Exploiting HI intensity maps in real space: a direct search for large-scale halos and filaments

Denis Tramonte

Xi'an Jiaotong-Liverpool University (XJTLU)
Suzhou, China

---

21 cm Cosmology Workshop 2023
Northeastern University & NAOC, Shenyang

July 16-19, 2023

Outline

1. Intro & motivation
2. Data set
3. Searching for halos
4. Searching for filaments
5. Conclusions

1

INTRO & MOTIVATION

Why HI, and what to do with it

Numerical simulations

HI effective tracer of low redshift cosmic web

(Popping+09,+14, Takeuchi+14, Horii+17)

Observational confirmation?

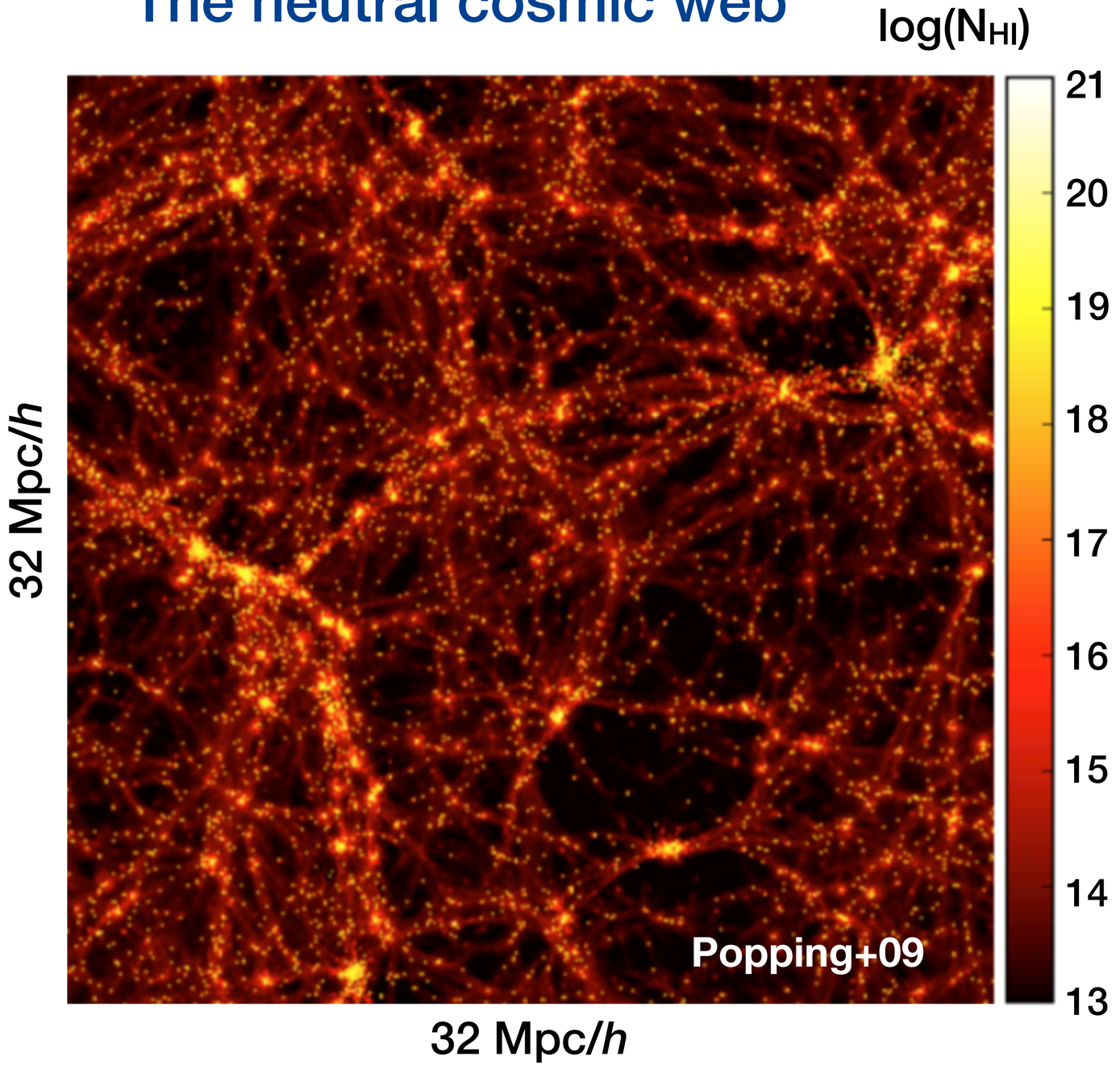
Nodes

HI content / distribution

Filaments

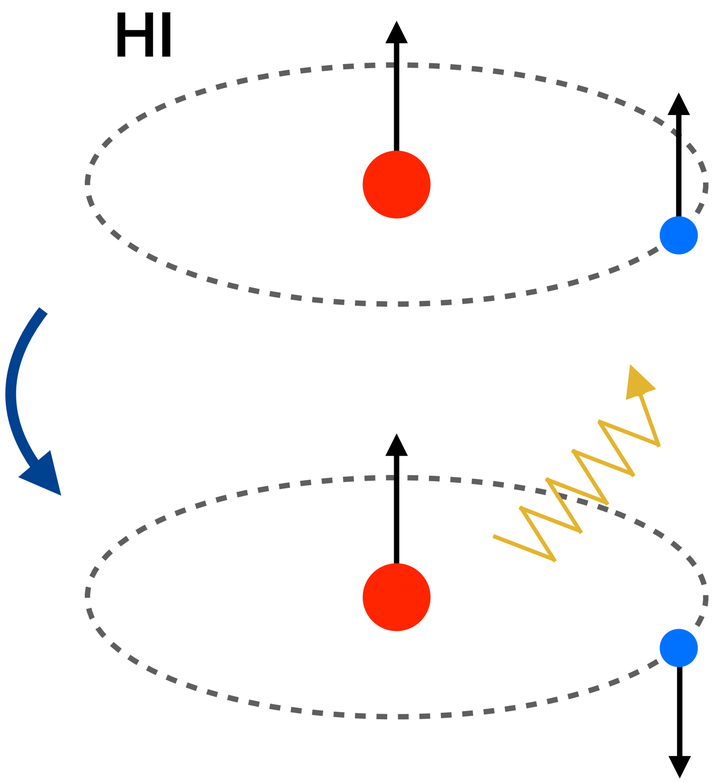
HI detection / upper limits

The neutral cosmic web



The HI 21-cm line

Spin-flip transition (HI ground state)



$\lambda = 21.1$ cm $\nu = 1420$ MHz

Radio line → tomography

Radio line → ground-based observations

Intensity mapping

low integration time

large angular coverage

statistical signal reconstruction

Foregrounds contamination

Combining HI maps and galaxy catalogs

Typically **in Fourier space** (cross-correlation power spectrum)

