3D Intensity Mapping & 21 cm cosmology

Réza Ansari

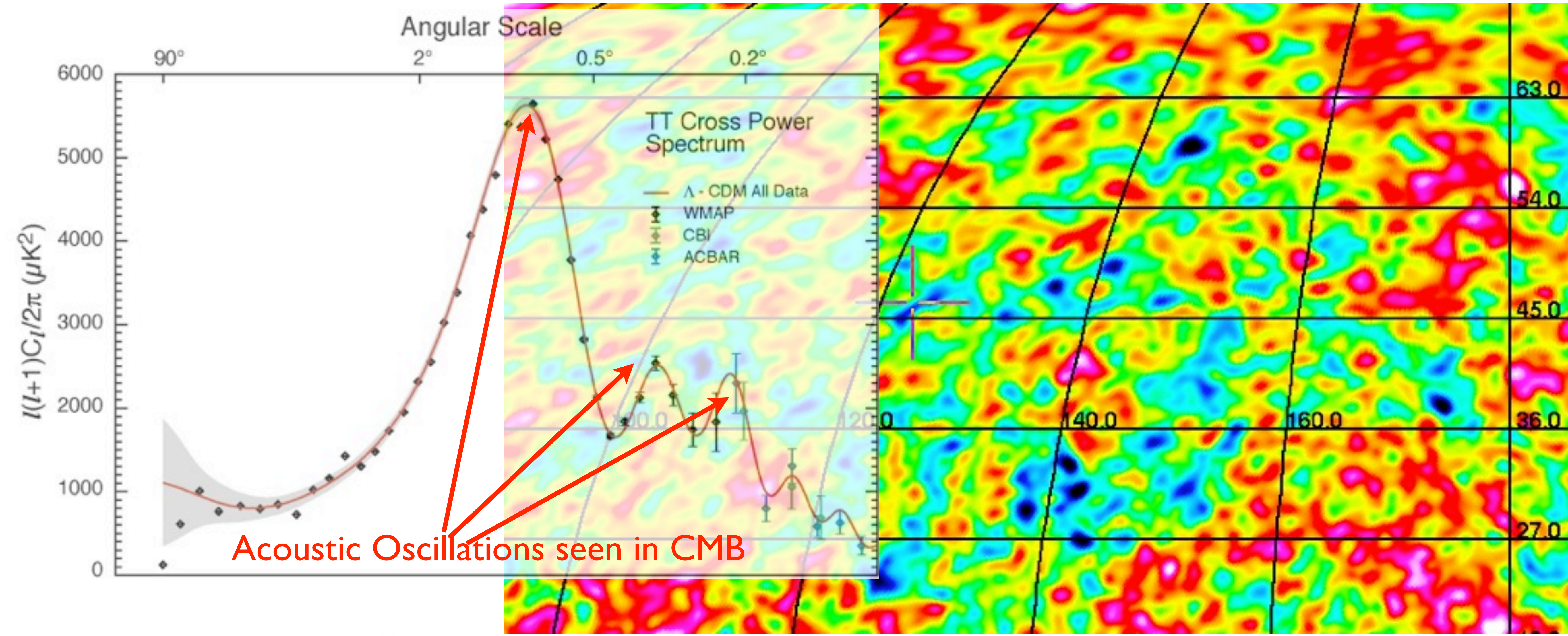
SKA-LOFAR radio days
IAP (Paris) February 2014

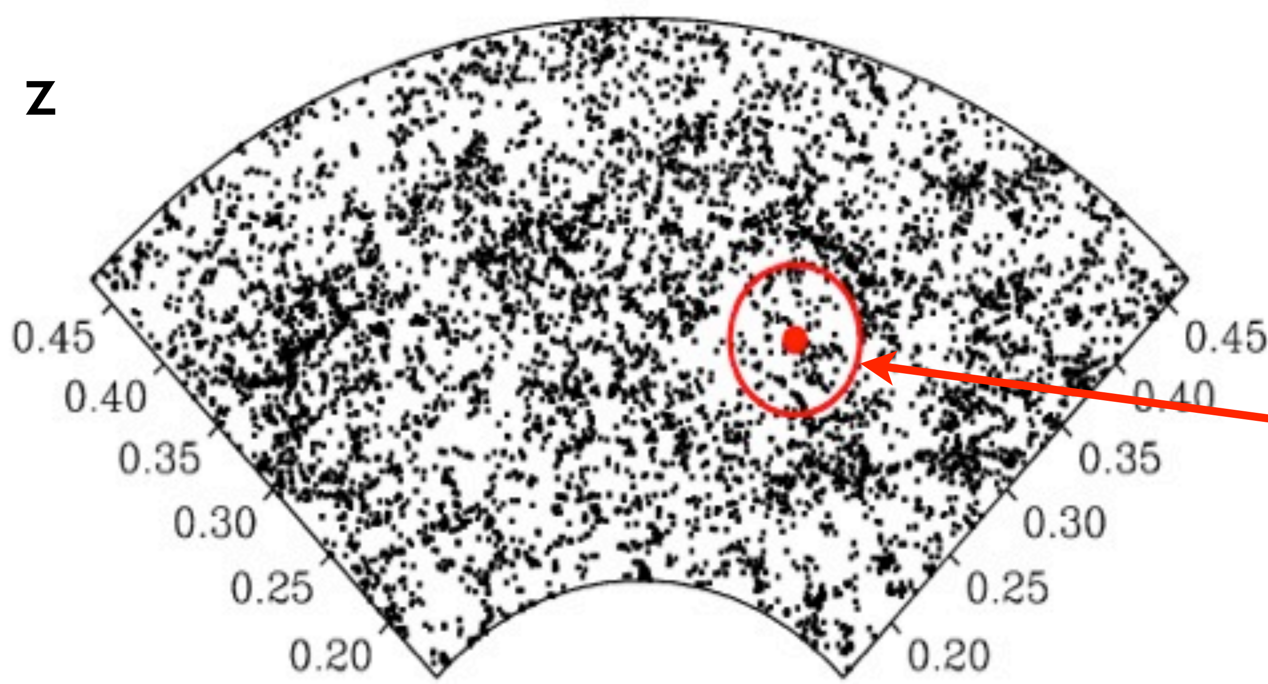
- Dark energy & BAO at 21 cm
  - DE and BAO
  - Galaxies at 21 cm at cosmological distances
- Intensity mapping
  - 3D mapping of 21 cm emission
  - Sensitivity to P(k) measurement
  - Foregrounds: extracting cosmological signals
- BAORadio: intensity mapping R&D in France
- CHIME , TIANLAI ... SKA (AA-mid)

Dark energy & BAO

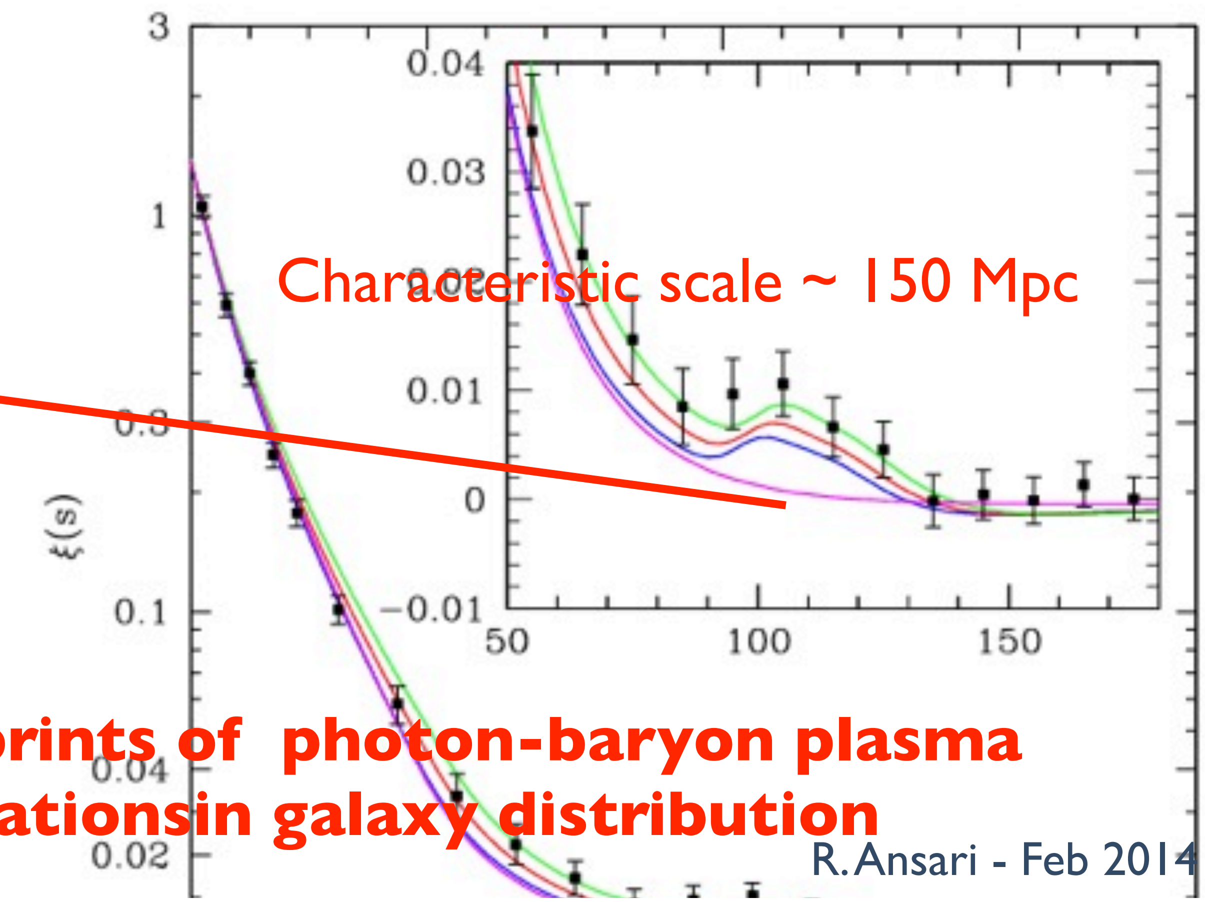
BAO :Baryon Acoustic Oscillations

- Imprints left by the baryon-photon plasma oscillations prior to decoupling, on dark matter and visible matter (galaxies ...) during structure formation after decoupling
- Wiggles in the distribution of matter, dominated by dark matter (and also visible matter / galaxies) : A preferential length scale (~ 150 Mpc) in the matter clustering
- Standard ruler type cosmological probe with a measurement @ z ~ 1100 (CMB anisotropies)



