Recovering 21cm intensity maps from post-reionization epoch

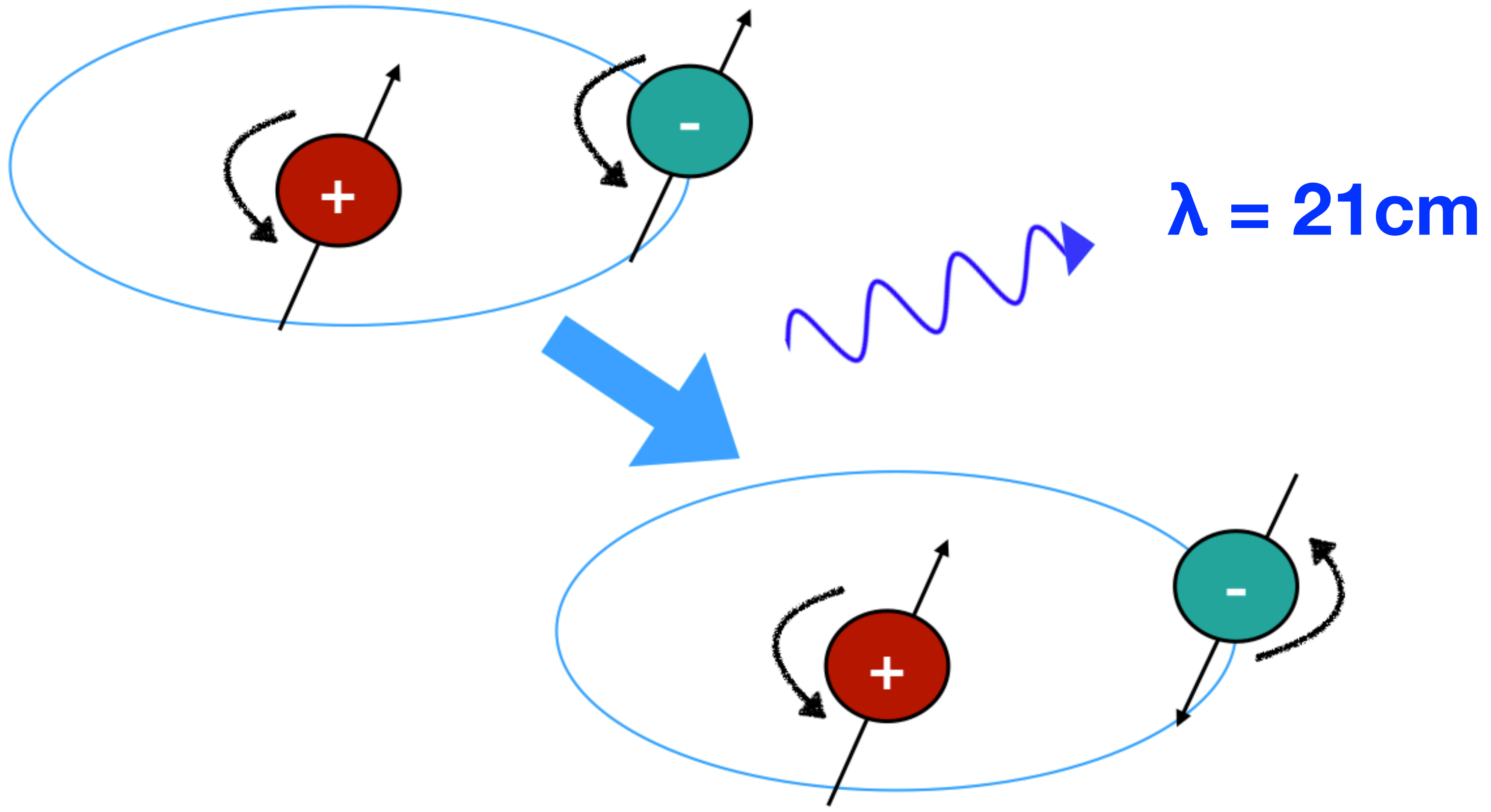
Isabella P. Carucci

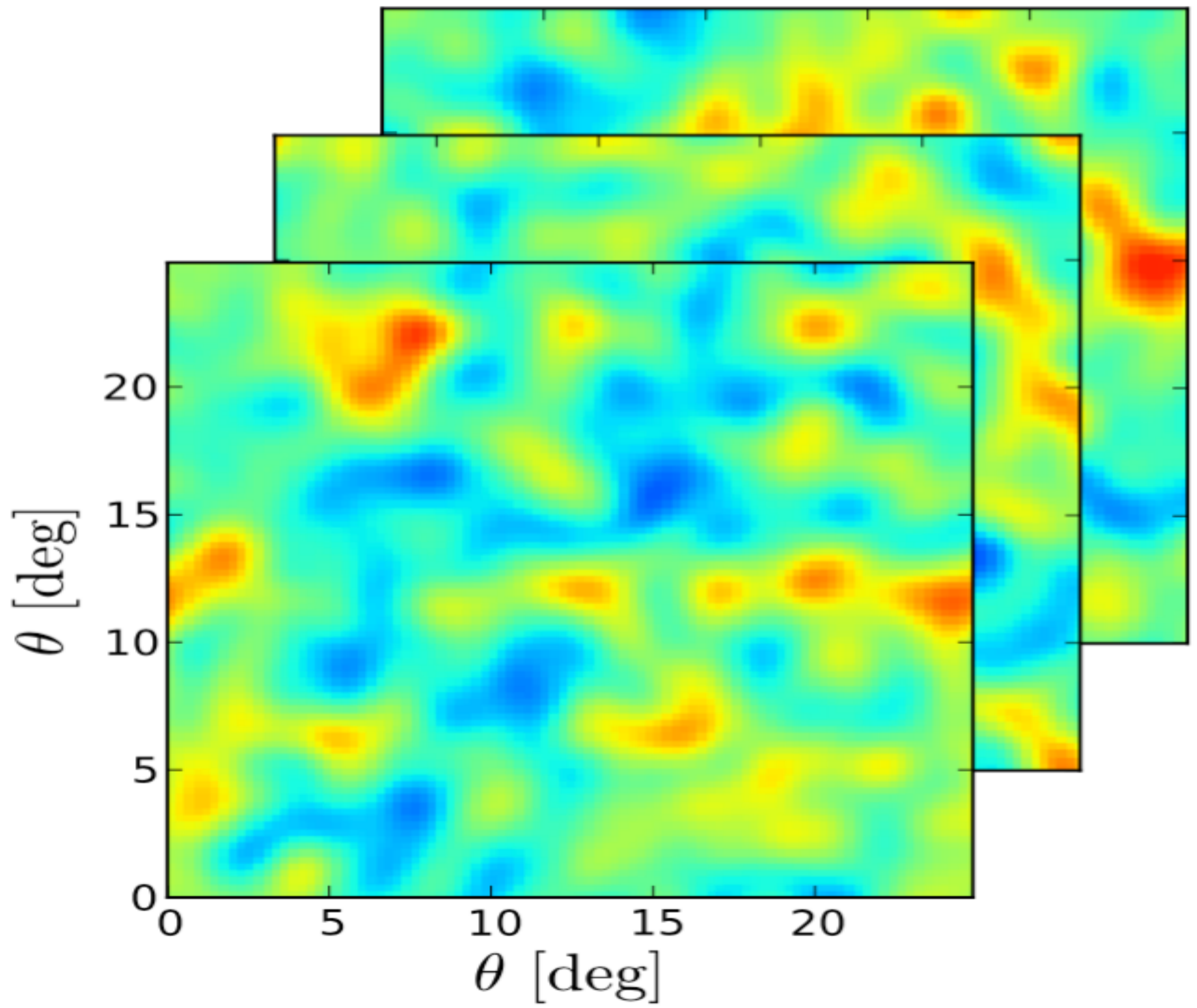
CosmoStat, CEA Paris-Saclay

21cm Cosmology Workshop - Orsay

21 October 2019

21cm intensity maps

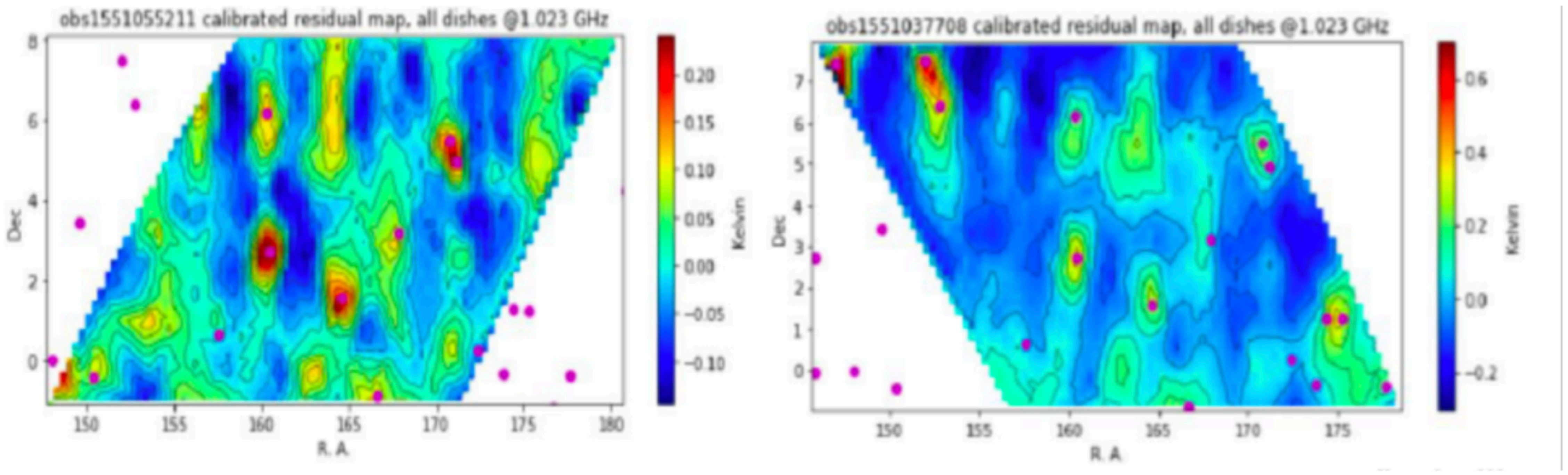




- spectroscopic nature
- large volumes (for cheap)
- Cosmology using HI as tracer!

The future is bright

- SKA (MeerKAT already, single dishes, up to z~1.45)
- Chime (interferometer, to z~2.5)
- Tianlai (interferometer, to z~2.5)
- Bingo (single dish, up to z~0.48)
- FAST (single dish)
- HIRAX (dishes)
- ORT
- …

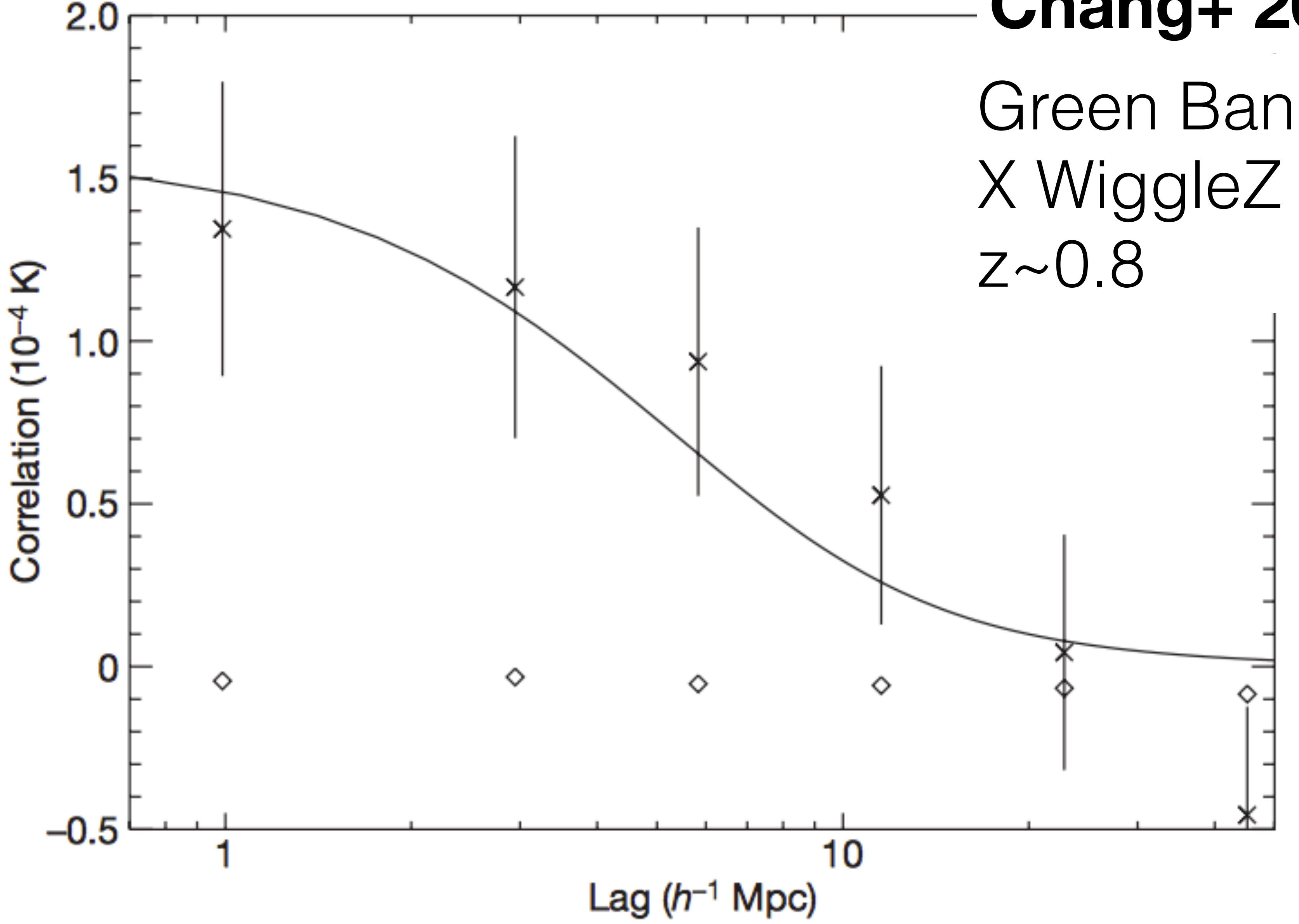


MeerKAT 21cm IM tests (courtesy of Mario Santos)

Measurements

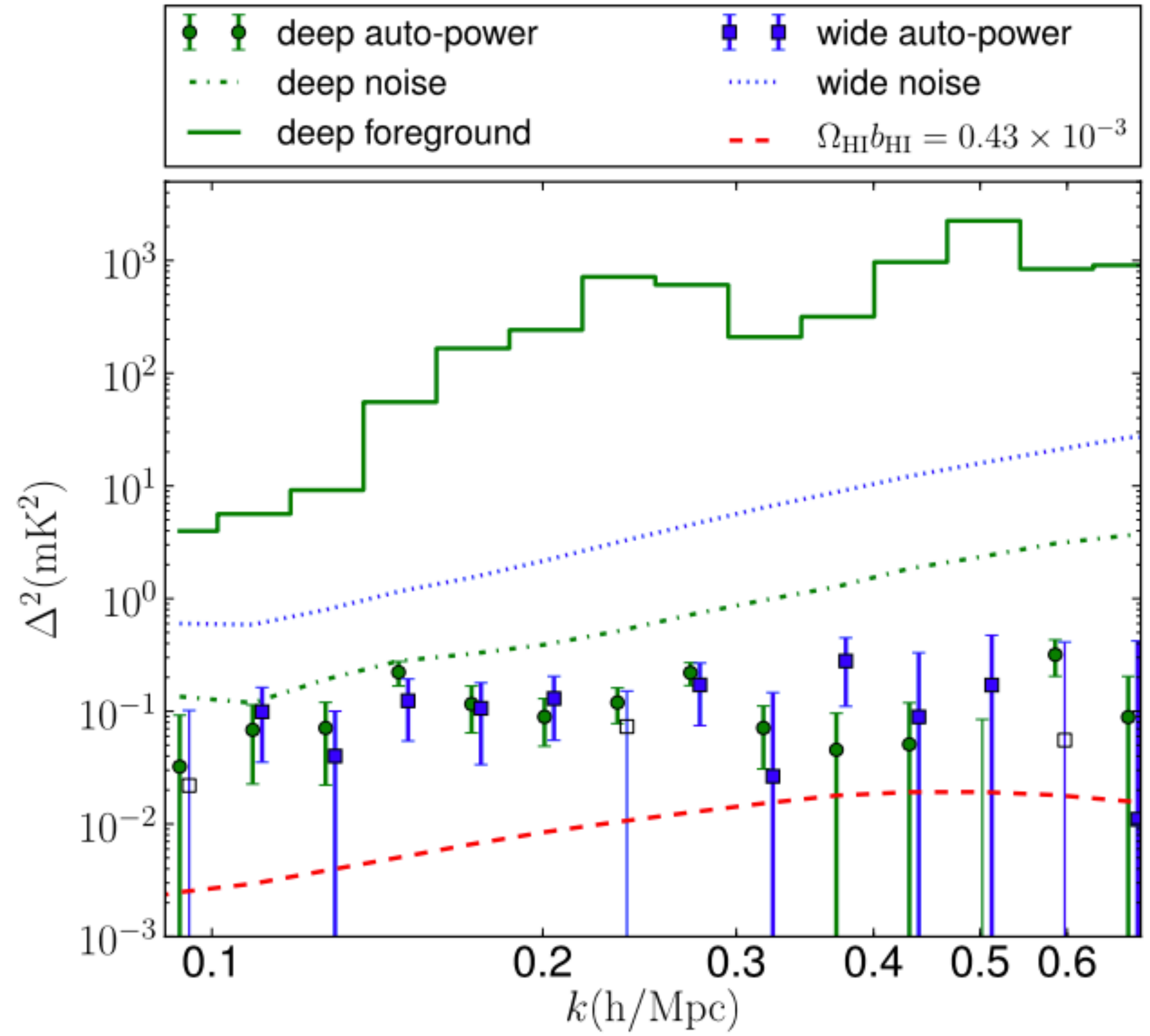
Chang+ 2010

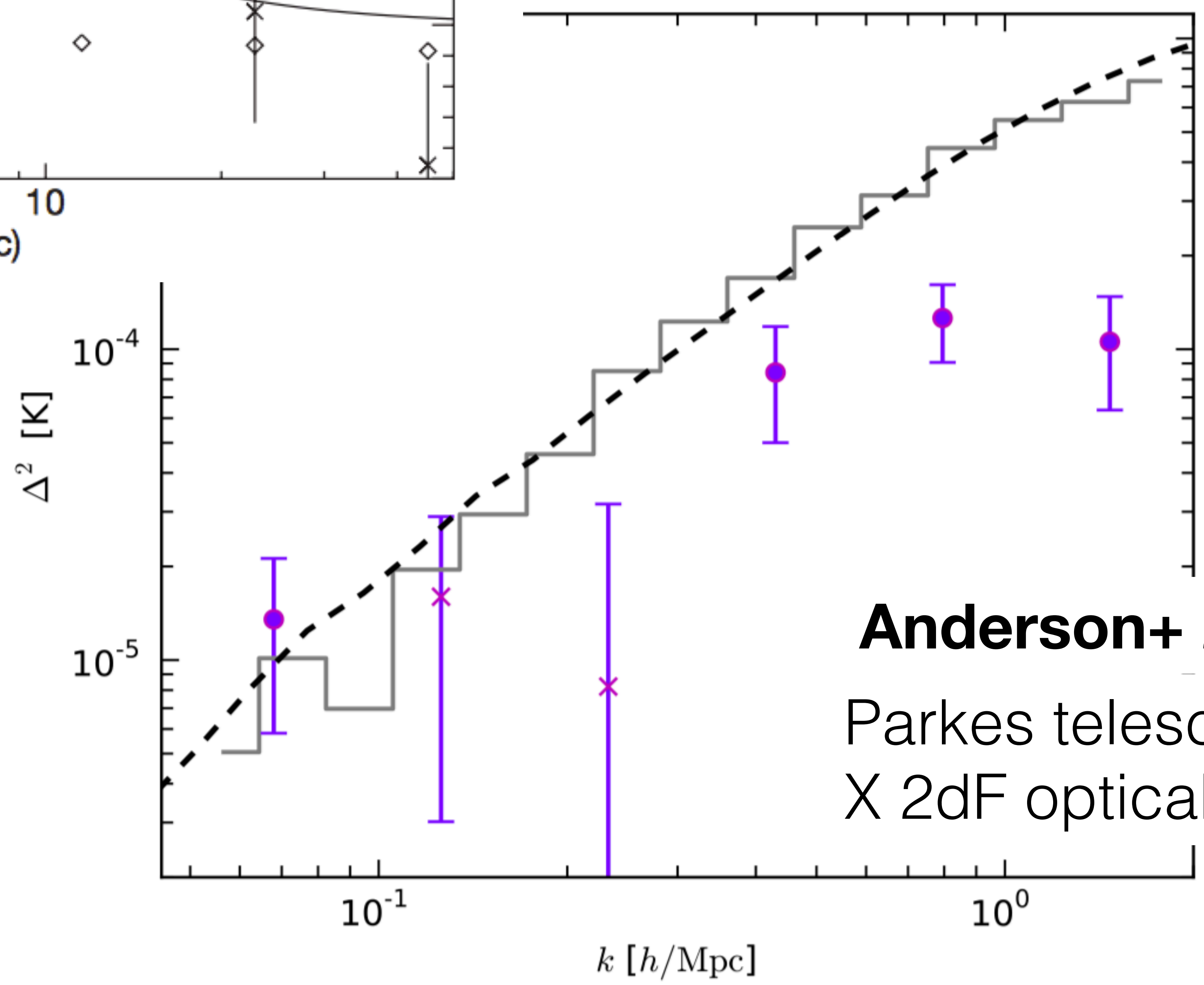
Green Bank Telescope
X WiggleZ galaxies
z~0.8



