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UNIVERSITÉ  
DE GENÈVE

# Astronomie générale - Les grandes missions spatiales pour l'Astrophysique - Saison 3

## Astronomie X

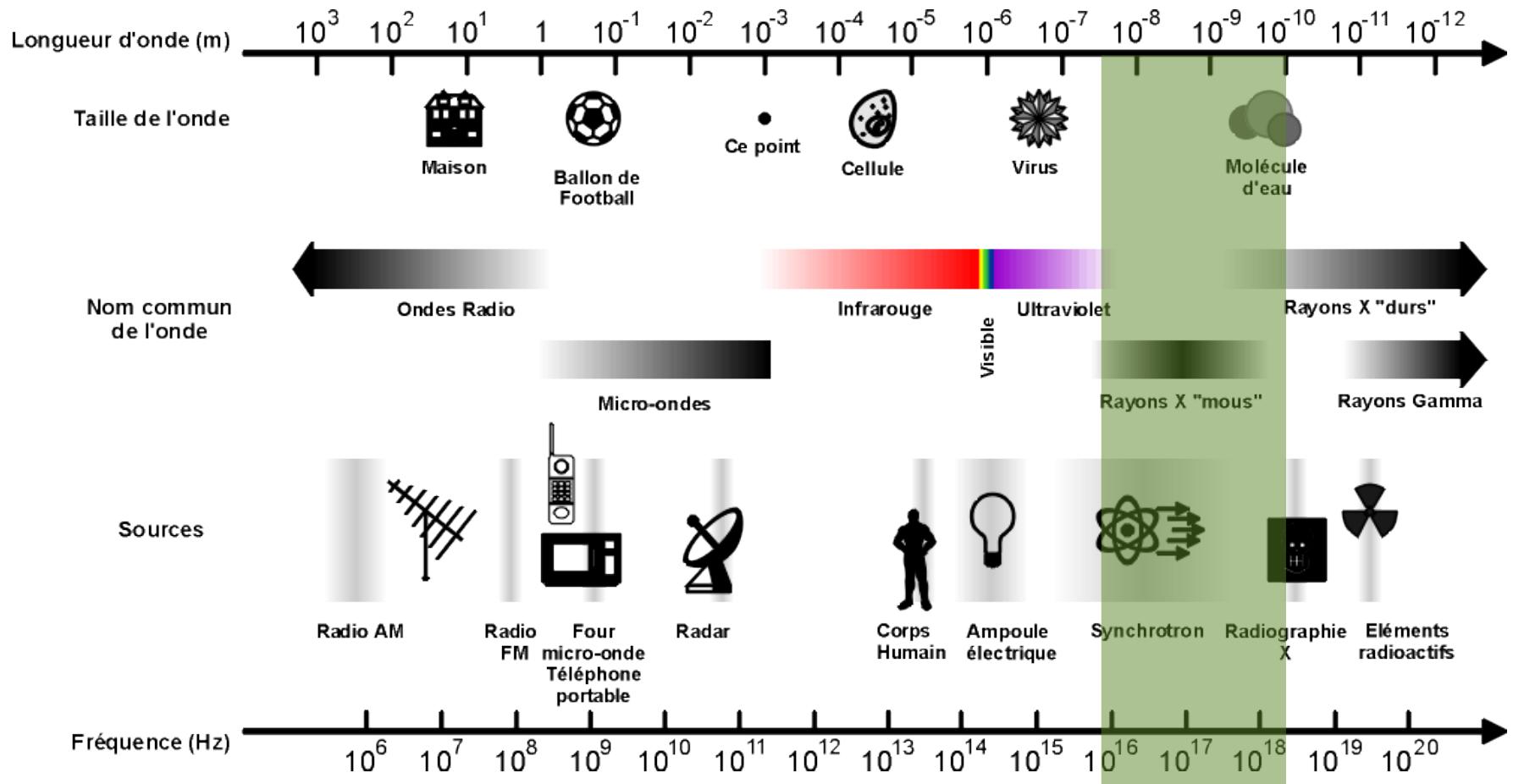
Stéphane Paltani



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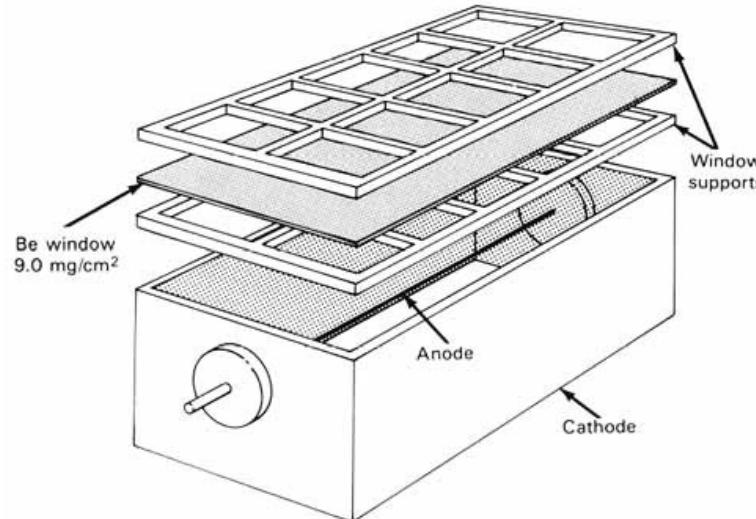
FACULTÉ DES SCIENCES  
Département d'astronomie

# Les rayons X



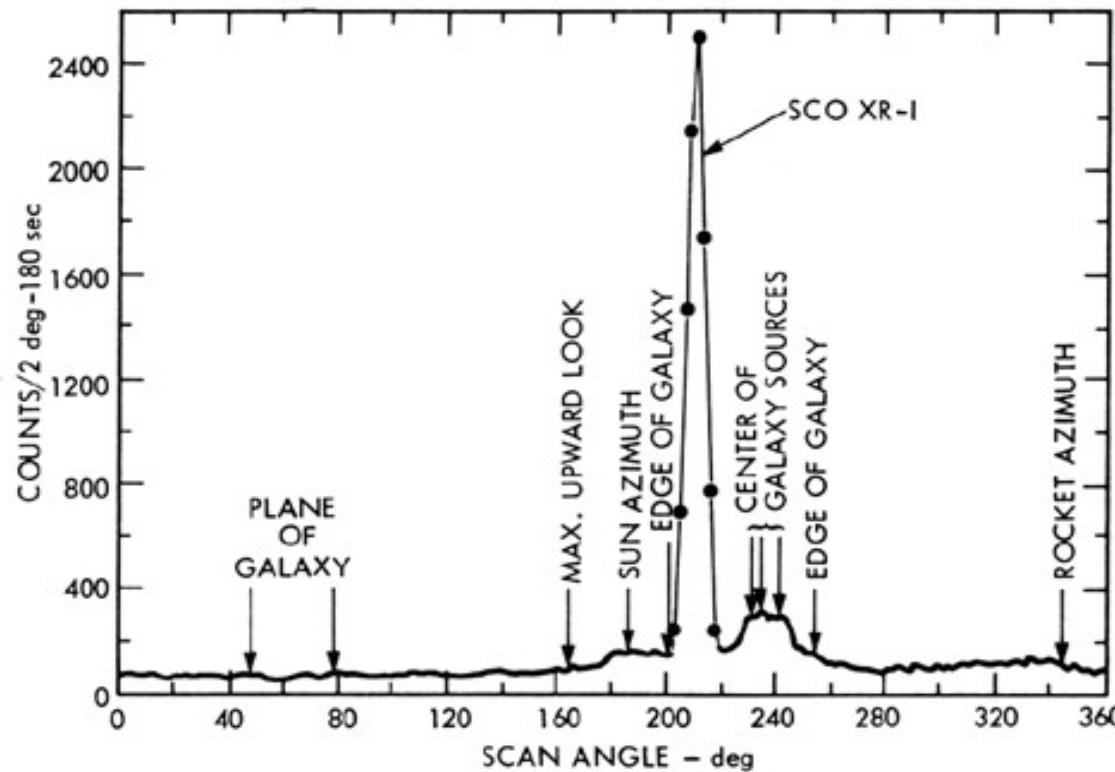
# Naissance de l'astronomie X

- 1962: Fusée Aerobee 170
- But: Déetecter des rayons X de la Lune
- Collimateur et compteur proportionnel

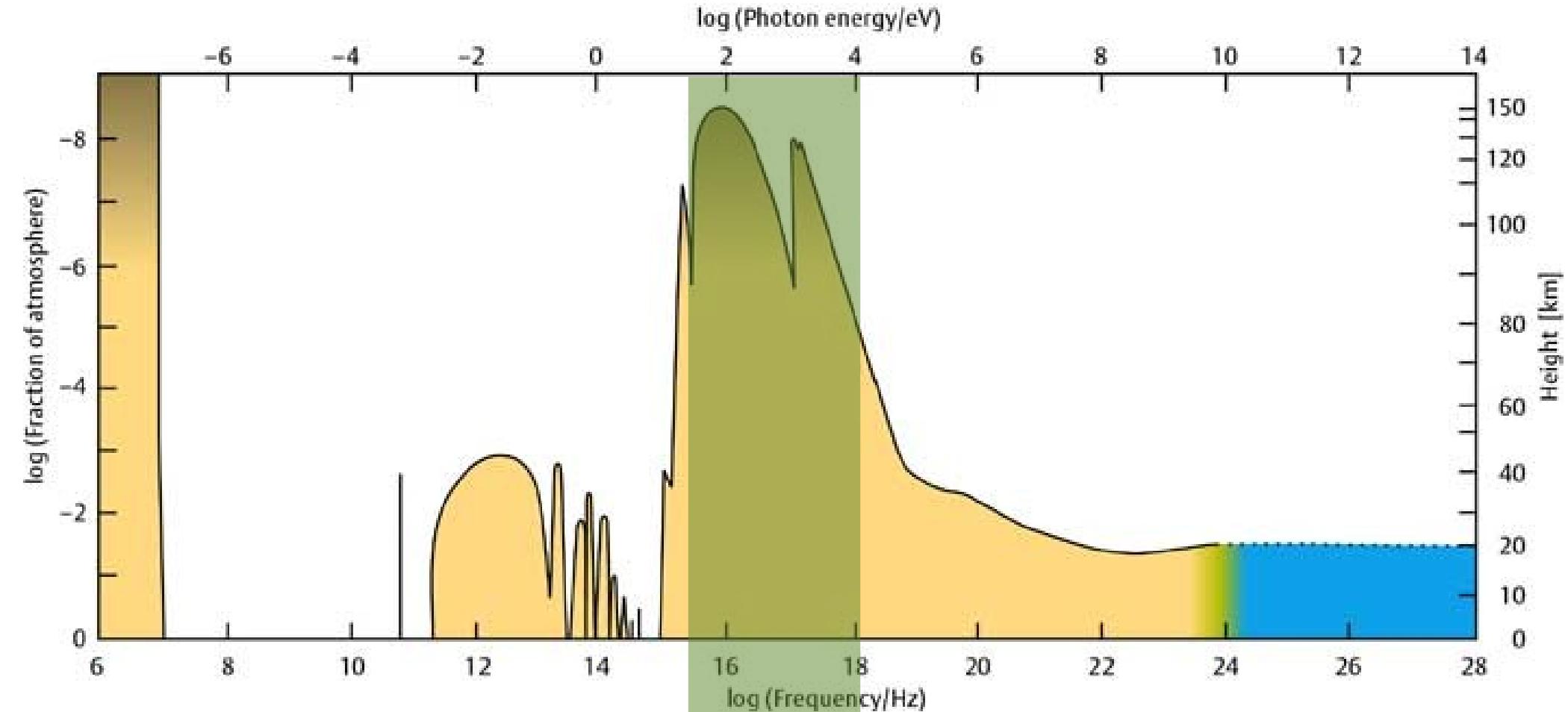


# Scorpio X-1

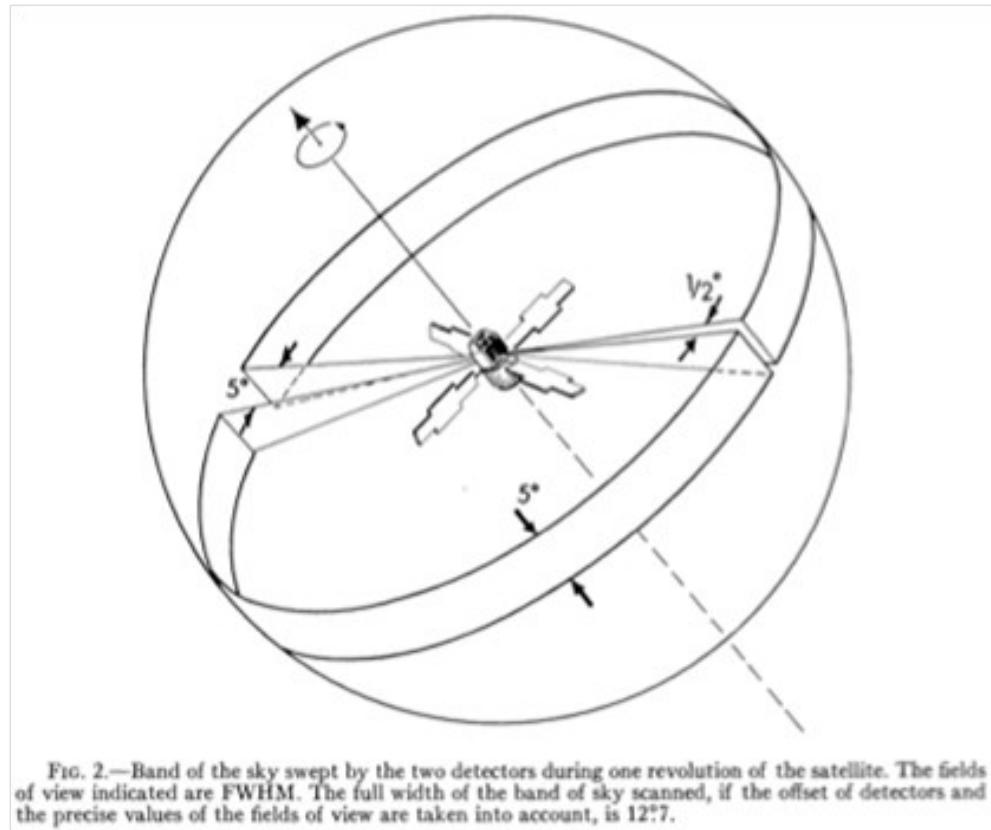
- Prix Nobel de Physique 2002 pour Riccardo Giacconi