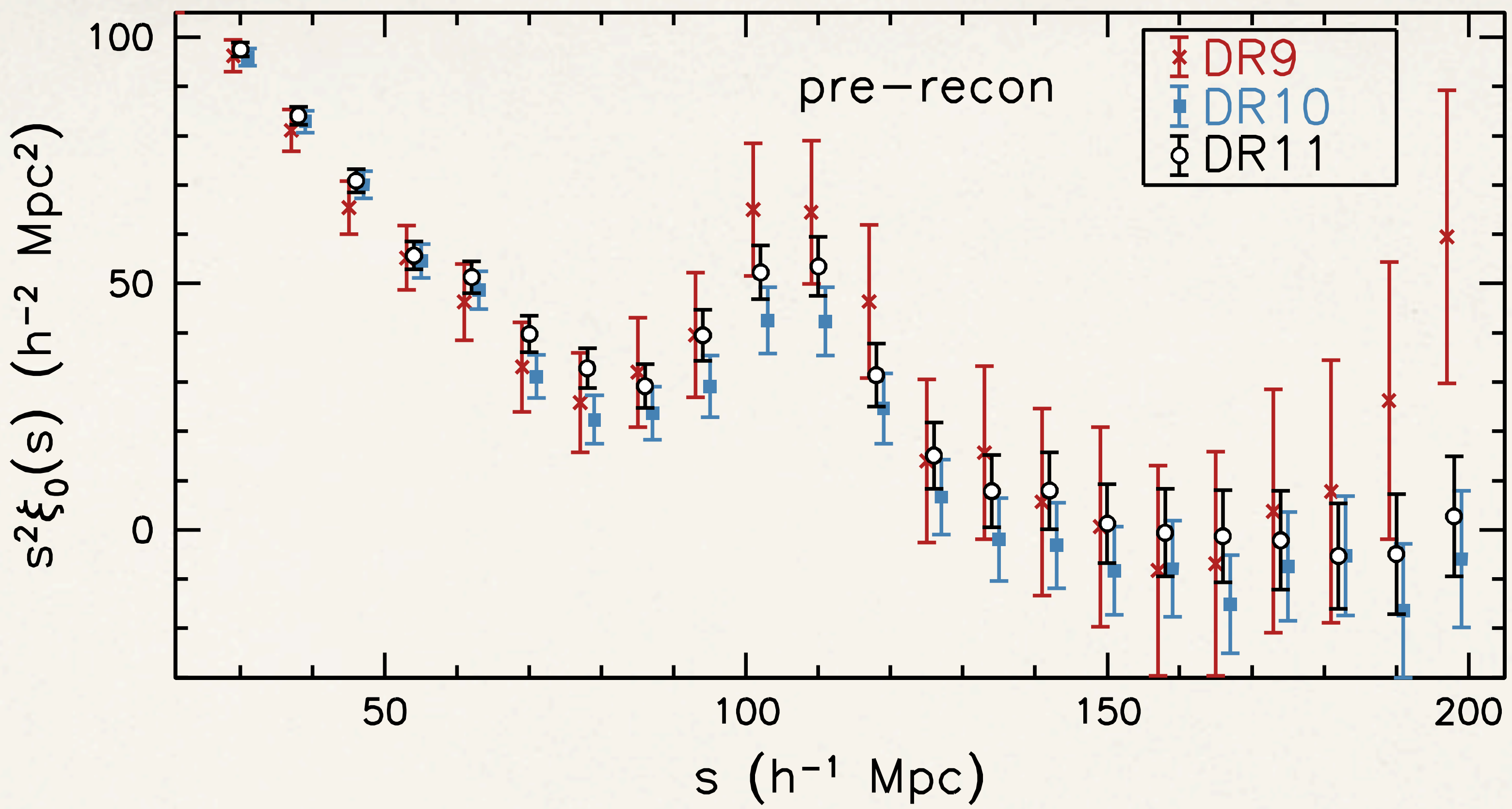


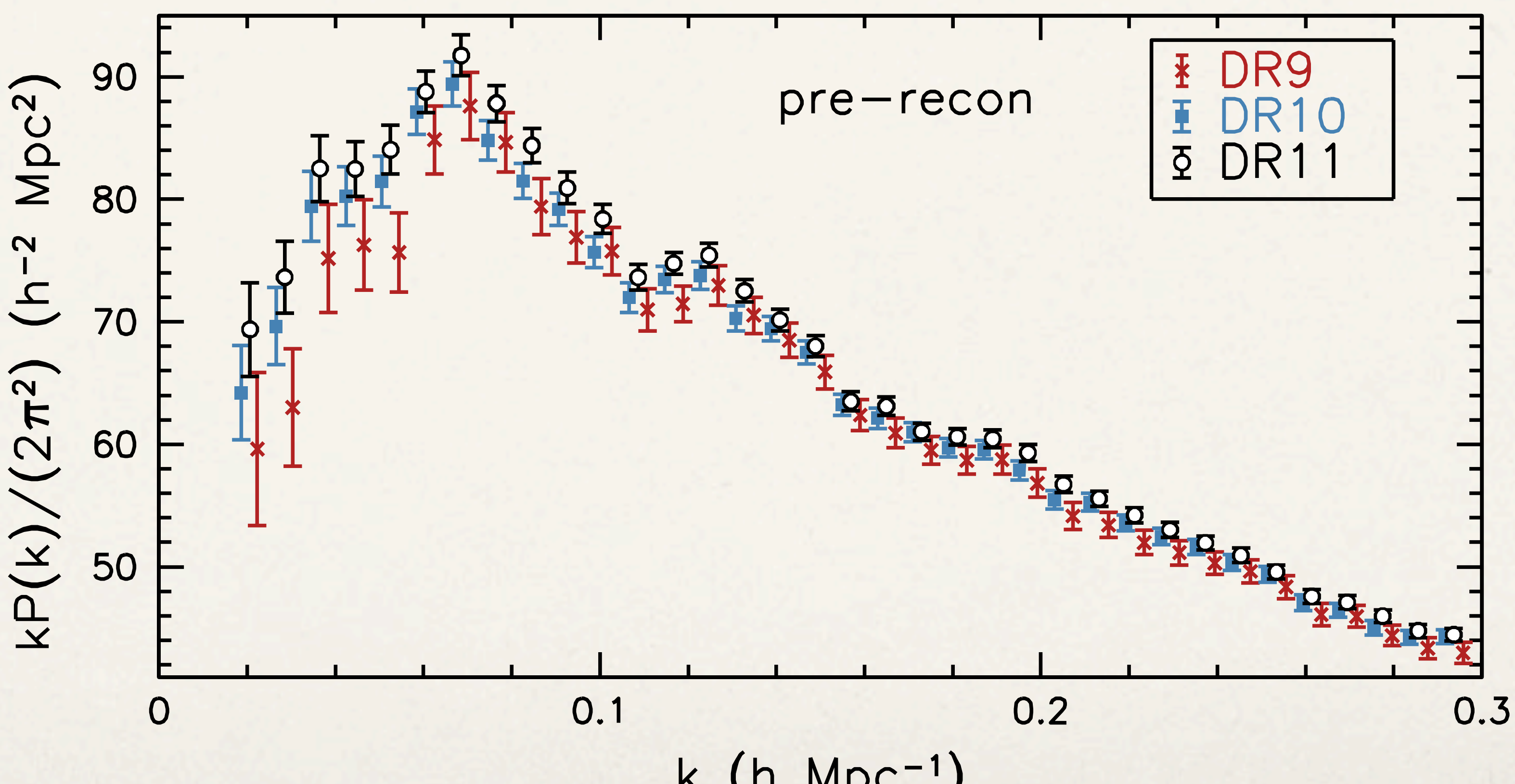
Galaxy distribution
(z, angle (α,δ)) plane



BAO: Imprints of photon-baryon plasma oscillationsin galaxy distribution

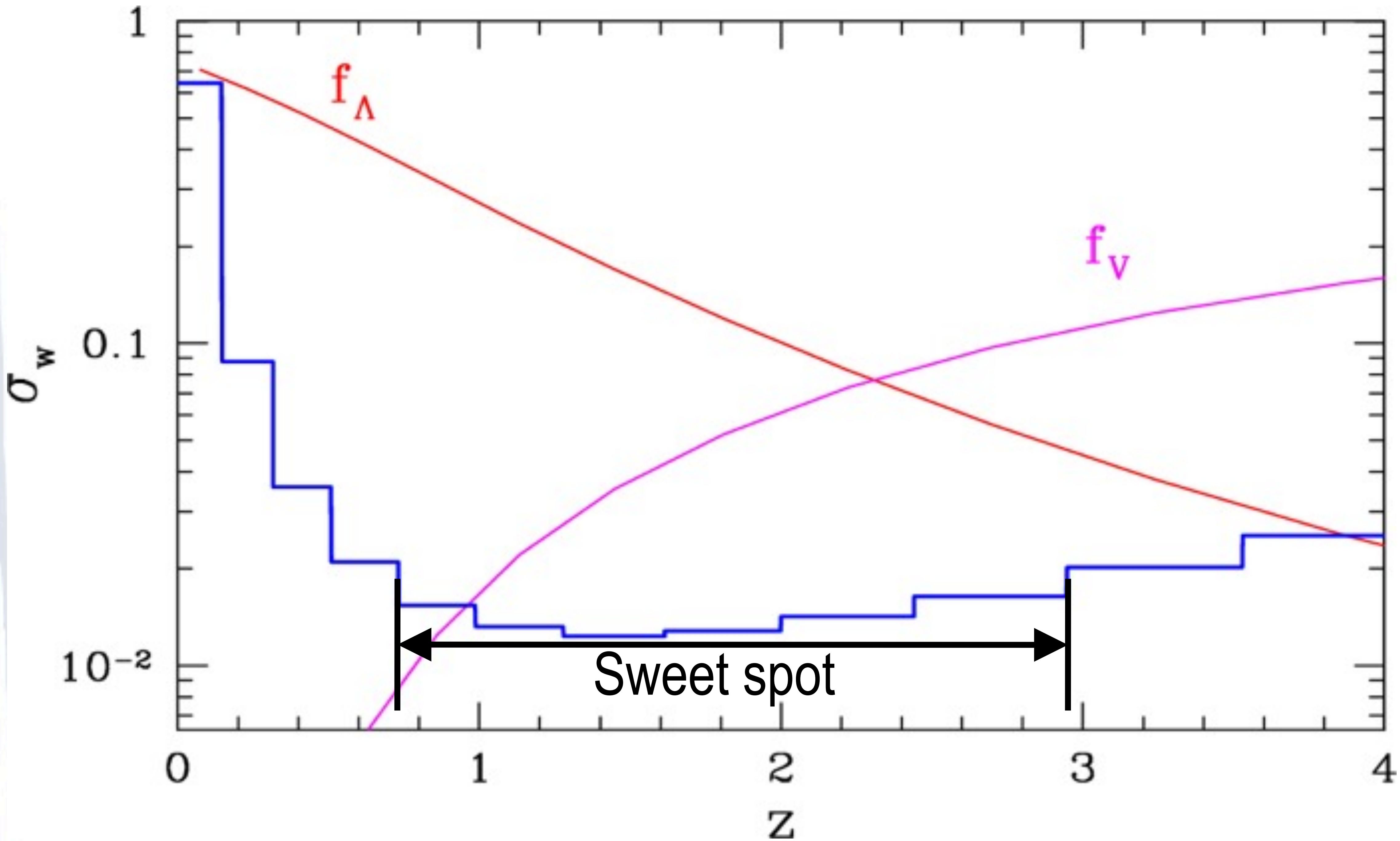
z ~ 0.57 (BOSS) ➠ z ~ 0.5 … 3 in future surveys





SDSS-III BOSS DR9/10/11 galaxy power spectrum & correlation function
Anderson et al, arXiv 1312.4877

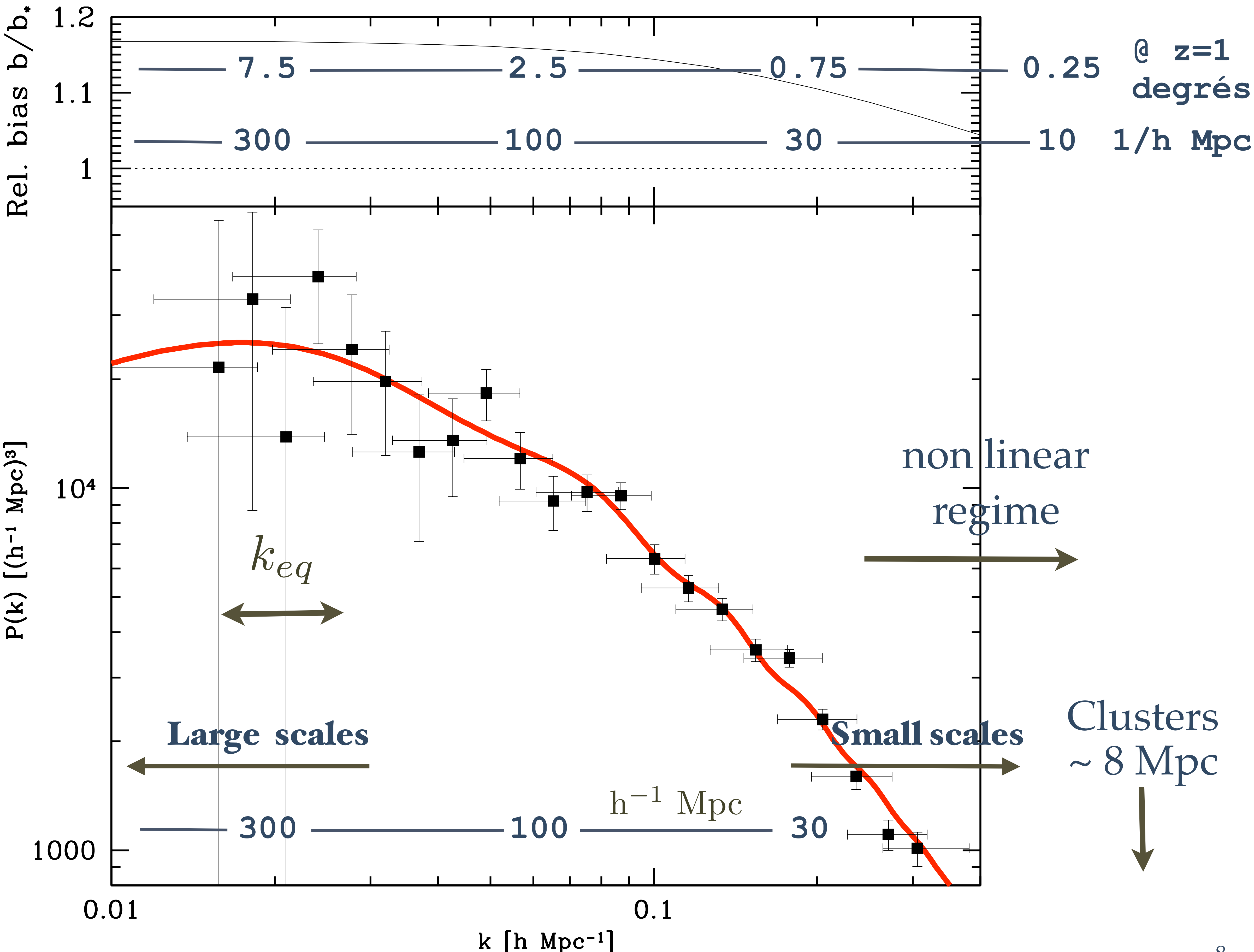
Baryon Acoustic Oscillations



Slide borrowed from A. Stebbins

SDSS - M. Tegmark et al.

ApJ , astro-ph/0301072**5**



R. Ansari - June 2012

BAO in radio

- As in optical surveys :
  - Identification of HI (21 cm) emission sources, determination of the angular position and redshift - Computation of the two point correlation function or the P(k) spectrum, using the catalogue of identified objets.
- Or similar to CMB observations :
  - 3D mapping of the HI (21 cm) emission - T21(α,δ,z) - Radio foreground subtraction, determination of the power spectrum P(k,z) on the 21 cm sky temperature data cubes.

