Simulation on hunting HI filament with pairwise stacking

Speaker: Diyang Liu (NEU)

😊 Collaborators:

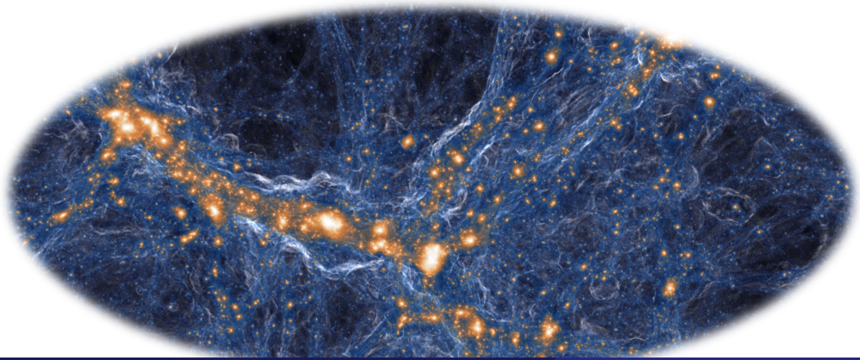
- Yichao Li (NEU), Denis Tramote (XJTLU), Furen Deng (NAOC),
- Jiaxing Wang (NEU), Yougang Wang (NAOC), Xin Zhang (NEU) and Xuelei Chen (NAOC)

Cosmic web

Definition

At large scales (above ~ 10 Mpc), the distribution of galaxies (and dark matter) shows an intricate interconnected network.

- nodes (dense regions typically hosting clusters of galaxies)
- voids (vast low-density regions)
- filaments (lines that connecting nodes)



Formation

- though: asymmetrical gravitional growth
- begin: in the Dark Ages
- process: voids became emptier, nodes and filaments grew UP!
- now: **nearly all galaxies are aligned along the filaments**

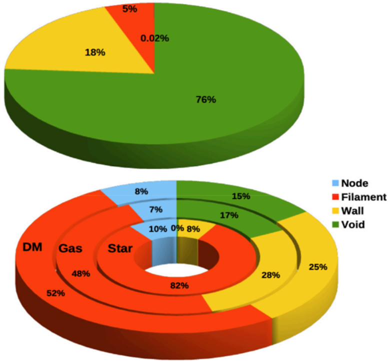
Importance

- formation and evolution of galaxies and structures.

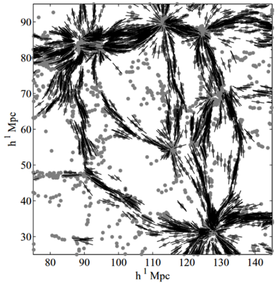
Filament features

- Dominated in the mass fraction
- Align halos and galaxies
- Spin
- Low density (Typical density contrast $\delta < 20$)

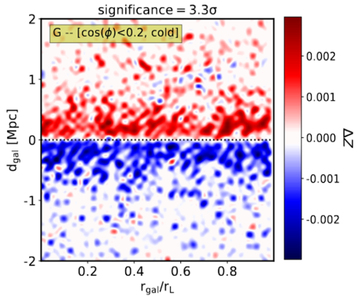
(Aragón-Calvo et al. 2010, MNRAS, 408, 2163)



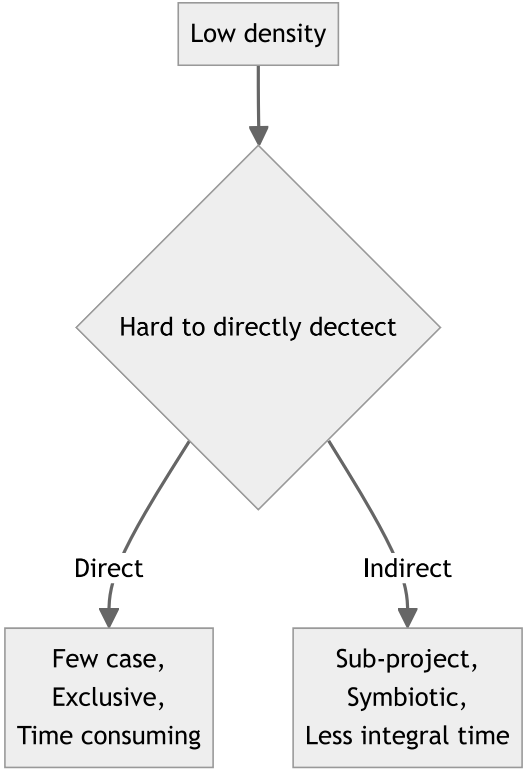
Ganeshaiah et al. 2019, MNRAS, 487 (OUP), 1607



