3D Intensity Mapping and 21 cm Cosmology

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Journées PNCG **25-26 Novembre 2014**

- Large Scale Structures and BAO's at 21 cm
  - 3D mapping of 21 cm emission
- BAORadio project in France
  - Electronic developments
  - HICluster program at Nançay
  - PAON interferometer
  - NeBuLA
- Tianlai
- Toward SKA : EMBRACE

LSS & BAO at 21 cm

Why DE / BAO at 21 cm ?

The Nature of Dark Energy

- No single technique can tell us everything: use multiple techniques
  - Different techniques have different strengths and weaknesses
  - Different systematic uncertainties in different techniques
  - Different techniques sensitive to new physics in different ways

- Dark Energy changes history of expansion rate of the universe
  - Measure distances as function of redshift (*i.e.,* luminosity distance by SNe)
  - Measure growth rate of structure as function of z $(\ddot{\delta}+2H\dot{\delta}-4\pi G\rho\delta=0)$
- Acceleration may be due to modified gravity (MG)
  - Measure growth rate of structure & infall of galaxies

Complementarity,
different systematics,
different bias,
probe HI

Ongoing & Future Dark-Energy Projects

Ongoing/planned projects without major DOE support (not all DE primary goal)

Location	Survey Type	Project	Comments
US	Spectroscopic	HETDEX	BAO
	Imaging	Pan-STARRS1, SkyMapper	SNe primary probe
	Space	WFIRST*	NASA, DOE scientist support
	Millimeter	ACTpol, SPTpol (SZ)	Clusters NSF/some DOE
	21cm	BAOBAB *, PAPER, MWA	Signal detection is initial goal, dark energy in future
Non-US	Spectroscopic	Subaru PFS (Japan+), PAU, JPAS (Spain+), 4MOST* (Europe)	BAO primary method
	Imaging	KIDS (Europe), Subaru HSC (Japan+)	WL is the primary probe
	Space	Euclid (Europe led + NASA)	DOE scientist support
	21cm	CHIME* (Canada+)	Other projects planned, but not primary dark energy
	Space	eROSITA (Germany+)	Galaxy Clusters via X ray

* Yet to obtain (to our knowledge) substantial funding.

28 August 2012 Presentation to HEPAP Rocky Kolb, University of Chicago

Slides from R. Kolb presentation to HEPAP (Aug 2012)

28 August 2012 Presentation to HEPAP R

Baryon Acoustic Oscillations

& redshift coverage …

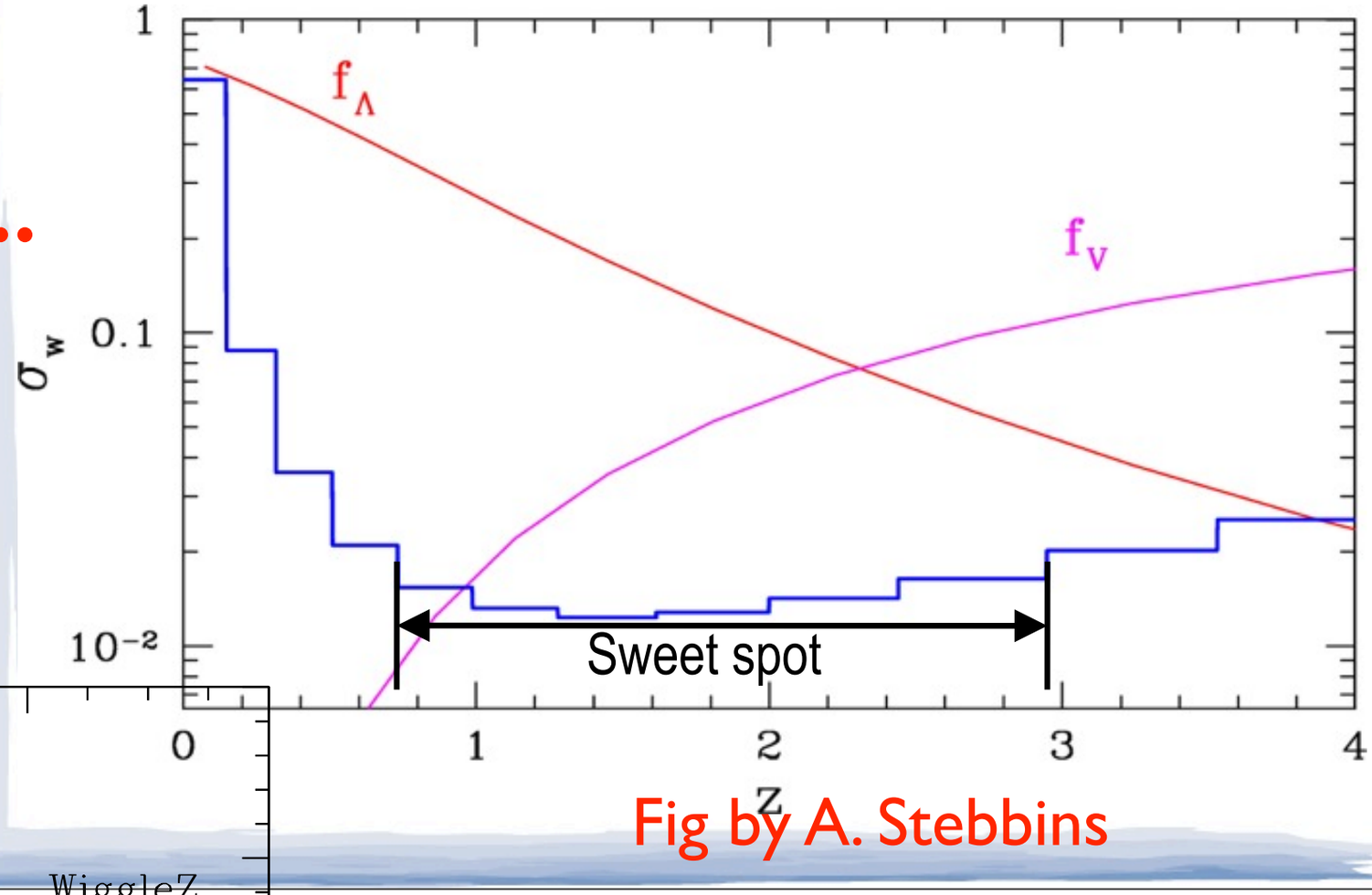
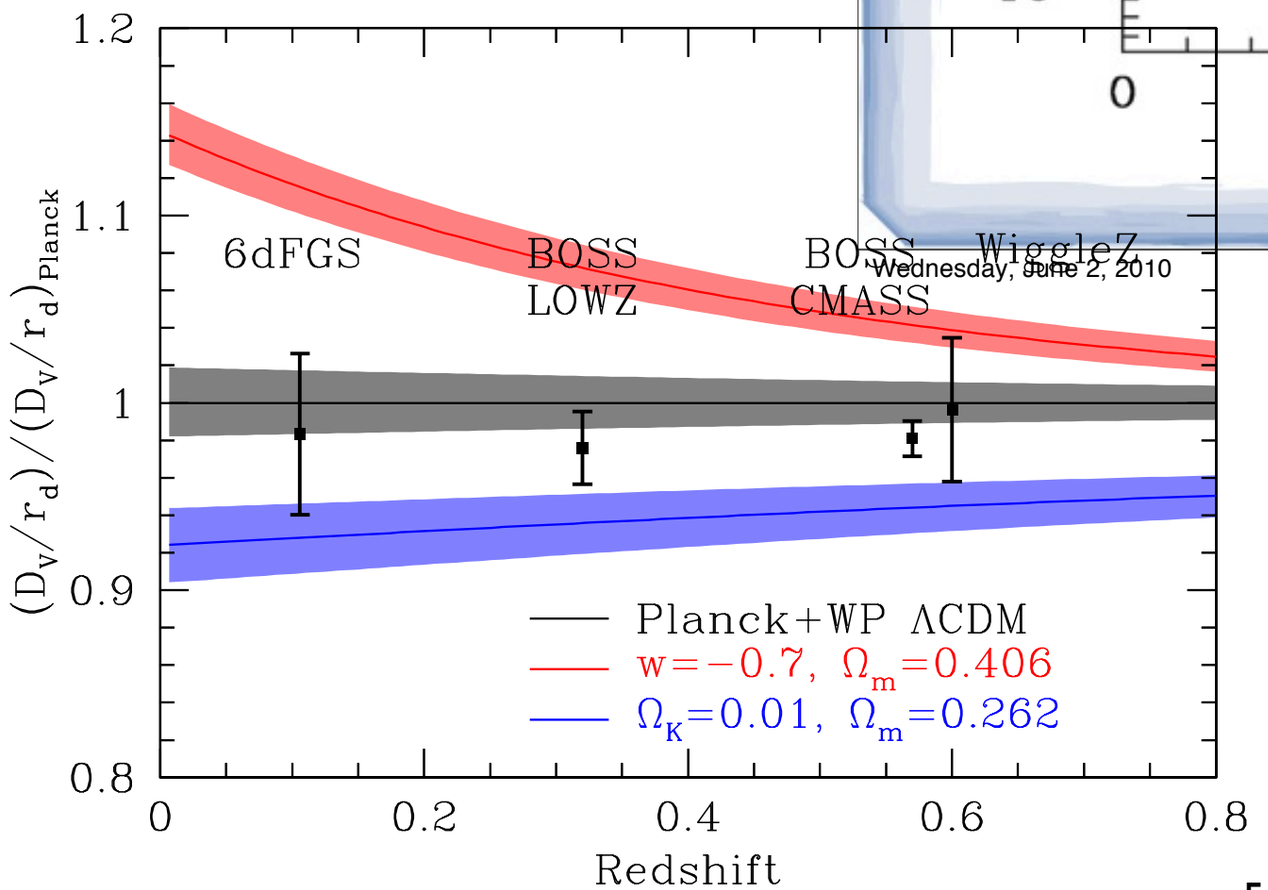


Fig by A. Stebbins



Wednesday, June 2, 2010

⬅ SDSS-III BOSS

Anderson et al, arXiv 1312.4877

5

21-cm 3D Intensity Mapping

LSS & BAO at 21 cm

- 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

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

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

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 !

