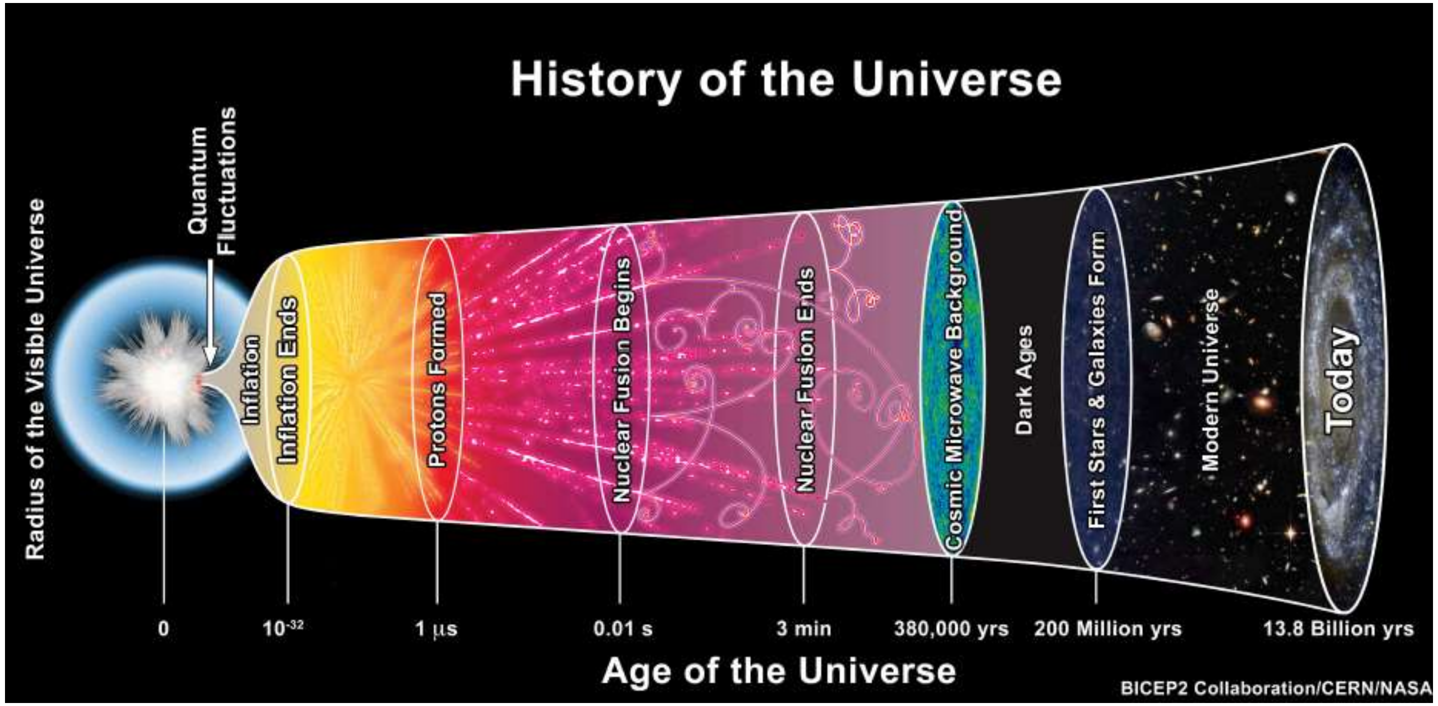
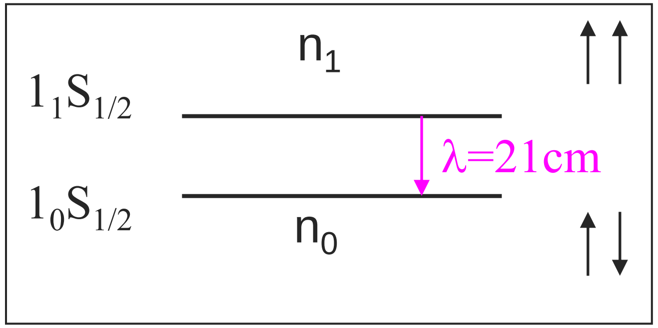
# End-to-End Simulation and EoR signal separation for SKA1-LOW Observation

朱正浩 （Zhenghao Zhu）

# Dark Age & Epoch of Reionization

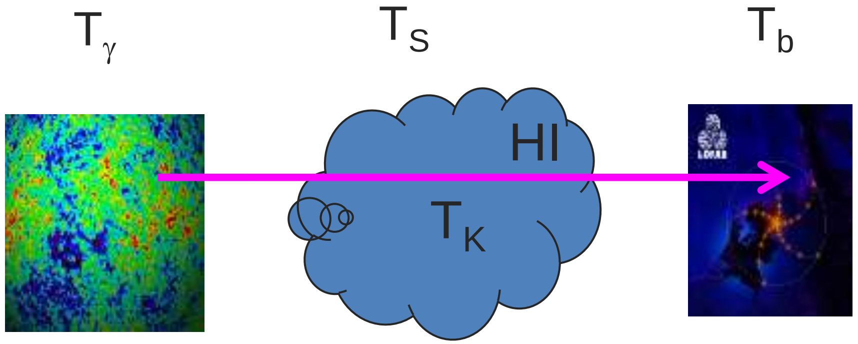



- HI hyperfine structure




$$n_1/n_0 = 3\ \exp(-h\nu_{21cm}/kT_s)$$

Use CMB backlight to probe 21cm transition



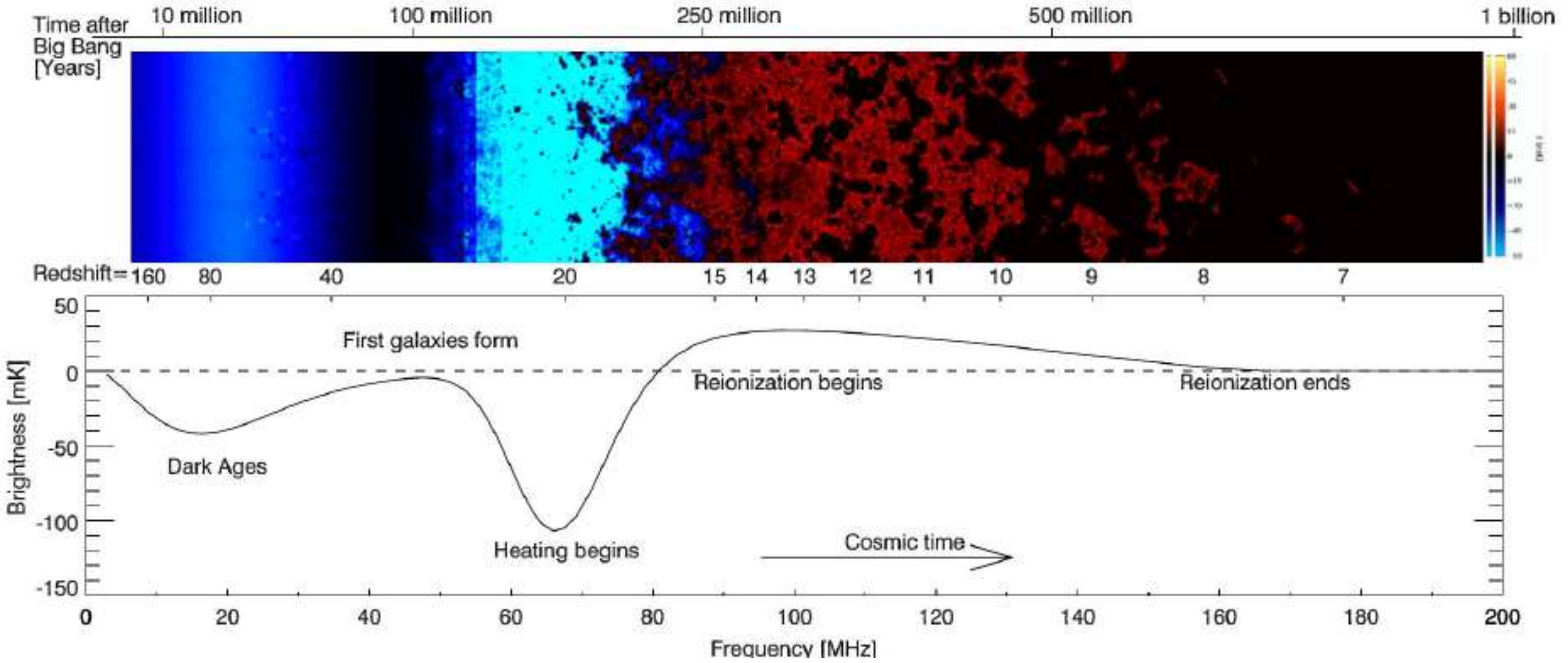

z=13

$f_{21cm}$=1.4 GHz

z=0

$f_{obs}$=100 MHz

# EoR Cosmology & Astrophysics




Astrophysics — Cosmology — Astrophysics

$$\delta T_b(\nu) \approx 27 X_{HI}(1+\delta_b)\left(\frac{0.15}{\Omega_M h^2}\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{\partial_r v_r}{(1+z)H(z)}\right)\ \mathrm{mK}$$

