

# 21cm cosmology with Tianlai

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université  
PARIS-SACLAY



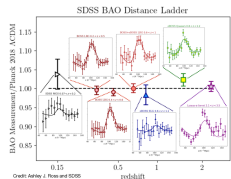
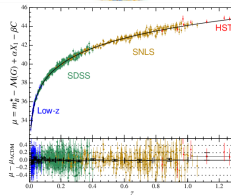
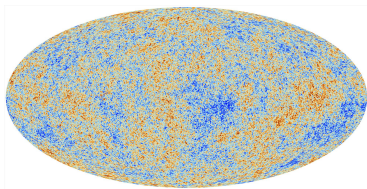
FCPPN/L Workshop - Bordeaux - June 2024

# Outline

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

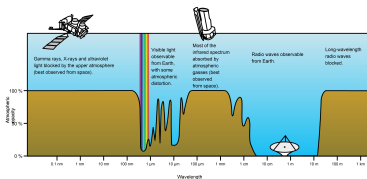
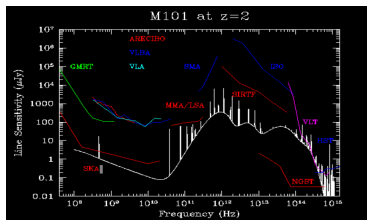
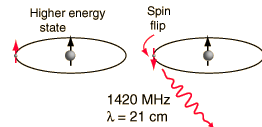
# Cosmology

- Very successful concordance model ( $\Lambda$  CDM) based on GR
- Accounts for many observations : CMB (Planck), Type Ia SNe (SNLS, Pantheon), BAO (BOSS/eBOSS),...
- Minimal set of parameters precisely measured (combinations and/or cross-correlations of probes)
- Extensions (inflation, neutrinos, DE) sought for by next gen. projects (CMB-S4, LiteBird, DESI, LSST, Euclid, ...)
- Some “tensions” i.e. 2-5  $\sigma$  offsets between measurements by different probes at different epochs/scales (e.g.  $H_0$ ,  $\sigma_8$ )

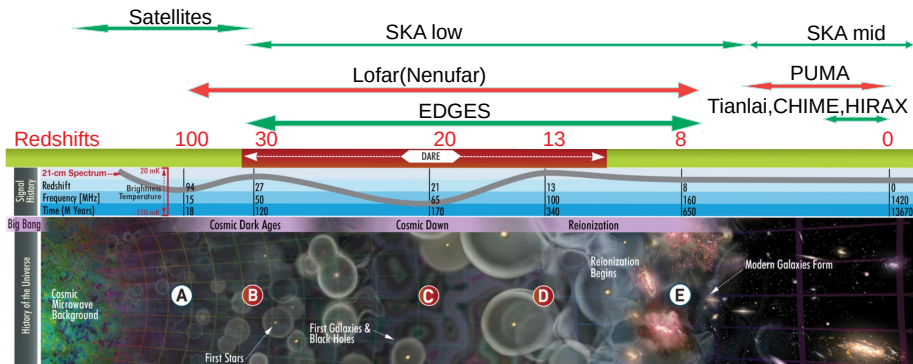


# The 21 cm Hydrogen line

- introduced in (for) astro (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, ..)