Switzer+ 2013

21cm IM auto-P(k)





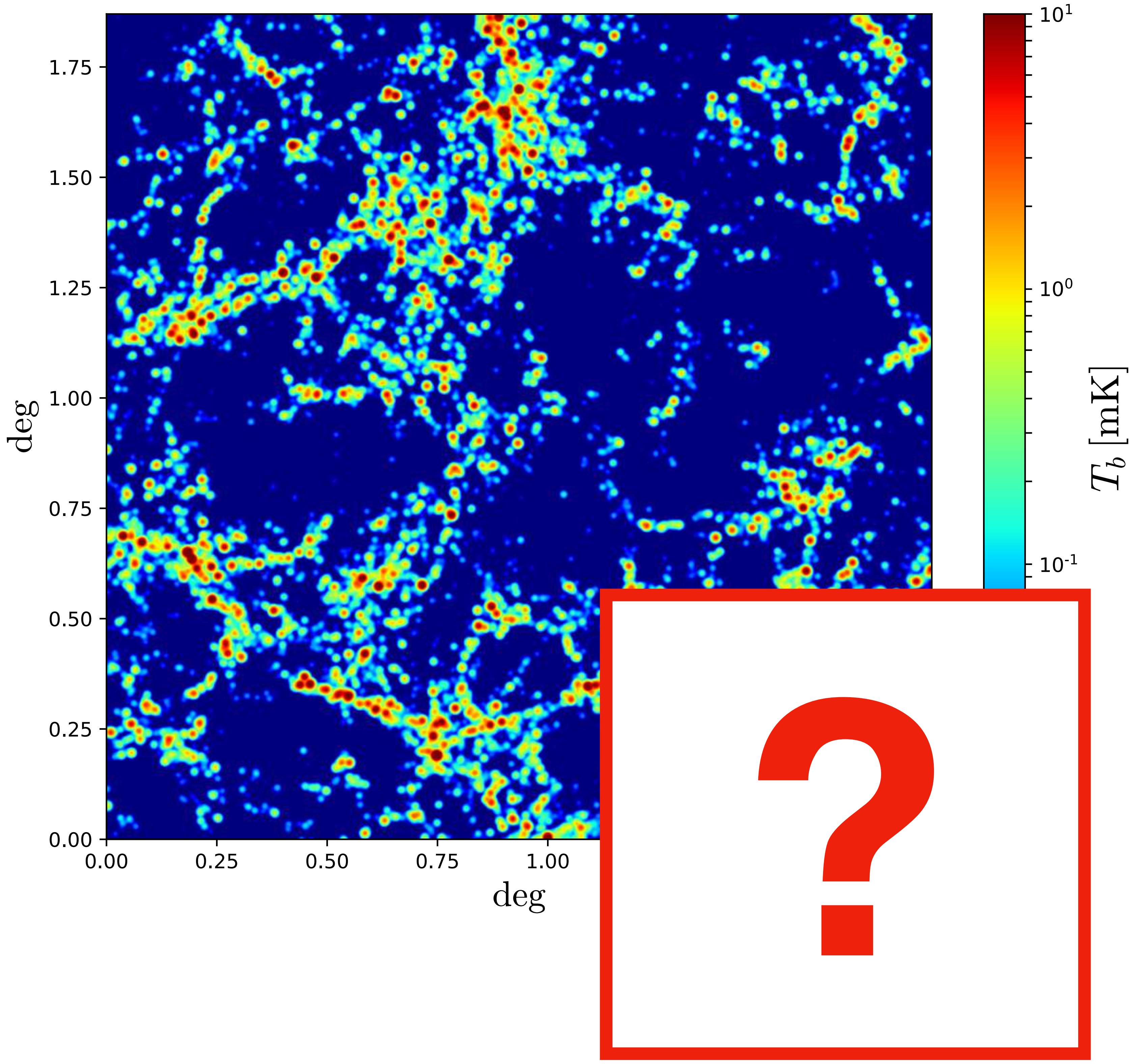
Anderson+ 2018

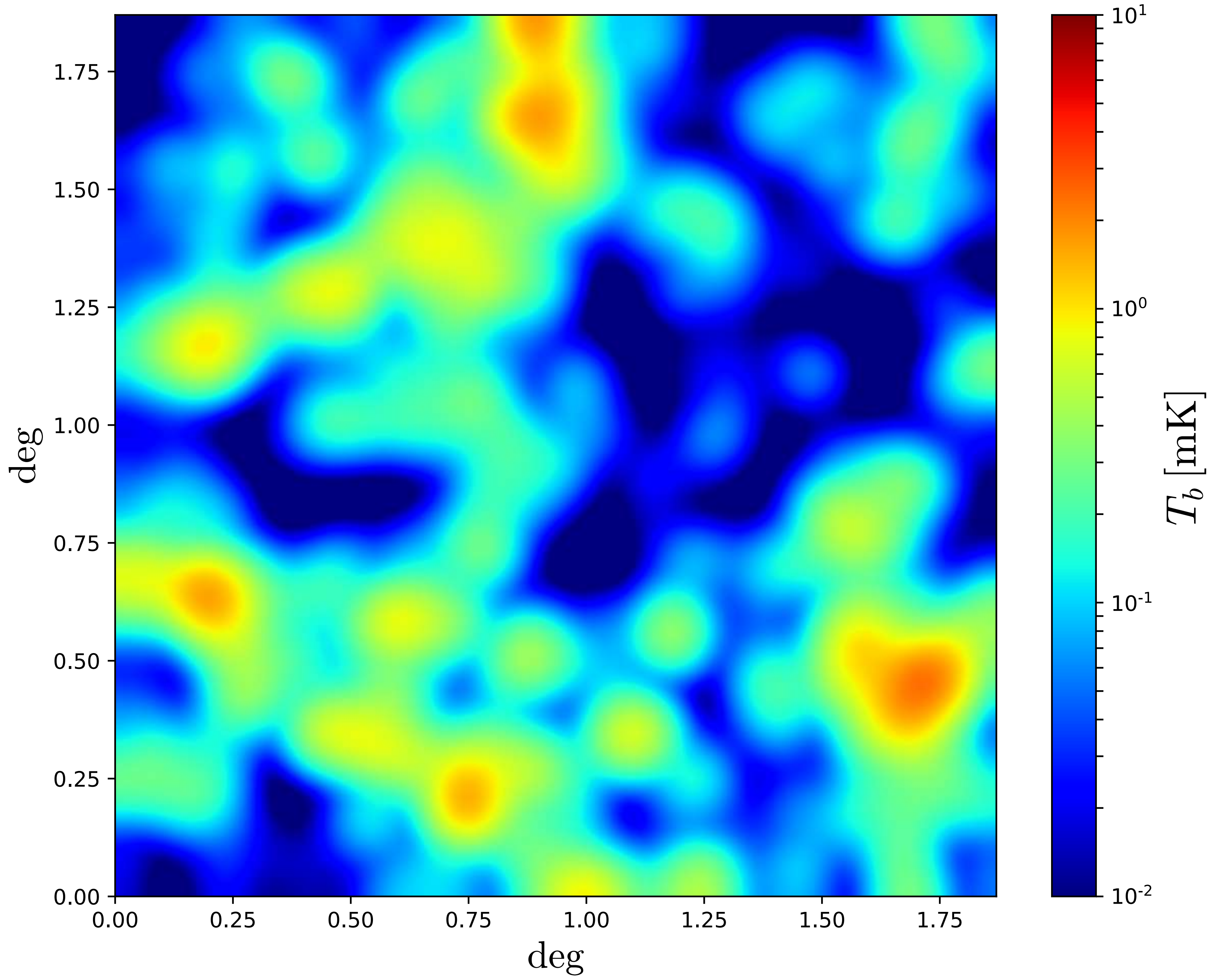
Parkes telescope
X 2dF optical galaxies

Recovering 21cm intensity maps from post-reionization epoch

- modelling
- synergies with other probes
- foreground cleaning and instrumental effects

modelling → forecasts





Villaescusa-Navarro, .. , IPC + 2018

Distribution of HI in the post-reionization universe

$b_{HI} \simeq 0.8$
at $z \sim 0$

- the clustering of **HI selected galaxies at $z \sim 0$** from the ALFALFA survey (Martin+ 2012, Guo+ 2017)

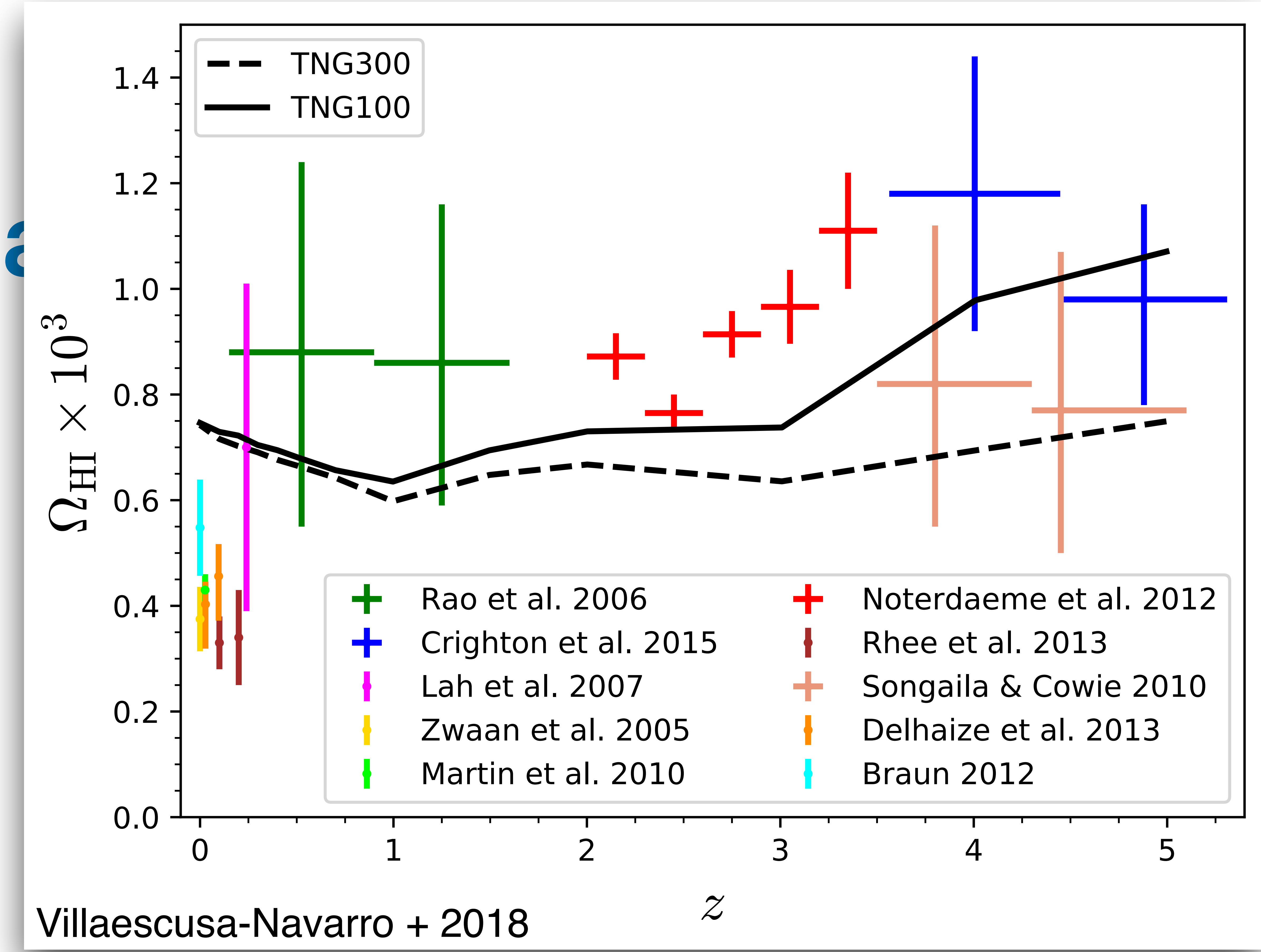
$b_{DLAs} = 1.99 \pm 0.11$
at $z \sim 2.3$

- the bias of the Damped Lyman-α systems **(DLAs) at $z \sim 2.3$** by BOSS collaboration (Perez-Rafols+ 2017)

$\Omega_{HI} \times b_{HI} = 0.62 \times 10^{-3}$
at $z \sim 0.8$

- HI cosmic abundance times its linear bias, from **21cm IM observations at $z \simeq 0.8$** performed with the GBT by (Switzer+ 2013)

