21cm Intensity Mapping with Tianlai

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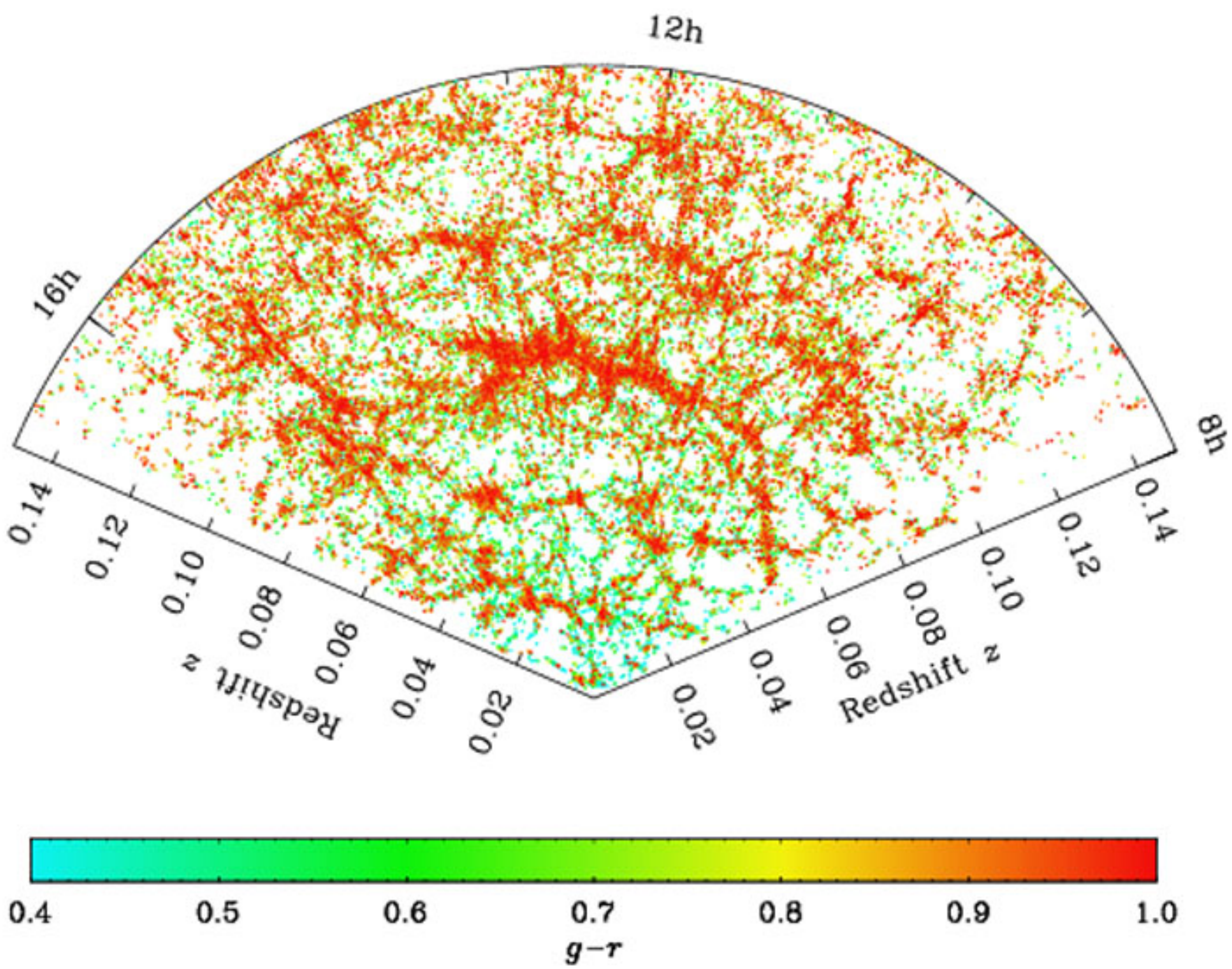
Cosmology in the Alps , Les Diablerets, Switzerland, March 2024

- Post-EoR 21 cm Cosmology and Intensity Mapping
  - Mapping LSS at 21cm
  - 21cm IM promises and challenges
- Tianlai (Cosmic Sound)
  - (Pre) History
  - Instrument
  - Cylinder array performance
  - Dish array (T16D) array performance and the NCP survey
  - T16D low-z survey plans and forecasts
  - Tianlai FRB backends
- PAON4 and IDROGEN

Post-reionisation cosmology with 21cm IM mapping

- Mapping LSS at 21cm
- 21cm Intensity Mapping promises and challenges

Structure formation and evolution
a cosmological probe



A slice through the SDSS galaxy 3D distribution

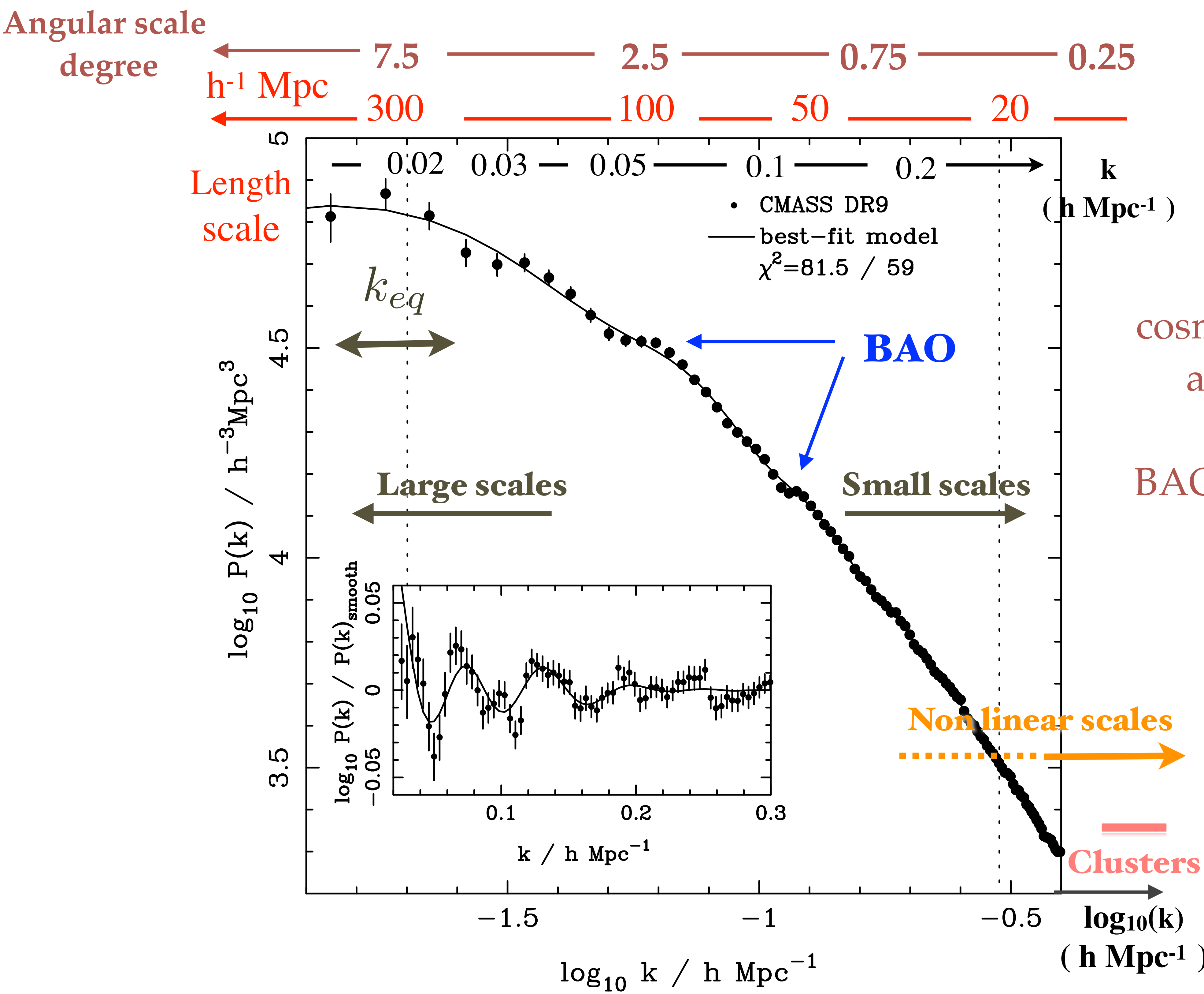
Zehavi et al. ApJ 2011, arXiv:1005.2413

Some major cosmological probes

Optical surveys:
SDSS - DES -
LSST - Euclid - DESI …

- Supernovae (SN)
- Weak Lensing (WL)
- Galaxy Clusters (CL)
- **Galaxy clustering (LSS / GC)**
- **BAO → $d_A(z)$, $H(z)$**
- **BAO/RSD** — **21cm IM**
- …

LSS : Power spectrum and different scales



Most of the LSS cosmological information at scales larger than few arc minutes

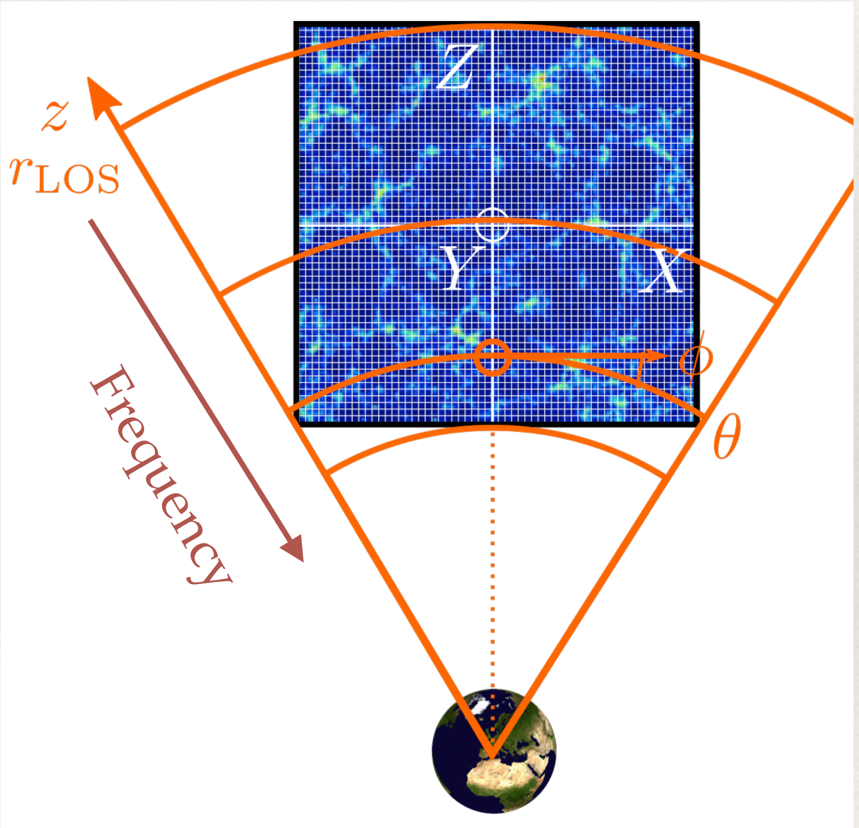
BAO: 0.5 to a few degrees

SDSS-DR9 , Anderson et al et al. 2012, arXiv:1203.6594

21 cm 3D Intensity Mapping

Dense Array Transit Interferometers

- Map the sky through drift-scan
- Reconstruct sky map from visibilities
- Visibilities correspond to transverse Fourier modes $k_\perp$
- **m-mode decomposition / map making with full EW scan**



Single Dish

- Map the sky through drift-scan or by active scanning

- Sys ~ 50 K , Foreground ~10K for an LSS signal ≲ 1 mK (ratio 10^4 - 10^5)
- Stage I : 10^4 m^2 , 10^3 feeds
- Stage II : 10^5 m^2 , 10^4 feeds
- 10 GB/s … 1000 GB/s raw visibility data @ 1 sec averaging

$$P_{21}(k) \sim (\bar{T}_{21})^2 \times P_{LSS}(k)$$

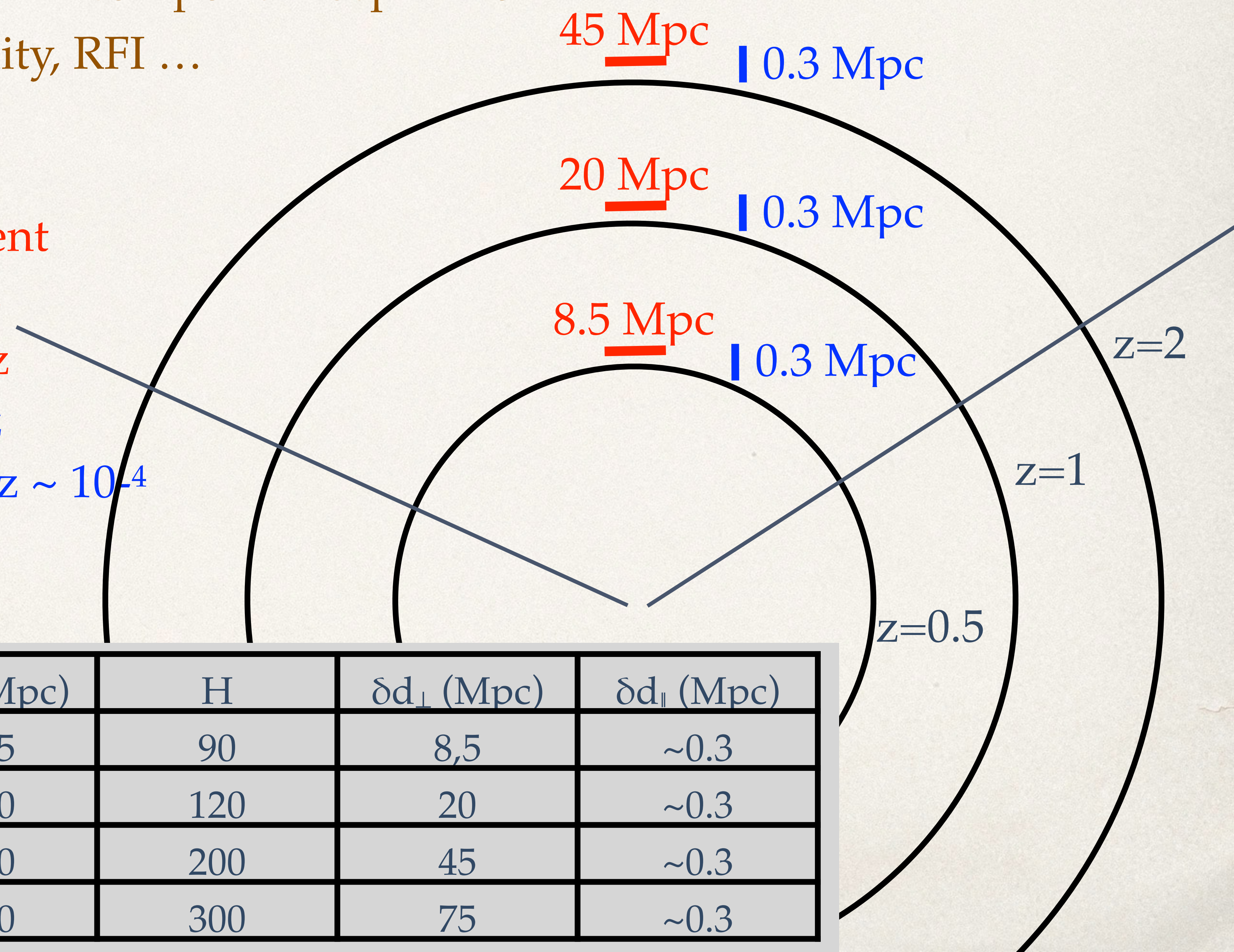
$$\bar{T}_{21} \simeq 4.7\,\mathrm{mK}\ \frac{\Omega_{H_I}}{10^{-3}}\ \frac{H_0(1+z)^2}{H(z)}$$