LoS velocity gradient

Fraction of HI

Baryon fractional overdensity

Spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

α => coupling constants

$T_\gamma$ => CMB

$T_\alpha$ => WF coupling

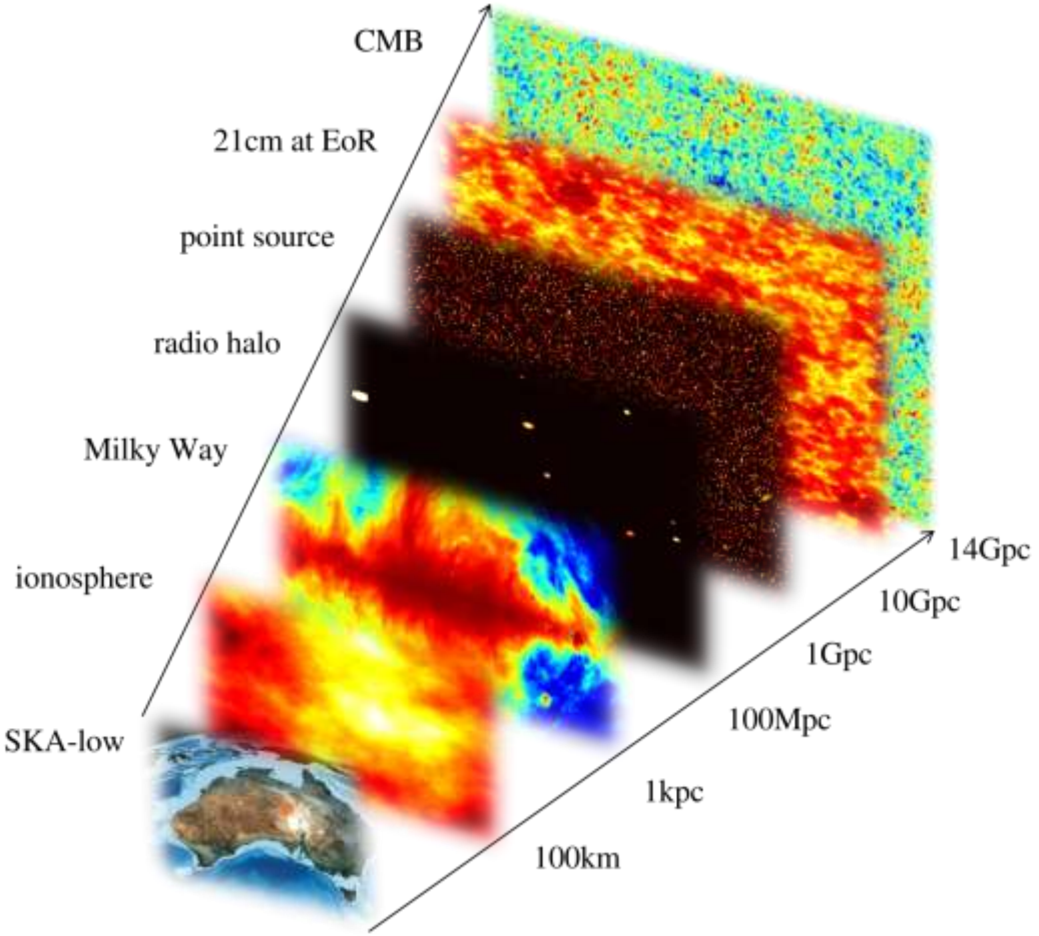
$T_K$ => scattering

$x_i$ => coupling constants

Derivation from Pritchard & Loeb (Rep. Prog. Phys., 2012)

# Why End-to-End Simulation

SKA-LOW prototype antenna (left half) and art image (right half)
Credit: SKAO

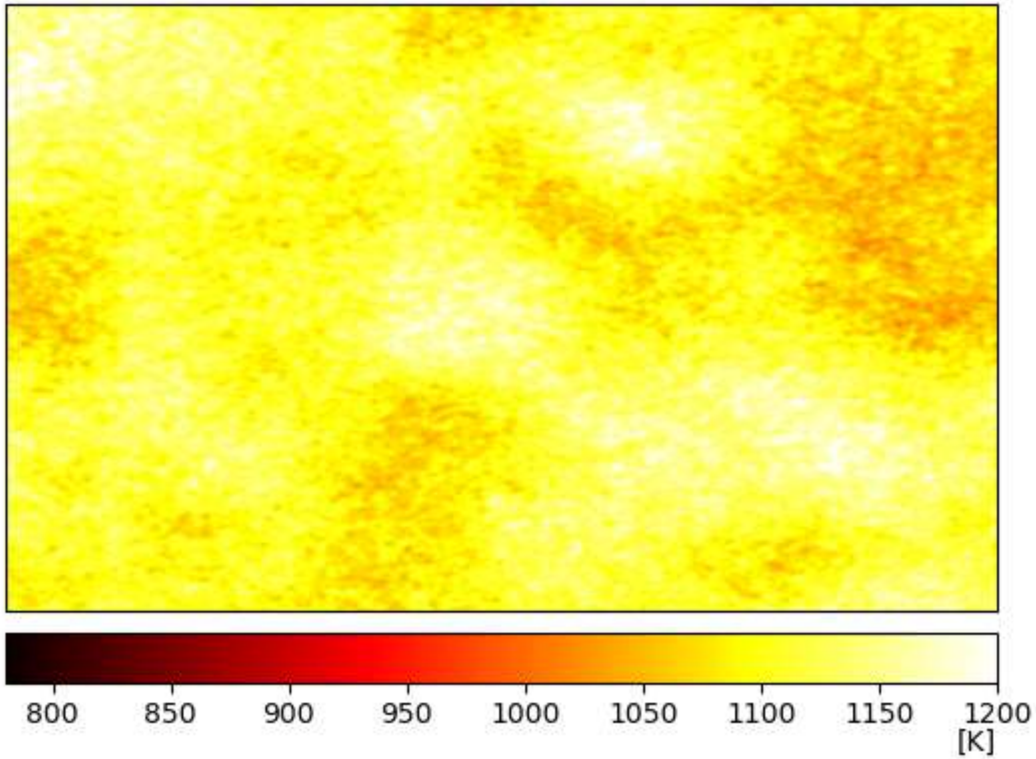



**EoR signal is drowned in the foreground that is 10^5 times stronger**

**Need realistic simulations to check the result**

# Skymap: Galactic Synchrotron emission

- Reference: Reprocessed Halsam 408MHz map[1]
- Spectral Index: All-sky synchrotron spectral index from Giardino et al. (2002)
- Add small scale fluctuation (Nside=8192, pixel size ~0.5 arcmin) following Remazeilles et al. (2015)
- Center of RA,DEC=0,-27



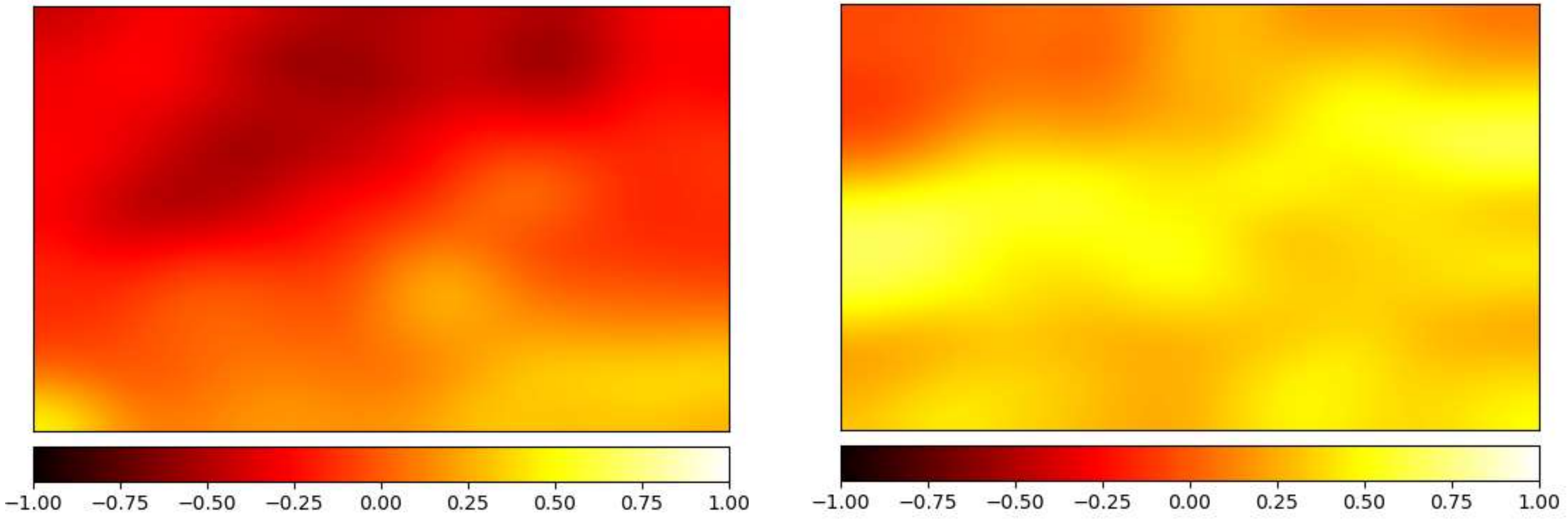

Brightness temperature of the simulated synchrotron emission from 110 MHz – 120 MHz

1. https://www.jb.man.ac.uk/research/cosmos/haslam_map Remazeilles et al. (2015)

# Skymap: polarization of the Synchrotron emission

## Polarization map from WMAP 9-year observation[1]

## Using K band (23GHz) polarization fraction for q and u component in all simulated frequencies




Fraction of stokes q(left) and u(right) component

1. https://lambda.gsfc.nasa.gov/product/wmap/dr5/mcmc_maps_fs_get.html Bennett et al. 2013

