Analysis of Tomographic 21-cm Data

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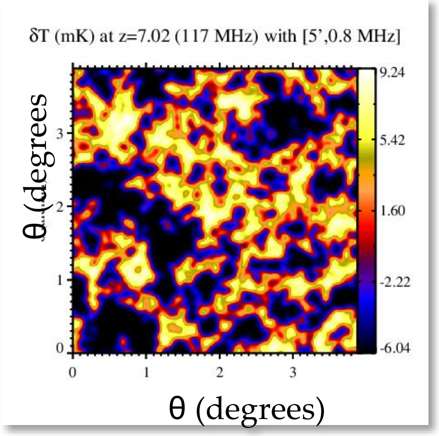
Agenda

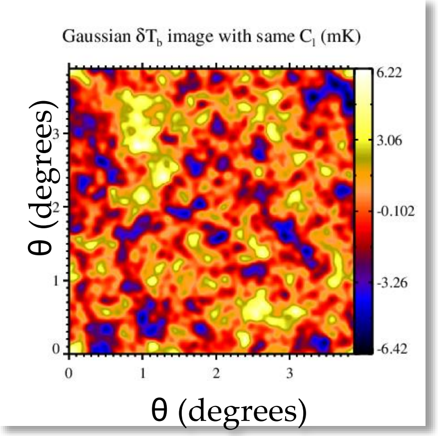
- **Question**: How to identify **ionized regions** in real tomographic 21-cm datasets?
- **Answer**: New method called "**superpixels**"
- **Bonus**: Superpixels also give you the global 21-cm signal and the ionizing photon flux density.

Tomographic Images is SKA Priority

- The 21-cm signal is strongly non-Gaussian
  - The spherically averaged power spectrum does not fully describe it

Simulated 21-cm image (non-Gaussian)





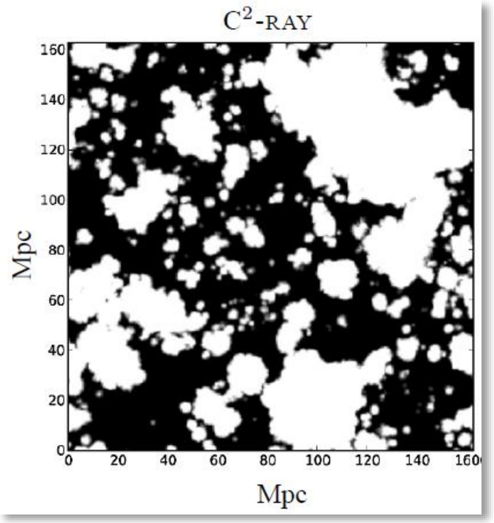
Gaussian image with the same power spectrum

- Different biases & calibration issues
- Connection to other observations (e.g. galaxy surveys).

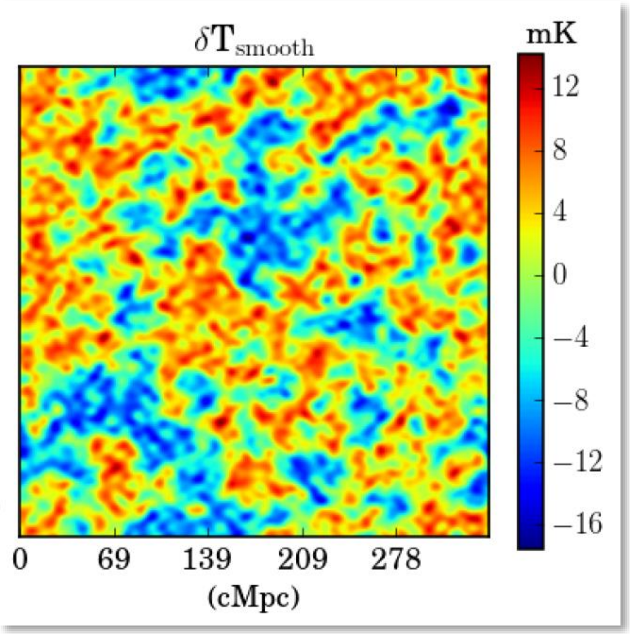
How to analyse tomographic images?

- We need statistical tools other than the power spectrum.
- Tools with physical interpretation attractive option.

