



中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES
CHINESE ACADEMY OF SCIENCES



中国科学院大学

University of Chinese Academy of Sciences



清华大学天文系

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CRAFTS for HI cosmology

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4.14.2026 @ Tianlai telecon

Supervisors: Prof. Yougang Wang, Prof. Xuelei Chen, Dr. Laura Wolz (UoM)

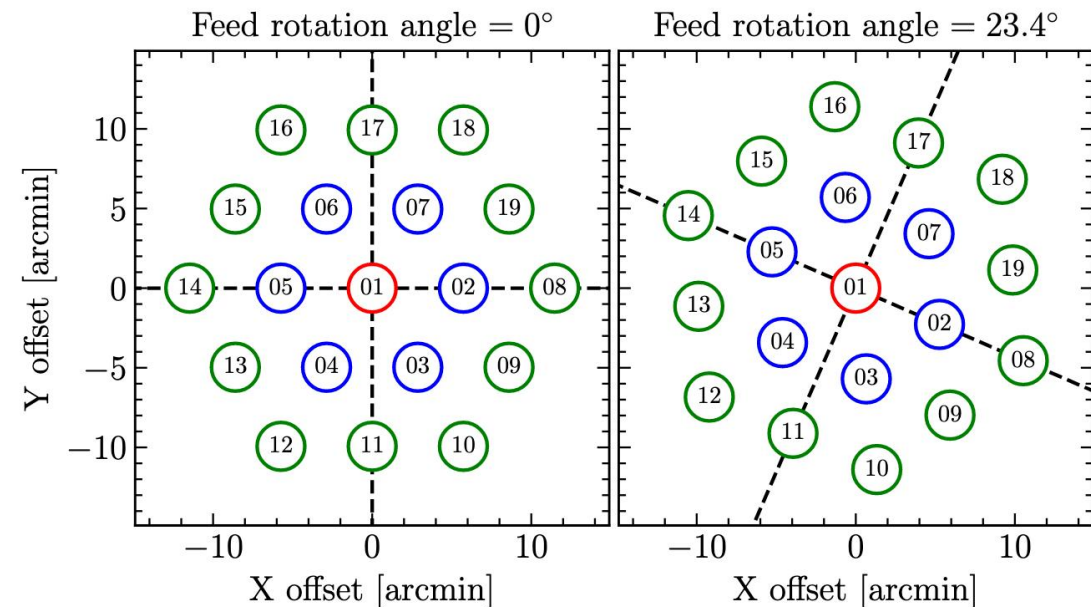
Collaborators: Yichao Li, Wenkai Hu, Keith Grainge, Steven Cunnington,
Furen Deng, Shifan Zuo, Shuanghao Shu, Xinyang Zhao, FAST collaboration et al.

Outline

- **Observation & Data processing**
 - FAST surveys, data, pipeline
- **Validation tests**
 - noise level, continuum sources, HI emissions
- **Preliminary results of intensity mapping**
 - IM, future plans
- **Summary**

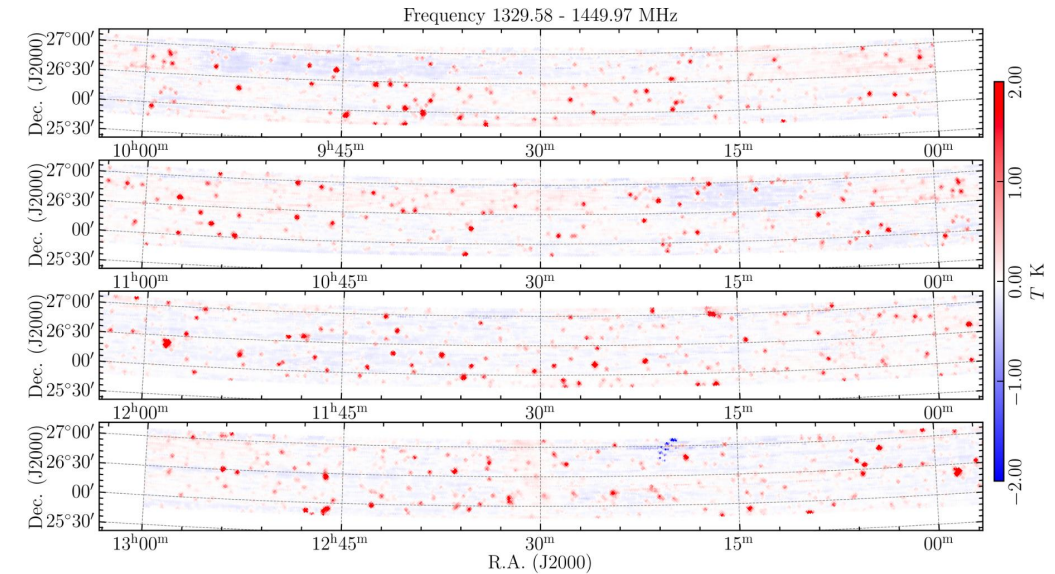
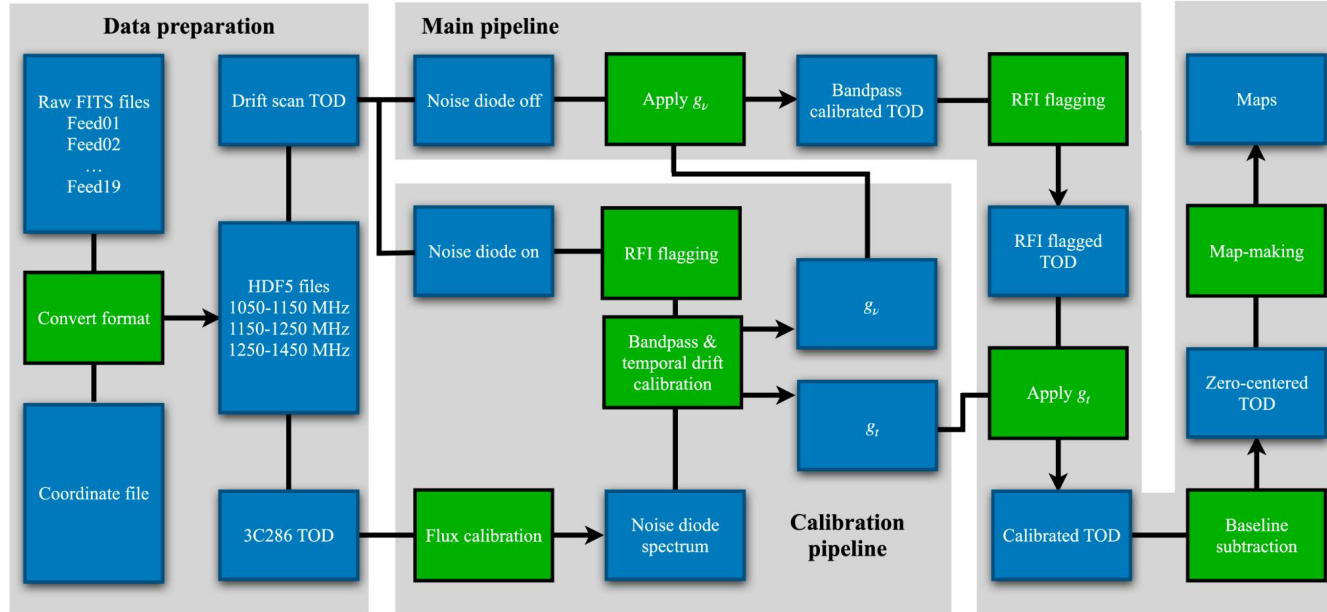
Observations

- **FAST (Five-hundred-meter Aperture Spherical radio Telescope)**
- Location: Guizhou, China, E 106.°86, N 25.°65
- Sky coverage: $-15^\circ \sim 65^\circ$
- $D_{\text{geo}} = 500\text{m}$, $D_{\text{illu}} = 300\text{m}$, $A_{\text{eff}} \sim 50,000\text{m}^2$ \rightarrow spatial resolution $\sim 3'$ @ 1420MHz
- L-band(1-1.5GHz) 19-beams receiver $\rightarrow z \sim 0 - 0.35$

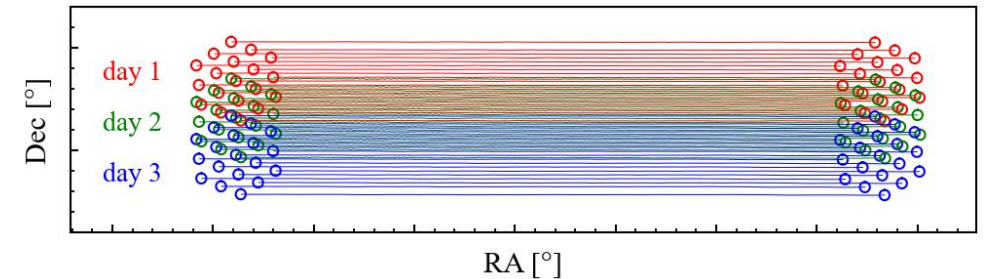


Observations

- **FATHOMER** (Fast neuTRal HydrOgen intensity Mapping ExpeRiment)



FATHOMER sky map



drift scan with L-band 19-beam receiver

FAST HI drift scan data analysis pipeline.
 Li Y.C., Wang Y.G. et al.
 2023, ApJ, 954, 139.
 liyichao@mail.neu.edu.cn