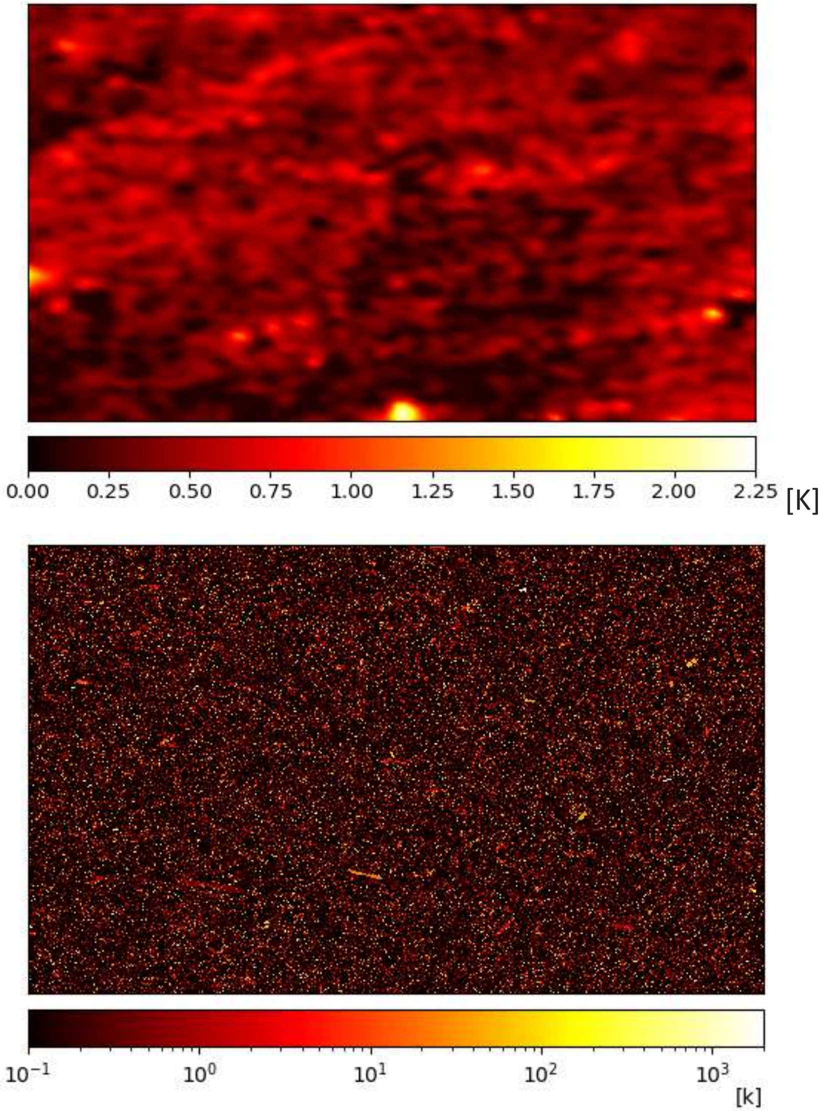
# Skymap: free-free emission & point source

## Free-free

- Hα survey data[1] , corrected for dust absorption,
- employing the tight relation between the Hα and free–free emissions due to their common origins[2]

## Extragalactic point source:

- Using simulation results from Wilman et al. 2008
  (1) Star forming and starburst galaxies
  (2) radio-quiet AGNs
  (3) Fanaroff–Riley type I and type II AGNs




Simulated free-free (upper) and point source (lower) emission from 110-120MHz

1. Finkbeiner 2003
2. Dickinson et al. 2003, and references therein

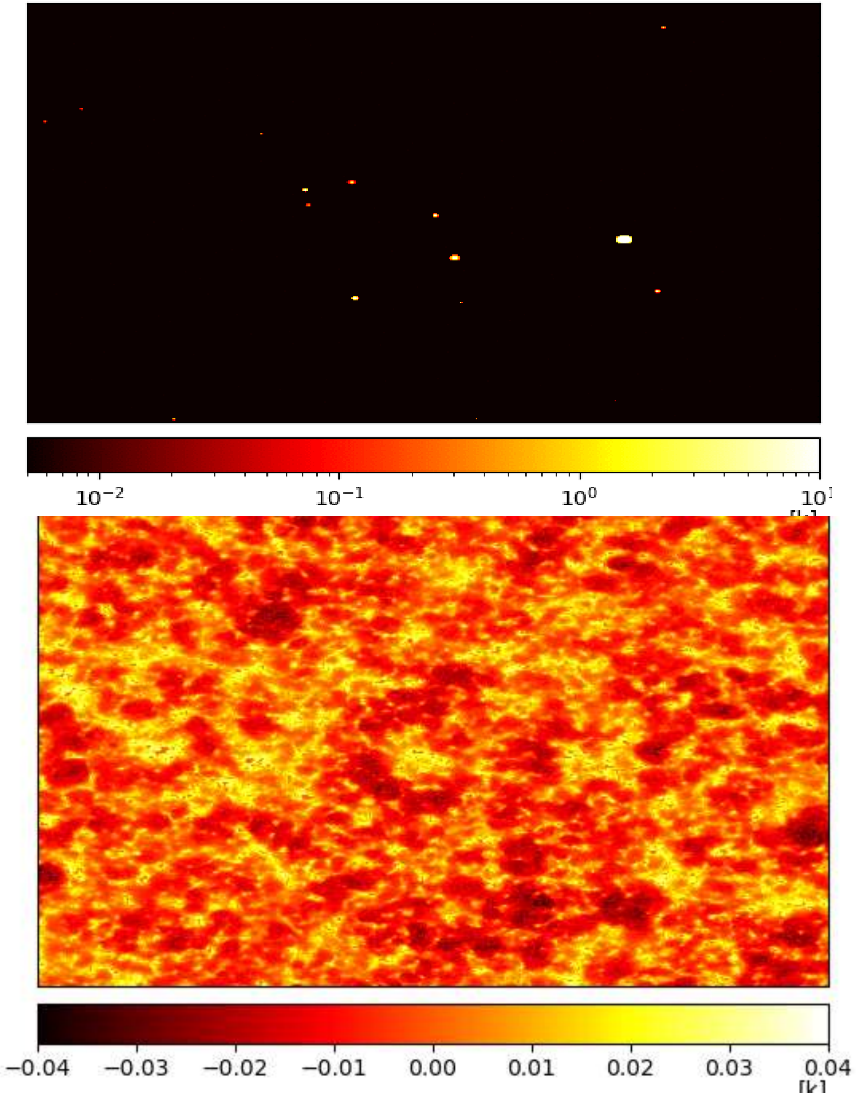
# Skymap: radio halo & EoR signal

## Radio halo

- Using the simulation result from Li et al. 2019
- Get merge history from PS theory
- Solving FP eqution & calculate radiation

## EoR signal

- Using the data from Evolution Of 21cm Structure project[1]

