

# L'origine des éléments légers dans l'Univers



**Guillaume HÉBRARD**

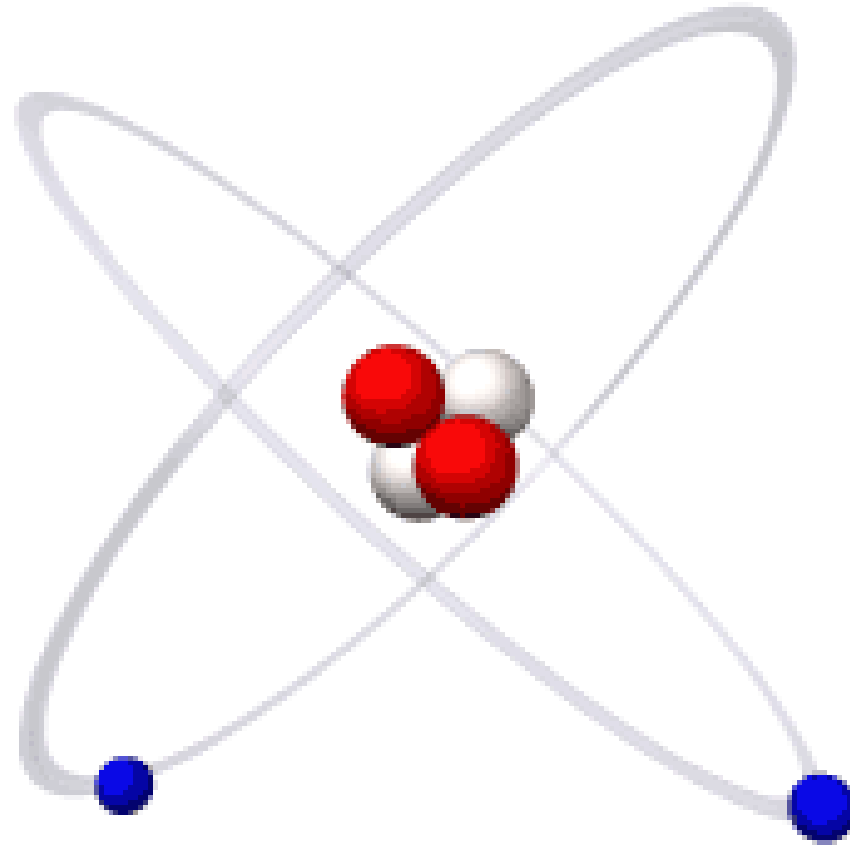
*Institut d'Astrophysique de Paris*

28 septembre 2006

*Commission cosmologie*

Société Astronomique de France, Paris

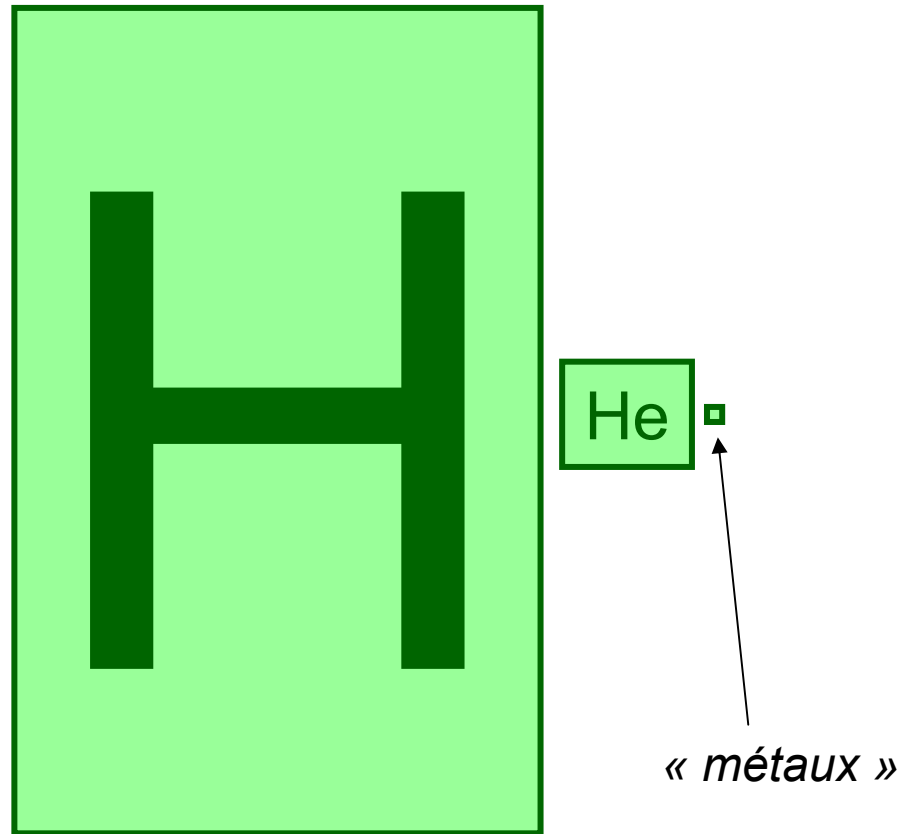
# Les atomes





élément	symbole	abondance approximative
Hydrogène	H	90 %
Deutérium	D	0.001 %
Hélium	He	10 %
Lithium	Li	$10^{-7}$ %
Béryllium	Be	$10^{-9}$ %
Bore	B	$10^{-8}$ %

# Tableau périodique des éléments simplifié pour astronomes

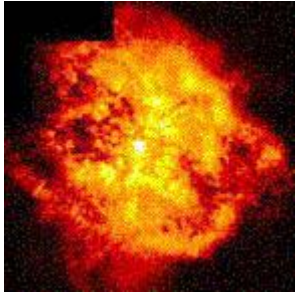


# Créer les noyaux atomiques : nucléosynthèse

Trois processus distincts :

- Nucléosynthèse primordiale
- Nucléosynthèse stellaire
- Réactions de spallation dans le gaz interstellaire

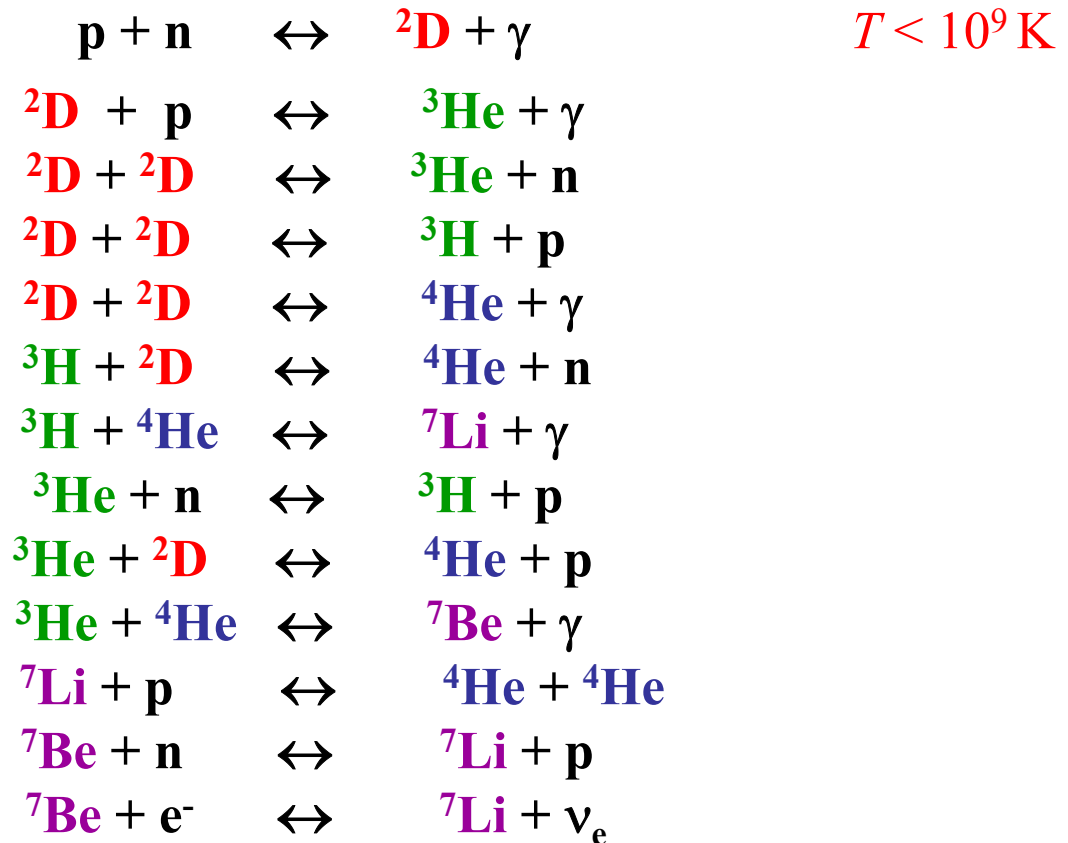
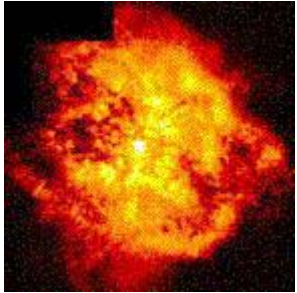
# Nucléosynthèse primordiale



$T > 10^9 \text{ K}$

George Gamow (1946)

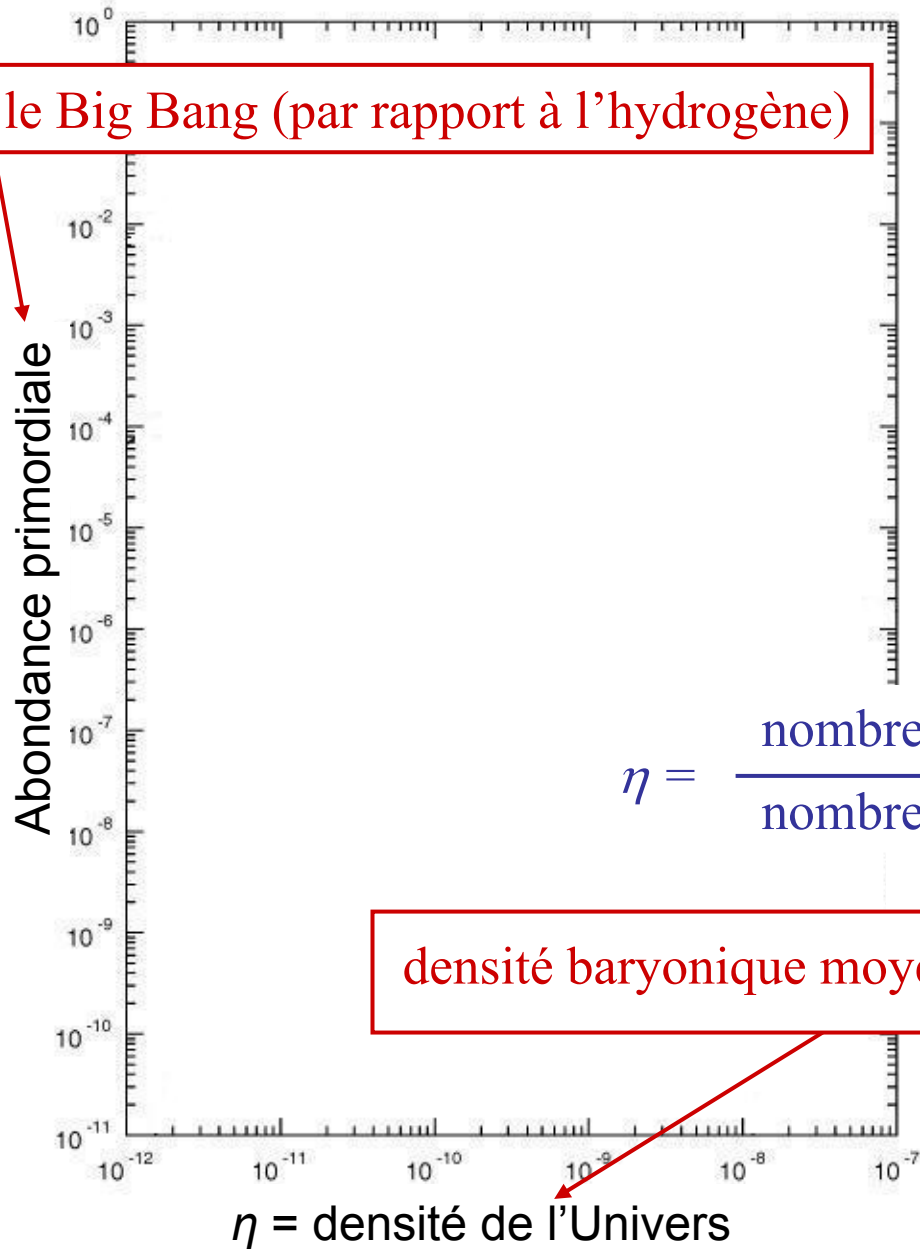
# Nucléosynthèse primordiale



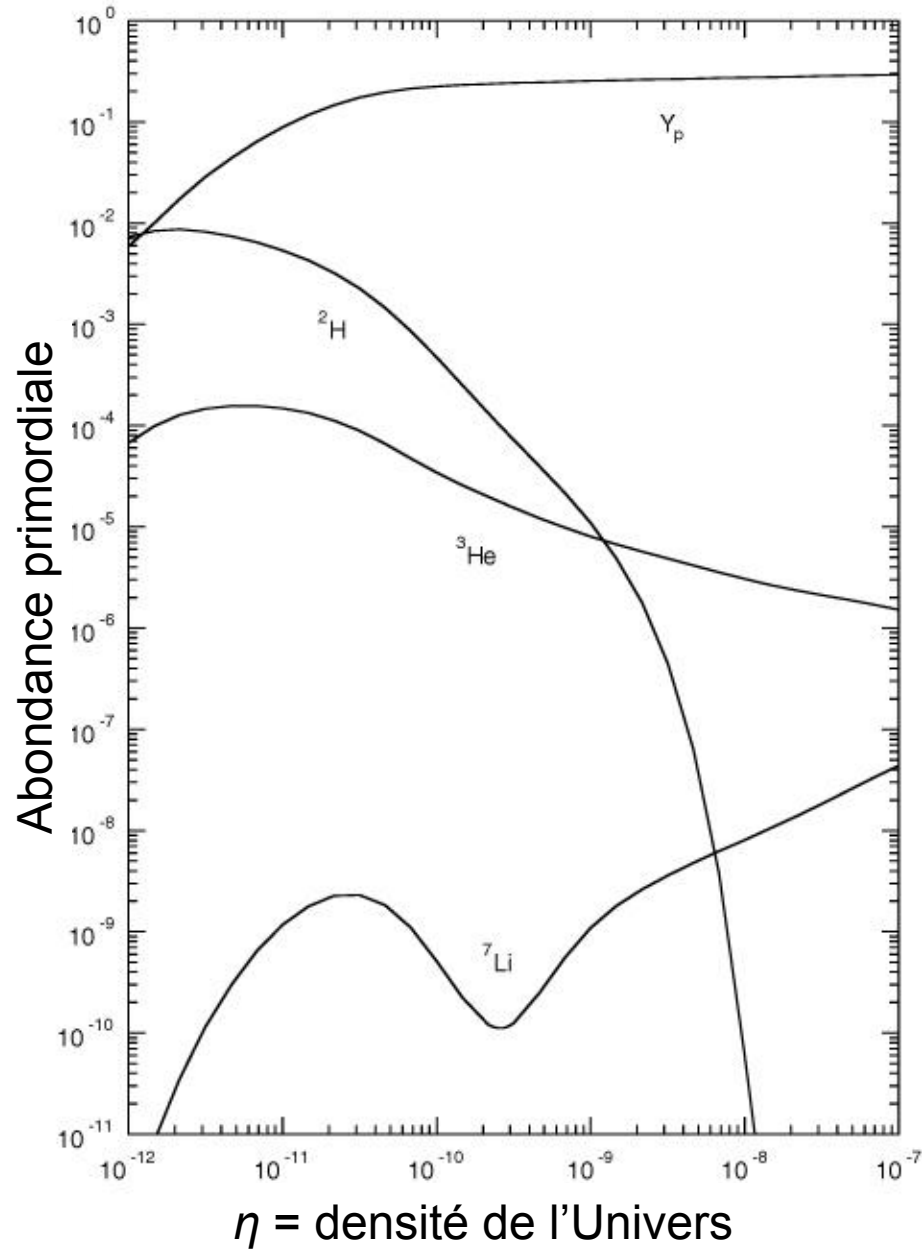


## Courbes « *abondances / densité* »

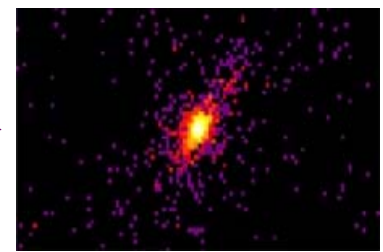
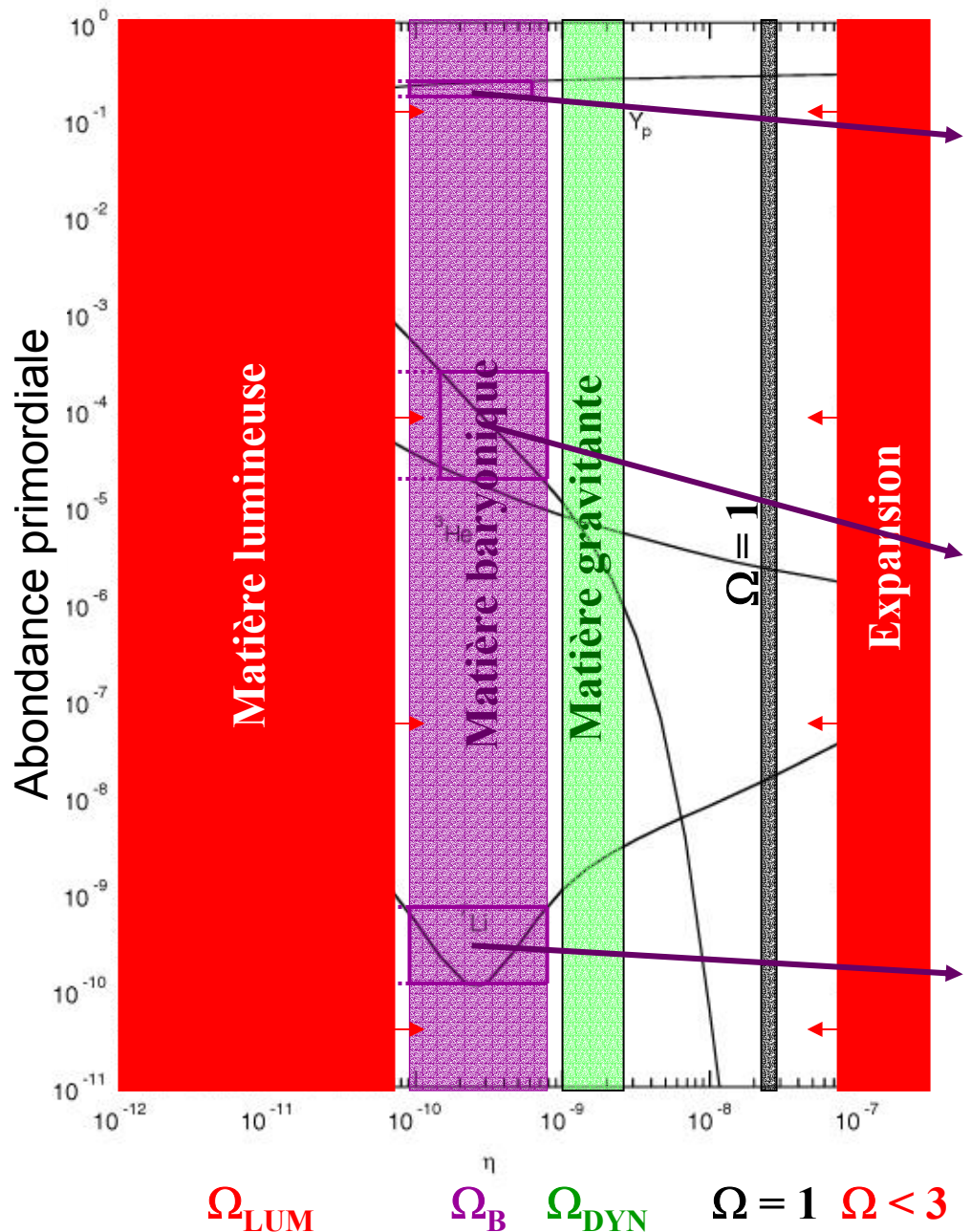
Abondance après le Big Bang (par rapport à l'hydrogène)