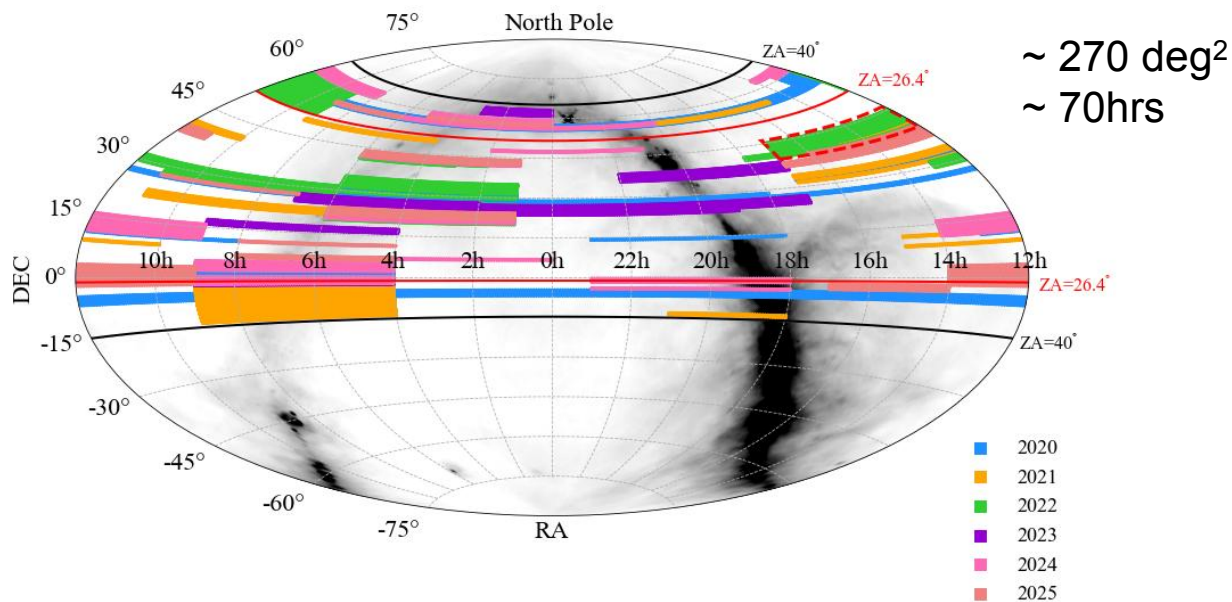
Y. Li, et al. 2023, ApJ, 954, 139

Observations

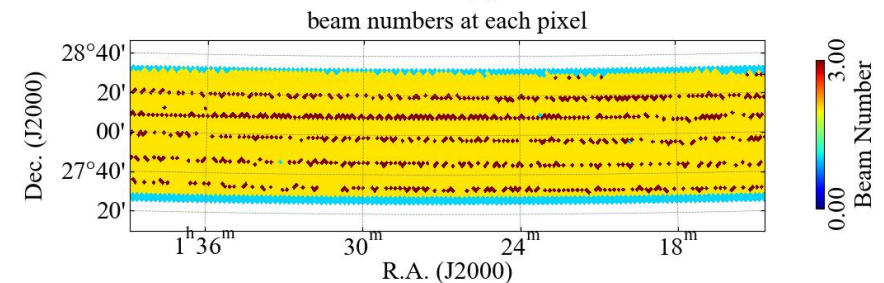
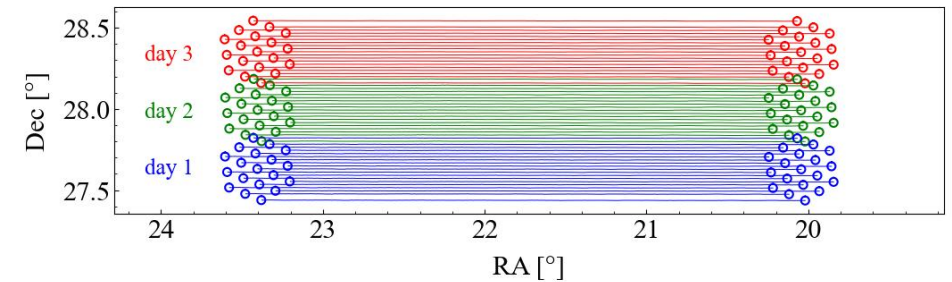
- **CRAFTS** (The **C**ommensal **R**adio **A**stronomy **F**AST **S**urvey)

Parameters	Pulsar Backend	Spectrum Backend (W)
Bandwidth	500 MHz	500 MHz
Channels	4096	65536
Time resolution (Δt)	98.304 μ s	~ 0.2 s
Frequency resolution ($\Delta \nu$)	~ 122 kHz	~ 7.6 kHz

- observation mode: drift scan • redshift: 0 ~ 0.35
- calibration mode: high-cadance noise injection ($T_{inj} \sim 196.608 \mu$ s)

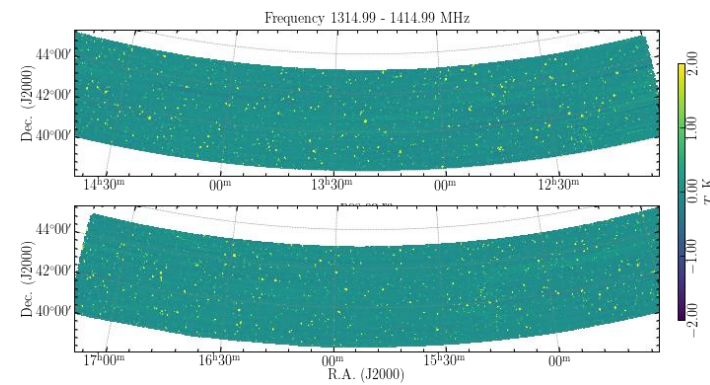
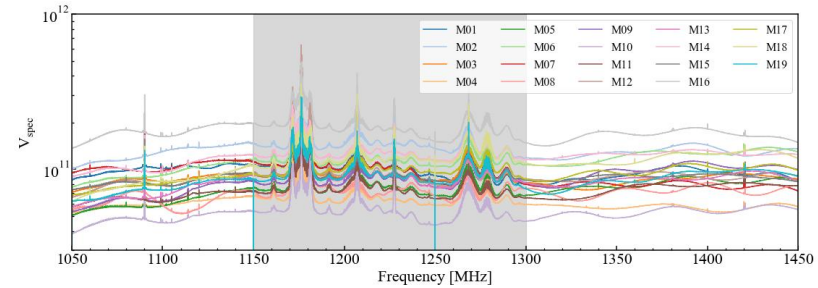
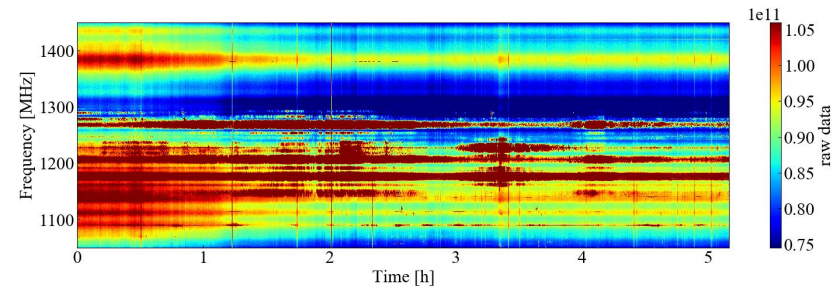
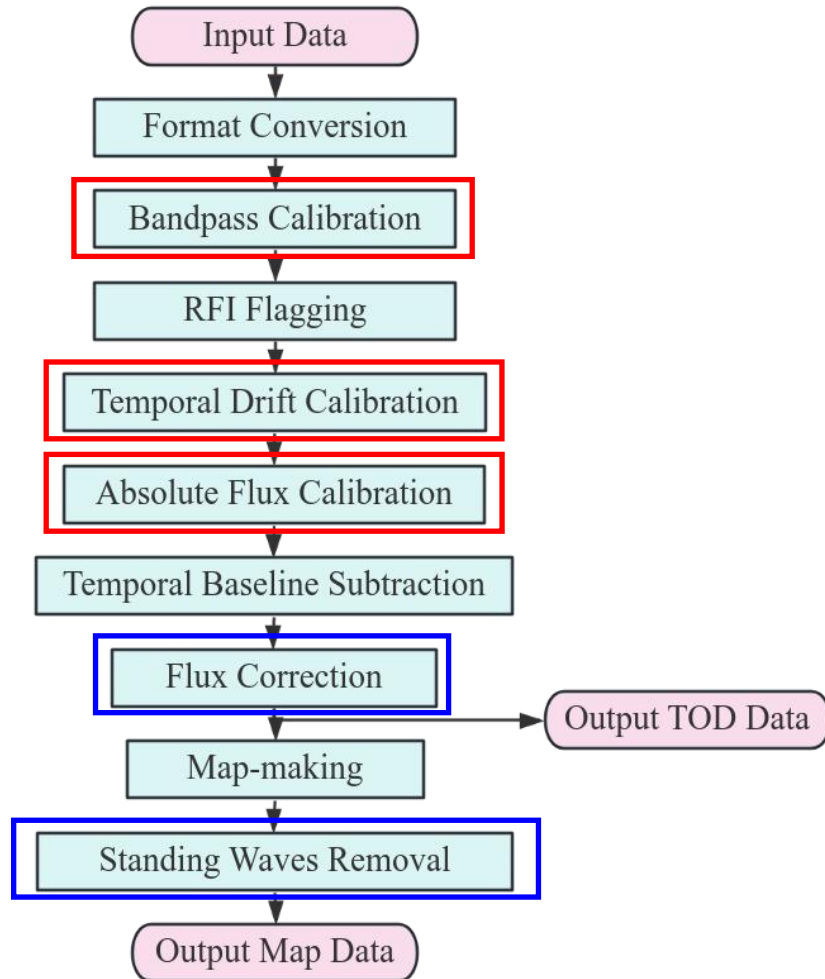


CRAFTS sky coverage



drift scan with L-band 19-beam receiver

Data processing



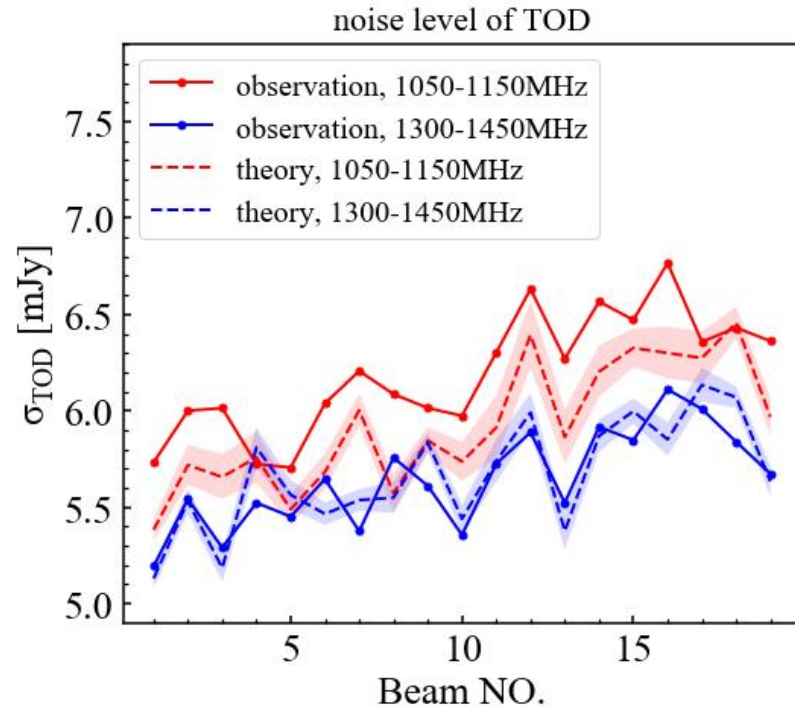
Input data
1050-1450MHz
 $\Delta t=0.2\text{s}$, $\Delta \nu=7.6\text{kHz}$,
19 beams, 2 polarizations
70hrs, 17 days