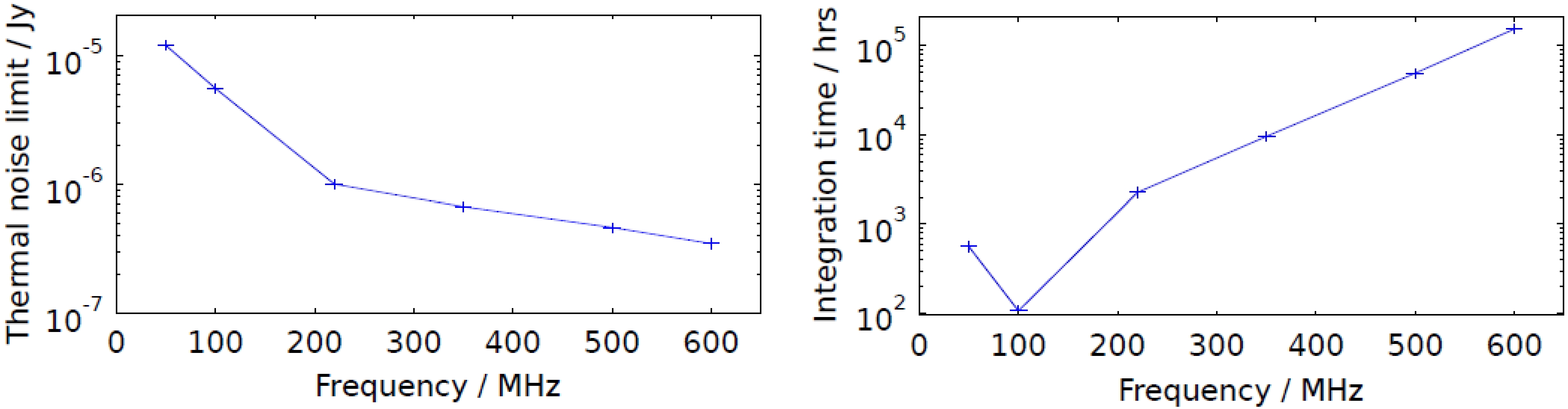



Simulated Radio halo (upper) and EoR signal (lower) from 110-120MHz

1. EOS project https://homepage.sns.it/mesinger/EOS.html Mesinger et al. 2016

# Thermal noise

## Thermal noise fluctuation on the antenna is added
## Using the noise level given in SKA memo153[1]




Thermal noise level of SKA1-LOW for 100kHz bandwidth

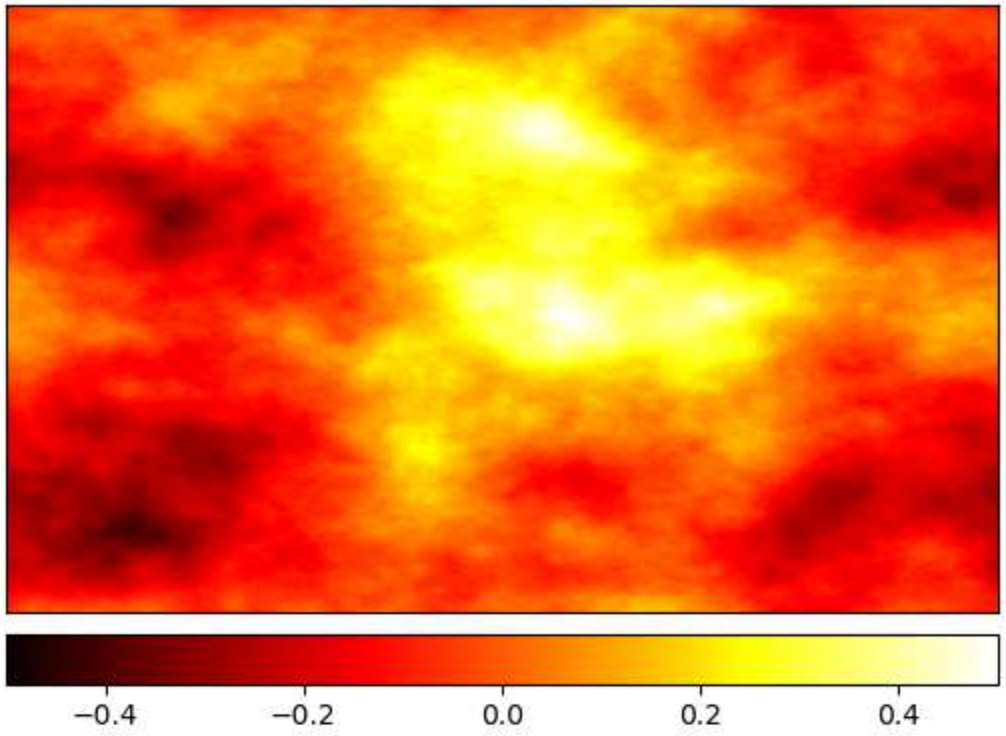
Credit: SKA memo 153

1.https://www.skatelescope.org/uploaded/23880_153_Memo_Sinclair.pdf

# Ionosphere、Phase & Gain Error

**Ionosphere**[1]
- **simple model: two layers**
  - **150 Km/h at 300km altitude**
  - **75 km/h at 310km altitude**
- **Using ARatmospy**[2]

**Gain Error**[3]**: 0.0198 dB**
**Phase Error**[3]**: 1.2 deg**




The phase screen used to model the ionosphere

1. https://fdulwich.github.io/oskarpy-doc/example_ionosphere.html
2. https://github.com/shrieks/ARatmospy
3. https://gitlab.com/ska-telescope/sim/ska-sim-low

# OSKAR, SKA1-Low configuration

## Using SKA1-Low array configure and antenna response[1]

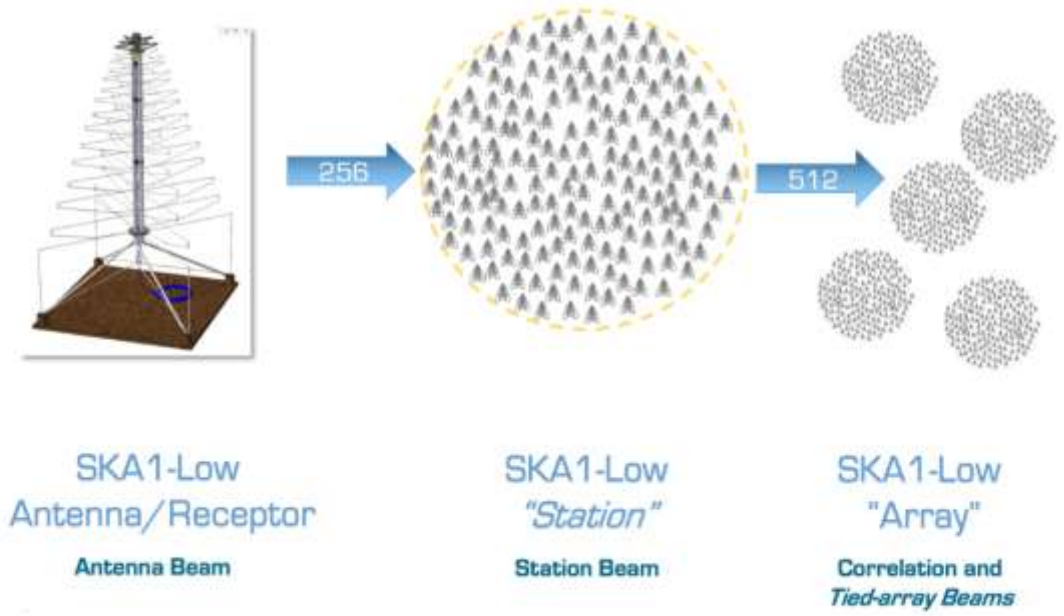



Illustration of SKA1-Low Antenna, Station, and Array concepts.
Credit: Braun et al. 2019

| **Nominal Frequency** | **110 MHz** | **300 MHz** |
|---|---|---|
| **Range [GHz]** | 0.05-0.35 | 0.05-0.35 |
| Telescope | Low | Low |
| FoV [arcmin] | 327 | 120 |
| Max. Resolution [arcsec] | 11 | 4 |
| Max. Bandwdith [MHz] | 300 | 300 |
| Cont. rms, 1 hr [μJy/beam][a] | 26 | 14 |
| Line rms, 1 hr [μJy/beam][b] | 1850 | 800 |
| Resolution Range for Cont. and Line rms [arcsec][c] | 12–600 | 6–300 |
| Channel width (uniform resolution across max. bandwidth) [kHz] | 5.4 | 5.4 |
| Spectral zoom windows x narrowest bandwidth [MHz] | 4 x 3.9 | 4 x 3.9 |
| Finest zoom channel width [Hz] | 226 | 226 |

Anticipated Performance of SKA1-LOW
https://arxiv.org/abs/1912.12699

1. https://gitlab.com/ska-telescope/sim/ska-sim-low/-/tree/master/rfi/data/telescope_files

# OSKAR, SKA1-Low configuration

## Using SKA1-Low array configure and antenna response[1]

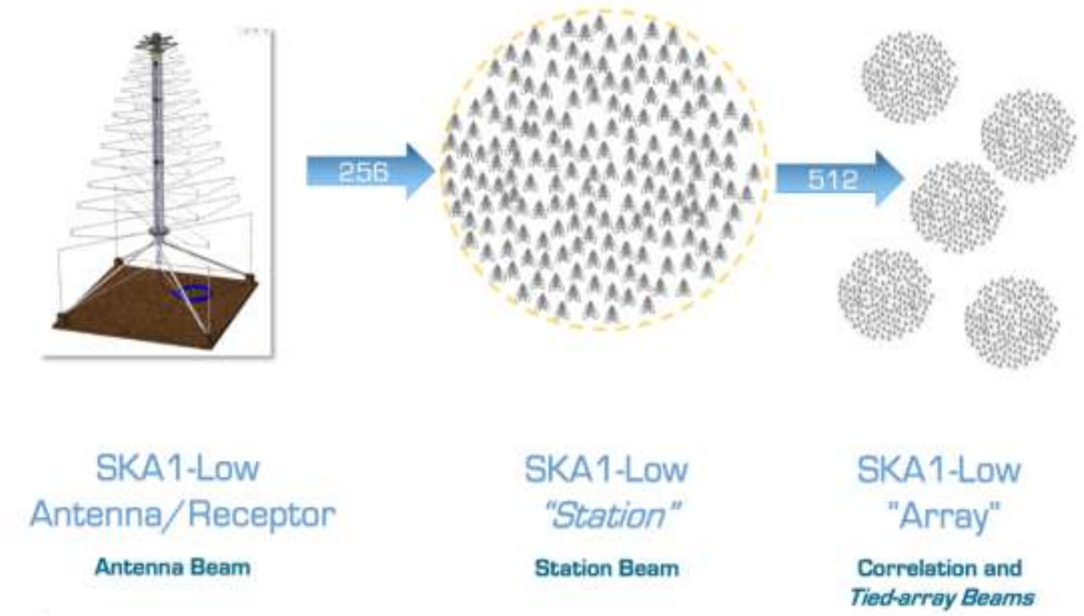
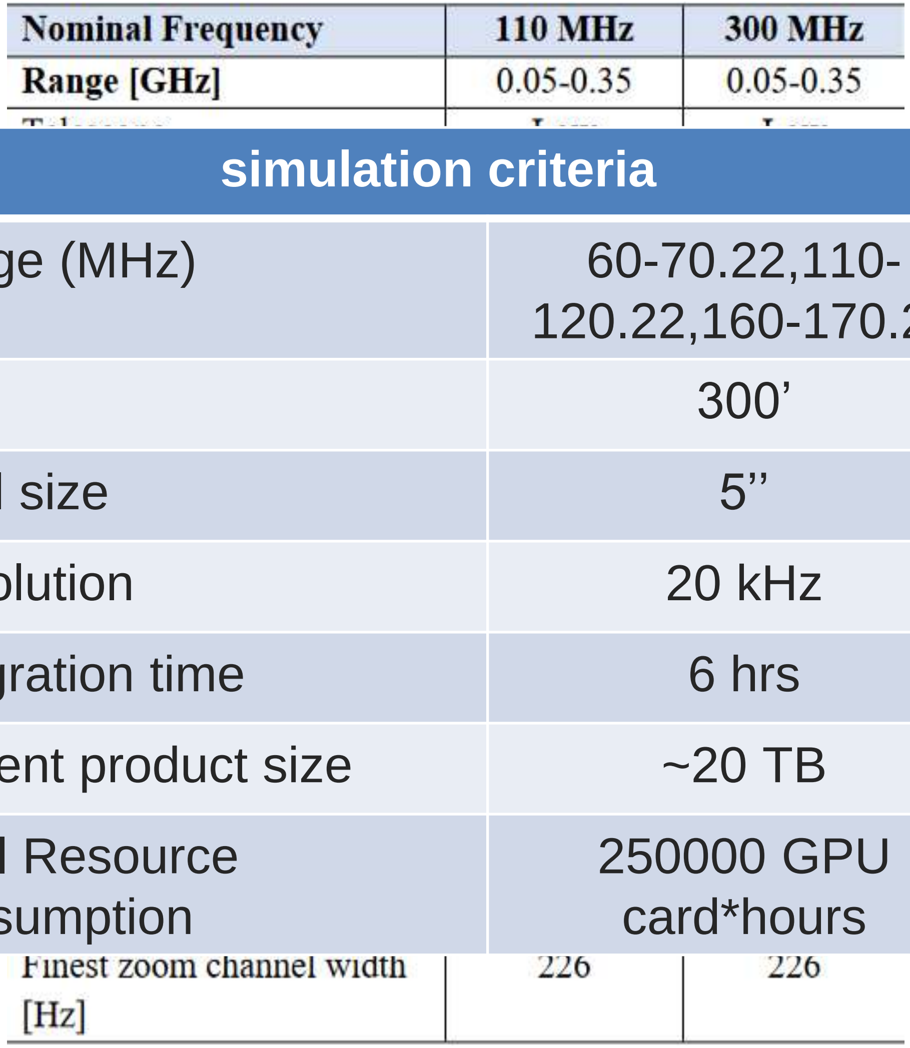



