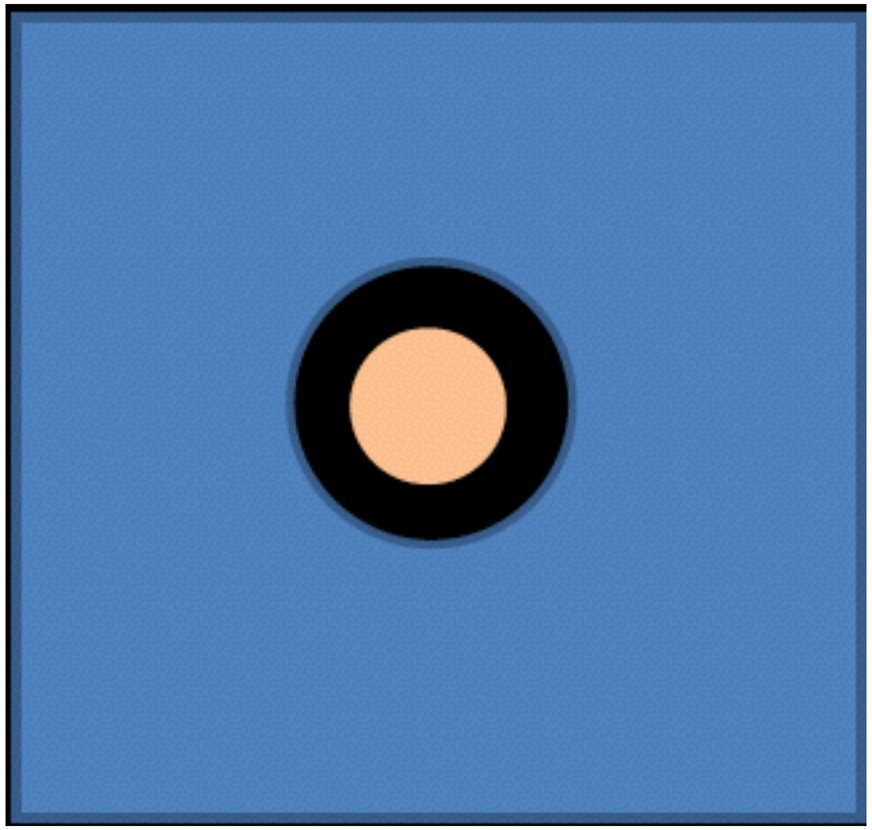
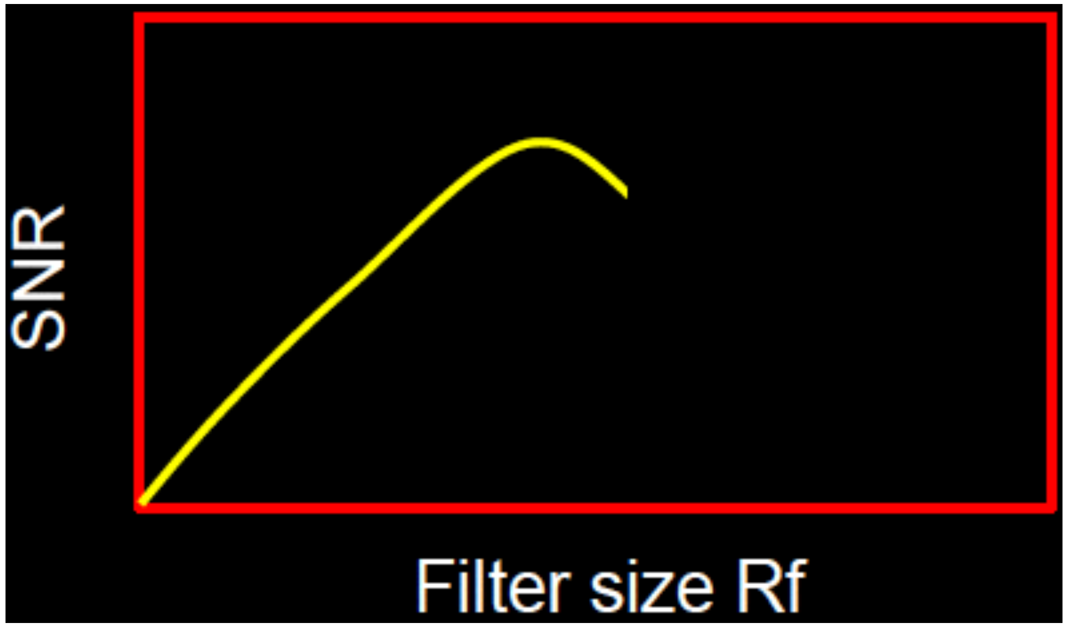