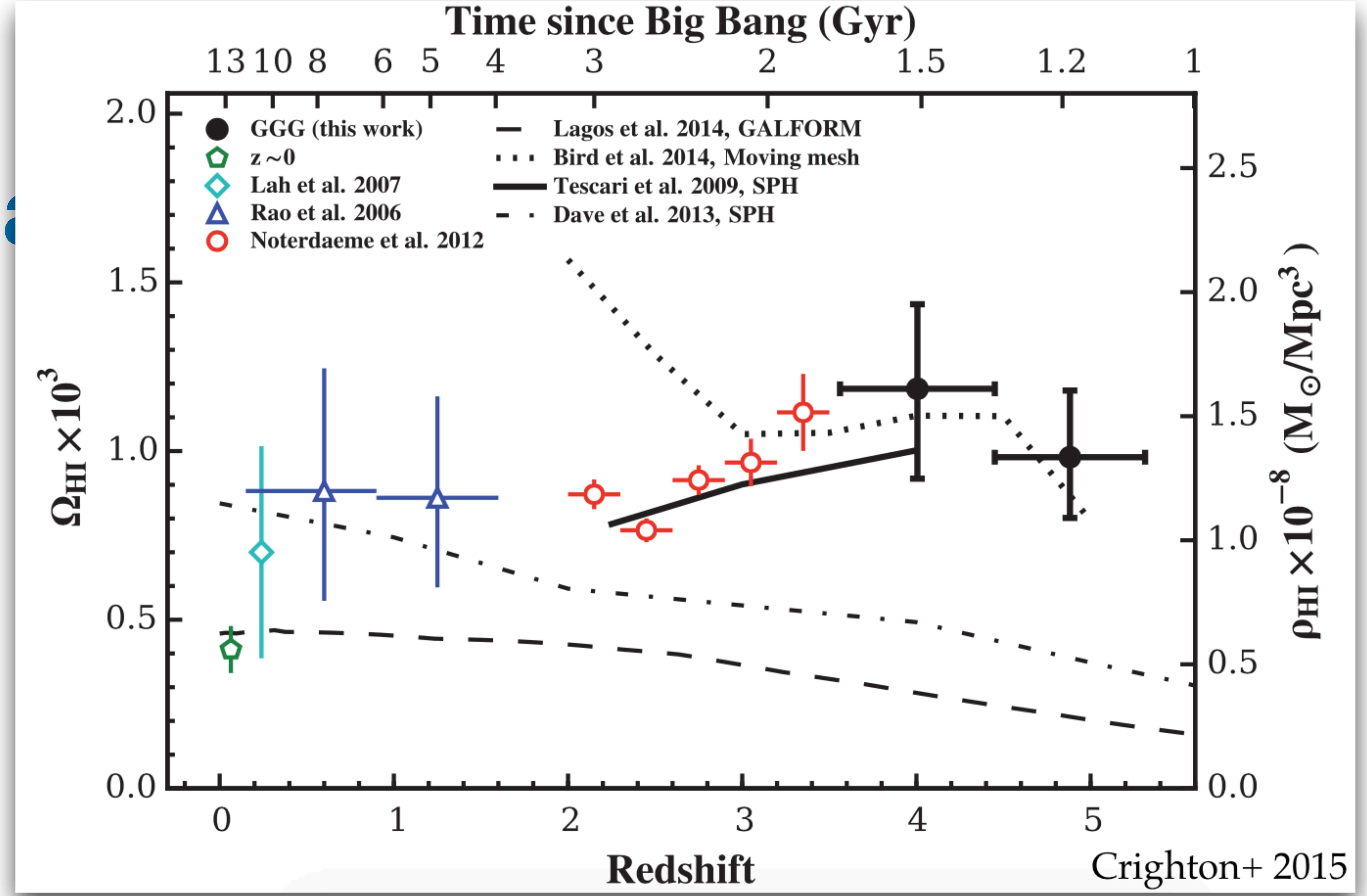
Distribution of HI in the post-reioniza



$\Omega_{HI} \times b_{HI} = 0.62 \times 10^{-3}$

at $z \sim 0.8$

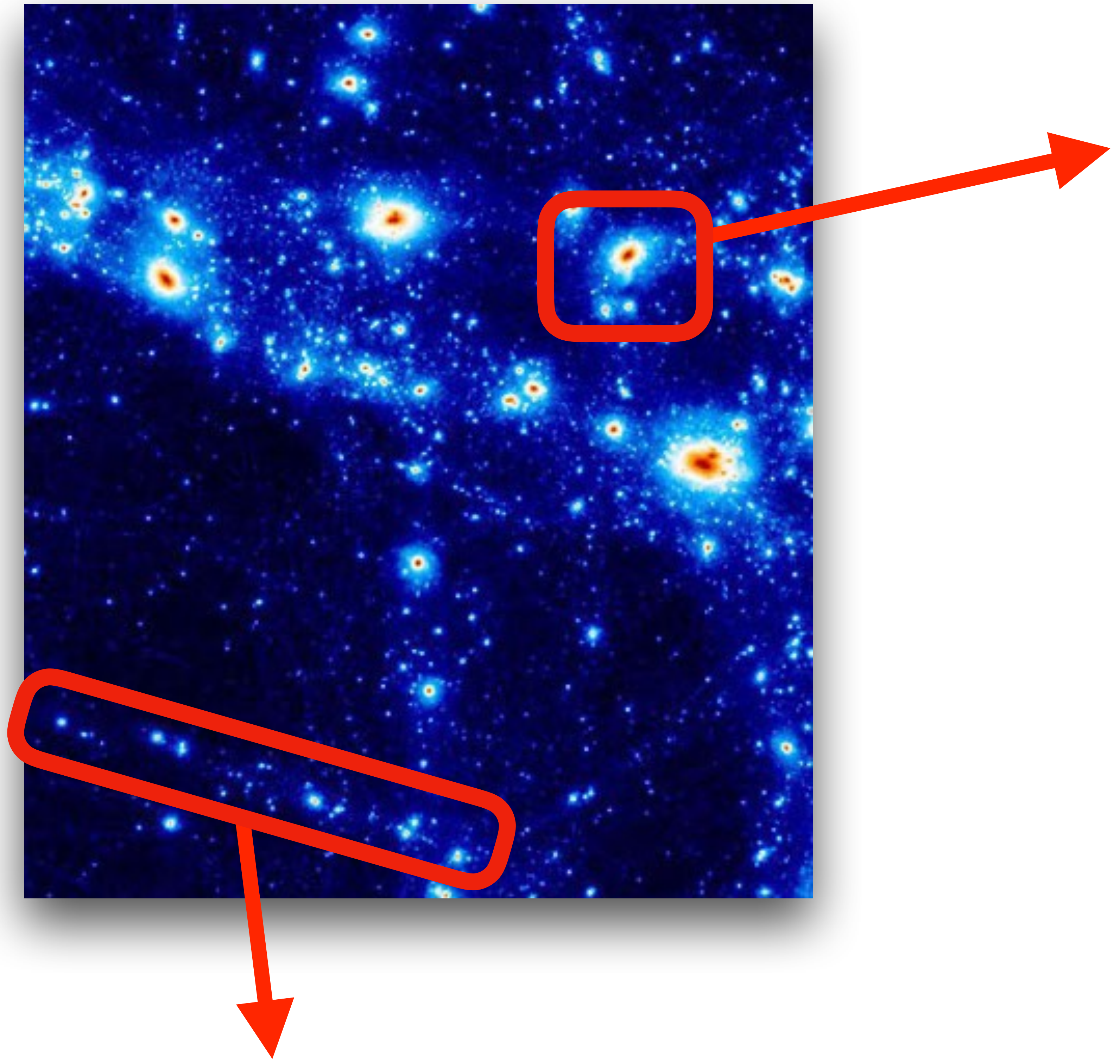
Distribution of HI in the post-reioniza



$\Omega_{HI} \times b_{HI} = 0.62 \times 10^{-3}$

at z~0.8

Distribution of HI
in the post-reionization universe

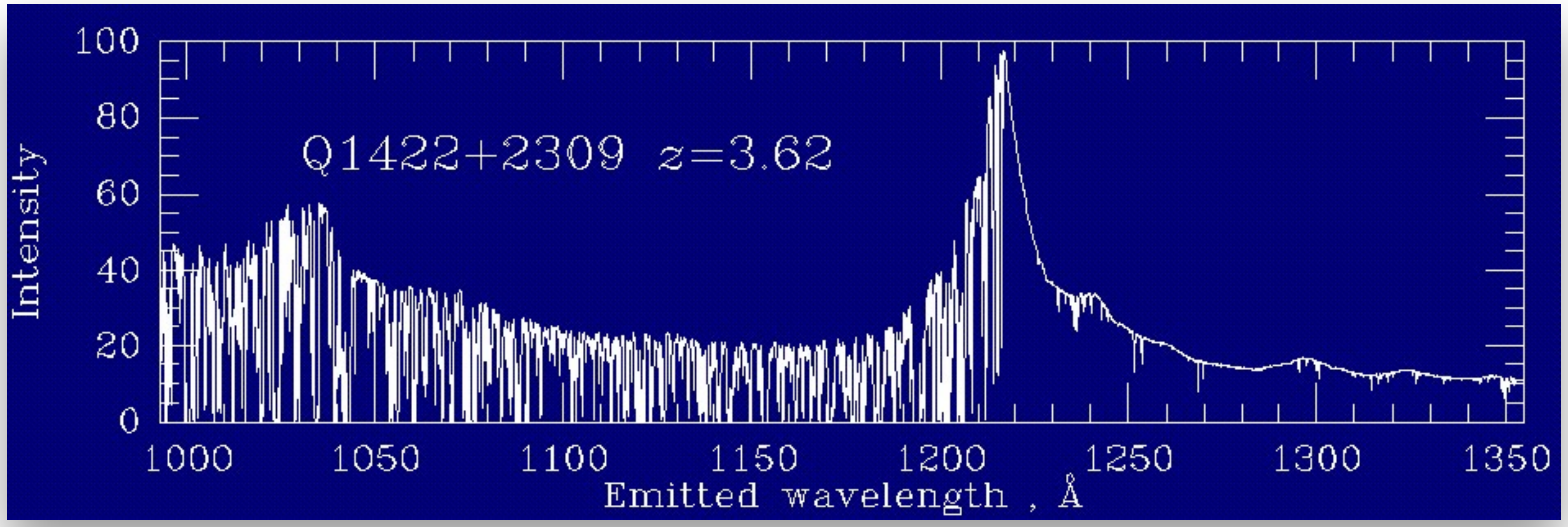


Halos **(DLAs, i.e. galaxies)**

Dense, self-shielding —> HI

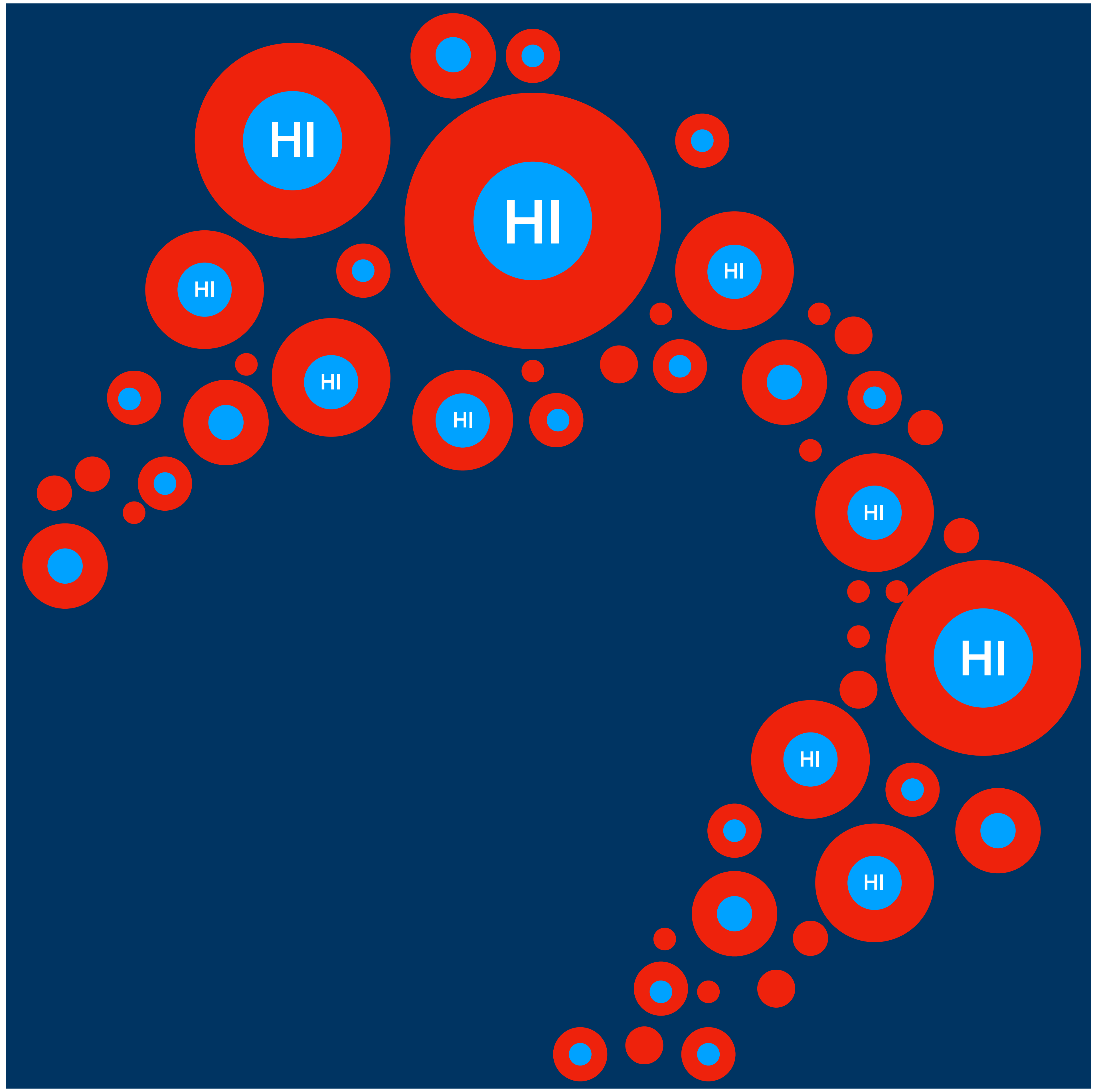
Filaments

mostly ionised H



Distribution of HI
in the post-reionization universe

Strategy 1:
HI resides in DM halos

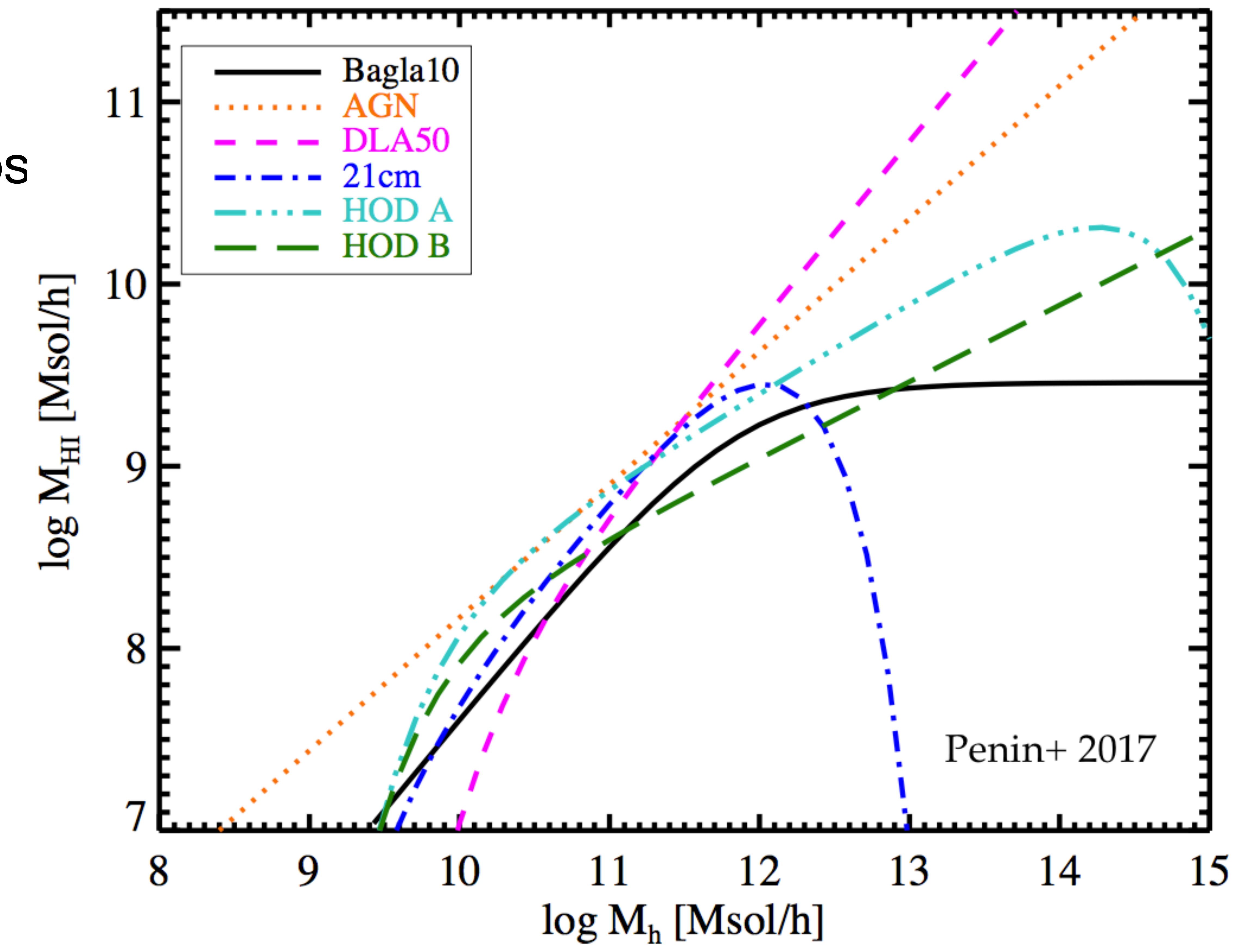


$M_{HI} = M_{HI}(M_{halo})$

if $M_{halo} > M_{min}$

Distribution of HI in the post-reionization universe

Strategy 1:
HI resides in DM halos



$M_{HI} = M_{HI}(M_{halo})$

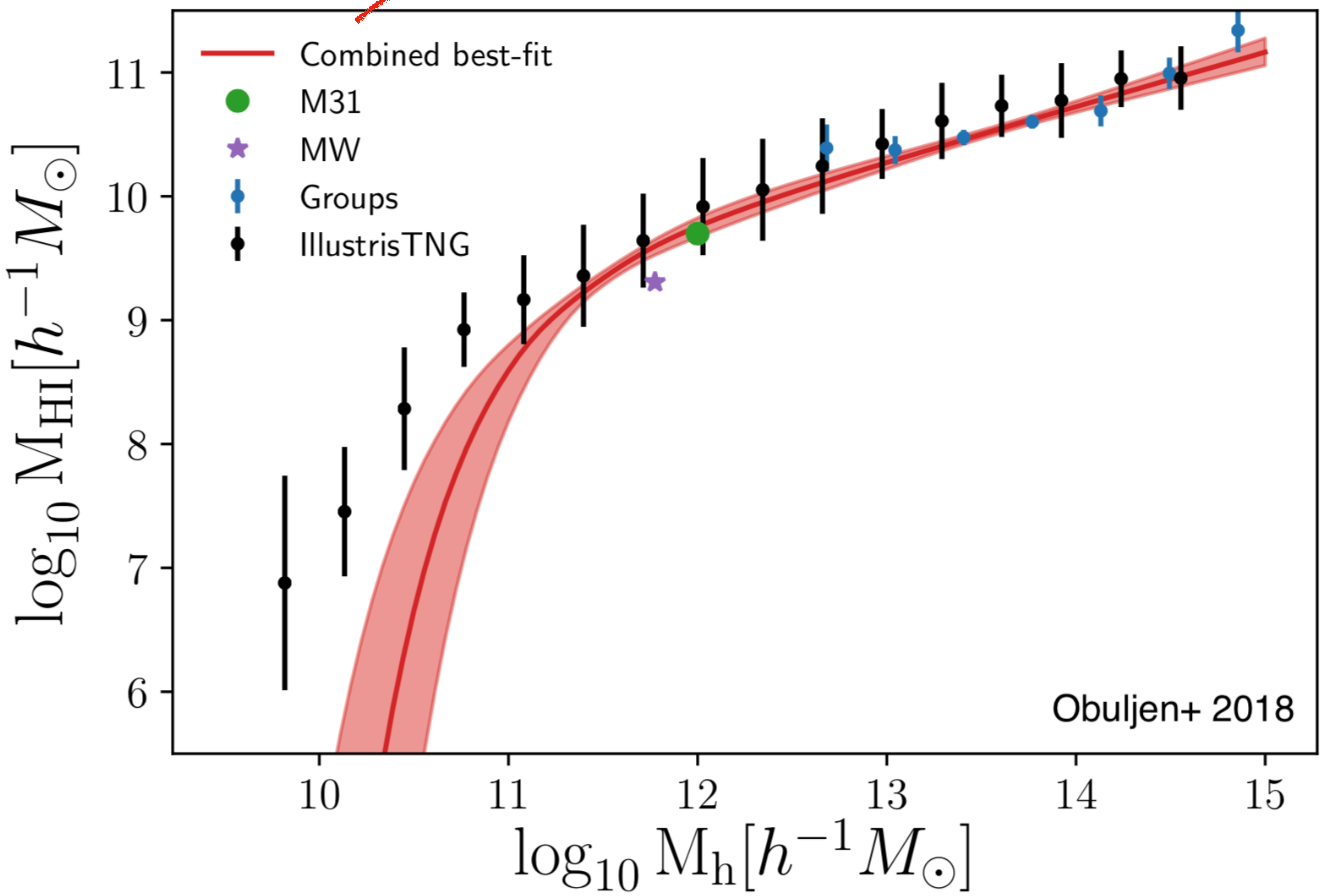
if $M_{halo} > M_{min}$

z = 1

Distribution of HI in the post-reionization universe

ALFALFA galaxies with SDSS groups

Strategy 1:
HI resides in DM



$M_{HI} = M_{HI}(M_{halo})$

if $M_{halo} > M_{min}$

$z = 0$

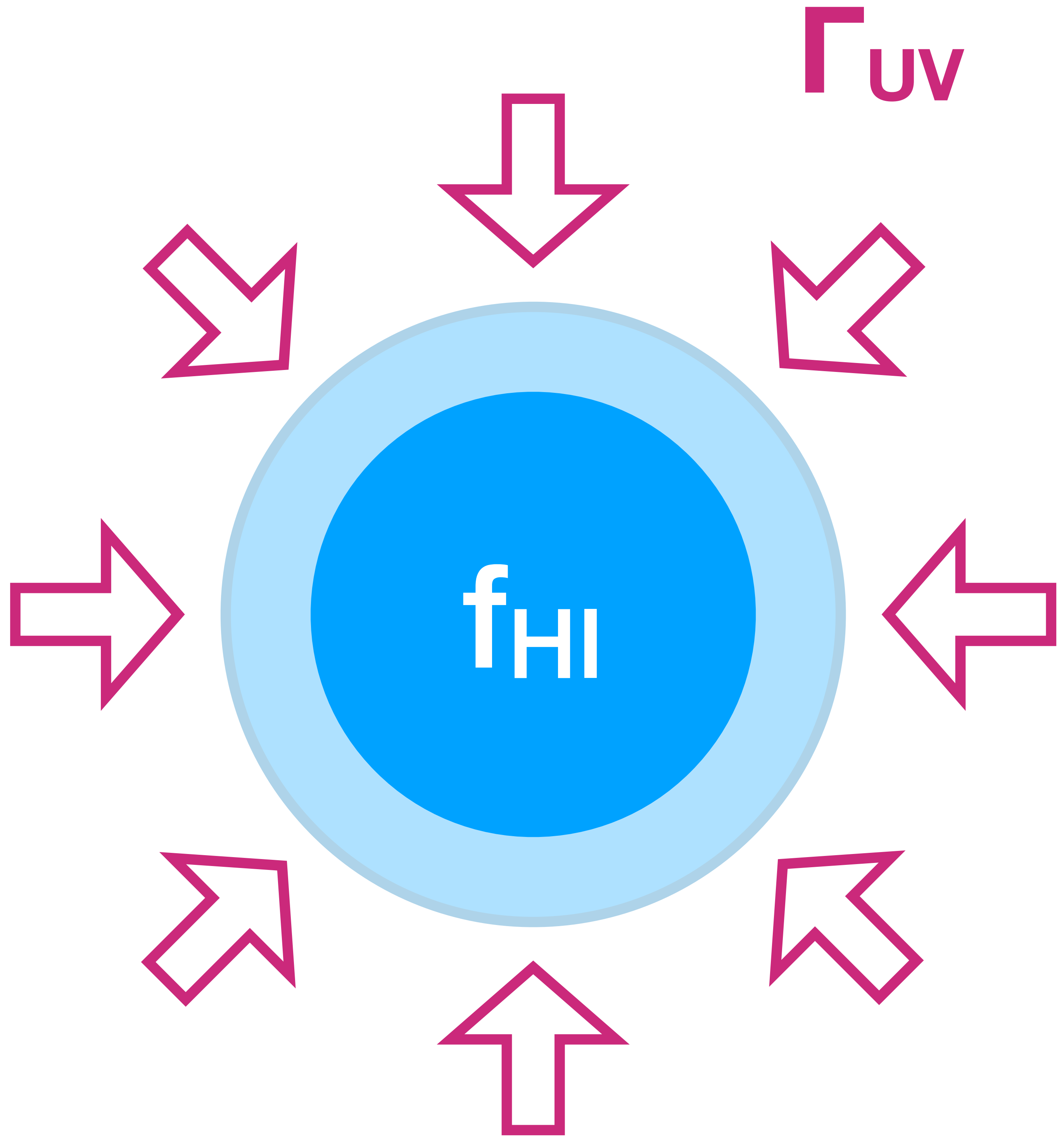
Distribution of HI in the post-reionization universe

Strategy 2:
Hydro sims

- assuming photo-ionization equilibrium, setting the HI/H fraction in order to reproduce the Lyman-α mean transmission flux

- mimicking HI self-shielding for high enough density regions

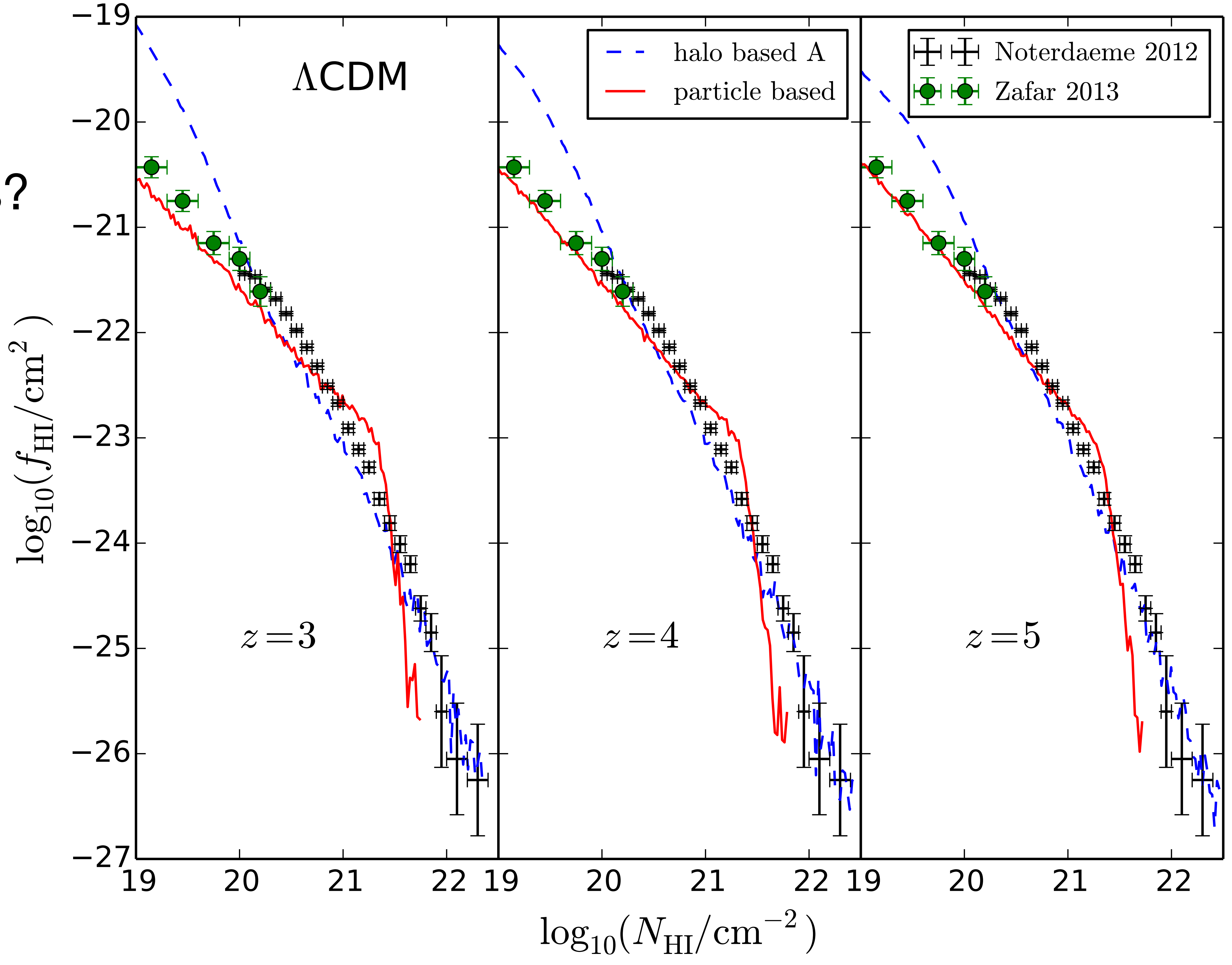
- letting H_2 forming for even denser regions