Illustration of SKA1-Low Antenna, Station, and Array concepts.
Credit: Braun et al. 2019



| Nominal Frequency | 110 MHz | 300 MHz |
|---|---|---|
| Range [GHz] | 0.05-0.35 | 0.05-0.35 |
| Finest zoom channel width [Hz] | 226 | 226 |

| simulation criteria | |
|---|---|
| Range (MHz) | 60-70.22,110-120.22,160-170.22 |
| FoV | 300’ |
| Pixel size | 5’’ |
| Resolution | 20 kHz |
| Integration time | 6 hrs |
| Current product size | ~20 TB |
| Total Resource Consumption | 250000 GPU card*hours |

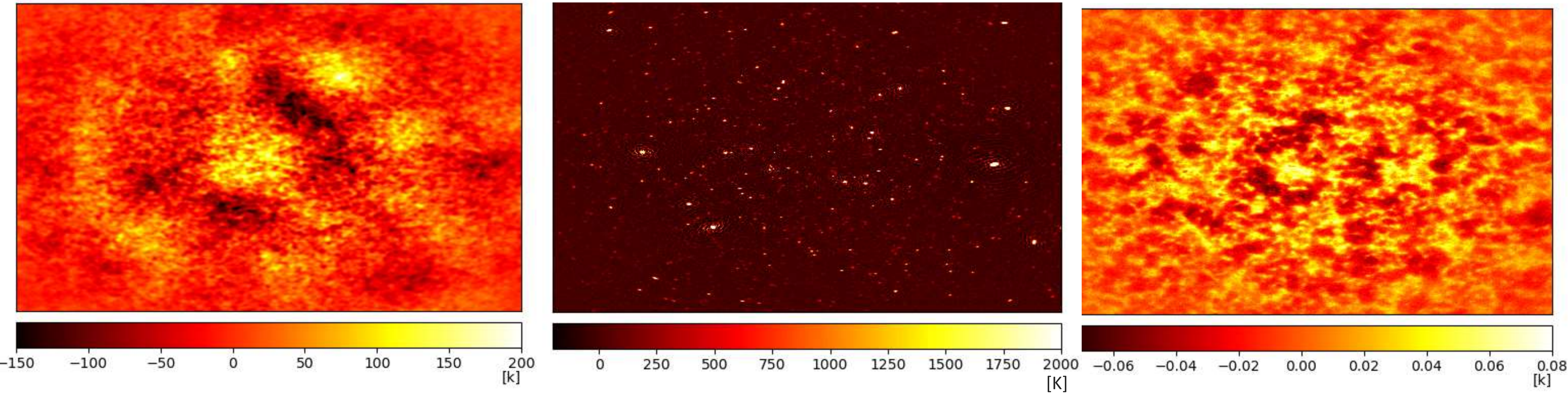
Anticipated Performance of SKA1-LOW
https://arxiv.org/abs/1912.12699

1. https://gitlab.com/ska-telescope/sim/ska-sim-low/-/tree/master/rfi/data/telescope_files

# Simulated dirty map

## Using wsclean[1] w-gridder

## Weight: Briggs 0




Simulated Galactic (left) and extragalactic (middle) foreground and EoR signal (right) from 110-120MHz

https://wsclean.readthedocs.io/en/latest/

# Smoothness of the spectrum

**Foreground spectrum is not smooth enough comparing to the EoR signal**

**Component separation method that relies on the spectral smoothness need to be treated carefully**

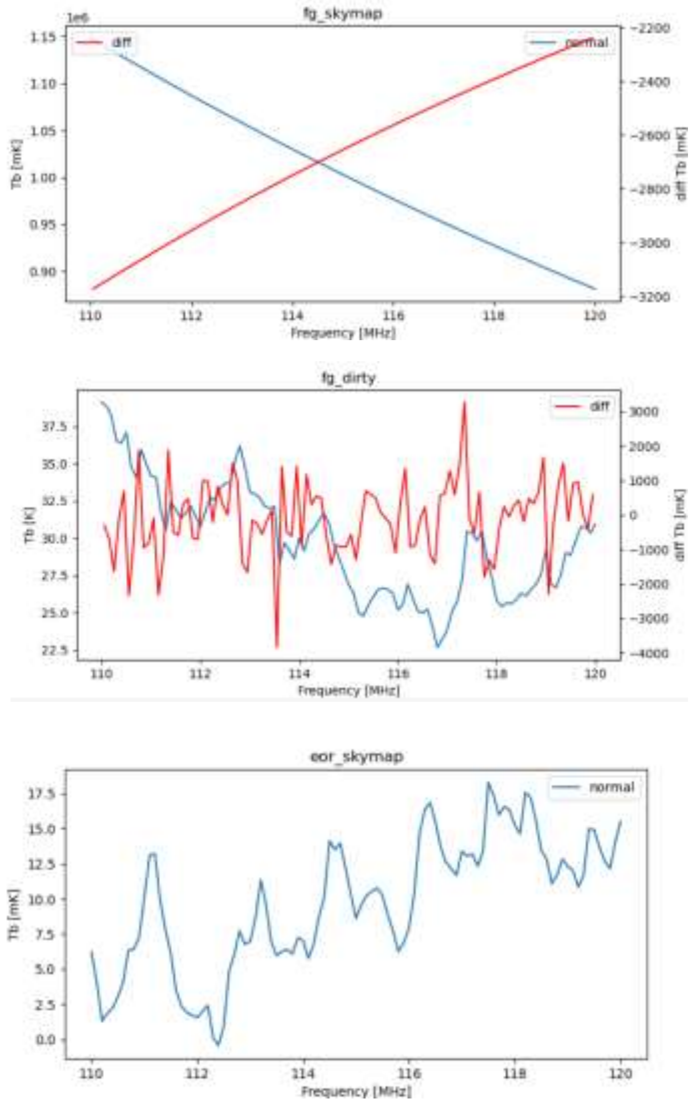
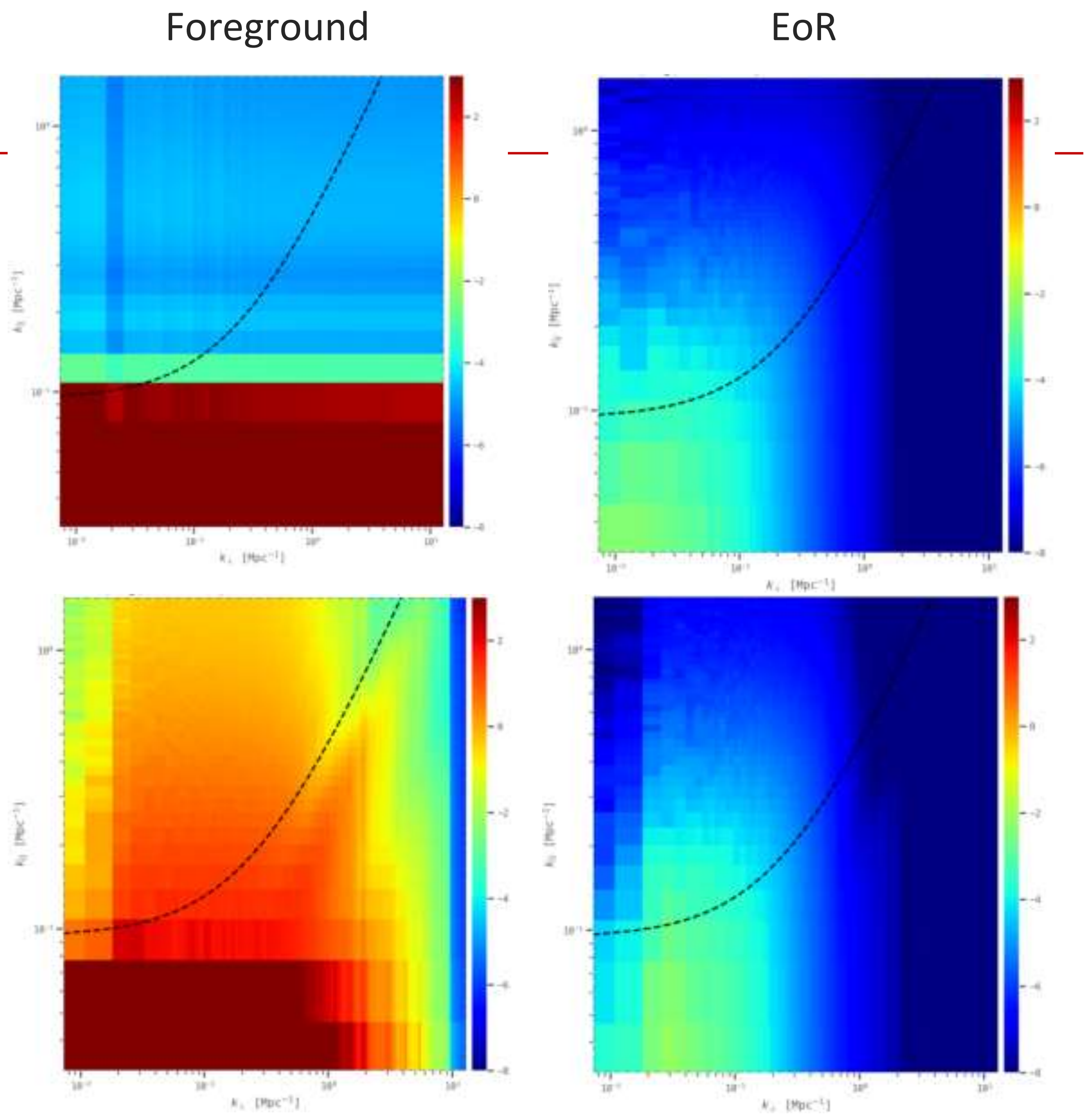