# 21 cm in cosmology



Planck,  
S4,  
Litebird

Euclid

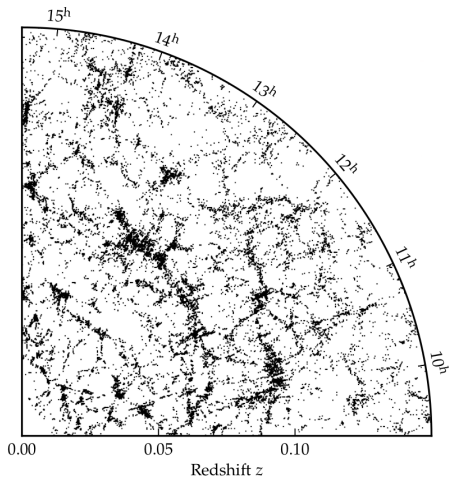
LSST, DESI

MSE

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

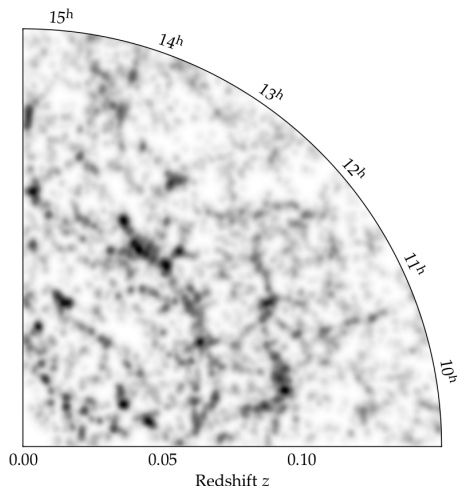
# LSS with galaxies

- Large Scale Structures statistics : tool to test cosmological models
- usual method :
- select galaxies
- measure  $z$  (spectrum or photo- $z$ )
- extract  $P_k$  in few  $z$  bins
- for cosmology (in particular BAO features) focus on  $O(1 \text{ degree})$  scales  $\Rightarrow$  **no need to measure individual galaxies**



# LSS from 21 cm line Intensity Mapping (IM)

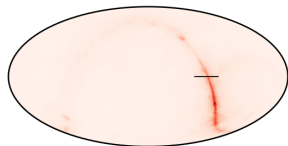
- broad  $\nu$  band, low angular resolution instrument
- measure intensity at “each” frequency  $\Rightarrow z$  : “easy” tomography
- prices to pay :
  - ▶ low signal (detected up to now only in X-corr with surveys)
  - ▶ very high level of **foregrounds**
  - ▶ **DAQ & calibration** challenging : huge data rate, few very bright sources
  - ▶ cosmological analysis : **HI power spectrum bias wrt matter's**



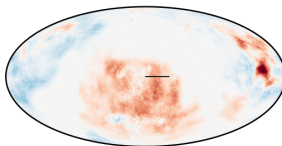
J. Petterson et al. arXiv:0902.3091

# Signal & foreground ( $\sim 400$ MHz)

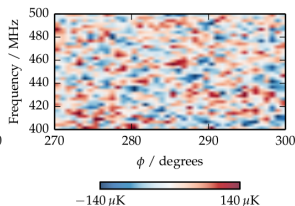
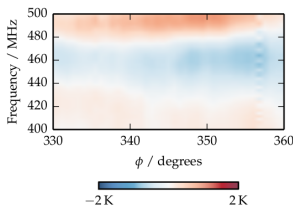
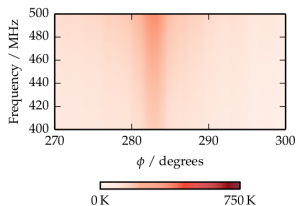
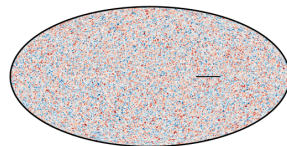
Unpolarised Foreground



Polarised Foreground (Q)



21cm Signal



Removal needs calibration to  $\pm 0.3\%$  (ampli),  $\pm 0.0063$  radians (phase), and beam to 0.1%

R. Shaw et al 2017



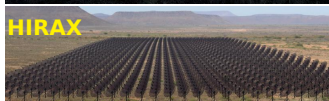
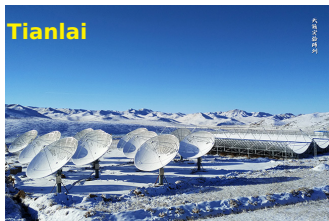
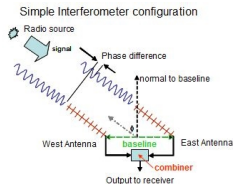
# The idealized setup

(some) Requirements :

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

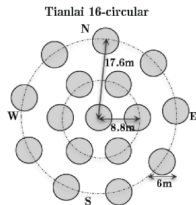
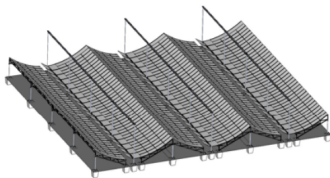
⇒ tentative solution(s) :