Output Map Data
1315 - 1415MHz
 $\text{pix} = 1.7^2\text{arcmin}^2$, $\Delta \nu=30\text{kHz}$
RA 12-15h, Dec 40-45deg
 $\sim 270\text{deg}^2$

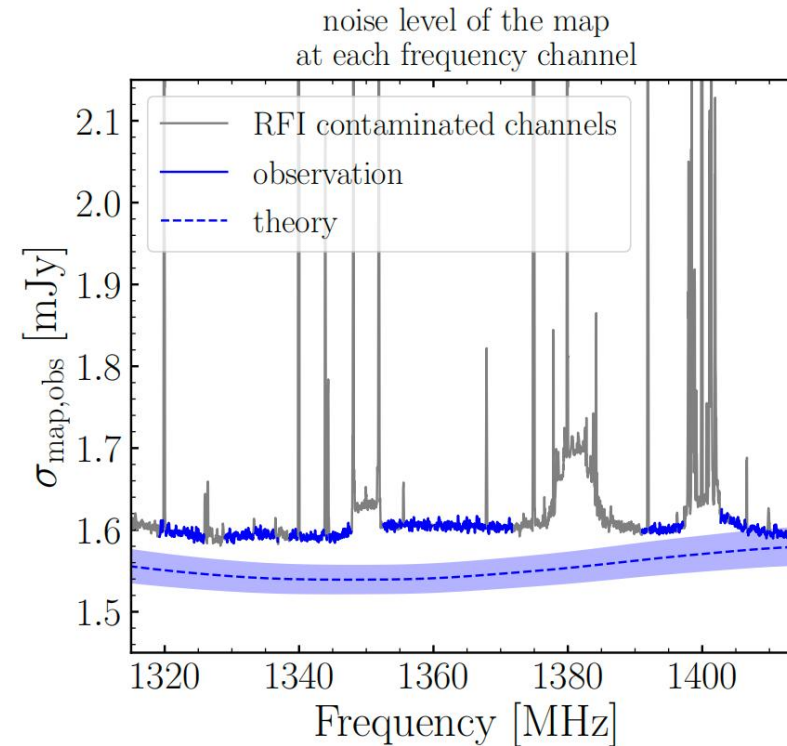
W. Yang, et al. 2025, ApJS, 279, 32

Validation tests - Data quality

- noise level $\sigma = \frac{2k_B T_{\text{sys}}}{\eta A_{\text{illu}} \sqrt{N_{\text{beam}} N_{\text{pol}} \Delta t \Delta \nu}}$



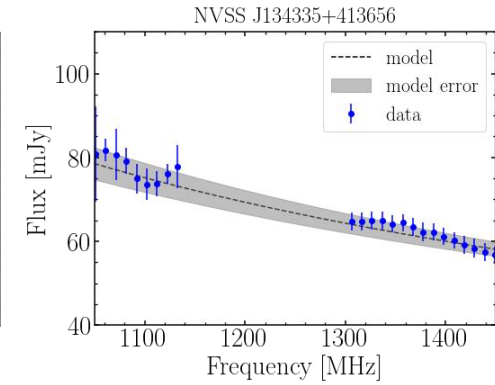
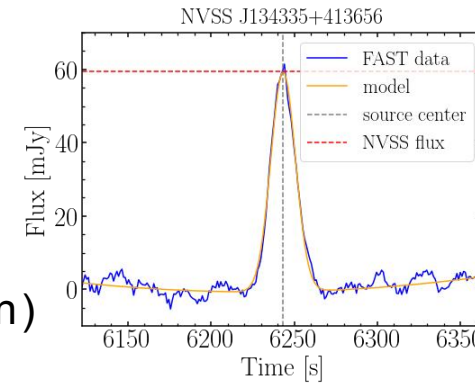
$\Delta t = 1\text{s}$, $\Delta \nu = 30\text{kHz}$, $N_{\text{beam}}=1$, $N_{\text{pol}}=1$



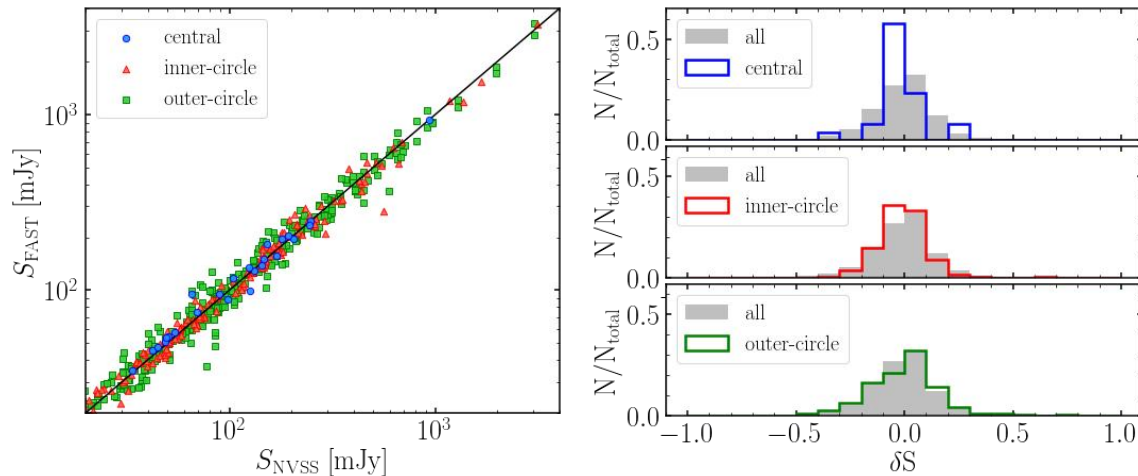
$\Delta t_{\text{pix}} \sim 14\text{s}$, $\Delta \nu = 30\text{kHz}$, $N_{\text{pol}}=2$

Validation tests - continuum point sources

- ~ 450 ideal sources from NVSS catalog
 - no neighbors (flux > 10%) within 9 arcmin;
 - not too faint (flux > 14mJy/beam)
 - well scanned (distance from beam center < 1.5arcmin)

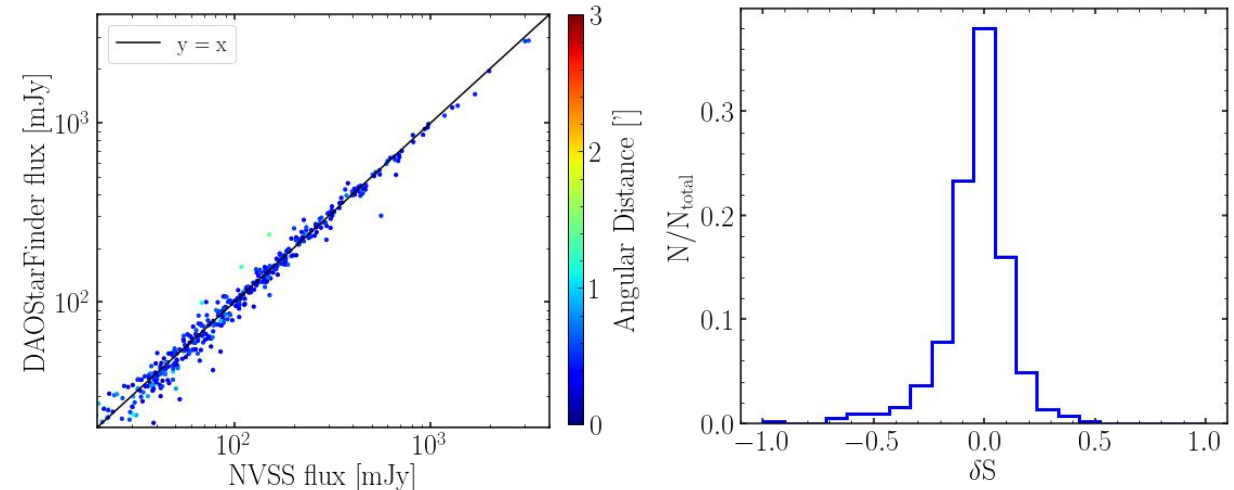


• TOD



• relative error ~ 8.3%

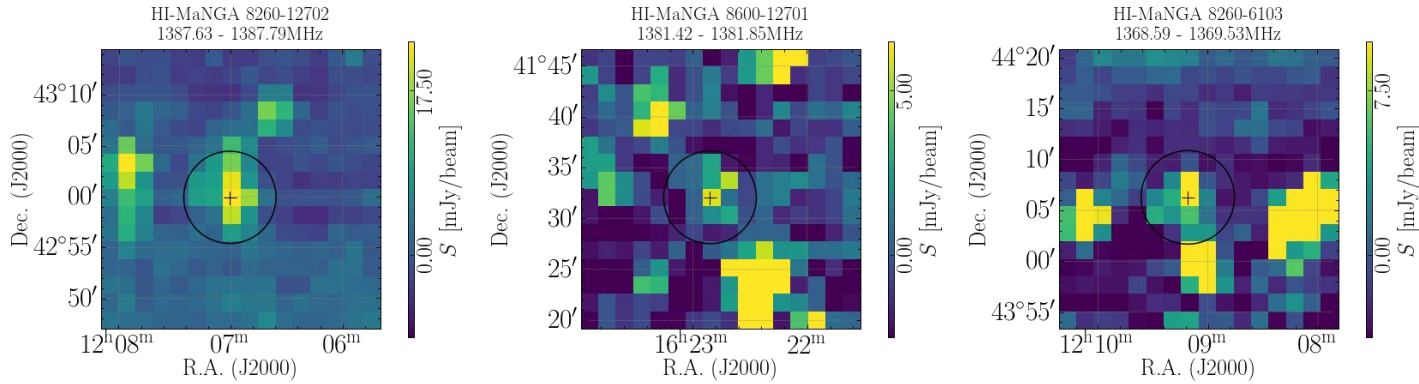
• map (DAOStarFinder)



