BAORadio

Réza Ansari

Intensity Mapping workshop
November 2012
St Anne's College, Oxford

- 21cm intensity mapping
  - Brief history of CRT & BAORadio
- BAORadio project
  - Electronic developments
  - BAORadio system with UNIBOARD inteconnexion
- Toward a large 21 cm survey for Dark Energy
  - PAON project (demonstrator array - France)
  - HSA-D (Hydrogen Structure Array Demonstrator) USA
  - Tianlai (China)

BAO @ 21 cm / Intensity mapping instrument concept

- Large field of view (10-100 deg^2) lobe synthesis/interferometer instrument
  - ➡ ~ 100-1000 simultaneous beams → Digital system
- Large bandwidth (100-500 MHz) ➞ significant redshift band $\Delta z \sim 0.5$
- Digital beam former / correlator : data rates ~ TO/s
- Cylinders or packed array of small (D ~ 5 m) dishes or tiles, or single dish (D ~50 - 100 m) with FPA / multi horn receiver
- Resolution 10 arcmin, Surface ~ 10 000 m^2
  - ➡ antenna / receivers distributed over ~ 100 m × 100 m

- 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
- 2009-2011 : discussions on instrument configuration, dish arrays vs. cylinders
- 2010-2012 : Collaboration with NAOC / X. Chen, the Tianlai project

21cm BAO R&D

2007-2012

cnrs IN2P3 Les deux infinis

Carnegie Mellon University

CITA ICAT

cea IRFU

CSIRO

NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

Fermilab

l'Observatoire de Paris

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

the David & Lucile Packard FOUNDATION

CRT prototype at Pittsburgh (CMU)

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

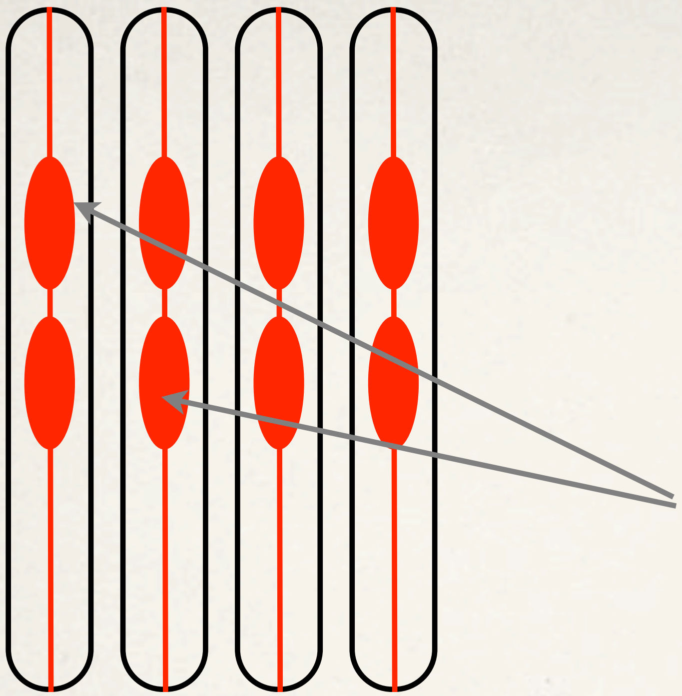
IRFU - CEA

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

Observatoire de Paris

P. Abbon
E. Delagnes
H. Deschamps
C. Flouzat
P. Kestener
P. Colom
J.M. Martin
J. Borsenberger
J. Pezzani
F. Rigaud
S. Torchinsky

BAORadio : electronic chain, acquisition & processing system overview



AS1 : Analog Stage 1

AEM

DIG

TFFT

Optical link / Ethernet

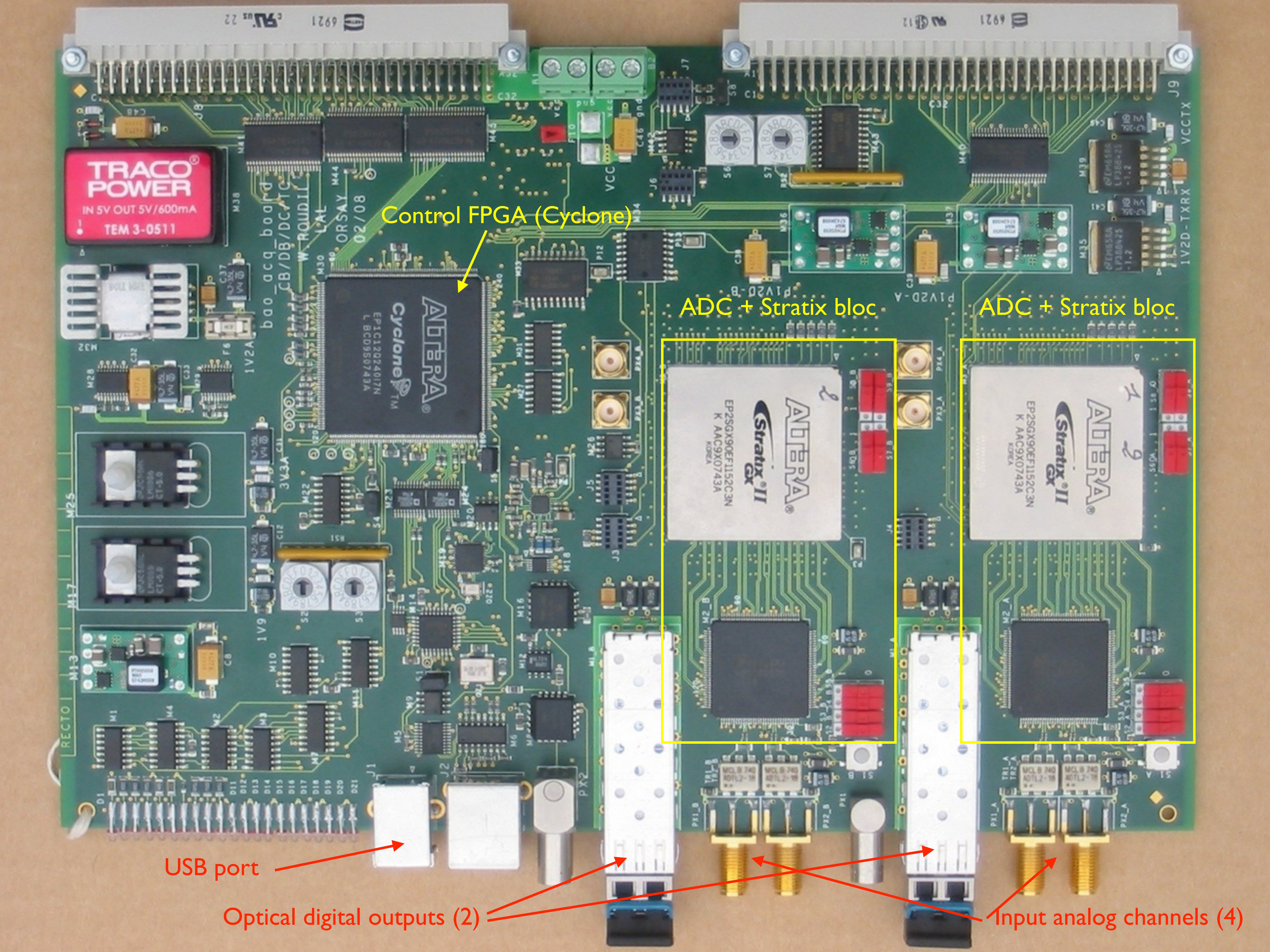
~ 250-500 optical links

APCCL

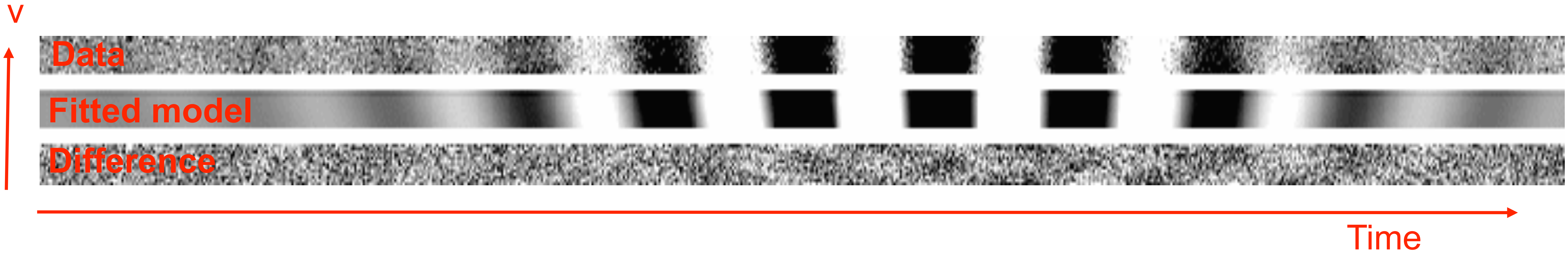
Acquisition and Processing Computer Cluster