LSS / BAO in radio with galaxies

$$S_{21}^{Jy} \simeq 0.021\,10^{-6}\ \text{Jy}\ \frac{M_{H_I}}{M_\odot} \times \left(\frac{1\text{Mpc}}{D_L}\right)^2 \times \frac{200\,\text{km/s}}{\sigma_v}\ (1+z)$$

$$S_{lim} = \frac{2\,k\,T_{sys}}{A\,\sqrt{2t_{integ}\,\Delta\nu}}$$

S_{lim} en μJy pour $t_{integ} = 86400$ s , $\Delta\nu = 1$ MHz

A (m^2)	Tsys (K)	Slim
5000	50	66
5000	25	33
100000	50	3.5
100000	25	1.7

S_{21} en μJy pour $M_{H_I} = 10^{10} M_\odot$

z	S21 (µJy)
0.25	175
0.50	40
1.0	9.6
1.5	3.5
2.0	2.5

> 100 000 m^2 → Need SKA !

21 cm cosmological observations
A comparison with optical observations

- 21 cm line is ± is the only spectral feature around 1 GHz ➡ spectro-photometric observations
- Band: ~ 100 MHz … 1500 MHz - ν = f(z) , z: 0 … 10

  1420 MHz @ z=0 , 946 MHz @ z=0.5 , 720 @ z=1 , 284 @ z=5, 129 @ z=10
- Diffraction limited, source confusion:

  700 MHz: D=100 m → ~20′ , D=1km → ~2′ , D=100 km → ~1″ , 2′ → 1 Mpc @ z = 1
- Intensity measurement in optical, amplitude & phase in radio; CCD in optics, but interferometry and spectroscopy in radio
- instrumental noise (read-out noise <5 e) often négligeable in optical, dominant in radio (Tsys~20-50 K)
- low ambient / parasitic light level in optical in good observatories; radio band polluted (RFI) by terrestrial emissions

Intensity mapping & dark energy surveys

BAO with 21 cm intensity mapping
T21(α,δ,z)

- 3D mapping of neutral hydrogen distribution through total 21 cm radio emission (no source detection)
- Needs only a modest angular resolution 10-15 arcmin
- Needs a large instantaneous field of view (FOV) and bandwidth (BW)

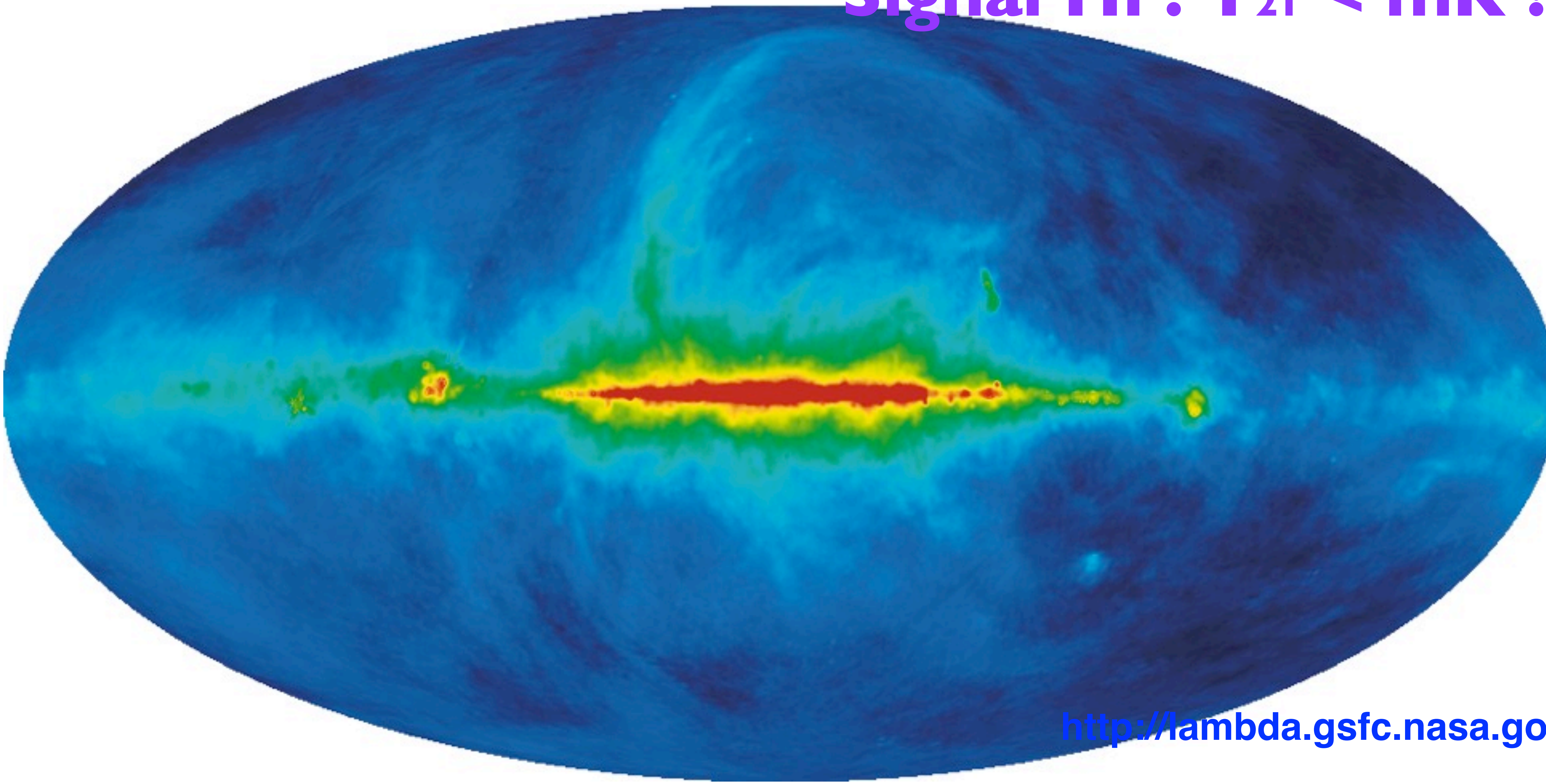
≡ Instrument noise (Tsys)

≡ Foregrounds / radio sources and component separation

- Peterson, Bandura & Pen (2006)
- Chang et al. (2008) arXiv:0709.3672
- Ansari et al (2008) arXiv:0807.3614
- Wyithe, Loeb & Geil (2008) arXiv:0709.2955
- Peterson et al (2009) arXiv:0902.3091
- Ansari et al (2012)

Foregrounds

Signal HI : T_{21} < mK !



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

Temp. T (Ech. Log)

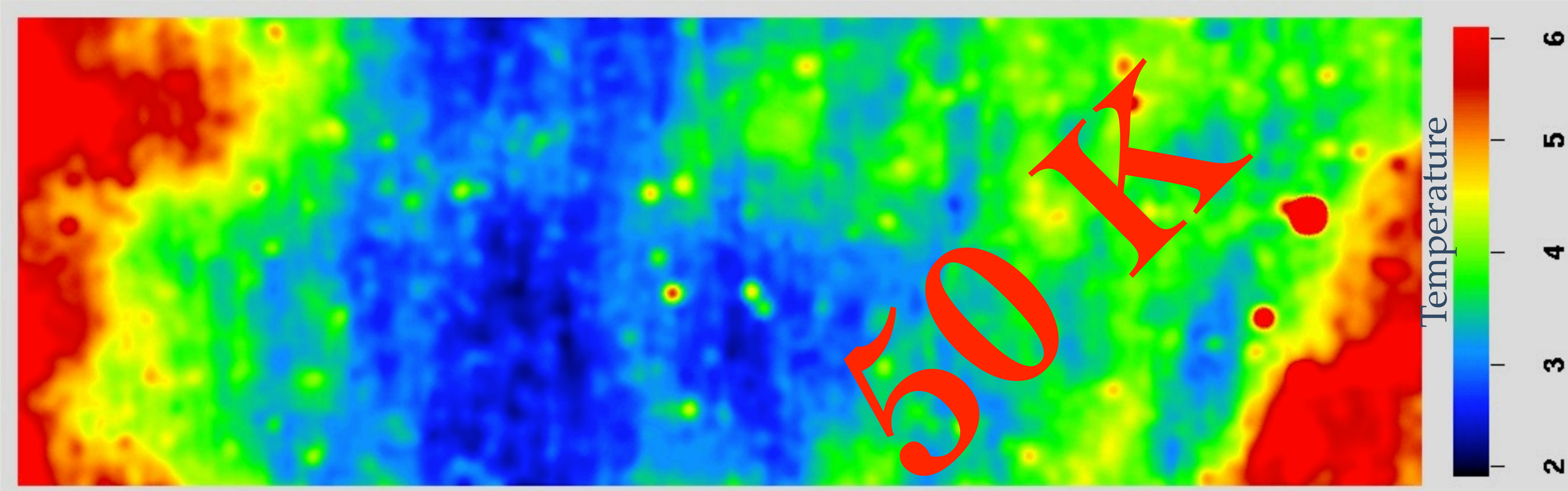
10 K ——— **250 K**

Haslam 408 MHz map (Galactic synchrotron emission)

R. Ansari

Radio foreground (GSM) @ 720 MHz (z=1.) - Kelvin

K



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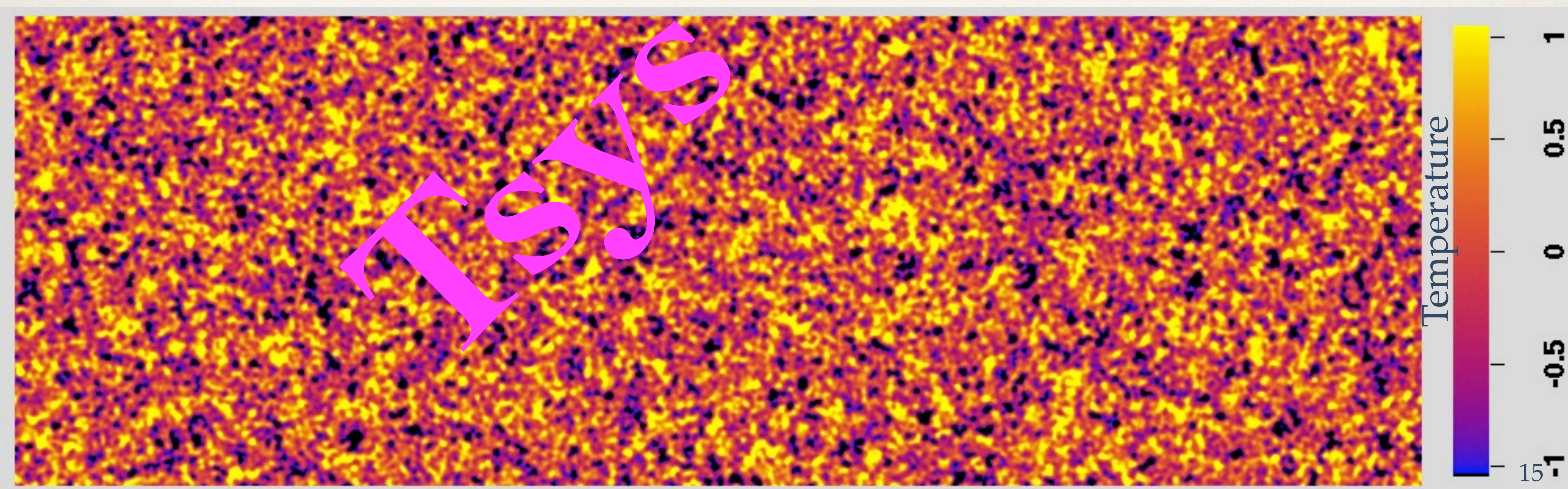
21 cm sky brightness @ 720 MHz (z=1.) - milliKelvin

