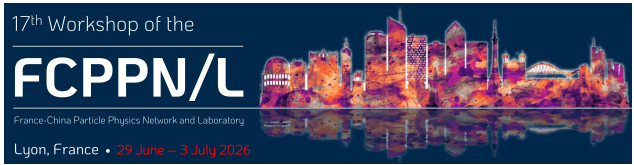
Status the Tianlai 21cm project

O. Perdereau (on behalf of Tianlai collaboration)

IJCLAB, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

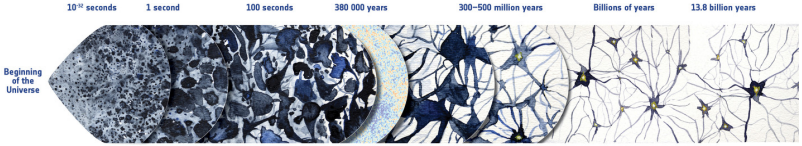


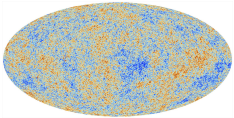
FCPPN/L Workshop - Lyon - June 30th 2026

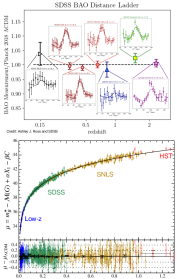
Outline

- Cosmology with the 21cm line
- Overview of Tianlai
- Some recent works & prospects in Tianlai
- Prospects

Cosmology



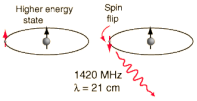


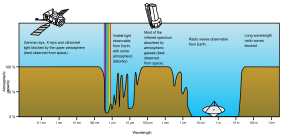


- Very successful concordance model (Λ CDM) based on GR
- Accounts for many observations : CMB (Planck), Type Ia SNe (SNLS, Pantheon), BAO (BOSS/eBOSS/DESI...),..
- Minimal set of parameters precisely measured (combinations and/or cross-correlations of probes)
- Some “tensions” i.e. 2-5 σ offsets between measurements by different probes at different epochs/scales (e.g. H_0, σ_8)
- Extensions (inflation, neutrinos, DE) sought for by present and future projects (CMB-S4, LiteBird, DESI, LSST, Euclid, ...)

The 21 cm Hydrogen line

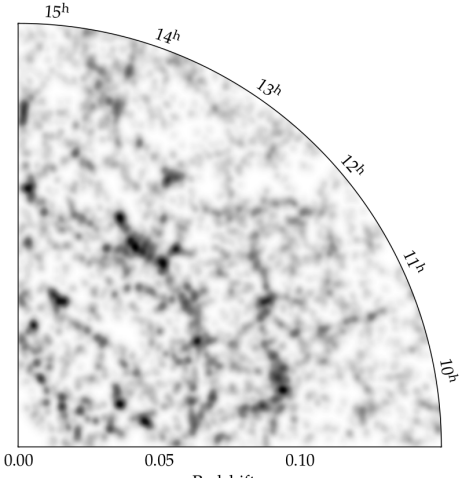
- introduced in (for) astrophysics (radio) in 1944
- intensity $\Leftrightarrow$ amount of H
- ¨isolated¨ line $\Rightarrow$ enables tomography : $z \Leftrightarrow \nu$
- ground observations possible down to $\sim$ 30 MHz (ionosphere) i.e. $z \sim 30$
  NB human-made perturbations (3/4/5G, TNT, FM, radars, ..)
- In cosmology :
  - "Late" epochs ($z \lesssim 6$) : HI traces matter distribution $\Rightarrow$ LSS studies (BAOs)
  - Early Universe : "global" spectrum probes very early history (dark ages, reionisation, ...)