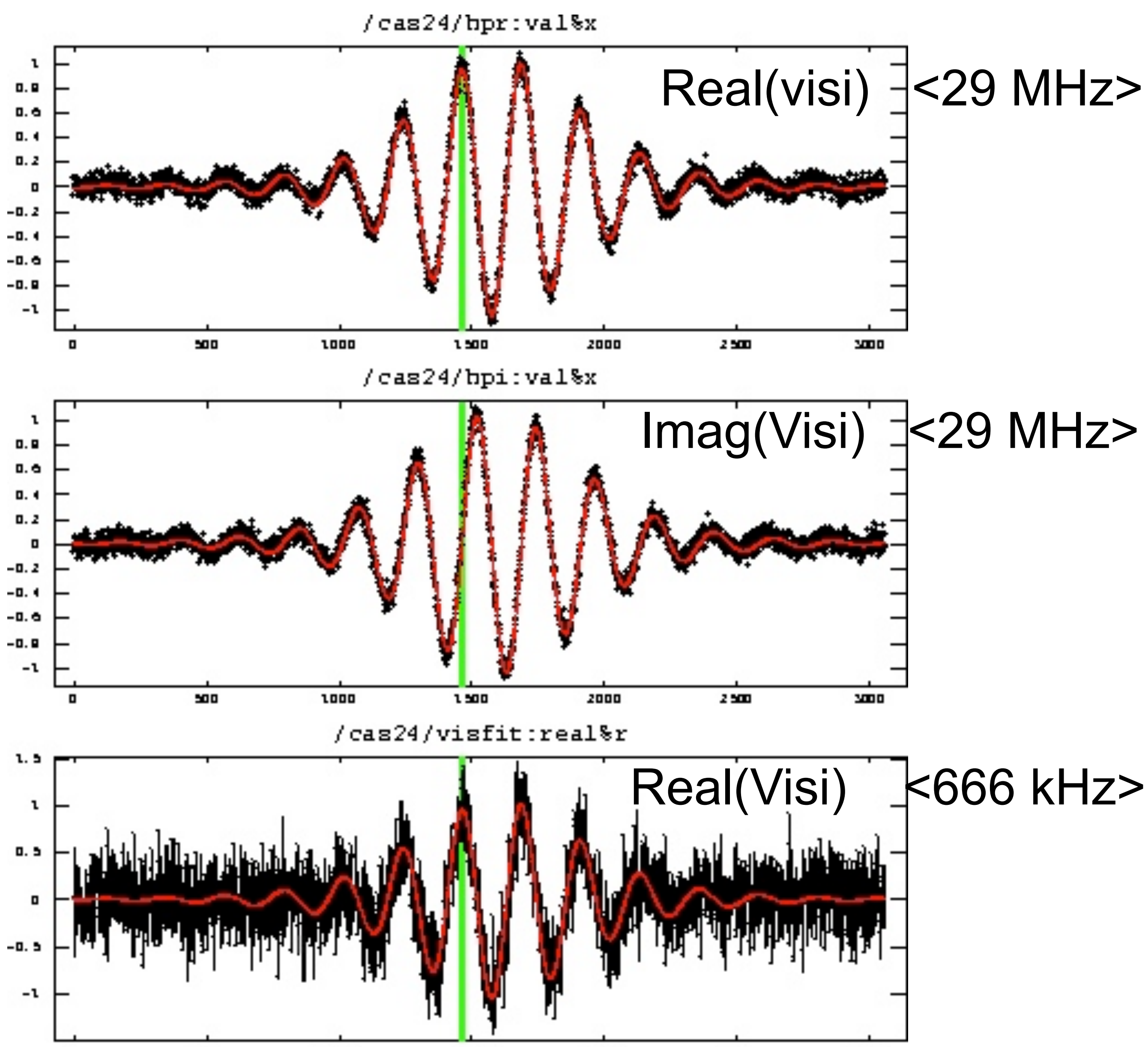
DCLK

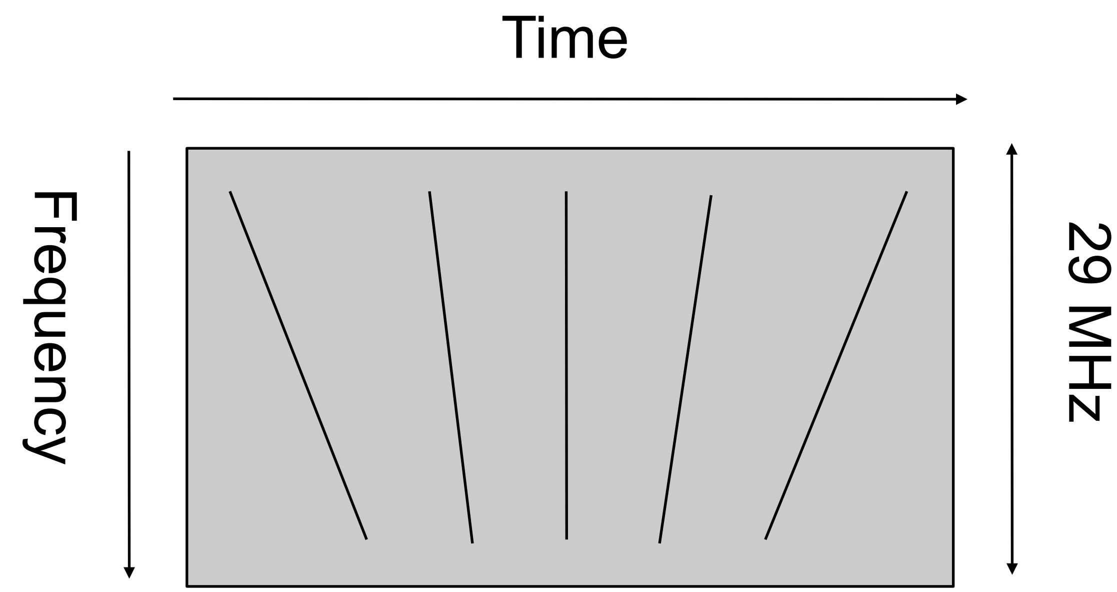
Ansari et al., Compte Rendu Physique (2012), Vol 13


Control FPGA (Cyclone)
ADC + Stratix bloc
ADC + Stratix bloc
USB port
Optical digital outputs (2)
Input analog channels (4)
TRACO POWER
IN 5V OUT 5V/600mA
TEM 3-0511