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)
- dense interferometer array (high sensitivity at low k) with small reflectors (→large FOV)

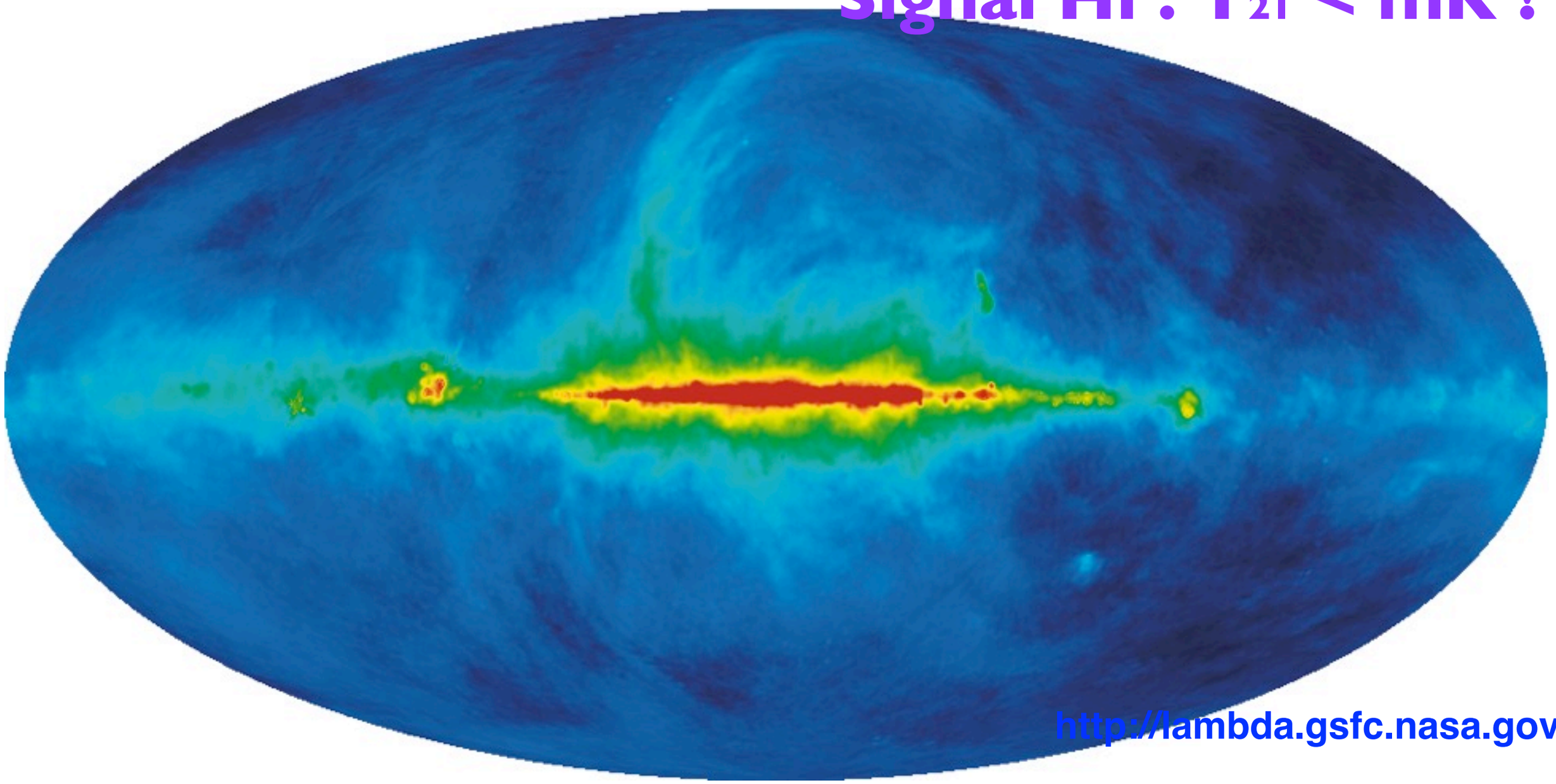
≡ Instrument noise (Tsys)

≡ 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) arXiv:1108.1474

Foregrounds

Signal HI : T_{21} < mK !



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

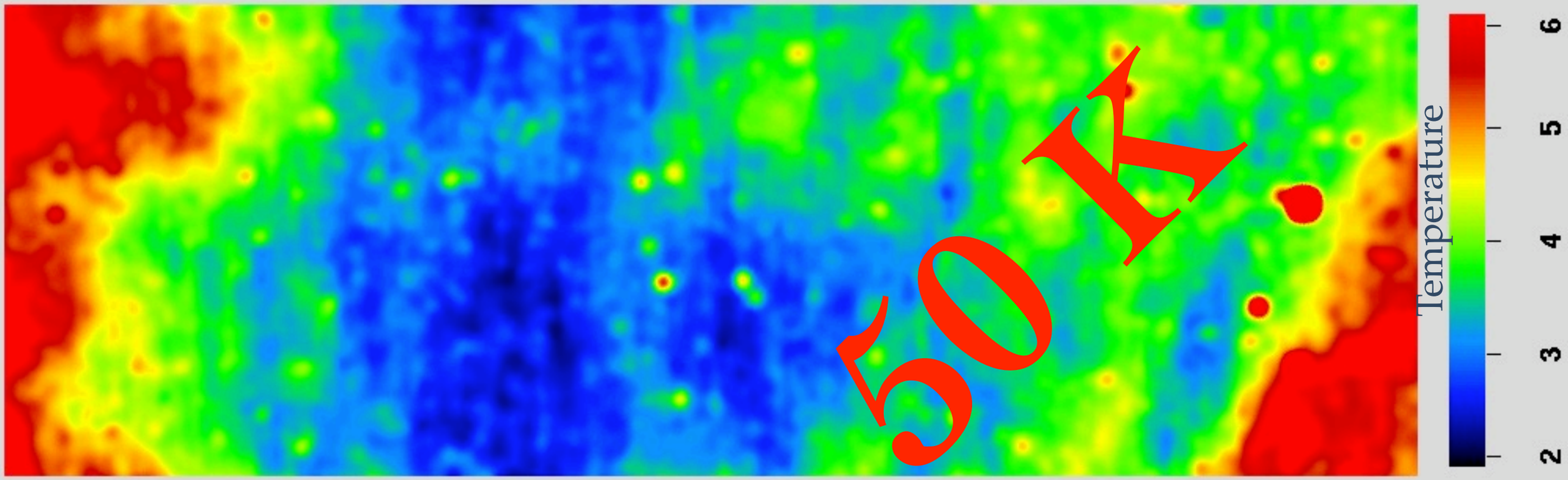
Temp. T (Ech. Log)

10 K ——— **250 K**

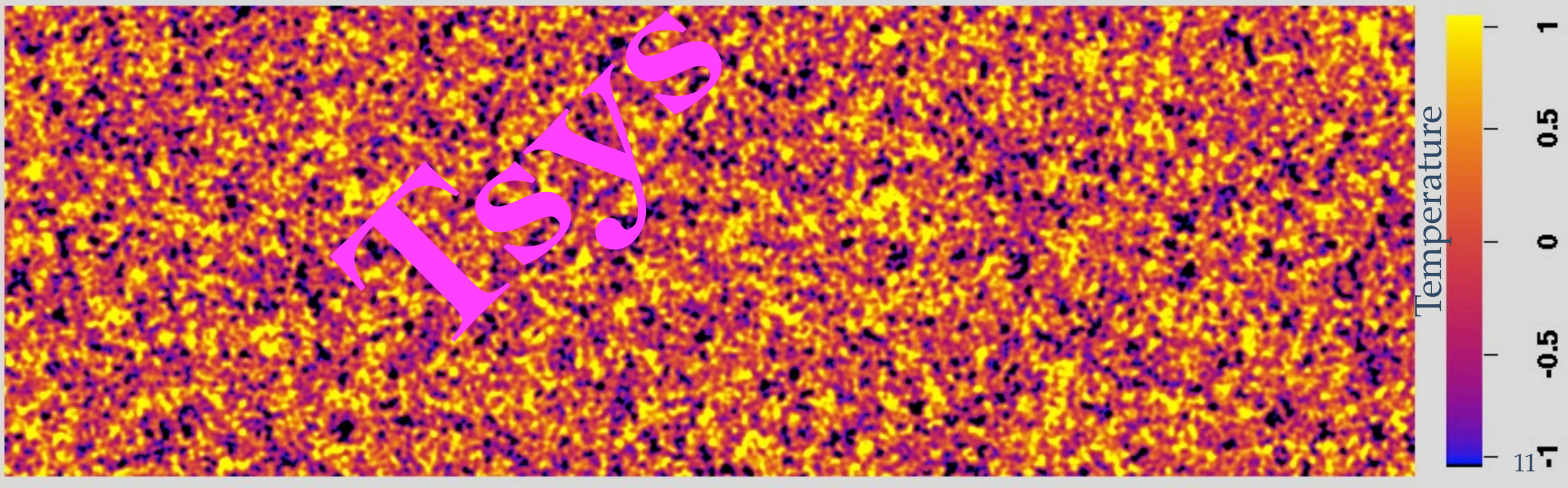
Haslam 408 MHz map (Galactic synchrotron emission)

R. Ansari

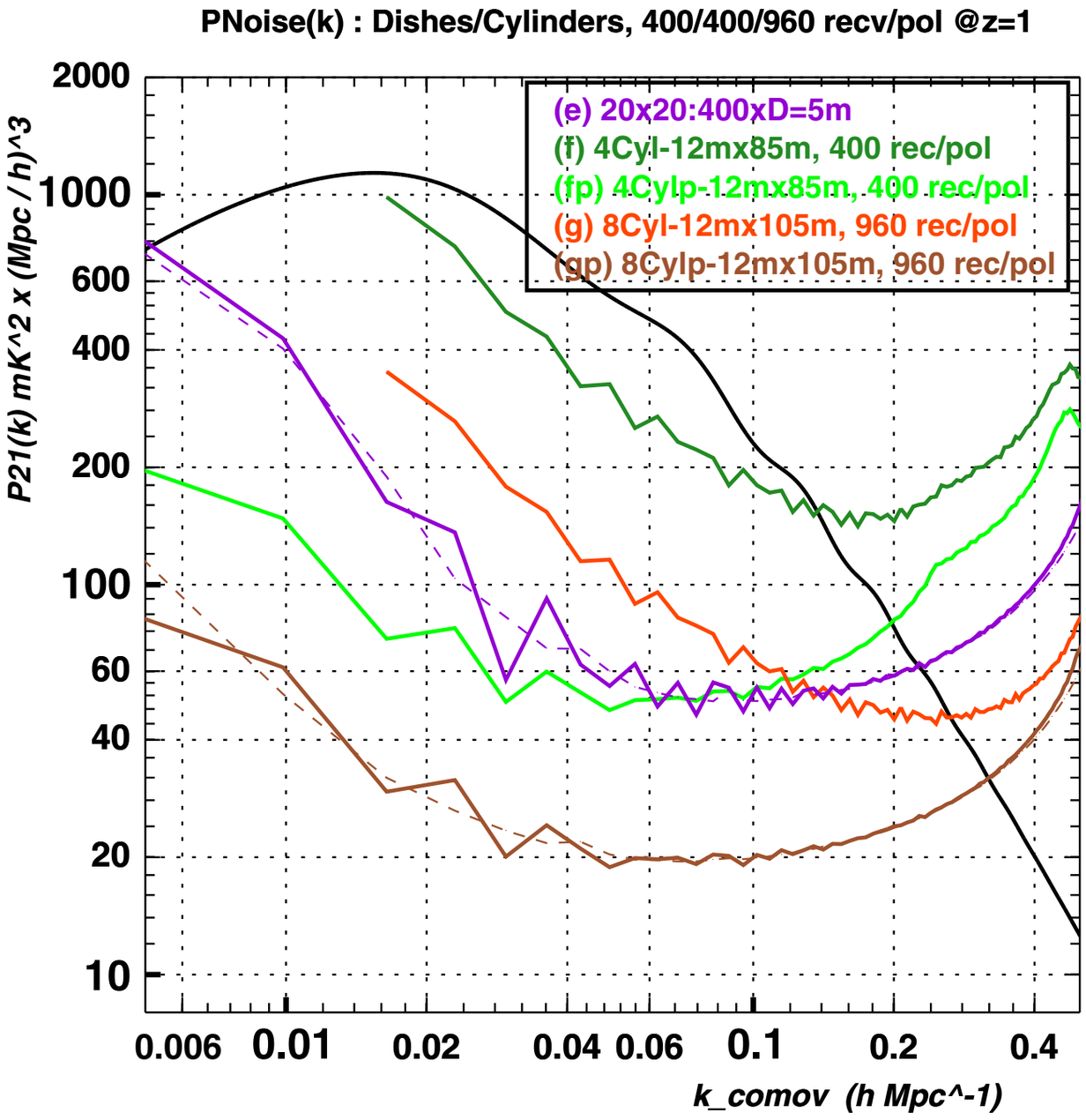
Radio foreground (GSM) @ 720 MHz (z=1.) - Kelvin