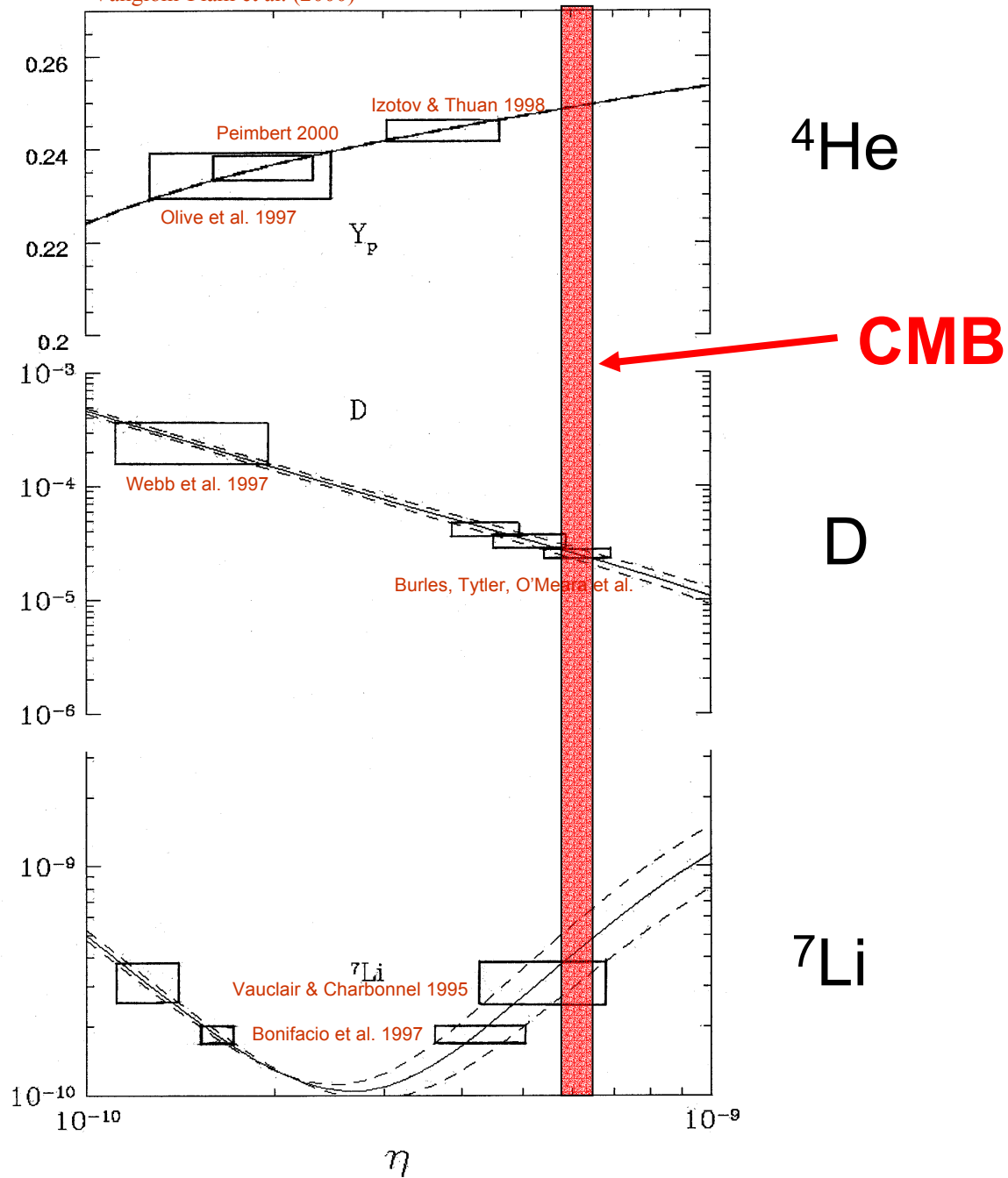
Courbes « *abondances / densité* »



$\eta$  = densité de l'Univers

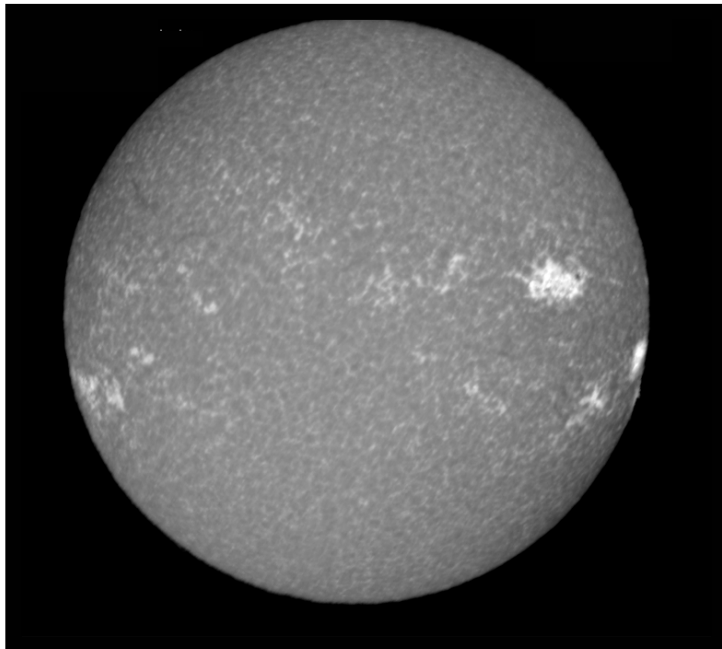
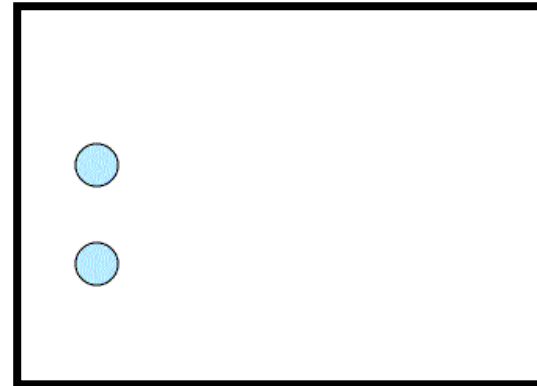
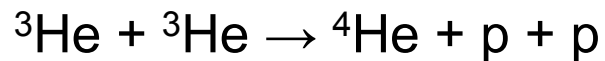
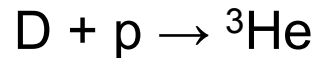
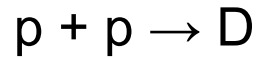


Vangioni-Flam et al. (2000)



# Nucléosynthèse stellaire

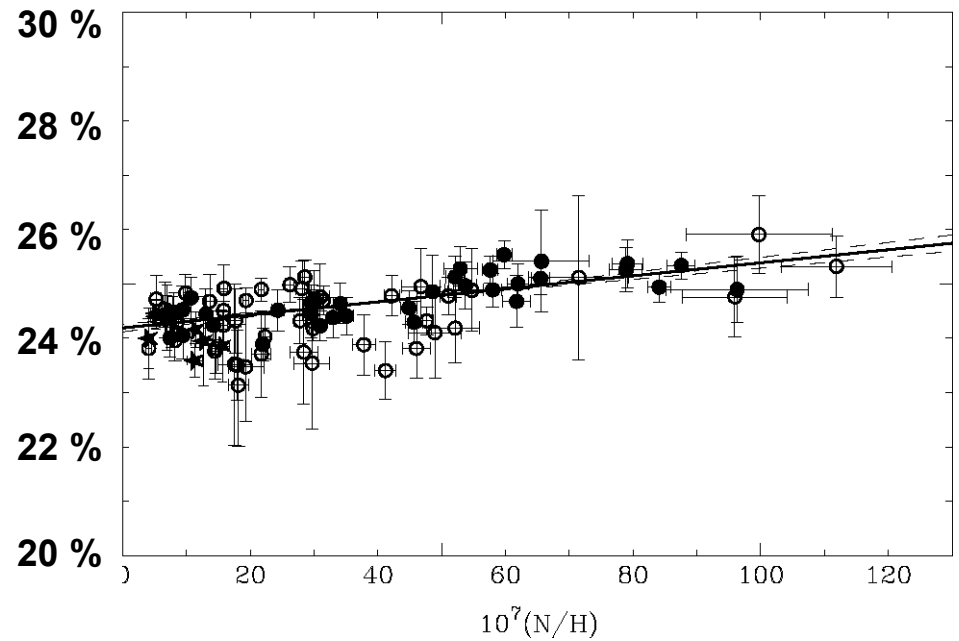
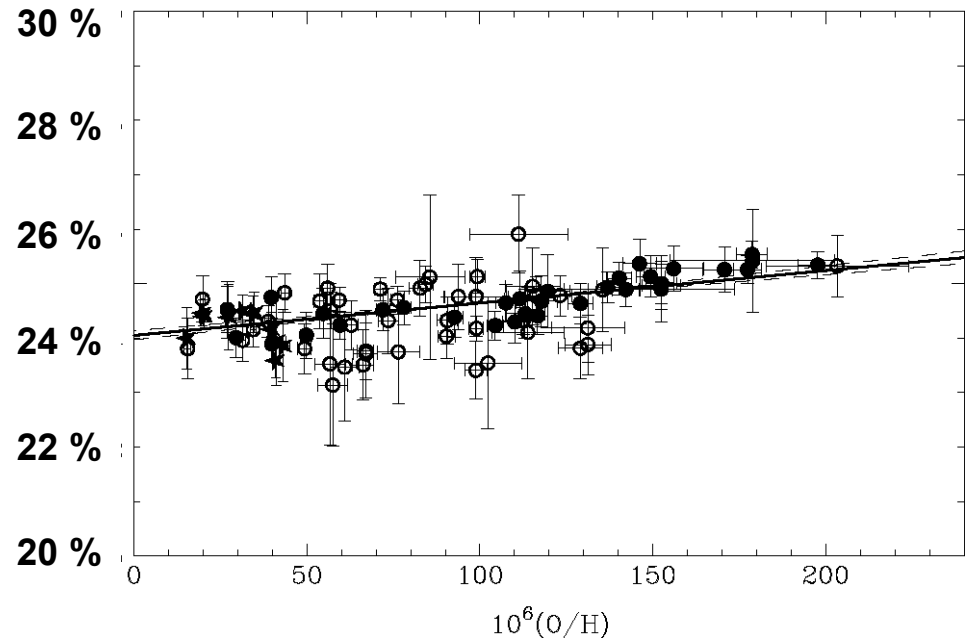
- Chaîne p-p



• étoiles

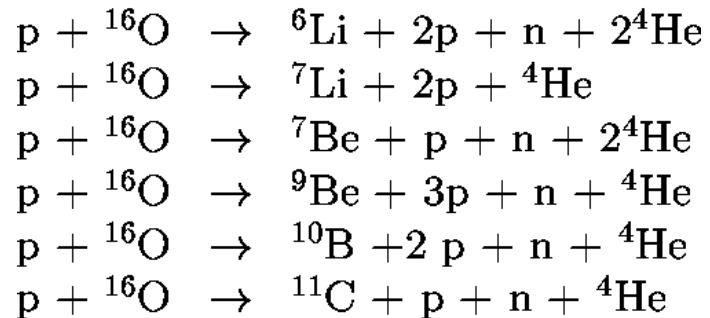
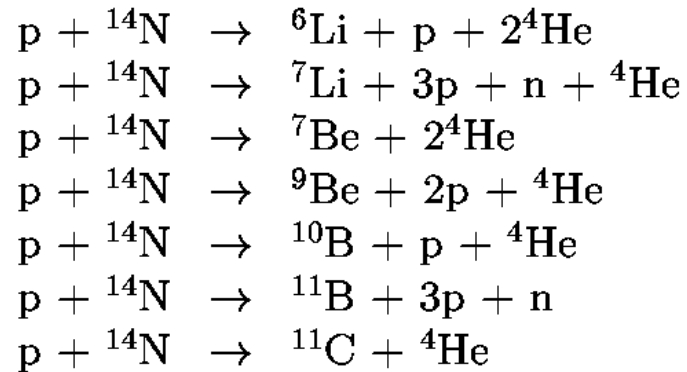
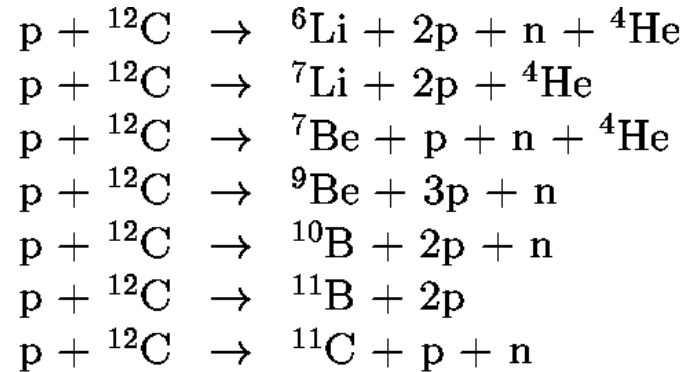
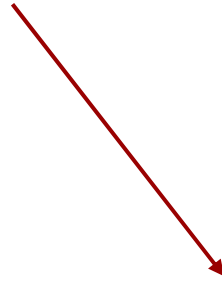
• → métallicité

# Abondance de l'hélium

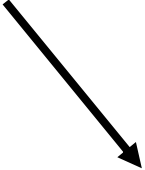
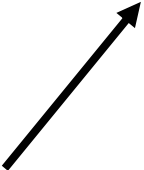
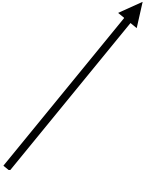
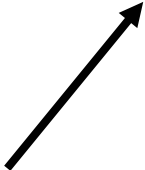
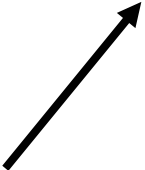


# Réactions de spallation dans le gaz interstellaire

Réactions de spallation  
entre un proton  
des rayons cosmiques  
et un noyau lourd  
du gaz interstellaire



Isotope	D	$^3\text{He}$	$^4\text{He}$	Li	Be	B
Abondance	0,001 %	0,001 %	10 %	$10^{-7}$ %	$10^{-9}$ %	$10^{-8}$ %
Origine présumée	Big Bang	Big Bang Étoiles	Big Bang Étoiles	Big Bang Étoiles Spallation	Spallation	Spallation

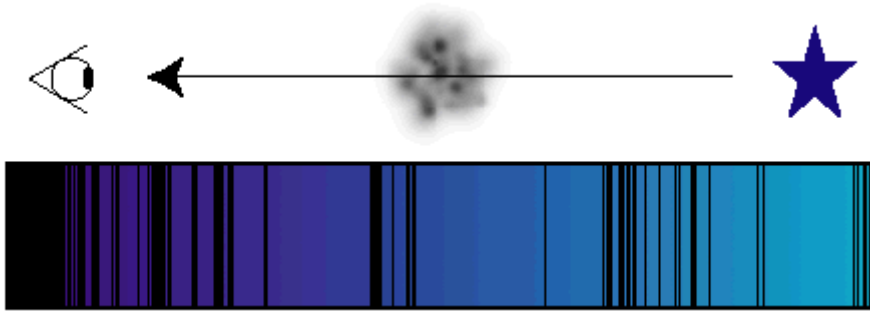
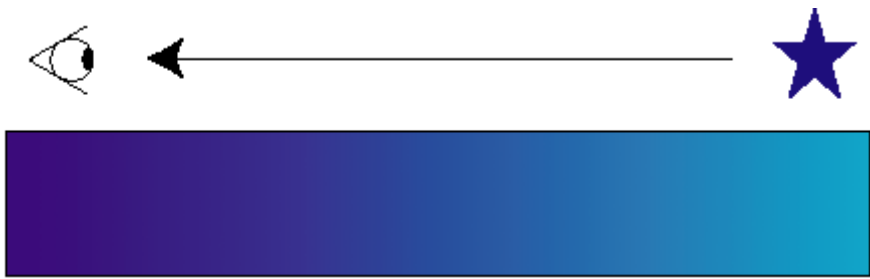
Isotope	D	$^3\text{He}$	$^4\text{He}$	Li	Be	B
Évolution de l'abondance		?				