Peterson, Aleksan, Ansari et al. (2009) arXiv:0902.3091

Ansari et al. (2012) arXiv:1108.1474

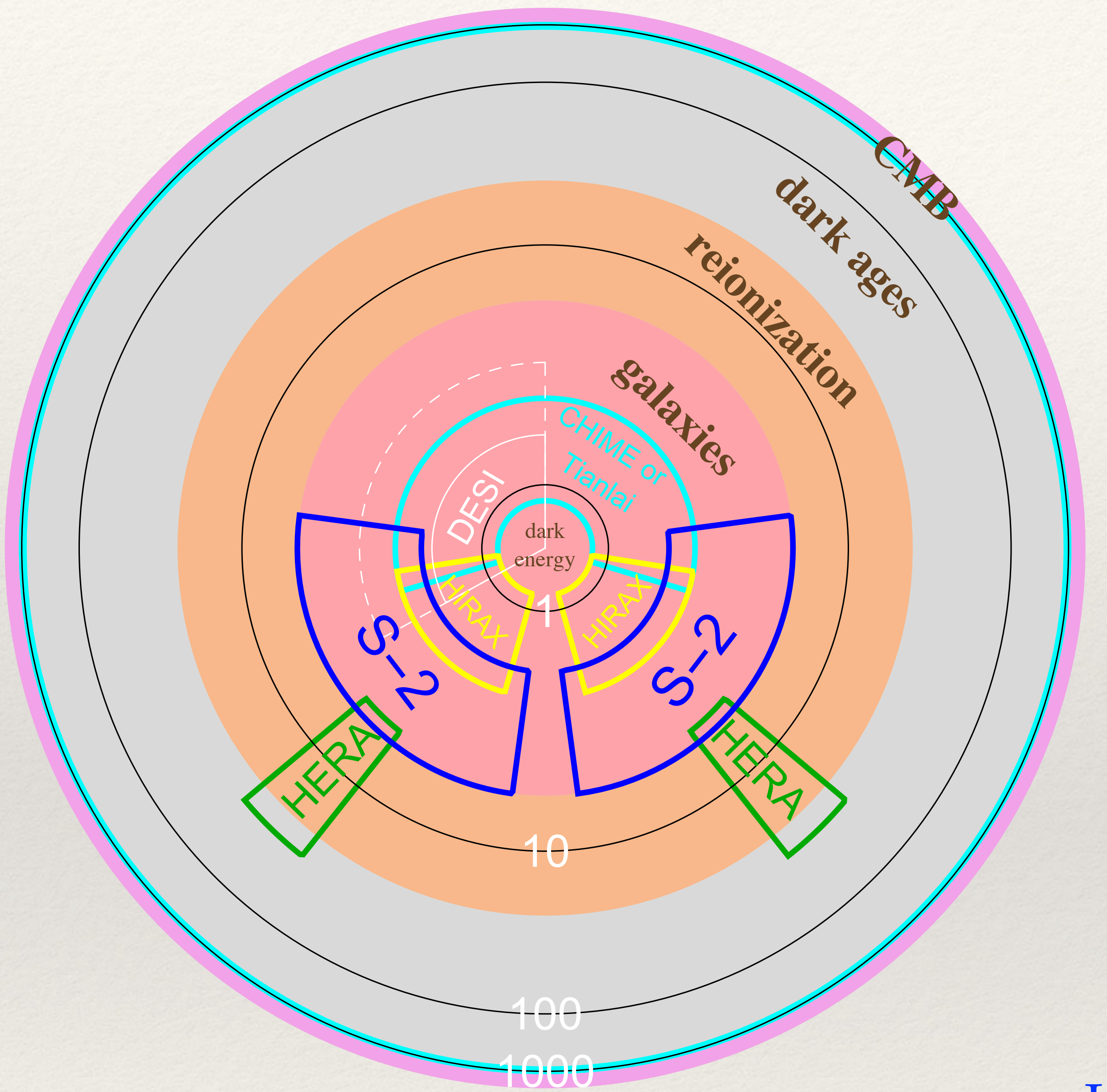
- Mapping LSS with 21cmIM ➙ few arc min resolution is sufficient
- ➙ Large instantaneous field of view (FOV>few deg) and bandwidth (BW > 100 MHz)
- Use of dense interferometric arrays (small size reflectors) to insure high sensitivity to low k and large instantaneous FOV
- Or a single dish with multi-beam focal plane receivers
- Instrument noise (Tsys)
- Foregrounds / radio sources and component separation
- Calibration, instrument stability, RFI …

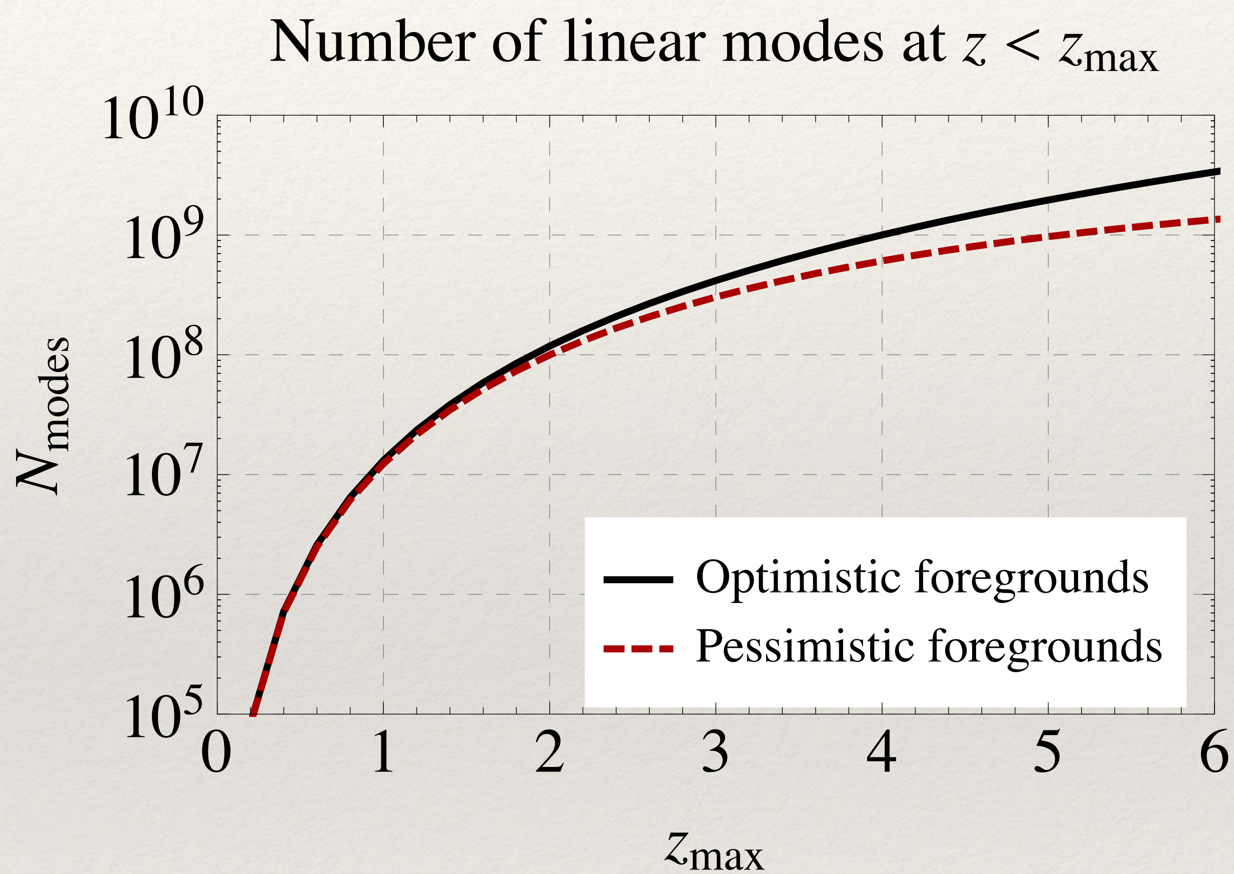
L=100 m array radio instrument
➙ ang. resolution $\delta\theta \sim \lambda/L$
deteriorating with redshift z
Spectral resolution 100 kHz
➙ excellent redshift precision $\delta z/z \sim 10^{-4}$



z	$\delta\theta$	d_{LOS} (Mpc)	H	$\delta d_\perp$ (Mpc)	$\delta d_\parallel$ (Mpc)
0,5	15′	1945	90	8,5	~0.3
1	20′	3400	120	20	~0.3
2	30′	5320	200	45	~0.3
3	40′	6320	300	75	~0.3

21cm : Single tracer can be used to survey a huge volume and reveal LSS and its evolution with redshift

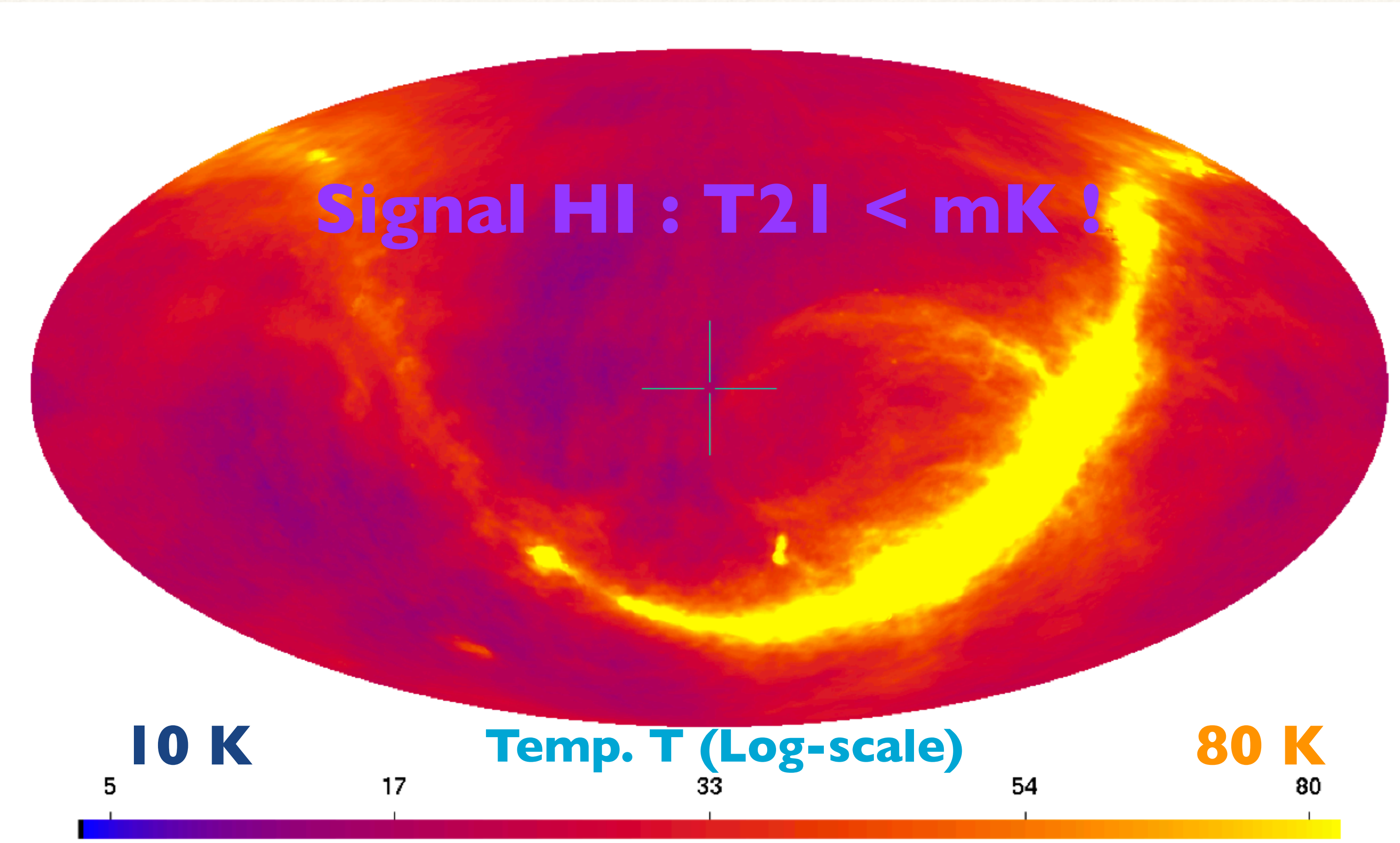




Inflation and Early Dark Energy with a Stage II Hydrogen Intensity Mapping Experiment

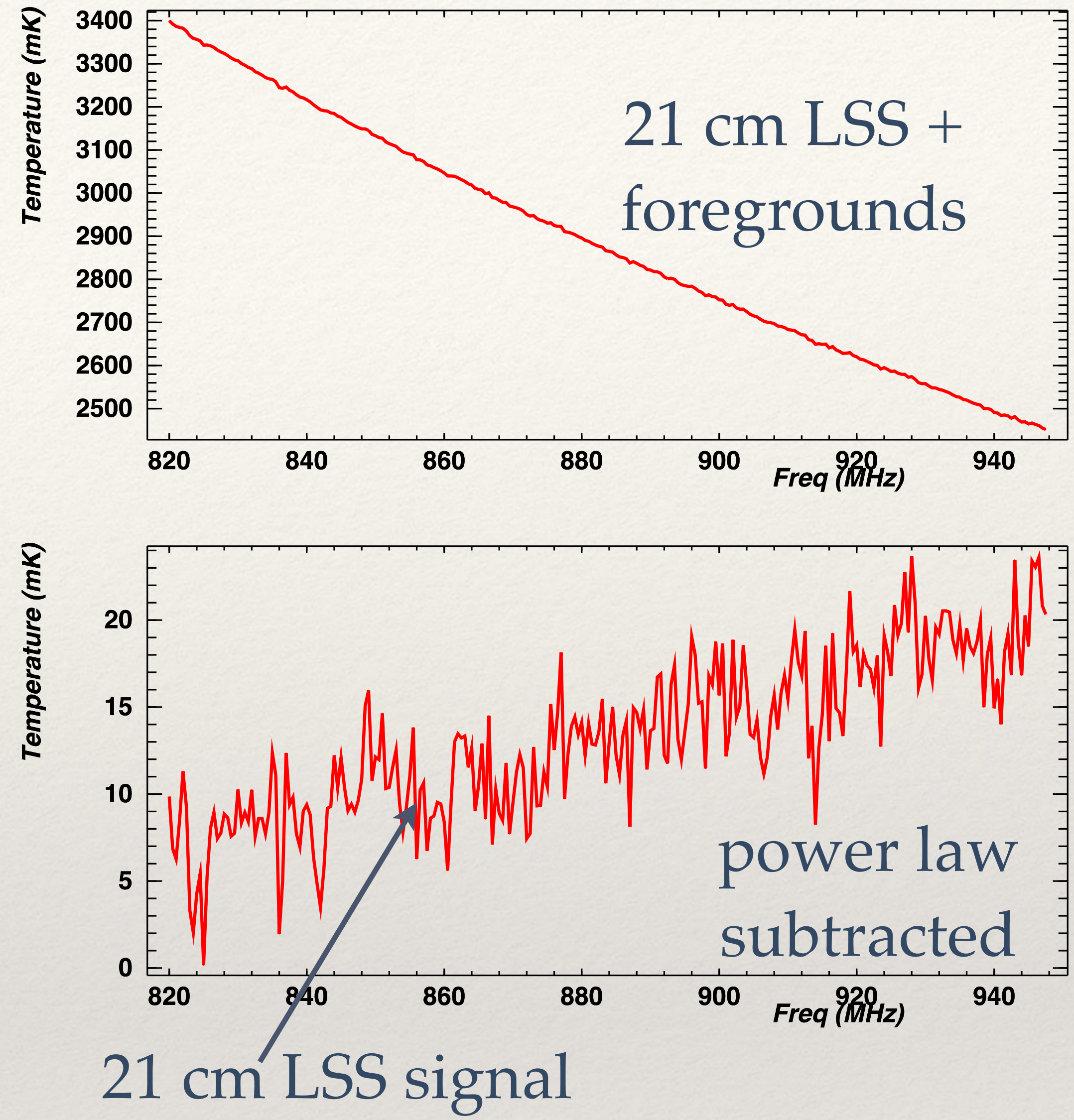
Cosmic Visions A. Slosar et al &RA , arXiv:1810.09572

Foregrounds



Galactic synchrotron emission

http://lambda.gsfc.nasa.gov/



- Exploit foregrounds smooth frequency dependence (power law ∝ ν^β) for Galactic synchrotron and radio sources
- Instrumental effects (mode mixing), Polarisation leakage / Faraday rotation …

Wang et al. 2006 (EoR)
Ansari et al. (2012) - A&A
Shaw et al (2015) ApJ
Wolz et al. (2016) - MNRAS
Zuo et al. (2019) - AJ
+ many more !