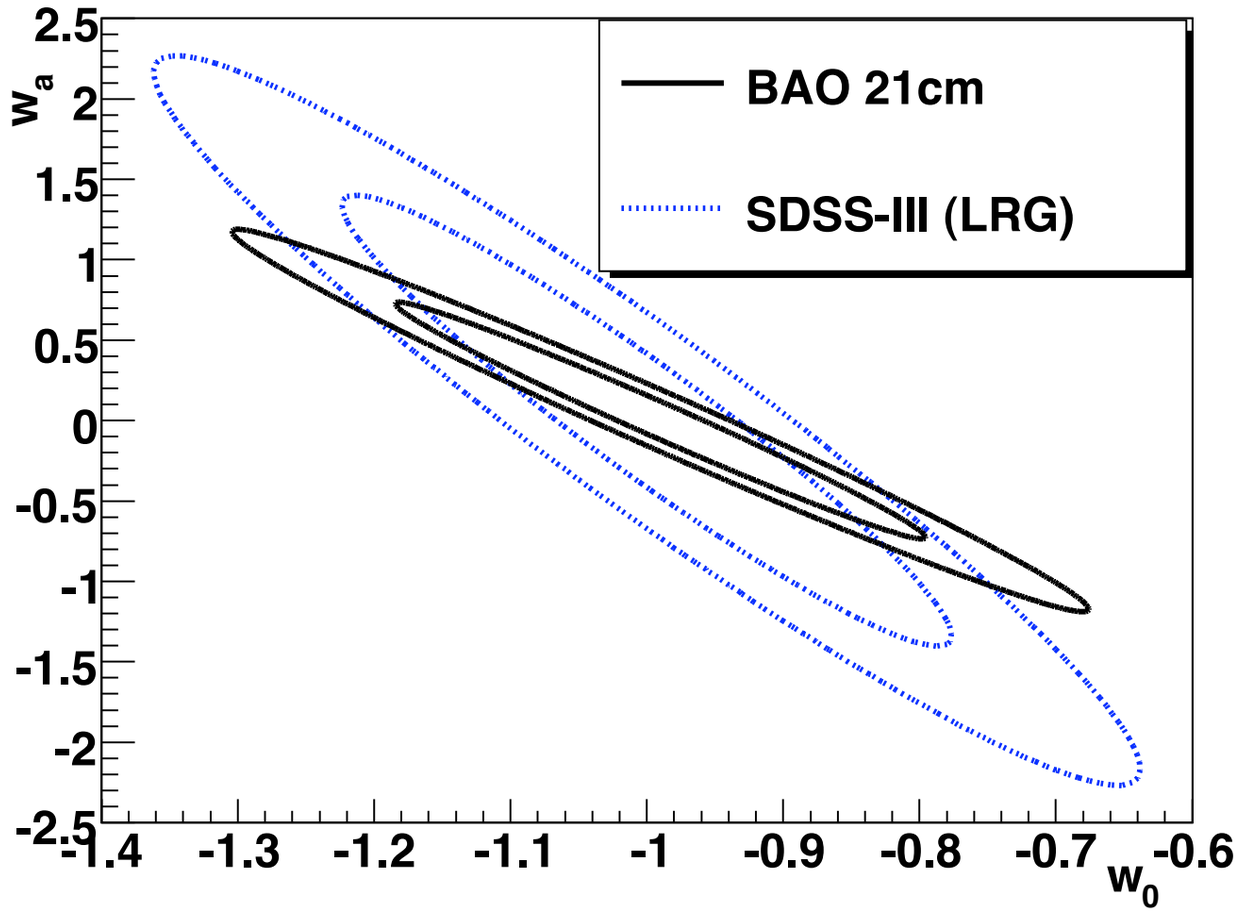
21 cm sky brightness @ 720 MHz (z=1.) - milliKelvin



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



- **z = 1** ($\nu \approx 710$ MHz)
- 10 000 sq.deg (π srad)
- 1 year observation
- Tsys = 50 K

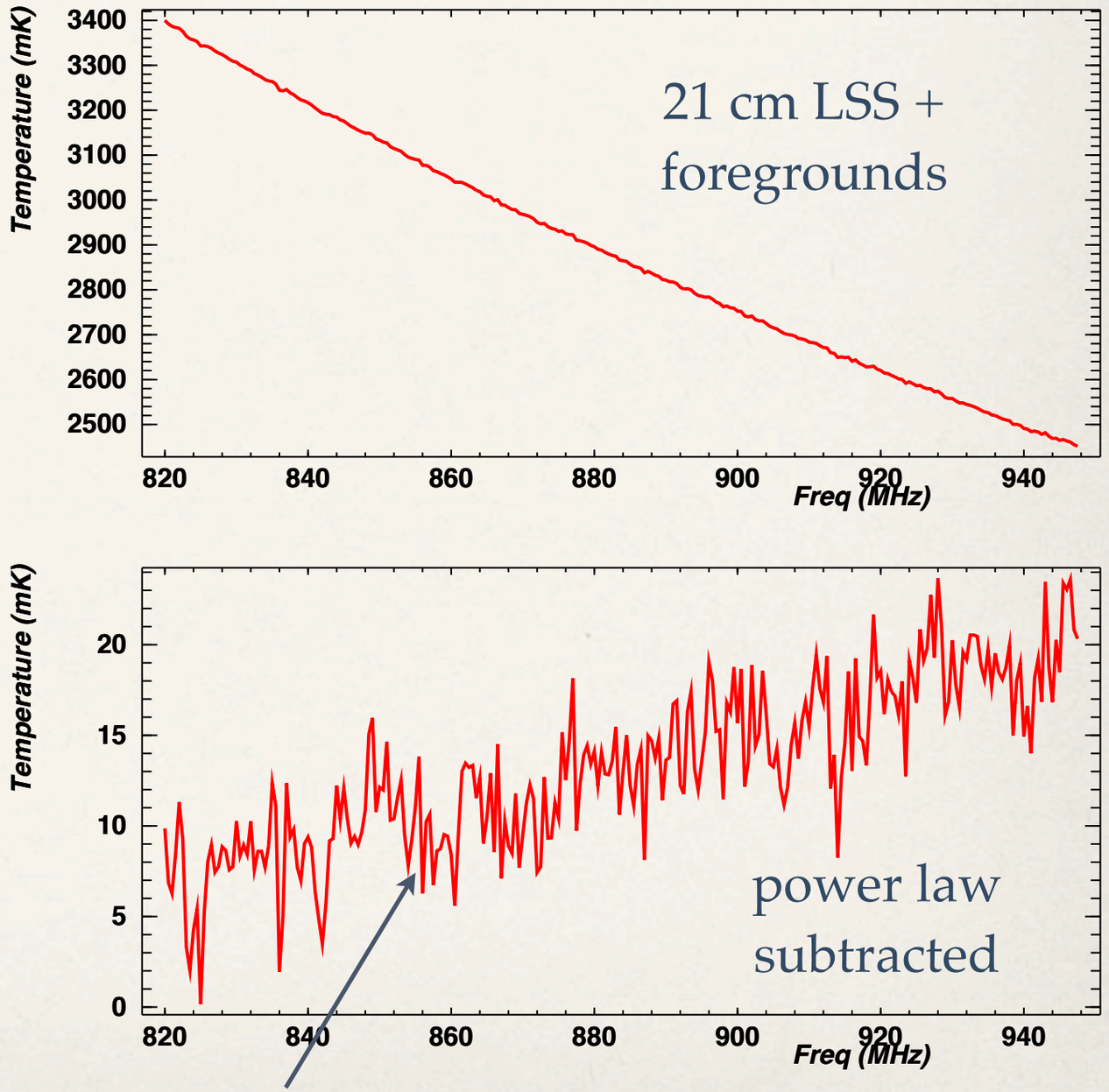


21 cm BAO vs optical redshift survey
10 000 sq.deg, 3 years survey, 5 redshift bands
(0.5 1.0 1.5 2.0 2.5)
10 000 m^2 collecting area, 400 beams

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

Foreground removal

- Exploit frequency smoothness and power law (∝ ν^β) behavior of foregrounds (synchrotron/radio sources)
- power law / polynomial / foreground model fit & subtraction
- Mode mixing, bias, error propagation …



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 Paris, LAL, PNCG

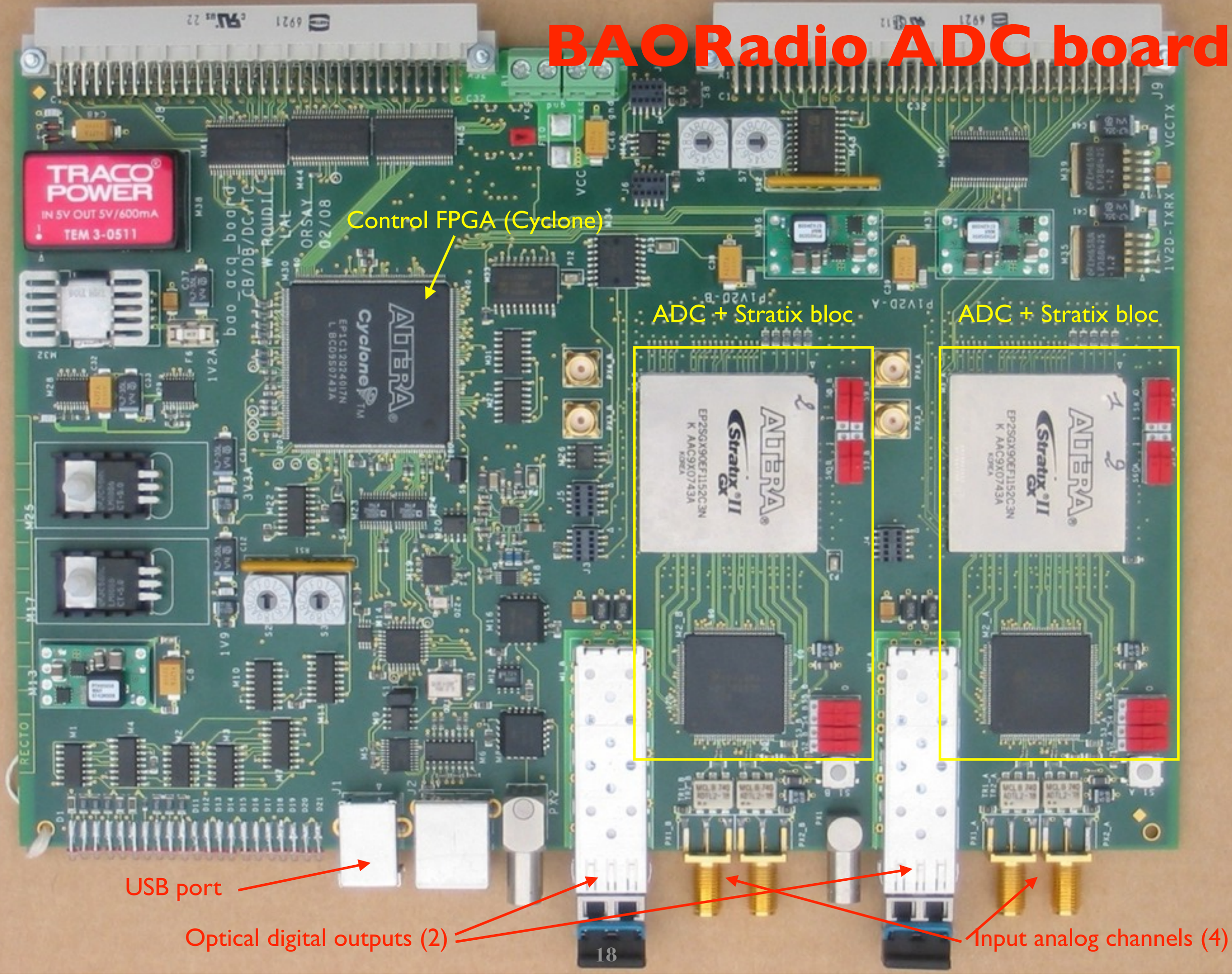
- 2006 : J. Peterson, Ue-Li Pen … CRT proposal (Moriond Cosmology), discussions in France (LAL, IRFU)
- 2007 : Start of BAORadio electronic design in France (LAL-IRFU), Prototype cylinder built in Pittsburgh
- 2008 : Observatoire de Paris & Nançay join the project in France, first tests of the electronic system at the NRT, FAN prototype at Nançay
- 2008-2009 : Fermilab group gets involved in the project , Site testing in Morocco
- 2009-2010 : Observation campaigns with the BAORadio electronic, acquisition/visibilities & processing software at Pittsburgh
- 2009-2012 : discussions on instrument configuration, dish arrays vs. cylinders - Observation programs with NRT, GBT …
- 2010-… : Collaboration with NAOC / X. Chen, the Tianlai project