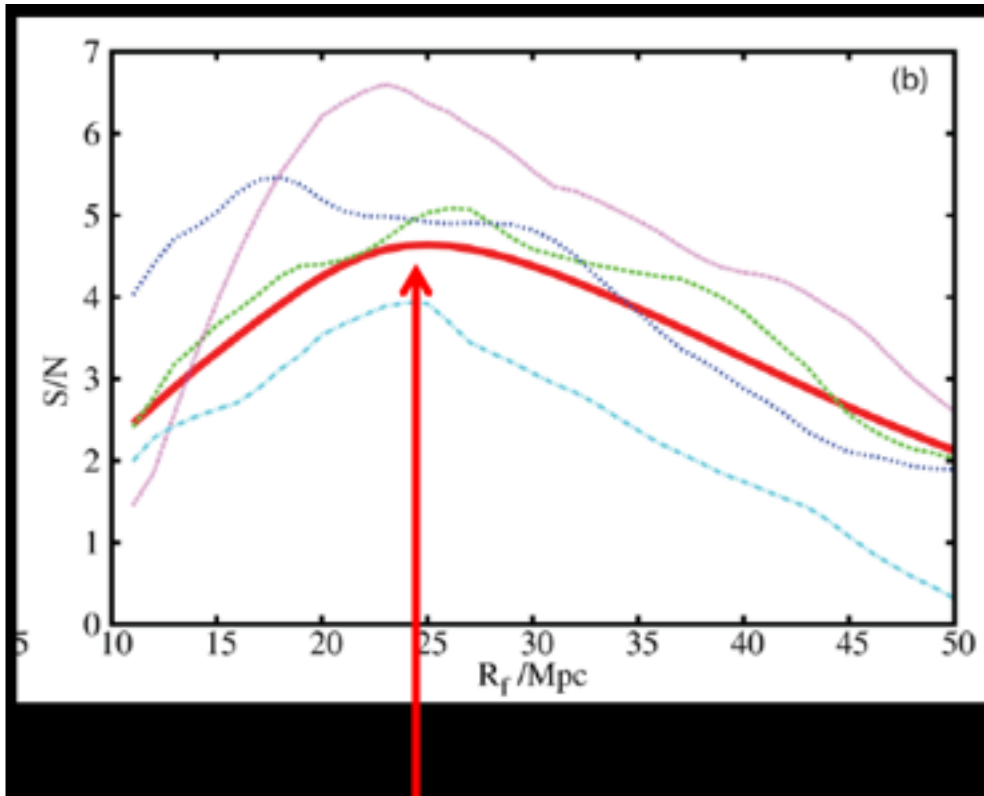


Matched filter method





Results from simulations for LOFAR



We obtain ionized bubble size from the peak

	H II region size (from filter) (cMpc)	H II region size (from total photon) (cMpc)
Early quasar	11.6	12.0
Late quasar	16.0	16.4
Large box	19.4 pm 4.06 24.9 pm 4.00	19.7 25.1