Comment réalise-t-on  
ces mesures d'abondances ?

→ **spectroscopie**





**Hydrogène (H)**



**Deutérium (D)**



**Hydrogène moléculaire (H<sub>2</sub>)**



**Carbone (C)**



**Azote (N)**



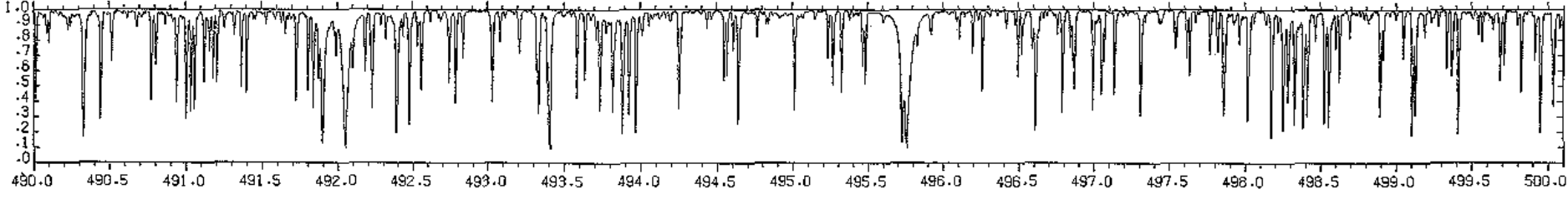
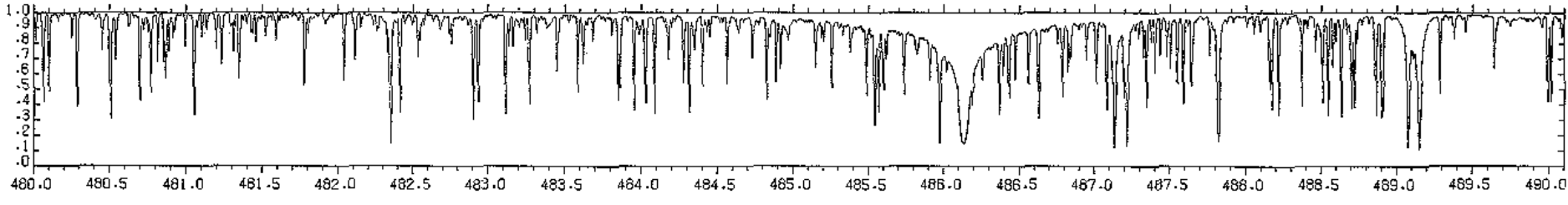
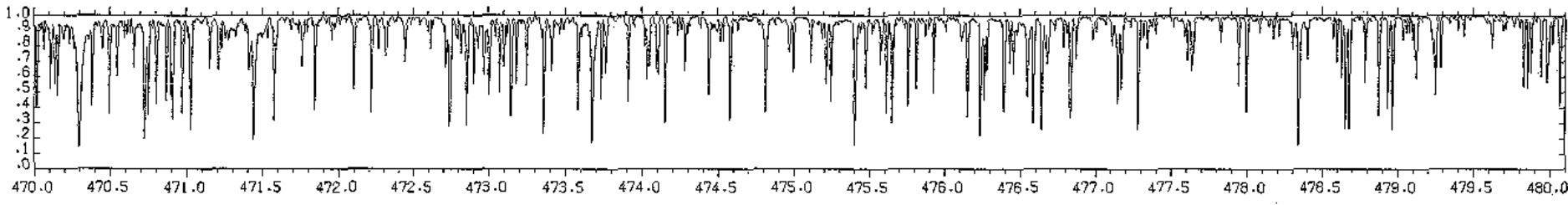
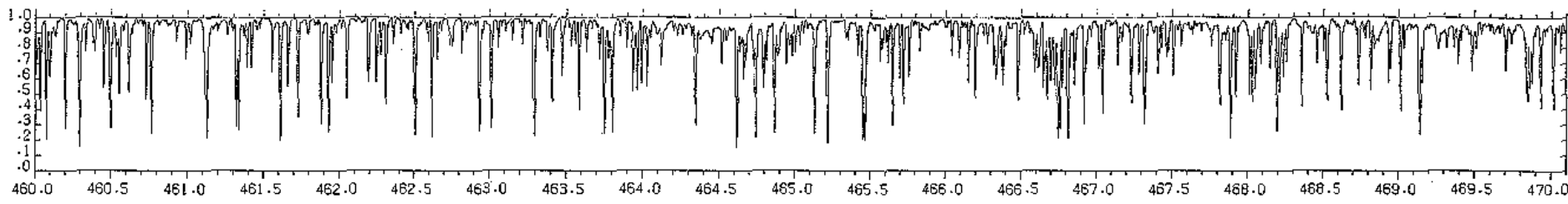
**Oxygène (O)**



**Fer (Fe)**

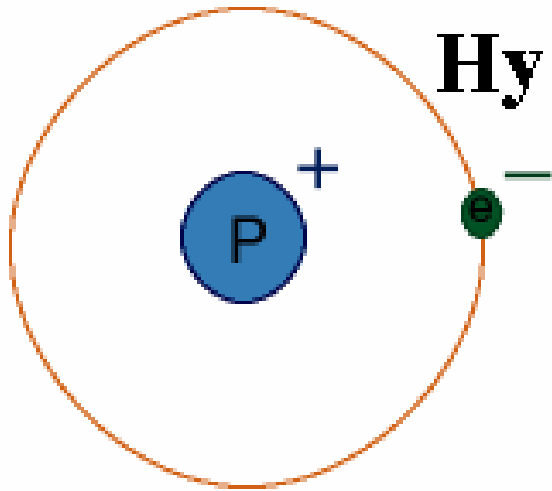


**H + C + N + O**

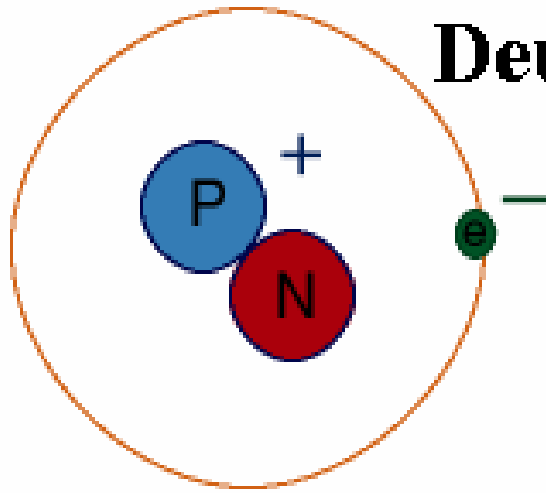


Spectre du Soleil

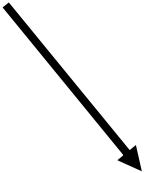
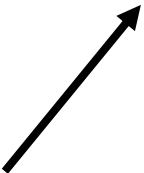
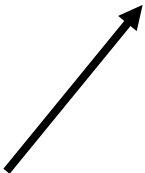
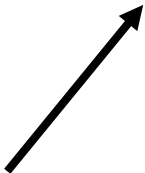
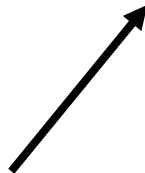
**Hydrogène**



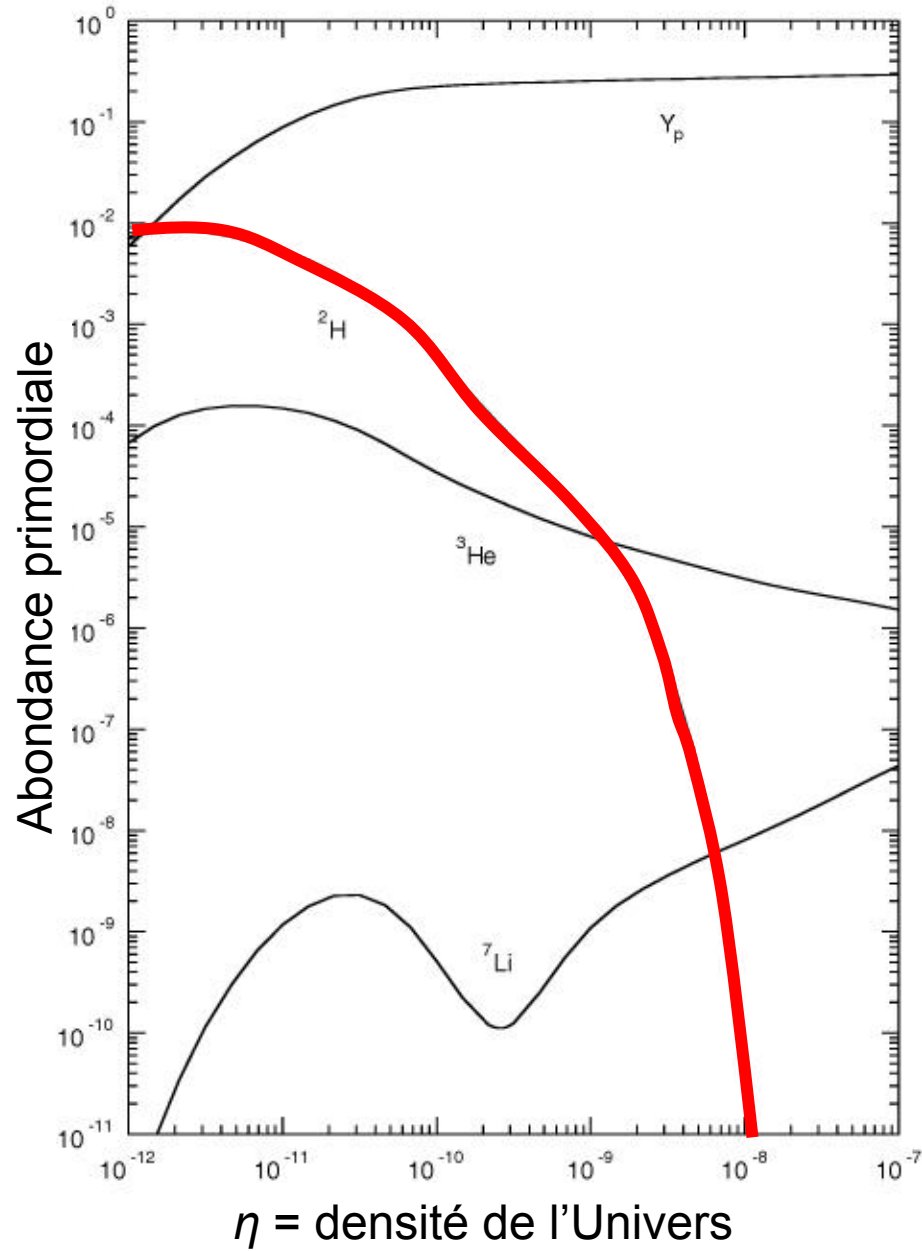
**Deutérium**



Isotope	D	$^3\text{He}$	$^4\text{He}$	Li	Be	B
Abondance	0,001 %	0,001 %	10 %	$10^{-7}$ %	$10^{-9}$ %	$10^{-8}$ %
Origine Présumée	Big Bang	Big Bang Étoiles	Big Bang Étoiles	Big Bang Étoiles Spallation	Spallation	Spallation

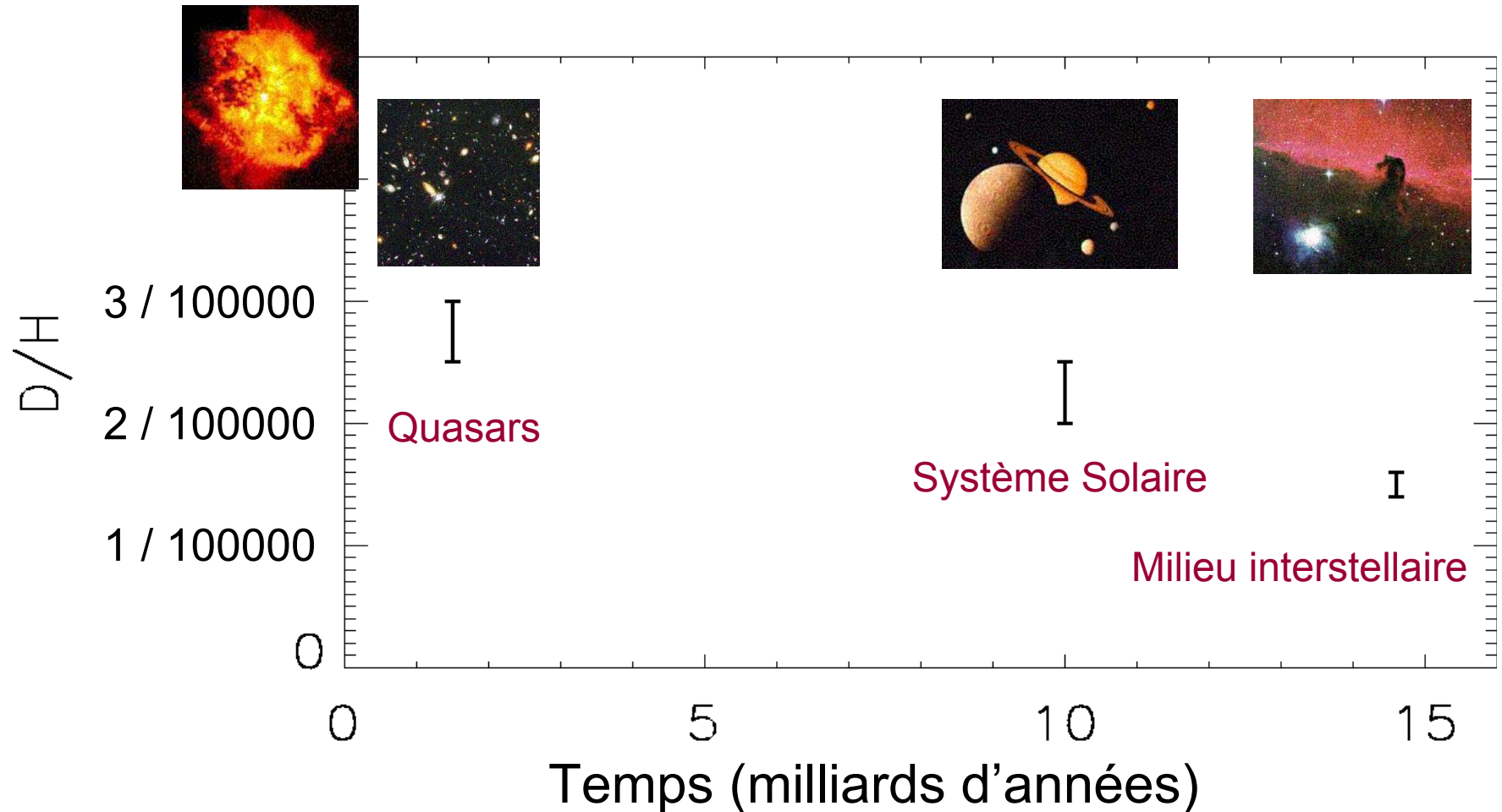
Isotope	D	$^3\text{He}$	$^4\text{He}$	Li	Be	B
Évolution de l'abondance		?				

Courbes « *abondances / densité* »



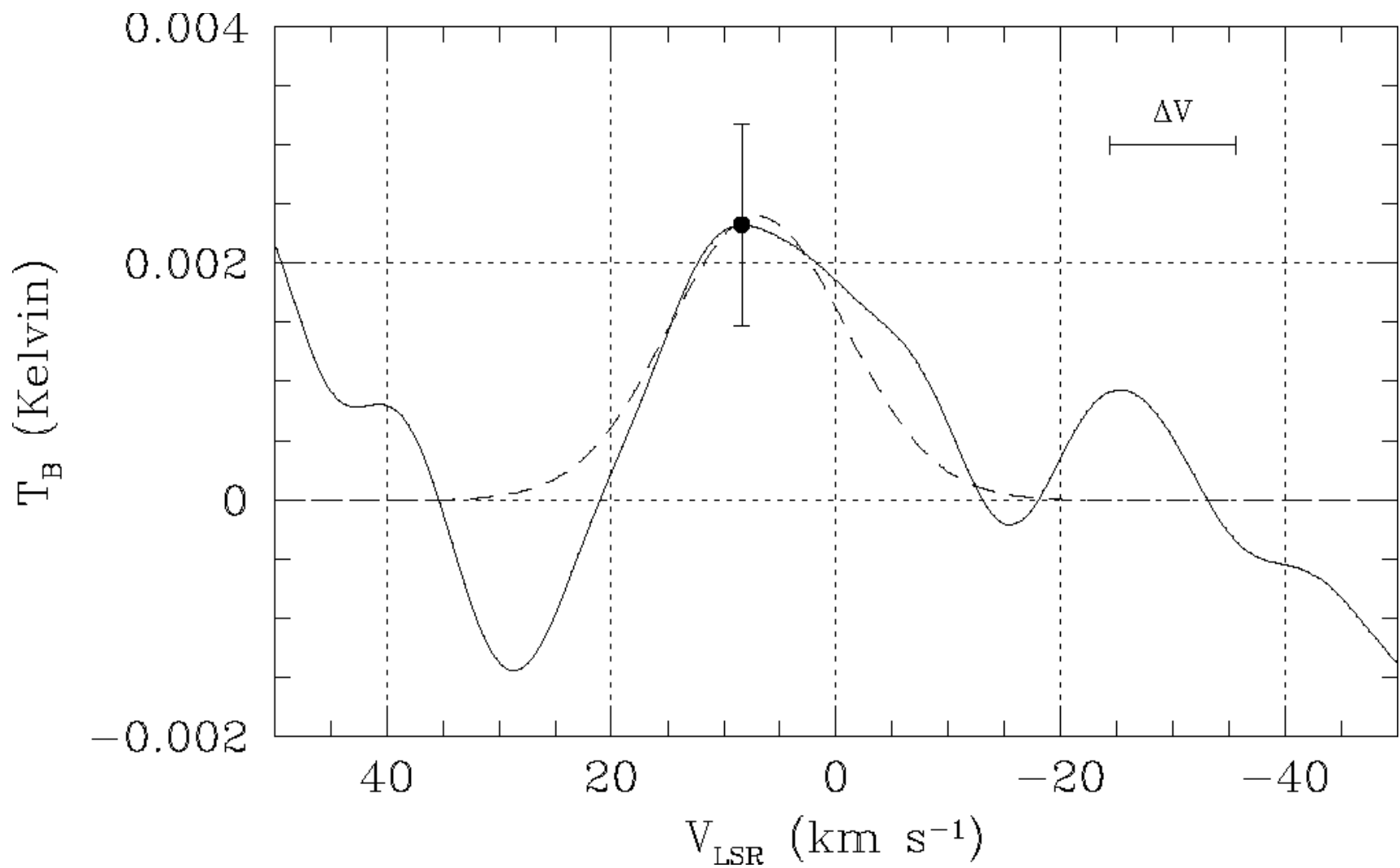
# Trois types de mesure d'abondance du deutérium :

- Primordiale (14 milliards d'années)
- Proto-solaire (4,5 milliards d'années)
- Époque actuelle (0 milliard d'année !)





