# 21 cm Intensity Mapping
# BAORadio & Tianlai

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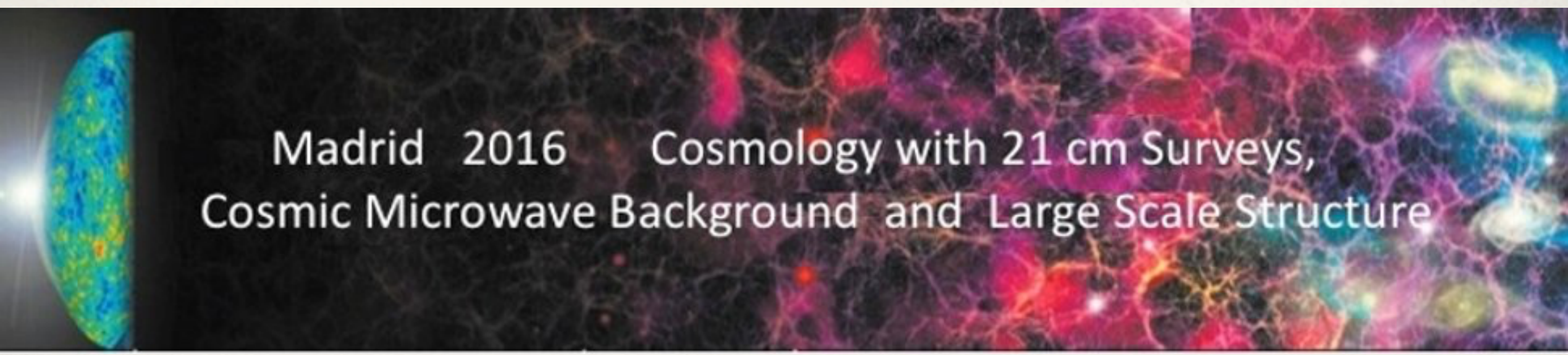
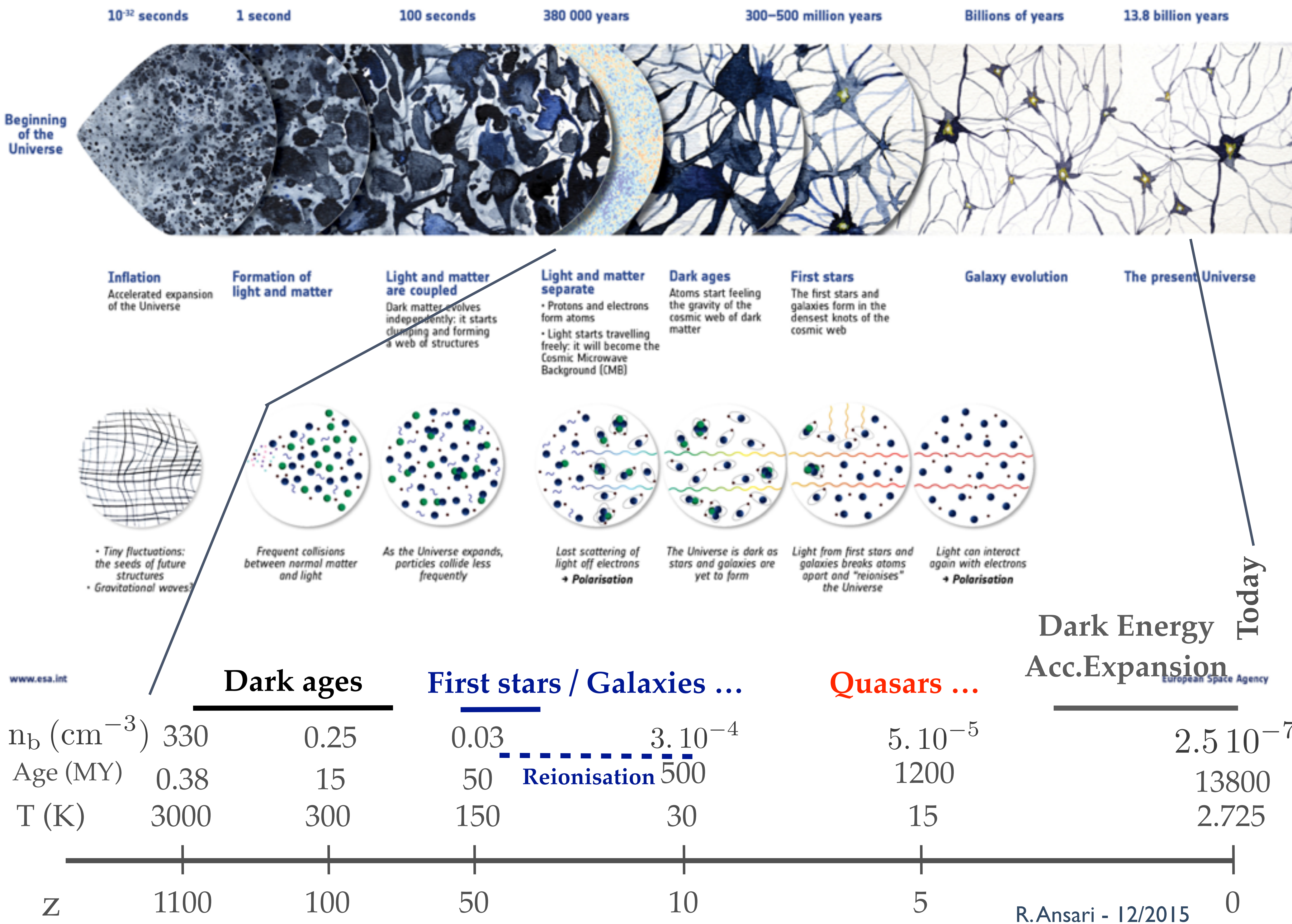



**Madrid** **13-17 June 2016**

- Large Scale Structure (LSS) & BAO's at 21 cm
  - BAO's as a cosmological proble
  - 3D Intensity Mapping
- Some of the Intensity Mapping challenges
  - Map making
  - Foregrounds, instrumental effects
- 21 cm Dark Energy surveys
  - CHIME, HIRAX
  - BINGO, GBT-HIM
  - BAORadio
  - Tianlai

# LSS & BAO at 21 cm

## 3D Intensity mapping


10⁻³² seconds
1 second
100 seconds
380 000 years
300–500 million years
Billions of years
13.8 billion years
Beginning of the Universe
Inflation
Accelerated expansion of the Universe
Formation of light and matter
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Galaxy evolution
The present Universe
• Tiny fluctuations: the seeds of future structures
• Gravitational waves?
Frequent collisions between normal matter and light
As the Universe expands, particles collide less frequently
Last scattering of light off electrons
→ Polarisation
The Universe is dark as stars and galaxies are yet to form
Light from first stars and galaxies breaks atoms apart and "reionises" the Universe
Light can interact again with electrons
→ Polarisation
www.esa.int
European Space Agency
Today
Dark Energy
Acc.Expansion
Dark ages
First stars / Galaxies …
Quasars …
Reionisation
$n_b$ (cm$^{-3}$) 330 0.25 0.03 3. 10$^{-4}$ 5. 10$^{-5}$ 2.5 10$^{-7}$
Age (MY) 0.38 15 50 500 1200 13800
T (K) 3000 300 150 30 15 2.725
z 1100 100 50 10 5 0
R.Ansari - 12/2015

# Cosmological probes and Dark Energy

- Baryon Acoustic Oscillations (**BAO**) : Measurement of characteristic scales → dA(z), H(z)
- Large Scale Structure & RSD : (**LSS, BAO/RSD**)
- Supernovae (**SN**) : Measure of apparent SNIa luminosity as a function of → dL(z)
- Weak lensing (**WL**) : Measure of preferred orientation of galaxies → dA(z), growth of inhomogeneities (structures / LSS)
- Galaxy Clusters (**CL**) : number count and distribution of clusters → dA(z), H(z), Structure formation (LSS)
- Integrated Sachs Wolf (**ISW**) effect : effect of evolving gravitational potential in large scale structures (with redshift)

**21cm IM**

?

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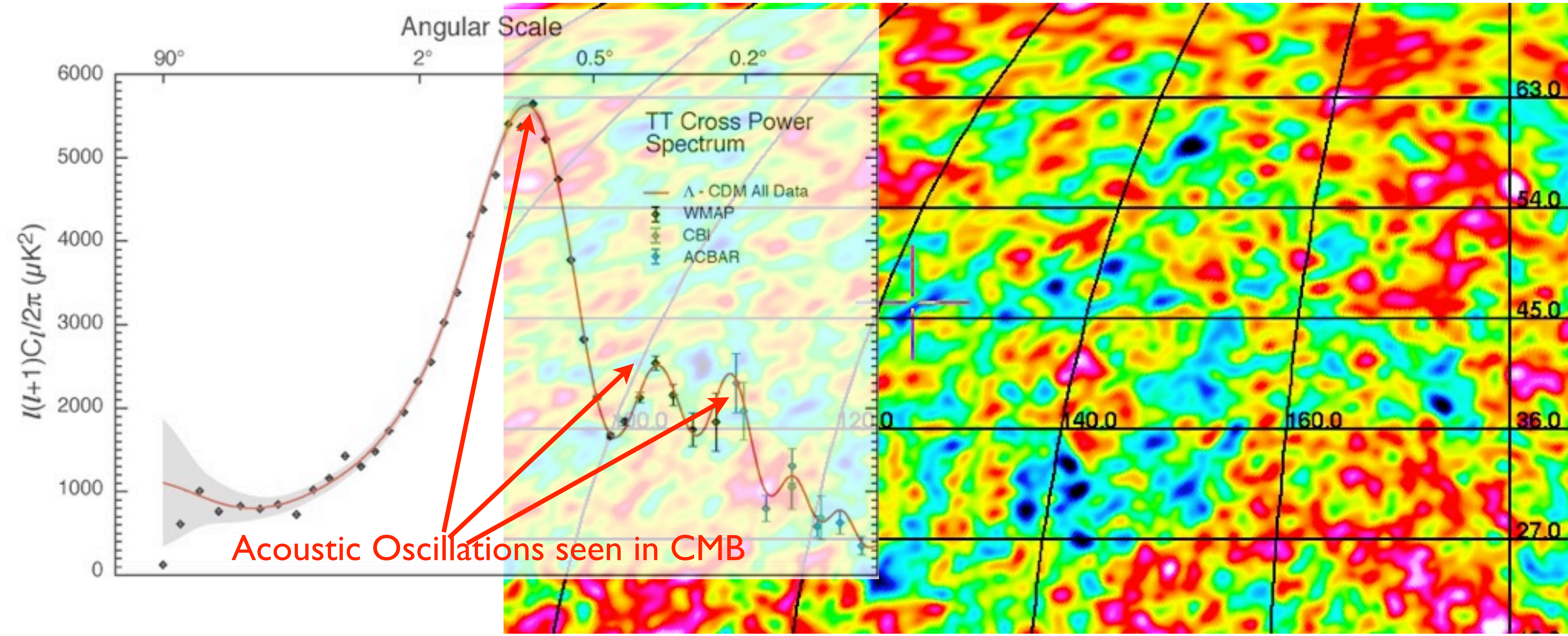
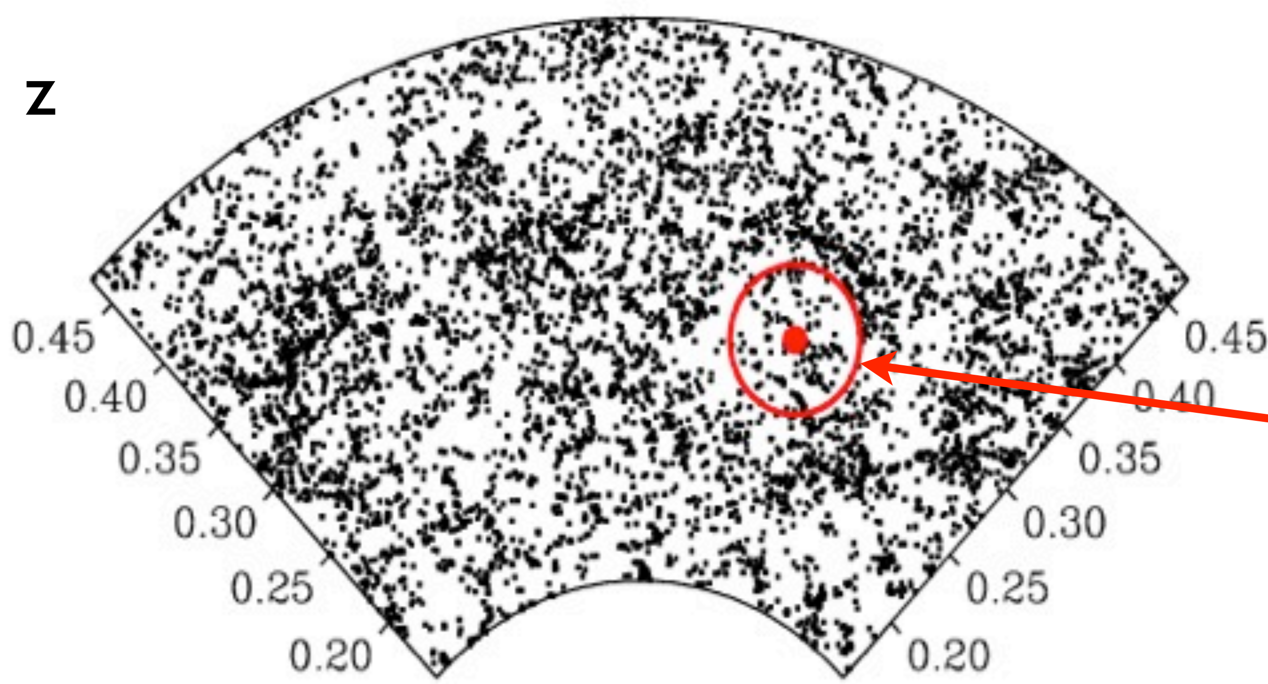
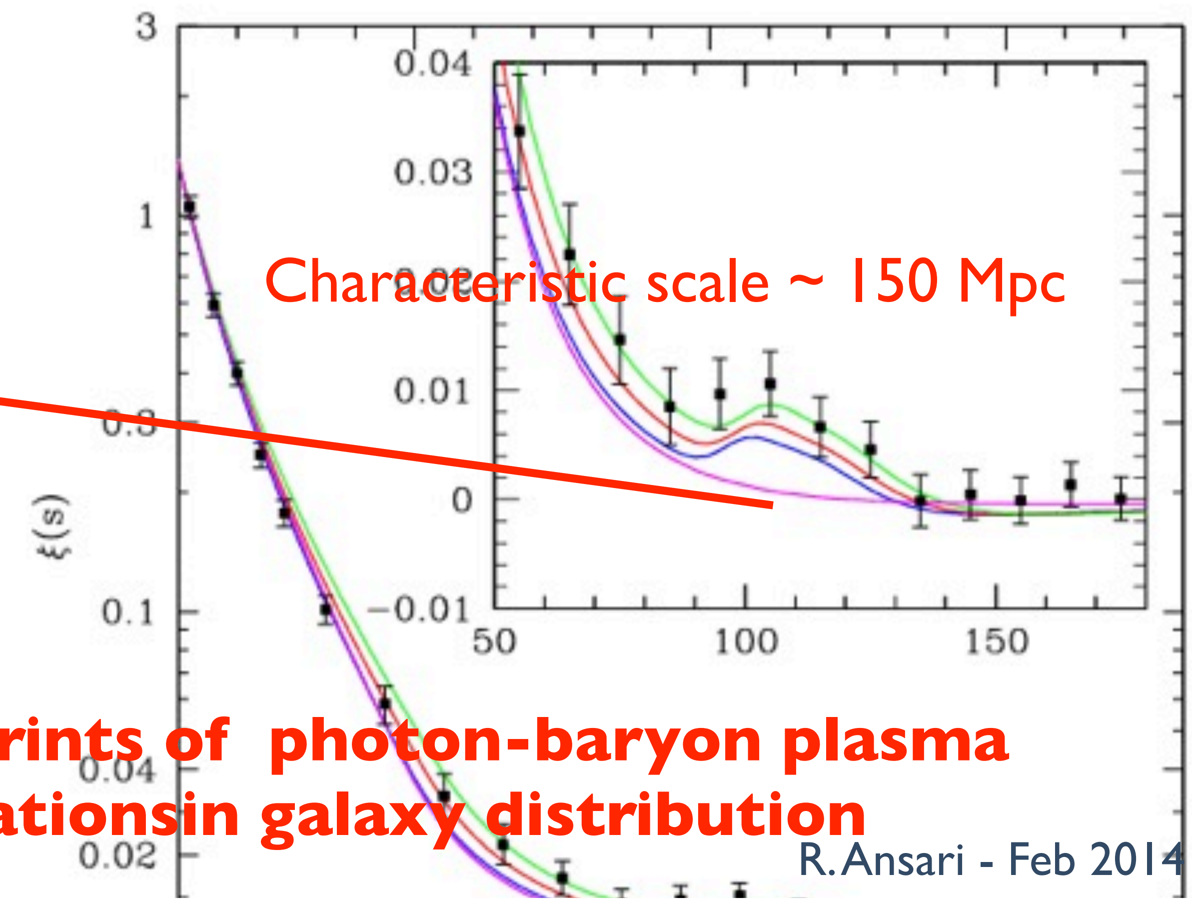
# LSS & BAO's as a cosmological probe

- Statistical properties of matter distribution in the universe and its evolution with time (redshift) is one of the major tools/probes to test the cosmological model, determine its parameters: Dark matter and dark energy properties, neutrinos masses …
- The analysis is usually done through the correlation function or the power spectrum P(k)
- **BAO**: 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**

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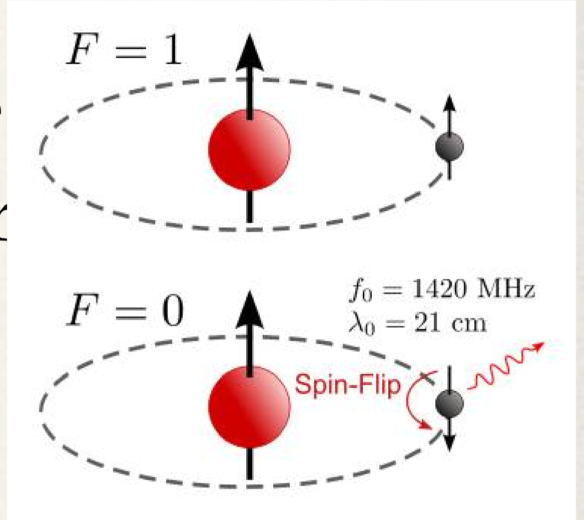
R. Ansari - Feb 2014

# Mapping LSS @ 21 cm (I)

- LSS usually mapped in the optical window, through the observation of galaxies, considered as tracer of the underlying matter (DM+baryons) distribution
- 3D maps are obtained through imaging + spectroscopy : slices of the universe at different times (ages) or redshifts
- Its is mostly light from stars in the galaxies which are seen in the optical
- A fraction of the baryonic matter in the universe is in the form of neutral atomic hydrogen (HI), both in galaxies or distributed in the intergalactic medium (although most IGM gas is ionised)
- Can be used to map matter distribution through the spin-flip transition at 21 cm (1420.4 MHz) in radio. The redshifted 21cm line gives directly access to the redshifts



# A typical galaxy at z ~ 0.3 DL ~ 1500 Mpc

⋆ **Optical**

- $10^9 - 10^{10} L_\odot \rightarrow \sim 10^{35}$ W (emitted power)
- $\lesssim 10^{-16} - 10^{-17}$ W/m$^2$ in a typical photometric ban
  ($\sim 10$ photons/m$^2$/s)

⋆ **21 cm emission (radio)** ← All in a very narrow frequency band

- $\sim 10^9\, M_\odot$ of $H_I \rightarrow 3.\, 10^{27}$ W (emitted power)
- $\lesssim 10^{-30}$ W/m$^2$/Hz or few photons/m$^2$/s
  assuming $\sim 200$km/s velocity dispersion
- $\lesssim 100\, \mu$Jy in a $\sim 1$MHz band

# Detecting galaxies at 21 cm at cosmological distances

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

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

$S_{lim}$ en $\mu$Jy 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 $\mu$Jy pour $M_{H_I} = 10^{10} M_\odot$

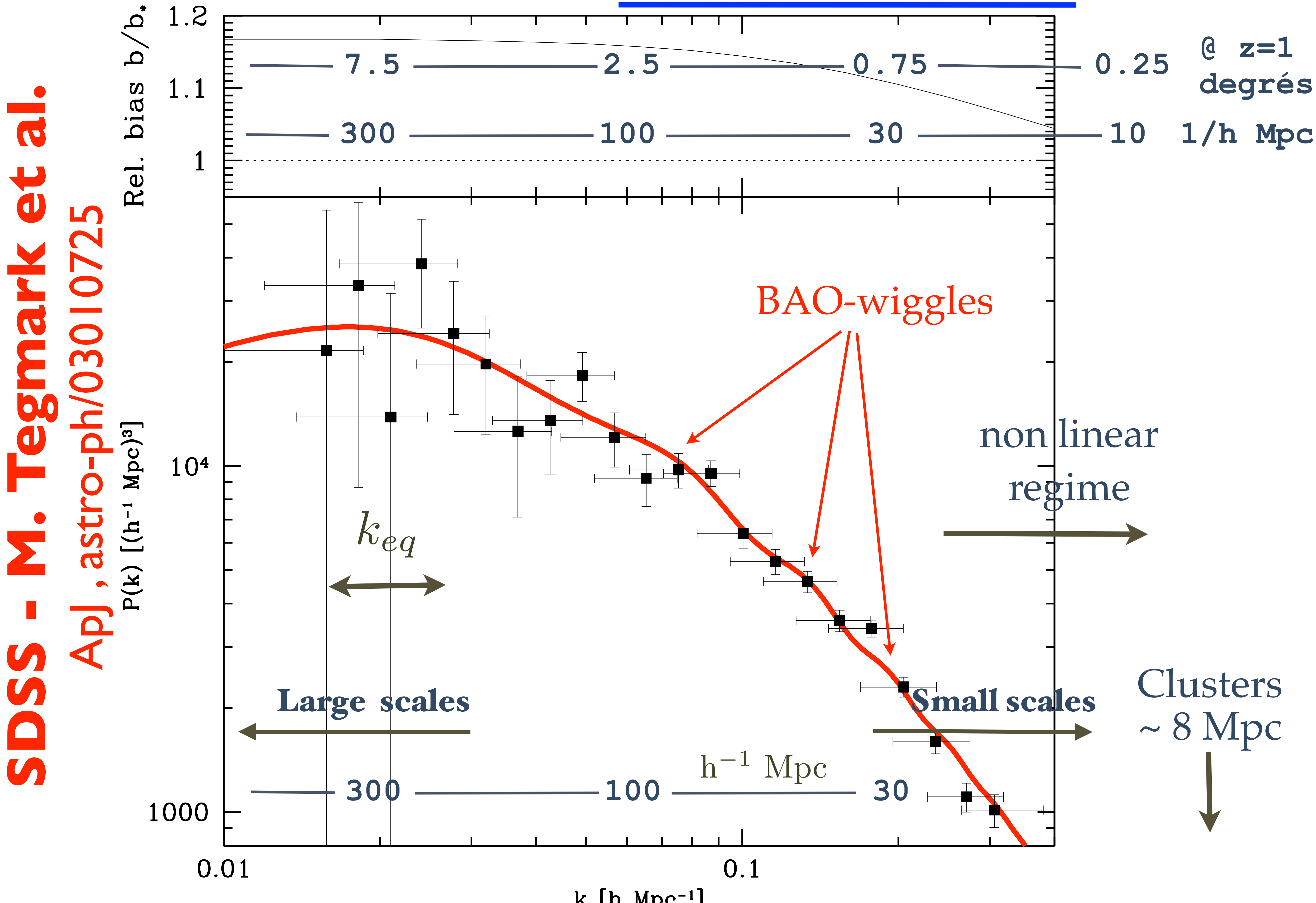
| z | S21 ( μJy) |
|---|---|
| 0,25 | 175 |
| 0,50 | 40 |
| 1,0 | 9,6 |
| 1,5 | 3,5 |
| 2,0 | 2,5 |

> 100 000 m^2 → SKA !