Tianlai

- Brief (pre) history
- Tianlai instrument & site
- Cylinder array performance
- Dish array (T16D) performance and NCP survey
- T16D low-z survey plans and forecasts
- Tianlai FRB backend

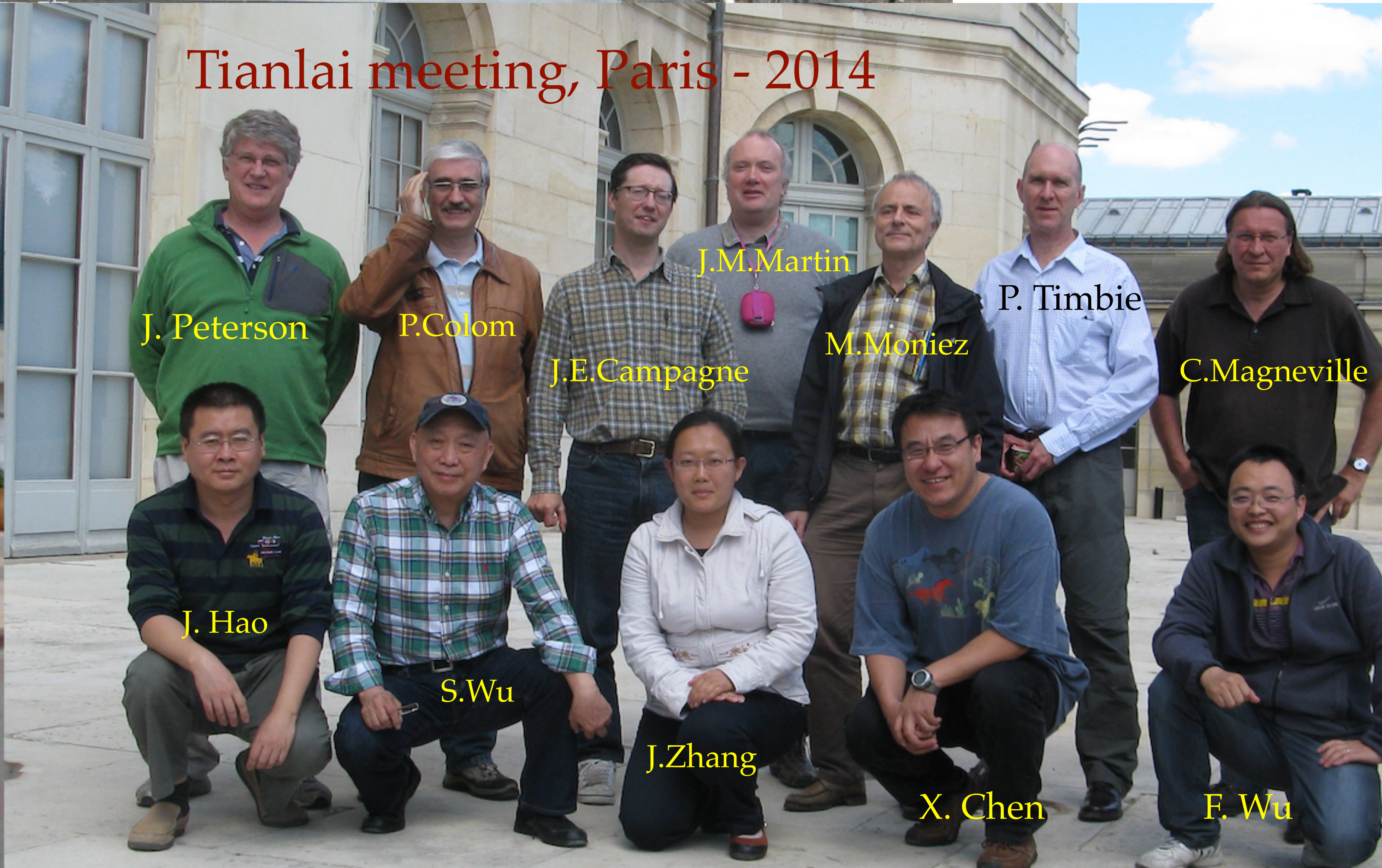
Xu, Wang & Chen (2014) arXiv:1410.7794

The Tianlai Collaboration


J. Peterson @ Moriond 2006 : CRT for 21cm galaxy survey
CRT prototype @ Pittsburg - 2009
U-HAUL

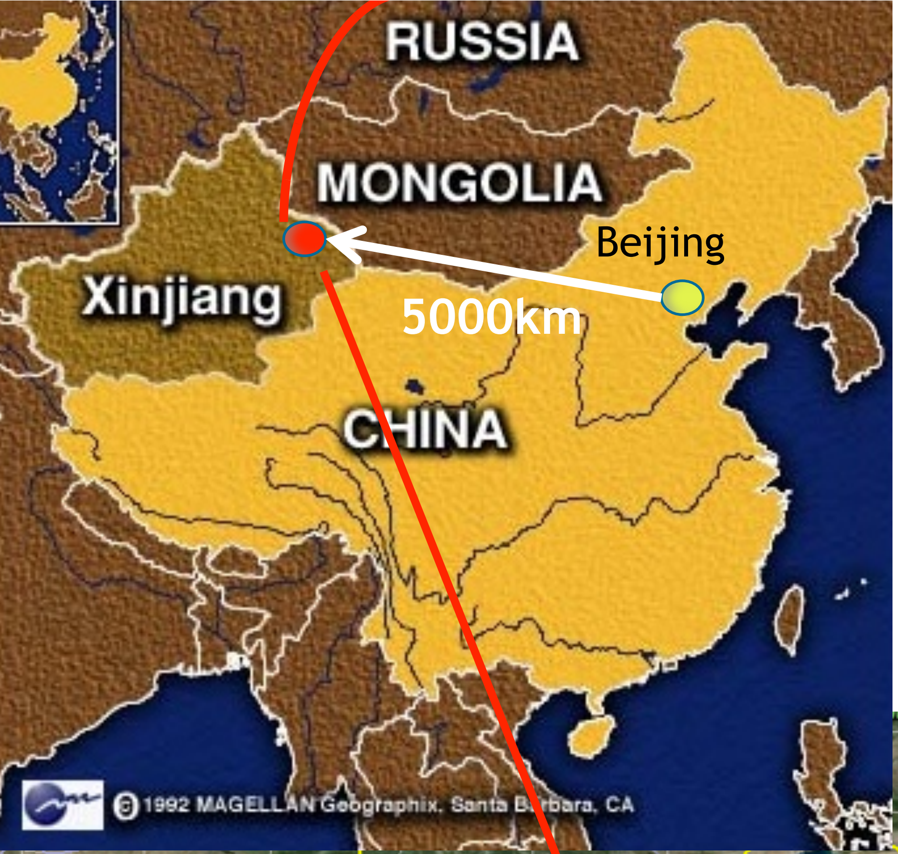

K. Bandura
Pittsburgh - 2009

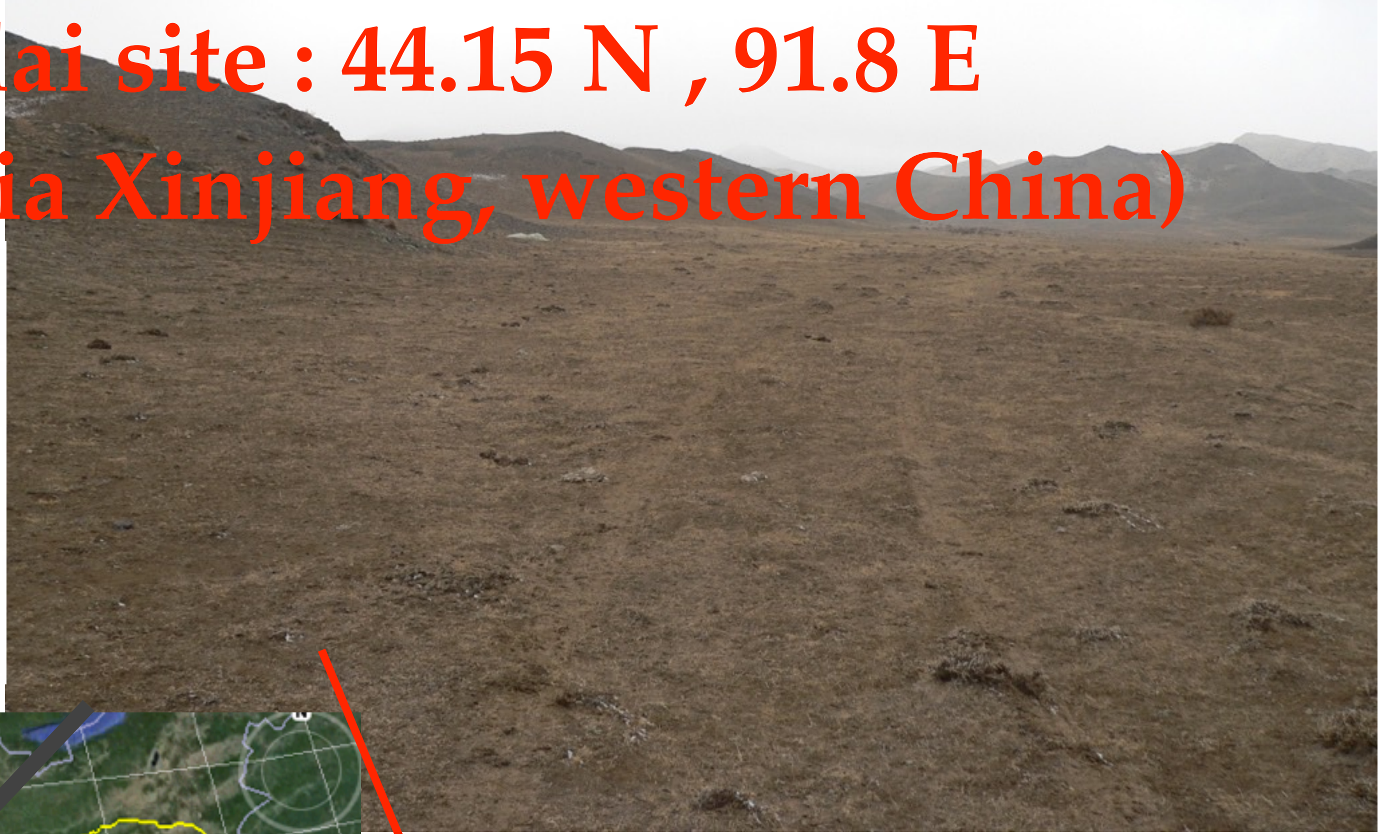

CRT meeting , Ifrane,
Morocco 2009
CENTRE DE BEAUTE
BEAUTIFUL
Coiffure
J.Rich
J. Peterson


Tianlai meeting, Paris - 2014
J. Peterson
P.Colom
J.M.Martin
J.E.Campagne
M.Moniez
P. Timbie
C.Magneville
J. Hao
S.Wu
J.Zhang
X. Chen
F. Wu

Tianlai site : 44.15 N , 91.8 E

Honglliuxia Xinjiang, western China)






16 x D=6m dish array
TIANLAI
3 Cylinders , 15mx40m

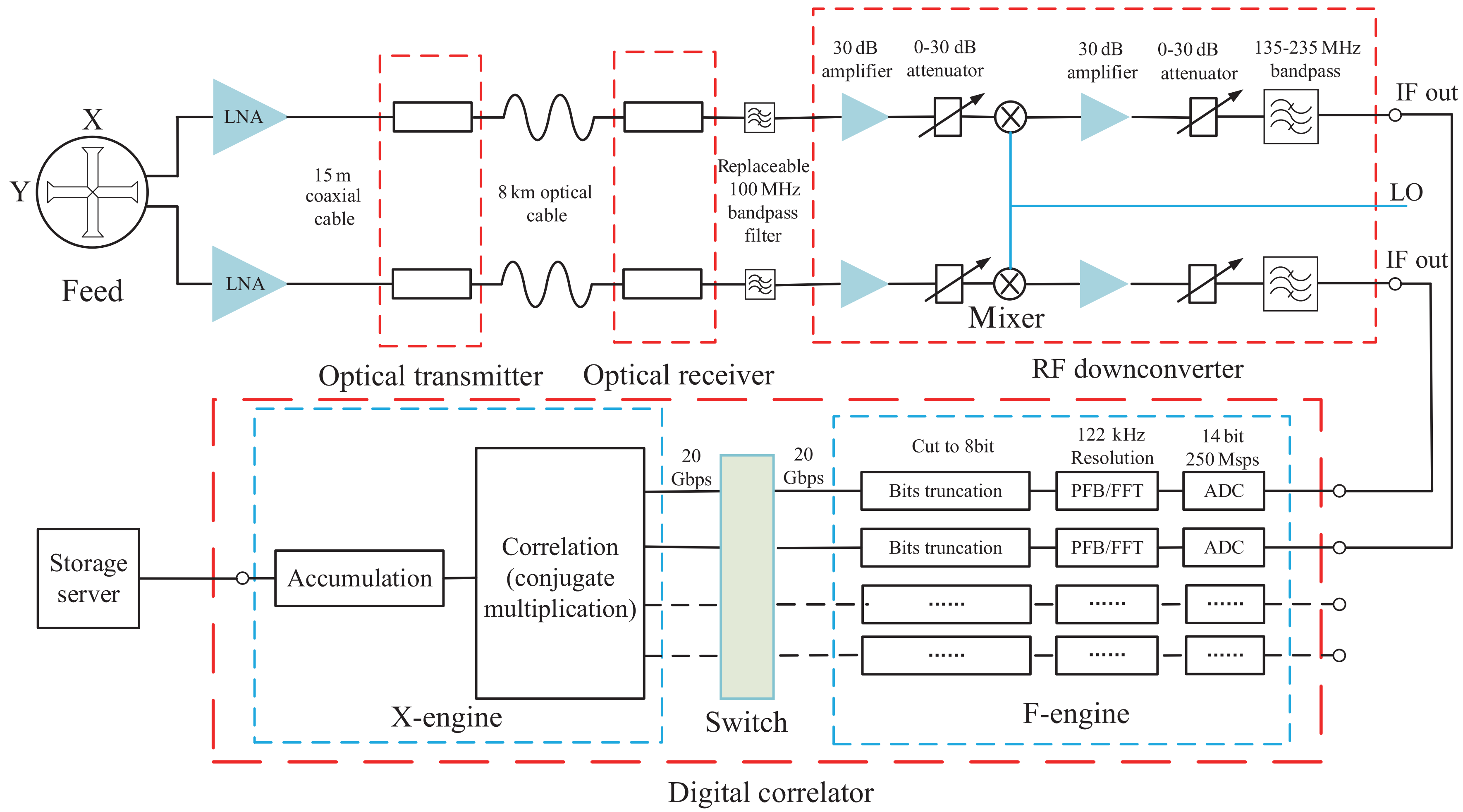
CNS
Calibrator Noise Source

Cylinder array

Dish array

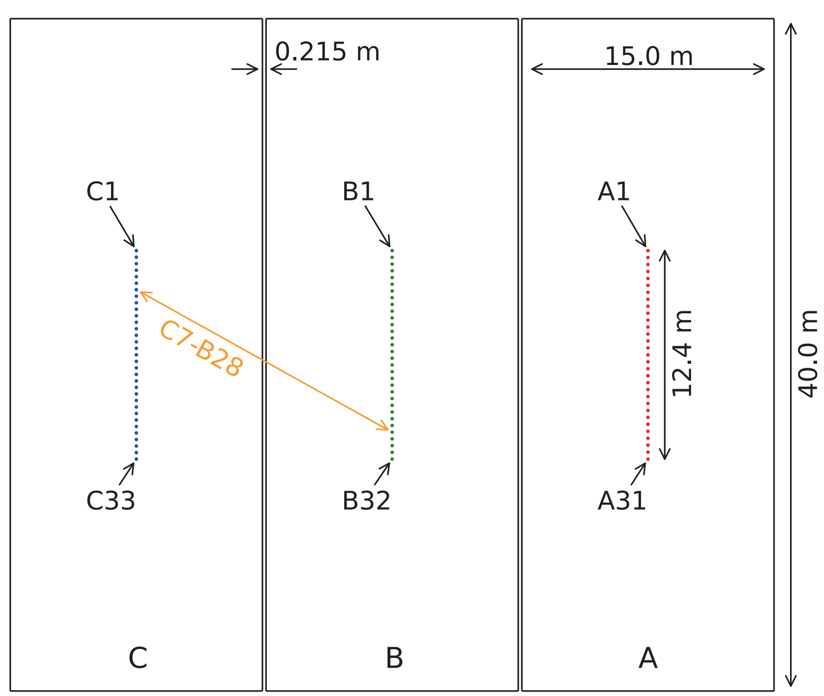
Tianlai cylinder array

Tianlai electronic chain and digital correlator
Signal path features optical RF signal transmission