# Raie D I à 92 cm



$$D/H = (3,9 \pm 1,0) \times 10^{-5}$$

# D dans les molécules

K. JEFFERTS, A. PENZIAS, AND R. WILSON (1973)

HD, DCN, CH<sub>3</sub>D...

$D/H = 10^{-2} - 10^{-6}$

(fractionnement moléculaire)

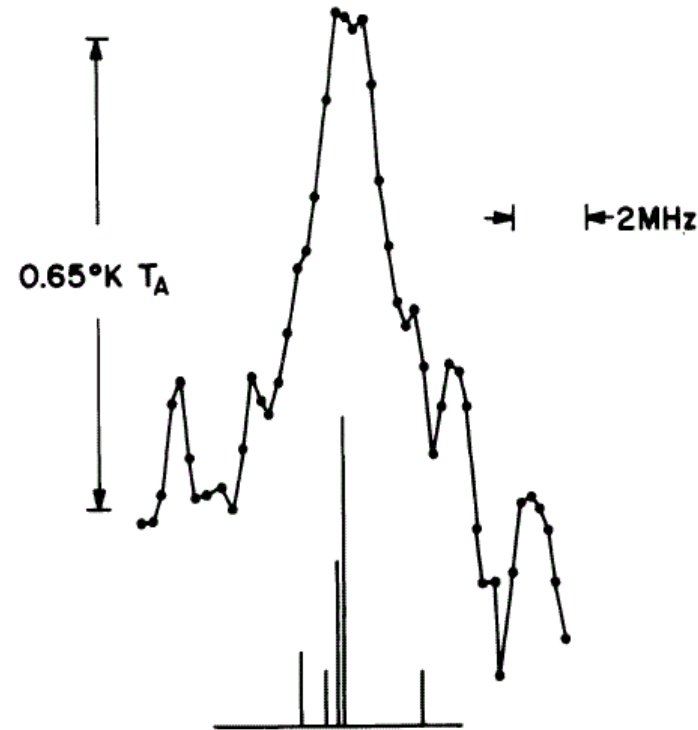
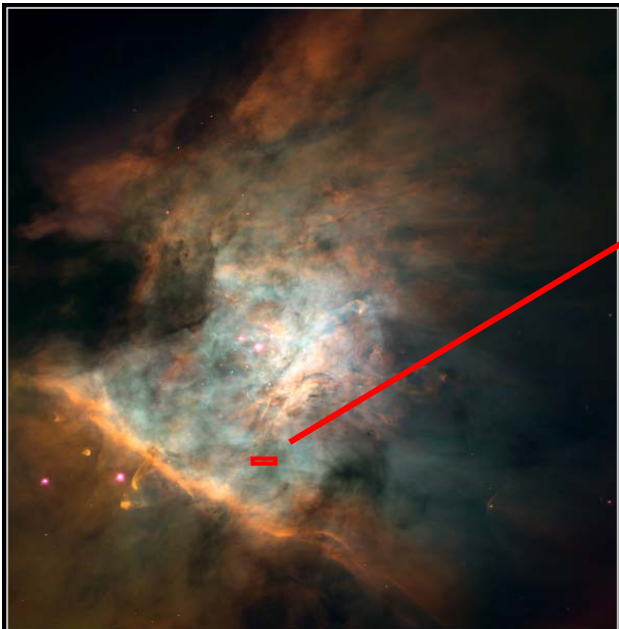
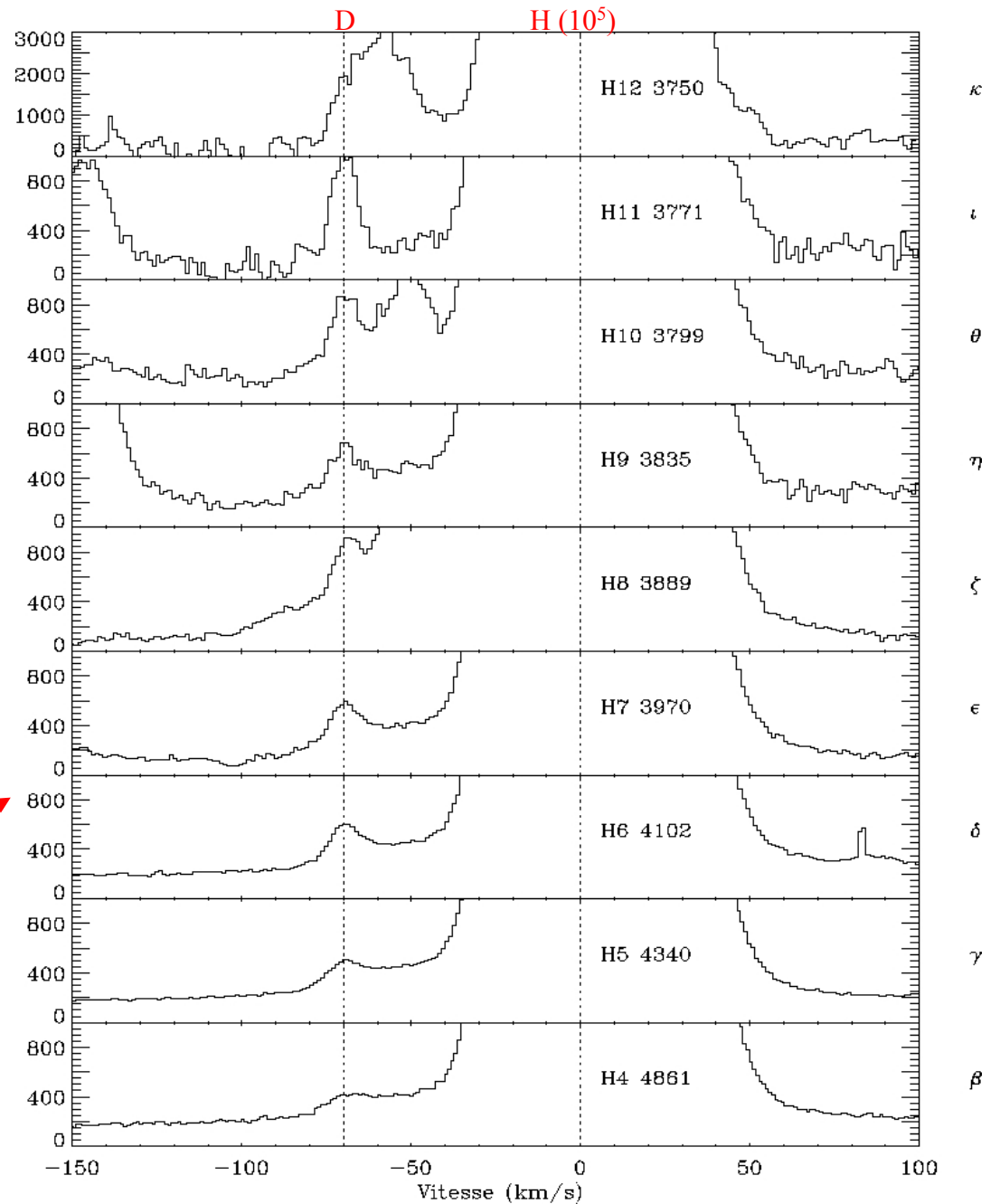


FIG. 1.—The 144,828-MHz line. The  $J=2$  to  $J=1$  DCN multiplet is plotted on the same frequency scale assuming an LSR velocity of  $9 \text{ km s}^{-1}$ . The data are plotted as received from the spectrometer smoothed between adjacent points using a 0.25, 0.5, 0.25 weighting function.

# Deuterium Balmer series

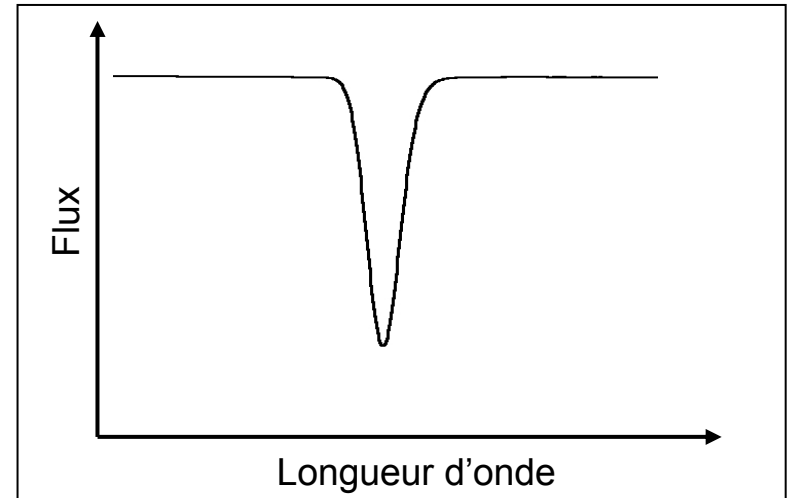
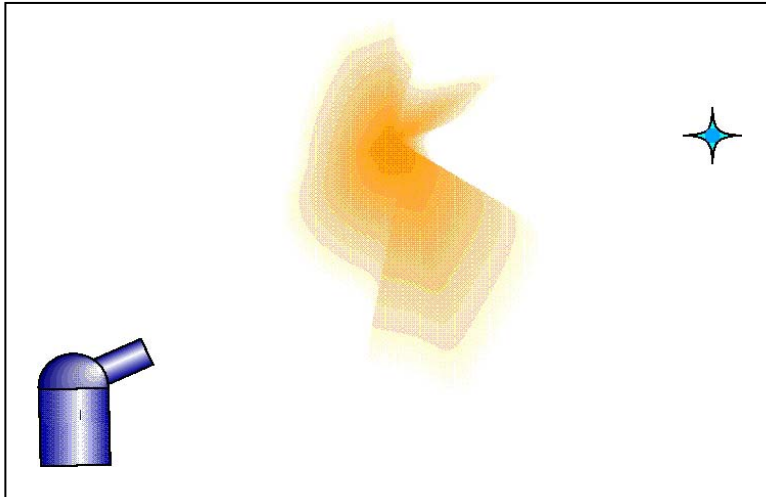


Orion Nebula Mosaic HST · WFPC2  
PRC95-45a · ST ScI OPO · November 20, 1995  
C. R. O'Dell and S. K. Wong (Rice University), NASA



# Série de Lyman

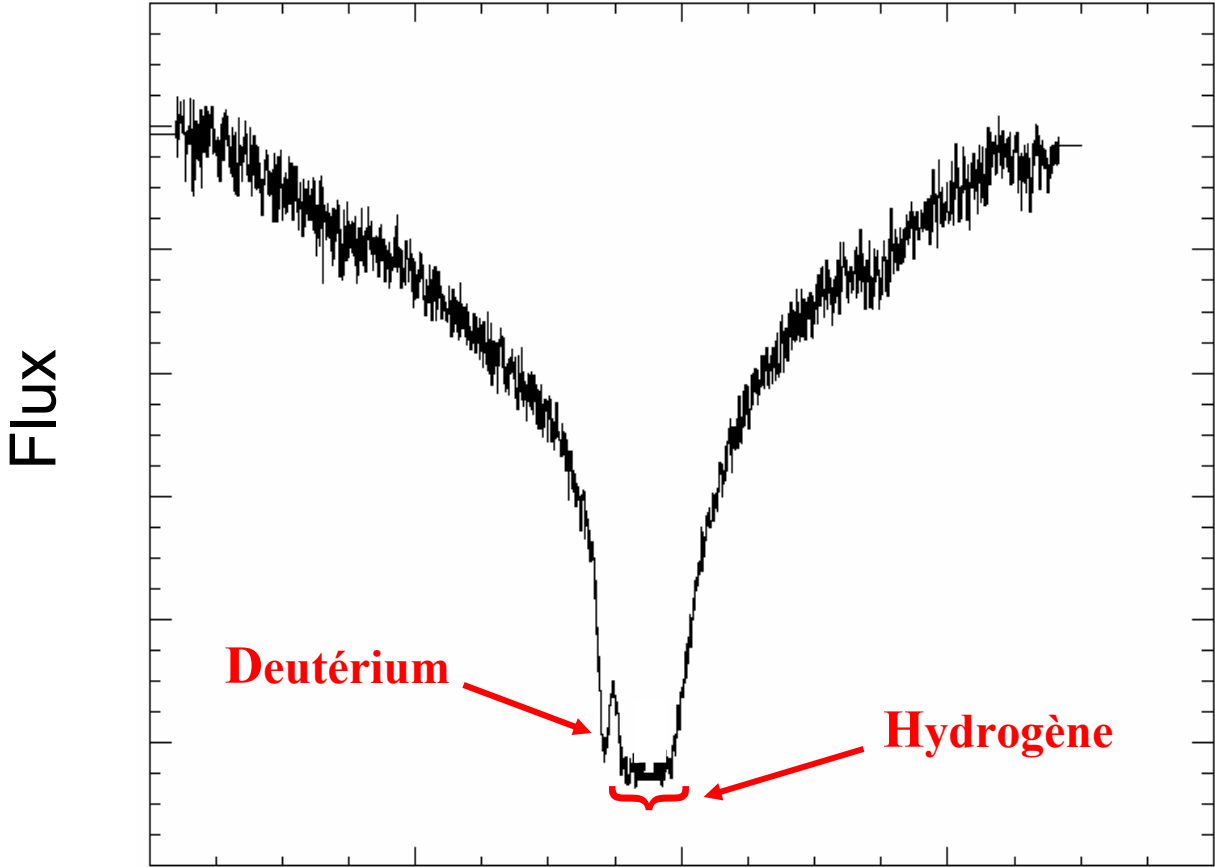
## Raies d'absorption interstellaires



- Densité de colonne ( $\text{cm}^{-2}$ )
- Vitesse radiale (km/s)
- Température ( $^{\circ}\text{K}$ )
- Vitesse de turbulence (km/s)

$$\left. \begin{array}{l} \text{Température } (^{\circ}\text{K}) \\ \text{Vitesse de turbulence (km/s)} \end{array} \right\} b^2 = (2kT / M) + v_{\text{turb}}^2$$