Hahn et al. 2009, MNRAS, 398, 1742



Wang et al. 2021, NA, 5, 839

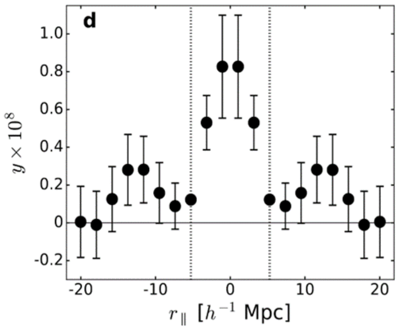


Tracing filament

Methods

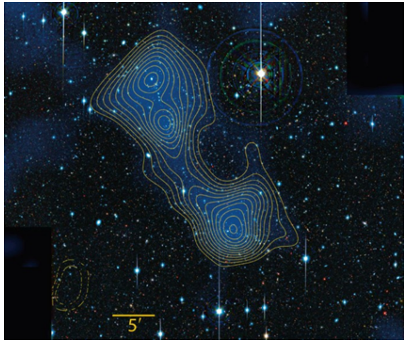
- Gravitational lensing
- Filament identifier
- Pairwise stacking

Sunyaev-Zel'dovich effect (Planck)



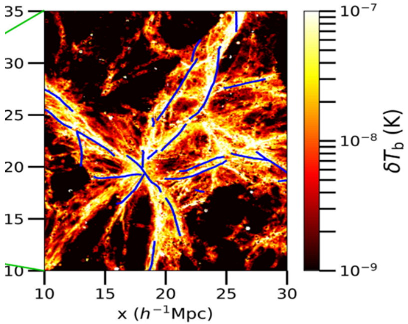
de Graaff et al. 2019, AA, 624, A48

Gravitational lensing (Photometic)



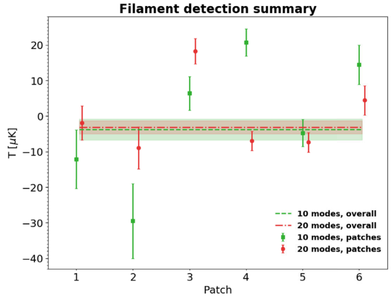
Dietrich et al. 2005, AA, 440, 453

HI emissions (Identifier)



Kooistra et al. 2019, MNRAS, 490, 1415

HI emissions (Stacking)



Tramonte et al. 2019, MNRAS, 489, 385

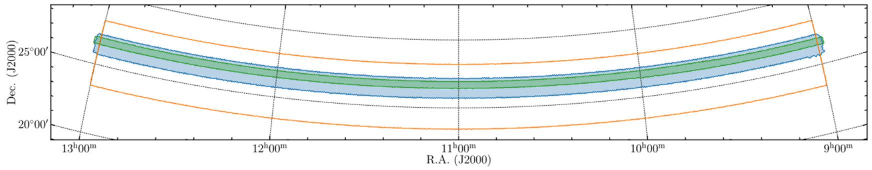
Limited by Parkes sensitivity.

FAST --most sensitive

	Diameter	Beam size	Frequency resolution	System temperature	Sky coverage
FAST	500 m	3 arcmin	7.6 kHz	20 K	~2500 deg2
Parkes	64 m	14 arcmin	1 MHz	21 K	~1300 deg2