Jixia Li et al, 2020 , arXiv:2006.05605

Unequal feed spacing

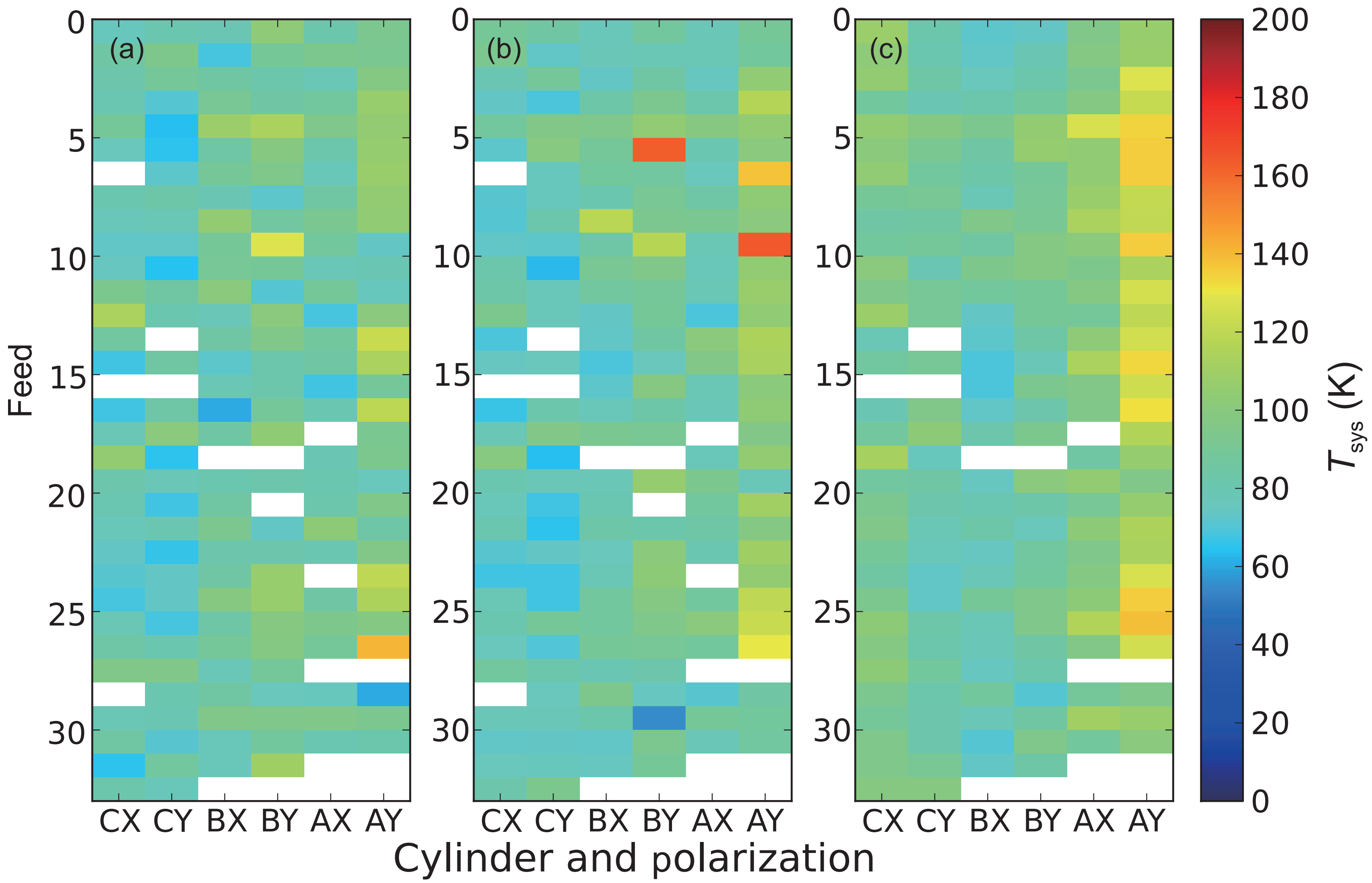


Avoiding grating lobes / spurious images
using different feed spacing along different cylinders :

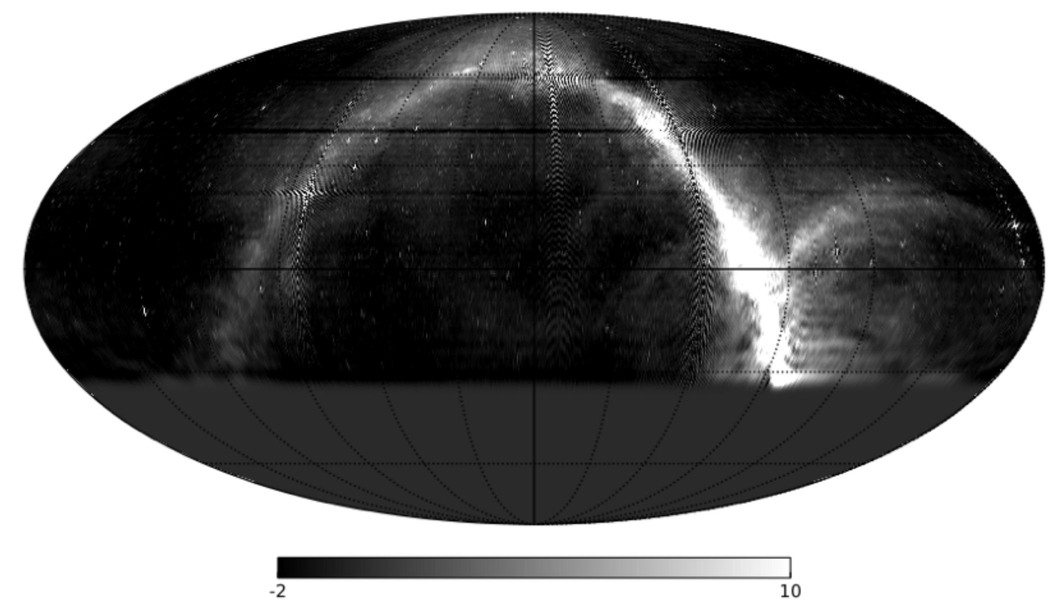
J. Zhang et al, 2016 , arXiv:1606.03830

Tianlai cylinder array performance

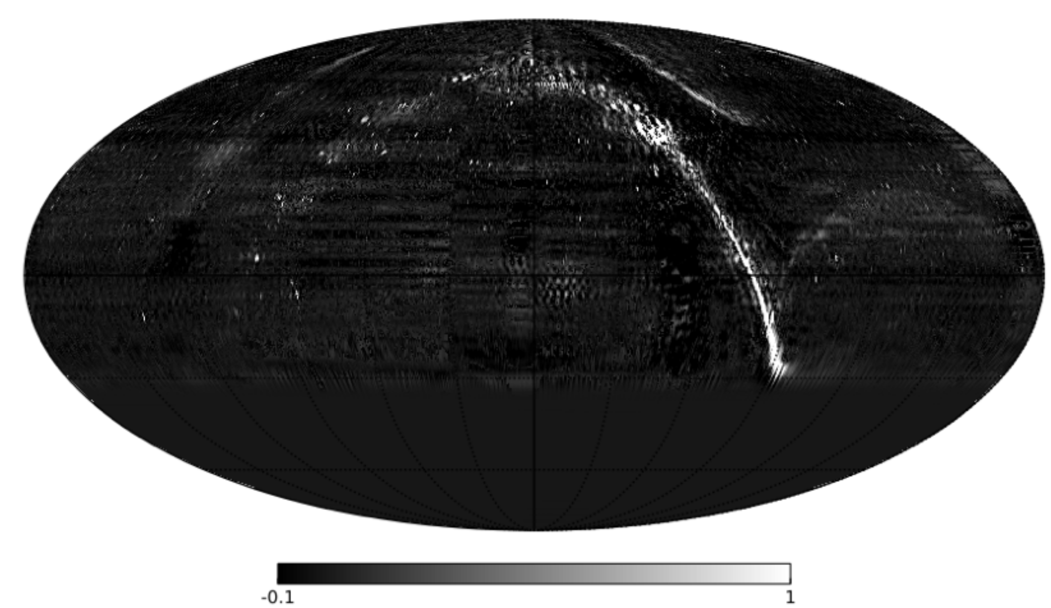
Feed by feed System temperature Tsys estimates, using auto-correlation level, fluctuations and cross-correlations