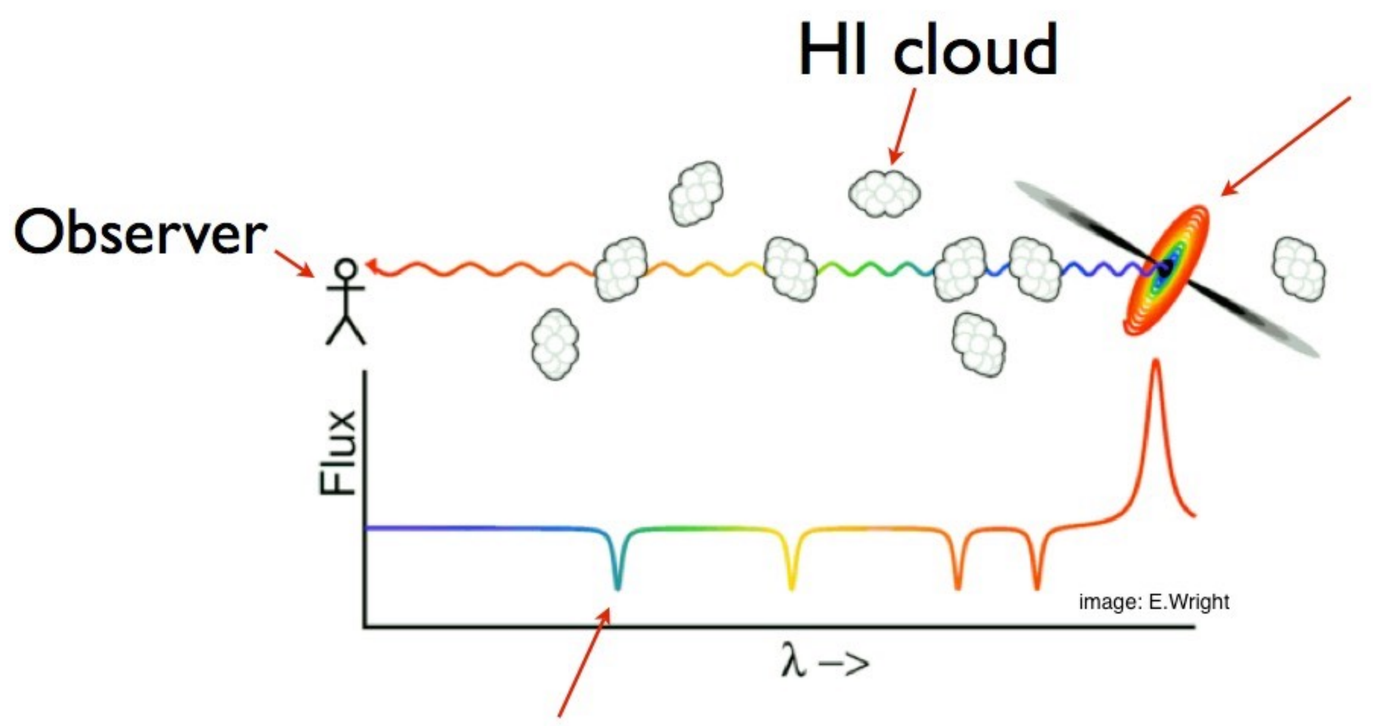
Davé+ 2013, Rahmati+ 2015, …

Distribution of HI in the post-reionization universe

How can we test these methods?



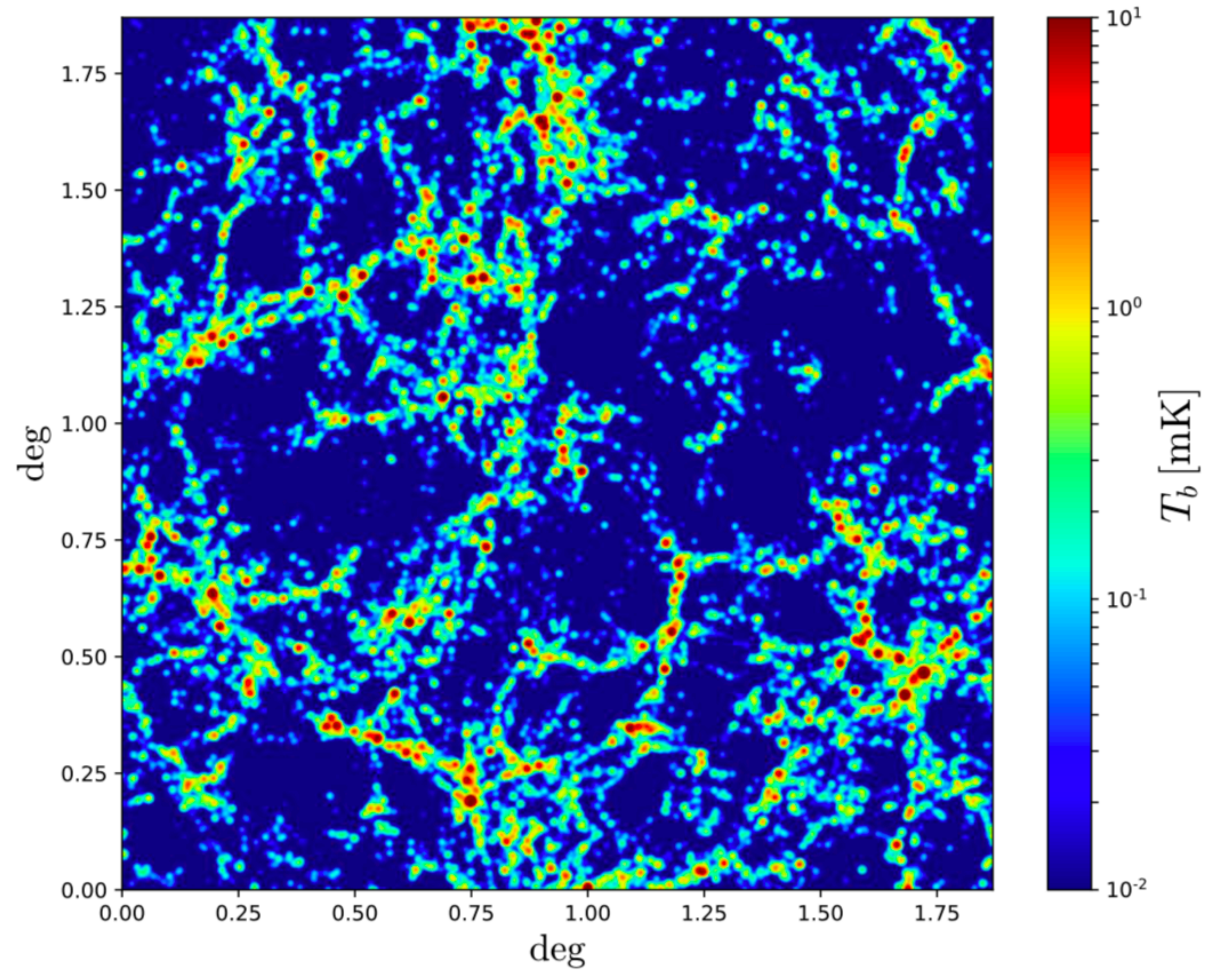
HI column density distribution function



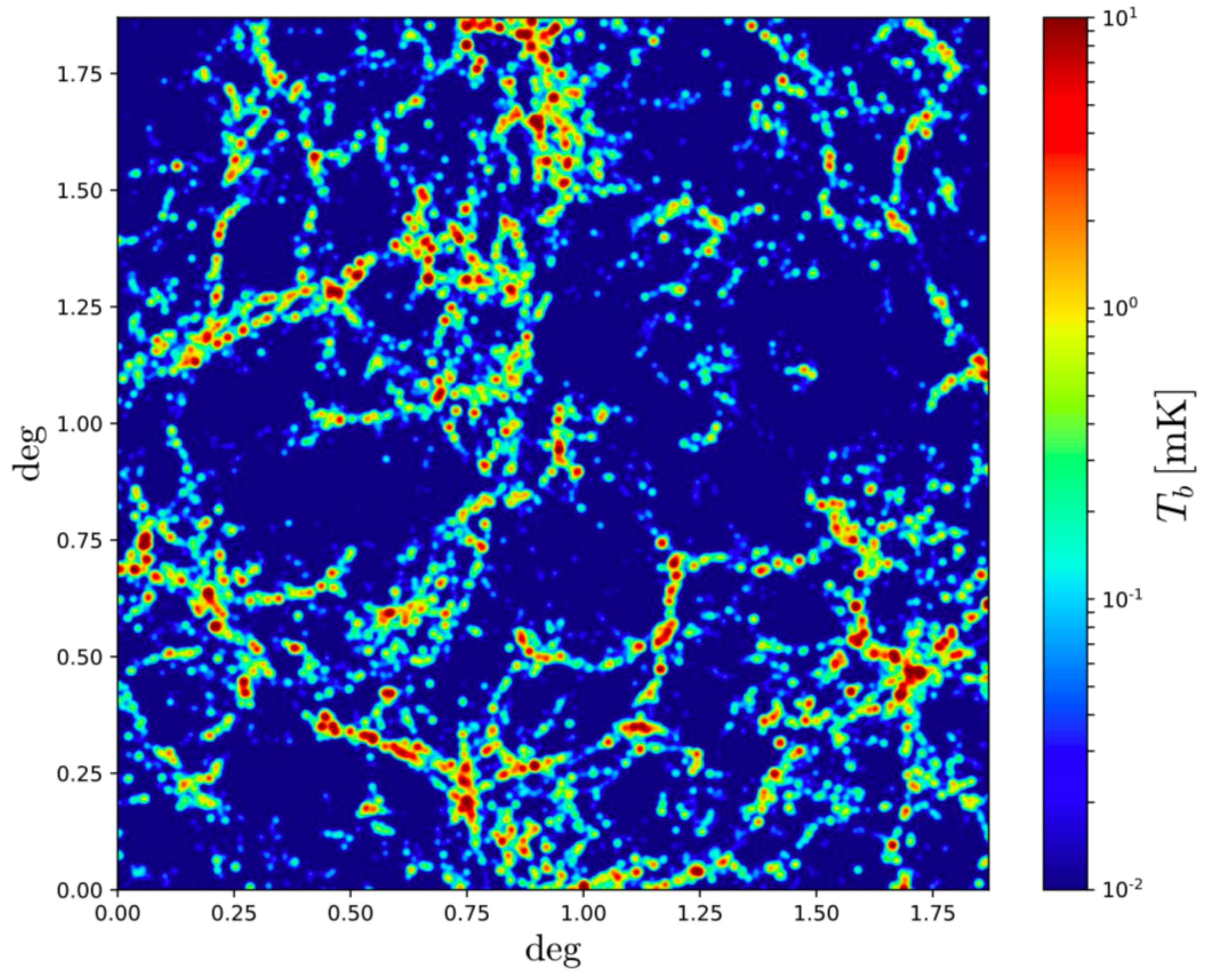
Carucci + 2015

Distribution of HI
in the post-reionization universe

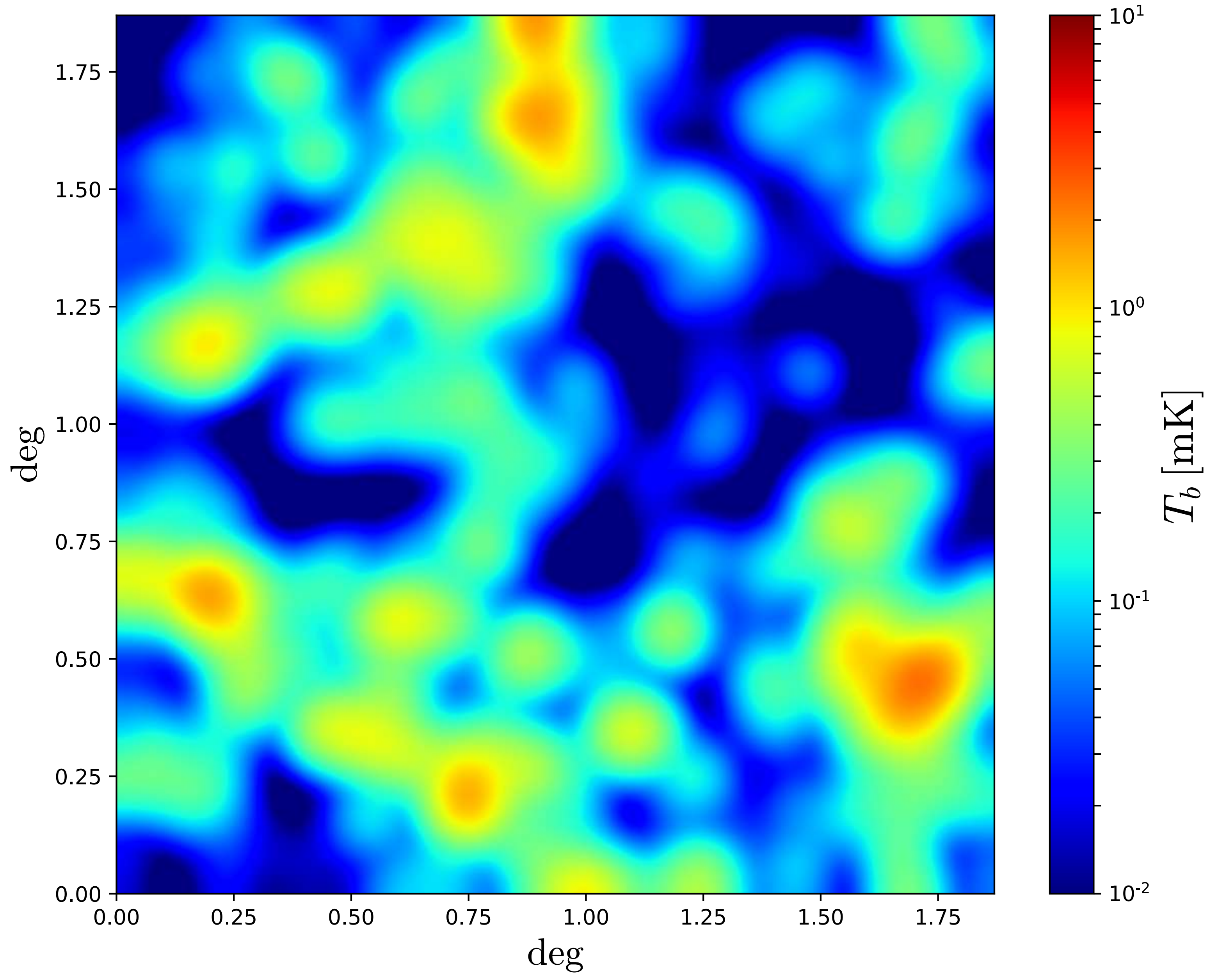
cheap Nbody



IllustrisTNG



forecasts

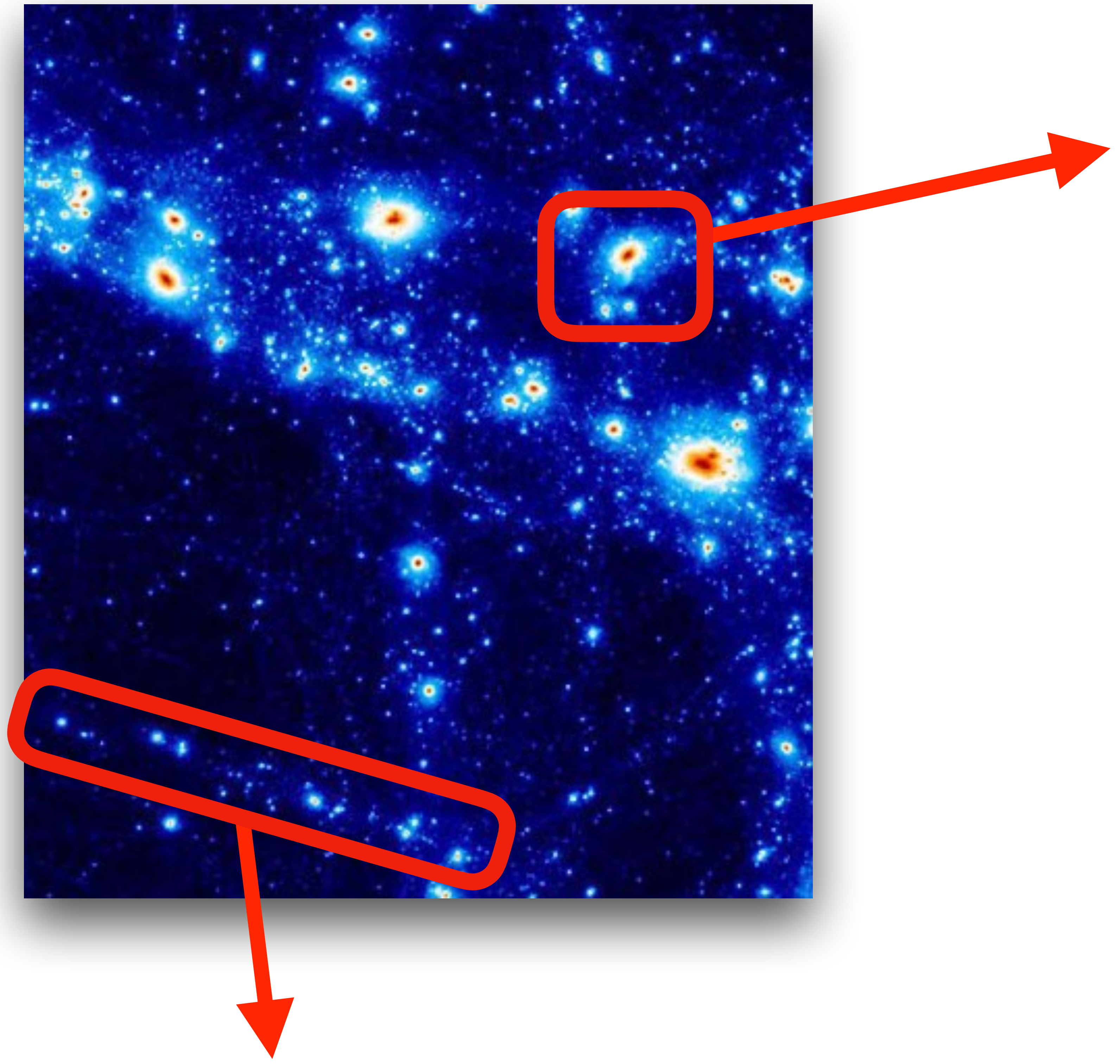


Villaescusa-Navarro, .. , IPC + 2018

Recovering 21cm intensity maps from post-reionization epoch

- modelling
- synergies with other probes
- foreground cleaning and instrumental effects

Cross correlating with the Lyman-α forest flux



21cm radiation in IM

- same epoch (high z probes!)
- different systematics
- different foregrounds
- future promising observations

(Ly-α flux already well measured at z >2)