BAORadio (french 21cm intensity mapping effort)

LAL/IN2P3 - SPP/IRFU (CEA) - Obs. de Paris 2007 - 2014

- 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 OptX21 wide band observations with NRT : BAORadio & WIBAR
- PAON test interferometer at Nançay
- NEBuLA - wide band digitizer (C. Viou, D. Charlet)

BAORadio ADC board



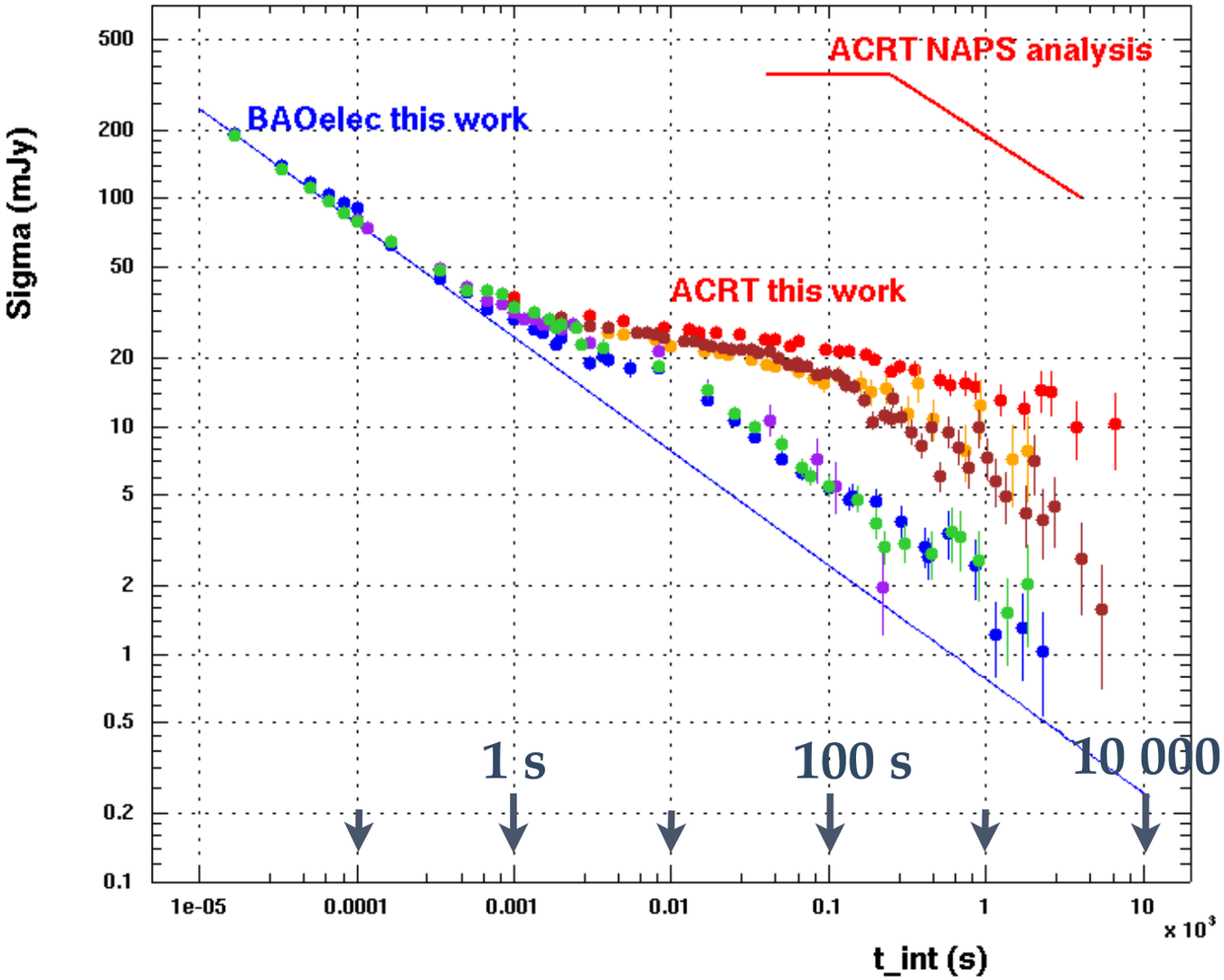
CRT (CMU, Pittsburgh)

BAORadio @ CRT-Pittsburgh - Nov 2009

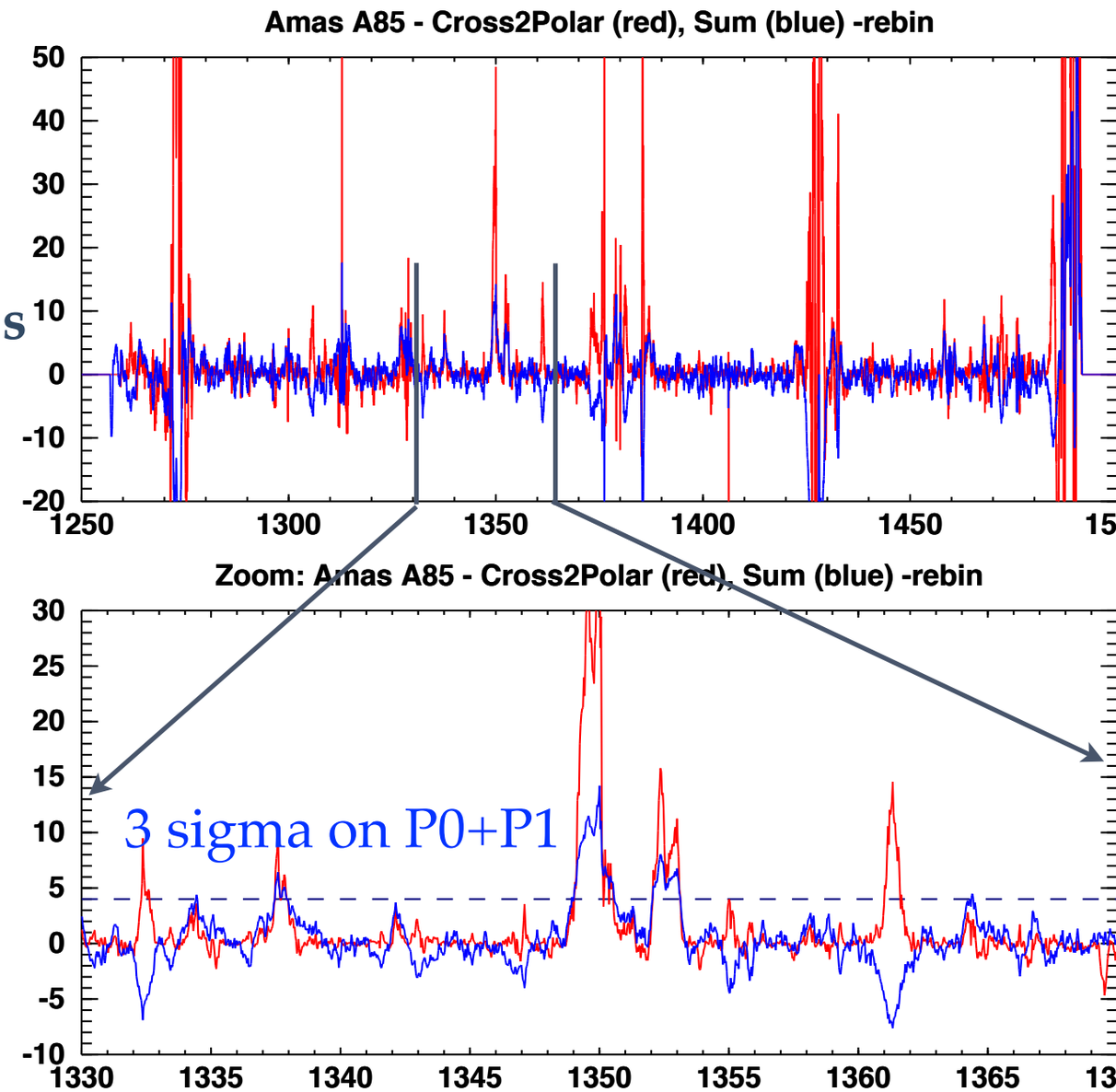
HICluster program at Nançay

- Observation of some nearby clusters (z ~ 0.1)
- Observation in parallel with the NRT auto-correlator & BAORadio electronic chain at **Nançay**
- Total of ~ 10 hours / target - distributed over a year
- Calibration, RFI cleaning, sensitivity estimates
- Reach mK level over a wide band
- OptX21 program started, using the BAORadio electronic and WIBAR system in parallel