Cylinder array



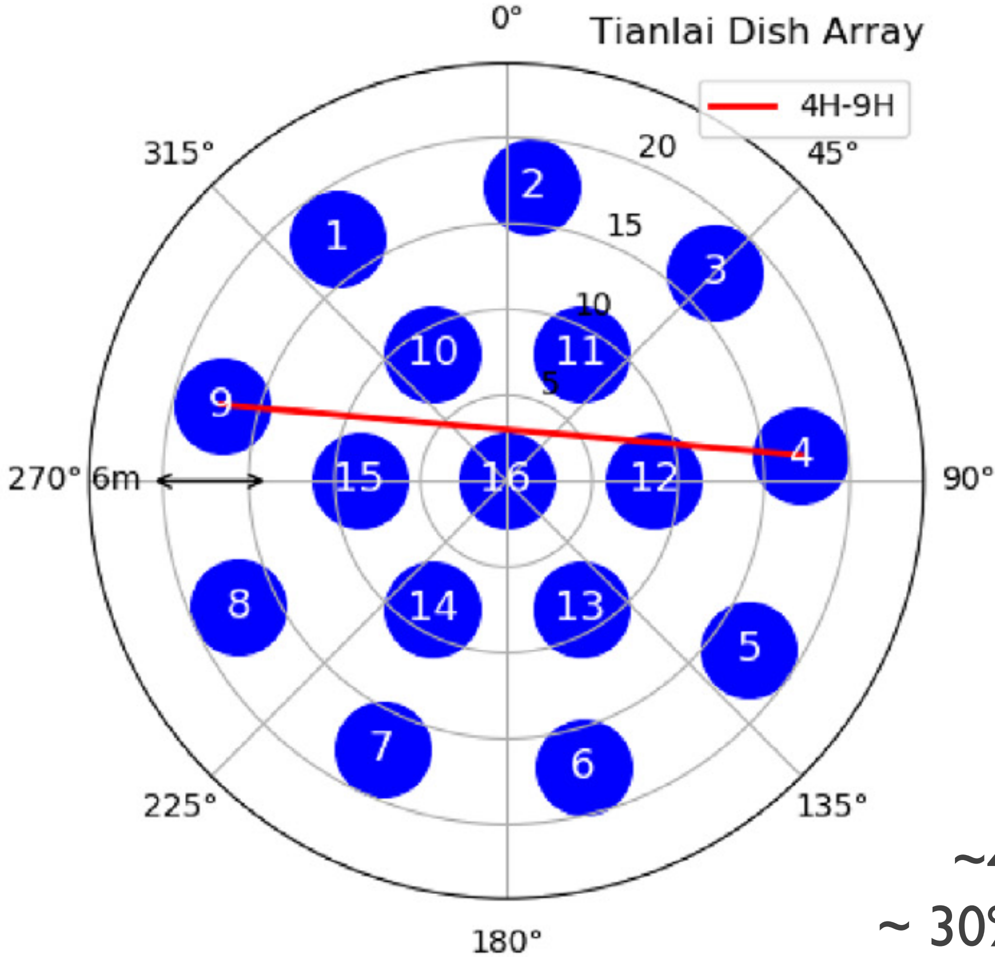
- simulated



Jixia Li et al, 2020 , arXiv:2006.05605

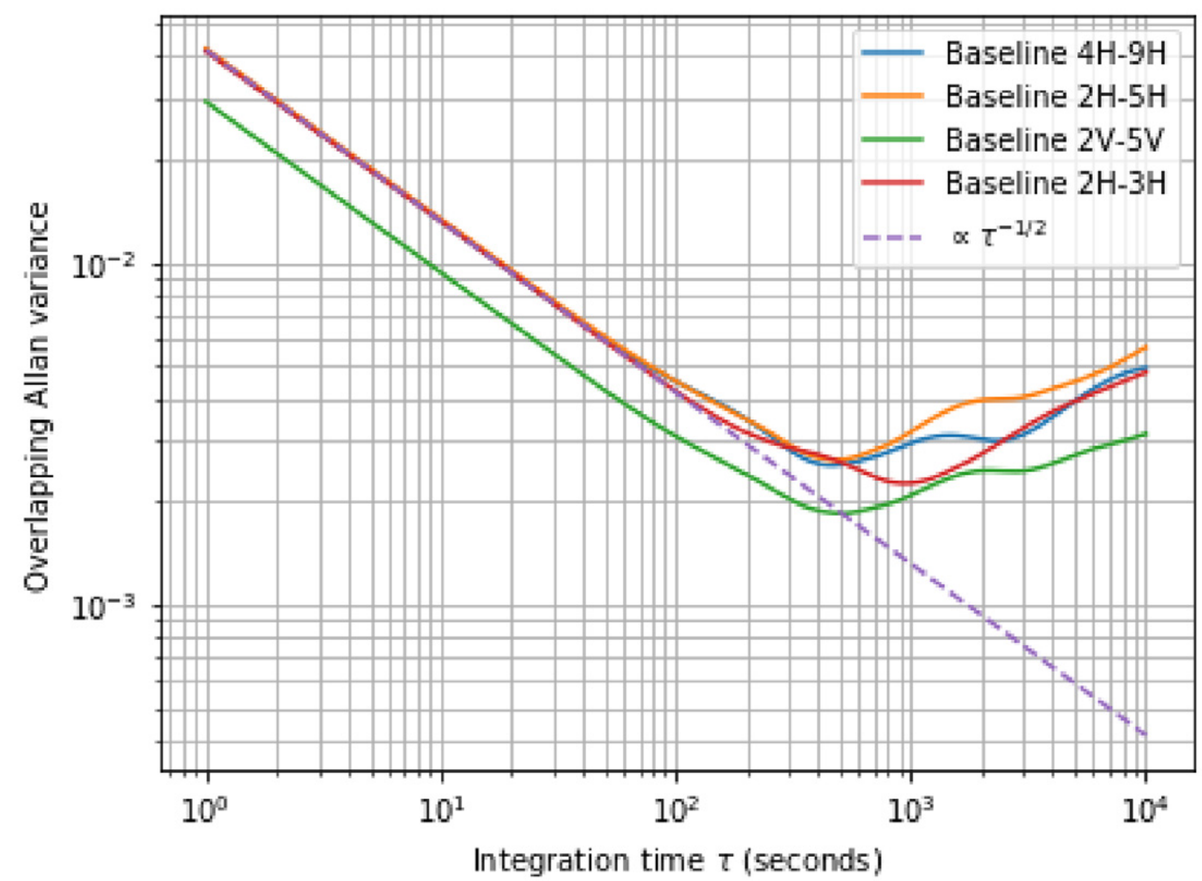
- observed

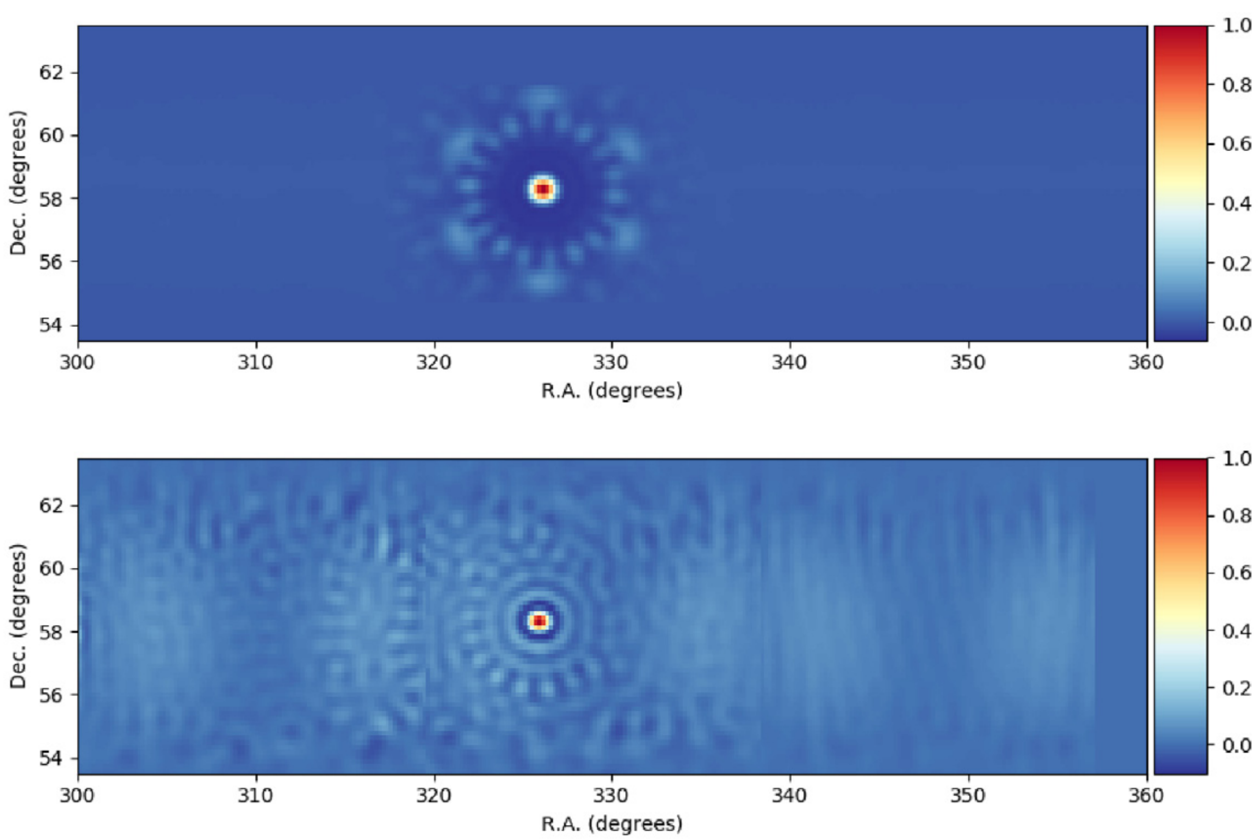
Tianlai dish array (T16D) performance



~450 m² ,
~ 30% fill factor

Allan variance - noise fluctuations decrease with integration time

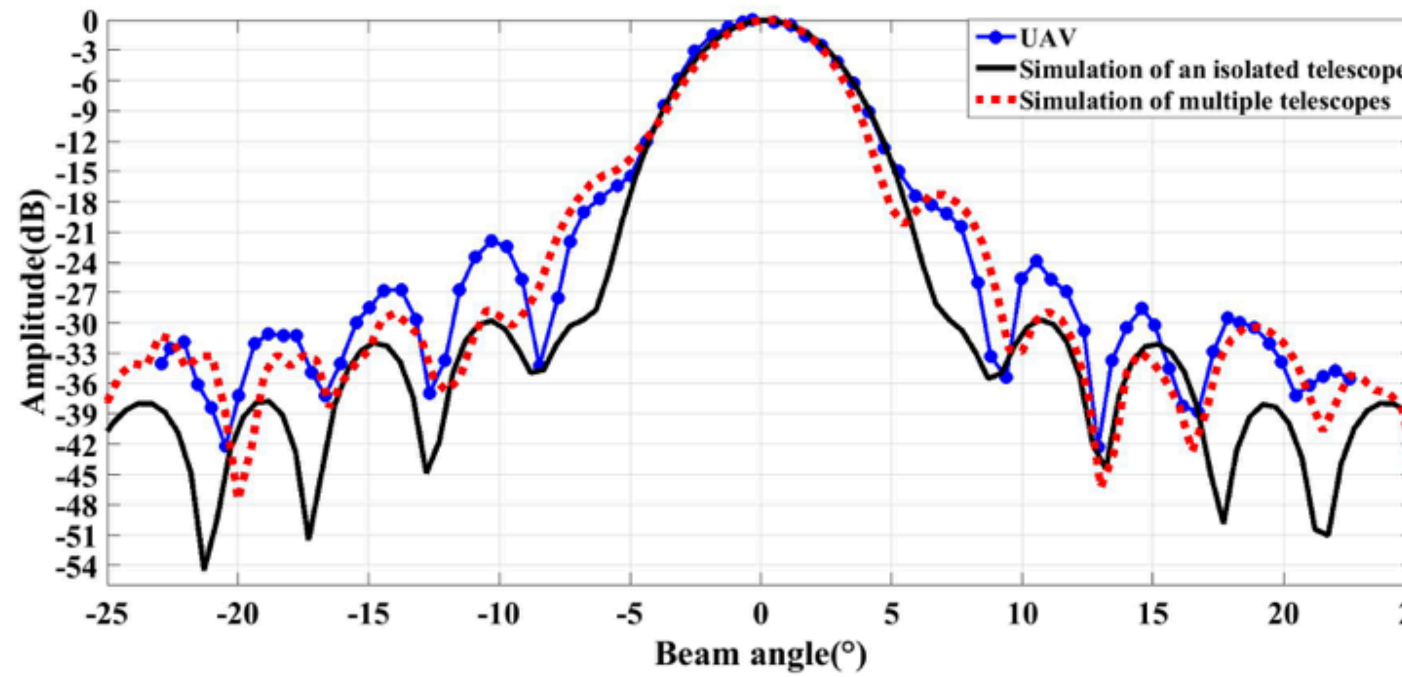


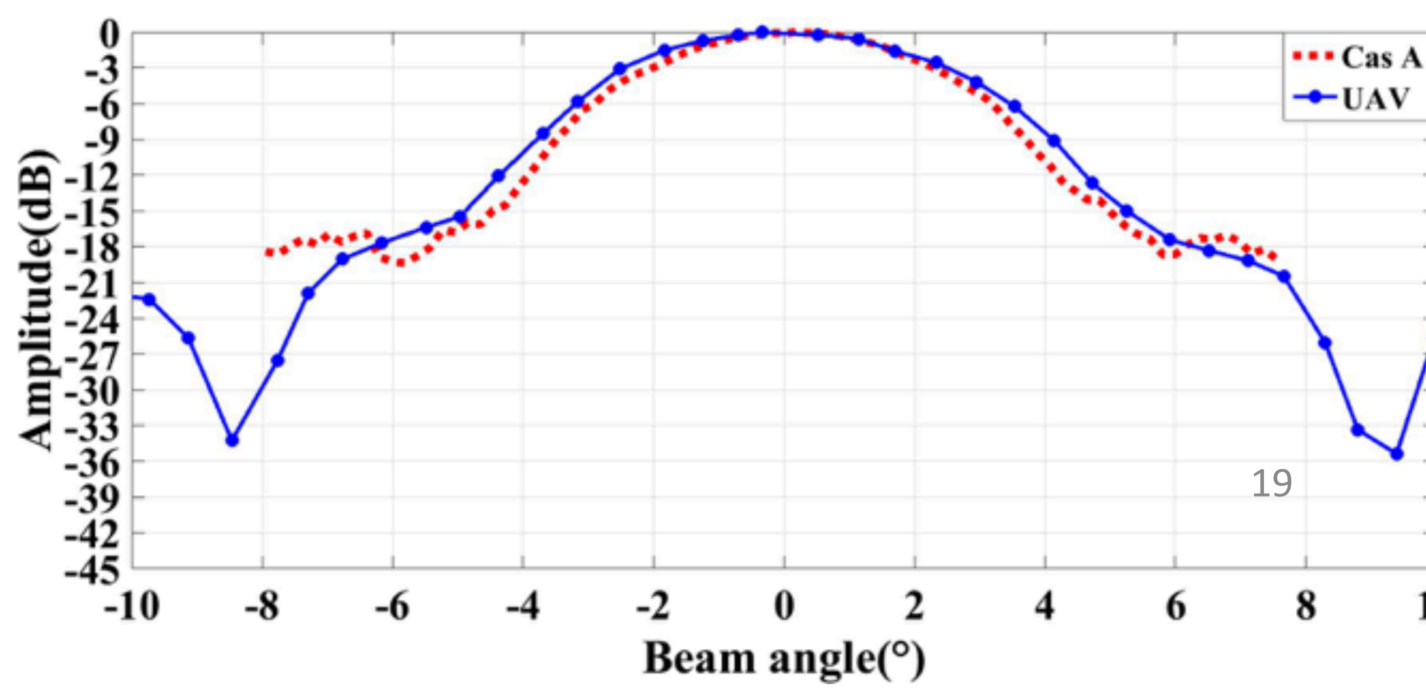


CasA transit - 4 hours of data
Top : QuickMap
Bottom: BFM

F. Wu et al, MNRAS 2021 , arXiv:2011.05946

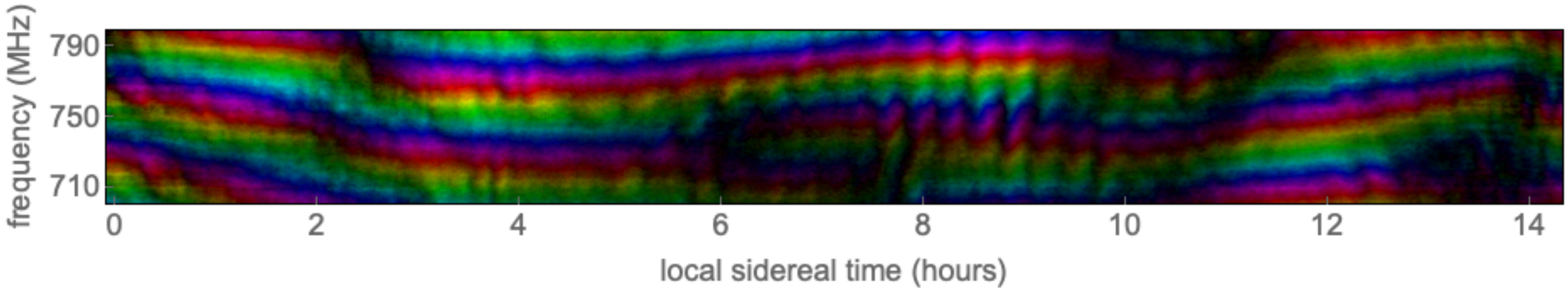
Dish Beam Calibration UAV/Cas A

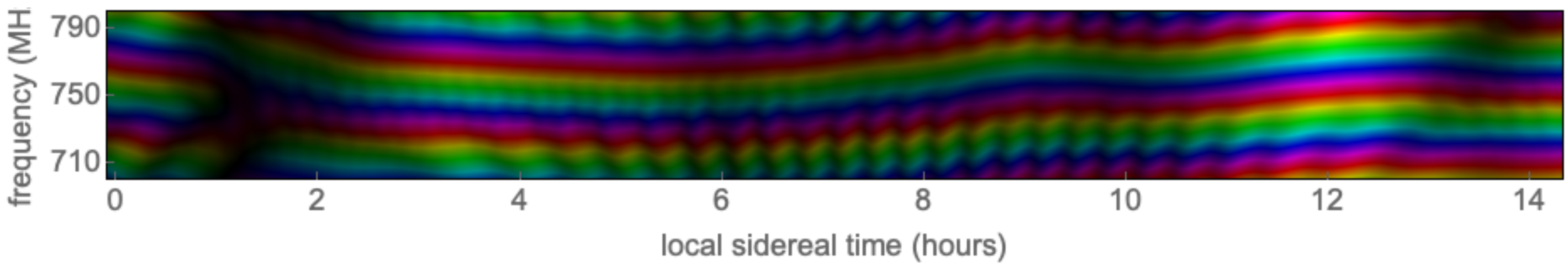




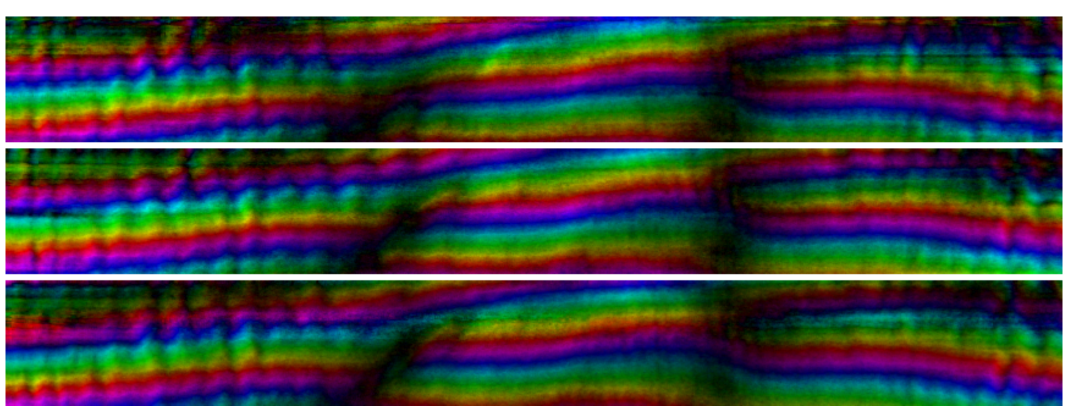
J. Zhang et al, 2020 , arXiv:2007.09351

Tiantai Dish Array- NCP survey

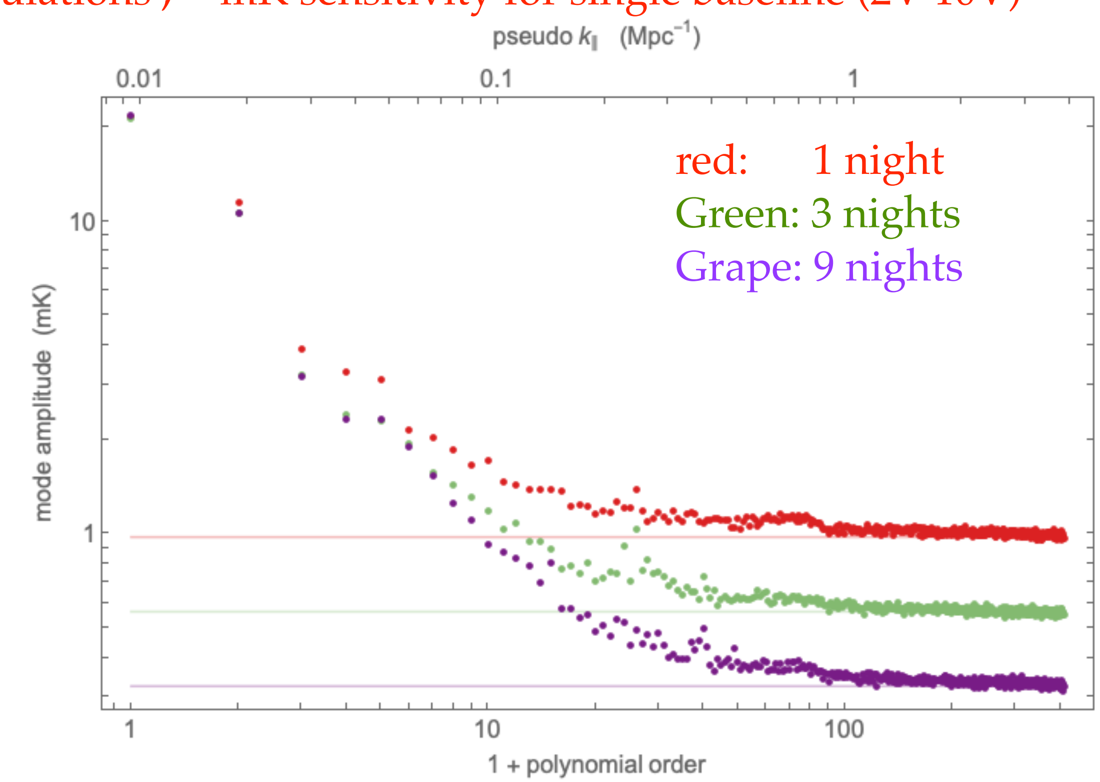




NCP observations - 10 nights averaging , top: data, bottom: simulations , ~ mK sensitivity for single baseline (2V-10V)