Chang+10	GBT x DEEP2	$z \in [0.53, 1.12]$	~2 deg^2
Masui+13	GBT x WiggleZ	$z \in [0.6, 1.0]$	~41 deg^2
Anderson+18	Parkes x 2dFGRS	$z \in [0.06, 0.10]$	~1,300 deg^2
Li+20	Parkes x WiggleZ	$z \in [0.73, 0.78]$	~380 deg^2
Wolz+22	GBT x WiggleZ, eBOSS	$z \in [0.6, 1.0]$	~100 deg^2
Cunnington+23	MeerKAT x WiggleZ	$z \in [0.400, 0.459]$	~200 deg^2

Our goal: measurement **in real space** (positional stacking)

Combining HI maps and galaxy catalogs

Typically **in Fourier space** (cross-correlation power spectrum)

Chang+10	GBT x DEEP2	$z \in [0.53, 1.12]$	~2 deg^2
Masui+13	GBT x WiggleZ	$z \in [0.6, 1.0]$	~41 deg^2
Anderson+18	Parkes x 2dFGRS	$z \in [0.06, 0.10]$	~1,300 deg^2
Li+20	Parkes x WiggleZ	$z \in [0.73, 0.78]$	~380 deg^2
Wolz+22	GBT x WiggleZ, eBOSS	$z \in [0.6, 1.0]$	~100 deg^2
Cunnington+23	MeerKAT x WiggleZ	$z \in [0.400, 0.459]$	~200 deg^2

Our goal: measurement **in real space** (positional stacking)

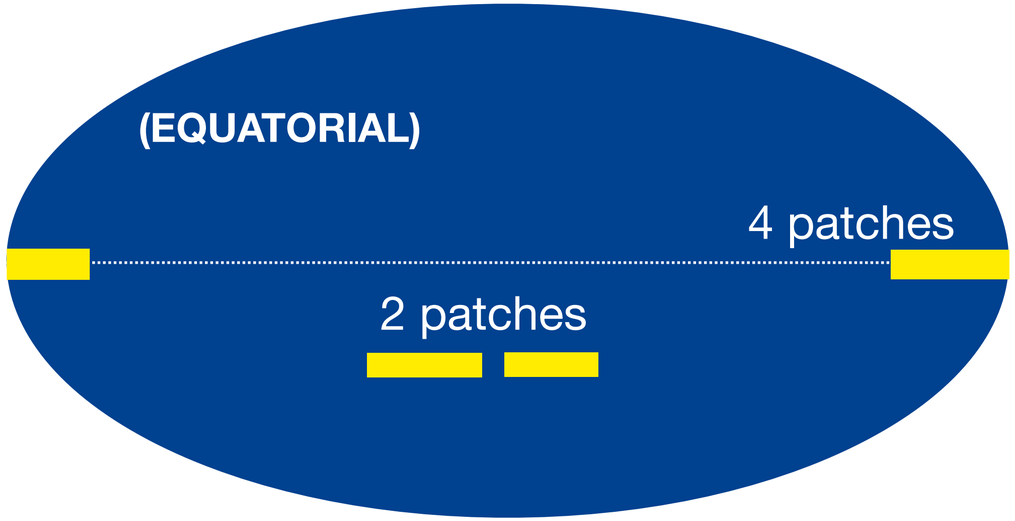
2

DATA SET

Parkes HI maps + 2dFGRS galaxies

The HI maps

Parkes Multibeam Receiver (Anderson+18)



Footprint and resolution

~ 1,300 deg^2 | 2 stripes

14’ beam | (6 patches)