Sensitivity (radiometer) curve
HI-Cluster program, BAORadio & NRT correlator



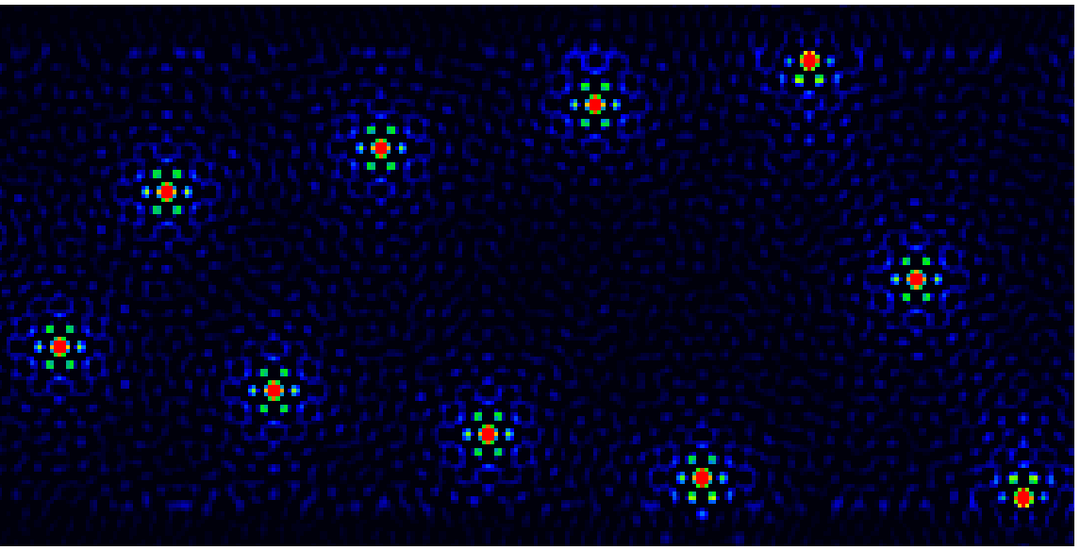
A85 signal : ~ 4 mJy.MHz

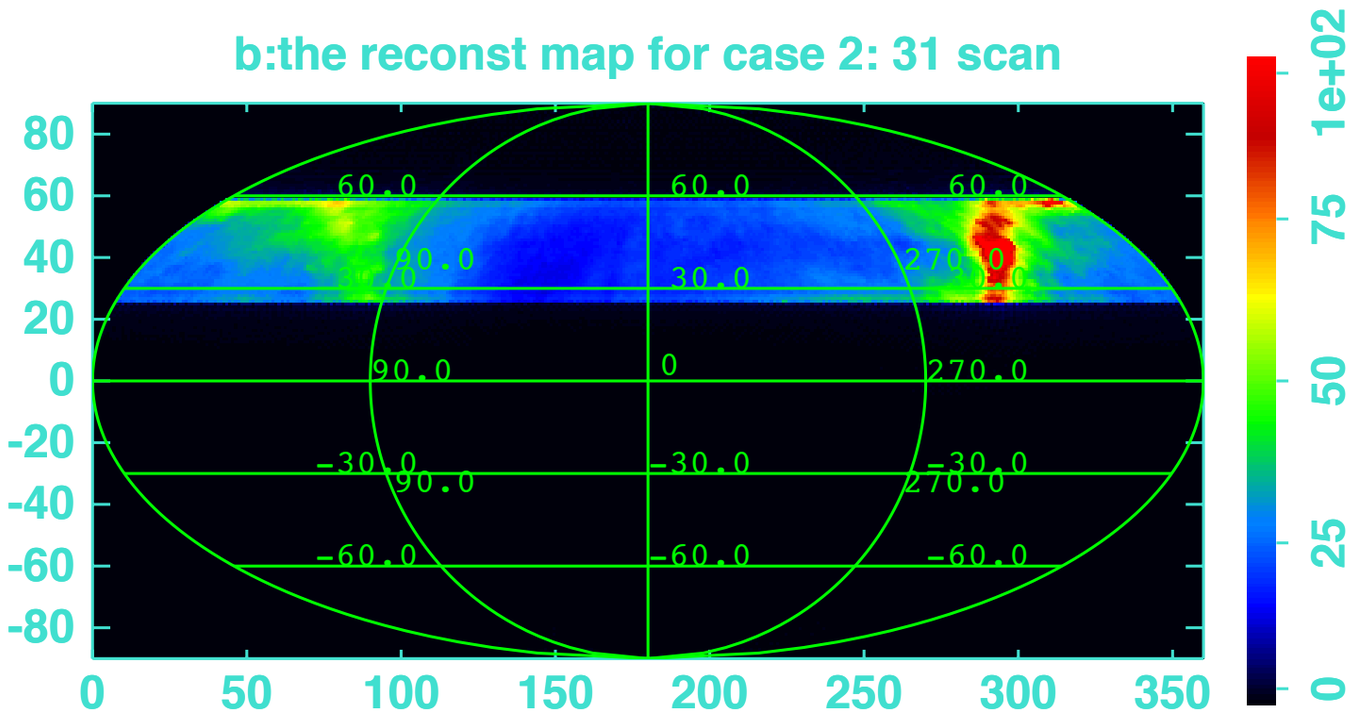


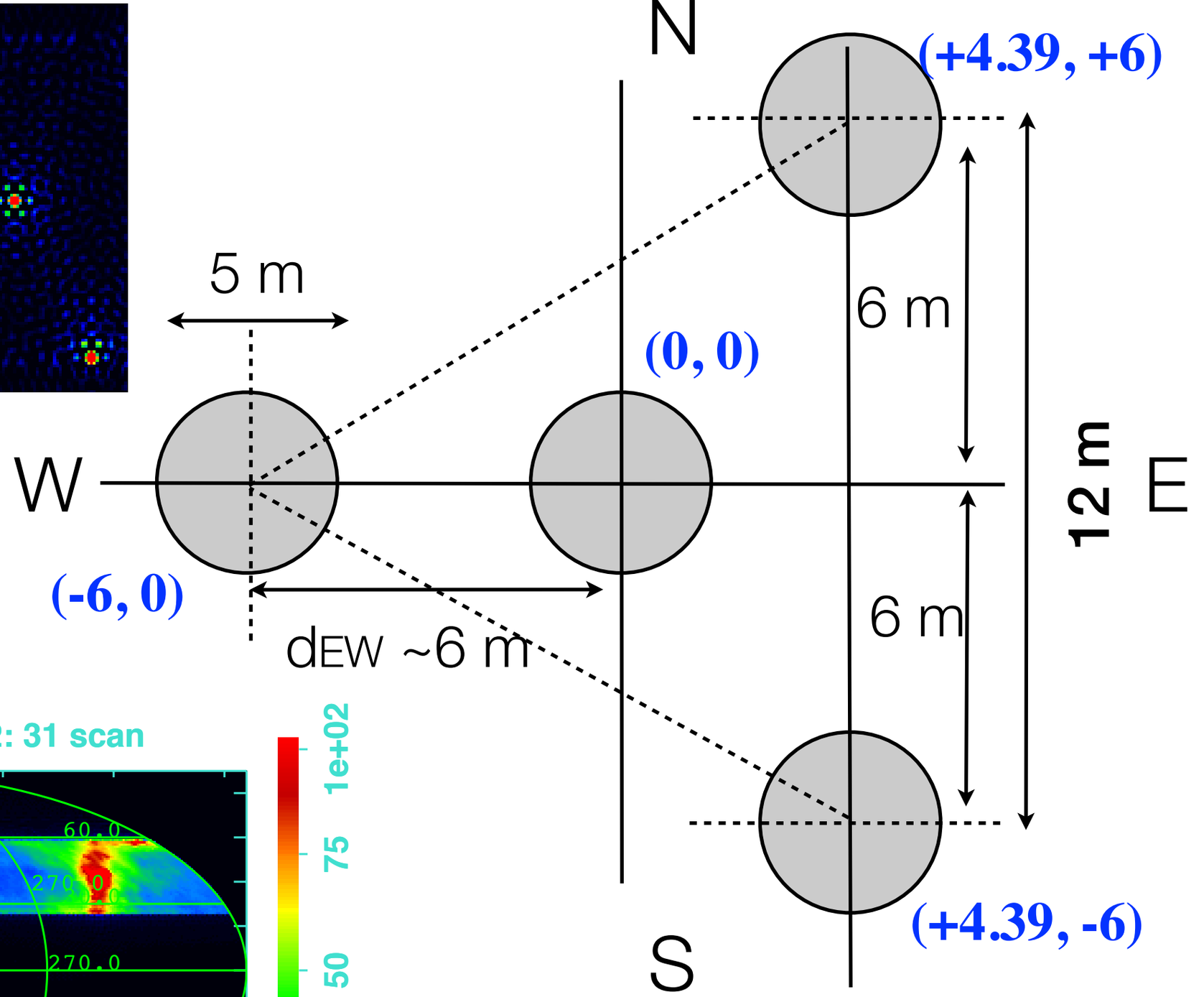
Publication being finalized

PAON interferometer

- PAON : PAraboles à l'Observatoire de Nançay
- PAON-4 : 4 D=5m dish, dense array transit interferometer
- ~ 75 m^2 total collection surface, 8 = 4 x 2 (pol) receivers , 36 visibilities - ~ 2 GBytes/s maximum data rate
- 38 S < Elevation < 15 N → 10 < δ < 60 at Nançay
- 250 MHz band , 1250-1450 MHz
- Interferometric resolution ~ 1 deg @ 1400 MHz
- Aims: RFI cleaning , Tsys measurement, test calibration and map making methods in transit mode
- Reach mK noise level (/per 1deg x 1 MHz pixels) over a wide frequency band - check instrument stability over long term







(x, y) : Antenna position in meters (x:WE, y:SN)

PAON-4 configuration at Nançay -

Latitude 47 deg 23’ - Longitude 2 deg 12’ E

PAON Test Interferometer

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

PAON-4

(F. Rigaud)