CasA24 - Pittsburgh/Nov 2009



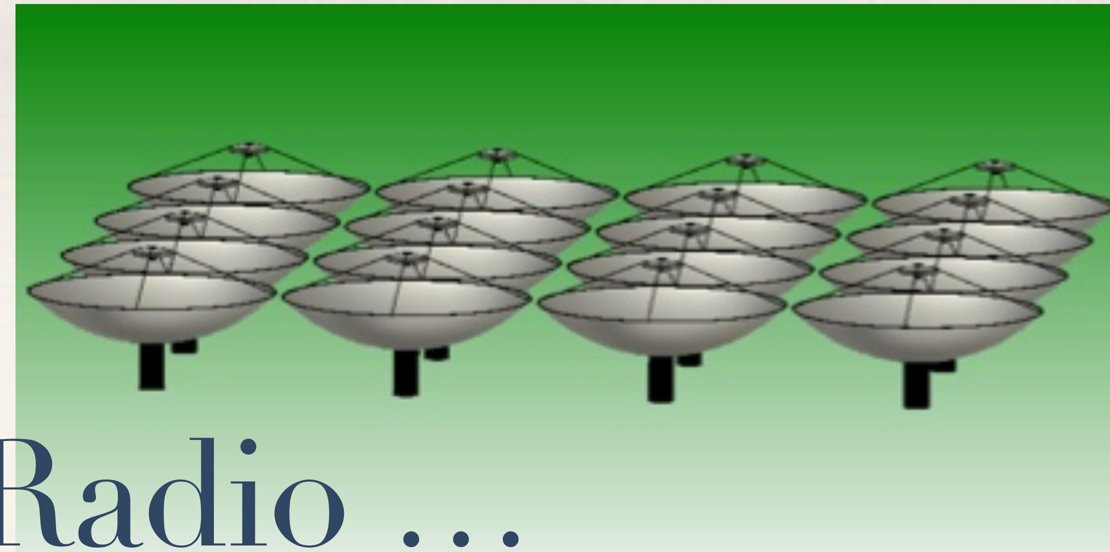


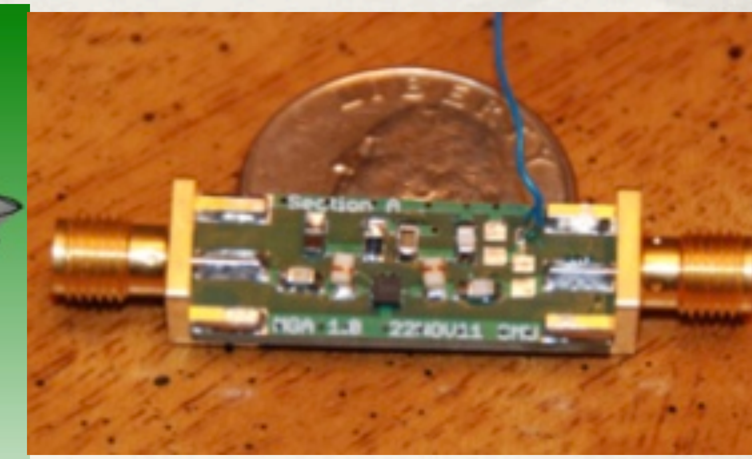


Enlarged fringe wave
for low frequencies

RFI cleaning,
calibration, beam
forming …

Ansari et al., in preparation





HSA - D

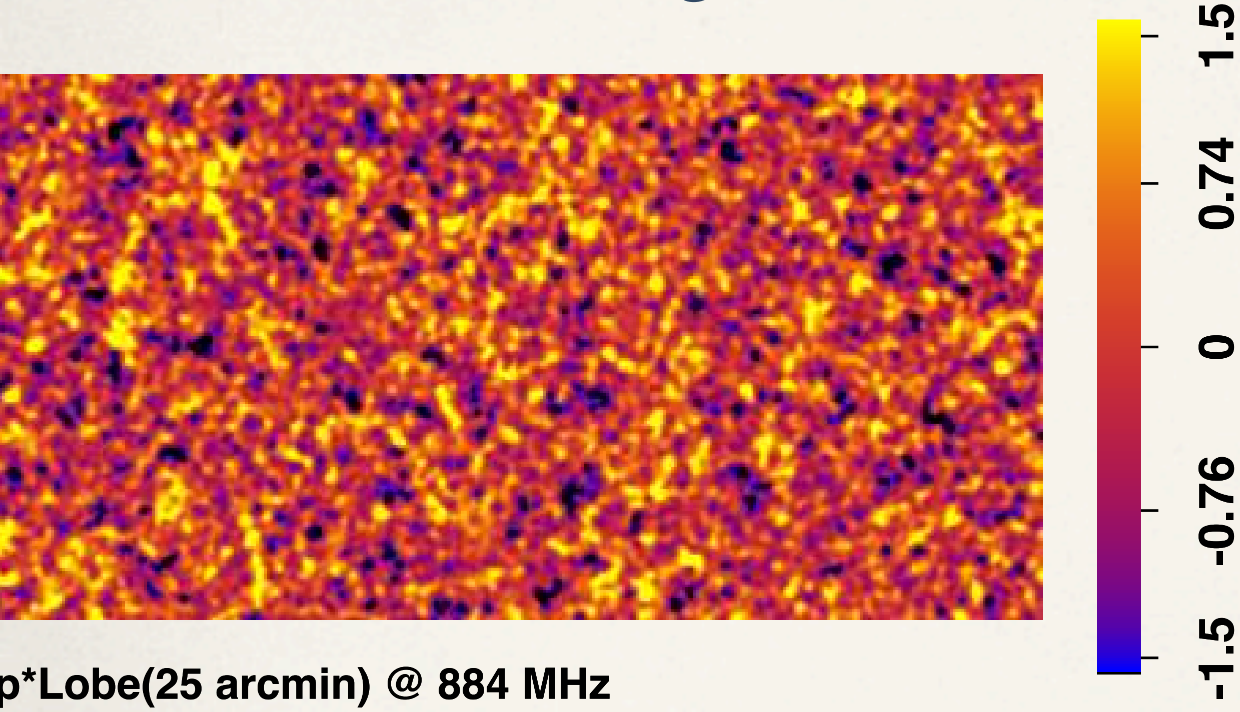
CRT / BAORadio …
Toward a large instrument and a collaboration for 21 cm DE survey

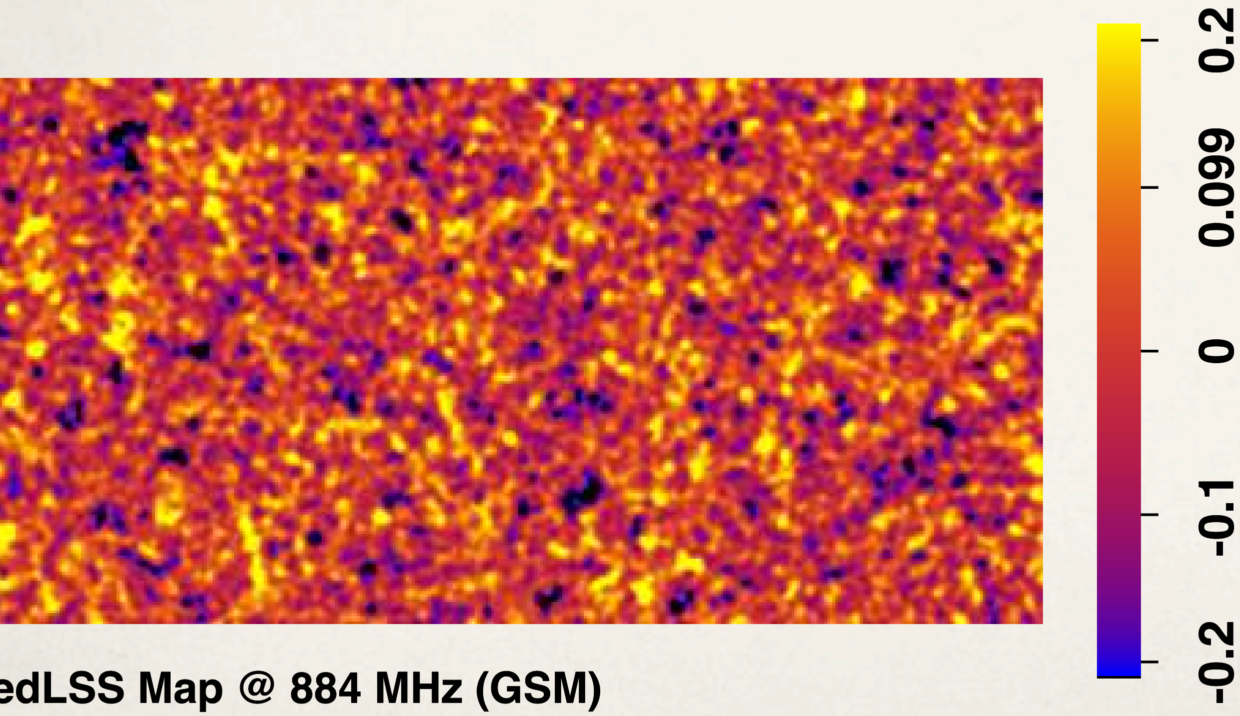
- Tianlai project (NAOC / China)
- HSA - D (US, P. Timbie, J. Peterson)
  Hydrogen Structure Array Demonstrator
  packed 4x4 array of D~5 m dishes + CASPER electronics + PC-GPU correlator
- PAON demonstrator (France)

Possible development plan for a 21 cm DE survey (Tianlai ?)