Datta et 2012, MNRAS

Imprints of sources during cosmic dawn

Differential Brightness temperature

$$\delta T_{\mathrm{b}}(\nu_{\mathrm{obs}}, \hat{\boldsymbol{n}}) \equiv \delta T_{\mathrm{b}}(\boldsymbol{x}) = 27\, x_{\mathrm{H\,I}}(z, \boldsymbol{x})[1 + \delta_{\mathrm{B}}(z, \boldsymbol{x})] \left(\frac{\Omega_{\mathrm{B}} h^2}{0.023}\right) \times \left(\frac{0.15}{\Omega_{\mathrm{m}} h^2} \frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_{\mathrm{CMB}}(z)}{T_{\mathrm{S}}(z, \boldsymbol{x})}\right] \mathrm{mK},$$

During reionization

$T_s >> T_{CMB}$

During Cosmic Dawn

$T_s <\sim T_{CMB}$

$x_{\mathrm{H\,I}} = 1$

Imprints of sources during reionization epoch

Differential Brightness temperature

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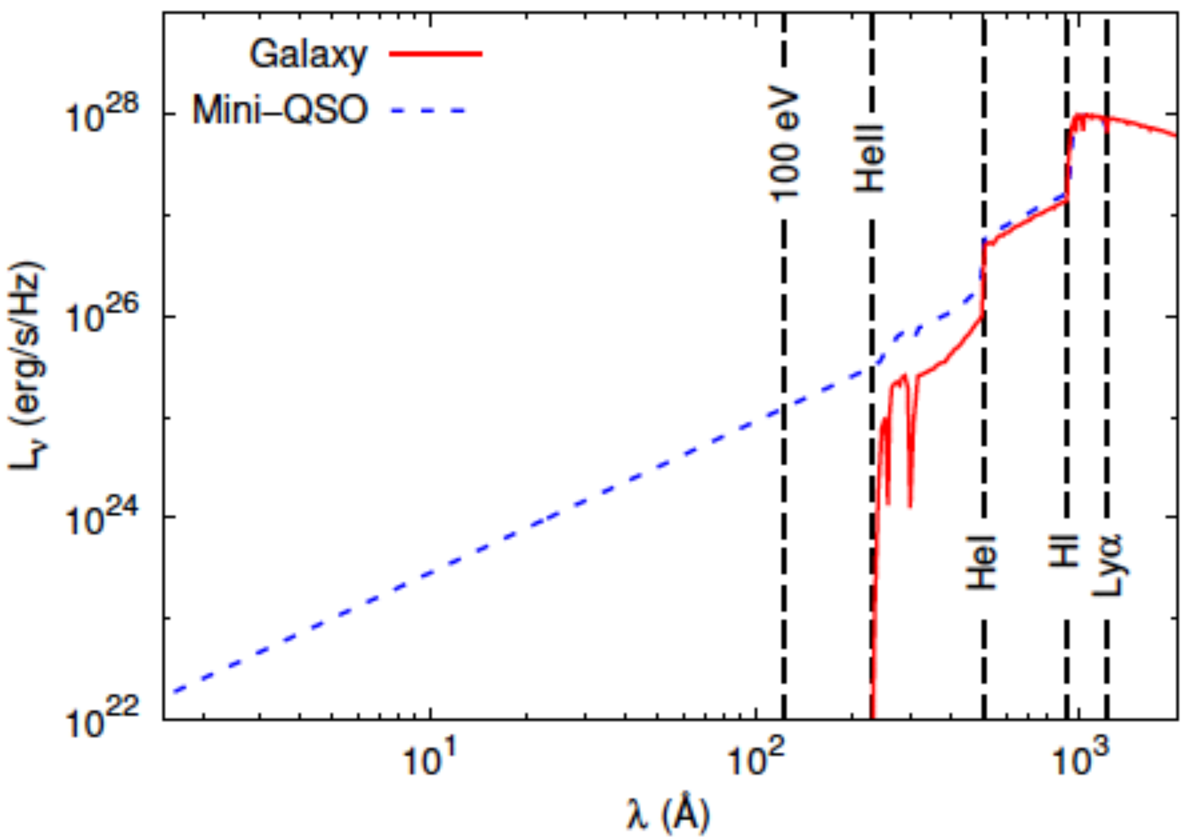
Modelling Sources during cosmic dawn



$M_\star = 10^8\ \mathrm{M}_\odot$.