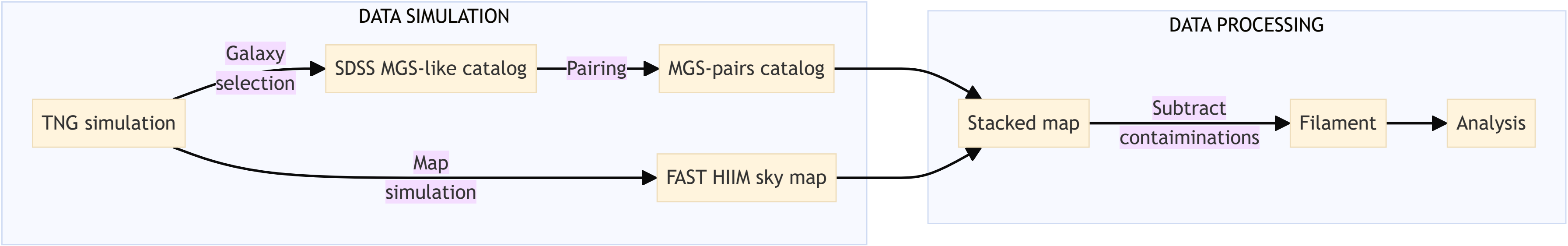
FAST HI surveys

- The FAST All Sky HI survey (FASHI, Zhang et al. 2024)
- The Commensal Radio Astronomy FasT Survey (CRAFTS; Li et al. 2018)
- FAST HI IM drift scan cosmic survey (Li et al. 2023)



Li et al. 2023, APJ, 954, 139

Work flow



Aims

- check the dectability using FAST HI IM survey
- devolpe a pipeline for filament stacking
- find out the optimize strategy for filament stacking

Simulation data

TNG project

A suite of large-volume, cosmological, gravo-magneto-hydrodynamical simulations run with the moving-mesh code Arepo (Springel 2010).

Run†	TNG50-1	TNG100-1	TNG300-1
Volume [cMpc^3]	51.7^3	106.5^3	302.6^3
$L_{\rm box}$, [cMpc/h]	35	75	205
$N_{\rm GAS,DM}$	2160^3	1820^3	2500^3
$N_{\rm Tracer}$	1×2160^3	2×1820^3	1×2500^3
$m_{\rm baryon}$, [M$\odot$/h]	5.7×10^4	9.4×10^5	7.6×10^6
$m_{\rm DM}$, [M$\odot$/h]	3.1×10^5	5.1×10^6	4.0×10^7

Select the snapshot 091 (at $z \sim 0.1$) of TNG100-1.

FAST HI intensity map construction

- calculate the brightness temperature
- considering the RSD effect
- add beam smoothing effect (3 arcmin)
- add thermal noise ($T_{sys} = 20\,\mathrm{K}, \Delta t = 48\,\mathrm{s}$)

SDSS MGS-like catalog construction

- Exclude non-galaxy subhalos (*Subfind_flag* labeled)
- Apply gas and star mass cut ($2 \times 10^8\,\mathrm{M}_\odot$)
- Magnitude cut ($r_p < 17.77$ for Main Galaxy Sample)

Pairwise stacking

Assumption

Galaxy pairs are connected by straight filaments.

Pairing condition

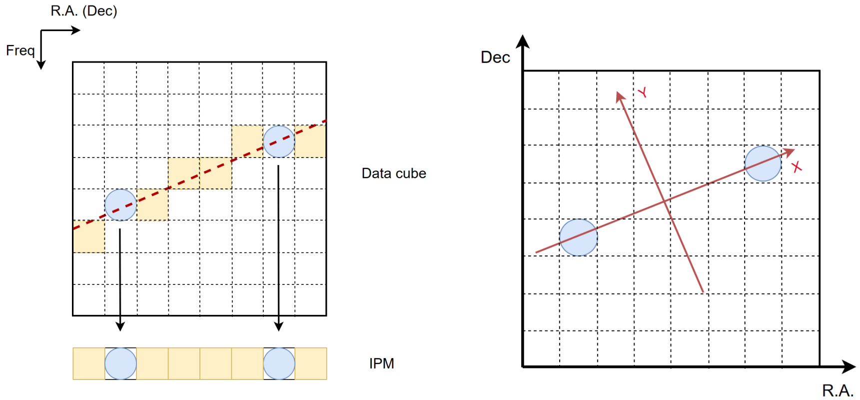
- Transversal separation: $6 - 14\,h^{-1}\mathrm{Mpc}$
- Radial separation: $< 5\,h^{-1}\mathrm{Mpc}$

To select

- A pair of galaxies that belongs to different clusters
- Filaments perpendicular to the line of sight