Frequency

ν_c = 1.3155 GHz

$\nu \in [1.28,1.35]$ GHz

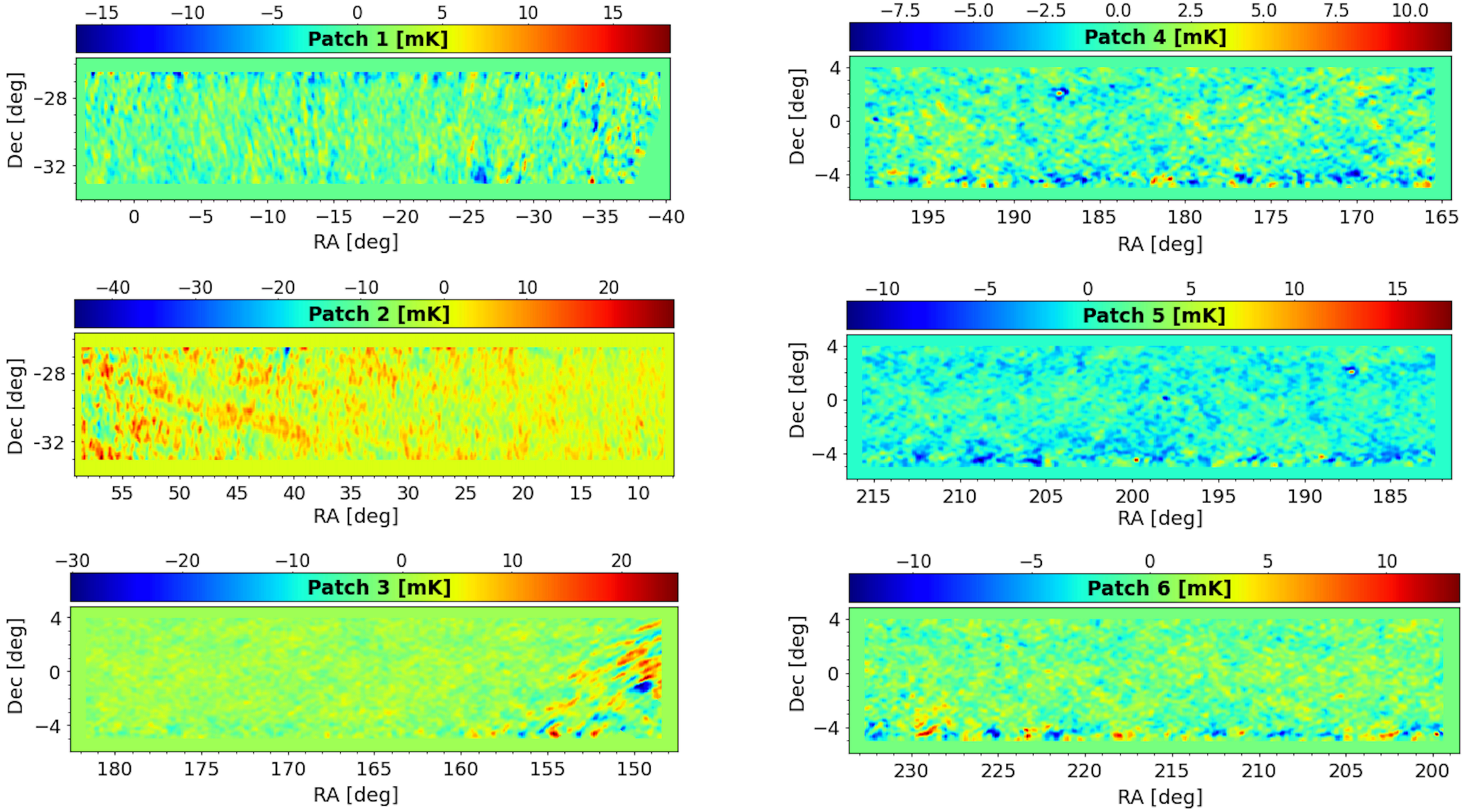
$\Delta\nu$ = 1 MHz

Redshift

$z \sim 0.08$

$z \in [0.06,0.10]$

$\Delta z \sim 8.2 \times 10^{-4}$



PCA foreground removal: both 10 and 20 removed modes cases

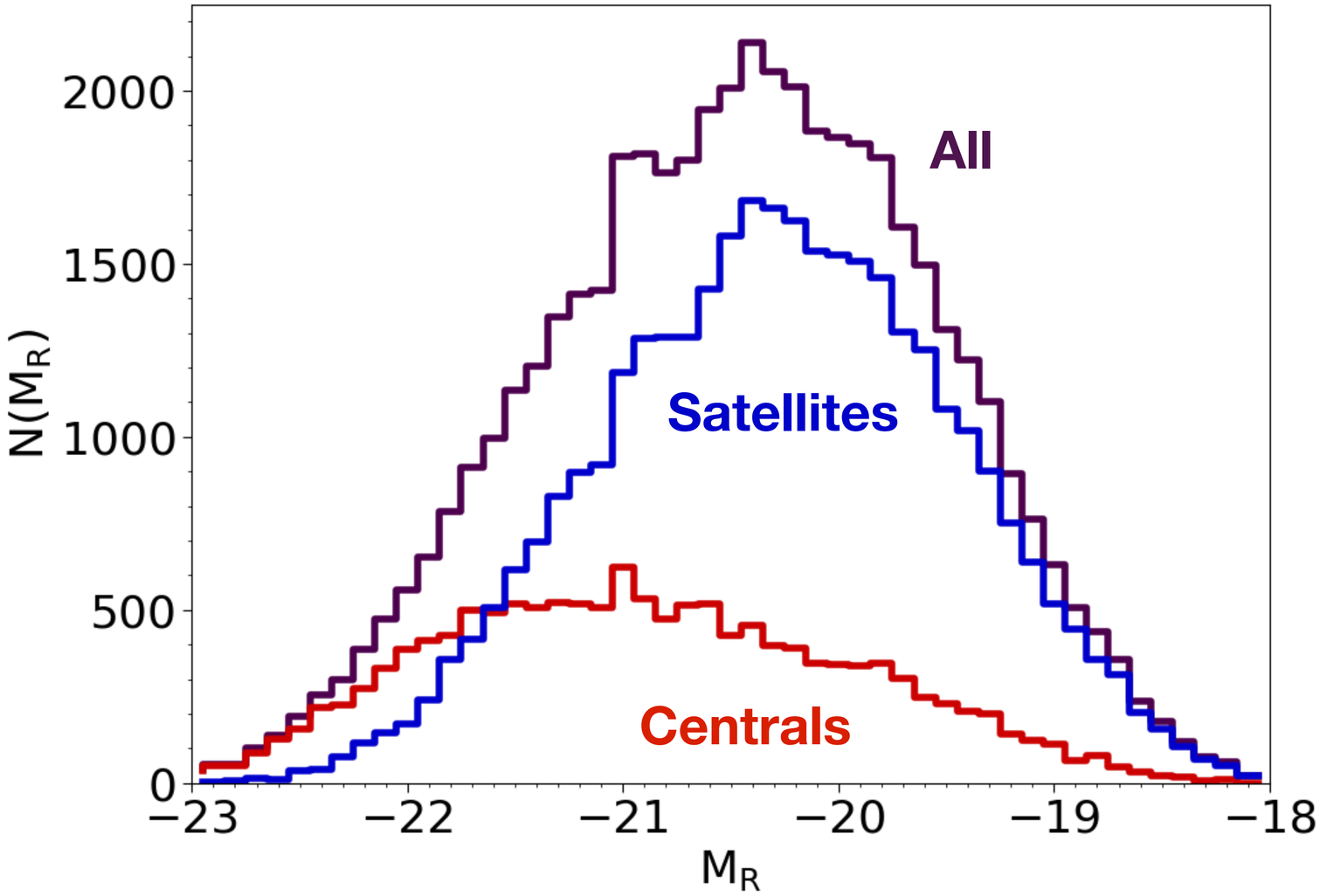
The galaxy catalog

2dFGRS (spectroscopic catalog, Colless+01) queried to match maps volume

Separate centrals and satellite galaxies based on magnitude

All	48,430
Centrals	13,979
Satellites	34,361

Explore dependence on local environment