Spectral index $\alpha = 1.5$

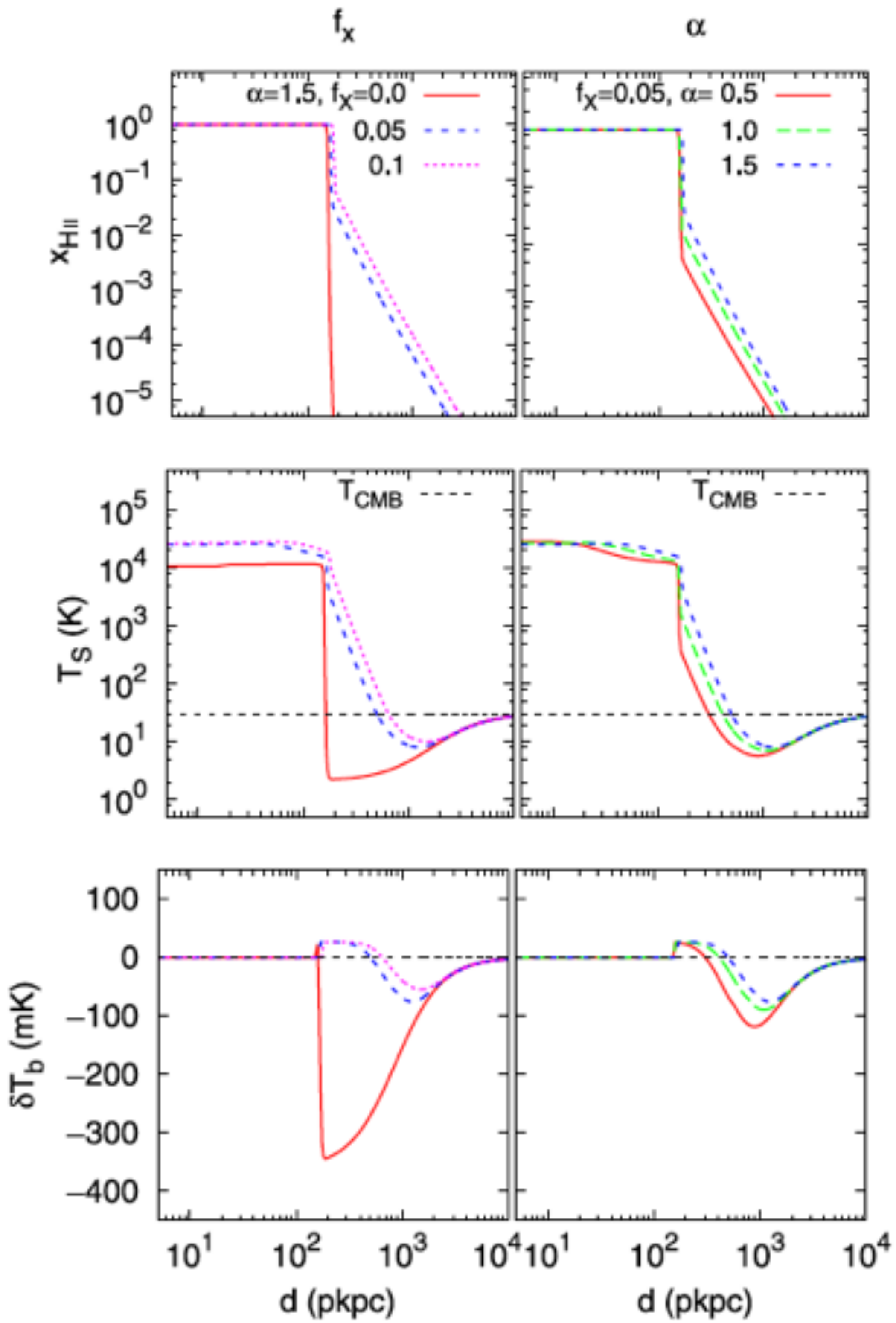
ratio of X-ray and UV luminosity $f_X = 0.05$