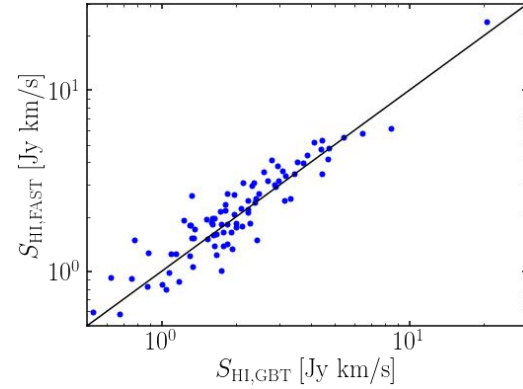
~ 6.6%

Validation tests - HI emissions

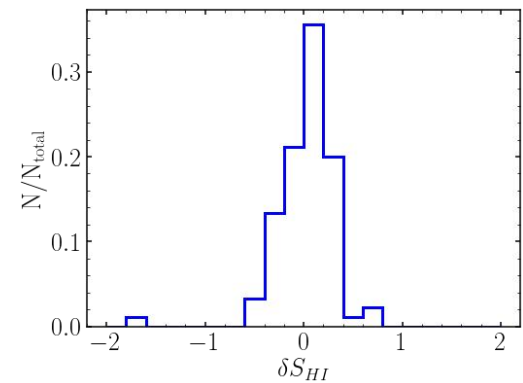
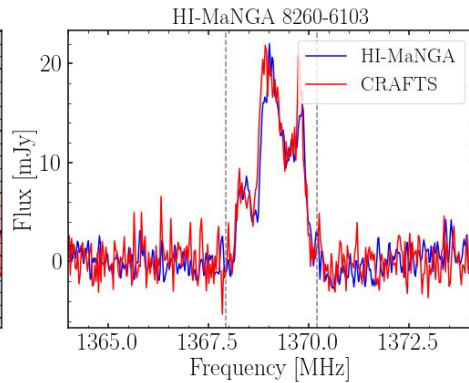
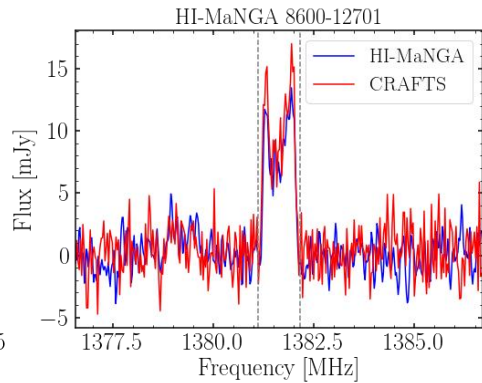
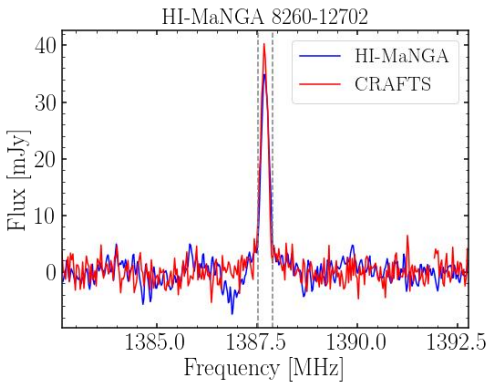
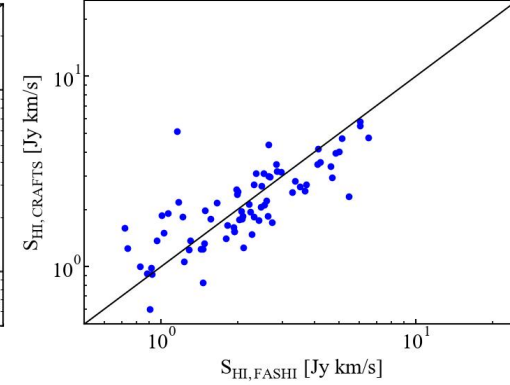
- HI emissions of galaxies



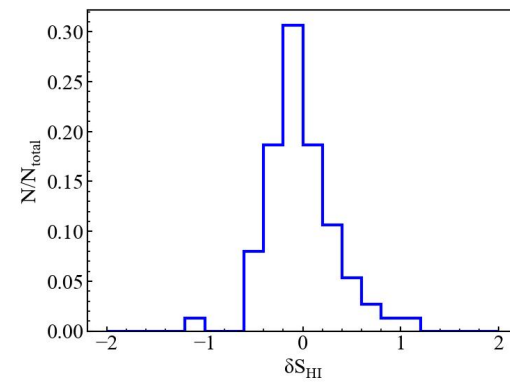
CRAFTS v.s. HI-MaNGA



CRAFTS v.s. FASHI



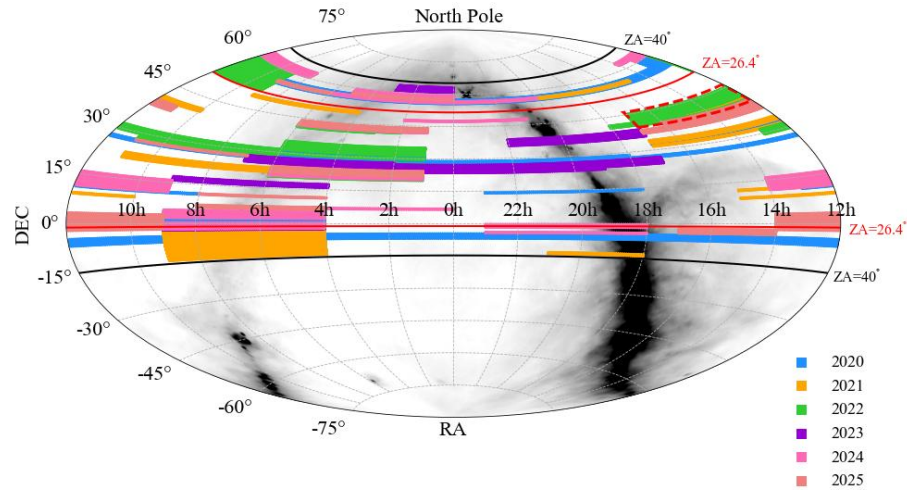
90 sources
relative error ~ 16.7%



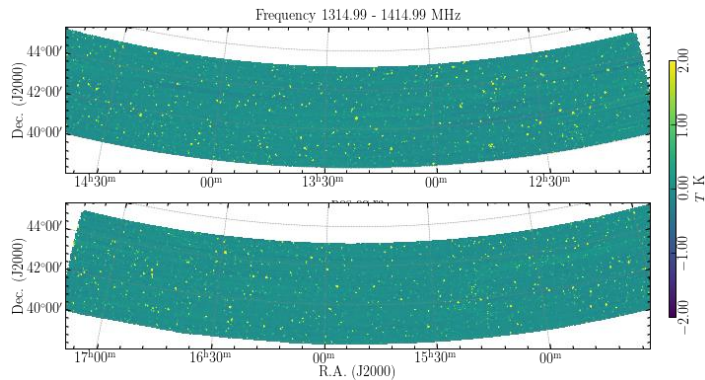
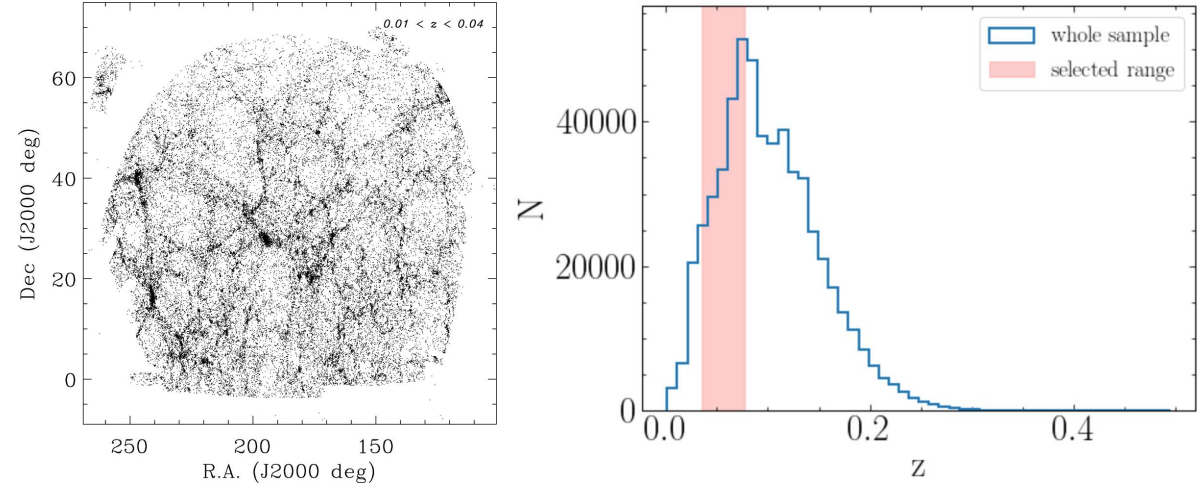
75 sources
relative error ~ 20%

Intensity Mapping - data

- HI data: CRAFTS



- optical sample: SDSS DR7 Main sample

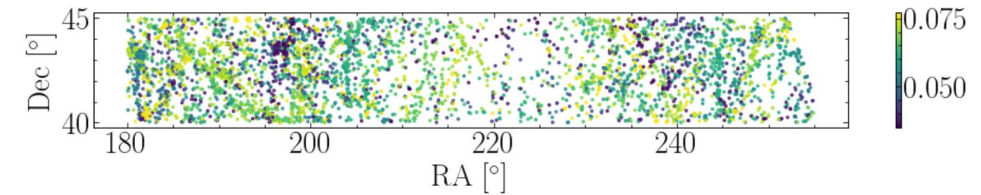


Processed Map Data

1319 - 1372MHz ($0.035 < z < 0.075$)