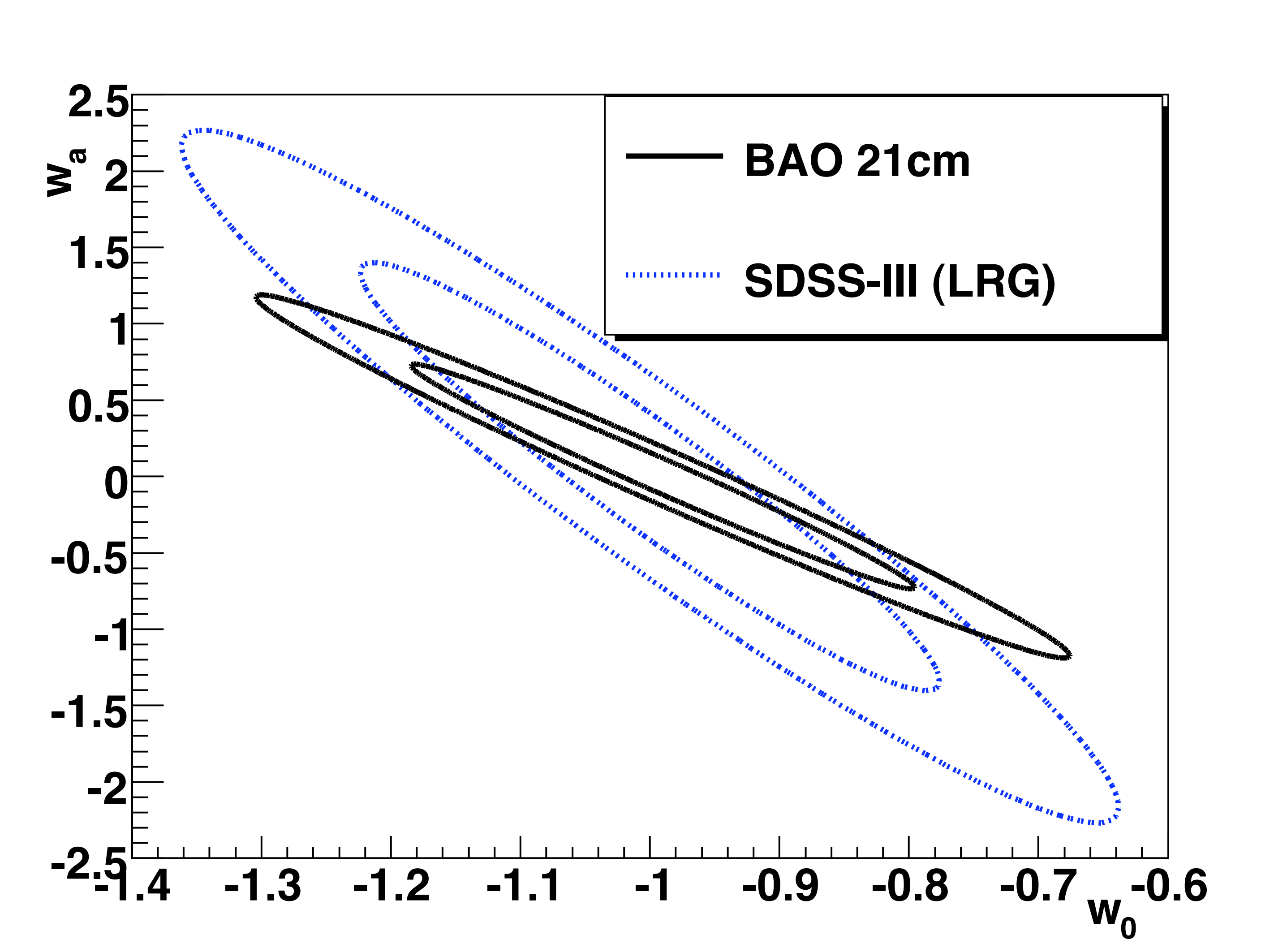
- Stage 0 : tests with cylinders, dishes, feed design, electronic development …
- Stage 1 : Engineering array, 32-48 feeds (2013-2014)
  - Aim : detect optical × 21cm cross correlation at z ~ 0.3-0.5
- Stage 2 : First science array, 256 feeds (2015-2016)
  - Aim: detect BAO with 21 cm signal at z ~ 0.7 - 1.0
- Stage 3 : DE survey, ≥ 1000 feeds
  - Aim: measure BAO with 21 cm signal in the redshift range 0.5…2.0

Component separation
Original 21 cm signal
Recovered signal





Sensitivity to DE parameters



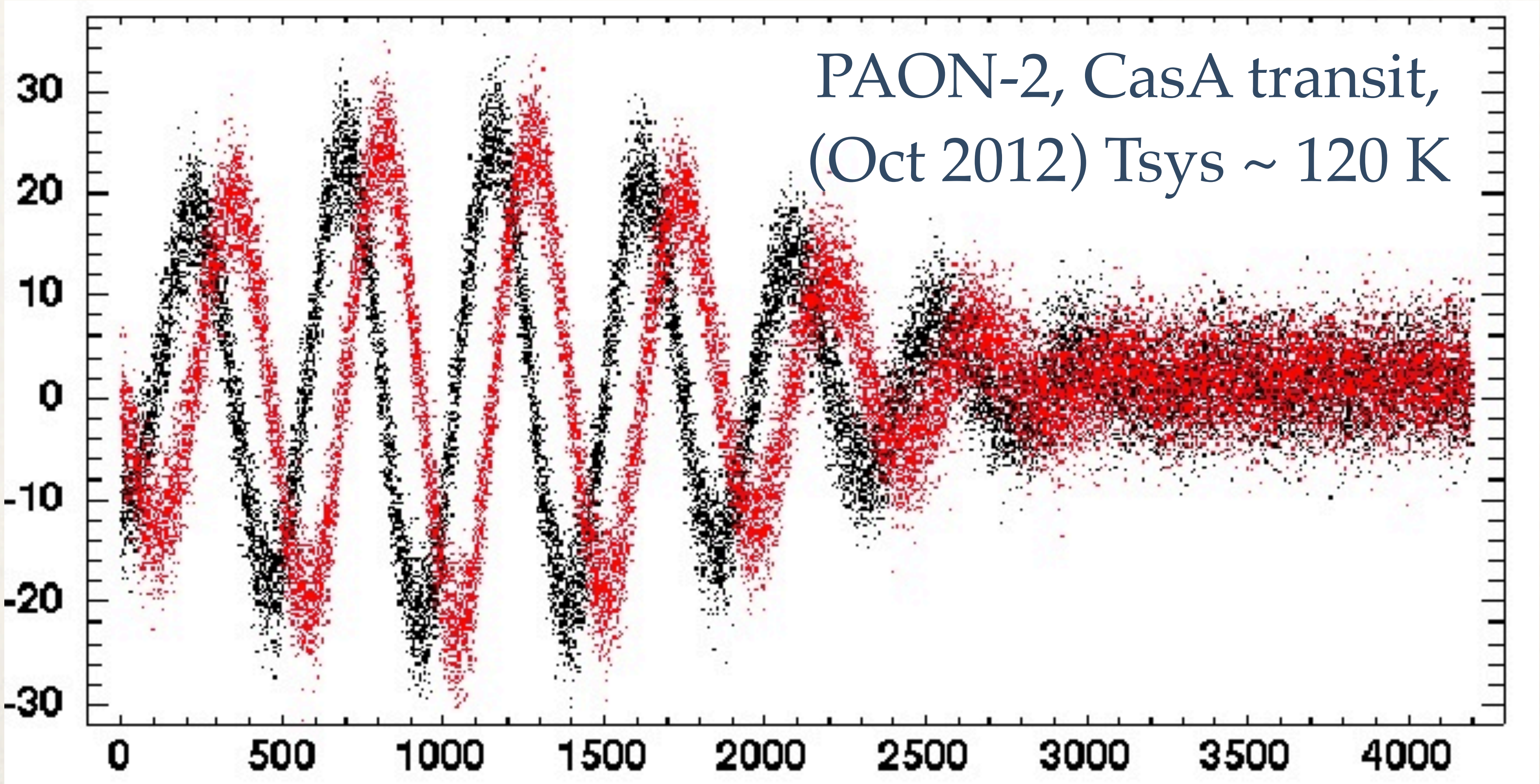
21 cm BAO vs optical redshift survey
10 000 sq.deg, 3 years survey, 5 redshift bands
(0.5 1.0 1.5 2.0 2.5)
10 000 m^2 collecting area, 400 beams

Ansari et al., A&A (2012) - 21 cm survey sensitivity & foreground subtraction

Test interferometer for an array of small dishes
(RAID concept)
PAON-2 : 2 × D=3 m dishes, currently operating
PAON-4 : 4 × D=5 m dishes, construction phase
Spring/Summer 2013

PAON

Paraboles A l'Observatoire de Nançay



PAON-2

Installed at
Nançay
September 2012

Outlook

- Exciting scientific perspectives (DE, HI mass distribution at z ~ 1.5 ...) for a cosmological radio survey
- Interesting technical problems (electronic/computing)
- Scientific challenge : data processing, 3D map making & foreground subtraction
- 21 cm BAO: new Cosmology & Astrophysics playground ?
  - ➡ 5-15 M€ (7-20 M$) project for 2014-2020 ?