Illustration of the smoothness of spectrum

# EoR window

**Instrumental/observational effects will contaminate the EoR windows**

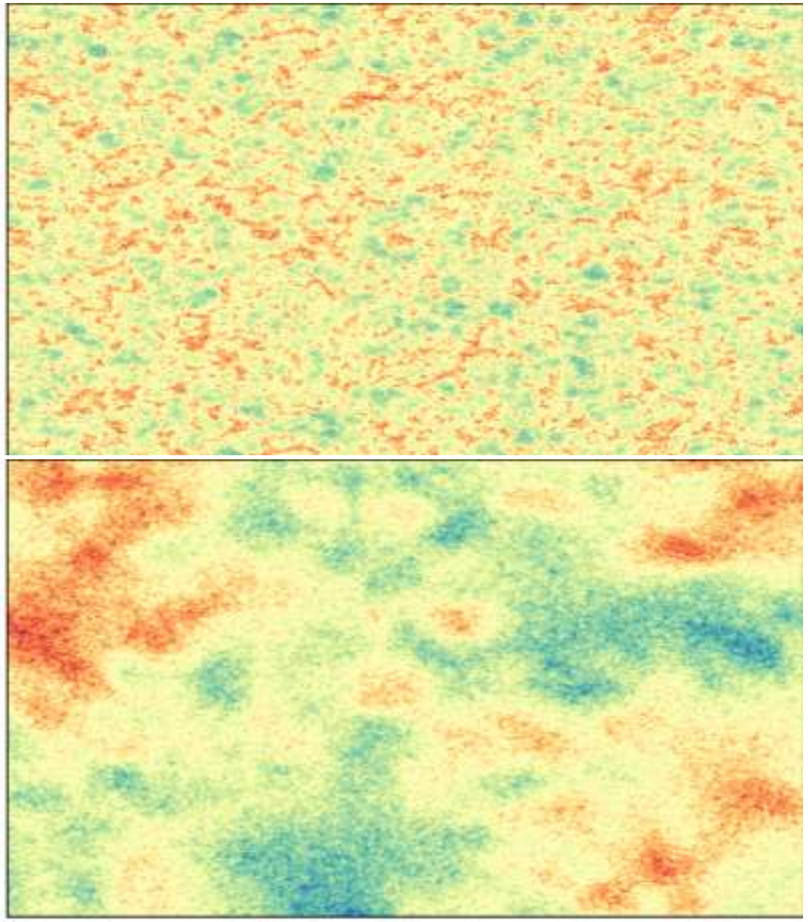
**Separation methods will be needed beside using the EoR window**



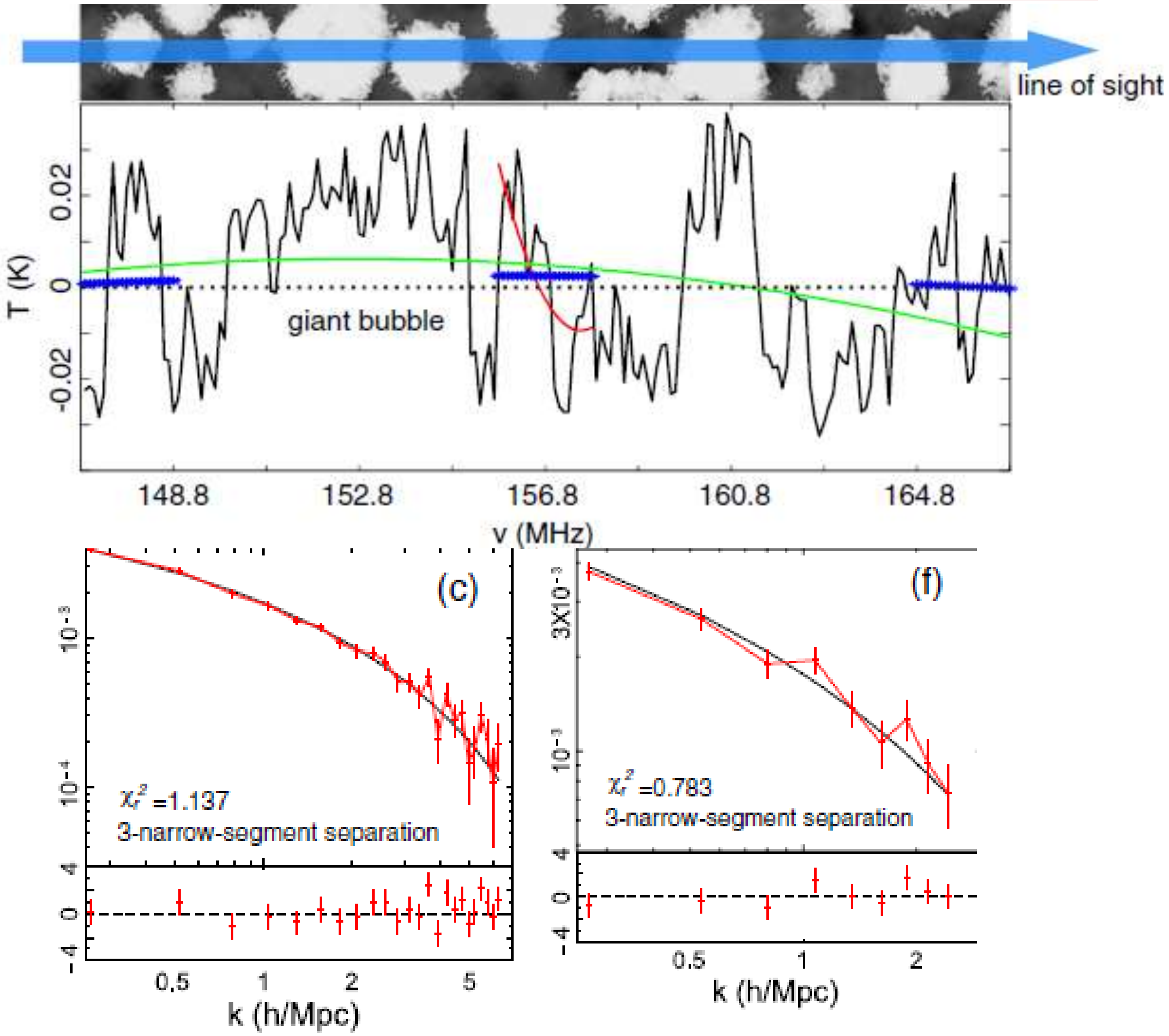

2D Power spectrum for sky maps(upper) and dirty maps(lower)