# L'atmosphère terrestre

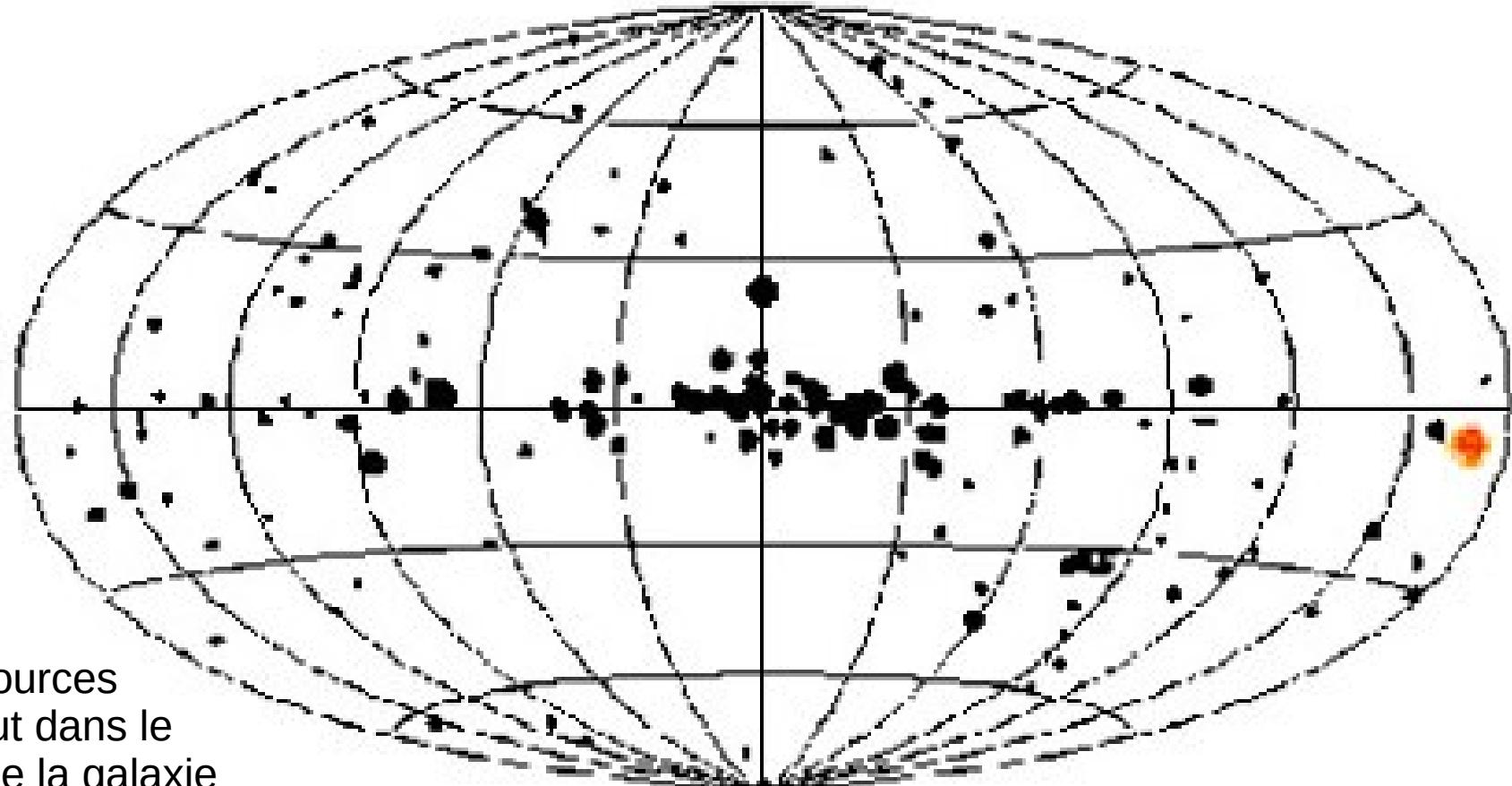


# Uhuru (1970-1973)



Deux collimateurs, observation de tout le ciel

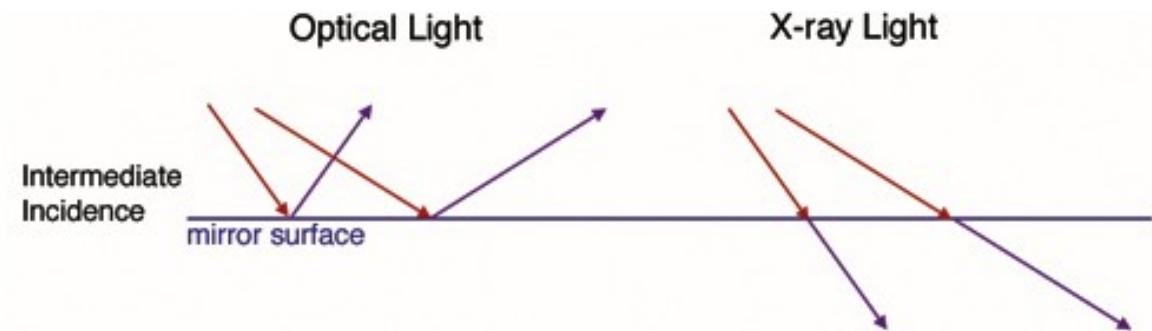
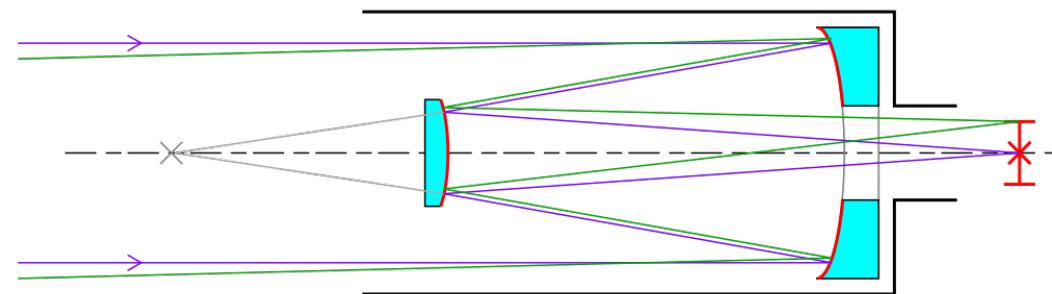
# Première carte du ciel en rayons X



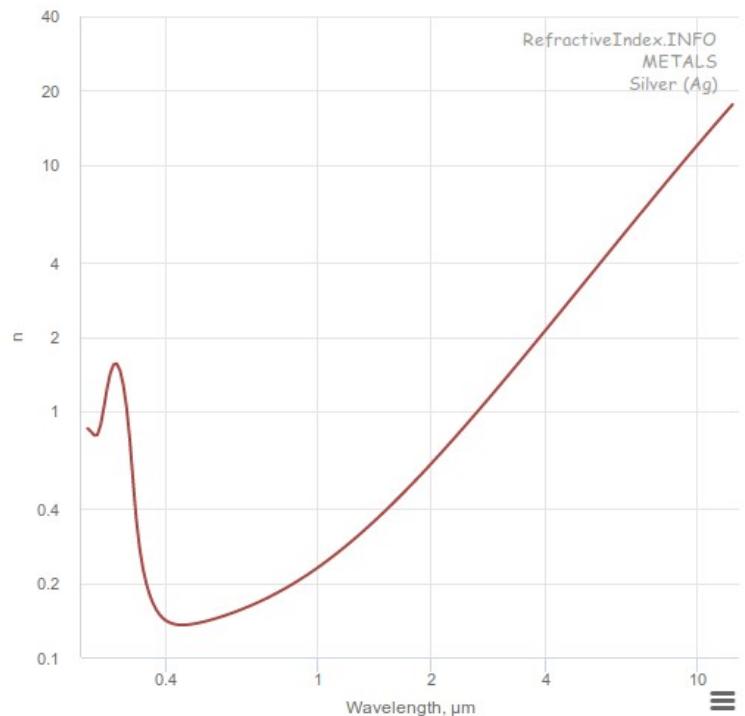
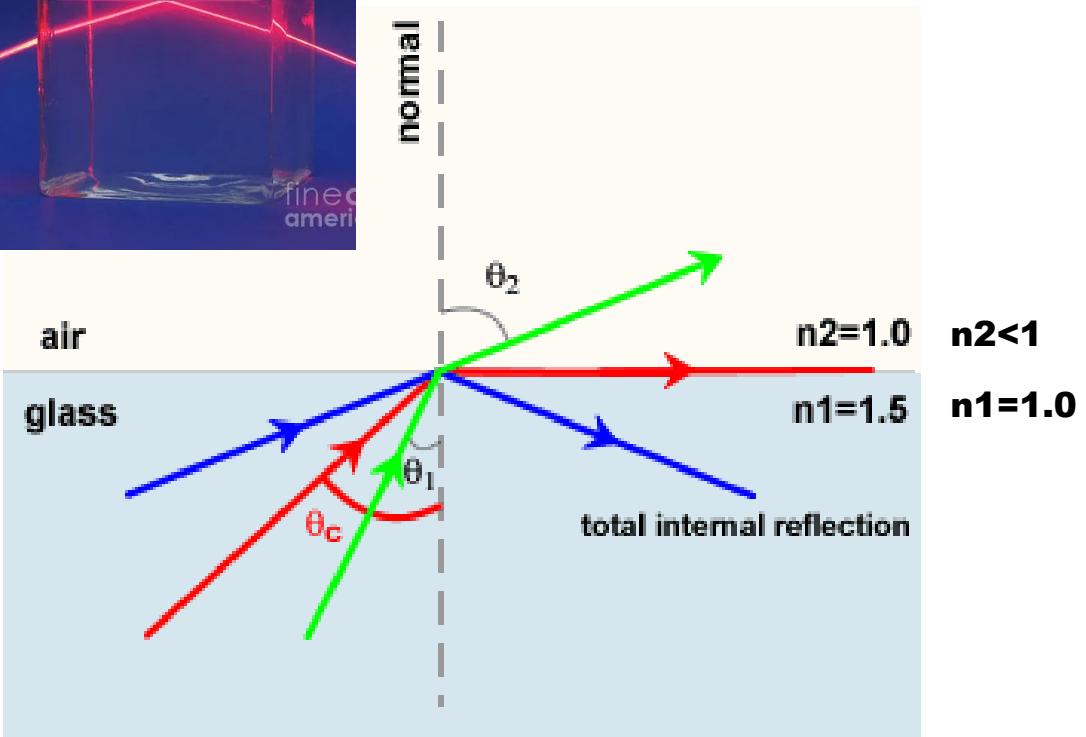
339 sources  
Surtout dans le  
plan de la galaxie

# Télescopes à rayons X

- Un télescope produit des images par réflexion
- Les rayons X ne se réfléchissent (normalement) pas

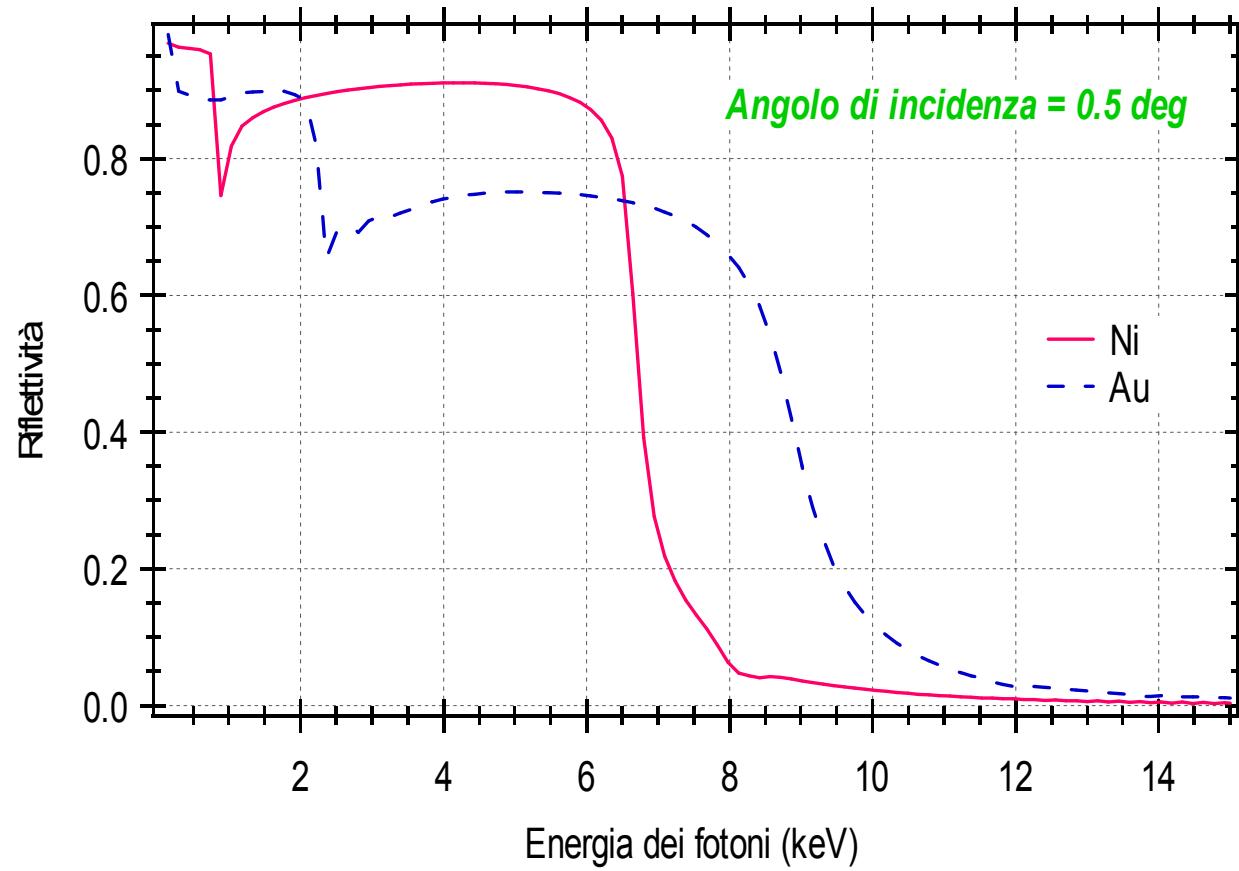


# Réflexion totale

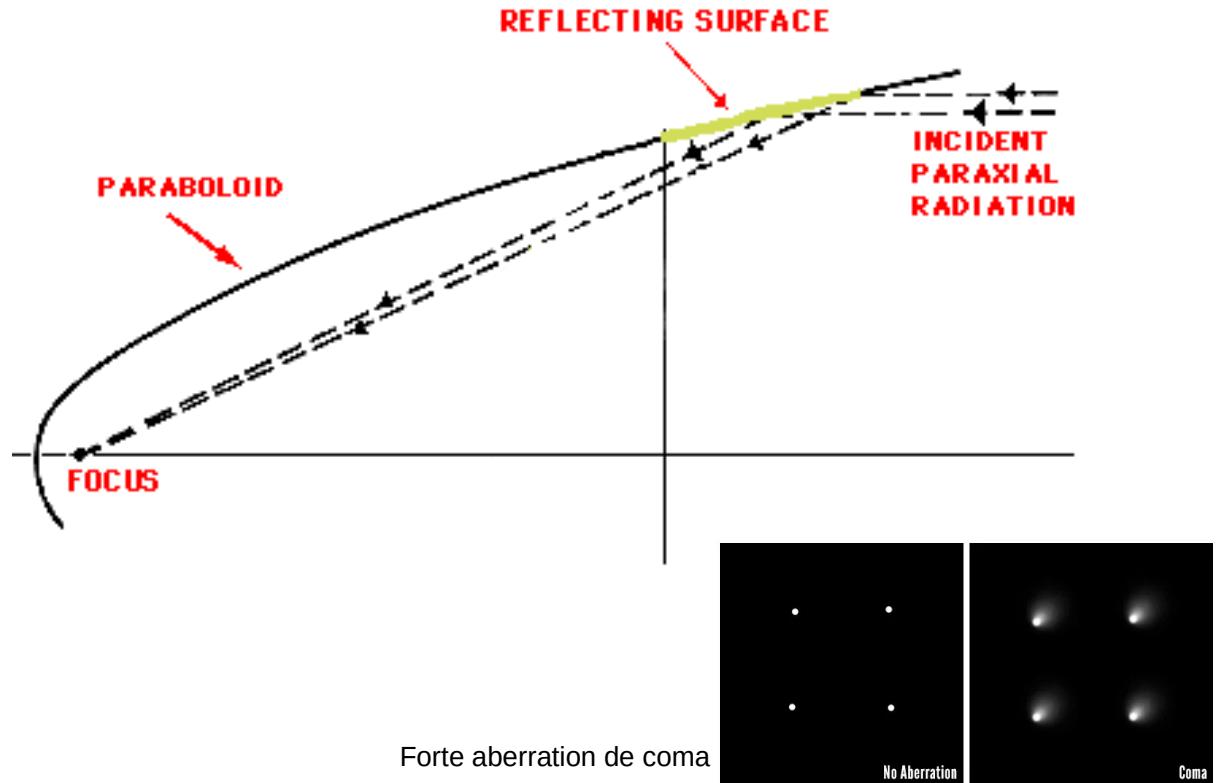
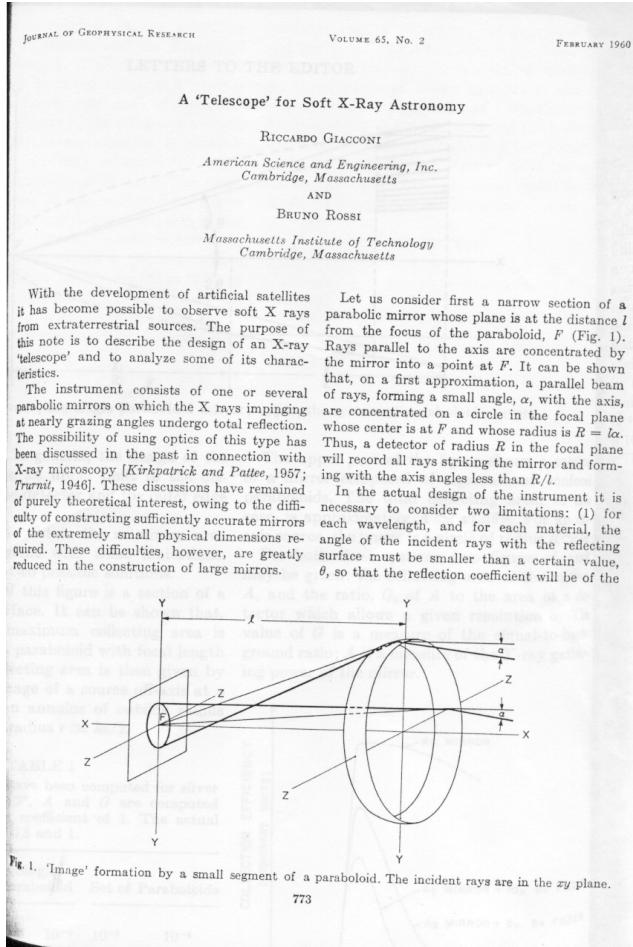