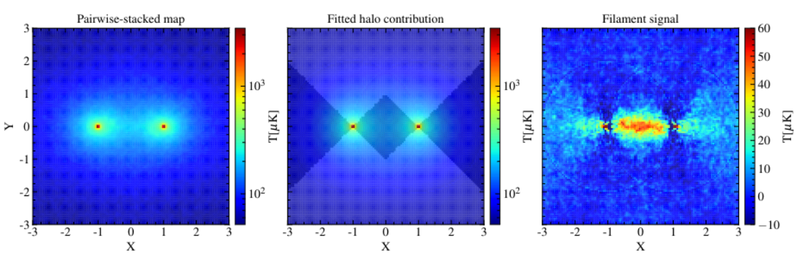
Stacking procedures

- Extract the 2D individual pair map (2D-IPM)
- Construct the aligned 2D-IPM
- Construct the 2D pairwise-stacked map (2D-PSM)



Subtract containimation

Subtract halo contribution

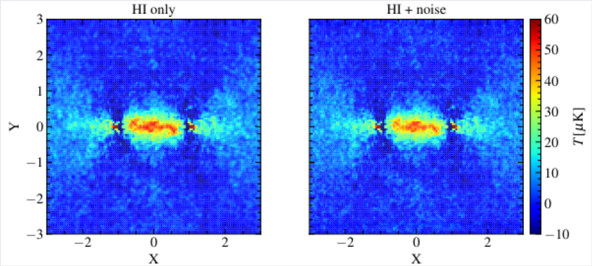


- Assuming a symmetrical halo profile.
- Shadowed area were masked during halo fitting

Subtract galaxy contribution

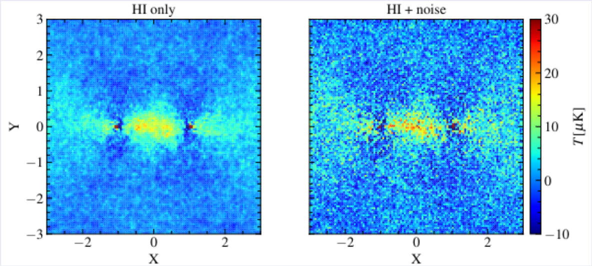
- Mask radius: $120\,h^{-1}\mathrm{kpc}$ (FAST main beam size)
- Mask frequency width: $0.3\,\mathrm{MHz}$ ($60\,\mathrm{km\,s^{-1}}$)

Mask MGS-like galaxies (Bright)



- No significant changes after masking!
- No evident impact of thermal noise!

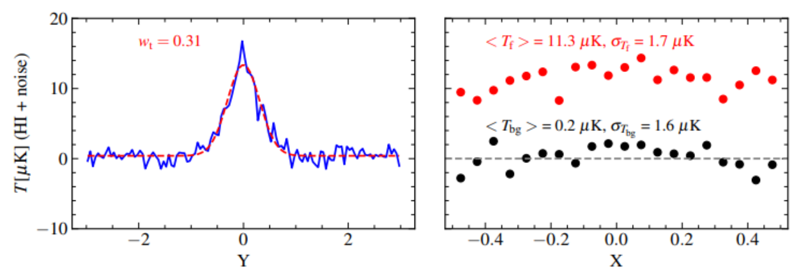
Mask all potential galaxies (Bright + Faint)



- Significantly reduced after masking!
- Evident impact of thermal noise!

Signal estimation

Width and Mean brightness temperatrue



- Use Gaussian function to estimate filament width
- Filament: within $1\,\sigma$
- Backround: within $3 - 4\,\sigma$

Comparison

	r $[h^{-1}\text{Mpc}]$	T_f $[\mu K]$	T_{bg} $[\mu K]$	SNR
	HI only			
Unmasked	1.46	35.6 ± 2.6	0.0 ± 1.7	20.9
Mask MGS	1.46	36.3 ± 2.5	0.1 ± 1.9	19.1
Mask all	1.72	11.4 ± 0.7	0.0 ± 0.4	28.5
	HI + noise			
Unmasked	1.46	35.2 ± 2.8	0.1 ± 1.7	20.7
Mask MGS	1.41	34.7 ± 2.6	0.2 ± 1.7	20.4
Mask all	1.56	11.3 ± 1.7	0.2 ± 1.6	7.1

- A consistent estimation of filament radius about $1.5\ h^{-1}\text{Mpc}$
- 'Mask all' decreased to $11.3\ \mu\text{K}$, indicating that faint galaxies contribute to about 70% of the total HI filament brightness temperature.