installation Nov 2013 - June 2014

4 D=5m dishes

PAON-2 →

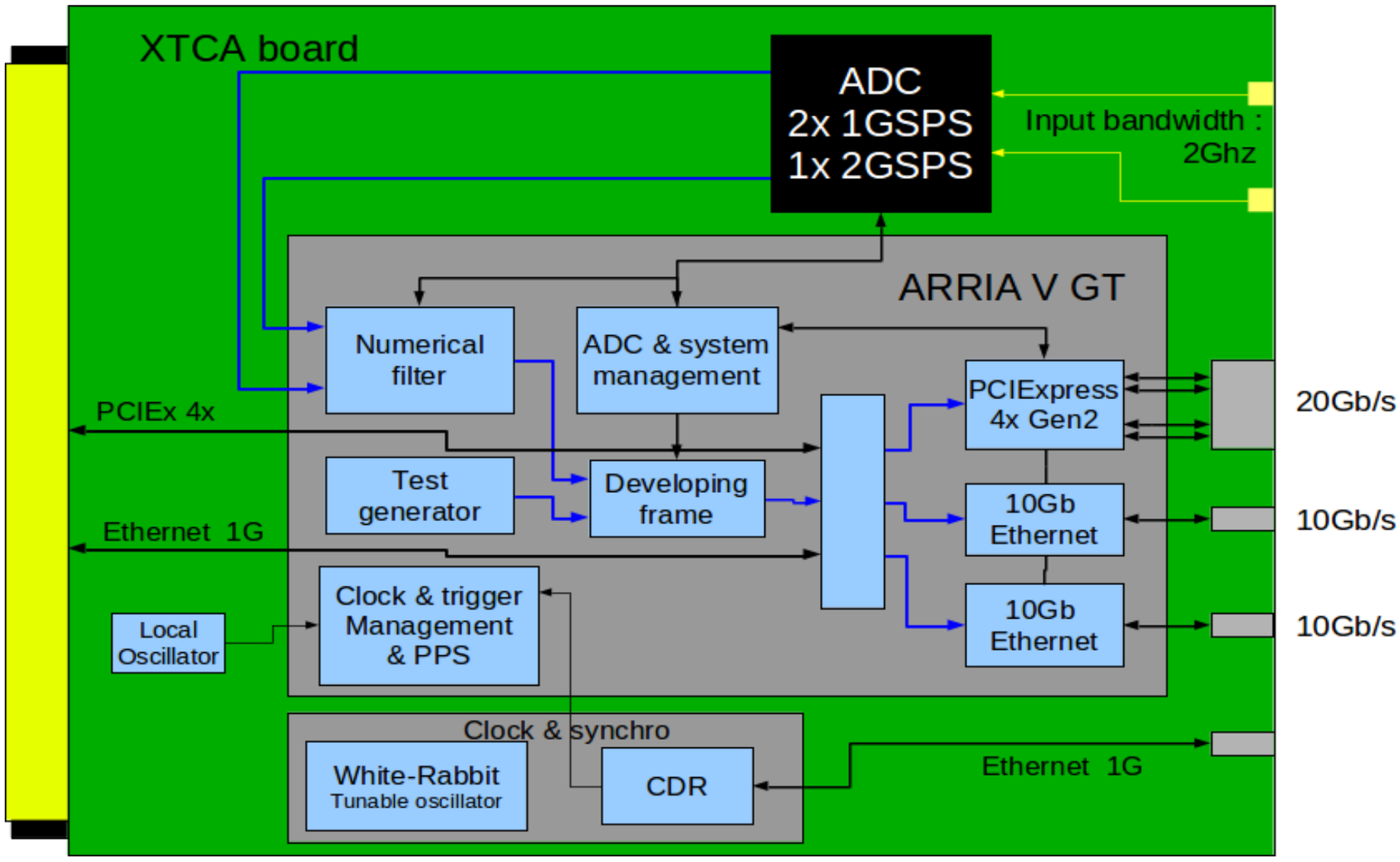
installed September 2012

PAON-4 Test Interferometer

November 2014

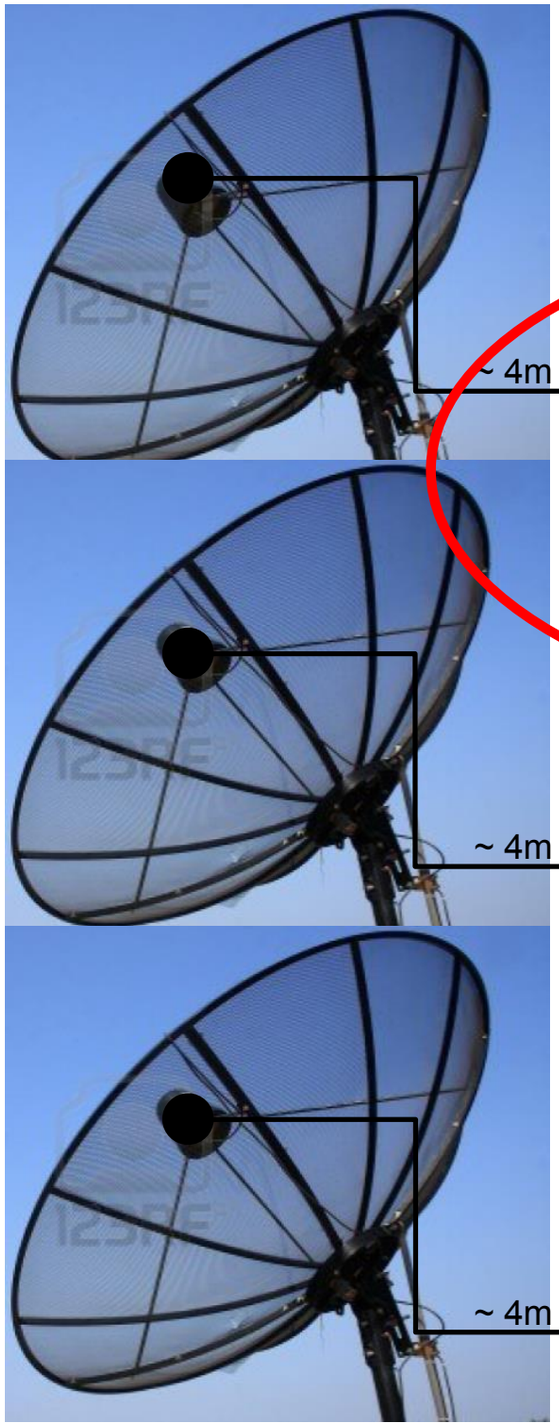
NEBULA Board

Réalisation d'un numériseur rapide.
- Numérisation en bande directe(2GHz).
- Minimisation des longueur coaxiales (implantation sous les antennes).
- Intégration de pré-filtrage ”on ligne”
- Réalisation courant 2015.



D. Charlet / C. Viou

PAON IV System



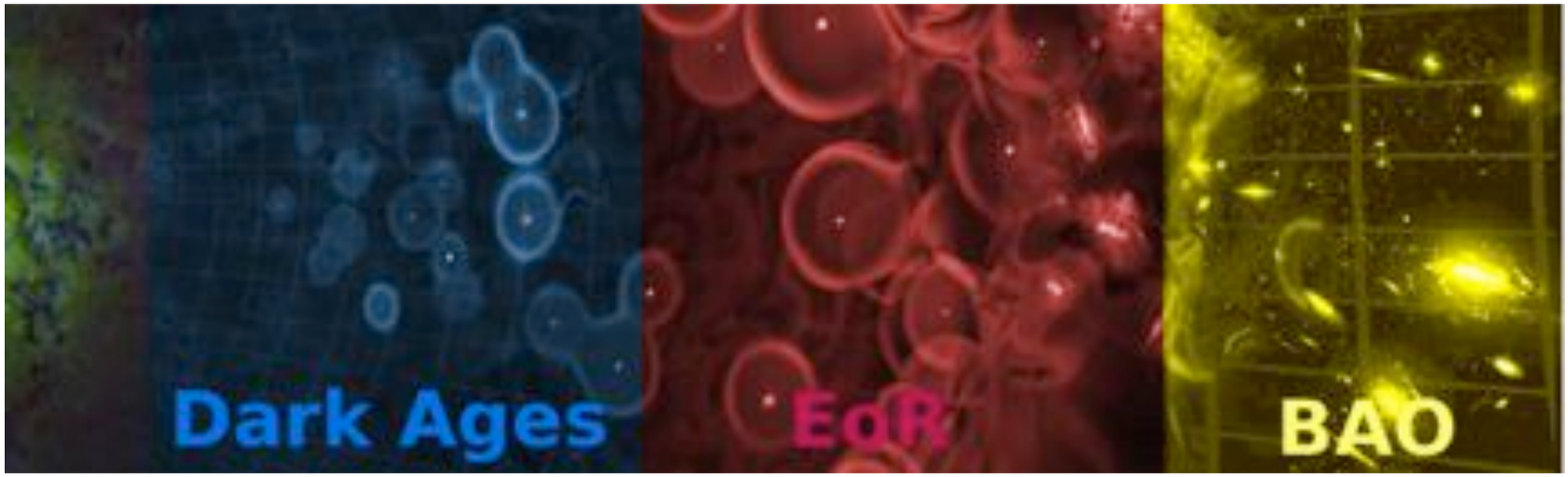
~ 4m
~ 60db
~ 2m
NEBULA Board
ADC
FPGA
~300m
~300m
~ 4m
~ 60db
~ 2m
NEBULA Board
ADC
FPGA
20GByt/s
PCIExExt
/Ethernet
~ 4m
~ 60db
~ 2m
NEBULA Board
ADC
FPGA
Clock & trigger
Distribution
(WR or custom)
UPGRADE
2015

Le but de cette nouvelle étude est de remplacer la chaîne précédente qui intégrait une transposition fréquentielle de 1250MHz vers 250MHz à un système avec un échantillonnage direct.

L'autre amélioration est la possibilité d'implanter cette carte au plus près de l'émetteur afin de s'affranchir des problèmes transmission de signaux large bande sur des coaxiaux.

Le système autorisera une synchronisation sur plusieurs km avec un delta t de l'ordre de la dizaine de ps pour plusieurs centaines de modules.