# Raie Lyman alpha

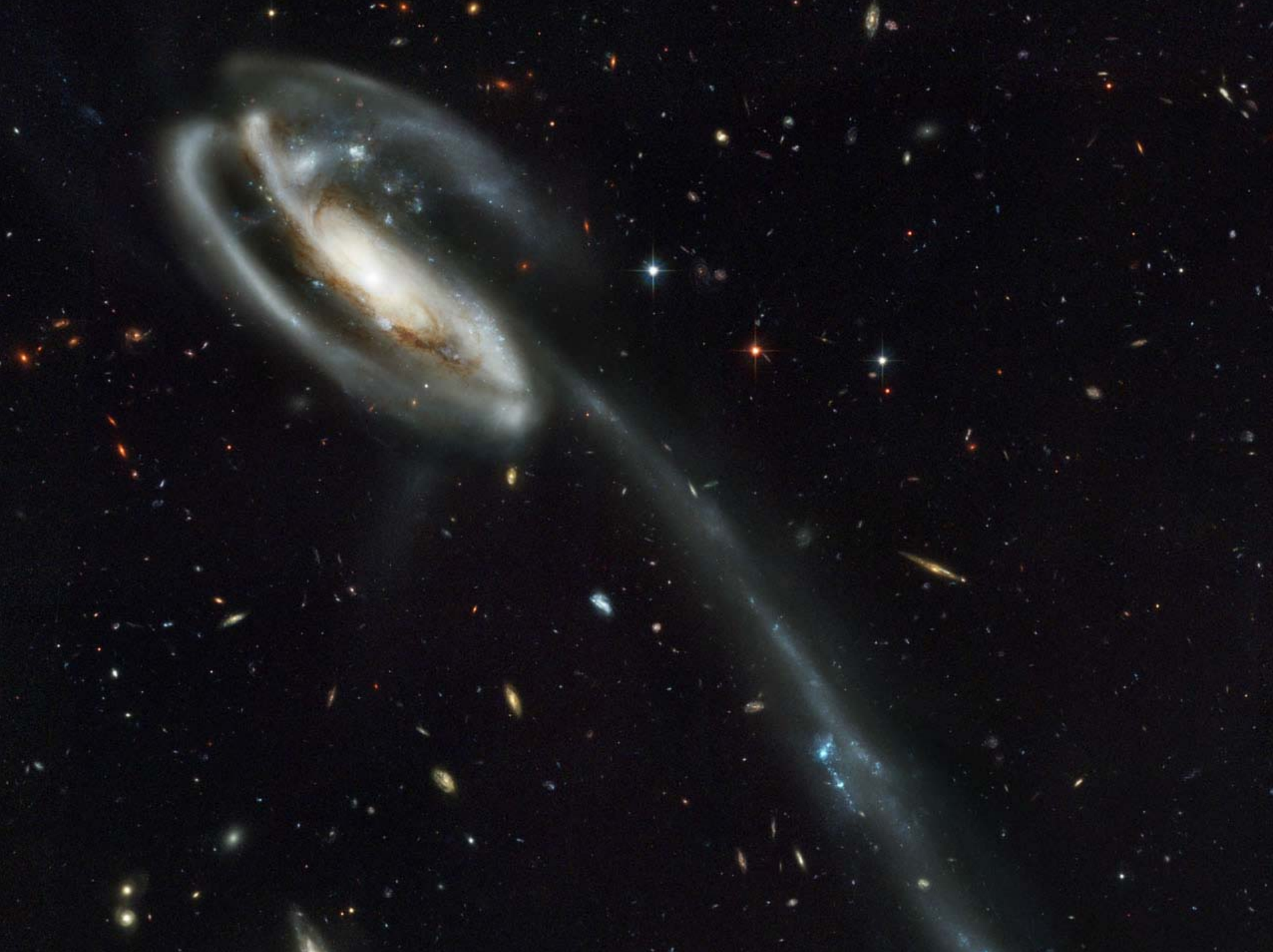


ultraviolets →

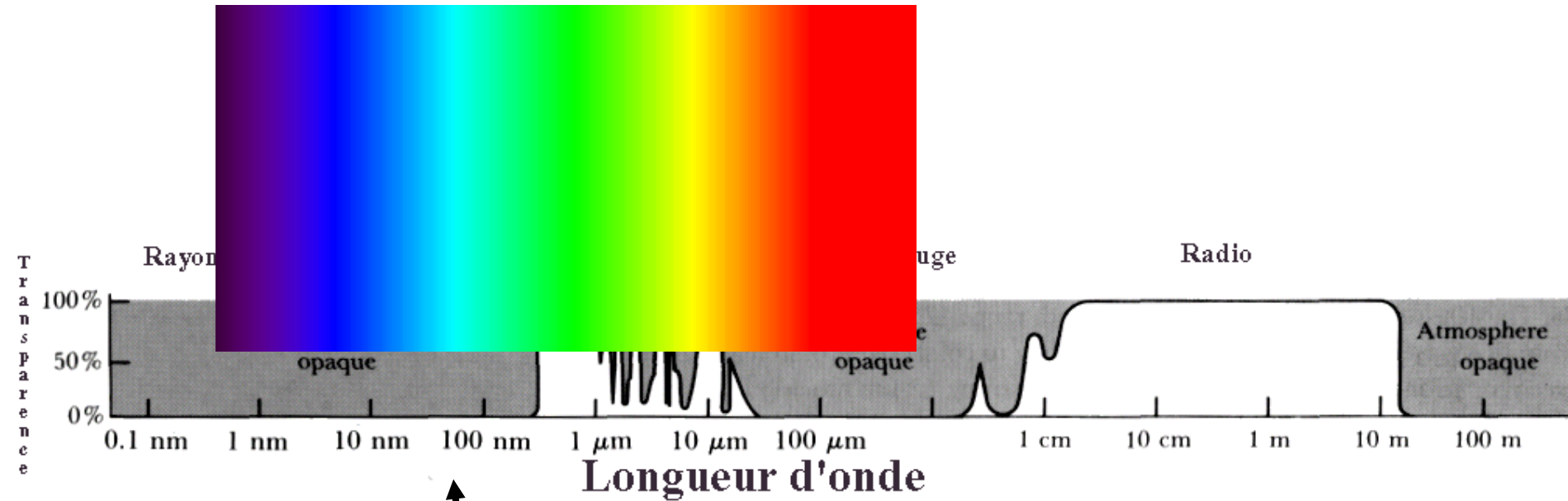
1212      1214      1216      1218      1220

Longueur d'onde (Å)





# La transparence de l'atmosphère

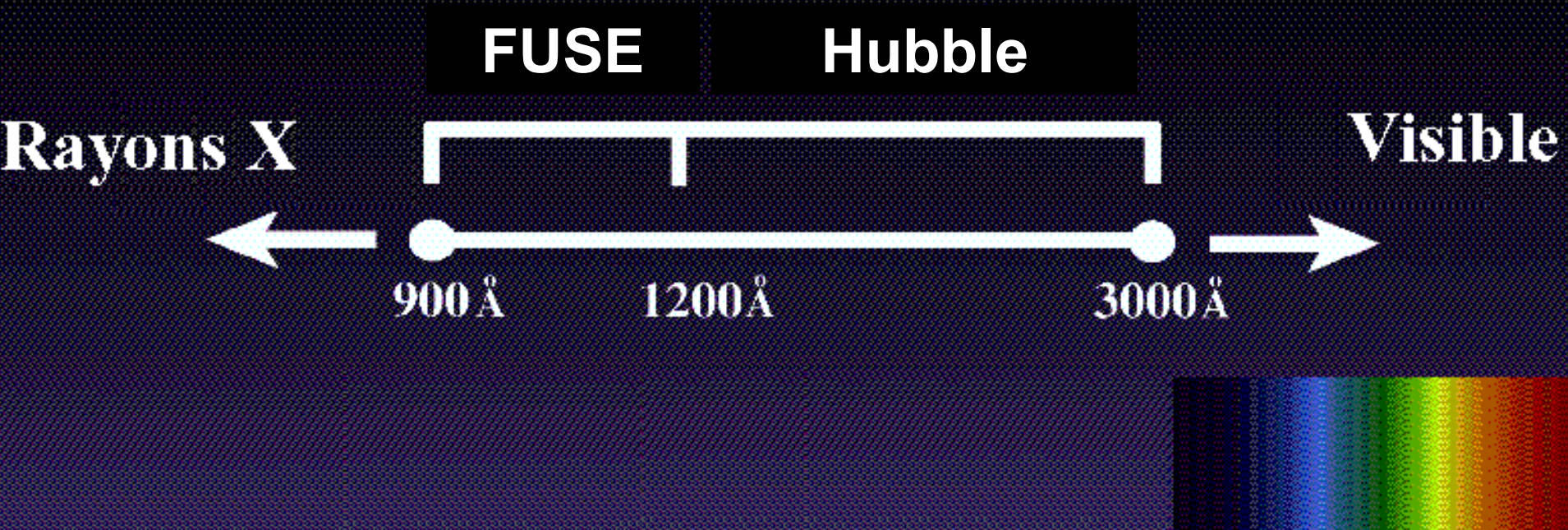


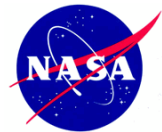
Raies du deutérium



# Deux télescopes pour l'ultraviolet :

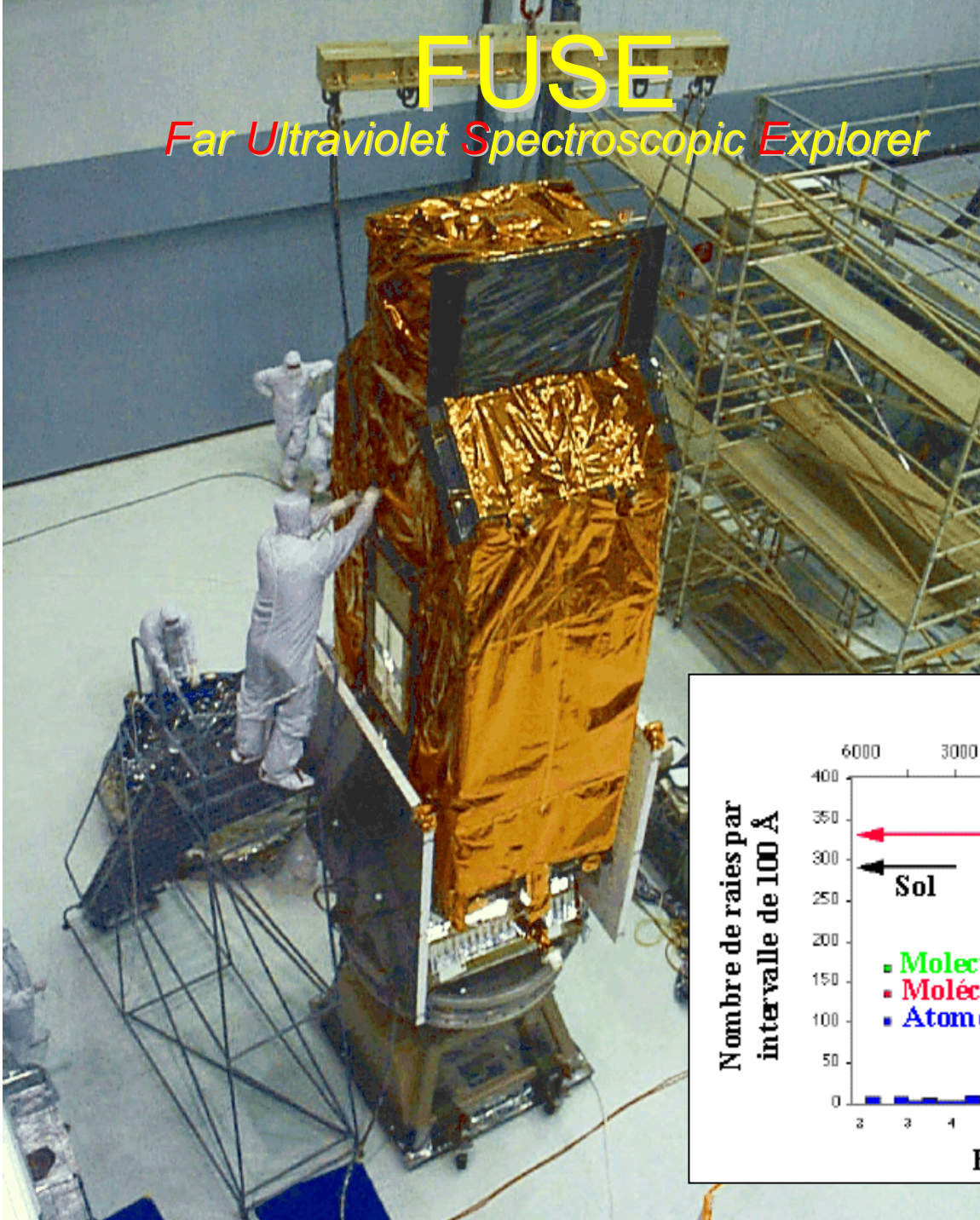
## FUSE et le Télescope Spatial Hubble



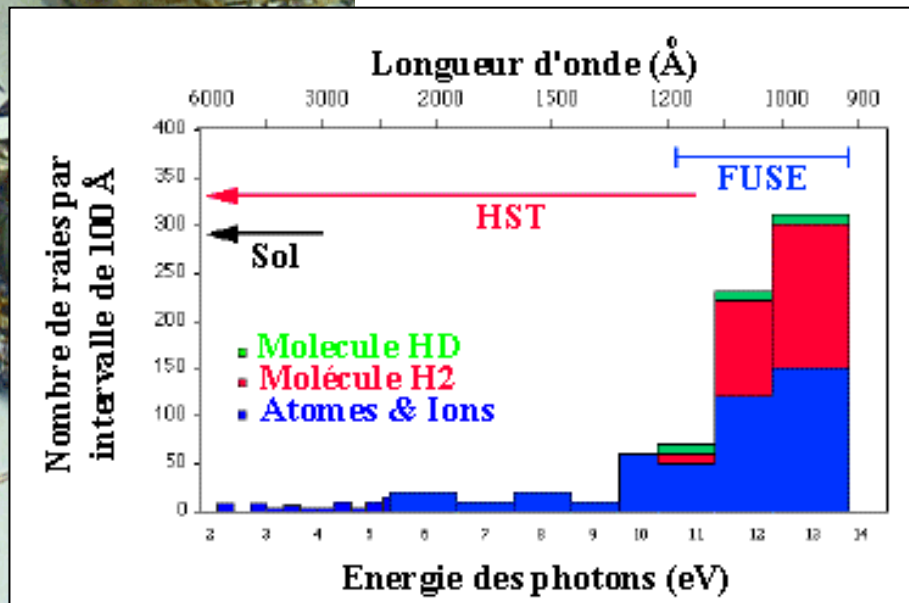


# FUSE

*Far Ultraviolet Spectroscopic Explorer*




<http://fuse.iap.fr>

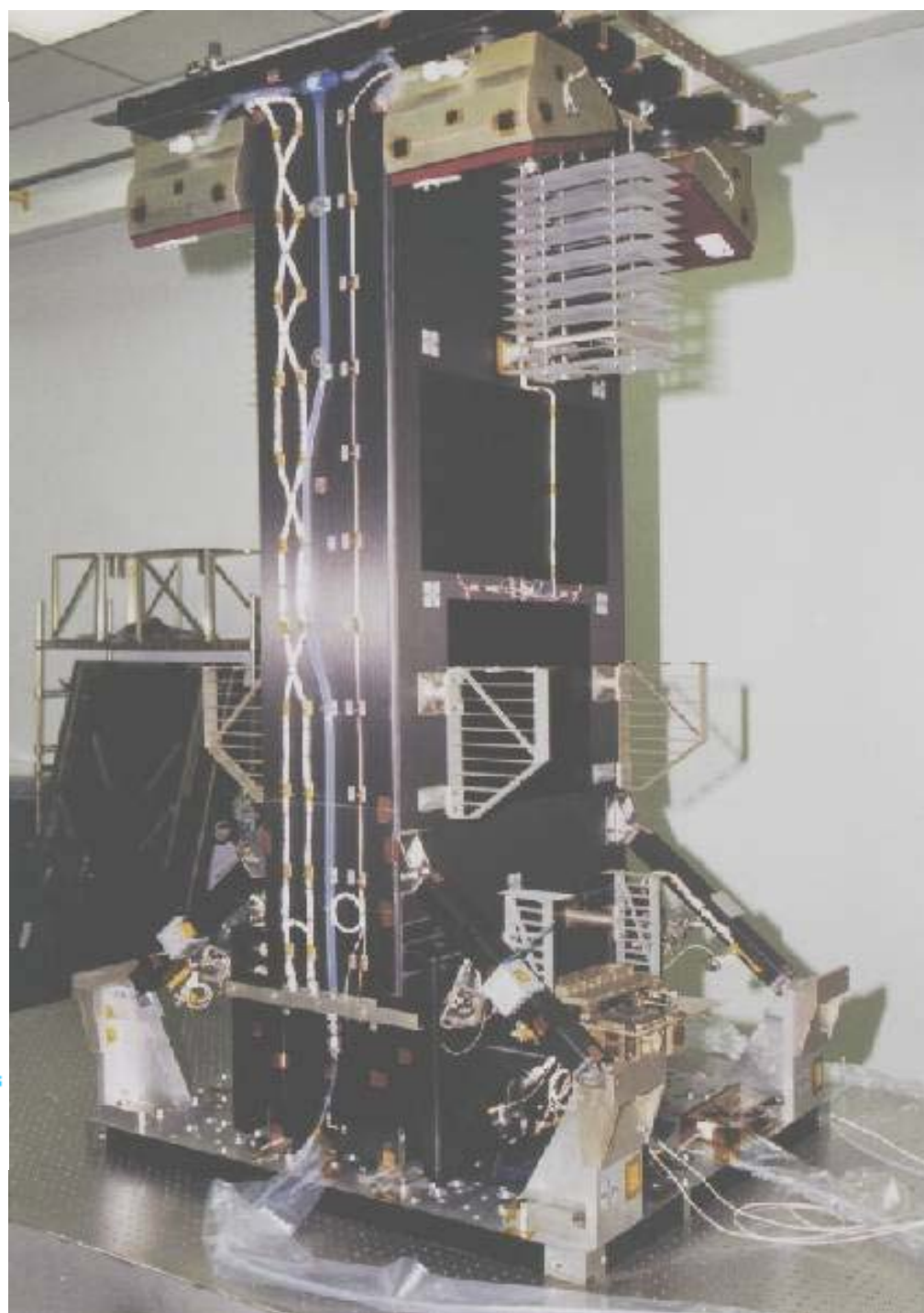
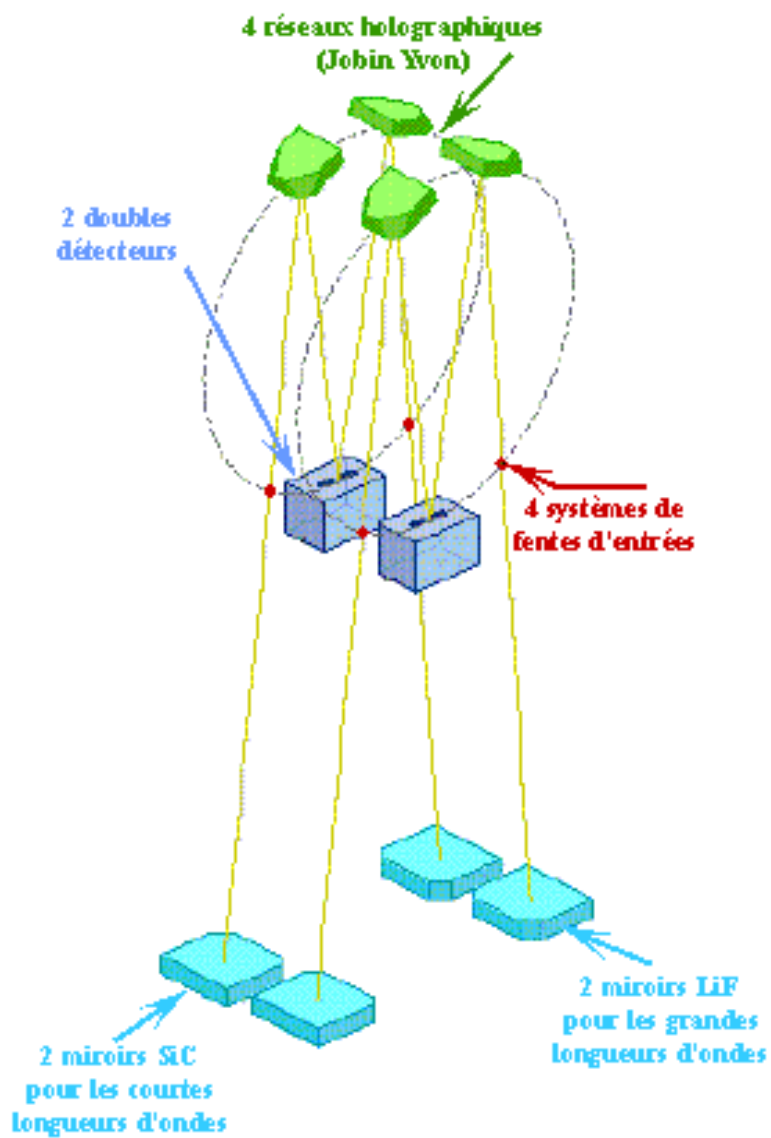