3

SEARCHING FOR HALOS

Stacking individual galaxies on the HI maps

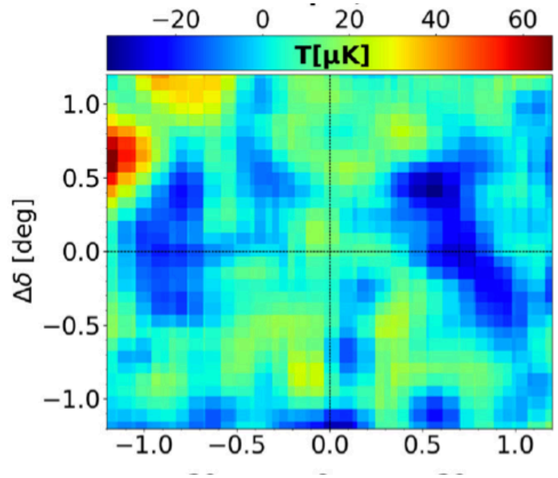
Stacking results

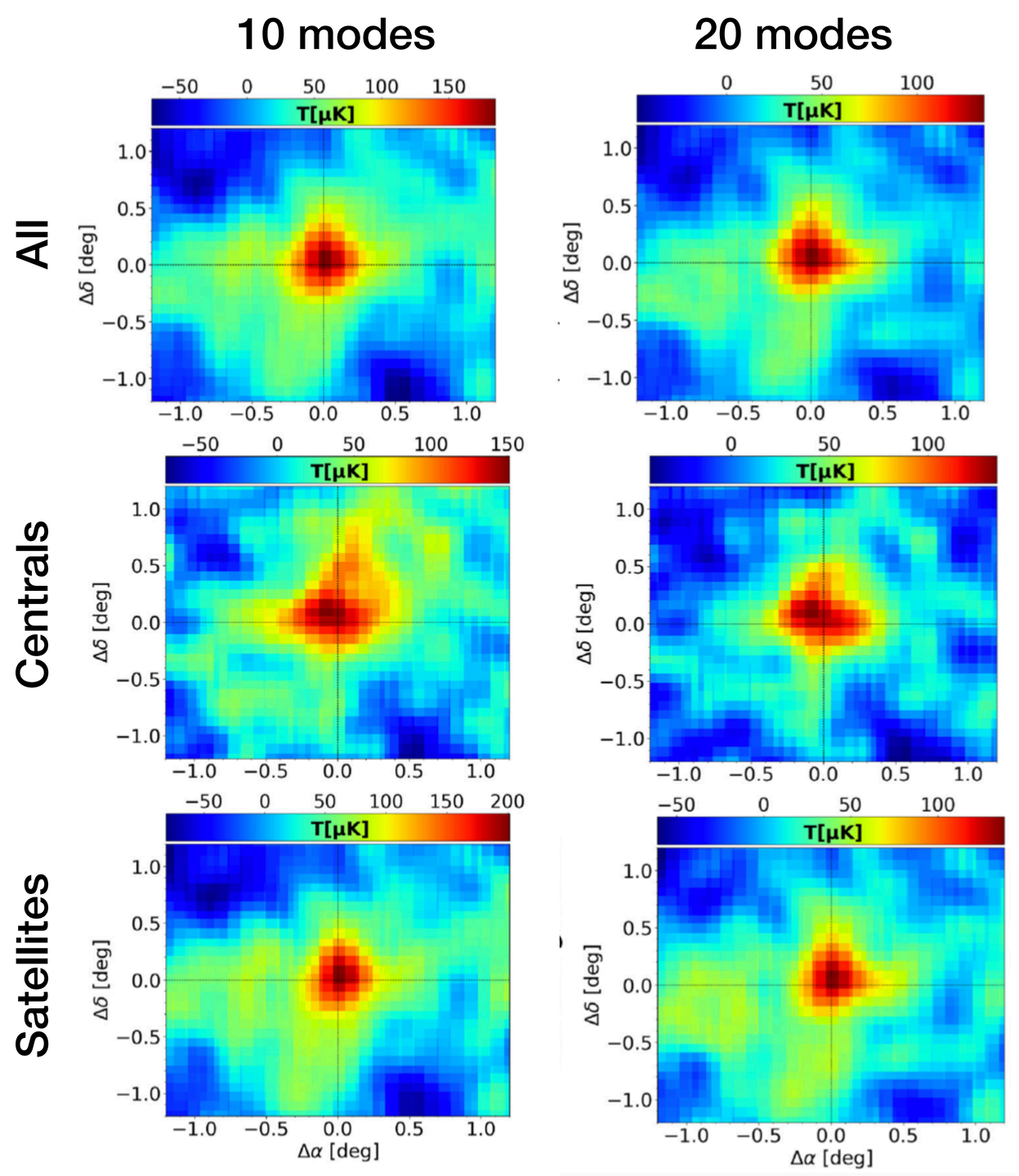
HI halo emission clearly detected

Centrals show less concentrated, more irregular pattern

Clear difference in amplitude between different PCA maps

Randomization completely removes the signal





HI temperature profiles

Resolved profiles ~13σ detection

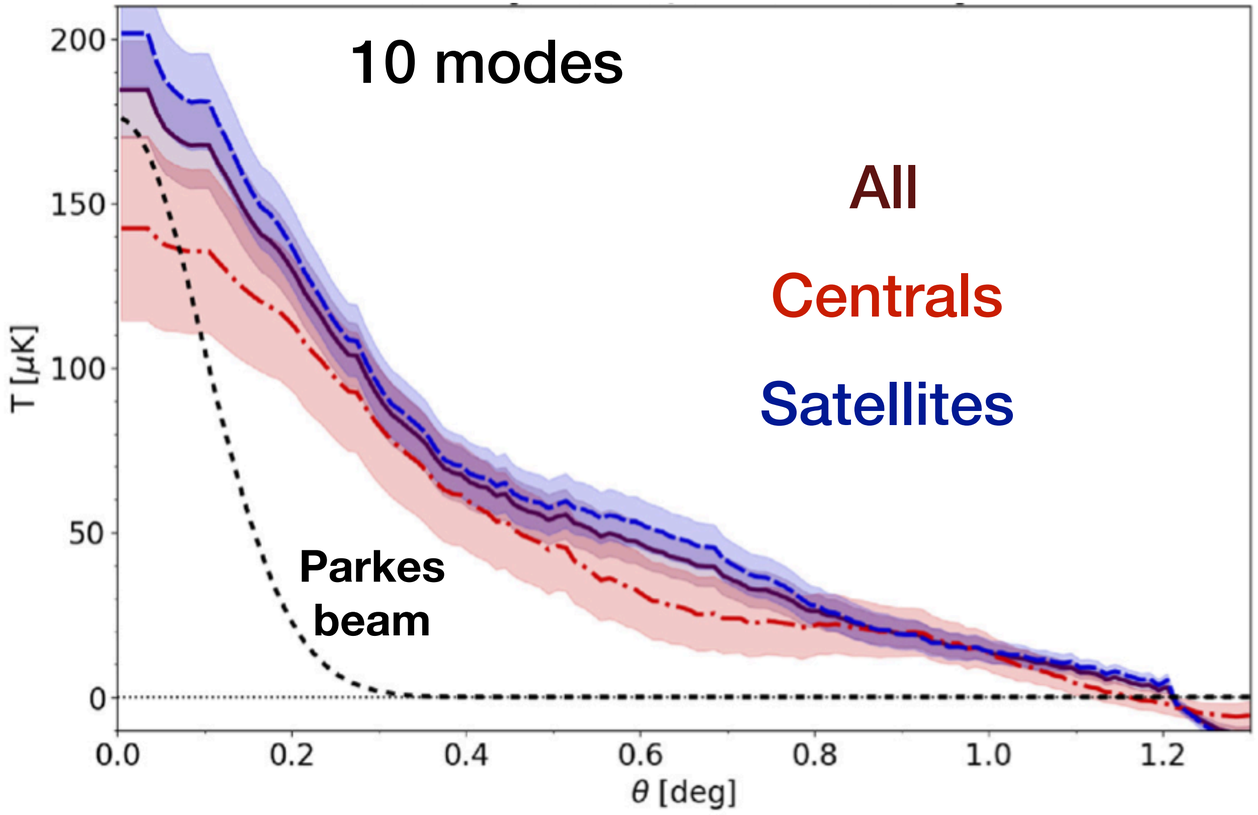
Satellites > All > Centrals

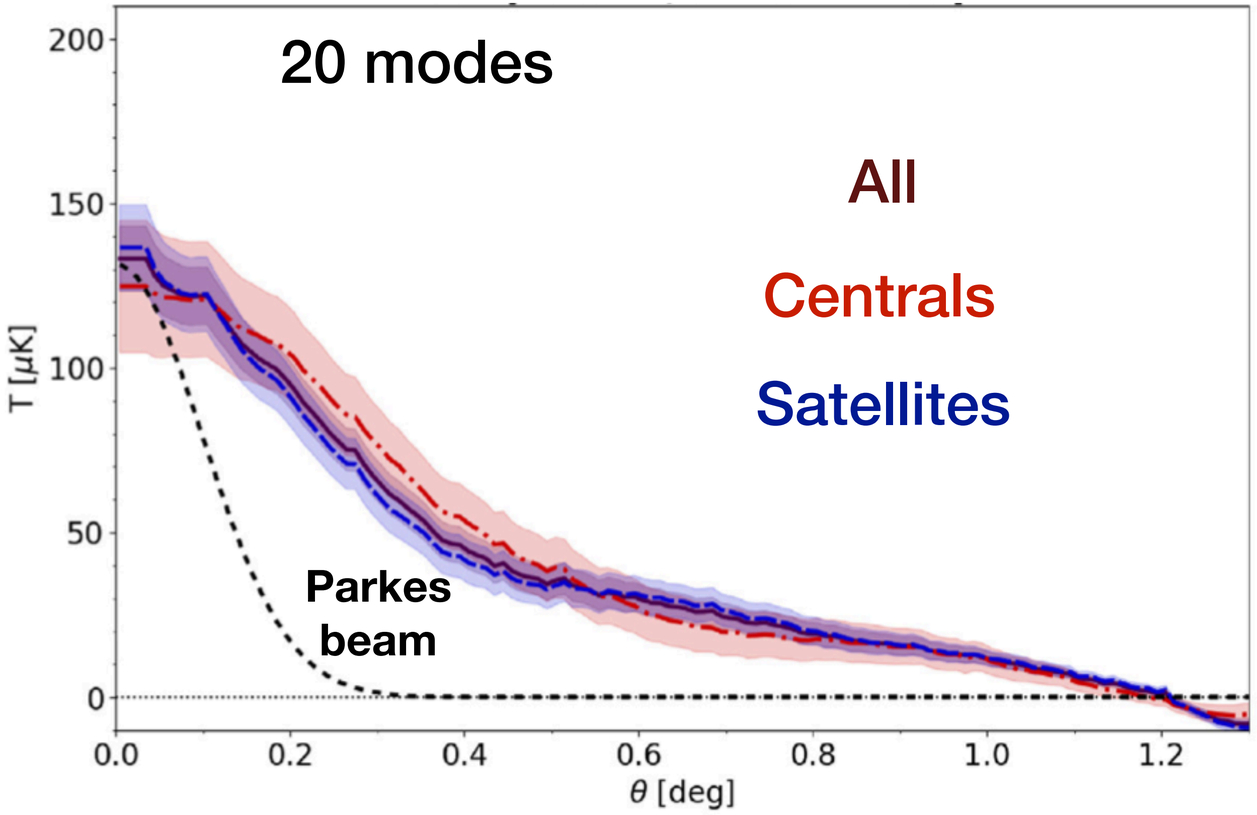
PCA dominant issue

Profiles extended over a few Mpc

These are not galactic HI profiles

Merged contribution of several galactic HI halos





Theoretical modeling

HI mass for halo virial mass

$$M_{\rm HI} = 2N_{10}M_{\rm v}\left[\left(\frac{M_{\rm v}}{M_{10}}\right)^{-b_{10}} + \left(\frac{M_{\rm v}}{M_{10}}\right)^{y_{10}}\right]^{-1}$$

(Padmanabhan+17)

Radial HI distribution

$$\rho_{\rm HI}(r) = \rho_0\left[\left(\frac{3}{4}+\frac{r}{r_{\rm s}}\right)\left(1+\frac{r}{r_{\rm s}}\right)^2\right]^{-1}$$

(Barnes+14, Padmanabhan+17)