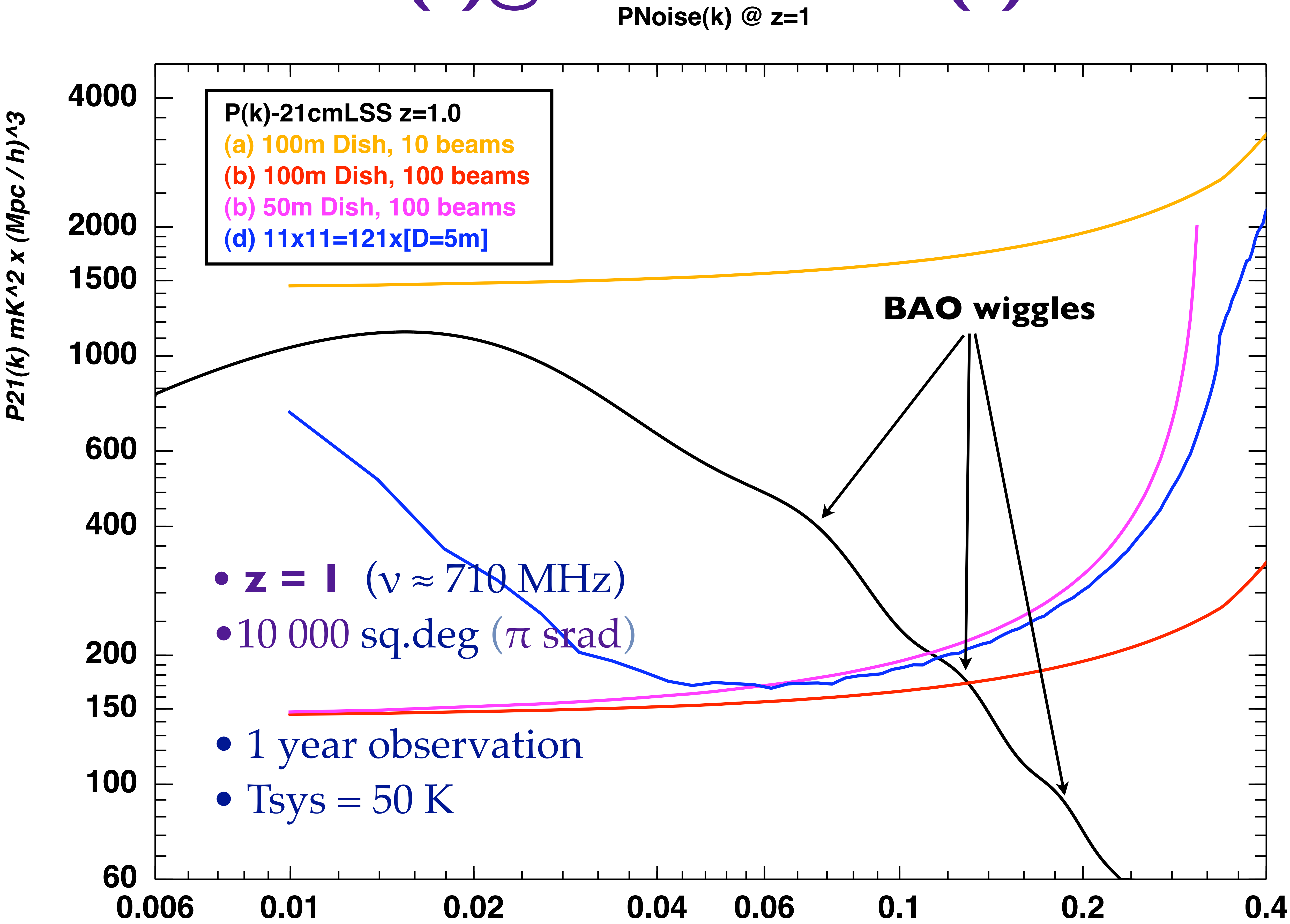
mK



mK sensitivity with Tsys ~ 50-75 K

- Large integration time (10^4-10^5 s) → $\propto 1/\sqrt{(t_{int} \Delta \nu)}$
- Instrument (Tsys, beam …) stability
- multi beam - large FOV radio telescope
- interferometer or FPA / multi feed receivers with single dish

P(k)@21cm - PNoise(k)



Ansari et al., A&A 2012, arXiv:1108.1474

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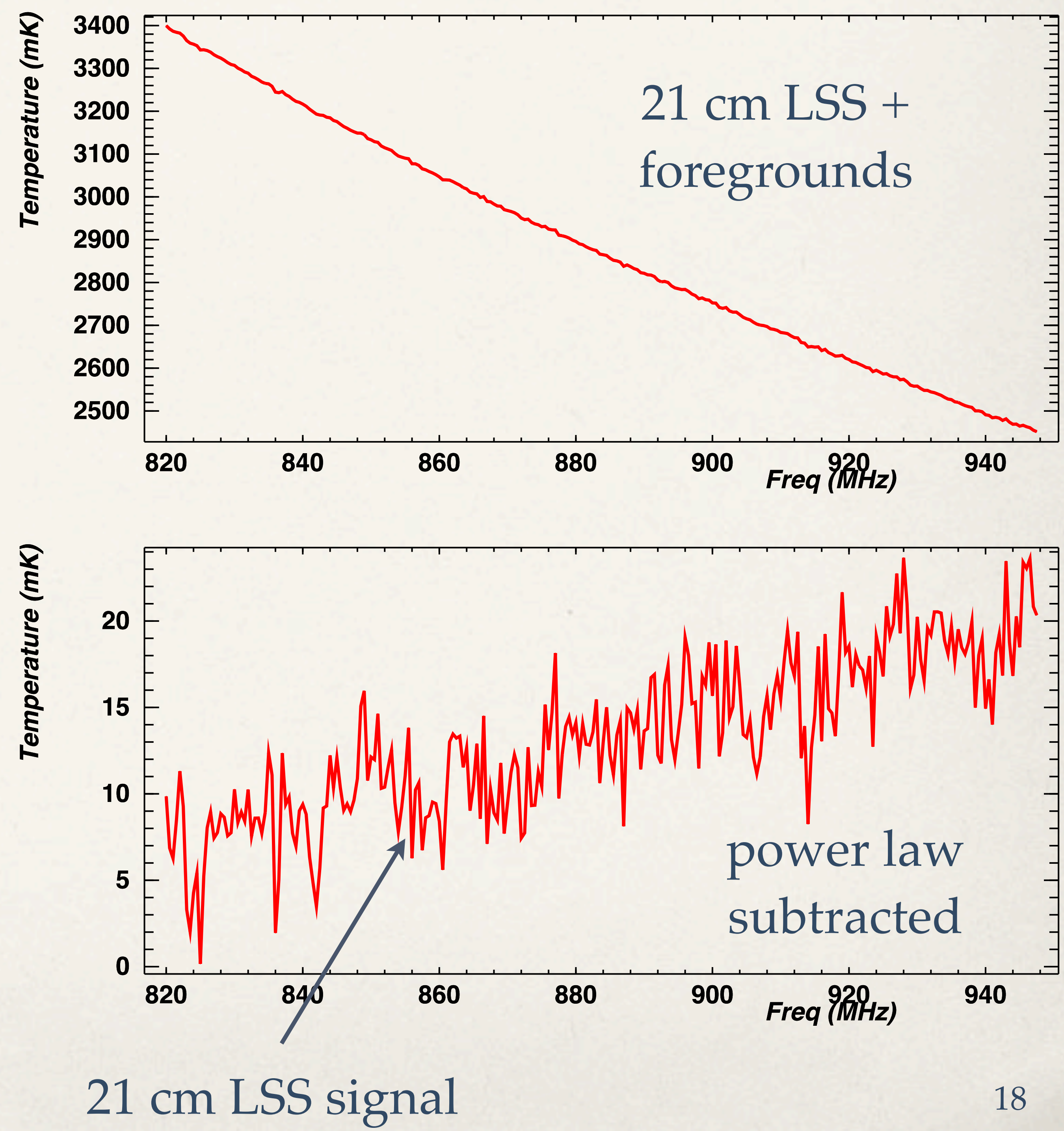
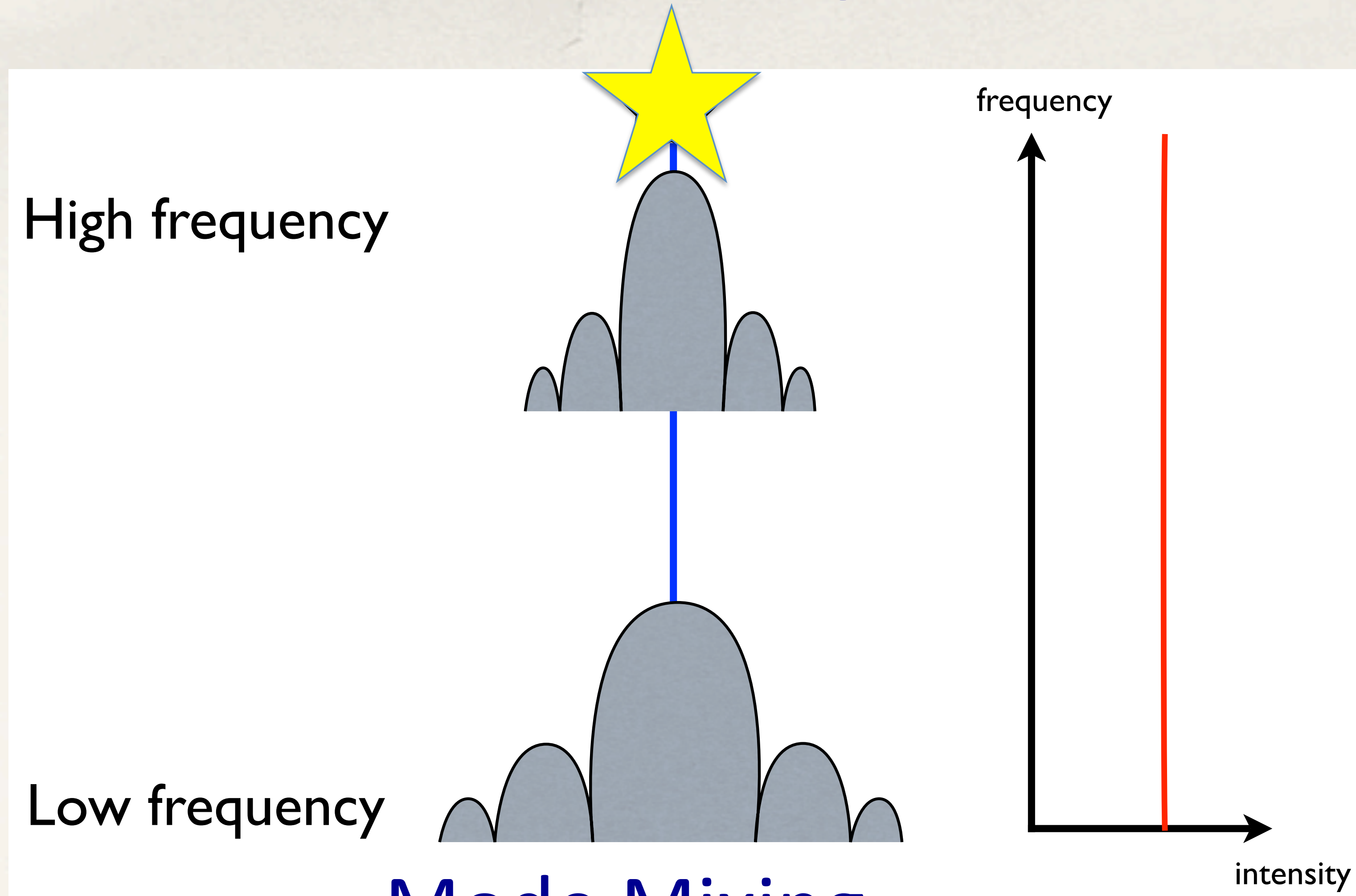
R. Ansari - Sep 2011

Foreground removal

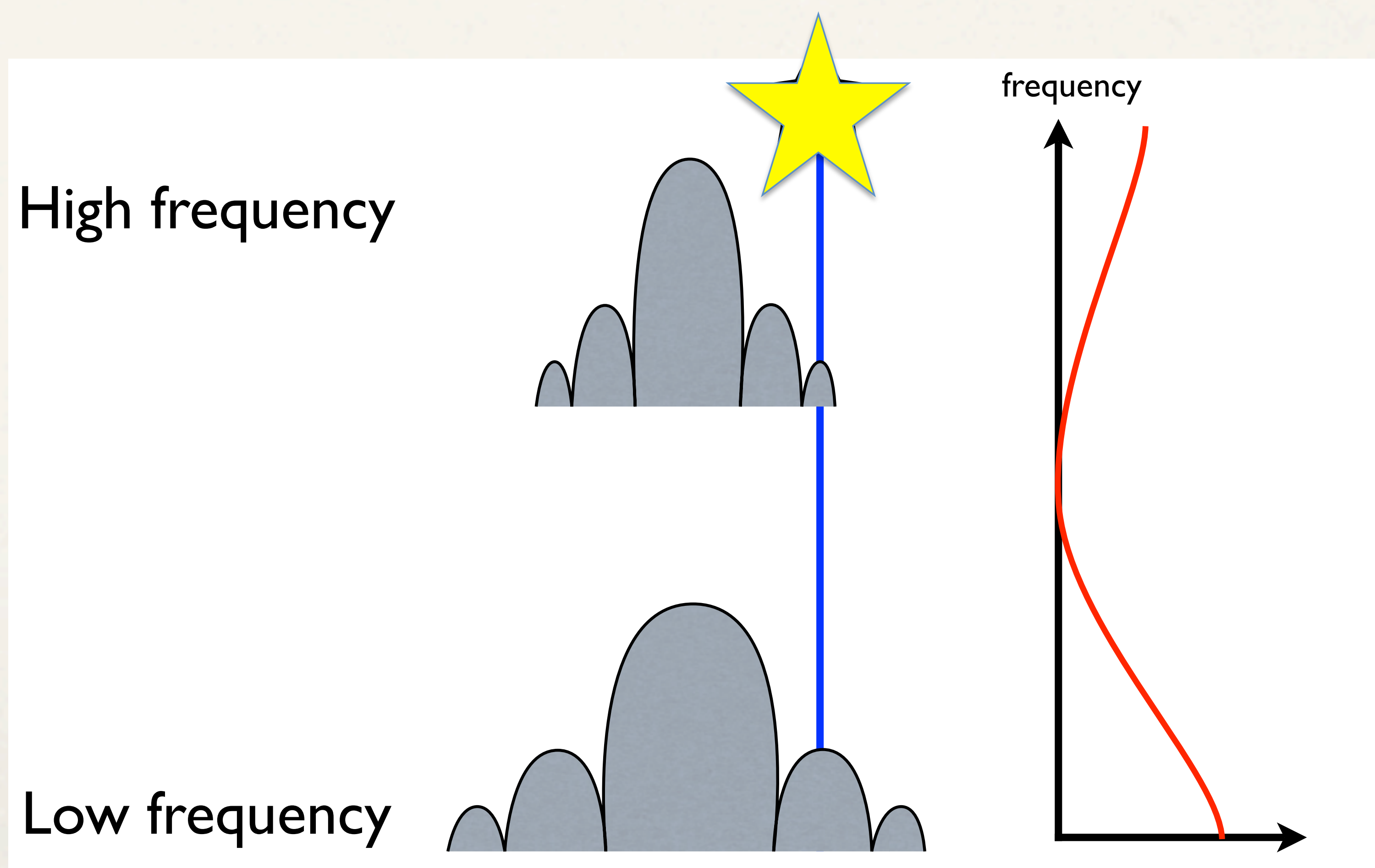
- Exploit frequency smoothness and power law ($\propto \nu^\beta$) behavior of foregrounds (synchrotron/radio sources)
- power law / polynomial / foreground model fit & subtraction
- Mode mixing, bias, error propagation …