3 nearly redundant baselines

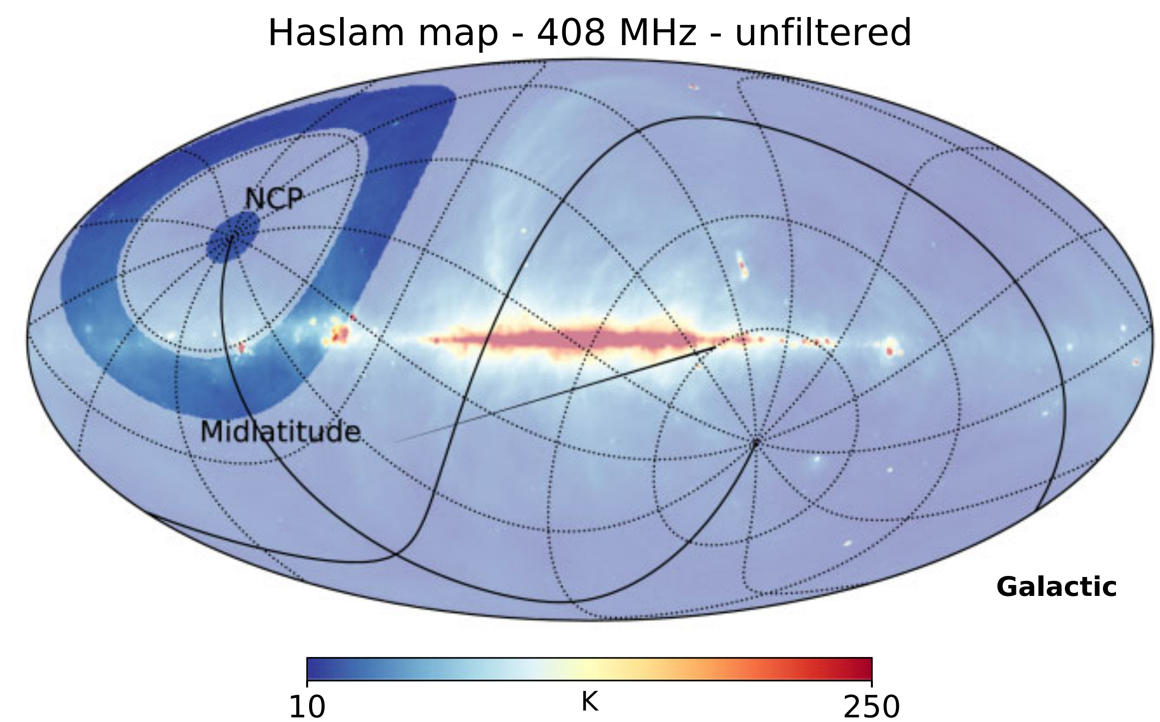


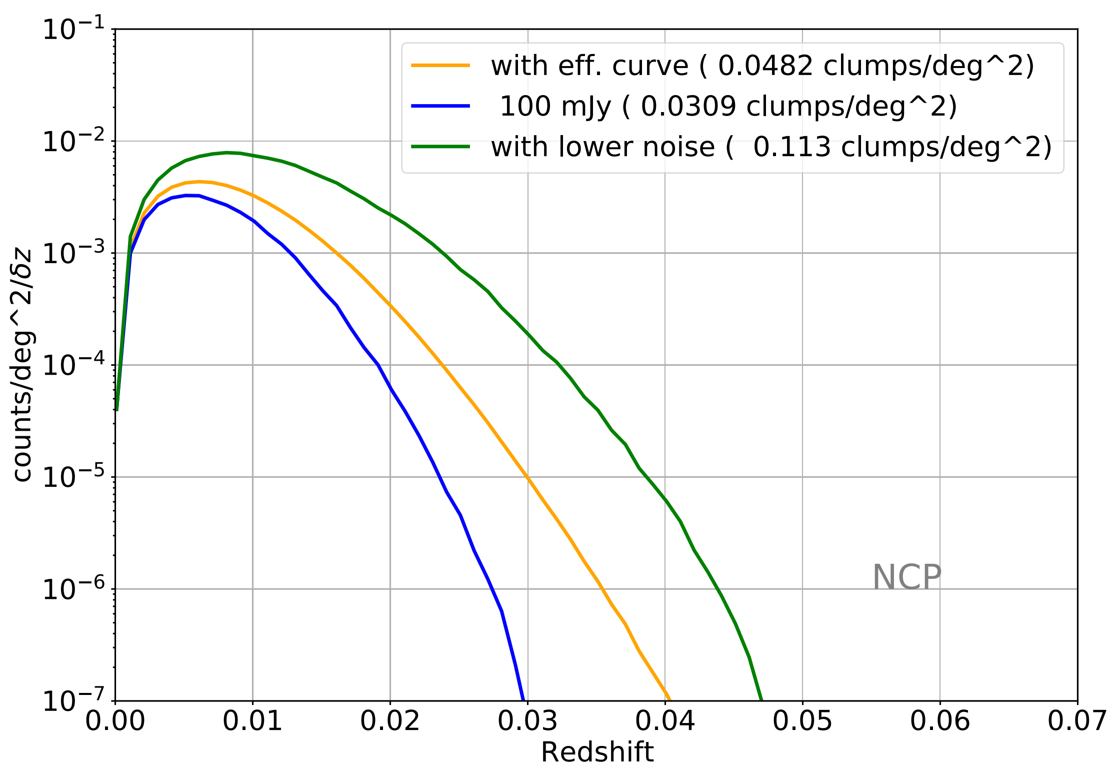
NCP k∥ Legendre mode decomposition

F. Wu et al, MNRAS 2021 , arXiv:2011.05946

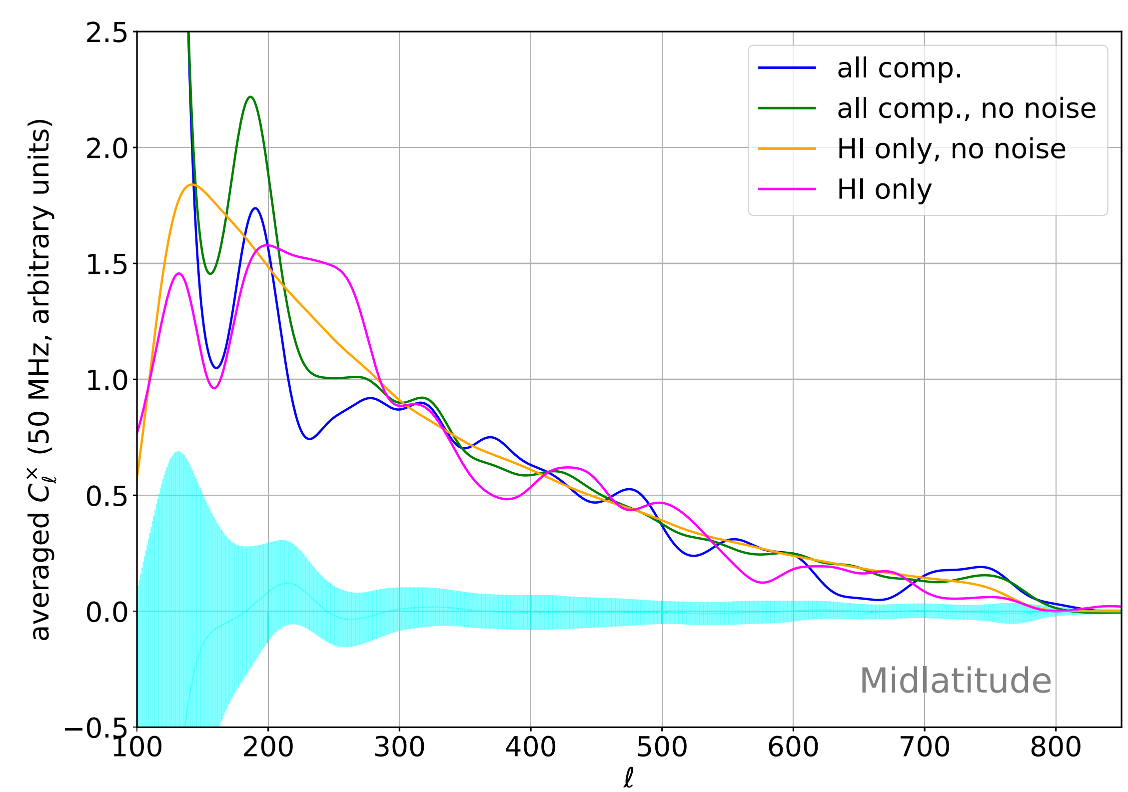
T16D low-z survey

- Plan to change RF filters and LO frequency to with to low-z, rest frame 21cm frequency
- Survey of a mid-latitude band - cross-correlation with SDSS
- Deep survey of NCP - cross-correlation with NCCS catalog
- Survey duration : about a year
- Spectroscopic survey of NCCS being finalised with WIYN telescope





Direct HI clump detection (NCP)

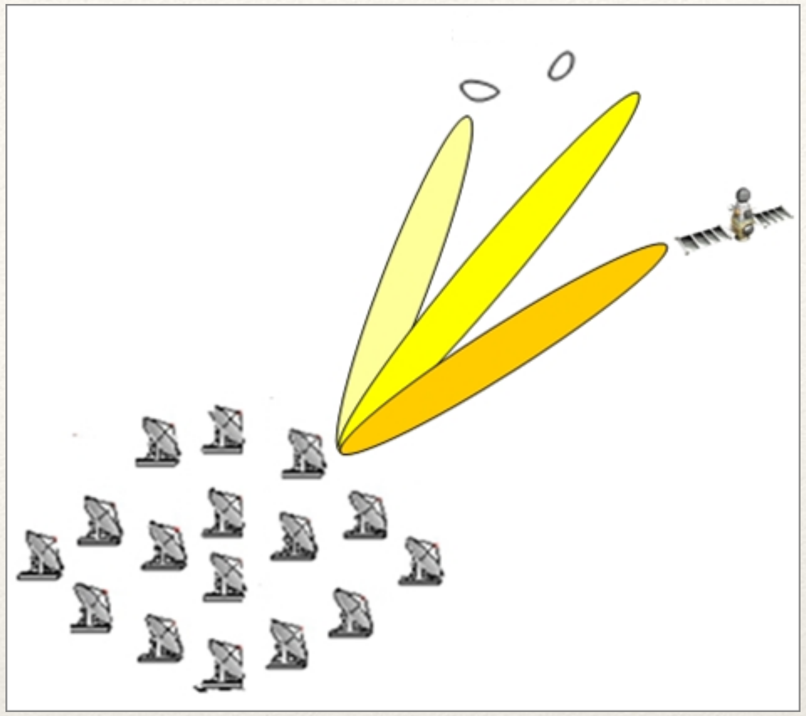


HI x optical (SDSS) cross-correlation (forecasts)

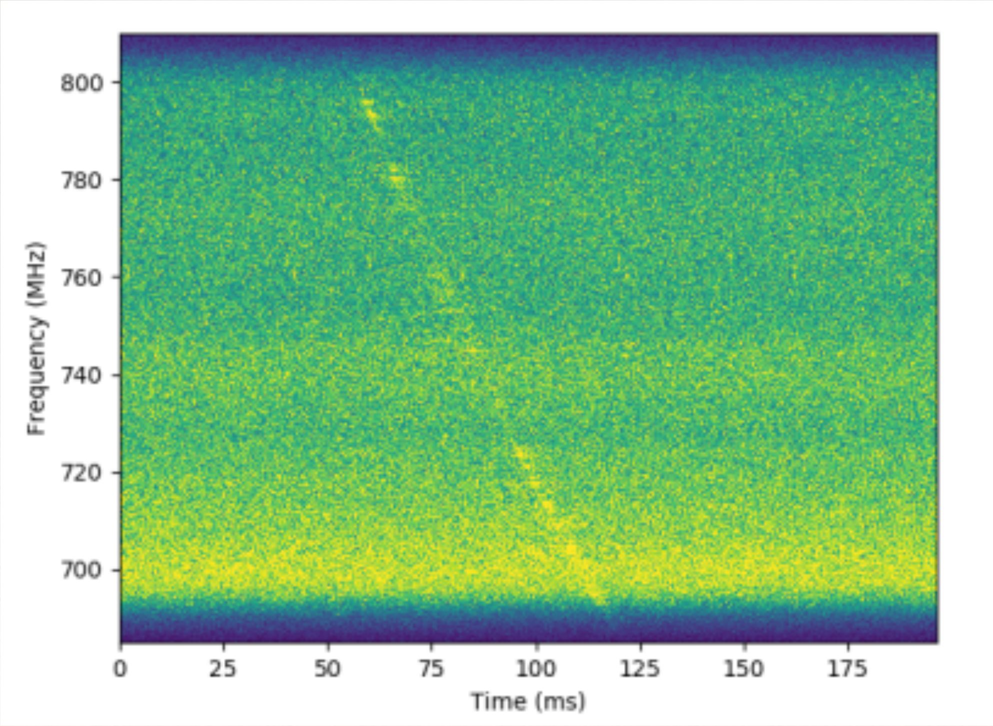
O. Perdereau et al, MNRAS 2022 , arXiv:2205.06086

Tianlai FRB backends

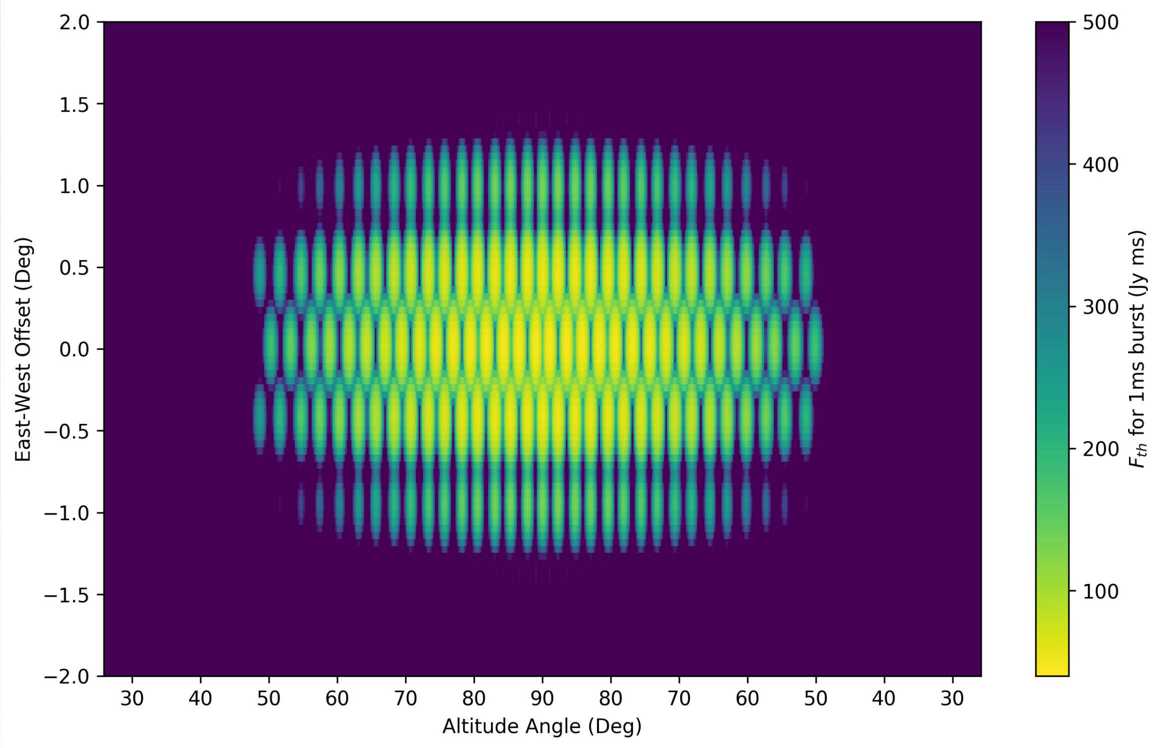
- More than 500 FRB's already detected by CHIME
  CHIME FRB catalog, arXiv:2106.04352
- 32-channel FRB backend for dish array
  2 snap2 boards, each with 16 RF input ports, GPU de-dispersion, ***16 beams, 0.1 ms time resolution***
- 192-channel FRB backend for cylinder array
  24 K7 boards, each with 8 RF input ports, 24 GPU for beam forming, 12 GPU's for de-dispersion, ***96 beams, 0.1 ms time resolution*** (**single polarisation** only currently)