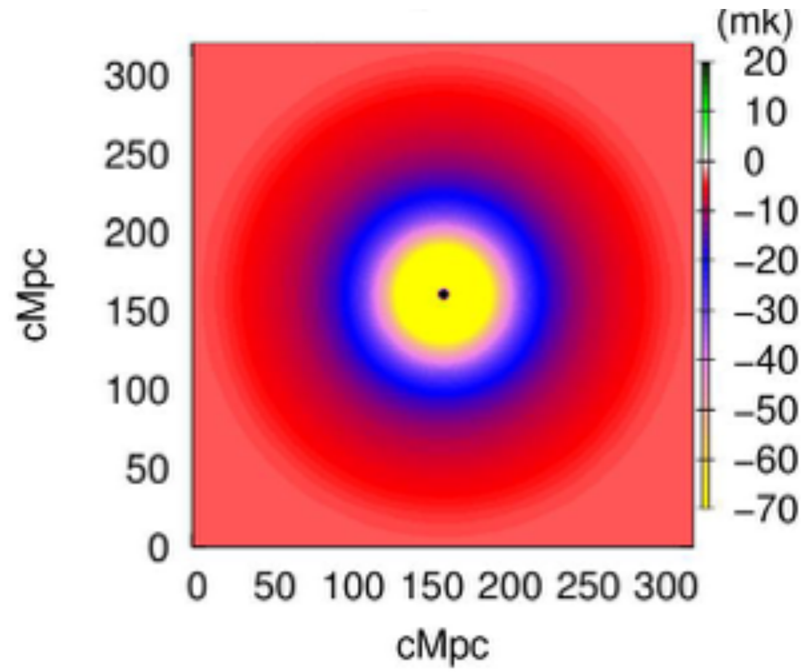
$f_{\rm esc} = 0.1$

$t_{\rm age} = 20\ \mathrm{Myr}$

Density contrast $\delta = 0$

Signal profile around mini-QSOs





Ghara, Choudhury, Datta, MNRAS, 2015

Square Kilometer Array (SKA)

Two separate telescopes

- **SKA -mid**: 350 MHz-14 GHz (South Africa)
- **SKA -low**: 50 -350 MHz (Australia)