Lyman-α forest flux

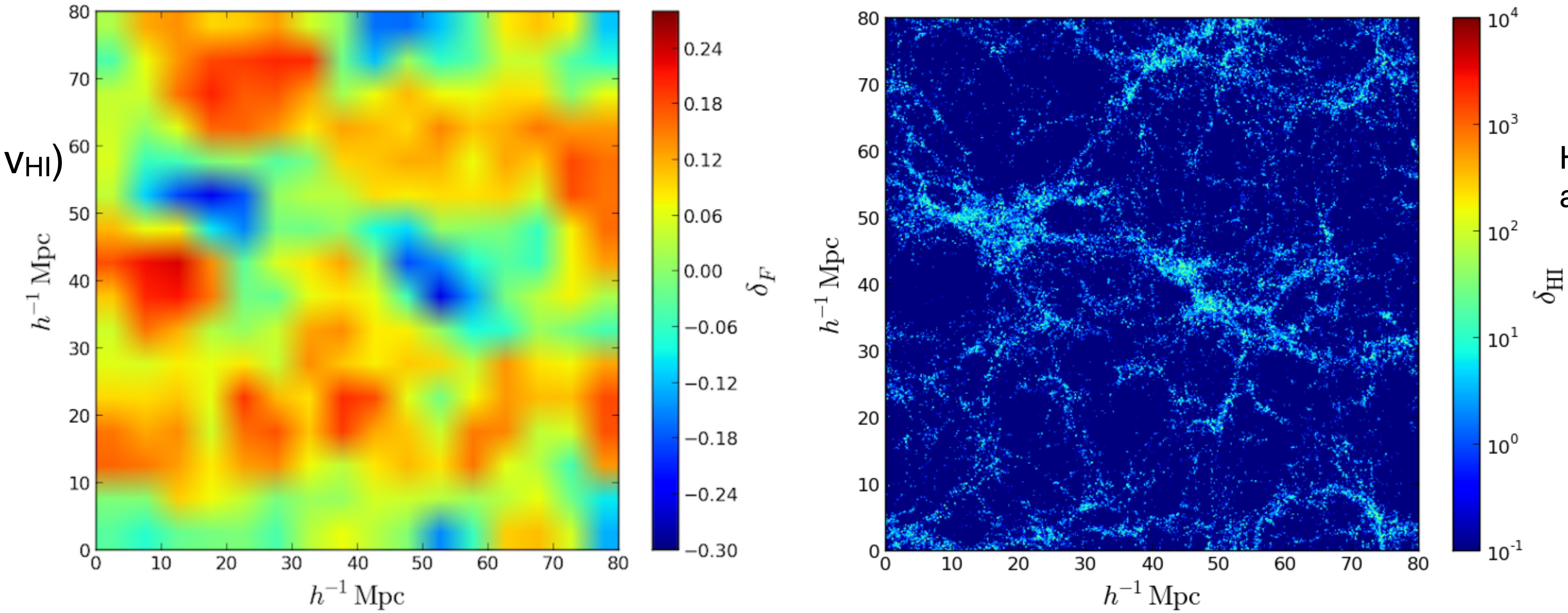
Cross correlating with the Lyman-α forest flux

Carucci, Villaescusa-Navarro & Viel 2017

$F = e^{-\tau}$

$\tau = \tau(\rho_g, f_{HI}, T_{HI}, v_{HI})$

SPH interpolation



Halo based HI assignment

Simulations from the Sherwood suite (Bolton+ 2017): State-of-the-art sims for the low density Universe: converging properties for intergalactic medium

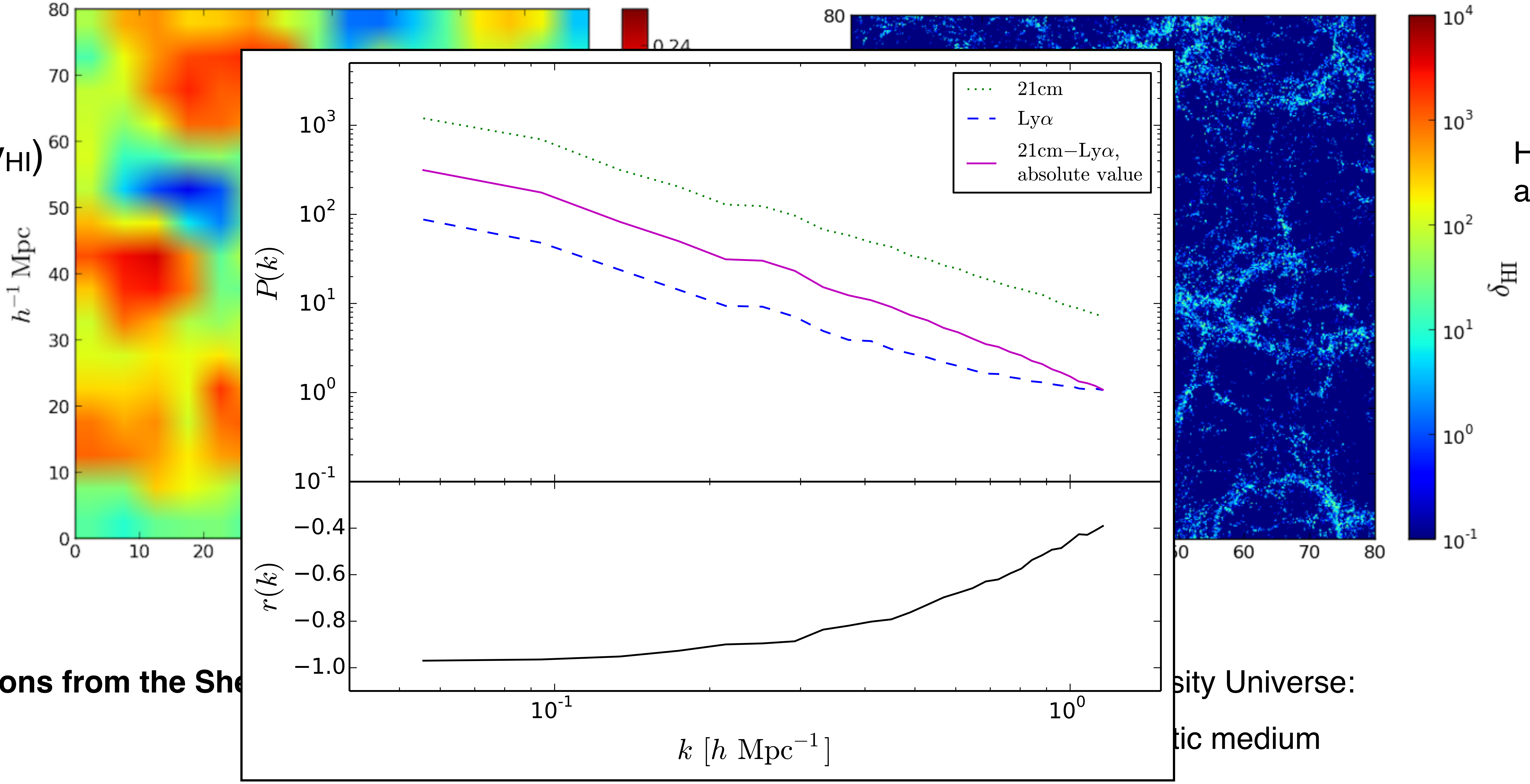
Cross correlating with the Lyman-α forest flux

Carucci, Villaescusa-Navarro & Viel 2017

$F = e^{-\tau}$

$\tau = \tau(\rho_g, f_{HI}, T_{HI}, v_{HI})$

SPH interpolation



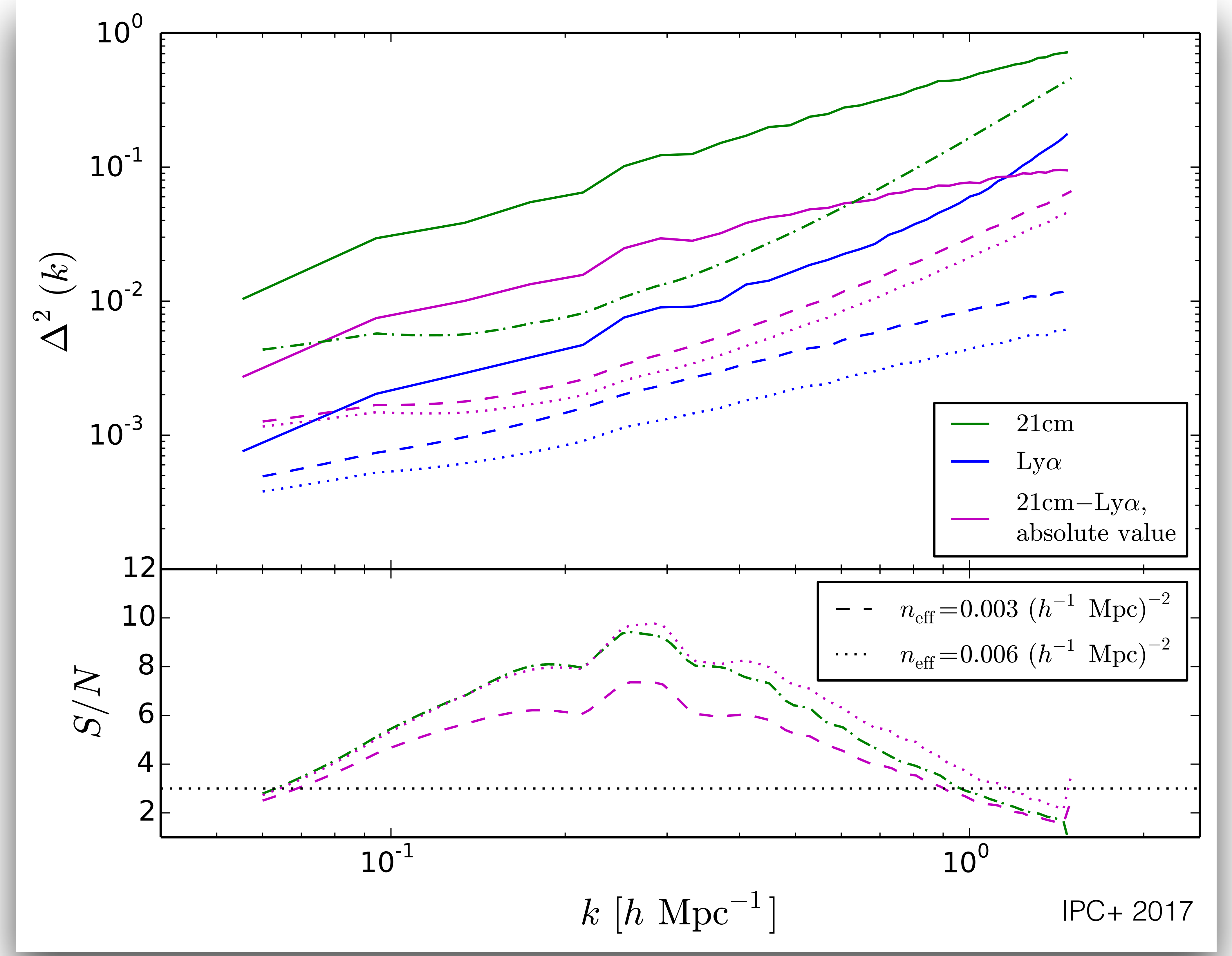
Halo based HI assignment

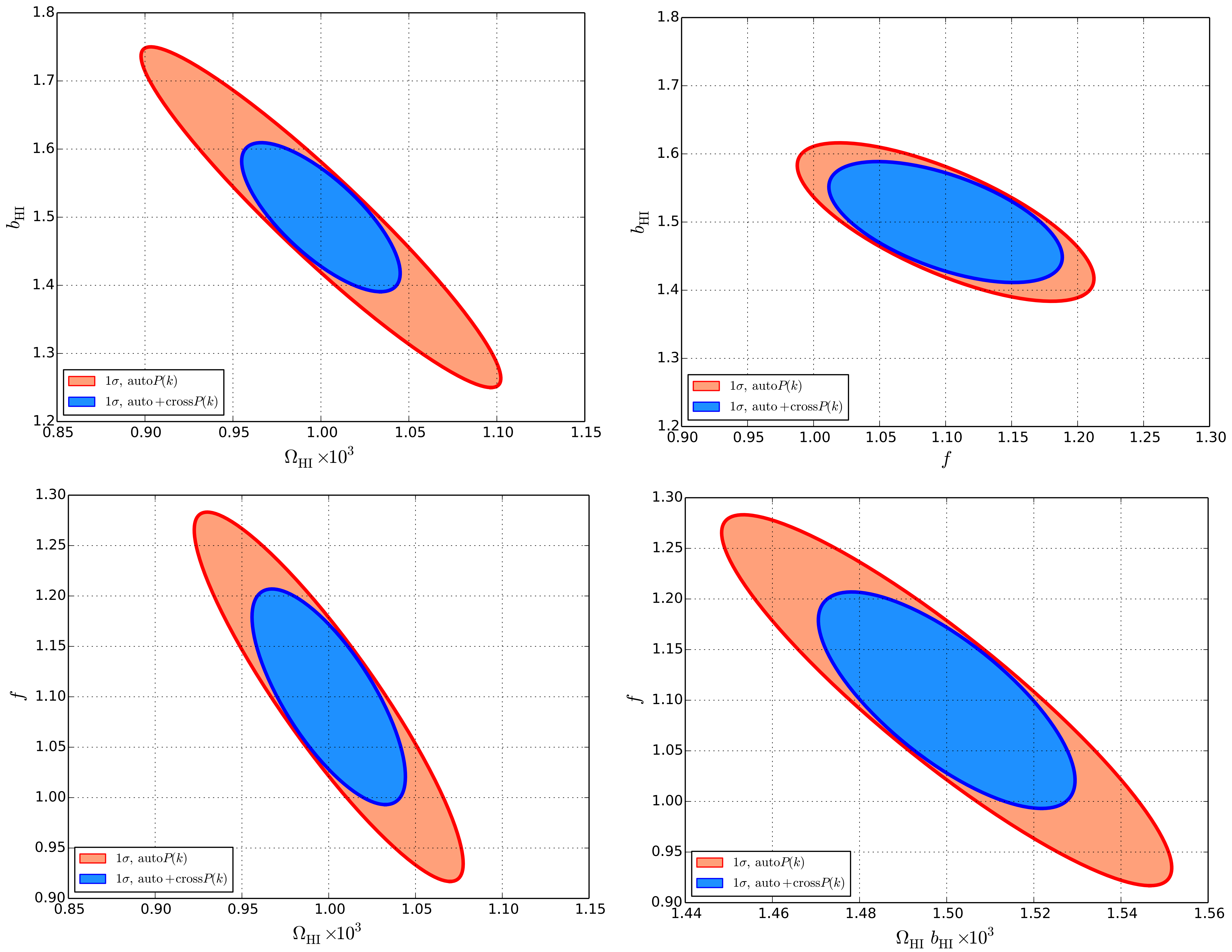
Simulations from the She

sity Universe:

tic medium

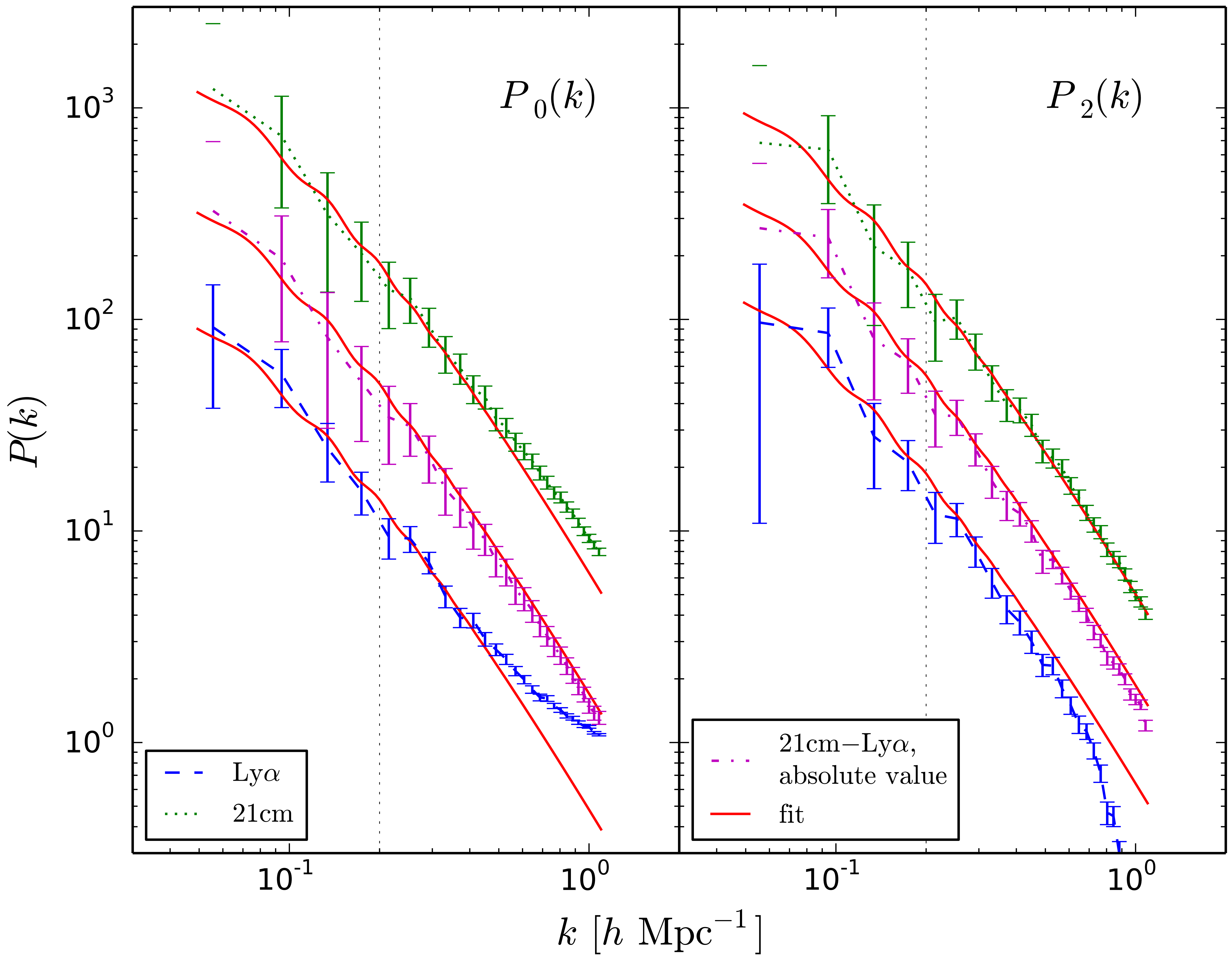
Cross correlating with the Lyman-α forest flux





$$P_{21\rm cm}(k,\mu) = A^2\Omega_{\rm HI}^2 b_{\rm HI}^2\left(1+\beta_{\rm HI}\mu^2\right)^2 P_{\rm m}(k) \qquad \beta_{\rm HI}\times b_{\rm HI} = f$$

Cross correlating with the Lyman-α forest flux



Carucci + 2017

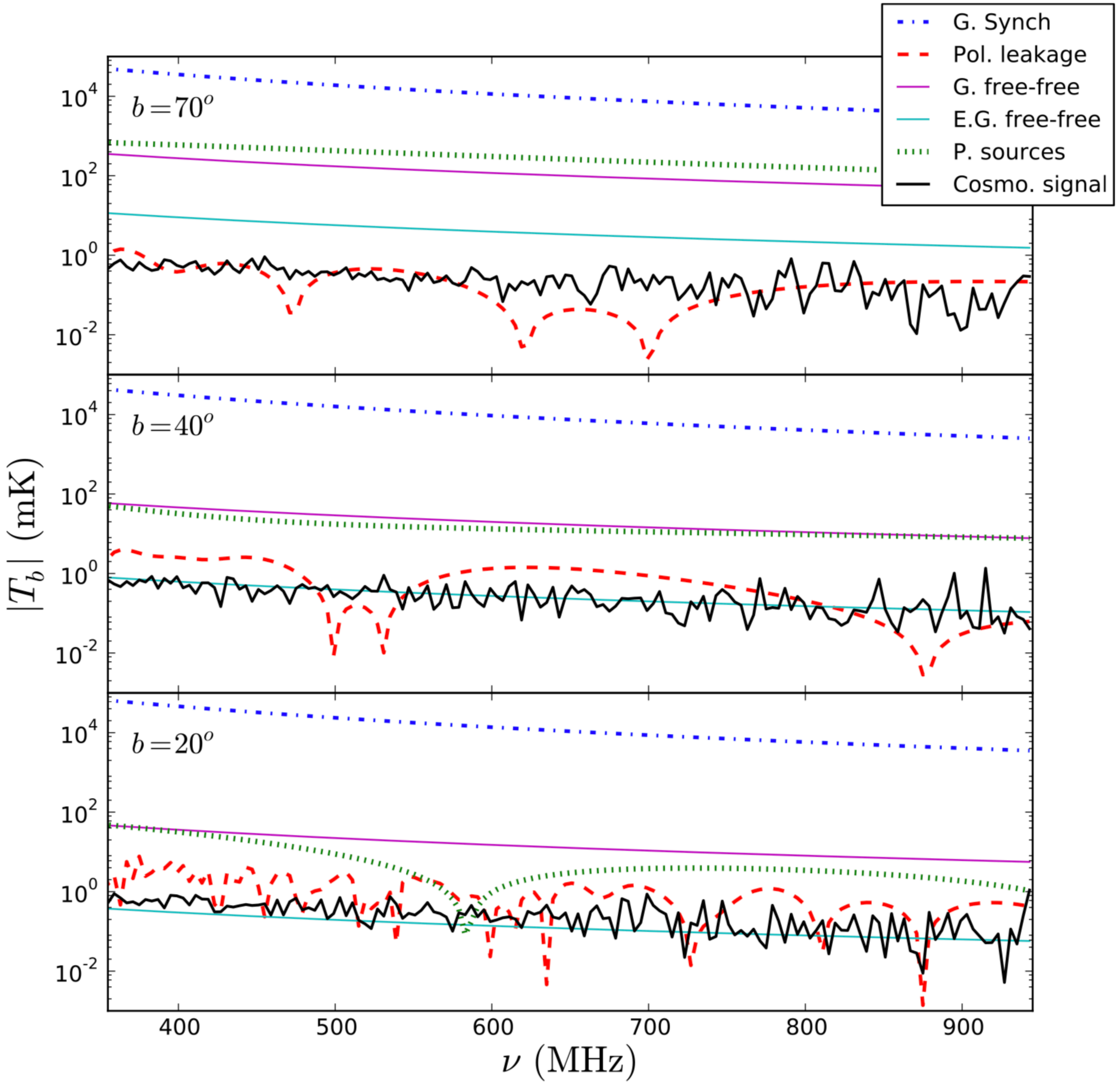
Recovering 21cm intensity maps from post-reionization epoch

- modelling
- synergies with other probes
- <u>foreground cleaning and instrumental effects</u>

21cm intensity mapping

buried
under the
foregrounds

Alonso+ 2014



foreground removal

Chang+ 2010

Green Bank Telescope
X WiggleZ galaxies
z~0.8

- **Polynomial fitting**.