RA 12-15h, Dec 40-45d ($\sim 270\text{deg}^2$)

pix = 1.7^2arcmin^2 , $\Delta\nu=30\text{kHz}$

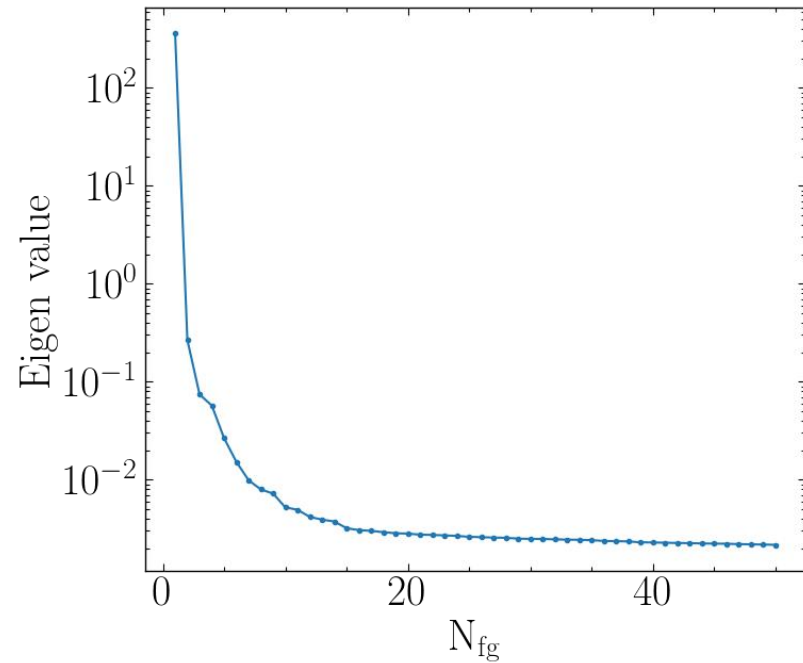


galaxy number ~ 4500

number density $\sim 1.4 \times 10^{-2} \text{ Mpc}^{-3} h^3$

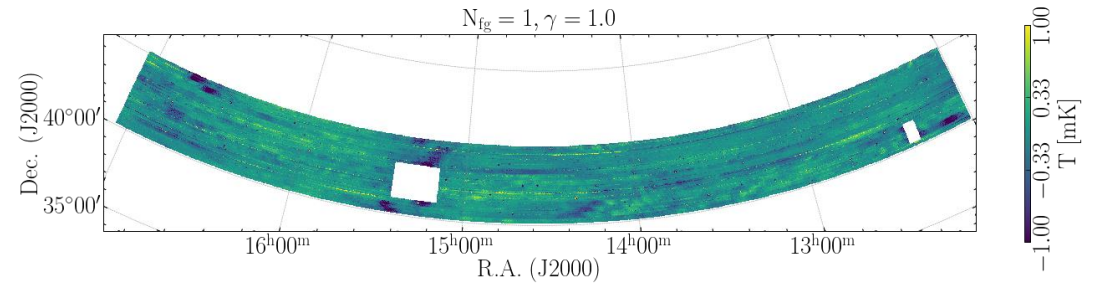
Intensity Mapping - foreground removal

- **PCA** (Principle Component Analysis)

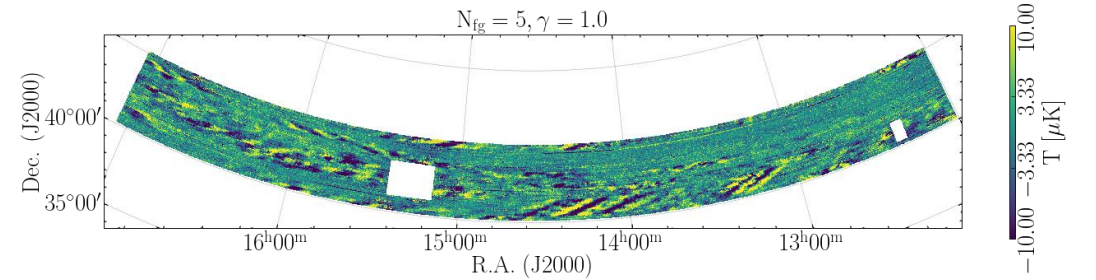


eigen values

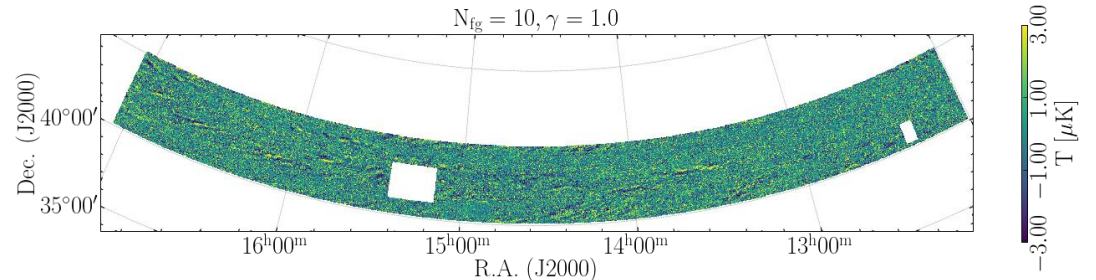
$N_{fg} = 1$



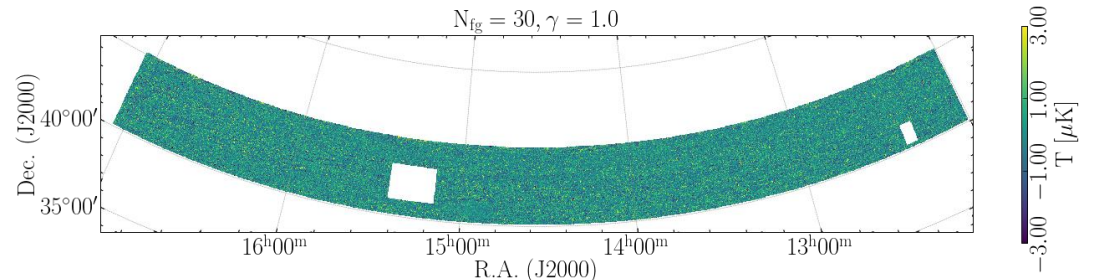
$N_{fg} = 5$



$N_{fg} = 10$

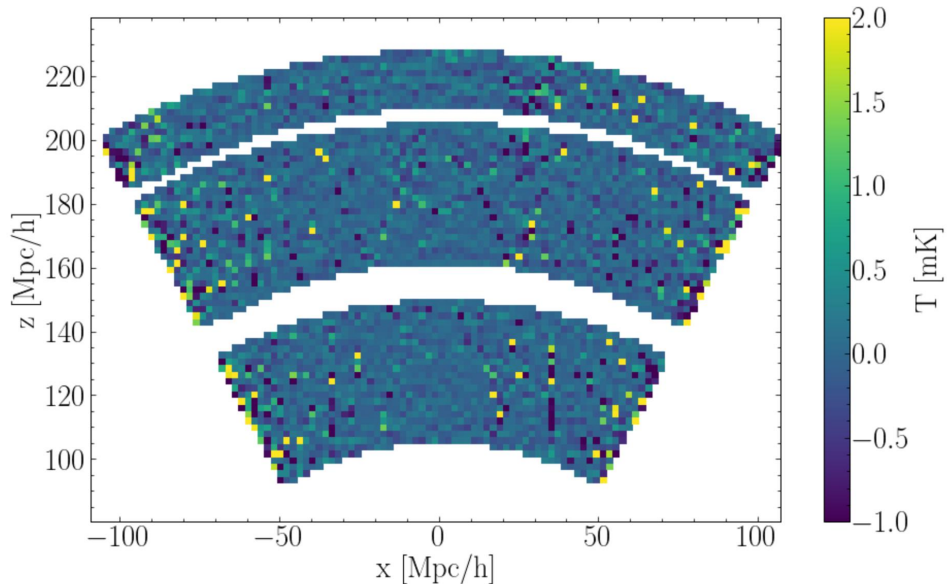
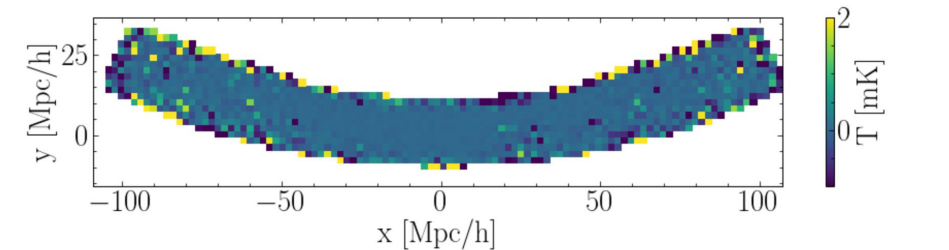


$N_{fg} = 30$

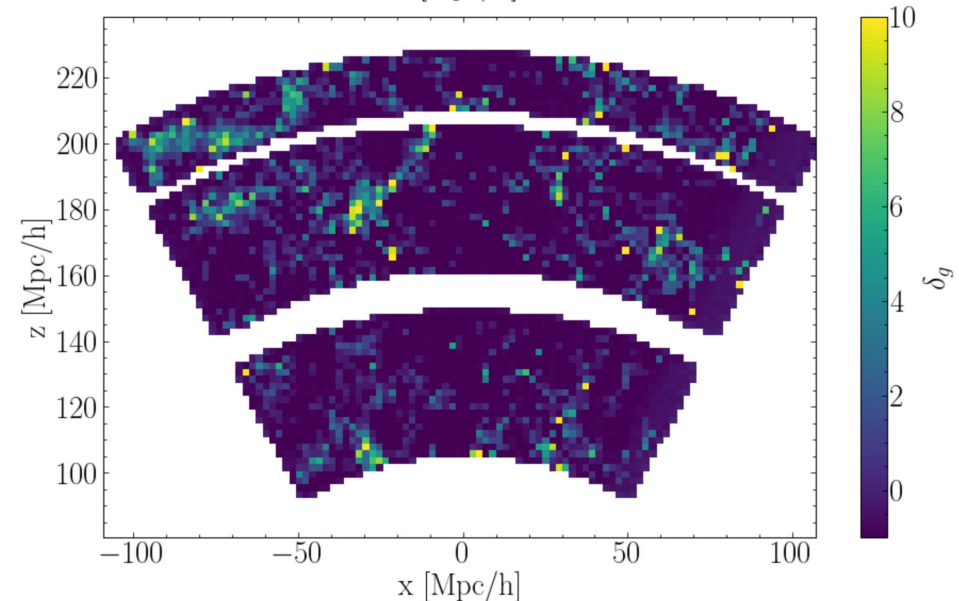
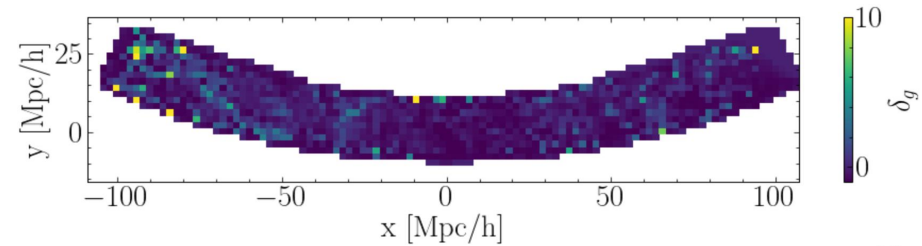