## Un des quatre réseaux holographiques courbés de FUSE



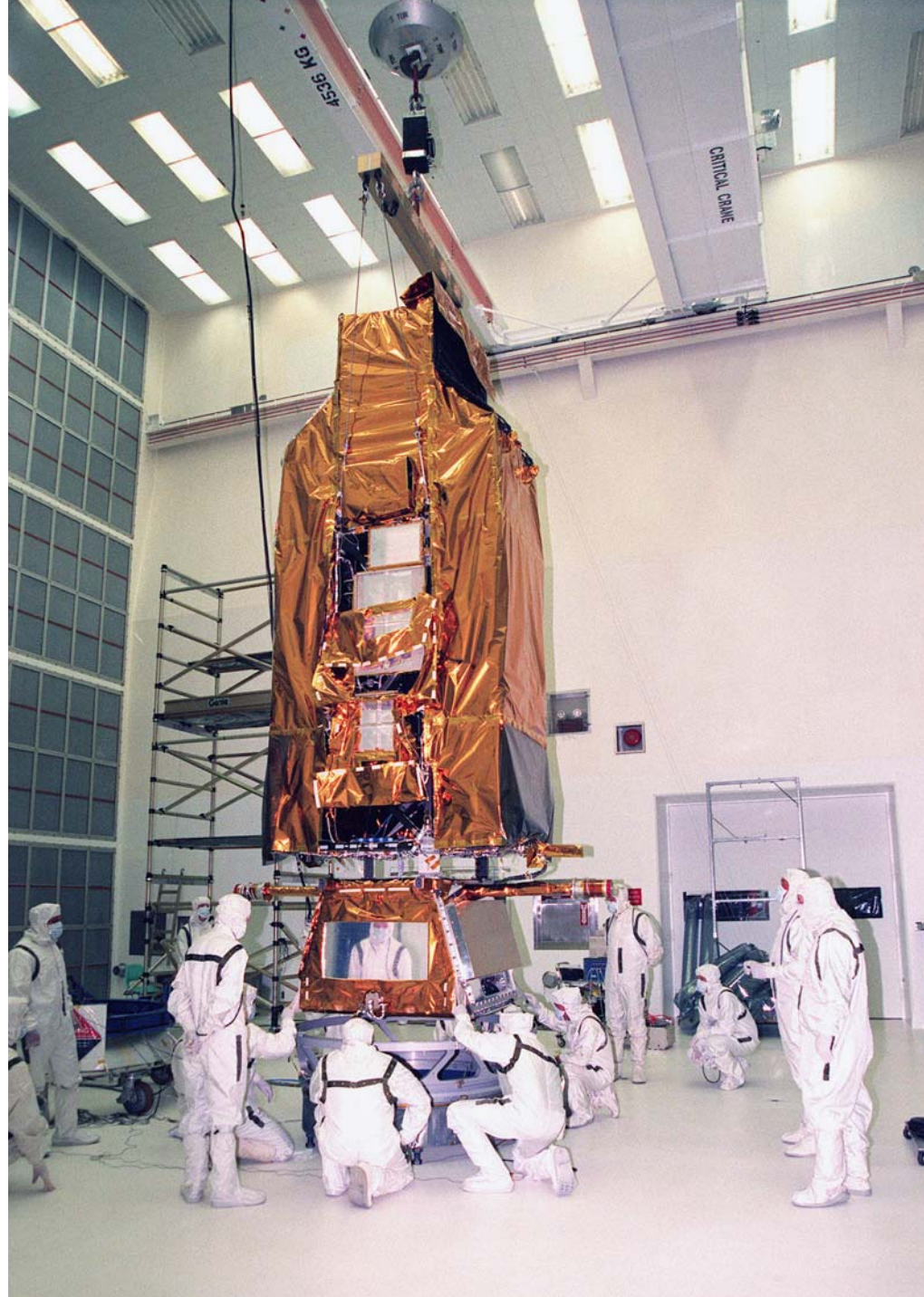
Ces réseaux ont été réalisés et testés en France.  
Leur taille est de 26,6 x 27,5 cm (dispersion x spatial).  
Leur densité de traits est 5767 tr/mm (SiC) ou 5350 tr/mm (LiF).  
Domaine spectral : de 900 à 1200 Å.  
Résolution spectrale : 15 km/s.



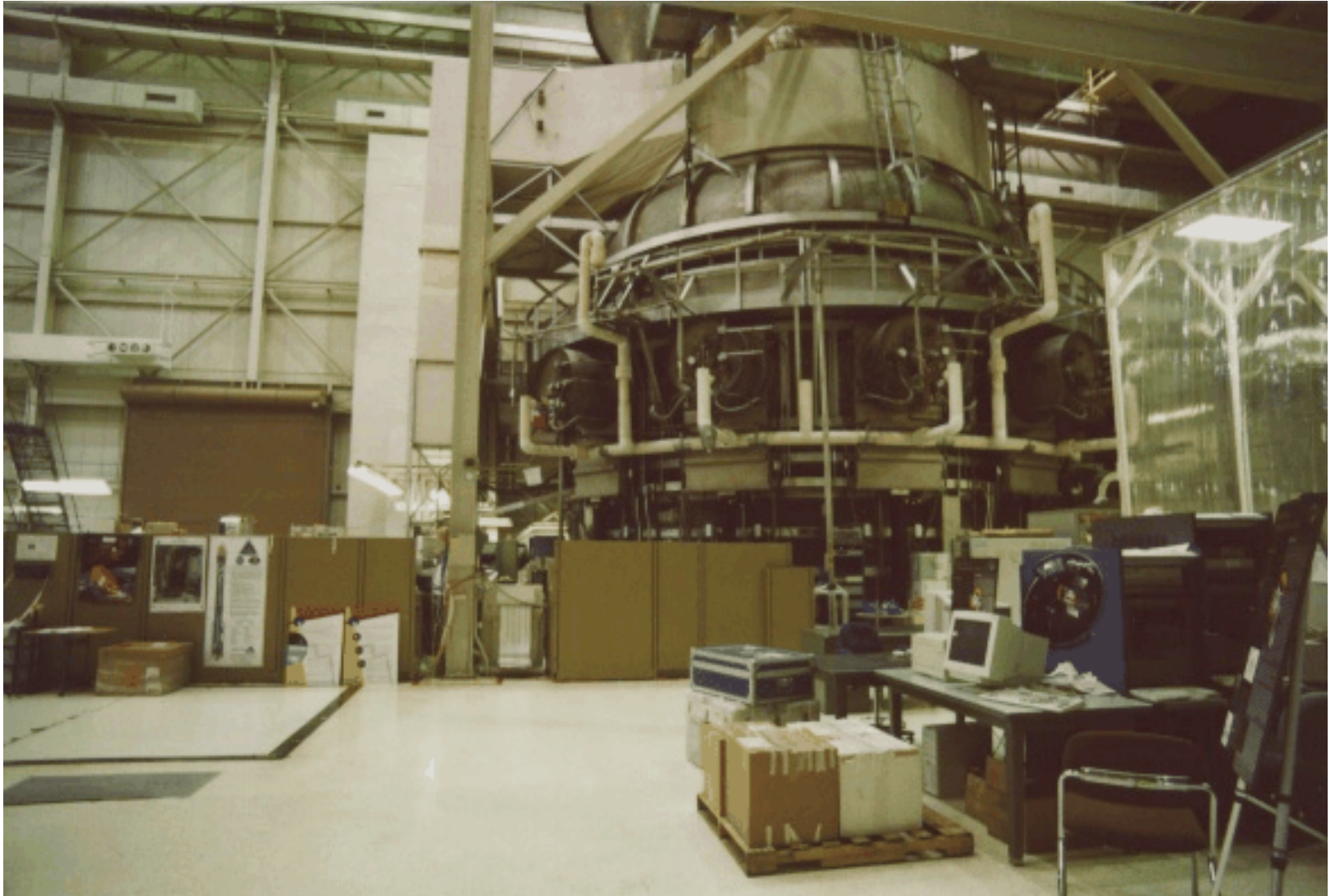


1360 kg

1,2m × 1,8m × 5,5m



# Simulateur d'environnement spatial





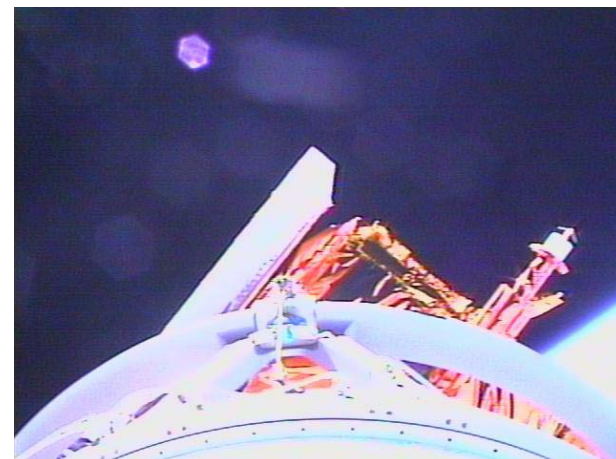
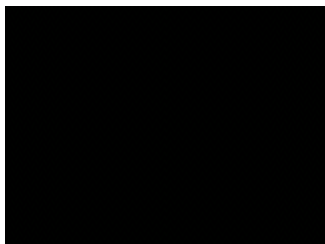


**24 juin 1999**  
**11:44**  
**Cap Canaveral**  
**Fusée Delta II 7320-10**



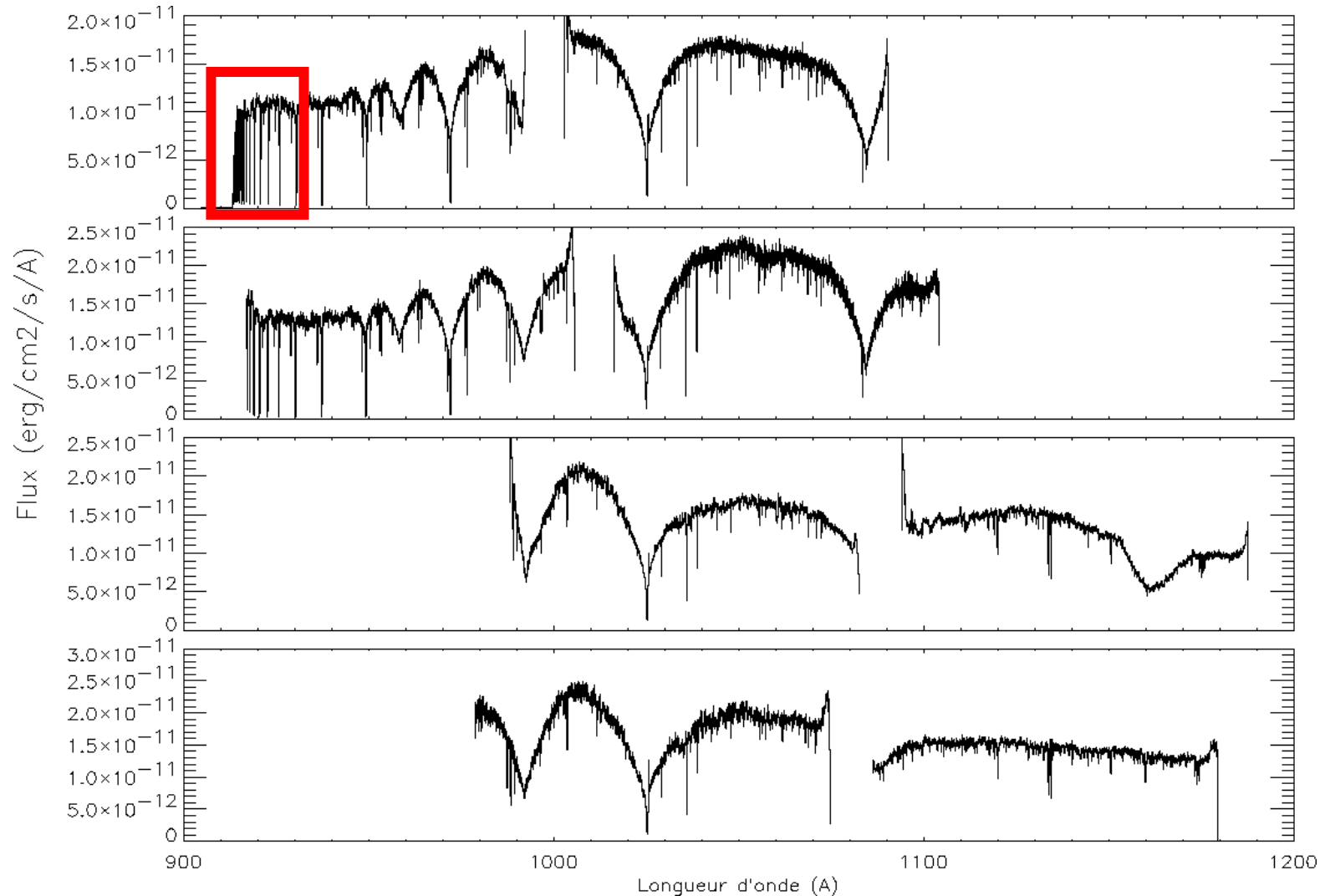


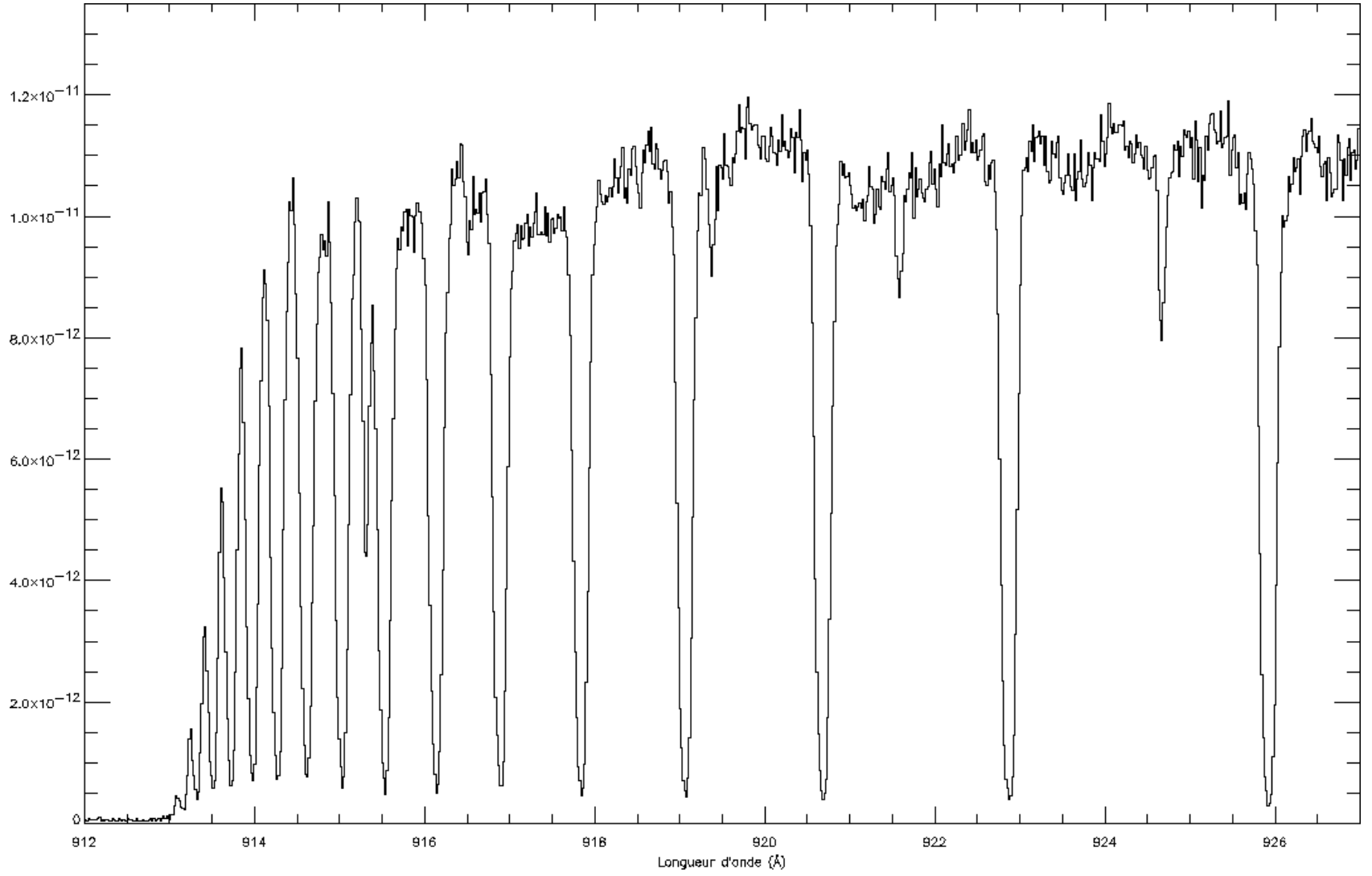
Orbite circulaire de 768 km d'altitude,  
inclinée à 25 degrés et  
de 100 minutes de période.