Switzer+ 2013

21cm IM auto-P(k)

- "Instrumental effects such as passband calibration and **polarization leakage** couple bright foregrounds into new degrees of freedom […]. The spectral functions describing these systematics cannot all be modelled in advance, so we take an **empirical approach to foreground removal by estimating dominant modes** from the covariance of the map itself."

Anderson+ 2018

Parkes telescope X 2dF optical galaxies

- Principal Component Analysis (**PCA**). Number of modes estimated from simulation.

- Also tested on simulations: independent component analysis (**ICA**) methods (e.g. most recently Cunnington+ 2019), and also **GNILC** (Olivari+ 2016) and **'Robust' PCA** (Zuo+ 2018)
- Alonso+ 2015: **ICA and PCA give equivalent results**, and better than polynomial fitting.

GMCA: Generalised Morphological Component Analysis

- BSS with **sparse** representation
- Iterative thresholding algorithm
- **No parameters to tune**

Bobin + 2007, 2008, 2012

wavelet basis

$$\min_{\mathbf{A},\mathbf{S}} \underbrace{\|\Lambda \odot \mathbf{S}\mathbf{W}\|_p}_{\text{Sparse regularisation}} + \frac{1}{2}\underbrace{\|\mathbf{X} - \mathbf{A}\mathbf{S}\|_F^2}_{\text{Data fidelity}}$$

Tested on **CMB** (data, e.g.Bobin+ 2016)

And for **EoR** signal (sims, Chapman+ 2013)

mixing matrix

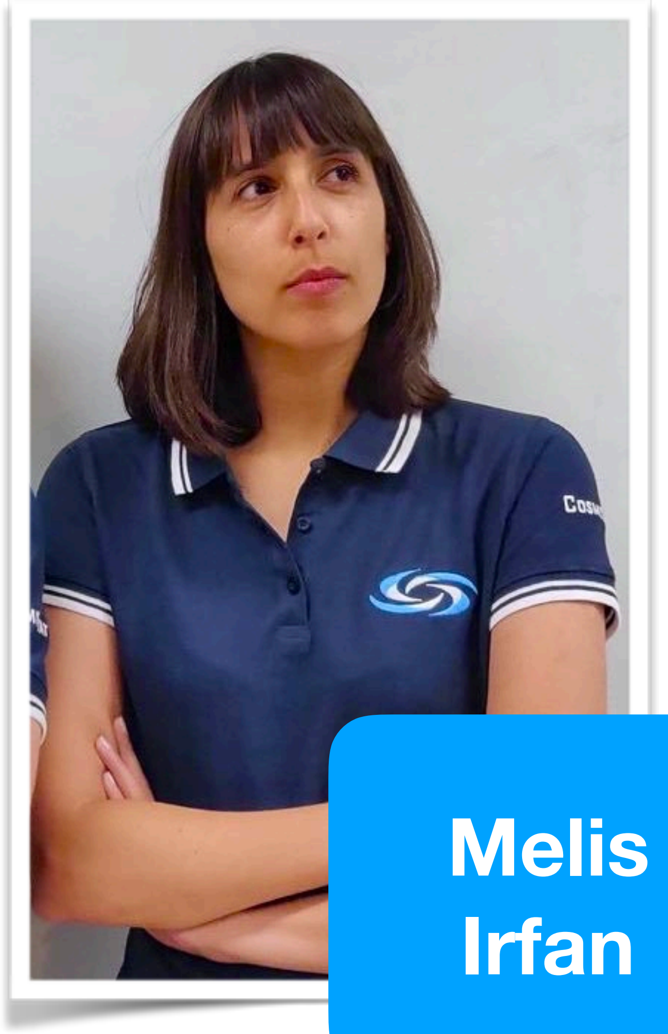
$$\mathbf{X} = \mathbf{A}\ \mathbf{S}$$

signal — sources (foregrounds)