LSS from 21 cm line Intensity Maping (IM)

- for $z \leq 6$ cosmology (in particular BAO features) focus on O(1 degree) scales ⇒ no need to measure individual galaxies
- broad ν band, low angular resolution instrument
- measure intensity at "each" frequency ⇒ z : "easy" tomography
- prices to pay :
  - low signal (X-corr with optical surveys)
  - very high level of foregrounds
  - DAQ & calibration challenging : huge data rate, few very bright sources
  - cosmological analysis : HI power spectrum bias wrt matter's



J. Petterson et al. arXiv:0902.3091

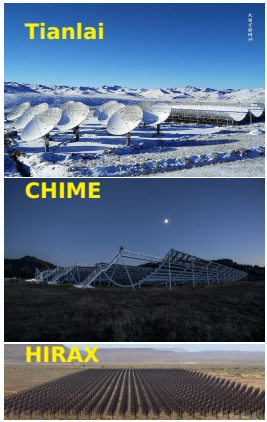
The idealized setup

(some) Requirements :

- large collecting surface (S/N ratio)
- large sky area
- moderate (0.1 deg) angular resolution
- broad ν range (large volume)

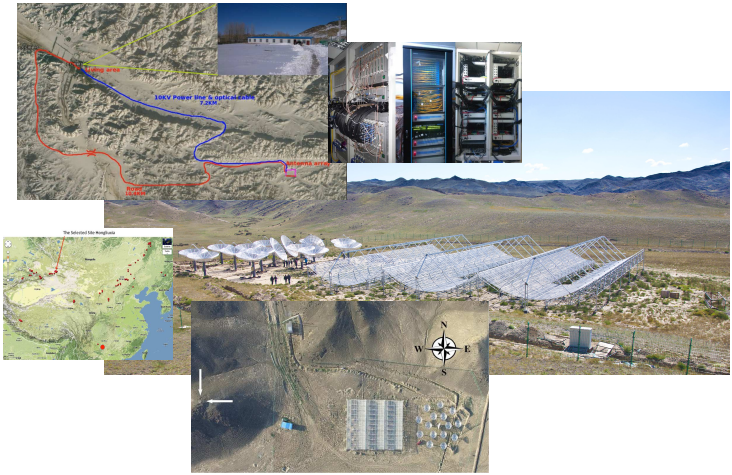
$\Rightarrow$ tentative solution(s) :

- packed interferometric array (moderate angular res., high S/N at BAO scale)
- (semi) fixed antenna(s) in transit mode (large sky coverage, cost)
- sampling of full signal waveform $\rightarrow$ FFT, digital correlation, beam forming



Tianlai

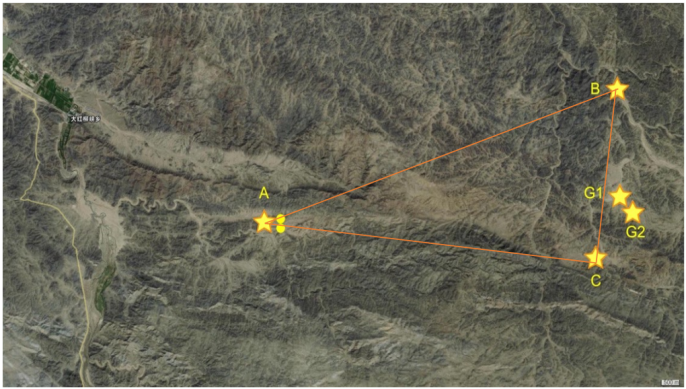
- 2 instruments : cylinders and dish array
- observations in transit mode
- in operations since 2016
- 700-800 MHz but tunable between 600 and 1420 MHz
- PI X. Chen (NAOC, Beijing)
- SKA pathfinder
- people involved for FCPPN : O. Perdereau (IJCLab), (R. Ansari DAP/CEA), X. Chen (NAOC), Y. Li (Shenyang NE Univ.)



Recent results and developments

- Short bibliographic selection :
  - Dish array overview paper, F. Wu et al. MNRAS (2020) + drone beam measurement paper
  - Low-z forecast for the dish array, O. Perdereau et al. (2022)
  - Design and Implementation of a Scalable Correlator Based on ROACH2+GPU Cluster for Tianlai 96-Dual-Polarization Antenna Array, Z. Wang et al. 2024
  - The Tianlai-WIYN North Celestial Cap Redshift Survey, R. Ansari et al 2025
  - 21 cm Power Spectrum Analysis of North Celestial Pole Observations with the Tianlai Dish Pathfinder Array, G. He et al. 2026
- Recent and on-going works :
  - installation of more cylinders and dishes to e.g. help in FRB localization on the sky
  - upgrade of correlator hardware, deployment of Fast Radio Bursts back-ends
  - Planned observations at lower z / higher frequencies (larger S/N, helps in understanding the instrument in depth, some HI physics) by using another set of RF filters

On-site developments

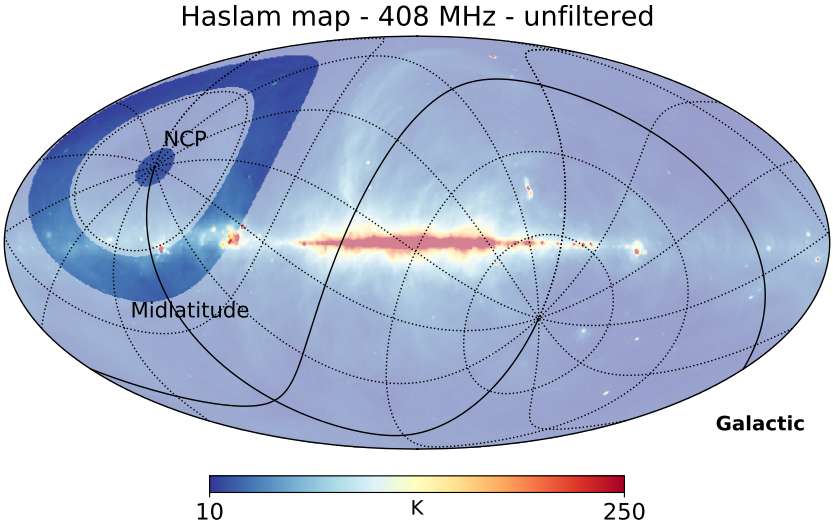


A : new dish (improve on-sky calibration) + cylinder ; B,C : new cylinders (FRB localization) G1,2 : 21cm global spectrum experiment
Also : more feeds, upgrade on correlators, repairs, drone measurements for cylinders (1300m altitude)....

Lower z observations ?

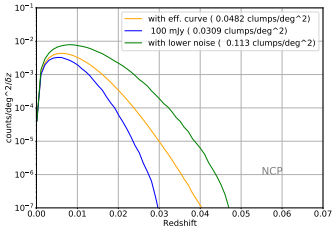
- Using the Tianlai 16 dishes array has pros wrt the cylinder (simpler systematics, beam, analysis ...) but lower collecting surface
- moving to lower z / higher frequency, integrations around NCP $\Rightarrow$ higher S/N
- main purpose : "prove the effectiveness of the dense interferometric dish array and transit mode observations of Tianlai" in particular with cross-correlation with optical surveys
- topics covered :
  - Forecasts
  - Building a galaxy catalog towards the North Celestial Pole region for cross-correlation

Footprints of foreseen surveys



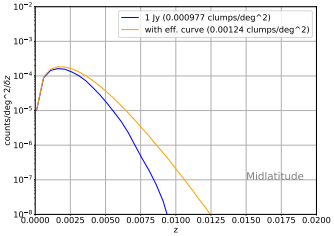
Direct HI source detection forecast

- estimate flux detection threshold using simulation
- HI mass function (from ALFALFA) + scaling relation ⇒ number of sources at redshift z
- combining both : number of expected detections



With $\sim 100 deg^2$:
~ 5 HI clumps at $z \lesssim 0.02$

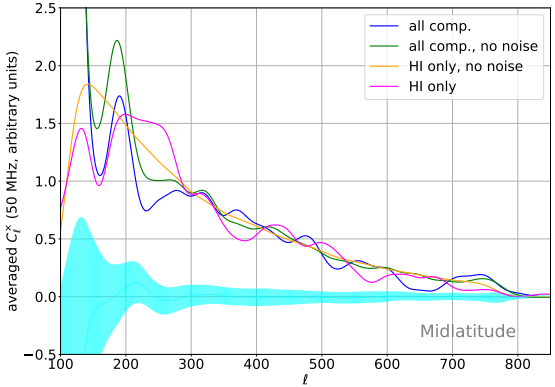
(~ 12 at $z \lesssim 0.03$ for lower noise)

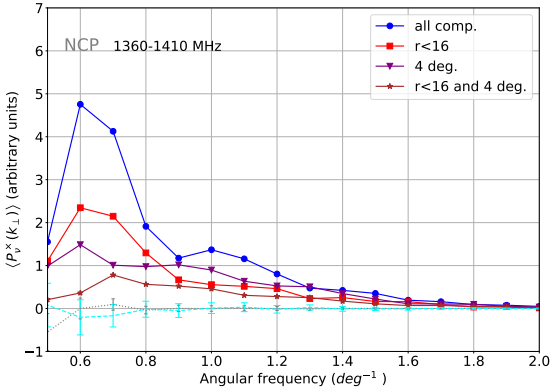


With $\sim 2400 deg^2$:

$\sim 1-2$ HI clumps at $z \lesssim 0.005$

Forecasted cross-correlations (1360-1410 MHz)





Both for NCP and midlatitude expect a very significant result

The WYIN spectroscopic survey

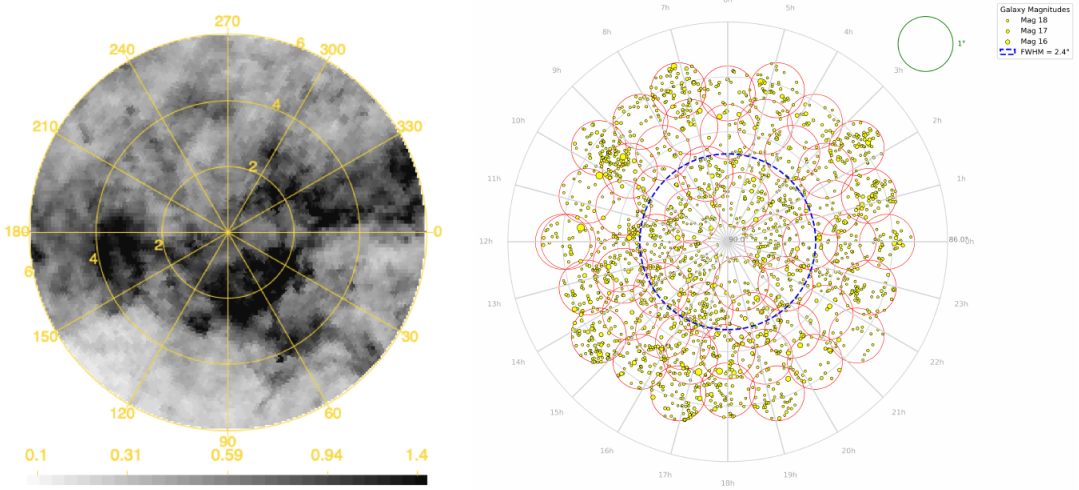
- Effort by our US colleagues to built a spectroscopic catalog in the NCP area
- Sources selected from the North Celestial Cap Survey (NCCS) (Gorbikov & Brosch 2014) using photometry & morphology classification
- Observations with the HYDRA fiber spectrometer on the 3.5m WIYN telescope (15 nights of gray time, Feb 2020 to May 2023)
- sensitivity limited by sky background ; S/N in general not very large
- home-made reduction pipeline
- several checks (target selection, redshifts) using cross-matches with GAIA-DR3 and 2MASS
- publication in arXiv, referee review with minor comments (catalog+spectra)

First Results of the Tianlai-WIYN North Celestial Cap Redshift Survey*

Reza Ansari,[1] Gabriela A. Marques,[2] John P. Marriner,[2] Olivier Perdereau,[3] Elena Pinetti,[2] Lily Robinthal,[4]
Albert Stebbins,[2] Haoxuan Sun,[5] Peter Timbie,[6] Gregory S. Tucker,[5] Eli Doyle,[5] Jocelyn Chu,[5]
E. Revsen Karaalp,[5] Xuelei Chen,[7] Jixia Li,[7] Fengquan Wu,[7]

(Tianlai collaboration)

Targets distribution

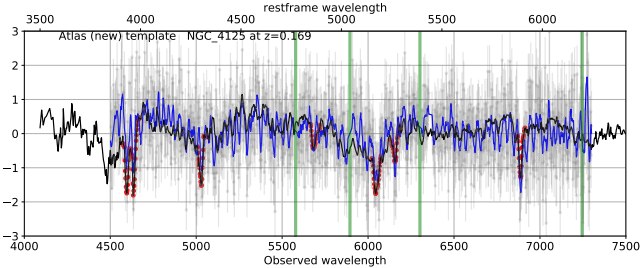


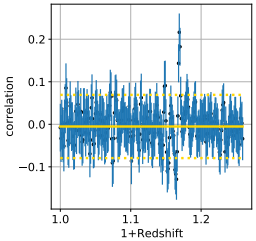
left : Planck A_V map ; right : plates & target distribution

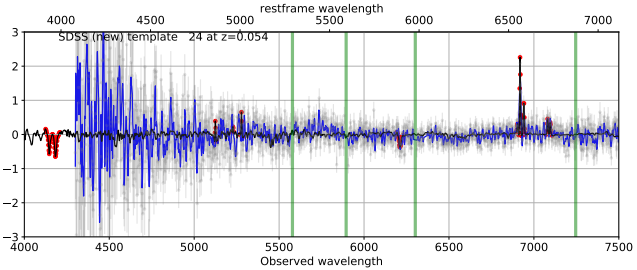
Reductions results

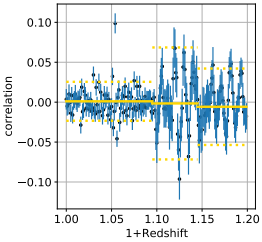
- 2103 target selected, 1868 with spectra
- initial redshift determination by eye ⇒ 787 redshifts
- cross-examination using known templates
  - systematics template-based removal
  - used a few galaxy spectra from litterature (e.g. auto-z package)
  - compute correlation between part of redshifted templates with known emission of absorption features
  - keep z with most significant correlation ($0 < z < 0.25$)
  - final check by (my) eye(s)
  - added infos : emission or absorption lines, S/N of correlation (final selection)
- $\sim$ 145 original (visual) redshifts not recovered, $\sim$ 230 more estimations
- origins of differences : systematics handling removes spurious detections, template guidance helps absorption line identification

Examples

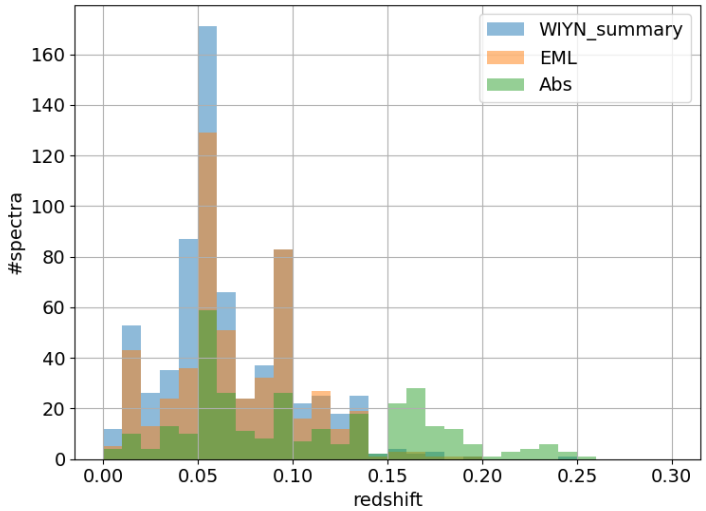

restframe wavelength
Atlas (new) template NGC_4125 at z=0.169
Observed wavelength


correlation
1+Redshift


restframe wavelength
SDSS (new) template 24 at z=0.054
Observed wavelength


correlation
1+Redshift

Redshifts



"WIYN Summary" $\Leftrightarrow$ visual method

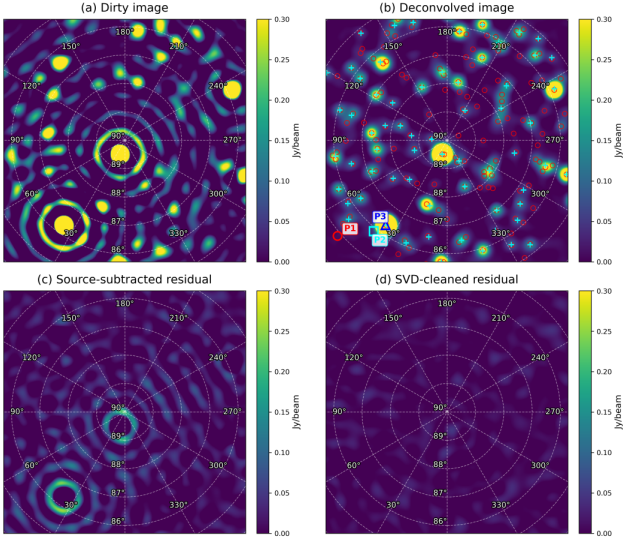
main emission line (EML) : H_α (6563 Å) - outside the spectra range above $z \gtrsim 0.11$

redshifted Ca HK doublet at 3969 Å falls in wavelength range with good S/N above $z \gtrsim 0.14$ (not important for HI X-cor)

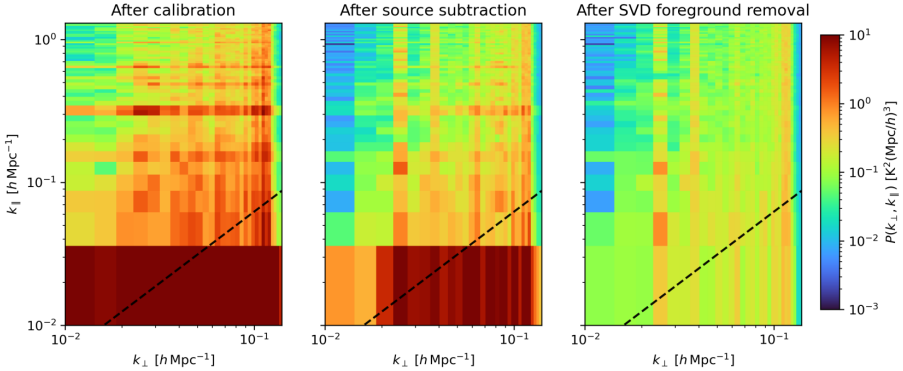
Map and spectra around NCP (He et al 2026)

- analysis of dish array data from ~ 14 nights (a first test)
- use of home made (RFI flagging) and public software tools (CASA suite) for analysis
- starts from the visibilities' FFT values vs time $\Leftrightarrow$ measurement in the (u, v) plane (transverse Fourier plane)
- Earth's rotation $\Rightarrow$ better coverage (aperture synthesis, Ryle & Hewitt Nobel prize 1974) but not complete
- (u, v) measurements $\mapsto$ image ? spectra ?
  1. self-calibration using sky model (point source catalog) to get rid of (complex) gain time & frequency variation
  2. angular beam deconvolution
  3. (frequency wise smooth) foregrounds removal (SVD)

Analysis steps



First 2D spectra

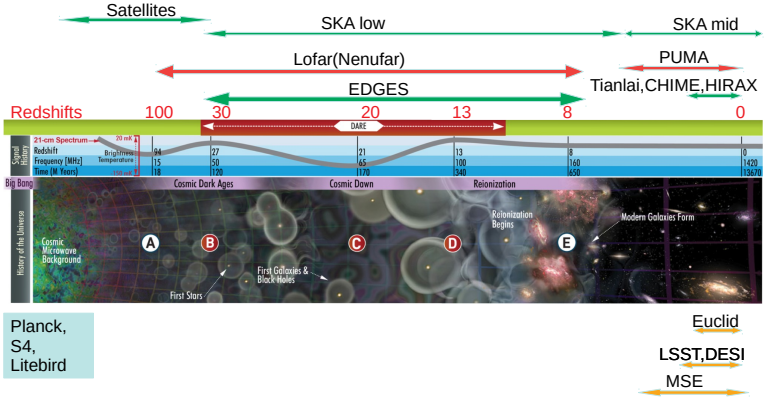


Promising but level much larger than expected statistical noise
Better control of systematics awaits larger dataset analysis !

Outlook and prospects

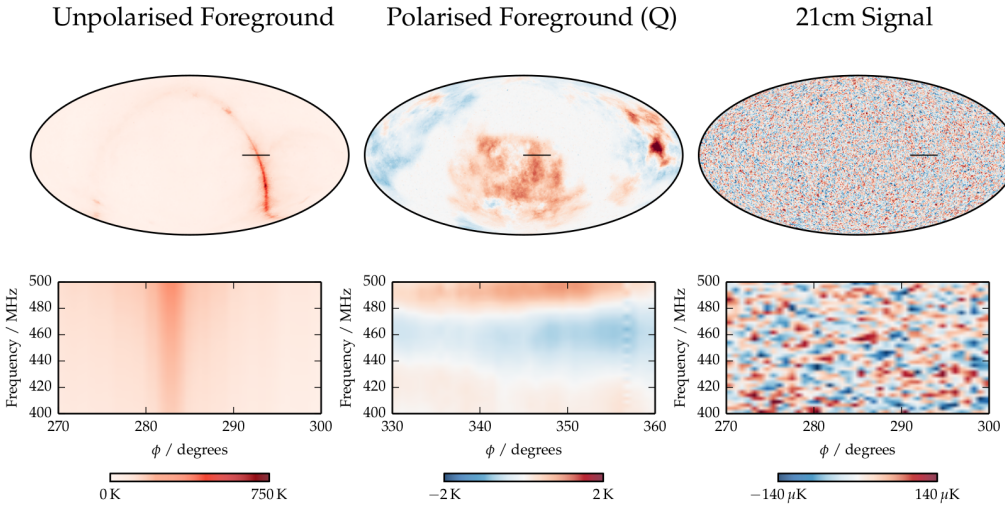
- recent works in Tianlai
  - installation of new elements (cylinders, dish) being finalized
  - upgrades on the correlator's electronics
  - switch to higher frequencies ($\sim 1300 - 1400$ GHz) under way (TBC)
  - collaboration meeting + 21cm cosmology workshop in Xian (07/2025), Shenzhen (12/2026)
- Fruitfull collaboration topics or exchanges between Orsay/Saclay and Chinese institutes (NAOC, Northeastern University in Shenyang)
- broader subjects discussed e.g. FAST data analysis, space projects

21 cm in cosmology



Two approaches : global spectrum shape (early universe), anisotropies (late epochs)

Signal & foreground (∼ 400 MHz)



Removal needs calibration to ±0.3% (ampli), ±.0063 radians (phase), and beam to 0.1%

R. Shaw et al 2017

Comparision with mocks from SDSS PRELIMINARY