- For high spin temperature: $\delta T_b = 0 \Leftrightarrow$ ionized regions
- **Ionized regions**:
  - Measures progress of reionization
  - Source of non-Gaussianity in 21-cm
  - Sensitive to properties of sources and small scale absorbers
  - Size distributions, topology, morphology, fractal dimension, …



Identification of IRs non-trivial



Simulated SKA1-Low image with noise (1000h; σ_{noise}=2.3 mK)

- Radio-interferometric images have
  - Finite resolution
  - Noise
  - No absolute flux calibration (what is $\delta T_b = 0$?)
  - Foreground residuals

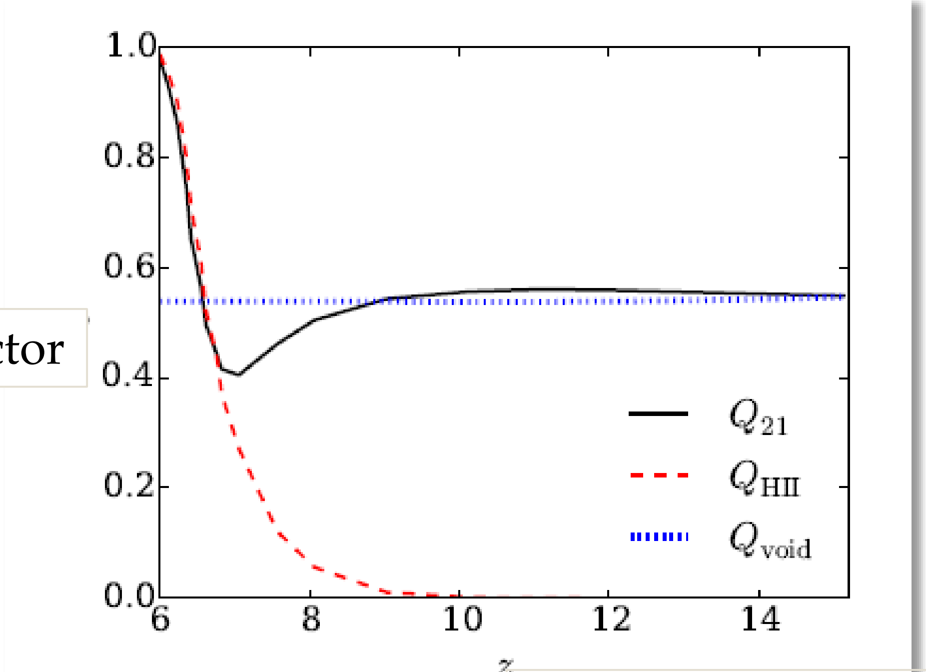
Method 1: Simple threshold

- Choose threshold: $\boldsymbol{\delta T_b = \langle \delta T_b \rangle}$
  ($\delta T_b = 0$ mK in interferometric images)

- For low $\langle x_{HII} \rangle$: **low density regions** counted as ionized.

- Works well for $\langle x_{HII} \rangle$ above ~0.4.

- Sensitive to noise.