- 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 → FFT, digital correlation, beam forming

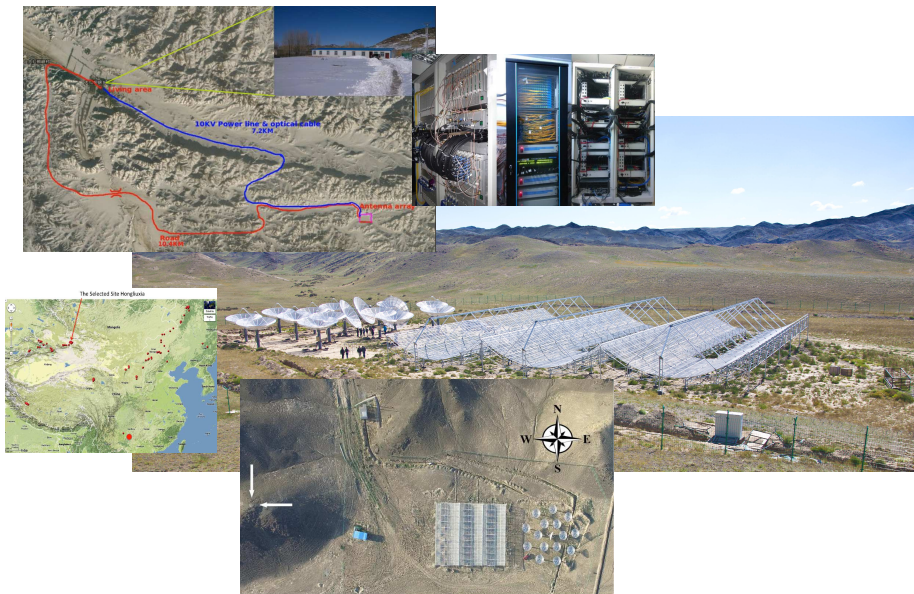


# Tianlai

- A small pathfinder experiment to check the basic principles and designs, find out potential problems
- 3x15x40m cylinders, 96 dual polarization receiver units
- 16 x 6m dishes
- observe 700-800MHz, can be tuned in 600-1420MHz
- If successful: expand to full scale 120mx120m, 2500 units



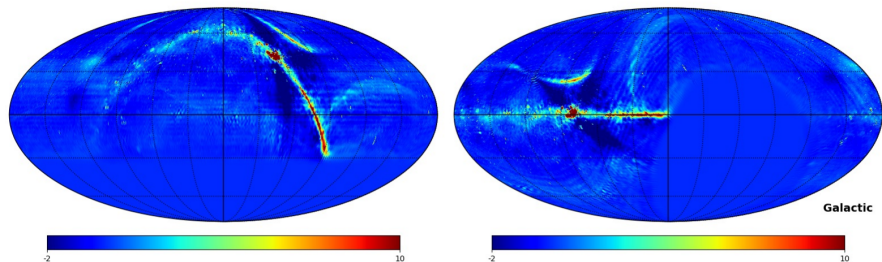
# Tianlai



# Recent results and developments

- Short bibliographic selection :
  - ▶ The Tianlai Cylinder Pathfinder Array: System Functions and Basic Performance Analysis, J. Li et al. + Standing wave paper, e.m. simulation paper, map-making simulation paper
  - ▶ Dish array overview paper, F. Wu et al. MNRAS (2020) + drone beam measurement paper
  - ▶ Data processing pipeline, S. Zuo et al 2021
  - ▶ Low-z forecast for the dish array, O. Perdereau et al. (2022)
  - ▶ FRB backend for the dish array, Z. Yu et al. (2022)
- Recent and on-going works :
  - ▶ 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
  - ▶ installation of more cylinders and dishes to e.g. help in FRB localization on the sky