For HI 21cm observations SKA -low can probe

- Redshift range: $3<z<27$
- Universe's age: 0.1 Gyr- 2 Gyr

Universe probed by SKA1 -low

SKA low

LOFAR
MWA, GMRT

Big Bang

0.1 Gyr

0.4 Gyr

1 Gyr

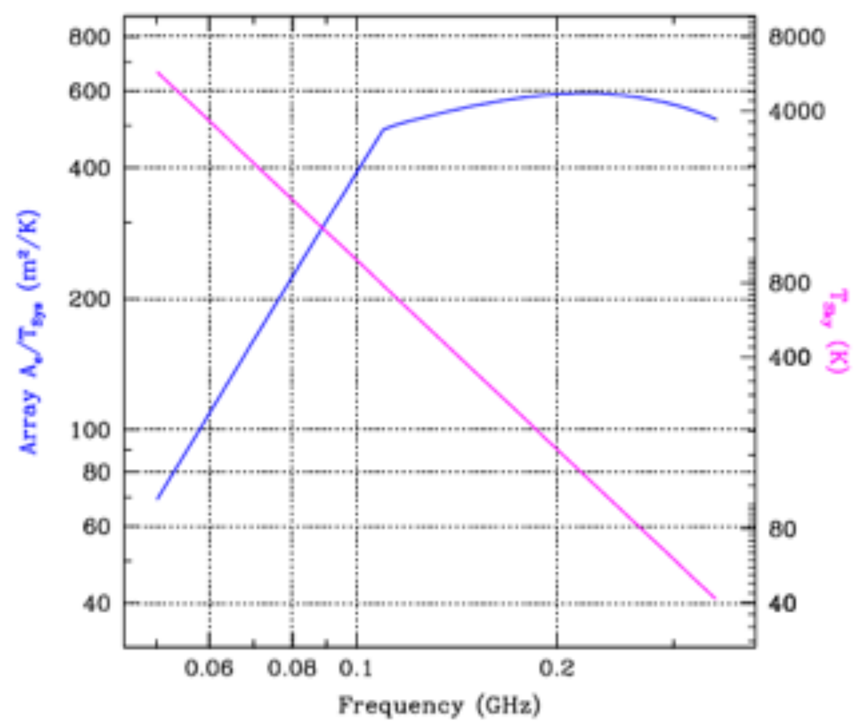
2 Gyr

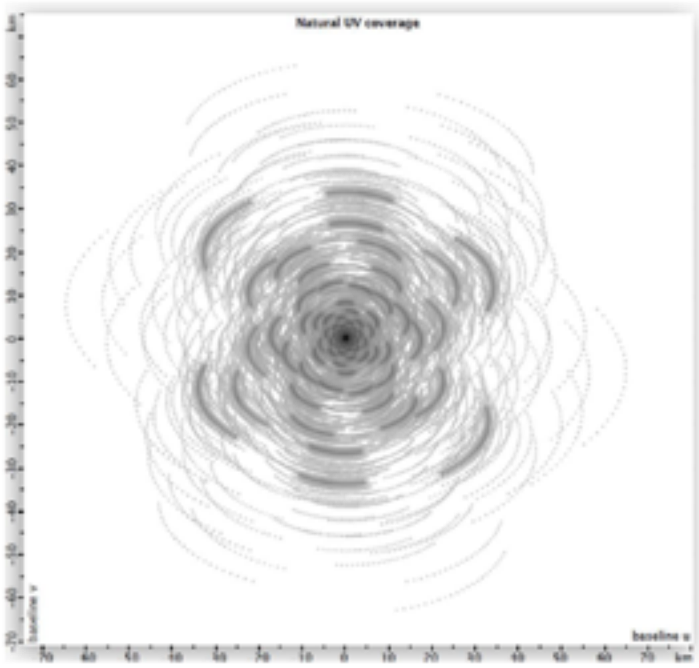
14 Gyr

SKA1-low Specifications

		GMRT	LOFAR	SKA1-low
A_{eff}/T_{sys}	m^2/K	250	61	559
FoV	deg^2	0.13	14	20.77
Receptor Size	m	45	39	35
Fiducial frequency	GHz	1.4	0.12	0.11
Survey Speed FoM	$deg^2\ m^4\ K^{-2}$	8.13×10^3	5.21×10^4	6.49×10^6
Resolution	arcsec	2	5	7
Baseline or Size	km	27	100	80
Frequency Range	GHz	0.15, 0.23, 0.33, 0.61, 1.4	0.03 – 0.22	0.050 – 0.350
Bandwidth	MHz	450	4	300
Cont. Sensitivity	$\mu Jy\text{-}hr^{-1/2}$	6.13	266.61	3.36
Sensitivity, 100 kHz	$\mu Jy\text{-}hr^{-1/2}$	411	1686	184
SEFD	Jy	11.0	45.2	4.9