Background level

	r [h^{-1}Mpc]	T_f [μK]	T_{bg} [μK]	SNR
		HI only		
Unmasked	1.46	35.6 ± 2.6	0.0 ± 1.7	20.9
Mask MGS	1.46	36.3 ± 2.5	0.1 ± 1.9	19.1
Mask all	1.72	11.4 ± 0.7	0.0 ± 0.4	28.5
		HI + noise		
Unmasked	1.46	35.2 ± 2.8	0.1 ± 1.7	20.7
Mask MGS	1.41	34.7 ± 2.6	0.2 ± 1.7	20.4
Mask all	1.56	11.3 ± 1.7	0.2 ± 1.6	7.1

- Without noise, background level decreased for 'Mask all' case, indicating that it's galaxy contributed.
- With noise, the backgroud level maintianed stable across three mask cases, indicating that impact of thermal noise dominated only when all galaxy contributions were removed.

Background level = Background variation + Themal noise

However, in reality we can only mask bright galaxies.

Large shallow survey vs Narrow deep survey

Given total integral time,

- narrow deep sky survey: compress the thermal noise only
- large shallow sky survey: compress both the thermal noise and background variation.

HI column density

HI Column density

$$\left(\frac{N_{\rm HI}}{\rm cm^{-2}}\right) = 1.82\times10^{12}\left(\frac{T_{\rm f}}{\mu\rm K}\right)\left(\frac{\Delta v}{\rm km\ s^{-1}}\right)$$

- Take $T_{\rm f} = 11.3\,\mu\rm K$ and $\Delta v = 60\,\rm km\ s^{-1}$, gives us $N_{\rm HI} = 1.2\times10^{15}\ \rm cm^{-2}$

HI density parameter

$$\Omega^{\rm f}_{\rm HI}(z) = \frac{\rho_{\rm H}(z)}{\rho_{\rm c}(0)} = 7.6\times10^{-3}\left(\frac{T_{\rm f}}{\rm mK}\right)\left(\frac{h}{0.7}\right)^{-1}(1+z)^{-2}E(z)$$

- Substituting $T_{\rm f} = 11.3\,\mu\rm K$ gives us $\Omega^{\rm f}_{\rm HI}(z\simeq0.1) = 7.7\times10^{-5}$

HI clumps thickness

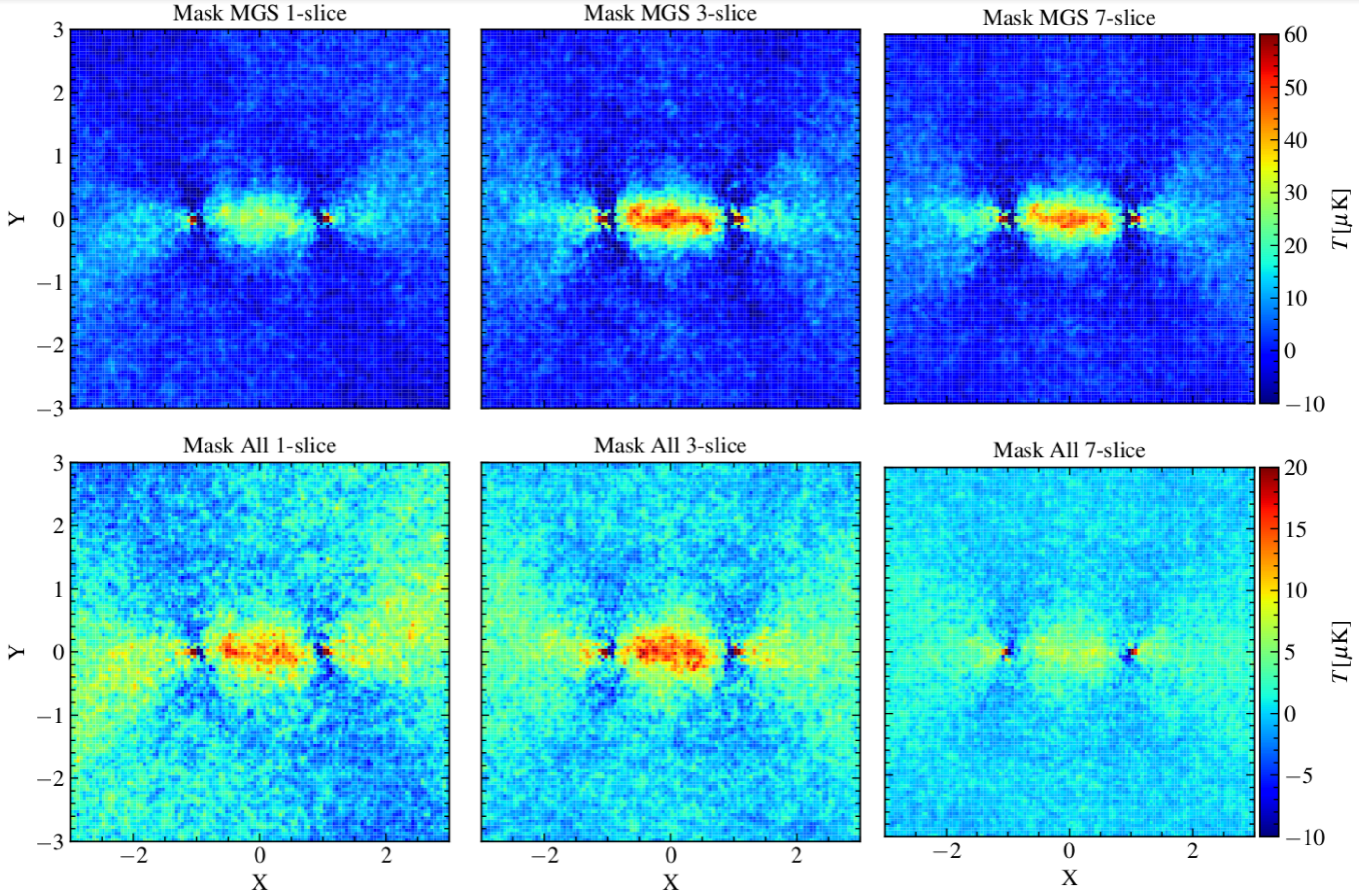
$$N_{\rm HI} = \frac{\Omega^{\rm f}_{\rm HI}\rho_{\rm c}}{m_{\rm HI}}(1+z)^3\Delta s$$

