Baryon Acoustic Oscillations at 21 cm

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LPNHE - Paris **April 2014**

- BAO's (Baryon Acoustic Oscillations)
  - BAO as a Dark Energy probe
  - Optical surveys, recent results
- BAO's at 21 cm
  - 3D mapping of 21 cm emission
- BAORadio, CHIME, BINGO, Tianlai
- HI-Cluster program at Nançay

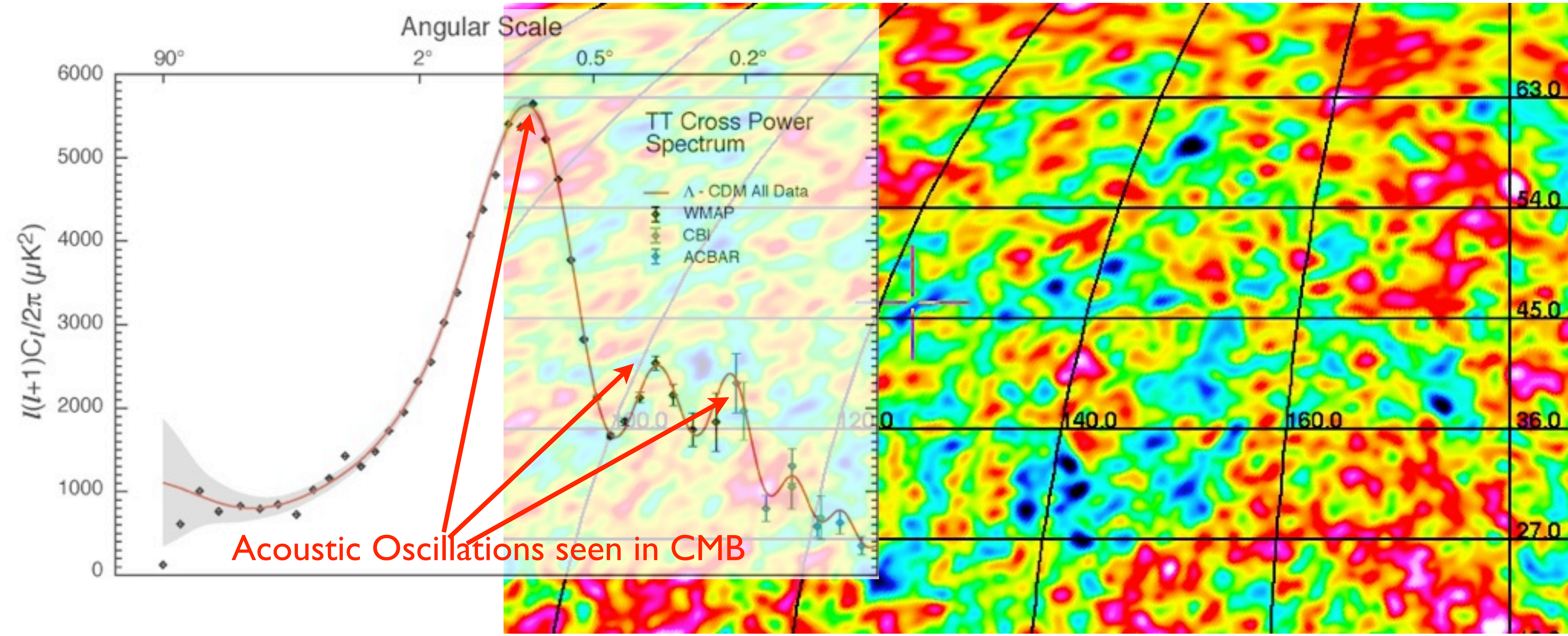
BAO's

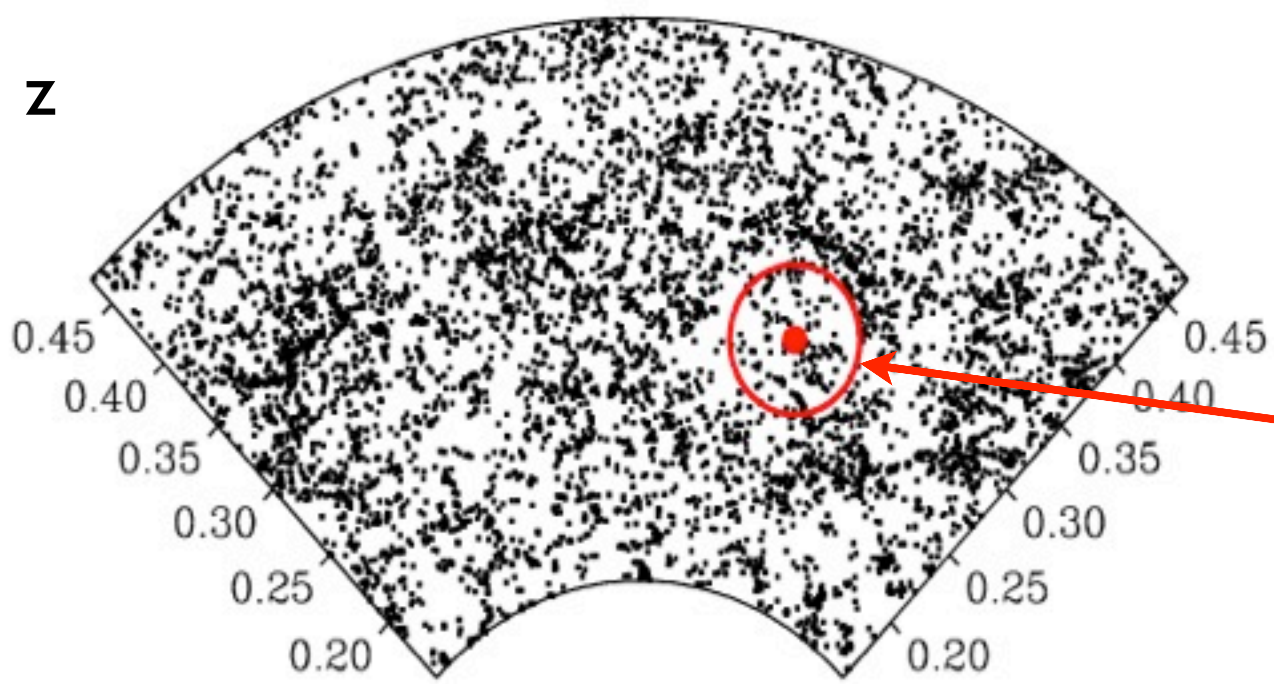
Cosmological probes and Dark energy

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

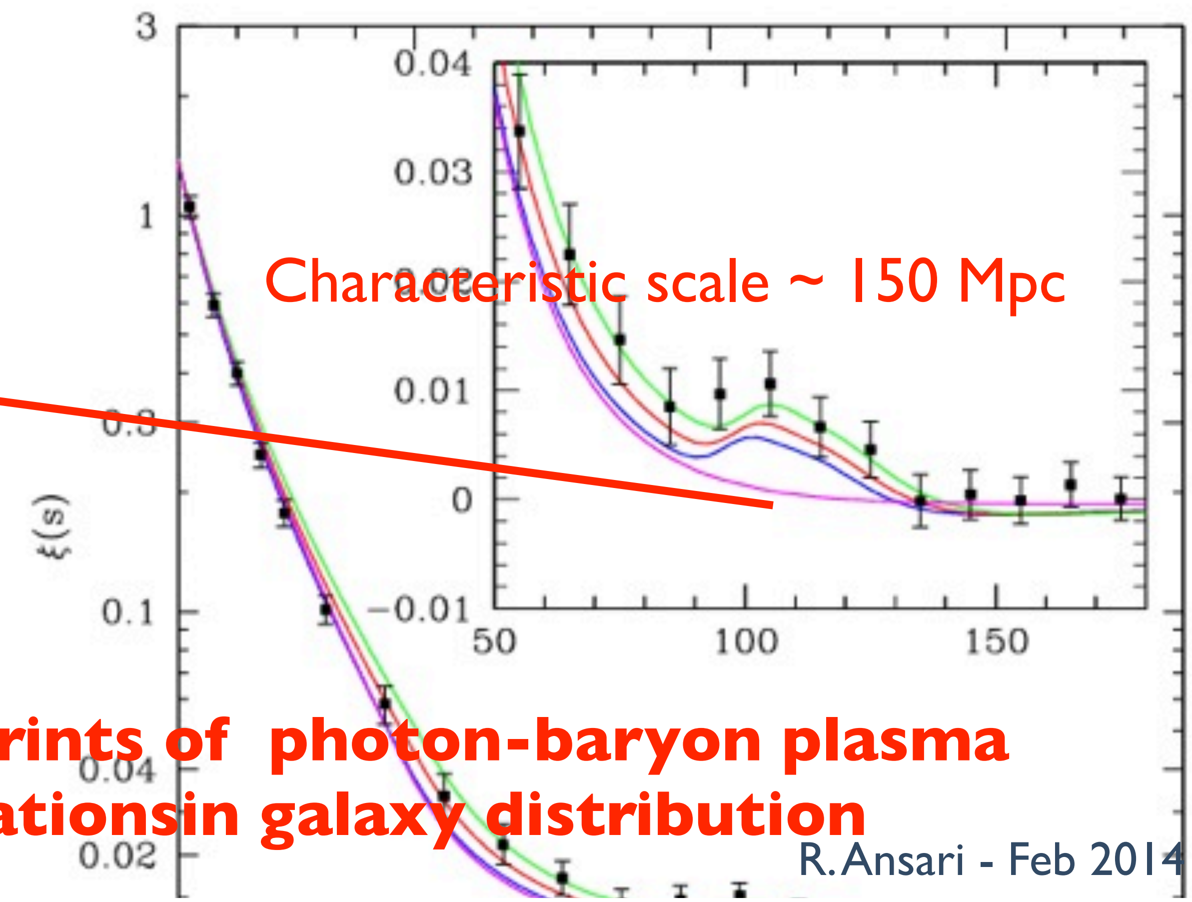
BAO :Baryon Acoustic Oscillations

- 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)

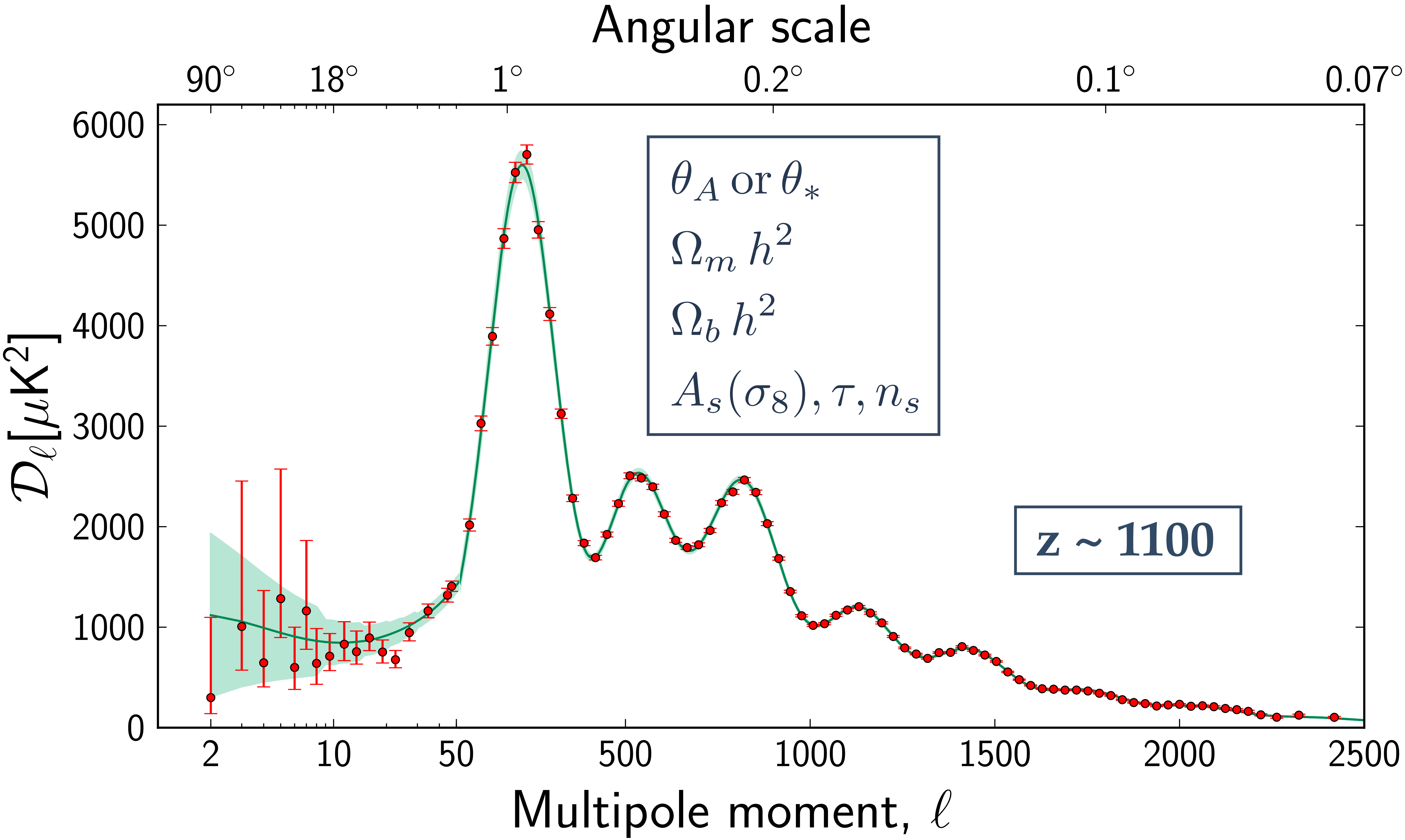




Galaxy distribution
(z, angle (α,δ)) plane



BAO: Imprints of photon-baryon plasma oscillationsin galaxy distribution



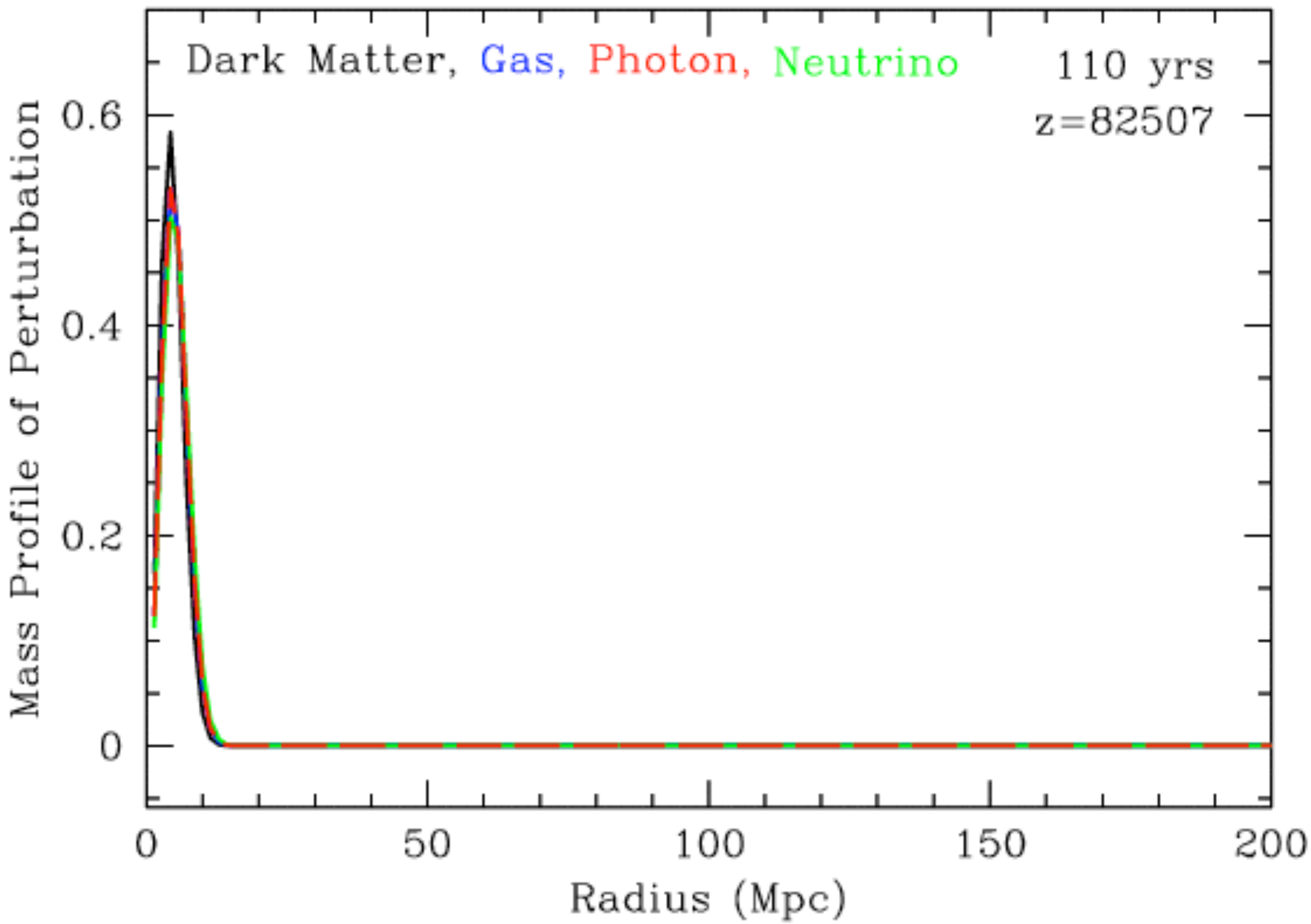
Planck TT power spectrum , Planck collaboration arXiv 1303.5075

8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the si[x]
[primar]y parameters included directly in the estimation process, and the bottom section contains constraints on derived parameters.

	Planck		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14305	0.1426 ± 0.0025
Age/Gyr	13.819	13.813 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.48	1090.43 ± 0.54
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{eq}	3402	3386 ± 69	3403	3391 ± 60

Planck cosmological parameters , Planck collaboration arXiv 1303.5075

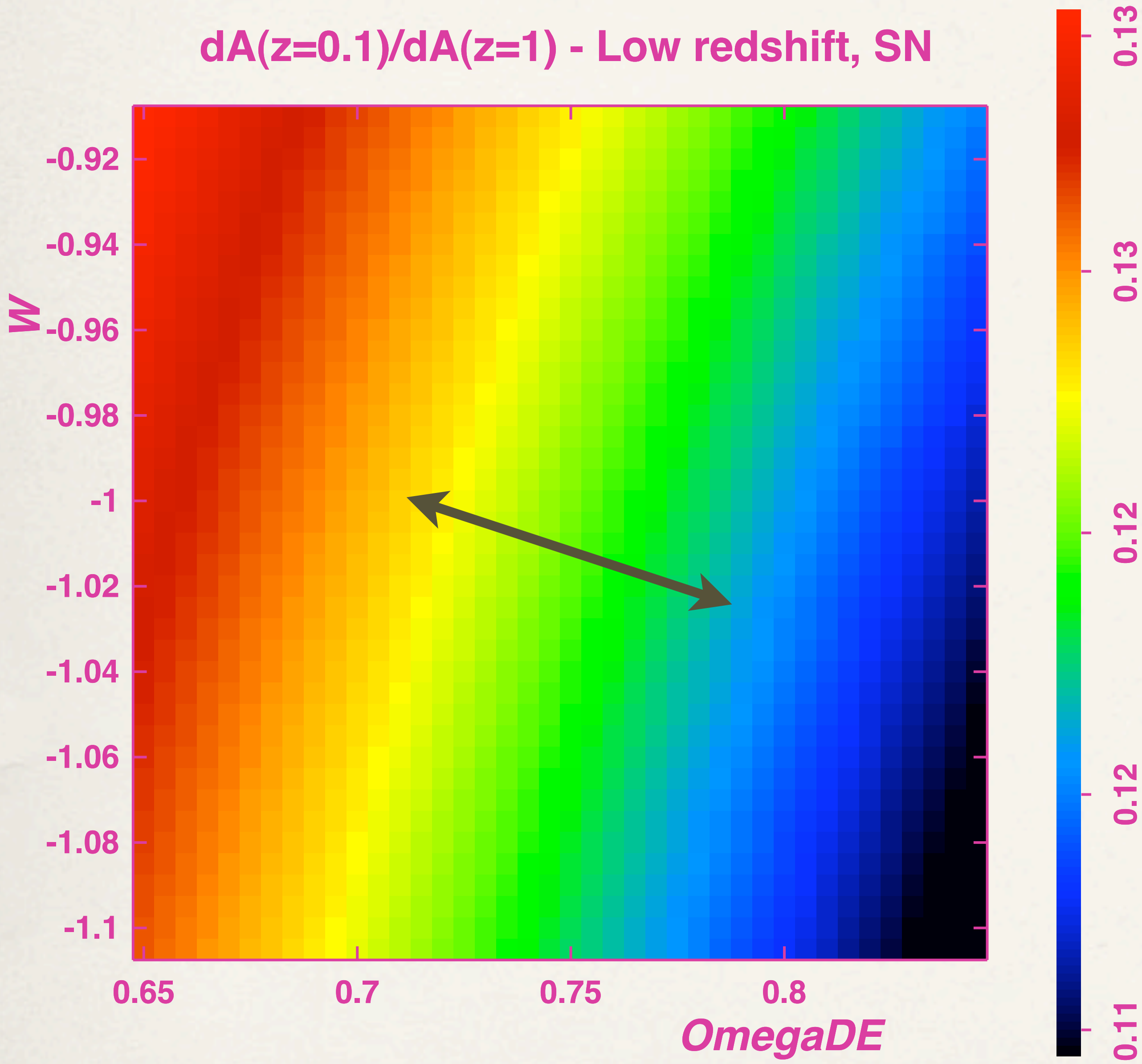
Matter clustering and Acoustic Oscillations

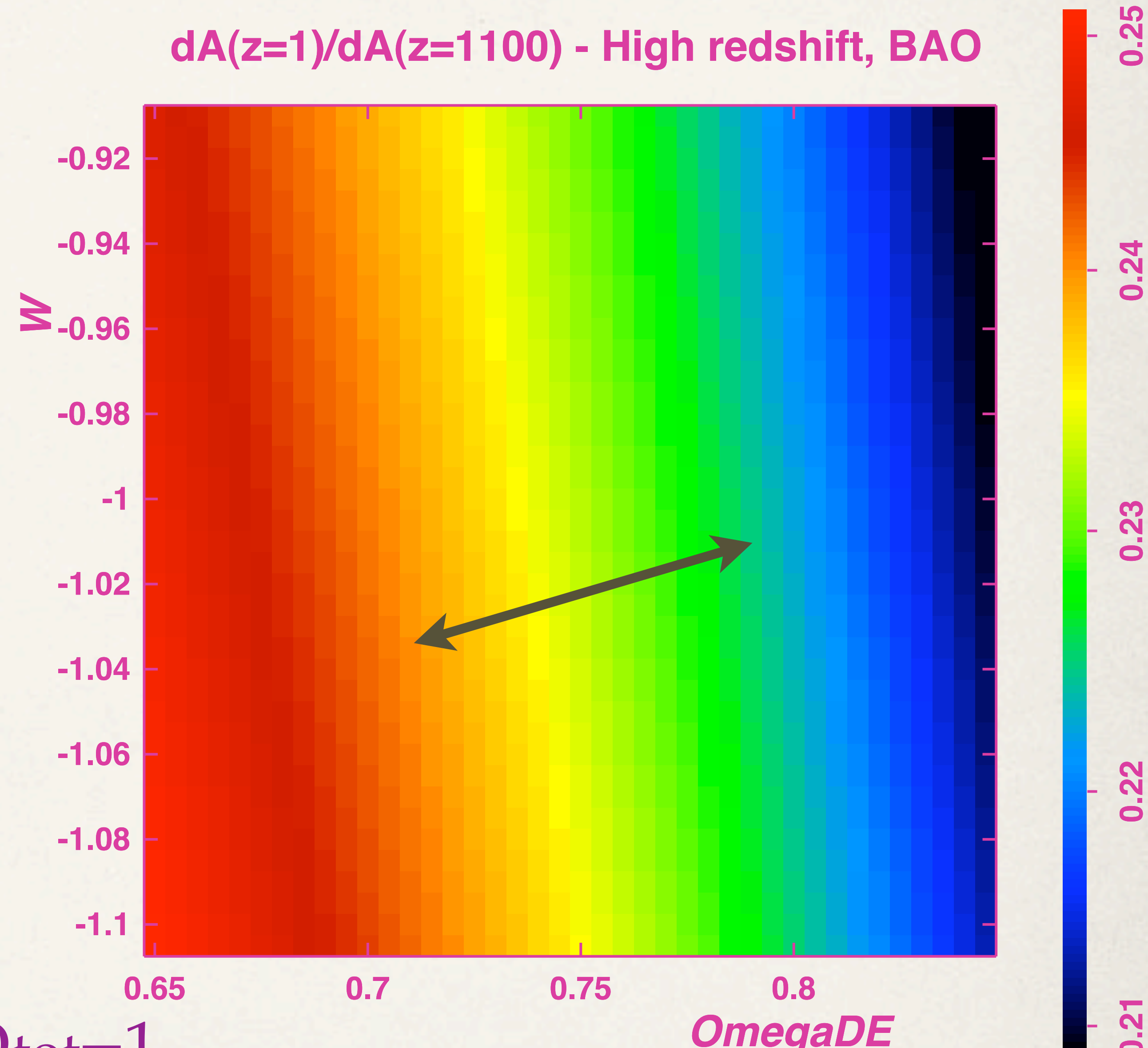


Animation : D. Eisenstein

BAO complementarity with other geometric probes

- Different systematics
- Different degeneracy respect to cosmological parameters





$\Omega_{tot}=1$

$d_A(z=0.1) / d_A(z=1.)$ (SN ...)

$d_A(z=1) / d_A(z=1100)$

BAO scale from CMB

R. Ansari - June 2010

Bias and systematic effects

- Exotic effects changing acoustic horizon
- P(k) & the non linear regime (distortion/shift of the correlation peak)
- Bias : tracers (galaxies) / dark matter, evolution of galaxies ...
- redshift space distortions
- Selection bias / survey geometry
- Other observational biases (photo-z ...)
- Foregrounds in radio : synchrotron, radio sources ...

Statistical uncertainties on P(k) estimates

- Intrinsic statistical error, determined by the number of observed Fourier modes (cosmic / sample variance)
- Shot (Poisson) noise due to the sampling of the underlying density fields by the observed galaxies

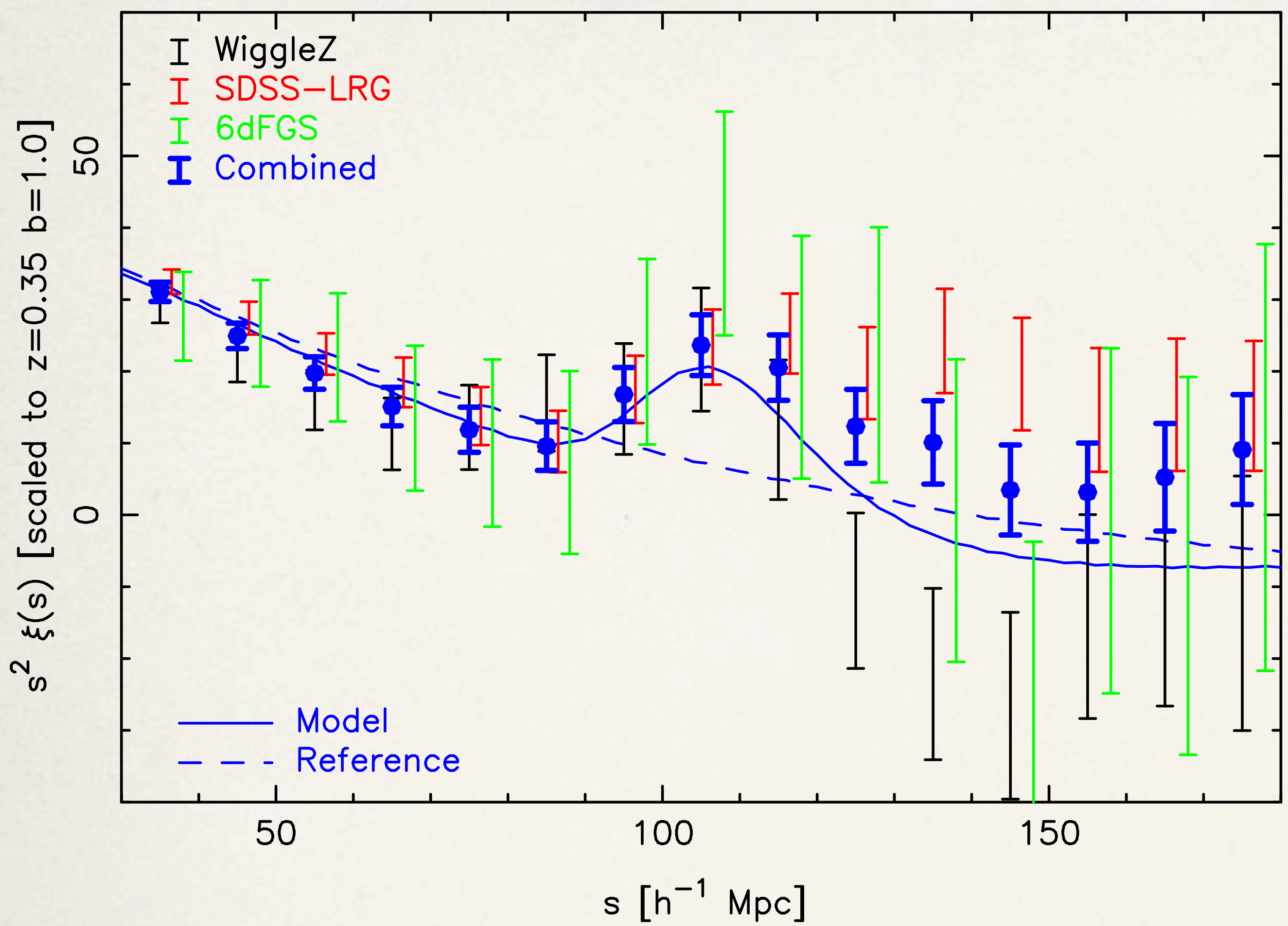
$$\sigma_P = \sqrt{\frac{4\pi^2}{k^2 \delta k \, V_{\mathrm{surv}}}} \left[P_{\mathrm{LSS}} + P_{\mathrm{noise}} \right]$$

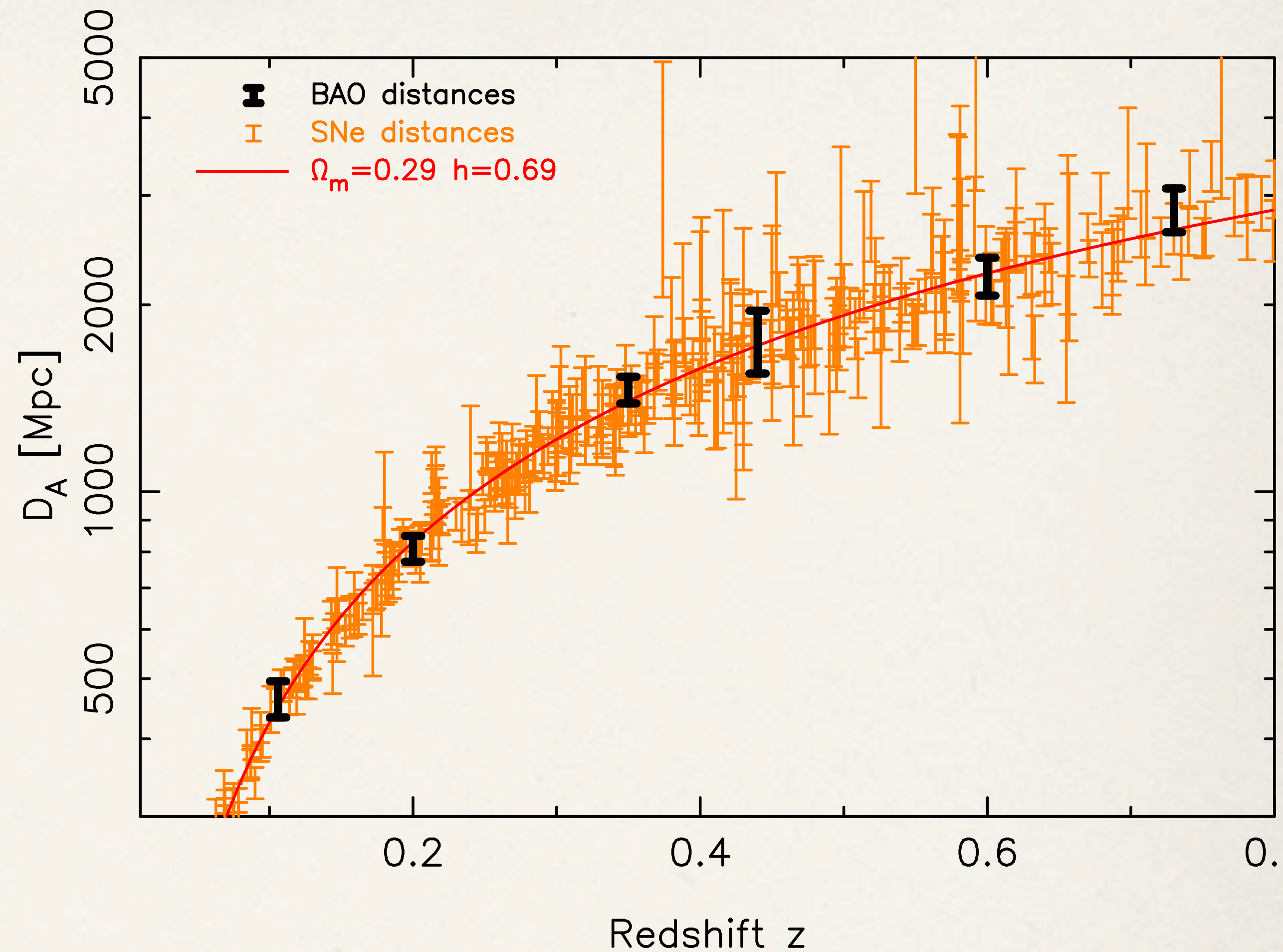
$$P_{\mathrm{shot-noise}} = \frac{1}{n_{\mathrm{gal}}} \qquad n_{\mathrm{gal}} : \text{Galaxy density}$$

- Noise (system temperature) in radio imaging (intensity mapping) mode
- Radio foregrounds : component separation increases the P(k) estimate statistical uncertainties

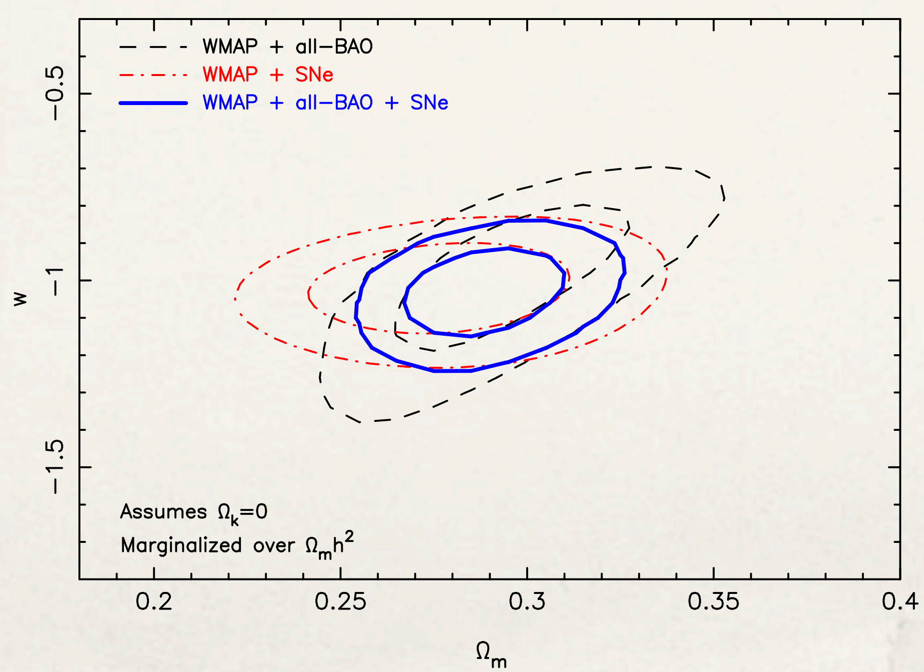
Some recent results …

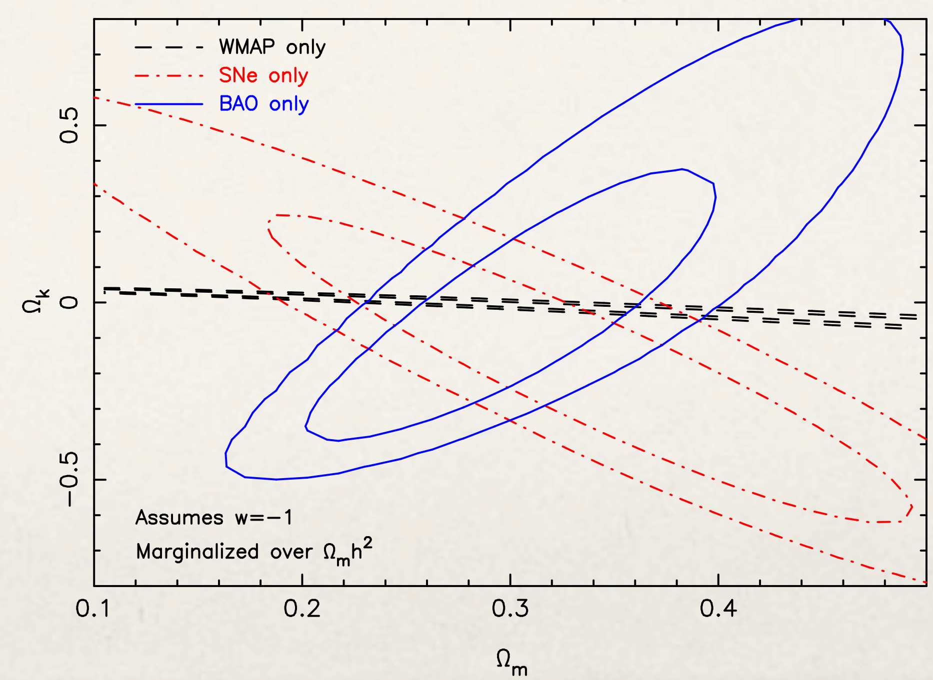
BAO - WiggleZ,6dF, SDSS
Blake et al, arXiv:1108.2635



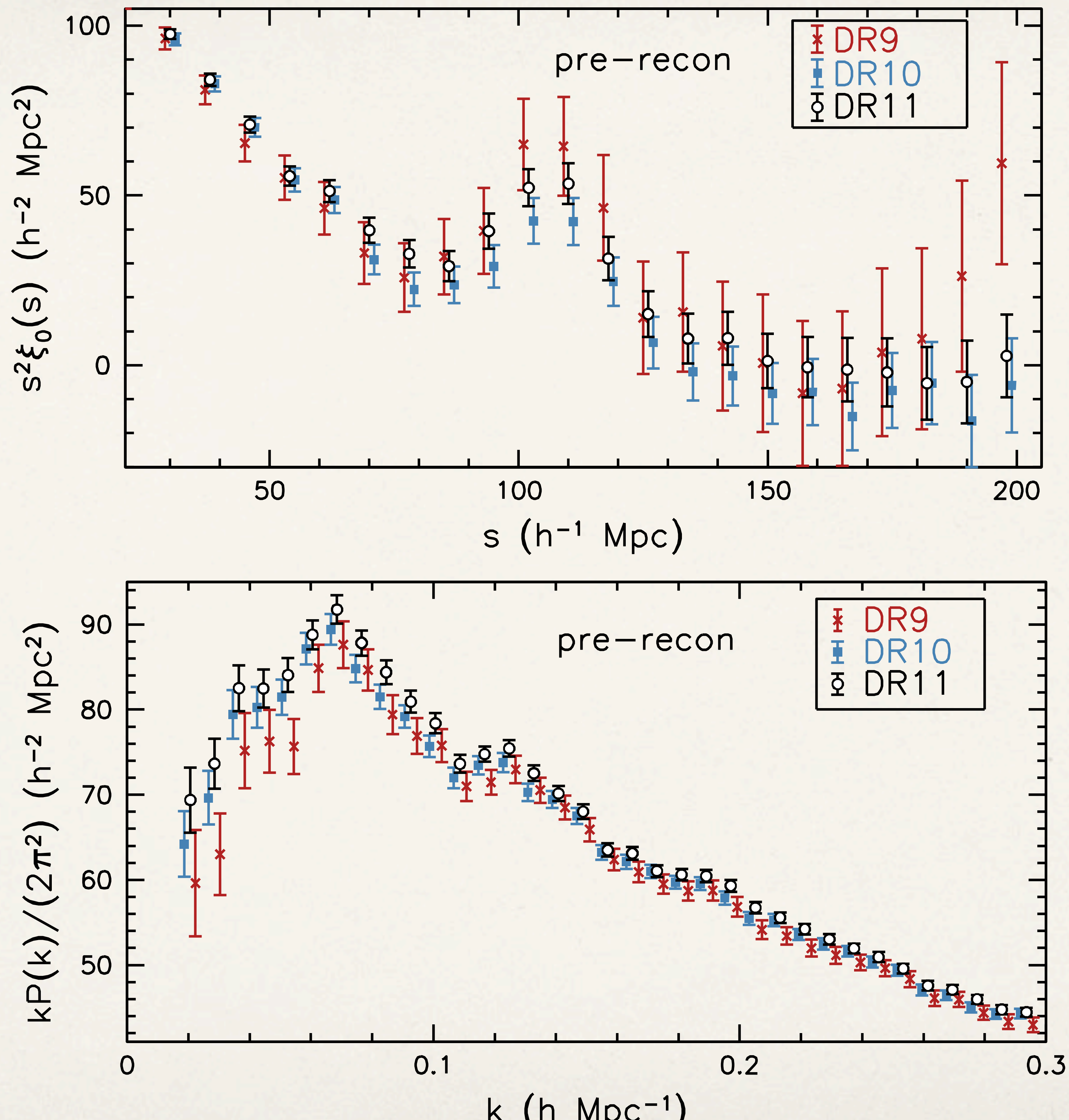


WiggleZ Survey: BAOs in redshift slices 17





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

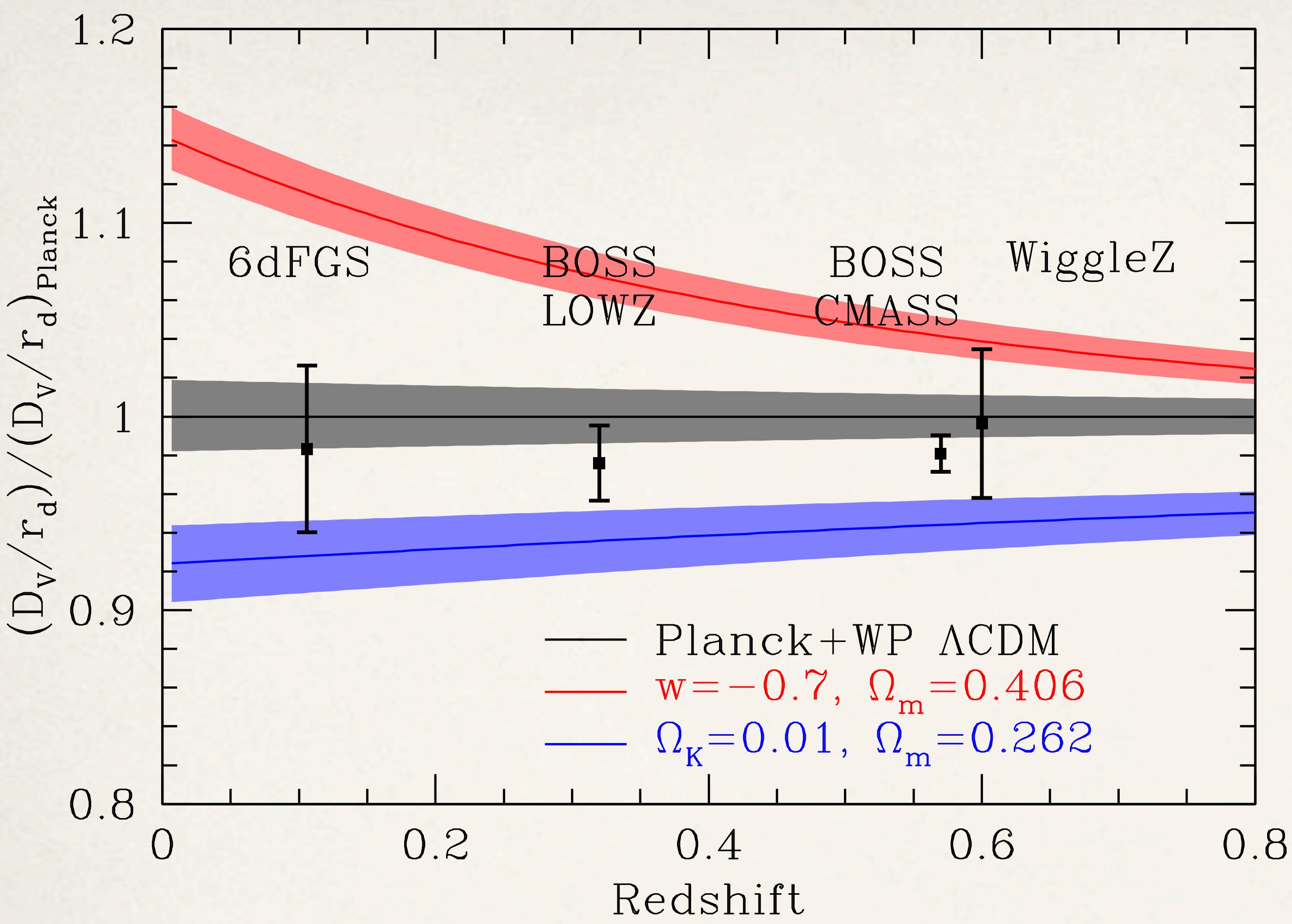


Figure 24. The $D_V(z)/r_d$ measured from galaxy surveys, divided by the best-fit flat ΛCDM prediction from the Planck data. All error bars are 1 σ. We now vary the cosmological model for the Planck prediction. Red shows the prediction assuming a flat Universe with $w = -0.7$; blue shows the prediction assuming a closed Universe with $\Omega_K = -0.01$ and a cosmological constant.

⬆ **SDSS-III BOSS** ⬆

Anderson et al, arXiv 1312.4877

Planck (Cosmo. Param)

⬇ **arXiv 1303.5076** ⬇

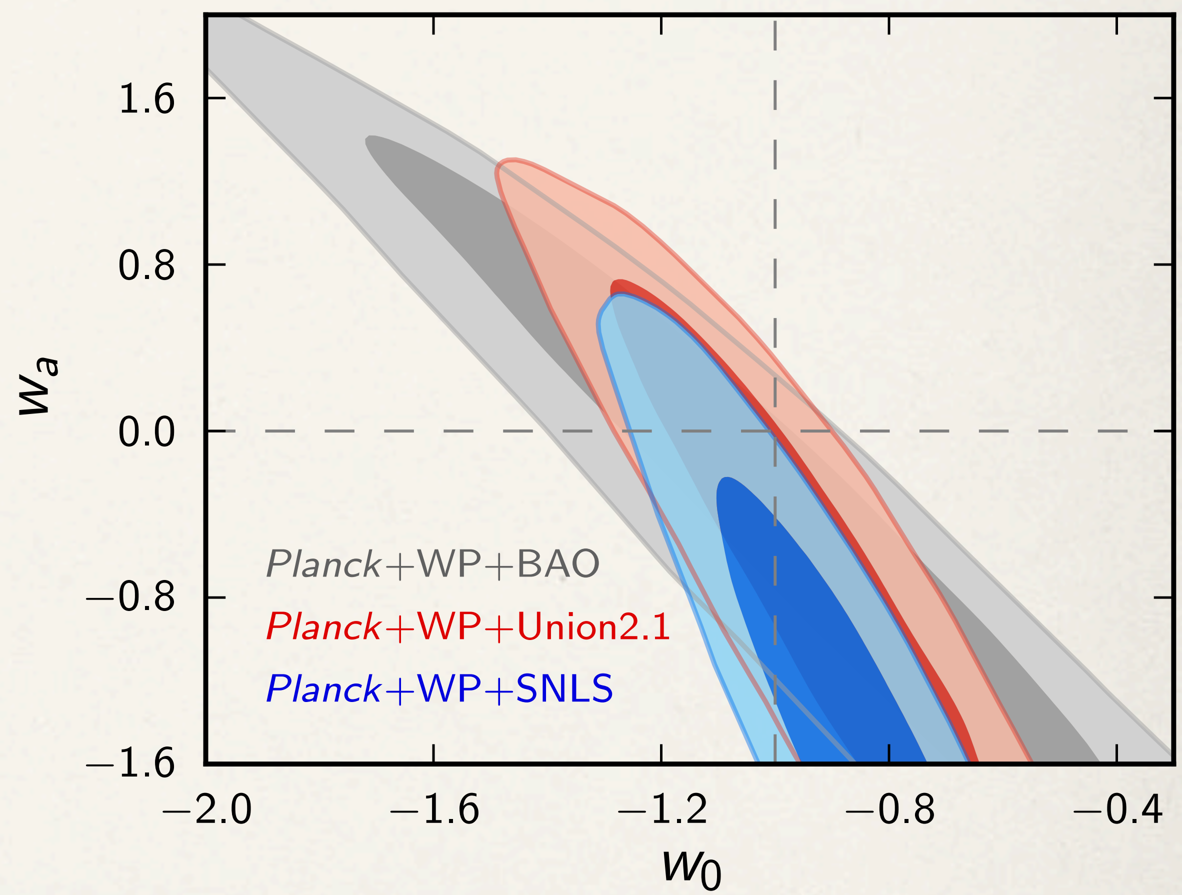
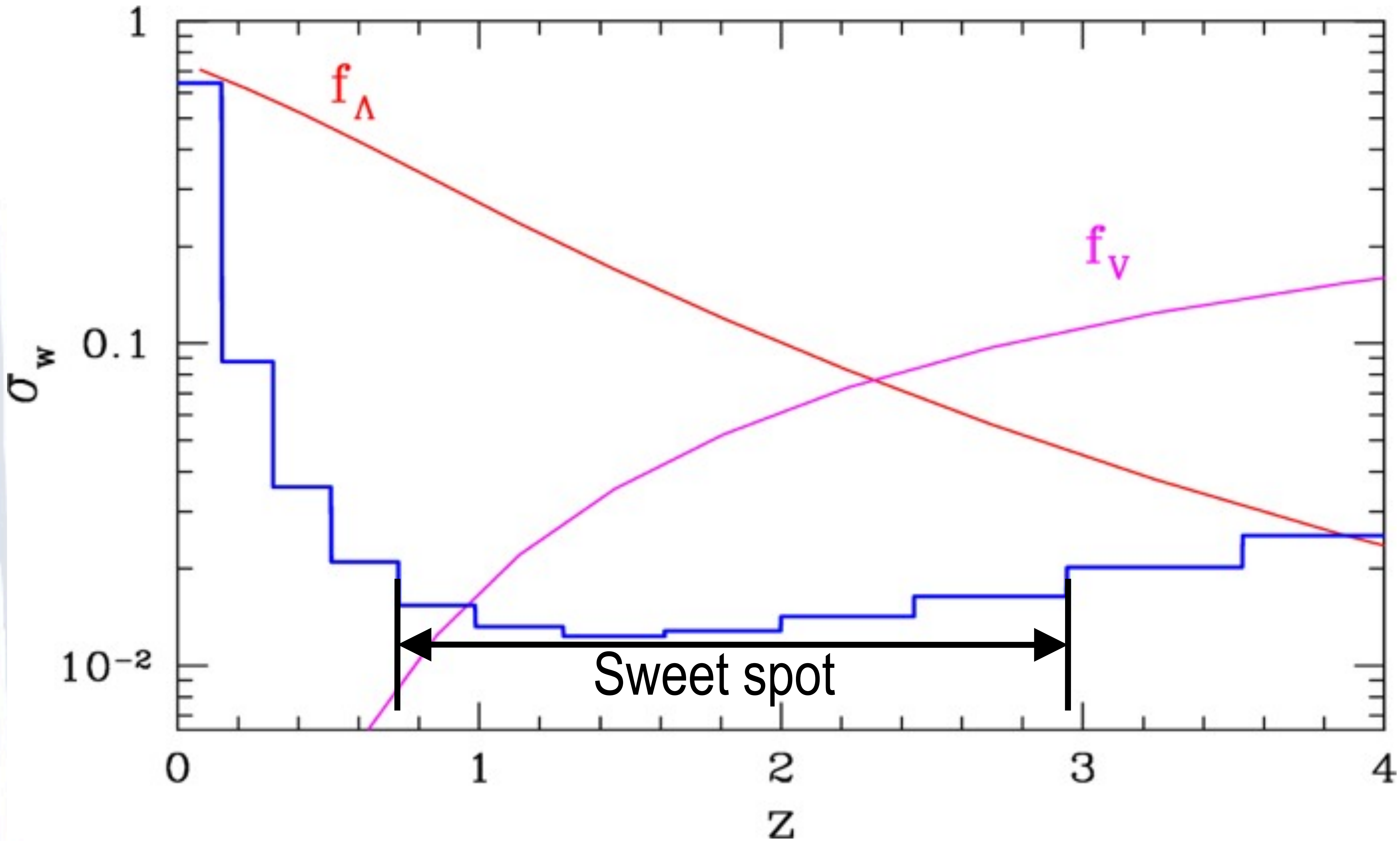


Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the cosmological constant solution.

Baryon Acoustic Oscillations



Wednesday, June 2, 2010

Slide borrowed from A. Stebbins

Cosmology & BAO at 21 cm

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

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

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

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

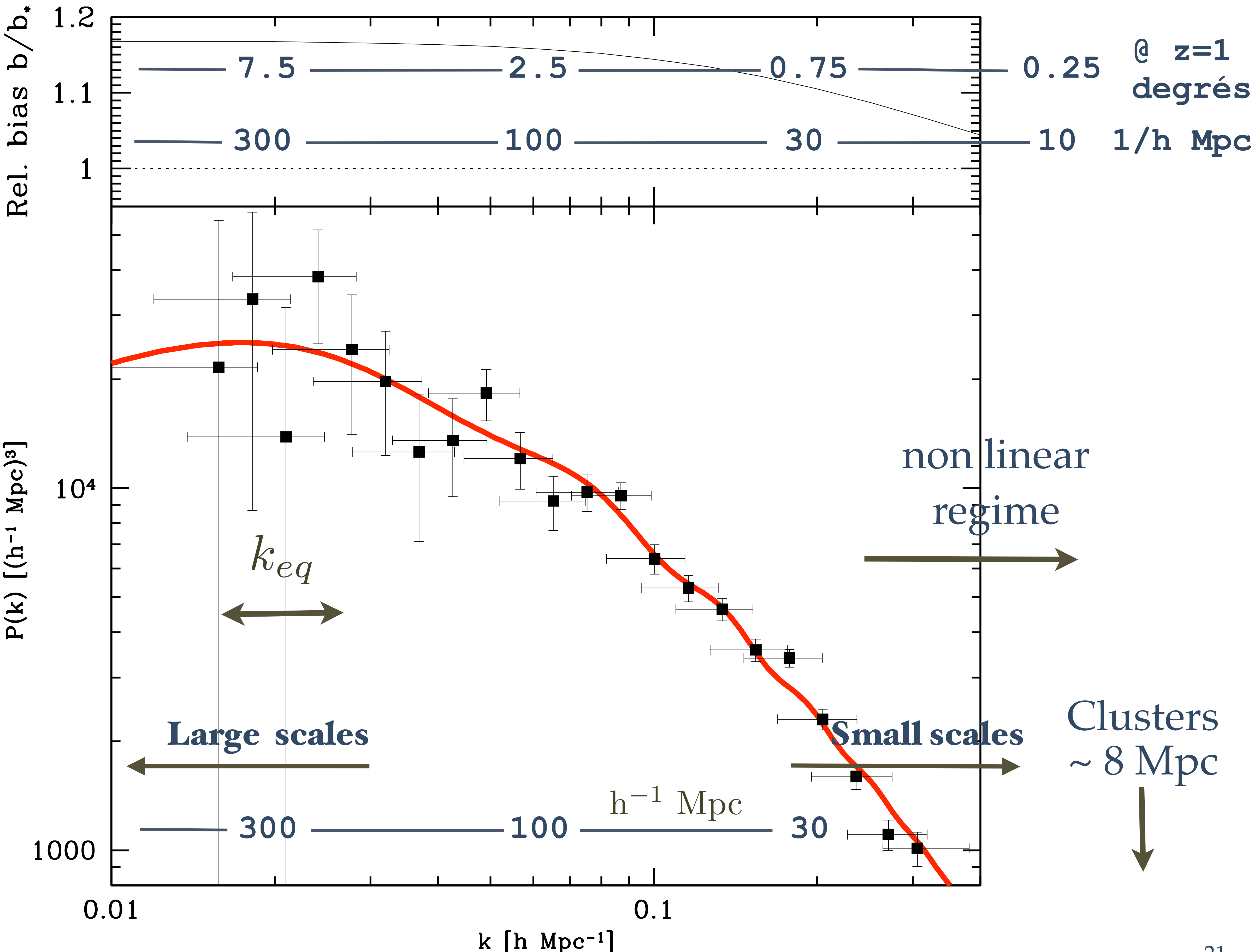
S_{21} en μJy pour $M_{H_I} = 10^{10} M_\odot$

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 !

R.Ansari - Sep 2011

SDSS - M. Tegmark et al.
ApJ , astro-ph/0301072 5



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)

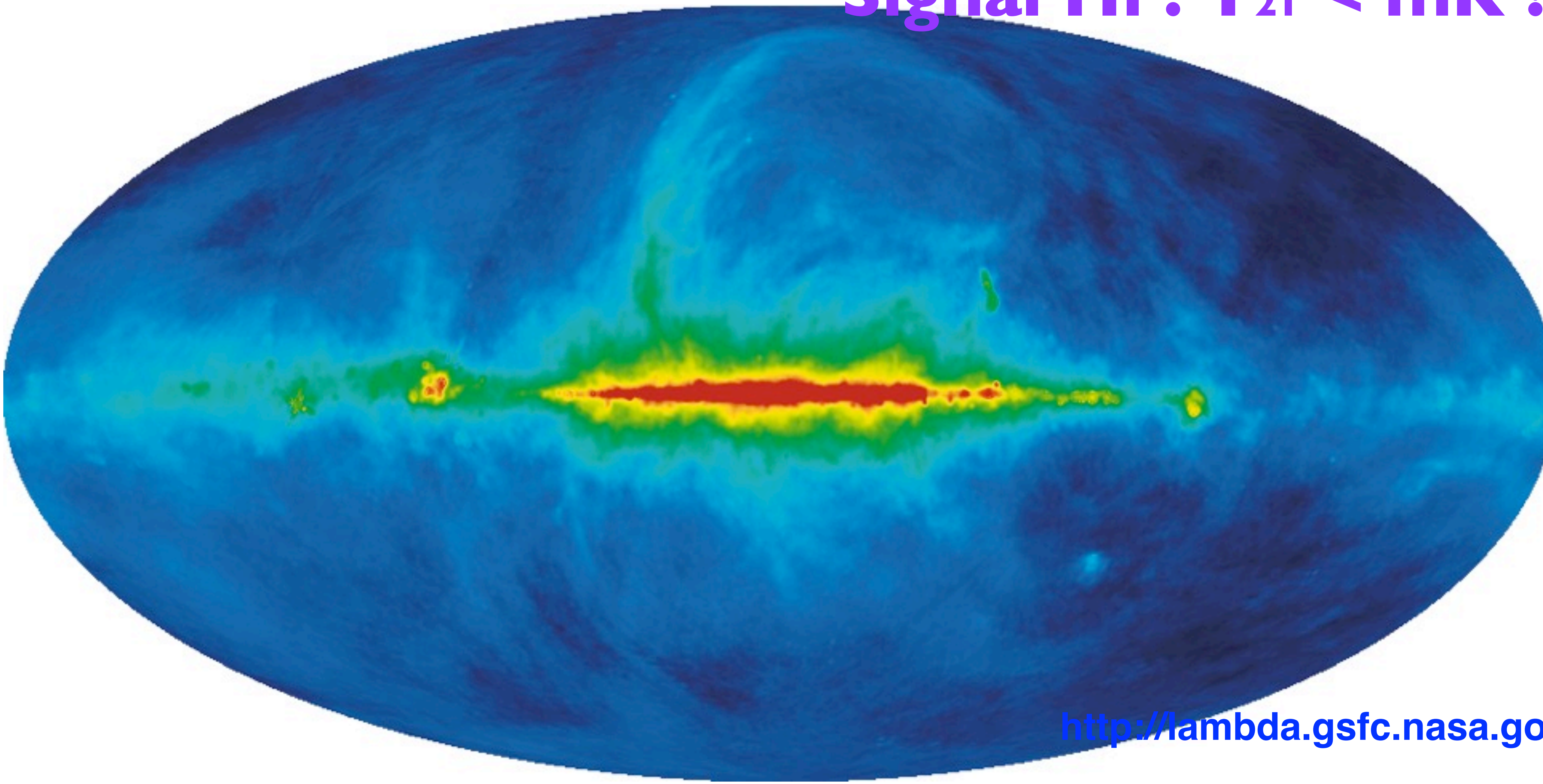
≡ Instrument noise (Tsys)

≡ 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) arXiv:1108.1474

Foregrounds

Signal HI : T_{21} < mK !



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

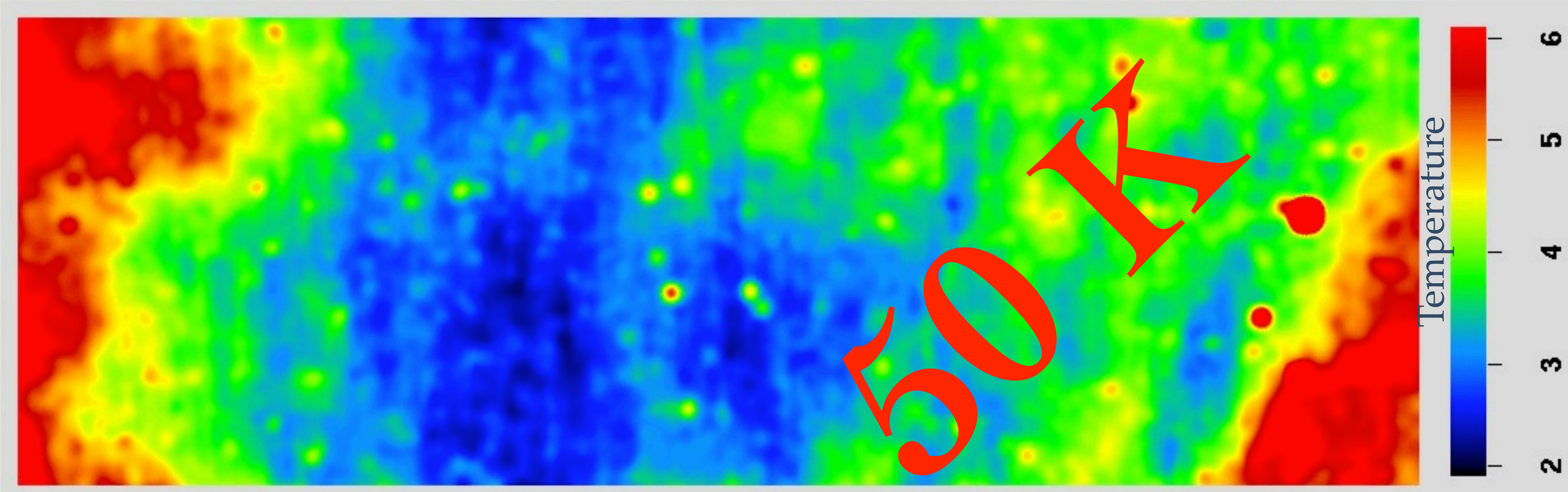
Temp. T (Ech. Log)

10 K ——— **250 K**

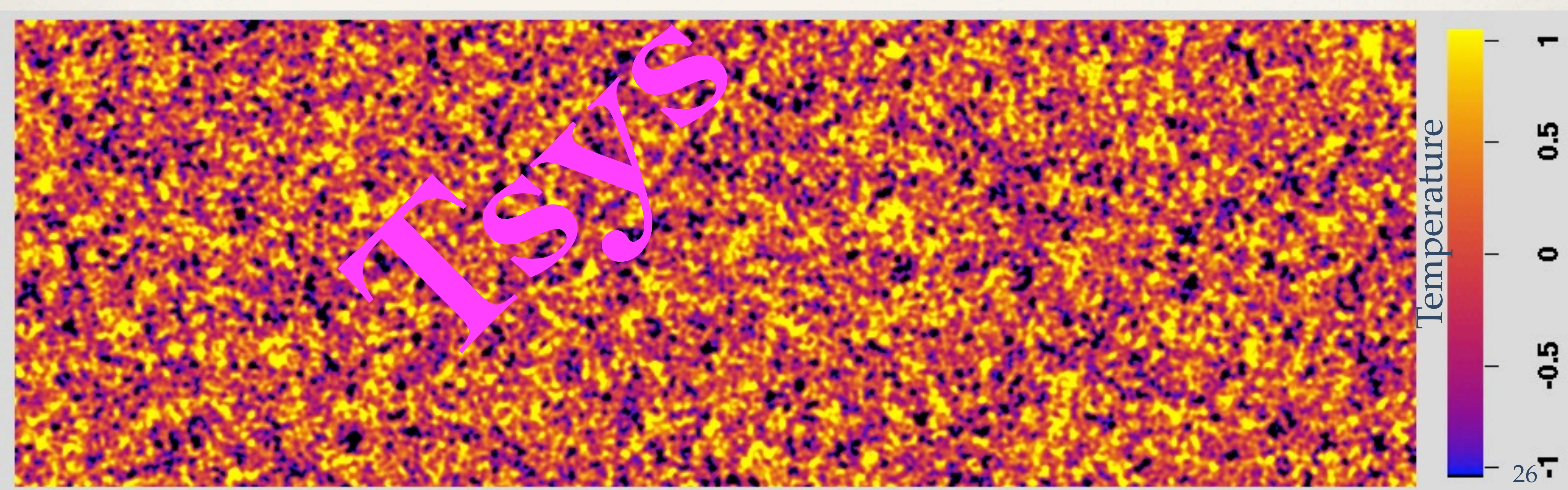
Haslam 408 MHz map (Galactic synchrotron emission)

R. Ansari

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



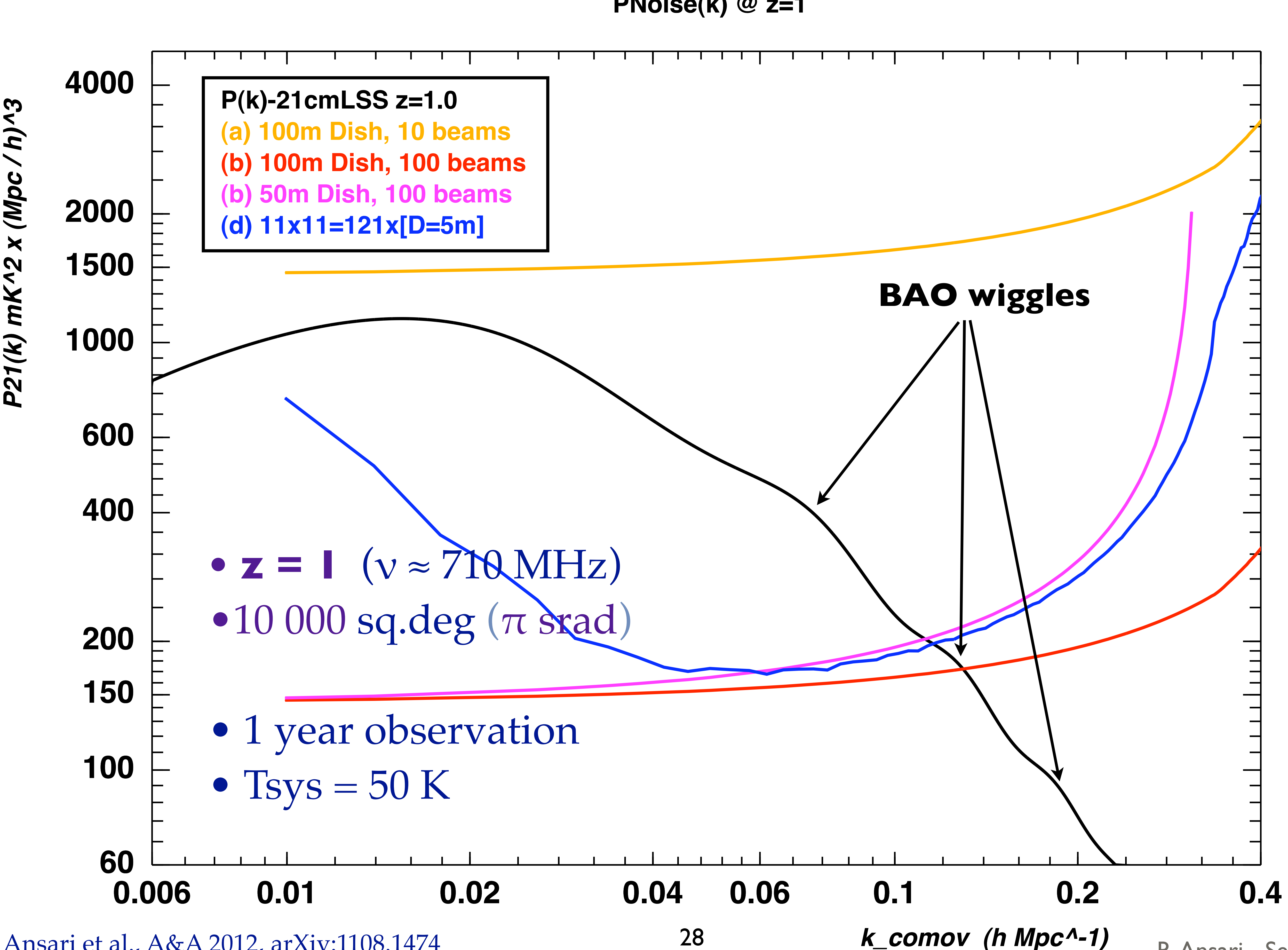
21 cm sky brightness @ 720 MHz (z=1.) - milliKelvin



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)

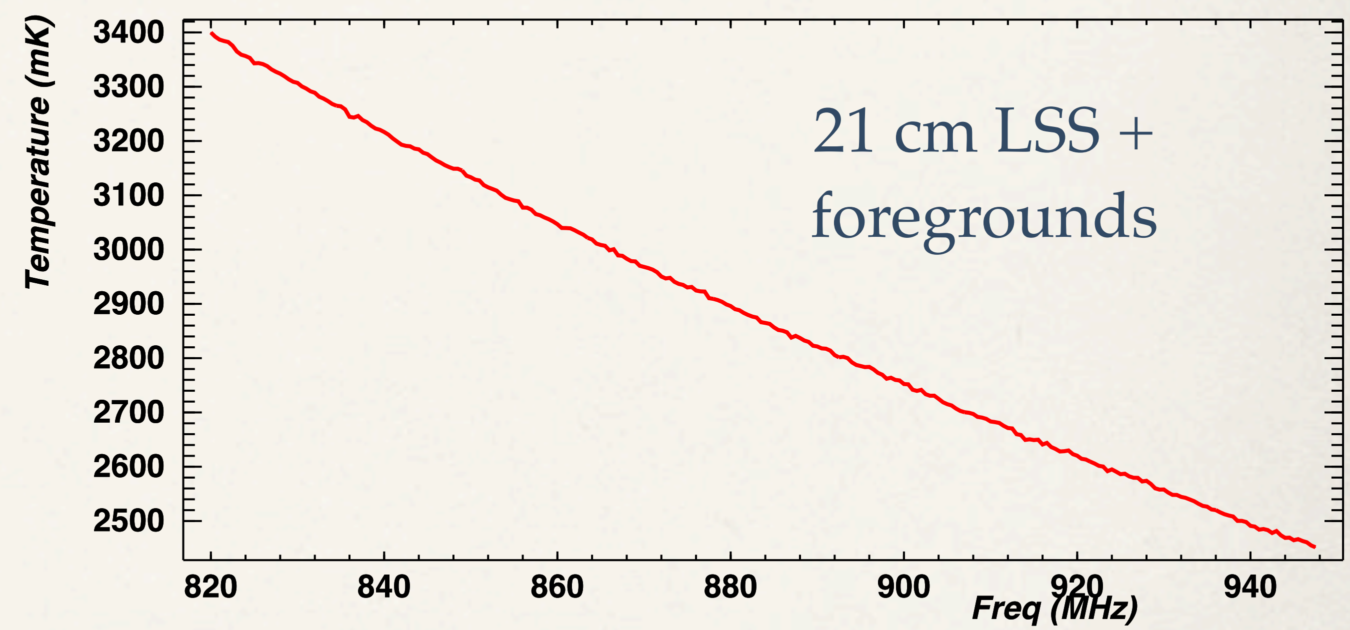


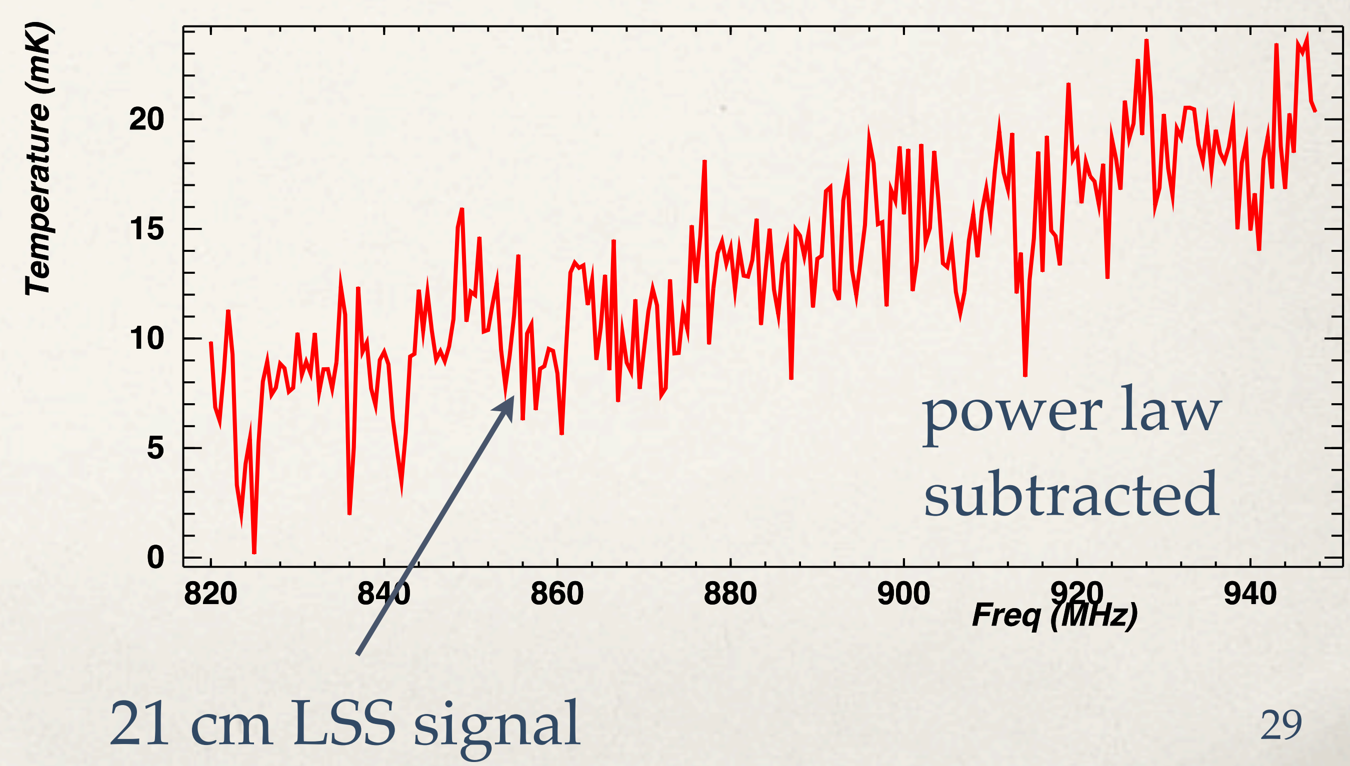
Ansari et al., A&A 2012, arXiv:1108.1474

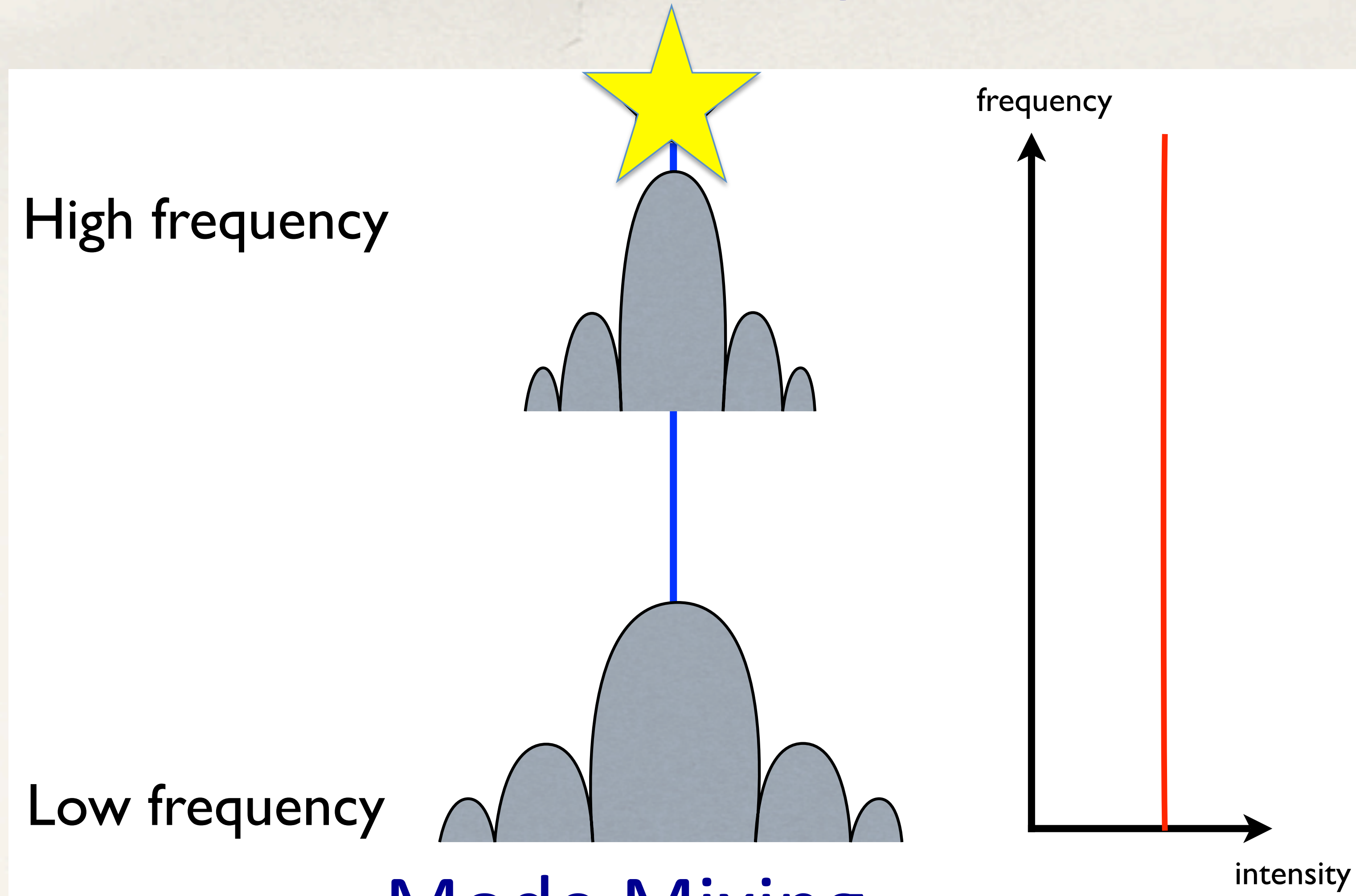
R. Ansari - Sep 2011

Foreground removal

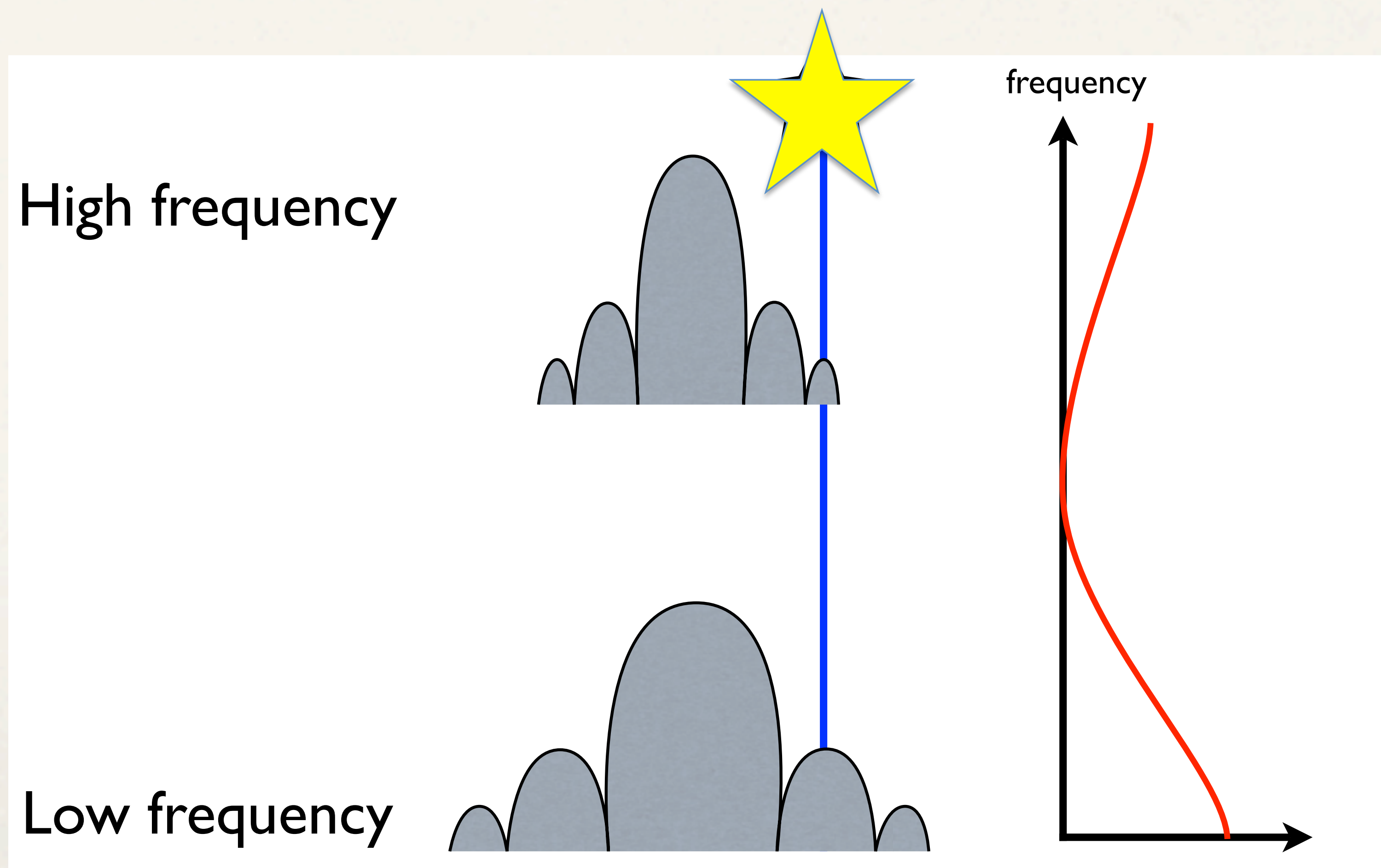
- Exploit frequency smoothness and power law (∝ ν^β) behavior of foregrounds (synchrotron/radio sources)
- power law / polynomial / foreground model fit & subtraction
- Mode mixing, bias, error propagation …







Mode Mixing



Slide by
Kris Sigurdson
UBC

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

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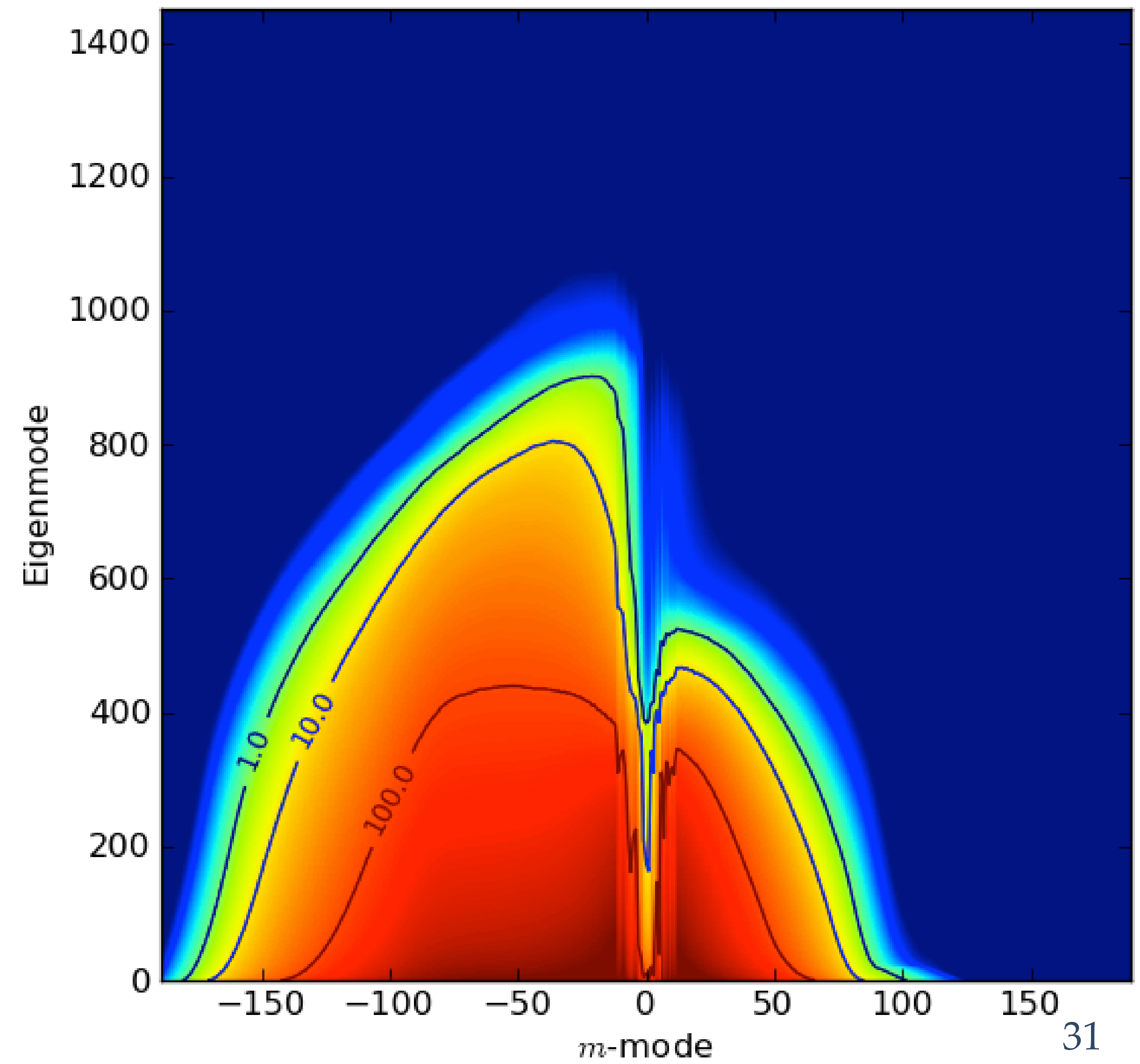
UBC

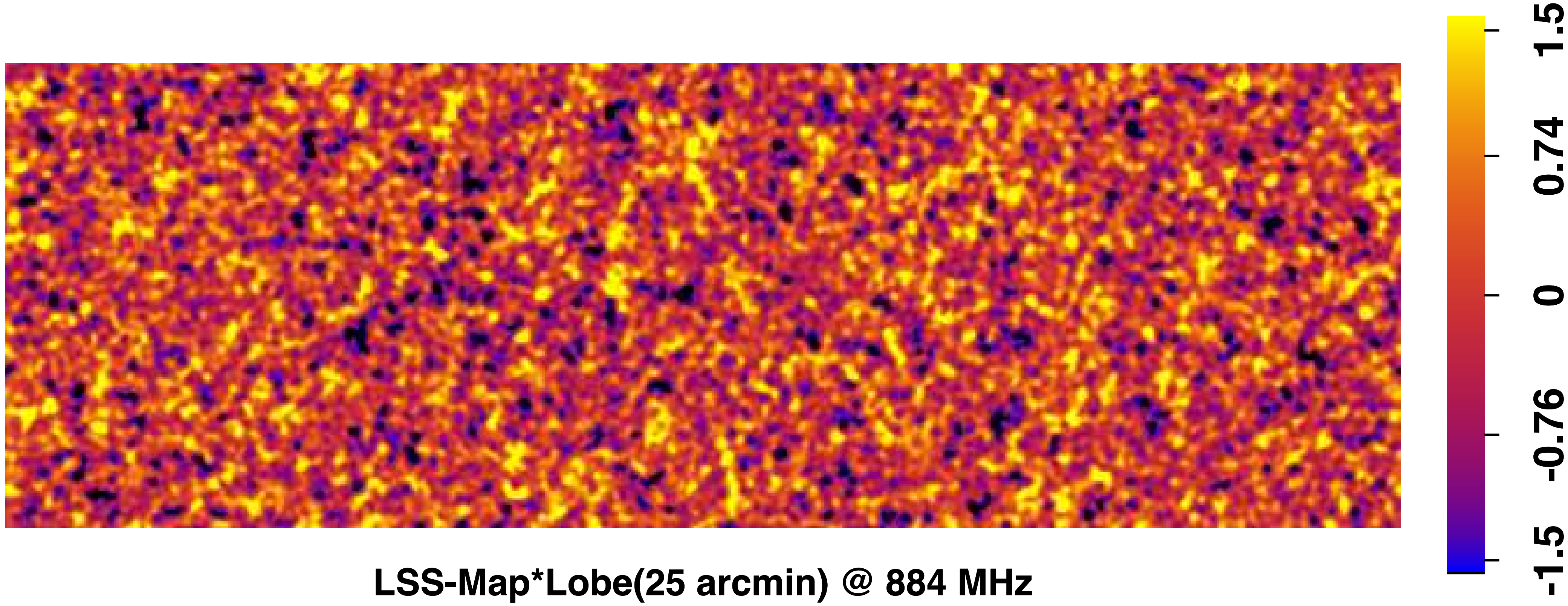
Signal/Foreground Spectrum



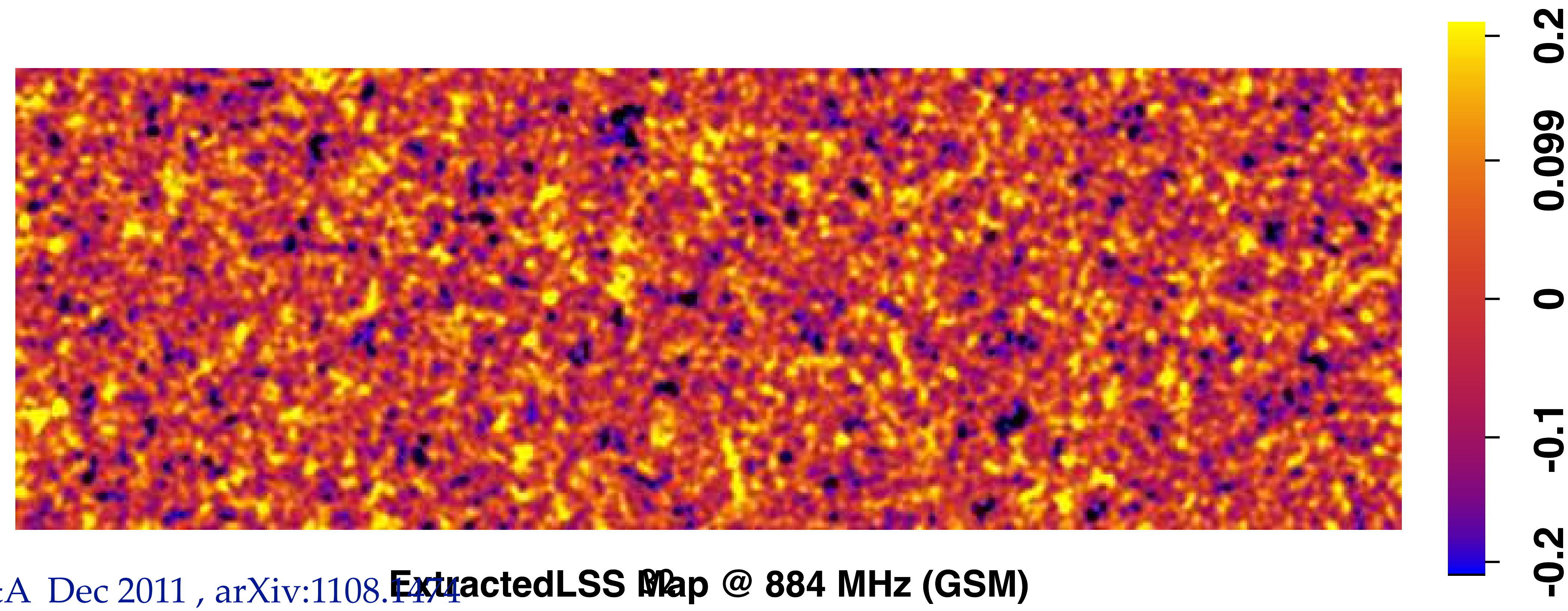
Richard Shaw, Ue-Li Pen Kris Sigurdson et al.
ApJ 2014, arXiv 1302.0327

Component separation
21cm LSS signal extraction @ z=0.6

Original simulated 21cm signal



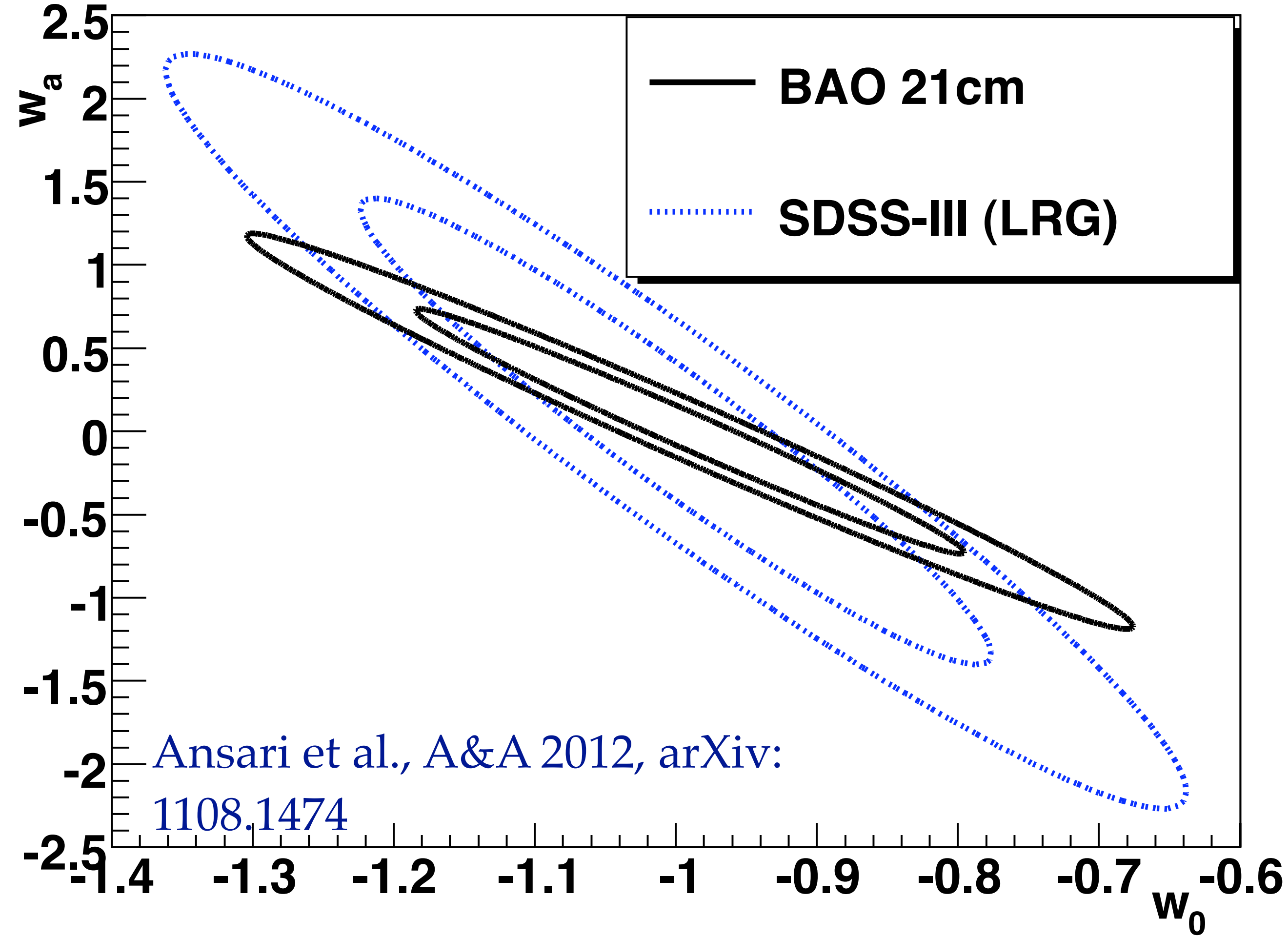
Recovered 21cm signal, in presence of continuum radio signals, and instrument response



Ansari et al. 2012, A&A Dec 2011 , arXiv:1108.1474

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

Observatoire de Paris

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

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

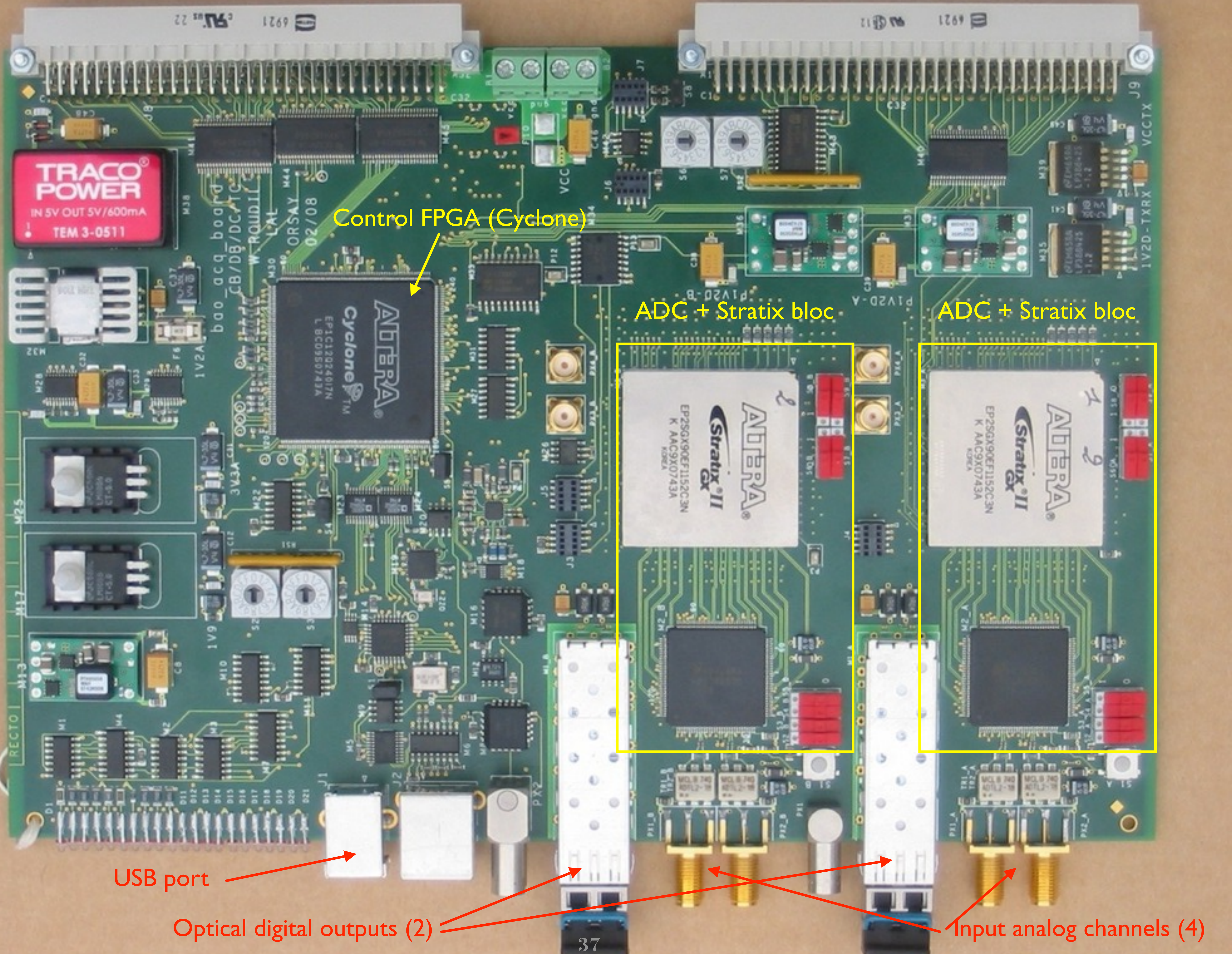
C. Magneville
C. Yèche
J. Rich
J.M. Legoff

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

- 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)

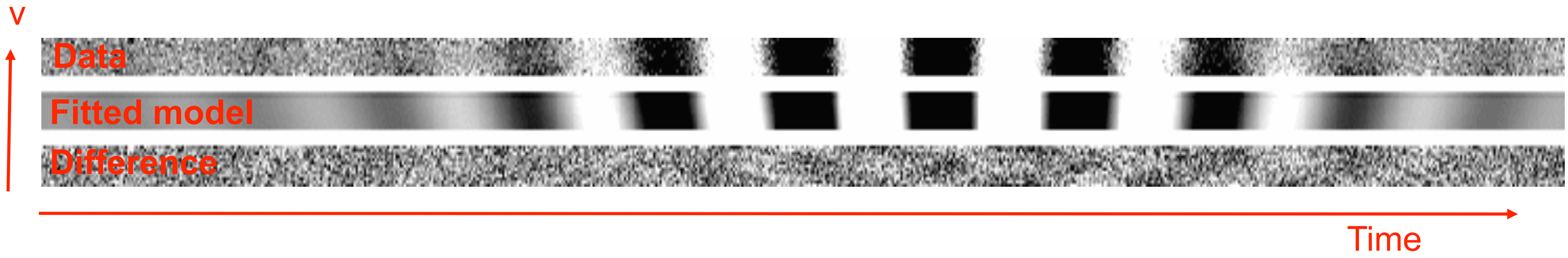
- Electronic, acquisition & processing software development
- FAN (J.M.Martin, P. Colom)
- Observations with CRT at Pittsburgh, calibration and beam synthesis
- **HI-Cluster wide band observation program with NRT OptX21 wide band observations with NRT : BAORadio & WIBAR**
- PAON test interferometer at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

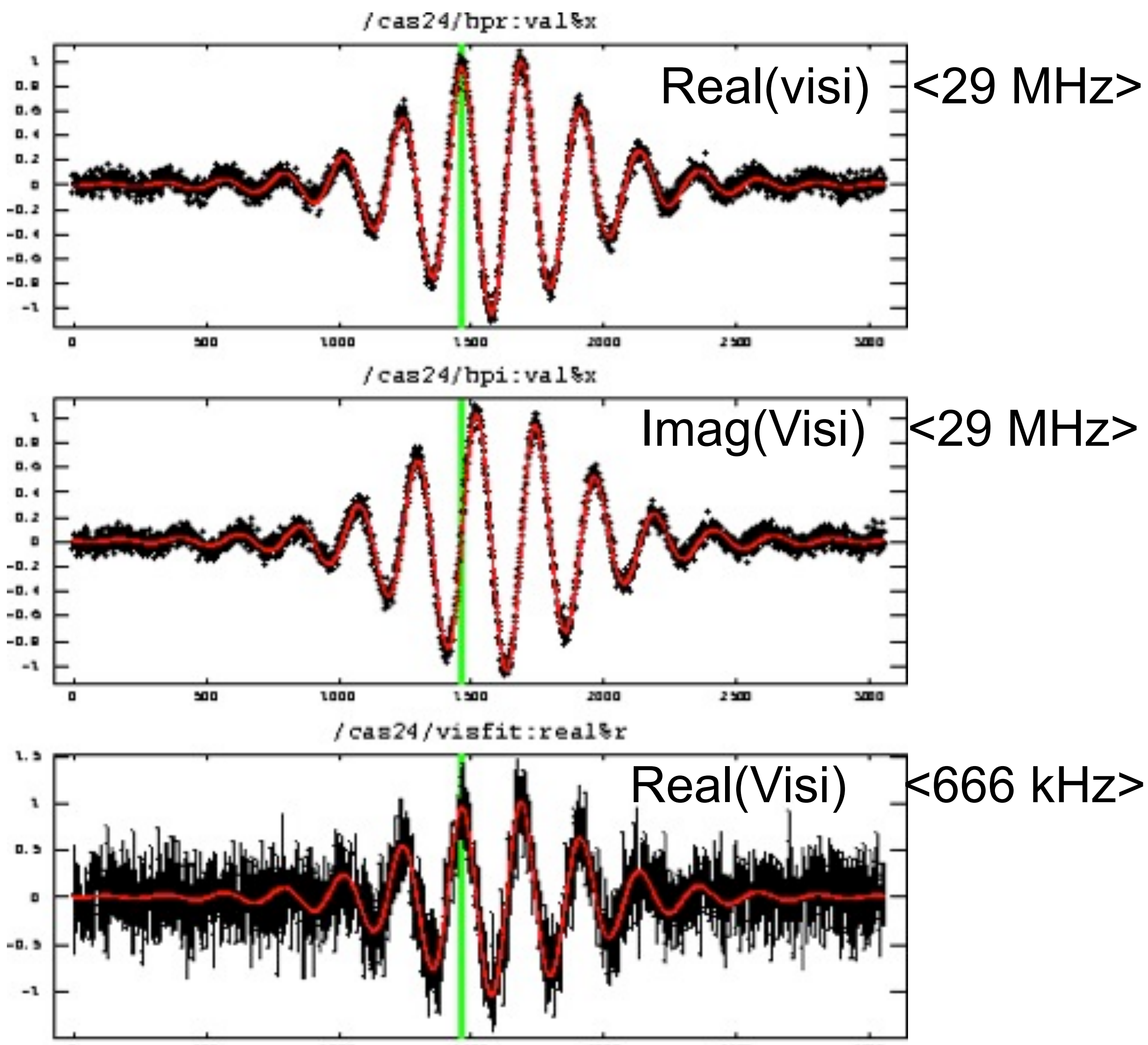


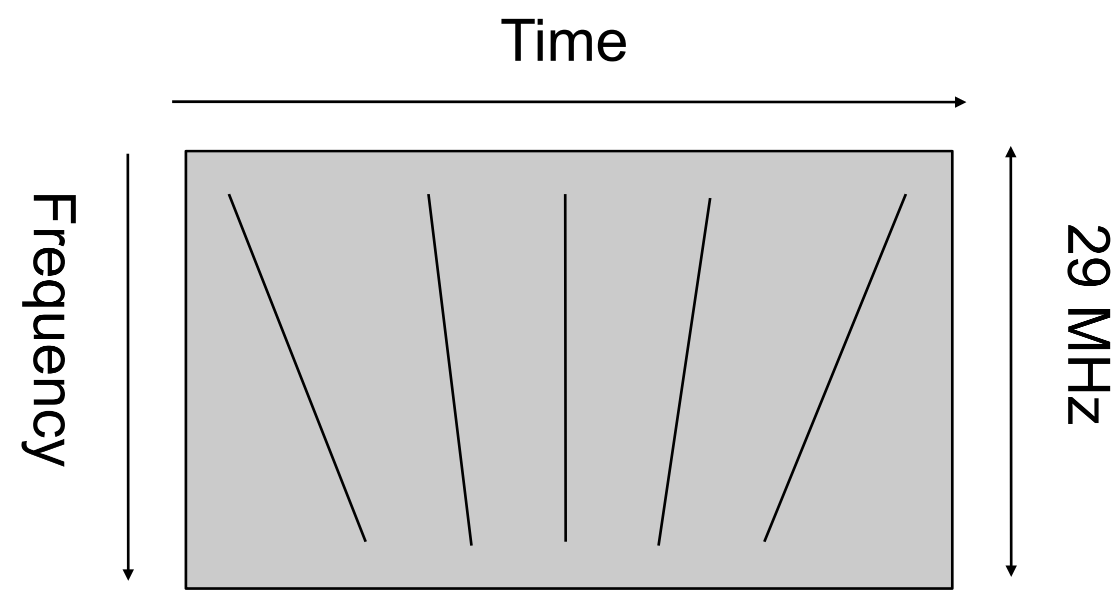
Control FPGA (Cyclone)
ADC + Stratix bloc
ADC + Stratix bloc
USB port
Optical digital outputs (2)
Input analog channels (4)
TRACO POWER
IN 5V OUT 5V/600mA
TEM 3-0511

Pittsburgh, Novembre 2009

CasA24 - Pittsburgh/Nov 2009







Enlarged fringe wave
for low frequencies

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

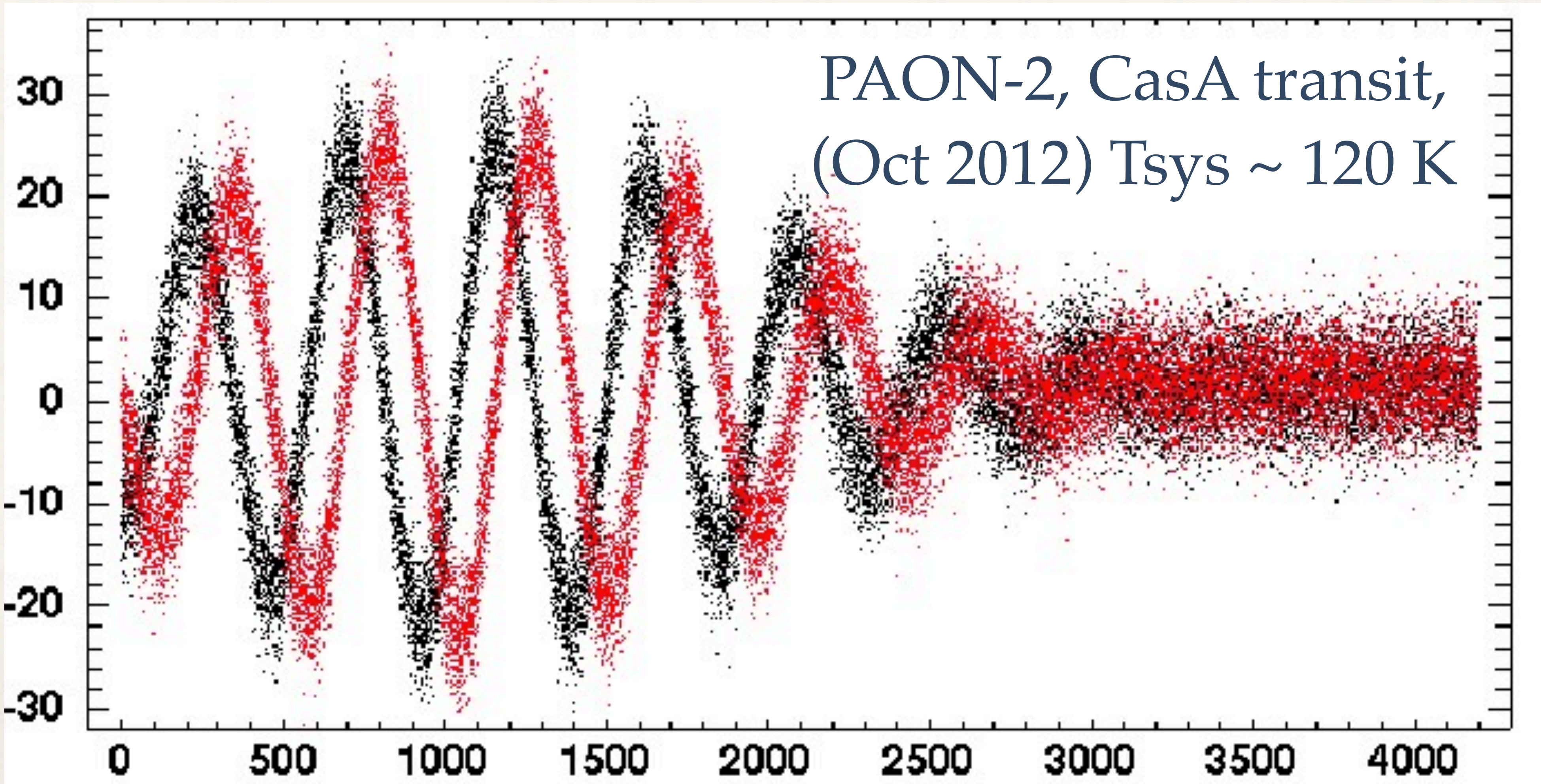
PAON-2 : 2 × D=3 m dishes (sep 2012 - sep 2013)

PAON-4 : 4 × D=5 m dishes, construction phase

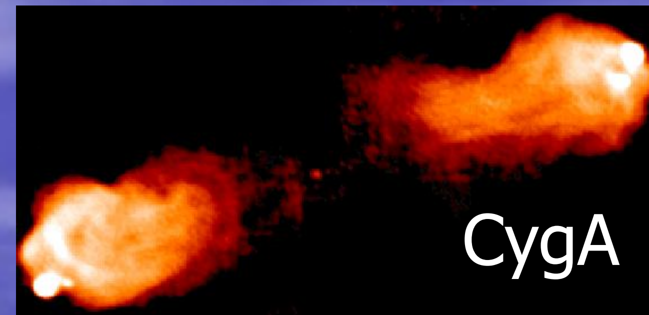
deployment : nov 2013 - march 2014

PAON

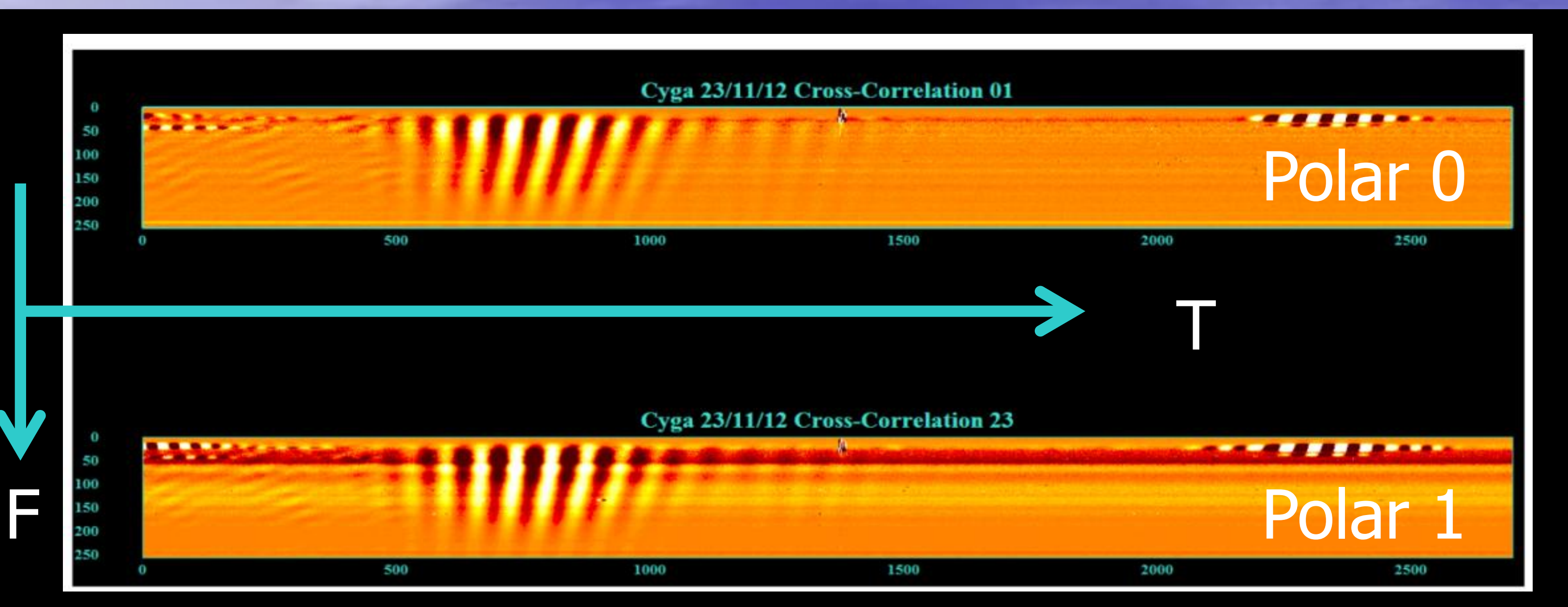
Paraboles A l'Observatoire de Nançay

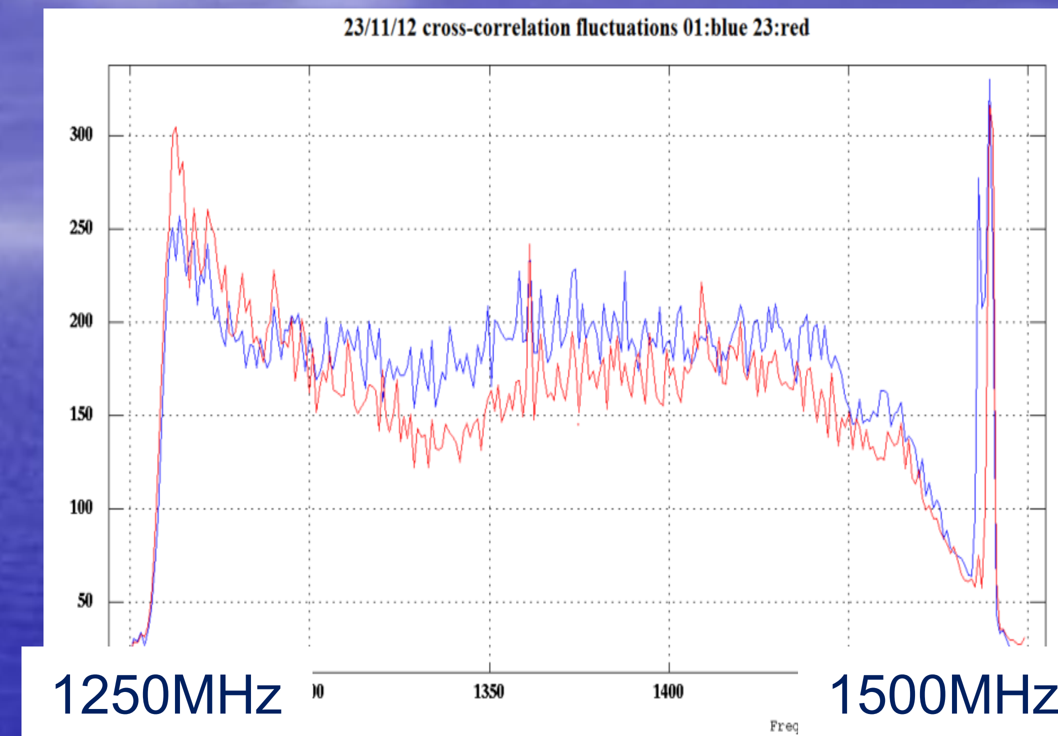


Transit de



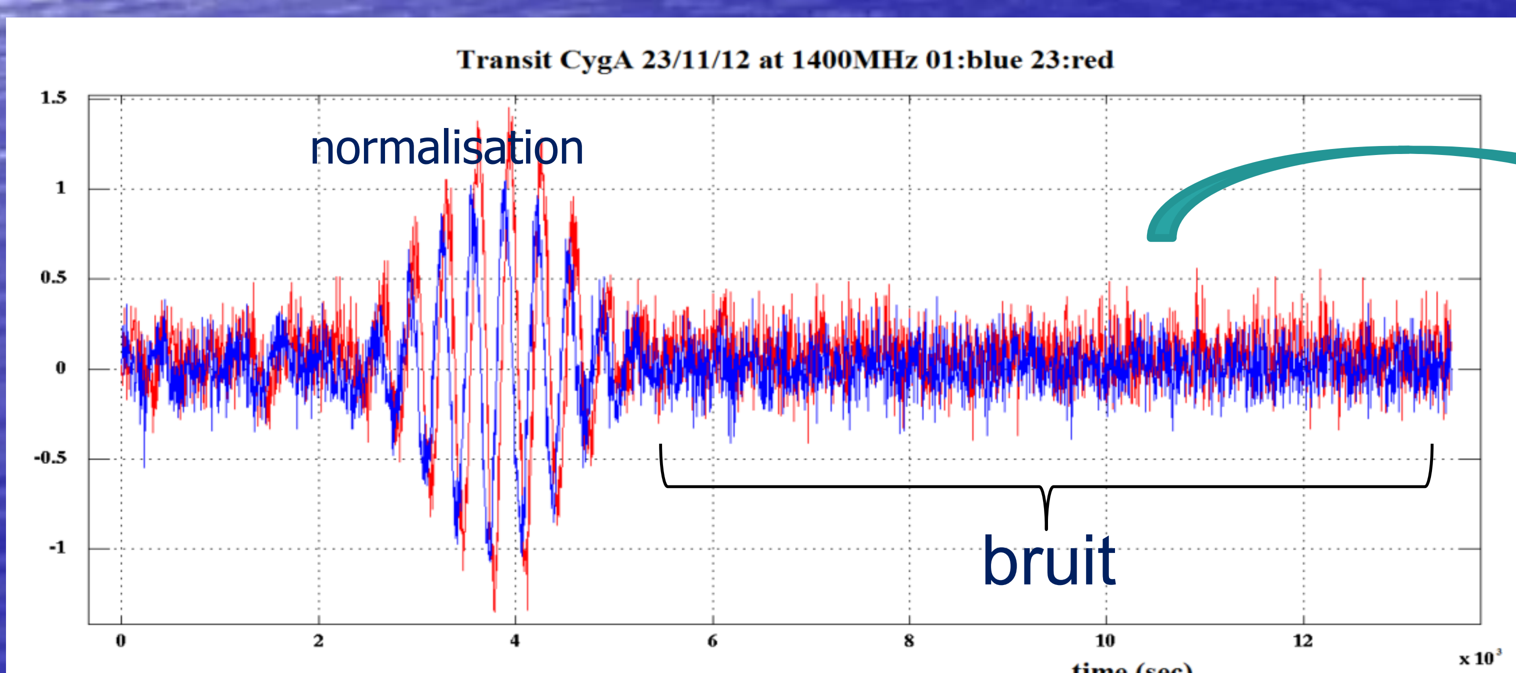
1600Jy ~ 4K
1400MHz

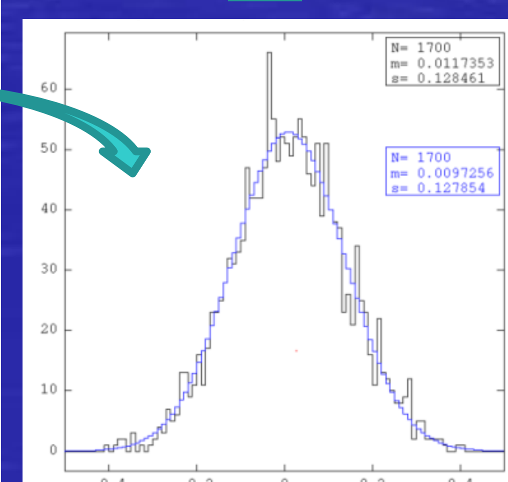




Observations de Cyg A durant 4h [1250-1500] MHz

Sigma -> T_{sys}





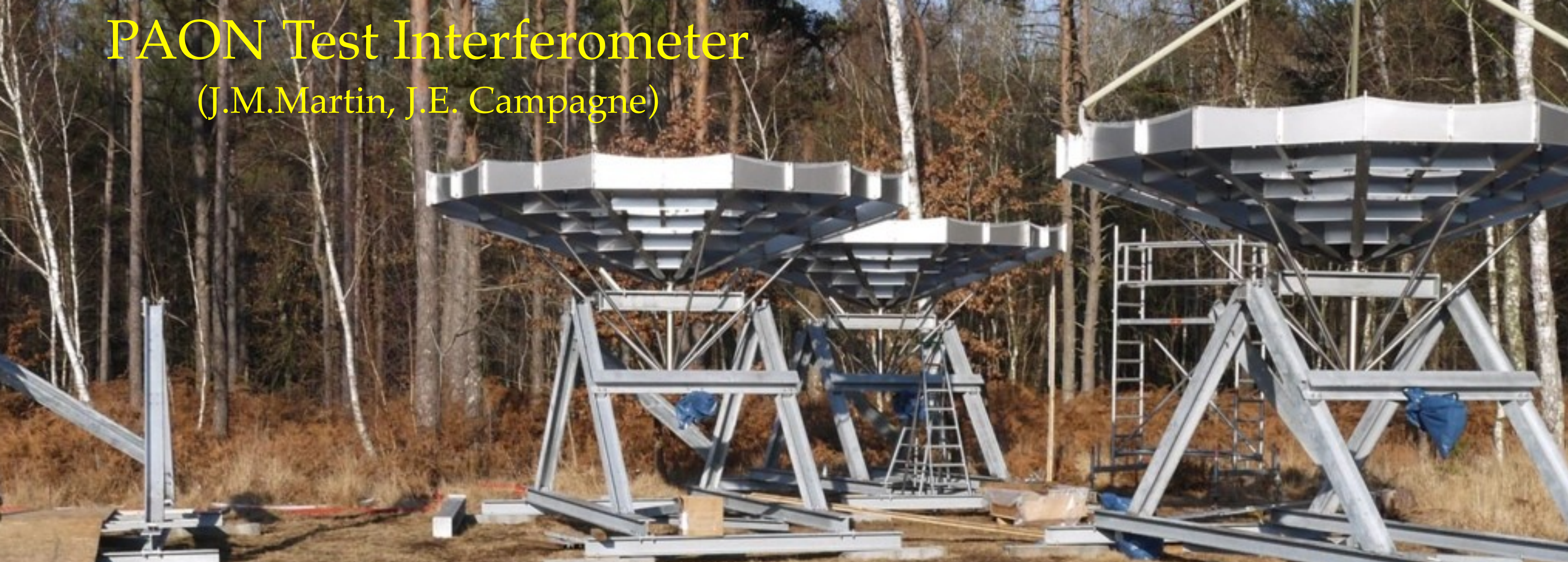
T_{sys} ~100K
1400MHz

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

Slide by J.E. Campagne

PAON Test Interferometer

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



PAON-4

(F. Rigaud)

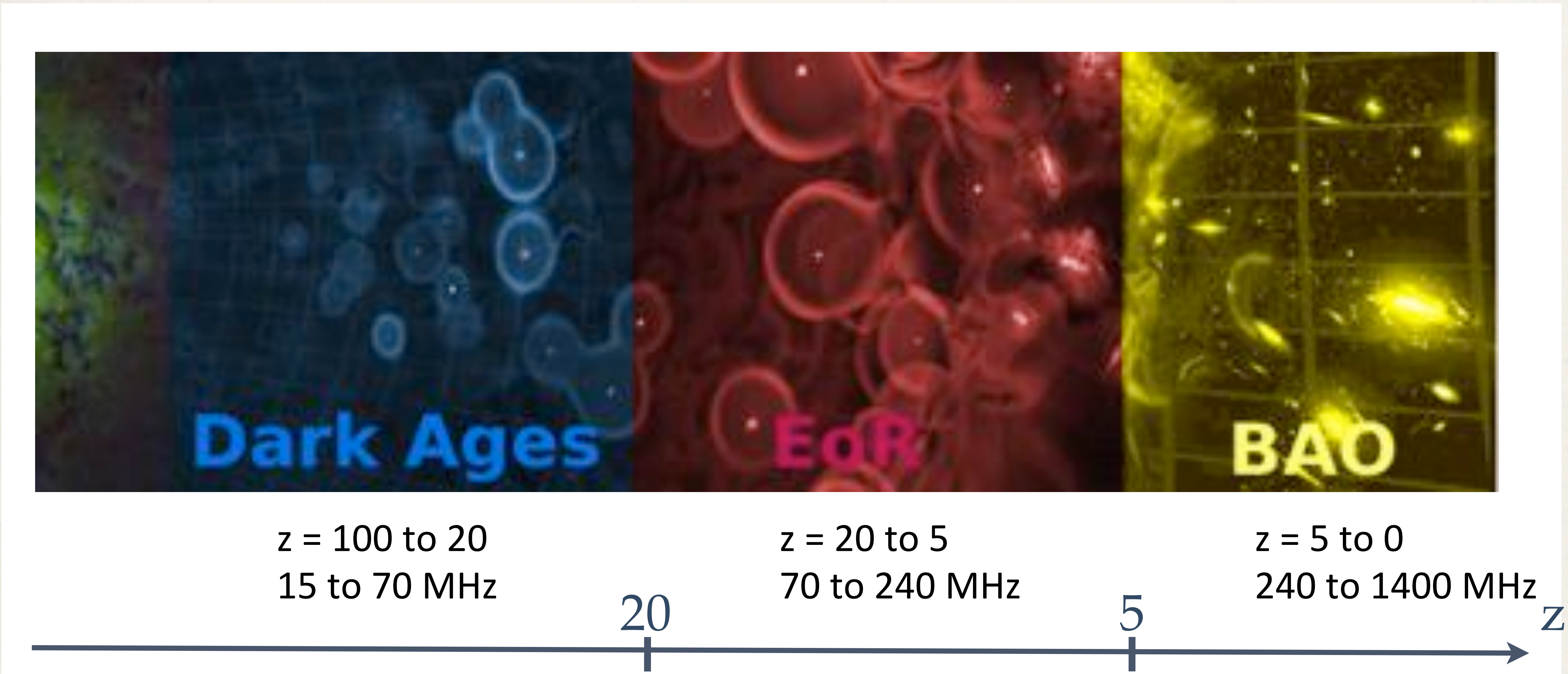
installation Nov 2013 - March 2014

4 D=5m dishes

PAON-2 →

installed September 2012

Other 21 cm BAO projects



- LOFAR
- GMRT
- MWA

- SKA-LOW
- HERA

- **CHIME**
- **Tianlai**
- GBT
- BAOBab
- BINGO

The University of Manchester

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

BINGO: A novel experiment for HI intensity mapping at z=0.1-0.5

(update since Moriond 2012)

Clive Dickinson

Jodrell Bank Centre for Astrophysics, The University of Manch

Recontres de Moriond, Cosmology 2014, March 22-29, 2014, La Thuille, Italy

Only major challenge: BINGO horns are big!

≈1.[illegible]m diameter, ≈4.[illegible]m long

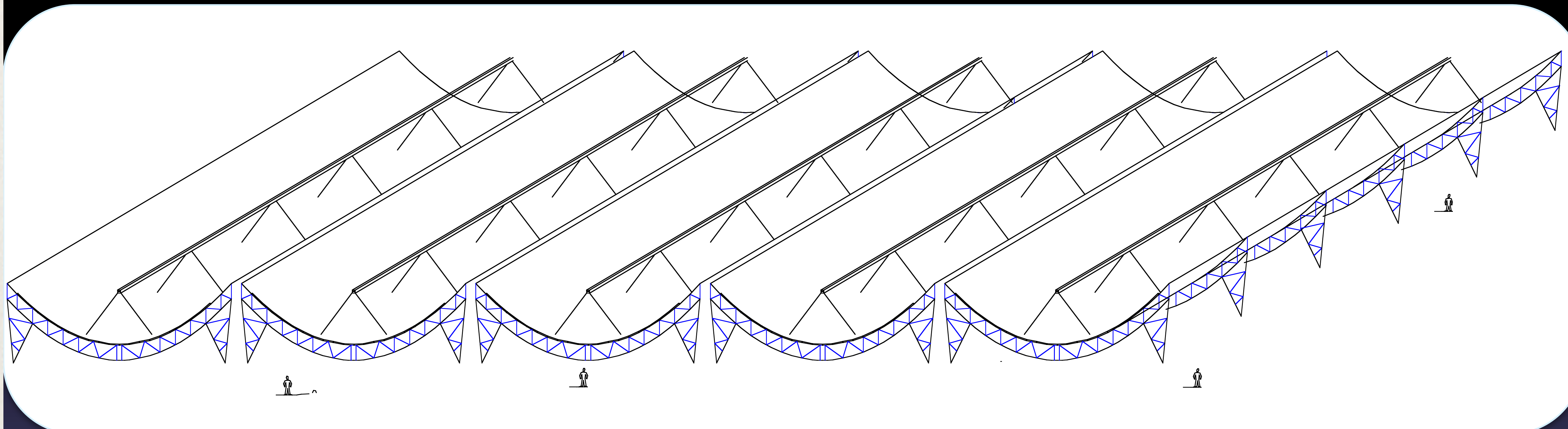
Credit: Ian Browne

Standard techniques expensive and heavy – alternatives being investigated

1) Foam covered in metal tape (Manchester) – potentially ~1/10th of cost

2) Bend corrugated Aluminium hoops and fix together (NPF)

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

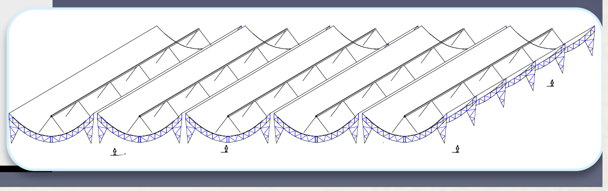
Slide by K. Bandura

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



funded (11 M$)

16 channel correlator now, 256 channel correlator by spring 2014

TIANLAI

中国科学院国家天文台

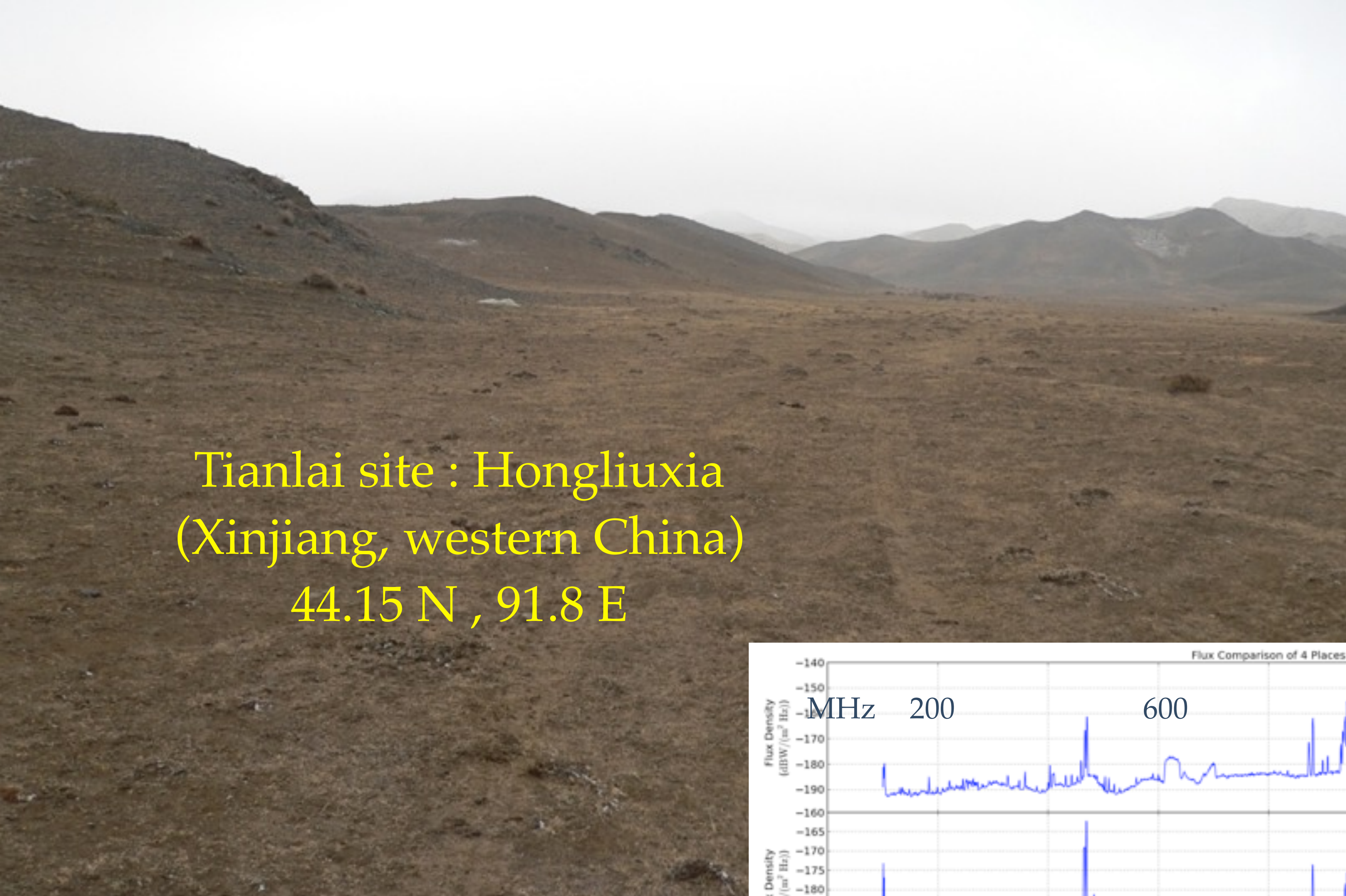
NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

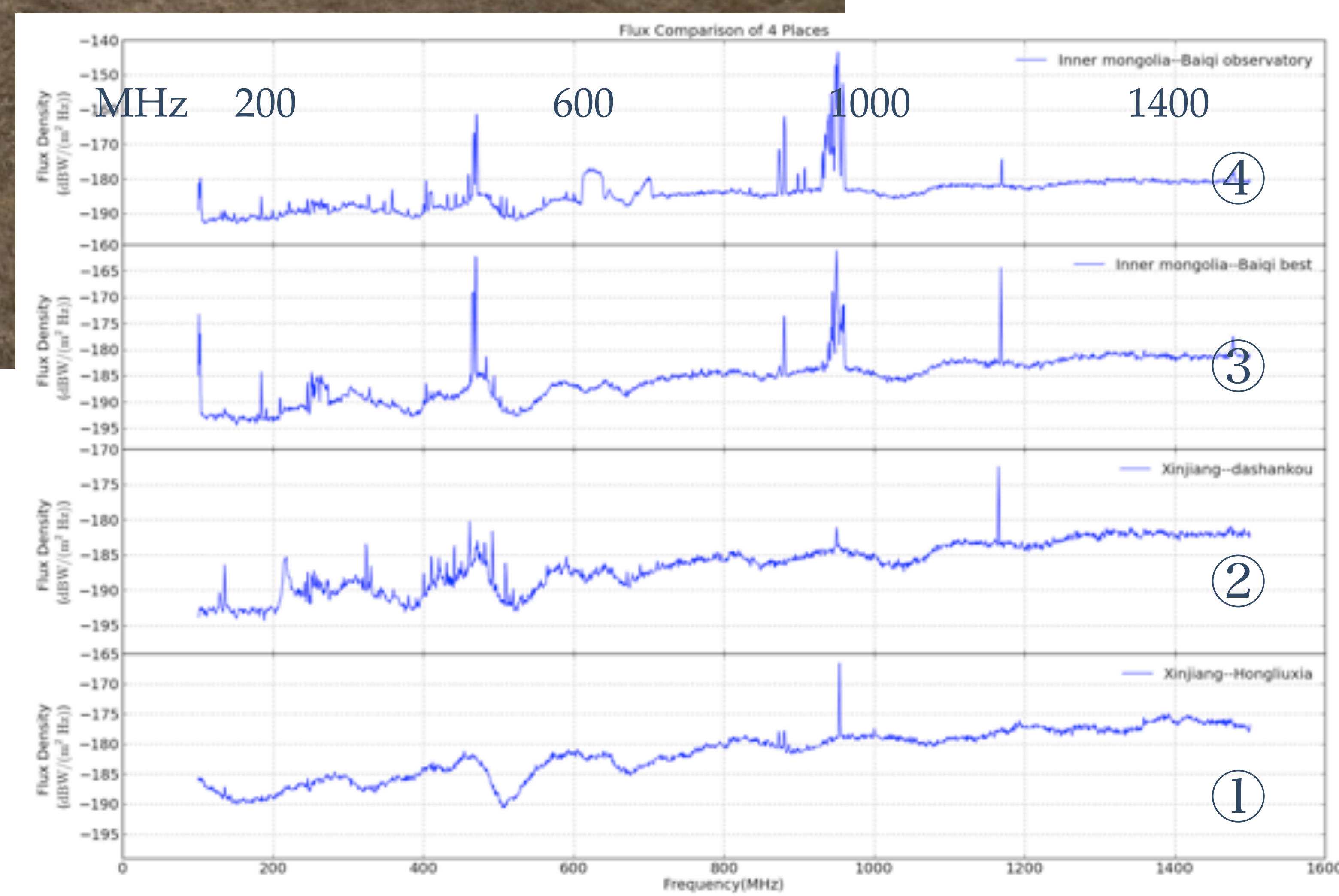
From CRT / BAORadio to… Tianlai

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)

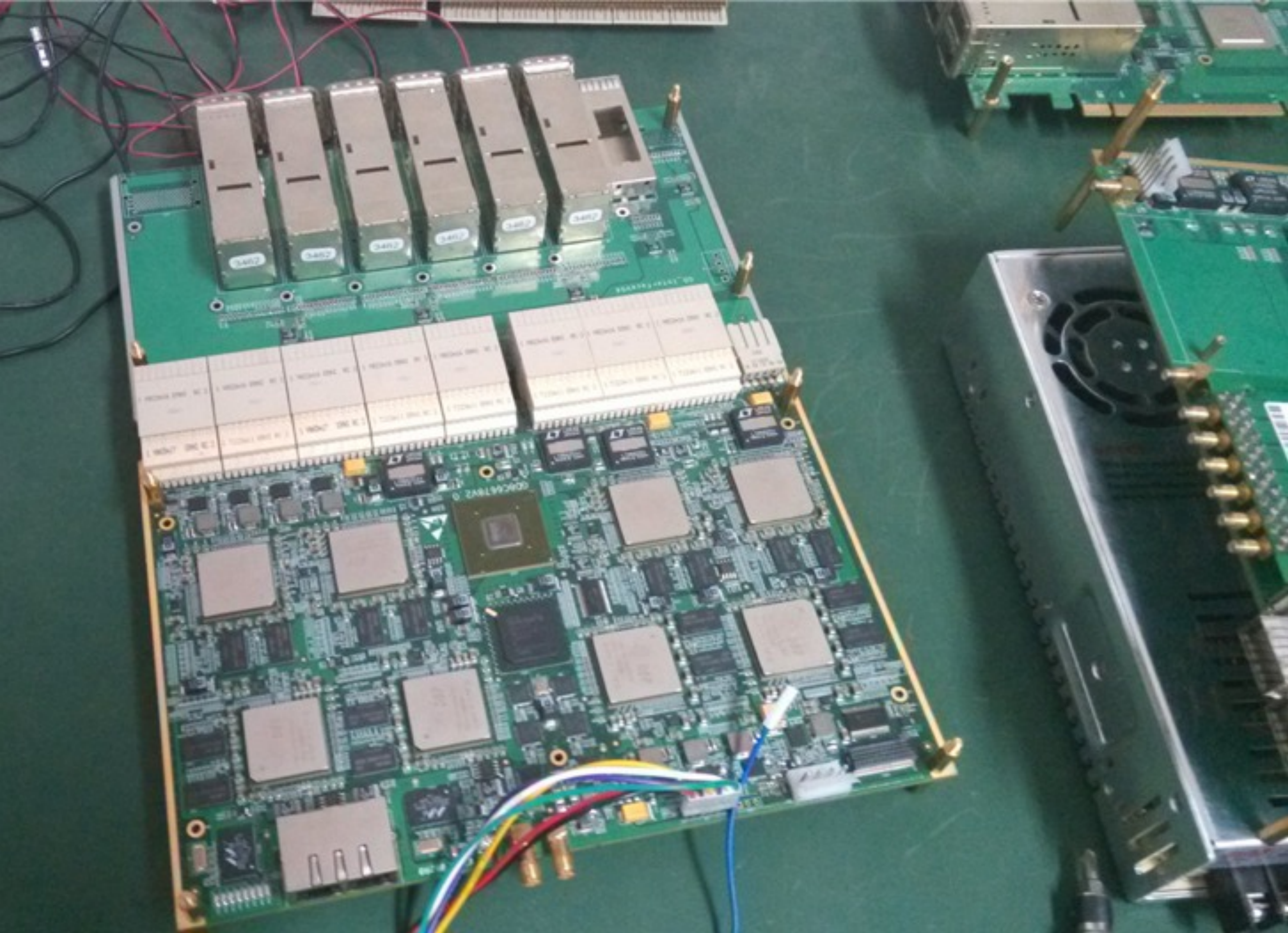




① - Xingjiang - Hongliuxia

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

HICluster program at Nançay

Paper being finalized, will be submitted soon for publication …

- 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

Résolution 3-20 arcmin

z_max ~ 0.03 … 0.15

δz ~ 0.0001

Sensibilité ~ mJy

Table B.1 Comparison of major blind HI surveys

Survey	Area	Beam	V_{max}	V_{res} [a]	t_s	rms [b]	N_{det}	min M_{HI} [c]	Ref
	(deg^2)	(arcmin)	(km/s)	(km/s)	(s)	(mJy)		(M_{sun})	
AHISS	65	3.3	-700 - 7400	16	var	0.7	65	1.9×10^6	1
ADBS	430	3.3	-650 - 7980	34	12	3.6	265	9.9×10^6	2
WSRT	1800	49.	-1000 - 6500	17	60	18	155	4.9×10^7	3
Nancay CVn	800	4 x 20	-350 - 2350	10	80	7.5	33	2.0×10^7	4
HIJASS	1115	12.	-1000 - 10000[d]	18	400	13	222	3.6×10^7	5
HIJASS-VIR	32	12.	500 - 2500	18	3500	4.	31	1.1×10^7	6
HIDEEP	60	15.5	-1280 - 12700	18	9000	3.2	173	8.8×10^6	7
HIZSS	1840	15.5	-1280 - 12700	27	200	15.	110	4.1×10^7	8
HICAT	21341	15.5	300 - 12700	18	450	13.	4315	3.6×10^7	9
HIPASS		15.5	300 - 12700	18	450	13.	(6000)	3.6×10^7	10
AUDS	0.4	3.5	-960 - 47000[e]	TBD	70 × 3600	0.02	(40)	0.6×10^6	11
AGES	TBD	3.5	-960 - 47000[e]	TBD	300	0.5	TBD	1.4×10^6	12
ALFALFA	7000	3.5	-2000 - 18000	11	28	1.6	(16000)	4.4×10^6	

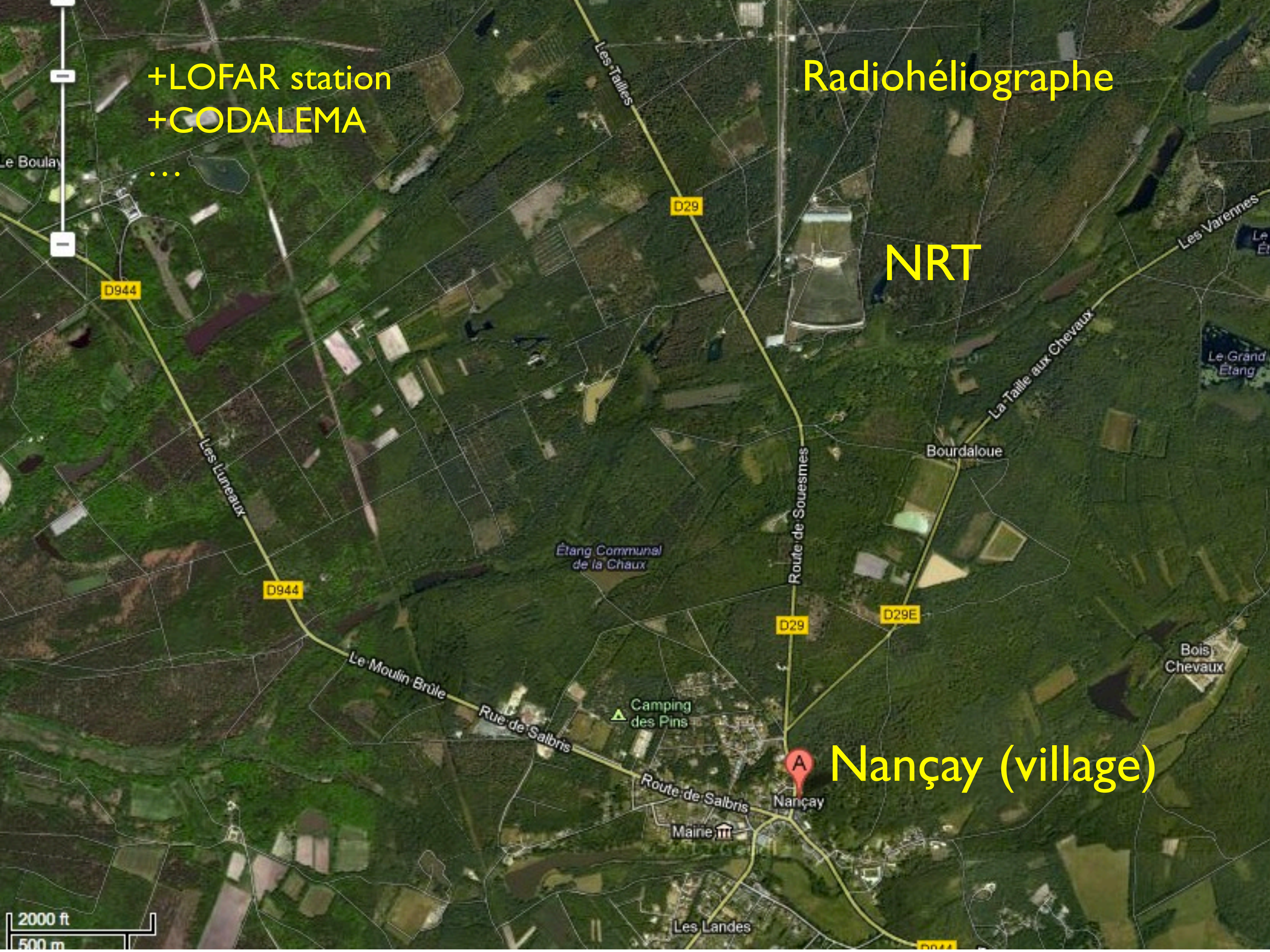
Arecibo

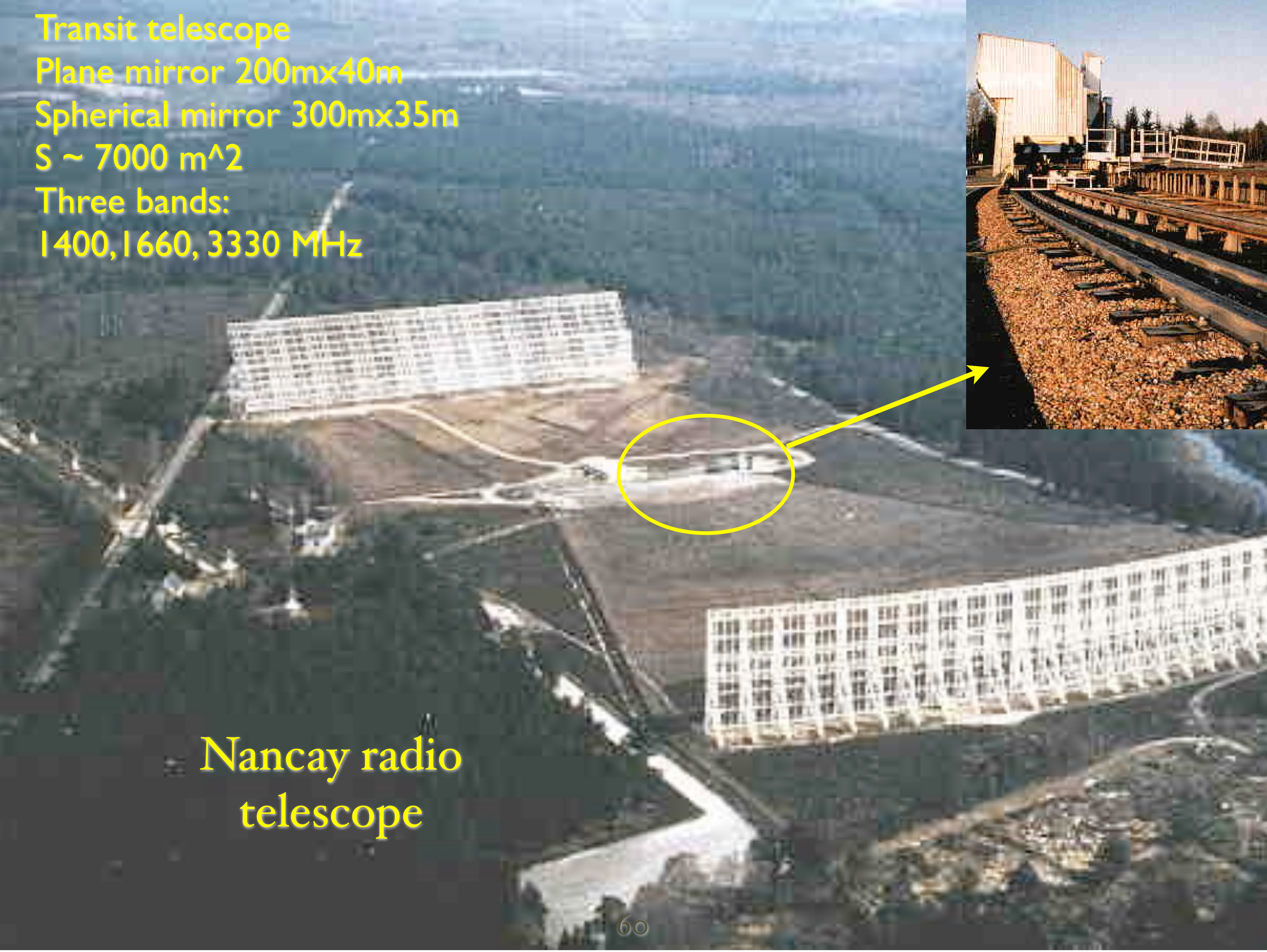
Voir : http://egg.astro.cornell.edu/index.php

z <~ 0.06

Comparison of few 21 cm surveys


Arecibo
∅ 305 m
S ~ 73 000 m^2
50 MHz … 10 GHz
http://www.naic.edu


+LOFAR station
+CODALEMA
...
Radiohéliographe
NRT
Nançay (village)
Le Boulay
D944
Les Tailles
D29
Les Varennes
Le Grand Étang
La Taille aux Chevaux
Bourdaloue
Les Luneaux
Route de Souesmes
Étang Communal de la Chaux
D944
D29
D29E
Bois Chevaux
Le Moulin Brûle
Rue de Salbris
Camping des Pins
Route de Salbris
Nançay
Mairie
Les Landes
2000 ft
500 m

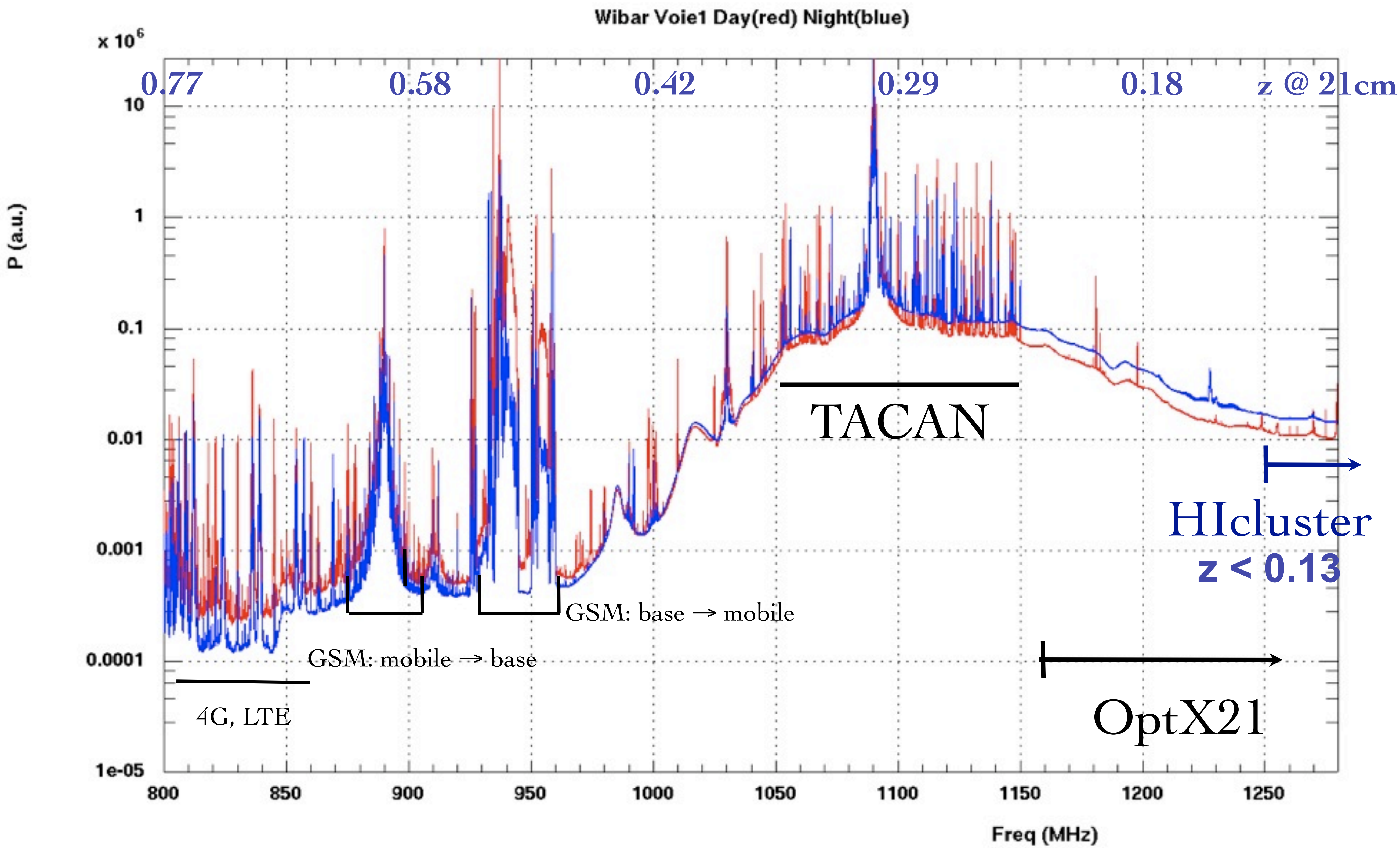

Transit telescope
Plane mirror 200mx40m
Spherical mirror 300mx35m
S ~ 7000 m^2
Three bands:
1400,1660, 3330 MHz
Nancay radio telescope
60

HI-Cliuster @ Nançay

- NRT : ~ 7000 m^2 collecting area
- plane mirror, delta pointing
- Cryogenic receiver, Tsys ~ 25-30 K, LF (21 cm band) 1.1-1.8 GHz HF (9 cm) 1.7-3.5 GHz
- Beam (@ 21 cm) : 4' (RA) x 22' (DEC)
- BAORadio for HI-Cluster: 1250-1500 MHz, 30 kHz freq. resolution,

Spectrum at Nançay (Measured with WIBAR)

Slide by A.S. Torrento



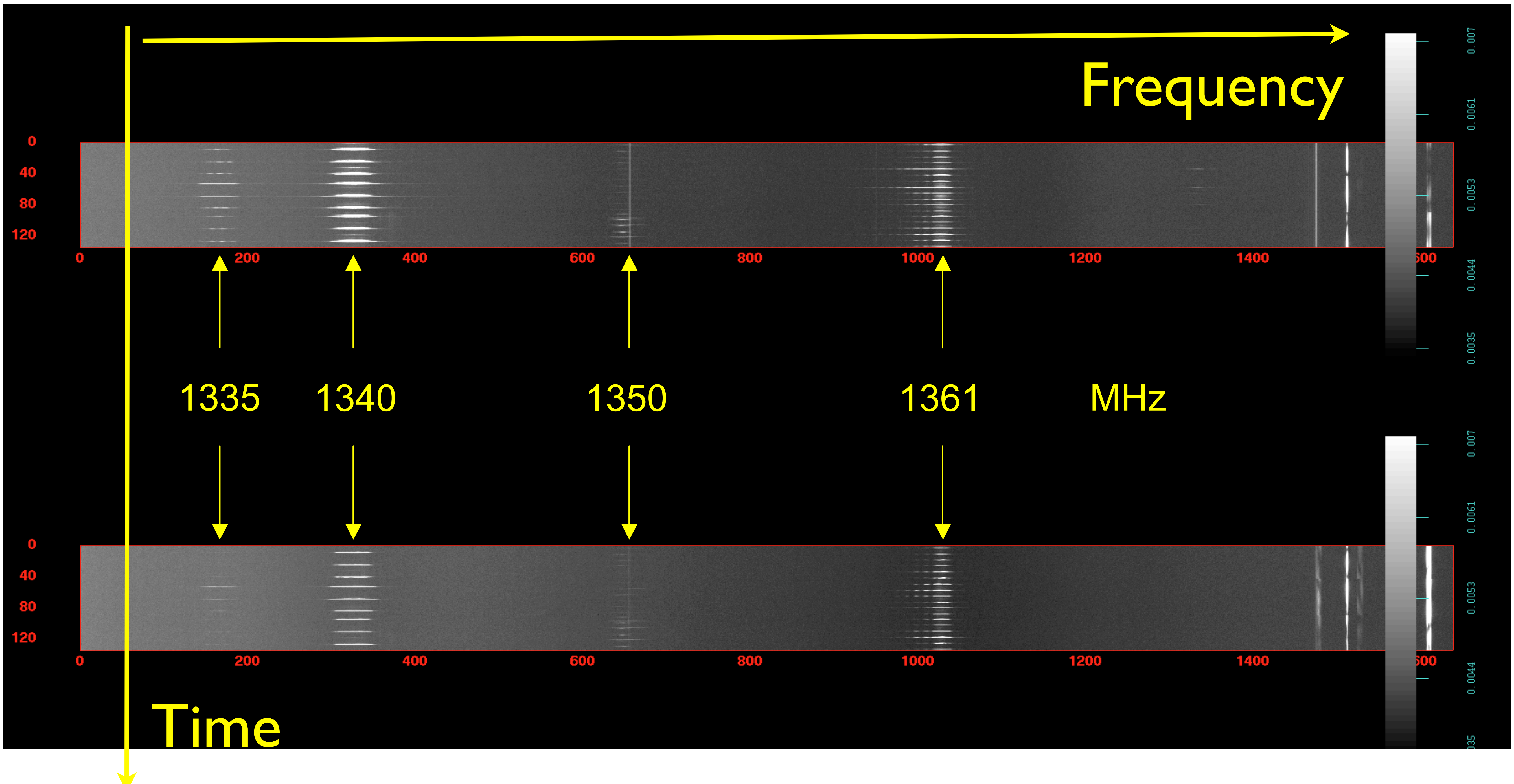
AmasHI@Nançay observations

Source	RA	Dec	z	ν_{obs} (MHz)	Observation period	SOU	MAP
Abell 85	$00^h43^m16.99^s$	-9°09'46.99"	0.05	1346.3	April – June 2011 (8 h)	1125.147 (gals)	239.147
Abell 1205	$11^h15^m08.37^s$	2°33'01.39"	0.078	1320.8	March 2011 – January 2012 (16 h)	1124.147 (gals)	241.147
Abell 2440	$22^h24^m33.30^s$	0°53'18.59"	0.095	1302.4	March – June 2011 (3.5 h)	1123.147 (center)	244.147
3C161	$06^h24^m43.09^s$	-5°51'14.00"	-	1420.4	9th Dec 2011 (6 m)	84.170	584.171

Useful integration time (On/Off ...)

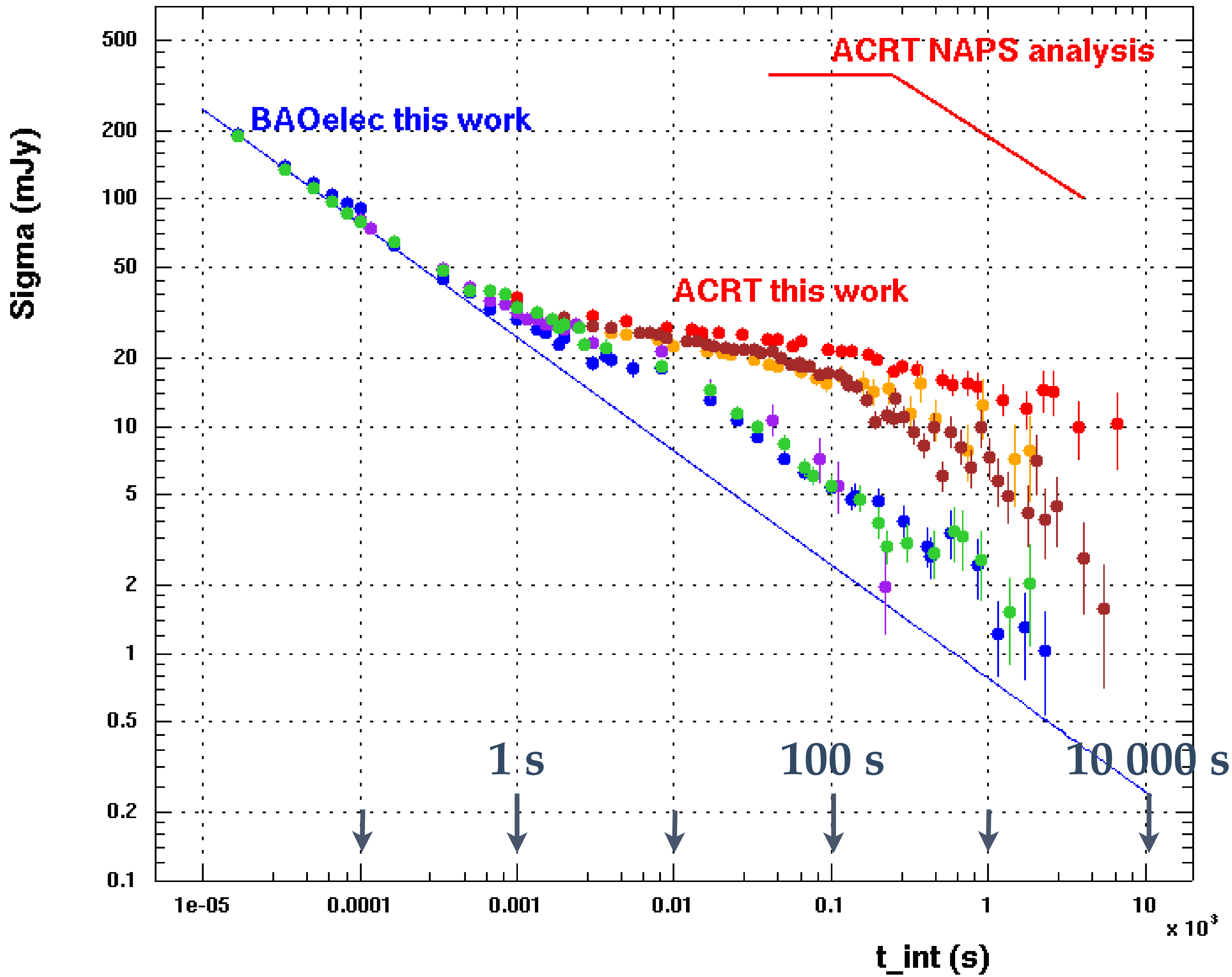
- 1 TB of data (waveform) / observation hour
- 100 TB total data set (processed at CC-IN2P3)

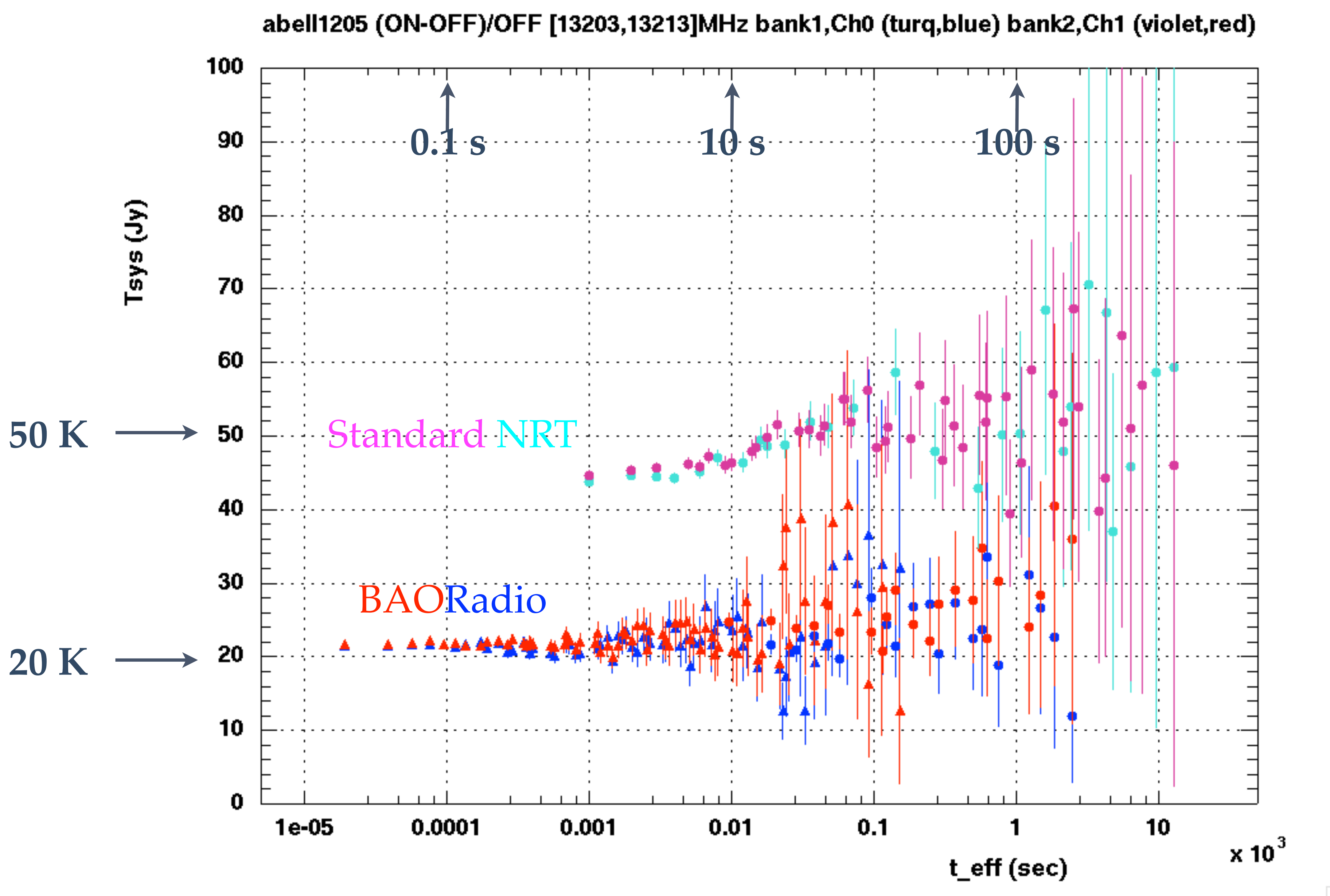
BAORadio / HI-Cluster



Intermittent RFI cleaning using fine time sampling ...

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

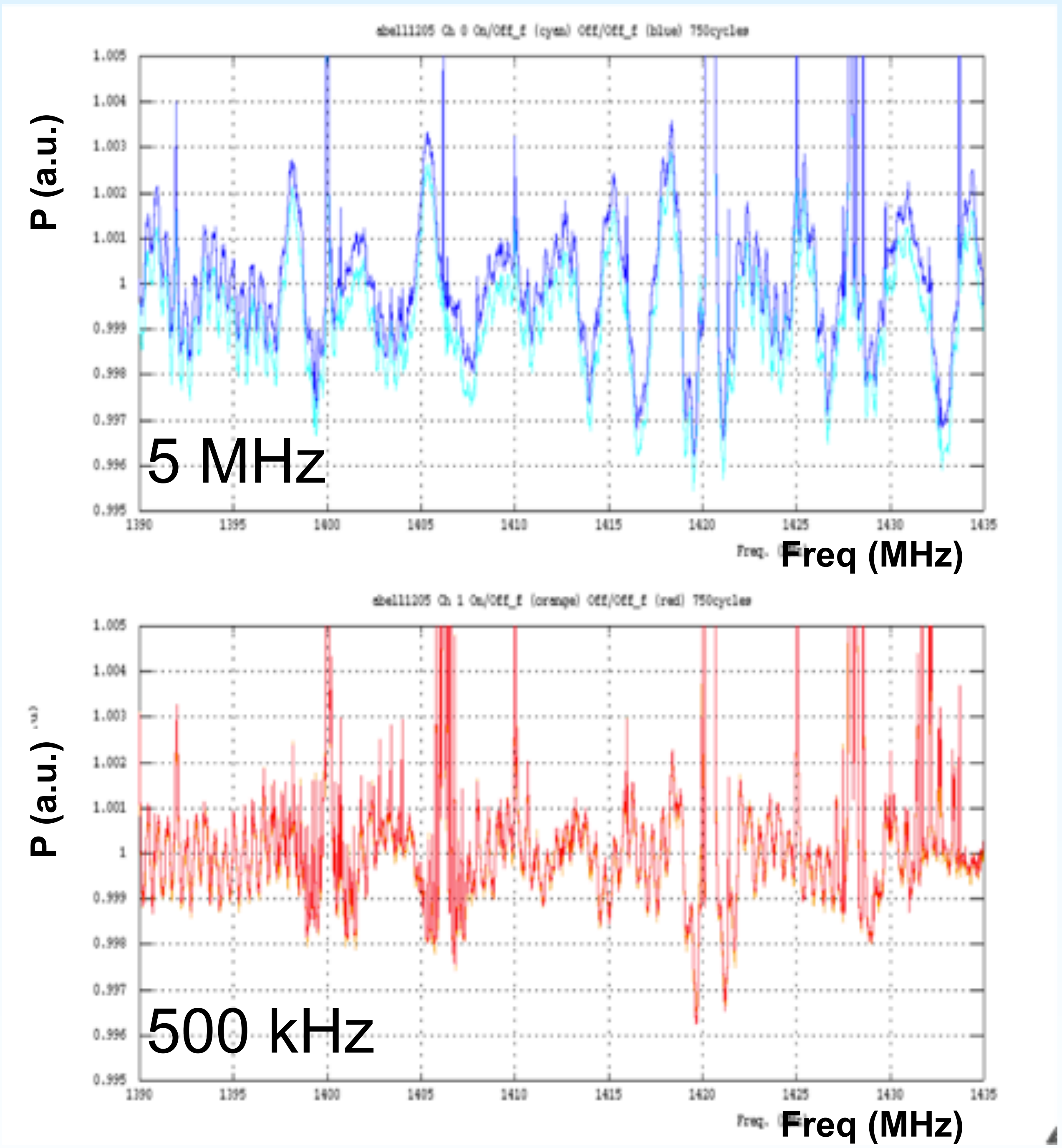




HI-Cluster : Sensitivity expressed as Tsys …
Comparison between BAORadio electronic & Acquisition system and standard NRT auto-correlator

Analysis by A.S.Torrento - 2013

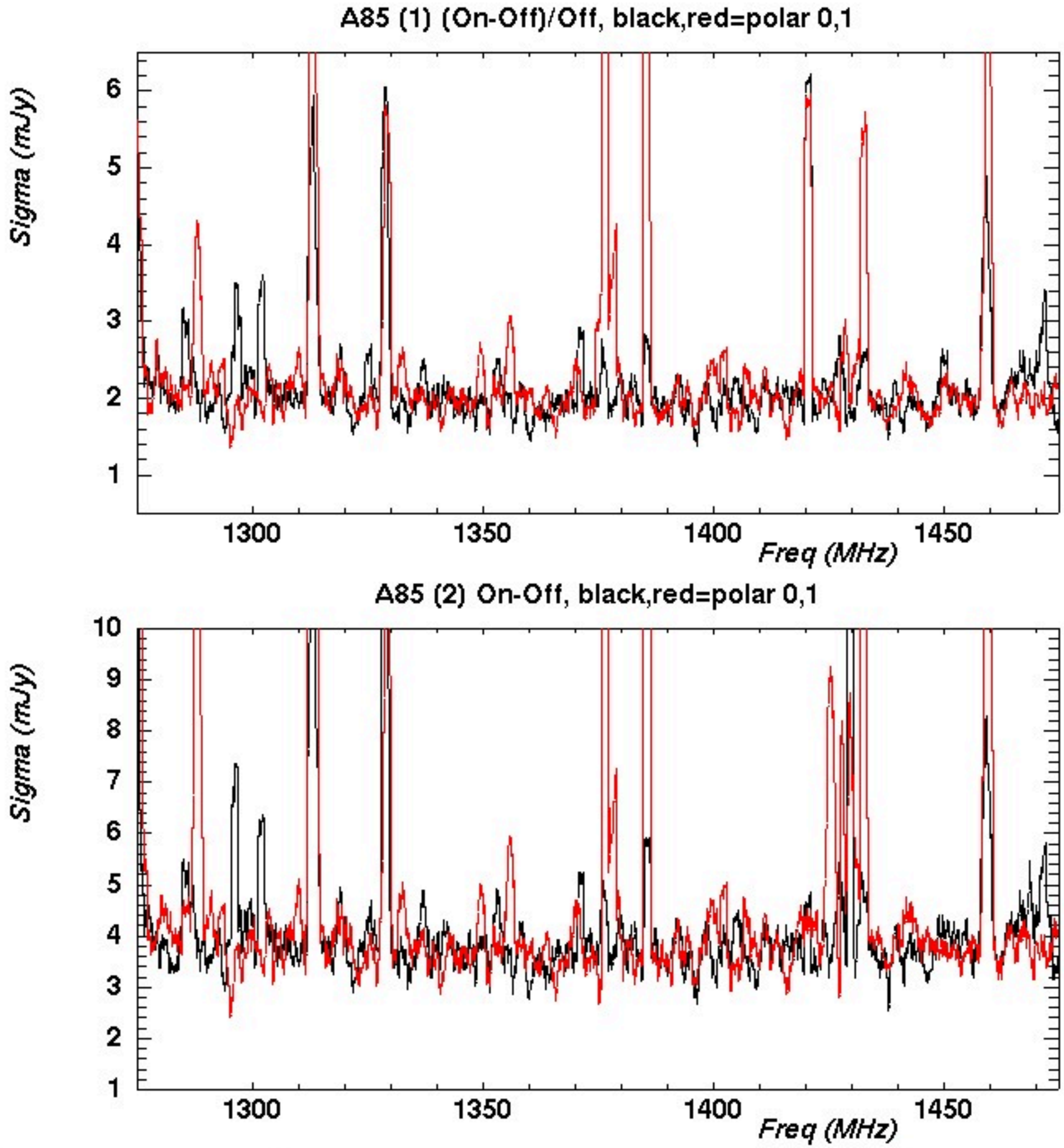
HI cluster: oscillations



- 5-MHz
  - present in BAORadio only
  - due to impedance mismatch
- 500-kHz
  - present in NançayCorr and BAORadio
  - due to noise reflexion between spherical mirror and chariot

    (*d* ~ 290 m).
- Normalisation per cycle by OFF spectrum and (ON-OFF)/OFF arithmetic cancels most of them.

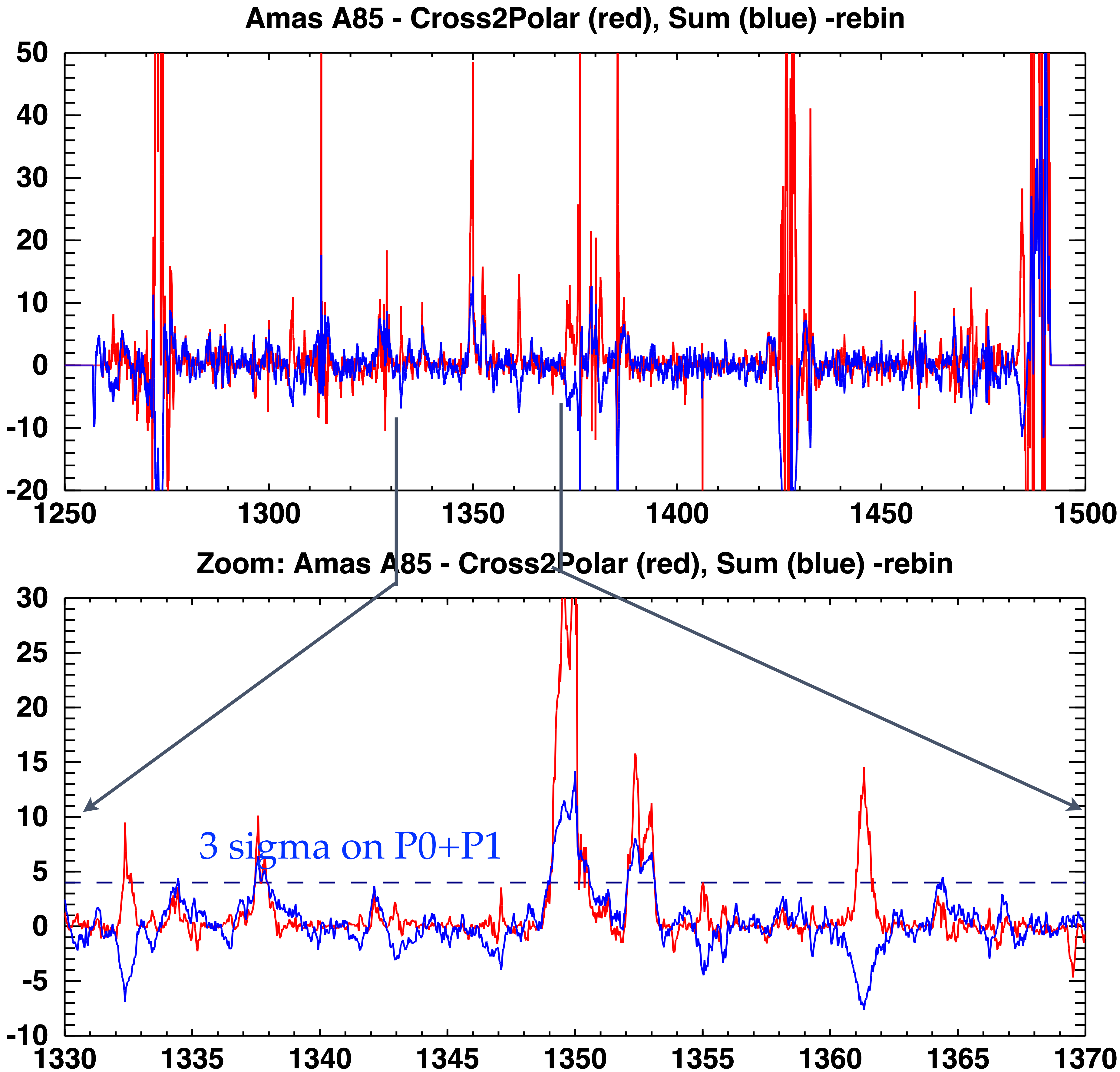
Slide by A.S. Torrento - 2013



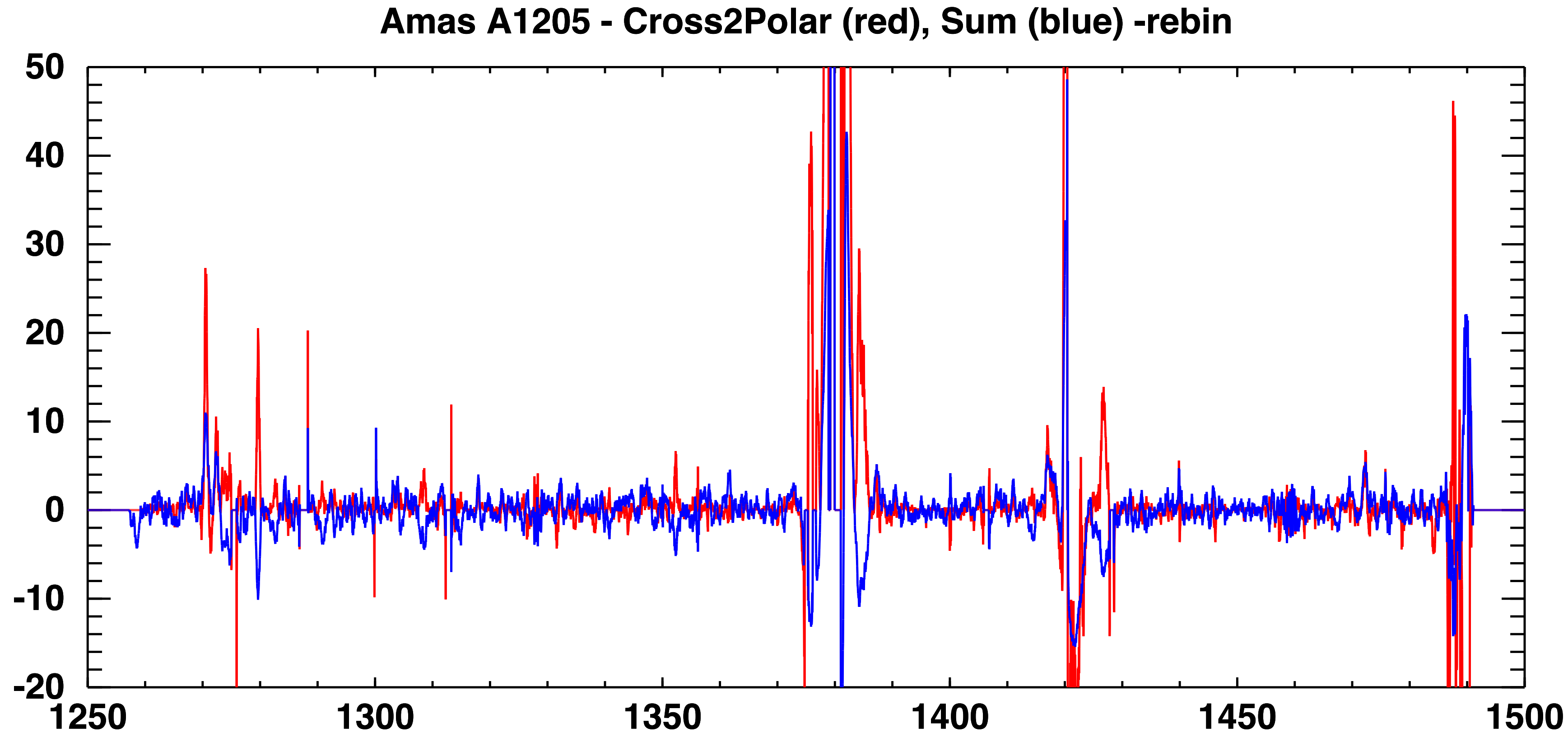
A85
Spectre du sigma (écart-type) en mJy

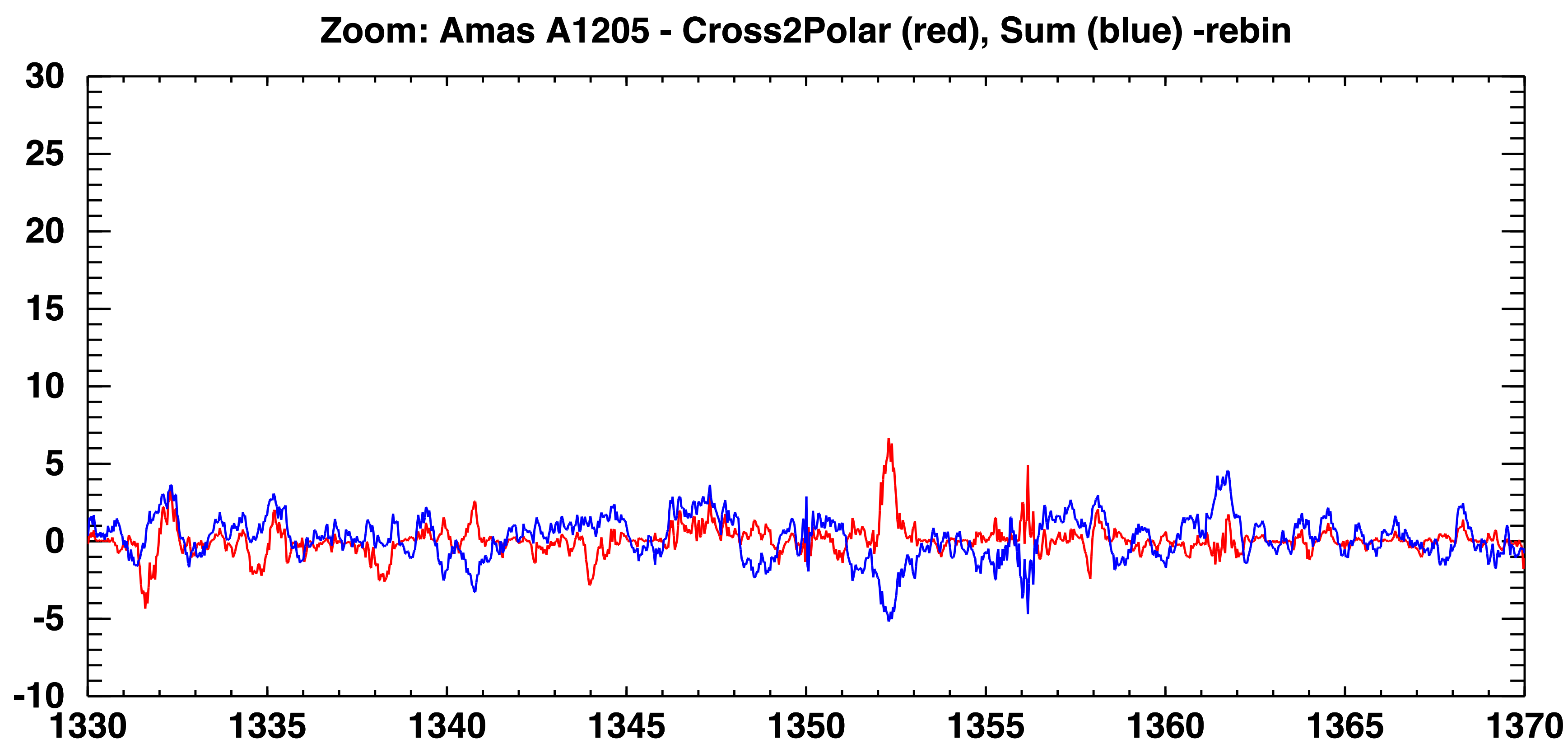
Fig. 2

A85 signal : ~ 4 mJy.MHz



A1205 , zoom over A85 frequency range





Estimation du signal attendu (2)

	f (MHz)	z	dL (Mpc)	P21* (mJy.MHz)
A85	1353	0.0498	228	3.86
A1205	1318	0.777	363	1.52
A2440	1300	0.926	438	1.0

P21* Puissance (en mJy.MHz) au sol
pour $M_{HI} = 10^{10}\ M_{sol}$

HI-Cluster summary

- HI-Cluster program: ~ 1mK noise level has been reached with t_int ~ 10 hours, over a wide band (~1280 - 1450 MHz), using the BAORadio system
- BAORadio Sensitivity about a factor 2 better than the standard NRT correlator, while keeping a much larger fraction of the data (fine time sampling)
- A85: HI detected - A1205: marginal detection or upper limit (publication being finalized)
- Should be careful about spectral structure due to standing waves in cables, feed-reflector …
- OptX21 : 21cm - optical correlation at z=0.2 pilot observations started in fall 2013 (BAORadio ,WIBAR)

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