SKA1 -low





Baseline coverage for 4 hrs observations at -30 degree declinations

Observing with SKA-low

Visibility

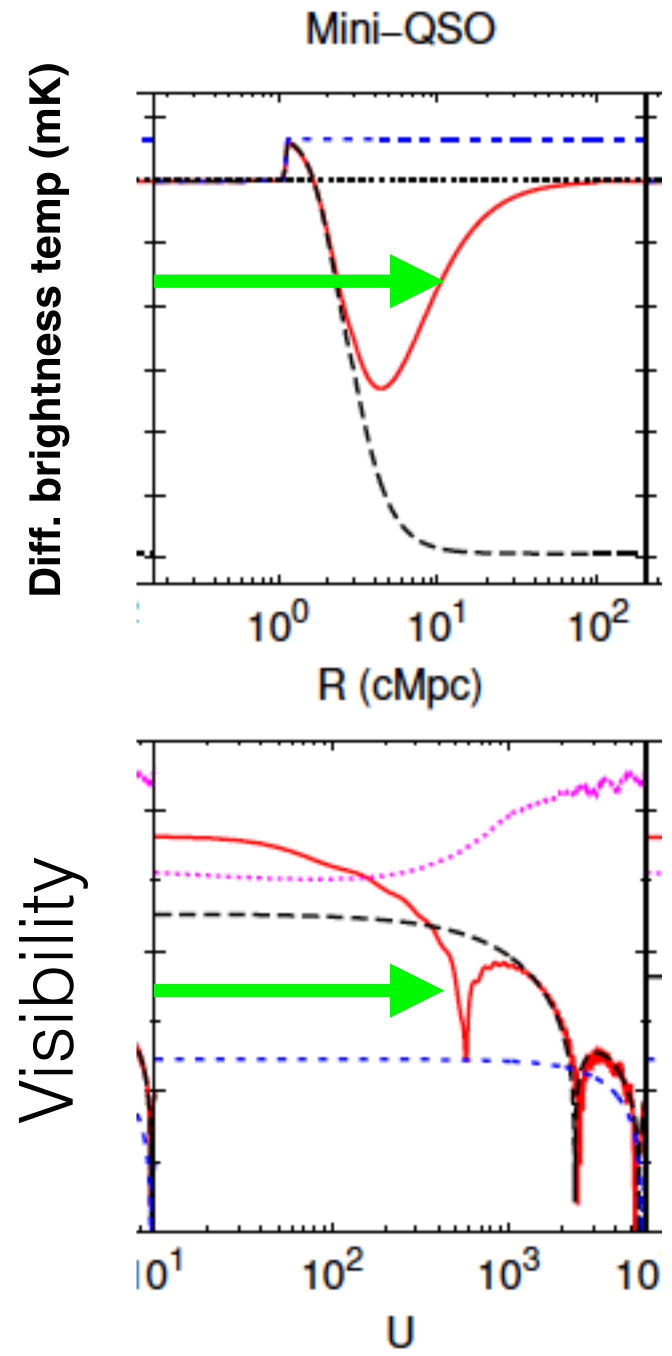
$$V(\vec{U},\nu) = \int d^2\theta \; I_\nu(\vec{\theta}) \; A(\vec{\theta}) \; e^{i2\pi\vec{\theta}\cdot\vec{U}},$$

Total Visibility

$$V(\vec{U},\nu) = S(\vec{U},\nu) + N(\vec{U},\nu)$$

System Noise

$$\sqrt{\langle N^2 \rangle} = \frac{\sqrt{2} k_B T_{\rm sys}}{A_{\rm eff}\sqrt{\Delta\nu_c \; \Delta t_c}}$$