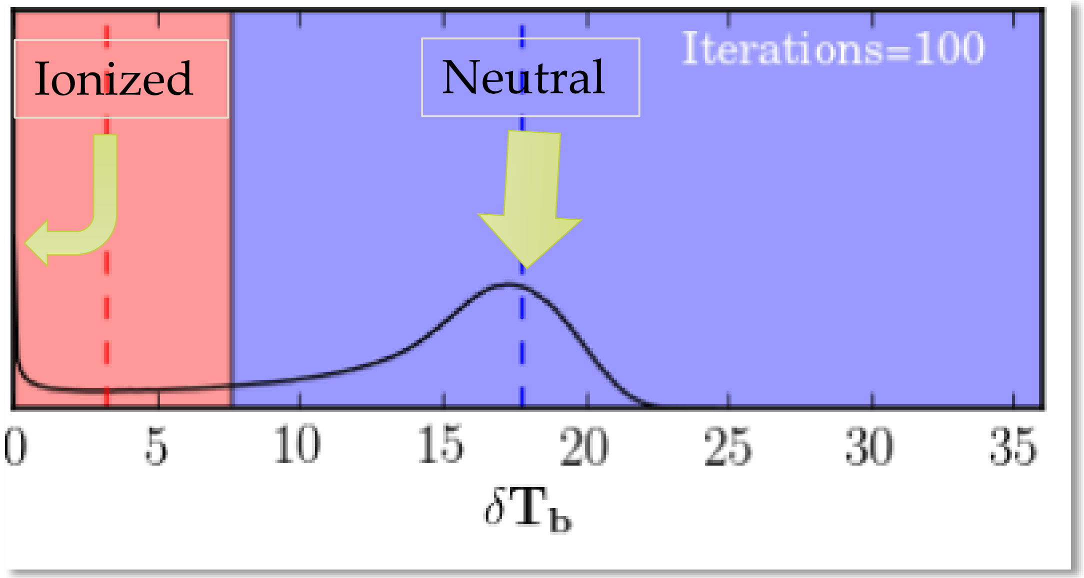


(Kakiichi et al. 2017)

Method 2: PDF-based threshold

- The 21-cm PDF is **bimodal**.
- Use this to label resolution elements as ionized or neutral (Otsu's method or K-means clustering).

- Works well if PDF is bimodal enough:
  - $<x_{HII}>$ above ~0.1.
  - Low noise contribution.

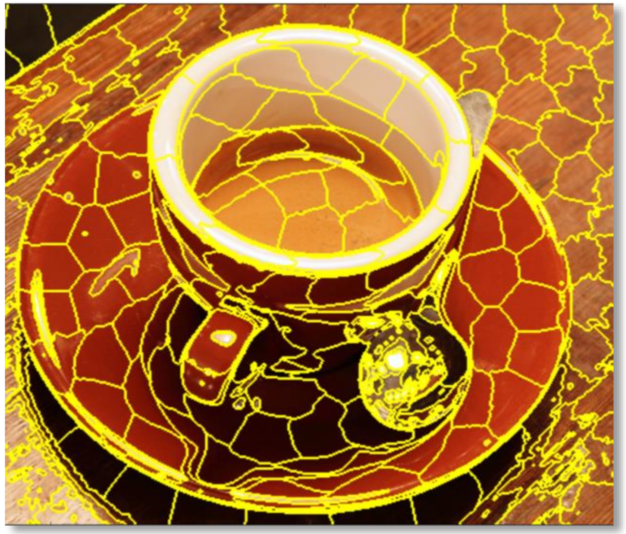


Giri, Mellema, et al. (2017), arXiv:1706.00665

Method 3: Superpixels

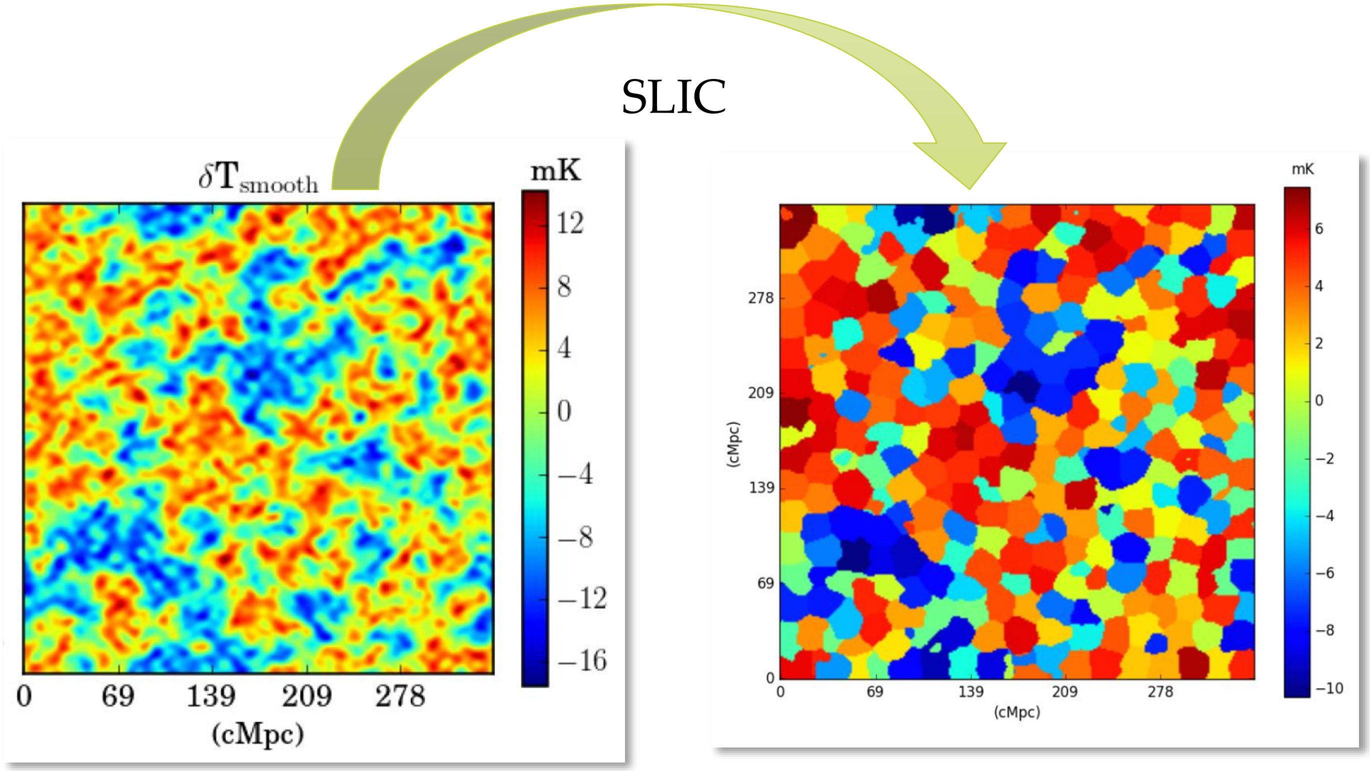
- Group resolution elements with similar properties into superpixels.
- Well known method from Computer Vision.
- Based on **distance recipe**
- SLIC = Simple Linear Iterative Clustering