Slide by
Kris Sigurdson
UBC



Mode Mixing



Signal-to-Noise Eigenmodes

- Measurement $\mathbf{v}$ is a combination of the sky $\mathbf{a}$ and noise $\mathbf{n}$

$$\mathbf{v} = \mathbf{B}\mathbf{a} + \mathbf{n} \quad (1)$$

- Construct the covariances of the signal and foregrounds

$$\mathbf{S} = \mathbf{B}\left\langle \mathbf{a}_s \mathbf{a}_s^\dagger \right\rangle \mathbf{B}^\dagger\,, \qquad \mathbf{F} = \mathbf{B}\left\langle \mathbf{a}_f \mathbf{a}_f^\dagger \right\rangle \mathbf{B}^\dagger \quad (2)$$

- Jointly diagonalise both matrices (eigenvalue problem)

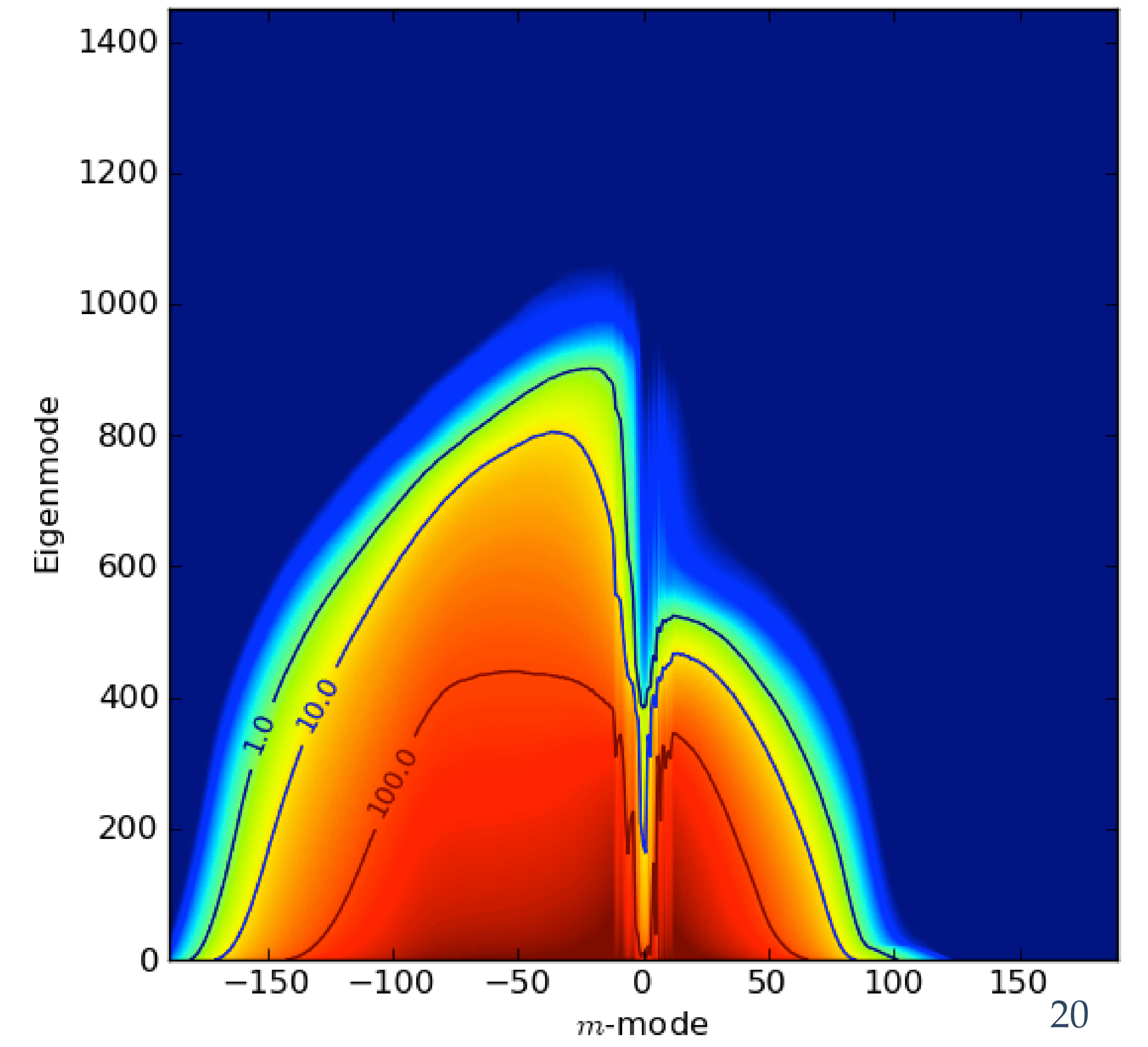
Karhunen-Loève (KL) Transform: $$\mathbf{S}\mathbf{x} = \lambda \mathbf{F}\mathbf{x} \quad (3)$$

- Gives a new basis, where we expect that all modes are uncorrelated. Eigenvalue λ_i gives ratio of signal to foreground variance for mode i.

cf. Bond 1994, Vogeley and Szalay 1996

Slide by
Kris Sigurdson
UBC

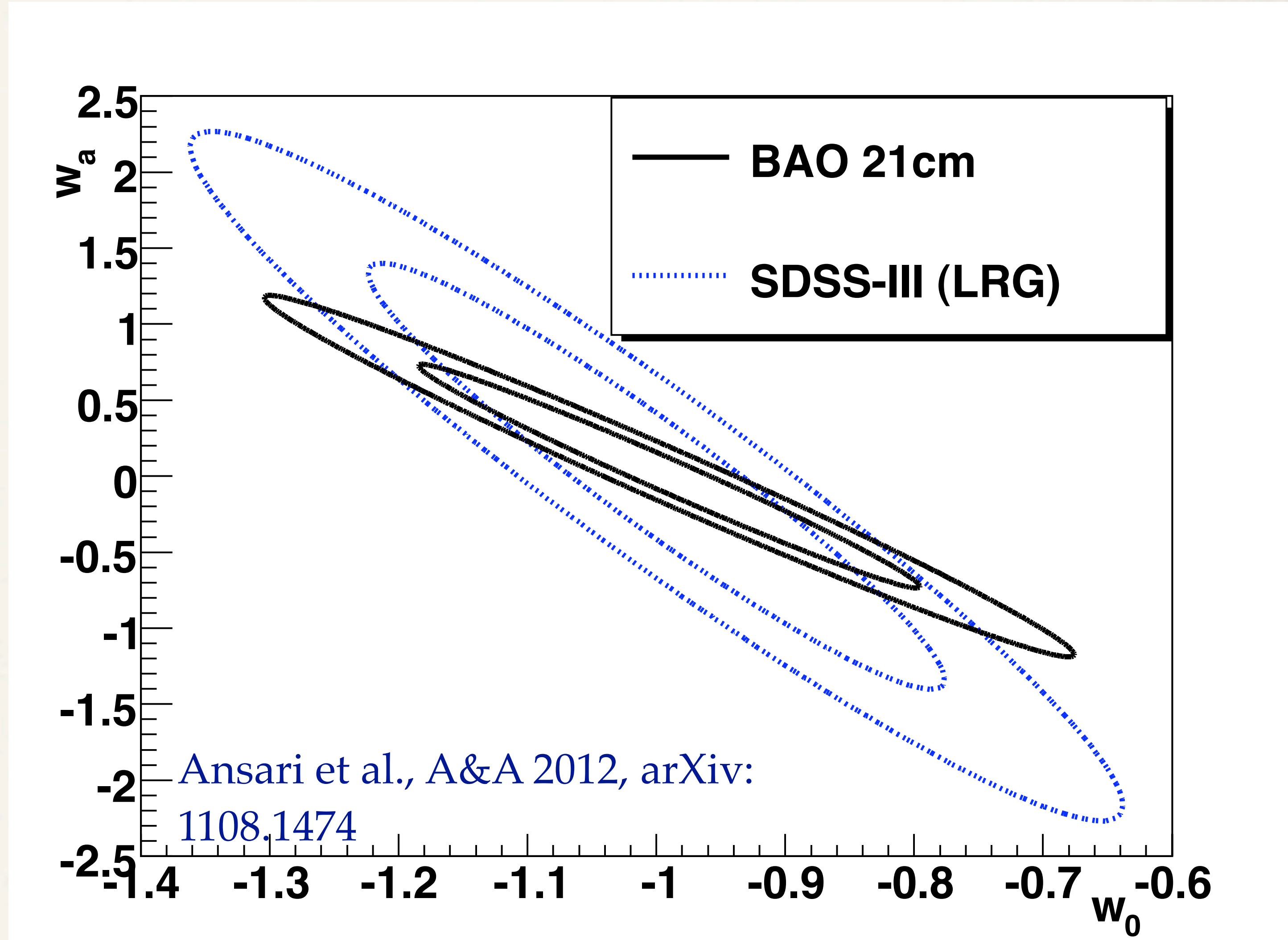
Signal/Foreground Spectrum



**Richard Shaw, Ue-Li Pen Kris Sigurdson et al.
ApJ 2014, arXiv 1302.0327**

21 cm Cosmology / DE

- Mapping cosmic matter distribution using neutral hydrogen as tracer
- Measure the HI density fluctuations and its power spectrum P21(k)
- Determine BAO scale kBAO pour 0.5 < z < 2-3
- Measure the HI gas fraction as a function of redshift, scale and environment
- Mapping of the radio foregrounds in the 500-1000 MHz band



21 cm BAO vs optical redshift survey
10 000 sq.deg, 3 years survey, 5 redshift bands (0.5 1.0 1.5 2.0 2.5)
10 000 m^2 collecting area, 400 beams