The End

Backup slides

Electronic chain modules

- AEM : Analog Electronic Module (Amplification, filtering, frequency shifter) - *(IRFU)*
- DISCLK : Clock and trigger distribution system *(IRFU)*
- DIG/FFT : Digitizer Frequency Separator (ADC-Board) 4 channel, 500 MHz sampling, with on the fly FFT capability, dual high speed optical data transfer *(LAL, IRFU)*
- PDR : PCI-Express data reception module *(LAL)*
- TAcq : Acquisition/control software *(LAL-IRFU)* parallel (multi-thread, multi node) OO/C++

- Ansari et al , Comptes Rendus Physique, 2012, Volume 13, p. 46 (Version abrégée en français arXiv:1106.5659)
- Ansari et al, NIM 2013 en préparation (Design and qualification of an electronic chain for 21 cm cosmology)

LSS / BAO in radio with galaxies

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

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

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 !**

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

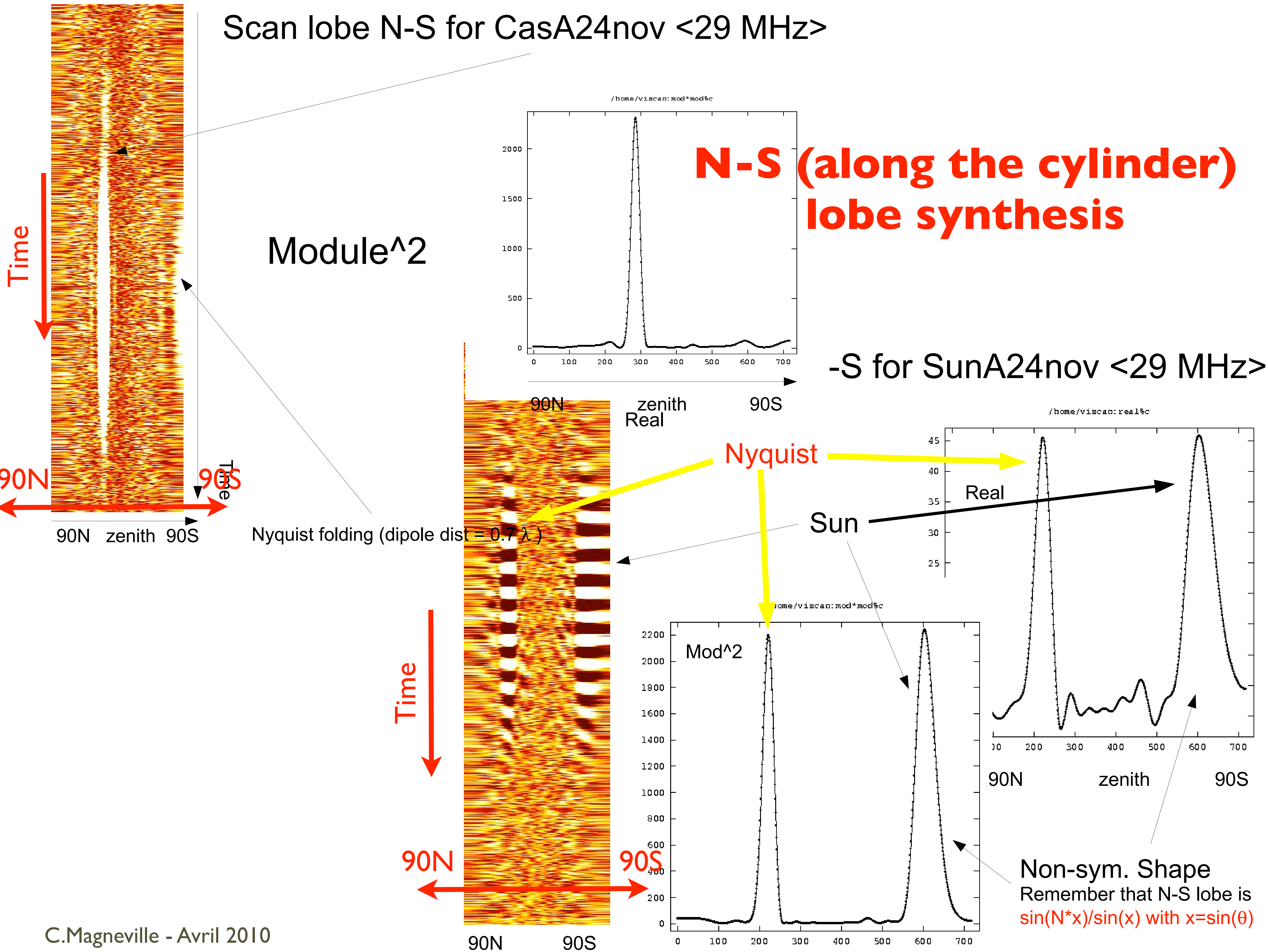
- Needs only a modest angular resolution 10-15 arcmin
- Needs a large instantaneous field of view (FOV) and bandwidth (BW)
- Instrument noise (Tsys)
- Foregrounds / radio sources and component separation

- 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)

mK sensitivity with Tsys ~ 50-75 K

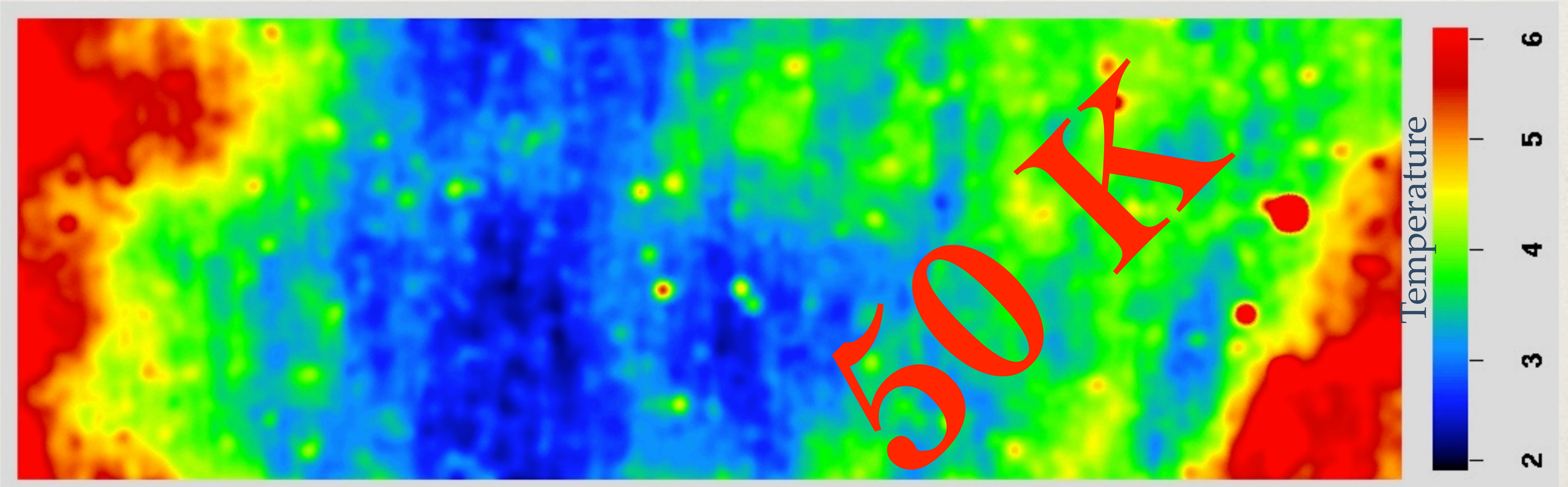
- Large integration time (10^4-10^5 s) → $\propto 1/\sqrt{(t_{int}\,\Delta\nu)}$
- Instrument (Tsys, beam …) stability
- multi beam - large FOV radio telescope
- interferometer or FPA/multi feed receivers with single dish