SLIC



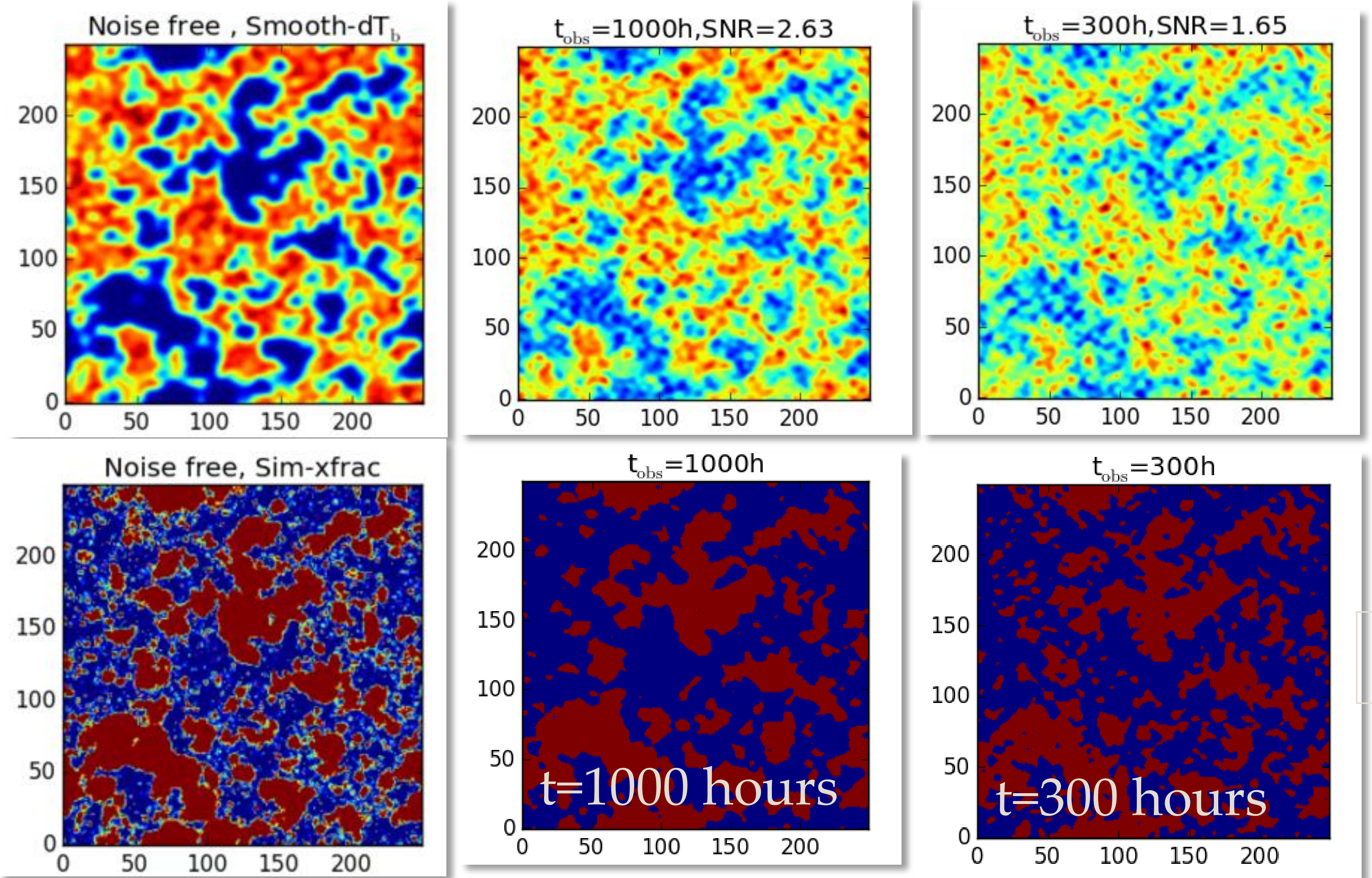
Method 3: Superpixels

- After segmentation: stitch similar superpixels together.
- Use PDF of stitched superpixels to find IRs.
- Much less affected by noise.



Giri, Mellema, et al., in prep.