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
- BINGO

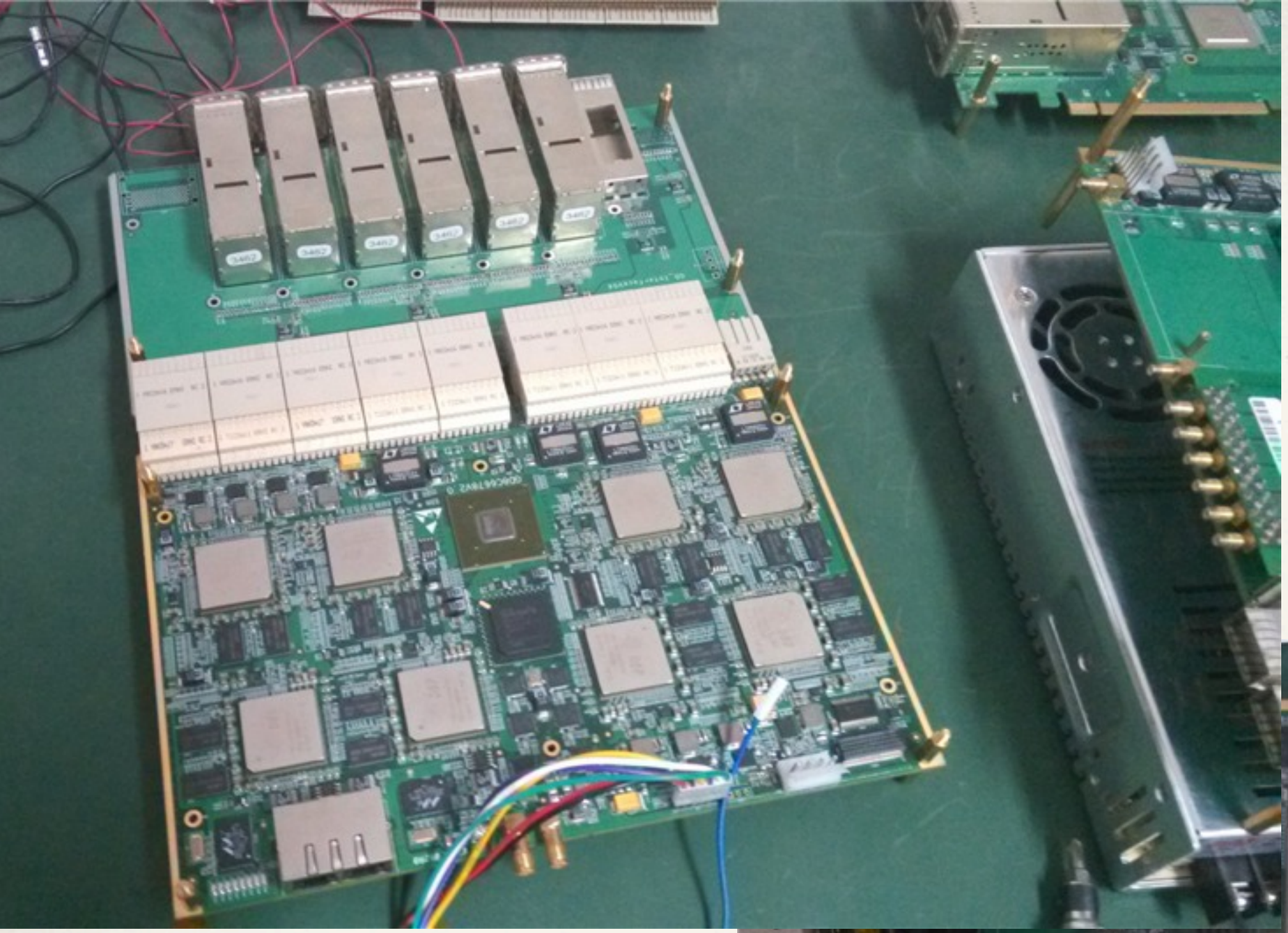
TIANLAI

中国科学院国家天文台

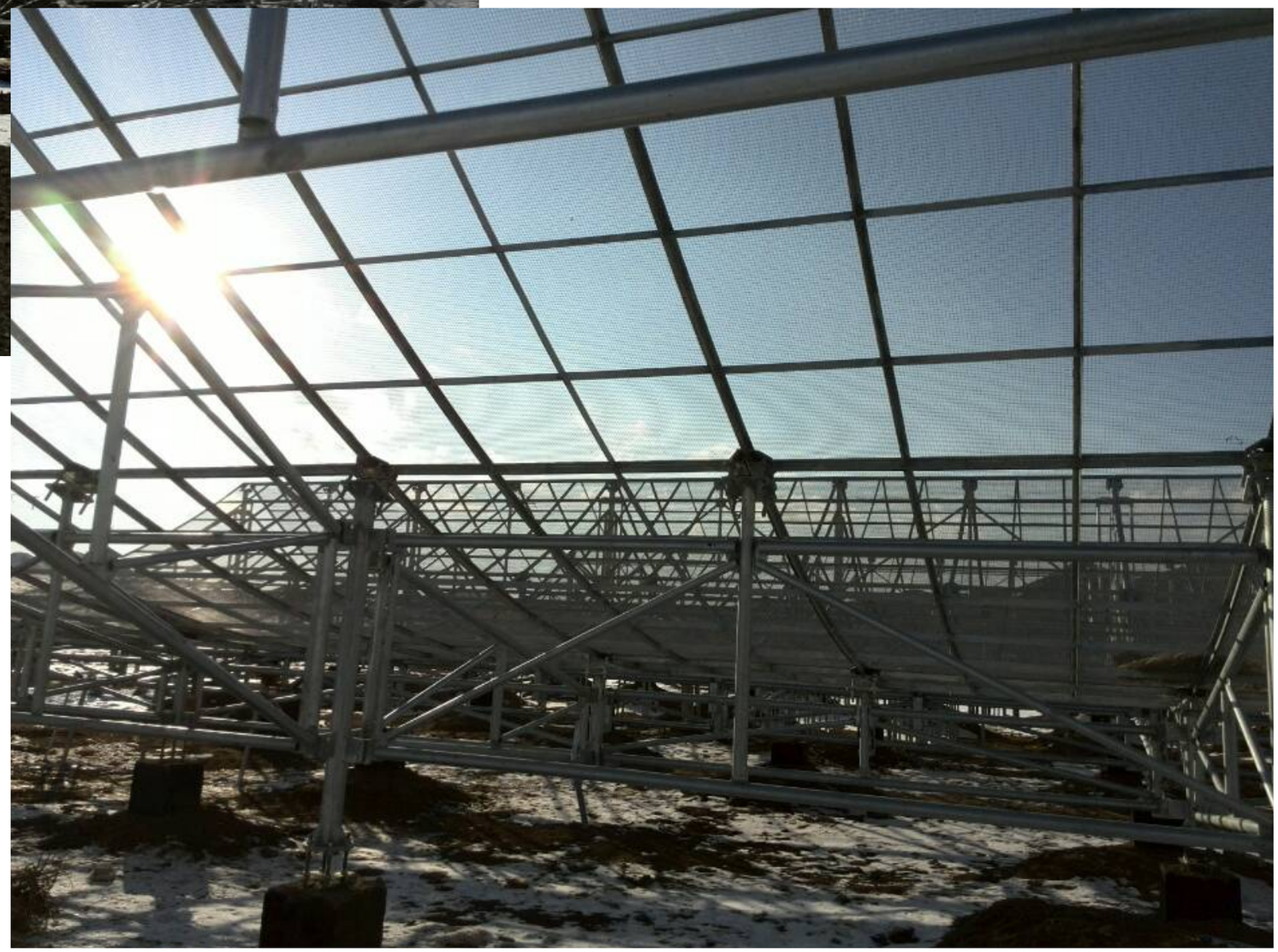
NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

Tianlai site : 44.15 N , 91.8 E

Hongliuxia Xinjiang, western China)



Tianlai correlator & ADC boards



Tianlai cylindrical reflector construction (Nov 2014)

Development plan for the Tianlai 21 cm DE survey

- 2014-2015 : CRT type instrument (3 Cylinder array)
- 2015 : TDA (Tianlai Dish Array) , 16 D=6m dish array
- 2015-2016 : Stage 1 - engineering array, 32 feeds
  - Aim : detect optical × 21cm cross correlation at z ~ 0.7-1
- 2018 ? : 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

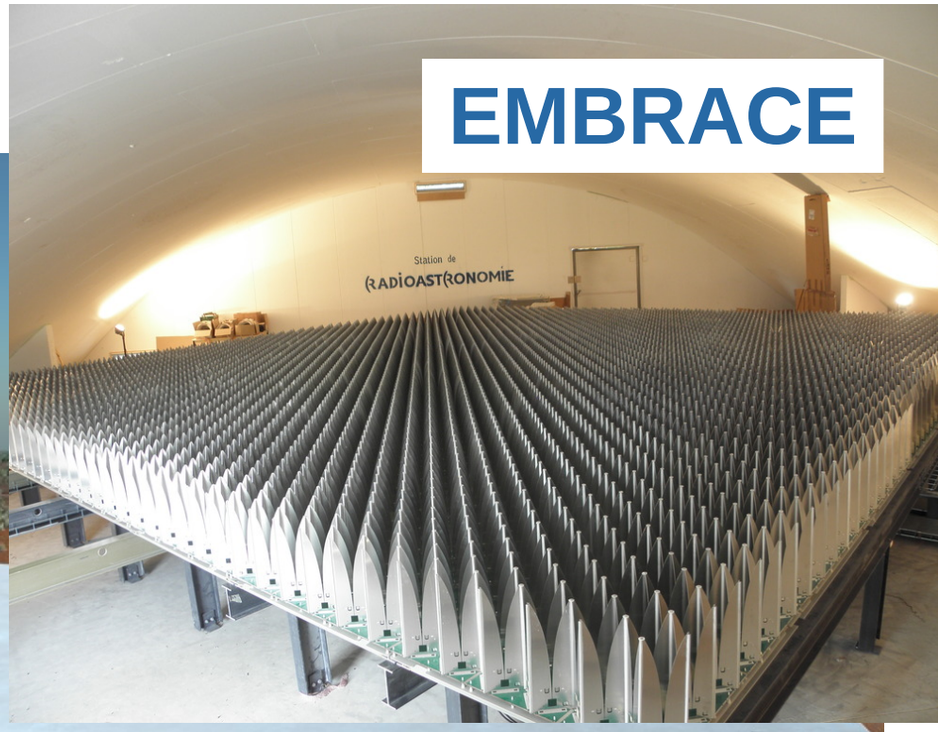
Toward SKA : EMBRACE

EMBRACE Pathfinder for SKA

Steve Torchinsky

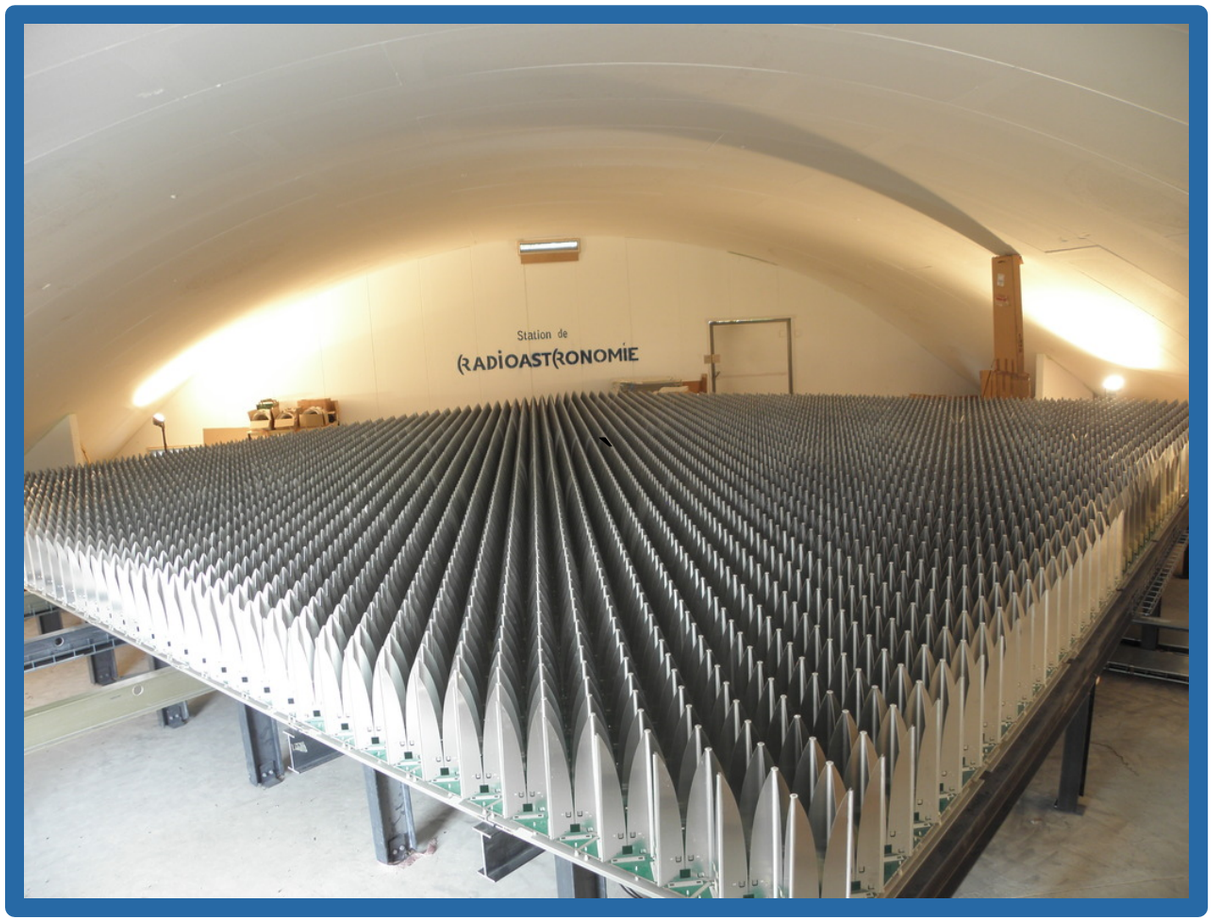
Station de Radioastronomie de Nançay

l'Observatoire de Paris



SKA SQUARE KILOMETRE ARRAY

Dense Aperture Plane Array



- Fully sampled, unblocked aperture
- Large field of view (~100 sq. deg)
- Extremely fast survey machine for HI at cosmological redshifts
- **Ideal for BAO survey**

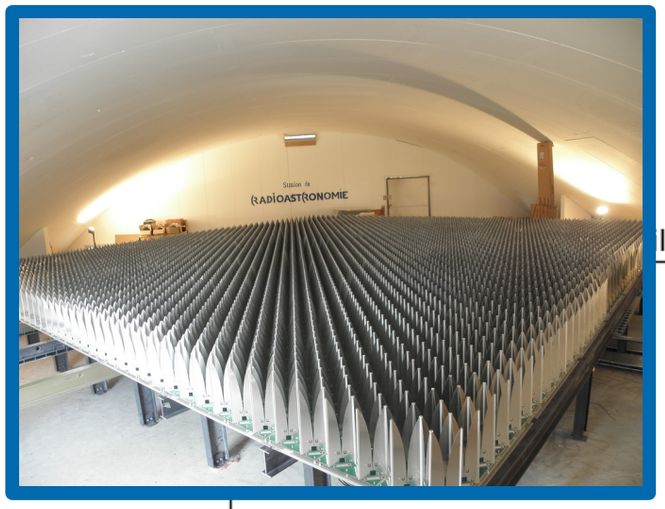
S. Torchinsky (Nançay)