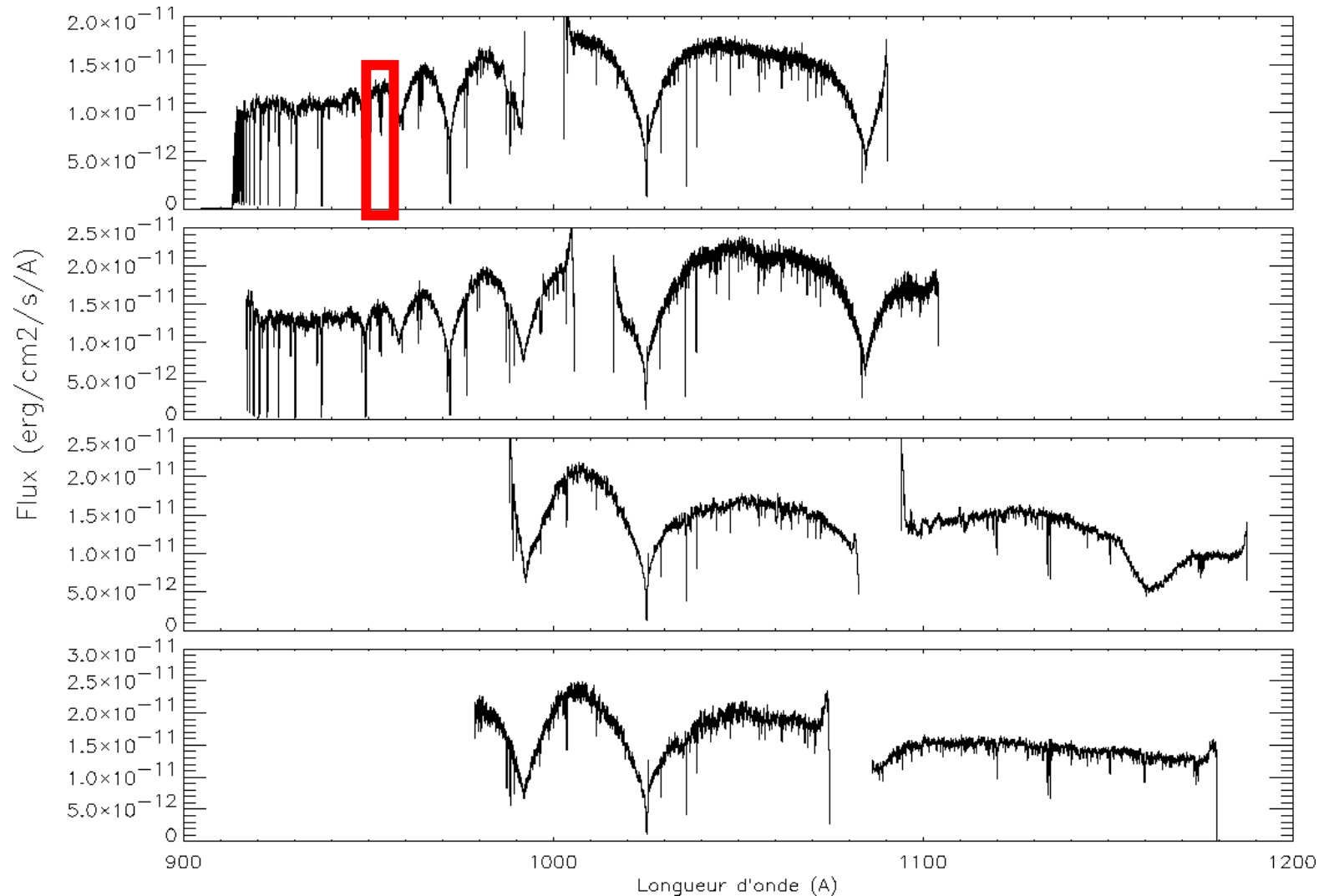


# Exemple de spectre FUSE

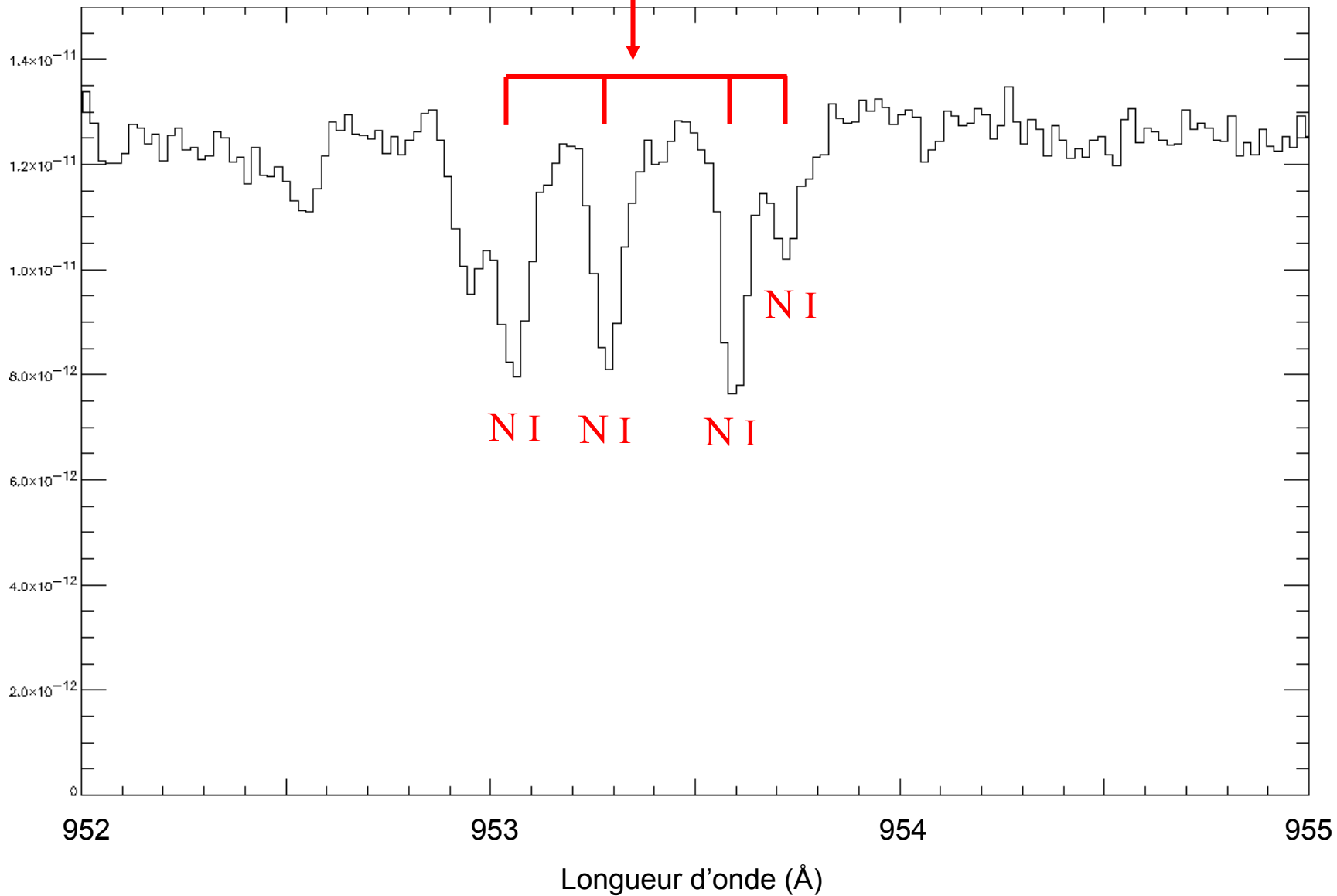




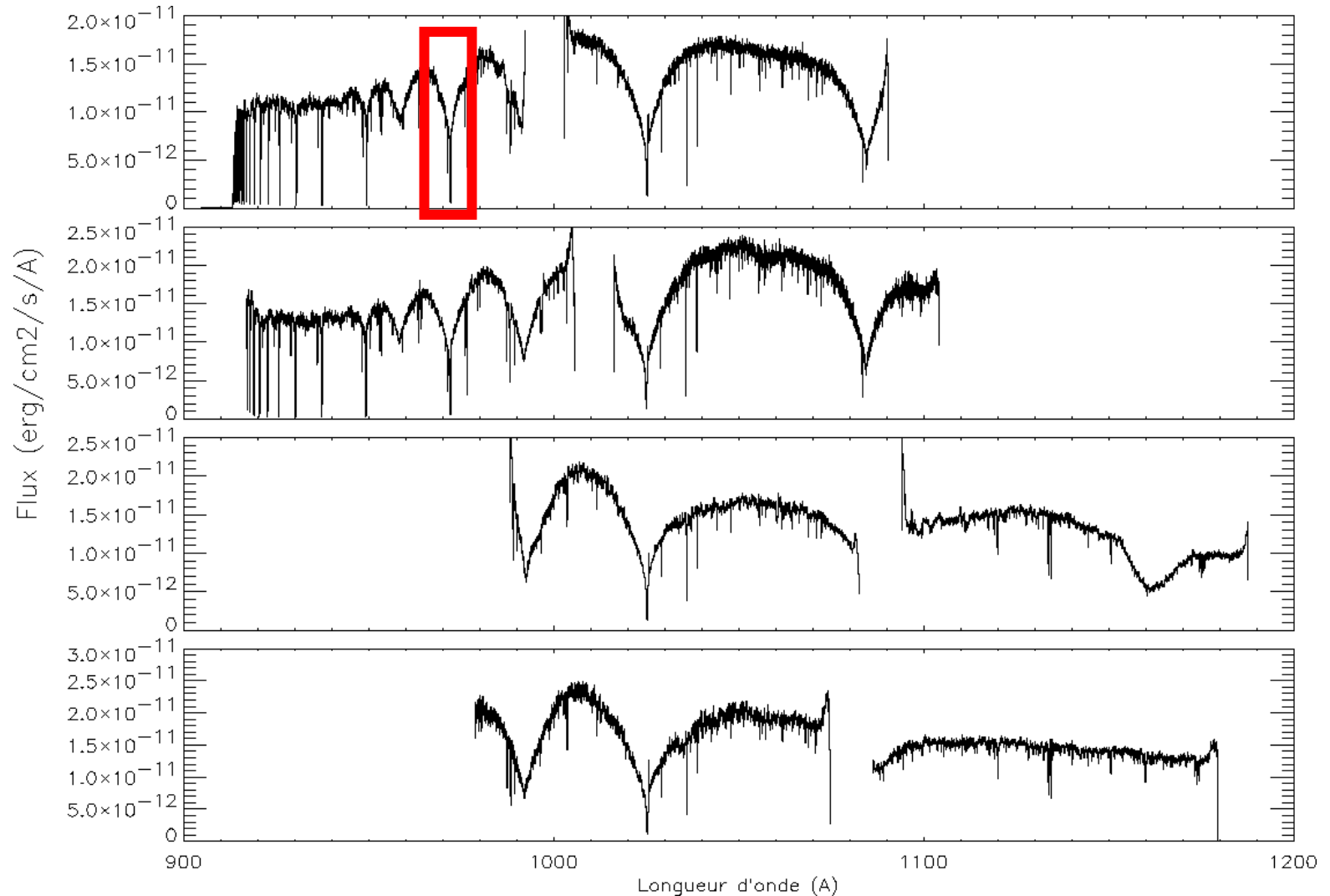
# Exemple de spectre FUSE



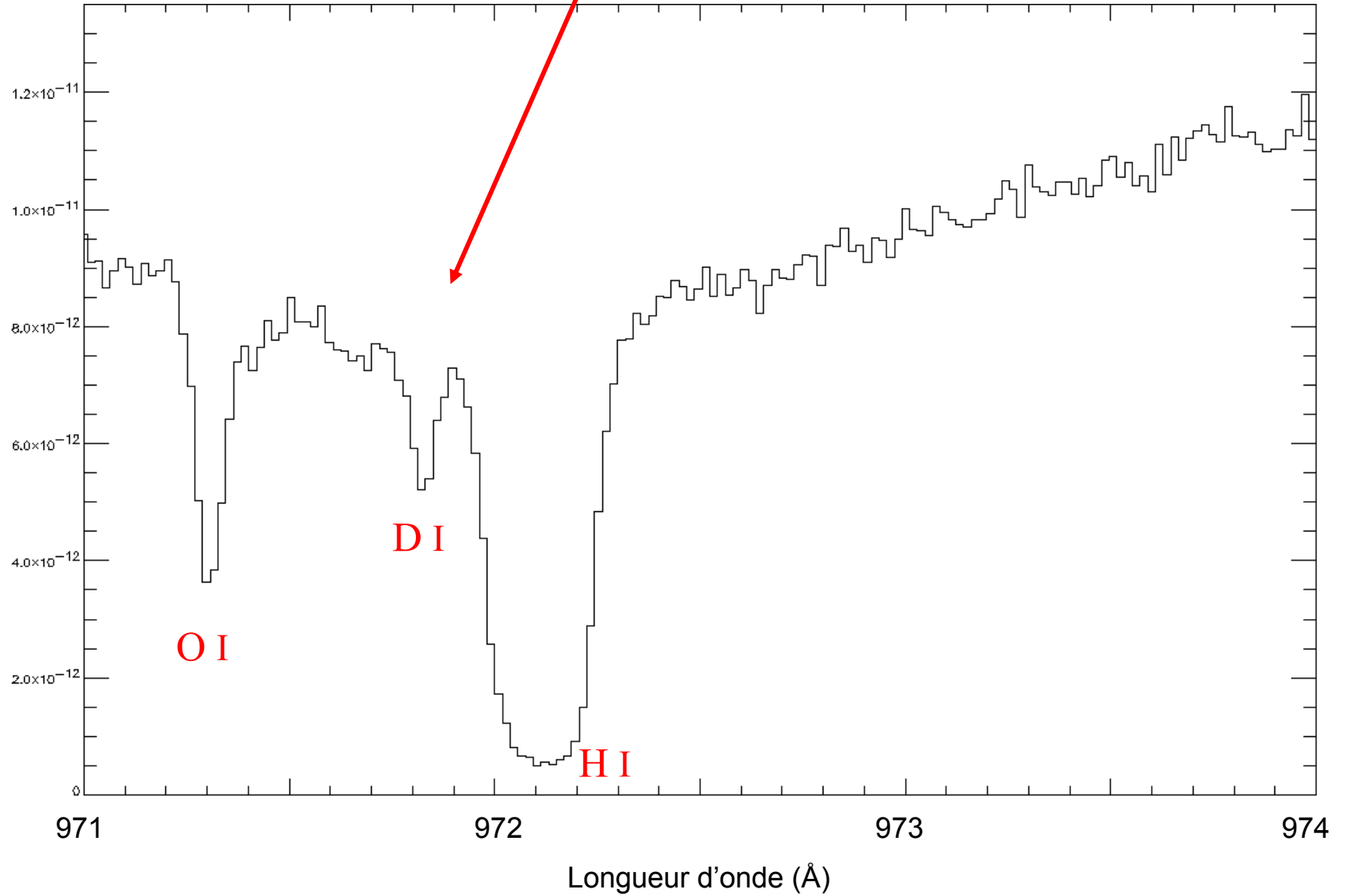
Azote



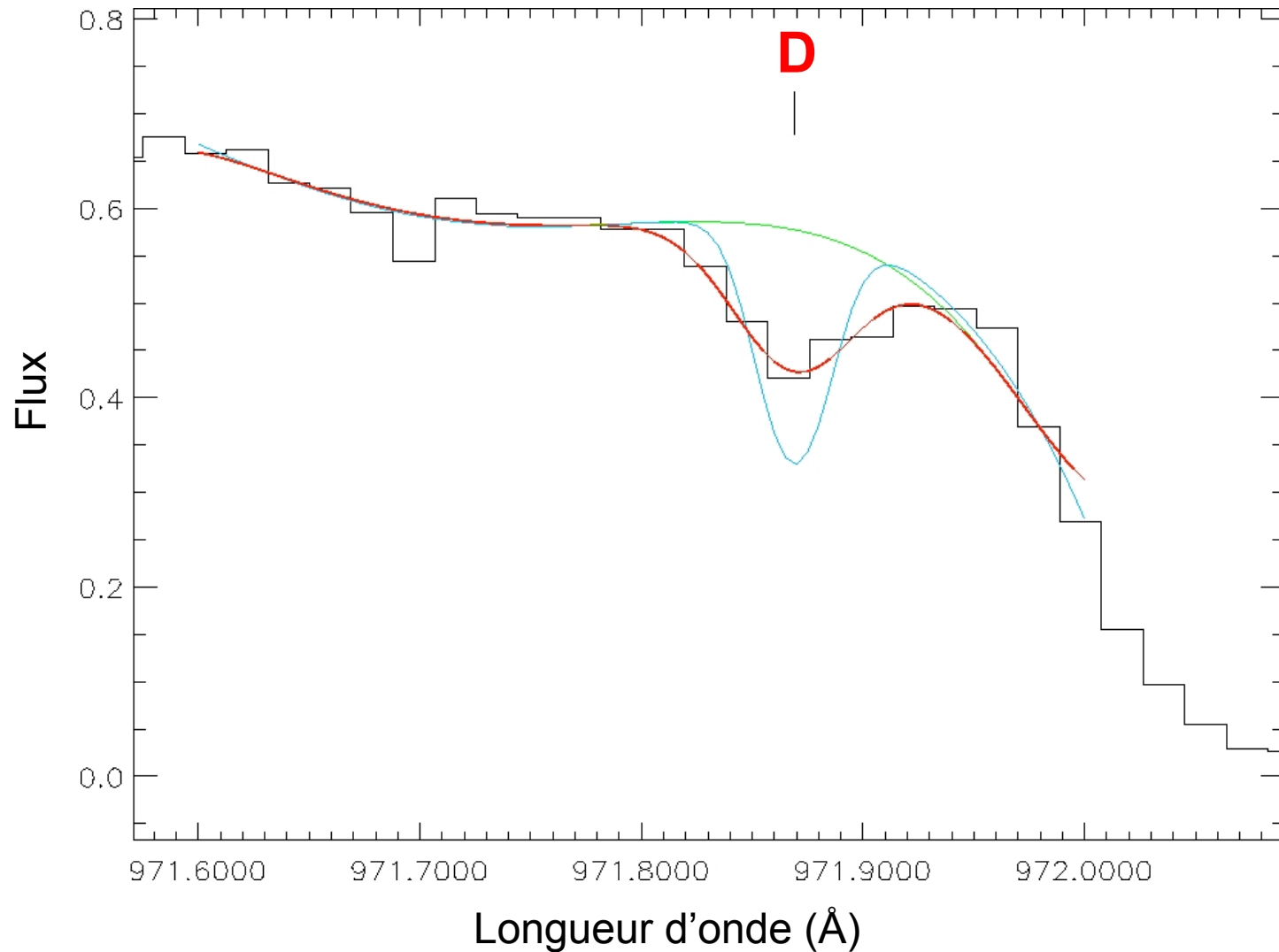
# Exemple de spectre FUSE



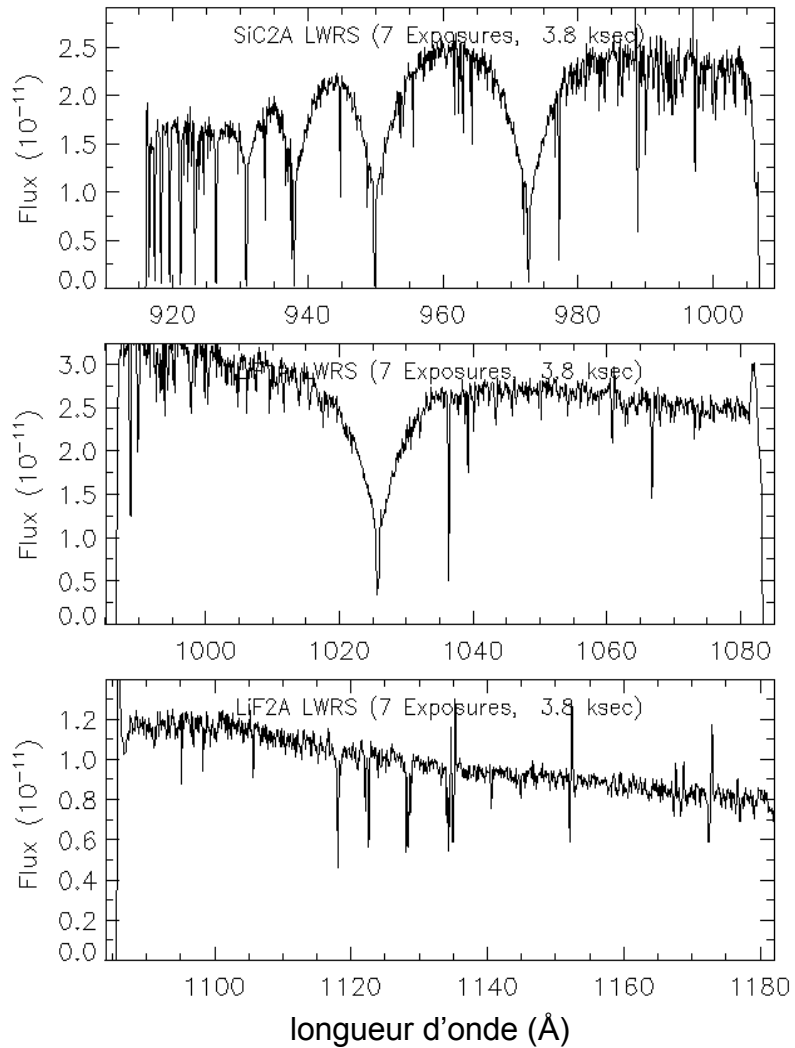
# Deutérium



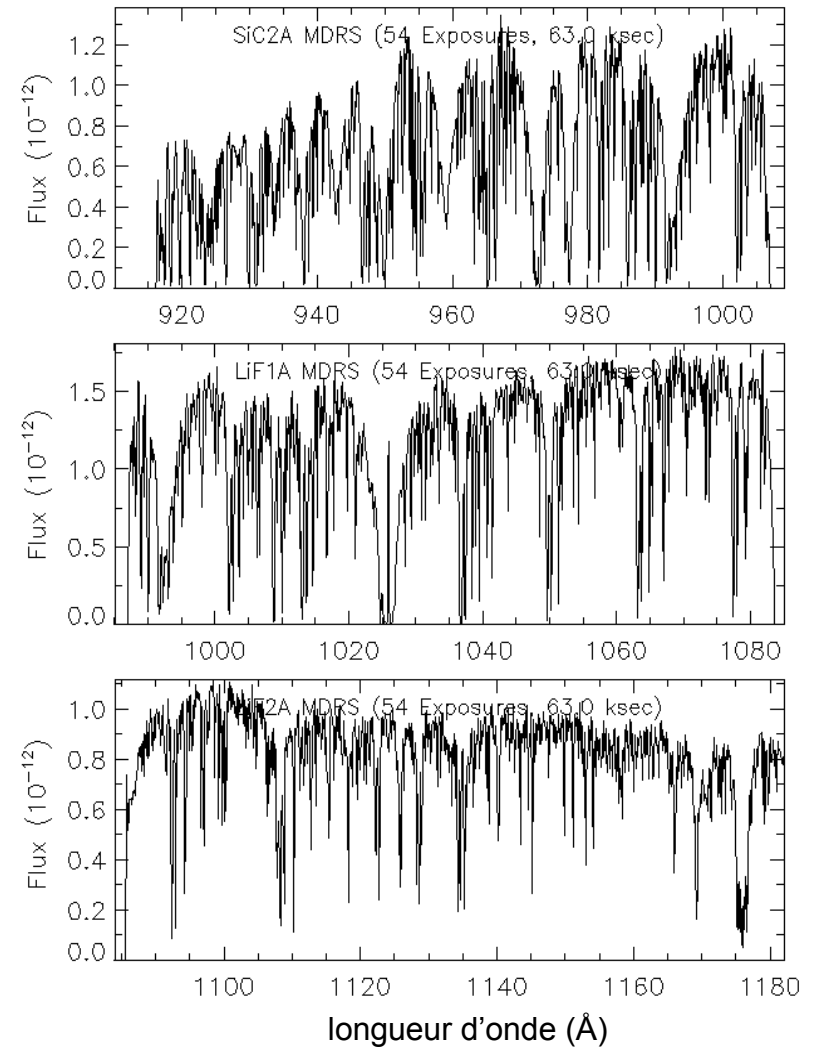
# Exemple d'ajustement de raie pour mesurer une abondance



# Milieu interstellaire local

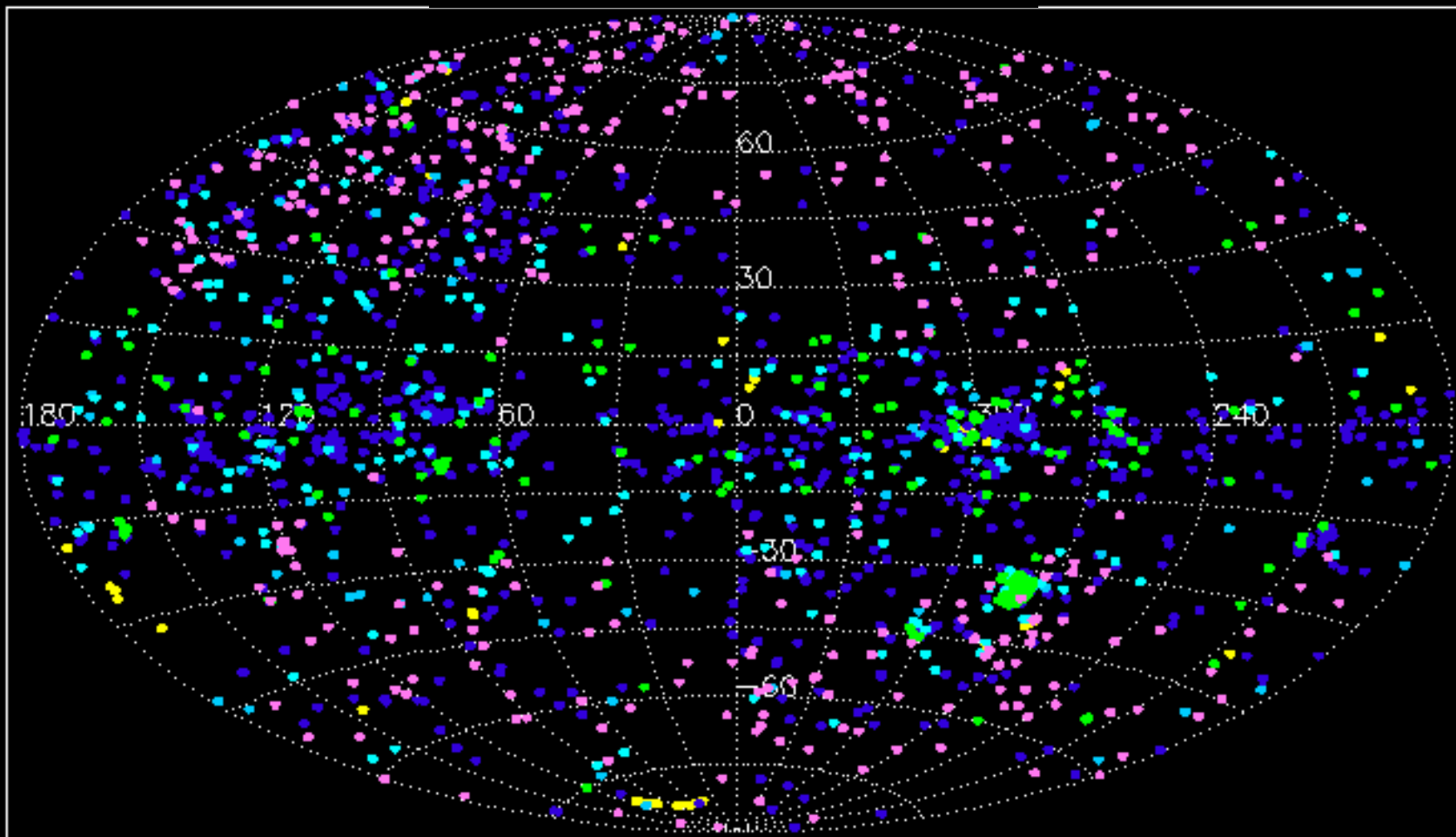