Superpixels deal well with noise



21-cm image
SKA1-Low

Ionization field

Superpixels are versatile

IRs: $\delta T_b = 0$

interferometry

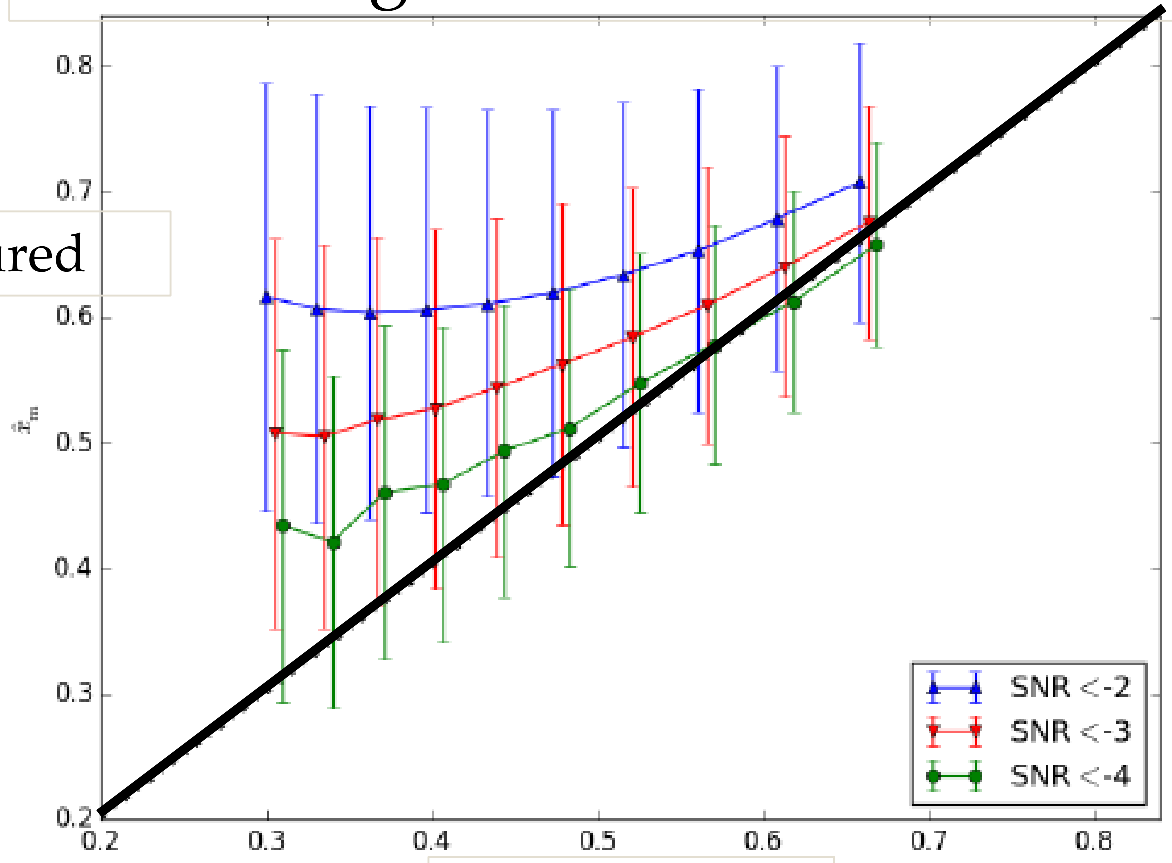
$\delta T_b \approx - < \delta T_b >$

(-**Global Signal**)