Ghara, Choudhury, Datta, MNRAS, 2016

Estimator

Adding the signal from all baselines and channels

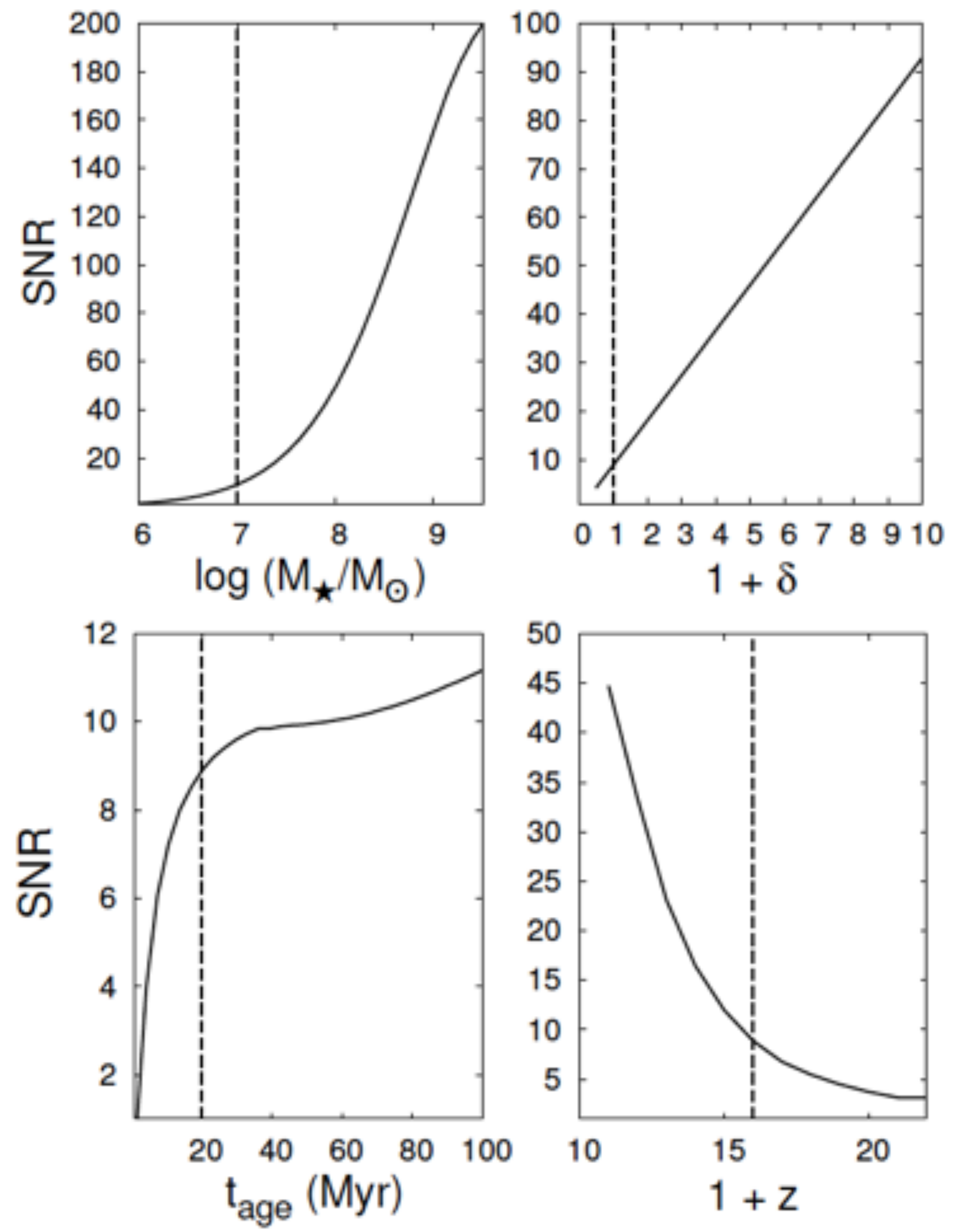
$$E = \Sigma_i \Sigma_j V(U_i, \nu_j)$$

Estimated signal to ratio

$$\mathrm{SNR} = \frac{1}{\sigma_N} \frac{\int d^2U \int d\nu \; n_{\mathrm{B}}(U,\nu) \; S(\vec{U},\nu)}{\int d^2U \int d\nu \; n_{\mathrm{B}}(U,\nu)}$$

$$\sigma_N = \frac{\sqrt{2} \; k_B T_{\mathrm{sys}}}{A_{\mathrm{eff}} \; \sqrt{t_{\mathrm{obs}} \; B_\nu \; N_{\mathrm{ant}}(N_{\mathrm{ant}} - 1)/2}}.$$

Detectability with SKA1-low (1000 hrs)



Ghara, Choudhury, Datta, MNRAS, 2016

Summary

- Detection of 21-cm signal around individual sources is a direct approach to probe EoR. It is also easy to interpret.
- Matched filter technique is a promising technique for individual ionised bubble.

- SKA -low is at least ~10 times more sensitive compared any existing low freq. telescope

- SKA -low should be able to detect the sources during cosmic dawn

- Various source parameters such as the mass, age and IGM density can be probed with 1000 hrs SKA1-low observations

Issues

- Targeted search around known QSO e.g, Mortlock QSO.
- Blind search
- Detailed study using foreground