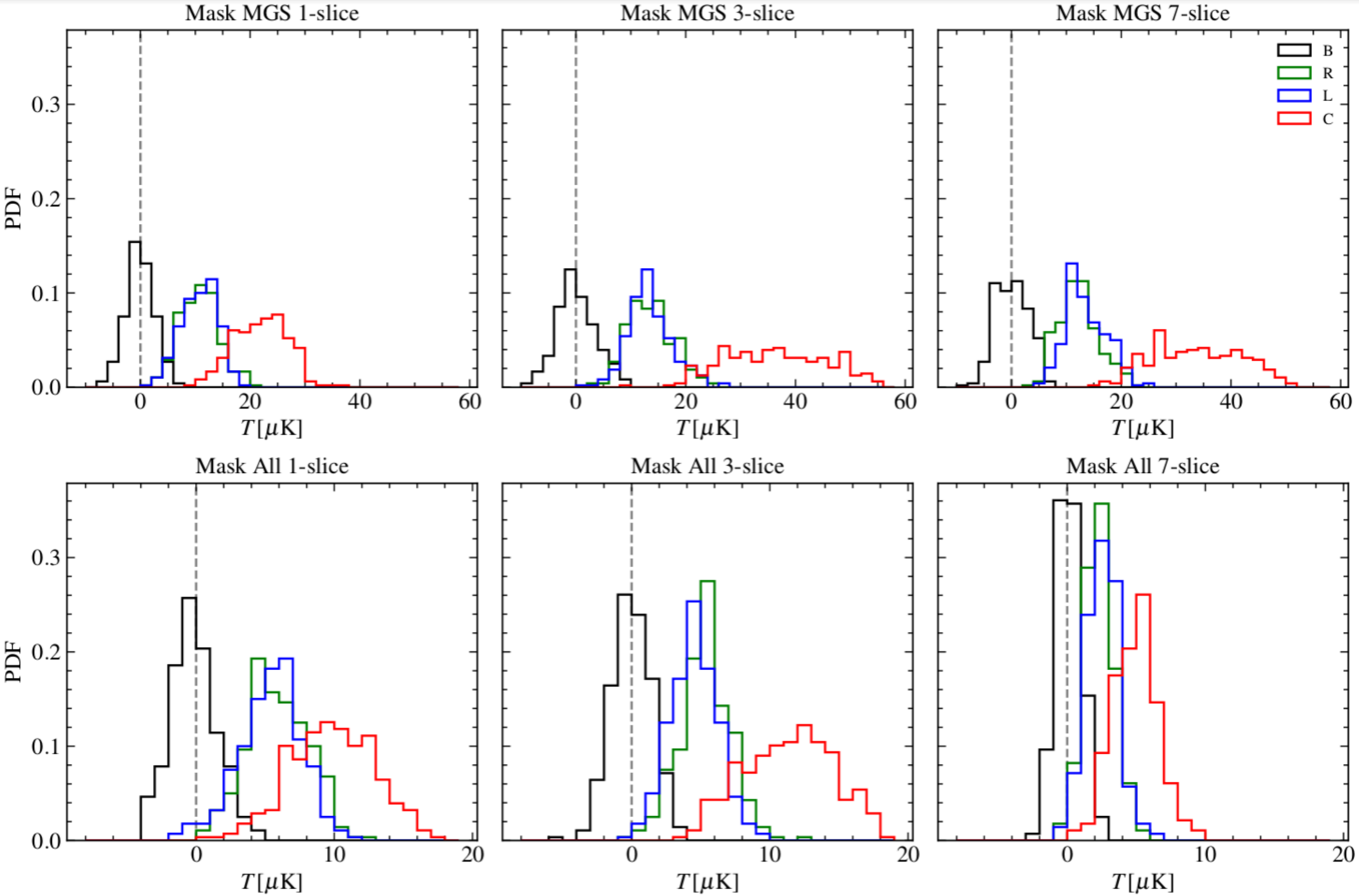
- Substituting $N_{\rm HI} = 1.2\times10^{15}\ \rm cm^{-2}$ and $\Omega^{\rm f}_{\rm HI}(z\simeq0.1) = 7.7\times10^{-5}$, gives us $\Delta s = 0.47\,h^{-1}\rm Mpc$.
- About 1/3, comparing to $1.5\,h^{-1}\rm Mpc$, indicating a sparsely distributed compact HI clumps inside filaments.