N-S (along the cylinder) lobe synthesis



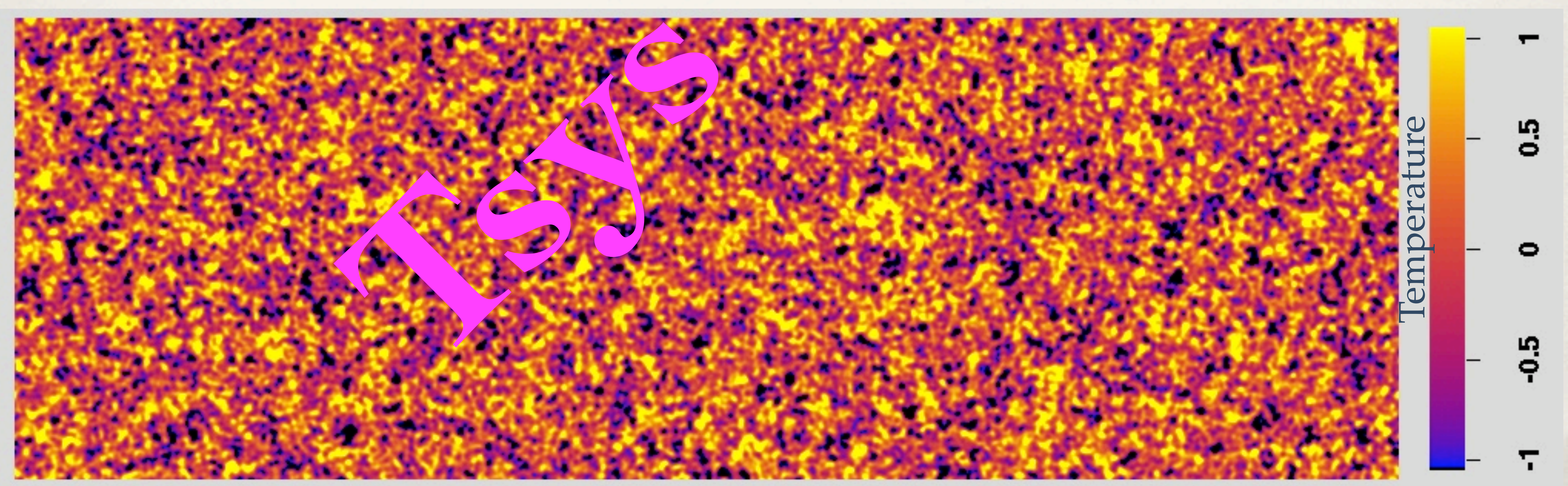
Radio foreground (GSM) @ 720 MHz (z=1.) - Kelvin

K

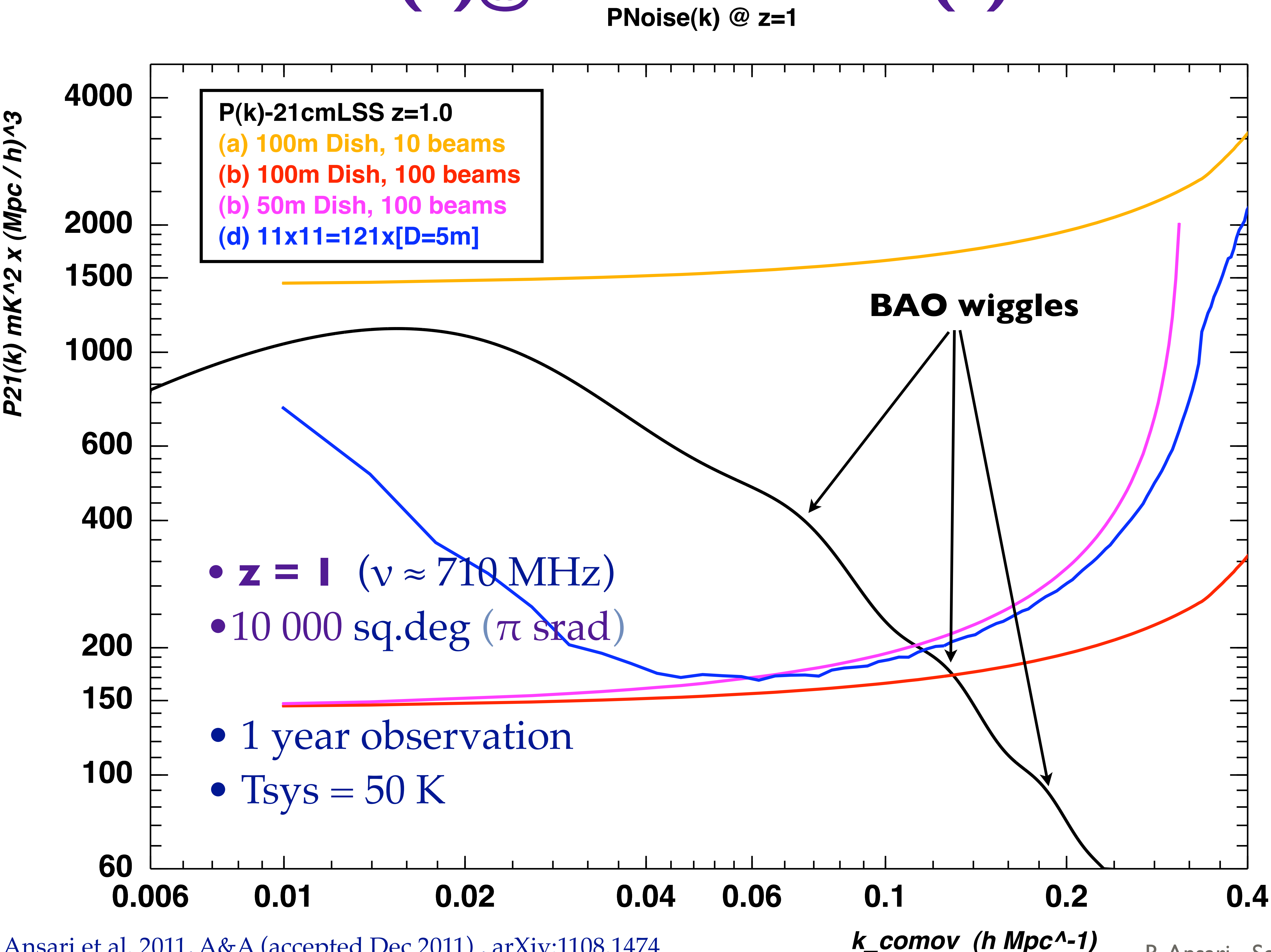


21 cm sky brightness @ 720 MHz (z=1.) - milliKelvin

mK



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



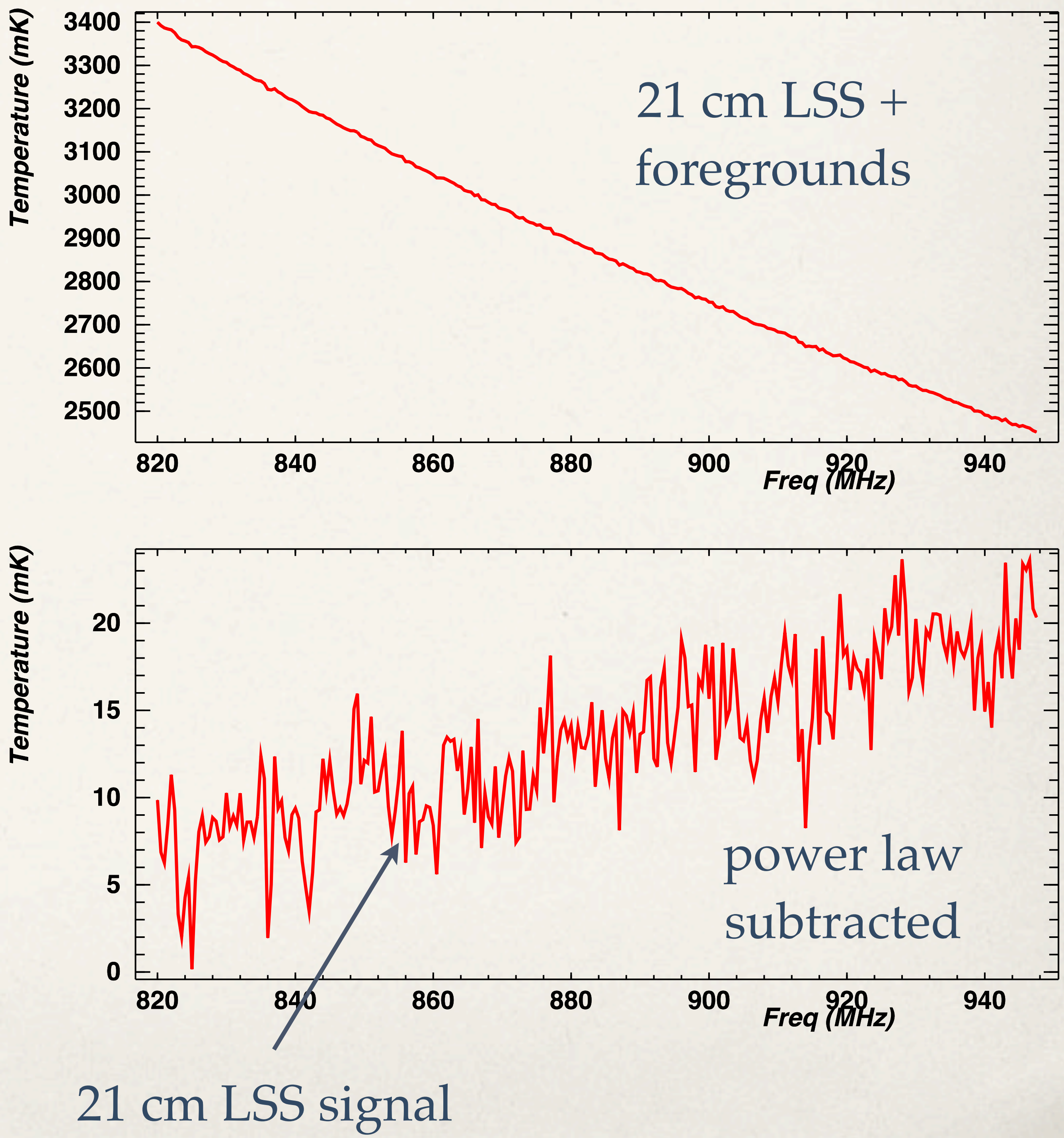
- **z = 1** (ν ≈ 710 MHz)
- 10 000 sq.deg (π srad)
- 1 year observation
- Tsys = 50 K