# If there is no observational effect

## EoR signal can be seperated



EoR signal （upper） &foreground （lower） without instrument effect




An illustration of polynomial fitting

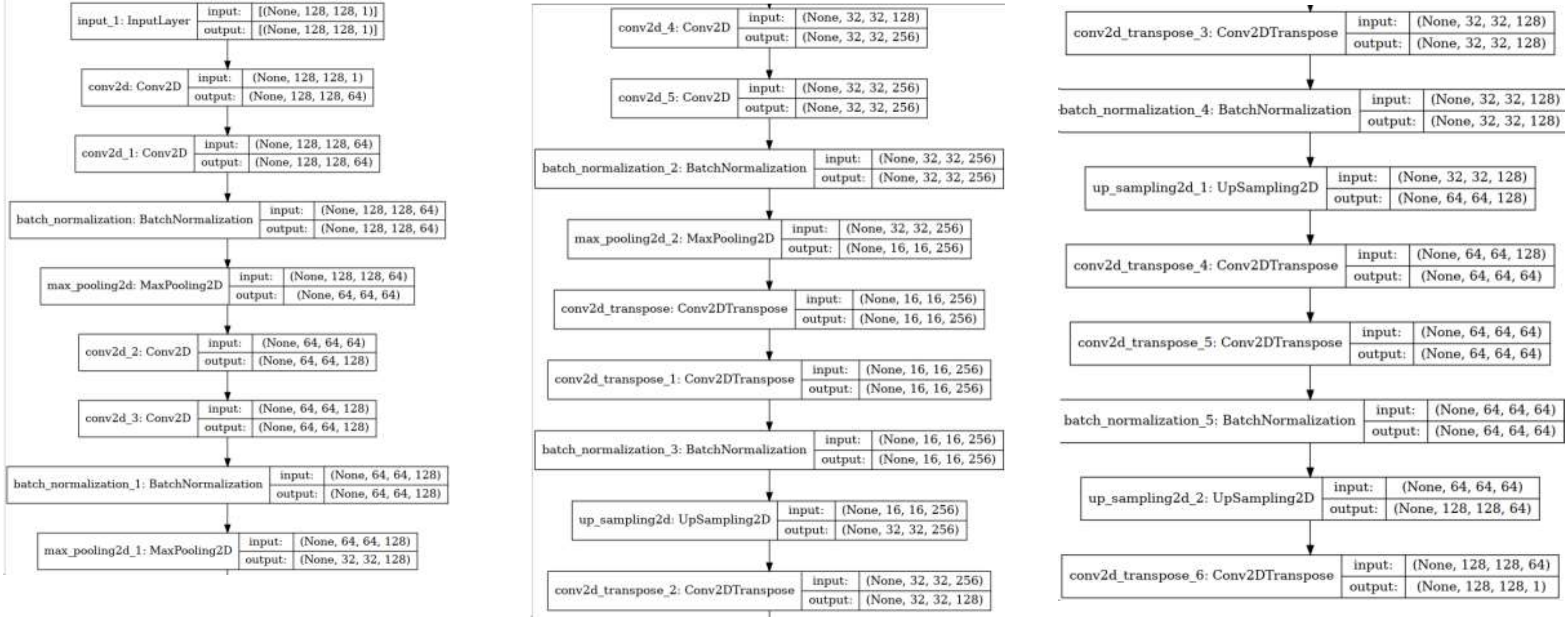
（Wang et al. 2013）

# IDEA: Machine learning for de-convolution

- **Training set:**
  - **Image CUBE：2048*2048*901，Central 1024*1024 are used**
  - **Three weighting（BRIGGS，NATURAL，UNIFORM)**

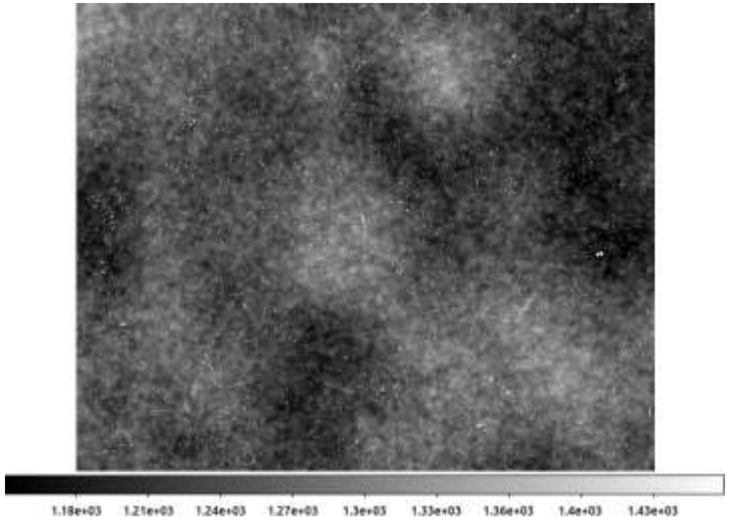
- **Division and normalization:**
  - **Normalized for each image cube（mean=0，std=1)**
  - **Cut the figure into the size of 128*128**

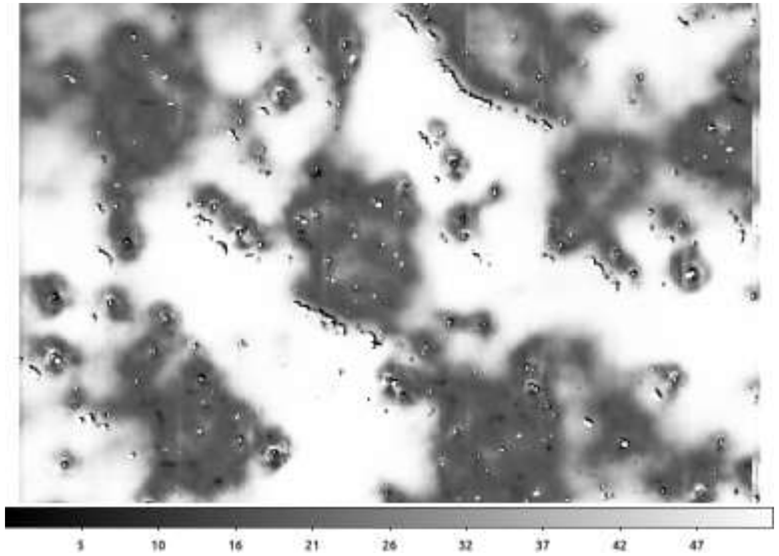
# U-Net network (for now)

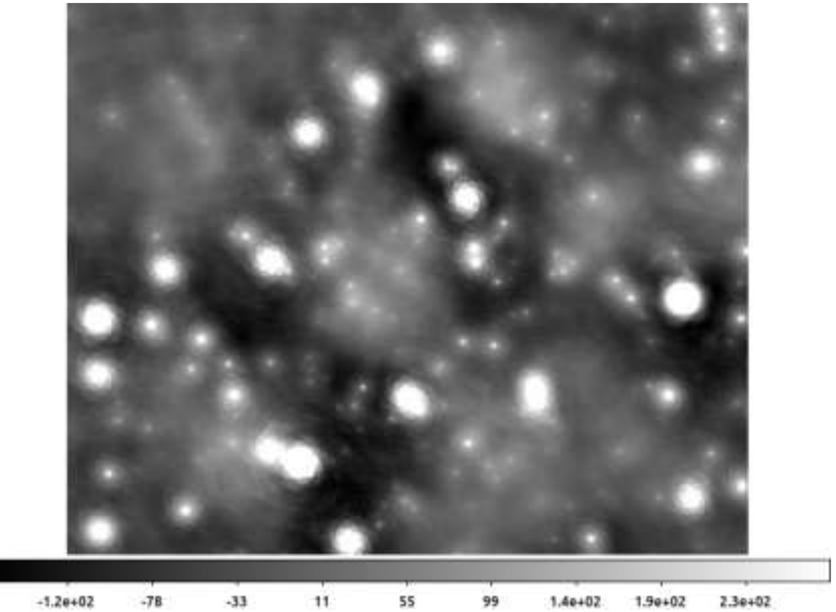



From left to right： 6 convolutions， 3 max-poolings， 6 transpose convolutions ， 3 up-samplings， 1 transpose convolution