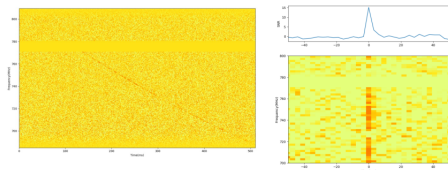
# Sky maps (cylinder array, one day, 750 MHz)



one day integration - observational and systematic artefacts

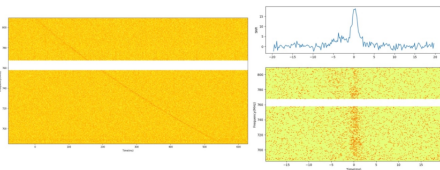
# FRB detections

cylinder



Blind Search 2022.04.14, 17:26:40.368 UT  
DM=208.1 $\pm$ 0.5 pc cm<sup>-3</sup>  
 $S_{\text{peak}}$  = 128.4 Jy, fluence = 204 Jy ms,  $z < 0.24$

Dish



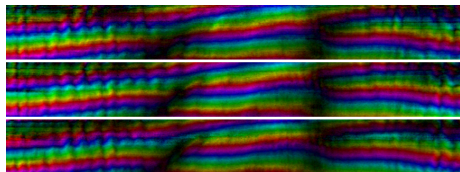
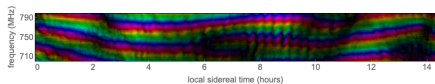
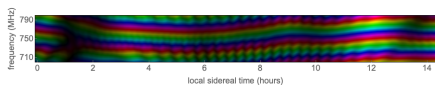
Observation of repeat FRB 20220912A  
detection on 2022.11.05 15:02:46.017 UT  
DM = 219.8  
 $S_{\text{peak}}$  = 285 Jy, fluency = 600 Jy ms

Signal dispersed by inter-galactic (ionised) medium  $\Rightarrow$   
dedicated correlator

# A North Celestial Pole survey with TianLai dish array

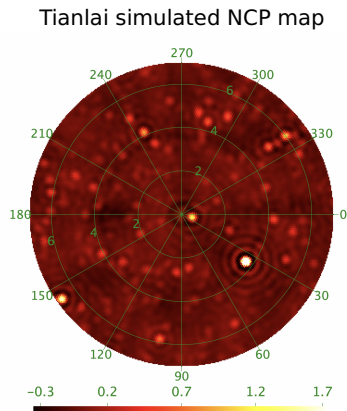
- 16 dish array : lower S/N than cylinders
- but less systematics, simpler beam
- dishes are the chosen approach for next generation projects (CHORD, HIRAX, PUMA)
- NCP is better for S/N per degree on the sky for Tianlai dish array data
- ~ 200 days accumulated in North Celestial Pole direction in 2018 (700-800 MHz)
- need (complex gain) calibration stability (no very bright source)

Tianlai 2018 data : Xcorrelation of pairs of dishes



# North Celestial Pole survey with TianLai

- more extended region around NCP observations at higher frequencies in 2023-4
- lower  $z \Rightarrow$  brighter 21cm signal : helps understanding the instrument in details
- together with optical spectro program (WYIN telescope) completed
- radio $\times$ optical cross-correlation : HI signal in low  $z$  galaxies, towards IM signal, instrumental performances
- observations of intermediate latitude (e.g. correlate with SDSS, Alfa, FAST) region(s) also planned
- Forecast paper : [O. Perdereau et al. MNRAS](#)
- Optical survey paper almost ready

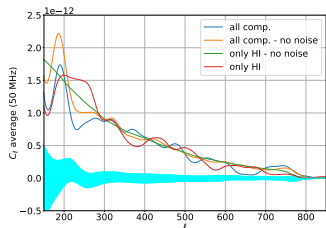
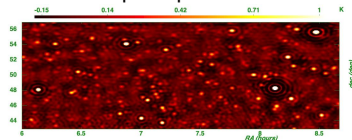