Ansari et al. 2011, A&A (accepted Dec 2011) , arXiv:1108.1474

R. Ansari - Sep 2011

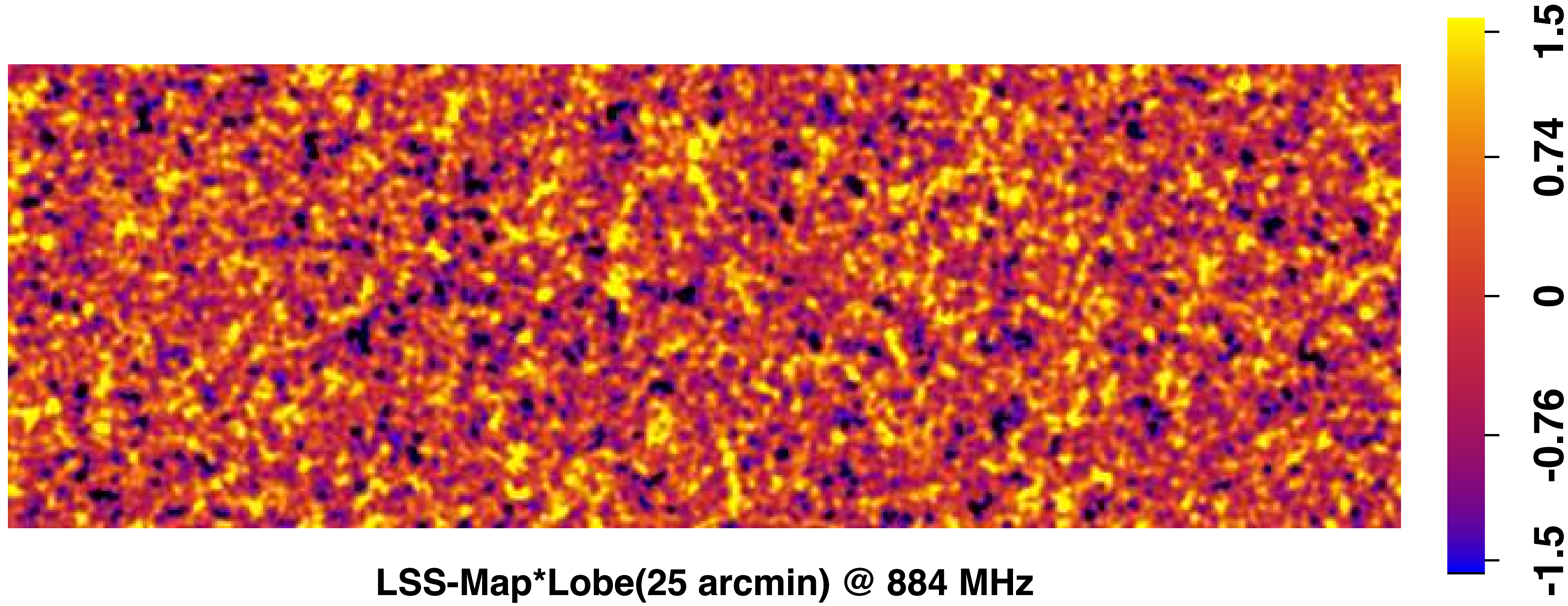
Foreground removal

- 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 …

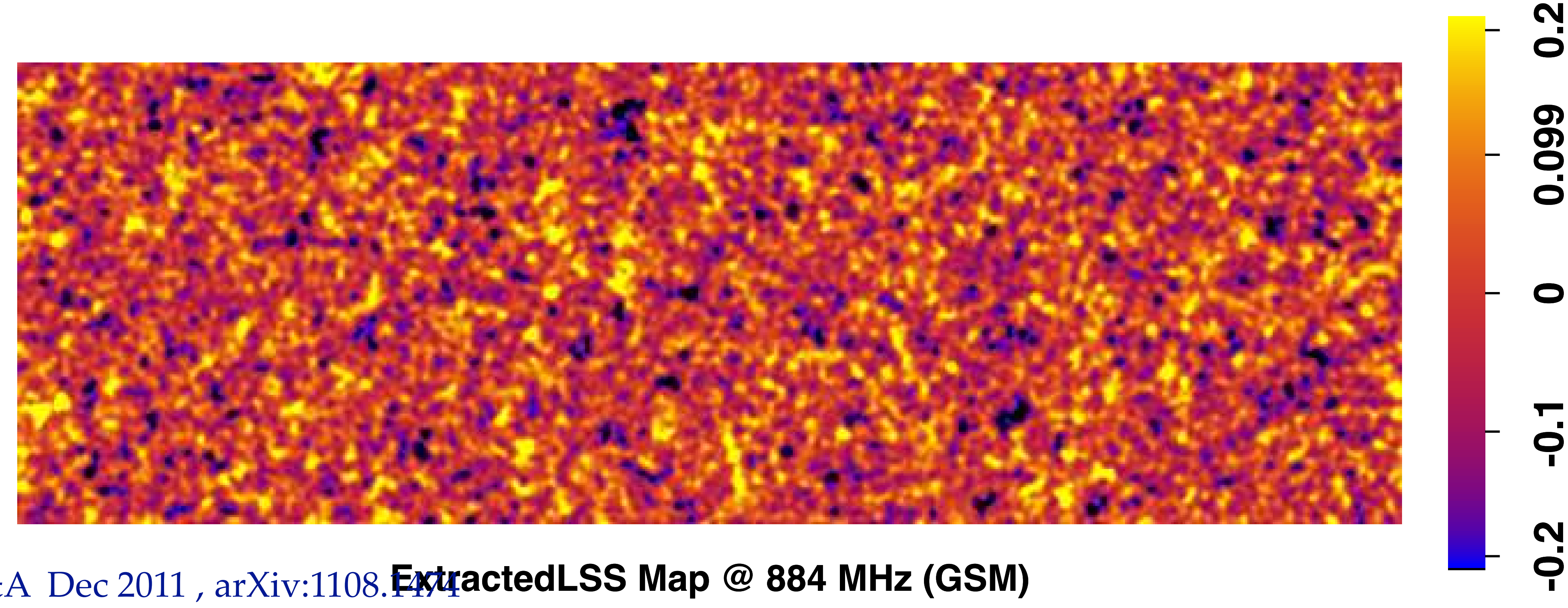


Component separation
21cm LSS signal extraction @ z=0.6

Original simulated 21cm signal



Recovered 21cm signal, in presence of continuum radio signals, and instrument response



Ansari et al. 2011, A&A Dec 2011 , arXiv:1108.1474

Signal-to-Noise Eigenmodes

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

$$\mathbf{v} = \mathbf{B}\mathbf{a} + \mathbf{n} \tag{1}$$

- Construct the covariances of the signal and foregrounds

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

- Jointly diagonalise both matrices (eigenvalue problem)

Karhunen-Loève (KL) Transform:

$$\mathbf{S}\mathbf{x} = \lambda \mathbf{F}\mathbf{x} \tag{3}$$

- 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.