16 beams CasA transit

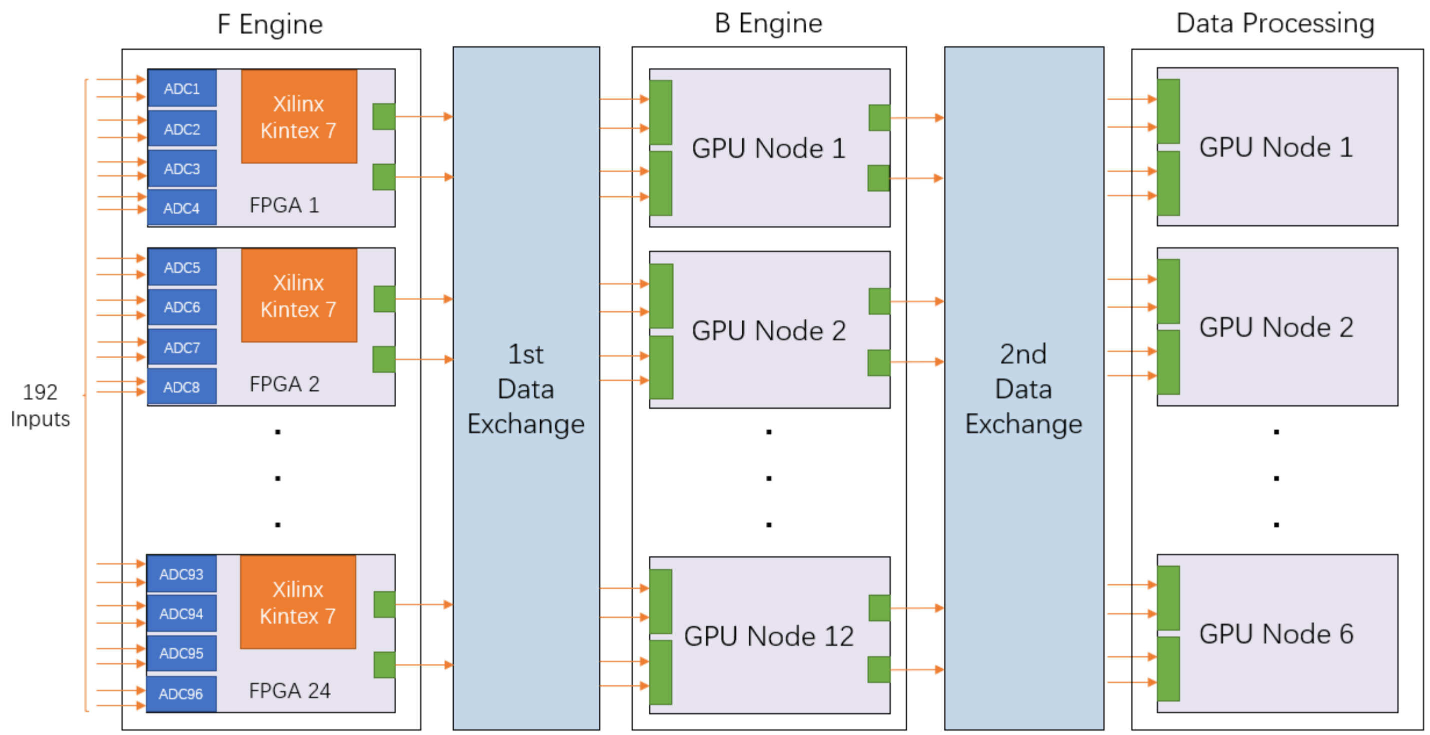


Pulsar B0329+24



96 beams sensitivity map (cylinder)

Tianlai Cylinder FRB backends



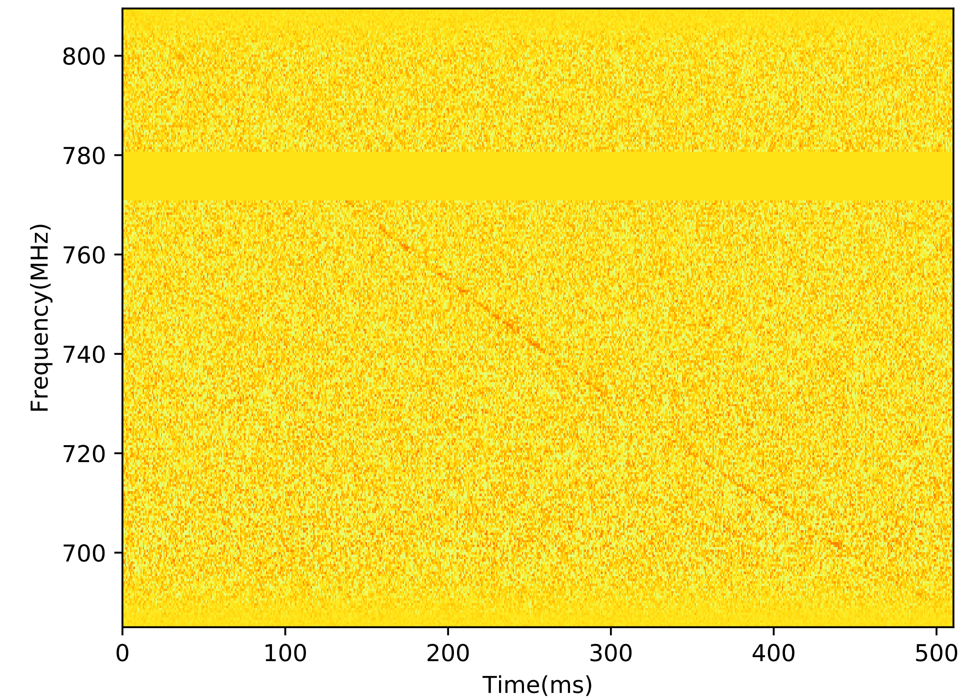


Figure 17. The raw waterfall plot of beam 41 for FRB 20220414A.

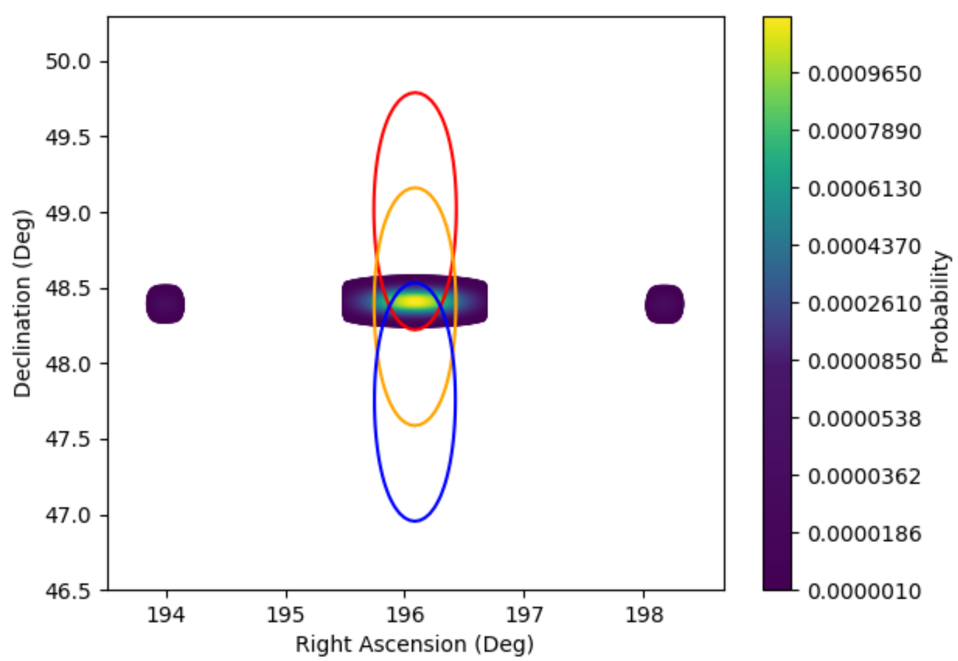
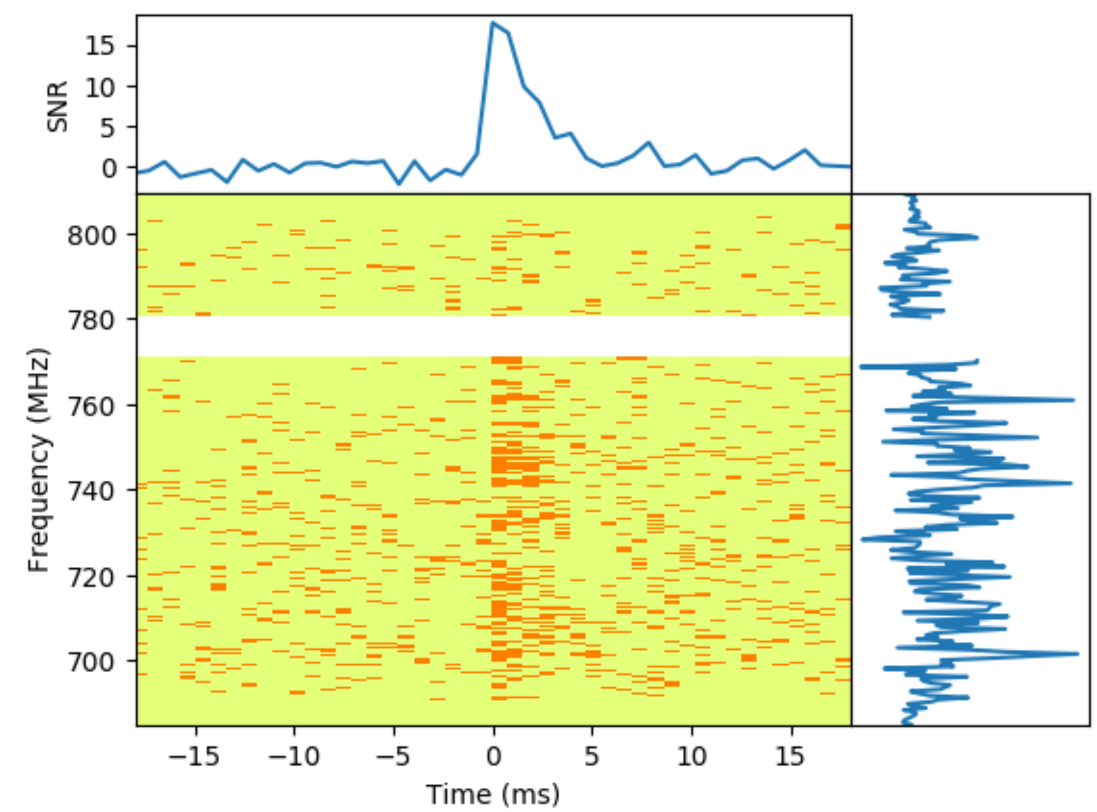


Figure 19. The FRB 20220414A localisation probability. The red, orange and blue circles labels the -3 dB gain range of beam 40, 41



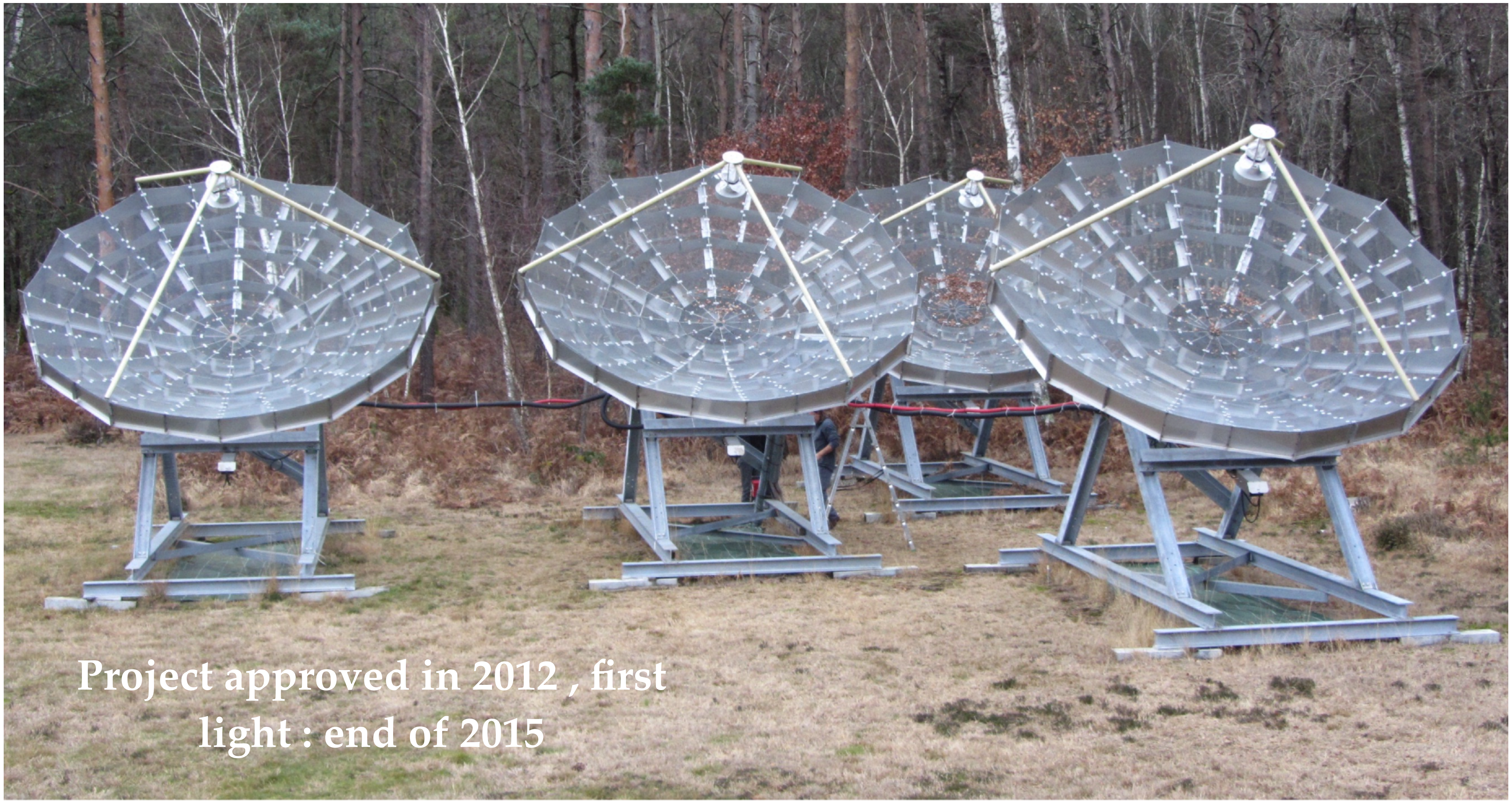
Z. Yu et al, 2024 (submitted)