LoS integration

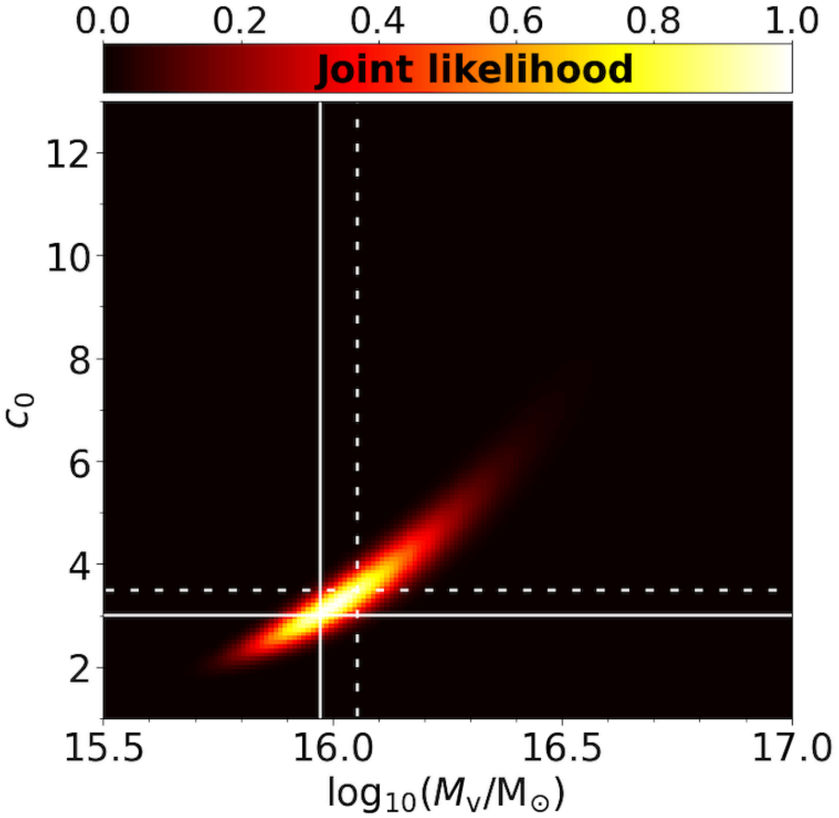
Instrumental effects

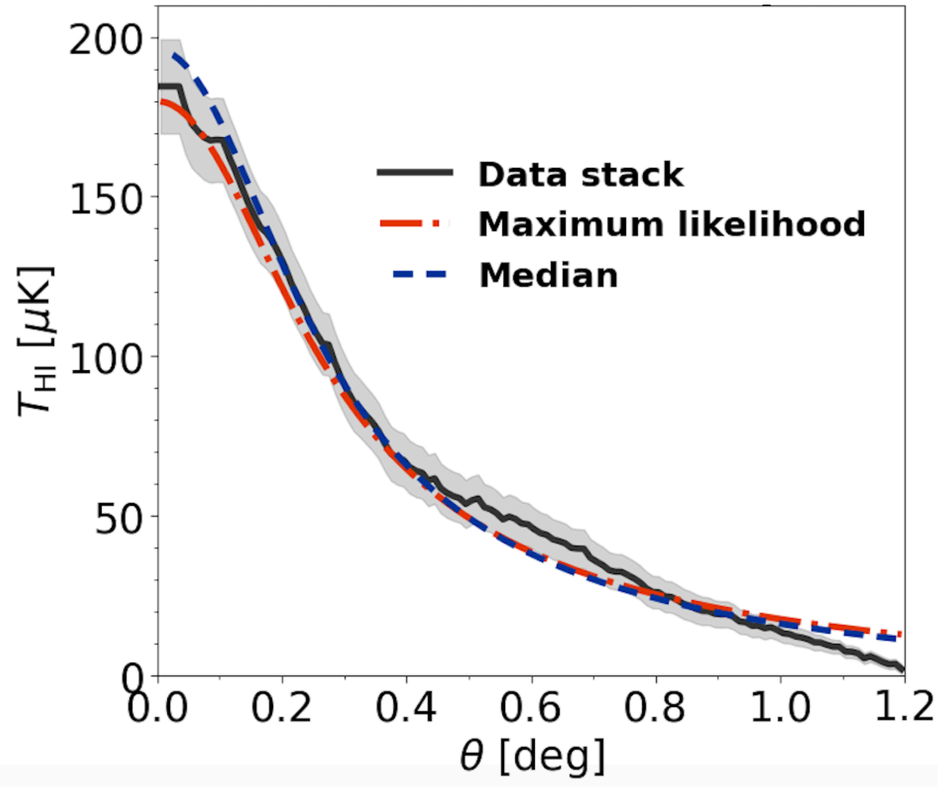
$T_{\rm HI}(\theta)$ prediction

Ideally: comparison data-theory to predict model parameters…

$T_{\rm HI}(\theta)$ measurement

… **in practice**: we don't know the halo masses → Fix scaling parameters → Fit for halo virial mass and HI concentration





$M_{vir} \sim 10^{16}\ M_\odot$

$c_{HI} = R_{vir} / r_s \sim 4$

Multiple galaxy integrated emission

Marginal difference satellites / centrals

(***caveat***: galactic models for supergalactic scales)

4

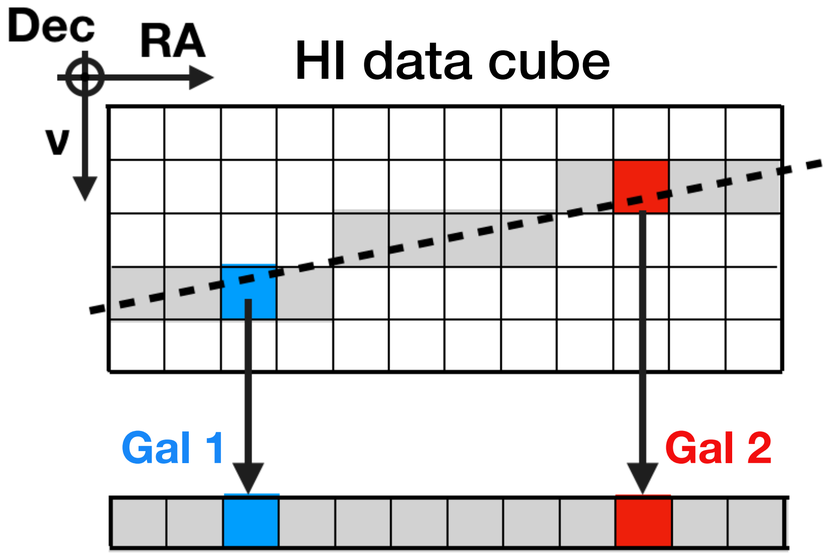
SEARCHING FOR FILAMENTS

Stacking pairs of galaxies on the HI maps

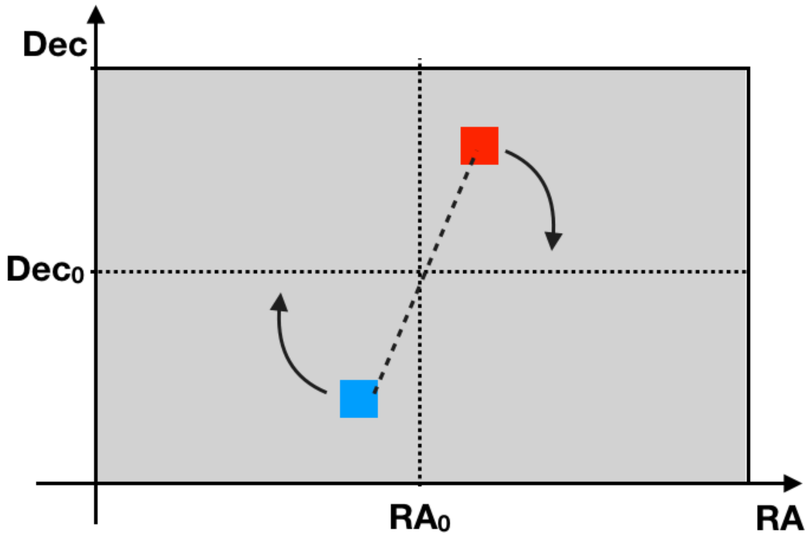
Identifying and stacking filaments

Identify potential filament endpoints	**Proj. separation** $d_T \in [6,14]$ Mpc/h	**LoS separation** $d_L < 6$ Mpc/h	**274,712 pairs** of 2dF central galaxies

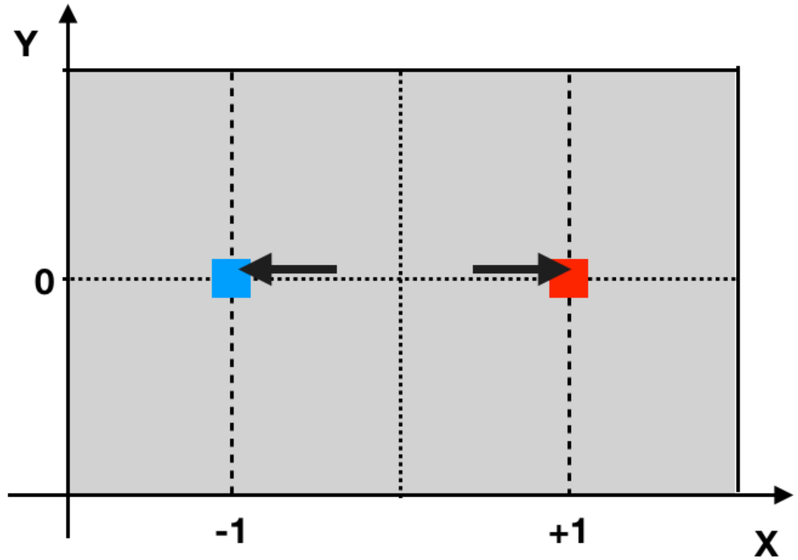
Coherent stack of pairs on HI IM data:



1. Projection



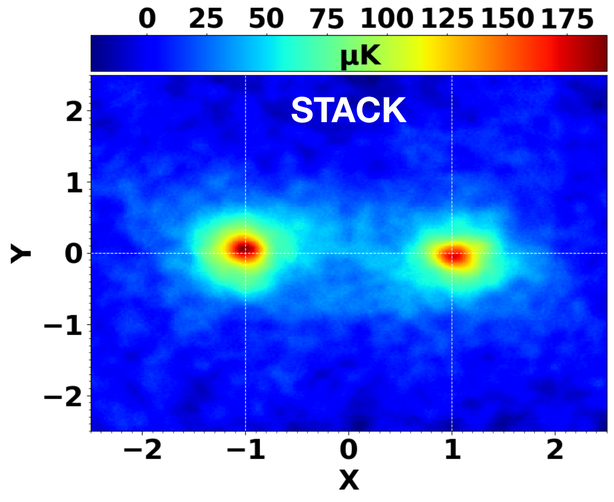
2. Rotation

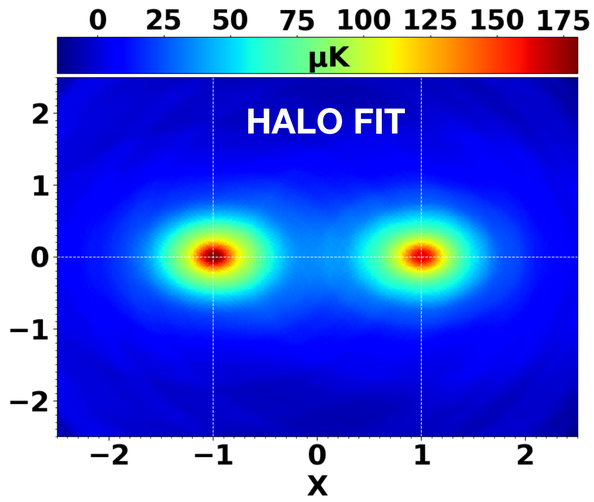


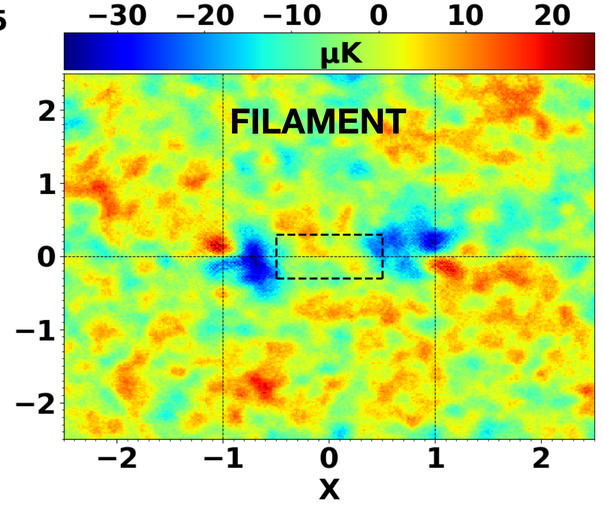
3. Scaling

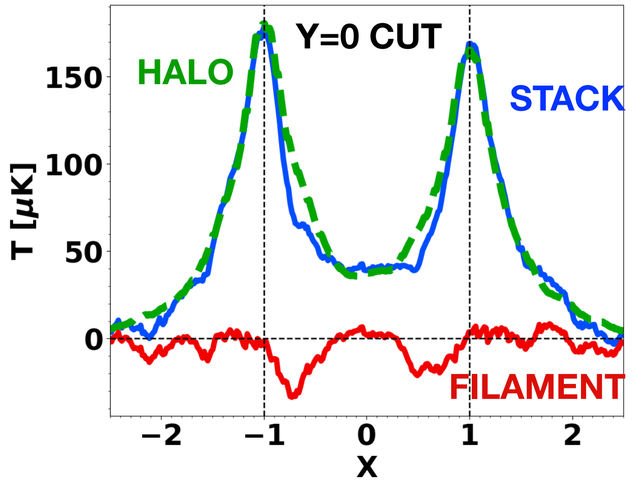
Stacking results

10 modes

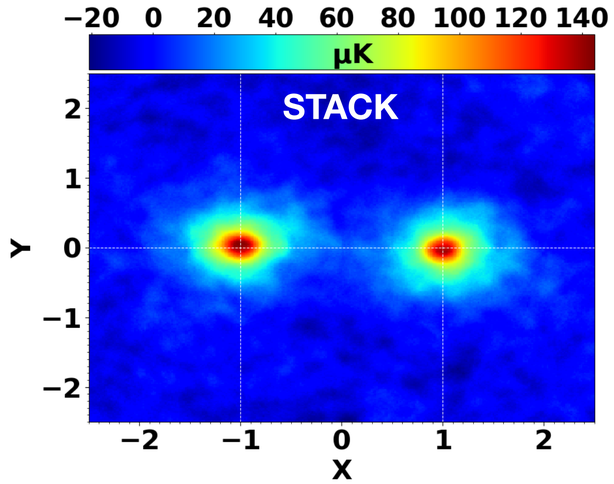


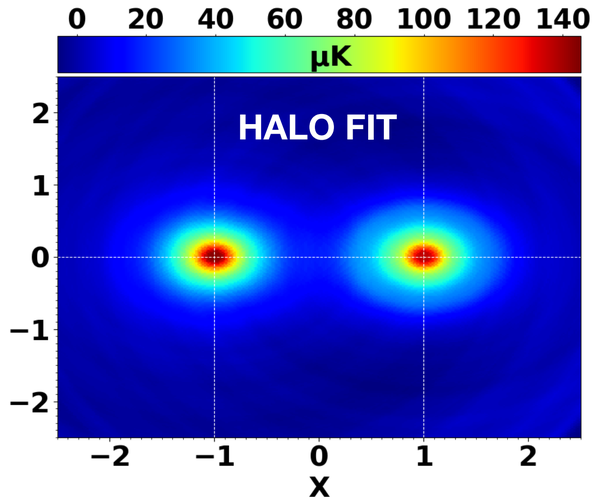


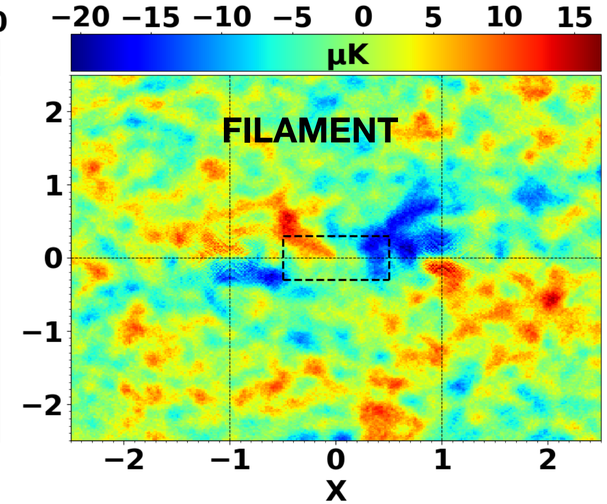


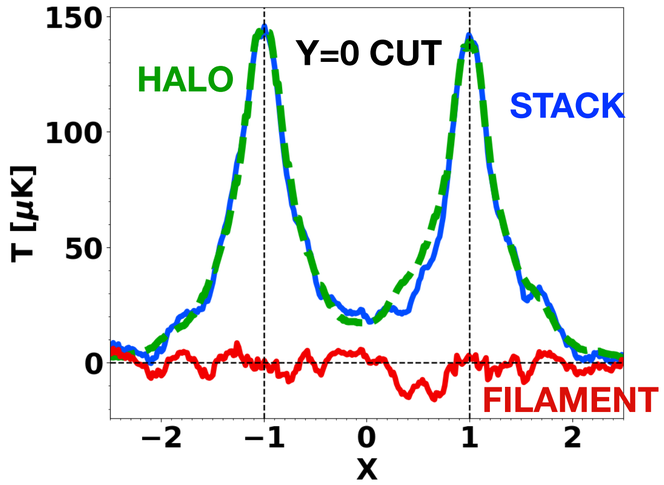


20 modes









Halo contribution at nominal endpoints

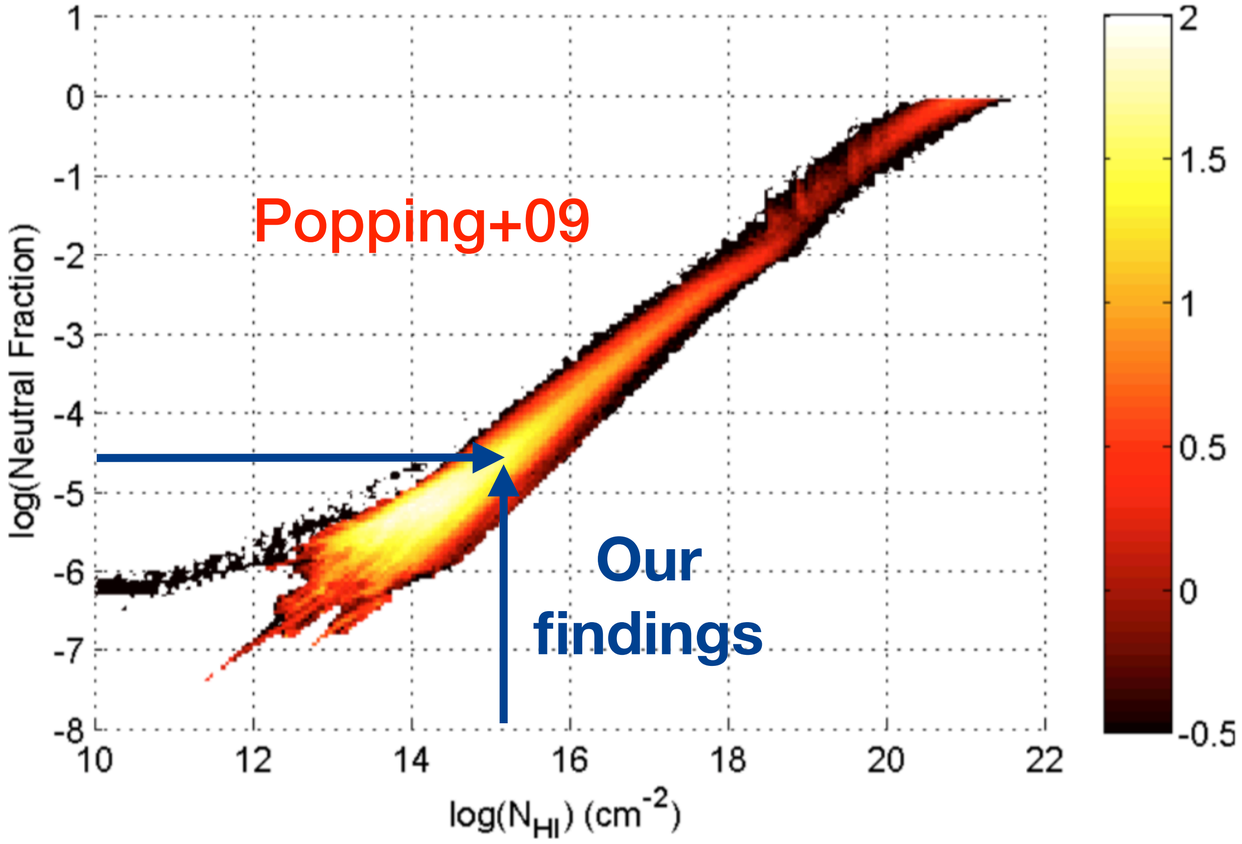
Halo contribution fitted and subtracted

No apparent filament residual in the centre

Sum of fitted profiles enough to account for central emission

Upper limits on filamentary HI

… in agreement with predictions from numerical simulations



HI brightness temperature

$T_{HI} < 7.5$ μK

T_{HI} ~ 1 -10 μK (Horii+17)

T_{HI} ~ μK (Takeuchi+17)

Neutral baryon fraction

$x_{HI}\ \delta_b < 6\times10^{-4}$

x_{HI} ~ 10^{-6} - 10^{-5}

δ_b ~ 10 - 100

(Takeuchi+17)

HI column density

$N_{HI} < 3.4\times10^{15}$ cm^{-2}

N_{HI} ~ 10^{15} - 10^{16} cm^{-2}

(Takeuchi+17)

Filament thickness

$\Delta s < 3$ Mpc

Δs ~ 1 Mpc

(Kooistra+19)

5

CONCLUSIONS

.. and what’s next

Stacks on IM maps useful technique beside traditional cross-correlations

Effective detection of halo HI / possible benchmark for theoretical models

Upper limits on filamentary HI consistent with simulation

New generation maps (FAST, SKA) to constrain halo HI models
(down to M_{vir}~10^{11}Msun at z<0.03) and possibly detect filamentary HI