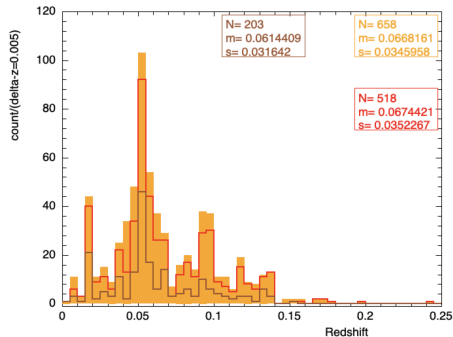
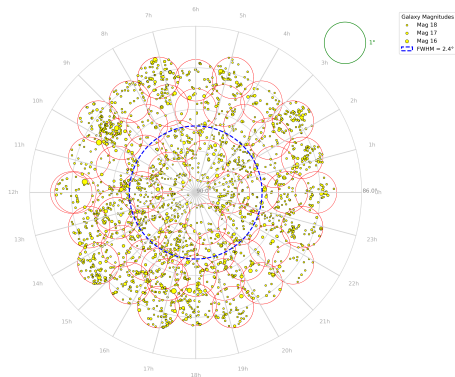
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Simulated map & spectra - midlatitude

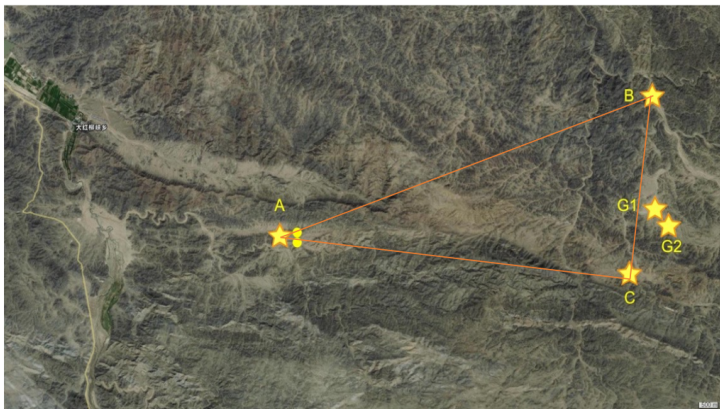


# optical NCP spectroscopic survey at WIYN (PRELIMINARY)



722 sources selected in NCCS (Gorbikov et al., 2014, MNRAS/443/725) with successful redshift measurement

# On-site developments

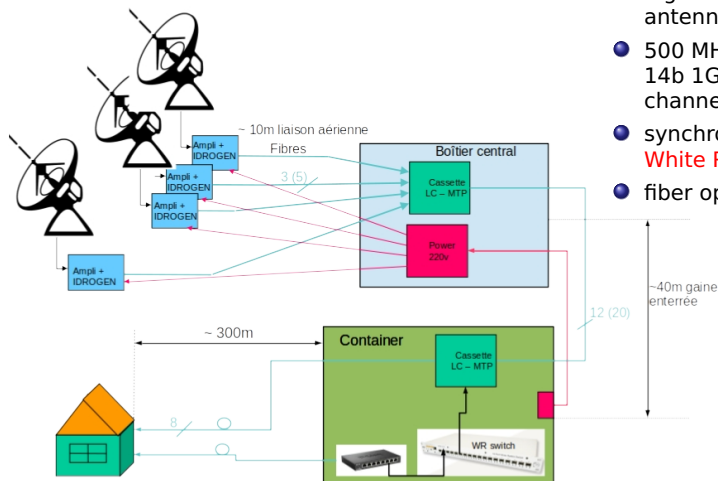


A : new dish (improve on-sky calibration) ; B,C : new cylinders (FRB localization) G,2 : 21cm global spectrum experiment  
Also : upgrade on correlators, repairs, ....