# Mapping LSS @ 21 cm (II)

- Analogous to the optical surveys
  - Observe the sky in radio, identify compact sources (galaxies), determine their positions ($\alpha$,$\delta$) through imaging and the redshift. Compute the correlation function of the power spectrum P(k) from the catalog of objects.
  - Very large collecting area 10^5 m^2 to km^2 needed to observe galaxies in 21 cm at cosmological distances ➠ **SKA** / **FAST …**
- 3D Intensity mapping, similar to CMB
  - Measure integrated emission (brightness temperature) of HI - from IGM and gas in galaxies, in cells (few Mpc)^3
  - Subtract foregrounds, and compute P(k,z) on 3D maps T21($\alpha$,$\delta$,$\nu$)

# BAO scales ≳ 0.2 degree




R. Ansari - 2008

# 21 cm observations compared to optical

- 21 cm line is the only spectral feature in L band (~GHz) ➡ Spectro-photometric observations
- Band: ~ 100 MHz … 1500 MHz - $\nu = f(z)$ , z: 0 … 10

  1420 MHz @ z=0 , 946 MHz @ z=0.5 , 720 @ z=1 , 284 @ z=5, 129 @ z=10
- Radio instruments are diffraction limited:

  700 MHz: D=100 m → ~20′ , D=1km → ~2′ , D=100 km → ~1″ , 2′ → 1 Mpc @ z = 1
- Intensity measurement in radio, amplitude & phase in radio;
  ➡ Interferometry and spectroscopy in radio
- Instrumental / electronic noise (RO noise <5 e) usually negligible in optical, dominant in radio (Tsys~20-100 K)
- Light pollution, atmosphere in optical / EM pollution (RFI) and ionosphere (lower frequencies) in radio

# LSS/BAO/RSD at 21 cm: 3D $T_{21}(\alpha,\delta,z)$ maps

- 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)
- 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 …

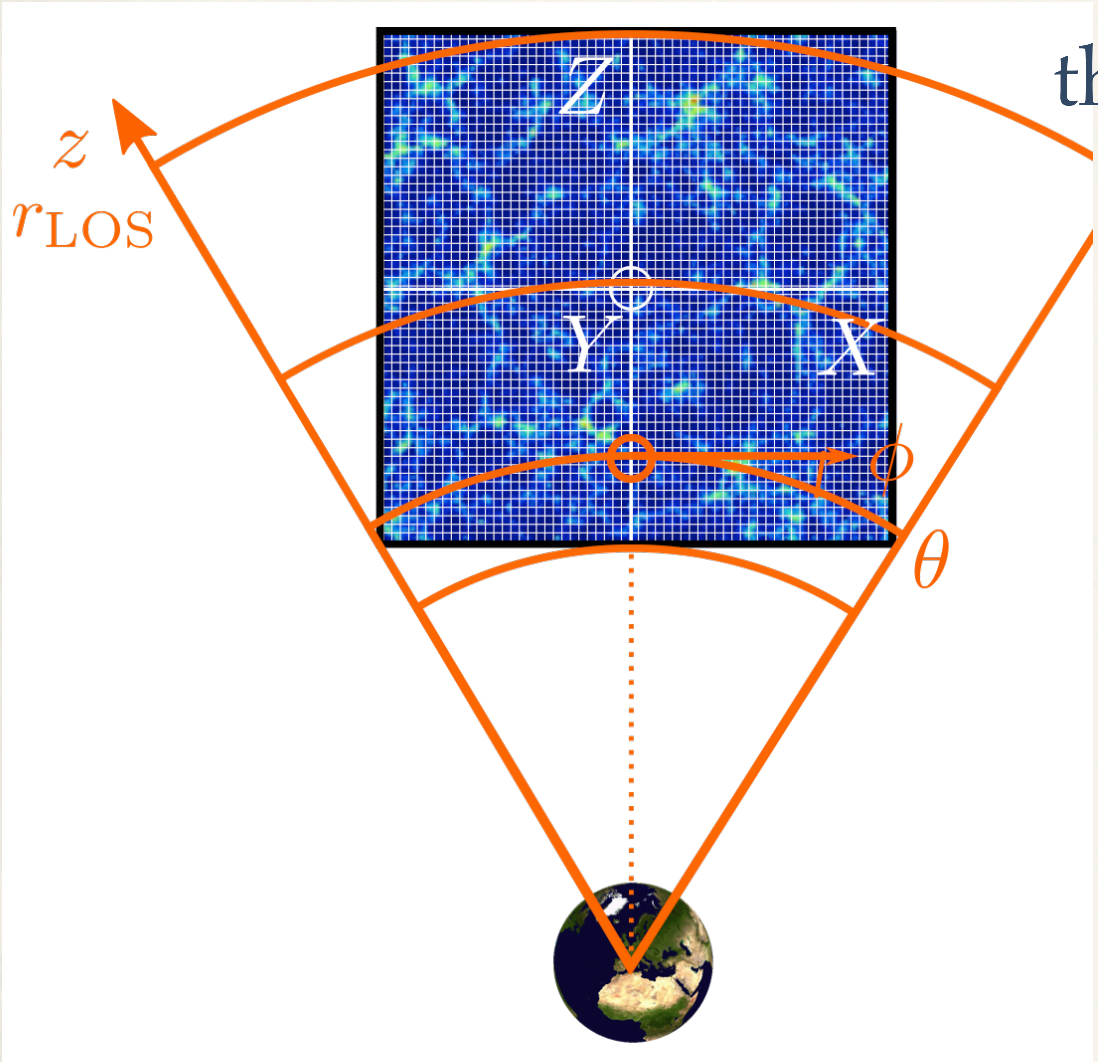

- Peterson, Bandura & Pen (2006)
- Chang et al. (2008) arXiv:0709.3672
- Ansari et al (2008) arXiv:0807.3614
- Wyithe, Loeb & Geil (2008) arXiv:0709.2955
- Peterson et al (2009) arXiv:0902.3091
- Ansari et al (2012)
- Shaw et al (2014, 2015)
- de Santos et al- Bull et al (2015)
- …

# Intensity Mapping Challenges

- Map making
- Foregrounds
- Noise
- Mode mixing

# 21 cm 3D Intensity Mapping

- redshift ↔ Frequency
- angular direction mapping through imaging




### Single Dish

- Map the sky through drift-scan or by active scanning
- Compute power spectrum P(k) or C(l, z1,z2) from sky maps
- project into appropriate basis (modes) to subtract foregrounds and extract cosmological signal

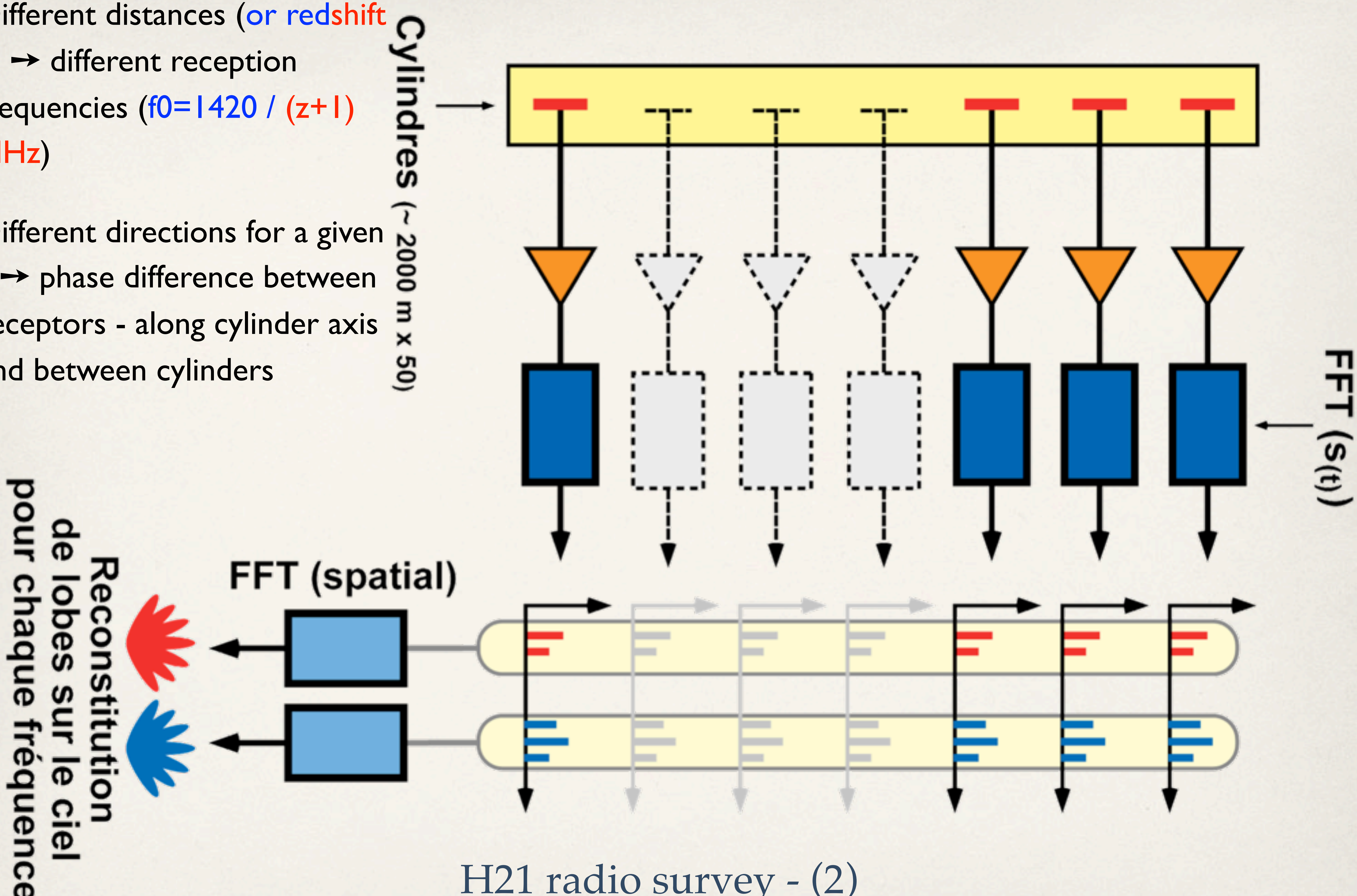
**R. Shaw et al. (2014, 2015) - ApJ**
J. Zhang, R.A et al MNRAS (2016)

### Transit Interferometers

- Map the sky through drift-scan
- Reconstruct sky map from visibilities
- **m-mode decomposition in case of full EW scan**
- visibilities correspond to transverse Fourier modes k⊥

Different distances (or redshift z) ➙ different reception frequencies (f0=1420 / (z+1) MHz)

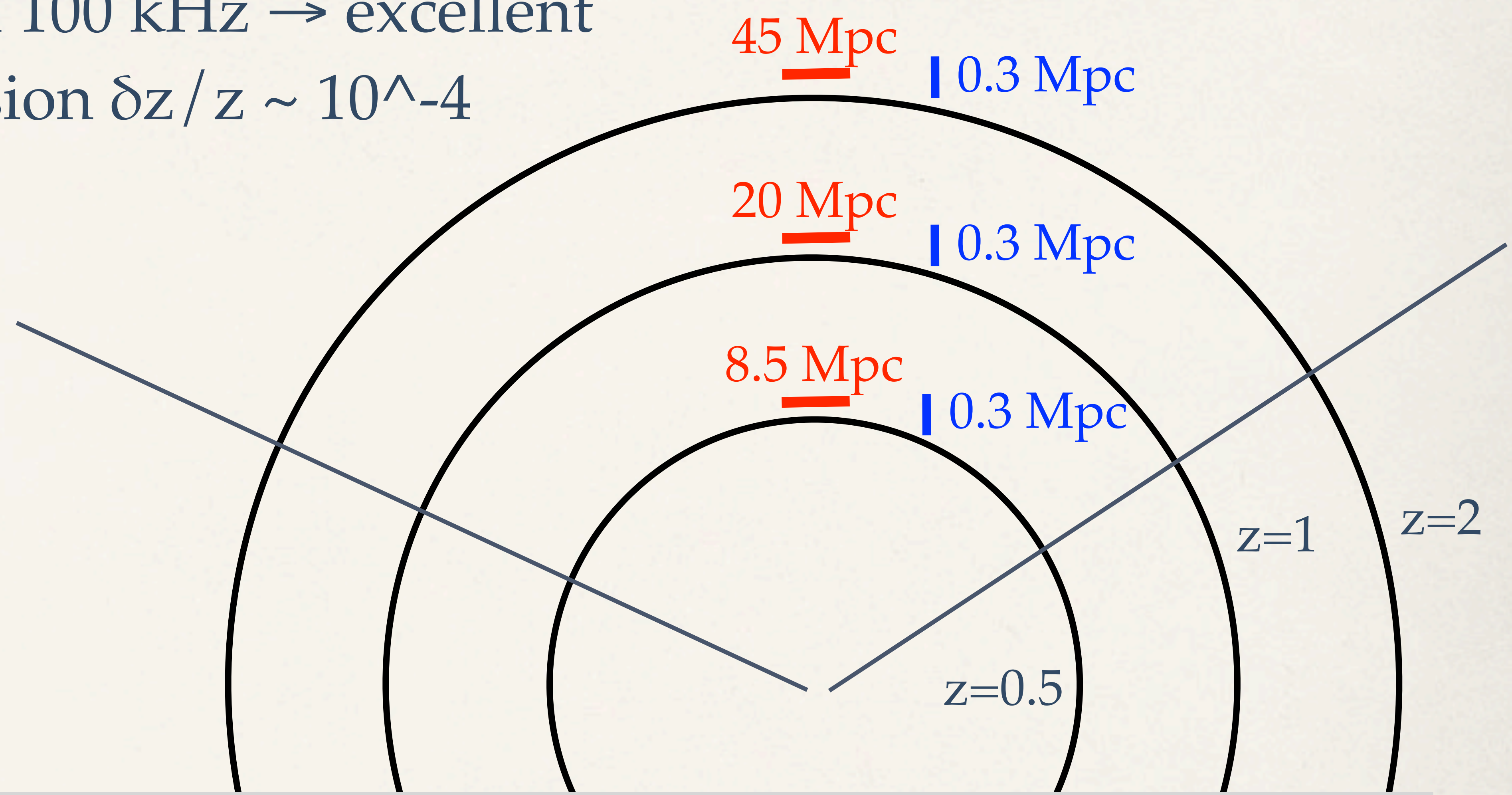
Different directions for a given z ➙ phase difference between receptors - along cylinder axis and between cylinders




# H21 radio survey - (2)
## Interferometric instrument - Aperture synthesis

R.Ansari - 2007

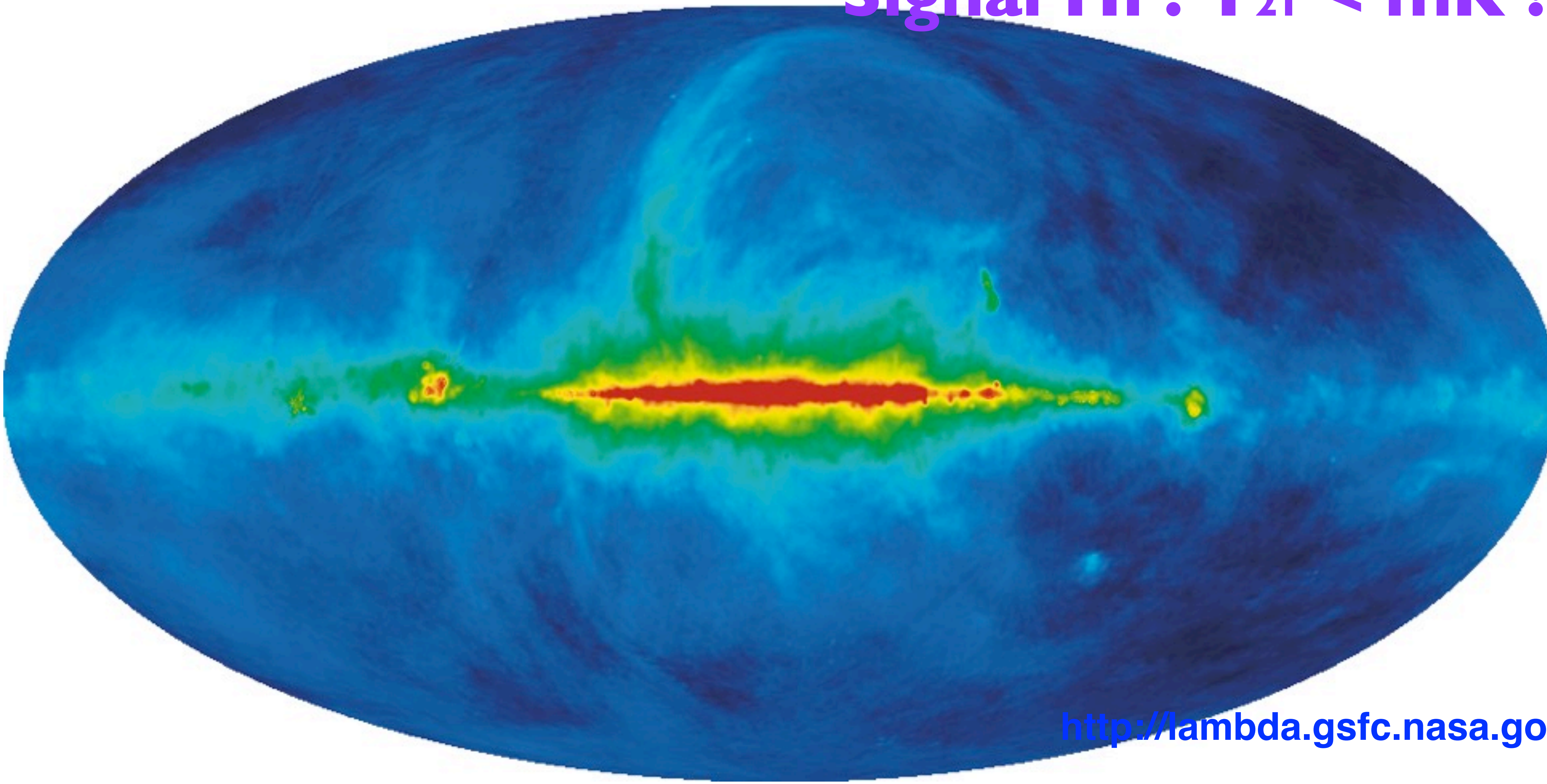
L=100 m array → ang. resolution $\delta\theta \sim \lambda/L$ , deteriorating with redshift z
spectral resolution 100 kHz → excellent redshift precision $\delta z/z \sim 10^{-4}$