# Training Result



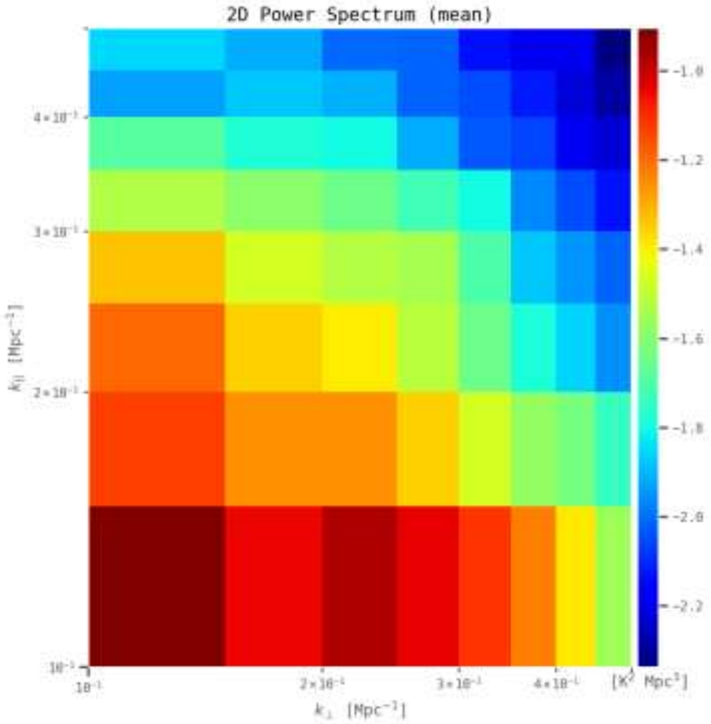



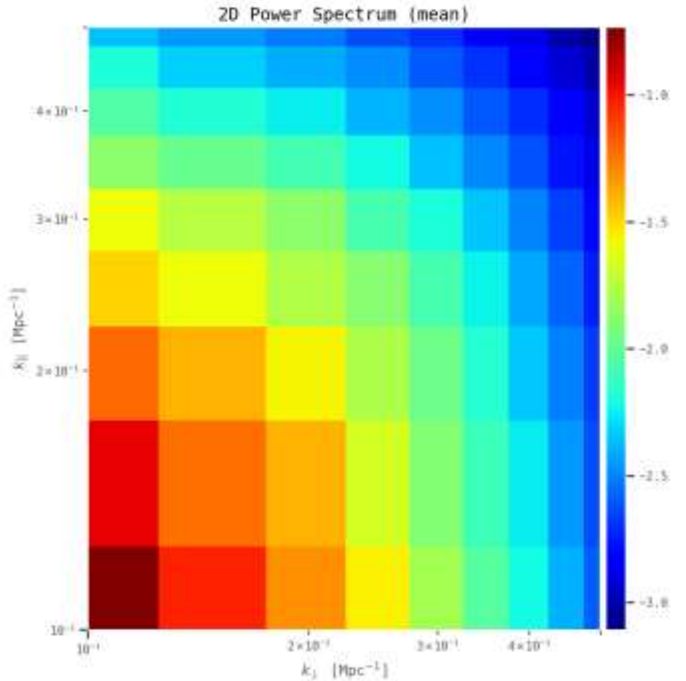




Upper left：skymap，left：dirty map，right：“cleaned” map from U-net network

Upper right：2D PS of EoR signal from polynomial fitting

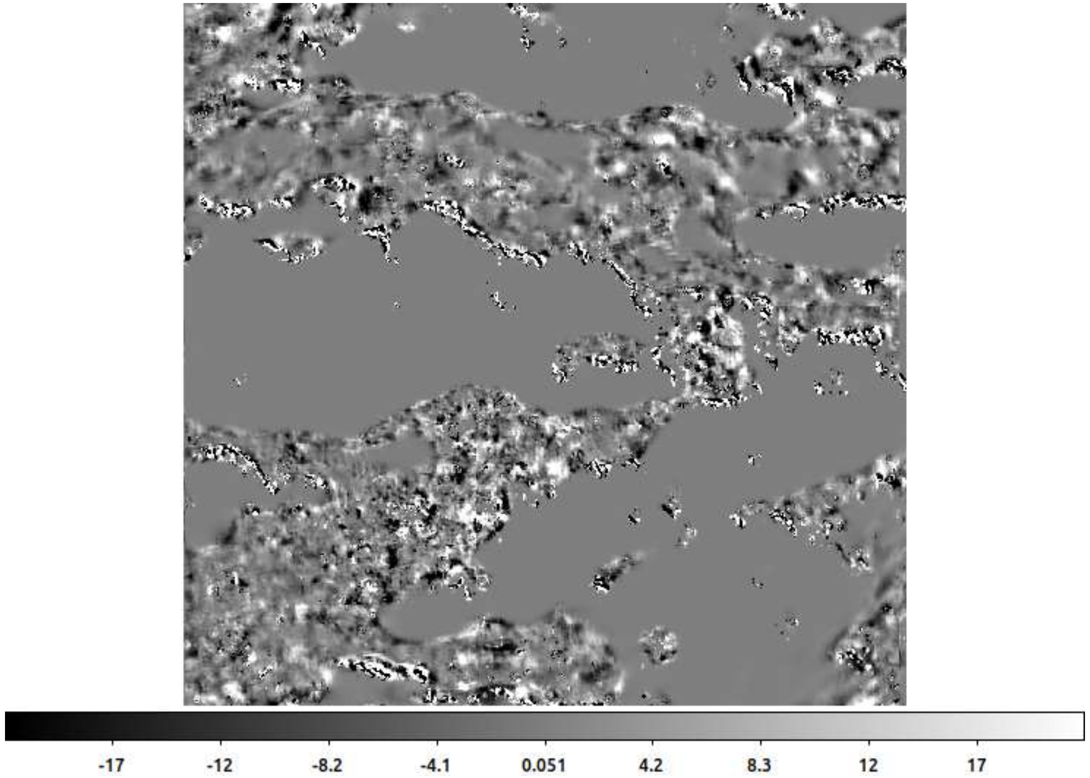
Lower right：True value of the input EoR PS.

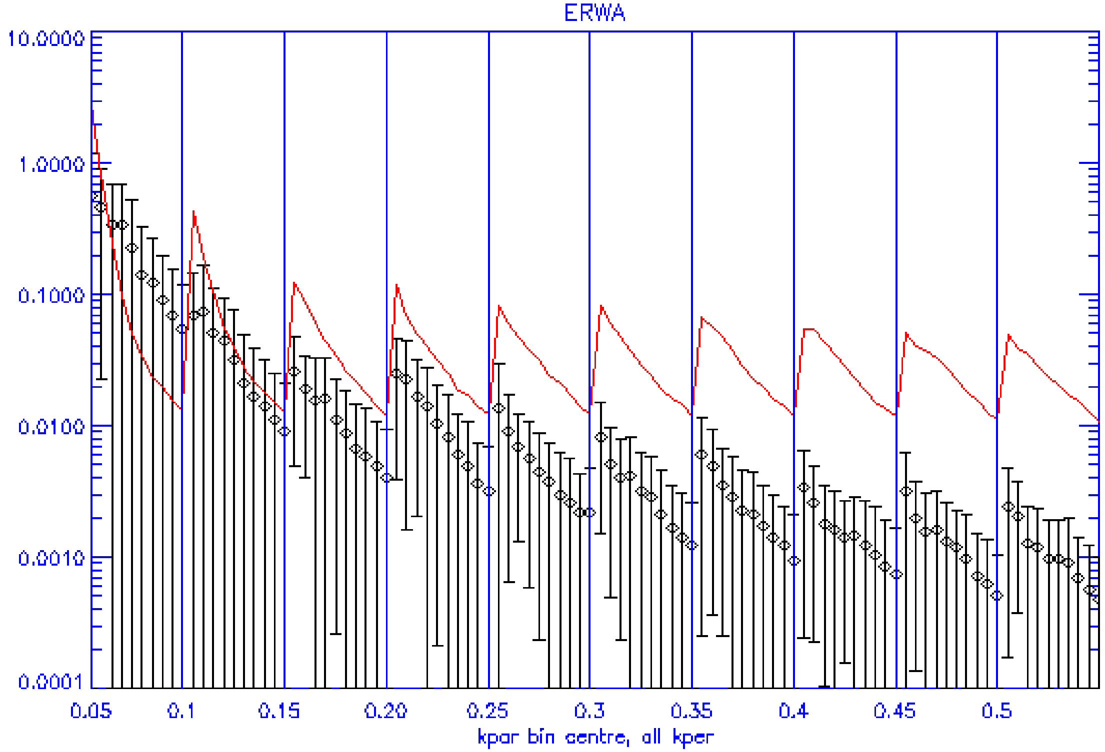


# SDC3：Result

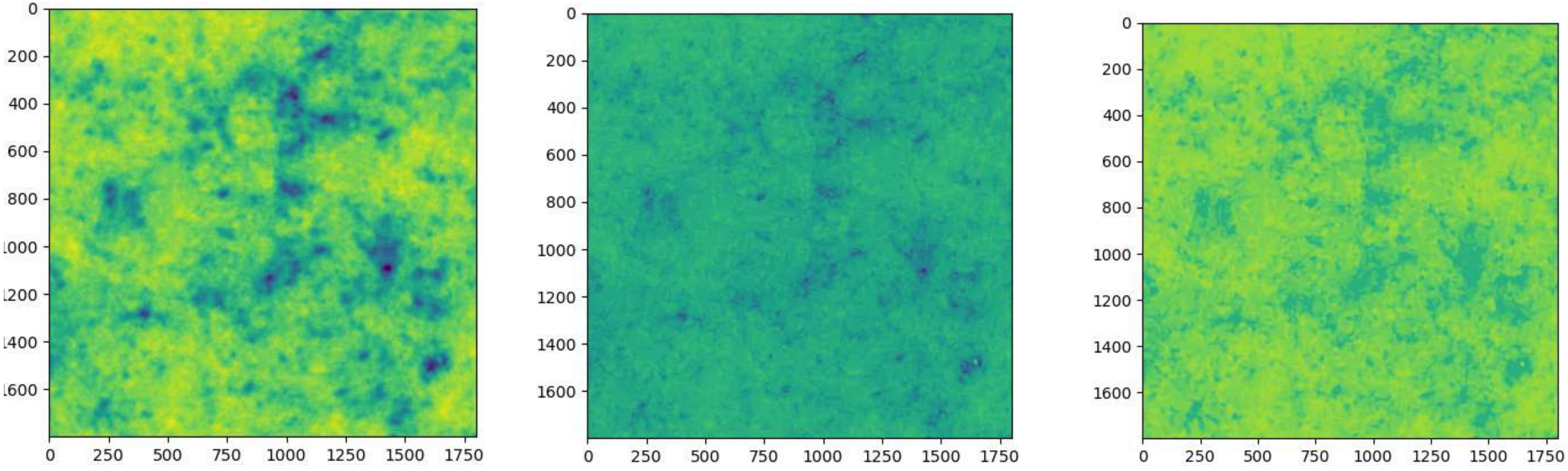
## Apply the U-Net network to SDC3 data，and separate the EoR signal use polynomial fitting




left：the EoR signal we got.
right：Comparison of the PS with true value.

# After SDC3: Future Plan




left： dirty map； middle： sky model; right： U-Net output

Updating the training set —— E2E STAGE I （7200*7200） * （512*3） *3*3

Updating the network: taking PSF into account

Better pre-processing…

**Thank you for listening!**
**Comments & Questions are welcome!**