Intensity Mapping - regridding

- sky coordinates (pixel, freq) -> Cartesian coordinates (x, y, z)
- Nearest Grid Point (NGP)



HI brightness map



galaxy over-density map

Intensity Mapping - theoretical modelling

- **theoretical modeling** (Bull et al. 2015)

- $P_{\text{HI},g}(k, \mu, z) = \bar{T}_b(z) (b_{\text{HI}} + f\mu^2) (b_g + f\mu^2) e^{-(k\mu\sigma)^2} P_m(k, z) D^2(z)$

$$\hat{\sigma}_{\text{HI},g}(k) = \frac{1}{\sqrt{2N_m(k)}} \sqrt{\hat{P}_{\text{HI},g}^2(k) + \hat{P}_{\text{HI}}(k) \left(\hat{P}_g(k) + \frac{1}{\bar{n}_g} \right)}$$

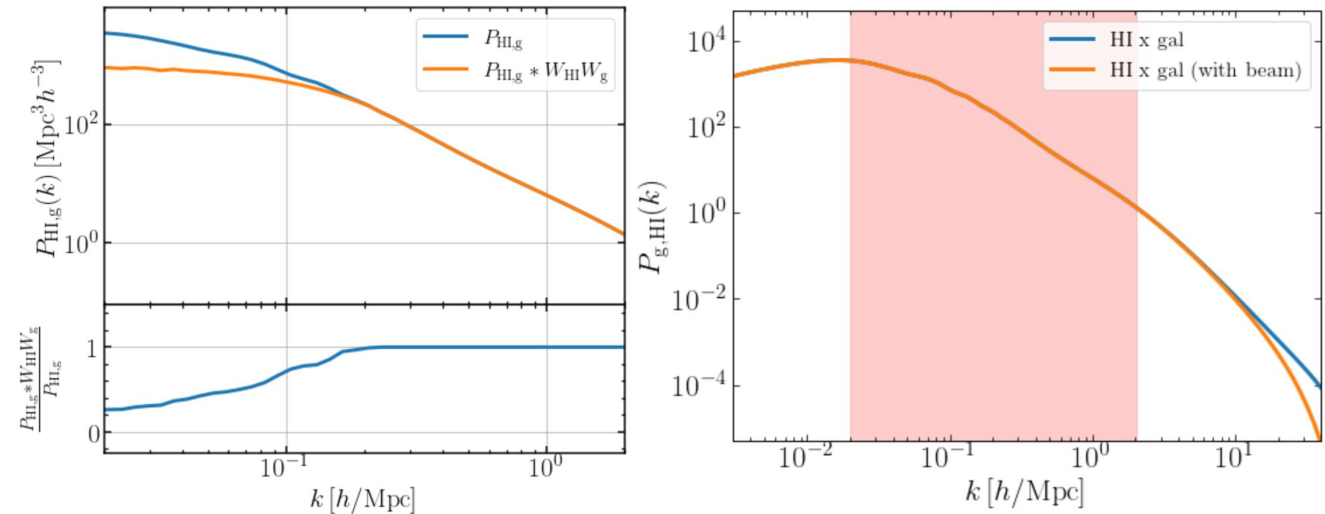
- **observational effects**

- window function

$$P_{\text{HI},g}(\mathbf{k}) \rightarrow P_{\text{HI},g} * W_{\text{HI}} W_g = \frac{\sum_i P_{\text{HI},g}(\mathbf{k}'_i) \text{Re} \{ \tilde{W}_g(\mathbf{k} - \mathbf{k}'_i) \tilde{W}_{\text{HI}}(\mathbf{k} - \mathbf{k}'_i)^* \}}{\sum w_g(\mathbf{x}) w_{\text{HI}}(\mathbf{x}) W_g(\mathbf{x}) W_{\text{HI}}(\mathbf{x})}$$

- beam / channel damping

$$B_{\perp}(\mathbf{q}) = \exp\left(-\frac{(q\theta_B)^2}{16 \ln 2}\right) \quad B_{\parallel}(y) = \exp\left(-\frac{(y\delta\nu/\nu_{21})^2}{16 \ln 2}\right)$$

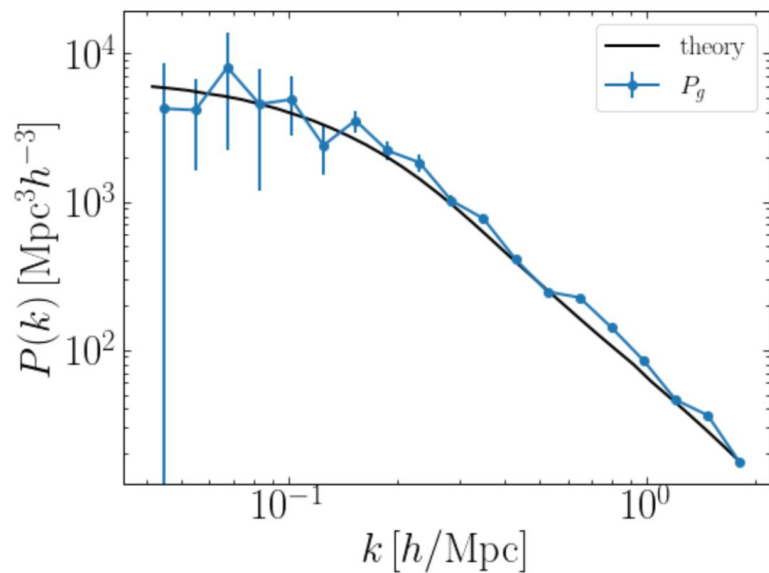


Intensity Mapping - power spectrum

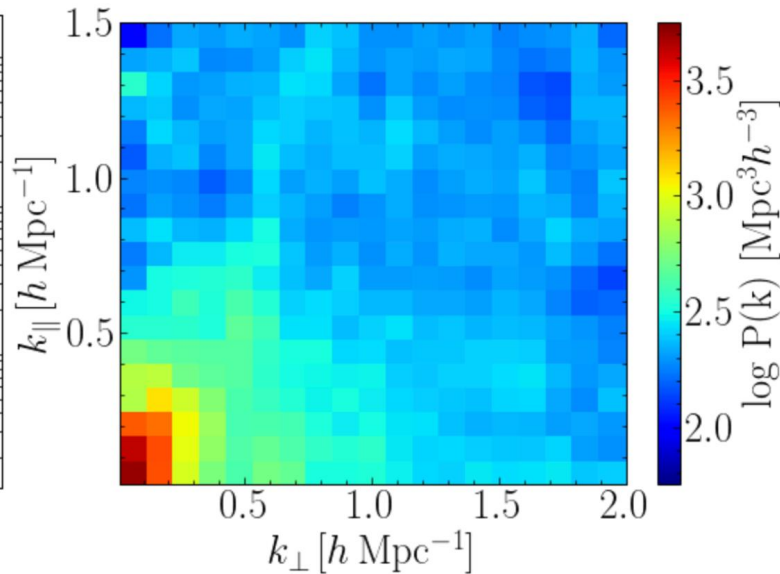
- optical galaxy sample

$$\tilde{F}_g(\mathbf{k}) = \sum_{\mathbf{x}} n_g(\mathbf{x}) w_g(\mathbf{x}) \exp(i\mathbf{k} \cdot \mathbf{x}) - N_g \tilde{W}_g(\mathbf{k})$$

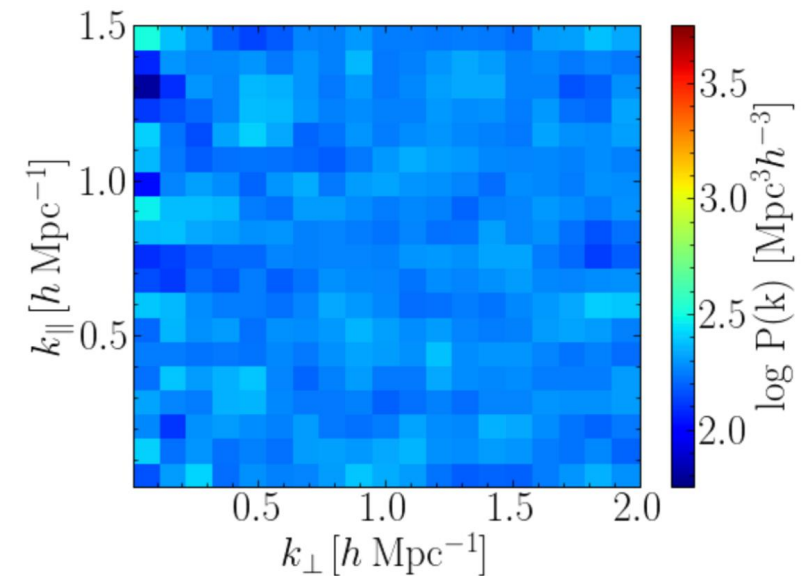
$$\hat{P}_g(k) = \frac{V_{\text{cell}}}{\sum_{\mathbf{x}} w_g^2(\mathbf{x}) W_g^2(\mathbf{x})} \left[|\tilde{F}_g(\mathbf{k})|^2 - S_g \right] \frac{1}{N_g^2}$$