FRB discovered during the commissioning

PAON4 and IDROGEN

- PAON4 : Paraboles A l'Observatoire de Nançay - A 4 dish transit interferometer
- IDROGEN : Digitiser/processing boards (F-engine)with White Rabbit clock synchronisation technology

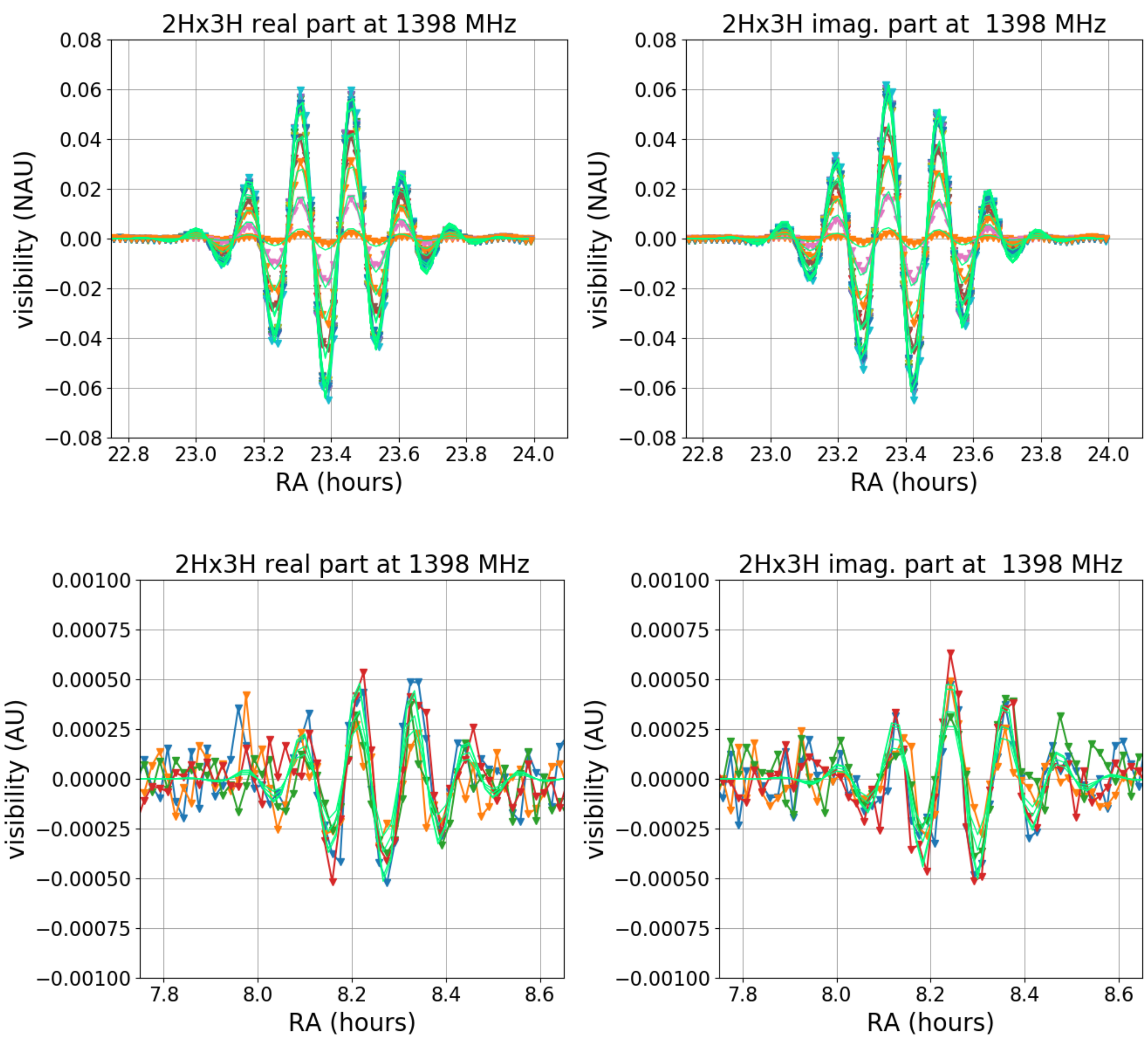
PAON4 @Nançay, (200 km south of Paris)



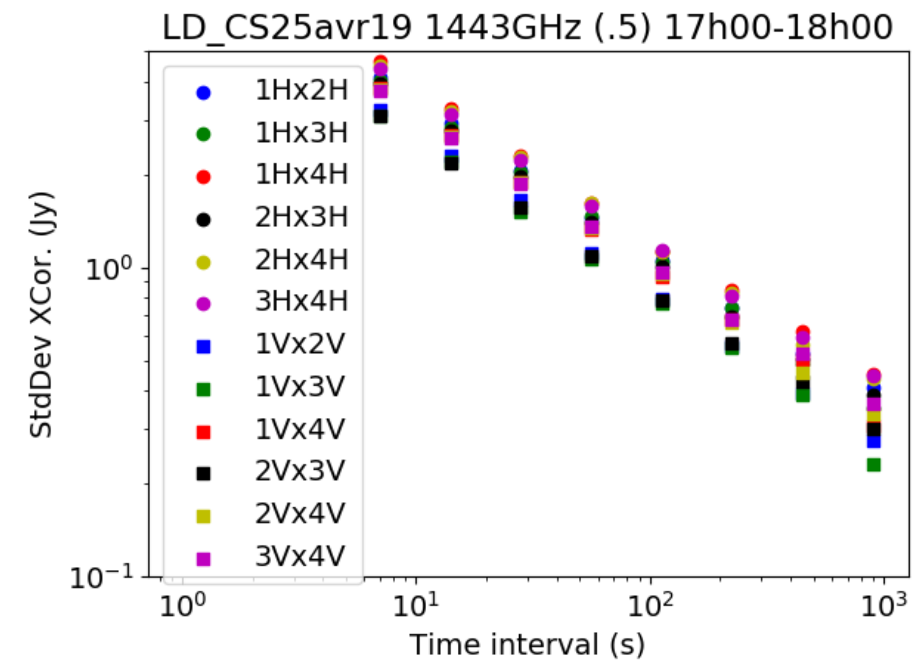
4 x 5m dishes, in compact transit interferometer configuration
L-band (~ 1250-1500 MHz → 1275 - 1475 MHz)

Serves as the qualification instrument for the IDROGEN board - new generation digitiser - F-engine board using WhiteRabbit for clock synchronisation - being deployed on PAON4

PAON4 : some results from 2018-2019 observations/analysis



CasA transits (top) , 3C196 (bottom) - PAON4 observations (different declinations) - compared with expected signals



Noise level evolution with integration time (cross-correlations)

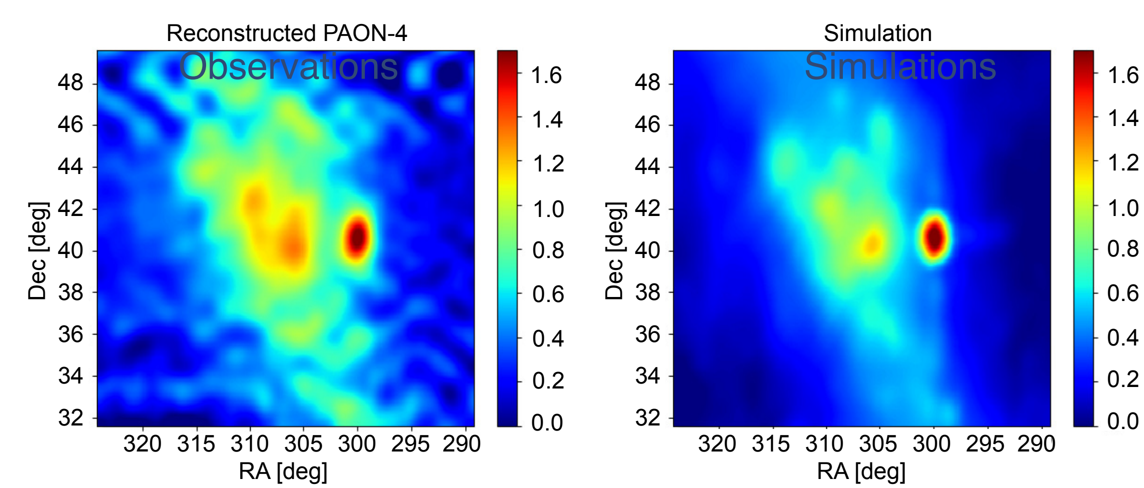


Figure 16. Example of a reconstructed map in a ~ 35° × 18° region around Cyg A, covering the area (32° < δ < 50°) in declination and (290° < α < 325°) in right ascension, from November 2016 data (left). Right panel shows the simulated map.(Huang 2019)

Reconstructed and simulated PAON4 maps

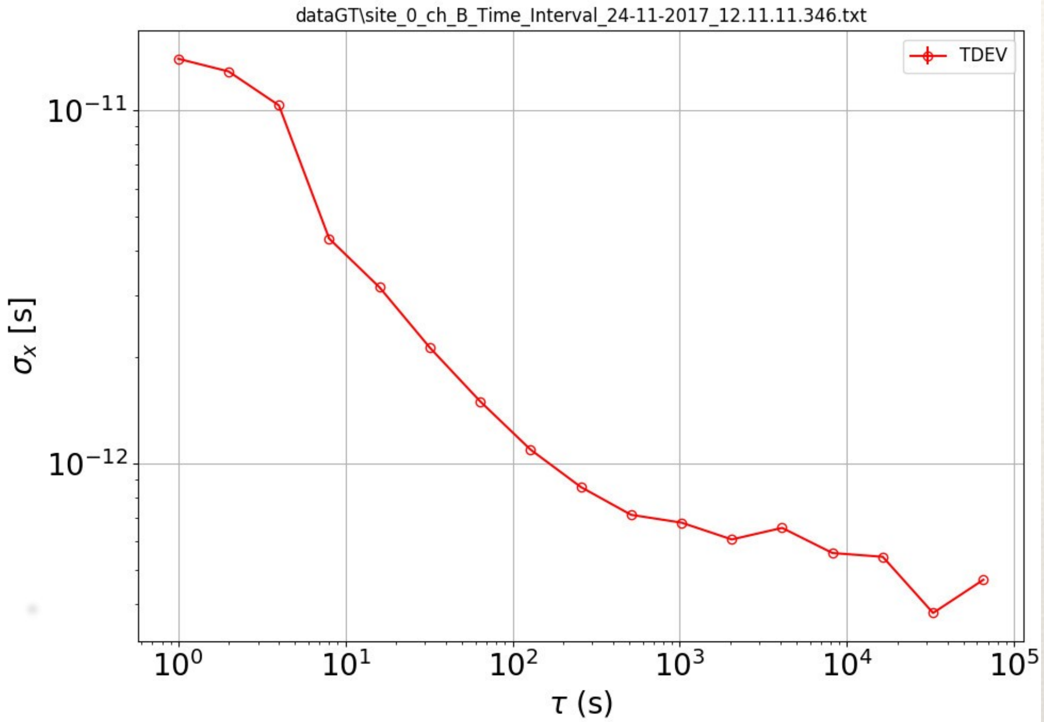
Geometry & Phase calibration using GPS, Galileo & Beidou satellite

R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

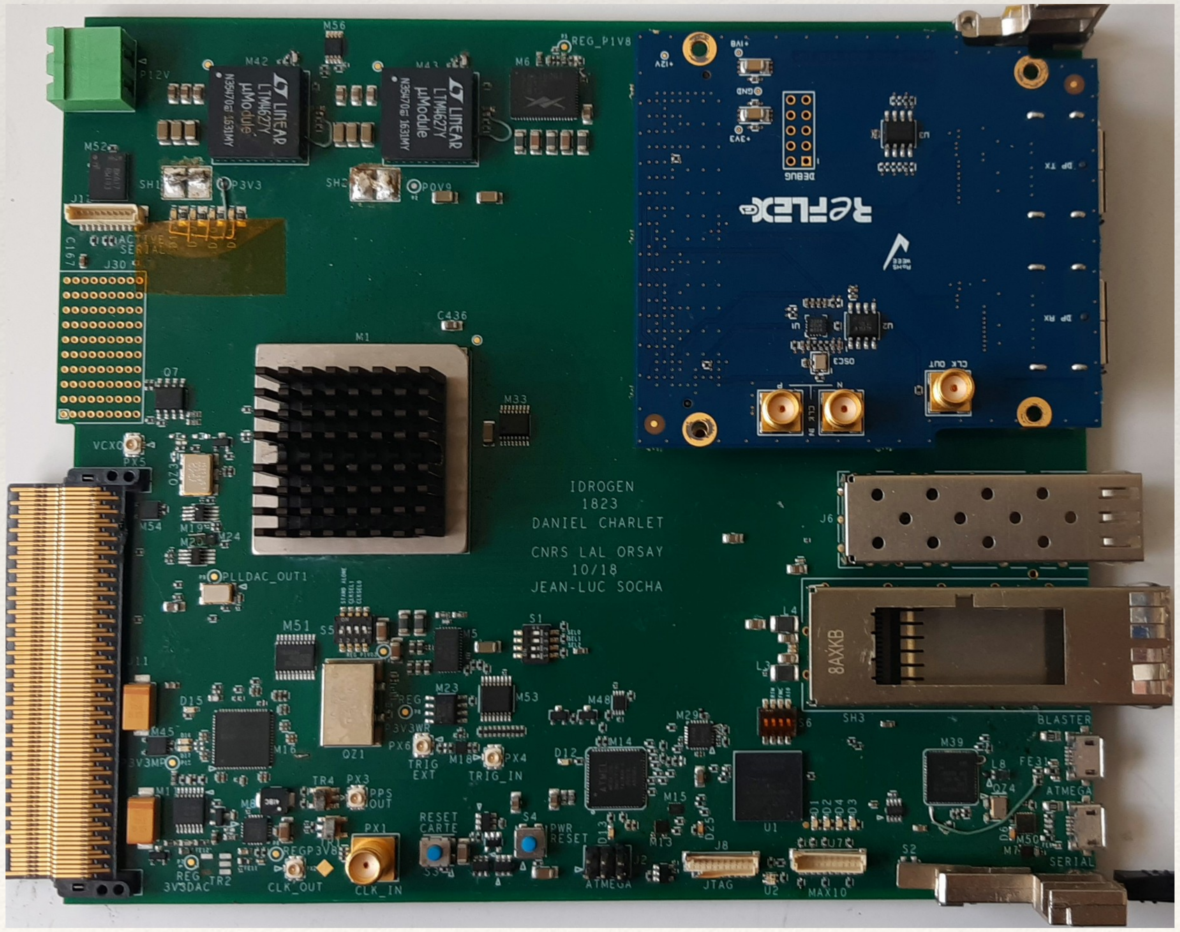
IDROGEN - White Rabbit direct sampling at the antenna

D. Charlet (LAL) , C. Viou (Nançay)

- Direct sampling after the LNA + filters (no mixer)
- Up to 500 MHz bandwidth
- designed to be put near the antennae
- optical data output & control / synchronisation
- White Rabbit technology for clock synchronisation through (optical) ethernet



- In collaboration with SYRTE
  - Observatoire de Paris
  - Time-Frequency laboratory
- 400 fs after 1000 s and 1 km fibre



New analog electronic - IDROGEN boards and optimised FX software correlator will be deployed on PAON4 in 2024

Where do we stand now

✔

Several years of observations with Tianlai dish and cylinder pathfinders
Good understanding of the instrument operation, specially in transit mode
Progress on RFI cleaning, calibration, map making
Encouraging results with the NCP T16D analysis

✘

Feed couplings in cylinder is an issue, but also in dishes
Some difficulties to deal with side lobes or ground pickup
Pollution due to the sun through side lobes during daytime (dishes)
Day time sun signal in cylinders

What's next

Calibration process refinement
More thorough assessment of the array stability
Further investigate feed / dish cross-couplings
Tianlai low-z NCP survey
WIYN spectroscopic survey of NCCS
Full deployment and operation of FRB backends
Cylinder outriggers being built
and two additional dishes being added