BAORadio

21 cm

LAL - IN2P3/CNRS

R. Ansari
J.E. Campagne
M. Moniez
A.S. Torrento
D. Breton
C. Beigbeder

T. Cacaceres
D. Charlet
B. Mansoux
C. Pailler
M. Taurigna

IRFU - CEA

C. Magneville
C. Yèche
J. Rich
J.M. Legoff

P. Abbon
E. Delagnes
H. Deschamps
C. Flouzat
P. Kestener

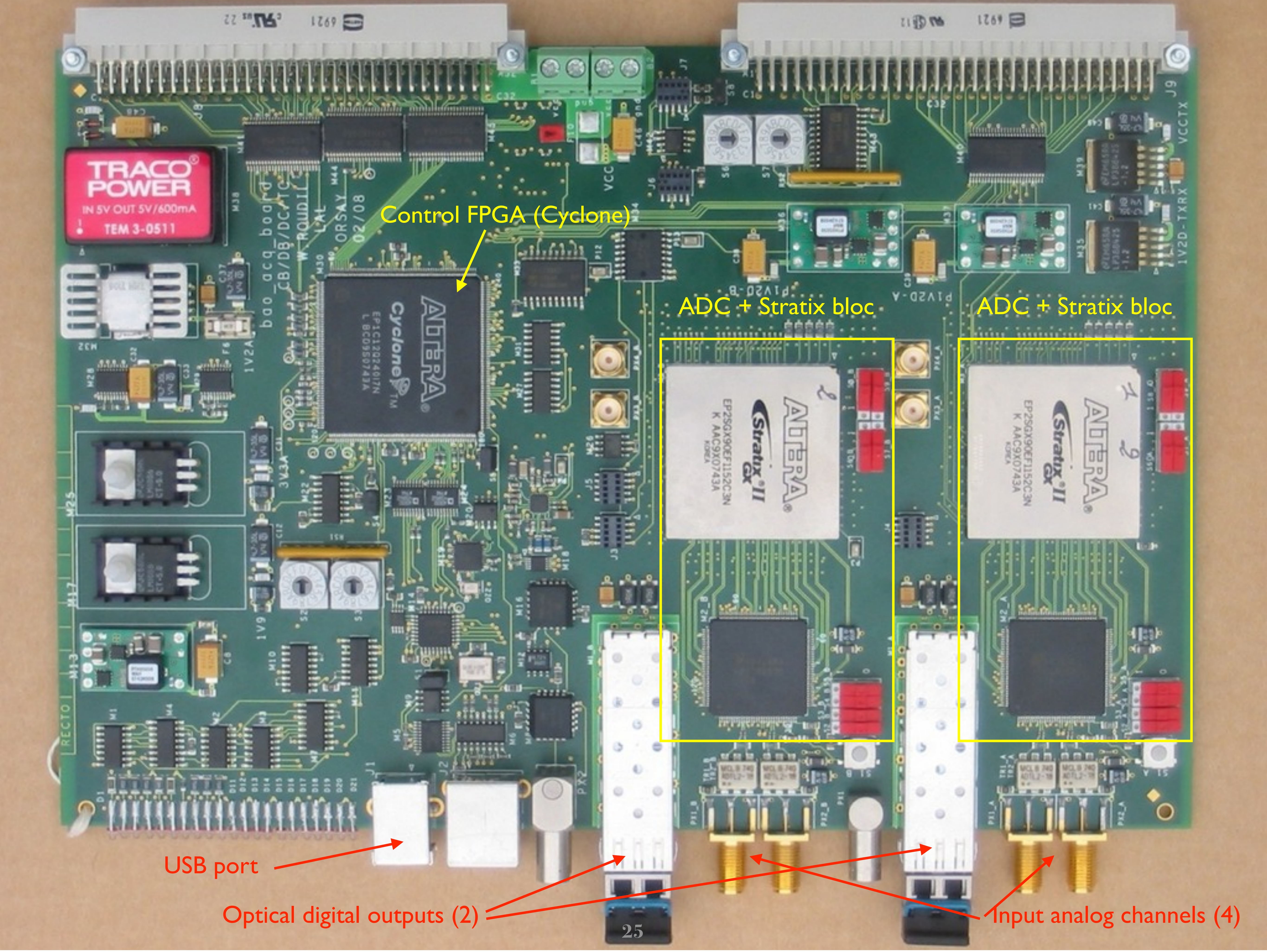
Observatoire de Paris

P. Colom
J.M. Martin
J. Borsenberger
J. Pezzani
F. Rigaud
S. Torchinsky
C. Viou

- In France, BAORadio project started in 2007
- LAL (IN2P3/CNRS), Irfu (CEA), Observatoire de Paris
- Development of the BAORadio analog & digital electronic system
- Focal plane array prototype FAN
- Electronic tests at Nançay, using the large radio telescope_
- Test using the CRT prototype at Pittsburgh
- PAON test interferometer with small dishes
- Financial support: IRFU, CNRS/P&U, P2I, Obs. de Parius, LAL, PNCG

BAORadio (french 21cm intensity mapping effort)

- Electronic, acquisition & processing software development
- FAN (J.M.Martin, P. Colom)
- Observations with CRT at Pittsburgh, calibration and beam synthesis
- *HI-Cluster wide band observation program with NRT (publication in preparation - 2014)*
- *OptX21 wide band observations with NRT : BAORadio & WIBAR*
- PAON test interferometer at Nançay
- NEBuLA - wide band digitizer (C. Viou, D. Charlet)


Control FPGA (Cyclone)
ADC + Stratix bloc
ADC + Stratix bloc
USB port
Optical digital outputs (2)
Input analog channels (4)

Pittsburgh, Novembre 2009

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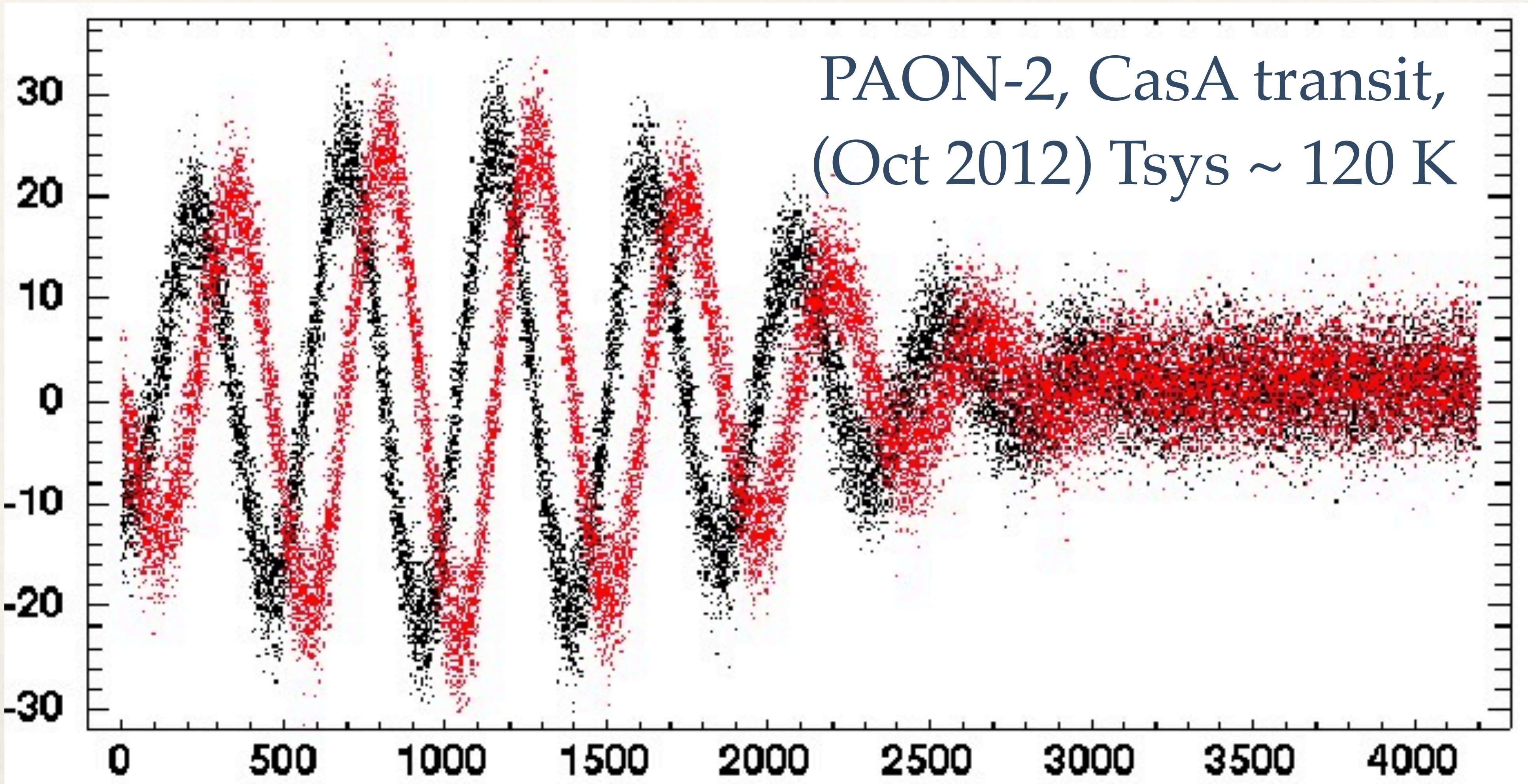
Test interferometer for an array of small dishes (RAID concept)

PAON-2 : 2 × D=3 m dishes (sep 2012 - sep 2013)

PAON-4 : 4 × D=5 m dishes, construction phase deployment : nov 2013 - march 2014

PAON

Paraboles A l'Observatoire de Nançay



PAON Test Interferometer

(J.M.Martin, J.E. Campagne)

PAON-4
(F. Rigaud)