1D galaxy ps



2D galaxy ps



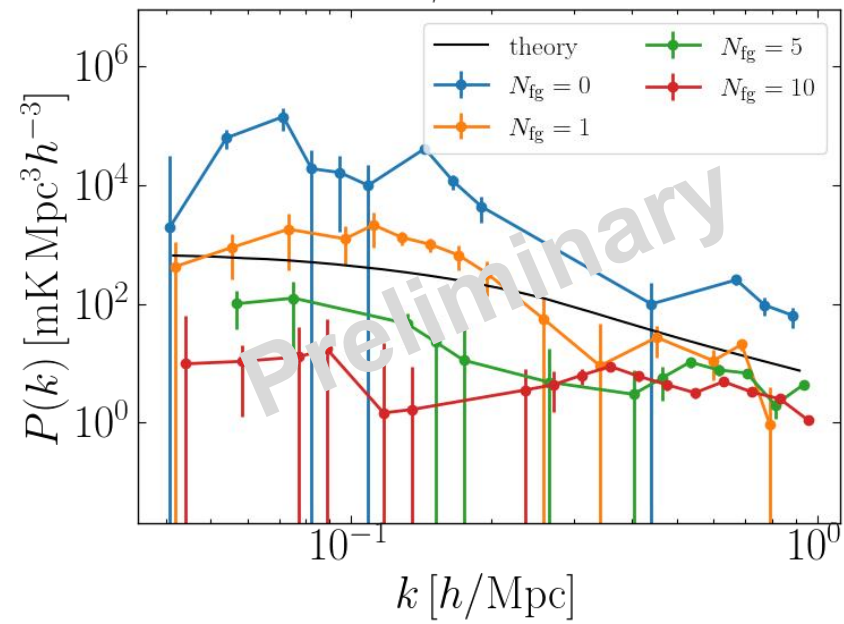
2D null test with random map

Intensity Mapping - power spectrum

- HI x galaxy

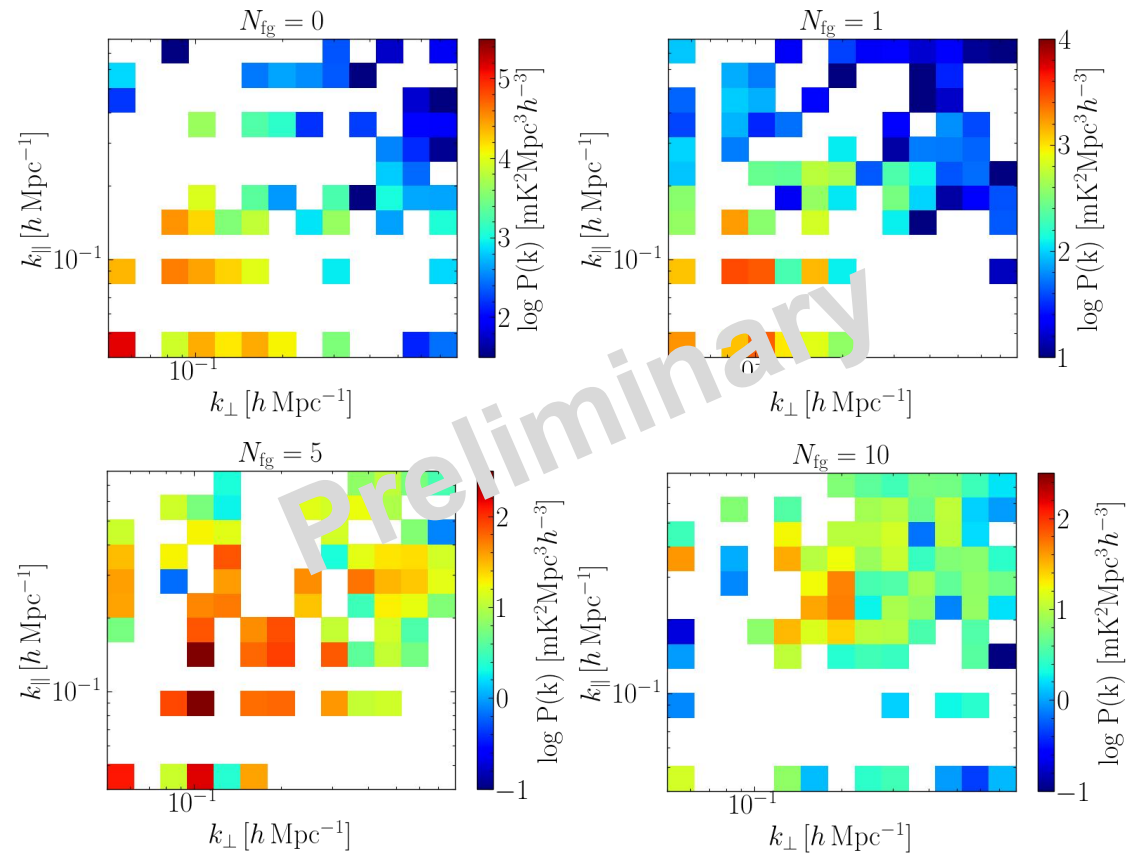
$$\tilde{F}_{\text{HI}}(\mathbf{k}) = \sum_{\mathbf{x}} \delta T_{\text{HI}}(\mathbf{x}) w_{\text{HI}}(\mathbf{x}) \exp(i\mathbf{k} \cdot \mathbf{x})$$

$$\tilde{F}_{\text{g}}(\mathbf{k}) = \sum_{\mathbf{x}} n_{\text{g}}(\mathbf{x}) w_{\text{g}}(\mathbf{x}) \exp(i\mathbf{k} \cdot \mathbf{x}) - N_{\text{g}} \tilde{W}_{\text{g}}(\mathbf{k})$$



1D cross ps

$$\hat{P}_{\text{HI,g}}(\mathbf{k}) = \frac{V_{\text{cell}}}{\sum_{\mathbf{x}} w_{\text{HI}}(\mathbf{x}) w_{\text{g}}(\mathbf{x}) W_{\text{g}}(\mathbf{x})} \text{Re} \left\{ \tilde{F}_{\text{HI}}(\mathbf{k}) \cdot \tilde{F}_{\text{g}}^*(\mathbf{k}) \right\} \frac{1}{N_{\text{g}}}$$



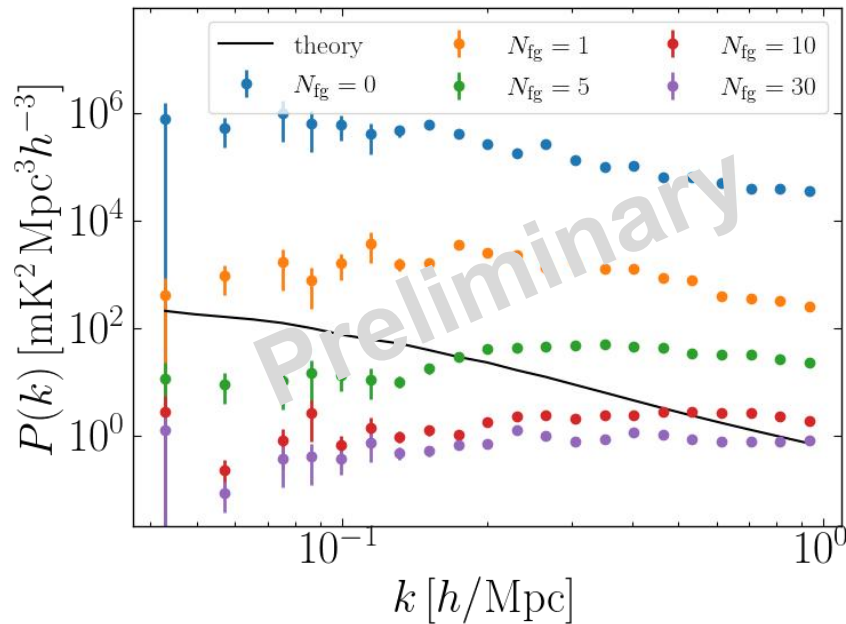
2D cross ps

Intensity Mapping - power spectrum

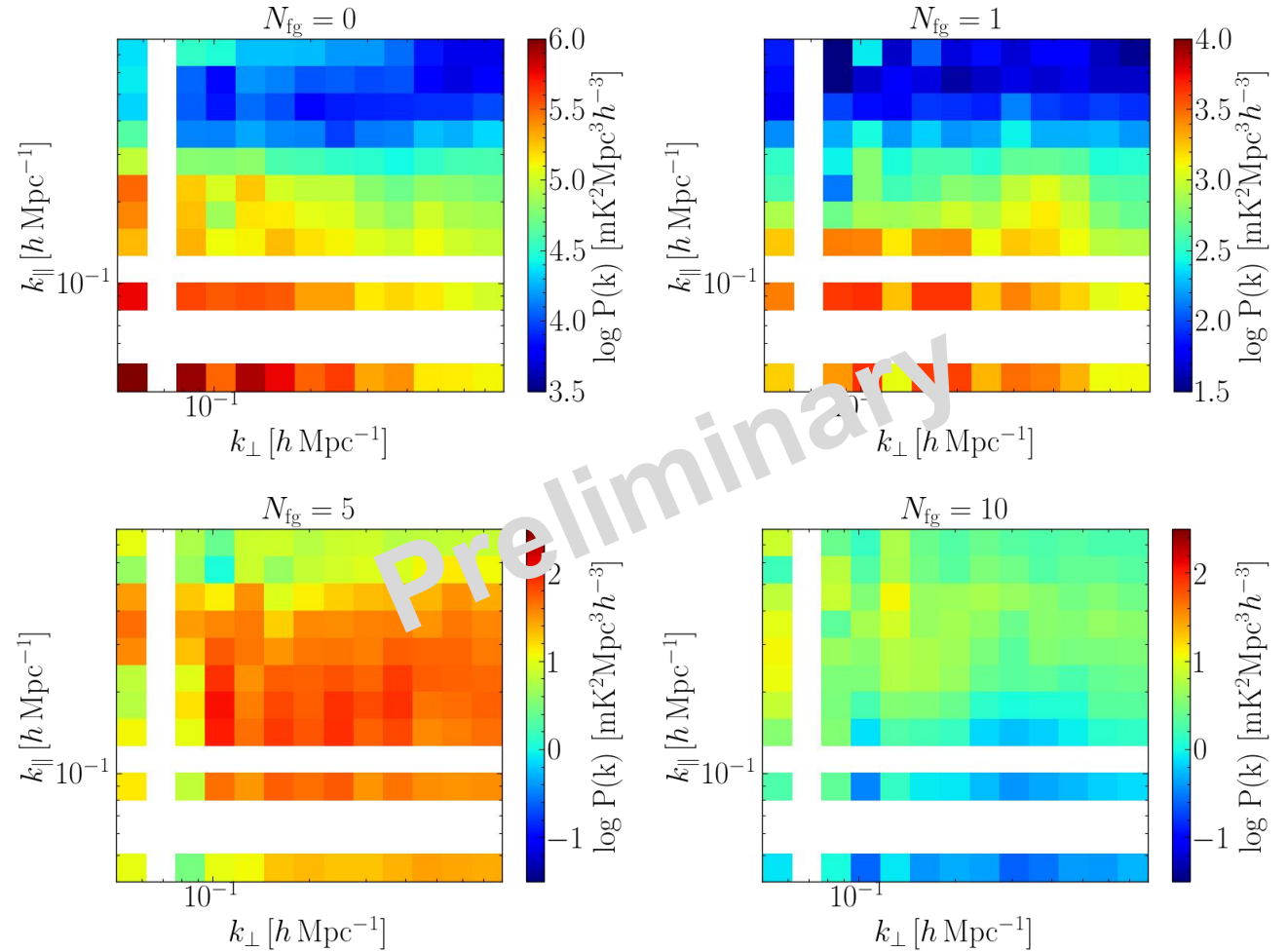
- HI

$$\tilde{F}_{\text{HI}}(\mathbf{k}) = \sum_{\mathbf{x}} \delta T_{\text{HI}}(\mathbf{x}) w_{\text{HI}}(\mathbf{x}) \exp(i\mathbf{k} \cdot \mathbf{x})$$