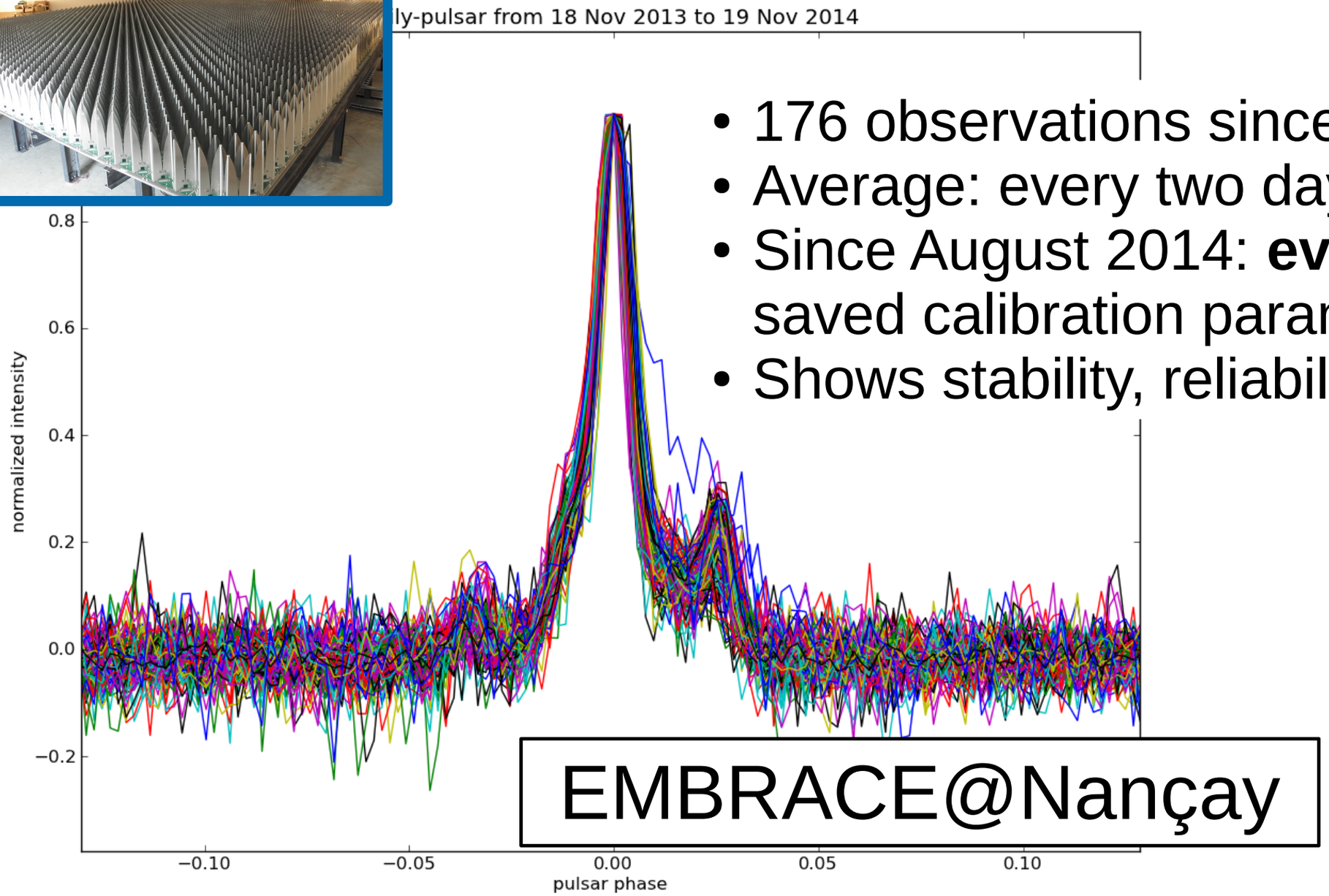
Electronic MultBeam Radio Astronomy ConcEpt

- **EMBRACE is an AAmid Pathfinder for SKA**
- Largely funded within EC FP6 Project SKADS (2005-09)
- For EMBRACE:
  - ASTRON: Project Leader, overall architecture, antennas, industrialization,...
  - Nançay: Beamformer Chip, Monitoring and Control Software
  - MPI Bonn and INAF Medicina: design of multiplexing circuits for RF reception, down conversion, command/control, power supply
- Two demonstrators built. One at Westerbork (132 tiles) and one at Nançay (64 tiles)

S. Torchinsky (Nançay)

Pulsar observing

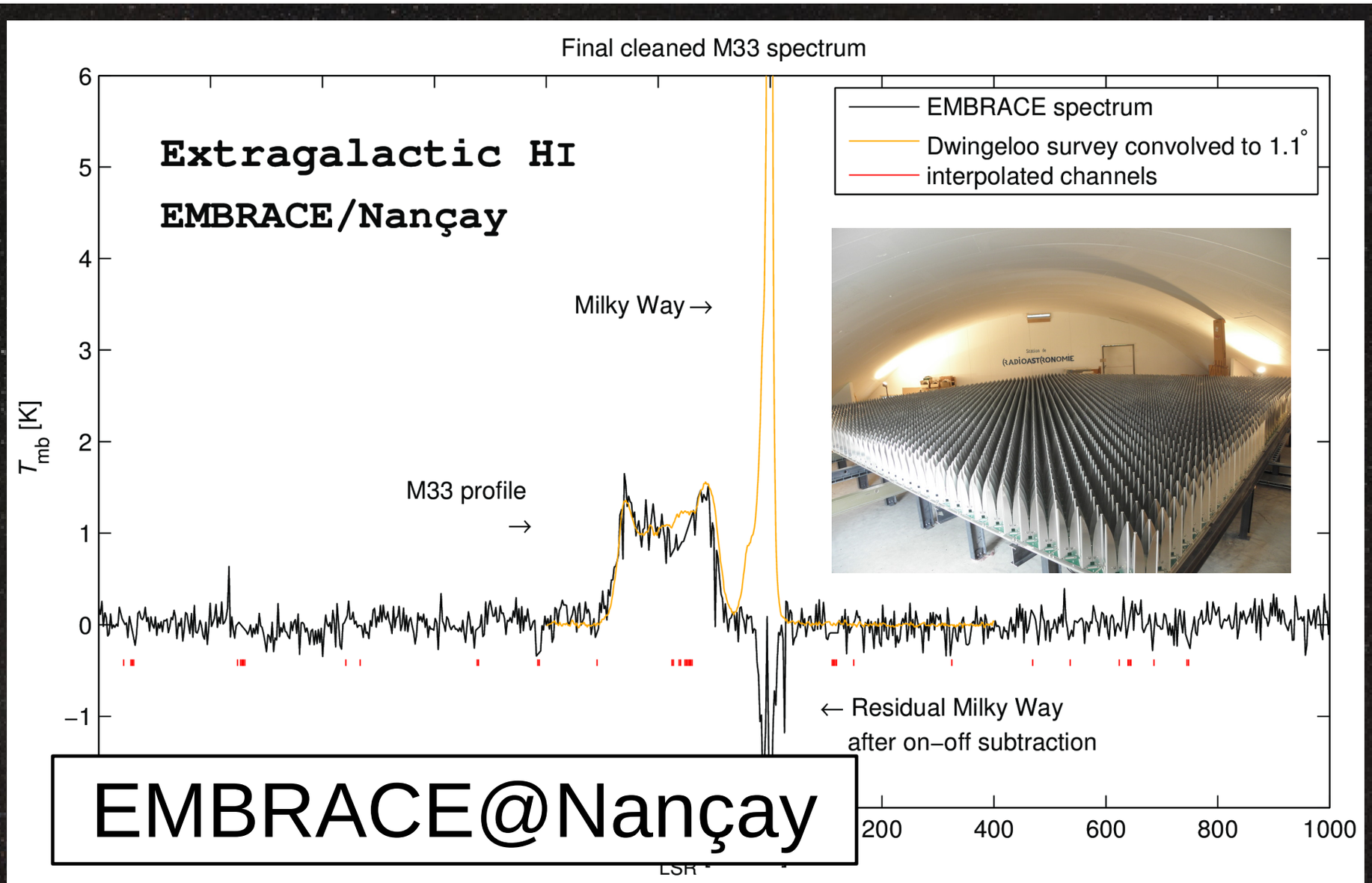


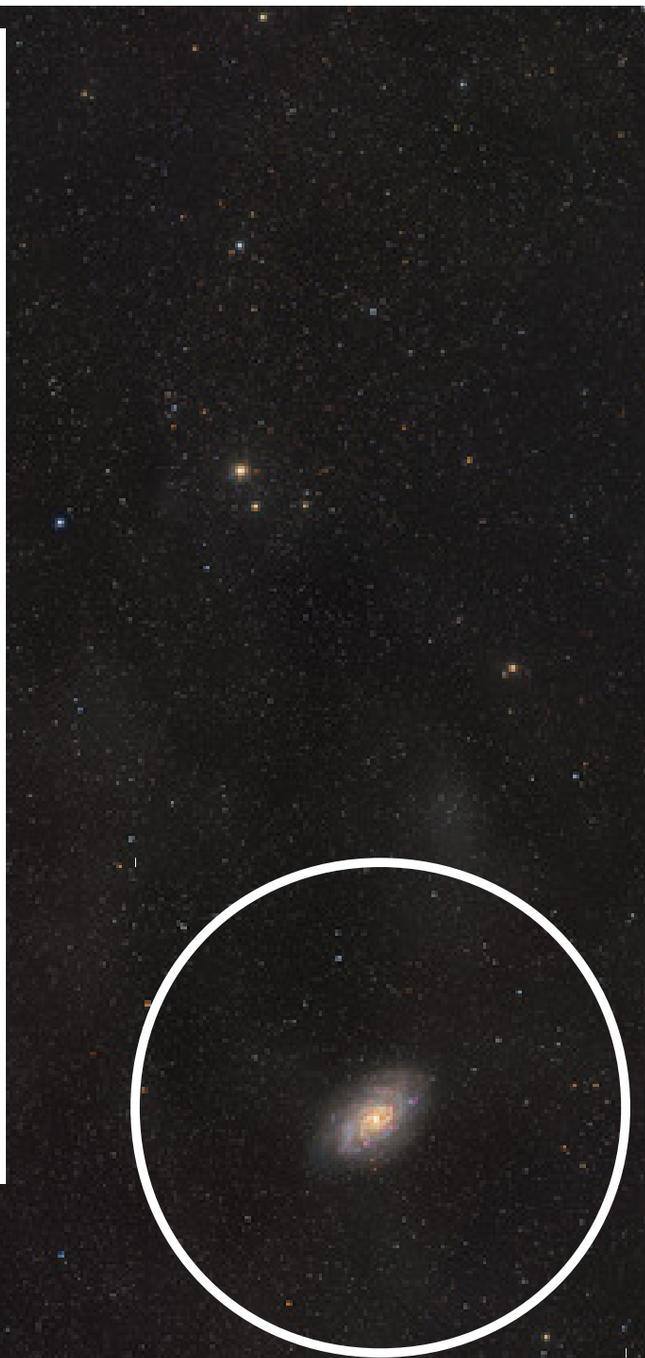


- 176 observations since 18 Nov 2013
- Average: every two days
- Since August 2014: **everyday,** using saved calibration parameters
- Shows stability, reliability.

EMBRACE@Nançay

EMBRACE detects M33





Billion galaxy survey … only 999 999 999 to go !

S. Torchinsky (Nançay)

Outlook

- Exciting scientific perspectives (DE, HI mass distribution and evolution at z ~ 1-2 …) for intensity mapping surveys
- PAON-4 & EMBRACE : testbed for data analysis, electronic developments …
- 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 …
- Contributions welcome !

The End