| 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 |

# Foregrounds

**Signal HI : $T_{21}$ < mK !**



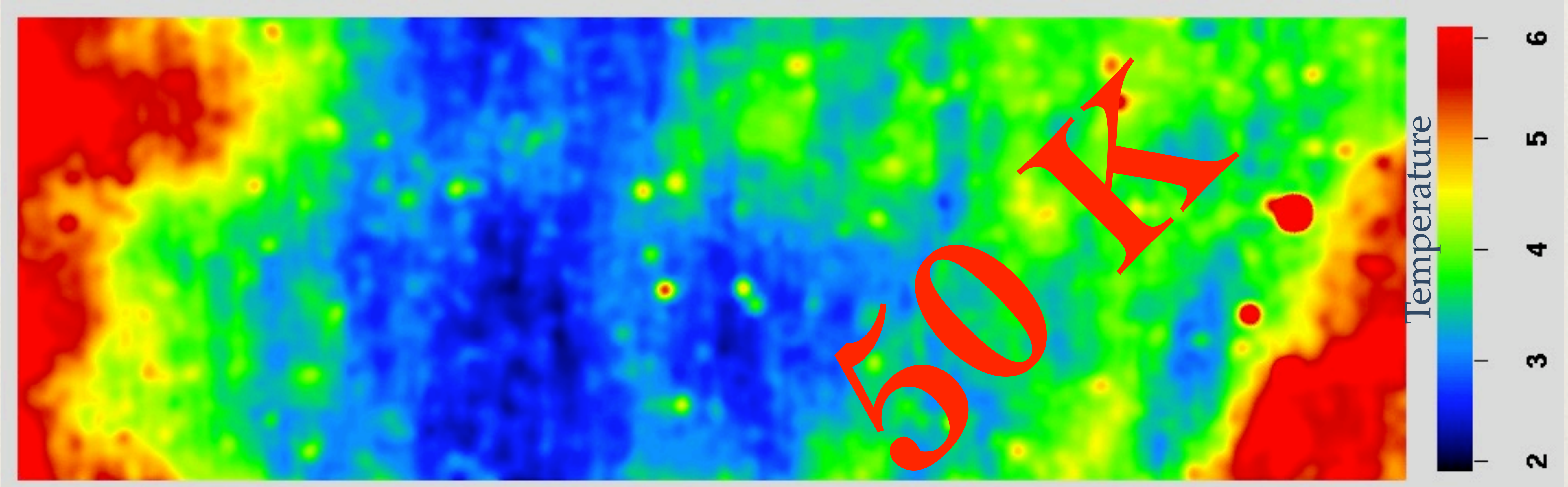

**Temp. T (Ech. Log)**

**10 K** ——— **250 K**

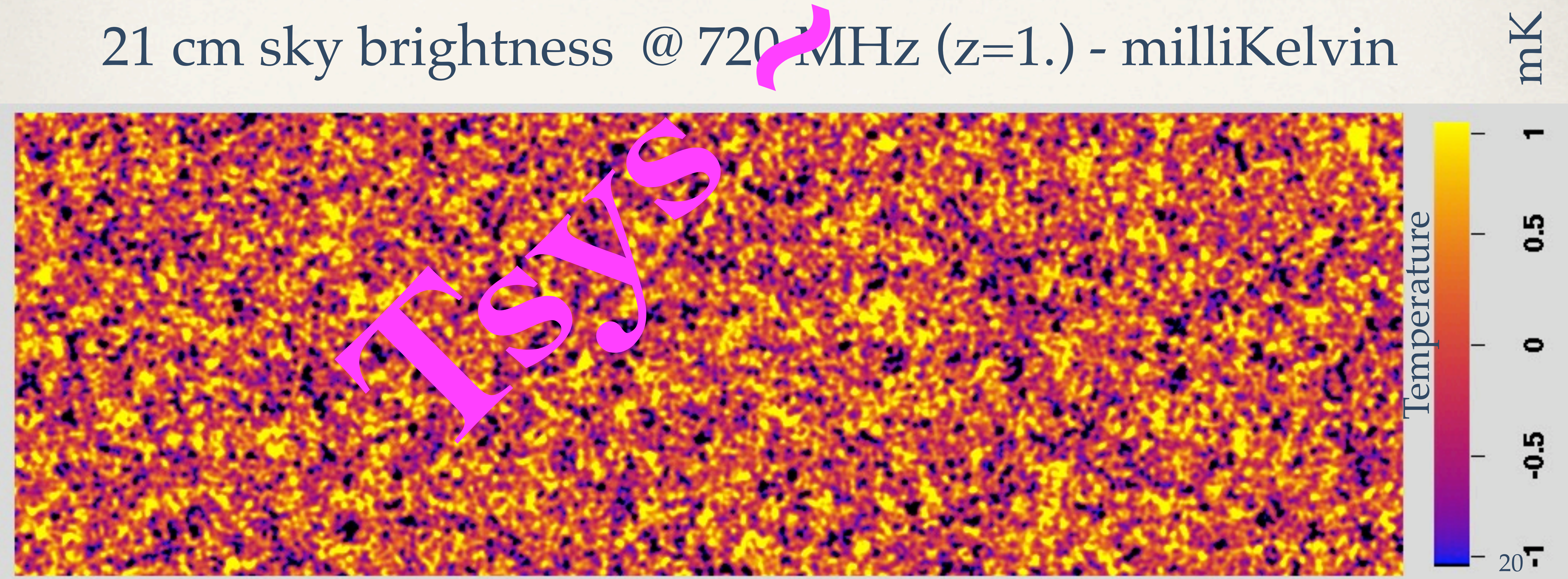
Haslam 408 MHz map (Galactic synchrotron emission)

R. Ansari - 2012

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




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

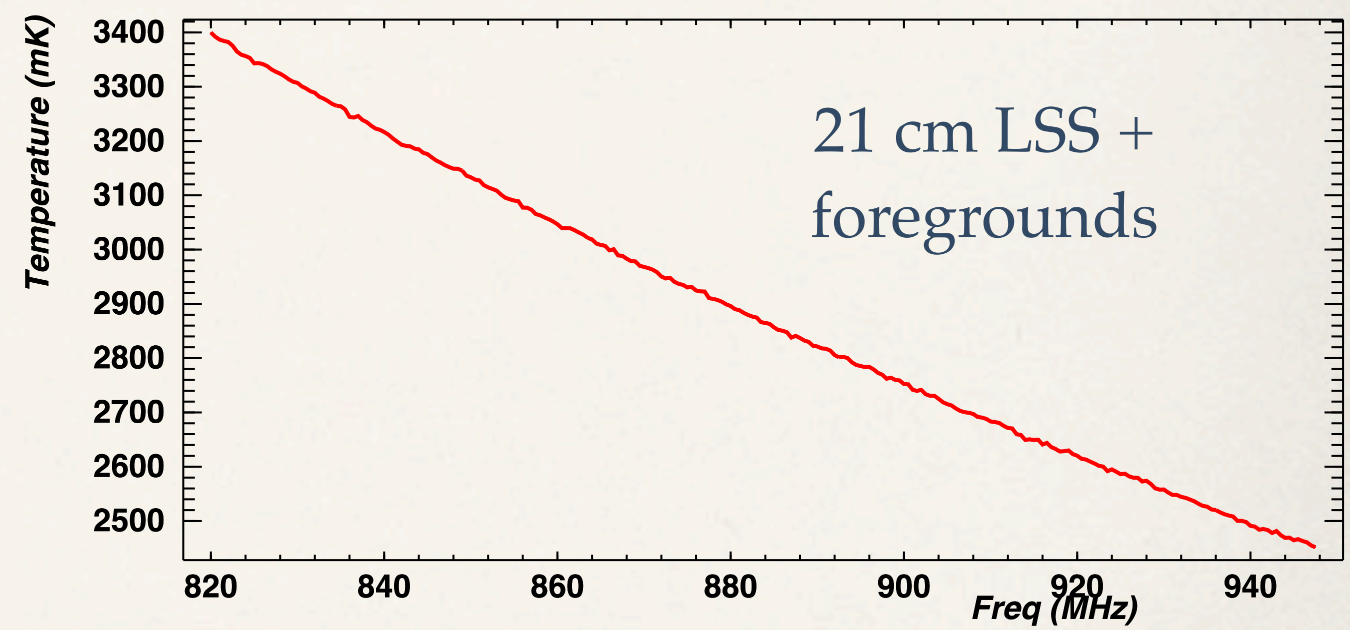


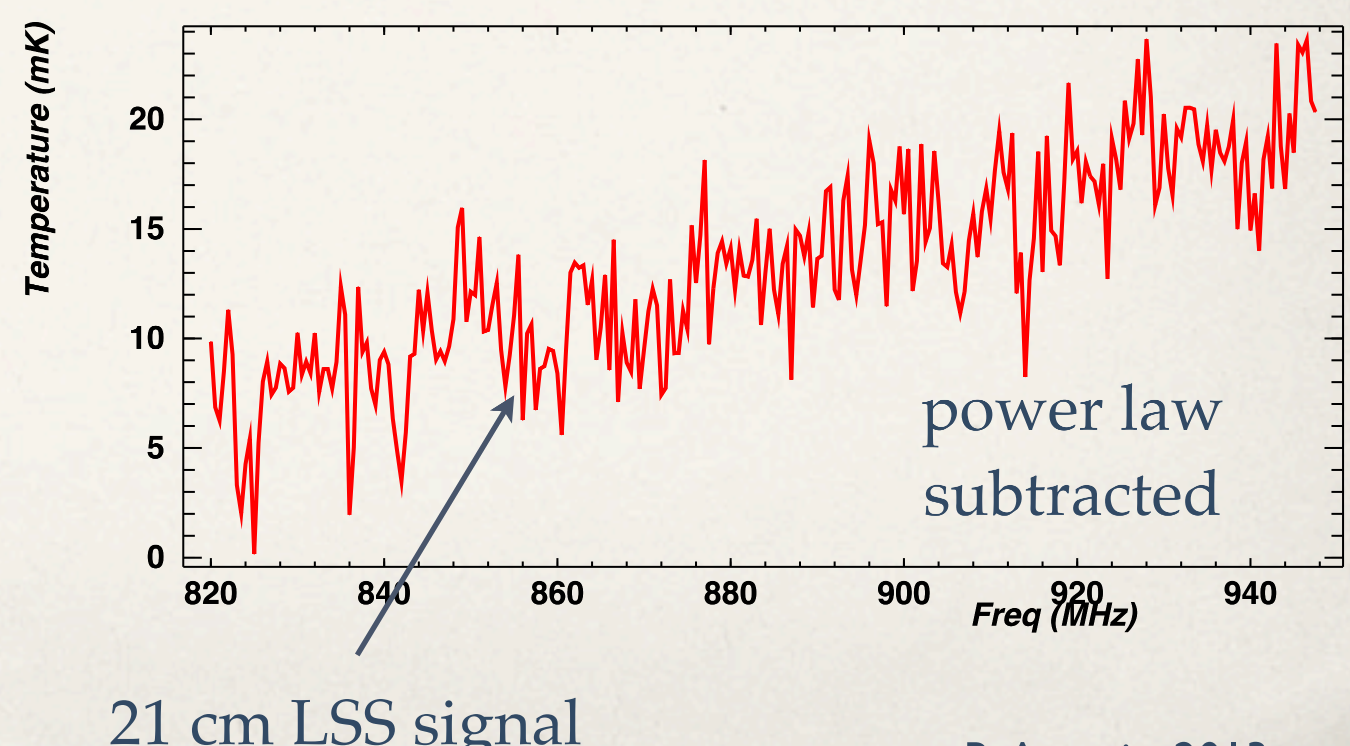
# How do we suppress foregrounds ?

- Exploit foregrounds known frequency dependence (power law ∝ $\nu^\beta$) for Galactic synchrotron and radio sources

- Instrumental effects (mode mixing), Polarisation leakage / Farady rotation …

Ansari et al. (2012) - A&A
Shaw et al. (2014) ApJ
Shaw et al (2015) ApJ

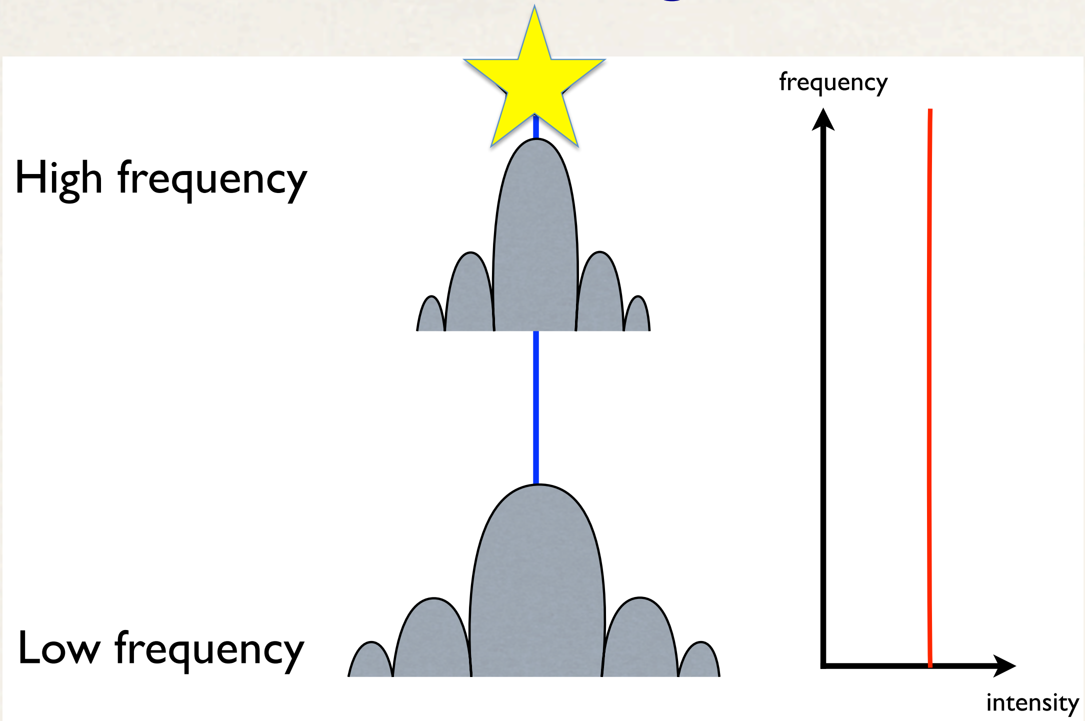



R.Ansari - 2013

# Mode mixing / foregrounds

## Mode Mixing




## Mode Mixing

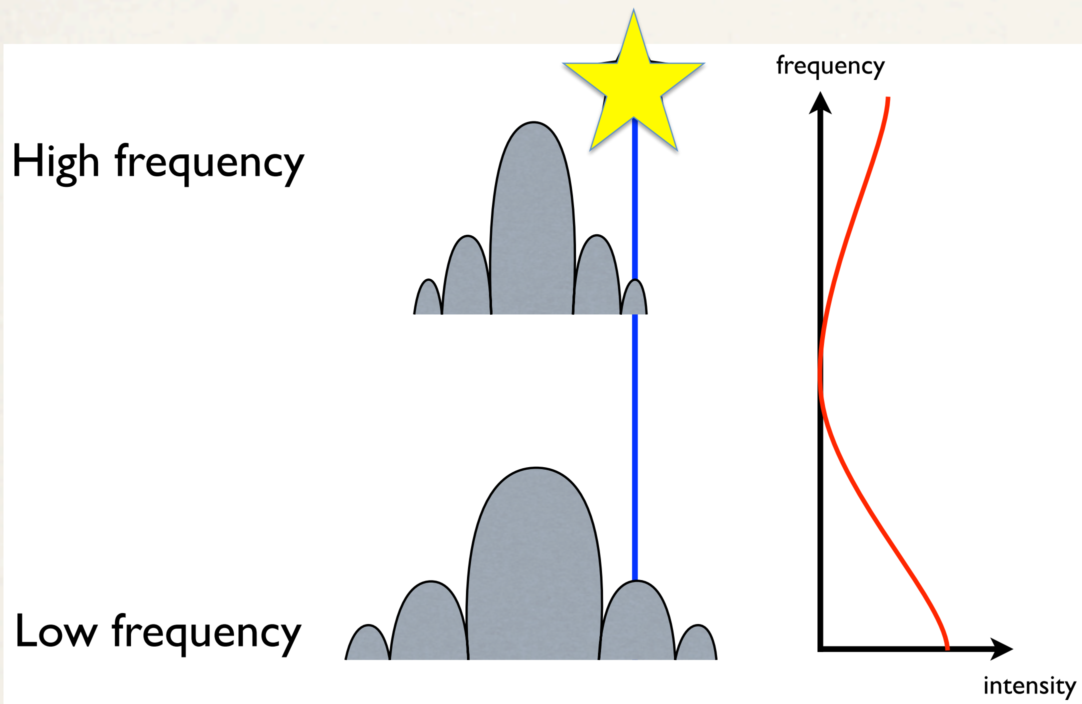



Illustration : R. Shaw


Richard Shaw, Ue-Li Pen,
K. Sigurdson, M. Sitwell, A. Stebbins

ApJ 2014, 2015

## 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

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

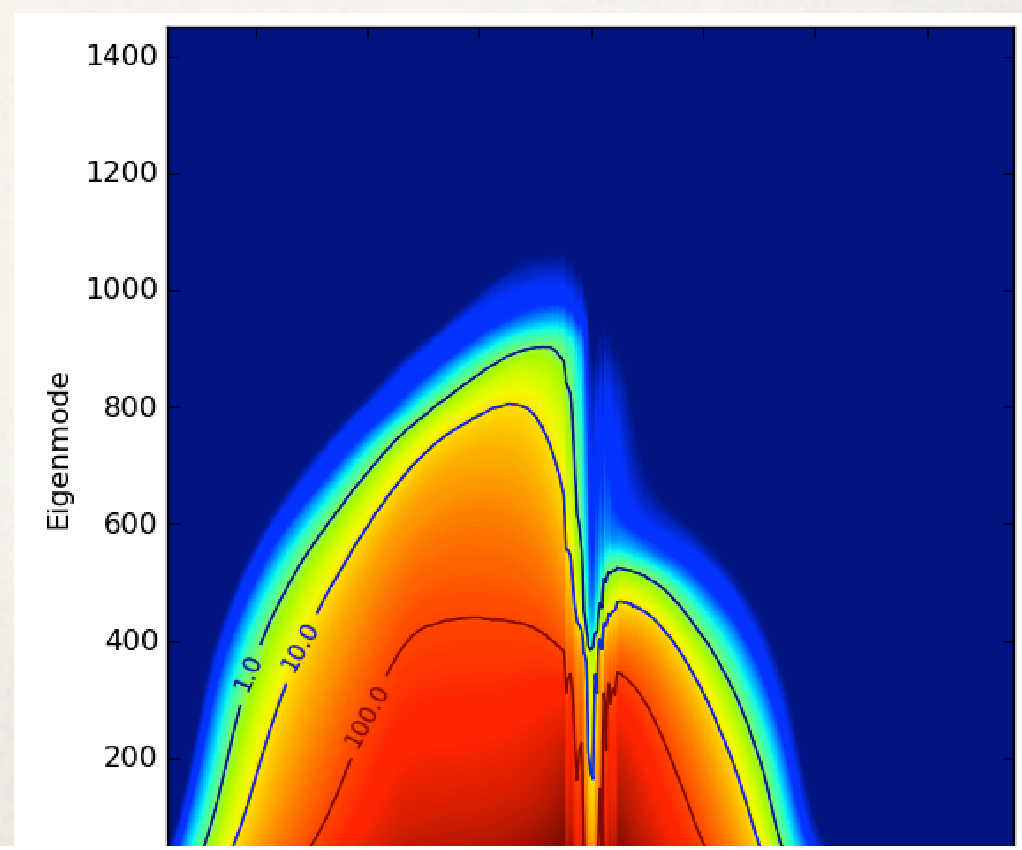
- Jointly diagonalise both matrices (eigenvalue problem)

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 $\lambda_i$ gives ratio of signal to foreground variance for mode $i$.

cf. Bond 1994, Vogeley and Szalay 1996

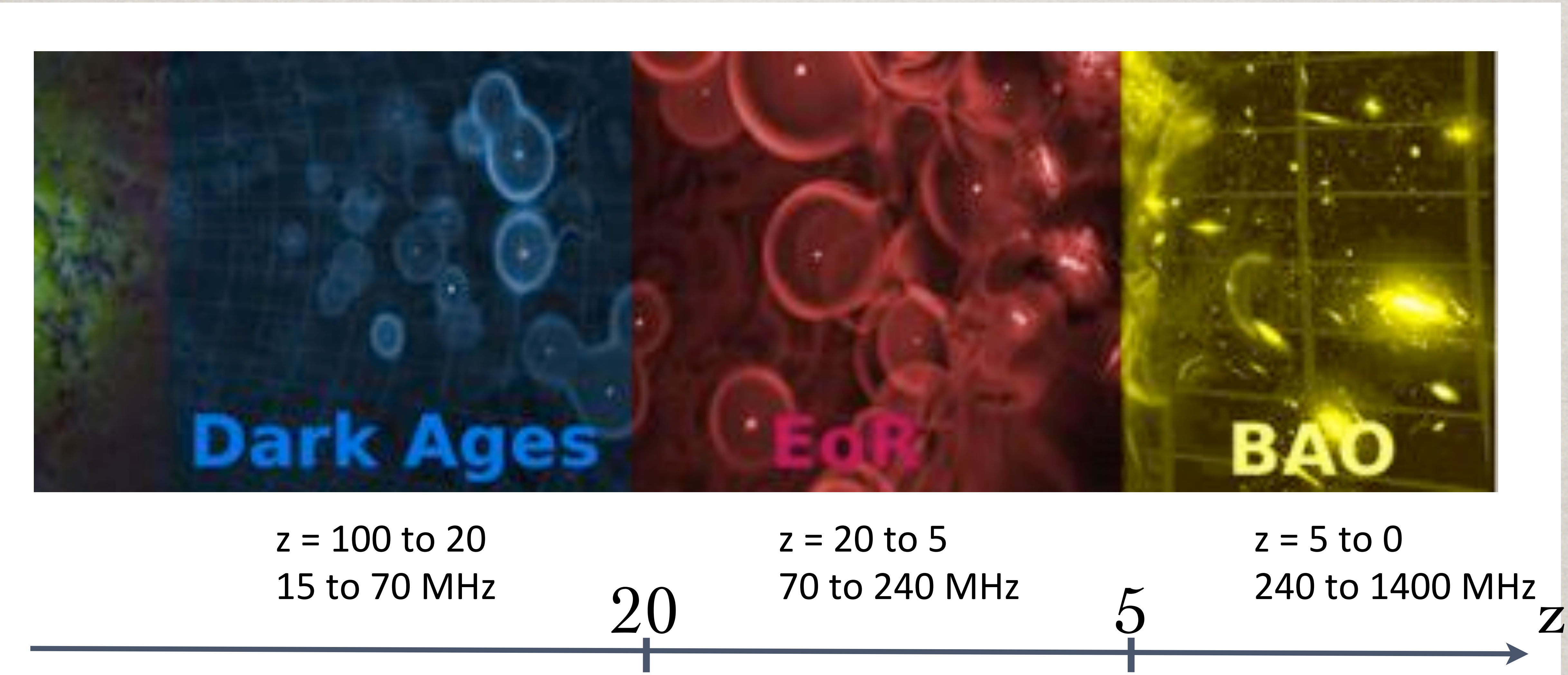
## Signal/Foreground Spectrum



# 21 cm Dark Energy surveys

# 21 cm experiments

- CHIME
- HIRAX
- BINGO
- GBT-HIM
- BAORadio
- Tianlai
- ...