# Milieu interstellaire distant





Observations FUSE (juin 1999- janvier 2005)



Système solaire

Étoiles chaudes

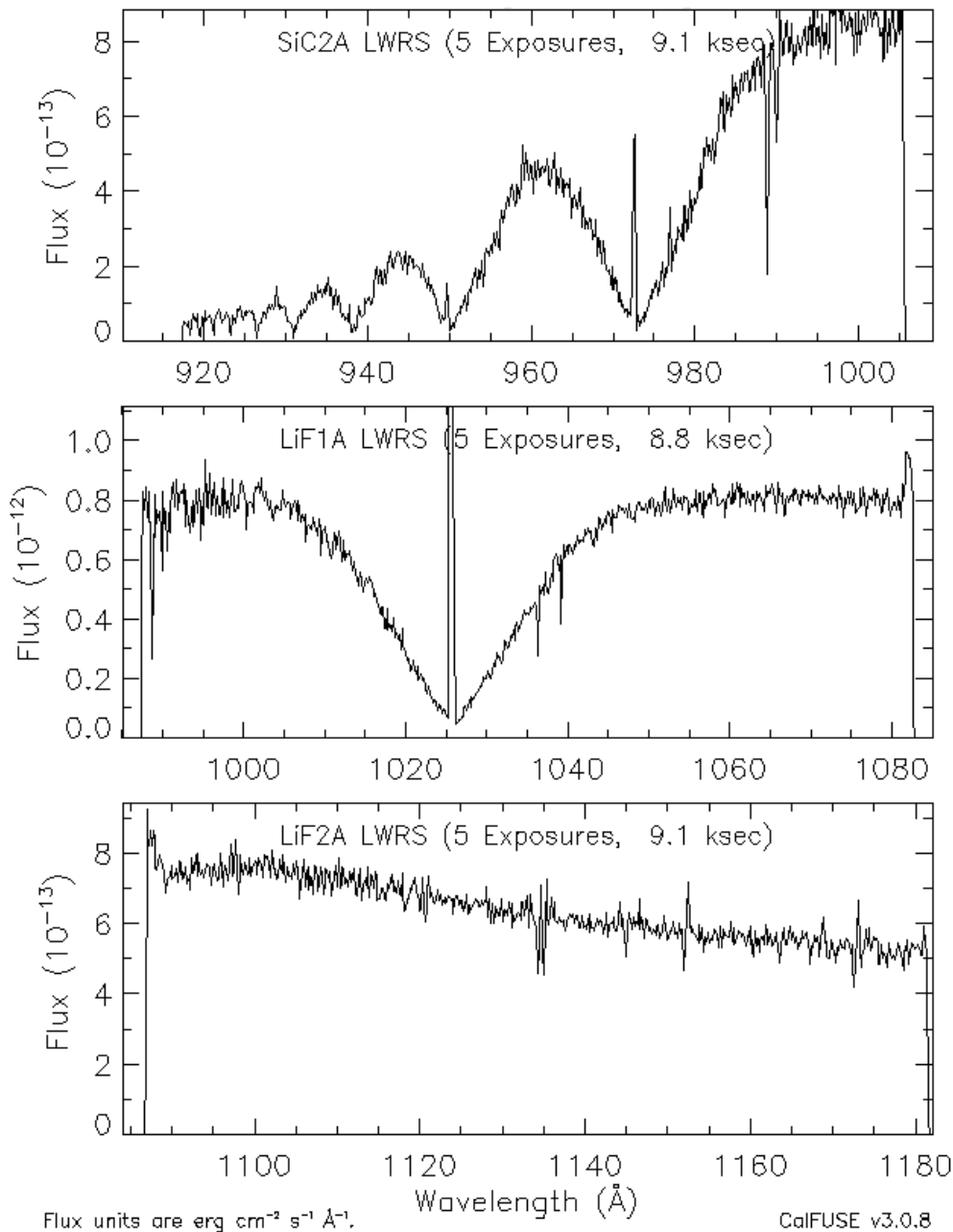
Étoiles froides

Étoiles variables

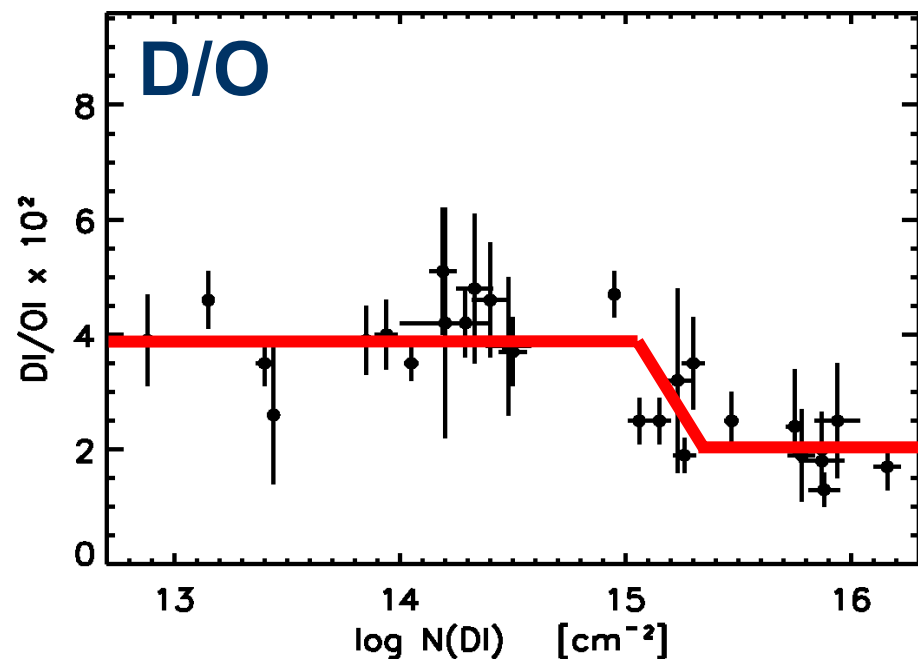
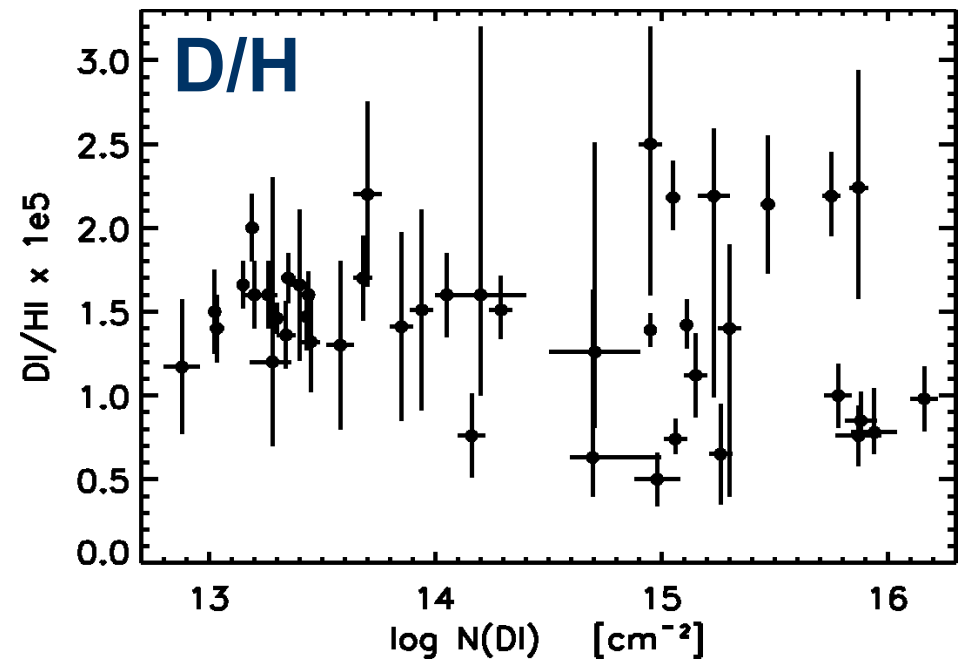
Nébuleuses

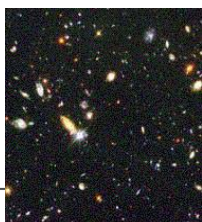
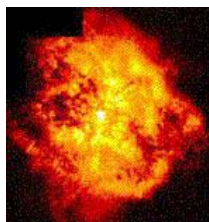
Galaxies





vendredi 22 septembre 2006





primordial

pré-solaire

Époque actuelle

$D/H$

3 / 100000

2 / 100000

1 / 100000

0

0

5

10

15

Temps (milliards d'années)