$< \delta T_b > \propto < x_{HII} (1+\delta) >$

(Mass weighted ionization fraction)

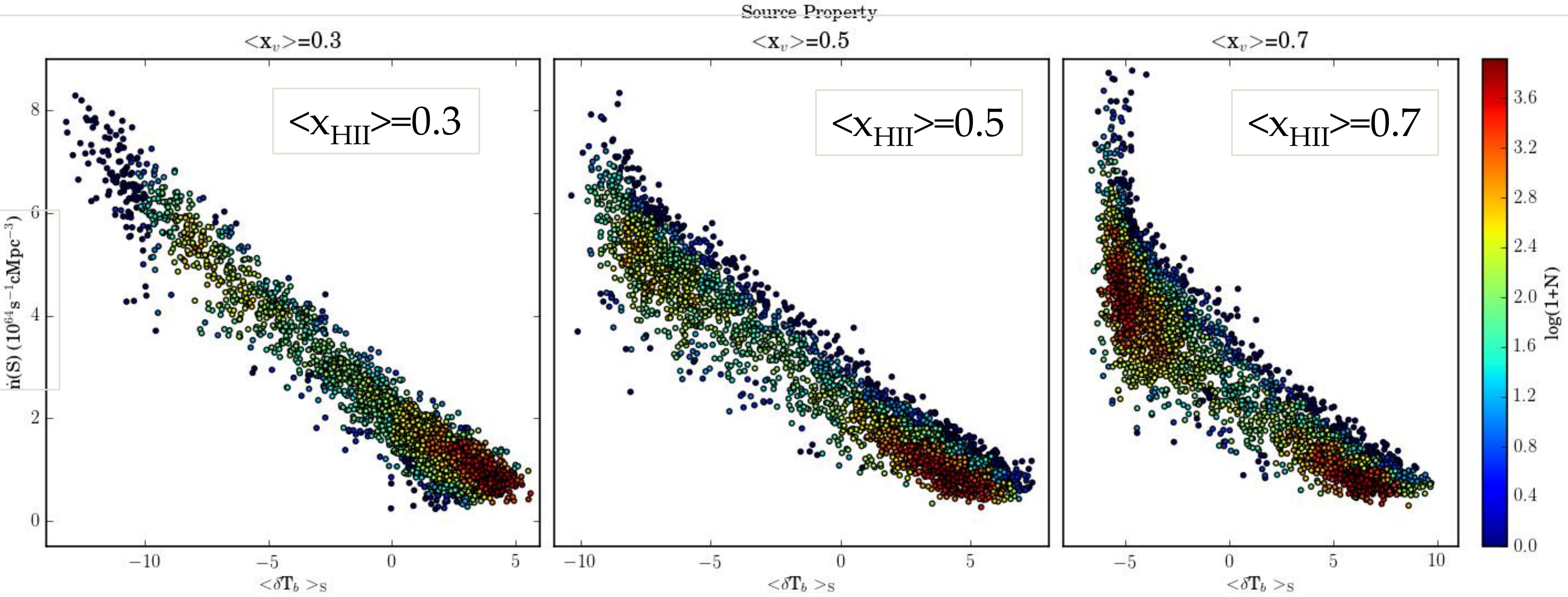
Mass weighted ionization fraction



Superpixels are versatile

Average **21-cm signal** in superpixels correlates with **ionizing photon flux density**

Ionizing photon flux density (10^{64} s^{-1} $cMpc^{-3}$)



Average 21-cm signal in superpixels (mK)

Summary

- Superpixel method most successful in identifying IRs in realistic 21-cm tomographic data sets.

- Distribution of IRs can then be analysed in many ways:
  - Ionized volume, power spectra, bubble size distributions, topology, etc.

- Superpixels also can be used to measure
  - Global signal
  - Ionizing photon density