- LOFAR
- GMRT
- MWA
- PAPER

- SKA
- HERA

- Parkes
- SKA

R. Ansari - June 2016

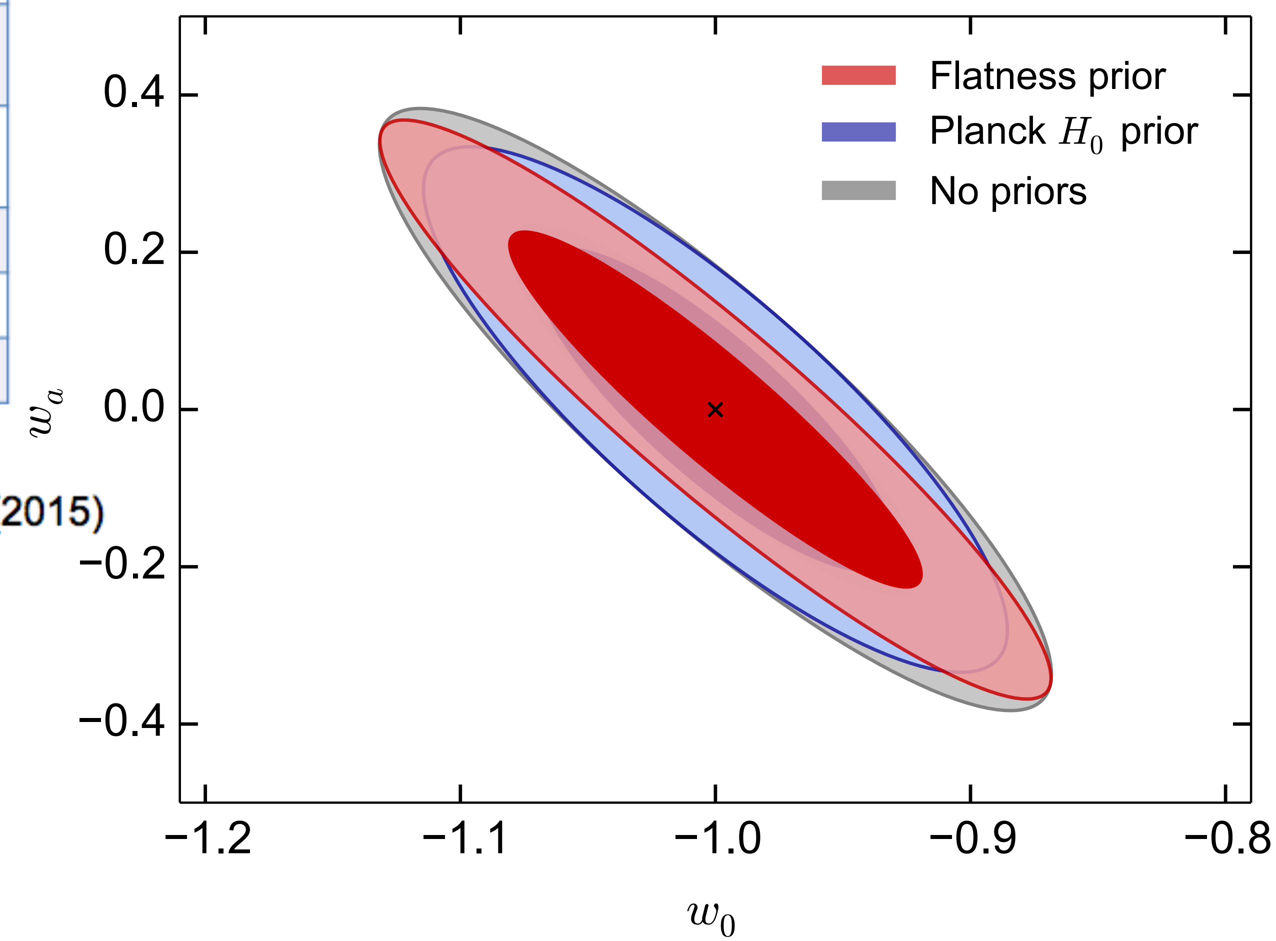
- Traditional single dish with tracking, equipped with multi-feed receiver array in the focal plane → GBT-HIM
- Transit type single dish with multi-feed receiver array and a correlation receiver → BINGO
- Dense transit type interferometers using cylinders as primary reflectors → CHIME , Tianlai
- Transit interferometers using a dense array of *small* dishes → HIRAX, TDA (Tianlai Dish Array), PAON-4 test interferometer

# Comparison of some 21 cm BAO projects

| | | $T_{inst}$ | $N_d x N_b$ | $D_{dish}$ (m) | $z_{min}$ | $z_{max}$ | S ($deg^2$) |
|---|---|---|---|---|---|---|---|
| single dish | GBT | 29 | 1x1(7) | 100 | 0.54 | 1.09 | 100 |
| | Parkes | 23 | 1x13 | 64 | 0.00 | 0.23 | 5,000 |
| | *BINGO* | *50* | *1x50* | *25* | *0.13* | *0.48* | *5,000* |
| | *FAST* | *20* | *1x20* | *500* | *0.42* | *2.55* | *2,000* |
| nterferometer | CHIME 4, 100 m cyl. | 50 | 1280x1 | 20 | 0.77 | 2.55 | 25,000 |
| | Tianlai 8, 120 m cyl. | 50 | 2048x1 | 15 | 0.00 | 2.55 | 25,000 |
| | HIRAX | 50 | 1024x1 | 5 | 0.77 | 2.55 | 15,000 |
| interf. + autocor. | *SKA1-MID* | *20* | *190x1* | *15* | *0.00* | *3.06* | *25,000* |
| | *SKA1-SUR* | *30* | *96x36* | *15* | *0.23* | *1.38* | *25,000* |

from Bull *et al.* ApJ 803 (2015)

Bull et al. (2015) - ApJ 803
arXiv:1405.1452




Constraints on Dark Energy from a survey like CHIME ou Tianlai-full

R.Ansari - March 2016


CHIME (Nov 2015)
Photos © Steve Torchinsky


See Richard Shaw's presentation

# HIRAX

## (a southern hemisphere 21 cm BAO survey)

- Project lead by South Africa (PI: J. Sievers) with contributions from Canada, US, France
- Funding (NRF / AFS) for a first phase obtained in 2015
- Will be located on the SKA site in the Karoo desert, one of the best sites in the world for radio-astronomy (protected by south-african legislation)
- Complementary with similar survey in the northern hemisphere (CHIME, Tianlai) - redshift coverage $z \sim 0.8 \ldots 2$

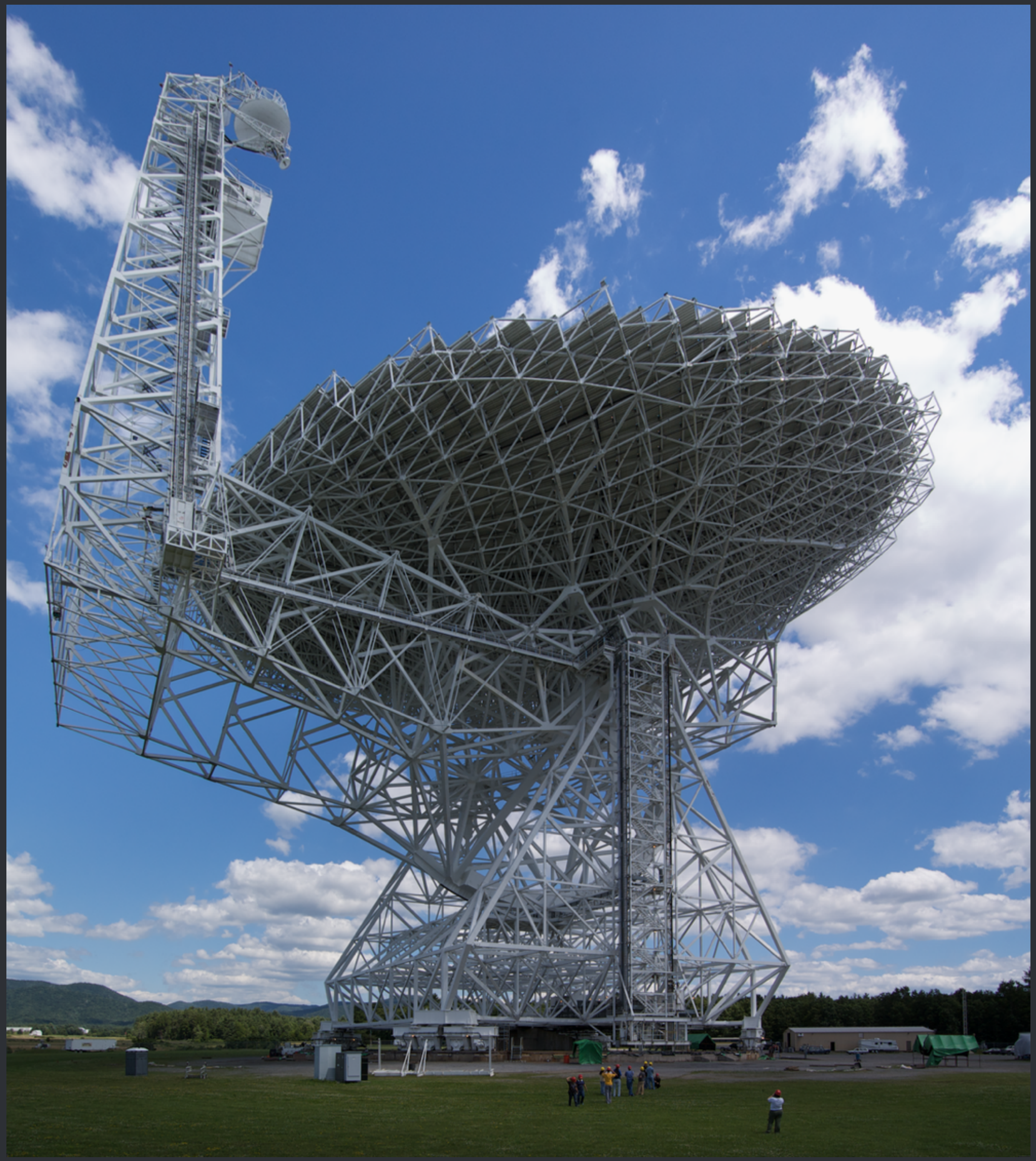
# GBT-HIM program

- Pilot HI Intensity Mapping program at GBT (Green Bank Telescope - 100 m fully steerable dish).
- 700-900 MHz, $0.6 < z < 1.0$, 15′ ang. resolution, cryogenic receiver
- 800 hours observations - first HI detection in cross-correlation with DEEP2 fields (Chang, Pen, Bandura, Peterson, Nature 2010)
- Fast Radio Burst (FRB) detection, Masui et al., 2015
- Commissioning of a 7 beam cryogenic receiver under way

GBT-HIM collaboration:
Victor Liao, Chun-Hao To (ASIAA), Chen-Yu Kuo (Chung-Shan U.),
Kiyo Masui (UBC), Eric Switzer (Goddard), Tabitha Voytek (UKZN),
Niels Oppermann, Ue-Li Pen, Richard Shaw (CITA),
Hsiu-Hisan Lin, Jeff Peterson (CMU), Yi-Chao Li (NAOC),
Chris Anderson, Peter Timbie (U. Wisc)
Yuh-Jing Hwang, Ching-Ting Ho, Chi-Chang Lin(ASIAA)
Rich Bradley, John Ford, Sri Srikanth, Steve White (NRAO)

# GBT-HIM

## Pilot program at the Green Bank Telescope (GBT)

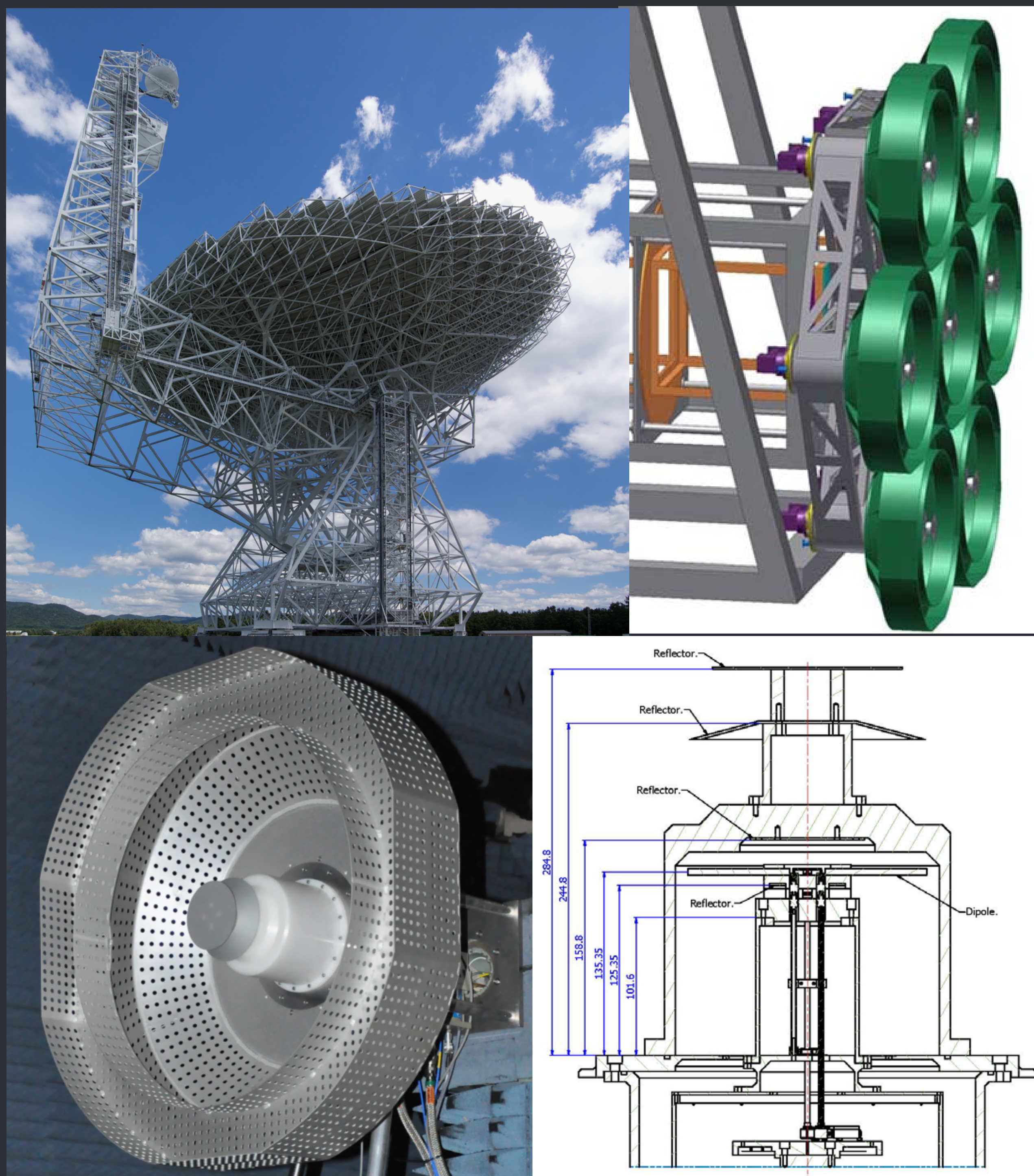


- Frequency: 700-900 MHz
  - $0.6 < z < 1$
- Spatial beam ~ 15”
  - 9 $h^{-1}$ Mpc at z~0.8
- Spectral channel ~ 24 kHz
  - binned to 0.5 MHz
  - ~2 $h^{-1}$ Mpc
- 100-m diameter. Large collecting areas
- First detection in cross-correlation with DEEP2 galaxies at z=0.8 (Chang, Pen, Bandura, Peterson, 2010, Nature)

Slide courtesy of Tzu-Ching Chang

# GBT-HIM

## 21cm Intensity Mapping for BAO & RSD studies




PI: T.-C. Chang. Co-I: Y.-J. Hwang, P. Timbie

- Building a 7-beam receiver at 700-900 MHz for redshifted HI survey at $0.6 < z < 1$ for BAO and RSD measurements.
- Use Short-backfire Antenna (SBA) with a edge-tapered reflector; with a cryogenic HDPE cover to reduce Tsys.
- Prototype tested on GBT in December 2014. CDR expected in summer 2016.
- Science results highlights:
    - First detection of 21cm IM signal in cross-correlation with DEEP2 galaxies at z=0.8 (Chang++10, Nature). Cross-power spectra (with WiggleZ) and auto-power spectrum limits (Masui++13, Switzer++ 2013).
    - First detection of Fast Radio Burst (FRB) with GBT with RM (Masui++15, Nature)
    - Detection of Redshift Space Distortions (RSD) with cross-power spectra (Chang++16, in preparation)

Slide courtesy of Tzu-Ching Chang

# BINGO project

- BINGO : **B**AO's **I**n **N**eutral **G**as **O**bservations
- 40 m diameter fixed single dish (2 reflector design, primary+secondary mirrors) - observing in transit mode
- 960-1260 MHz, 0.12 < z < 0.48 , 40 ang. resolution
- 50 dual polarisation feeds - room temperature Tsys ~ 50 K
- Located in Uruguay - UK, Brazil, Uruguay
- Digital correlator (X reference beam oriented toward the celestial pole)
- Science: HI power spectrum, FRB, Galactic science (radio recombination linesand continuum)

## BINGO players

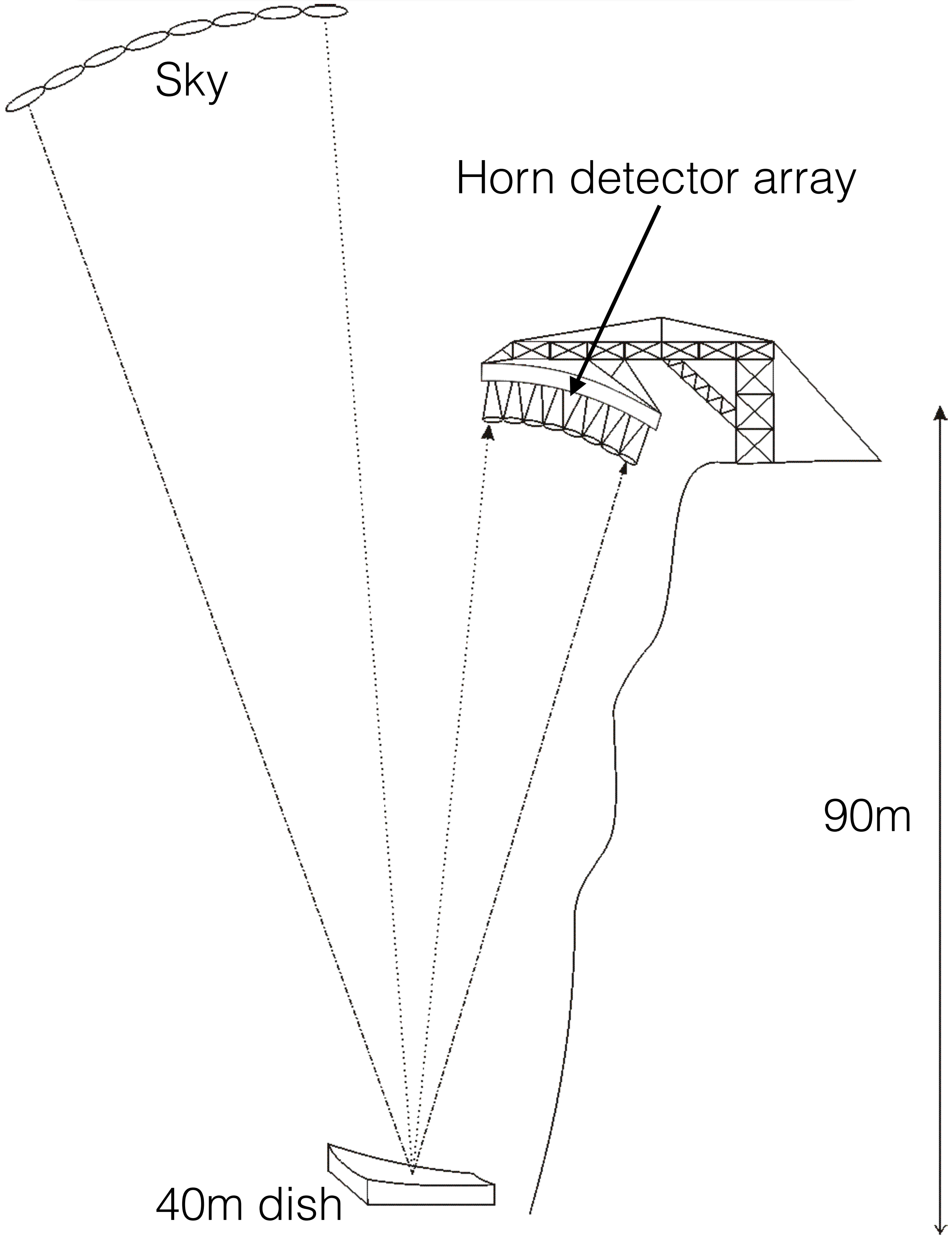
- **U. Sao Paolo, Brazil**
  - Elcio Abdalla (P.I.), Raul Abramo, Andreia Pereira de Souza (engineer), Benjamim Galvão (engineer, industry liaison), Marcos Lima
- **INPE, Brazil**
  - Alex Wuensche, Thryso Villela, Renato Branco (engineer)
- **U. Montevideo, Ministry of Communications, Uruguay**
  - Gonzalo Tancredi, Manuel Calas, Emilio Falco, Ana Mosquera
- **JBCA, Manchester, UK**
  - Richard Battye, Ian Browne, Tianyue Chen, Peter Dewdney (SKAO), Richard Davis, Clive Dickinson, Keith Grainge, Stuart Harper, Lucas Olivari, Mike Peel (-> FAPESP fellow), Mathieu Remazeilles, Sambit Roychowdhury, Peter Wilkinson
- **ETH, Zurich, Switzerland**
  - Alex Refregier, Adam Amara, Christian Monstein
- **UCL, London, UK**
  - Filipe Abdalla
- **IAS, Paris, France**
  - Bruno Maffei (ex-Manchester)
- **U. Cardiff, UK**
  - Giampaolo Pisano
- **UKZN, South Africa**
  - Yin-Zhe Ma (ex-Manchester)
- **U. Portsmouth, UK**

# BINGO concept

**Guiding principle : simplicity!**

**BAOs In Neutral Gas Observations**

- **Key specifications:**
  - Dish diameter : 40 m
  - Resolution: ~2/3 deg
  - Frequency range : 960 - 1260 MHz **(z=0.12-0.48)**
  - Number of feeds: 50 (dual pol)
  - Field-of-view: ~15 deg
  - **No cryogenic cooling** : Tsys ~ 50K
  - Digital correlation receiver
  - Channel width << 50 MHz (Δz<0.05)
  - **Majority of receiver components "off-the-shelf"**
  - **Transit telescope (no moving parts): observe declination strip with drift scans**
  - 2 years observing (~1 year on source)



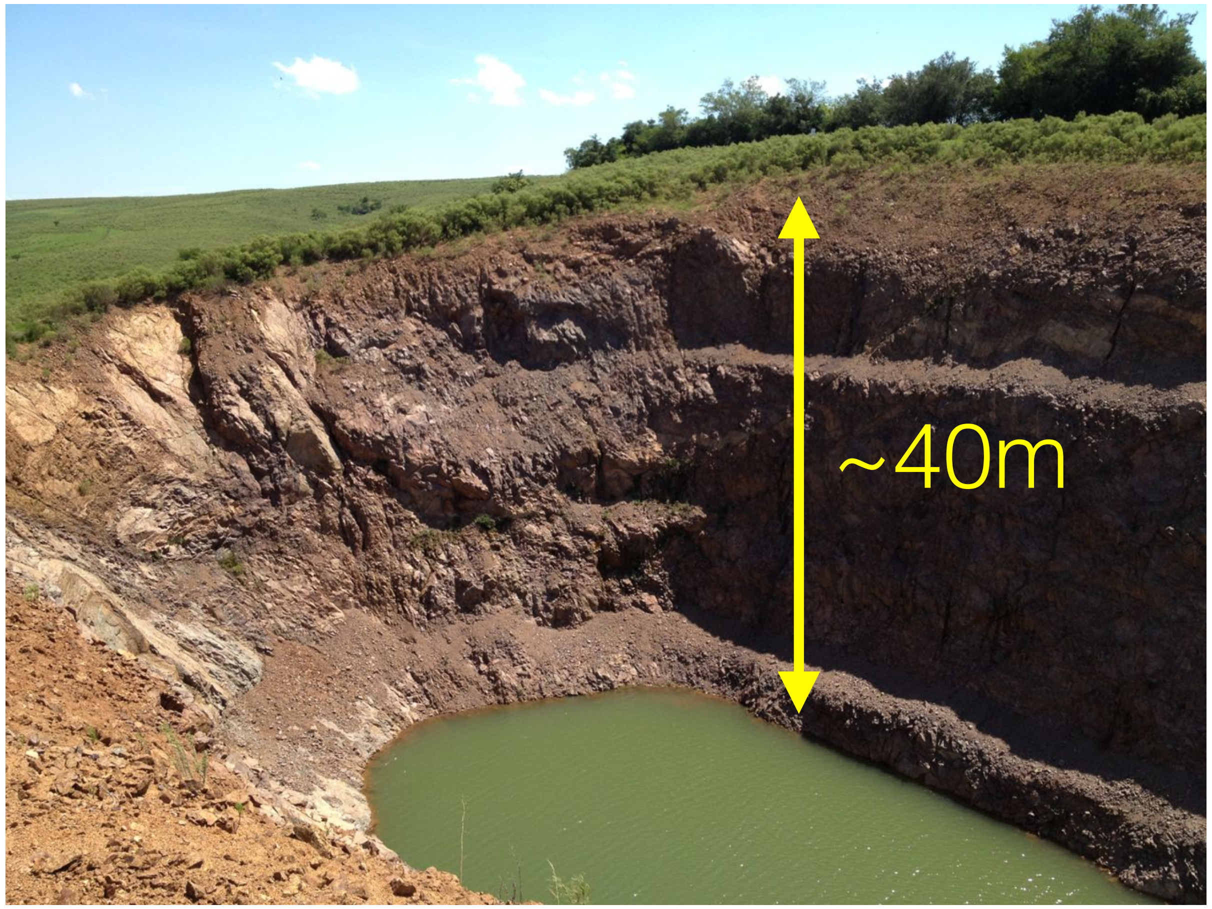

Battye, Browne, Dickinson, Heron, Maffei, Pourtsidou, 2013, MNRAS, 434, 1239 [arXiv:1209.0343]

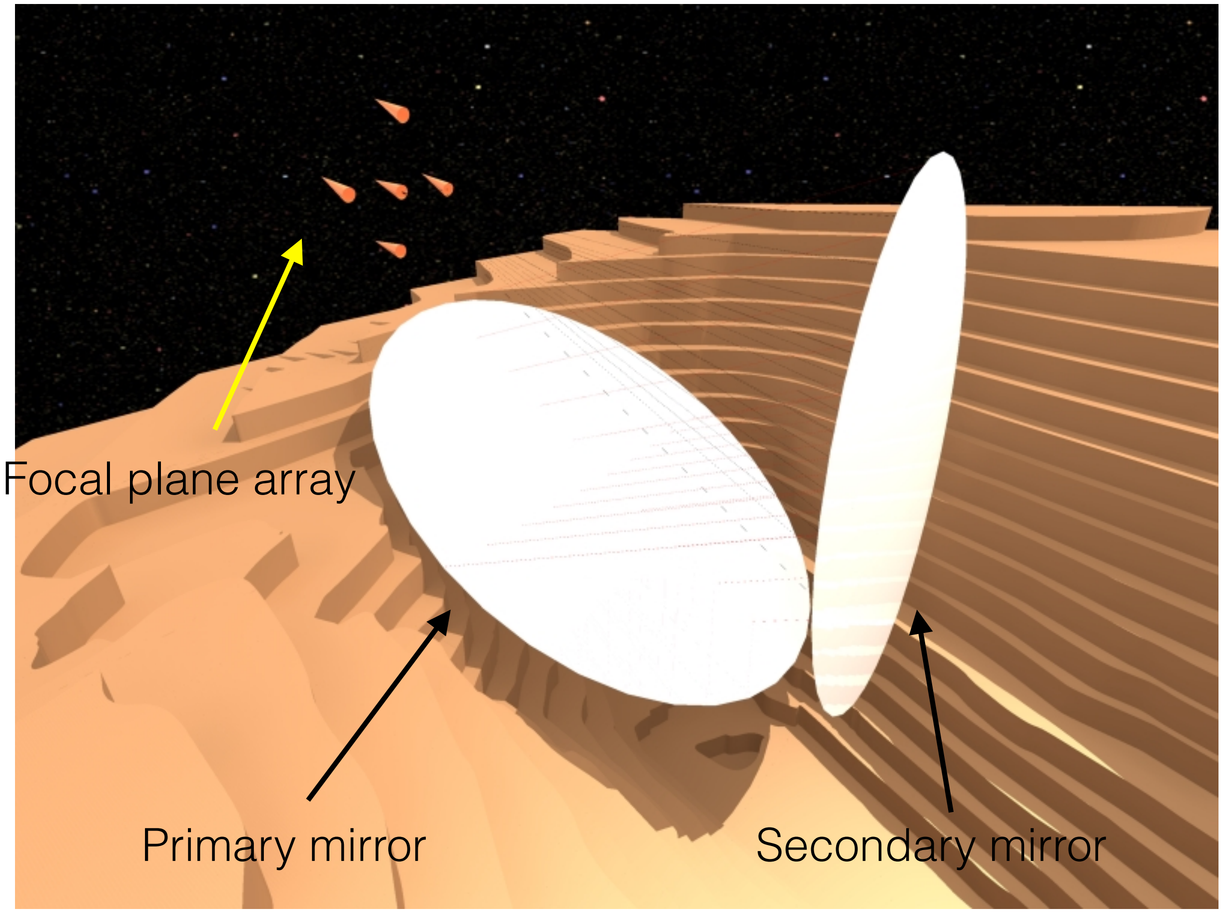
Slide courtesy of Clive Dickinson


# Site selection

After a long process we have found a suitable suite Quary Castrillon in Northern Uruguay

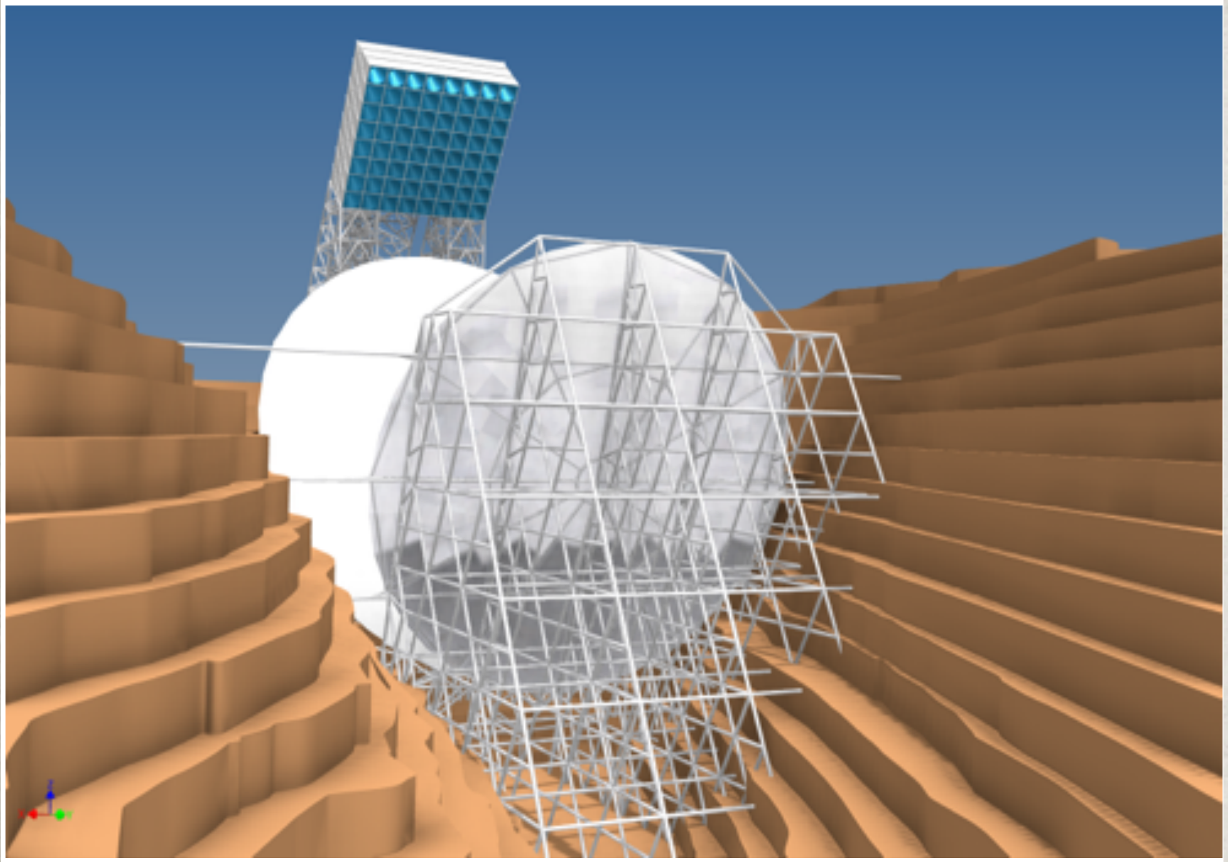
2-dish design easier to deal with and has better performance

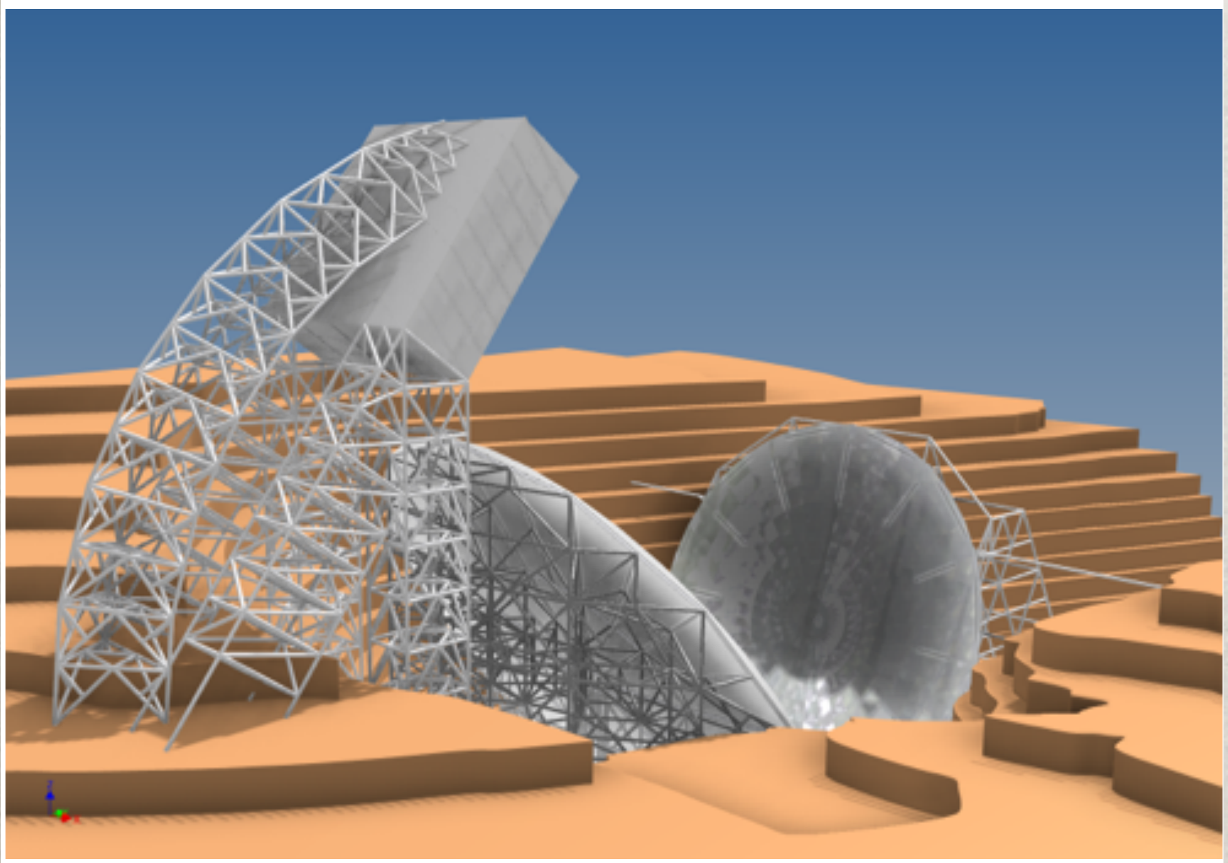



Slide courtesy of Clive Dickinson

# BINGO Optical design (B. Maffei et al.)



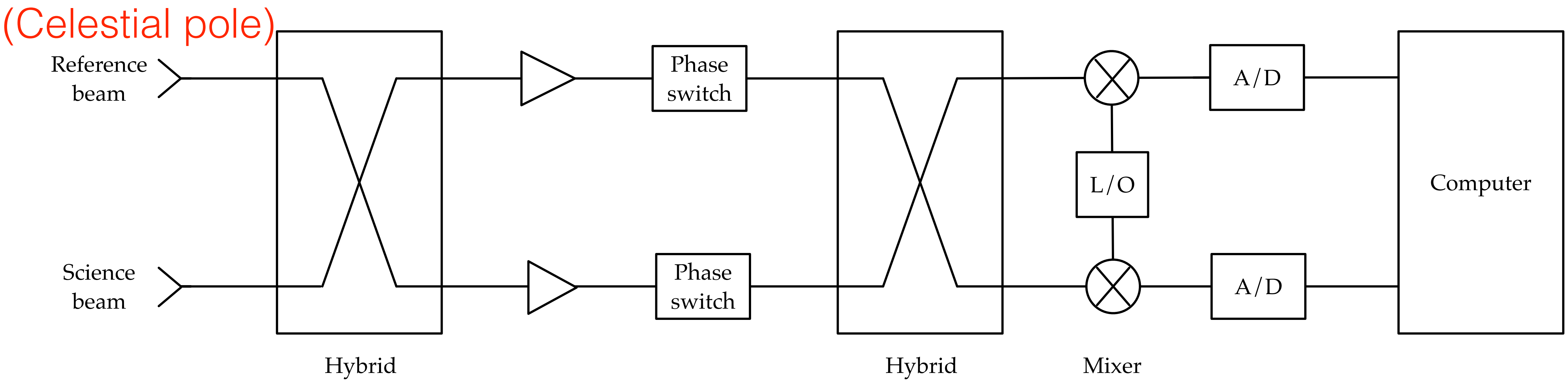


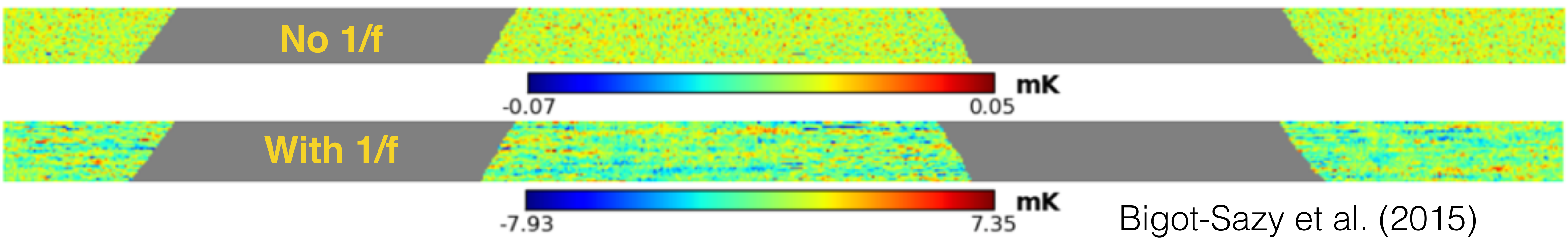
# BINGO horns

- BINGO horns are BIG!
  - 1.7 m diameter
  - 4.7 m in length
  - 50-60 of them!
- Corrugated horns essential for good beam / low sidelobe response
- Standard techniques are **expensive** and **heavy**
  - New alternatives being investigated

Illustrations: courtesy of Clive Dickinson

# Correlation receiver




Bigot-Sazy et al. (2015)

- 1/f knee frequency of typical receivers ~1 Hz
  - Produces long time-scale fluctuations of total-power (1/f noise)
  - -> larger noise level, stripes in the map…
- Perfect pseudo-correlation (e.g. WMAP/Planck) can remove 1/f noise
- Use (South) Celestial Pole as reference

Battye et al. (2013)

Slide courtesy of Clive Dickinson

# 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*

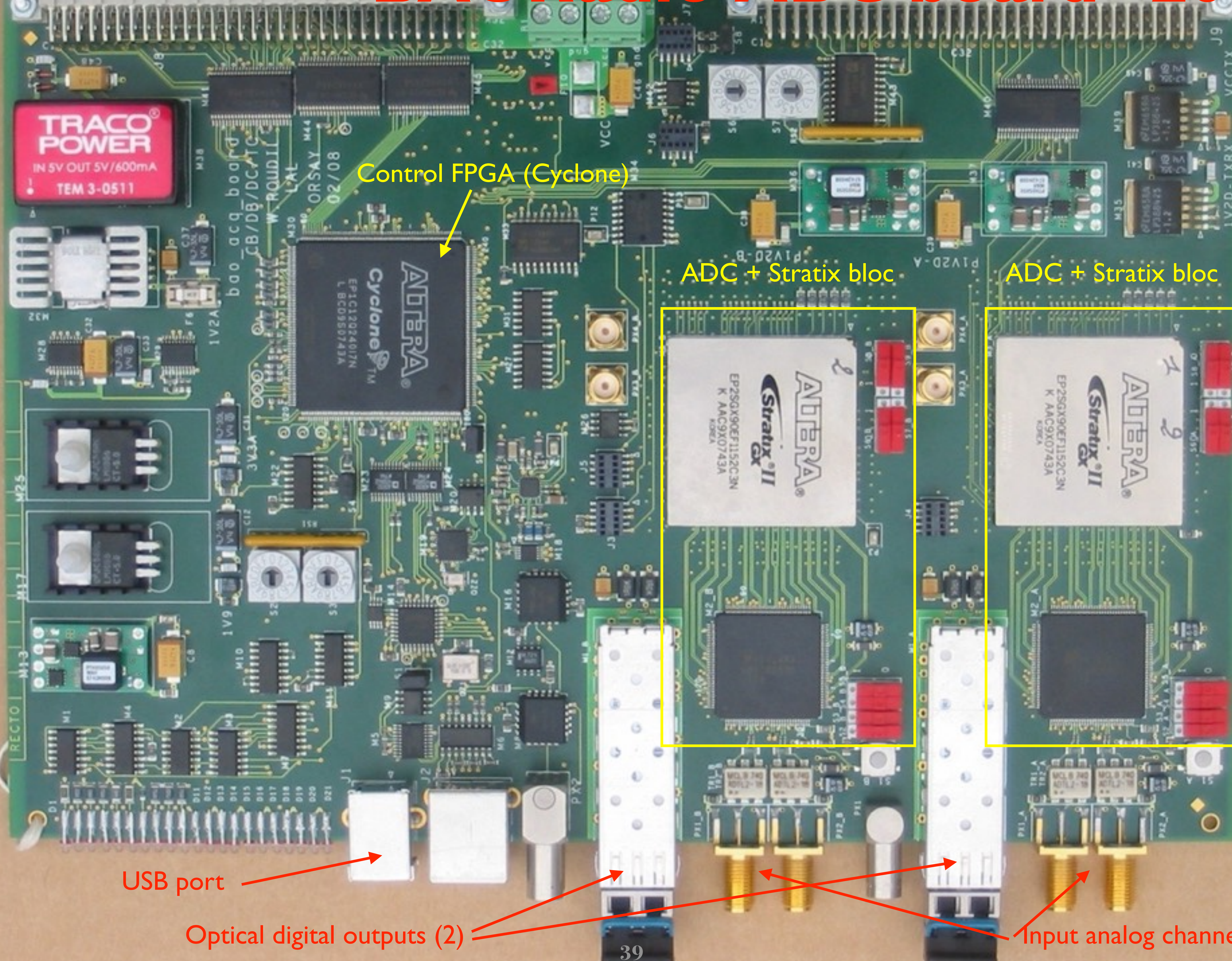
P. Abbon
*E. Delagnes*
H. Deschamps
C. Flouzat
*P. Kestener*

### Observatoire de Paris

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

- 2007: BAORadio project initiated in France
- LAL (IN2P3/CNRS), Irfu (CEA), Observatoire de Paris
- 2007-2009: development of the BAORadio (electronic/ acquisition) system - Tests at Nançay (NRT)
- 2009-2010: Tests on theCRT prototype at Pittsburgh
- 2011-2012: FAN, HI-Cluster, contacts with NAOC
- 2012-2014: PAON, Tianlai
- 2015-2016: NEBuLA, PAON4, Tianlai
- Financial support: IRFU, CNRS/P&U, IN2P3, P2I, Obs. de Paris, LAL, PNCG

# BAORadio ADC board- 2008

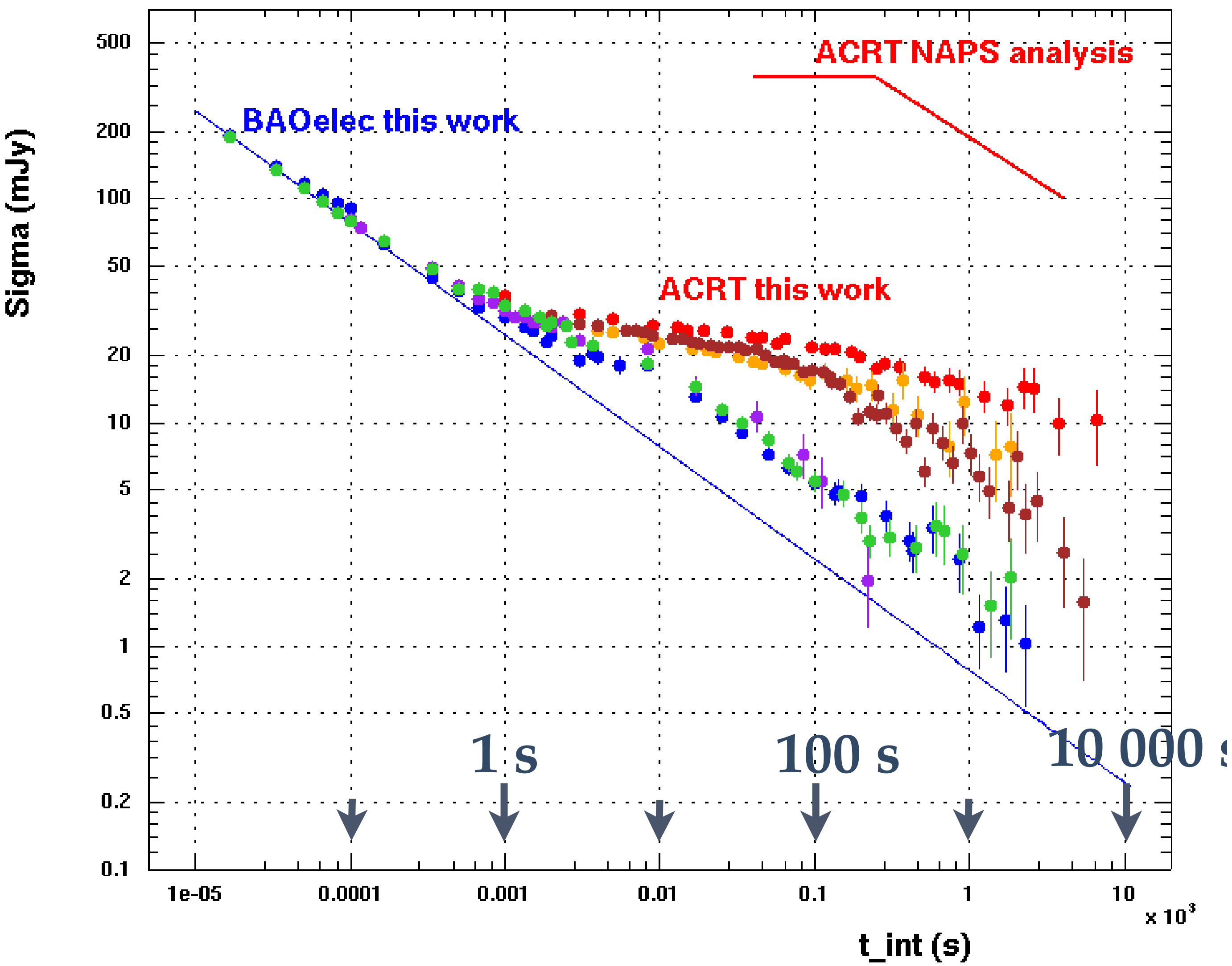


# CRT (CMU, Pittsburgh)

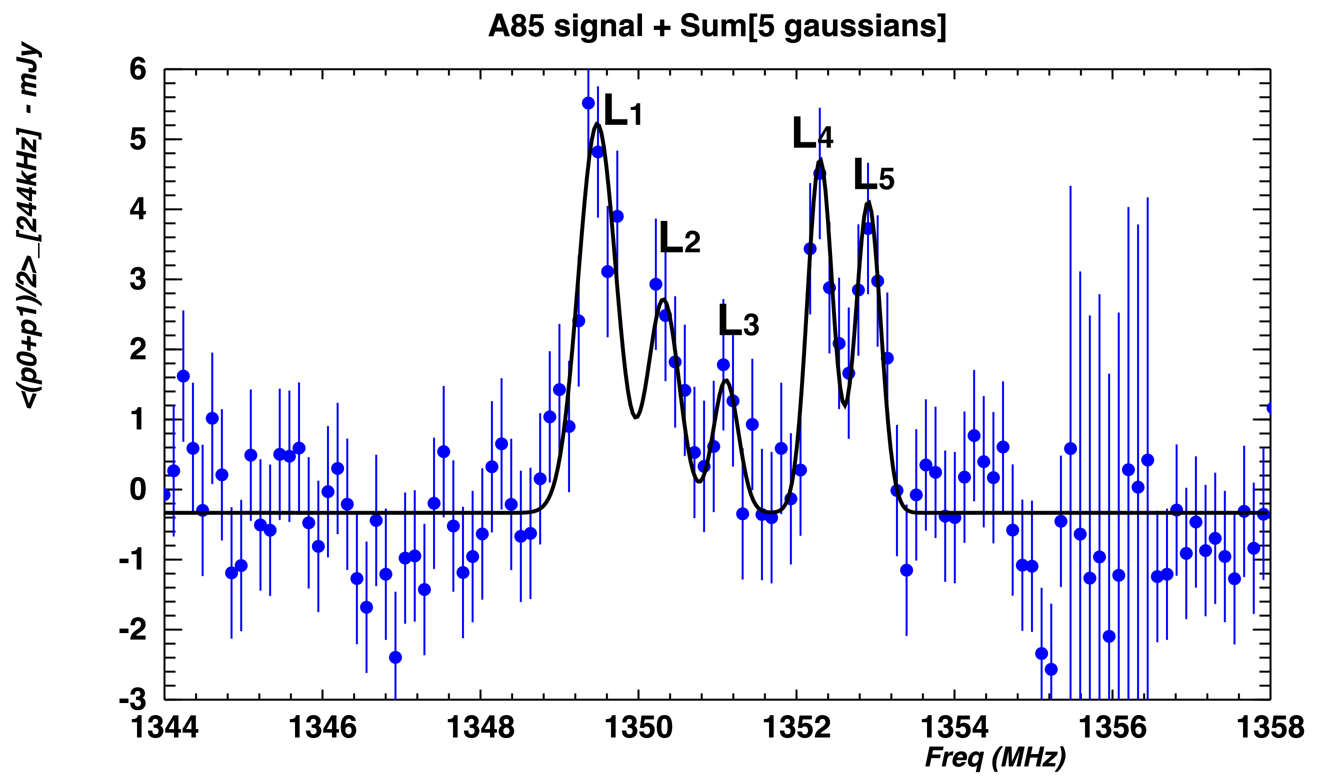
BAORadio @ CRT-Pittsburgh - Nov 2009

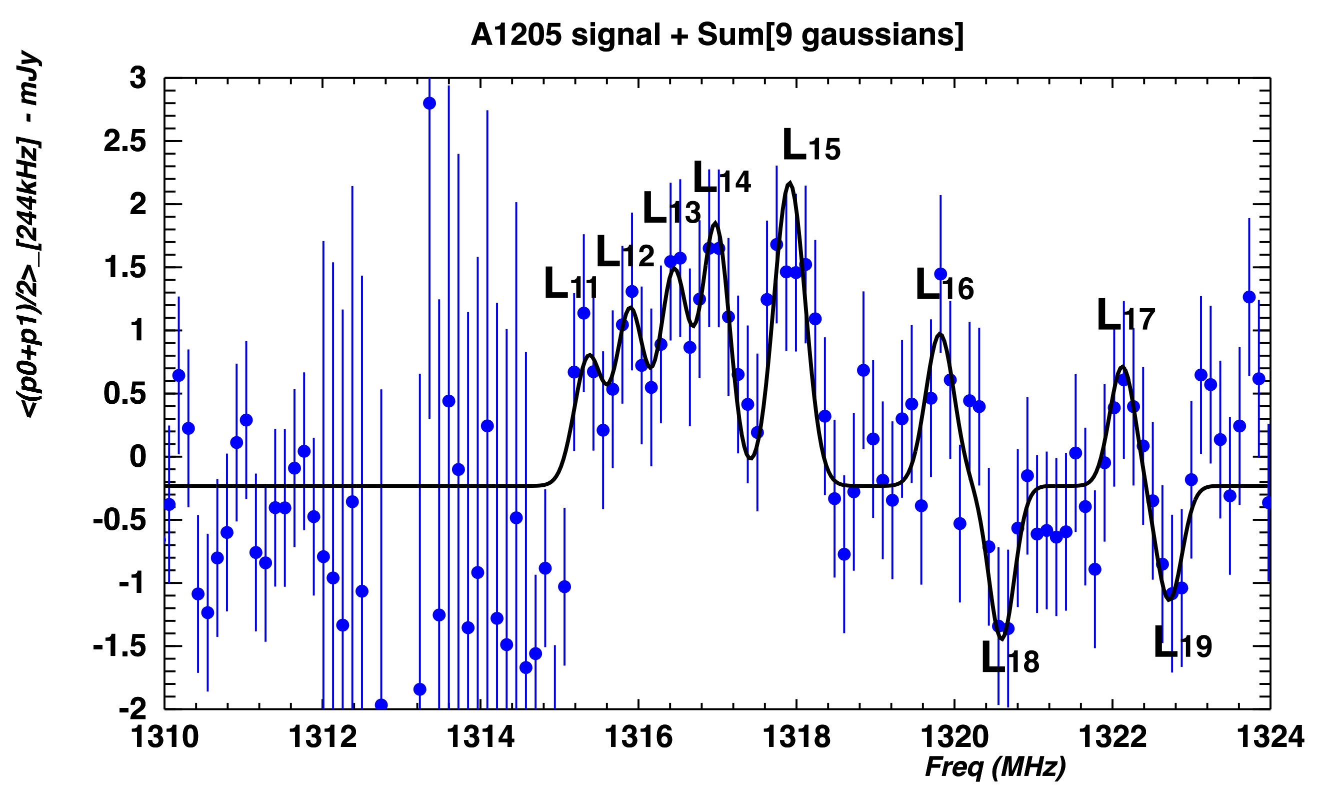
40

# Noise/sensitivity (radiometer curve)
# HI-Cluster, BAORadio & NRT correlator




## Signal HI A85 / A1205




# HICluster

Ansari et al. (2015) - Exp. Astronomy
arXiv:1505:02623

# PAON-4 / NEBuLA

- PAON : PAraboles à l'Observatoire de Nançay
- PAON-4 : 4 D=5m reflectors, dense array configuration, transit observation mode
- Total surface ~ 75 m^2, 8 = 4 x 2 (pol) récepteurs , 36 visibilities ~ 2 GBytes/s maximum data flow
- 38 S < Elevation < 15 N → 10 < δ < 60 at Nançay
- 250 MHz band , 1250-1450 MHz
- Reconstructed map resolution ~ 1 deg @ 1400 MHz
- Aims: RFI cleaning , Tsys and antennae correlation, test of calibration and 3D transit mode map making
- Sensitivity level ~50 mK (/ 1deg^2 x 1 MHz pixels) over ~ 5000 deg^2
- NEBuLA : Numériseur à Bande Large pour l'Astronomie - New generation digitiser board that could be deployed close to the antennae, over ~ km sized area …

# PAON-4 (PI: J.E. Campagne, J.M. Martin) - Technical projet leaders:
F. Rigaud (Mechanics) - D. Charlet (Electronic, Computing, Commissioning)

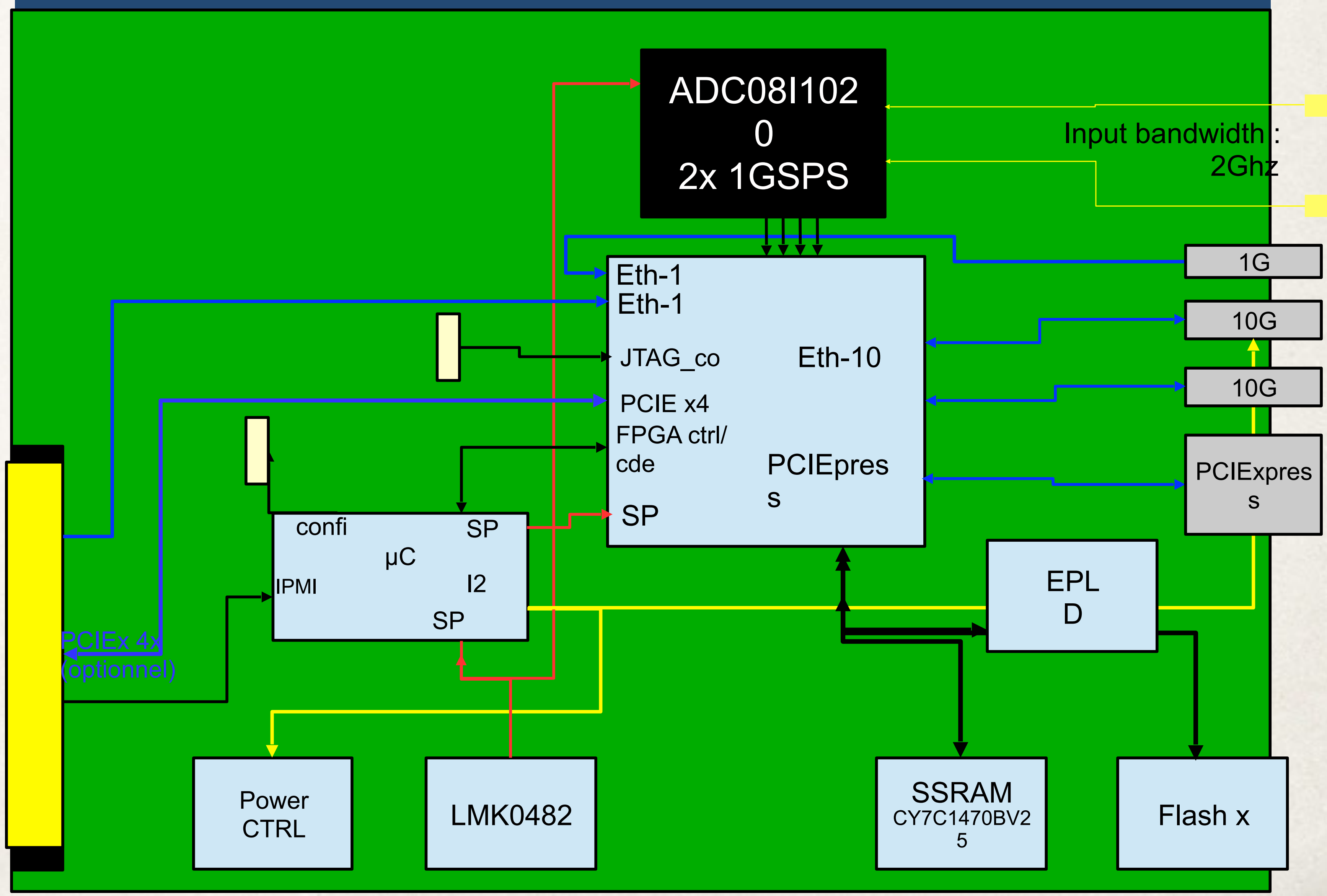
**PAON-2 →**

September 2012

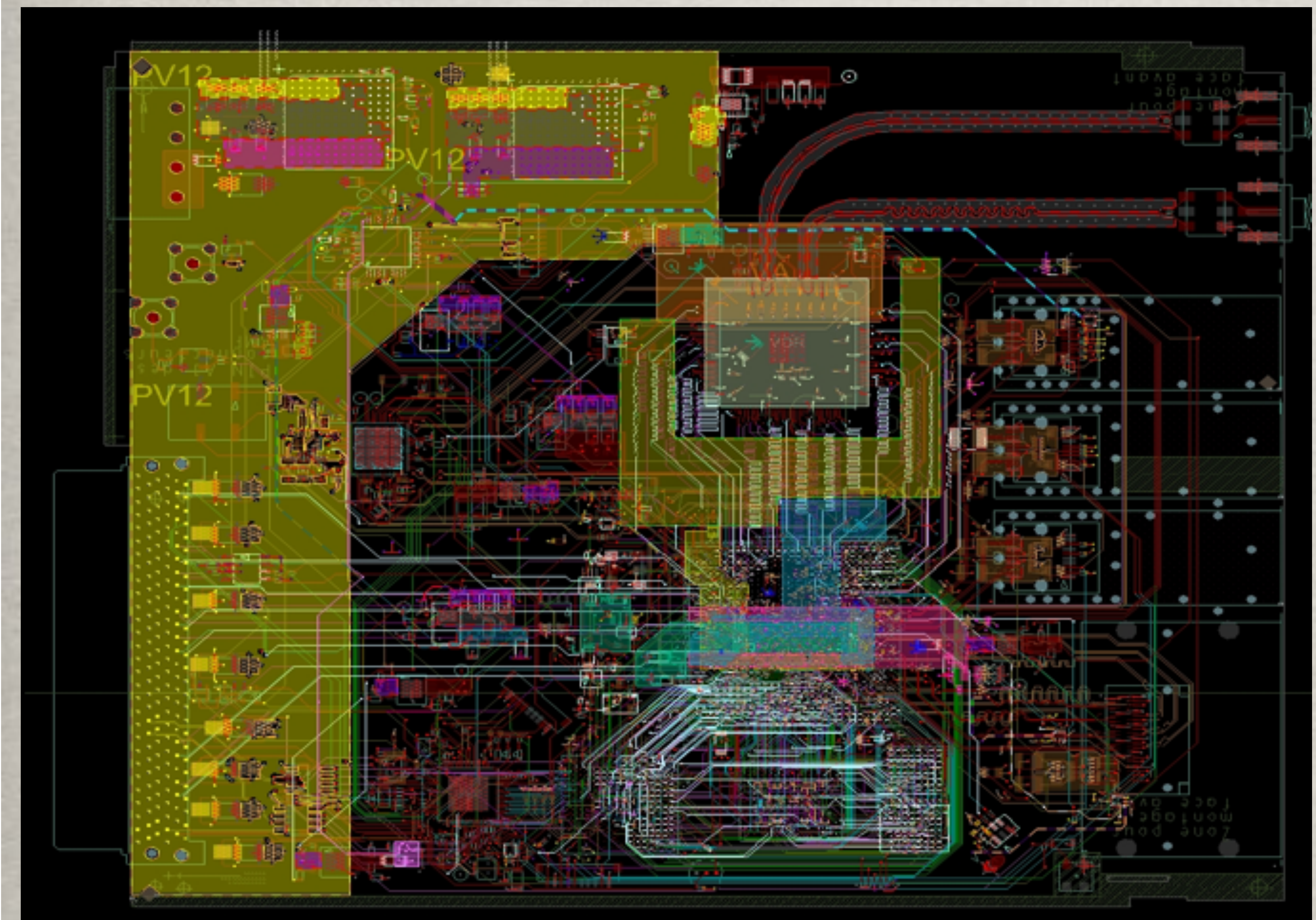
# NEBuLA (D. Charlet - LAL , C. Viou - Nançay)

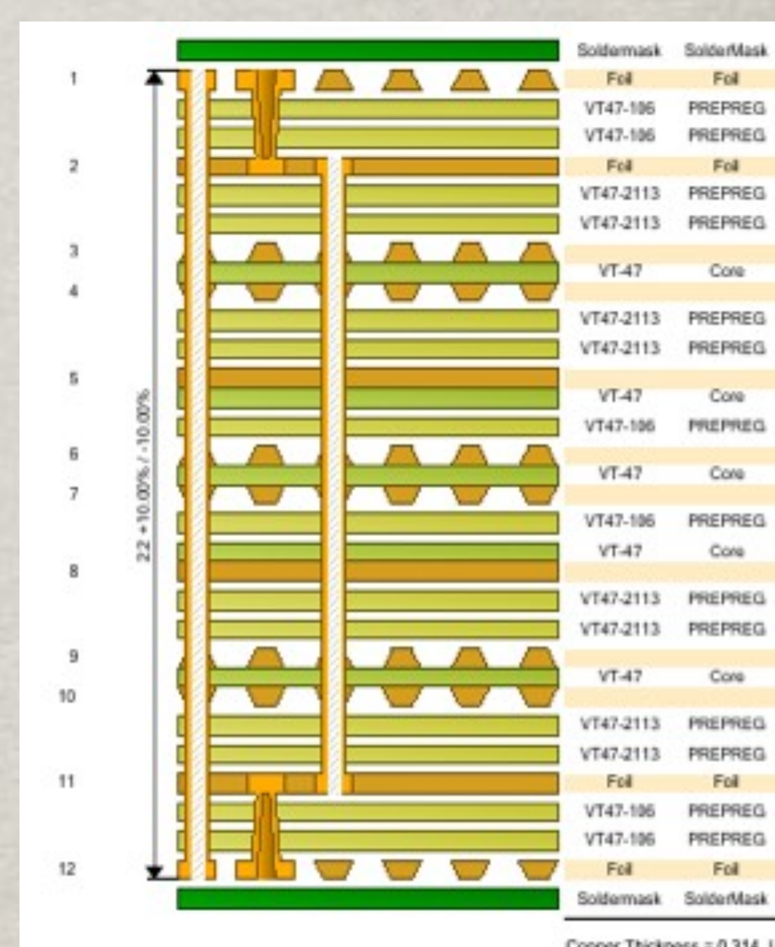
- Direct sampling after the LNA + filters (no mixer)
- Up to 500 MHz bandwidth
- designed to be put near the antennae
- optical data output & control / synchronisation

- Projet Nançay-LAL-Irfu accepté par le CS Obs. de Paris (CSAA) Décembre 2013, 17k€ (proto) Porteurs: Cédric Viou (Nançay) & Daniel Charlet (LAL)
- Par rapport à l'électronique actuelle dont le design date de 2006-7:
  - On s'affranchit de la partie Mélangeur
  - On réduit la longueur du câble coax.
  - On passe de 250 MHz à 500 MHz de bande
  - Transmission passe à 100% de temps Ciel
  - Ethernet & PCI Express Externe (accès direct mémoire des PCs)
  - à usage PAON et NRT/RadioHéliostat, voire TIANLAI



# NEBuLA board design (D. Charlet)




LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

cnrs

Carte prototype en cours de fabrication (Juin 2016)

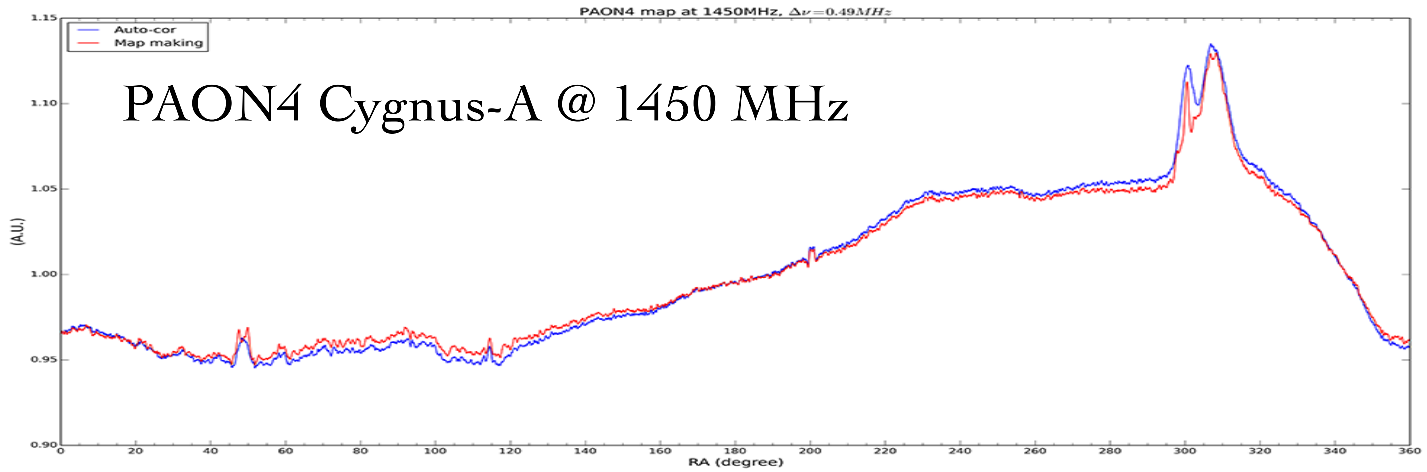
# Map from visibilities (single scan) I

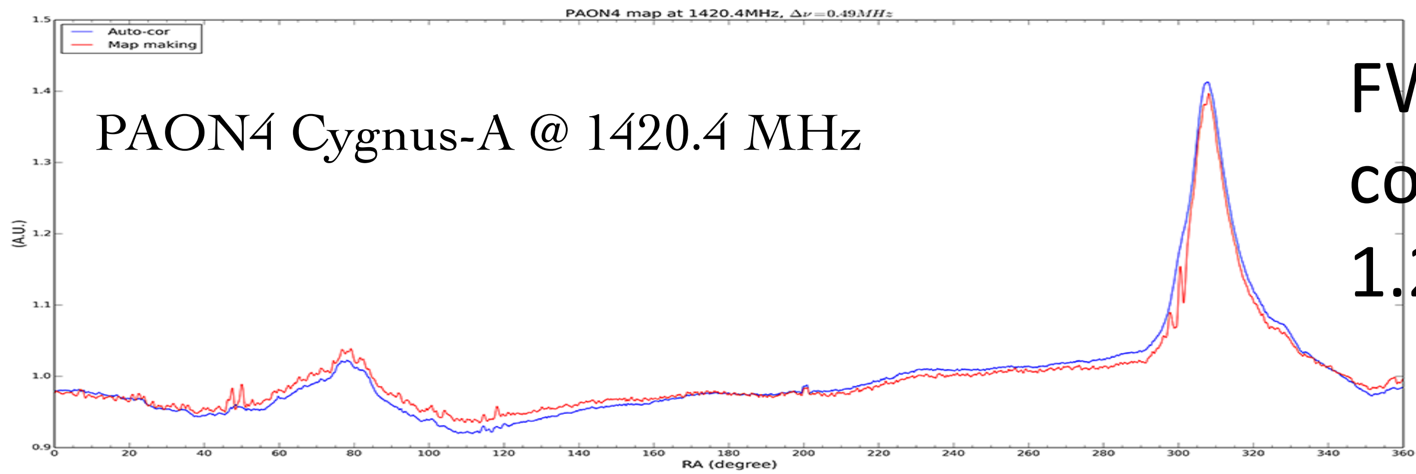
Slide by Qizhi Huang (LAL/NAOC PhD)

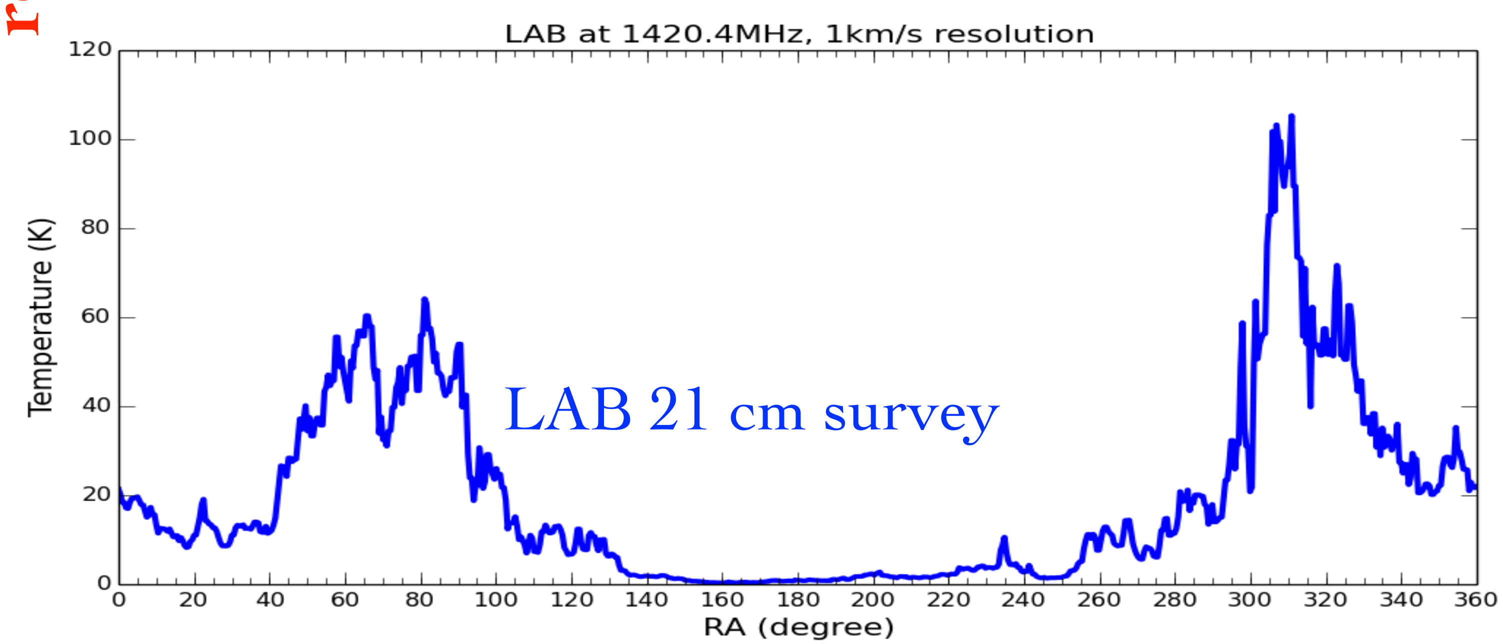
PAON4 CygA

blue : autocorrelation (single dish)

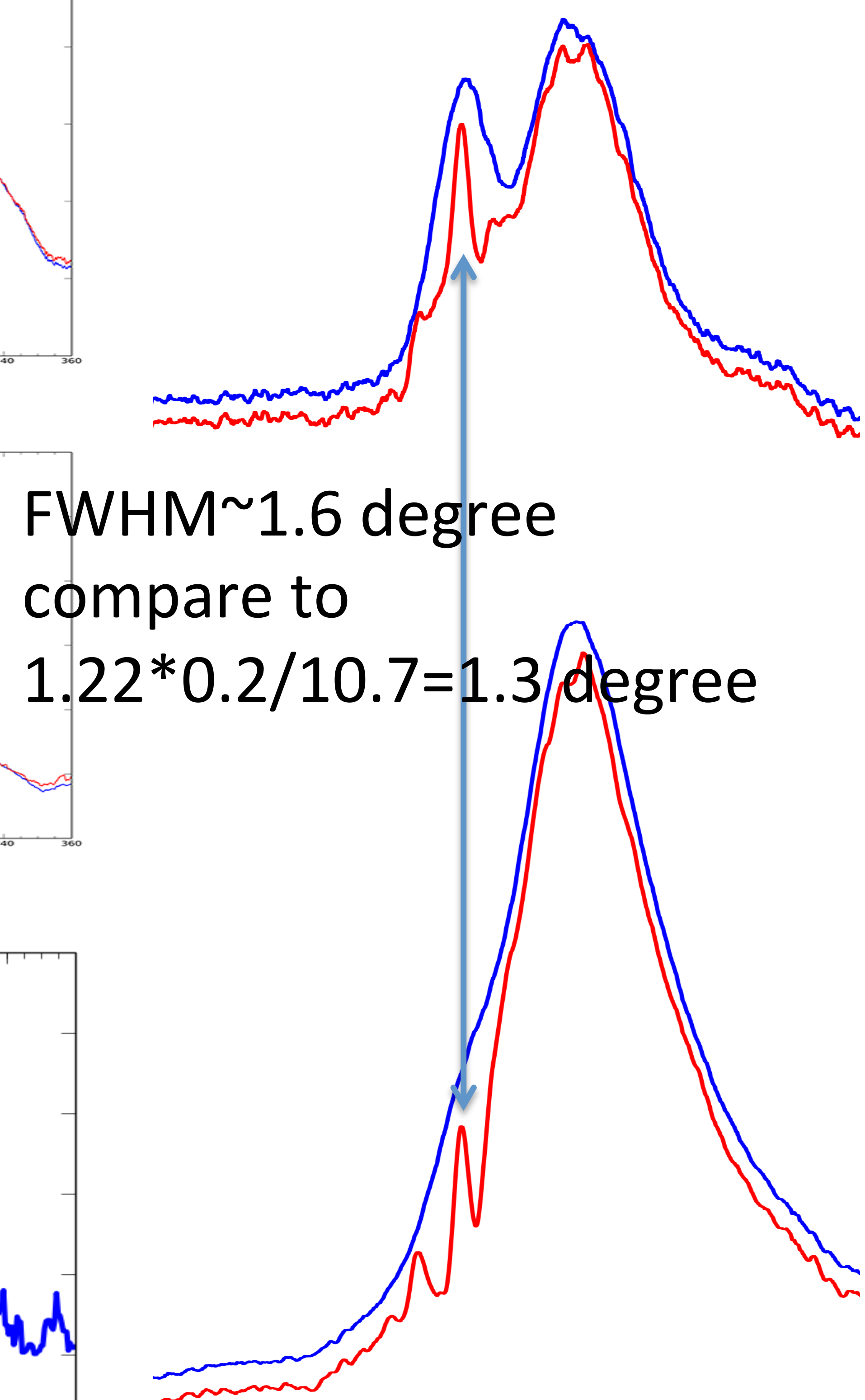
red: combined visibilities (4 dishes)




PAON4 CygA @ 1450 MHz




PAON4 CygA @ 1420.4 MHz

Nov. 2015

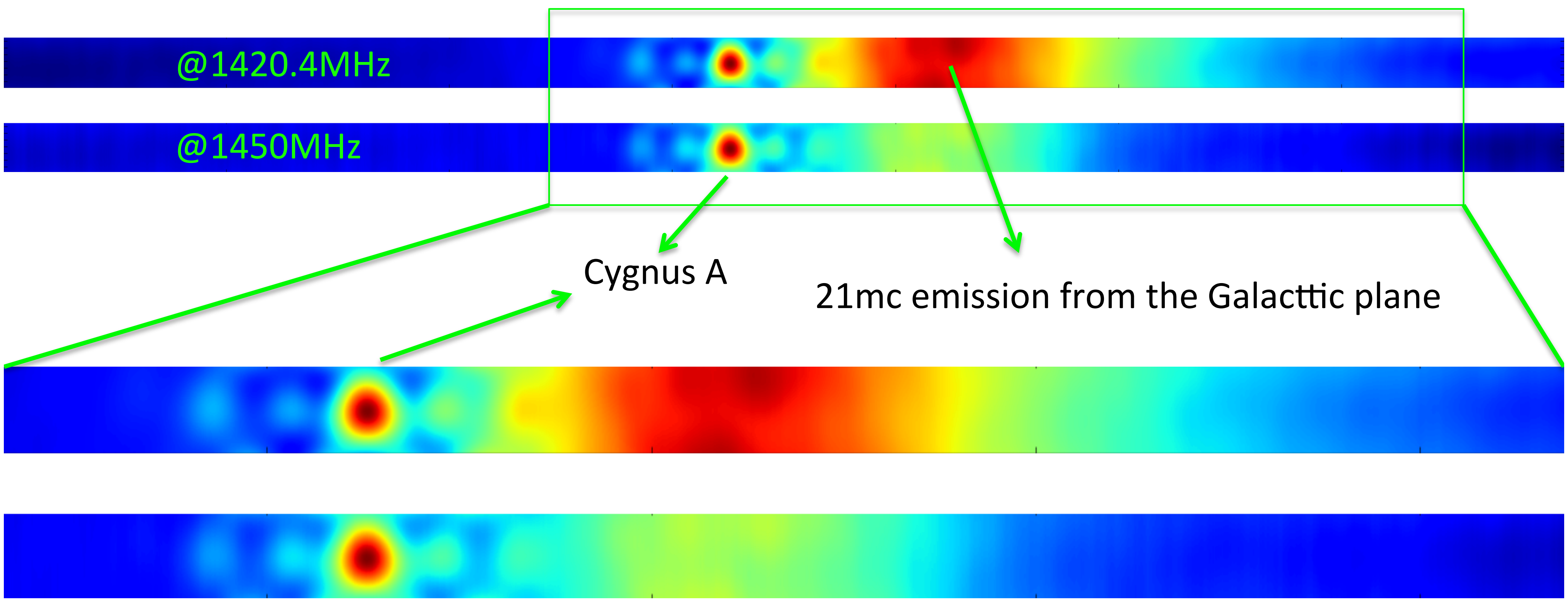
# Map from visibilities (single scan) II

Slide by Qizhi Huang (LAL/NAOC PhD)

## Final maps

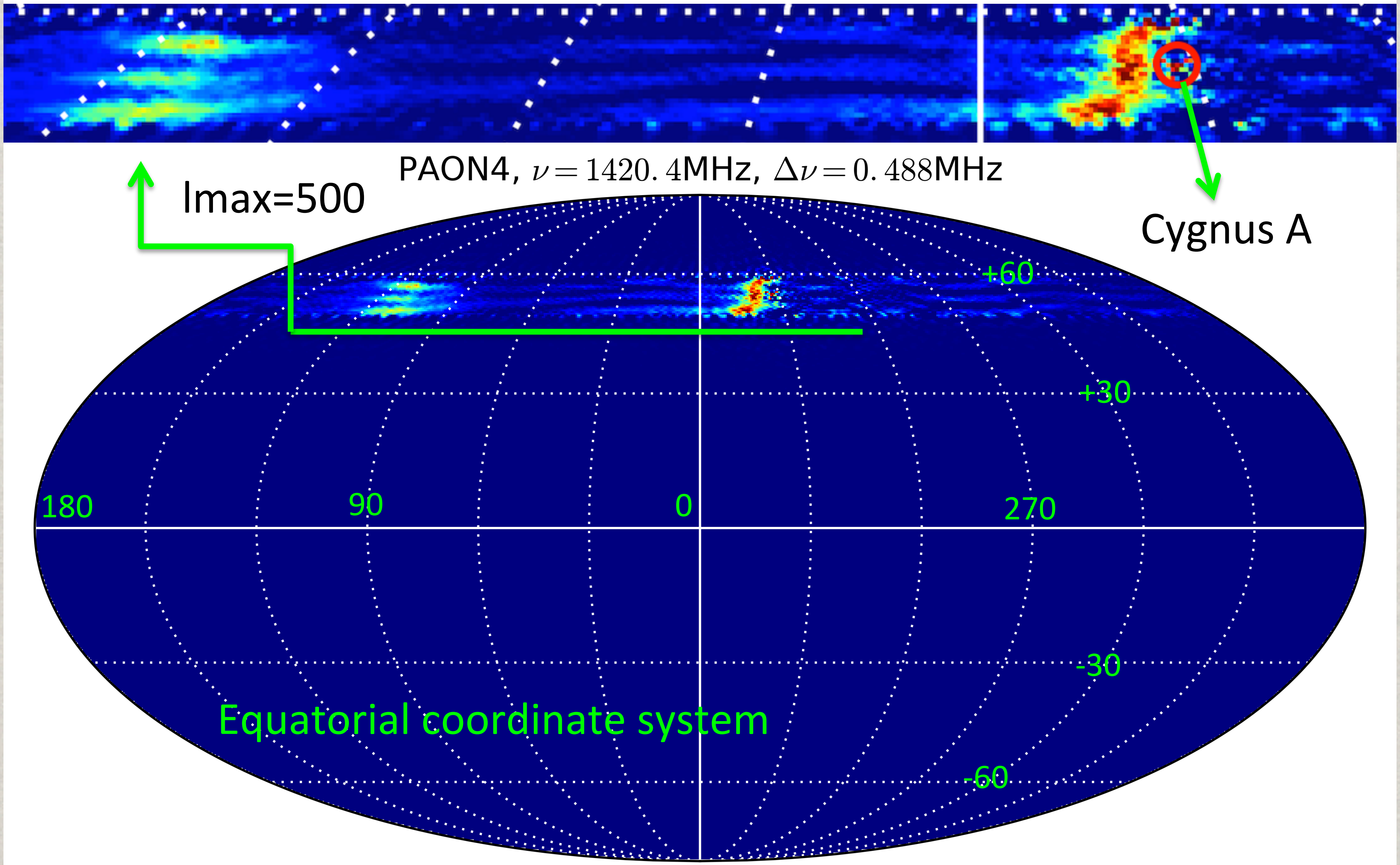
Nov. 2015

CygA24h11mai15 is one day 24 hours observation, we just have one transition. Hower, we can add and special phase to the visibilities to simulate the case that turnning the antennas to other declinations and observate.



# PAON-4 reconstructed maps

## Map making using Jiao's program (2)




Calibration: Q. Huang, m-mode map making : J. Zhang (April 2016)

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 IRFU

WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

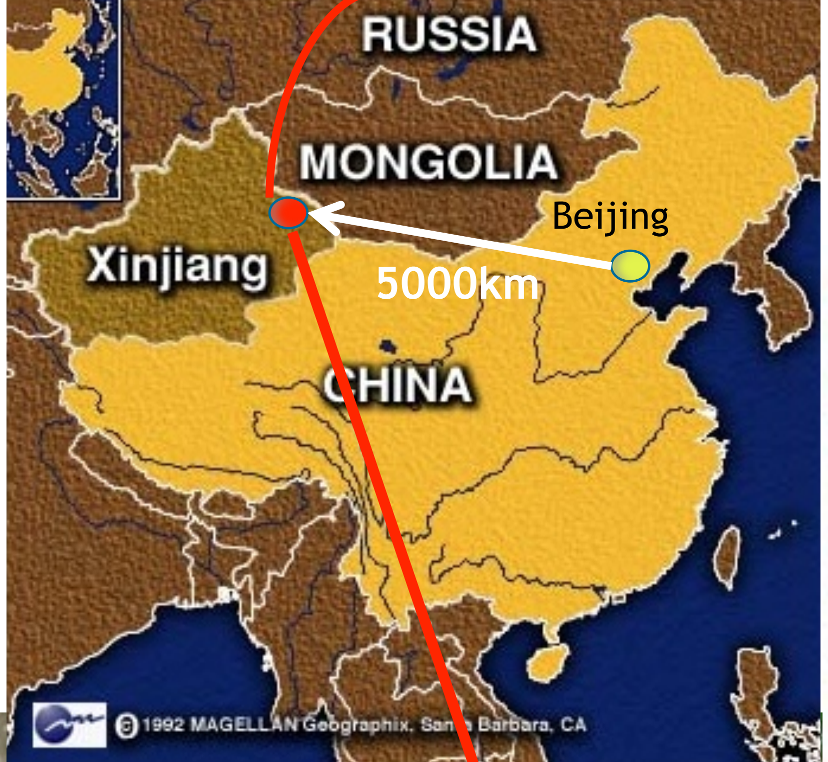
Fermilab

49

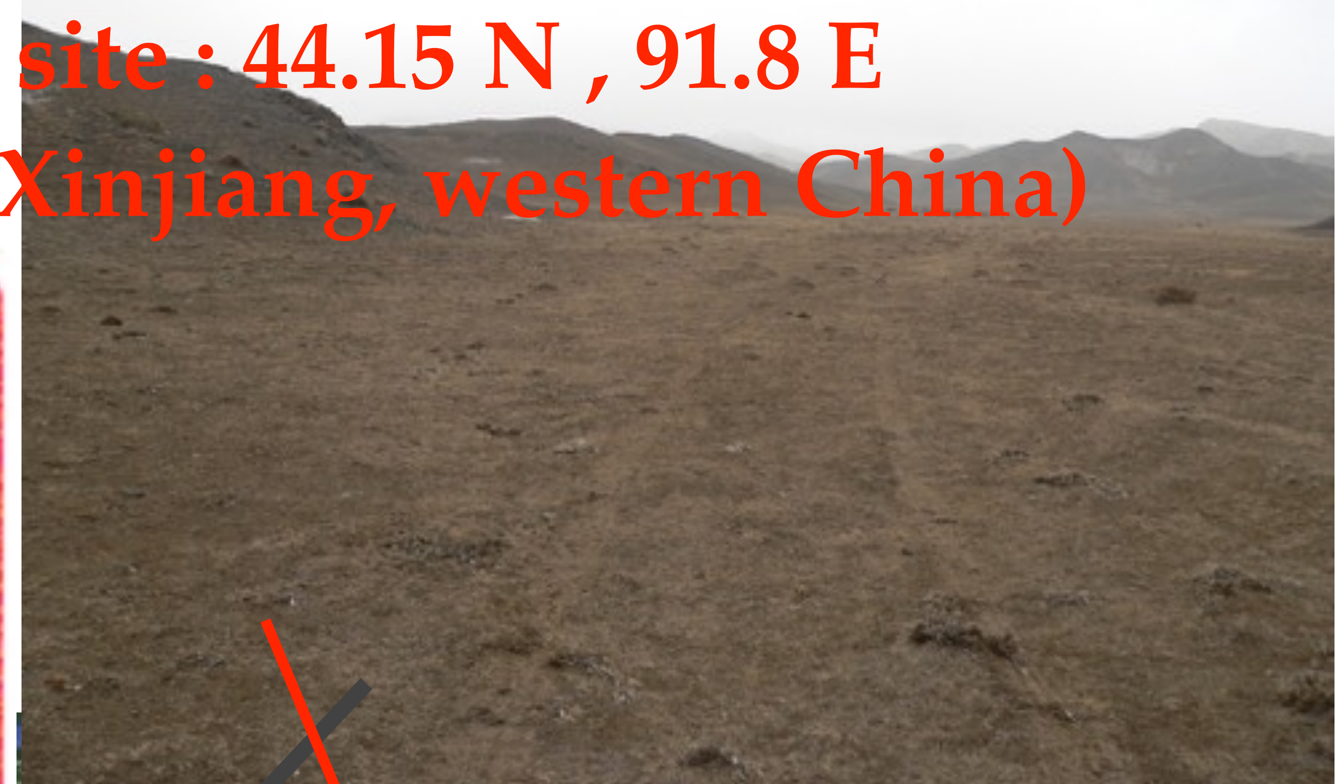
# Tianlai

- Tianlai project led by NAOC (PI: Prof. Xuelei Chen)
- International partners: Canada, États-Unis, Corée du Sud, **France**
- Collaboration started in 2011-2012 - Chinese financial grant from MOST granted in 2012 (?) for the pathfinder phase
- In china: *Institute of Automation* (digital electronic) and *Institute 54* (Antenna, analog electronic) + …
- Site search / site testing - Site selected in 2013
- Start site preparation work in summer 2014: construction of road (dirt road) et 10 kV electric power line, optical fiber cable (7 km) from closest village - Construction of the living quarters and acquisition/control rooms
- 3 cylinders (15m x 40m) and 16 dishes (D=6 m) arrays constructed/ deployed in summer 2015
- Tianlai pathfinder phase: 96 (dual-pol) receivers on the 3 cylinders - 192 channels correlator (FPGA+DSP Inst.ofAut) + corrélateur 32 channel correlator for the16 dish array (100 MHz bandwidth)

# Tianlai site : 44.15 N , 91.8 E
# Hongliuxia Xinjiang, western China)



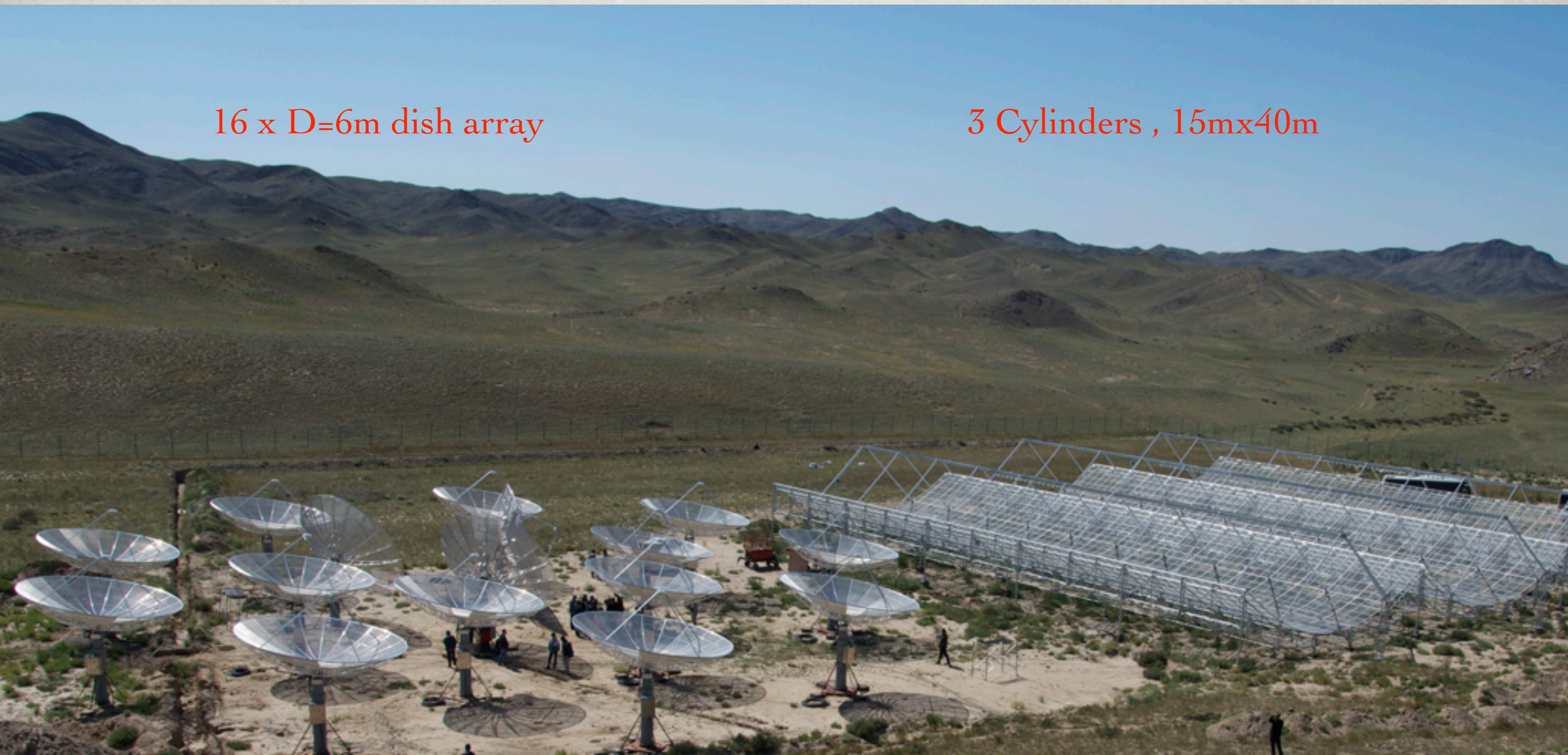

天籁 TIANLAI




Sep. 2015

# Tianlai

Visit to the site during the Balikun (Sep. 2016) workshop

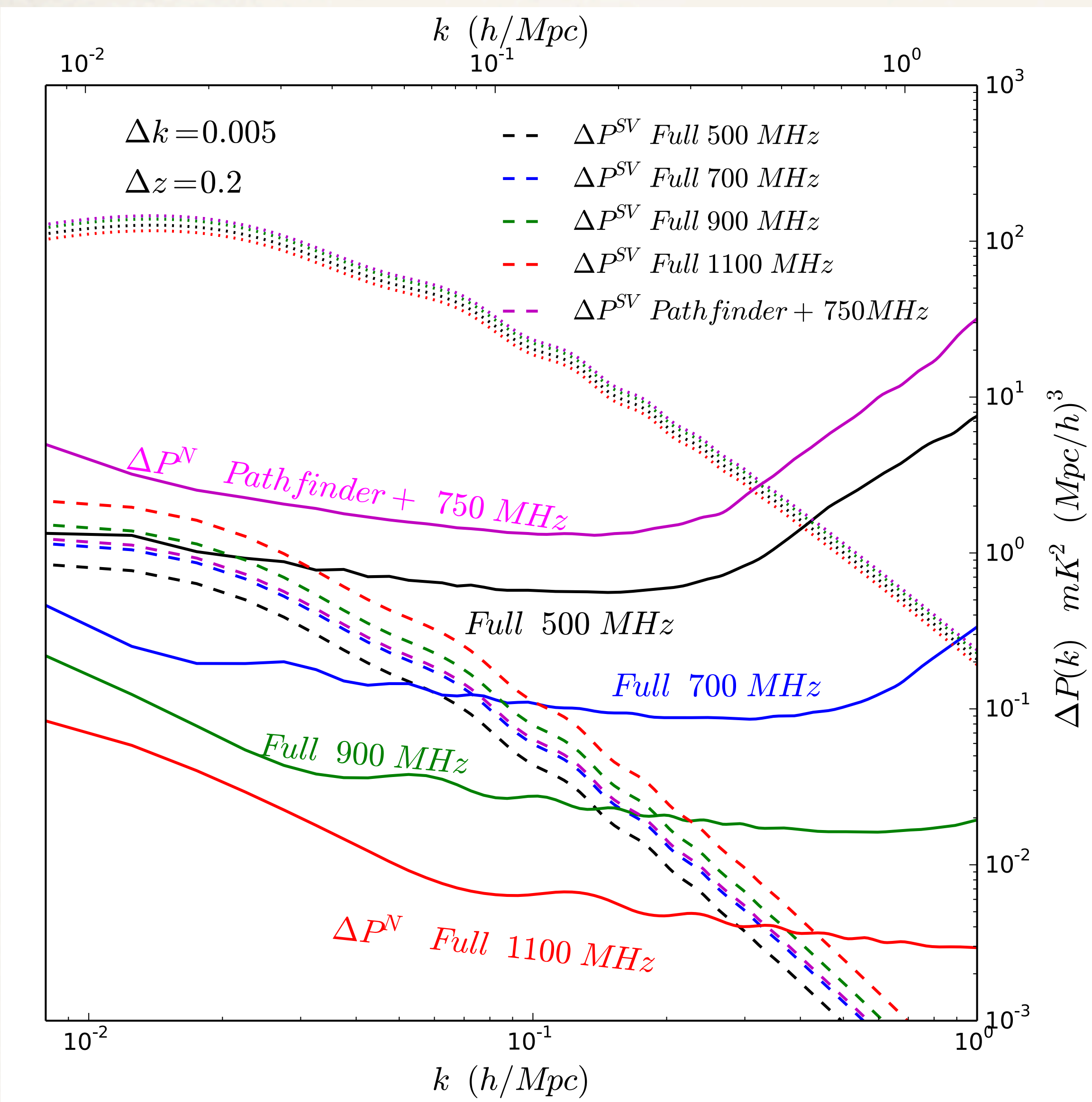


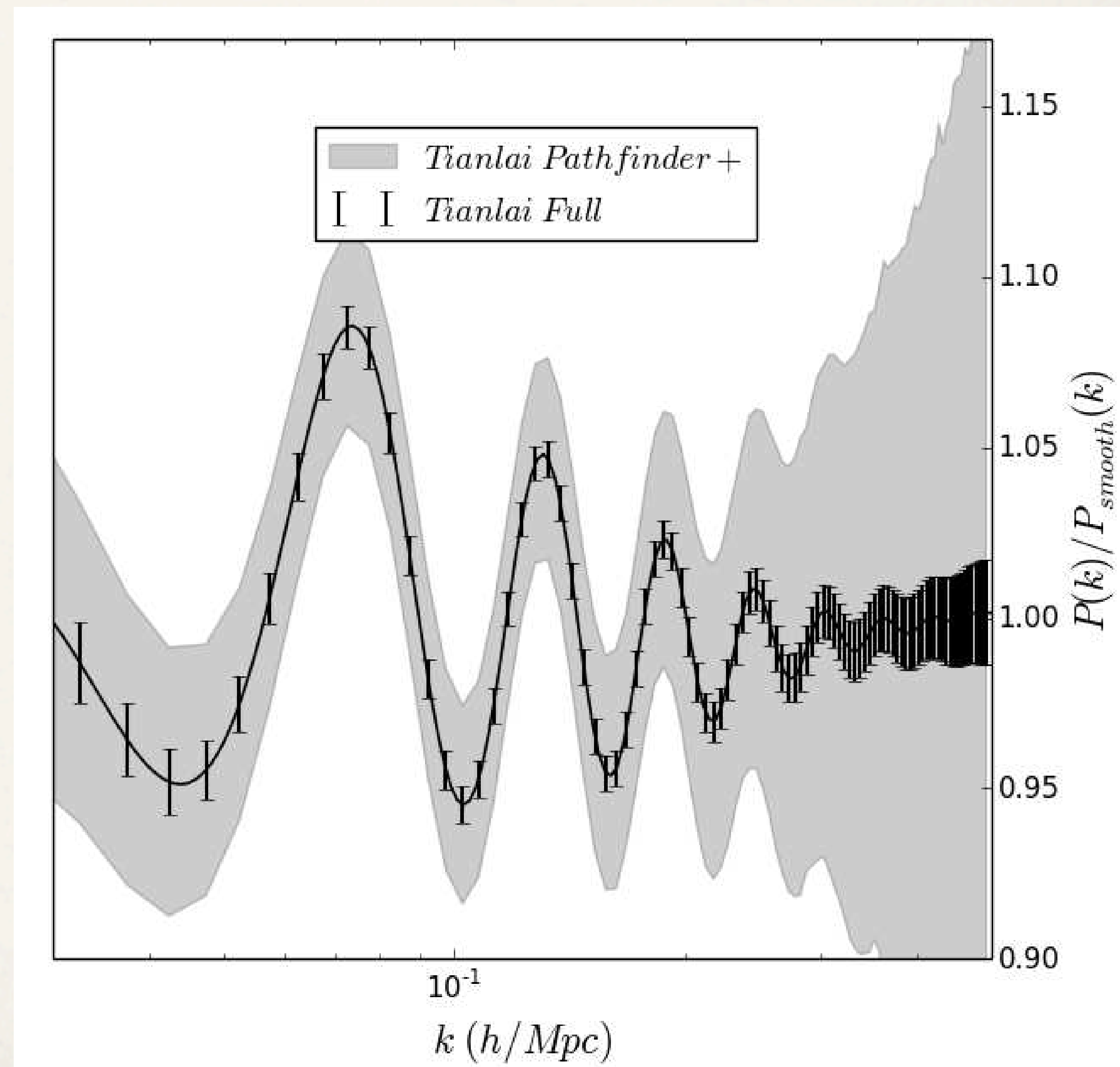

R. Ansari - March 2016

# Tianlai

Table 1: The experiment parameters for Tianlai.

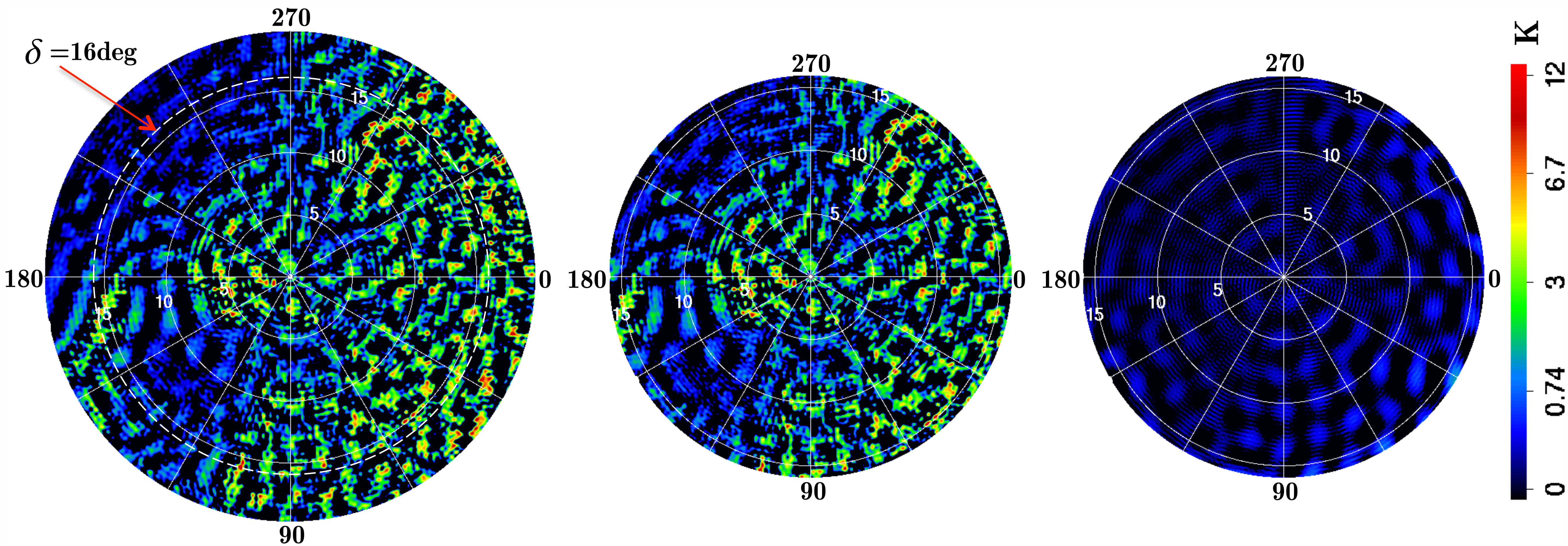
| | cylinders | width | length | dual pol. | units/cylinder | Frequency |
|---|---|---|---|---|---|---|
| Pathfinder | 3 | 15 m | 40 m | | 32 | 700 – 800 MHz |
| Pathfinder+ | 3 | 15 m | 40 m | | 72 | 700 – 800 MHz |
| Full scale | 8 | 15 m | 120 m | | 256 | 400 – 1420 MHz |




Y. Xu, X. Wang, X. Chen (2015) - ApJ
arXiv:1410.7794

# Tianlai Dish Array Polar Cap survey




Polar cap survey - sky map reconstruction by Tianlai 16 dish array & m-mode decomposition

**Map Making Papers-I J. Zhang et al (2016), MNRAS (accepted) arXiv:160603090 [ Dishes, PAON4, Tianlai]**

MNRAS **000**, 1–17 (2016) Preprint 30 May 2016 Compiled using MNRAS LaTeX style file v3.0

**Sky reconstruction from transit visibilities: PAON-4 and Tianlai Dish Array**


Jiao Zhang[1,2,3], Reza Ansari[2] ⋆, Xuelei Chen[1,3,4], Jean-Eric Campagne[2], Christophe Magneville[5], and Fengquan Wu[1]

[1] *Key Laboratory of Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*
[2] *Université Paris-Sud, LAL, UMR 8607, F-91898 Orsay Cedex, France & CNRS/IN2P3, F-91405 Orsay, France*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Center for High Energy Physics, Peking University, Beijing 100871, China*
[5] *CEA, DSM/IRFU, Centre d'Etudes de Saclay, F-91191 Gif-sur-Yvette, France*


**Map Making Papers-II J. Zhang et al (2016), RAA (accepted) arXiv: [Tianlai cylinders]**

**Research in Astronomy and Astrophysics** manuscript no.
(LaTeX: jmapcylinder.tex; printed on May 31, 2016; 18:04)

**Sky reconstruction for the Tianlai cylinder array**

Jiao Zhang[1,2,3], Shifan Zuo[1,3], Reza Ansari[2], Xuelei Chen[1,3,4] ,Yichao Li[1,3], Fengquan Wu[1,3],Jean-Eric Campagne[2], Christophe Magneville[5]

# Conclusions / Outlook

- Broad and interesting scientific outcomes from 21cm surveys at z ~ 1-2: (DE, HI mass distribution and its evolution around z ~ 1-2, detailed study of foregrounds, *pulsars* …)
- Reionisation at higher redshifts (LOFAR, SKA-Low, HERA)
- Tianlai, CHIME, HIRAX, BINGO, GBT… will enable us to develop the 3D intensity mapping method, opening the way to more ambitious instruments, as well as SKA-mid / AA (Aperture Arrays)
- PAON-4 & EMBRACE : test beds for developing the data analysis methods and for electronic developments (NEBuLA) …
- Scientific and technical challenges : high throughput on the fly digital processing (correlator / beam-former) **calibration**, **3D map making, component separation (foregrounds)** …

# The End