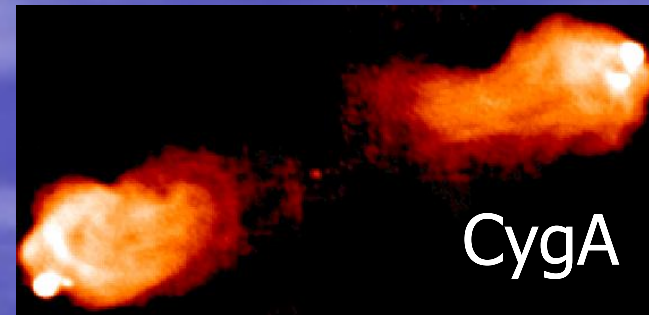
installation Nov 2013 - March 2014

4 D=5m dishes

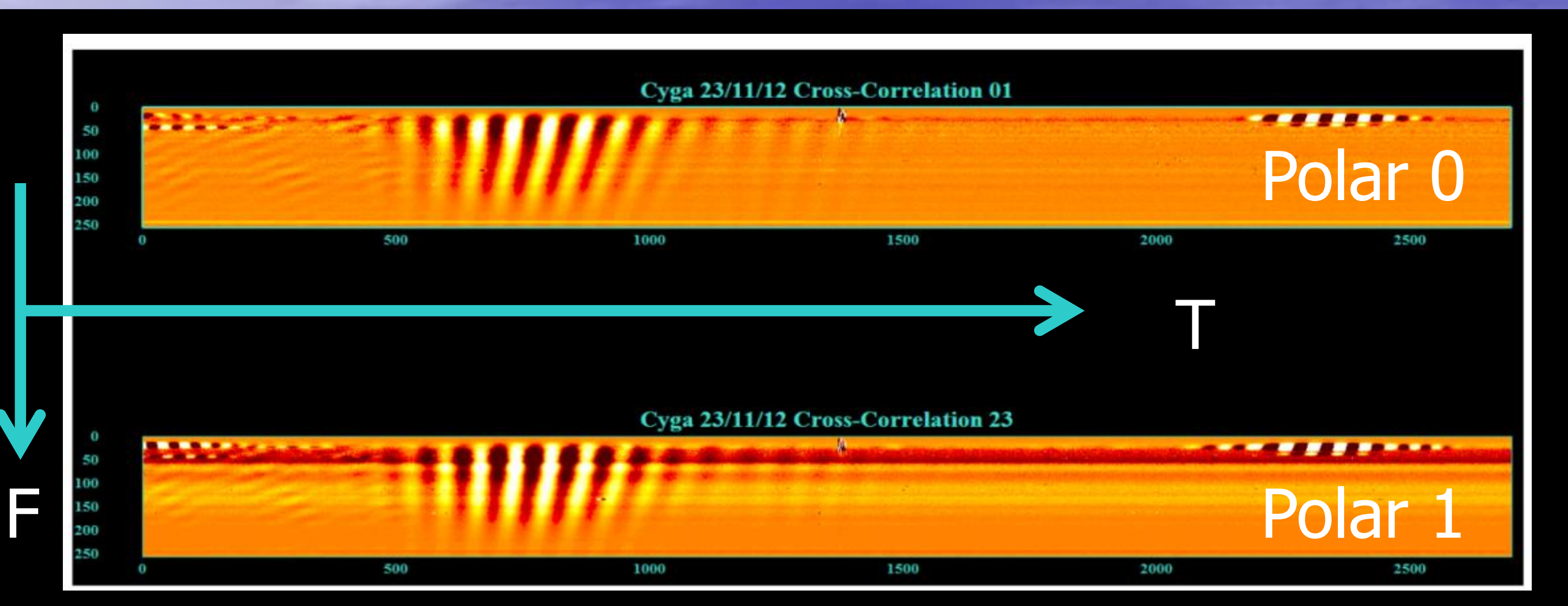
PAON-2 →

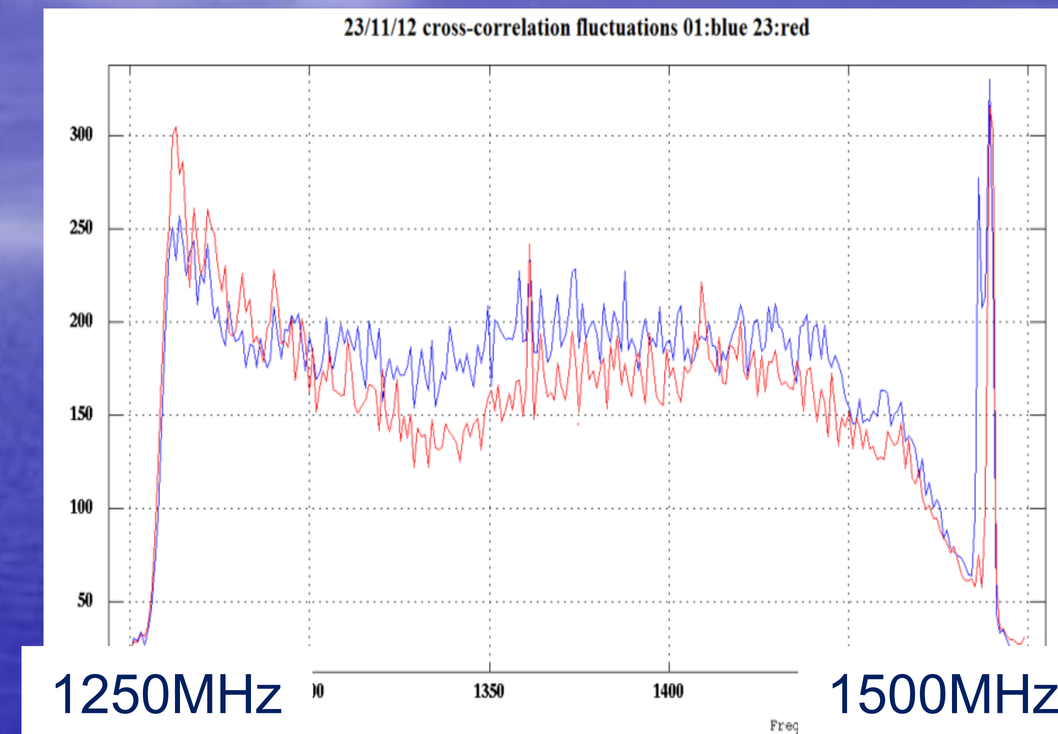
installed September 2012

Transit de



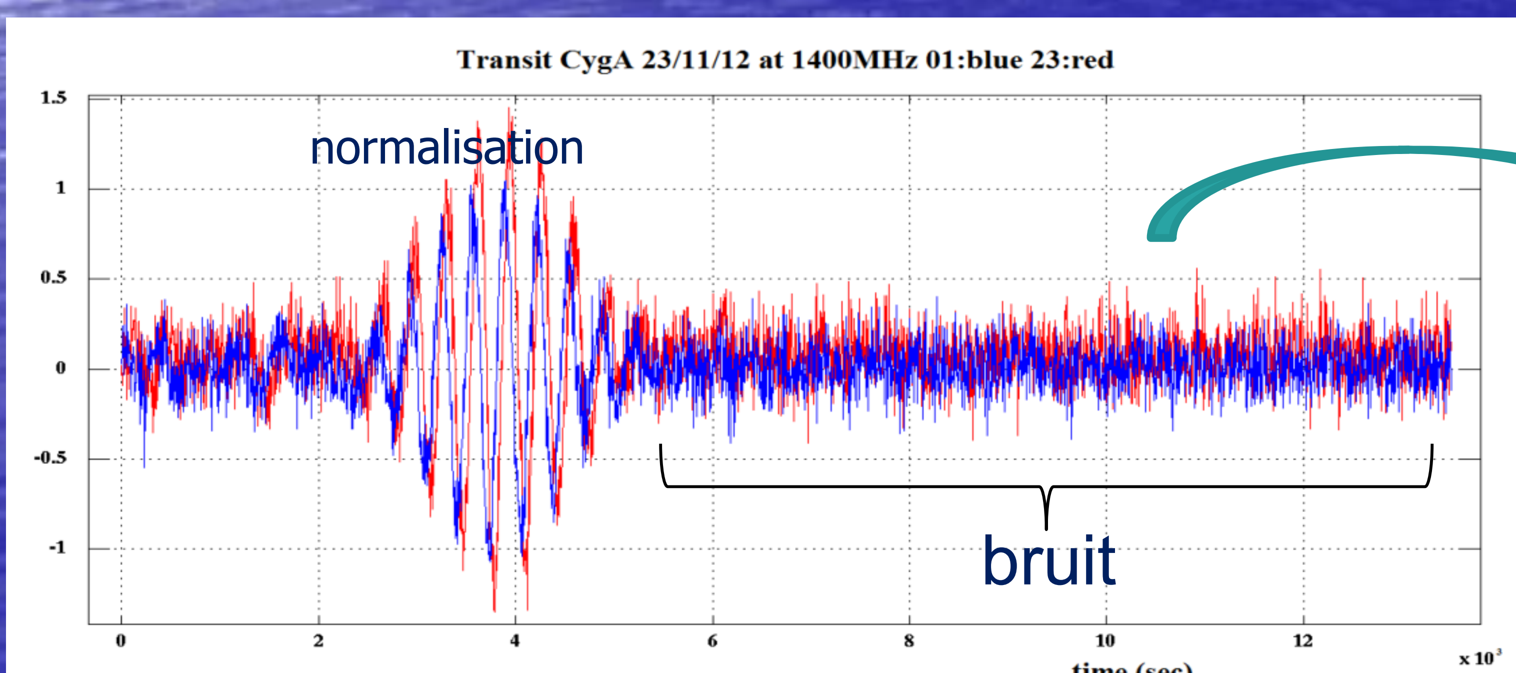
1600Jy ~ 4K
1400MHz

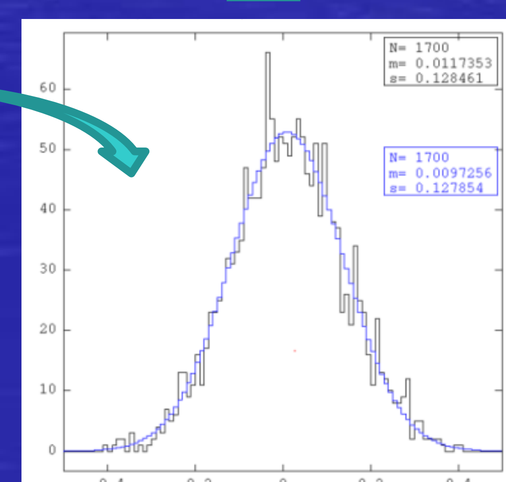




Observations de Cyg A durant 4h [1250-1500] MHz

Sigma -> T_{sys}



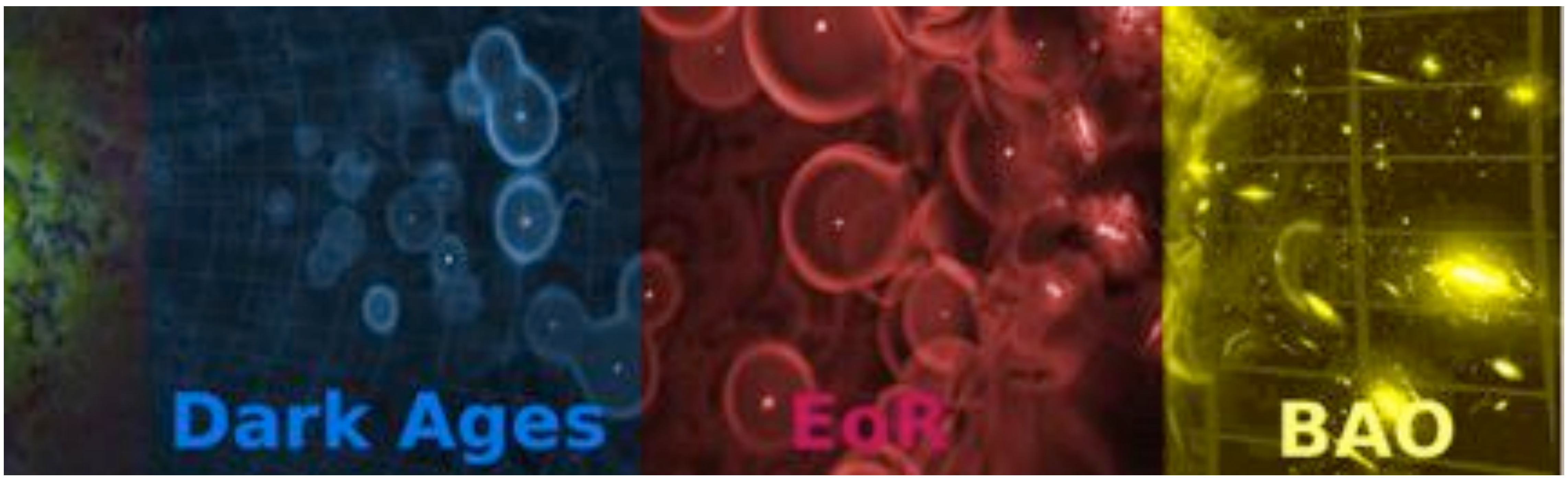


T_{sys} ~100K
1400MHz

NRT: 50K
Avant-plans~O(K)
Signal HI O(mK)

Slide by J.E. Campagne

Other 21 cm BAO projects



z = 100 to 20 15 to 70 MHz	z = 20 to 5 70 to 240 MHz	z = 5 to 0 240 to 1400 MHz

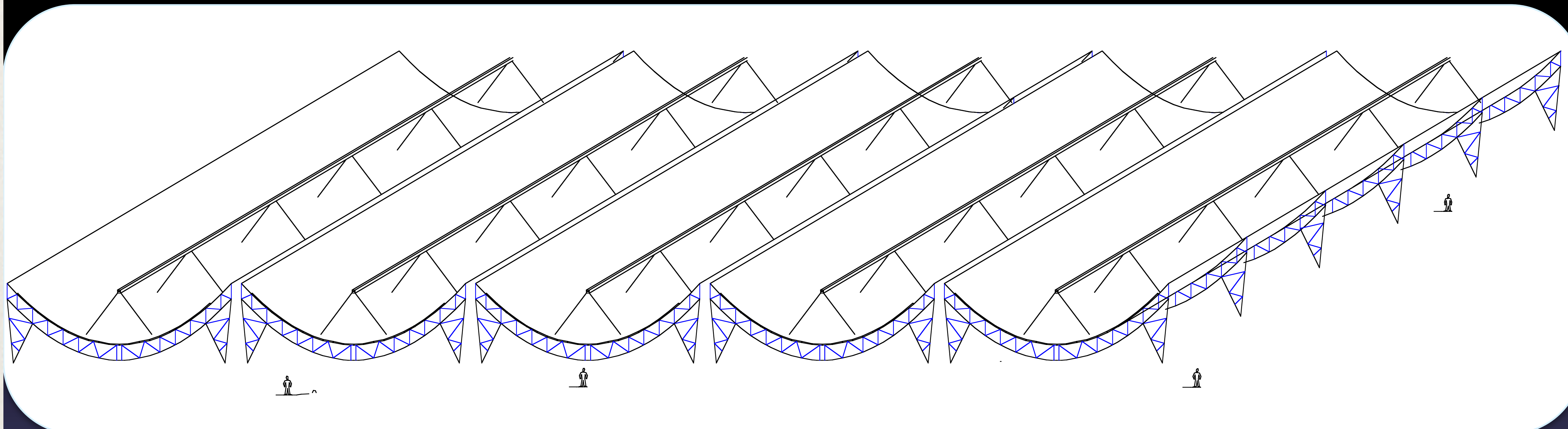
20 — 5 — z

- LOFAR
- GMRT
- MWA

- SKA-LOW
- HERA

- **CHIME**
- **Tianlai**
- GBT
- BAOBab
- SKA-mid

Canadian Hydrogen Intensity Mapping Experiment (CHIME)



THE UNIVERSITY OF BRITISH COLUMBIA

DRAO

NRC · CNRC

UNIVERSITY OF TORONTO

McGill

Kevin Bandura
CHIME Collaboration

Slide by K. Bandura

The CHIME Pathfinder

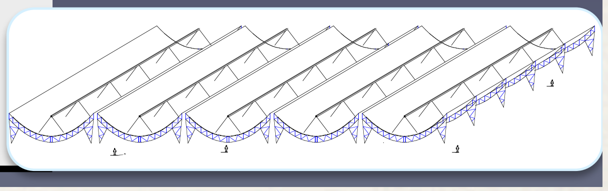
Slide by K. Bandura

CHIME Fact Sheet

Full CHIME Layout		
Structure	5 cylinders, 100m x 20m each	
Bandwidth	400-800 MHz	*Digitize 8bits at 800 MSPS*
Number Feeds/cylinder	256 dual pol feeds per cylinder (2560 digitizers total)	~31cm spacing
Frequency Channels	512 frequency channels, 781 kHz wide (1.28 μs)	(for cosmology, you can channelize further!)
Data Rate	$2N_{FEEDS}$ x 3.2 Gbit/s = 8 TeraBit/s	(assumes 4bit truncation)

Observing Frequency	400 MHz to	800 MHz
Wavelength	75 cm	37 cm
21cm Redshift	z=2.5 *(11 Gyr ago)*	z=0.8 *(7 Gyr ago)*
Beam Size	0.52°	0.26°
E-W FoV	2.5°	1.3°
N-S FoV	-45° to +135° (max possible) 0° to +90° (more likely)	
Time/pixel/day	10min, 14min, 24hrs equator, 45deg, ncp	5min, 7min, 24hrs equator, 45deg, ncp
Receiver Noise Temperature Flux Conversion Daily Sensitivity Final Survey	50k ~2K / Jy ~50 μJy / pixel ~1.5 μJy/pixel *(Approximate – for planning purposes only)*	