$$\hat{P}_{\text{HI}}(\mathbf{k}) = \frac{V_{\text{cell}}}{\sum_{\mathbf{x}} w_{\text{HI}}^2(\mathbf{x})} |\tilde{F}_{\text{HI}}(\mathbf{k})|^2$$



1D HI ps



2D HI ps for different N_{fg}

The road to HI IM

- **next steps**

- quantify signal loss (transfer function)
- constraints on parameters ($\Omega_{\text{HI}} \dots$)

- **other improvements / tests**

- foreground removal methods
- RFI, standing waves
- calibration accuracy
- cross-correlate sub-datasets of FAST

Summary

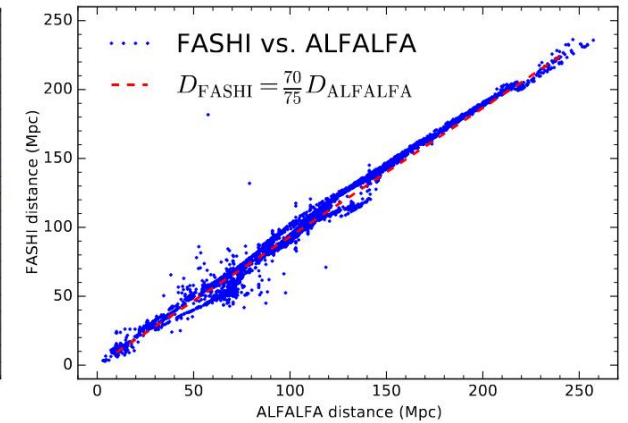
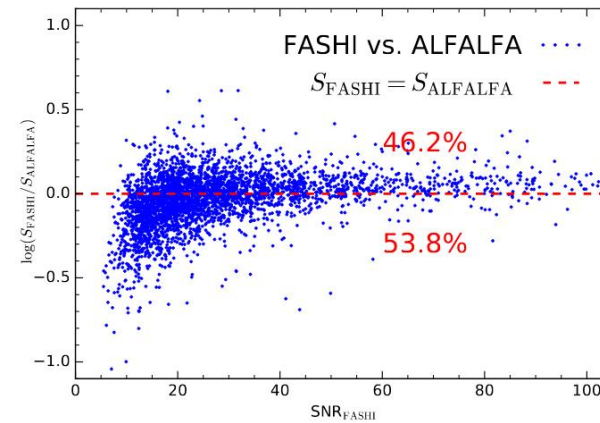
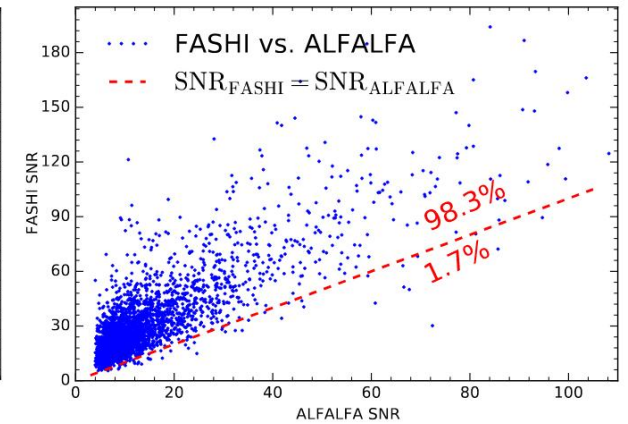
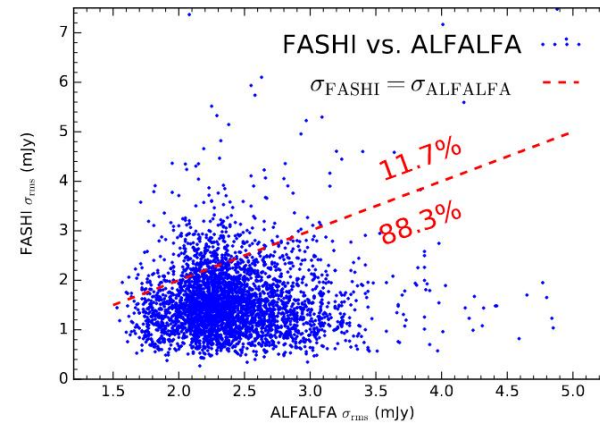
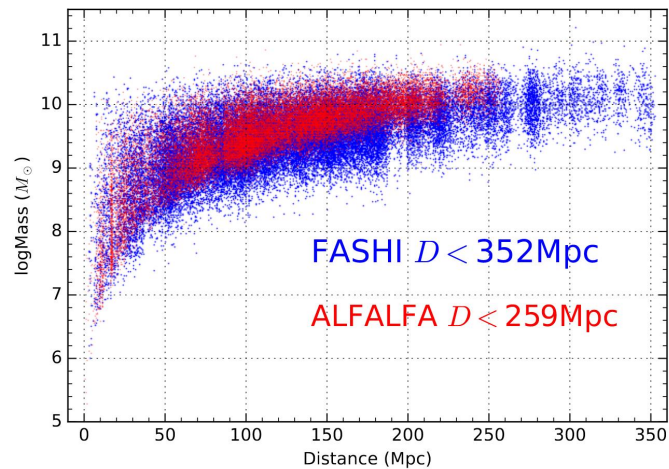
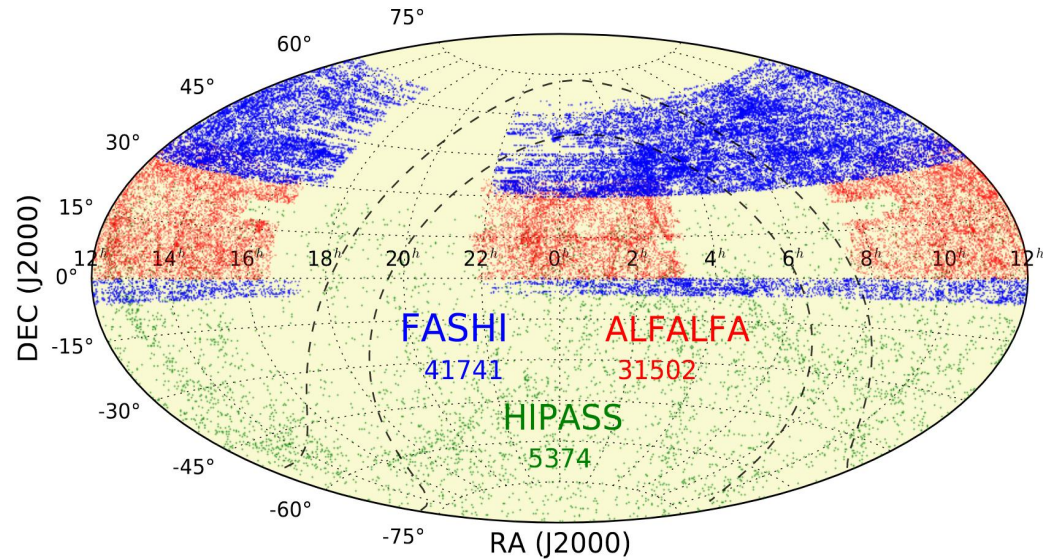
- large surveys with FAST: FATHOMER, CRAFTS, FASHI ...
- data processing pipeline
- validation tests: noise level, continuum point sources, HI emissions
- preliminary results: optical galaxy ps, cross ps, HI ps
- next steps: signal loss; constrain parameters; other improvements...

Thanks!

◆ wxyang@nao.cas.cn

Observations

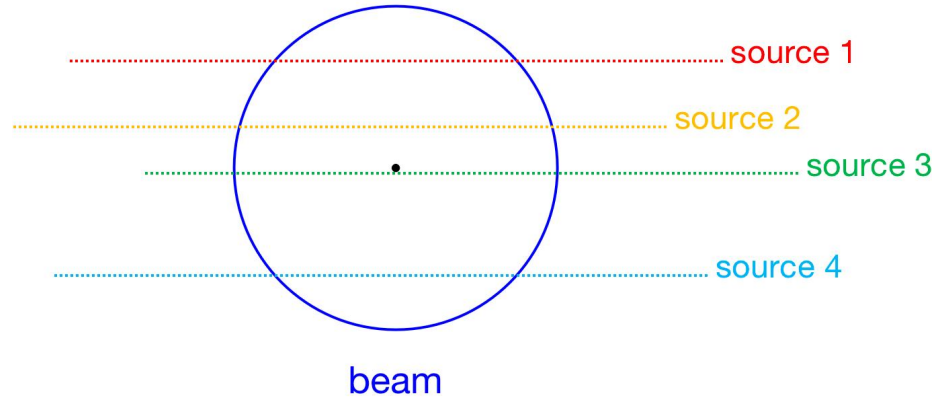
- FASHI (FAST All Sky HI Survey)



C. Zhang, et al. 2024, SCPMA, 67, 219511

Beam model

- scanning 1668 ideal NVSS sources



- fit with Zernike polynomial (ZP) modes