Argent

# Réflectivité des rayons X

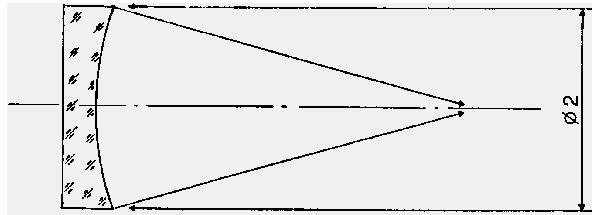


# Focalisation des rayons X



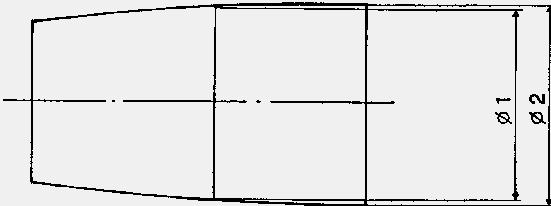
# Focalisation des rayons X

Miroir optique



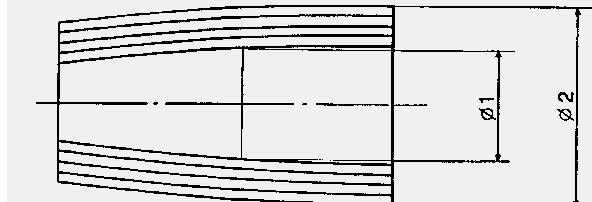
$$S_v = \frac{\pi \phi_2^2}{4}$$

Miroir X



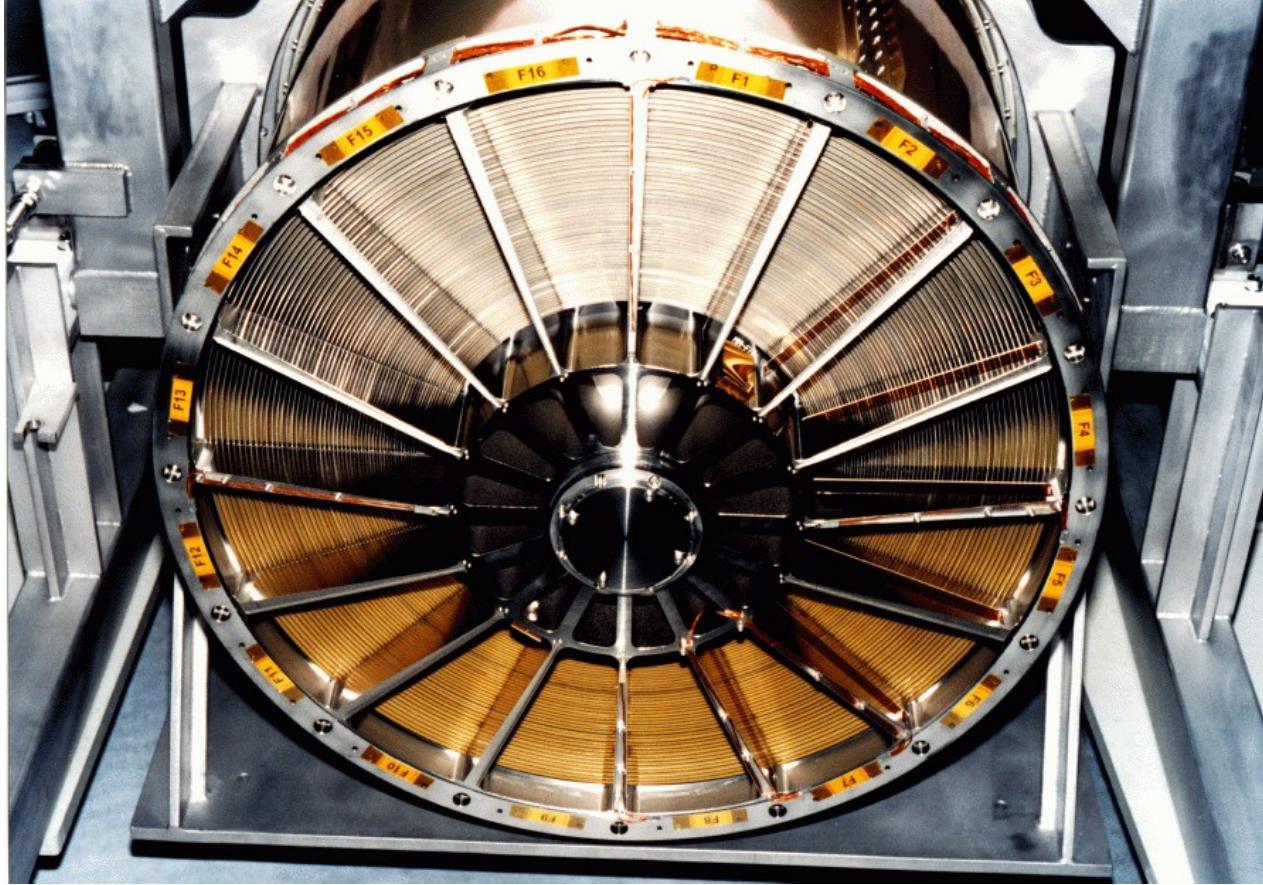
$$S_1 = \frac{\pi (\phi_2 - \phi_1)^2}{4}$$

Miroirs répliqués  
“Woltjer I”

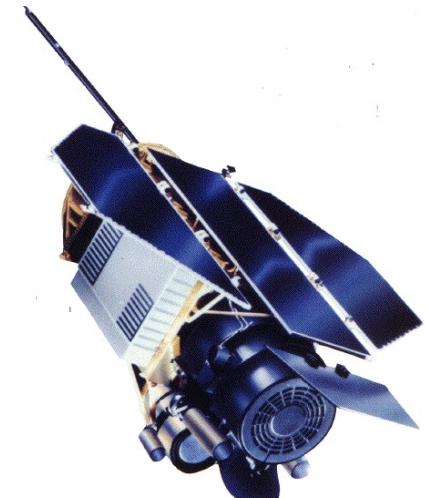
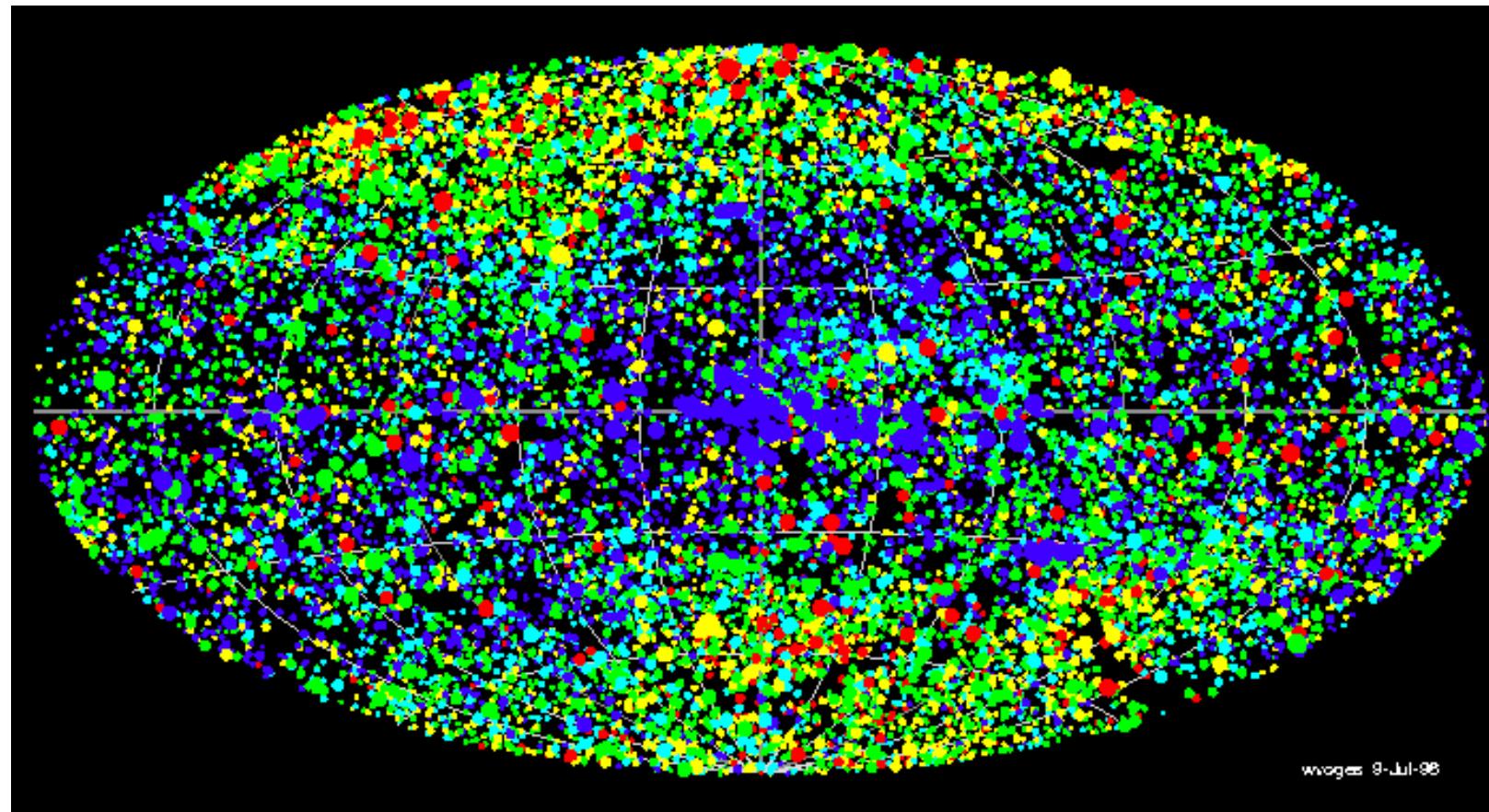


$$S_x = \frac{\pi (\phi_2 - \phi_1)^2}{4}$$

# Télescopes en rayons X

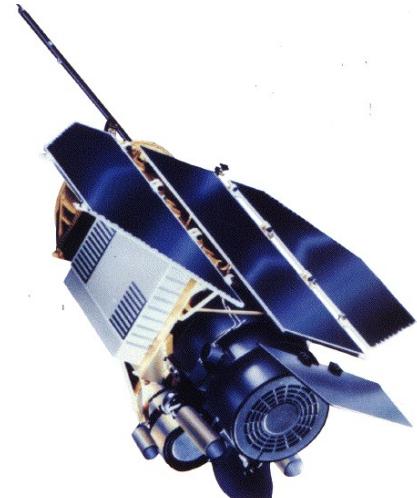
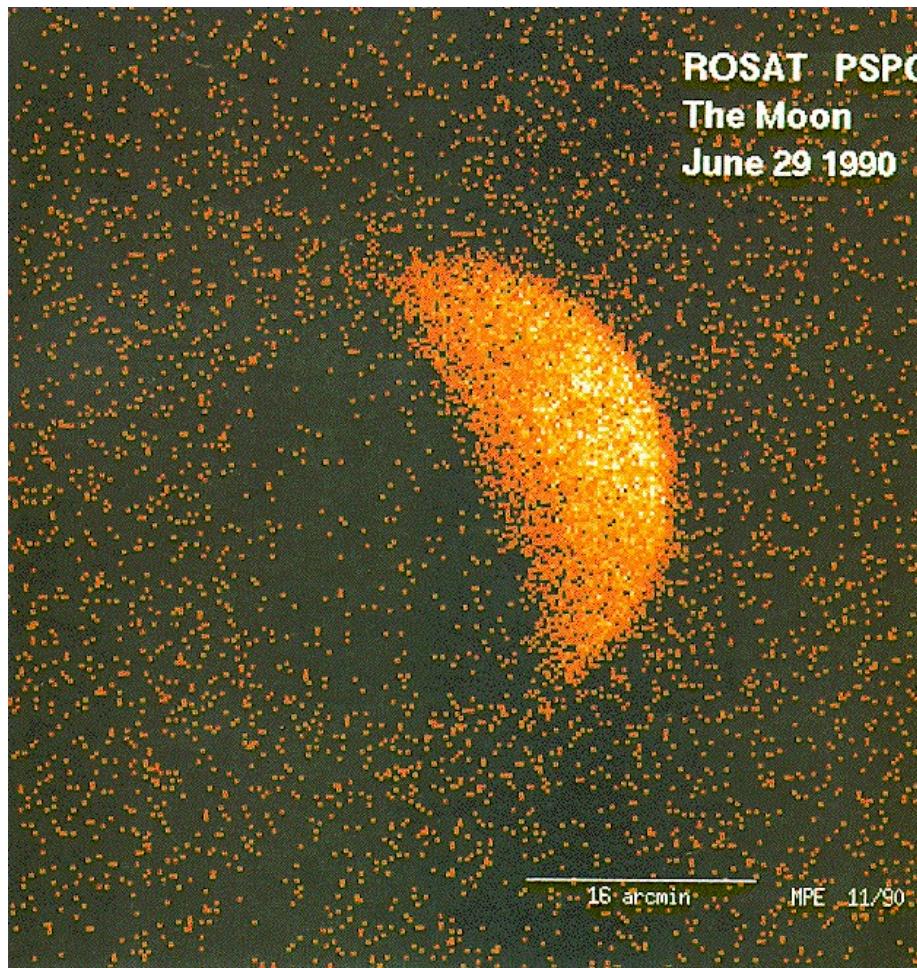


# ROSAT (1990-1999)

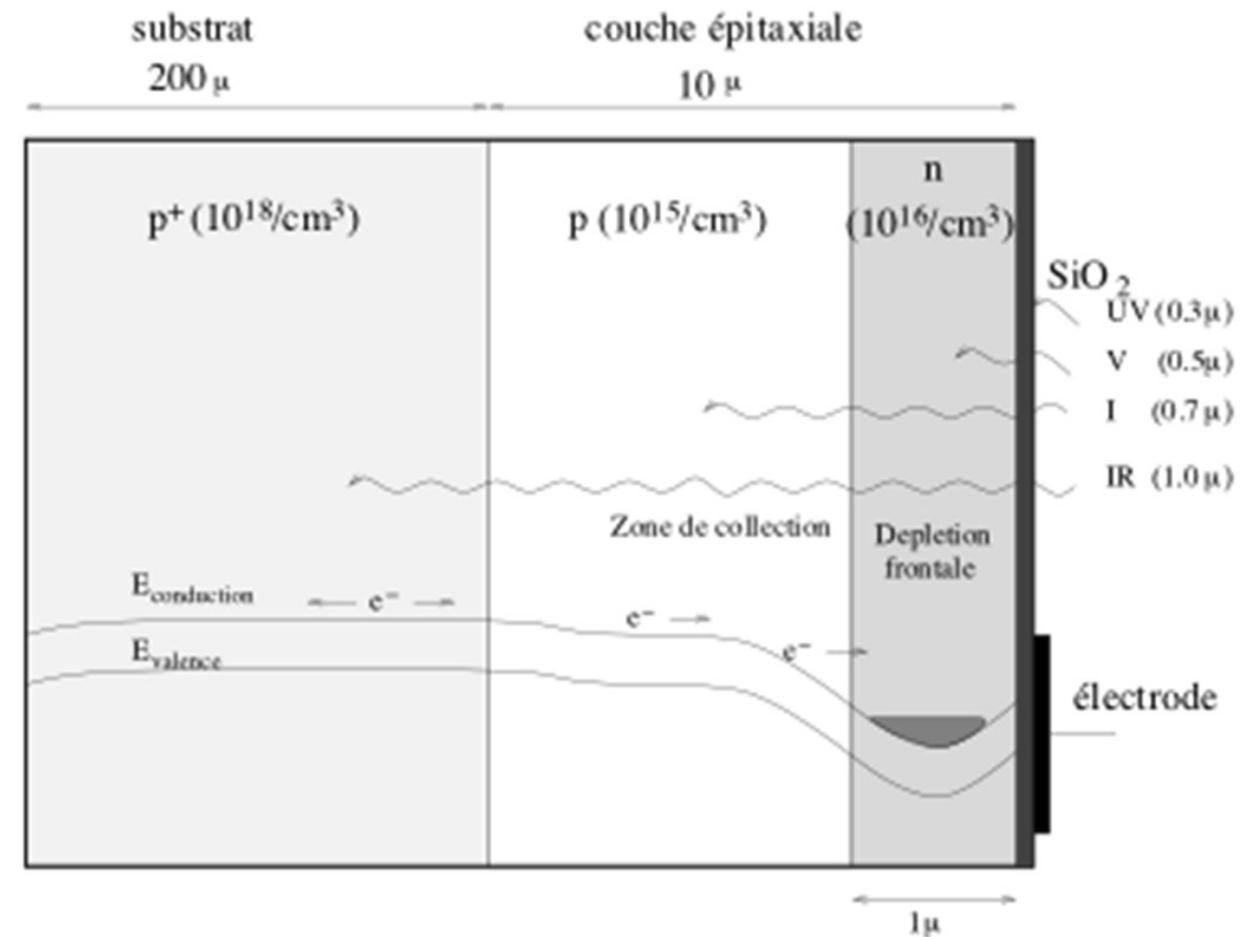
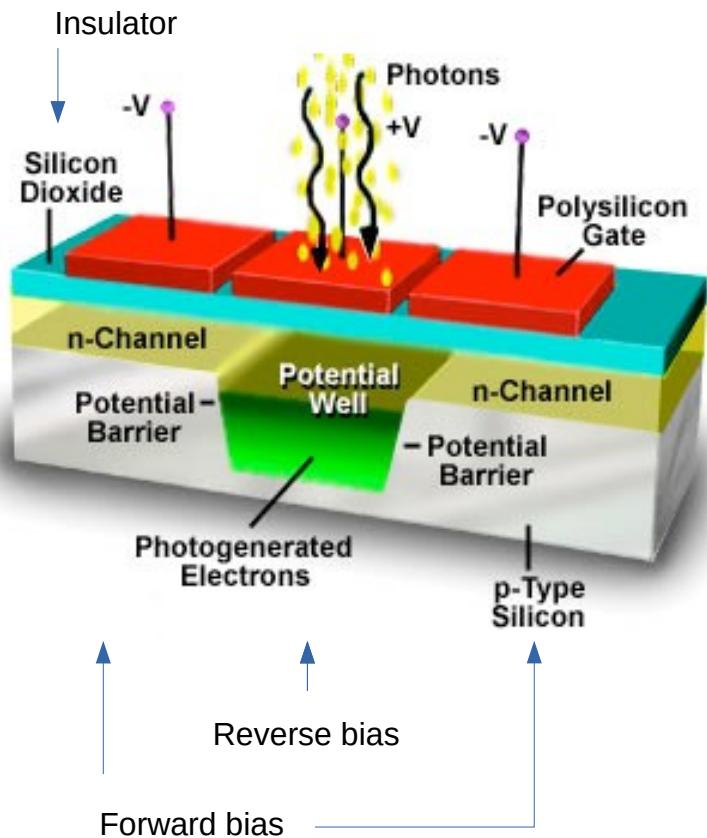