Slide by
K. Bandura



16 channel correlator now, 256 channel correlator by spring 2014

天籁

TIANLAI

TIANLAI

NAOC 中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

cnrs IN2P3 Les deux infinis

CITA ICAT

Carnegie Mellon University

l'Observatoire de Paris

cea IRF

WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

Fermilab

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From CRT / BAORadio to…

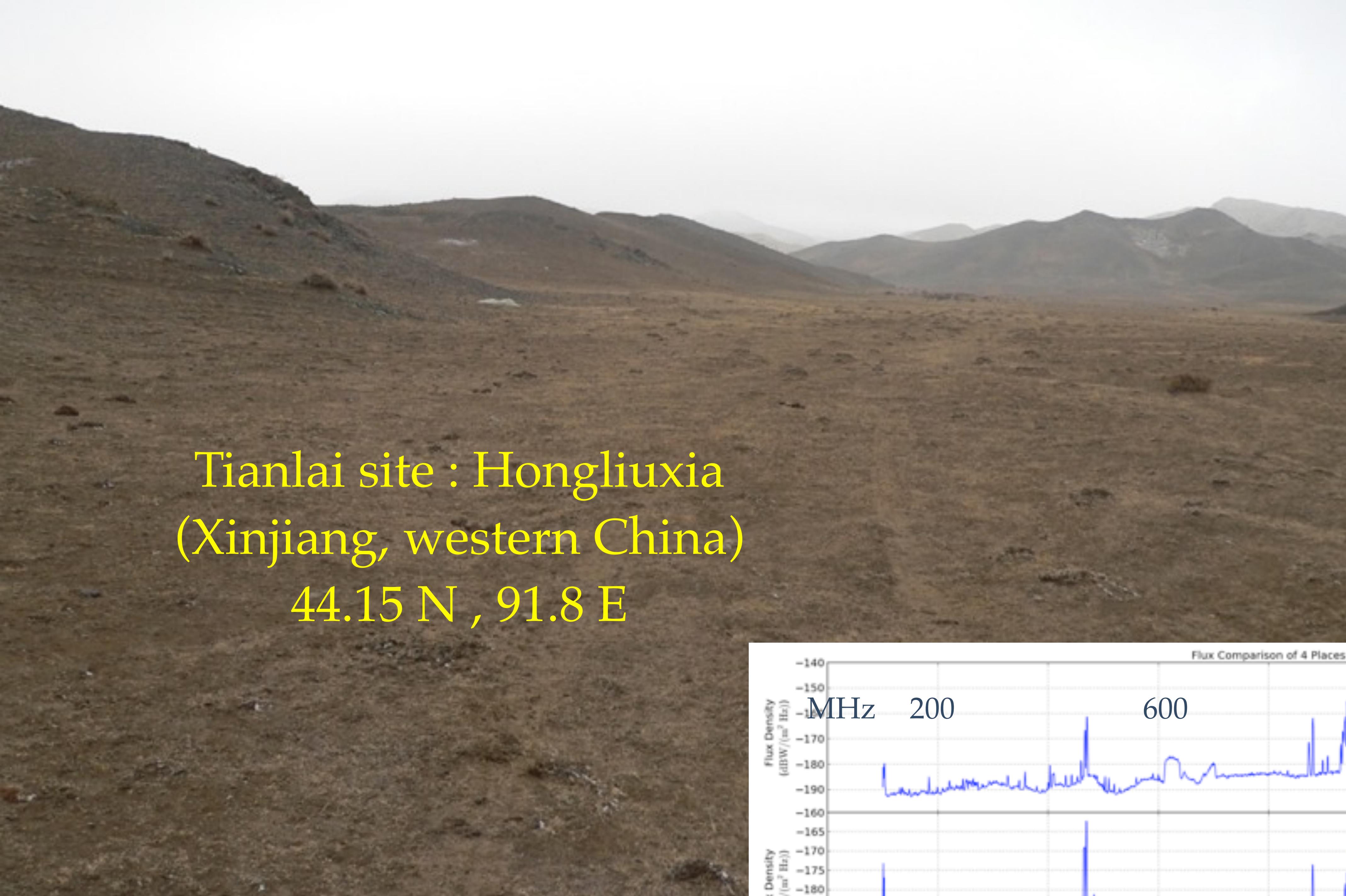
Tianlai

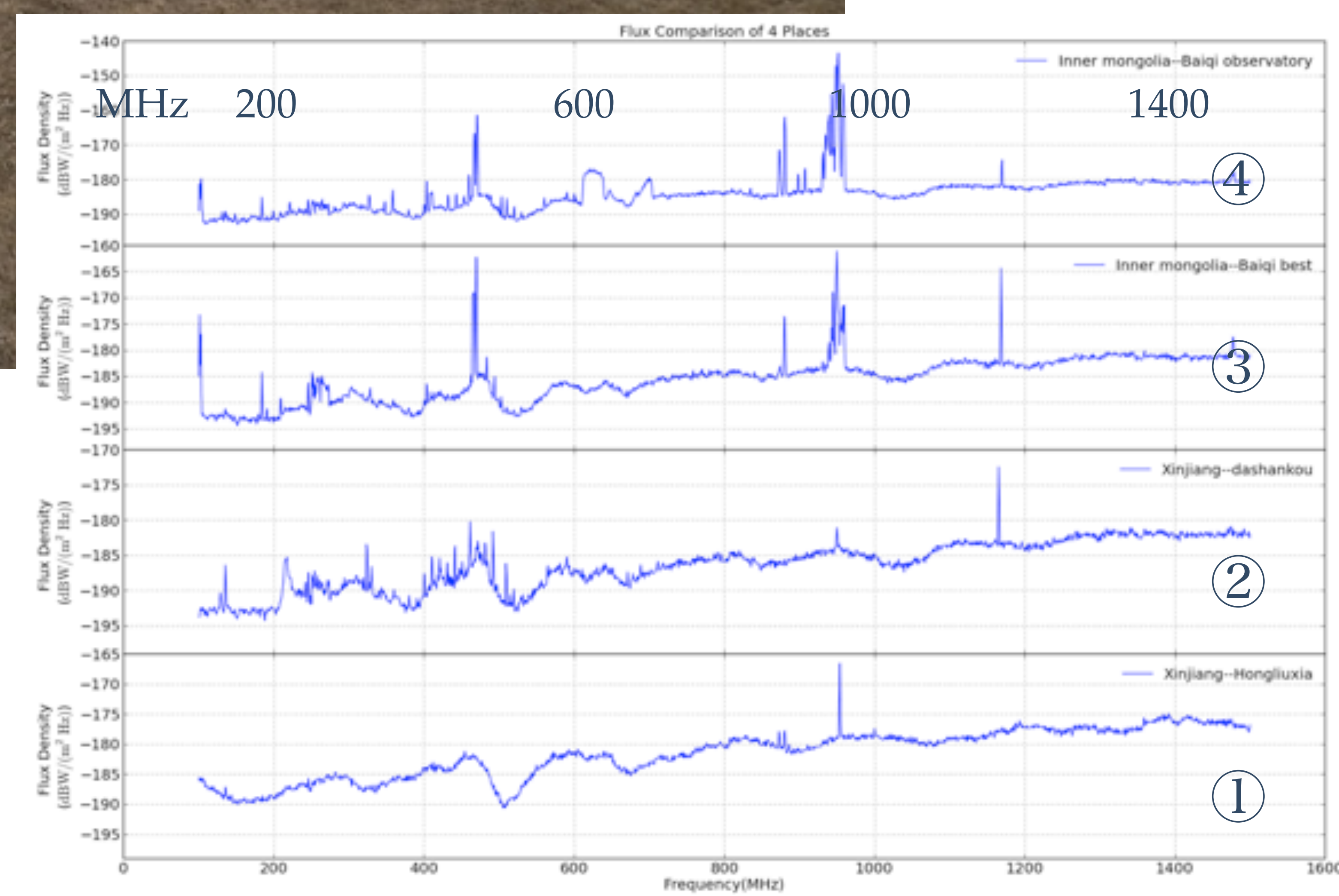
Toward a large instrument for 21 cm DE survey

- Tianlai project led by NAOC (China) - Prof. Xuelei Chen
- TDA (Tianlai Dish Array) and PC-GPU correlator (US, P. Timbie, J. Peterson)
- PAON demonstrator

Tianlai site (Xinjiang, western China)

Tianlai site (Xinjiang, western China)

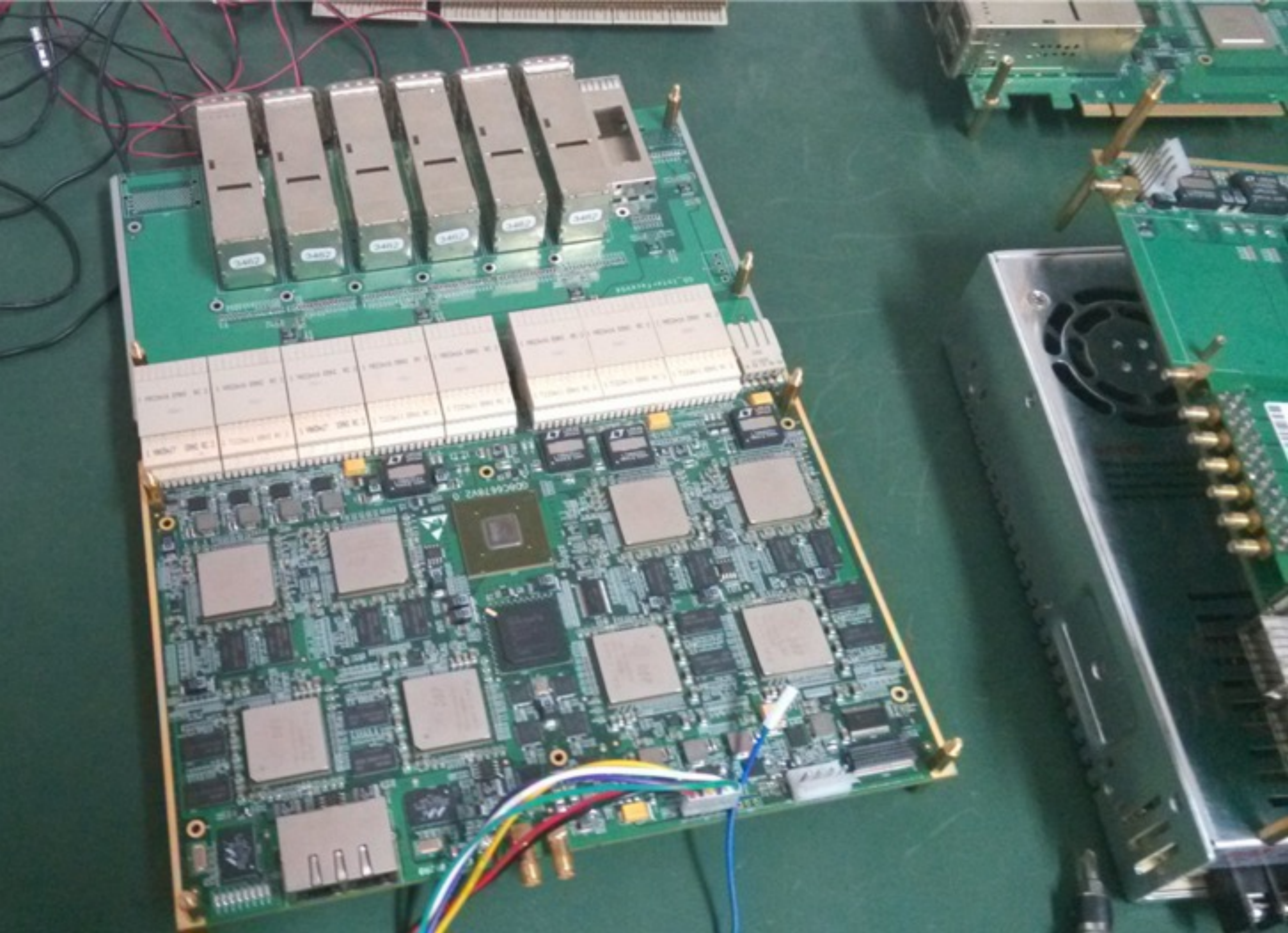




① - Xingjiang - Hongliuxia

② Xingjiang - Dashankou

③ ④ Inner Mongolia , Baichi



Tianlai correlator & ADC boards

Development plan for the Tianlai 21 cm DE survey

- 2014-2015 : TDA (Tianlai Dish Array) , 16 D=6m dish array
- 2015 : CRT type instrument (3 Cylinder array)
- 2015 : Stage 1 - engineering array, 32 feeds
  - Aim : detect optical × 21cm cross correlation at z ~ 0.7-1
- 2016 : Stage 2 - first science array, ~ 200 feeds (2016-2018)
  - Aim: detect BAO with 21 cm signal at z ~ 0.7 - 1.0
- 2020 ? : Stage 3 DE survey, ≥ 1000 feeds
  - Aim: measure BAO with 21 cm signal in the redshift range 0.5…2.0

Outlook

- Exciting scientific perspectives (DE, HI mass distribution at z ~ 1.5 …) for intensity mapping surveys
- CHIME, Tianlai can serve as testbeds to develop intensity mapping and open the way for larger instruments (SKA-mid, Aperture Arrays)
- Scientific challenge : data processing, 3D map making & foreground subtraction

Intensity mapping workshop :
Paris Observatory/CIAS, 4-6 June 2014

* **1 to 2 days OPEN MEETING ON INTENSITY MAPPING**
* **1 day** Tianlai collaboration workshop
* **June 7** visit of Nançay radio astronomy station)

Organization: JM.Martin (GEPI), R.Ansari (LAL), CIAS
Announcement soon via SF2A, PNCG, list SKA-LOFAR

Focal Array at Nançay (FAN) workshop :
Paris Observatory/CIAS, end of may 2014 (TBC)
*** 1 day workshop**

→ **discussion of the scientific case for a multibeam receiver for the Nançay decimetric Radio Telescope (NRT)**
Organization: JM.Martin (GEPI), P.Colom (LESIA), CIAS
Announcement via SF2A, SKA-LOFAR lists