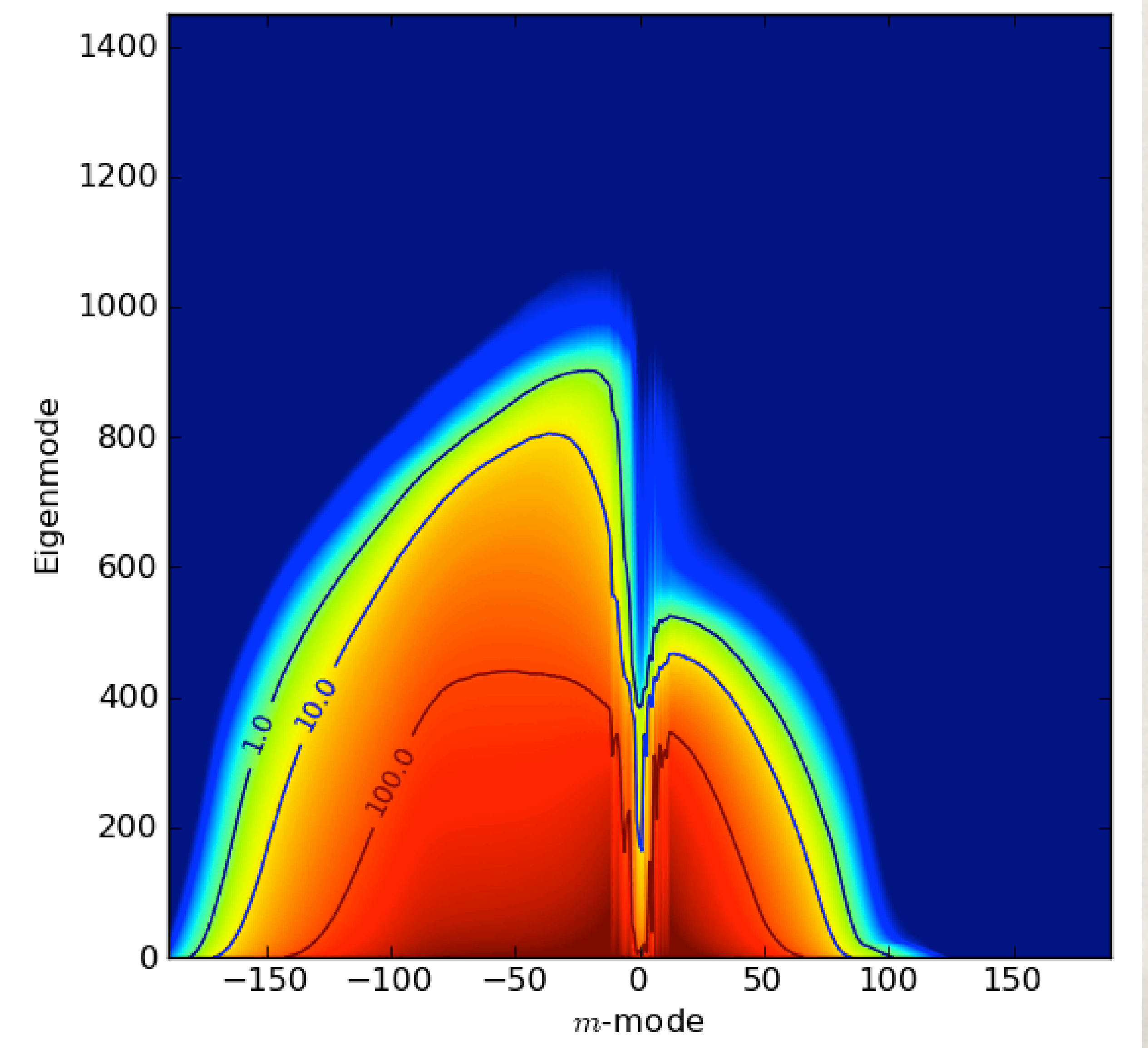
cf. Bond 1994, Vogeley and Szalay 1996

Slides by

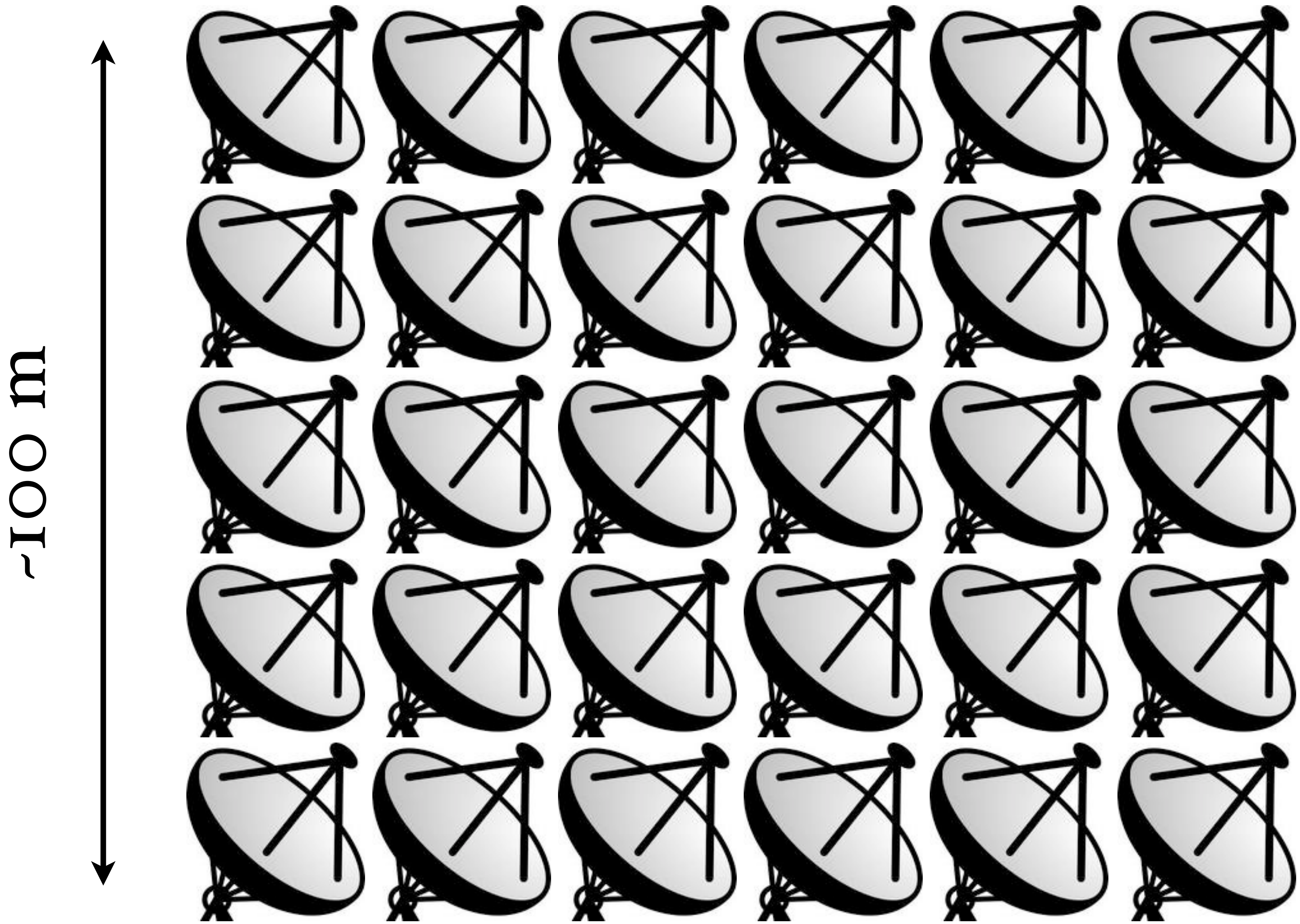
Kris Sigurdson

UBC

Signal/Foreground Spectrum



Richard Shaw, Ue-Li Pen (CITA)
Kris Sigurdson, Michael Sitwell (UBC)
ArXiv 1204.???



RAID
Radio Array of Inexpensive
Dishes

21cm intensity mapping dark energy survey instrument
concept - Dense interferometric array
8-12 cylindrical reflectors (CRT)
OR
100-400 parabolic 5-6 meter diameter dishes **(RAID)**
200-1000 receiver elements - Data flow : 0.1 - 1 TBytes/s