18'811 sources  
(60x UHURU)

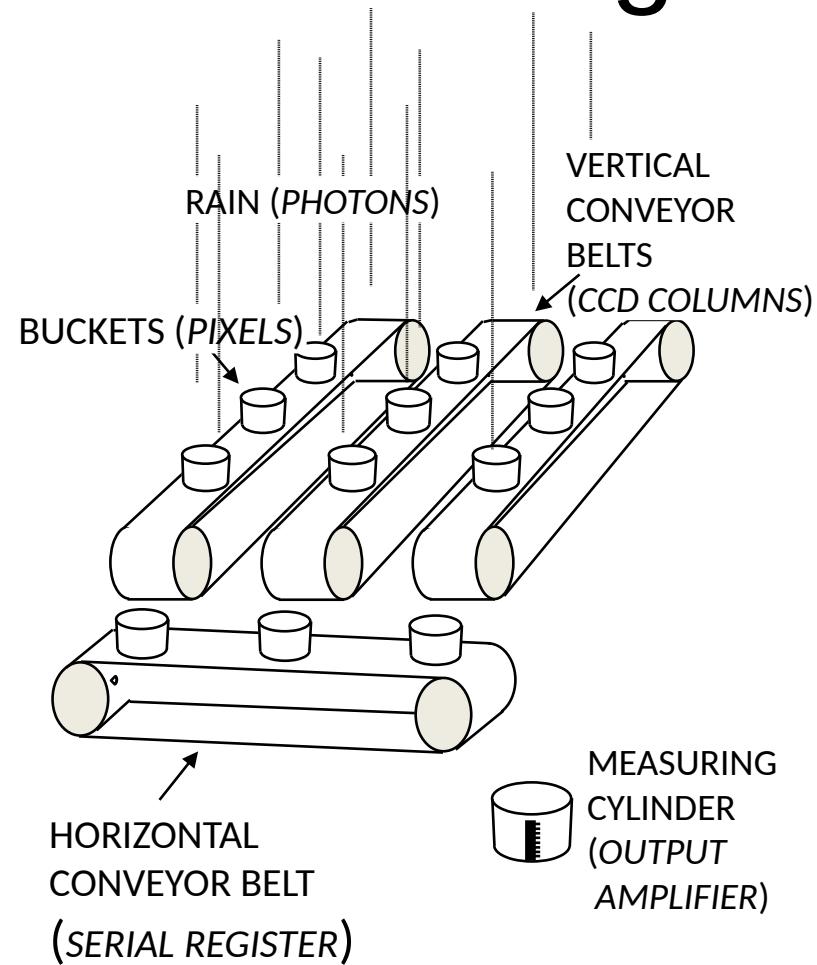
# La Lune vue par ROSAT

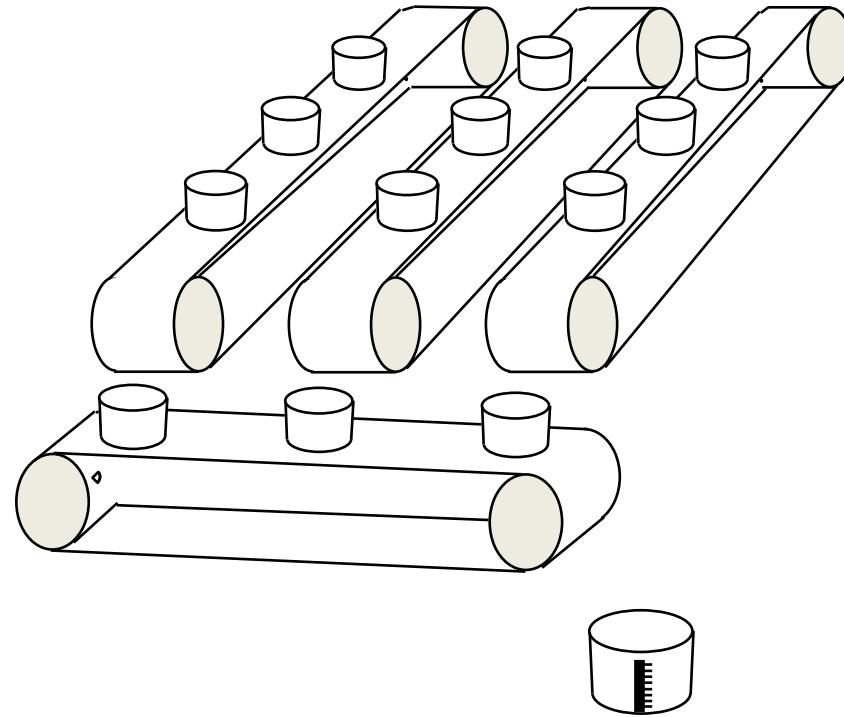


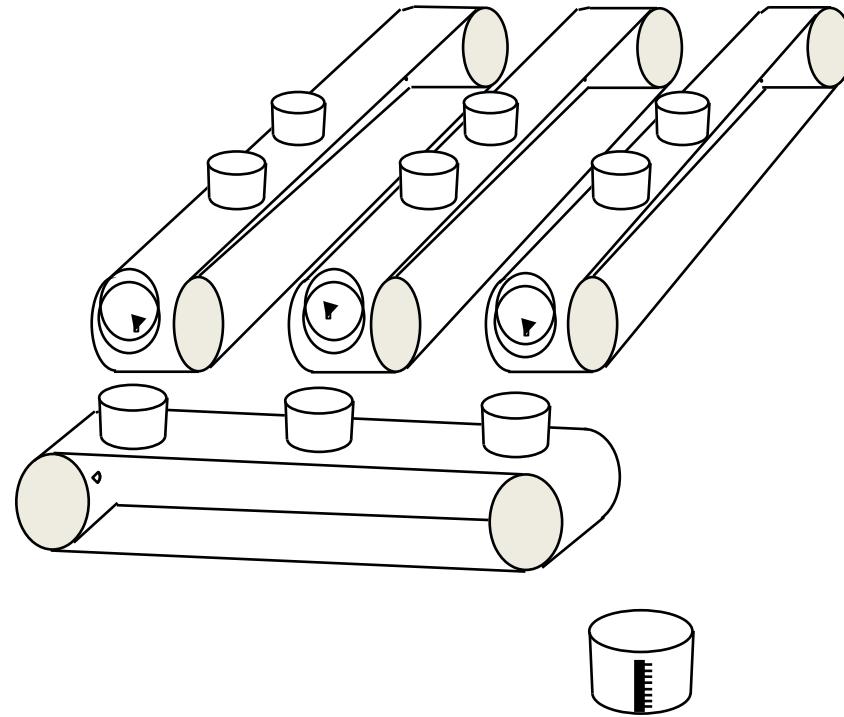
# Les CCD

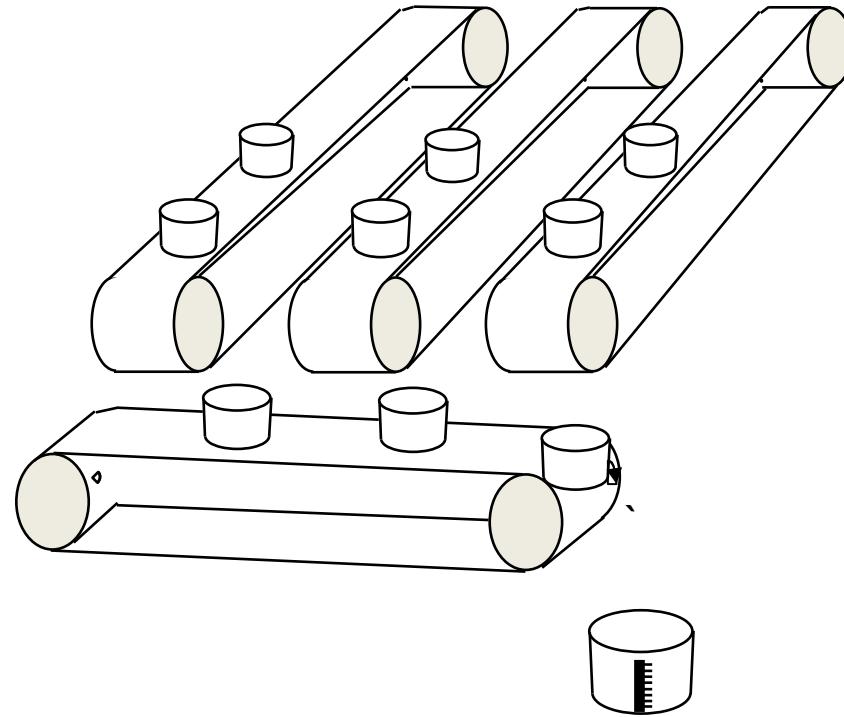


# Une analogie





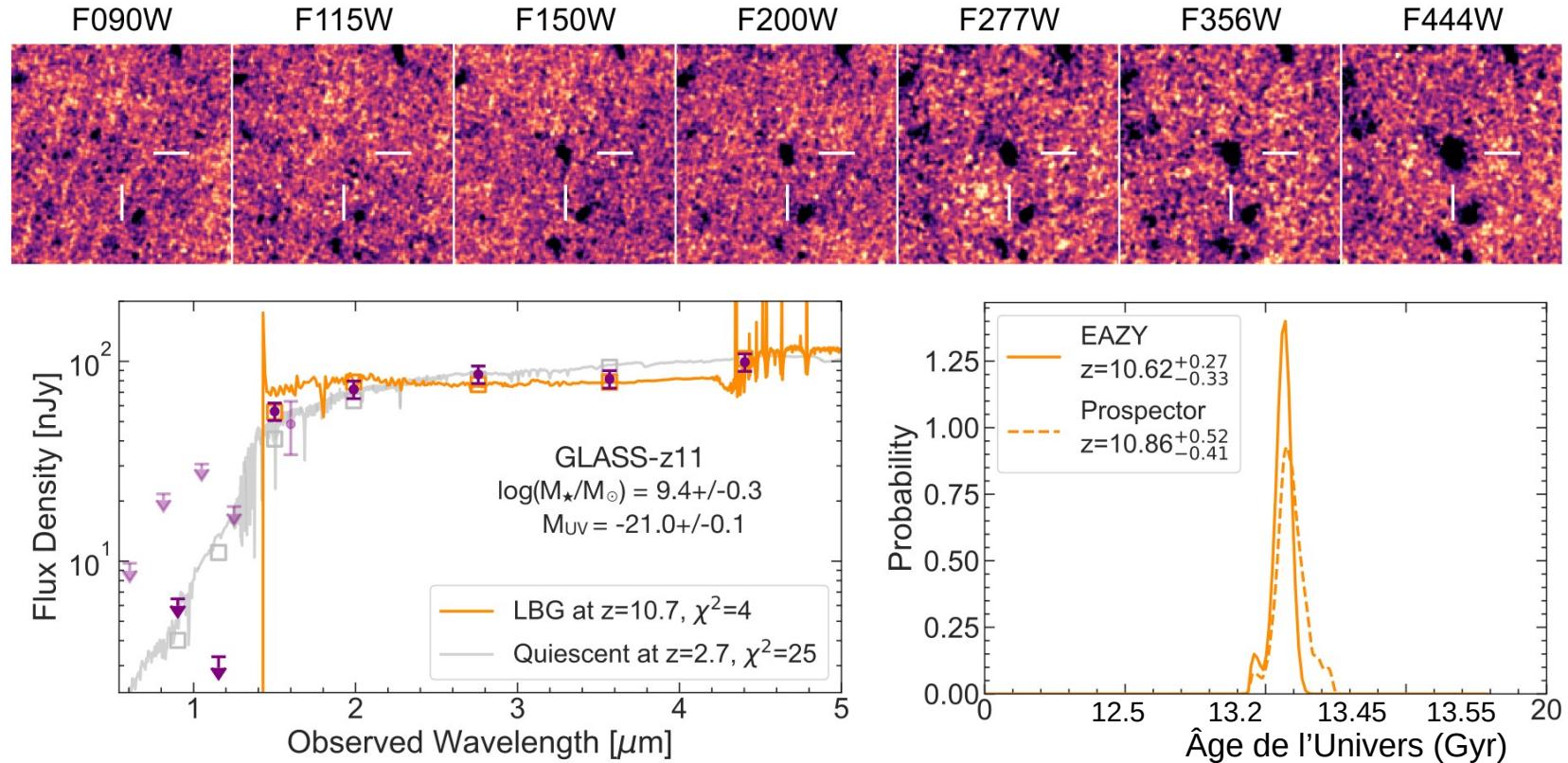




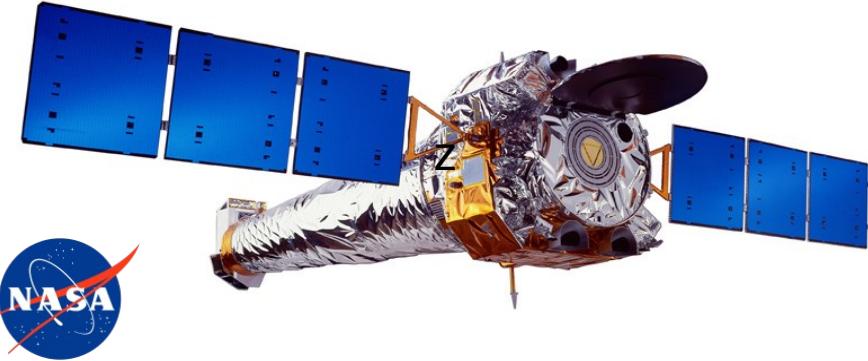
# CCD dans les rayons X

- $E_{\text{Gap}} \sim 1.1 \text{ eV}$  (unité d'énergie), correspondant à l'énergie d'un photon infrarouge
  - Un seul électron est arraché et collecté
- $E_{\text{x-ray}} \sim 1 \text{ keV}$ , soit  $\sim 1000$  fois plus
  - L'électron arraché a suffisamment d'énergie pour arracher plusieurs centaines d'autres électrons
  - Plus l'énergie est grande, plus le nombre d'électrons arrachés est grand
  - On peut ainsi mesurer l'énergie de chaque photons!

# Analogie dans le visible/IR



# Chandra et XMM-Newton (1999)

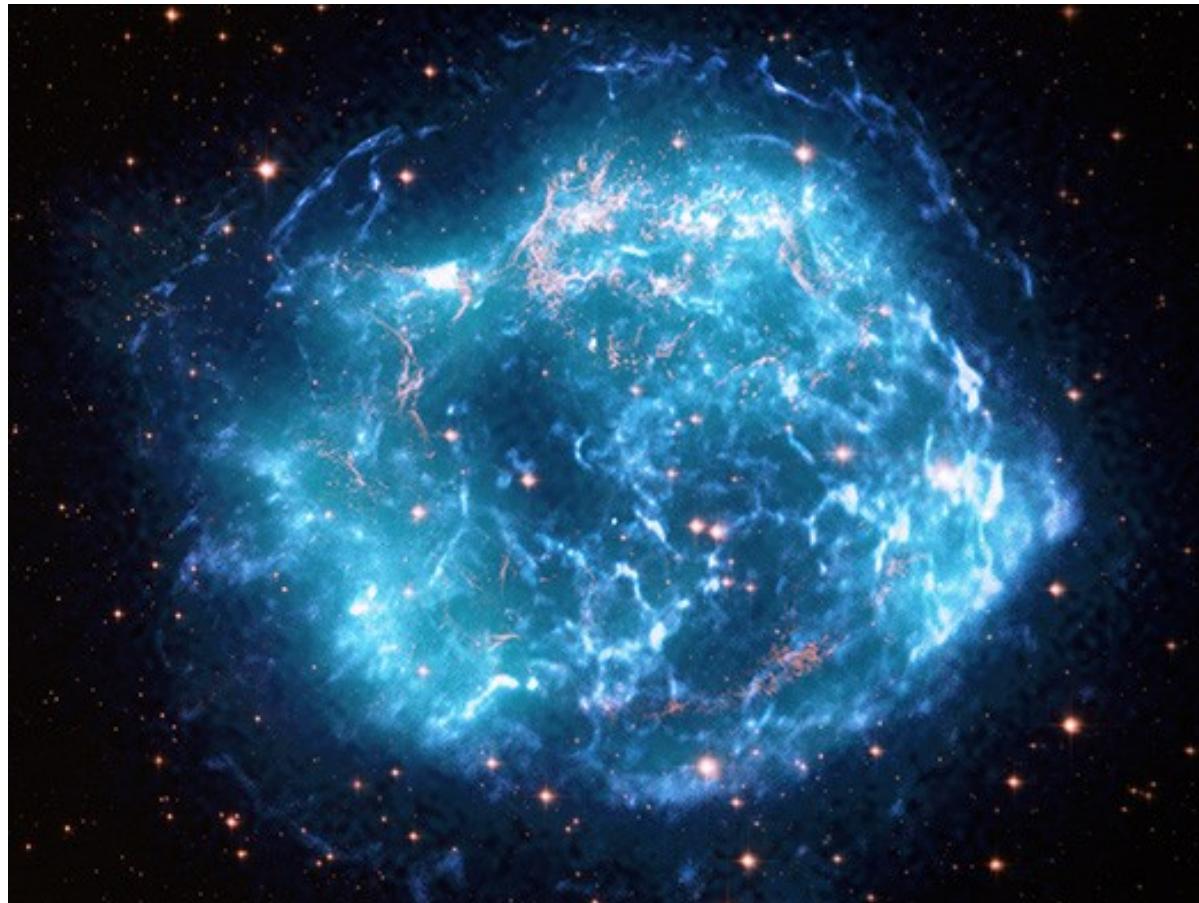


Credits: NASA

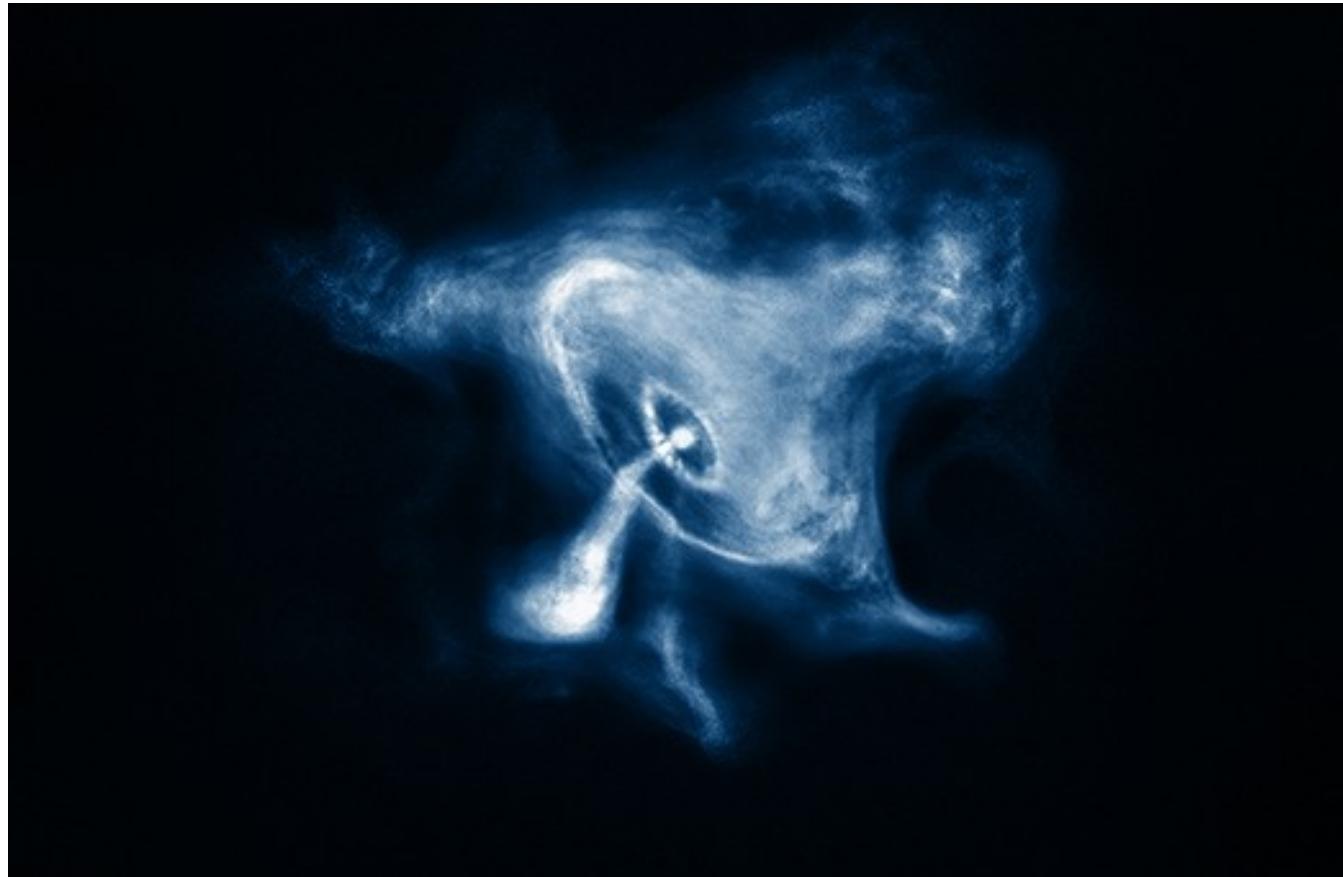


Credits: ESA

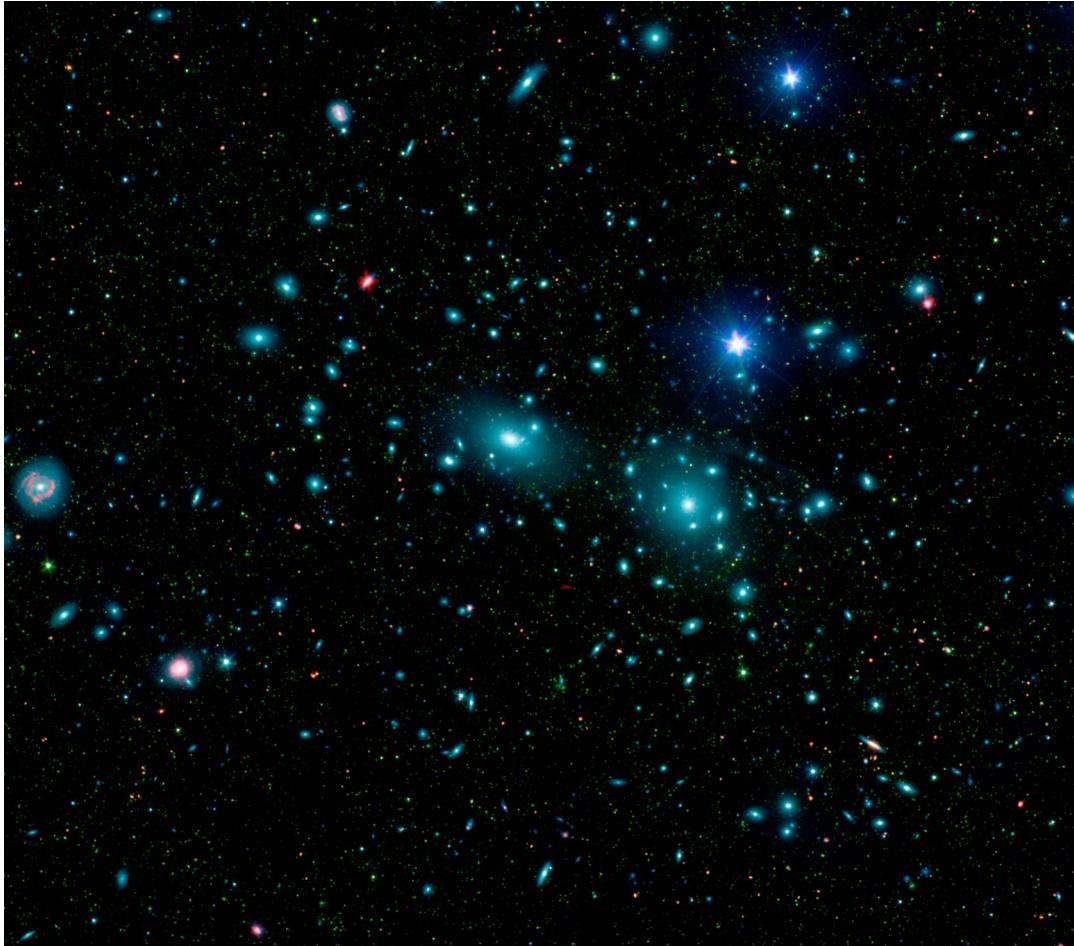
# Cassiopeia A (Chandra)



# La Nébuleuse du Crabe (Chandra)



# Les amas de galaxie



Amas de Coma

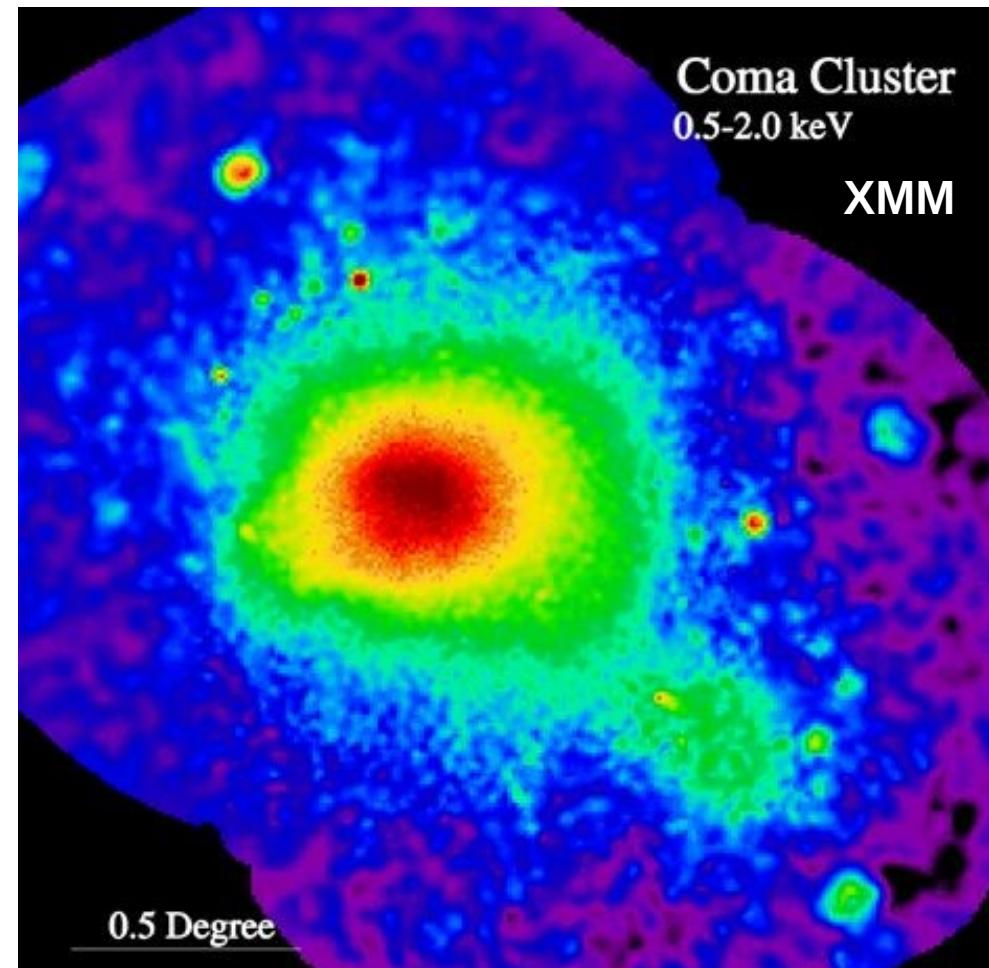
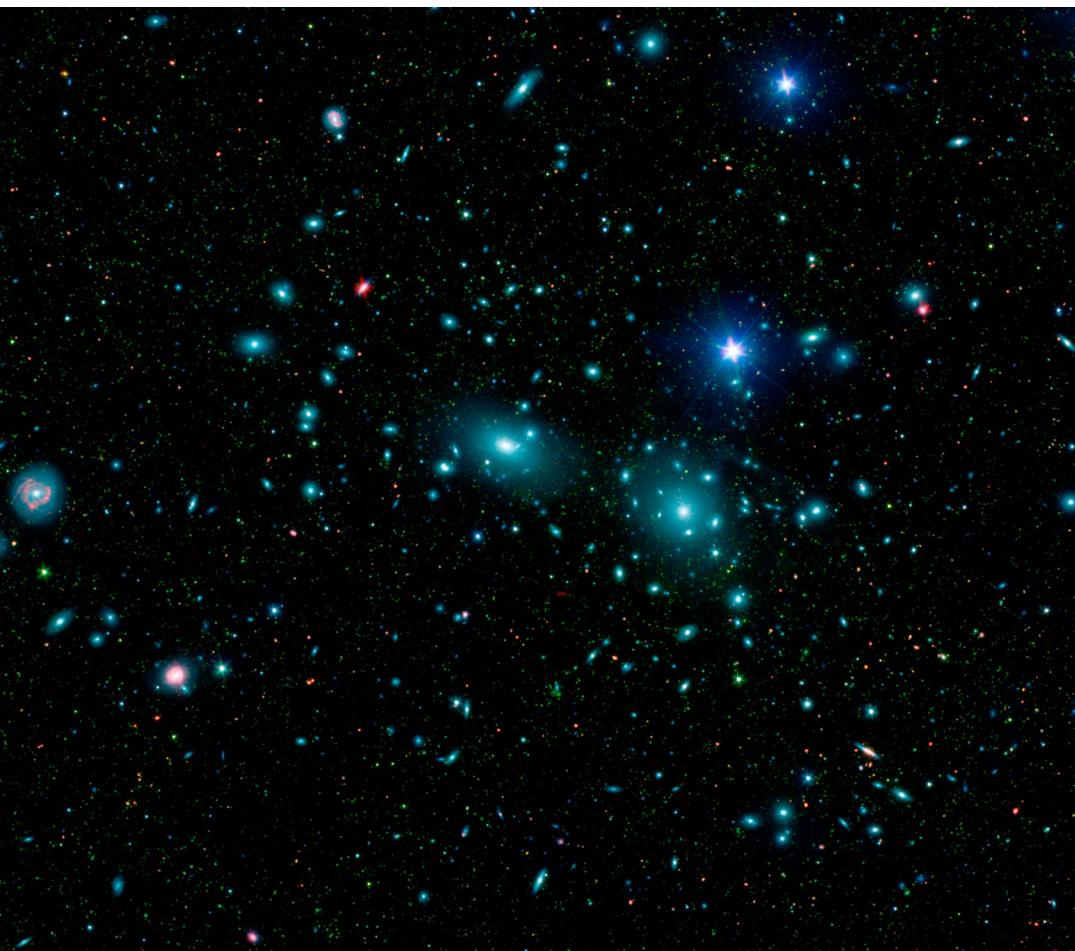
Plus de 1000 galaxies

Dispersion des vitesses  
~1000 km/s

# Masse de Coma

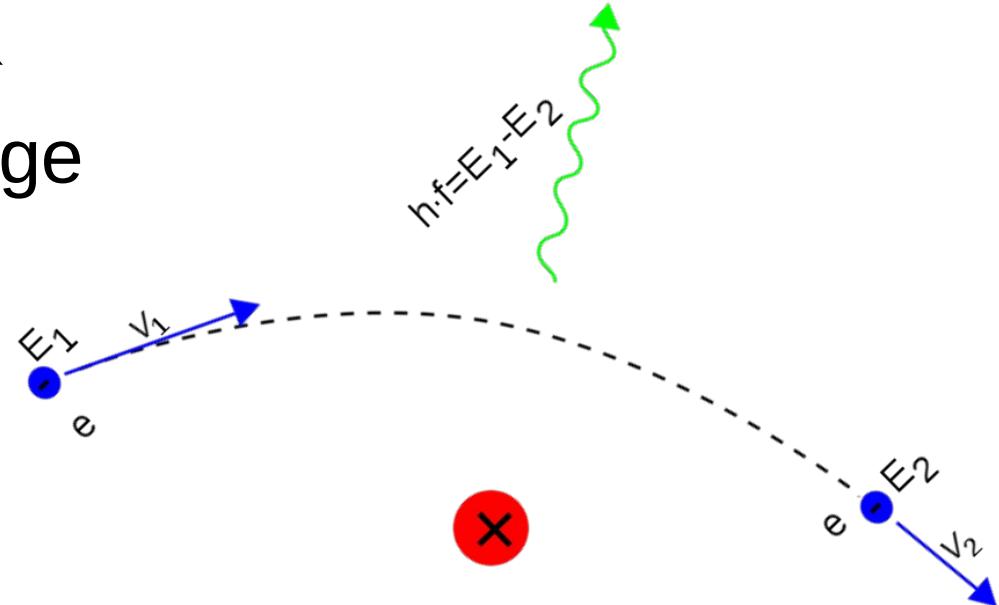
- Si chaque étoile est identique au Soleil
  - $1L_\odot \equiv 1 M_\odot$
  - $M_{\text{Visible}} = 3 \cdot 10^{13} M_\odot$
- Masse gravifique nécessaire pour faire tourner des galaxies à  $1000 \text{ km s}^{-1}$  (théorème du viriel)
  - $E_{C,\text{Total}} = -\frac{1}{2} E_{P,\text{Total}}$
  - $M_{\text{Total}} = 2 R_{\text{Total}} \langle v^2 \rangle / G = 5 \cdot 10^{15} M_\odot$
  - $M_{\text{Total}} \gg M_{\text{Visible}}$

# Coma en rayons X

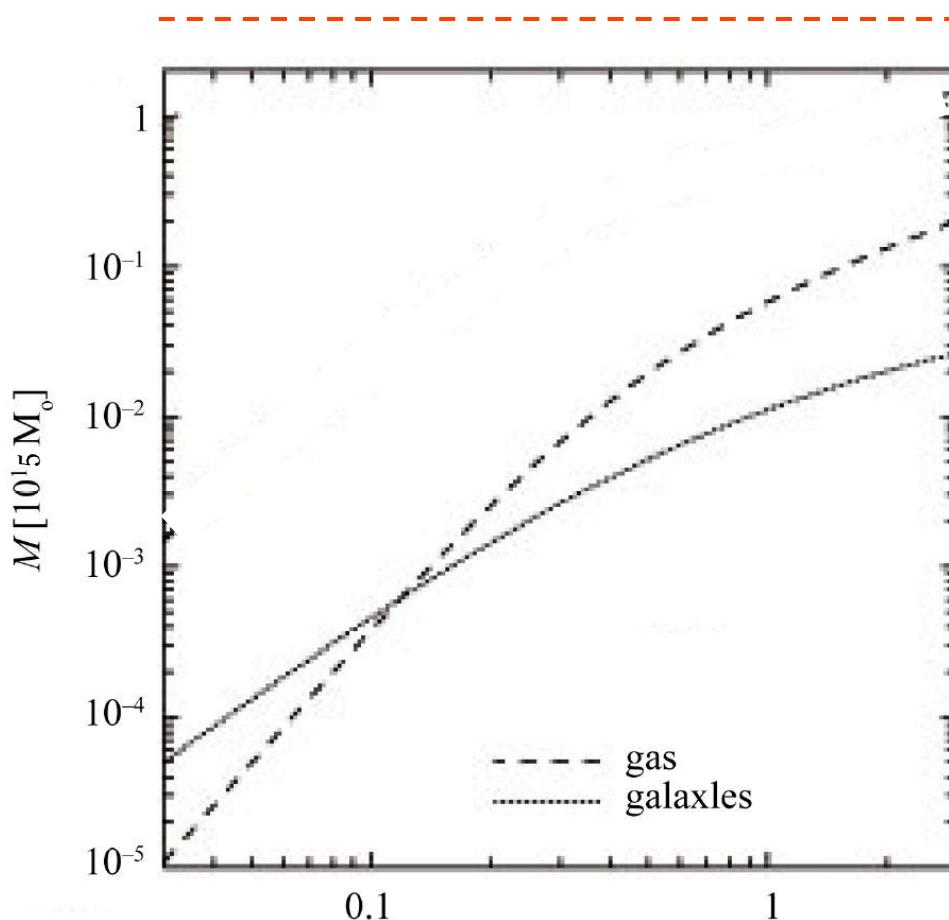


# Coma en rayons X

- Un électron plongé dans un amas doit avoir une énergie cinétique de:  $E_C = Gm_p M_T / R$ 
  - $\sim 10 \text{ keV}$  pour Coma, soit l'énergie d'un rayon X
  - $E_C = 3/2 kT \rightarrow T = 10^8 \text{ K}$
- Rayonnement de freinage (Bremsstrahlung)
  - $L_X \approx c \cdot n^2$



# Profil de masse



Masse gravifique

Il manque encore plus de 90% de la masse

→ Matière noire  
(Zwicki 1933)

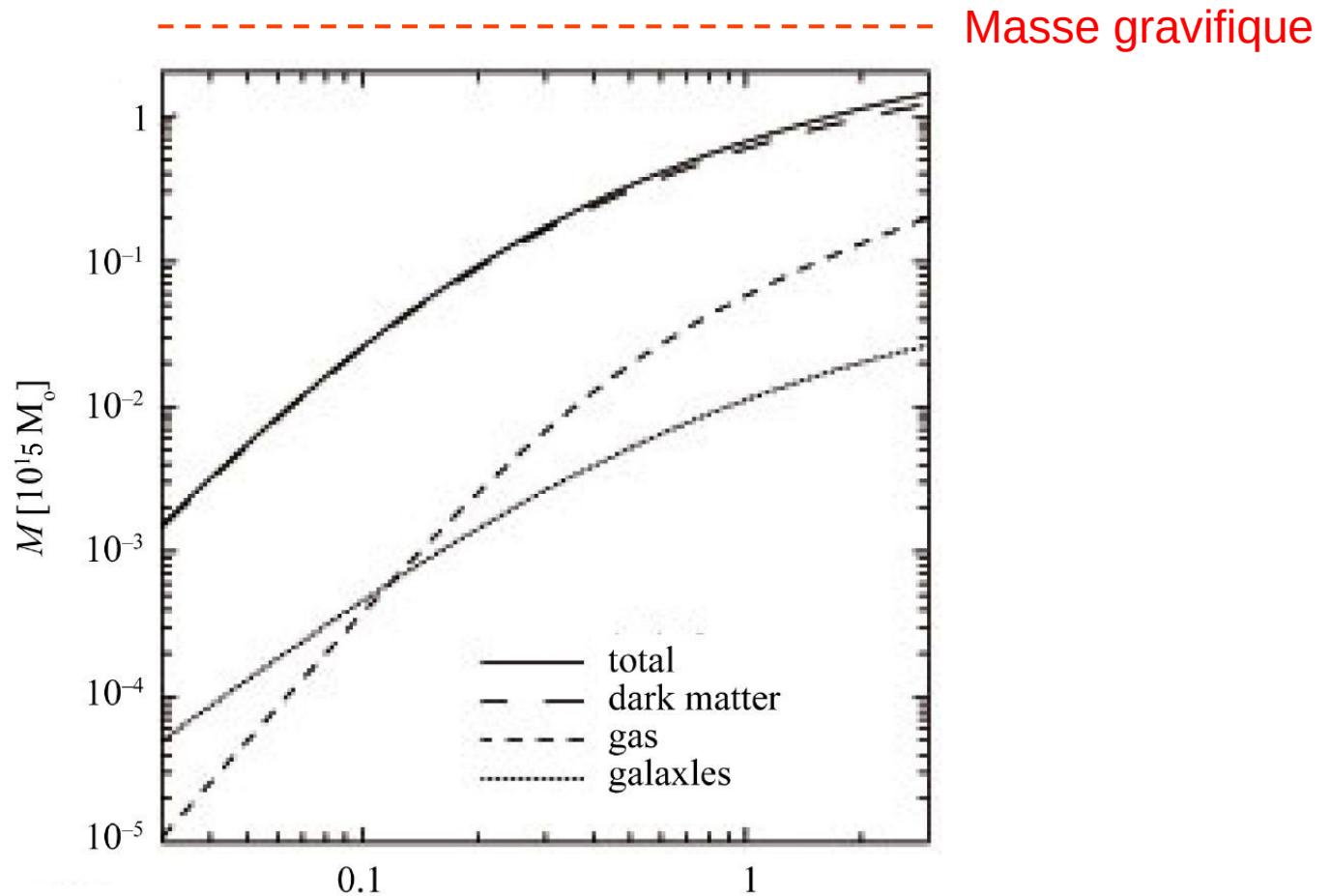
# Équilibre hydrostatique

- Équation des gaz parfaits:  $P = nkT$ 
  - $n$  et  $T$  peuvent être obtenus par rayons X
- Équilibre hydrostatique:

$$\frac{dP}{dr} = \frac{-GM(r)n(r)}{r^2}$$

- On peut donc obtenir  $M(r)$

# Profil de masse

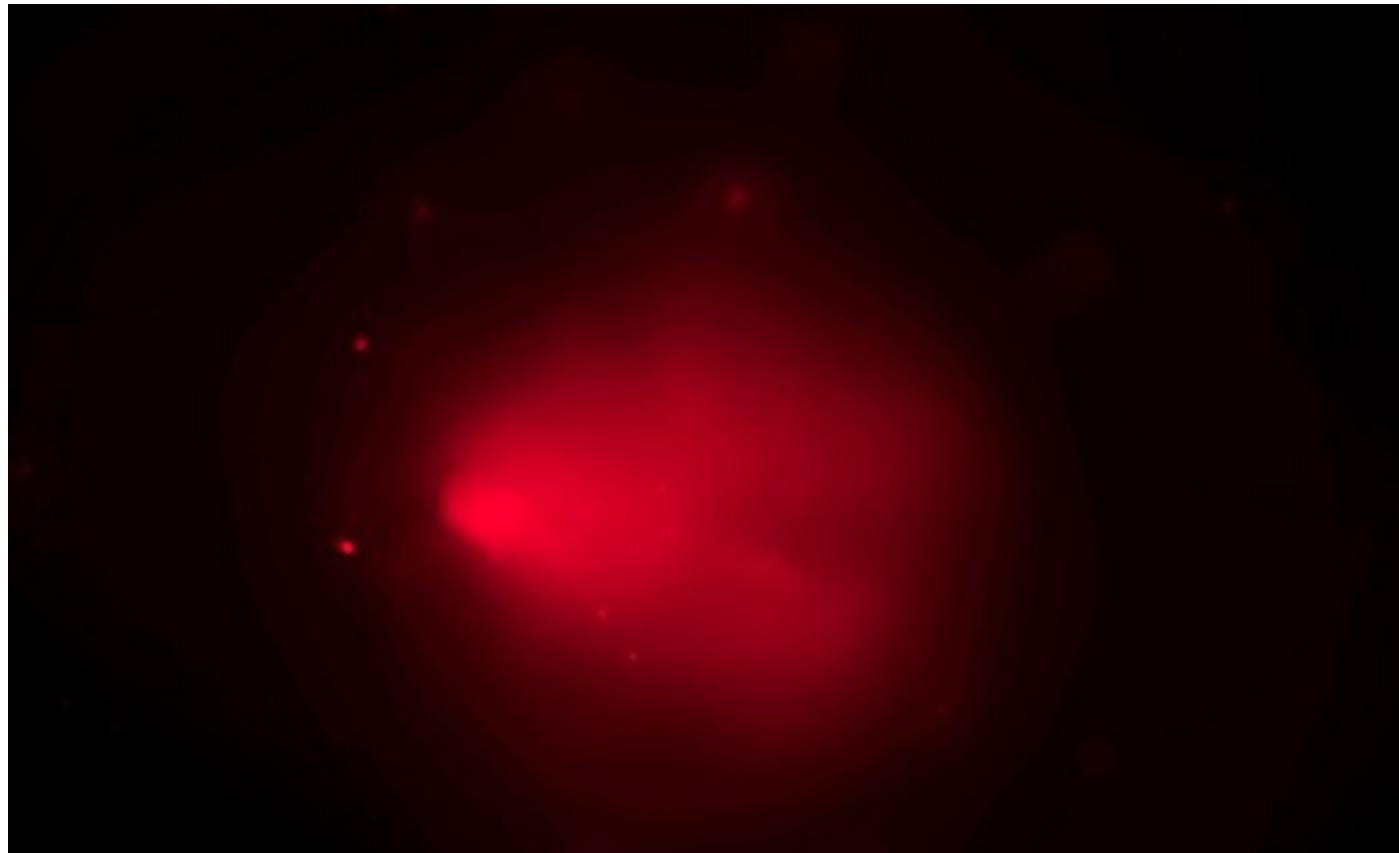


# Bilan de masse

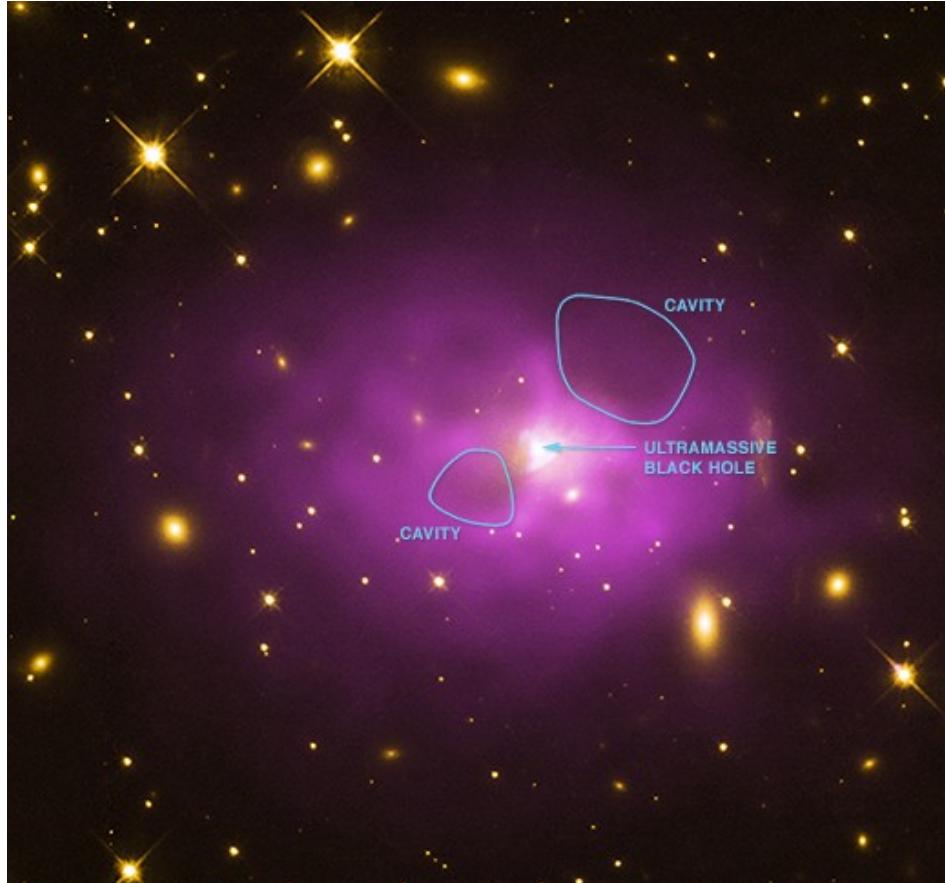
- Bilan de masse de Coma:

- Étoiles :  $3 \cdot 10^{13} M_{\odot}$  2%
- Gas:  $2 \cdot 10^{14} M_{\odot}$  11%
- Matière noire:  $1.3 \cdot 10^{15} M_{\odot}$  87%

# El Gordo (Chandra)



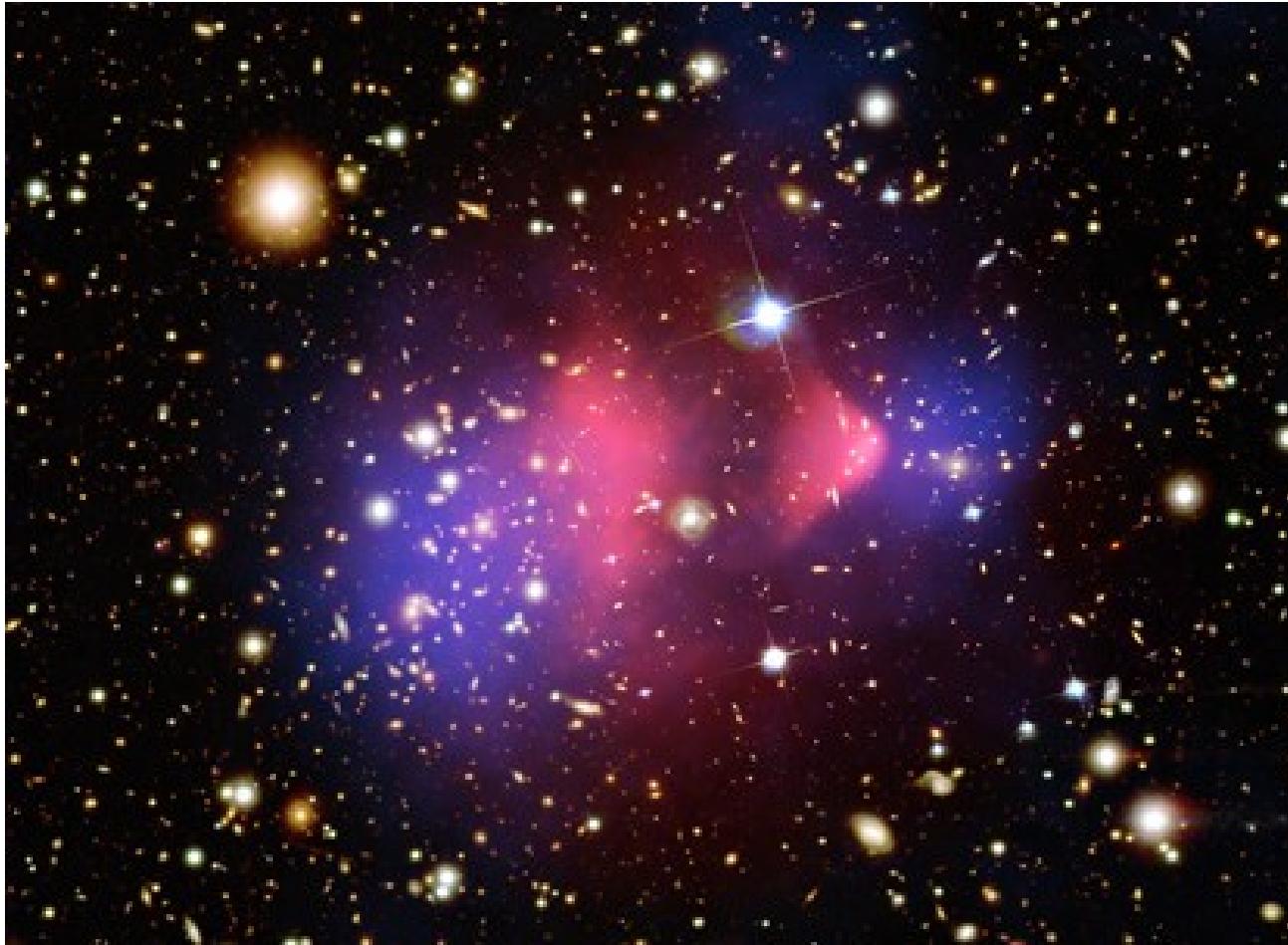
# PKS 0745-19 (Chandra)



# L'amas du Boulet (Chandra+WL)

Gaz

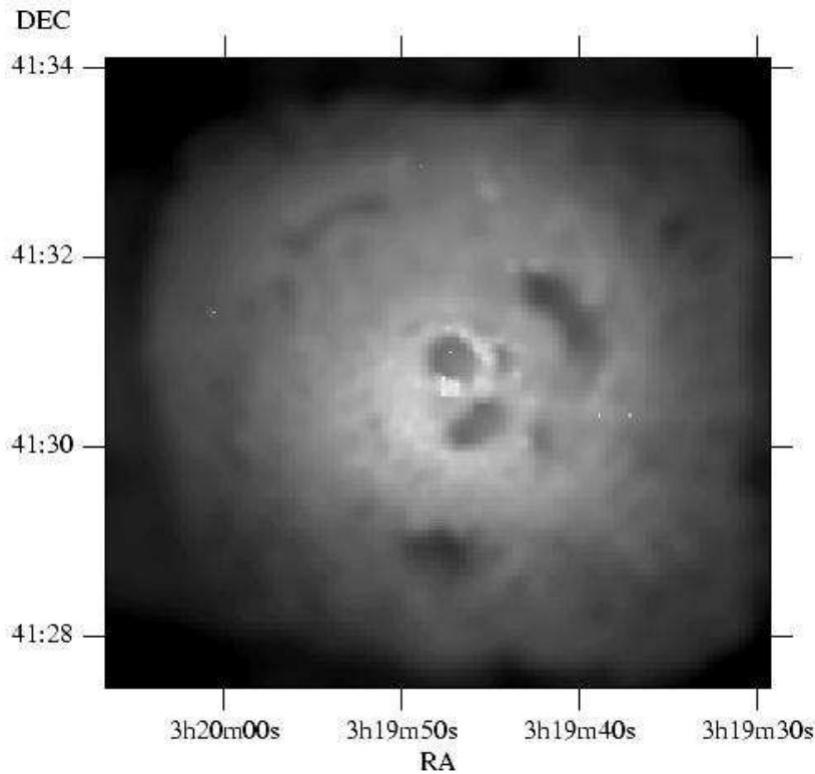
Masse



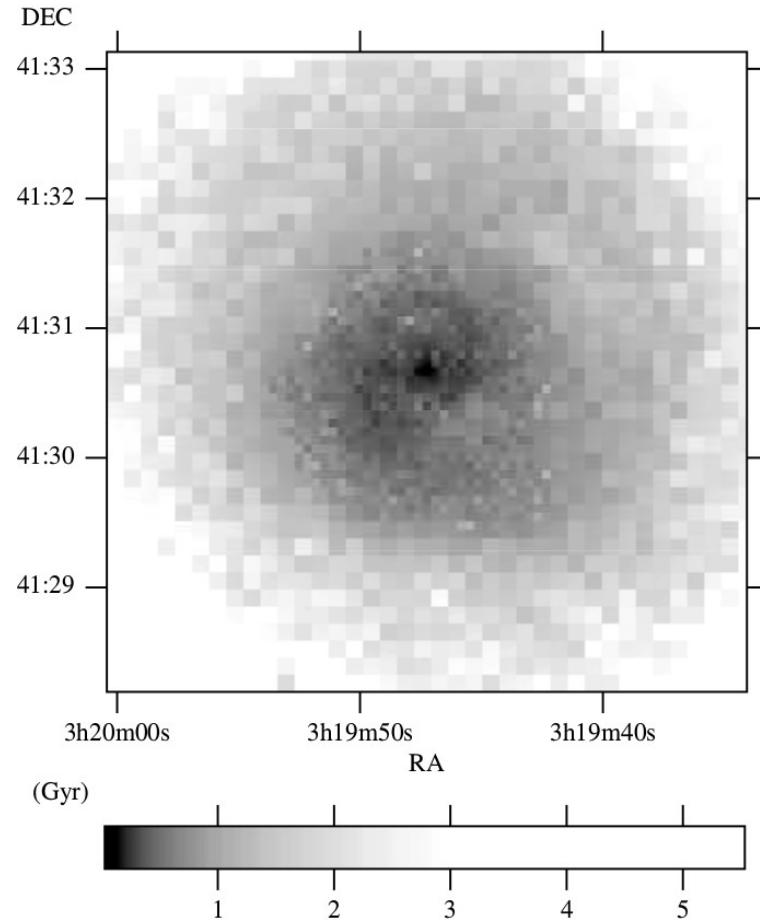
# Temps de refroidissement

- $t = E / L_x \simeq 6000 T^{1/2} n^{-1}$  ans
- $n \sim 10^{-3} \text{ cm}^{-3}$ ,  $T \sim 10^{7-8} \text{ K}$ 
  - $t \sim 10^{10}$  ans
- Au centre de l'amas,  $n \nearrow, T \searrow$  :  $t \ll 10^{10}$  ans
  - Les amas devraient être froids au centre
    - Condensation rapide du gaz
    - Formation d'étoiles intense
  - Mais ce n'est pas observé

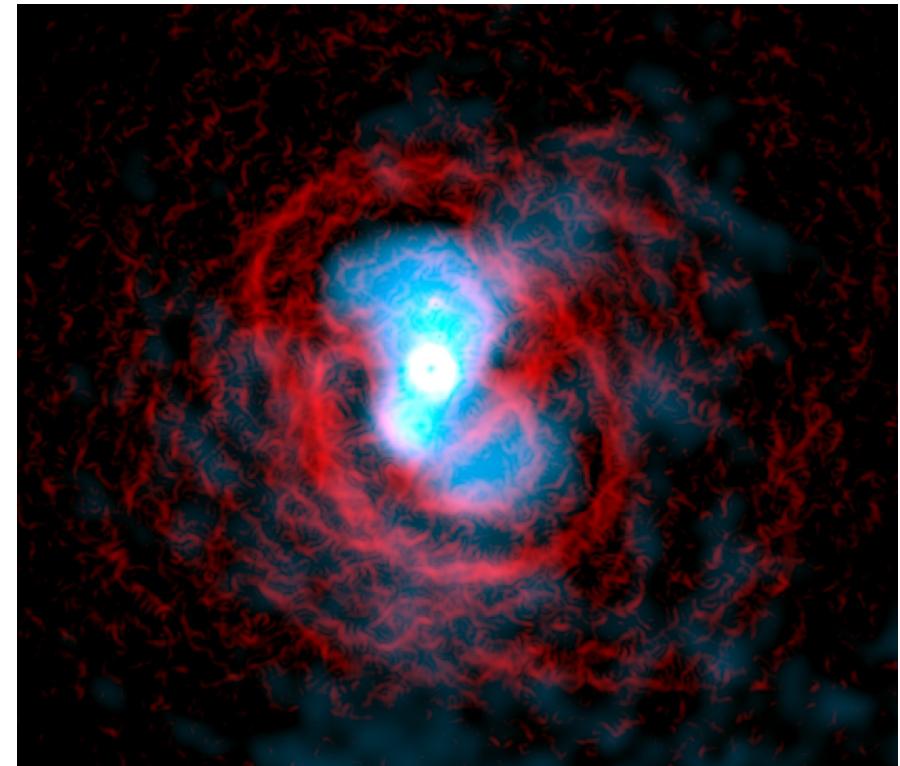
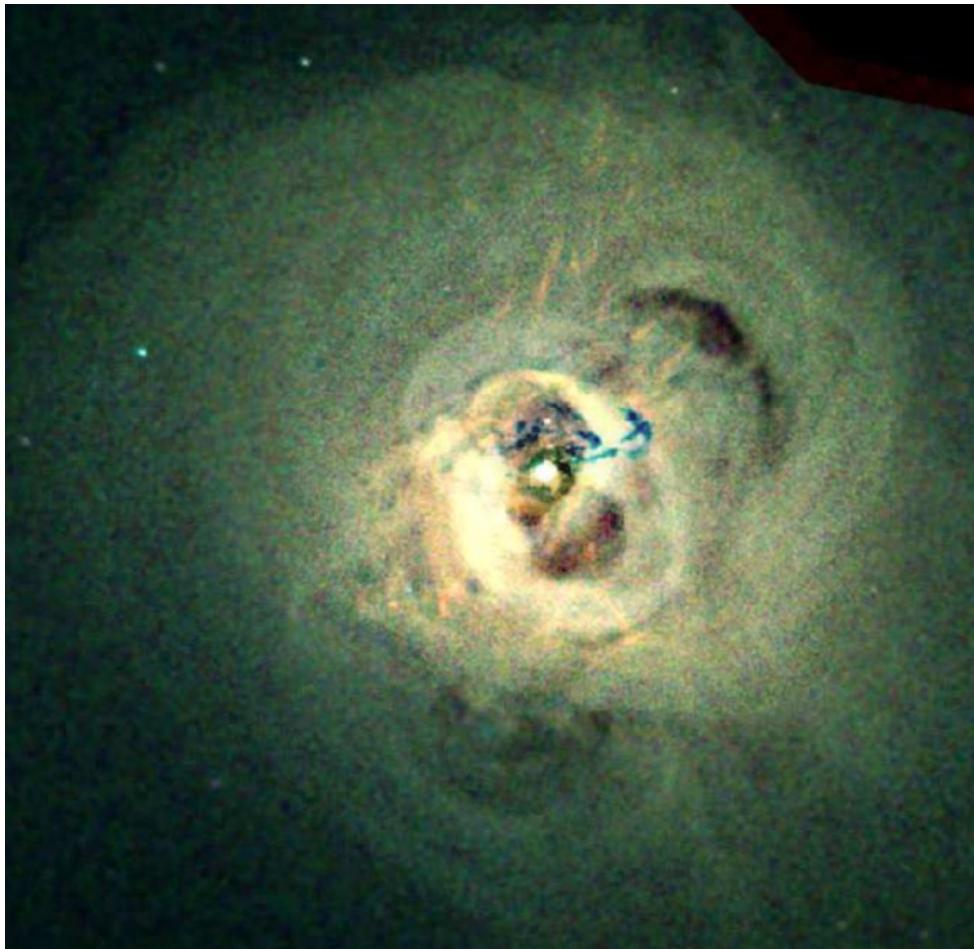
# Temps de refroidissement



Amas de Persée

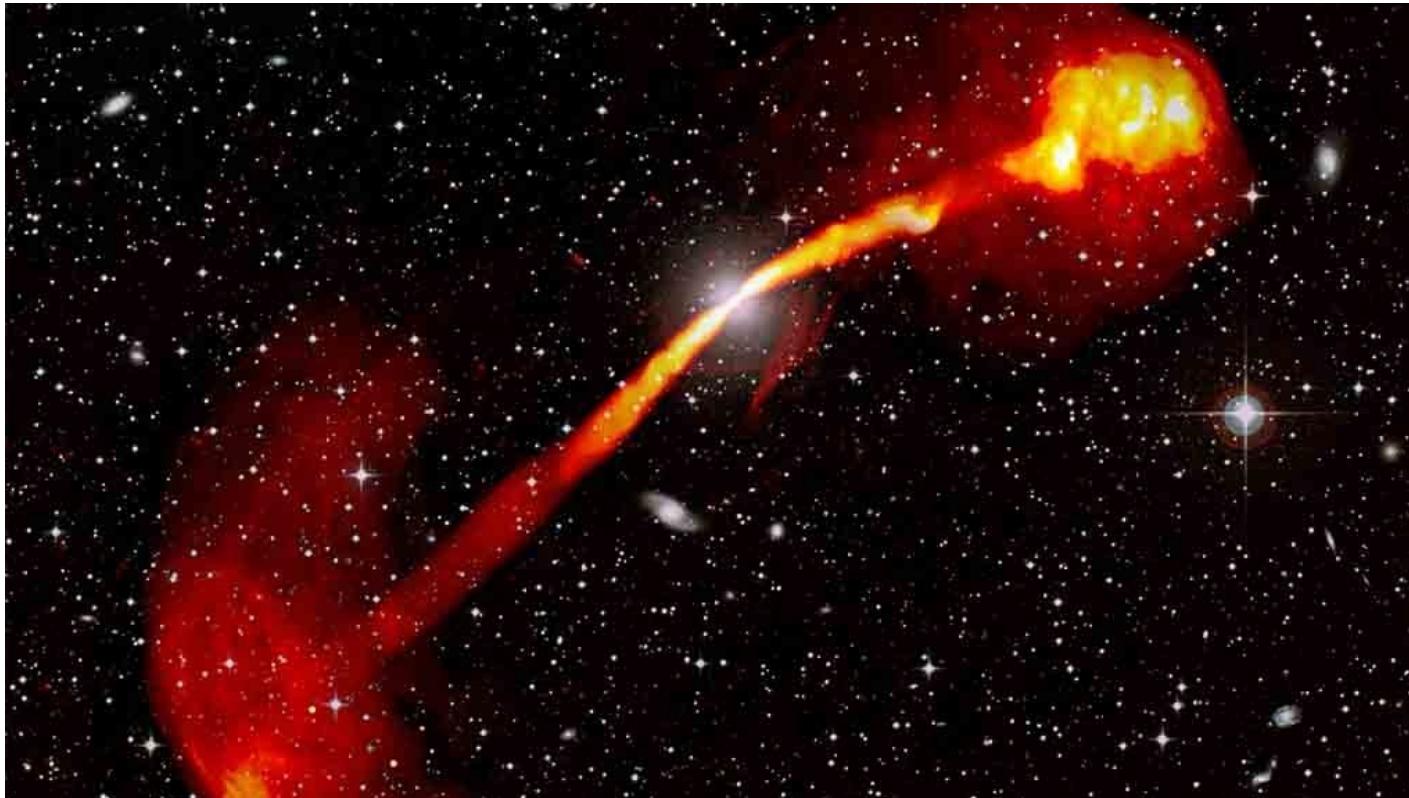


# Injection d'énergie



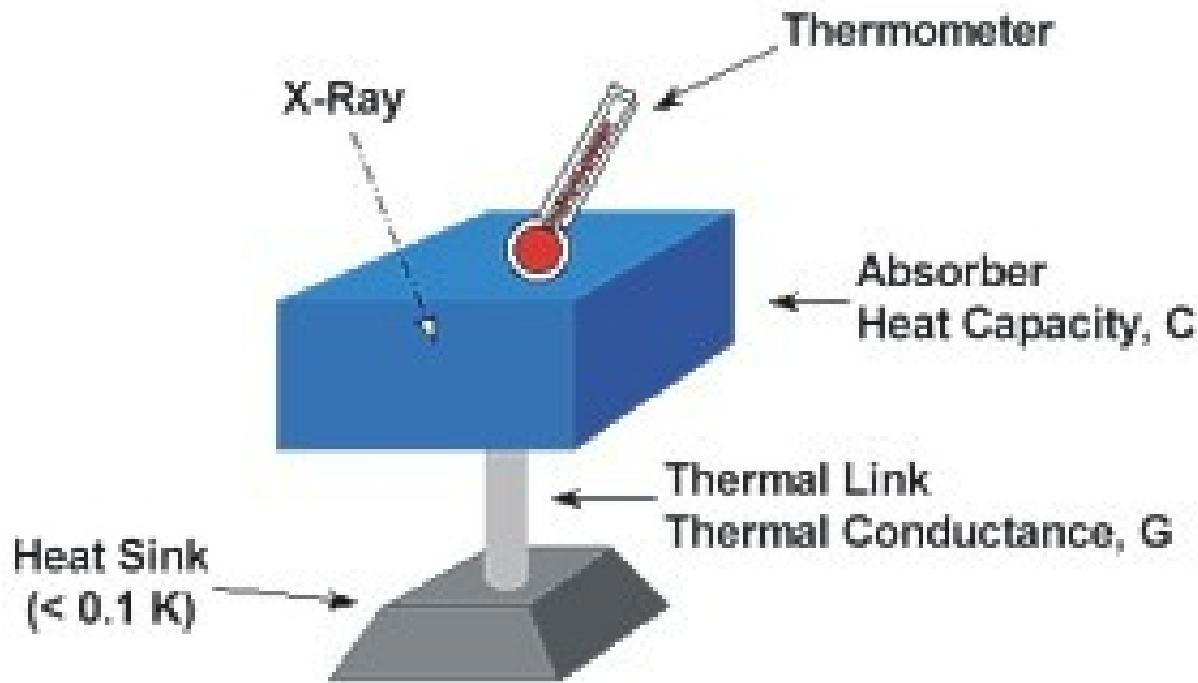
Trou noir supermassif au centre de l'amas

# Jets relativistes de trous noirs

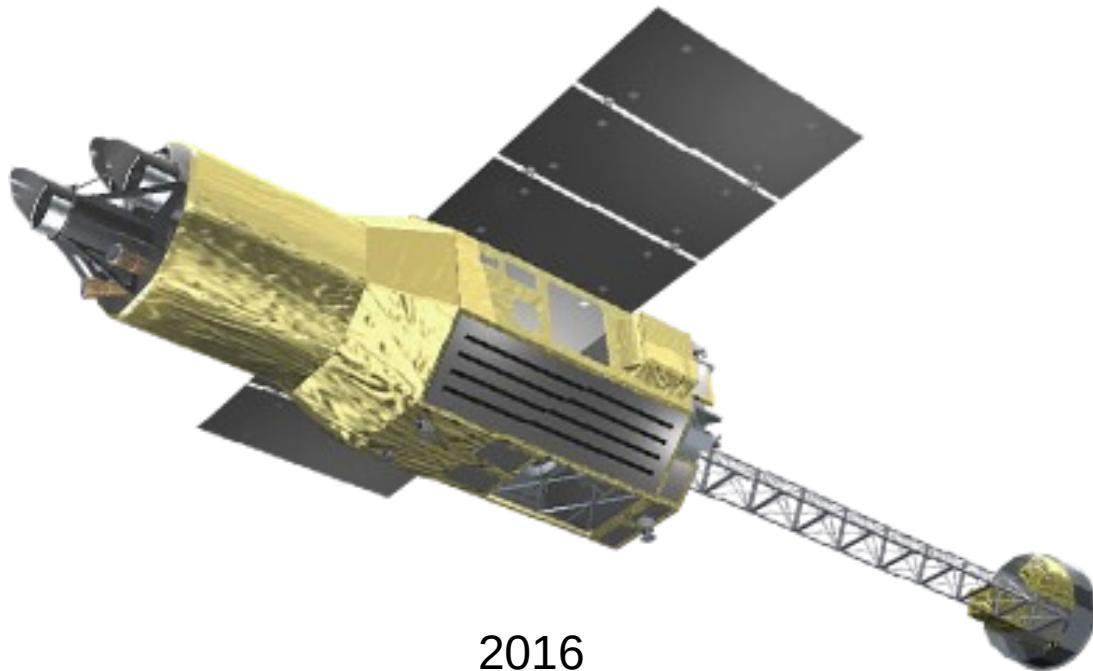


IC 4296

# Micro-calorimètre

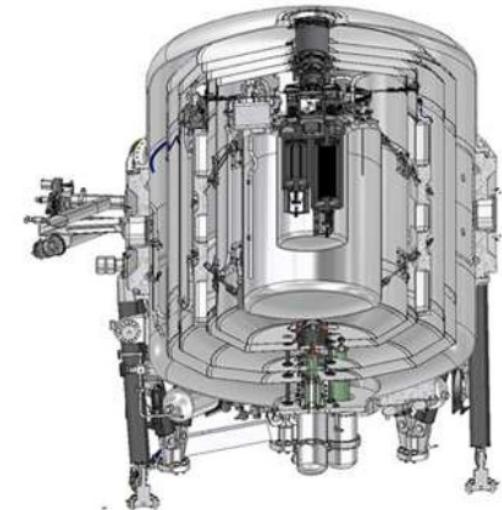
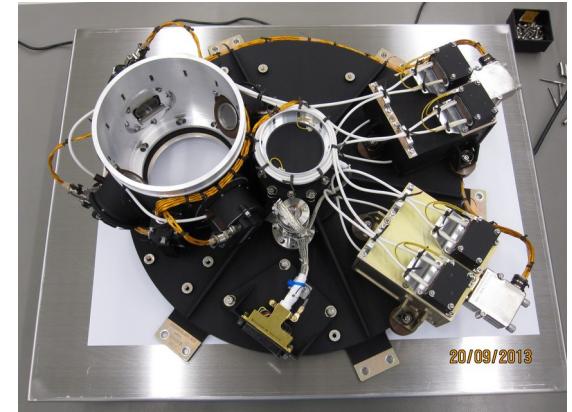


# ASTRO-H/Hitomi

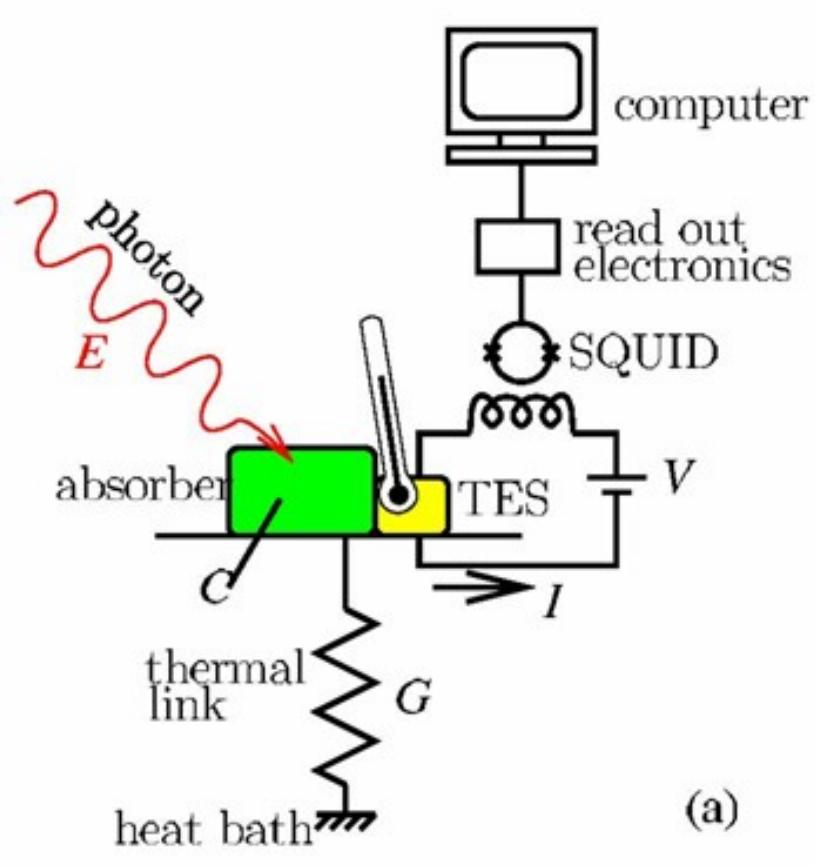


2016

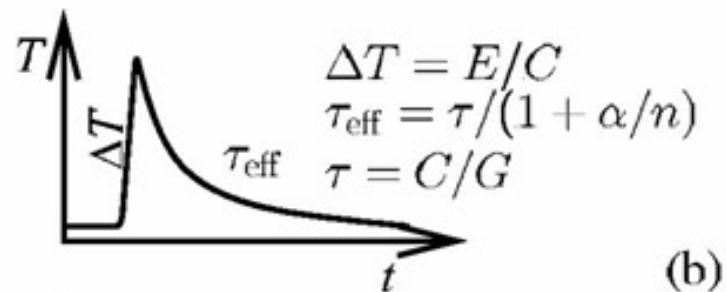
XRISM (2023)



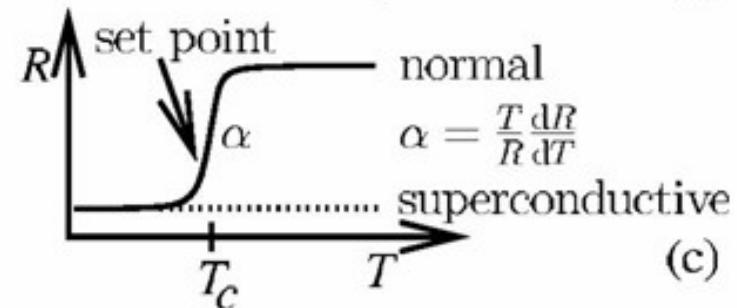
# Transition Edge Sensors



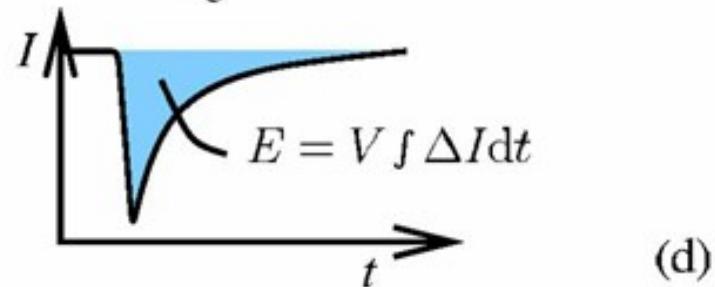
(a)



(b)

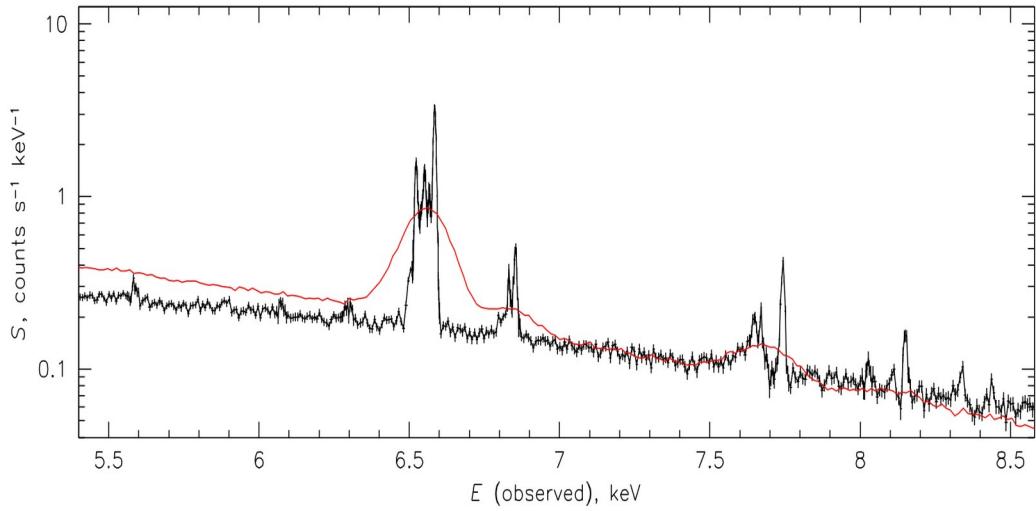
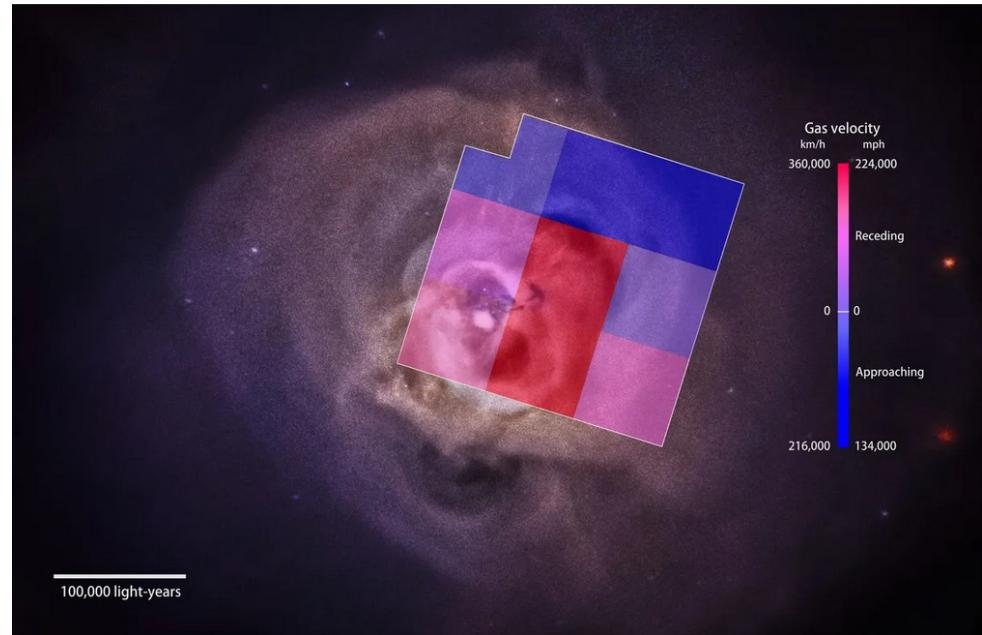


(c)

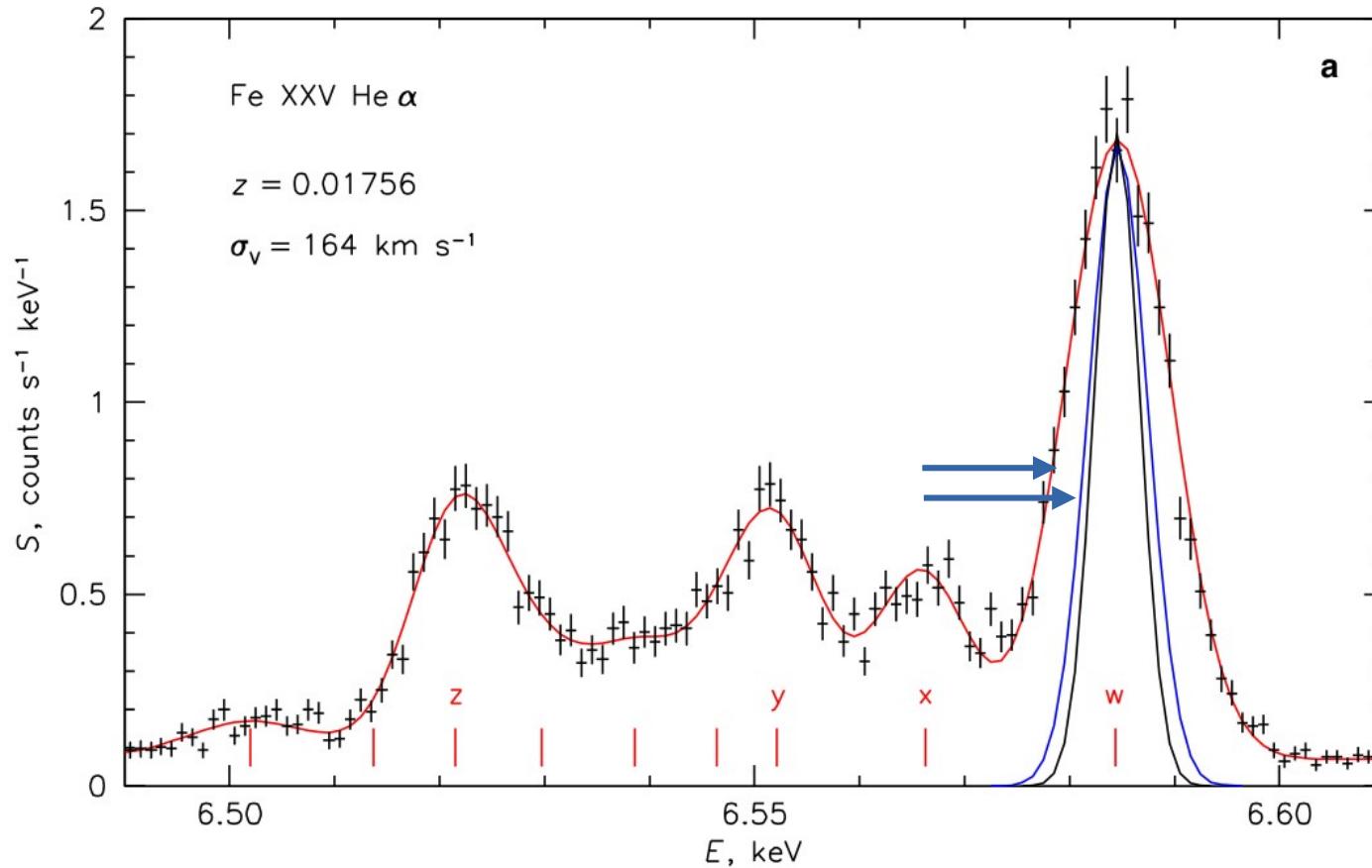


(d)

# L'amas de Persée vu par Hitomi



# L'amas de Persée vu par Hitomi



Présence de turbulence

Indication sur le mécanisme de transfert de l'énergie du trou noir au gaz de l'amas

# Conclusions

- L'astronomie X permet de voir les objets très chaud ( $> 1$  millions de degrés) et les objets où la densité d'énergie est très grande
- Les amas de galaxies sont les objets liés les plus grands de l'Univers, et sont particulièrement bien observables en rayons X
- Ils constituent des sondes essentielles de la composition de notre Univers