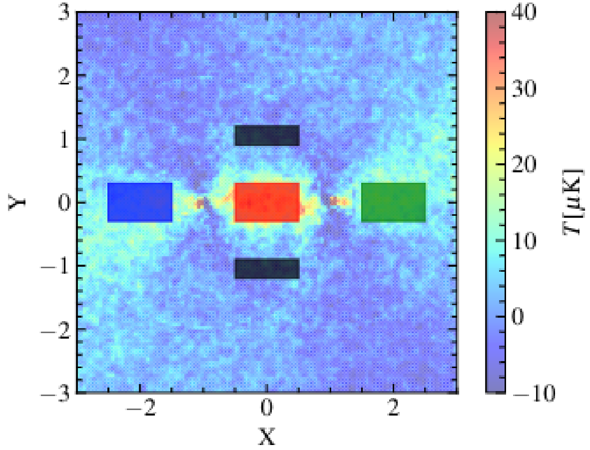
Conclusion

- We employed an end-to-end simulation to investigate the effectiveness of isolating faint HI filament signals from the FAST HI intensity mapping survey through the galaxy pairwise stacking method.
- We found that the contributions of those galaxies living in or near the filaments are the dominating term, about 70%, especially the weak sources not detected by optical telescope.
- If we masked all the galaxy contributions, the signal level decrease from $35.2 \pm 1.7\,\mu\mathrm{K}$ to $11.3 \pm 1.7\,\mu\mathrm{K}$, with a corresponding HI column density $1.2 \times 10^{15}\,\mathrm{cm}^{-2}$.
- Our simulation showed that a shallow large sky survey of FAST is a good way to do filament stacking.
- We also estimated the HI cloud thickness at $\Delta s = 0.47\,h^{-1}\mathrm{Mpc}$, which is much smaller than the filament radius $1.5\,h^{-1}\mathrm{Mpc}$, indicating a sparsely distributed compact HI clumps inside filaments.

Thank You 😃


Mask MGS 1-slice
Mask MGS 3-slice
Mask MGS 7-slice
Mask All 1-slice
Mask All 3-slice
Mask All 7-slice
X
Y
$T[\mu K]$


Mask MGS 1-slice
Mask MGS 3-slice
Mask MGS 7-slice
Mask All 1-slice
Mask All 3-slice
Mask All 7-slice
PDF
T[μK]
B
R
L
C


3
2
1
0
−1
−2
−3
Y
−2
0
2
X
40
30
20
10
0
−10
$T[\mu K]$