Codes are made publicly available at www.cosmostat.org

testing **GMCA** on post-reionization 21cm IM

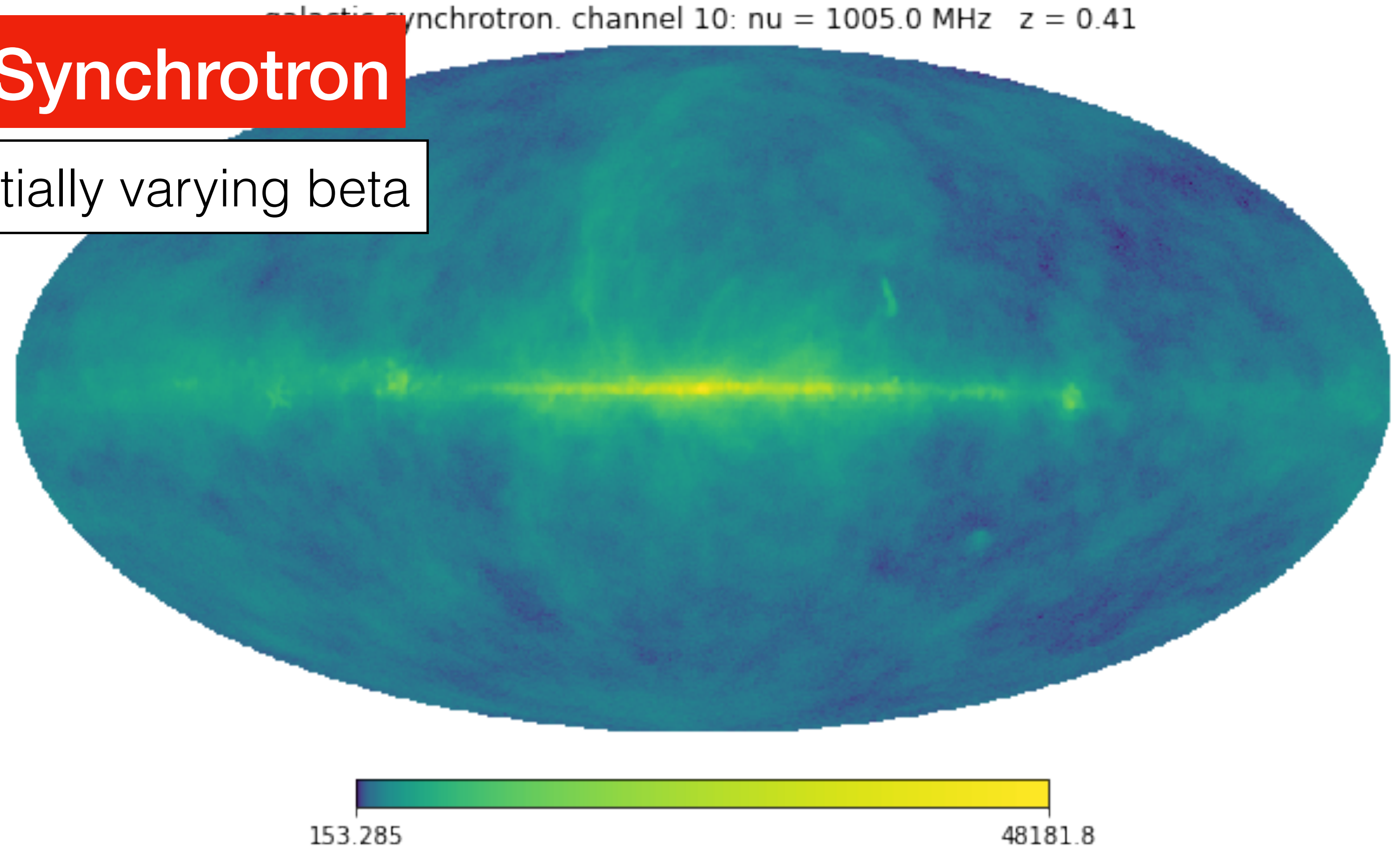
Jérôme Bobin



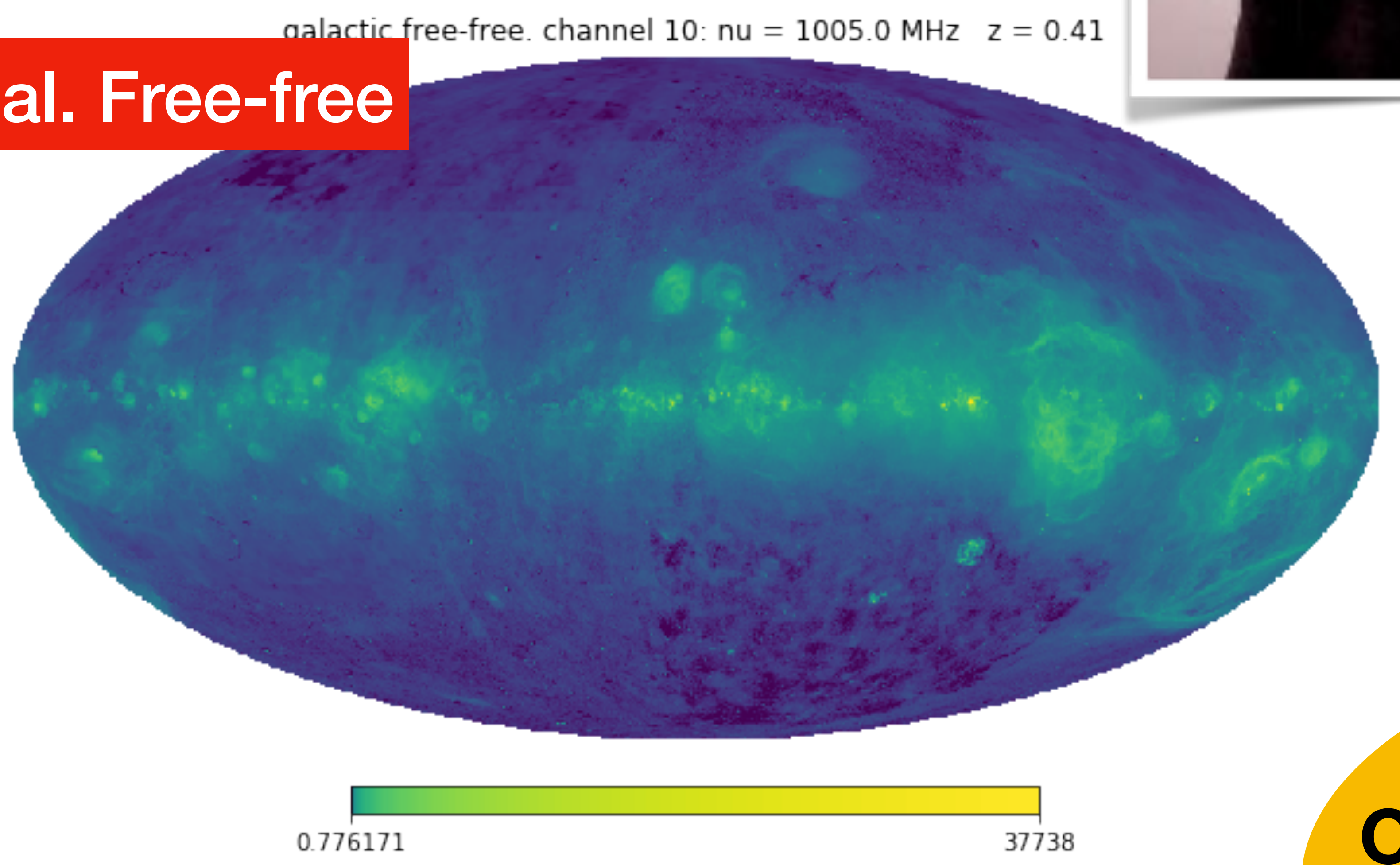
Melis Irfan

Gal. Synchrotron

w/ spatially varying beta



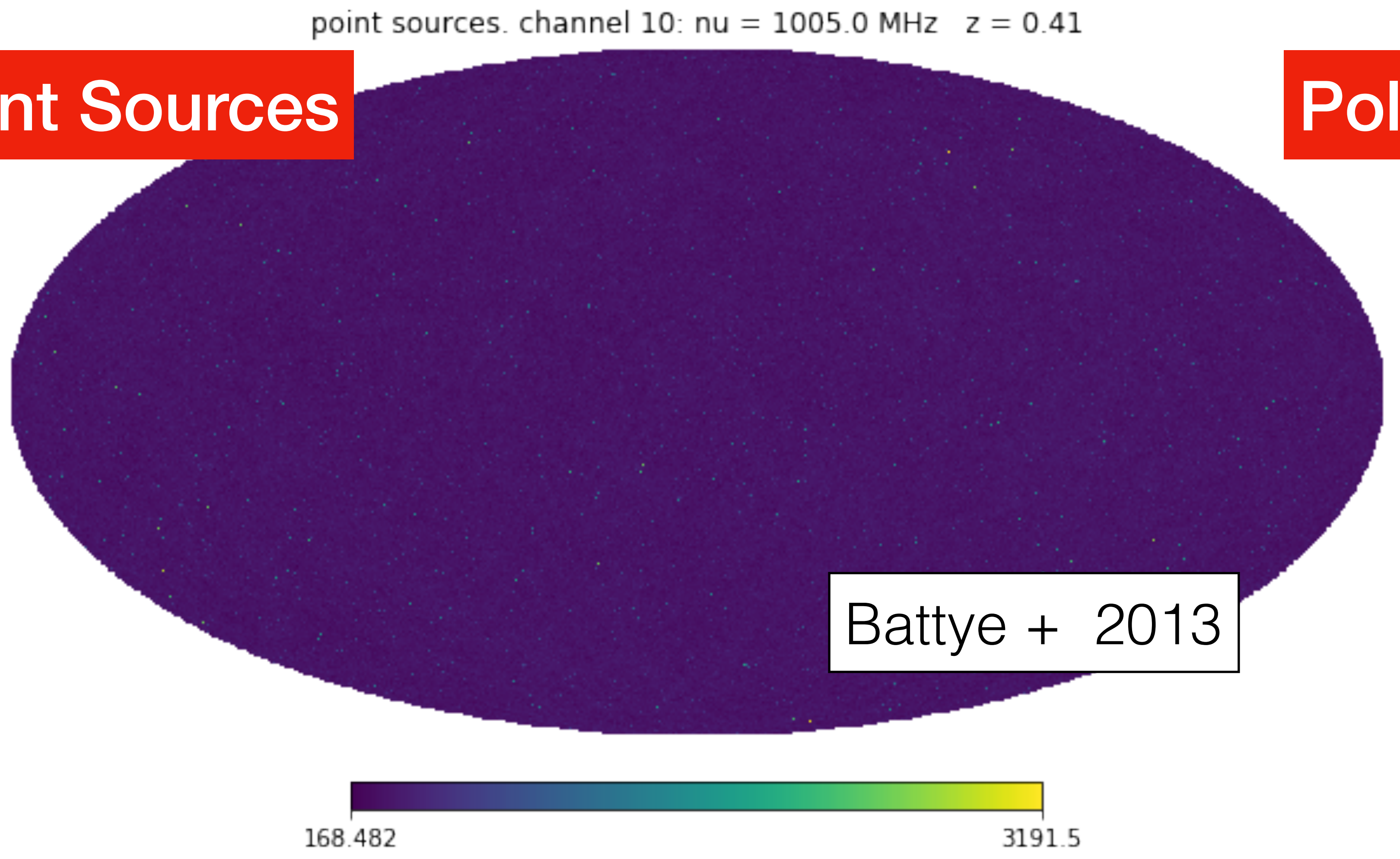
Gal. Free-free



Cosmological Signal -> lognormal

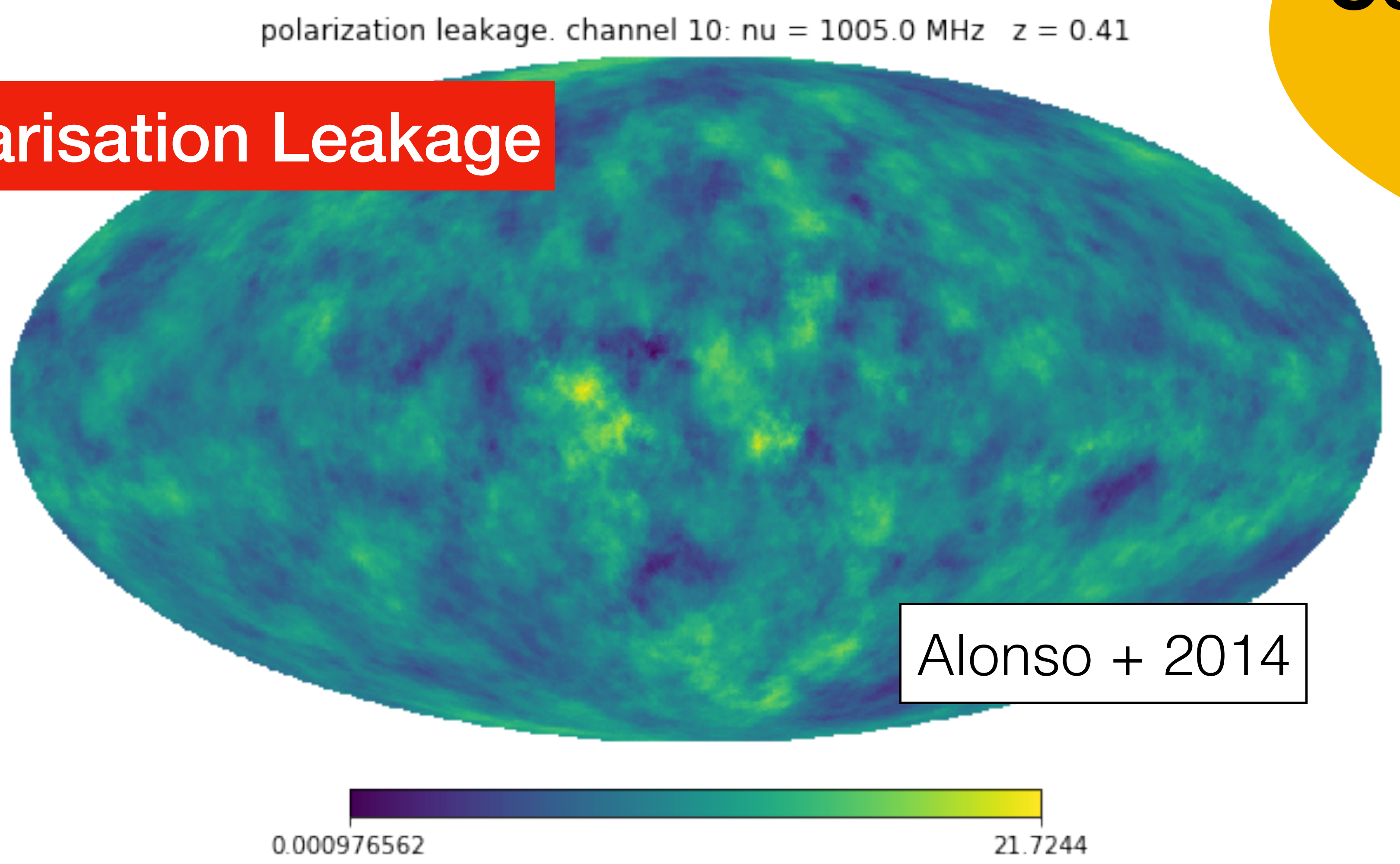
Noise -> MeerKLASS specs

Point Sources



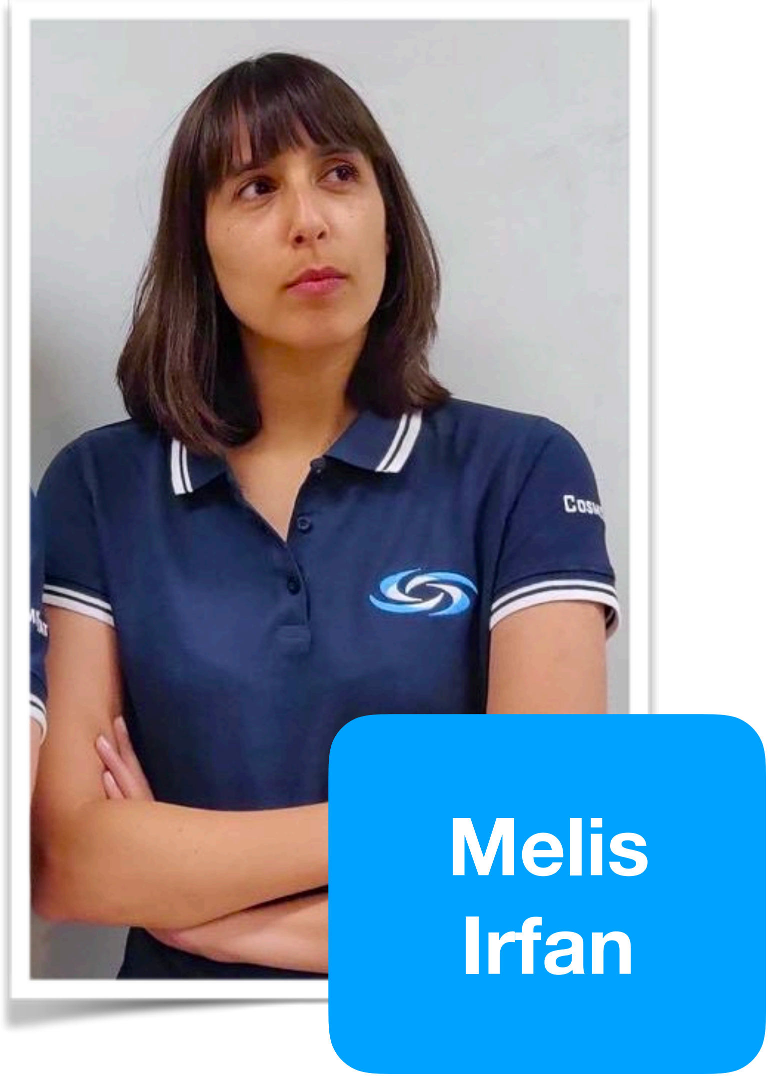
Battye + 2013

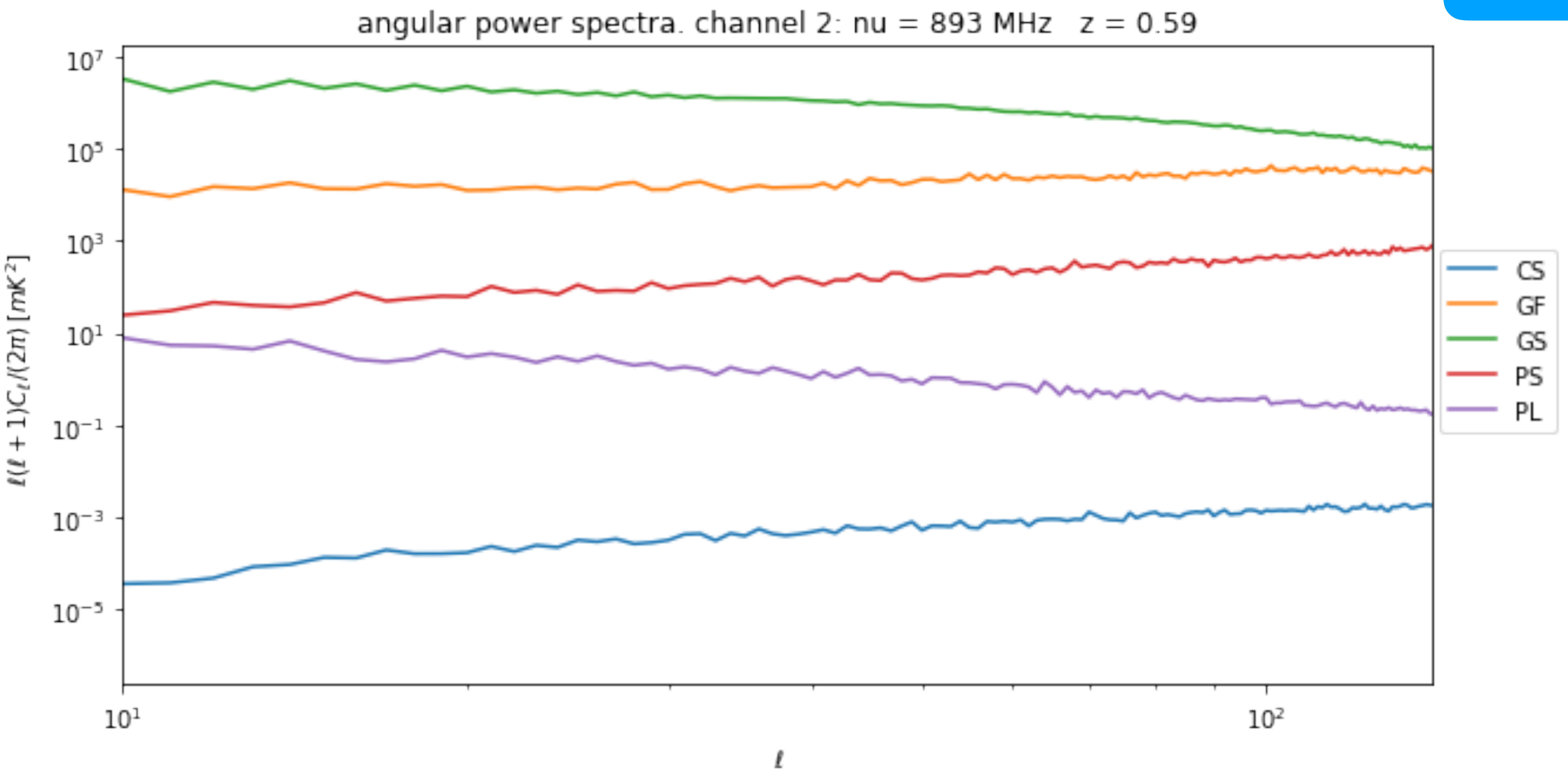
Polarisation Leakage



Alonso + 2014

testing GMCA on 21cm IM





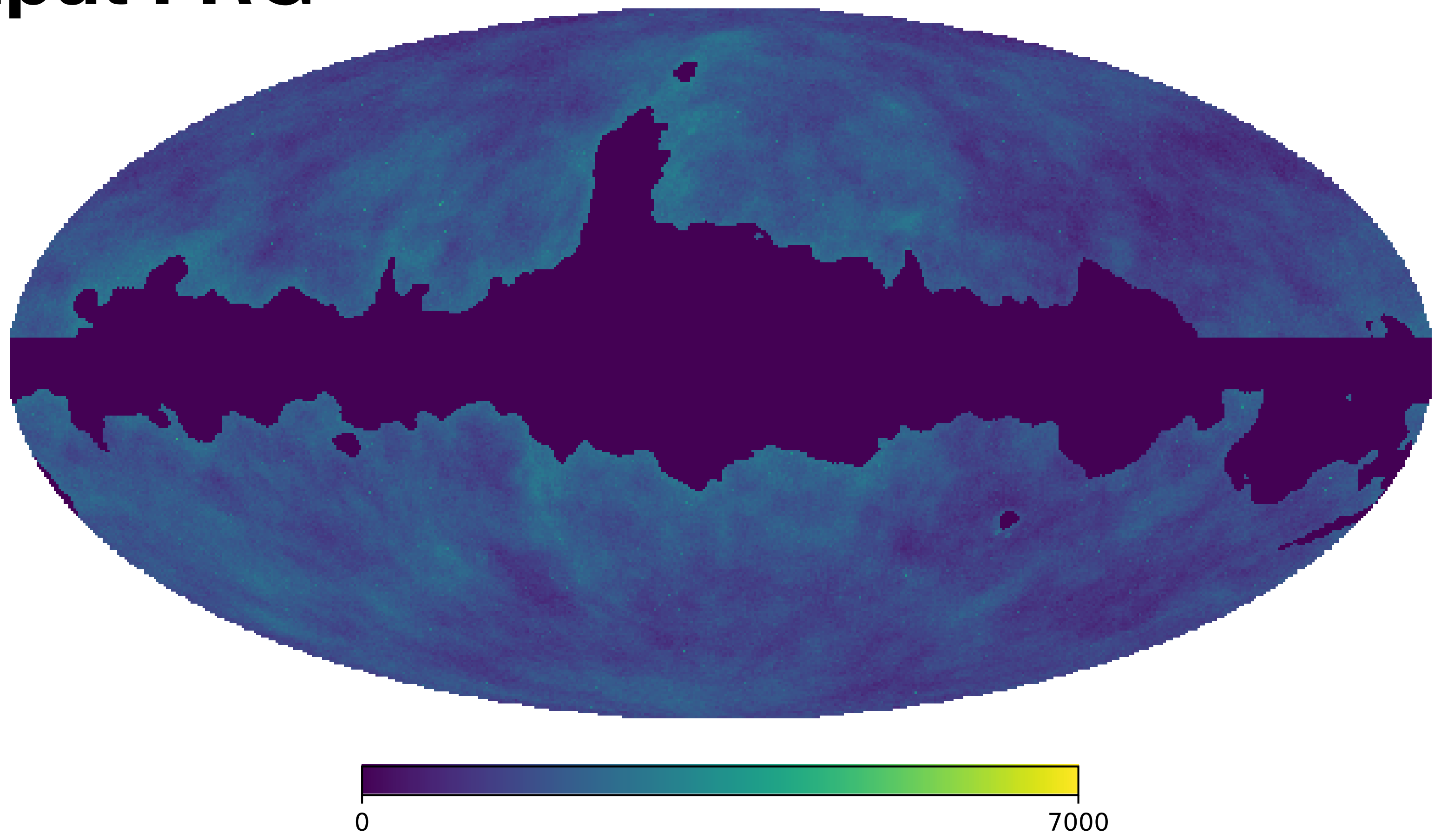
20 channels, 993 - 1159 Mhz (delta_nu = 14 MHz)