Proper foreground removal still major issue in IM analysis

HI in halos

Tramonte+20

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **498,** 5916–5935 (2020) doi:10.1093/mnras/staa2727
Advance Access publication 2020 September 15

The neutral hydrogen distribution in large-scale haloes from 21-cm intensity maps

Denis Tramonte [1,2,3★] and Yin-Zhe Ma [1,2,3]

[1] *Purple Mountain Observatory, No. 8 Yuanhua Road, Qixia District, Nanjing 210034, China*
[2] *NAOC-UKZN Computational Astrophysics Center (NUCAC), University of Kwazulu-Natal, Durban 4000, South Africa*
[3] *School of Chemistry and Physics, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban, South Africa*

HI in filaments

Tramonte+19

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **489,** 385–400 (2019) doi:10.1093/mnras/stz2146
Advance Access publication 2019 August 5

Searching for H I imprints in cosmic web filaments with 21-cm intensity mapping

Denis Tramonte,[1,2★] Yin-Zhe Ma,[1,2] Yi-Chao Li[1,3] and Lister Staveley-Smith [4,5]

[1] *School of Chemistry and Physics, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban, South Africa*
[2] *NAOC-UKZN Computational Astrophysics Center (NUCAC), University of Kwazulu-Natal, Durban, 4000, South Africa*
[3] *Department of Physics & Astronomy, University of the Western Cape, Cape Town 7535, South Africa*
[4] *International Centre for Radio Astronomy Research (ICRAR), M468, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*
[5] *ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia*