

COSMOLOGIE À 21 CM

R. ANSARI - UNIV. PARIS-SUD, LAL - CNRS/IN2P3

46ÈME ÉCOLE DE GIF
COSMOLOGIE APRÈS PLANCK
APC - PARIS - SEPTEMBRE 2014

1. Spectre électromagnétique et l'émission à 21 cm
2. L'évolution cosmique de l'hydrogène
 - a. la raie à 21 cm comme sonde cosmologique
3. Observations en radio :
 - a. Principes
 - b. HI extragalactique
 - c. l'interférométrie , synthèse de lobe
 - d. LOFAR, MWA, SKA ...
4. Cartographie 3D à 21 cm (Intensity Mapping) et les BAO's
 - a. Tianlai et BAORadio

SPECTRE EM ET LE RAYONNEMENT 21 CM

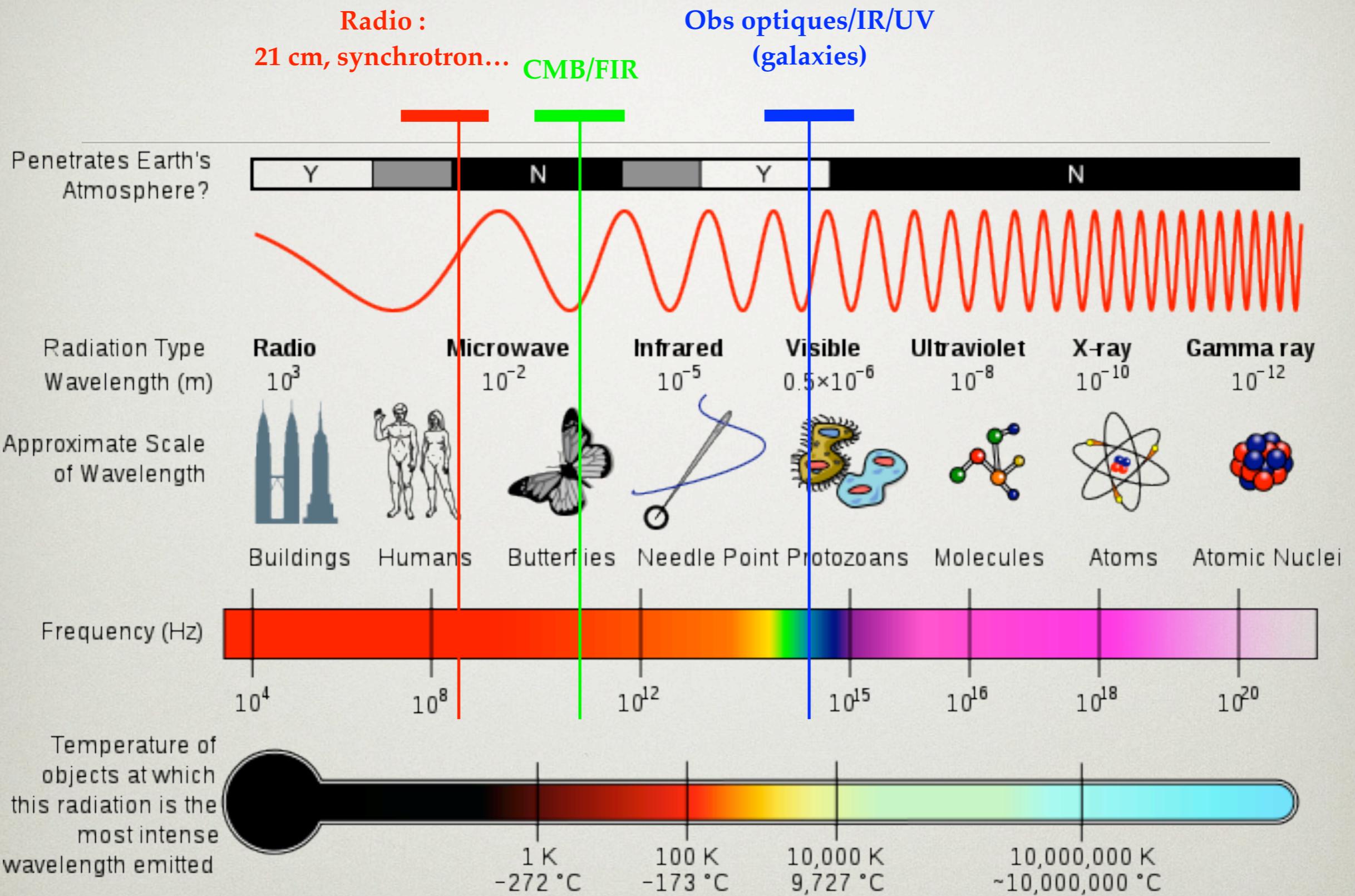
TEMPÉRATURE, LONGUEUR D'ONDE

$$E_\gamma = h \nu = h \frac{c}{\lambda} \quad E_{th} \sim k_B T$$

$$h = 6.62 \cdot 10^{-34} J/s \quad k_B = 1.38 \cdot 10^{-23} J/K$$

$$T_{rad} \simeq \frac{h}{k_B} \nu \quad T_{rad} \simeq \frac{h c}{k_B} \frac{1}{\lambda}$$

E	λ	ν	T (K)	
1 eV	$\sim 1 \mu\text{m}$	$\sim 100 \text{ THz}$	~ 10000	Visible
1 meV	$\sim 1 \text{ mm}$	$\sim 100 \text{ GHz}$	$\sim 10 \text{ K}$	micro-ondes
10 μeV	$\sim 10 \text{ cm}$	1 GHz	$\sim 0.1 \text{ K}$	radio



Le spectre électromagnétique

http://en.wikipedia.org/wiki/File:EM_Spectrum_Properties_edit.svgv

R. Ansari, E2Φ 2012

RAYONNEMENT DU CORPS NOIR

- loi de Planck (rayonnement du corps noir) - Unité SI (W/m²/Hz/srad)

$$B(\nu) = L(f) = \frac{2h\nu^3}{c^2 [\exp(h\nu/(kT)) - 1]}$$

- Pour $h\nu \ll kT$ (domaine de Rayleigh-Jeans)

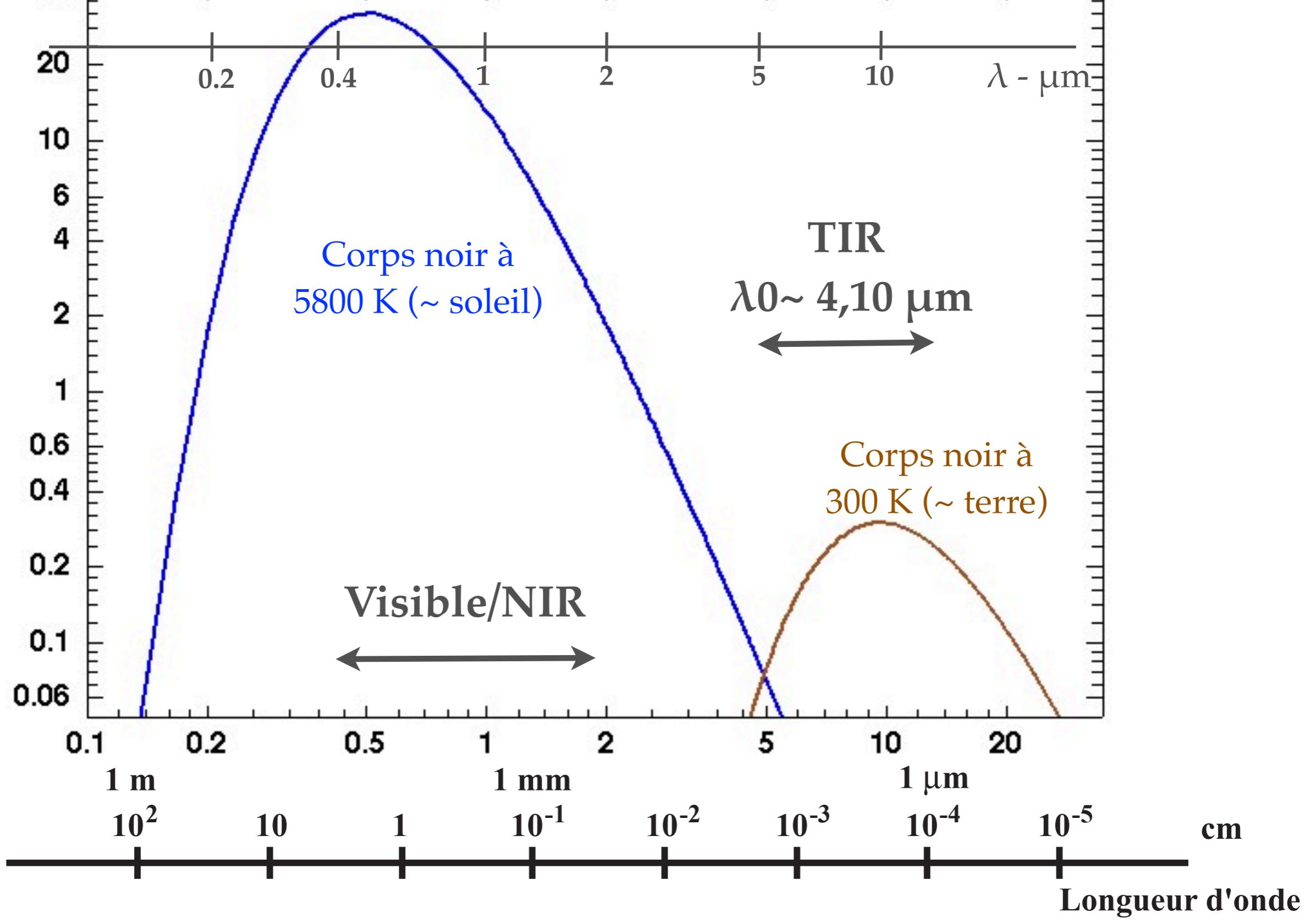
$$B(\nu) = L(f) \simeq \frac{2kTf^2}{c^2} = \frac{2kT}{\lambda^2} \quad \lambda \gg \frac{hc}{kT}$$

- La puissance totale émise $\propto T^4$ (Loi de Stéphan)

$$I_{\text{tot}} = \sigma T^4 \quad \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

- Le pic de l'émission

$$\lambda_{\text{max}} = \frac{c}{\nu_{\text{max}}} = \frac{A}{T} \quad \text{avec} \quad A = 2.898 \times 10^{-3} \text{ K.m}$$



Radio - Télévision
téphones mobiles

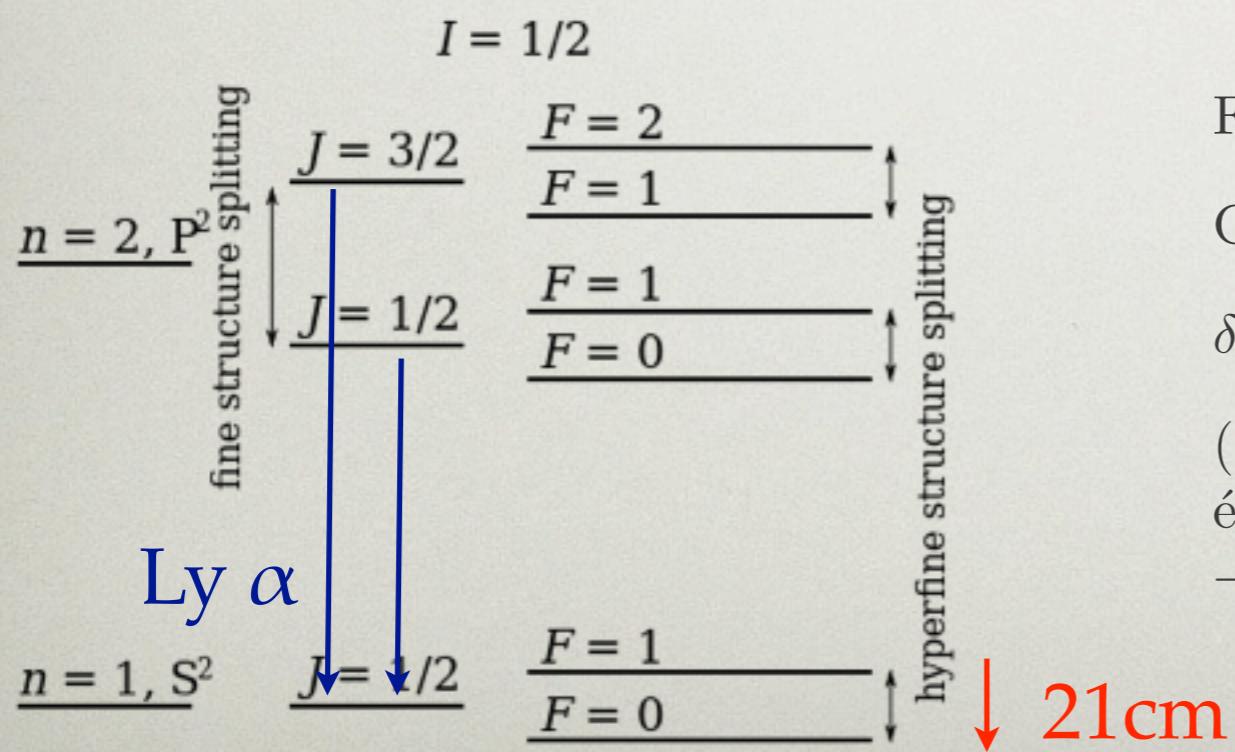
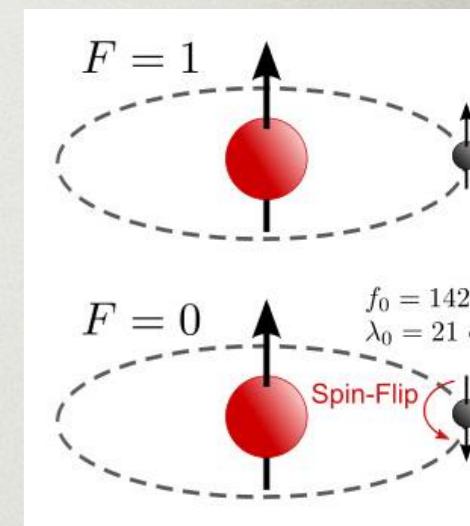
Micro-ondes

IR UV

Lumière visible (0.4 - 0.8 μm)

RAYONNEMENT À 21 CM

- Niveaux atomiques: >100 THz (visible, UV), vibrations moléculaires (0.1...100 THz), rotation moléculaires (10...1000 GHz)
- Effets électroniques collectifs : kHz ... 10 GHz
- Niveau hyperfine de l'hydrogène atomique : transition de spin (spin-flip) de l'électron dans le champ magnétique du moment dipolaire du noyau



Fréquence d'émission : $\nu_{21} = 1.4204 \cdot 10^9$ Hz

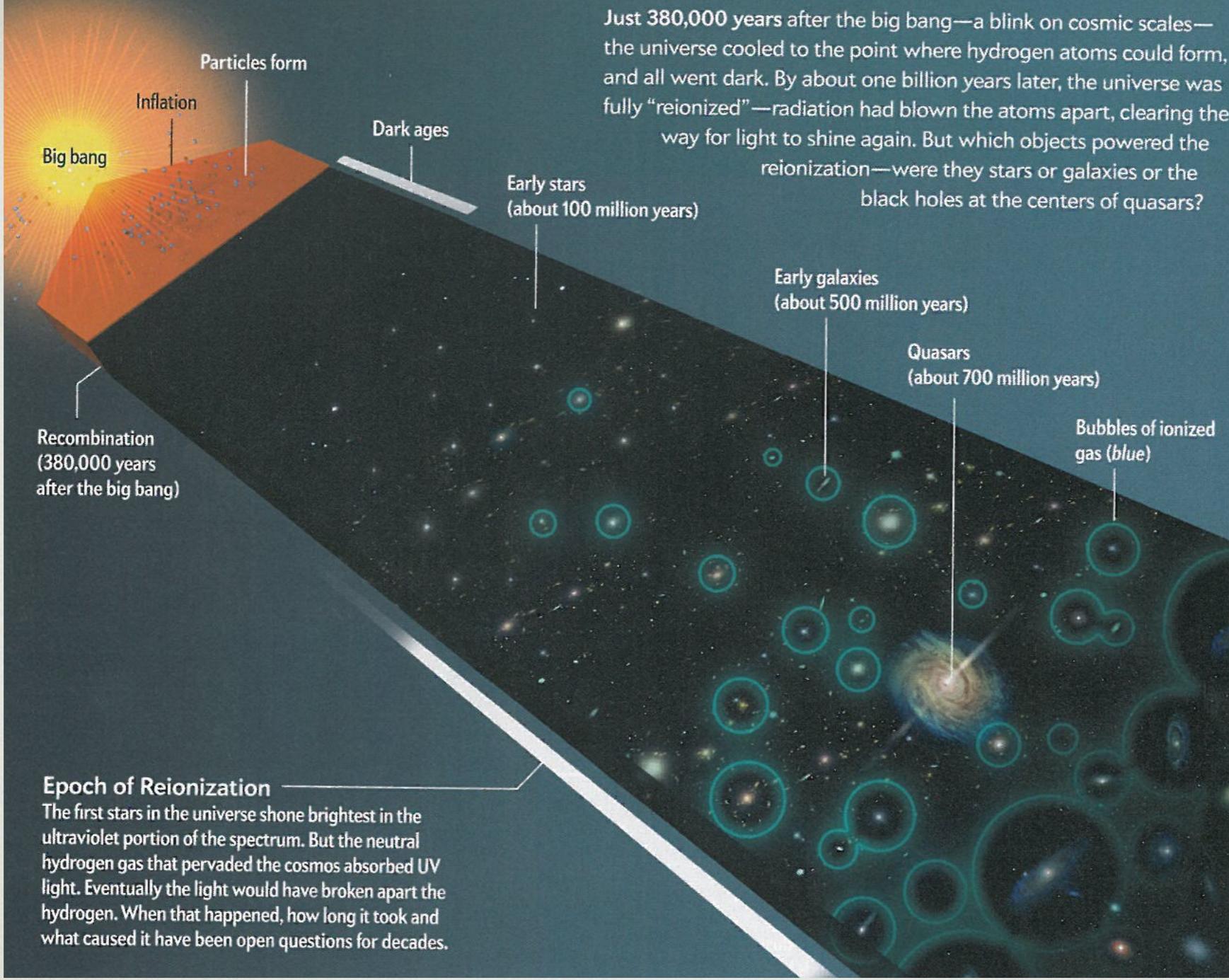
Coefficient émission spontanée : $A_{21} = 2.87 \cdot 10^{-15} s^{-1}$

$$\delta T_{21} = h\nu_{21}/k \simeq 0.0682 K \ll T_{CMB} = 2.725 K$$

(+) triplet, (-) singulier et le niveau inférieur un singulet.
équirépartition des atomes sur (+)/(-) si $T_s \gg \delta T_{21}$
 $\rightarrow N^+ = 3/4 N_{H_I}$.

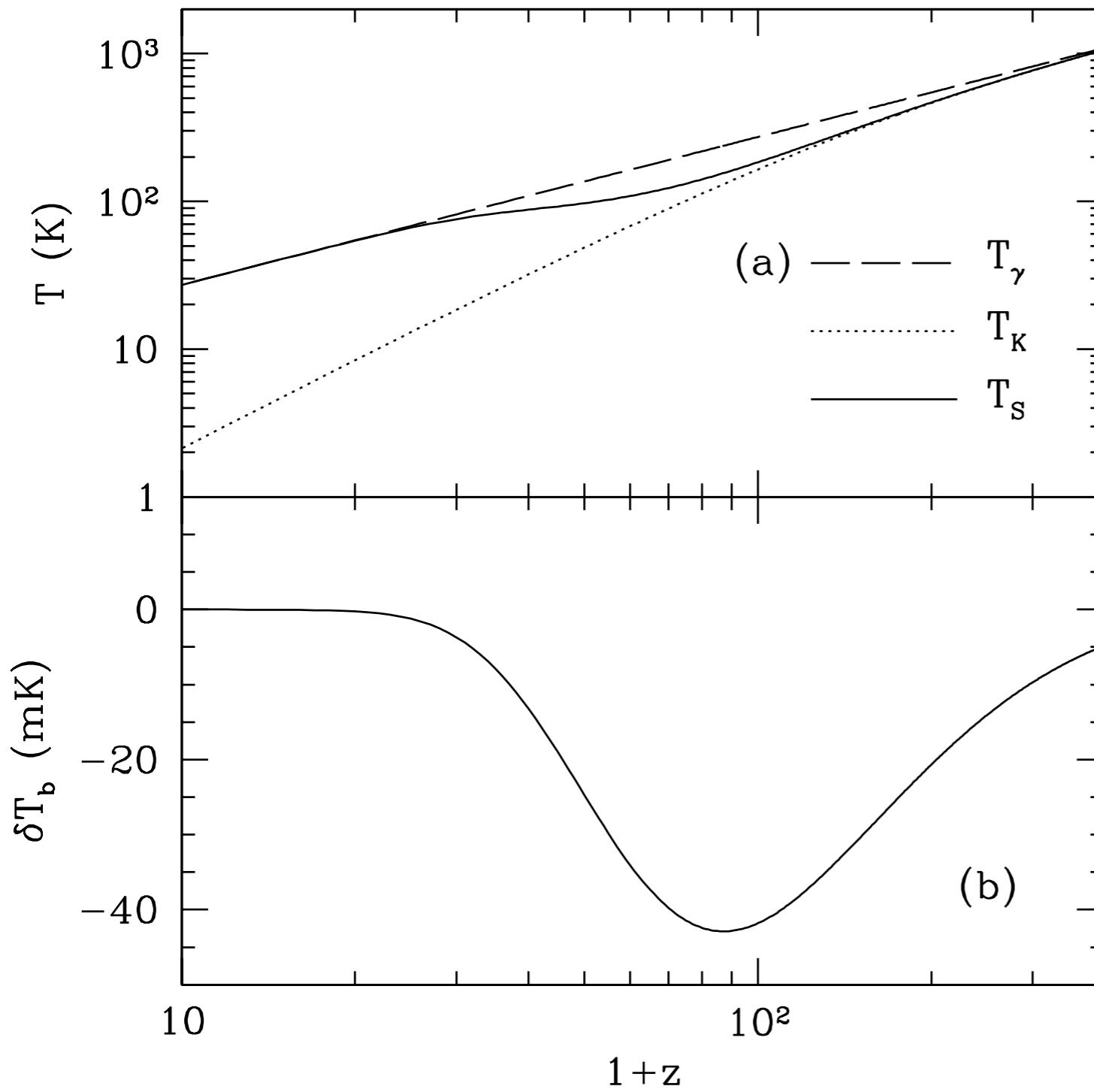
HI À TRAVERS LES
ÂGES
LA RAIÉ À 21 CM
COMME SONDE
COSMOLOGIQUE

Illustration : Scientific American, April 2014



Reionisation

	<u>Dark ages</u>	<u>First stars / Galaxies ...</u>	<u>Quasars ...</u>	Today
n_b (cm^{-3})	330	0.25	0.03	$3 \cdot 10^{-4}$
Age (MY)	0.38	15	50	500
T (K)	3000	300	150	30
Z	1100	100	50	10
	+	+	+	+
	1100	100	50	10
	5			0



S. Furlanetto, S. Peng Ho, F. Briggs, Phys.Rept. 433 (2006),
arXiv:0608032

température du rayonnement
(CMB) T_γ

$$T_\gamma \propto (1 + z)$$

Température cinétique du gaz
(Hydrogène neutre) T_K

$$T_K \propto (1 + z)^2$$

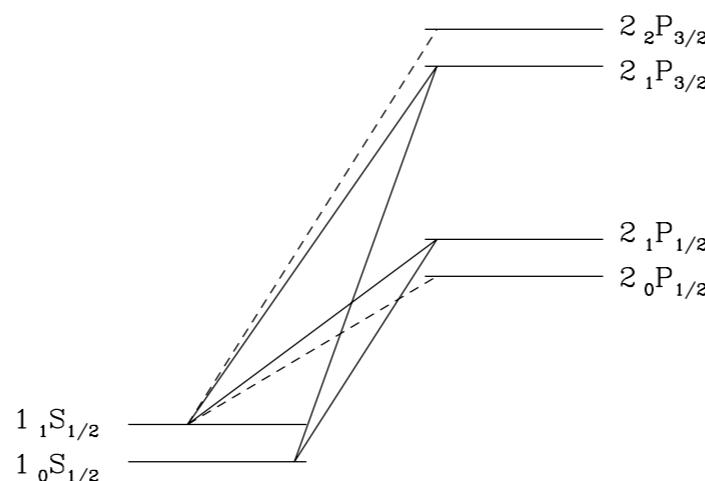
Température de spin T_S

$$\begin{aligned} \frac{n_+}{n_-} &= \frac{g_+}{g_-} \exp\left(-\frac{E_{21}}{kT_S}\right) \\ &= 3 \exp\left(-\frac{T_*}{T_S}\right) \\ T_* &\simeq 0.068 K \end{aligned}$$

Pas de signal à 21 cm si $T_S = T_\gamma$

Mécanisme de couplage $T_K T_S$ (température cinétique, température de spin)

- Collisions entre atomes d'hydrogène - diminue lorsque la densité baisse
- Effet Wouthuysen-Field : population deux deux états de spin à travers des transitions Lyman, dans un bain de photons UV
- Le gaz (hydrogène atomique) est plus froid que le gaz de photons (CMB), sauf lorsqu'il est réchauffé par le rayonnement X émis des étoiles très massives / quasars
- ...

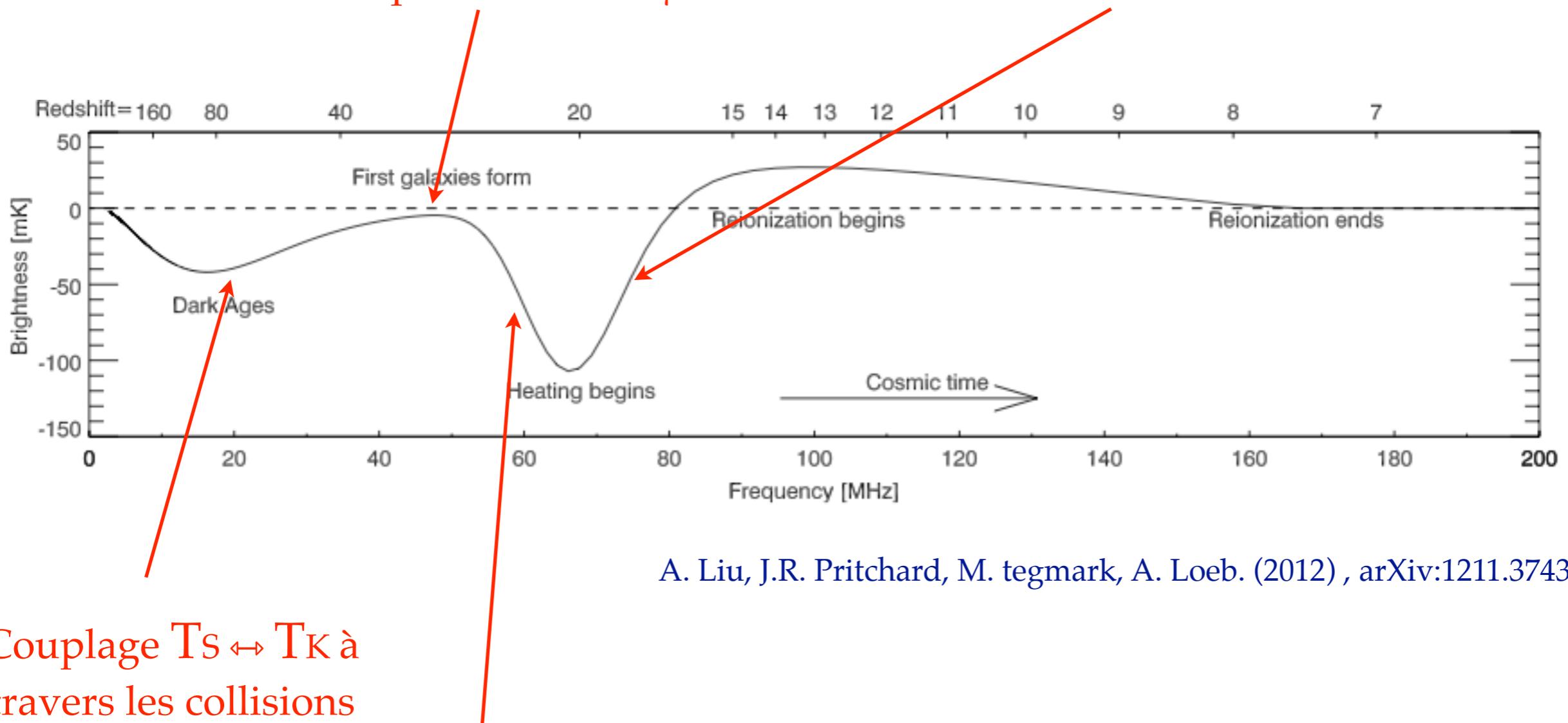


S. Furlanetto, S. Peng Ho, F. Briggs, Phys.Rept. 433 (2006)

J. Pritchard, S. Furlanetto, MNRAS (2006)

Baisse de densité: T_s
s'équilibre avec T_γ

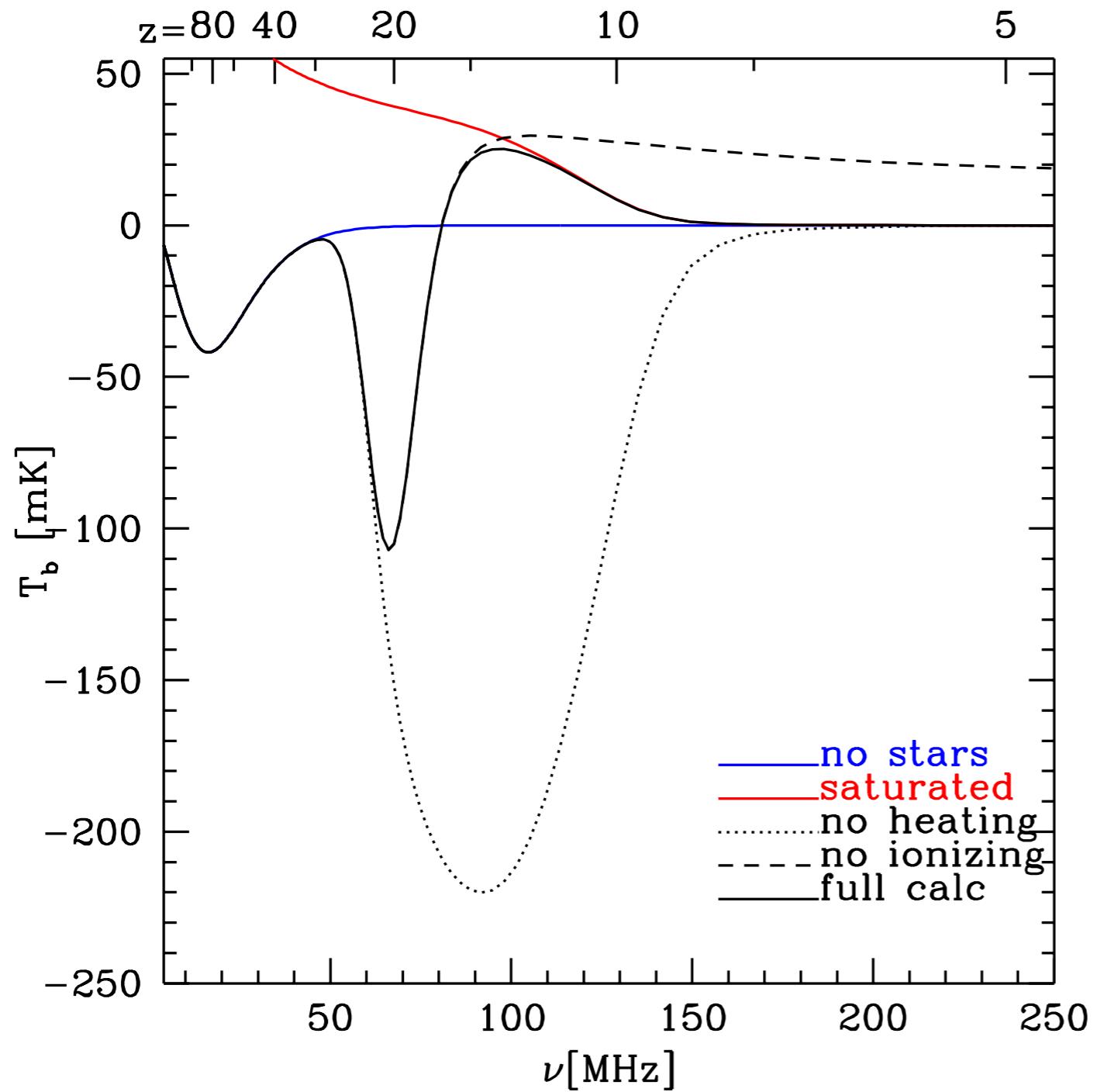
Chauffage du gaz (photons X) -
augmentation de T_K donc de T_s



A. Liu, J.R. Pritchard, M. tegmark, A. Loeb. (2012) , arXiv:1211.3743

Couplage $T_s \leftrightarrow T_K$ à
travers les collisions

Couplage $T_s \leftrightarrow T_K$ à
travers l'effet
Wouthuysen-Field,
dans le bain des
photons UV des
premières étoiles



Évolution de la température de brillance du
gaz HI avec le redshift

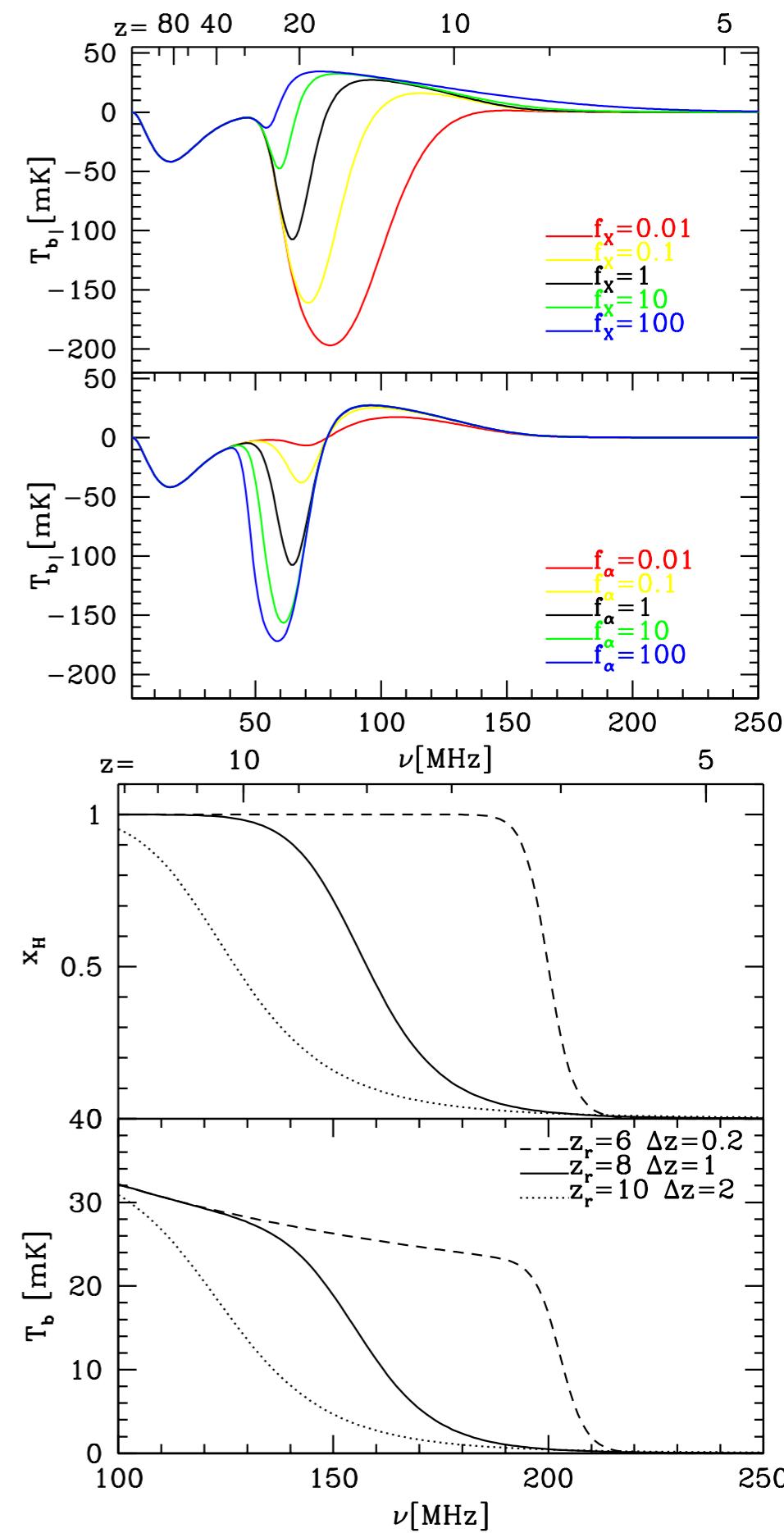
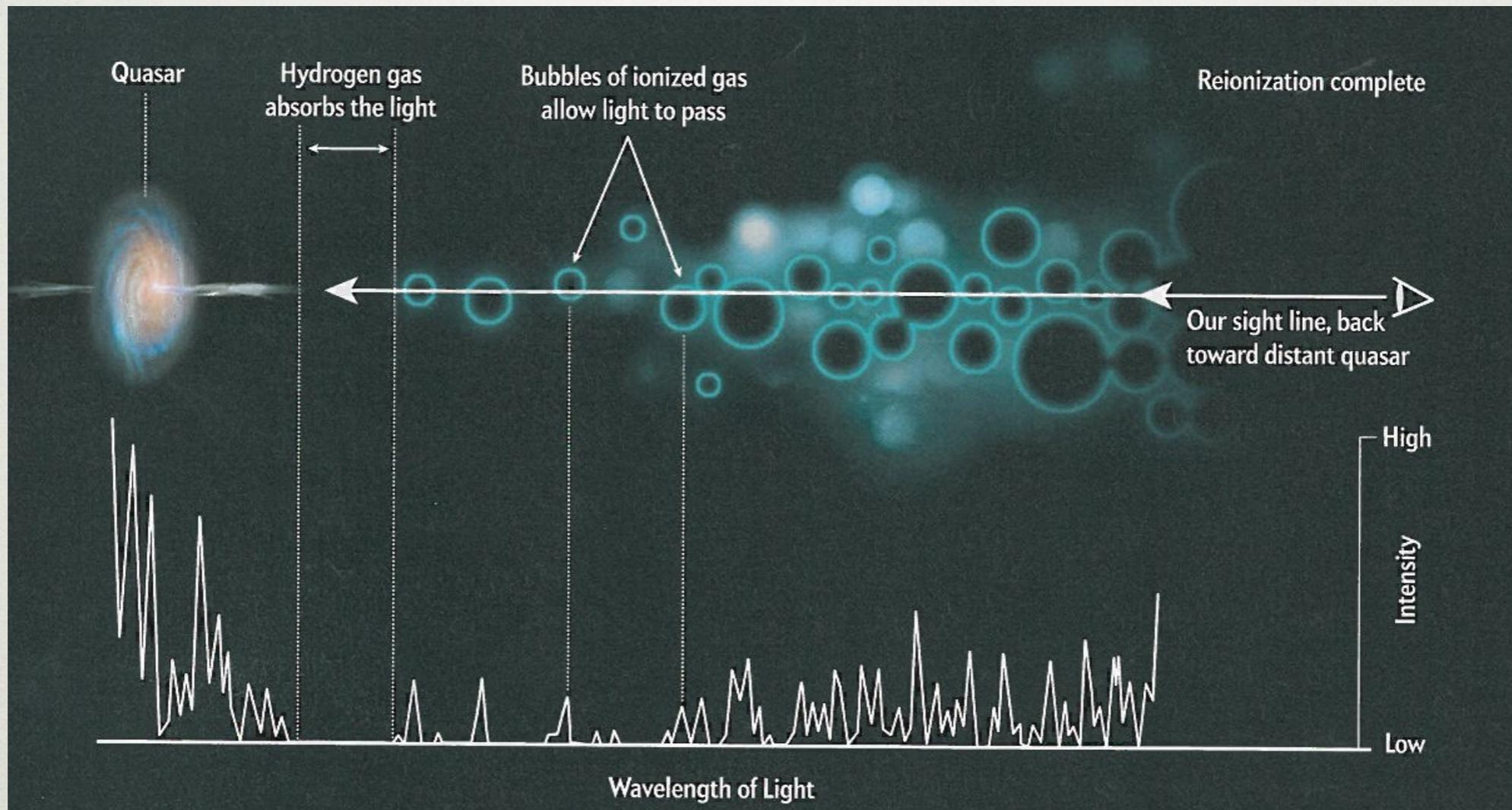


FIG. 6: Evolution of the neutral fraction x_H and brightness temperature T_b for a *tanh* model of reionization (see Eq.8)

- L'étude de l'évolution des grandes structures dans l'univers est un outil fondamental en Cosmologie
- Utilisation de différents traceurs (galaxies, amas, quasars ...) pour cartographier ces structures
- L'utilisation de l'imagerie (cartes (α,δ)) et de la spectroscopie (z-redshift) en optique
- La raie à 21 cm en radio permet des observations / une cartographie en 3D ($\alpha,\delta,v \mapsto z$)
- Sondage directe de l'époque de réionisation et la formation des premières étoiles / galaxies
- Cartographie (3D) des grandes structures “avant la formation de galaxies” $10 \leq z \leq 30$
- Étude des grandes structures / de l'Énergie Noire (BAO's) avec 21cm-Intensity-mapping pour $z \leq 3$ (HI dans les galaxies)
- Etudes des grandes structures à 21cm, par une méthode analogue aux forêts Ly- α

Illustration : Scientific American, April 2014

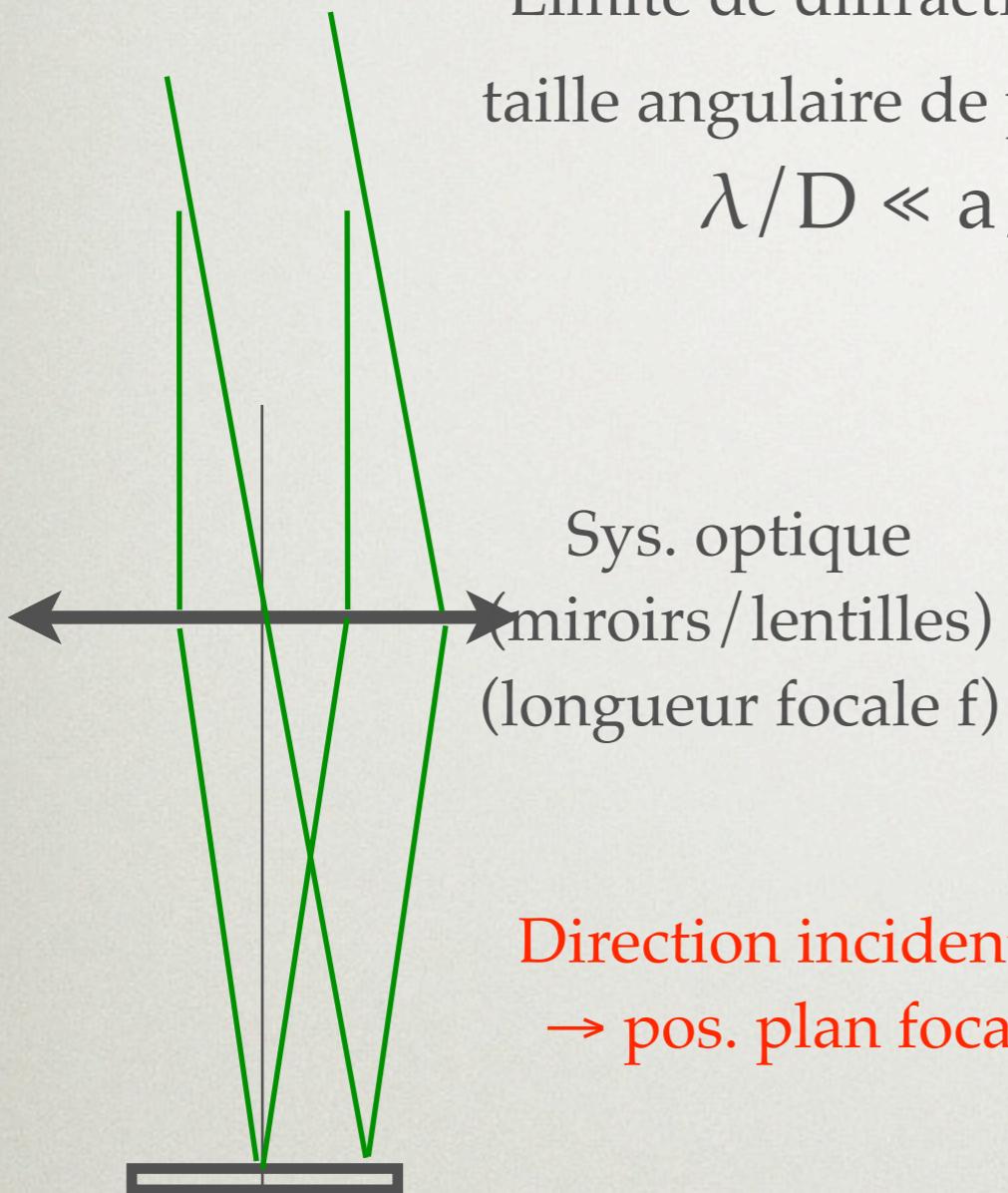


Forêt Ly- α

OBSERVATIONS EN RADIO

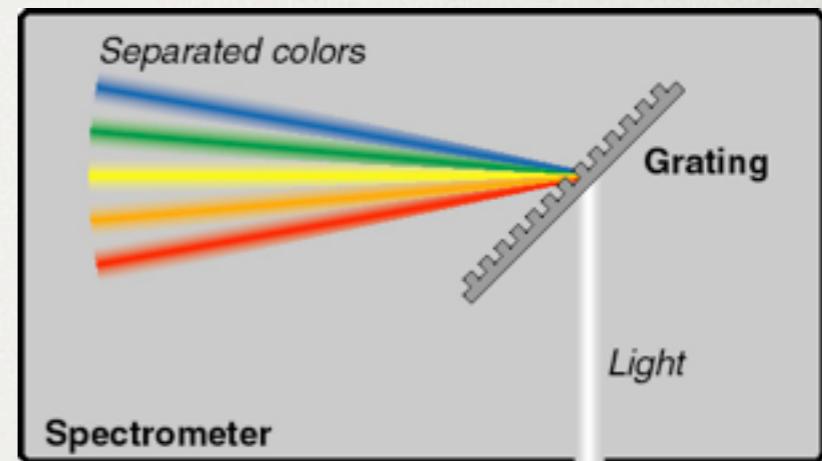
- En optique / IR / UV : Un système optique constitué de miroirs et lentille - un détecteur multi-pixels (CCD, ...) - interaction photon-électron
- On mesure une charge (/courant) proportionnelle au nombre de photons (/flux) de photons incidents - La phase/fréquence de l'onde n'est pas mesurée
- La limite de diffraction (λ/D) est en général bien inférieur à la résolution des détecteurs - sauf dans l'infra-rouge lointain
- Grâce à l'intégration en temps, le bruit du détecteur, de l'électronique est négligeable devant les fluctuations de Poisson du nombre de photons
- La lumière parasite provenant de l'environnement est souvent négligeable dans les bons observatoires - le fond de ciel (atmosphère terrestre) peut néanmoins constituer une limite pour la détection des objets faibles / lointains
- Les mesures spectrales (fréquence) s'effectuent en utilisant des prismes et des réseaux

Télescope / instrument optique



Limite de diffraction λ/D
taille angulaire de pixel a/f
 $\lambda/D \ll a/f$

Détecteur multi-pixels
(CCD ...) - (taille des pixels a)
Mesure de $I \propto E^2$



Spectroscopie / réseaux

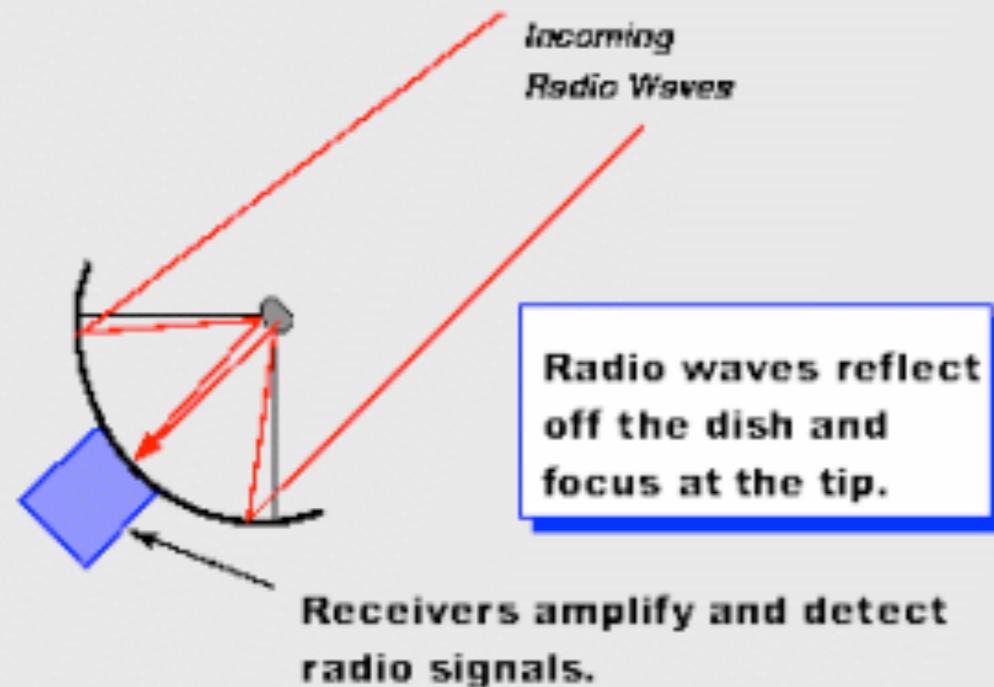
$\lambda = 1 \mu\text{m}$
 $a=20 \mu\text{m}, f= 5 \text{ m} \rightarrow a/f = 0.8''$
Champ de vue $\sim 10' \dots \text{deg}$

D	S	λ/D
1 m	0.78 m^2	$0.2''$
8 m	50 m^2	$0.025''$

- En radio : réflecteur (surface métallique / grillagé) - récepteur (feed) constitué d'un guide d'onde (cornet), d'une antenne (élément conducteur)
- Courant induit proportionnel au champ électrique - mesure de la forme d'onde après amplification
- le niveau de bruit instrumental (électronique) peut être limité par l'utilisation de récepteur (ampli) cryogénique
- Le signal mesuré étant proportionnel au champ électrique, on a accès directement au spectre du signal (fréquence)
- On peut également combiner les signaux provenant de plusieurs antennes : interférométrie, synthèse de lobe
- Le bruit est dominé par les signaux électromagnétiques d'origine terrestre (humaine) : les bons sites se trouvent dans les coins reculés du globe

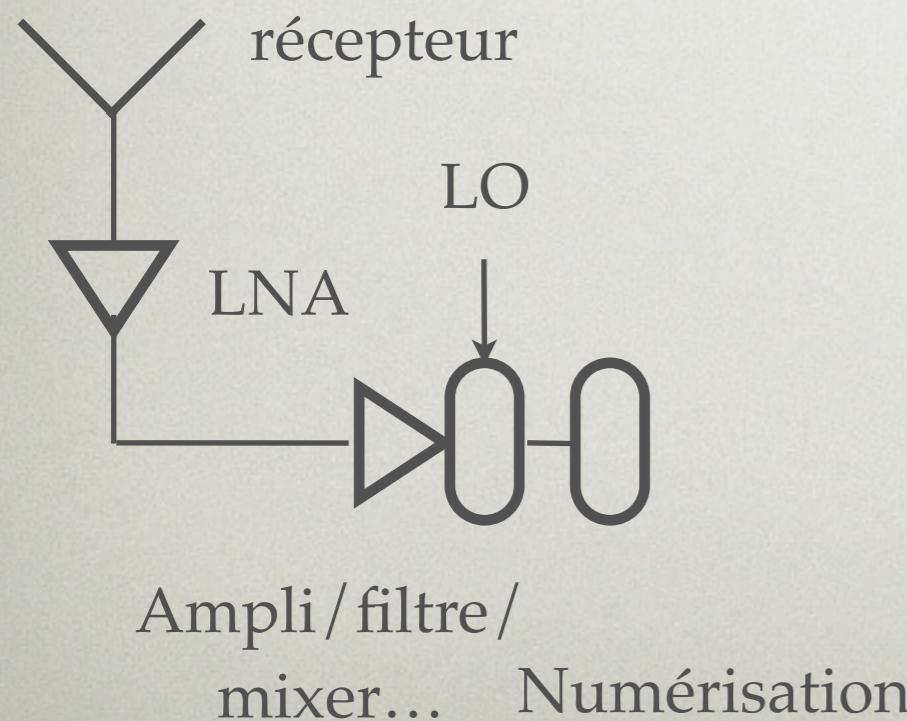
Télescope / instrument radio

Radio Telescope



$$\lambda = 21 \text{ cm} ; v = 1420 \text{ MHz}$$

D	S	λ/D
10 m	78.5 m ²	1.2 deg
50 m	2000 m ²	15'
300 m	70 000 m ²	2.5'



- Un réflecteur - un seul récepteur au foyer
- Un réflecteur - plusieurs récepteurs au foyer (max que dizaines)
- Un réflecteur et un réseau phasé au foyer
- Plusieurs antennes réparties - interférométrie
- Réseau dense d'antennes : synthèse de lobes

- Température de brillance

$$B(T, \nu) = \frac{2kT \nu^2}{c^2} \quad \text{W/srad/m}^2/\text{Hz}$$

- Température système Tsys

$$\begin{aligned} T_{sys}^2 &= T_{elec}^2 + T_{env}^2 \\ \sigma_T &= (1, \sqrt{2}) \frac{T_{sys}}{\sqrt{t_{int}} \sqrt{\Delta\nu}} \quad (1 - \text{pol}, 2 - \text{pol}) \end{aligned}$$

- Tsys dominé en général par les émissions parasite - Tsys \sim 30-100 K @ 1 GHz

Radio télescope de Nançay

<http://www.obs-nancay.fr/>

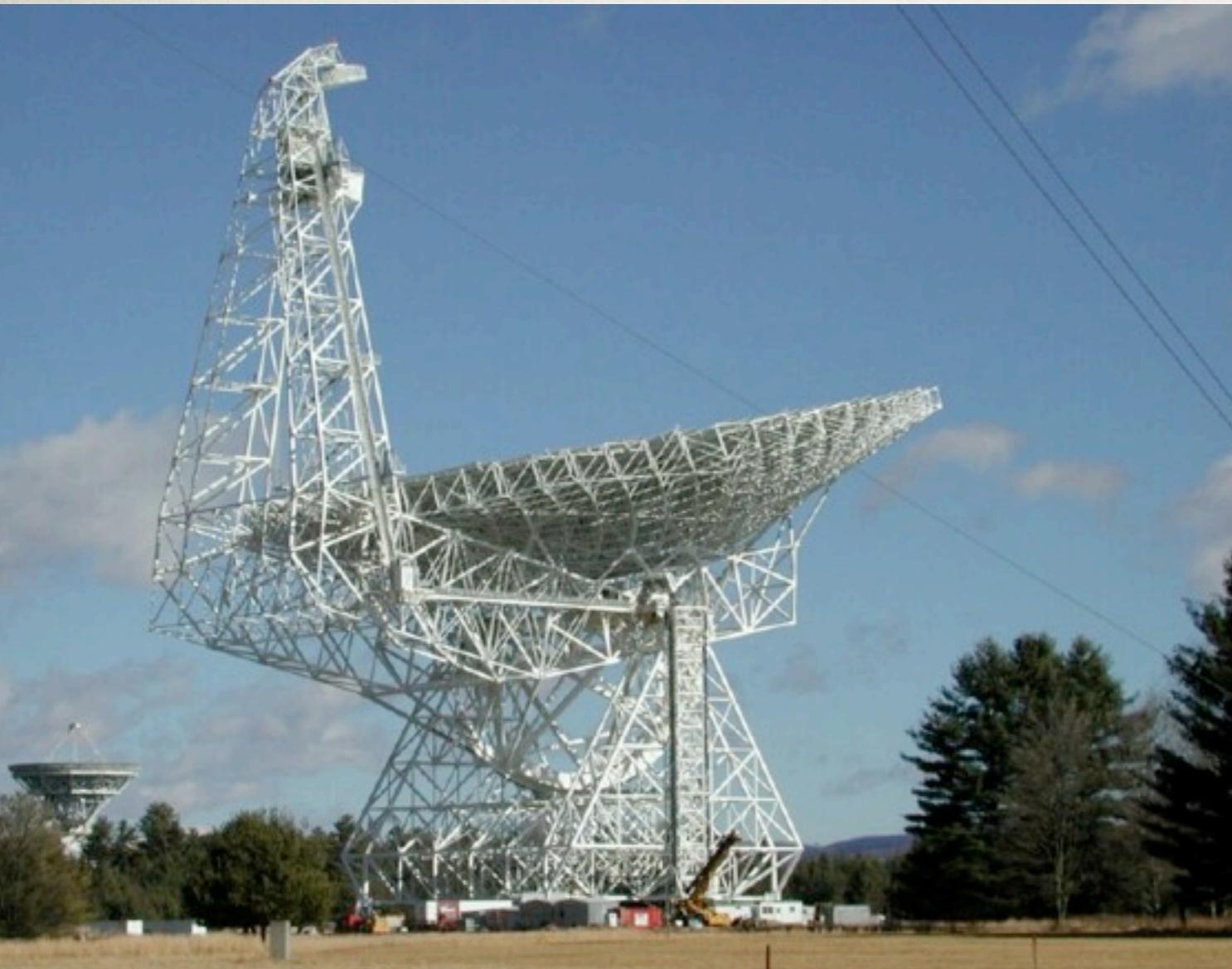
- Miroir plan (200mx40m) + miroir sphérique (300mx35m) (~ 7000 m 2 de surface effective) + Chariot mobile au niveau du plan focal - Situé à Nançay , France
- Trois bandes : 1400 MHz, 1660 MHz et 3330 MHz



GBT: Green Bank Telescope

- 1 réflecteur orientable de 100x110 m
- De 290 MHz à 49 GHz (en bande L : 1.15-1.73 GHz)

<http://www.gb.nrao.edu/GBT/GBT.shtml>



Effelsberg

- Un réflecteur orientable de 100 de diamètre en Allemagne
- De 400 MHz à 96 GHz (1.3-1.7 GHz en bande L)



http://www.mpifr-bonn.mpg.de/div/effelsberg/index_e.html

LES GALAXIES À 21 CM

- ▶ Transition hyperfine de l'hydrogène atomique :
 $\nu \approx 1,420405 \text{ GHz} \rightarrow \lambda \approx 21 \text{ cm}$
- ▶ Gaz: $\sim 0.1 \dots 0.5 \times$ masse dynamique,
 - Masse H_I $\sim 0.3 \dots 0.7 \times$ (masse du gaz)
- ▶ Puissance émise à 21 cm $\approx 3 \cdot 10^{18} \text{ W} \times M_{\text{HI}} / M_{\text{sol}}$
(pour $\Delta\nu \sim 10^6 \text{ Hz}$)
 - luminosité solaire $L_{\text{sol}} \approx 3.8 \cdot 10^{26} \text{ W}$
- ▶ Densité de galaxies $\approx 0.05 \text{ Gal} / \text{Mpc}^3$ avec $M_{\text{HI}} > 10^9 M_{\text{sol}} \approx 0.01 \text{ Gal} / \text{Mpc}^3$ avec $M_{\text{HI}} > 10^{10} M_{\text{sol}}$

UNE GALAXIE À $z \sim 0.3$, DL ~ 1500 Mpc

- ▶ Radio, 21 cm emission
 - 10^9 Msol de HI $\rightarrow 3 \cdot 10^{27}$ watts (puissance émise)
 - $< 10^{-24} \text{ W/m}^2 / \Delta v \sim 1 \text{ MHz}$ (qque photons / m^2 / s)
 - $\rightarrow < 10^{-30} \text{ W/m}^2/\text{Hz} , < 10^{-4} \text{ Jy}$ ($100 \mu \text{Jy}$)
- ▶ Optique
 - $10^9 - 10^{10}$ Lsol $\rightarrow \sim 10^{35}$ watts (puiss. émise)
 - $< 10^{-16} \text{ W/m}^2 , \sim 10^{-17} \text{ W/m}^2$ dans une bande photométrique (~ 10 photons / m^2 / s)

HI extragalactique

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

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

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

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

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

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

> 100 000 $\text{m}^2 \rightarrow \text{SKA} !$

Résolution 3-20 arcmin

Sensibilité ~ mJy

Table B.1 Comparison of major blind HI surveys

Survey	Area (deg ²)	Beam (arcmin)	V _{max} (km/s)	V _{res} ^a (km/s)	t _s (s)	rms ^b (mJy)	N _{det}	min M _{HI} ^c (M _{sun})	Ref
AHISS	65	3.3	-700 - 7400	16	var	0.7	65	1.9x10 ⁶	1
ADBS	430	3.3	-650 - 7980	34	12	3.6	265	9.9x10 ⁶	2
WSRT	1800	49.	-1000 - 6500	17	60	18	155	4.9x10 ⁷	3
Nancay CVn	800	4 x 20	-350 - 2350	10	80	7.5	33	2.0x10 ⁷	4
HIJASS	1115	12.	-1000 - 10000 ^d	18	400	13	222	3.6x10 ⁷	5
HIJASS-VIR	32	12.	500 - 2500	18	3500	4.	31	1.1x10 ⁷	6
HIDEEP	60	15.5	-1280 - 12700	18	9000	3.2	173	8.8x10 ⁶	7
HIZSS	1840	15.5	-1280 - 12700	27	200	15.	110	4.1x10 ⁷	8
HICAT	21341	15.5	300 - 12700	18	450	13.	4315	3.6x10 ⁷	9
HIPASS		15.5	300 - 12700	18	450	13.	(6000)	3.6x10 ⁷	10
AUDS	0.4	3.5	-960 - 47000 ^e	TBD	70 × 3600	0.02	(40)	0.6x10 ⁶	11
AGES	TBD	3.5	-960 - 47000 ^e	TBD	300	0.5	TBD	1.4x10 ⁶	12
ALFALFA	7000	3.5	-2000 - 18000	11	28	1.6	(16000)	4.4x10 ⁶	

z_{max} ~ 0.03 ... 0.15

δz ~ 0.0001

Comparison of few 21 cm surveys

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

Arecibo

- Réflecteur parabolique (sphérique) fixe de $\varnothing=305$ m. $S \sim 73000\text{ m}^2$
- Couverture spectrale : 50 MHz ... 10 GHz

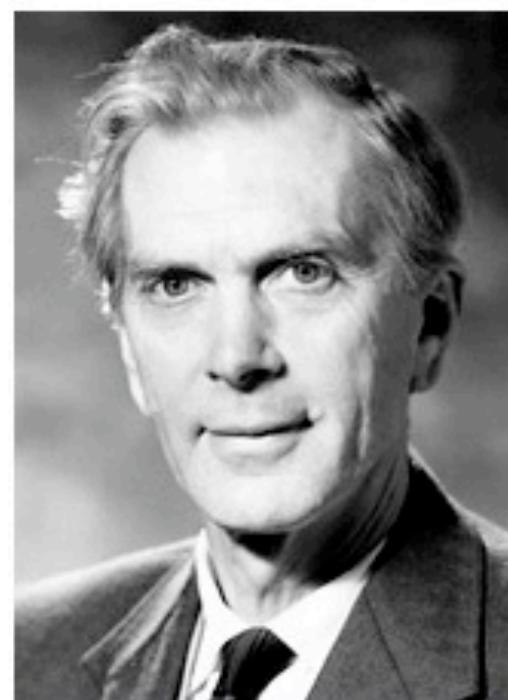


INTERFÉROMÉTRIE



The Nobel Prize in Physics 1974

"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"



Sir Martin Ryle

1/2 of the prize



Antony Hewish

1/2 of the prize

[http://www.mrao.cam.ac.uk/
telescopes/ryle/](http://www.mrao.cam.ac.uk/telescopes/ryle/)

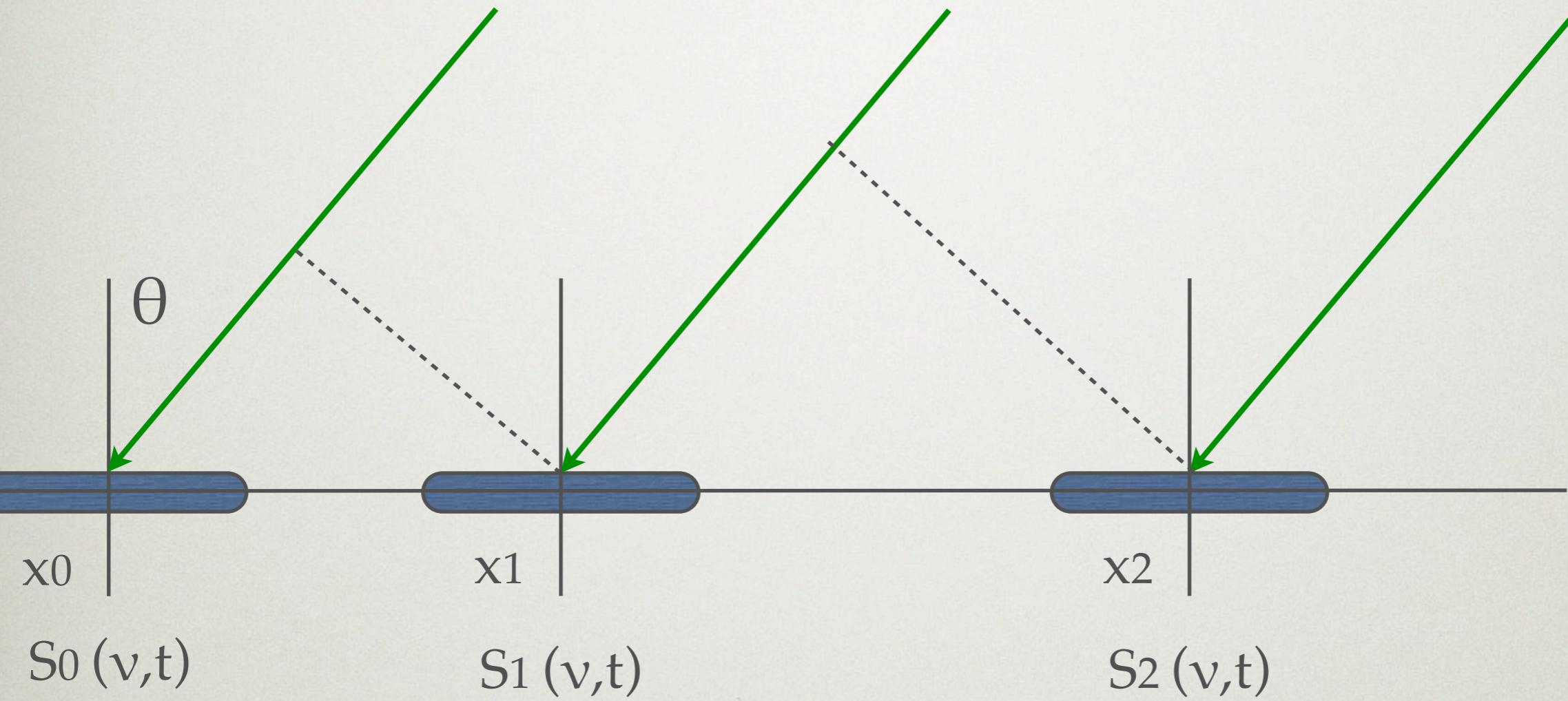
The Ryle Telescope

- Interféromètre radio avec 8 éléments (réflecteurs)
- fonctionnant à 15 GHz
- Grand Bretagne (UK)
- Utilisé principalement pour le CMB



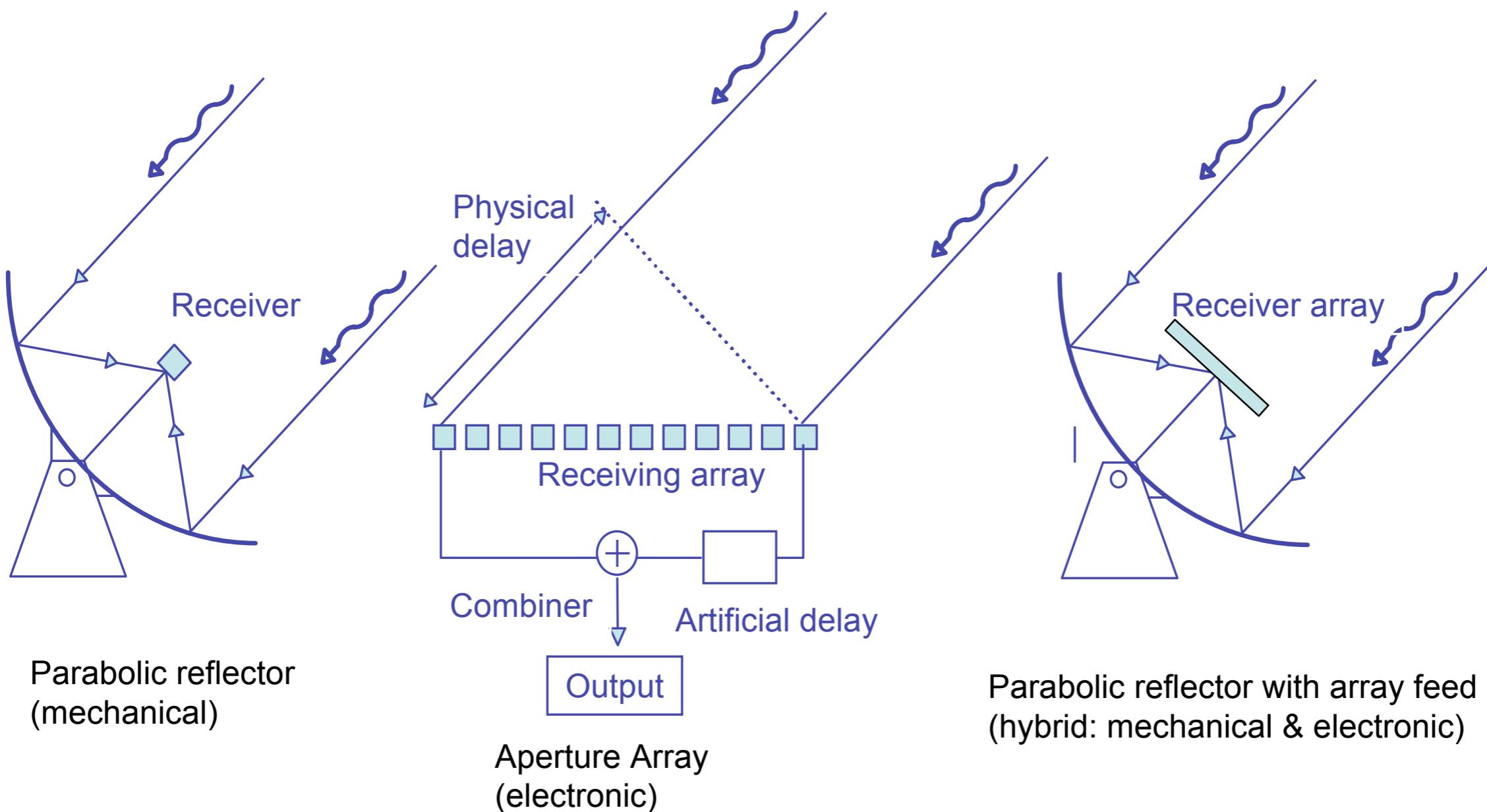
$$\Delta\varphi = \frac{\Delta\ell}{\lambda}$$

$$(\Delta\ell)_{i,j} = (x_j - x_i) \cos \theta$$

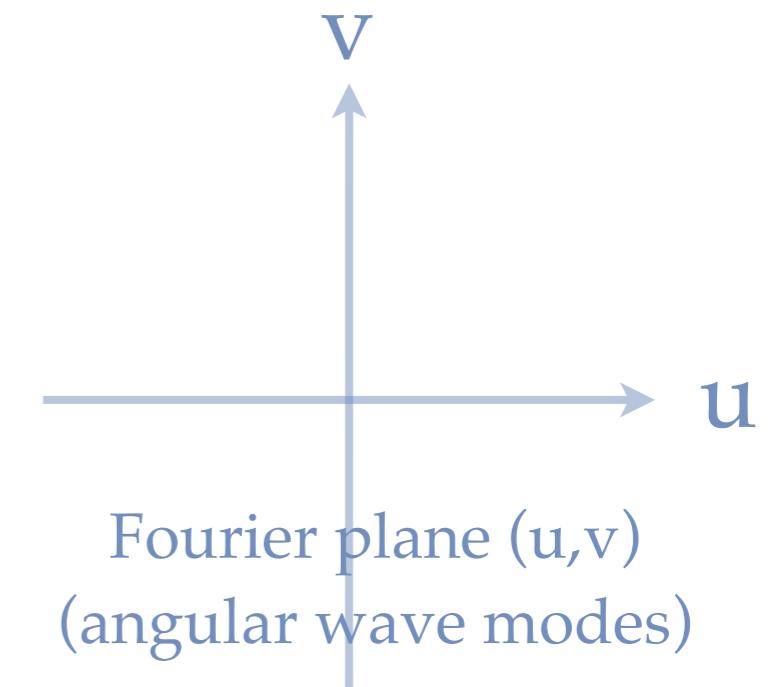
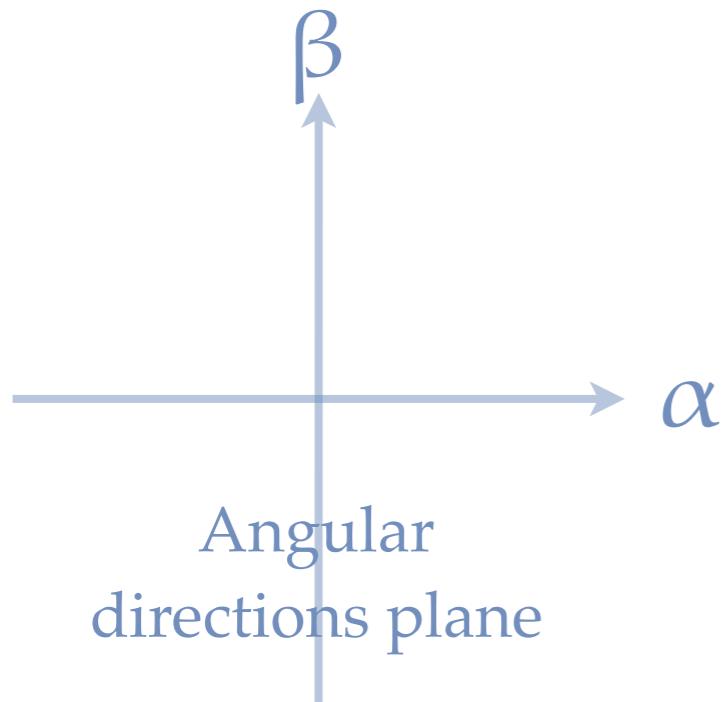


L'information sur la direction de propagation est encodée dans les déphasage des signaux entre les antennes.

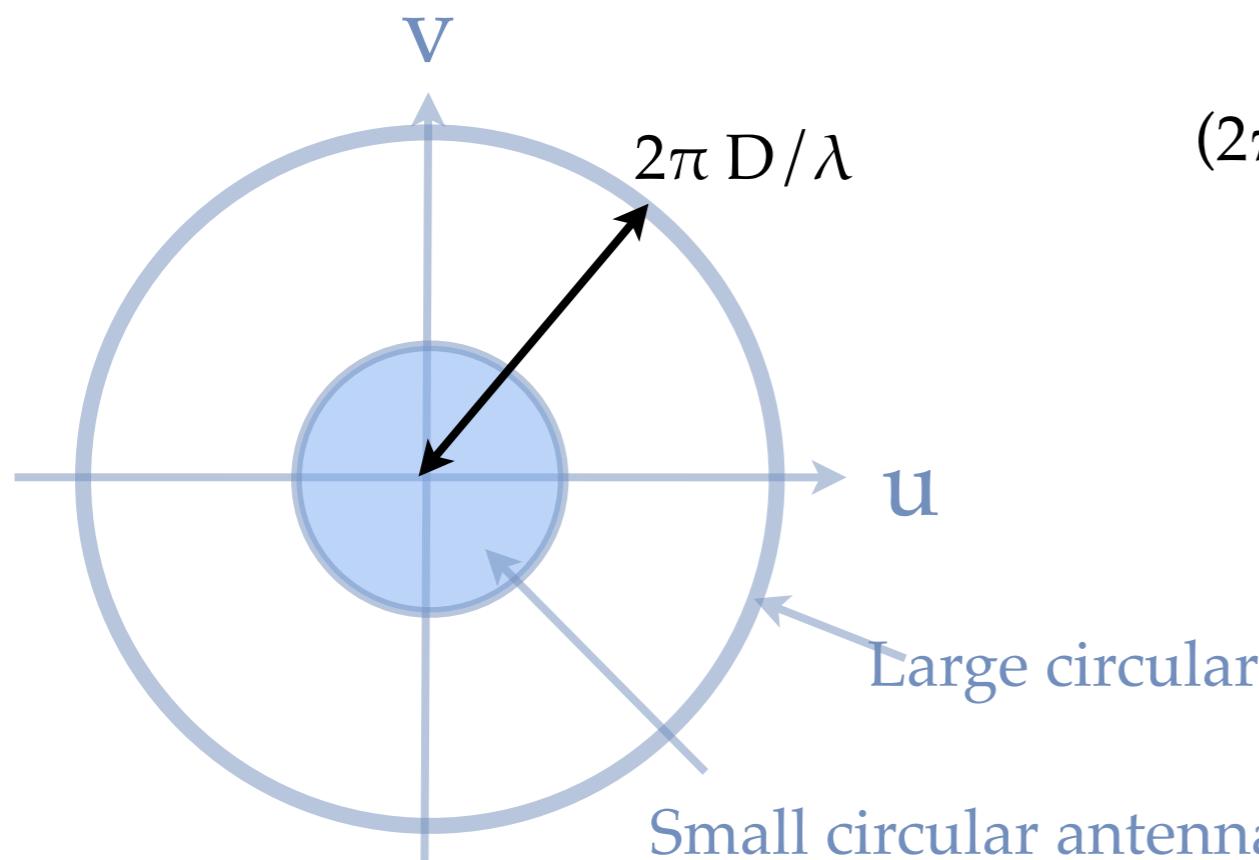
Aperture Arrays versus Reflectors



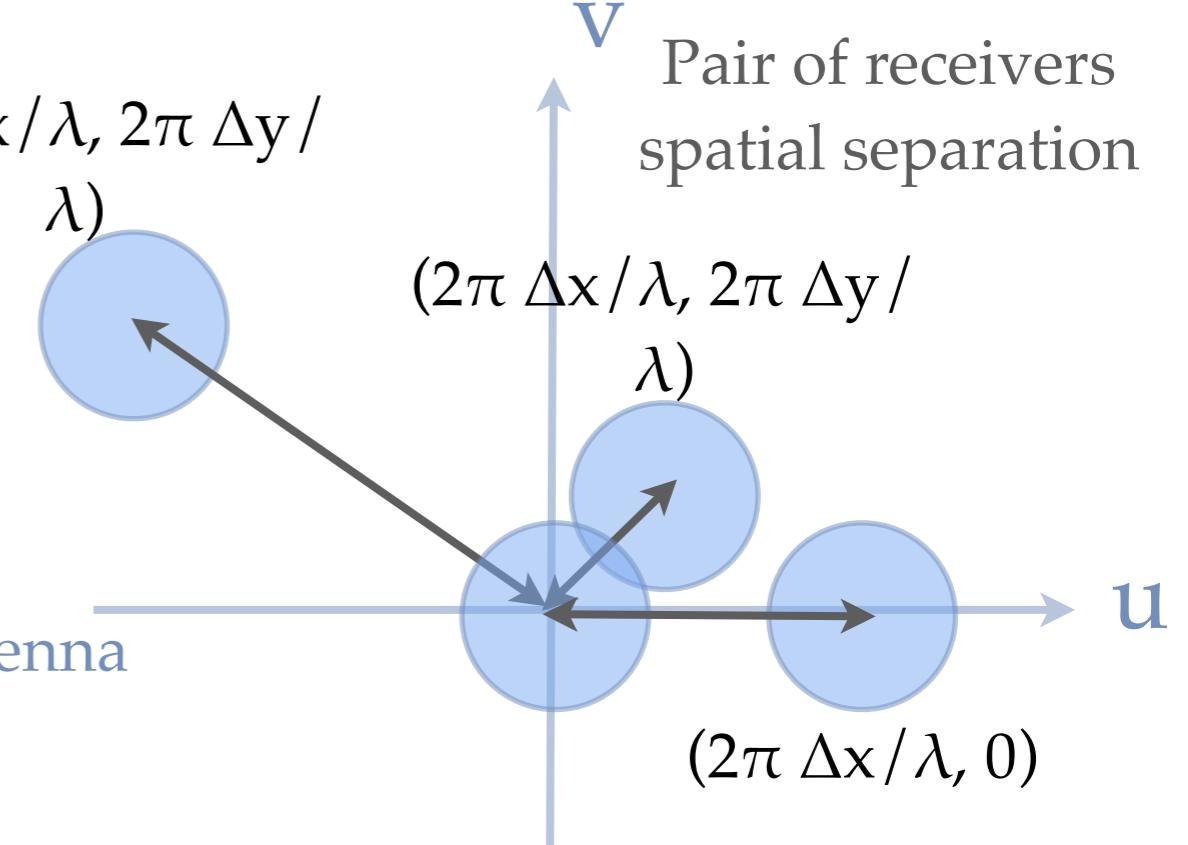
Slide borrowed from Ger de Bruyn (Astron/NL)



(u,v) plane response



$$(2\pi \Delta x / \lambda, 2\pi \Delta y / \lambda)$$

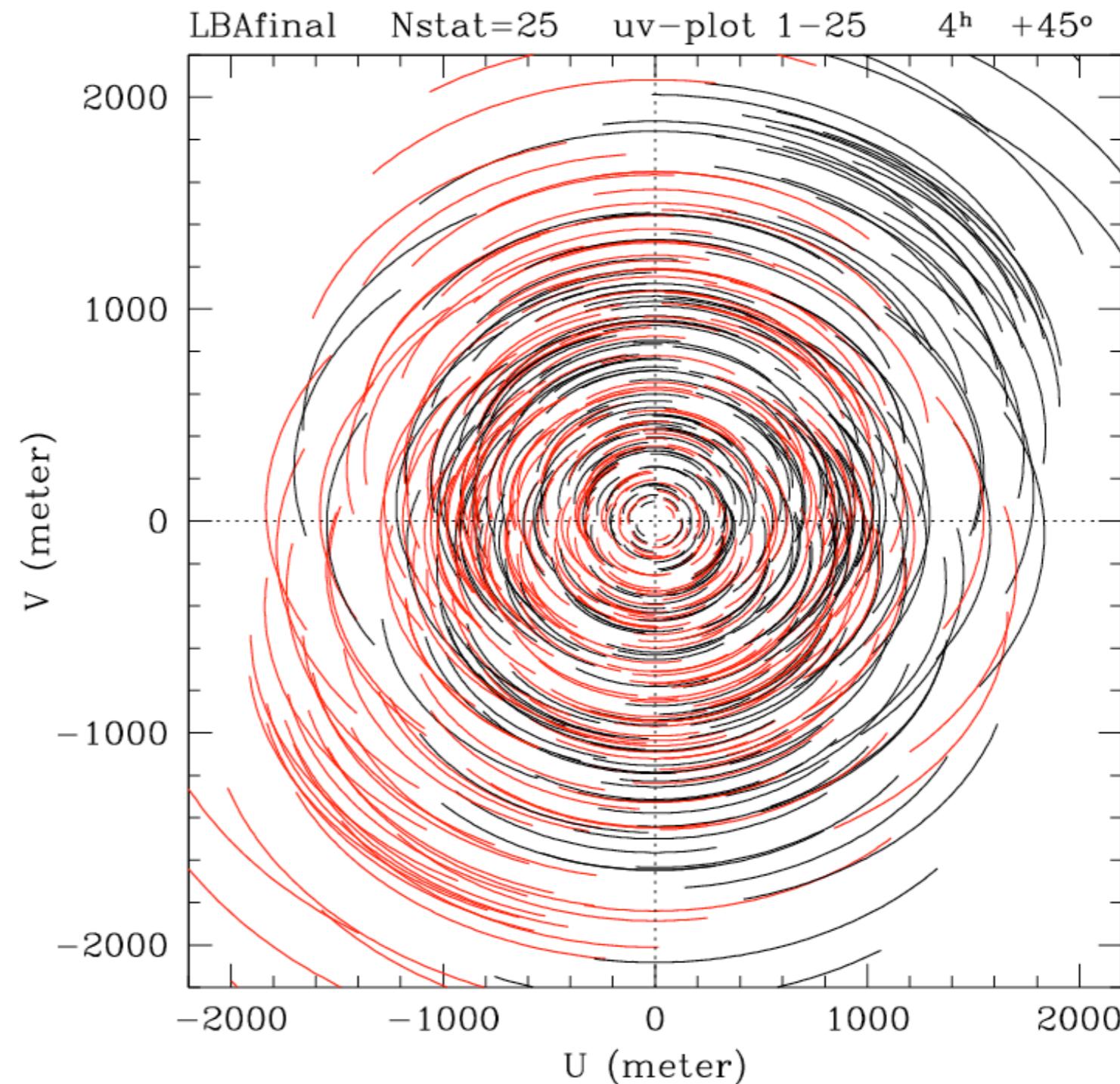


uv-coverage for LOFAR LBA (core only)

25 stations

4h synthesis

+45°



Slide borrowed from Ger de Bruyn (Astron/NL)

VLA:Very Large Array

<http://www.vla.nrao.edu/>

- 27 réflecteurs paraboliques de 25 mètres de diamètres ($\sim 13000 \text{ m}^2$)
- Interférométrie haute résolution ($\sim 0.05''$)
- de 70 MHz à 50 GHz, y compris en bande L (1.34-1.72 GHz)
- Relevé NVSS : @ 1.4 GHz du ciel complet pour $\delta > -40$

<http://www.vla.nrao.edu/nvss>

Receivers Available at the VLA

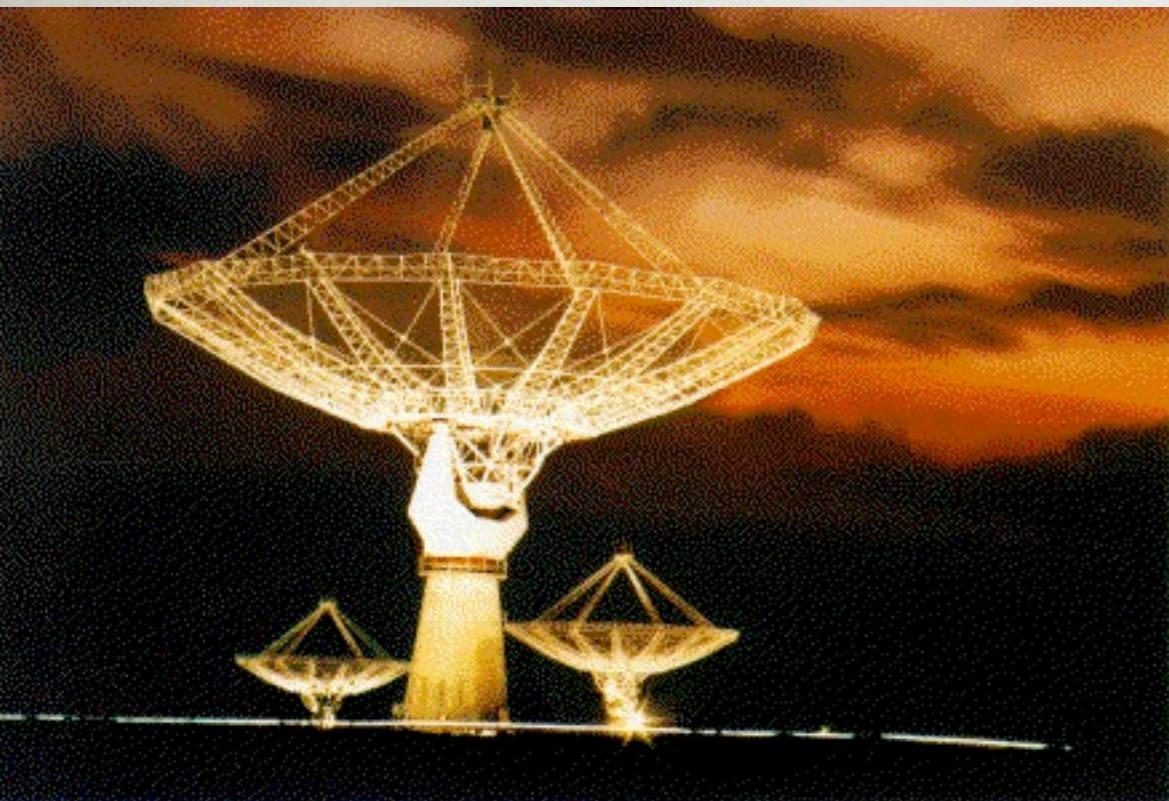
	4 Band	P Band	L Band	C Band	X Band	U Band	K Band	Q Band
Frequency (GHz)	0.073-0.0745	0.30-0.34	1.34-1.73	4.5-5.0	8.0-8.8	14.4-15.4	22-24	40-50
Wavelength (cm)	400	90	20	6	3.6	2	1.3	0.7
Primary beam (arcmin)	600	150	30	9	5.4	3	2	1
Highest resolution (arcsec)	24.0	6.0	1.4	0.4	0.24	0.14	0.08	0.05
System Temp	1000-10,000.K	150-180.K	37-75.K	44.K	34.K	110.K	50-190.K	90-140.K

R.Anvari - Jan 2008

GMRT : Giant Metrewave Radio Telescope

<http://www.gmrt.ncra.tifr.res.in/>

- 30 réflecteurs paraboliques de 45 mètres de diamètres, près de Pune, en Inde (~ 47000 m²)
- Interférométrie haute résolution avec distance max ~25 km
- Six bandes de fréquences: 50, 153, 233, 325, 610, 1420 MHz

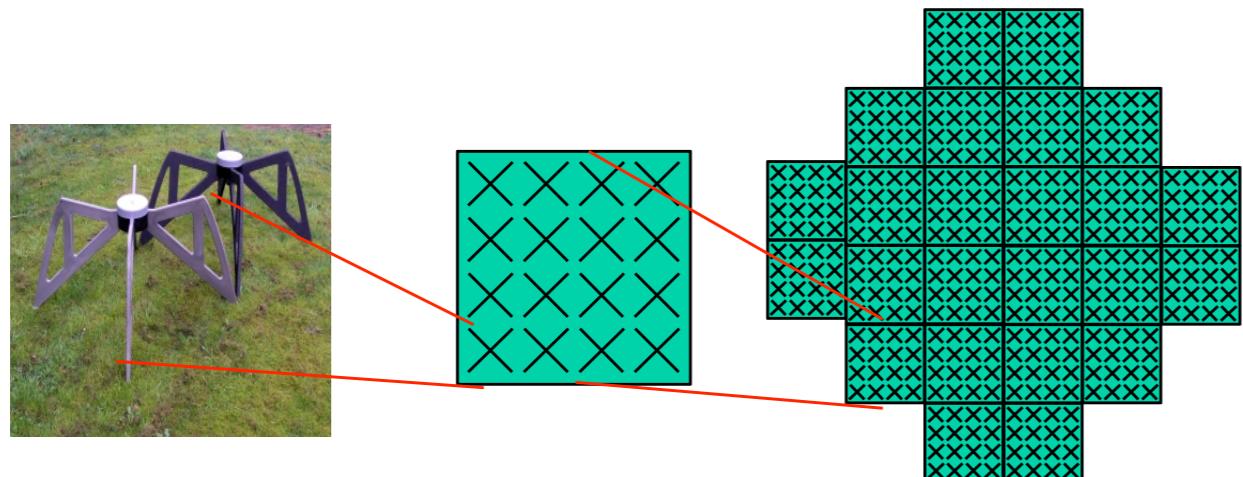


R. Ansari - Jan 2008

The LOFAR observatory

- **LBA** (10) 30 - 90 MHz
- isolated dipoles

HBA 115 - 240 MHz
tiles (4x4 dipoles)



Core	2 km	23+ stations
NL	80 km	18+ stations
Europe	>1000 km	8+ stations

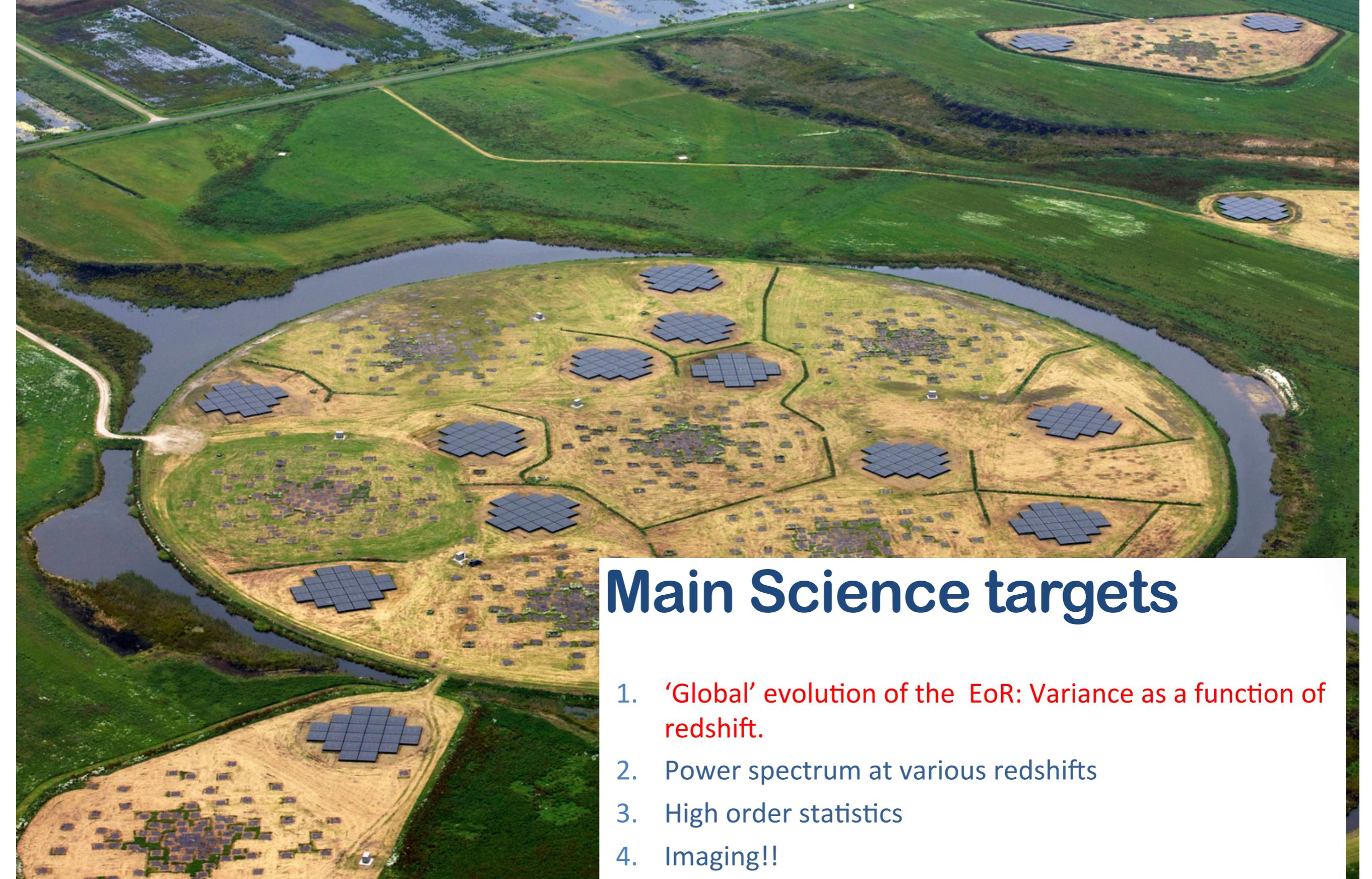
Total # of HBA dipoles: ~ 50000.

Timeline:

1. Official opening: June 2010
2. Data for our project starts: Dec. 2012
3. First results (hopefully) 2014



Slide borrowed from S. Zaroubi



Main Science targets

1. ‘Global’ evolution of the EoR: Variance as a function of redshift.
2. Power spectrum at various redshifts
3. High order statistics
4. Imaging!!
5. Cross-correlation with other probes
6. The 21 cm forest

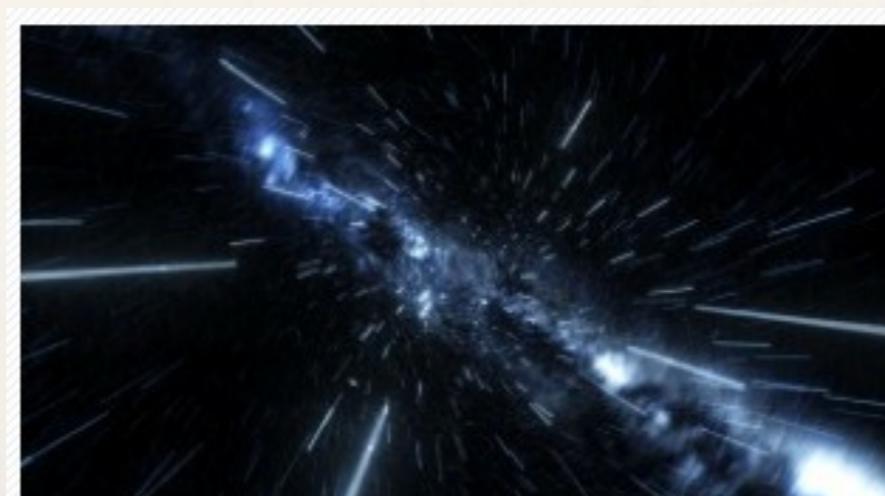
LOFAR



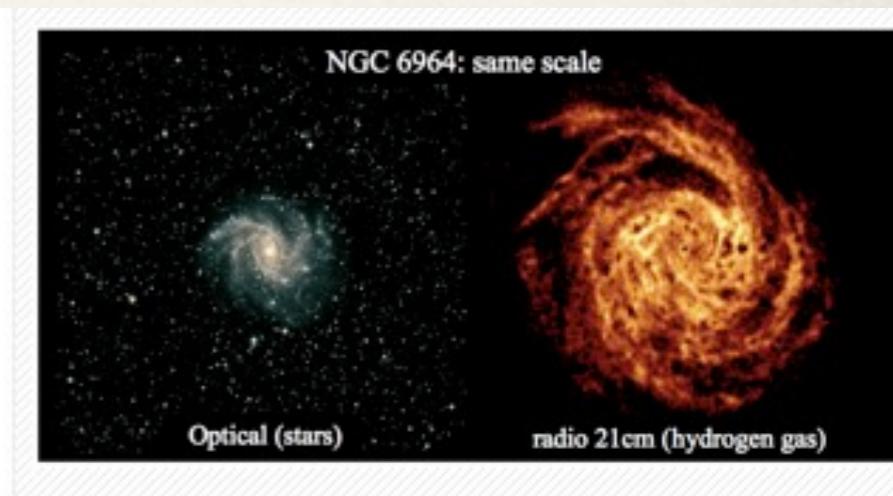
The Square Kilometre Array
Exploring the Universe with the world's largest radio telescope

Five Key Science projects

- ❖ Galaxy evolution, Cosmology and Dark Energy
- ❖ Strong-field tests of gravity using pulsars and black holes
- ❖ Origin and evolution of cosmic magnetism
- ❖ Probing the dark ages
- ❖ Cradle of life



What is mysterious dark energy?



How are galaxies born and how do they evolve?

Great Observatories for the coming decades



Slide by R. Braun
SKA Science director

Square Kilometre Array: radio
Construction start 2017/18

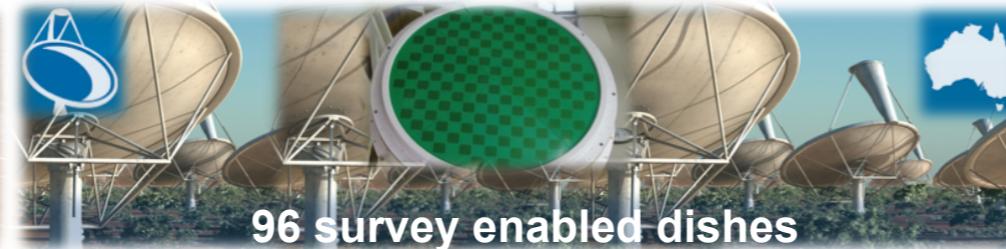
Exploring the Universe with the world's largest radio telescope



Phase I : 2020



250,000 element
Low Frequency Aperture Array



96 survey enabled dishes



254 dishes

Slide by R. Braun
SKA Science director

Phase II : 2024



>250,000 element
Low Frequency Aperture Array



Mid Frequency Aperture
Array

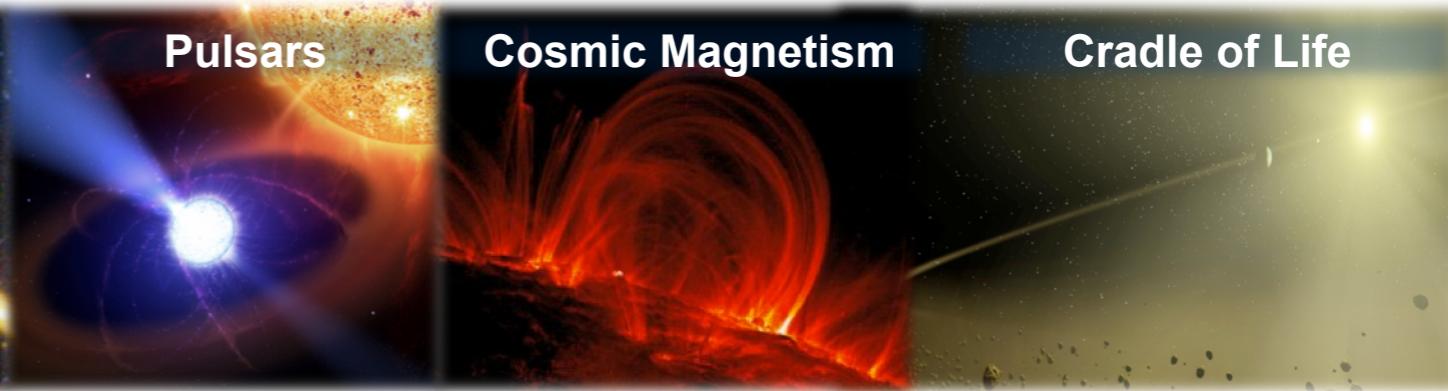


2500 dishes

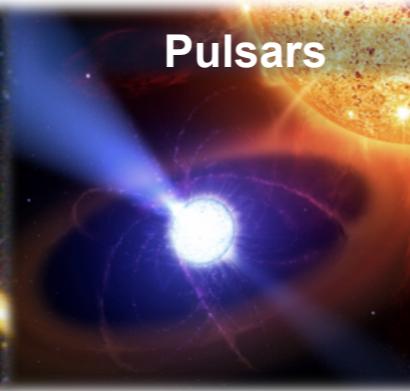
Science



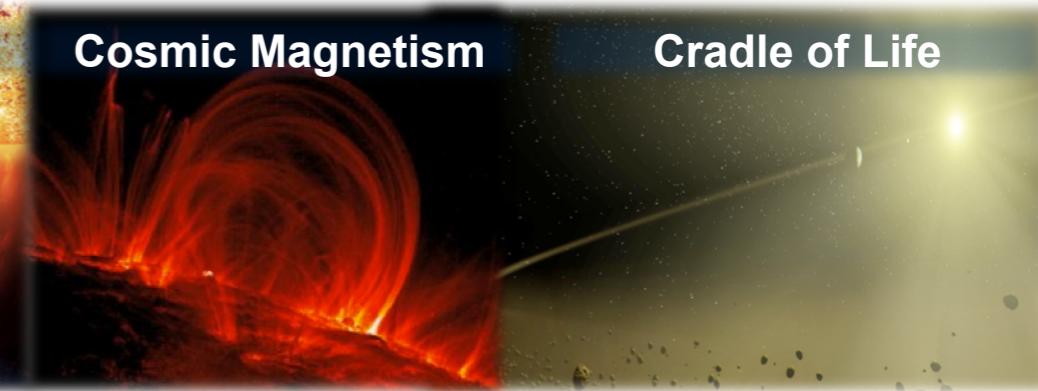
Cosmic Dawn & Reionization



Cosmology &
Galaxy Evolution



Pulsars



Cosmic Magnetism

Cradle of Life

50 MHz

100 MHz

1 GHz

10 GHz

How does SKA1 baseline redefine state-of-art?



		JVLA	MeerKAT	SKA1-mid	ASKAP	SKA1-survey	LOFAR-NL	SKA1-low
A_{eff}/T_{sys}	m ² /K	265	321	1630	65	391	61	1000
Survey FoV	deg ²	0.14	0.48	0.39	30	18	6	6
Survey Speed FoM	deg ² m ⁴ K ⁻²	0.98×10 ⁴	5.0×10 ⁴	1.0×10 ⁶	1.3×10 ⁵	2.8×10 ⁶	2.2×10 ⁴	6.0×10 ⁶
Resolution	arcsec	1.4	11	0.22	7	0.9	5	11

$A_{\text{eff}}/T_{\text{sys}}$:

Survey Speed: 6xJVLA
Slide by R. Braun 100x
SKA Science director

6xJVLA

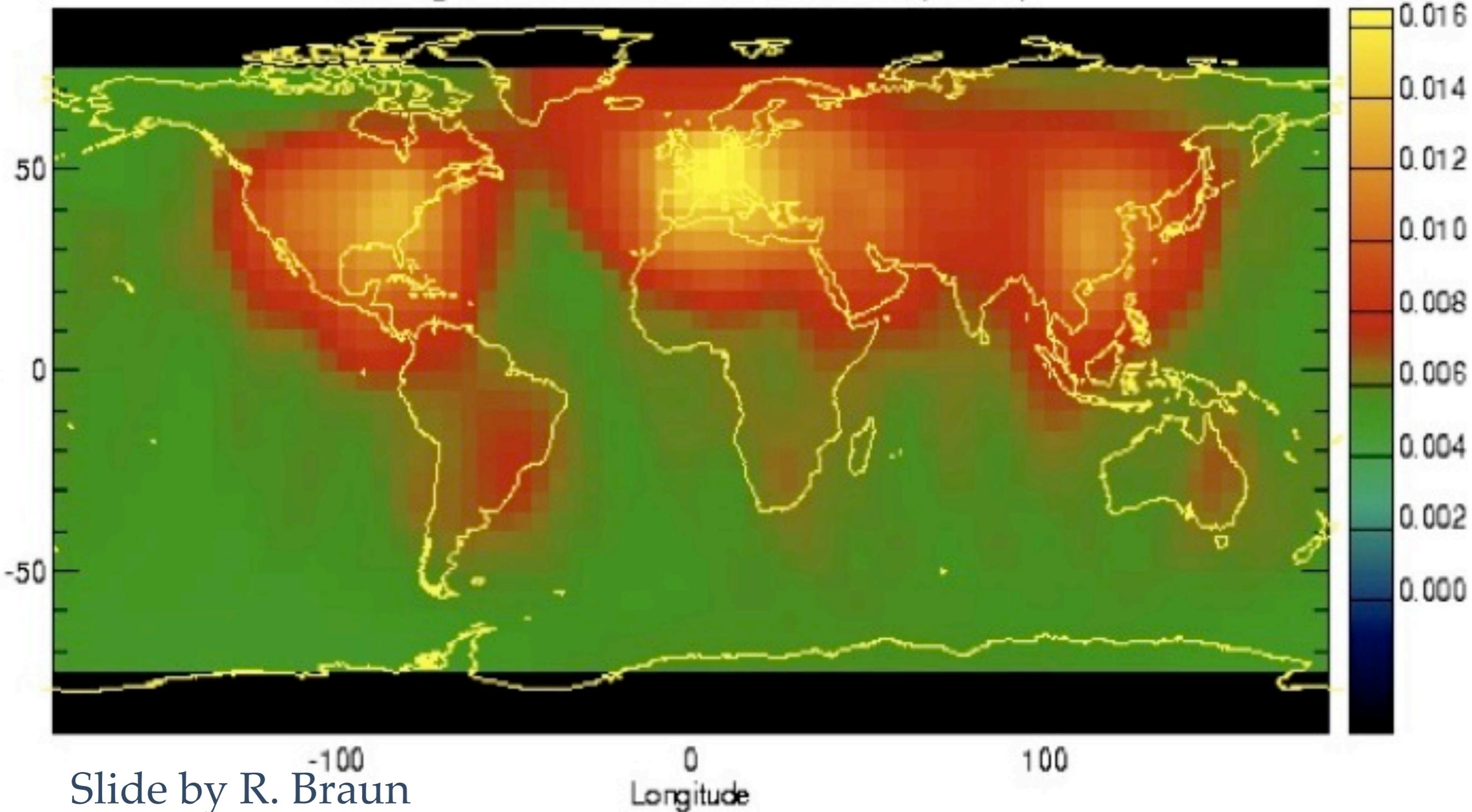
6xASKAP 16xLOFAR
22xASKAP 270x
280xJVLA

Exploring the Universe with the world's largest radio telescope

How did we choose the site?



Background Radiation at 131.0 MHz (mV/m)



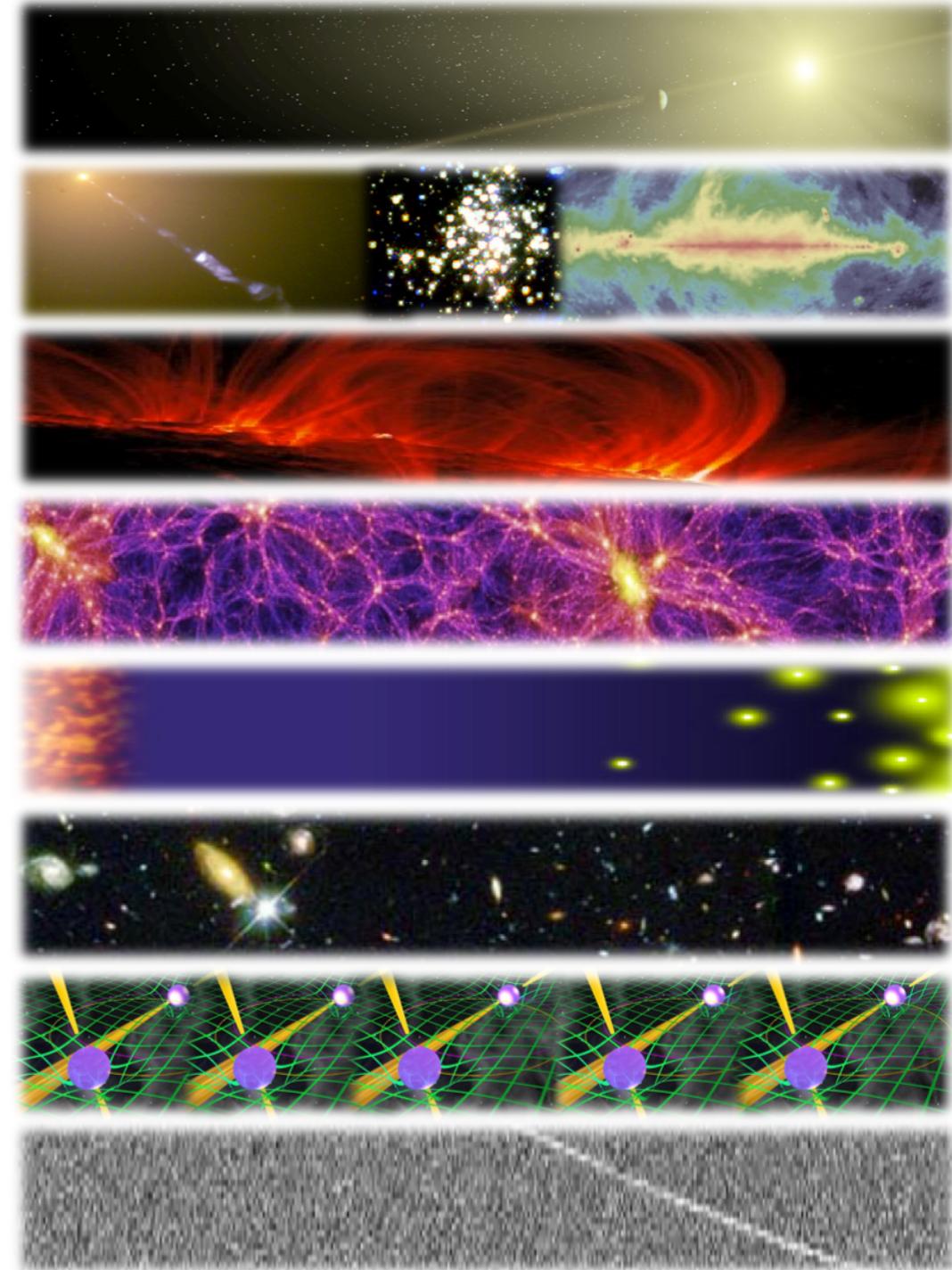
Slide by R. Braun
SKA Science director

Exploring the Universe with the world's largest radio telescope

The Science Working Groups

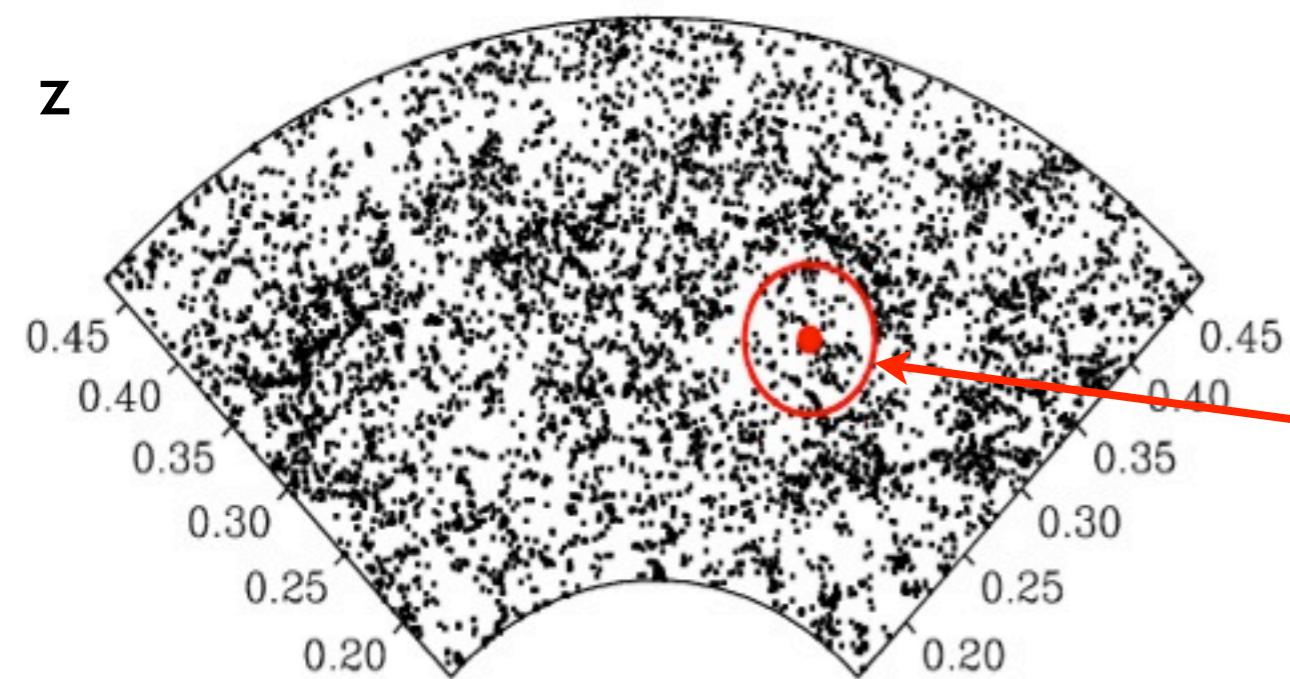
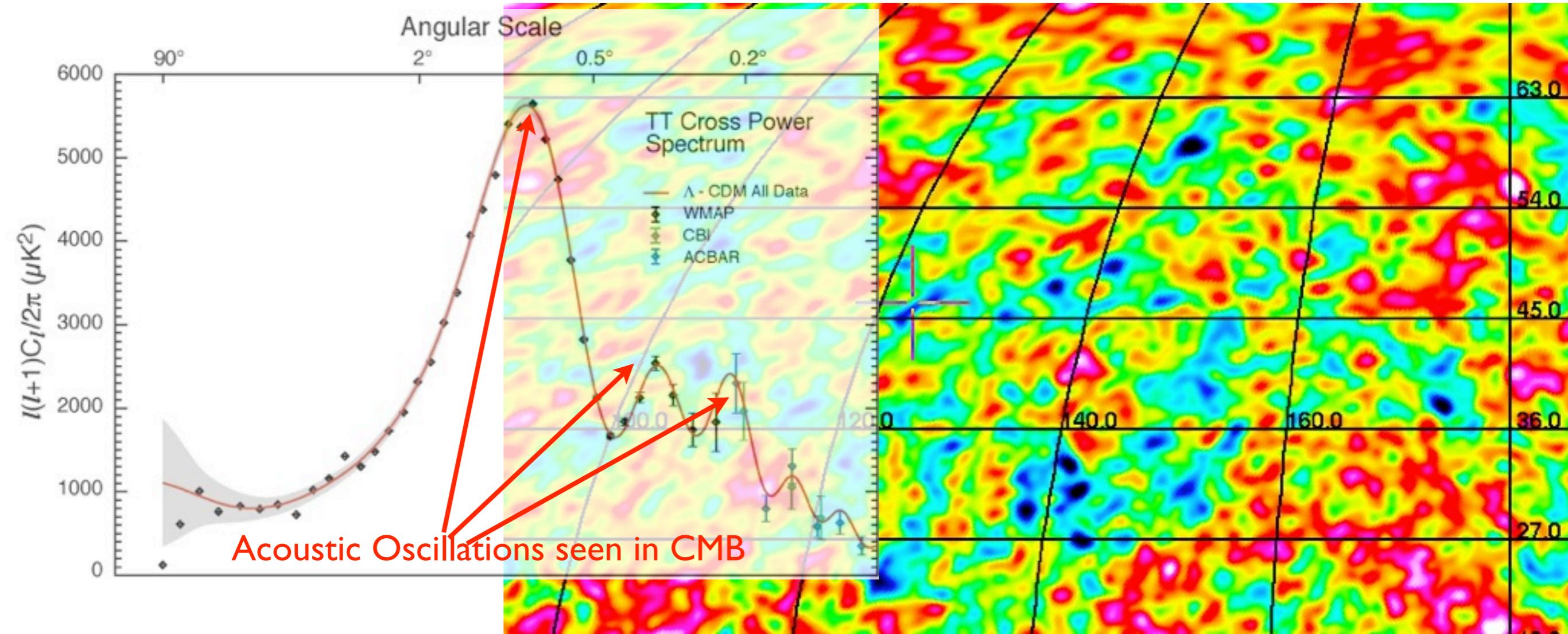


- **Astrobiology (“The Cradle of Life”)**
 - *Project Scientist:* Tyler Bourke
 - *Working Group Chair:* Melvin Hoare
- **Galaxy Evolution – Continuum**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chairs:* Nick Seymour & Isabella Prandoni
- **Cosmic Magnetism**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Melanie Johnston-Hollitt & Federica Govoni
- **Cosmology**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chair:* Roy Maartens
- **Epoch of Reionisation & the Cosmic Dawn**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chair:* Leon Koopmans
- **Galaxy Evolution – HI**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Lister Staveley-Smith & Tom Osterloo
- **Pulsars (“Strong field tests of gravity”)**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Ben Stappers & Michael Kramer
- **Transients**
 - *Project Scientist:* Tyler Bourke
 - *Working Group Chair:* Rob Fender

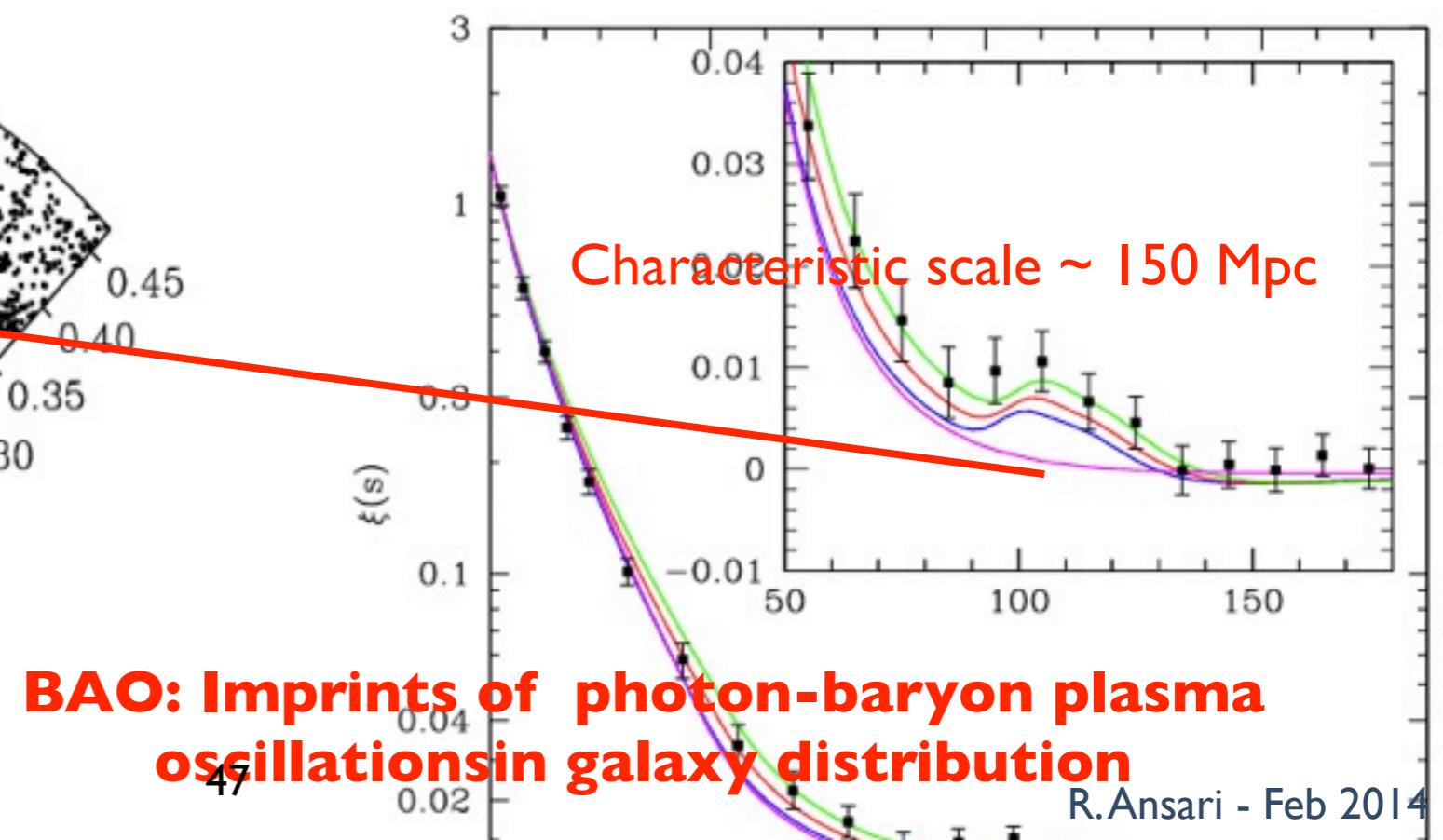


Slide by R. Braun
Exploring the Universe with the world's largest radio telescope
SKA Science director

Énergie Noire, BAO's et cartographie 3D à 21 cm (Intensity mapping)

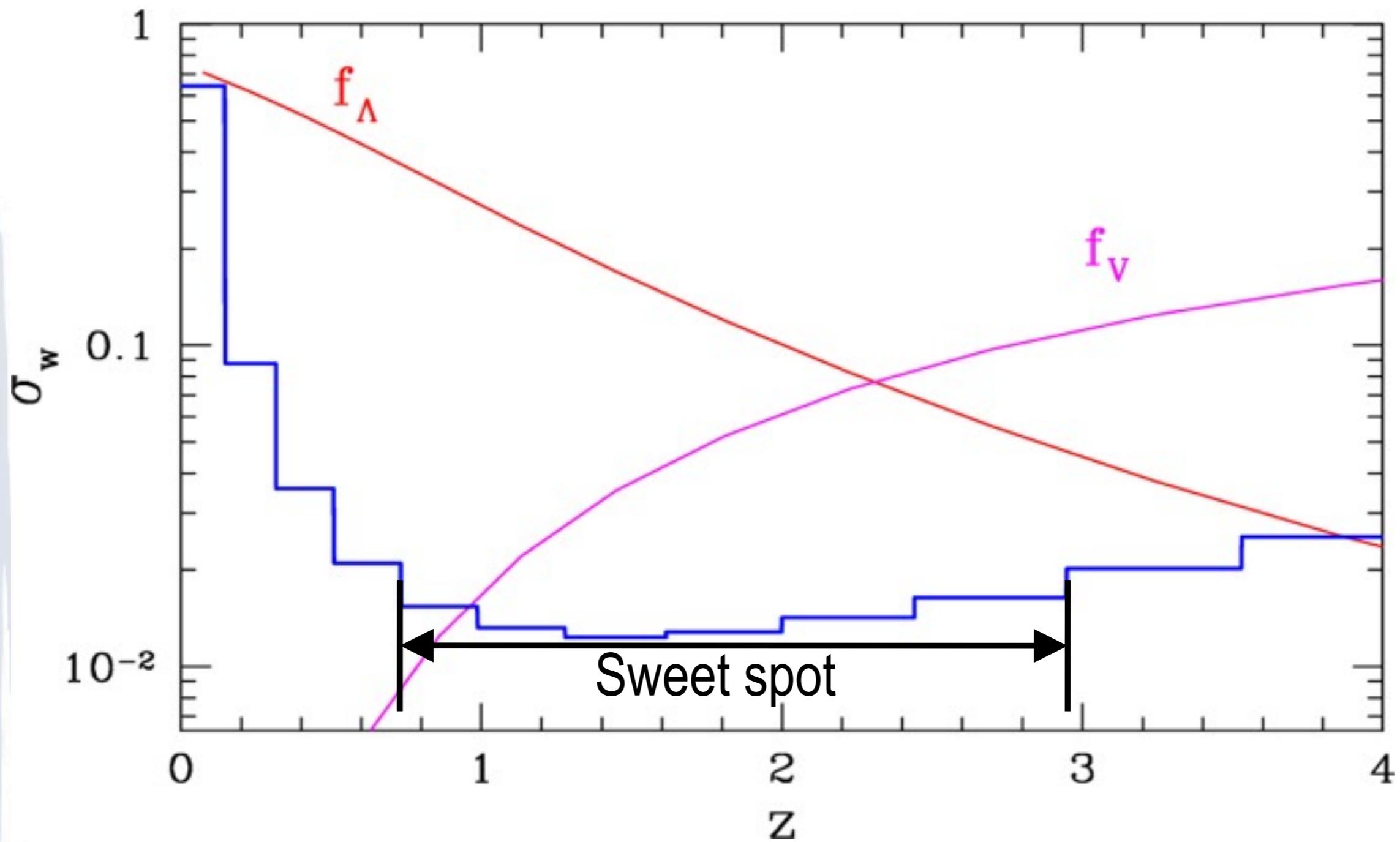


Galaxy distribution
(z , angle (α, δ)) plane



BAO: Imprints of photon-baryon plasma oscillations in galaxy distribution

Baryon Acoustic Oscillations



Wednesday, June 2, 2010

Slide borrowed from A. Stebbins

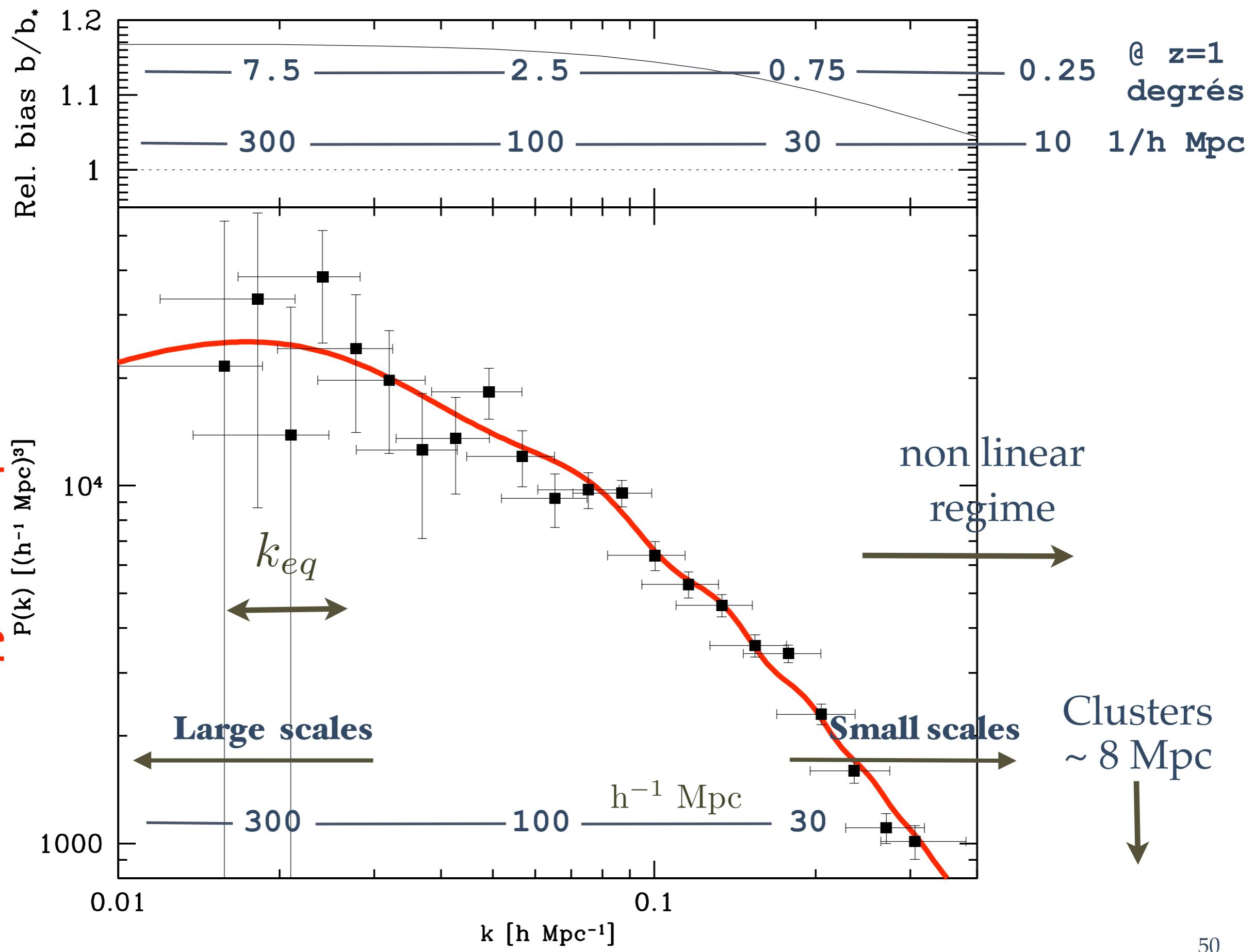
BAO in radio

- ✿ 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 objects.

- ✿ Or similar to CMB observations :
 - ≡ 3D mapping of the HI (21 cm) emission - $T_{21}(\alpha, \delta, z)$ - Radio foreground subtraction, determination of the power spectrum $P(k, z)$ on the 21 cm sky temperature data cubes.

SDSS - M. Tegmark et al.

ApJ, astro-ph/03010725



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 (T_{sys})
- ≡ 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

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 objects.
- ✿ Or similar to CMB observations :
 - ≡ 3D mapping of the HI (21 cm) emission - $T_{21}(\alpha, \delta, z)$ - Radio foreground subtraction, determination of the power spectrum $P(k, z)$ on the 21 cm sky temperature data cubes.

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: $\sim 100 \text{ MHz} \dots 1500 \text{ MHz}$ - $v = f(z)$, $z: 0 \dots 10$
 $1420 \text{ MHz} @ z=0, 946 \text{ MHz} @ z=0.5, 720 @ z=1, 284 @ z=5, 129 @ z=10$
- Diffraction limited, source confusion:
 $700 \text{ MHz}: D=100 \text{ m} \rightarrow \sim 20', D=1\text{km} \rightarrow \sim 2', D=100 \text{ km} \rightarrow \sim 1'', 2' \rightarrow 1 \text{ Mpc} @ z = 1$
- Intensity measurement in optical, amplitude & phase in radio;
CCD in optics, but interferometry and spectroscopy in radio
- instrumental noise (read-out noise $< 5 \text{ e}$) often négligable in optical, dominant in radio ($T_{\text{sys}} \sim 20\text{-}50 \text{ K}$)
- low ambient/parasitic light level in optical in good observatories;
radio band polluted (RFI) by terrestrial emissions

21 cm signal strength and foregrounds

$$T_{21}(\Theta, \lambda(z)) = \frac{3}{32\pi} \frac{h}{k_B} A_{21} \lambda_{21}^2 \times \frac{c}{H(z)} (1+z)^2 \times n_{HI}(\Theta, z)$$

$$P_{T_{21}}(k) = (\bar{T}_{21}(z))^2 P(k) \quad (T_s \gg \frac{h\nu_{21}}{k}, T_{CMB})$$

$$\bar{T}_{21}(z) \simeq 0.084 \text{ mK} \frac{(1+z)^2 h_{100}}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{\Omega_B}{0.044} \frac{f_{H_I}(z)}{0.01}$$

Z	0.5	1	2
T ₂₁ (mK)	0.1	0.15	0.20
T _{sync} (K)	3	21	145

Signal &
foreground (mK)

$$T_{sync} \propto \nu^\beta \quad \beta \sim -2.8$$

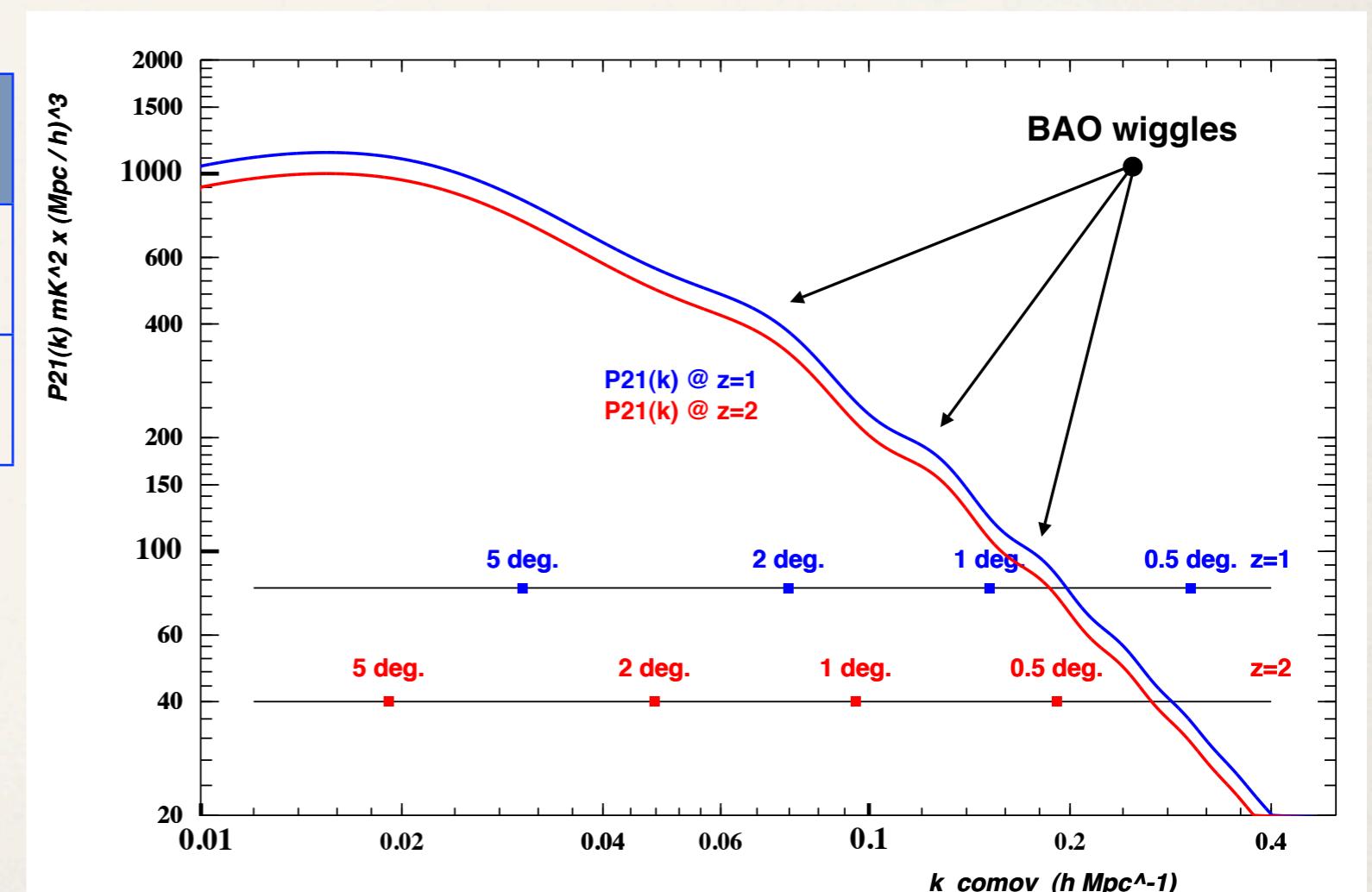
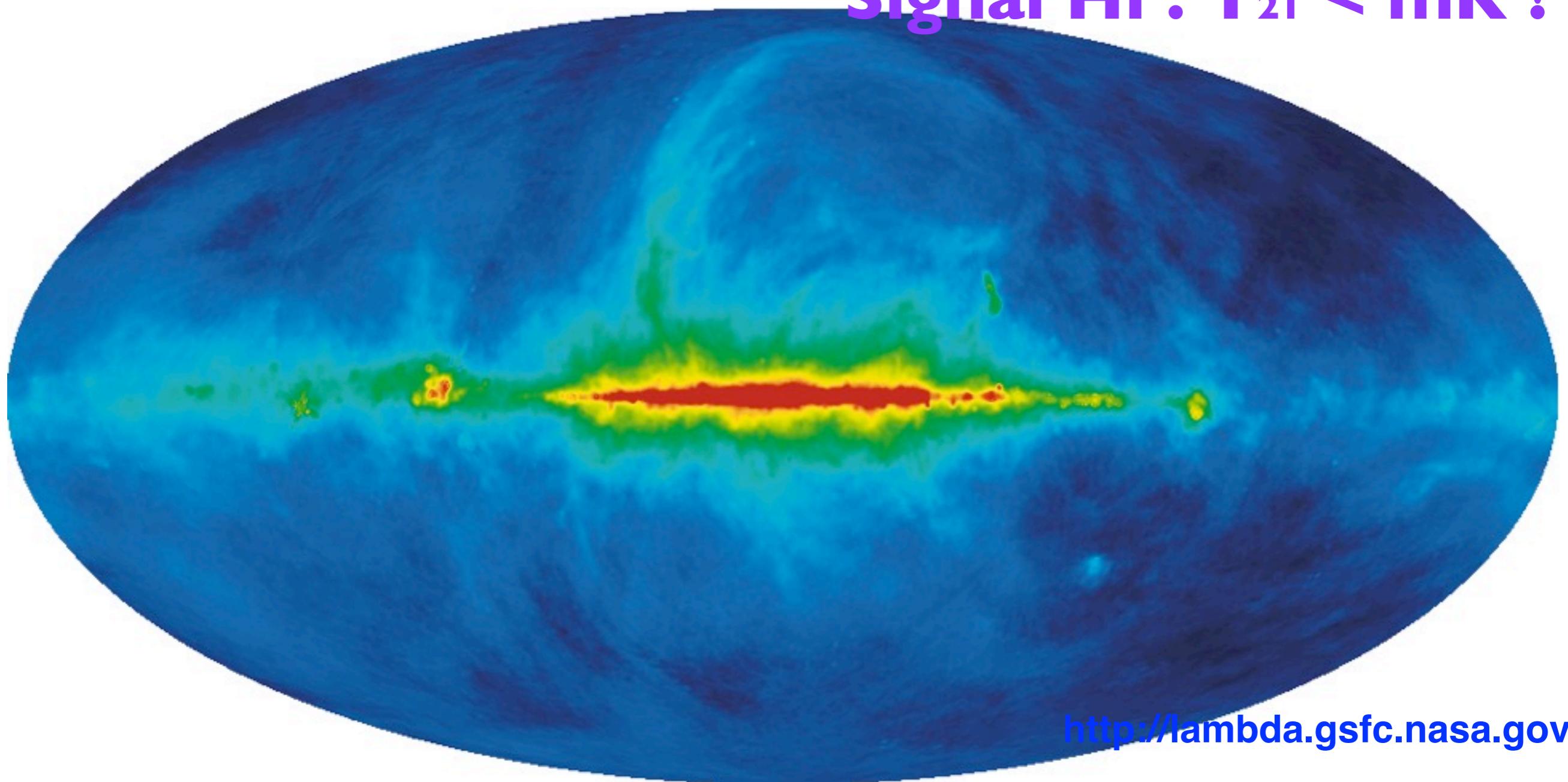


Fig. 1. H_I 21 cm emission power spectrum at redshifts z=1 (blue) and z=2 (red), with neutral gas fraction $f_{H_I} = 2\%$

Foregrounds

Signal HI : $T_{21} < \text{mK}$!

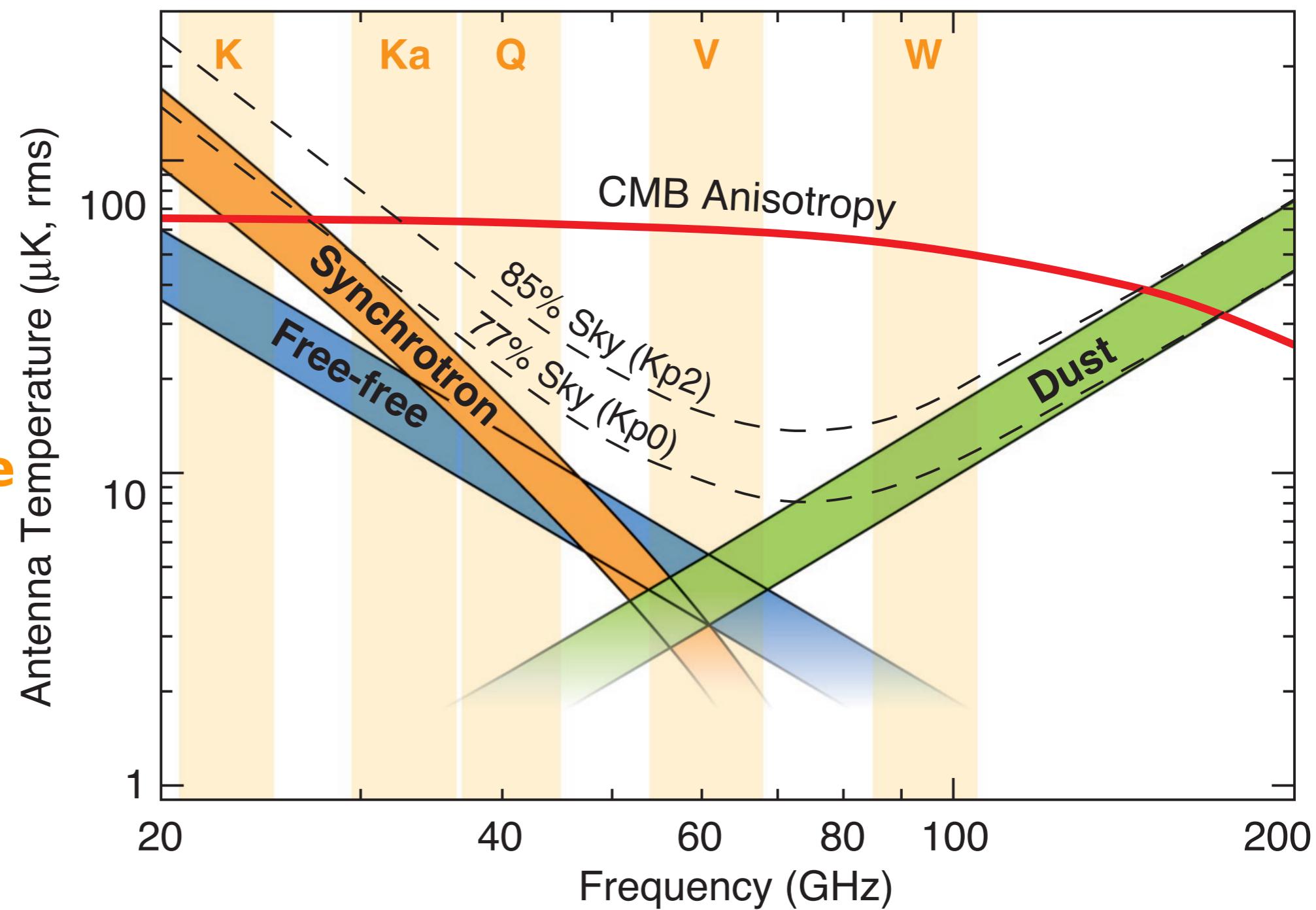


Temp. T (Ech. Log)
10 K ————— 250 K

Haslam 408 MHz map (Galactic
synchrotron emission)

R.Anvari

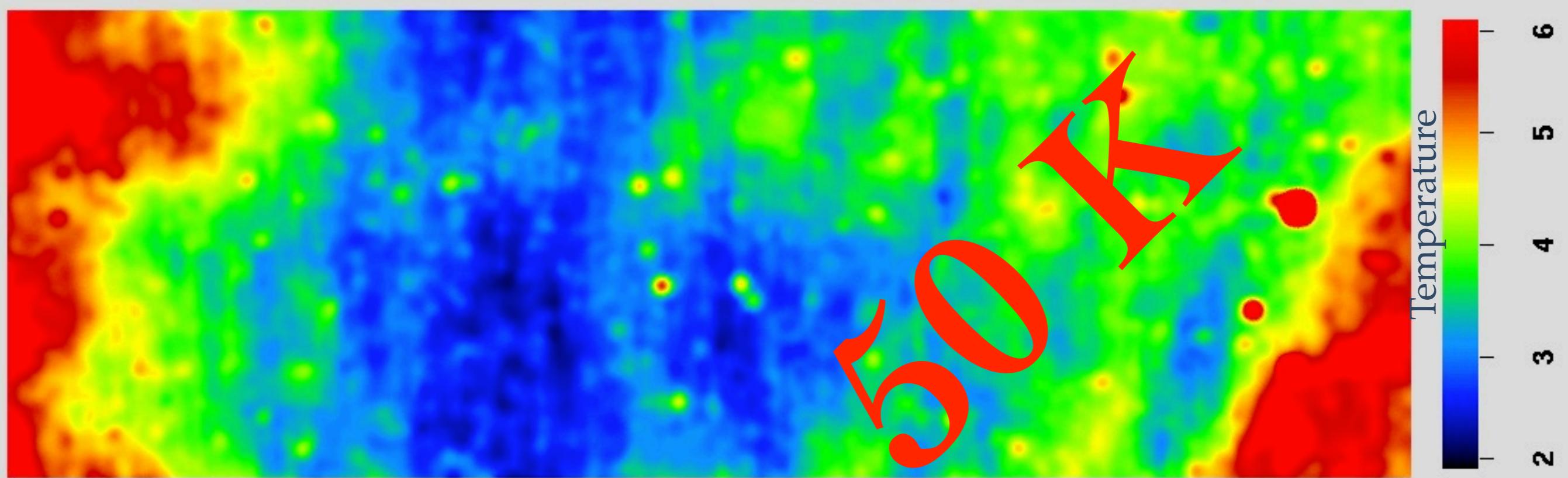
+ les sources
radio à spectre
large (AGN,
quasar ...)



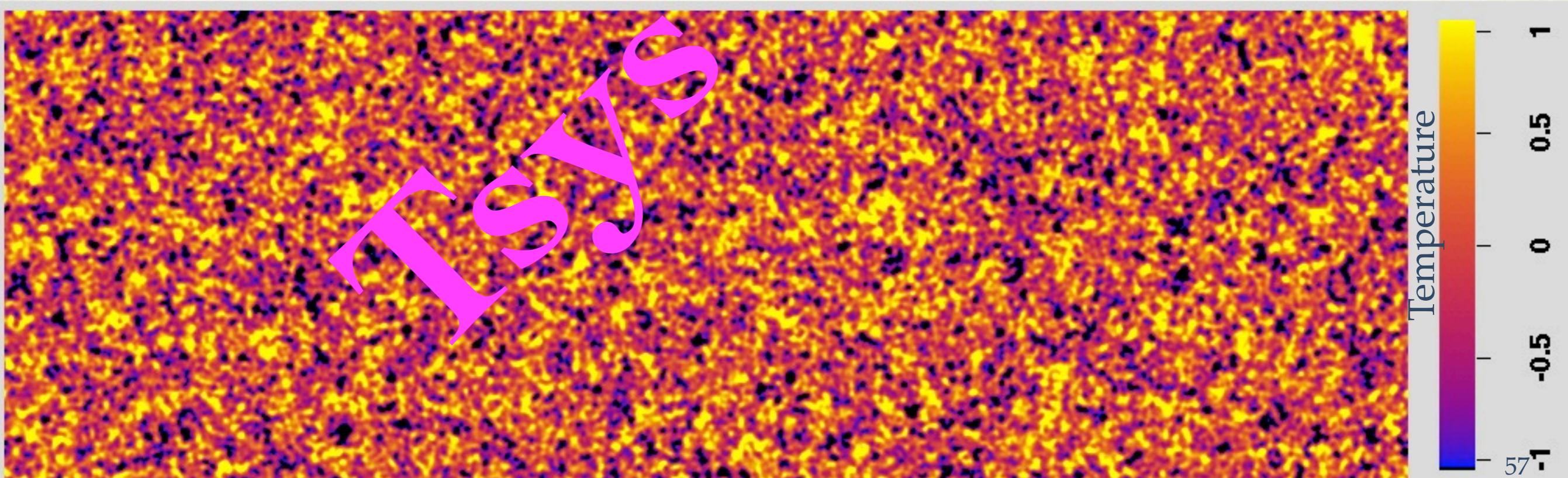
Spectre des anisotropies des avant-plans

Bennet et al 2003, ApJS 148

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



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

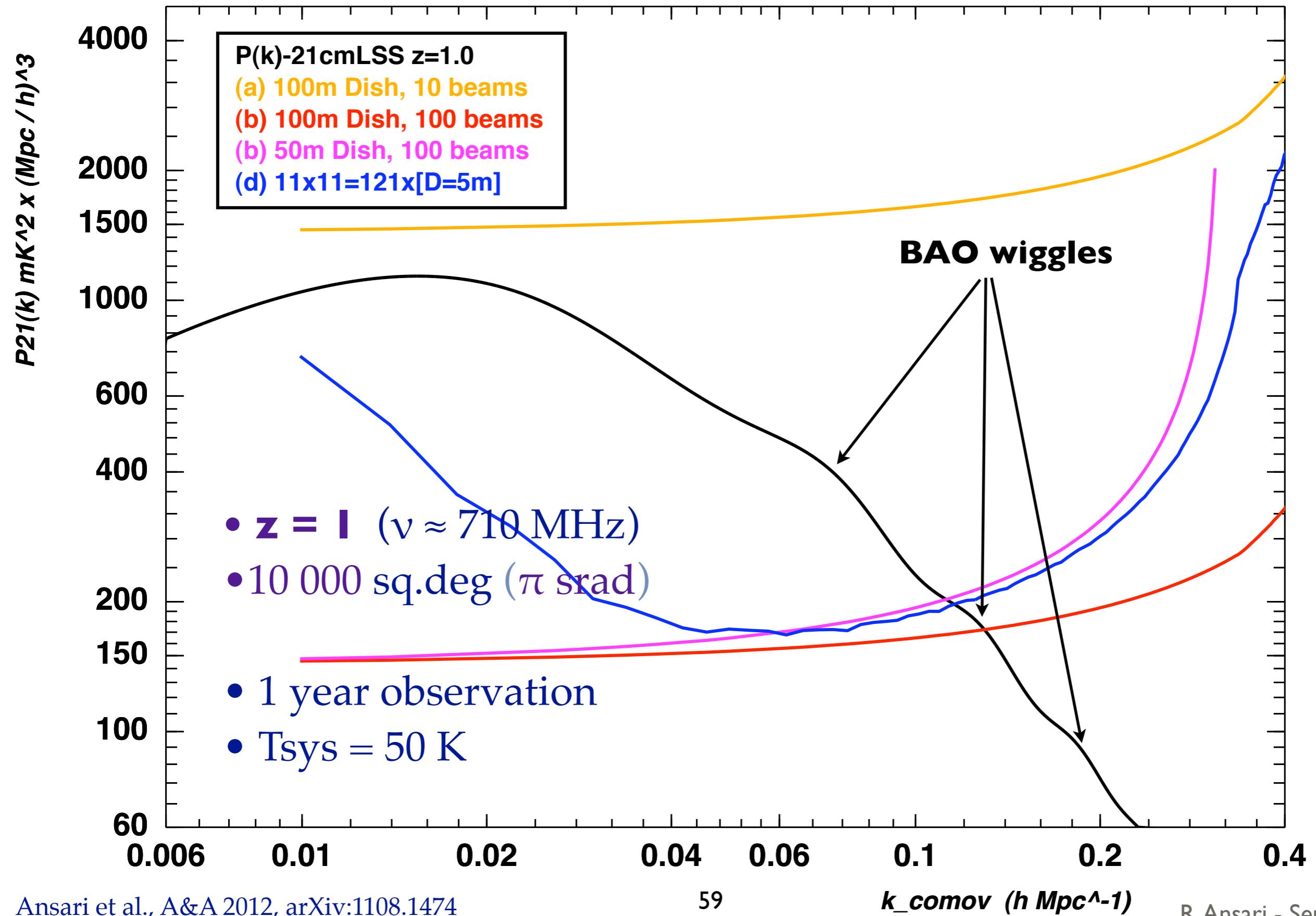


mK sensitivity with T_{sys} \sim 50-75 K

- Large integration time (10^4 - 10^5 s) $\rightarrow \propto 1 / \sqrt(t_{\text{int}} \Delta v)$
- Instrument (T_{sys}, beam ...) stability
- multi beam - large FOV radio telescope
- interferometer or FPA / multi feed receivers with single dish

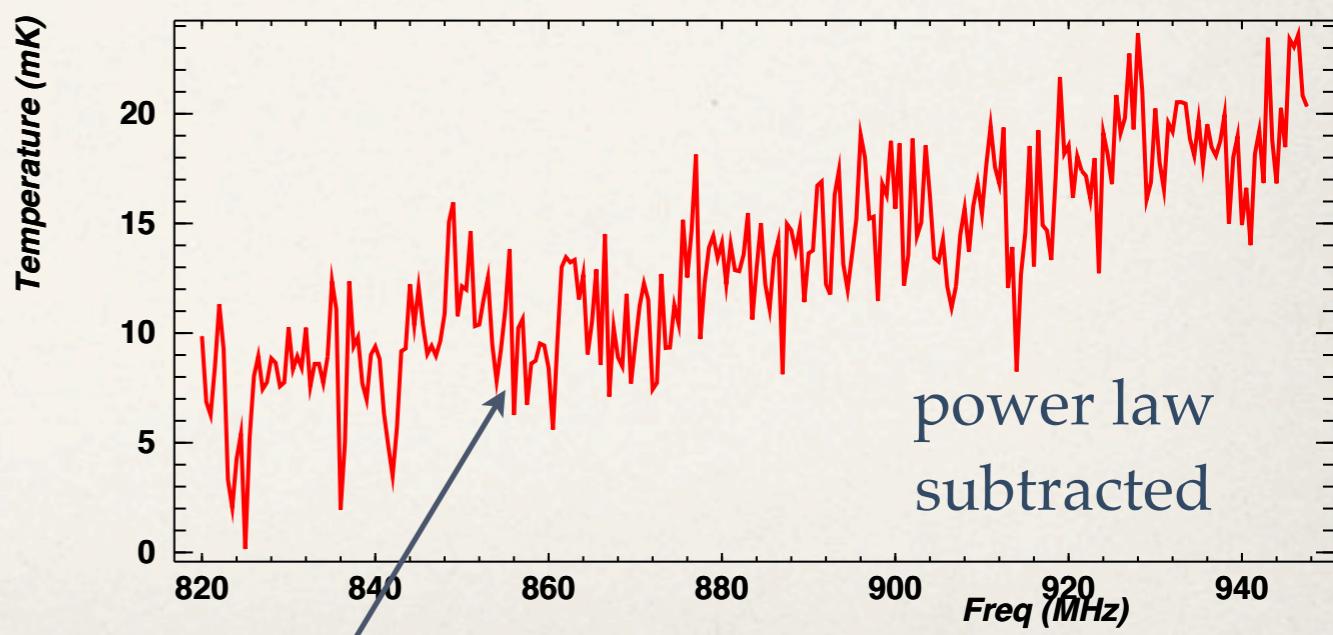
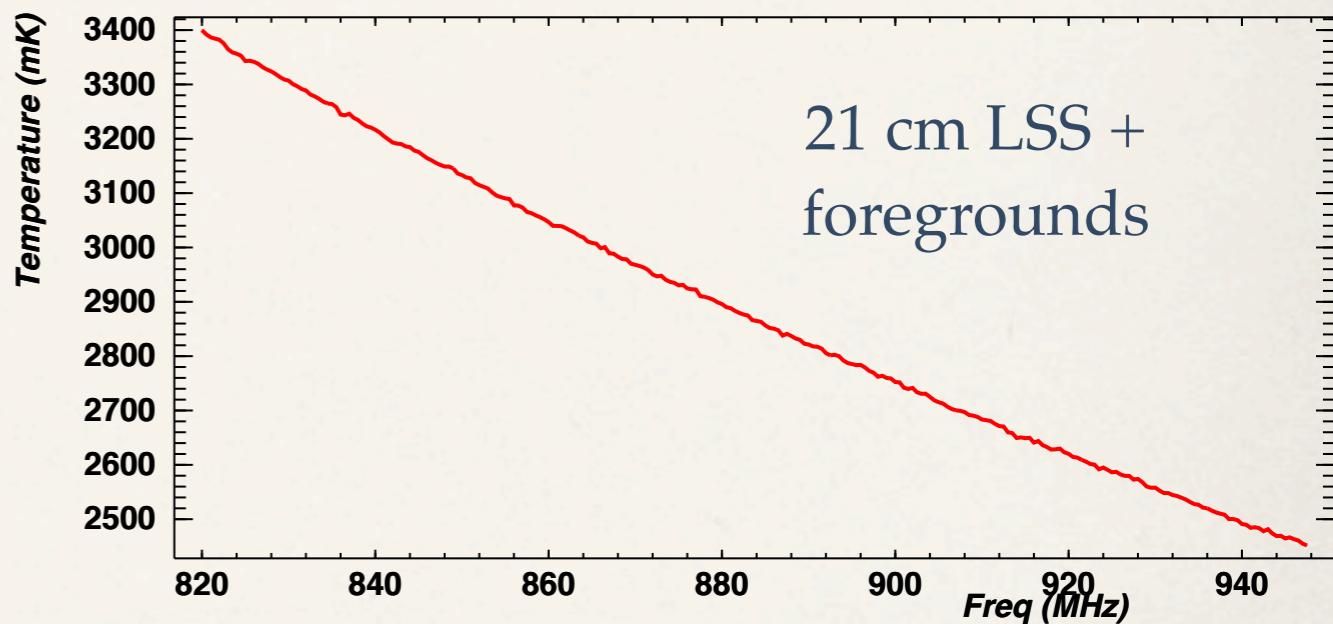
$P(k)@2\text{ cm} - P\text{Noise}(k)$

$P\text{Noise}(k) @ z=1$



Foreground removal

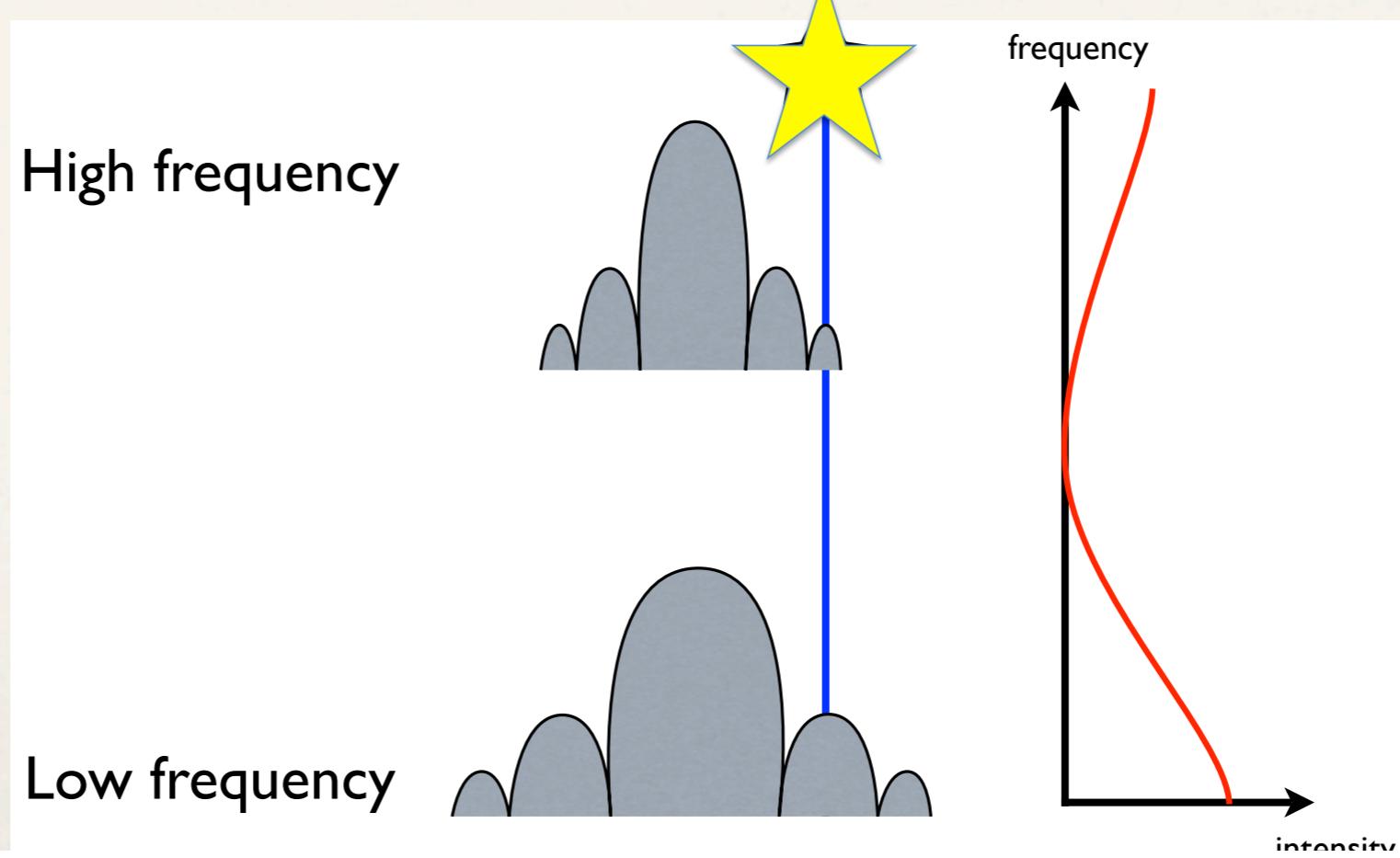
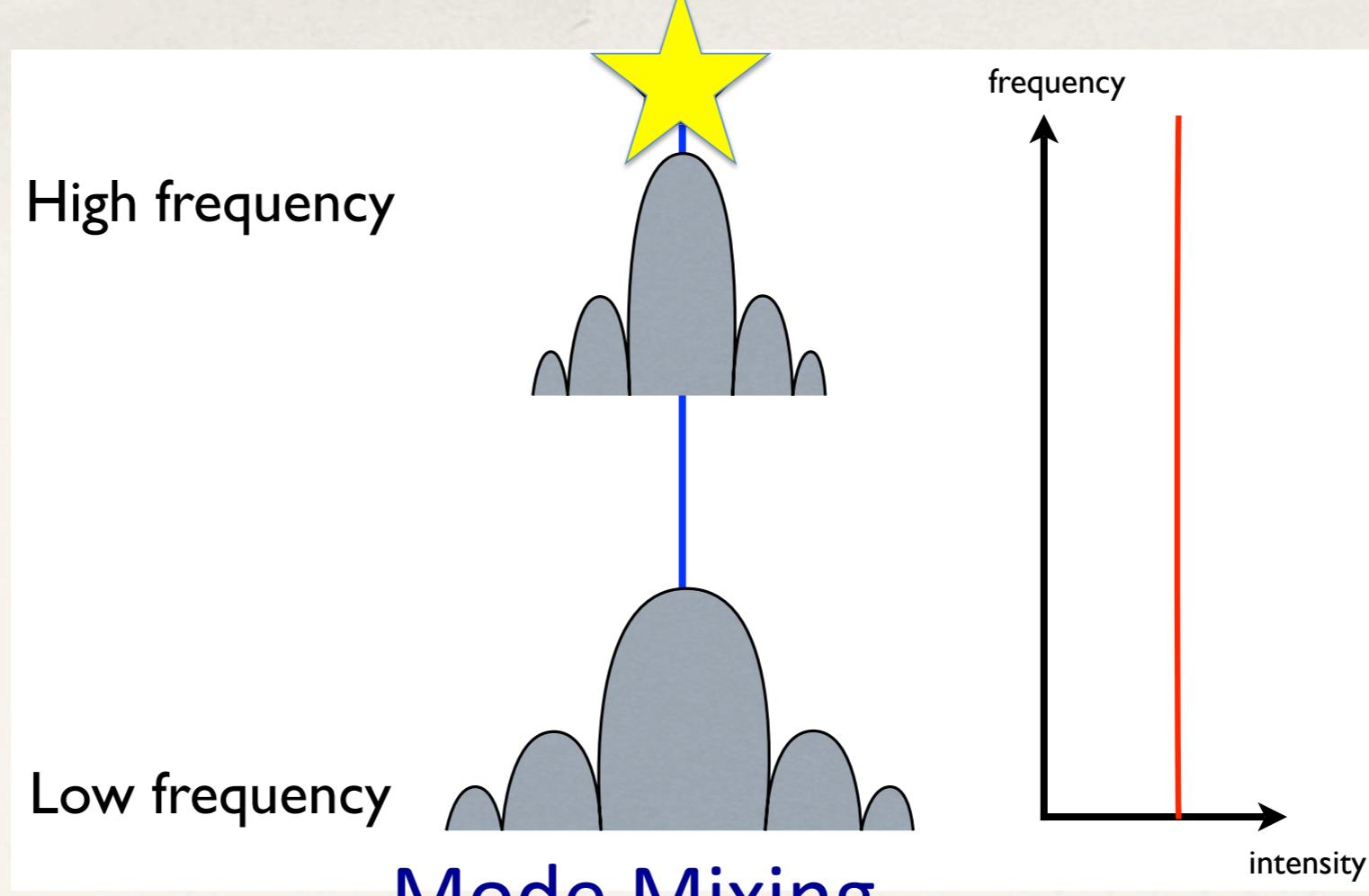
- Exploit frequency smoothness and power law ($\propto \nu^\beta$) behavior of foregrounds (synchrotron/radio sources)
- power law / polynomial / foreground model fit & subtraction
- Mode mixing, bias, error propagation ...



21 cm LSS signal

60

Slide by
Kris Sigurdson
UBC



Signal-to-Noise Eigenmodes

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

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

- Construct the covariances of the signal and foregrounds

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

- Jointly diagonalise both matrices (eigenvalue problem)

Karhunen-Loëve (KL) Transform: $\mathbf{Sx} = \lambda \mathbf{Fx}$ (3)

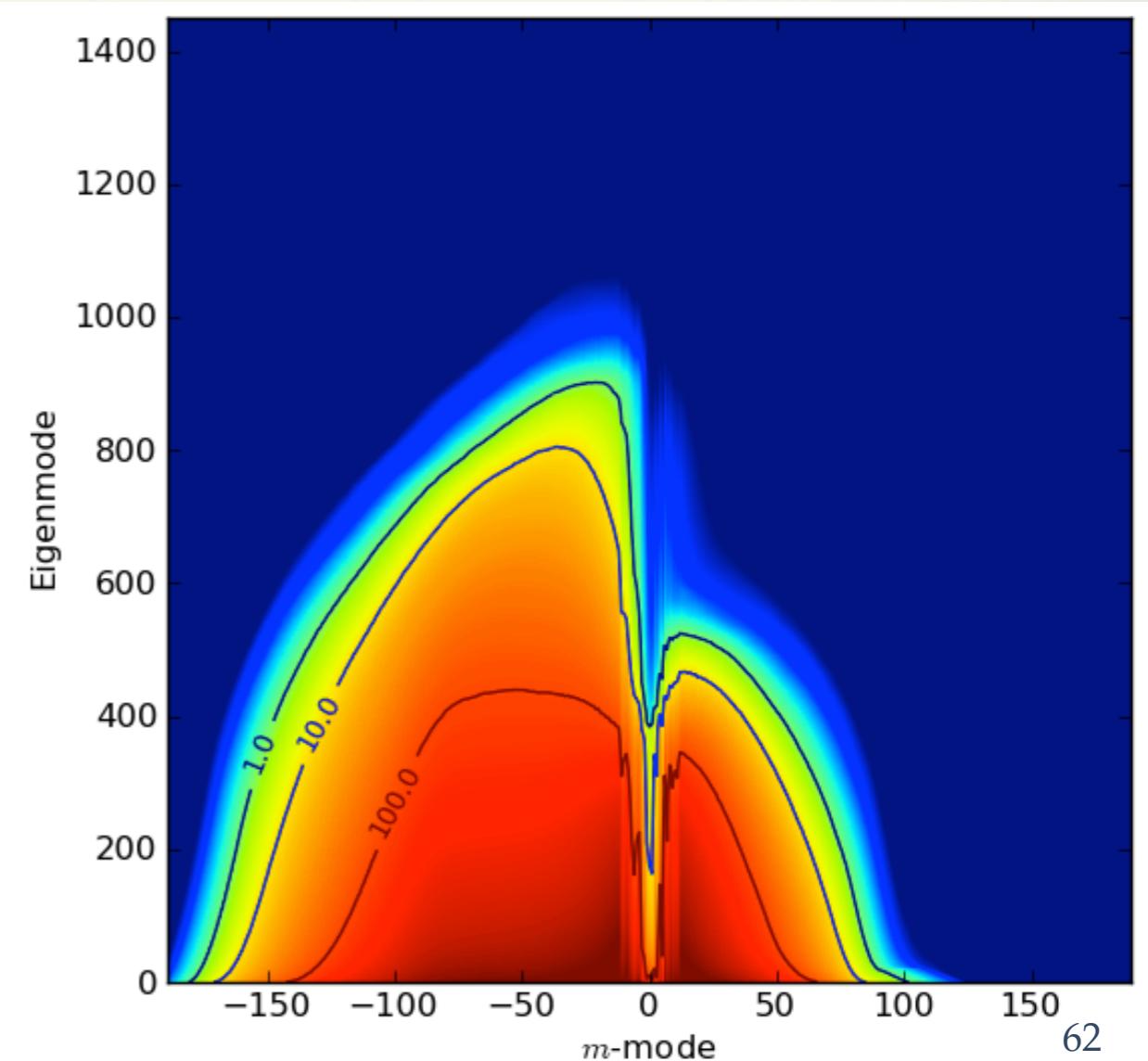
- Gives a new basis, where we expect that all modes are uncorrelated. Eigenvalue λ_i gives ratio of signal to foreground variance for mode i .

cf. Bond 1994, Vogeley and Szalay 1996

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

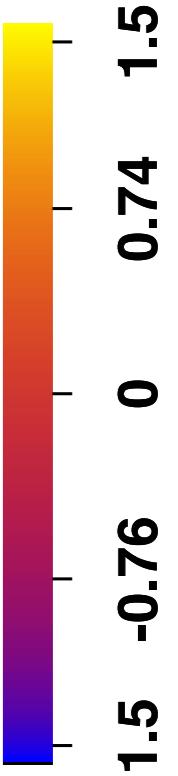
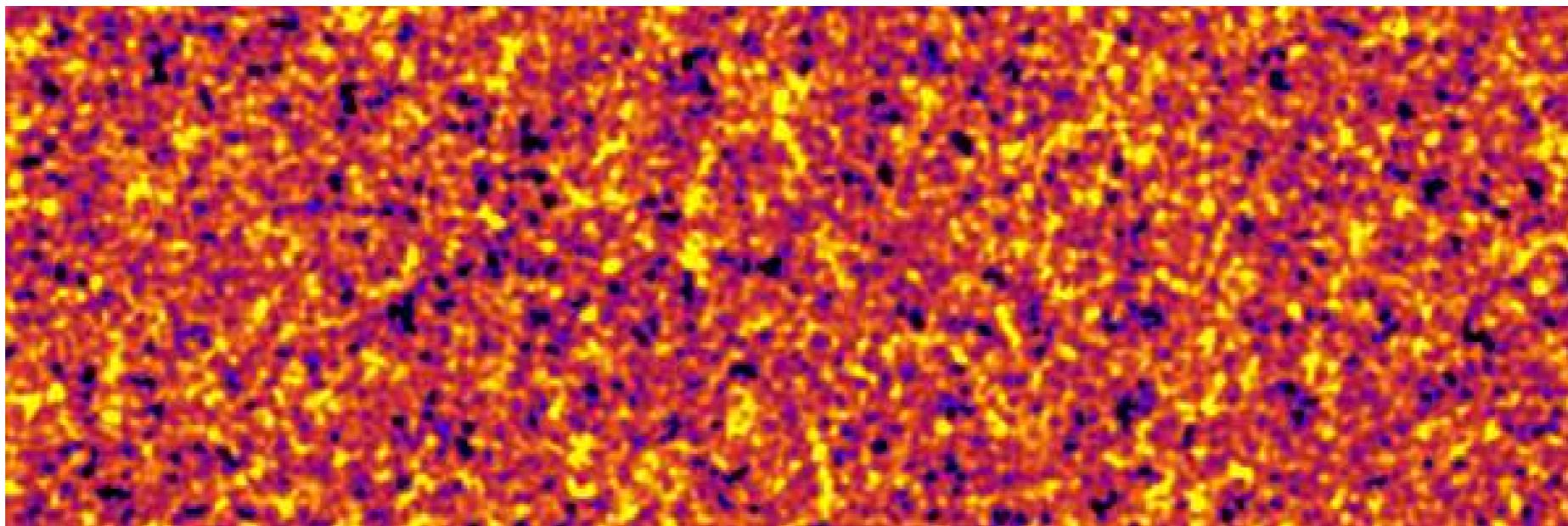
Slide by
Kris Sigurdson
UBC

Signal/Foreground Spectrum

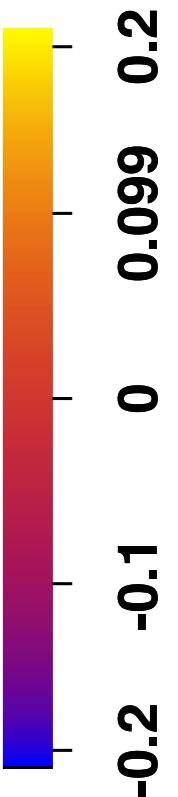
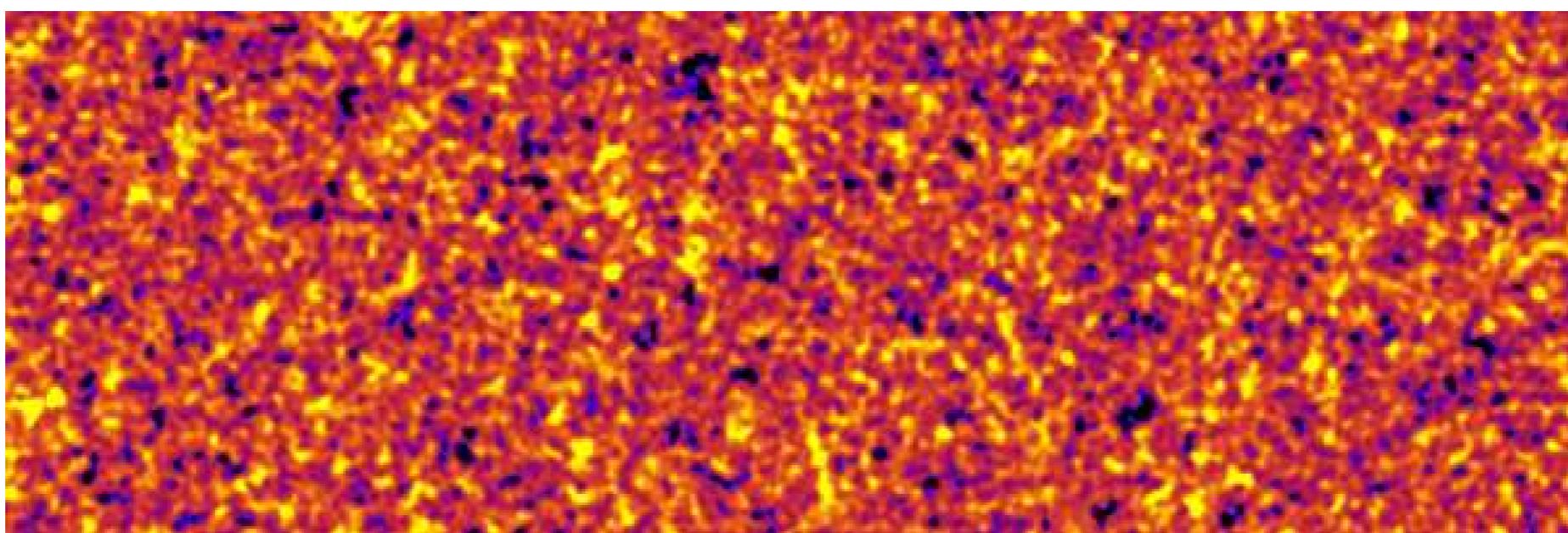


Component separation 21cm LSS signal extraction @ z=0.6

Original simulated 21cm signal



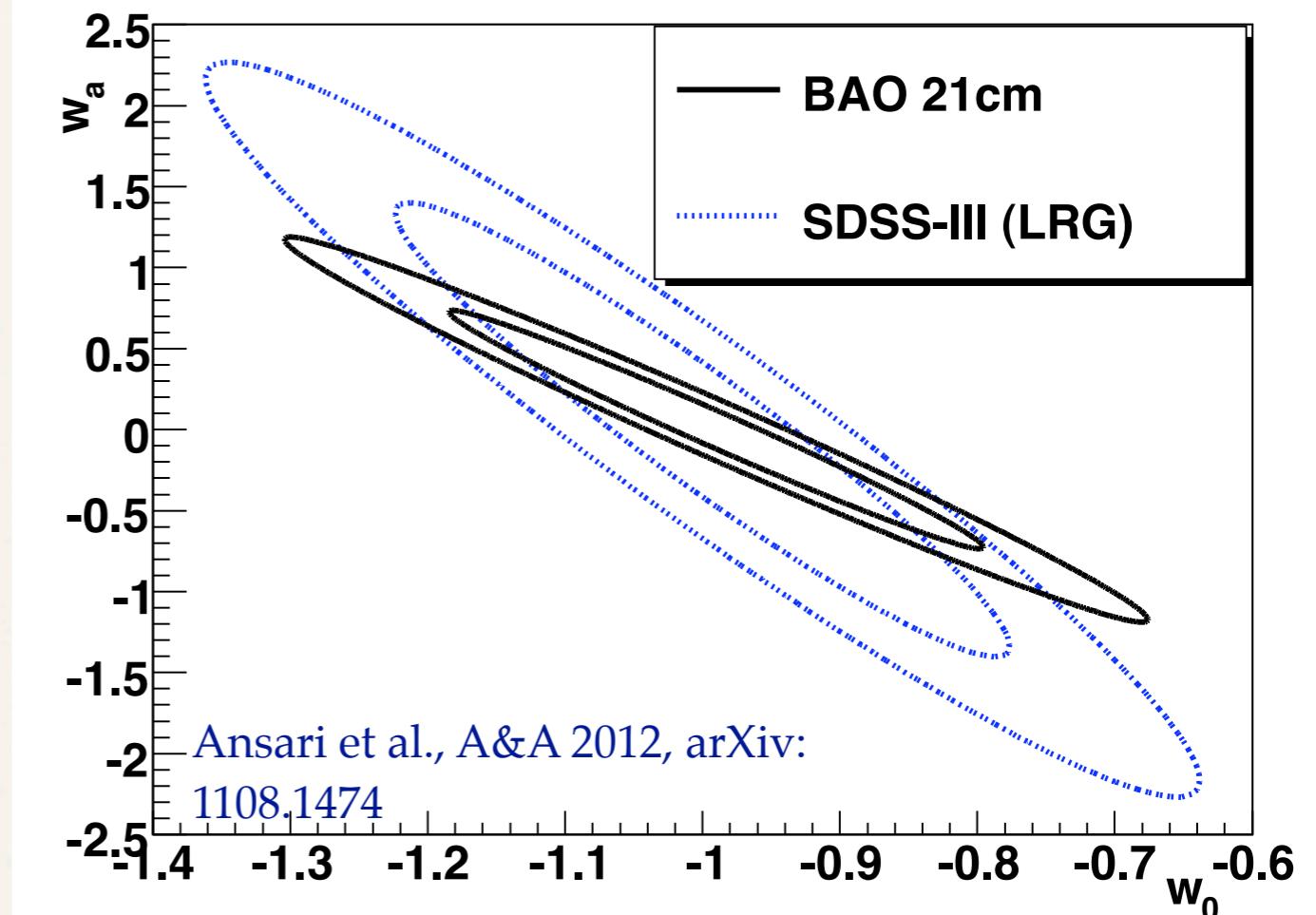
Recovered 21cm signal, in presence of continuum radio signals, and instrument response



Ansari et al. 2012, A&A Dec 2011 , arXiv:1108.1474 ExtractedLSS Map @ 884 MHz (GSM)

21 cm Cosmology / DE

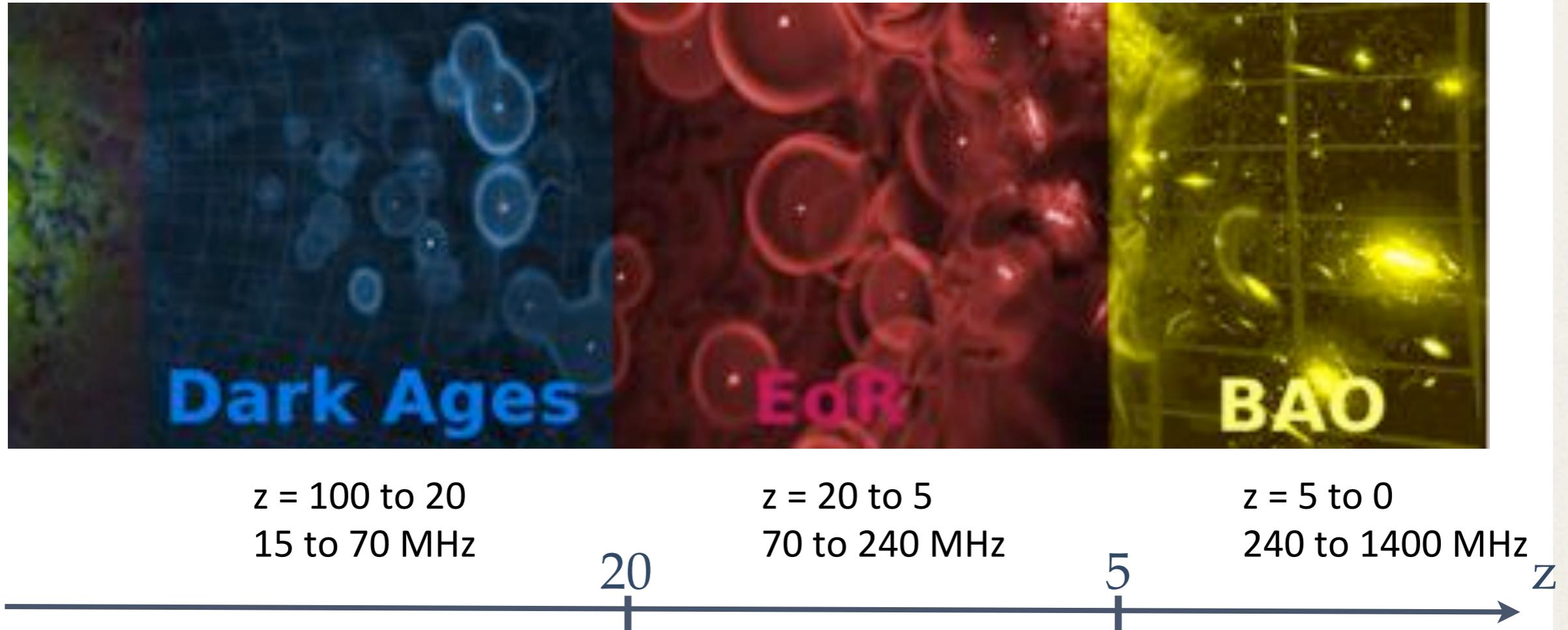
- Mapping cosmic matter distribution using neutral hydrogen as tracer
- Measure the HI density fluctuations and its power spectrum $P_{21}(k)$
- Determine BAO scale k_{BAO} pour $0.5 < z < 2-3$
- Measure the HI gas fraction as a function of redshift, scale and environment
- Mapping of the radio foregrounds in the 500-1000 MHz band



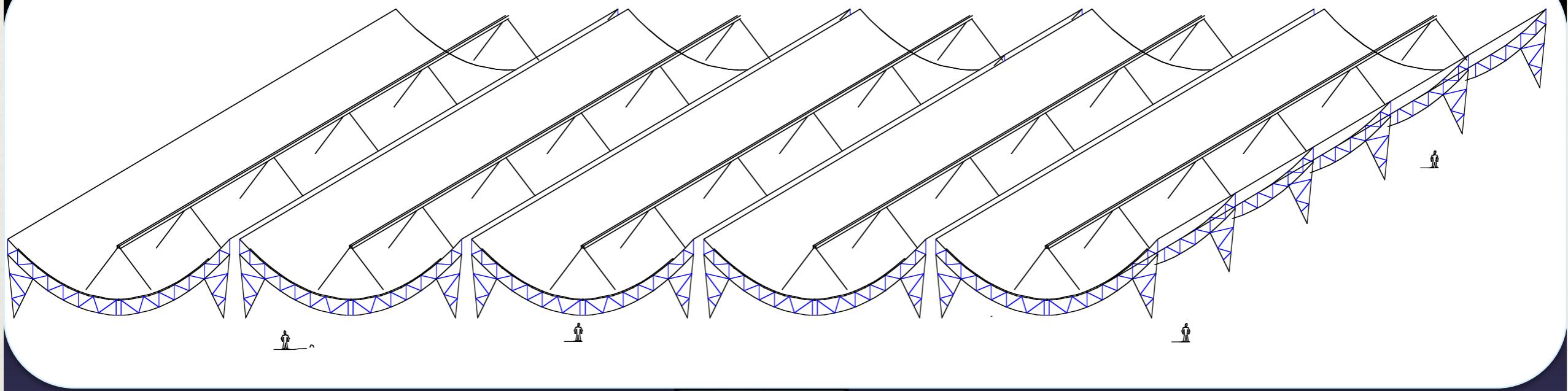
21 cm BAO vs optical redshift survey
10 000 sq.deg, 3 years survey, 5 redshift bands
(0.5 1.0 1.5 2.0 2.5)

10 000 m² collecting area, 400 beams

Other 21 cm BAO projects



Canadian Hydrogen Intensity Mapping Experiment (CHIME)



THE
UNIVERSITY OF
BRITISH
COLUMBIA



UNIVERSITY OF
TORONTO



McGill

Kevin Bandura
CHIME Collaboration

Slide by K. Bandura

The CHIME Pathfinder



Slide by K. Bandura

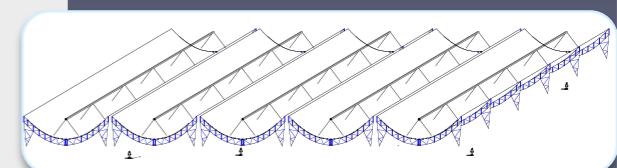
CHIME Fact Sheet

Full CHIME Layout

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

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

Slide by
K. Bandura

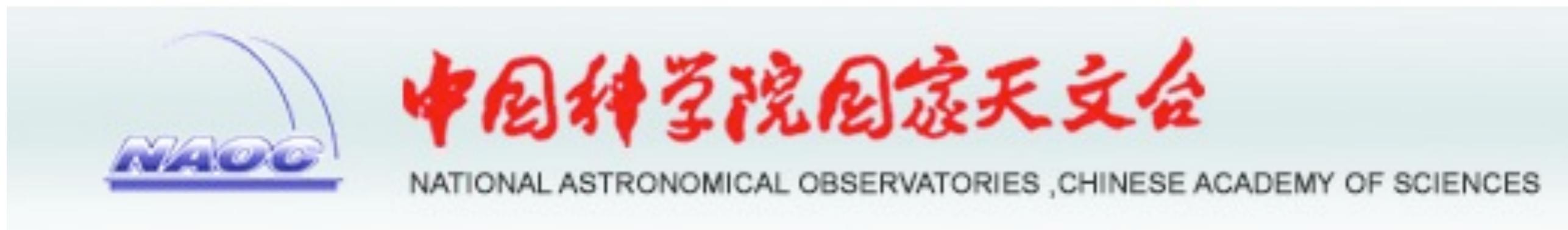


funded (11M\$)

16 channel correlator now, 256 channel
correlator by spring 2014



TIANLAI



From CRT / BAO Radio 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 / CONSTRUCTION



September 2014



BAORadio

LAL - IN2P3/CNRS

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

T. Caceres
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

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



END