testing **GMCA** on 21cm IM

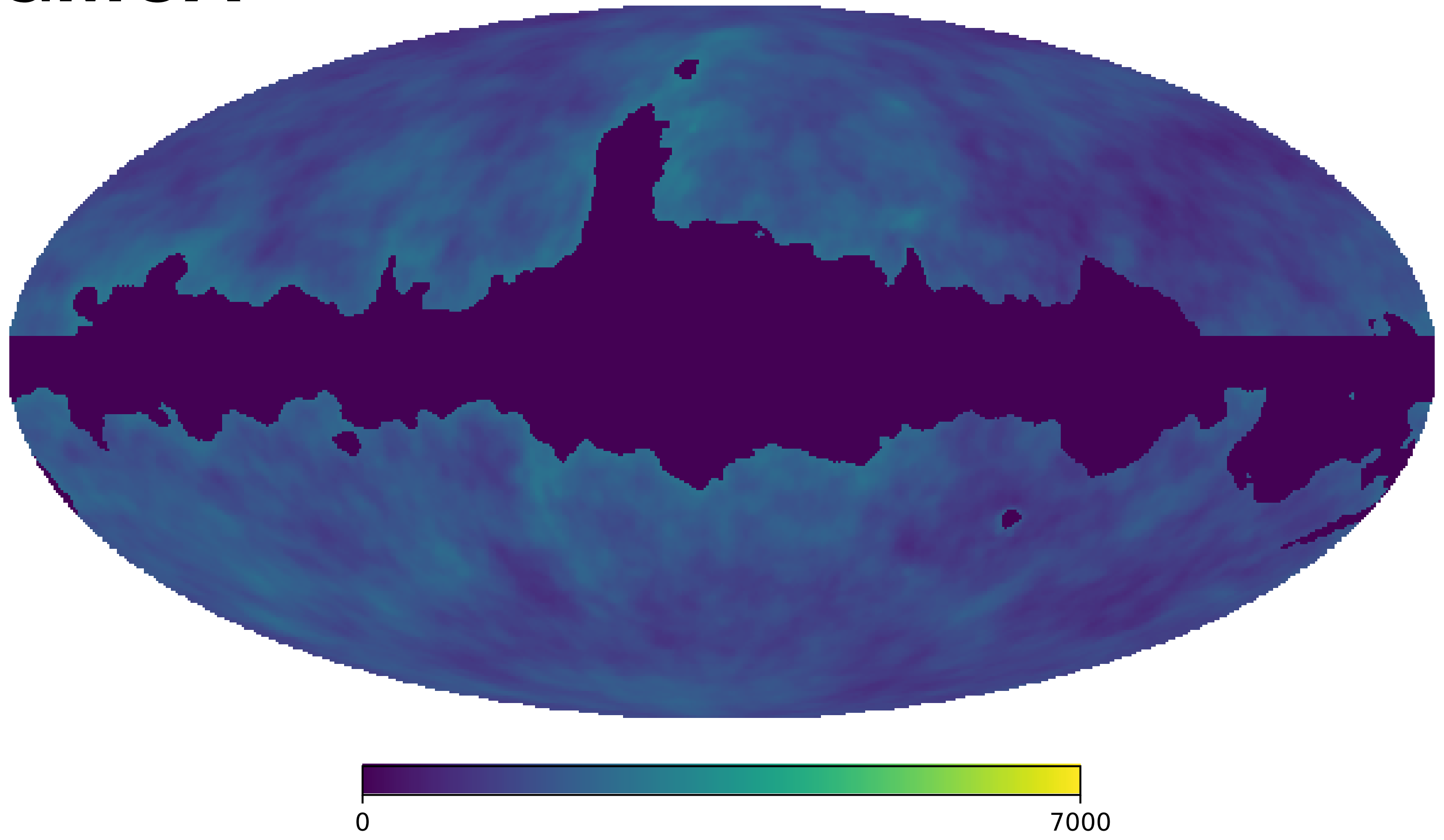
PRELIMINARY

gal. synch. +
gal. free-free +
point sources +
polarisation leakage

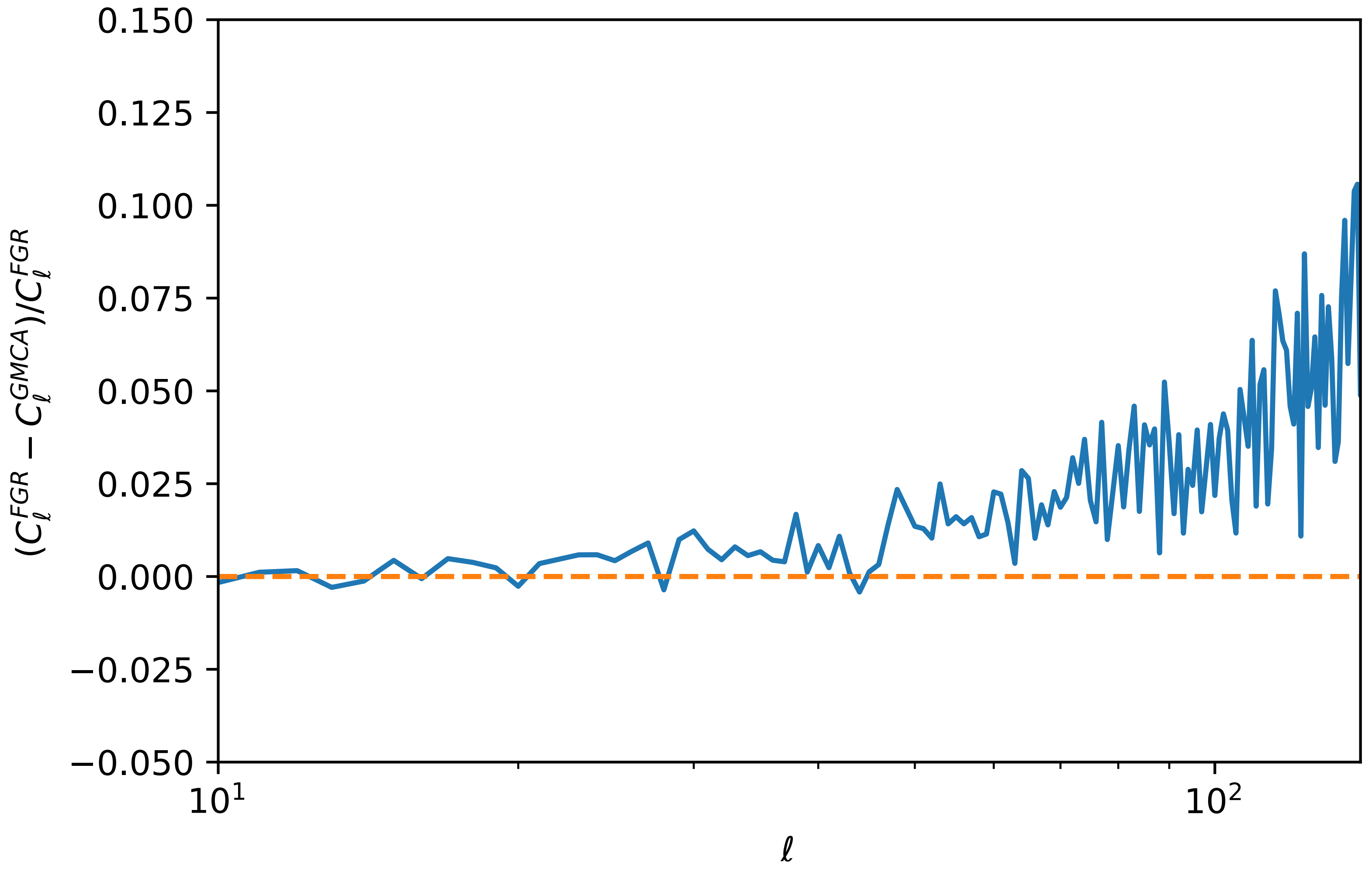
Input FRG



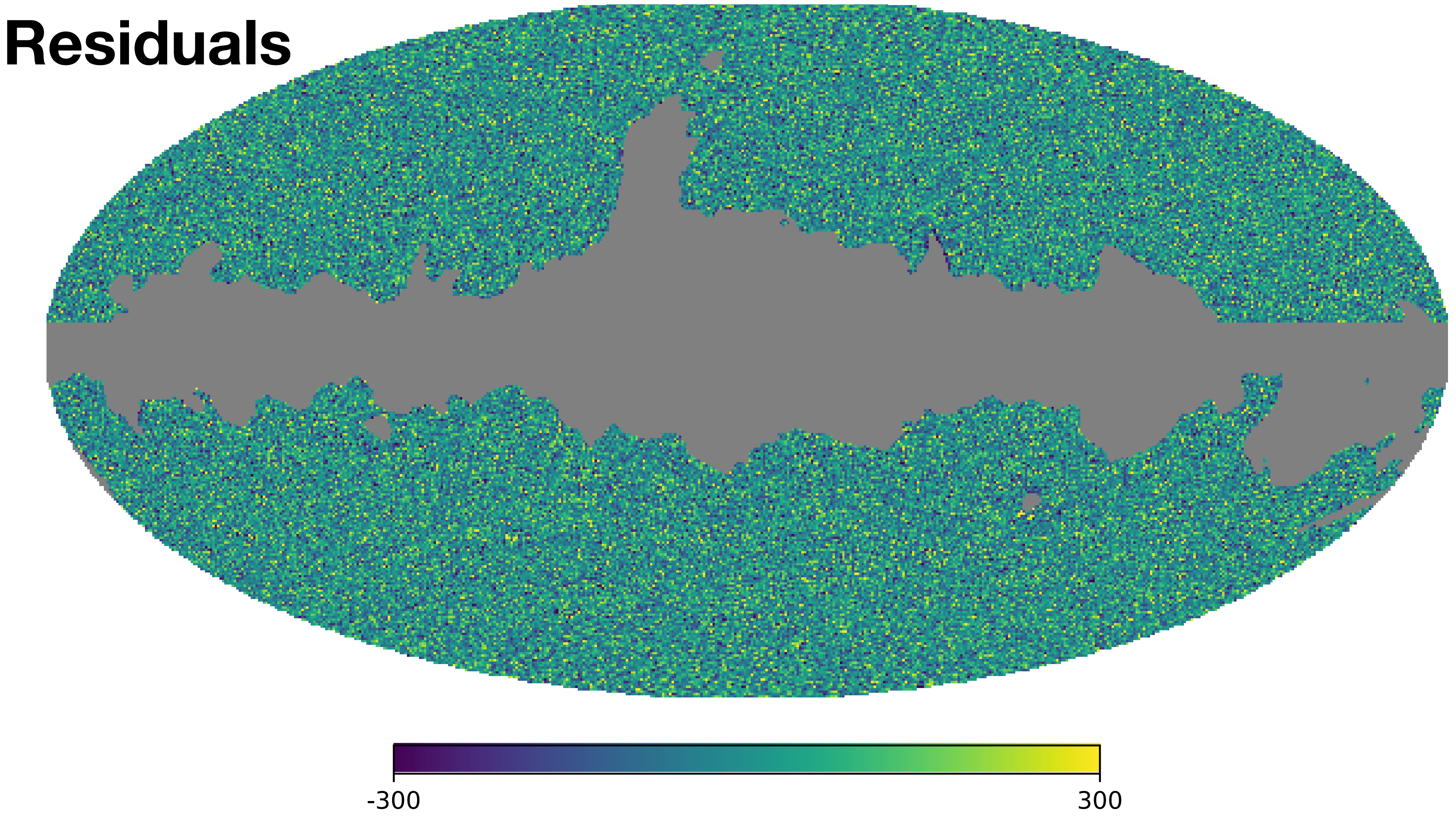
GMCA



Beam and noise as in MeerKAT

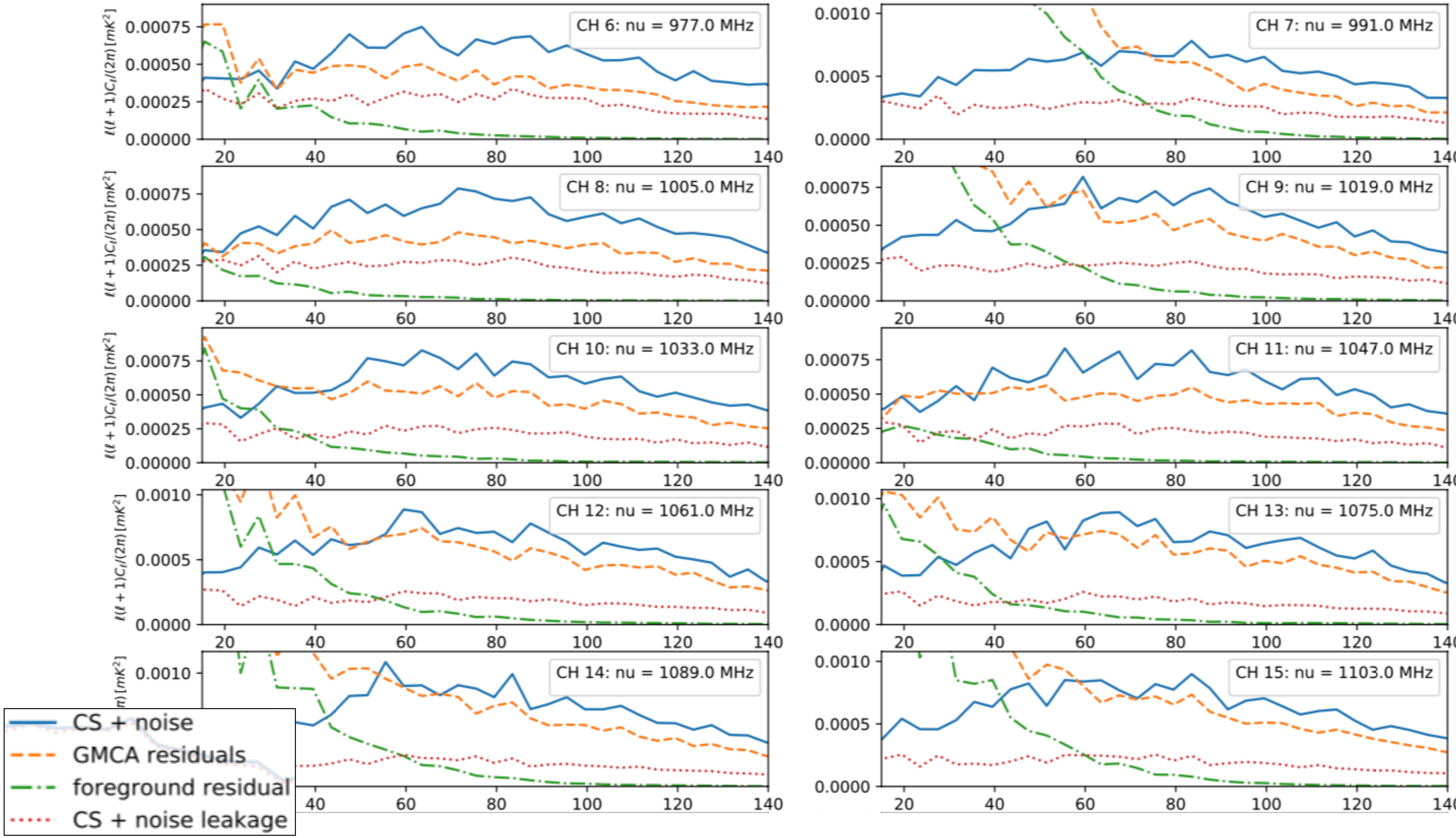


Residuals



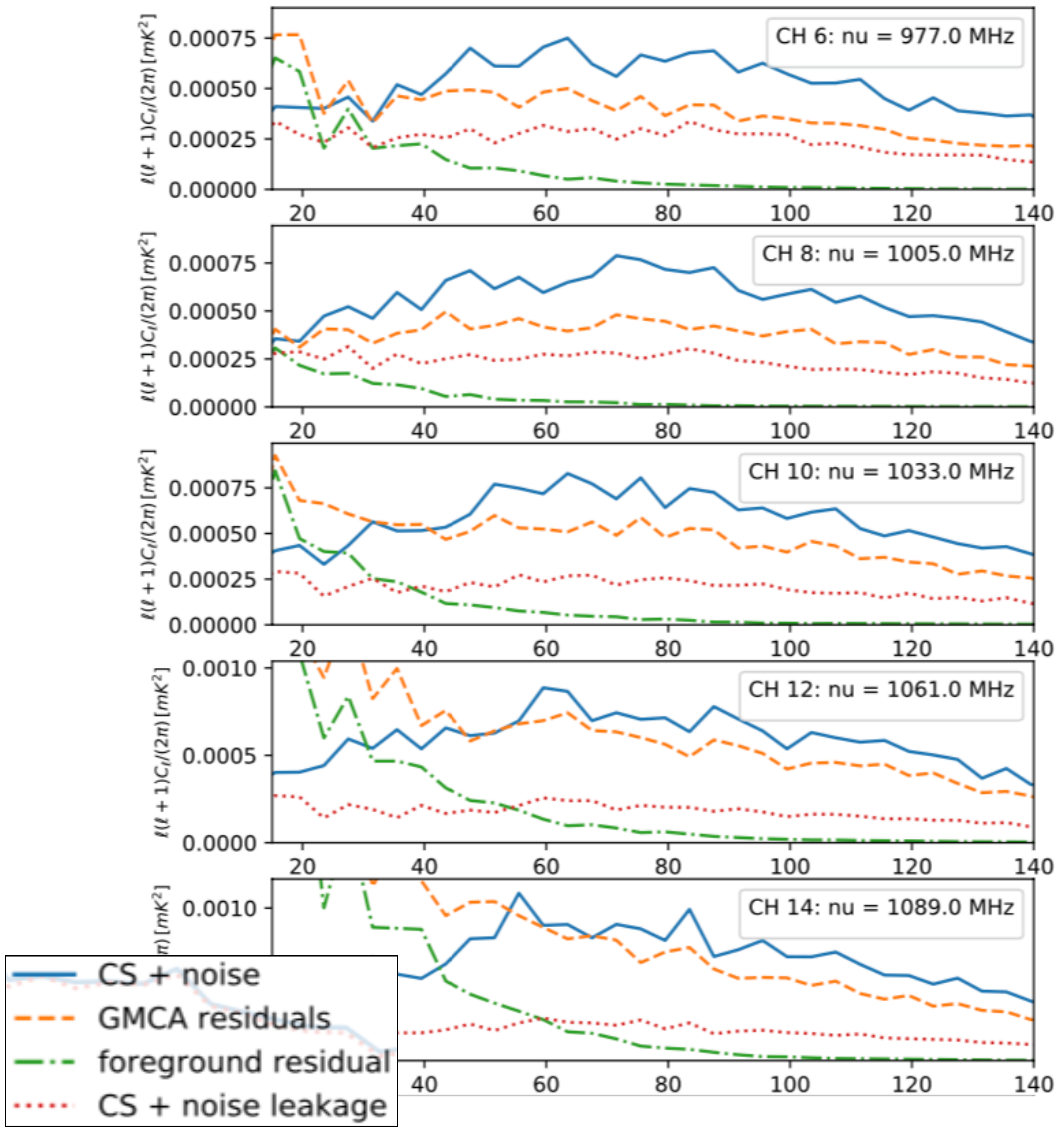
testing **GMCA** on 21cm IM

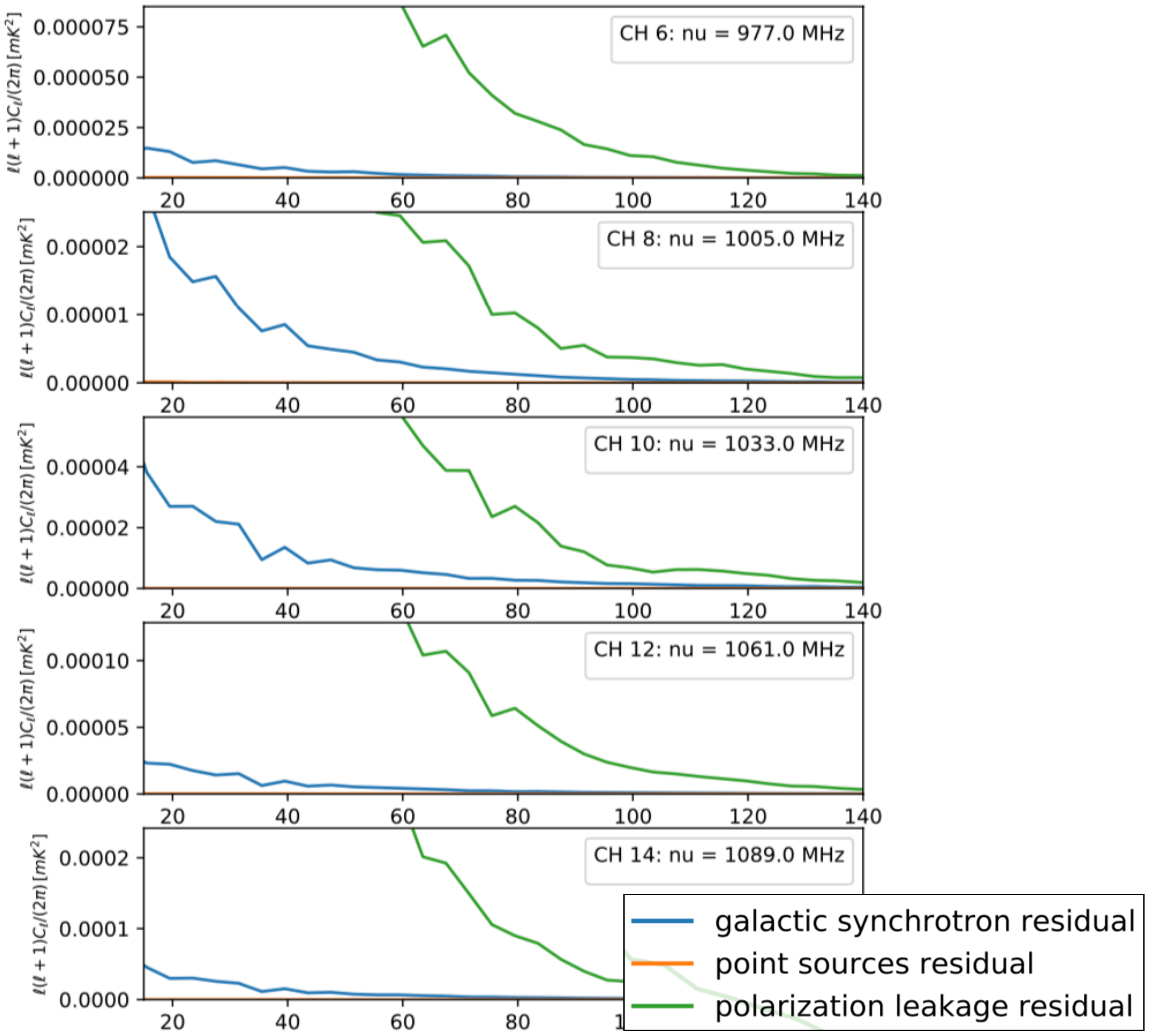
PRELIMINARY



testing GMCA on 21cm IM

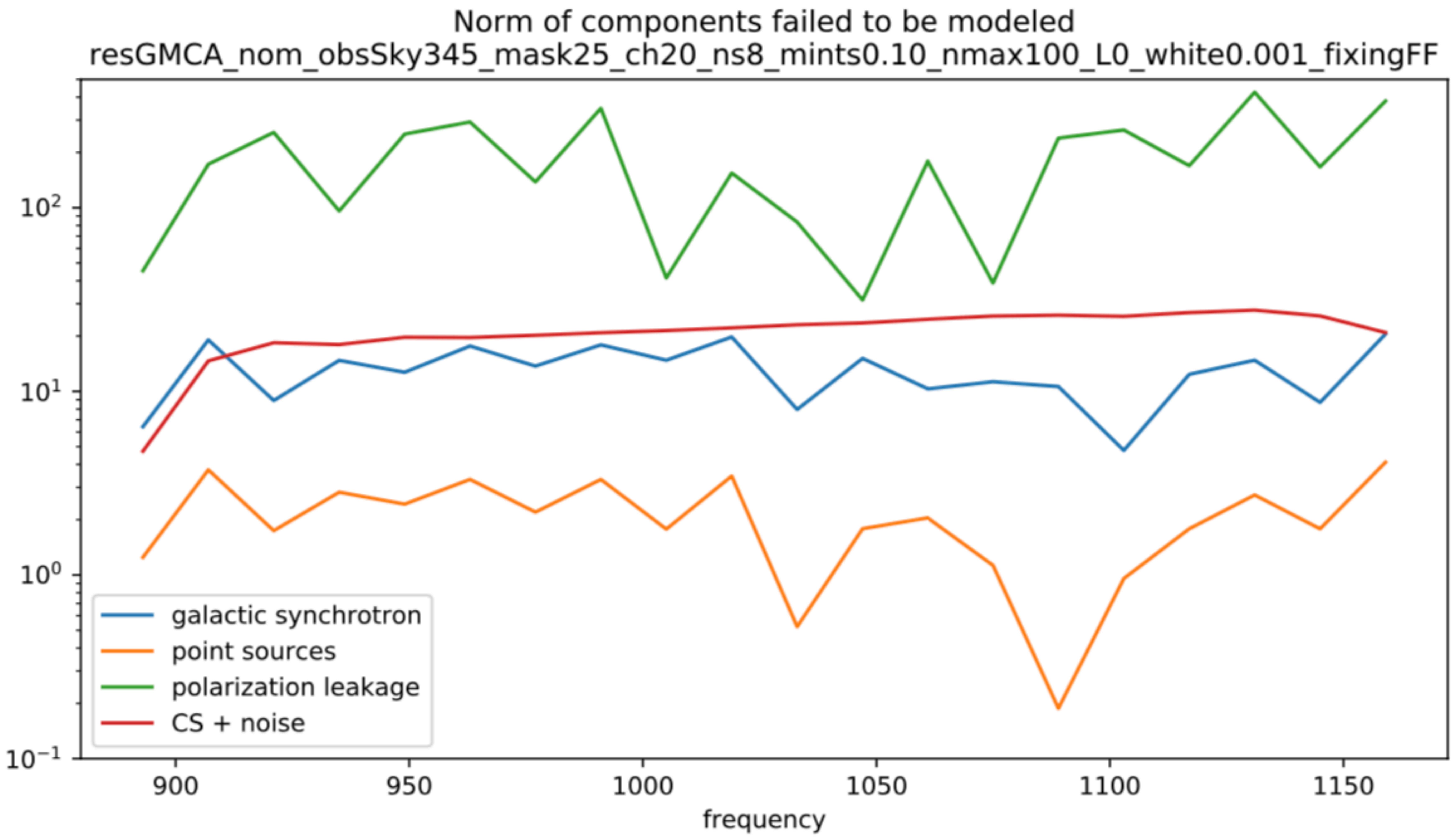
PRELIMINARY





testing GMCA on 21cm IM

PRELIMINARY



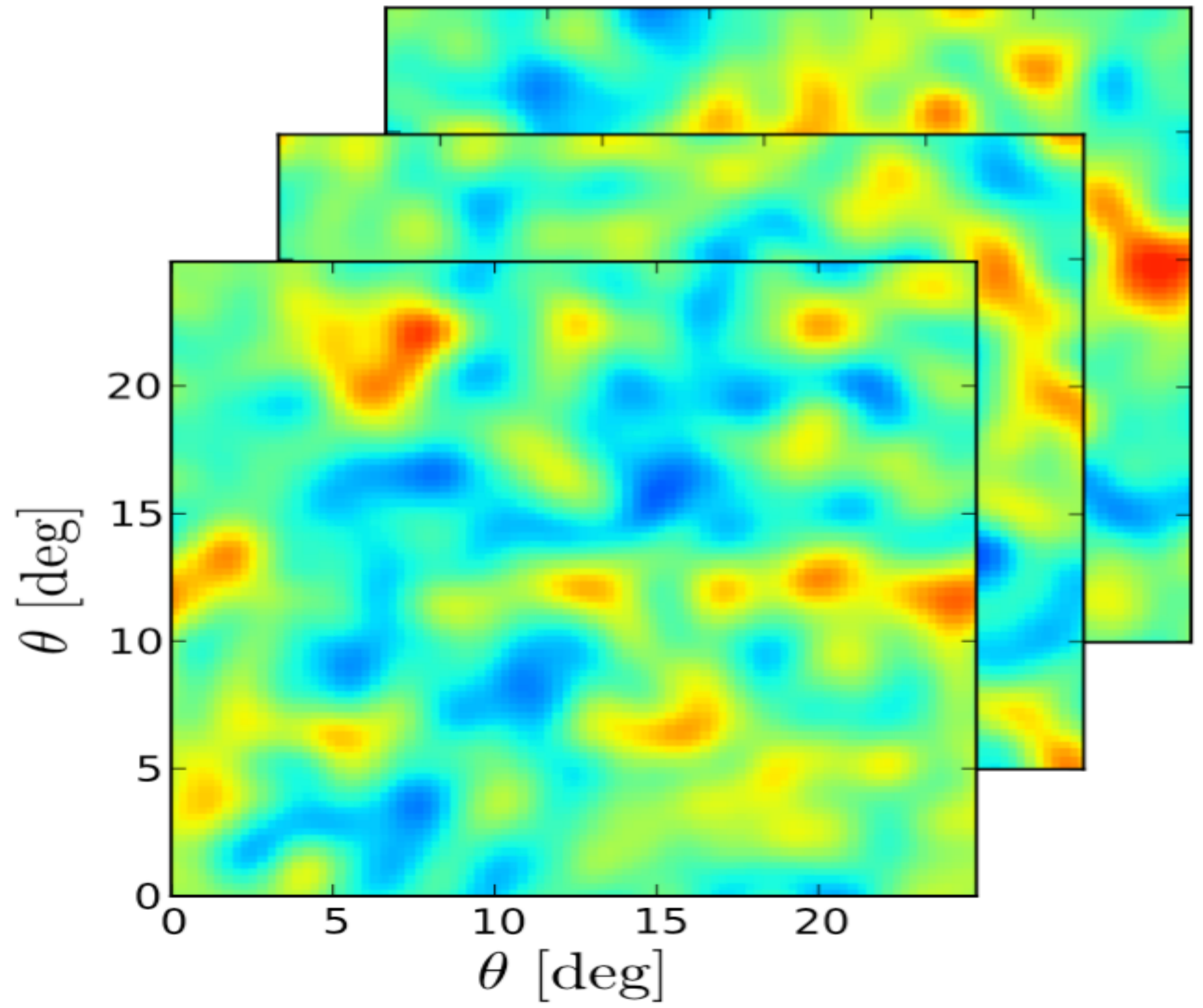
Next

- L - GMCA: using GMCA locally
- Maybe adding a prior on the cosmological signal could help (so far we haven't used any)
- Start using the channels > 1.4 GHz in a wise way

Summary

- We will soon start doing **cosmology** with **21cm IM** at z<6

- **High complementarity with the other LSS probes**



- We are testing/optimising **GMCA** to perform foreground subtraction on 21cm IM: the sparsity based component separation is very well adapted to capture galactic foregrounds.