# new architecture

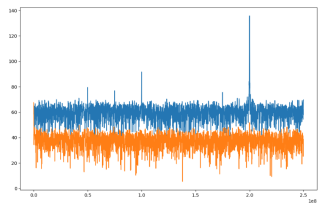
- new analog stage
- digitization at the antennas
- 500 MHz bandwidth, 14b 1Gsp/s ADC (2 channels)
- synchronization with **White Rabbit**
- fiber optics network



# IDROGEN + mezzanine FMC ADC 500MSPS

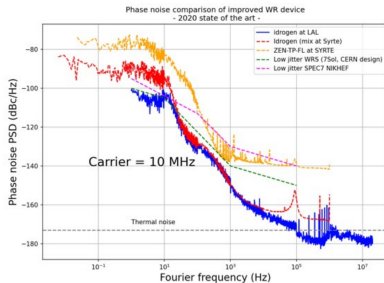
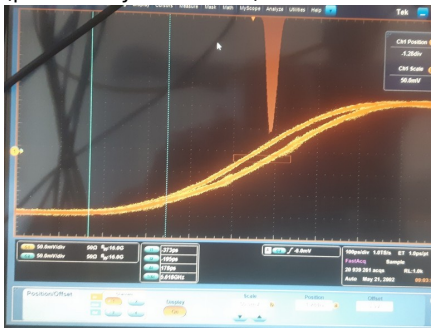


- \* Bandwidth 500 MHz to 1.5GHz
- \* Synchro & timing by WR
- \* Data transfer 2x 10G Ethernet
- \* Configuration by IPBus 10G
- \* ADC 1GSPS version currently in test

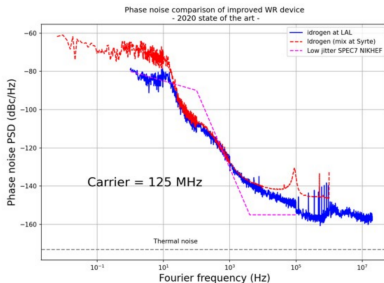


# WR with IDROGEN

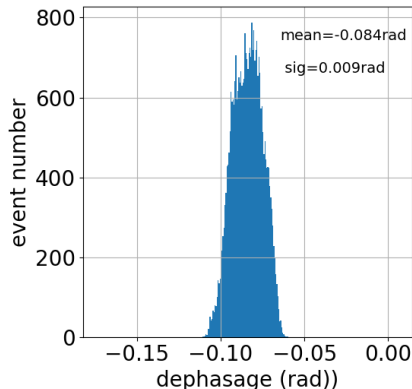
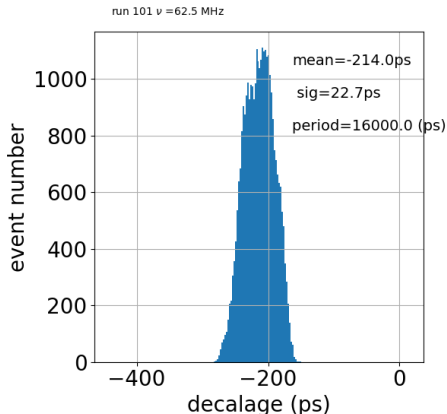
- qualification and calibration of IDROGEN boards WR parameters
- two boards, 25 and 125m optical fiber link to WR switch (master)  
→ ~ 50 ps dispersion of PPS (preliminary calibration)



- phase noise tests at SYRTE (right) : best in marker



# ADC samples first timing checks (NEW)



2 Idrogen boards + prototype mezzanines (500 Msp ADCs)  
fed with sine wave; measurements of relative phase shift  $\leftrightarrow$   
time difference (effect of system's initialisation)



# Outlook and prospects

- Tianlai : (also look at Zuhai (2023)'s talk by S. Zuo)
  - ▶ installation of new elements (cylinders, dish) has started or will start soon
  - ▶ upgrades on the correlator's electronics
  - ▶ switch to higher frequencies ( $\sim 1300 - 1400$  GHz) soon
  - ▶ collaboration meeting (2024 : in Hangzhou)
- Ongoing R&D in Nançay (PAON4) on generic DAQ board (to be used in many areas e.g. nuclear physics , accelerator, GW,...)
- Fruitfull collaboration topics or exchanges between Orsay/Saclay and Chinese institutes (NAOC, Northeastern University in Shenyang)
  - ▶ student exchange : administrative process to welcome Q. Zhang in IJCLab is starting
  - ▶ broader subjects e.g. FAST data, space projects ?
- **THANK YOU !**